Table of Contents

Forward

Dan Patterson wrote the original Linac Rookie Book in 1986. In 1991, the Linac was upgraded from 200 MeV to a 400 MeV accelerator. A group of operators, with Cons Gattuso as editor, wrote a Klystron book in 1997 to cover the changes made to the Linac.

Essentially, not much of the original book by Dan had changed except for the high-energy end of Linac, which starts after tank number five.

I took Dan's book and Cons' book and joined them together, rewriting what had to be rewritten and modifying the language so the book looks like it was writing by a single author.

The book could not have been written without the help of the following people:

Todd Sullivan
Elliott McCrory
Charles Schmidt
Lester Wahl
Robert Florian

Bruce Worthel
April 2004

Chapter 1, Introduction

The FNAL Linac produces pulses of H- ions for injection into the Booster accelerator. Linac uses H- ions due to the nature of its magnet power supply system, which resonates at 15 Hz. The Linac cycle time is $1/15^{th}$ of a second.

The Linac begins with an electrostatic Preaccelerator based on the Cockcroft-Walton design. It produces H- ions with an energy of 750 keV (1 eV = one electron volt).

Accelerator History

In May of 1928, Ernest Walton (who had been trying to produce "fast electrons") realized the indirect method he was using to create fast electrons wasn't going to work. The problem was that the lighter the ion the higher the voltage requirements. He proposed to Sir Ernest Rutherford, then head of Cambridge University's Cavendish Laboratory, a method of accelerating positively charged particles. The proton's high mass eased the need for high voltages at high frequencies.

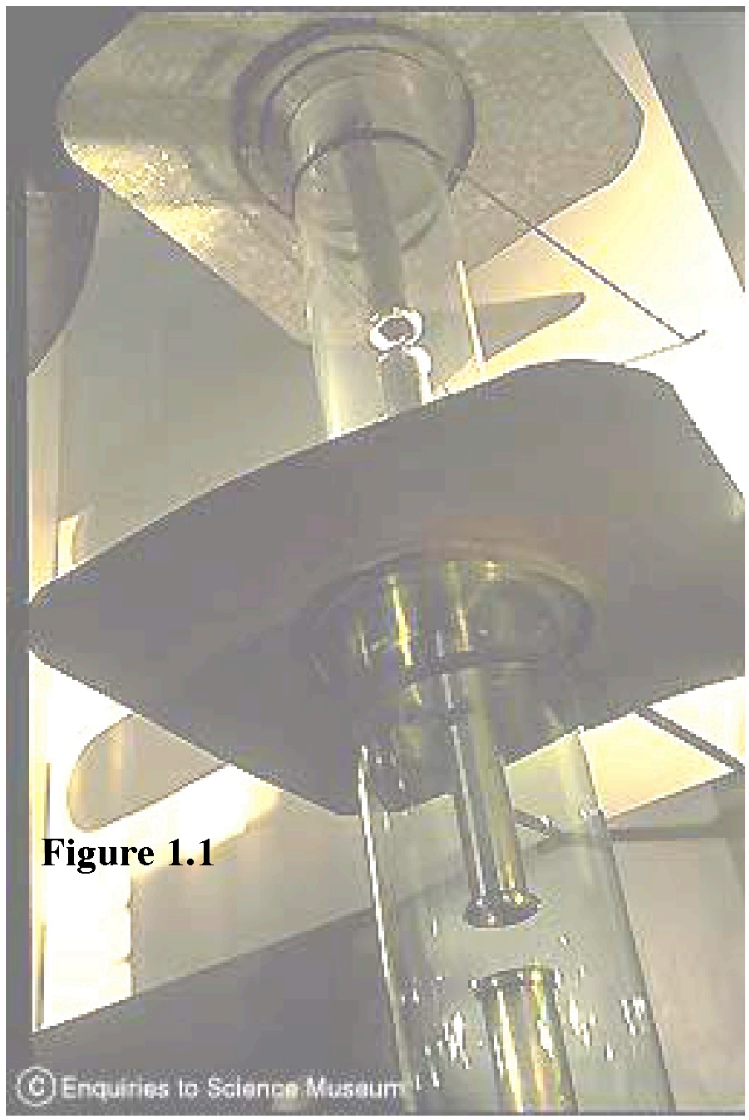
John Cockcroft, using Gamow's theory of tunneling, had also proposed using protons as a means of disintegration. Walton built most of the high voltage and accelerator apparatus while Cockcroft solved many of Walton's engineering problems.

Figure 1.1 is a picture of Cockcroft and Walton's original accelerator.

The Cockcroft-Walton design, completed at Cavendish in 1932, was the first linear accelerator.

Their work on the transmutation of lithium not only corroborated Gamow's theory, but it was the initial verification of Einstein's law concerning the equivalence of mass and Energy, $E=mc^2$.

The larger machines of the 1950s and 60s and high-energy physics as we know it, are a direct result of the fundamental research performed by John Cockcroft and Earnest Walton. As Rutherford said, "it's the first step that counts."



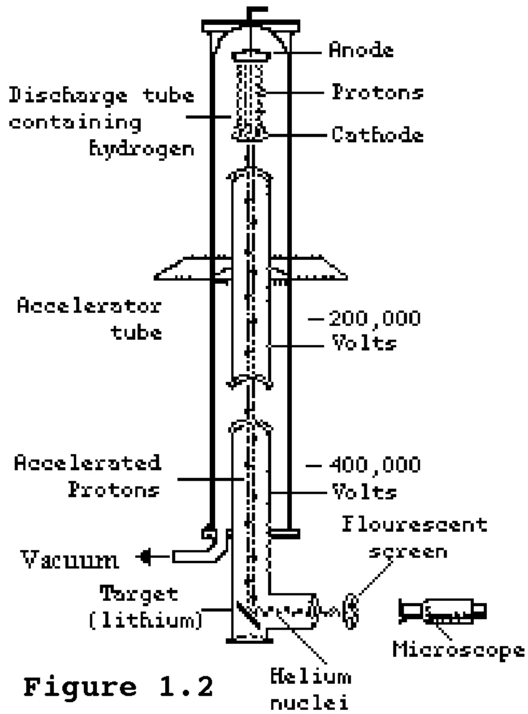


Figure 1.2

Above (figure 1.2) is a diagram of the original Cockcroft-Walton accelerator, Cavendish Laboratory, Cambridge, c. 1932. But the accelerator was not the only significant achievement; the high voltage multiplier was just as important.

In 1951, during Professor I. Waller's presentation of the Nobel Prize in Physics, Waller said:

> The work Cockcroft and Walton was a bold thrust forward into a new domain of research. Great difficulties had to be overcome before they were able to achieve their first successful experiments at the beginning of 1932. By then, they had constructed an apparatus, which, by multiplication and rectification of the voltage from a transformer, could produce a nearly constant voltage of about six hundred thousand volts. They had also constructed a discharge tube in which hydrogen nuclei were accelerated. Causing these particles to strike a lithium layer, Cockcroft and Walton observed that helium nuclei were emitted from lithium. Their interpretation of this phenomenon was that a lithium nucleus into which a hydrogen nucleus has penetrated breaks up into two helium nuclei, which are emitted with high energy, in nearly opposite directions. This interpretation was later fully confirmed.
>
> Thus, for the first time, a nuclear transmutation was produced by means entirely under human control.

Chapter 2, Preaccelerator

The beamline begins with one of the two Cockcroft-Walton style electrostatic Preaccelerators, each capable of producing beams of H- ions at energies up to 750 keV. (1 eV equals one electron volt.) Each Preacc has an H- ion source inside a dome kept at a potential of -750 kV.

Due to this potential, the negative ions accelerate as they pass from their source toward the grounded Preaccelerator wall. A transport line, one from each Preacc, guides the ions from the source to the Linac.

"H-" and "I-" are the names of the two Preaccelerators and their supporting equipment. Each source is virtually identical, only their transport lines differ. Here is a list of *normal* operating parameters for the two sources:

Device	Settings
Arc Supply Voltage	355V
Arc Voltage	-135V
Arc Current	-160A
Cathode Temperature	High (400˚ c)
Source Pressure	20 μT
Magnet Current	8-10A
Extraction Voltage	18-25kV
H- Beam Current	65-70 mA

Haefely

The Emil Haefely Company, CIE AG, Bern, Switzerland, built Fermi's voltage multiplier. The multiplier takes 5 kHz, 75 kV AC and converts it to the -750 kV DC used to initially accelerate the ions. The dome was also built by Haefely, but the term *Haefely* generally refers to just the power supply.

The Haefely is a simple 5-stage diode voltage multiplier. Figure 2.1 shows two stages of the multiplier. The multiplier consists of two stacks of capacitors, linked by an array of diodes. The capacitors on the right side of the diagram are DC and hold a relatively constant charge. The capacitors on the left side of the diagram are coupling capacitors. They hold a charge but also couple the AC from the source at the bottom of the stack.

The AC transformer at the bottom of the stack provides a voltage at point A of V_0sinwt. Point B is ground. During the first part of the cycle, capacitor A-C couples the voltage at point A to point C. When C becomes more positive than B then a charge flows through diode B-C. This charges capacitor A-C to a value of $-V_0$. The voltage at C is the sum of the DC and AC components:

$$-V_0 + V_0 \sin wt$$

On the next half of the cycle, the minimum voltage at C, which measures $-2V_0$, charges capacitor B-D through diode C-D. The voltage at D is held constant at $-2V_0$ because current cannot flow back through the diode.

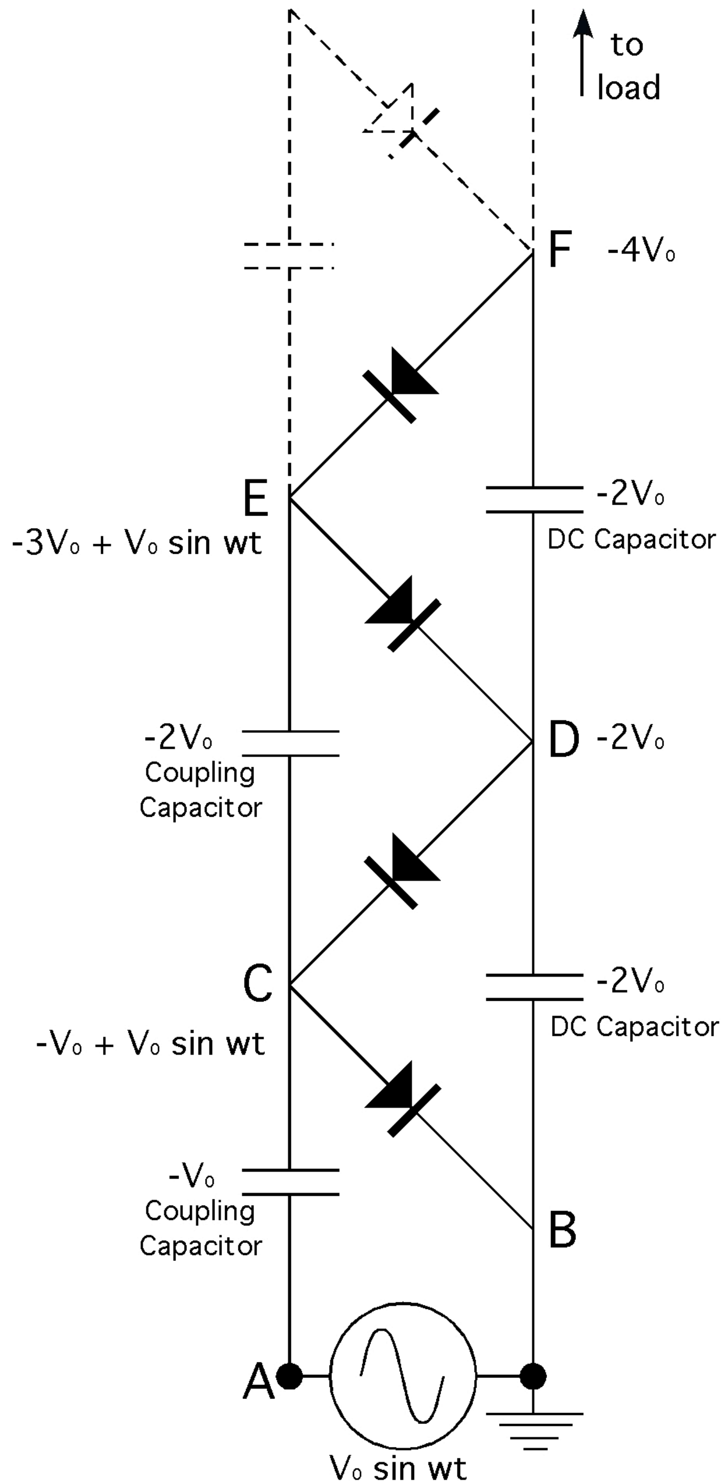


Figure 2.1
Diode Voltage Multiplier

The second stage of the multiplier works the same as the first. The maximum voltage at C is zero; this causes capacitor C-E to charge to $-2V_0$ (the voltage at D), through diode D-E. The voltage at E is then the sum of the voltages on the DC capacitors A-C and C-E plus the AC component (coupled for C to E through capacitor C-E):

$$-V_0 + (-2V_0) + V_0 \sin wt = -3V_0 + V_0 \sin wt$$

The minimum voltage at E ($-4V_0$) charges capacitor D-F through diode E-F to the maximum voltage at E, or $-2V_0$ (remember that the voltage at D is a constant $-2V_0$). The voltage at F is a constant $-4V_0$ because the current cannot flow back through the diode. As you see, each additional stage adds another $-2V_0$.

Figure 2-2 shows a schematic of an actual Haefely. Note that there are two legs with coupling capacitors connected to a common DC leg, also connected to the dome at the top, at the bottom, and to ground through the current-measuring circuitry in the Preacc control room.

The use of two coupling legs reduces the ripple at the output of the multiplier. A separate 75 kV AC transformer drives each coupling leg. The five stages give a maximum output of $5(-2V_0)$ that equals $-10V_0$ or -750 kV DC.

Note: All Haefely drawings outside of this document show diode orientation for positive, not negative high voltage. The diode orientation in figure 2-2 is correct. The actual physical layout of the Haefely power supply is shown in figure 2-3.

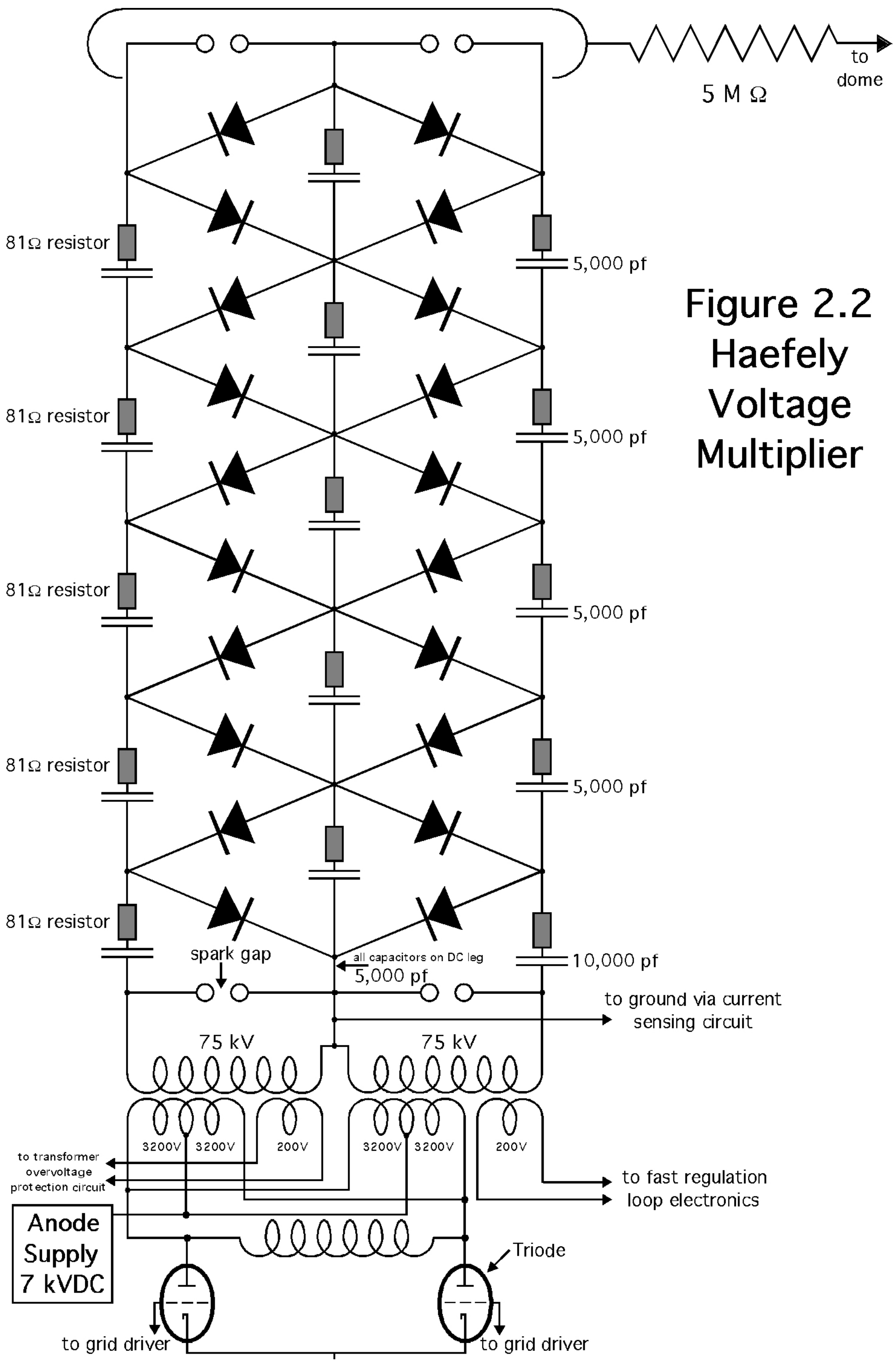
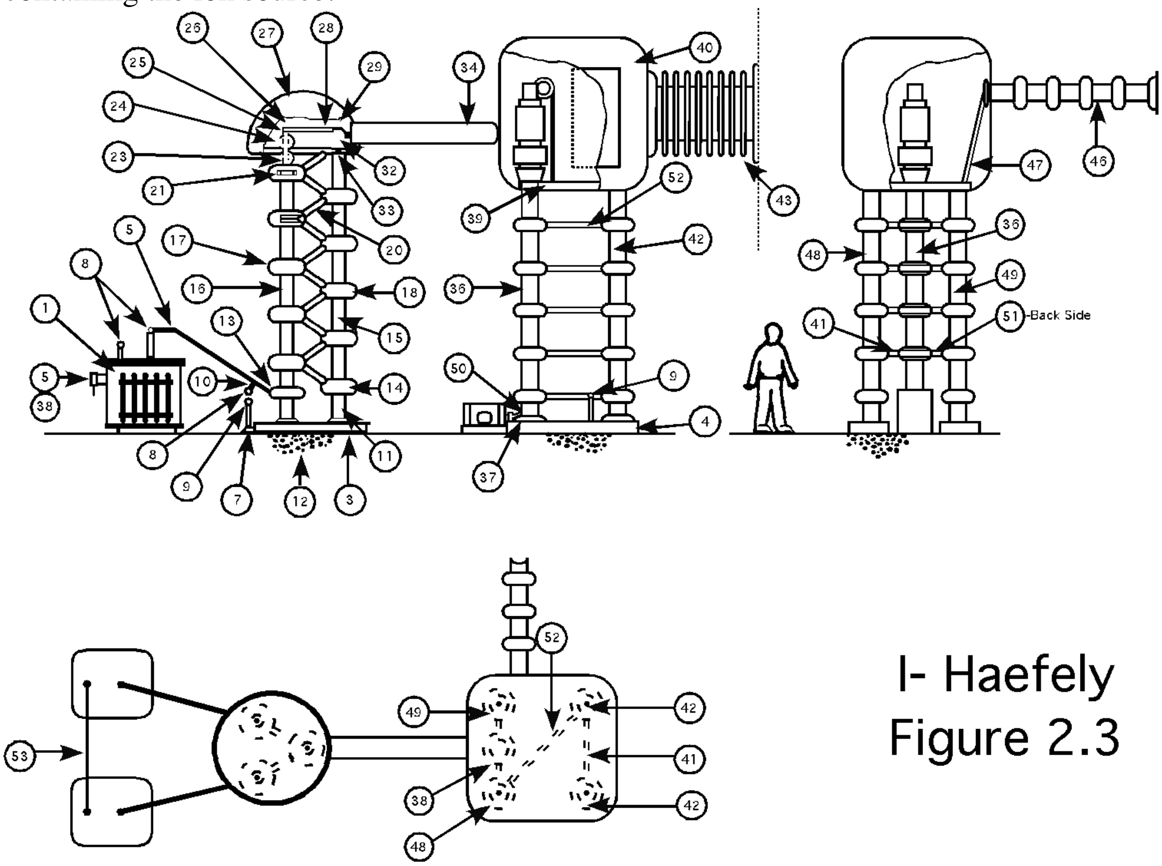


Figure 2.2 Haefely Voltage Multiplier

The two high-voltage transformers each have two 3200 volt primary windings, a 75 kV secondary, and a 200 volt tertiary winding. The 200-volt winding from one transformer provides over voltage protection. The other winding is used as one of the voltage regulation feedback loops, which will be discussed later. Both transformers are located in the Preaccelerator pit, along with the voltage multiplier and the dome containing the ion source.



I- Haefely
Figure 2.3

1. High Voltage Transformer
2.
3. Ground Plate
4. Ground Plate
5. Transformer Connecting Rod
6.
7. Foot
8. Spark-Gap
9. Ball
10. Spacer Bar
11. Support Column
12. Support Column
13. Shield
14. Shield
15. Capacitors
16. Capacitors
17. Shield
18. Shield
19.
20. Rectifier
21. Flange
22.
23. Support
24. Ball
25. Spacer
26. Threaded Rod
27. Shielding Head
28. Support Frame
29. Support Frame
30.
31.
32. Column-Isolator
33. Flange
34. Resistor
35.
36. Insulator
37. Shielding
38. Junction Box
39. High Voltage Table
40. Shielding Head
41. Resistor
42. Column Capacitor
43. Accelerating Column
44. Ball
45. Spark-Gap
46. Potentiometer
47. Brace
48. Steering Potentiometer
49. Cylindrical Isolator
50. Cylindrical Isolator
51. Braces
52. Braces
53. Braces

The output voltage at the top of the multiplying stack is sent to the dome through a 5 MΩ current limiting resistor. A series of bleeder resistors with a total resistance of 4250 MΩ isolates the dome itself from ground. These resistors are contained in one of the five “legs” that support the dome (figure 2-4). The bleeder resistor for the I- system is also in parallel with a series of capacitors and resistors that were part of the bouncer circuit. The increased capacitance to ground of the I- system makes the voltage droop during beam time only 3-4 kV, where it is about 7 kV for H-. Neither of these droops is significant for operating purposes as long as the droops are consistent.

A metering resistor, which runs from the side of the dome to the pit wall, monitors the dome's potential via a voltage divider. This metering resistor consists of 600 precision resistors in series with capacitors and wired together in five elements of 425

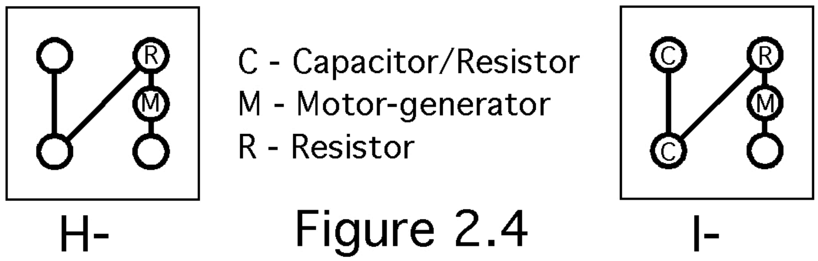


Figure 2.4
Dome Leg Assignments

MΩ each for a total resistance of 2125 MΩ. (There was an oil circulating system for cooling this resistor, but it was never needed.) The resistor terminates at the pit wall in a small aluminum box containing capacitors and resistors, which completes the voltage divider and drives the analog HV meter on the Haefely control panel as well as the voltage regulation loop electronics.

Two feedback loops, which act to keep the voltage within a tolerance of 0.25% at –750kV, handle the dome's high voltage regulation. A slow feedback loop corrects for fluctuations up to a frequency of about 1 Hz; a fast loop handles frequencies up to about 15 Hz. The slow loop actually compares the measured voltage to the command voltage to produce an error signal. The fast loop looks at the 200-volt tertiary winding in one of the HV transformers and samples successive peaks in the voltage; this sampling is compared with the command voltage to create a second error signal. The two error signals are then summed together along with the command voltage to drive the transformer.

The slow loop begins at the voltage divider. The monitor/control module in the Haefely control racks tracks the output voltage (about 4.5776 V at –750 kV) via a twinax BNC. The voltage is sampled and held while a 14-bit A/D digitizes it. The digitized monitor voltage is then fed through 14 optical isolators (light links) to isolate the input circuitry from ground and reduce noise due to ground loops. The signal then travels to a latching register that is sampled by the computer to produce the analog readback in the main control room. A second path leads to the data selector, which takes the digitized monitor and command voltages and sends them to the LED displays on the front of the module. The digitized command voltage comes from a 14-bit binary command generator, which is in turn fed by either a computer command or local knob input.

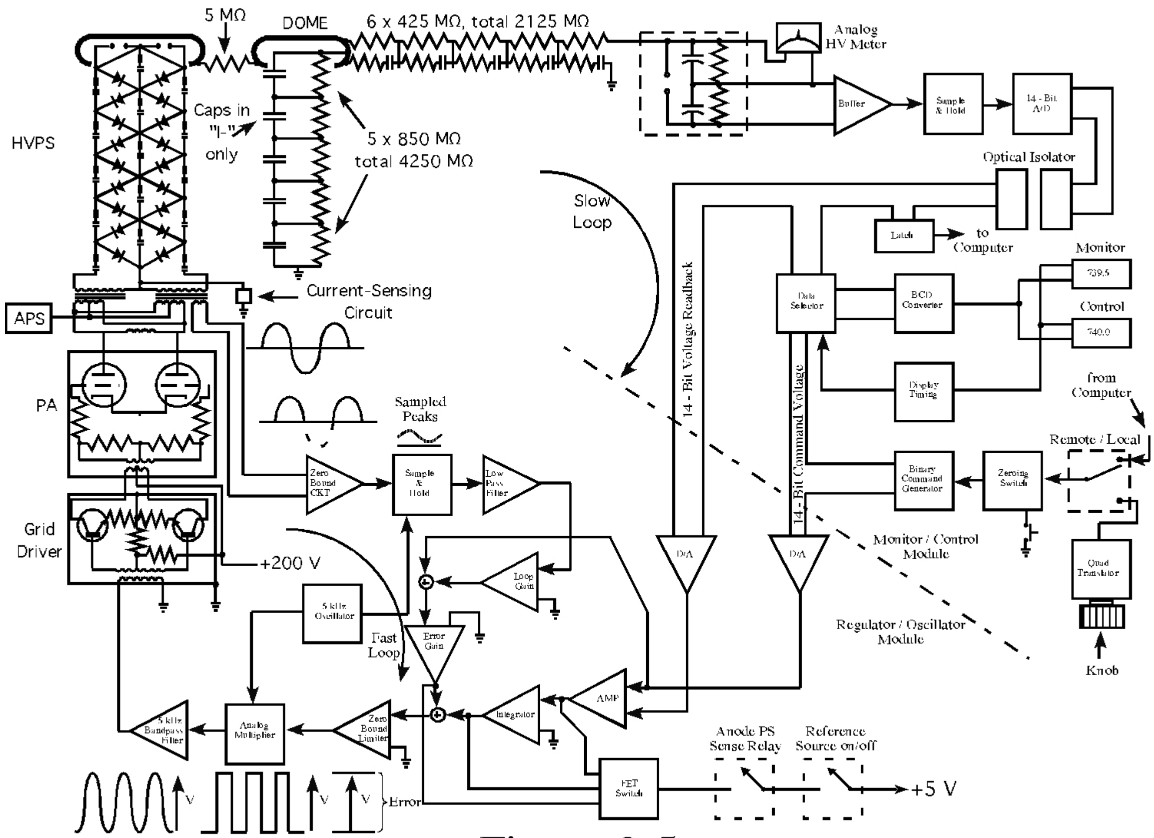
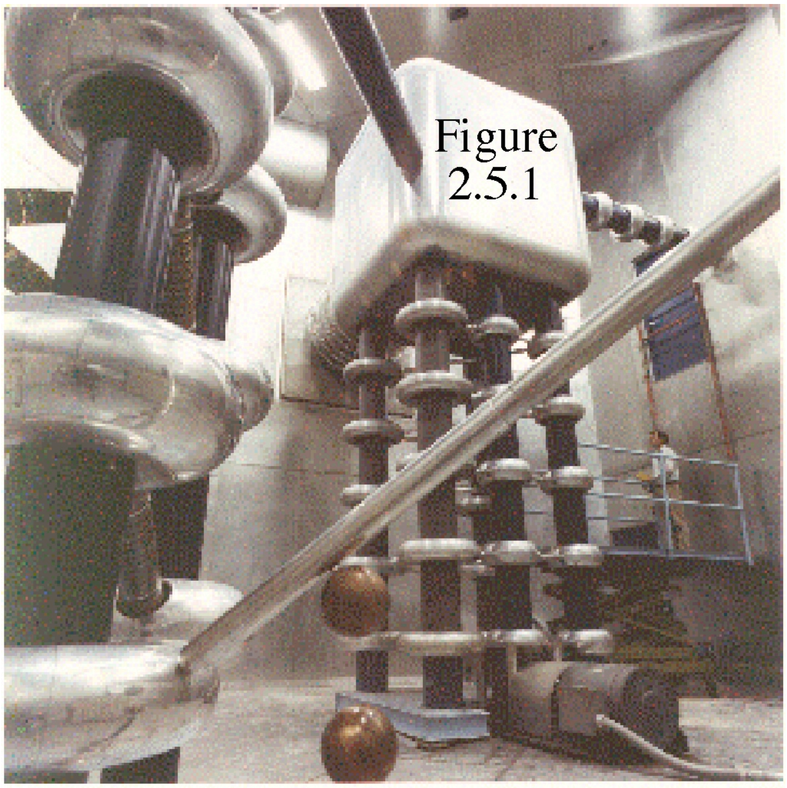


Figure 2.5
Haefely Monitoring and Regulation Systems

The digitized monitor and command voltages are also sent via the crate wiring to the adjacent regulator/oscillator module. There the signals are converted back to analog voltages and fed into a differential amplifier to create an error signal, which is then integrated and summed with the output of the fast regulation loop. To protect the power amplifier tubes from being turned on with no drive signal, the anode power supply on/off status and the reference source on/off switch controls a FET switch that zeroes the slow loop error signal and disconnects the fast loop input. This reduces the HV power supply output to zero.

The fast loop begins at the 200 V winding in one of the HV transformers. A zero-bound circuit removes the negative portions of the 5 kHz sinusoidal output signal. A sample and hold signal, synchronized to a 5 kHz, samples the peak voltages that are then fed through a low-pass filter to roll off all frequencies above 15 Hz. This signal represents the variation in the drive voltage of the transformer. It is summed with the command voltage (from the same A/D as the slow loop) and then with the slow loop error. A zero-bound limiter insures that the resultant drive amplitude lies between zero and some predetermined maximum voltage. An analog multiplier modulates the drive signal to produce a 5 kHz square wave, which then is smoothed by a fourth-order, multiple feedback bandpass filter. The resultant sine wave then drives the grid driver amplifier that in turn modulates the voltage on the grids of two triodes, which comprise the power amplifier that drives the transformer primary windings. For the I- system, these tubes are located in racks in the Preaccelerator control room, next to the I- anode supply. The power amplifier and anode supply for the H- system are cleverly hidden beneath the stairs leading to the second floor of the Preacc annex.



The voltage multiplier (far left), and dome installation (center) are shown in figure 2.5.1 and in the hand drawing, figure 2.5. The multiplying stack is rather impressive, being just short of 19 feet tall. Plexiglas tubes filled with a synthetic silicon fluid encase diodes and the corona rings cover capacitors. The five legs of the dome consist of G-10 tubes (a glass epoxy insulator) encircled by corona rings at the points where the segments meet. In the H- system, three legs are hollow and the fourth contains the 4250 MΩ bleeder resistor. The I- source is the same except for the bouncer circuit capacitors that remain in the two otherwise hollow legs, linked by horizontal-running resistors.

The dome contains the power supplies, vacuum pumps, and microcomputer necessary to run the ion source. At a potential of –750 kV, a moment's thought will convince you that running power cables to the dome is inadvisable. A 15 kW generator (more correctly, an alternator) located in the dome supplies the 208 and 120 VAC for the dome. A rotating G-10 shaft runs up the fifth leg of the dome and drives the generator. A 25 kW electric motor located on the floor of the Preaccelerator pit drives the shaft. Turning off the motor-generator kills all power to the dome, and even if quickly restored it will upset normal source operation for a time.

A Plexiglas tube runs along the top of the metering resistor between the dome and the pit wall. This tube carries fiber-optic cables used for communicating with the microprocessor in the dome and for video signals. A nitrogen gas line supplies pressure to operate a vacuum valve in the dome.

Haefely Operation

The Haefely HVPS is controllable either through the local control panels or through the computer system. The computer system communicates with the Haefely by way of a shielded, twisted pair of wires (MIL-STD-1553B digital bus) that run from the local microcomputer to interface cards mounted in a Eurobus crate. This small crate is located in the rack containing the Haefely control relays at the ground stations.

Figure 2.6 is a sketch of the control panels for the H- Haefely. At the upper left is a keyswitch labeled MAINS; turning this key clockwise removes power from the upper control panel, PA filaments, and motor-generator. Pressing the enormous orange HAEFELY EMERGENCY button on the lower panel can cause the same result. But don't remove power if the source is in use, as it will shut the anode supply off for five minutes and the source for even longer.

The I- control panel is only slightly different from the H-. The I- has a "Local/Remote" knob instead of a switch, and "Elevator Up/Down" status lights replace the "Q4 Center Off/On" lights.

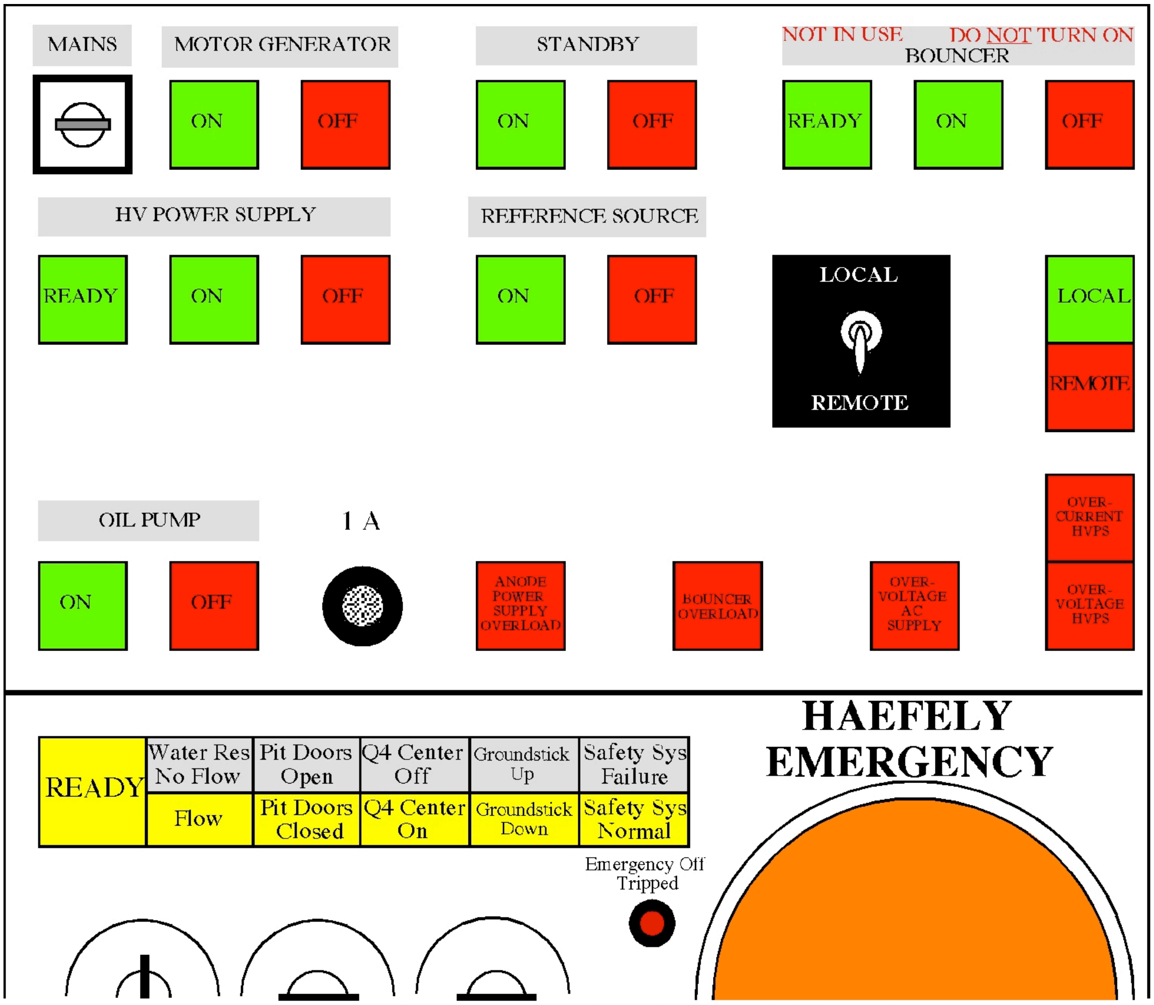


Figure 2.6: Haefely Control Panel

♦ The following is an explanation of each Haefely switch and status light:

The **MOTOR GENERATOR ON/OFF** switches control the power to the 25 kW motor that supplies power to the dome. (You'd better have a very good reason ready before turning this off!)

STANDBY ON/OFF controls the PA tube's filament supply. When turned on, a timer prevents the anode supply from coming on for five minutes. This time is activated whether or not the filaments are cold. It is not necessary to turn the filaments off unless there is work being done on the tubes themselves.

The **BOUNCER** switches aren't connected to anything.

HV POWER SUPPLY ON/OFF controls the anode supply for the PA tubes. It must be on before the reference source will turn on (this is done to protect the tubes).

READY is the sum of anode power supply and safety system interlocks, which will be described shortly.

REFERENCE SOURCE OFF zeroes the HV transformer drive signal in the monitor/control module. This causes the output of the HV transformer to go to zero, and the dome HV will bleed down through the 4250 MΩ resistor. The anode power supply is cycled on and off in this state; it must be off before an access to the Preaccelerator pit is made.

The **LOCAL/REMOTE** switch disables/enables control through the computer system. All functions are available remotely.

OIL PUMP ON/OFF controls nothing, but it must be on so that other interlocks in the Haefely control circuitry will permit the supply to be turned on.

- ♦ The following anode power supply interlocks must be made up before **HV POWER SUPPLY READY** (anode power supply ready) will be lit:

NO COOLING is the sum of water flow and temperature switches on the PA water system, as well as PA cooling fan power. The I- system also has a water pressure switch.

ANODE POWER SUPPLY OVERLOADED is an overvoltage trip of (what else) the anode supply.

BOUNCER OVERLOADED is not connected.

- ♦ The next three interlocks will trip off the reference source, but leave the HVPS on:

OVERVOLTAGE AC SUPPLY is an overvoltage trip of the HV transformer. This circuit looks at the “other” 200 V transformer winding.

OVERVOLTAGE HVPS is an overvoltage trip of the voltage multiplier stack and dome. It is simply the trip point on the analog voltage meter located in the panel above the upper control panel.

OVERCURRENT HVPS is sensed by a Thyratron circuit that looks at the current actually being drawn by the voltage multiplier. This circuit is electrically in the path from the base of the DC leg of the multiplier to ground. It is physically located in a box below the metering resistor voltage divider.

- ♦ The following safety interlocks must be made up before **HV POWER SUPPLY READY** (anode power supply ready) will be lit:

The **DOOR OPEN** indications (**NORTH** and **SOUTH** for H-, **SIDE** and **PIT** for I-) are connected to microswitches on the pit doors. The NORTH DOOR OPEN circuit for the H- system is also connected to a storage room door that is only accessible from inside the pit.

Q4 CENTER OFF (H- only) refers to the center element of the first quadrupole triplet in the H- 750 keV transport line. If this element is off, the H- Haefely is turned off to prevent unacceptable levels of X-ray radiation in the H- 750 keV transport line area, which would be caused by high-energy electrons striking the 45° bending magnet.

ELEVATOR UP (I- only) indicates that the elevator in the I- pit is not all the way down. The H- elevator is portable and is not interlocked.

GRNDSTICK UP (groundstick up) indicates that the groundstick in the pit is not stored in its proper place. For the I- minus system, this is across the lower pit door entrance. For H-, it is across the bottom of the pit stairway.

SAFETY SYS. FAILURE indicates that the Linac safety system is down and that the beam stop in the downstream 750 keV transport line has not closed (OPBULL 717) (a critical device failure). The Haefelys for both H- and I- systems are then automatically shut down to prevent beam from leaving the Preaccelerators.

- There are also interlocked keys for each system (two for I-, three for H-) that open the appropriate pit doors. These keys must be in their slots and turned clockwise in order for the **READY** sum to be made up.

The procedure to access the I- or H- dome (OPBULL 486) requires two operators and they must proceed as follows:

- Turn off the reference source and the high voltage power supply.
- Pull one of the keys on the lower panel (not the key on the upper panel!) and use it to open the lower (north) pit door.
- Across the doorway (across the bottom of the stairs) is a groundstick.
- Use the groundstick to ground the HV transformer and the multiplying stack, working from the bottom up. Ground the top of the multiplying stack and the dome.
- Hang the groundstick from the top of the multiplying stack. A second groundstick may be hung from the dome. (This second stick is not interlocked.)
- Raise the elevator to the up position.
- Take a second key from the lower panel and the key to the dome, which is hanging on the Haefely control rack. Use the key from the lower panel to open the upper (south) pit door.

To leave the dome:

- Close the dome door and upper (south) pit door.
- Go back through the lower (north) pit door and lower the elevator all the way (the H- elevator isn't interlocked, but the door to the storage room is. Make sure that it is closed.).
- Remove the groundsticks and place the one across the entrance back in its holder, making sure that is makes contact with both microswitches.
- Close the lower (north) door and return the keys to the lower panel in the Haefely control rack.
- Turn on the HVPS, and finally, the reference source.

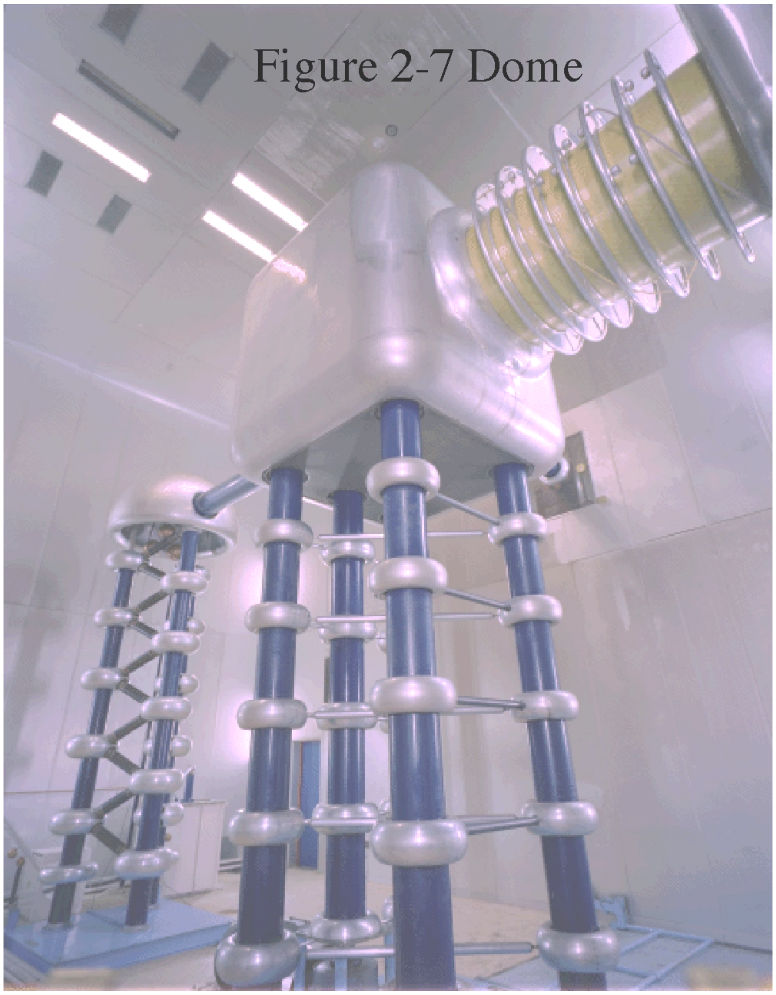


Figure 2-7 Dome

If the Haefely won't maintain full voltage, check the current being drawn by the supply (normally 1-3mA) and the conductivity in the water system for the water resistors. If the conductivity is poor (greater that 1.1 μmho/cm), the Haefely will draw more current and may trip off before it reaches full voltage.

Of course, it is a good idea to check the pit itself in these situations and look for major component failures or water leaks.

Sources

The ion sources are the direct-extraction magnetron type, conceived at Novosibirsk around 1972 and developed at Brookhaven and FNAL for use in particle accelerators. The first operational use of the magnetron negative-ion source at FNAL was in 1978. Magnetrons have supplanted the duoplasmatron type source that produced protons and is still encountered in older documentation.

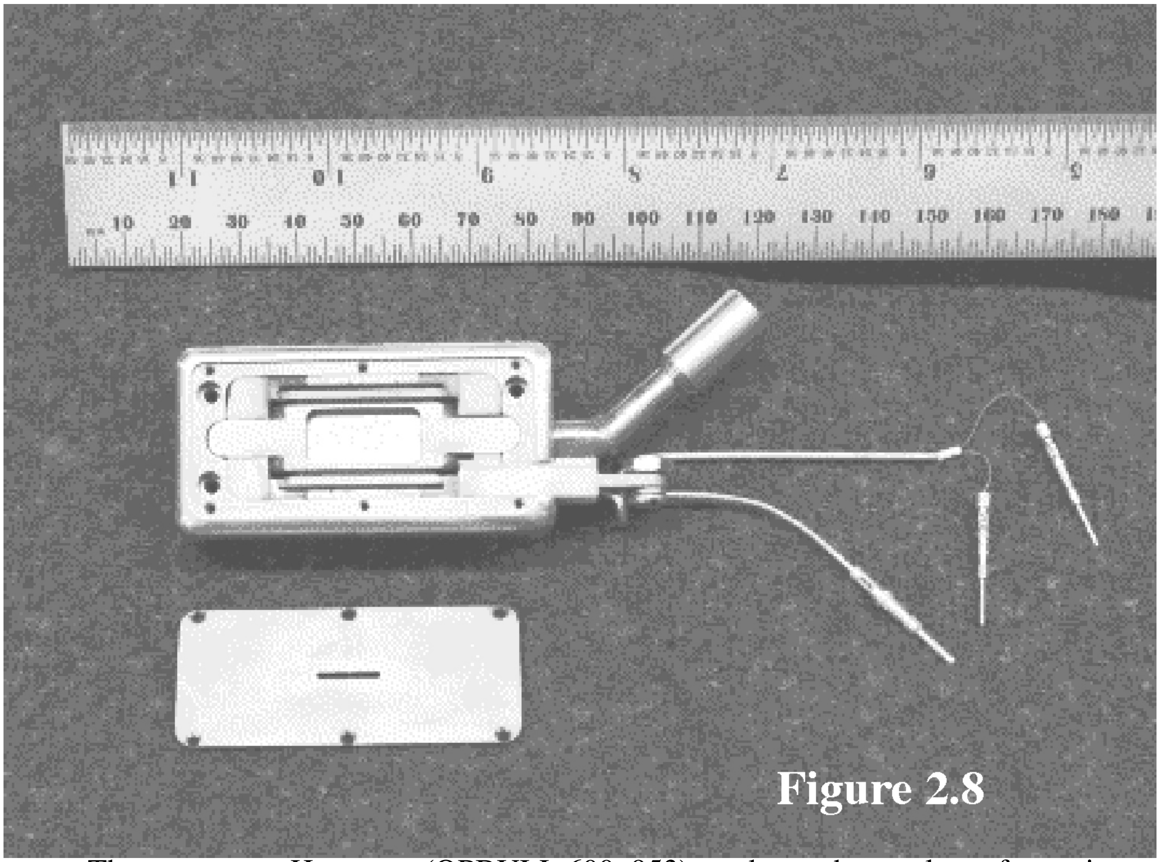


Figure 2.8

The magnetron H- source (OPBULL 600, 953) produces short pulses of negative ions at the Linac repetition rate of 15 Hz. These ions come from plasma formed near a metal surface. A pulse valve introduces hydrogen gas at low pressure into the volume between two molybdenym electrodes: a matchbox-sized, oval-shaped cathode and a surrounding anode, separated by 1 mm and held in place by glass ceramic insulators. An external magnet provides a 1-1.5 kG magnetic field parallel to the cathode surface. A low-impedance pulse-forming network strikes an 80 μsec, 40-amp arc between the electrodes. Electrons in the arc, spiraling about the magnetic field lines, efficiently ionize the gas to form a dense plasma of H+ ions and electrons in the gap.

H+ ions strike the cathode and occasionally pick up two electrons or "sputter" H- ions from the surface. H- ions are repelled from the cathode and charge-exchange with neutral hydrogen atoms at the plasma boundary to produce H- ions with a smaller energy spread. A pulsed electrostatic extractor then accelerates the negative ions out of the source.

Introducing cesium vapor into the source coats the electrodes and lowers the surface work function, enhancing the production of negative ions by the cathode. Cesium vapor is supplied by vaporizing solid cesium in an electrically heated cesium boiler. The vapor then travels through a heated tube to the source. Five grams of cesium is enough for about a year of source operation.

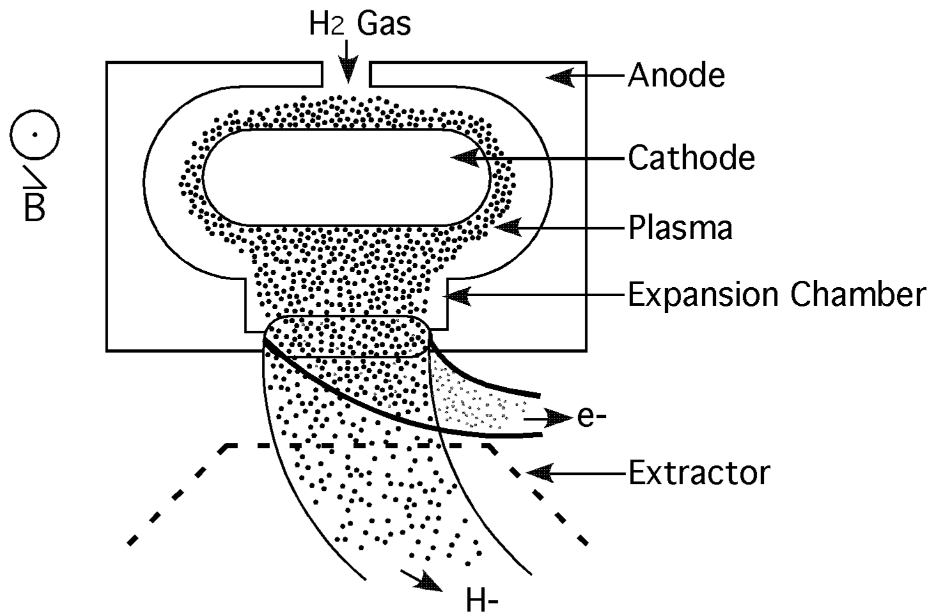


Figure 2.9: Magnetron Negative-ion Source

A 30ft[3] gas bottle located inside the dome supplies extremely pure hydrogen gas at 10-30 PSIG. This is enough gas for about six months of source operation. A piezoelectric crystal valve controls gas pressure in the source. When a voltage pulse is applied to the crystal, it bends, admitting gas to the source. A second DC supply on the crystal is used to compensate for temperature changes that affect the operating point of the valve. Modulating the width of the voltage pulse that opens the valve regulates source gas pressure. This task is handled by a servo loop residing in computer software that acts to keep the pressure near the set point chosen by the operator.

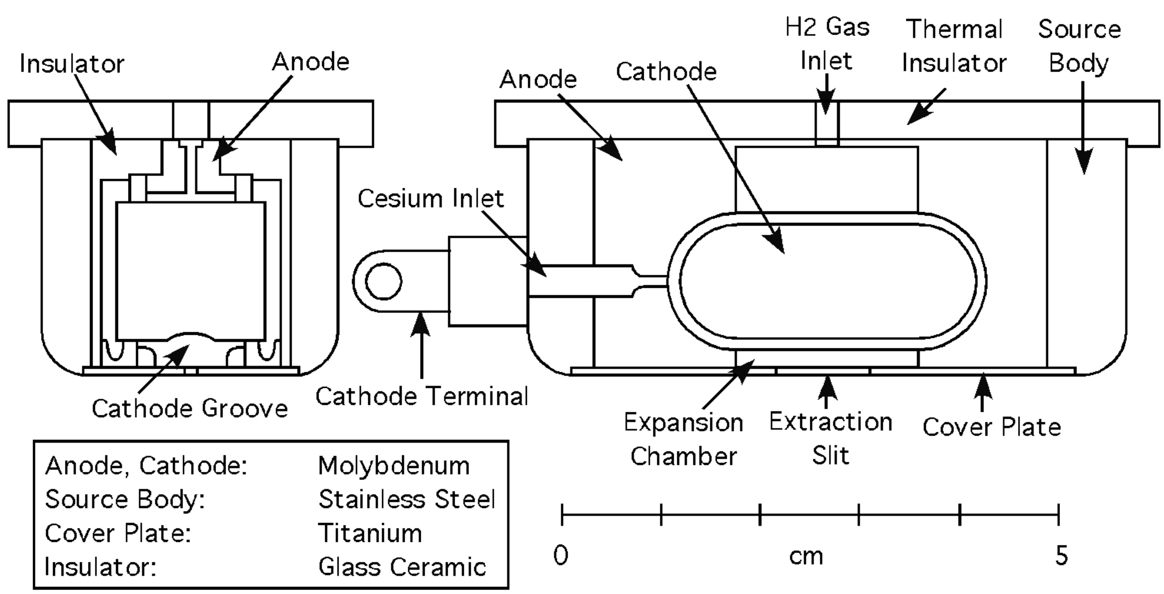


Figure 2.10 Magnetron Case

Extractor and Magnet

A 1 x 10 mm aperture in the source body allows negative ions and electrons to exit the source when an electrostatic extractor, 2 mm below the aperture, is pulsed to about 18 kV (figure 2.11).

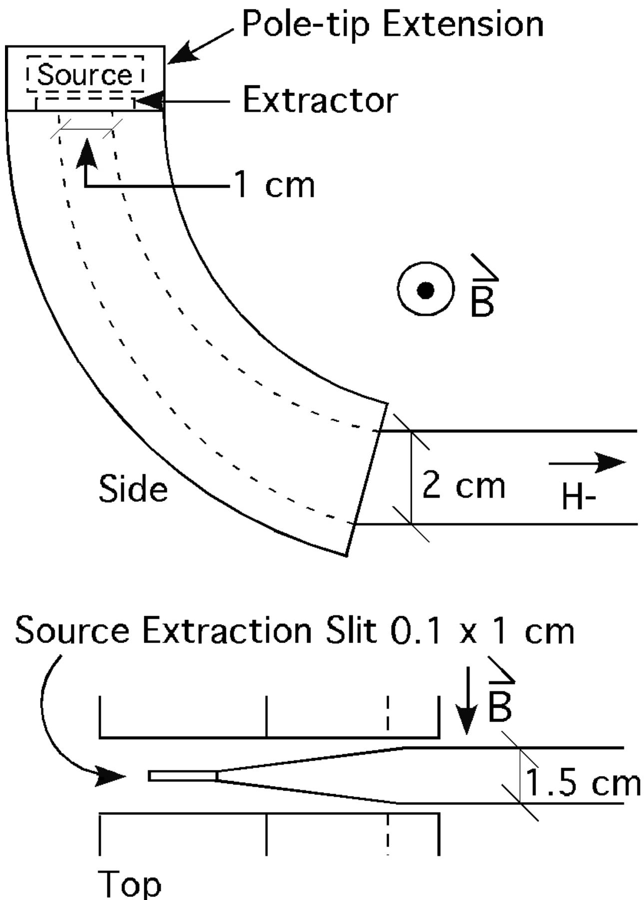
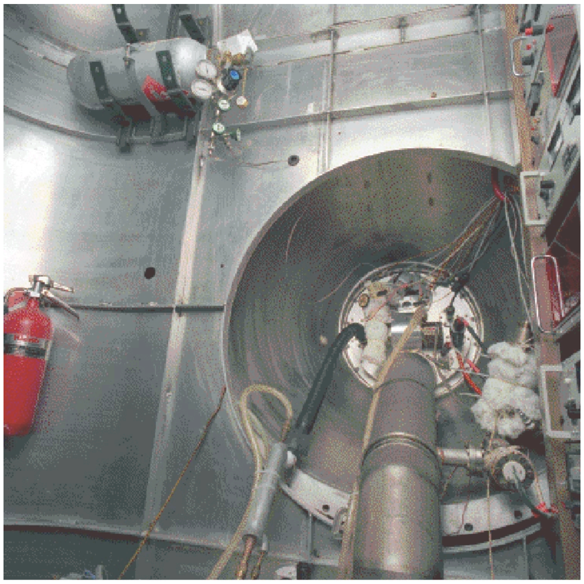


Figure 2.11
Extractor and Magnet

The high-density (1 A/cm^2) beam exiting the source has a high divergence due to space charge forces and the defocusing effect of the extractor. To control this, a high-gradient 90˚ bending and focusing magnet reduces beam divergence from 250 mrad to about 37 mrad. The pole faces of this magnet are slanted to produce a quadrupole field and focus the beam. Pole-tip extensions on the top straddle the source and provide the magnetic field necessary to sustain the plasma. Extracted electrons are separated from the H- beam by the magnetic field. The pole pieces, cooled to –30˚ C by a Freon refrigerator located in the dome, also capture wayward cesium atoms that are extracted from the source and could cause sparking in the accelerating column if not removed. The ion beam leaving the 90˚-bending magnet is about 50-80 mA and 1.5 x 2 cm in size.

Sixty percent of the gas that flows through the source is drawn off by a 400 liter per second turbomolecular pump located in the dome. Source pressure is actually measured in the vacuum line to this pump, which may be isolated by a valve, but is normally left open for operation. The valve is operated by nitrogen gas supplied by a tube leading from the outside world. The valve is manually controlled. The hydrogen gas not removed by the turbo flows through the accelerating column and is removed by a 2400 liter/sec ion pump (powered by four separate supplies) located outside the Preaccelerator pit.

All the hardware necessary to run the source is contained in the dome, which is actually a hollow aluminum cube with rounded corners. Inside the cube are the following items:



- the source assembly
- hydrogen gas supply
- gas valve pulser
- arc supply and pulser
- source heater
- cesium boiler power supply
- cesium tube and valve heaters
- extractor power supply and pulser
- magnet power supply
- magnet pole refrigerator
- ion gauges for measuring vacuum
- roughing and turbo vacuum pumps
- turbo pump controller
- cooling system for turbo pump & magnet coil
- generator and breaker panel
- oscilloscope and TV cameras
- control microprocessor

Figure 2.12

Communication with the control microprocessor in the dome is done by way of fiber optic cables run from the Preacc control room. The same is true of clock signals and the TV camera video. The control and clock cables are blue, and the video cables are orange or red.

Source Assembly

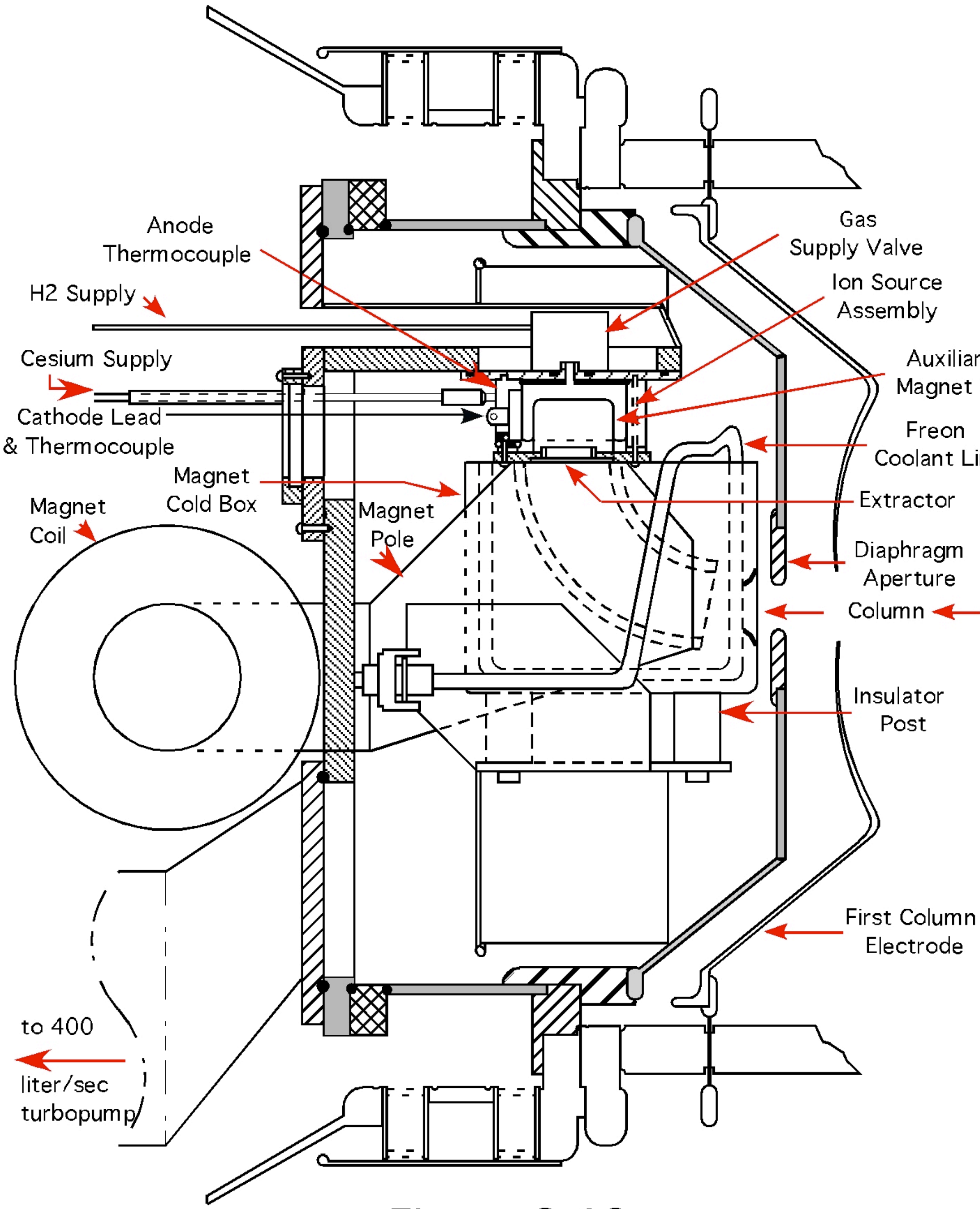


Figure 2.13
Preaccelerator Ion Source Assembly

Five centimeters from the exit edge of the bending magnet the beam enters the accelerating column (figure 2.13). The column consists of seven perforated, disk-shaped titanium electrodes that are designed to guide the ion beam during its acceleration to ground potential. Titanium was chosen by virtue of its high work function, to reduce the number of stray electrons in the column. Ceramic rings insulate the electrodes from the outside world and one another. Two water resistors passing from the dome through the outer edges of rings (connected to the electrode disks via rods) to the pit wall maintain roughly equal potential differences between the disks. The distance between the electrodes is small compared to their radius for good field quality on the axis. This also reduces the defocusing effects of any charge picked up by the insulating rings. Holes near the outer edge of the electrodes ease the task of vacuum pumping. A set of these electrodes may be seen on the west side of the second floor of the central laboratory.

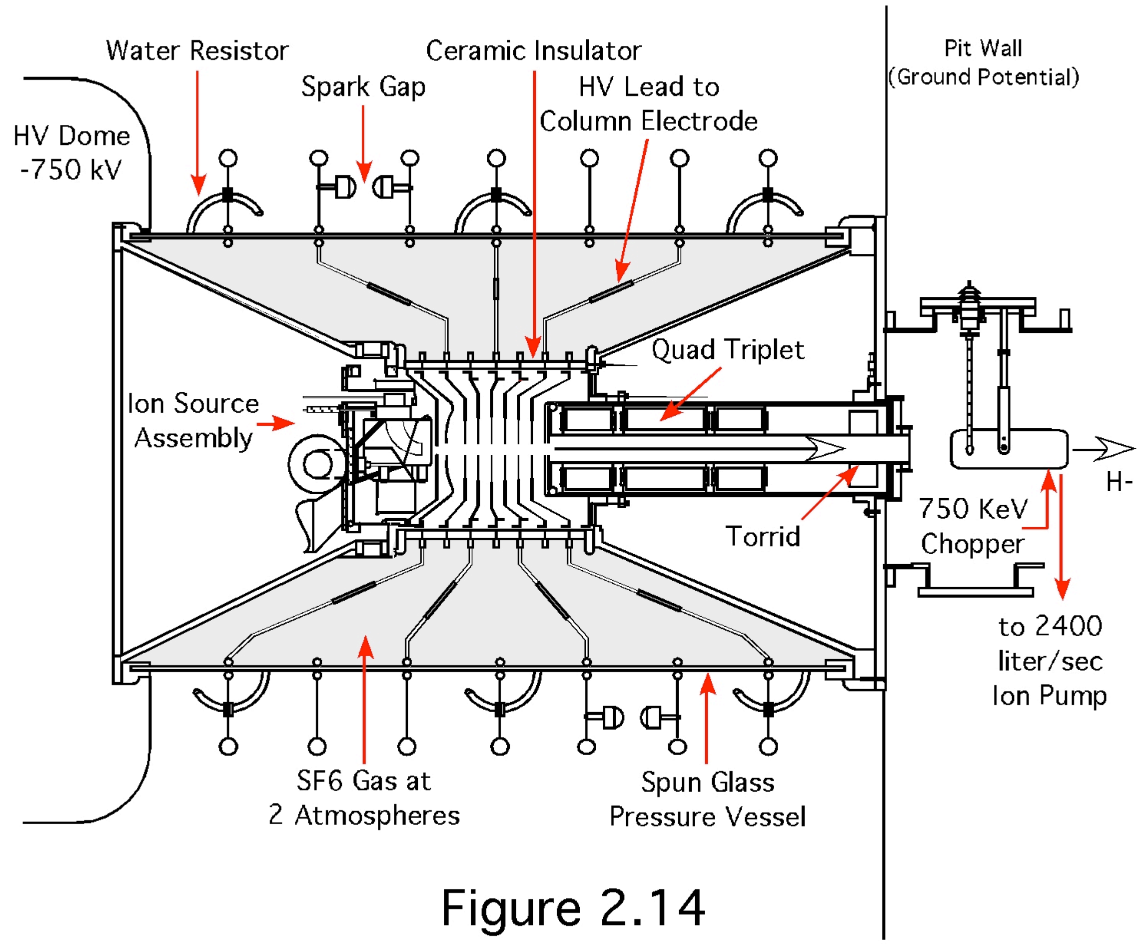


Figure 2.14
Ion Source & Accelerating Column

The column is encased in a spun glass pressure vessel containing sulfur hexafloride gas at two atmosphere's pressure. This gas is a good insulator and acts to reduce the possibility of the column leads arcing to each other or ground. Spark gaps at the outer edge of the electrode rings protect the column by handling most of the current as a result of a spark of bad voltage distribution. Vacuum in the column is maintained by the 2400 liter/sec. Ultek ion pump located outside the pit.

Source Operation

Figure 2.15 is a Linac parameter page L49, used to monitor and control operation of the sources. This particular page represents a healthy source in the H- Preaccelerator; thus all parameter names start with “H.” Identical parameters for the I- source start with “I.”

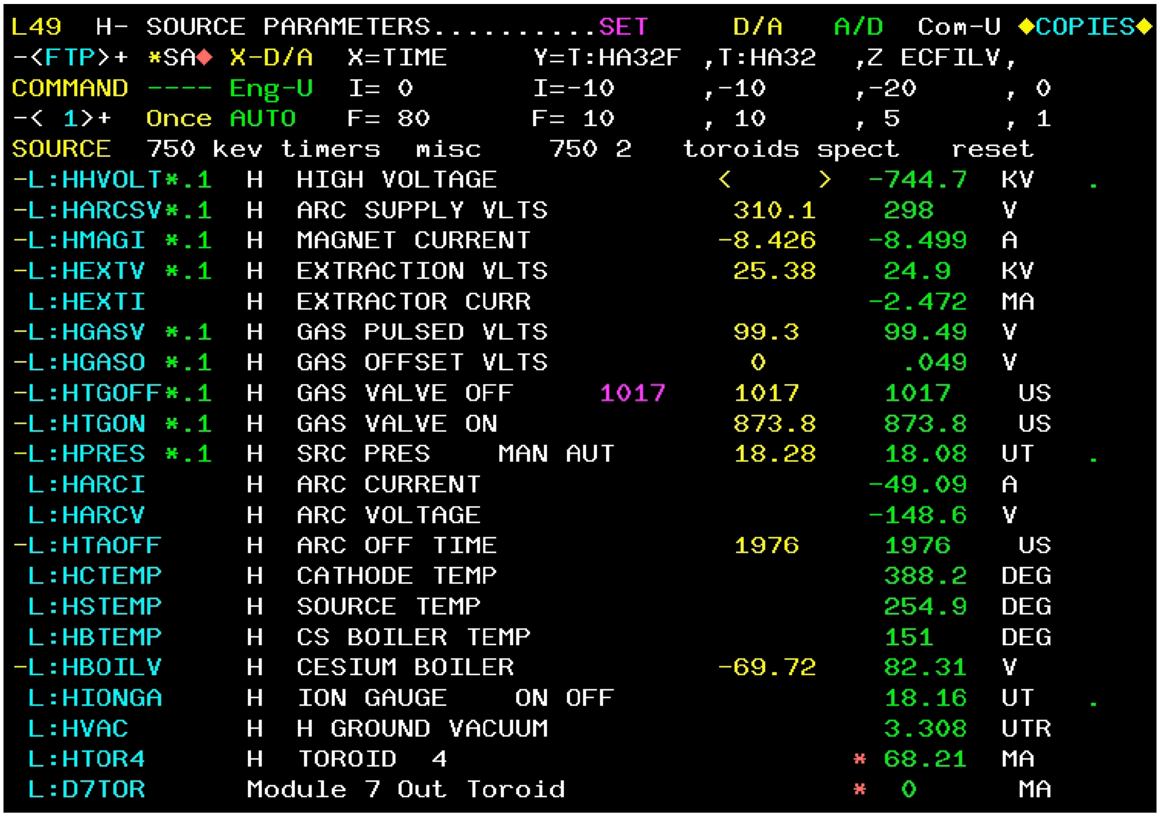


Figure 2.15

The source gas pressure and the source temperature are vital to proper operation. The cathode optimally runs at a temperature of about 400˚C, with a cesium coating of 0.6 of a monolayer. If the temperature is too low, cesium tends to condense on the electrodes. Too high a temperature results in an insufficient coating of cesium on the cathode, and extreme cases may damage the piezoelectric gas valve. The cathode temperature L:HCTEMP is controlled by varying the current in a resistive heater in the source body (controlled manually by Variac in the dome). The source body temperature itself, L:HSTEMP, is quite a bit cooler than the cathode; the difference is due to heating of the cathode by the arc.

Gas pressure affects both the quality of the arc and ion production rates. Too low a pressure results in an unstable production arc. Increasing the pressure (by raising the servo loop set point L:HPRES) stabilizes the arc, but may reduce beam current by stripping the H- ions in the source as the ions collide with gas molecules. High source pressure also increases the load on the ion pump and can induce sparking in the extractor. Nominal source pressure is about 20 μtorr.

Source pressure is regulated by a servo loop that samples the pressure in the vacuum line to the turbo at 15 Hz. Fifteen samples are made, followed by one correction, resulting in an adjustment to the gas pulse width about once a second. If the source pressure is within a set deadband of ~ 0.2 μtorr, no pulse width change occurs. Between the deadband and a set window, a one-μsec correction per second continues until the pressure is back within the deadband. This guards against pressure bursts. If the source pressure is outside of the window, some correction occurs, but operator intervention may be required. The source pressure threshold sets the center of the loop's deadband.

During startup or recovery from "loss" of a source, the cathode must be brought to the correct temperature and have a sufficient coating of cesium before reasonable ion production can be expected. Once the cesium boiler and cesium transfer line heaters have been turned on, the source can be started after 1-2 hours. In the "old days," it was advised to raise the source pressure, increase the arc pulse length, and raise the magnet current to speed up heating of the cathode. Recent experience has shown that equally good results can be obtained by simply setting all parameters to nominal operating values and waiting. Stubborn sources may benefit by temporarily raising the source pressure to 40 μtorr or so. Arc voltage will initially be high and arc current low as the cathode warms up and acquires cesium. As the arc improves it is possible to slowly decrease the source pressure. Good output current (L:HTOR4 for H-, and L:ITOR1 for I-) should be seen within an hour of good arc operation. In any event, the nominal source values should not be changed without good reason and you must add a note to the logbook.

Figure 2.16 shows a familiar oscilloscope trace that shows source operation at a glance. This trace is sent form a TV camera in the dome via the light link. The upper trace is the sum of the arc voltage and gas valve voltage pulse. (The gas valve voltage pulse occurs much earlier than the arc voltage pulse, so it is necessary to adjust the scope trigger time L:ITSCOP or L:HTSCOP earlier to see it.) The time at which the source parameters are sampled is visible as a glitch on the upper trace. The lower trace is the sum of the extractor voltage (upper dip) and the arc current (lower dip). If the extractor is arcing, the lower trace will jump around considerably. If turning down the source pressure doesn't cure the problem it may be necessary to reduce the extractor voltage. Be forewarned that the extractor voltage and magnet current both affect the steering of the beam through the column, as well as the rest of the Linac. <u>Do Not change nominal values without consulting specialists</u>.

Source lifetimes vary from source to source; the reasons why this is aren't well understood. After a time the output of a source will start to decrease, usually visible as a pronounced slope in the arc current trace. It must then be removed and cleaned of cesium hydride and other sputtered deposits (molybdenum, etc.).

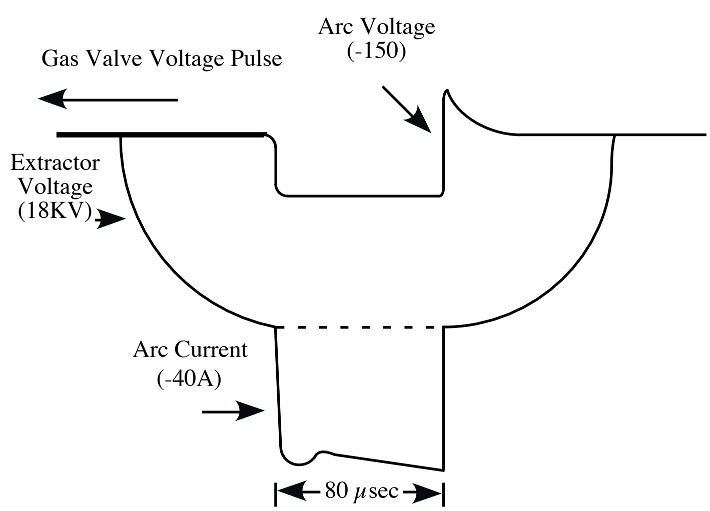


Figure 2.16
Ion Scope Traces

For a temporary shutdown of a source, first shut off the cesium boiler and transfer line heaters. Shut off the source body heater (sometimes called the anode heater) and close the cesium supply valve (located in the dome). Wait two hours, then shut off the magnet and arc supplies. Wait another two hours, then turn off the H_2 gas supply.

If you're shutting down the source permanently, just turn off everything except the gas supply until the source cools, and then turn off the gas as well.

Spare power supplies for the source heaters, magnet, and arc supplies are found in the Preacc control room.

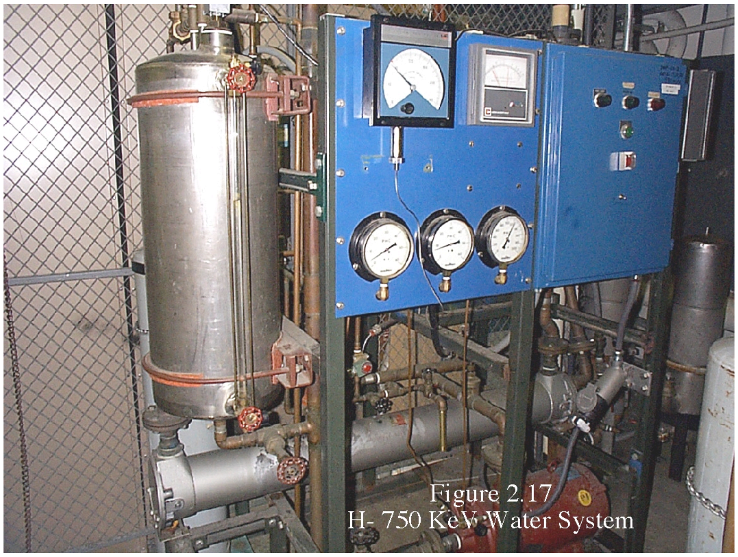


Figure 2.17
H- 750 KeV Water System

Preaccelerator Water Systems

Two cooling systems service the Preacc. The distribution of the load is a bit uneven due to the different ages of the Preacc systems. (I- predates H- by a few years.) One system cools the I- 750 keV line, the I- Haefely power amplifier. This system is in the lower Linac gallery just outside the door to the Preacc control room (figure 2.18). The water resistors for both H- and I- systems have their own water skid located on the south side of the parts cage. The other system cools the H- 750 keV line and the H- Haefely power amplifier. It is located by the water system for Linac RF station #1 and is readily distinguished by its blue front panel (figure 2.17). Both systems have local control of pump motors, and local readouts of pressures, temperature, and conductivity.

The quadrupoles and 45/90˚ magnets in the 750 keV transport lines are water-cooled, with flow switches to trip off their power supplies if there is insufficient water flow. (The trims are air-cooled.) The status of the flow switches, temperature-sensing klixons, and other interlocks are shown at the top of the relay racks that contain the power supplies, located in the Preacc control room. The flow switches for the I- 750 keV line are mounted in a box on the wall to the left of the upper door to the I- pit. Valves for the individual elements are located beneath the floor plates there. The flow switches for H- 750 keV line are mounted in a box on the wall at the west end of the catwalk over the 750 keV line; valves are mounted on the wall beneath the box.

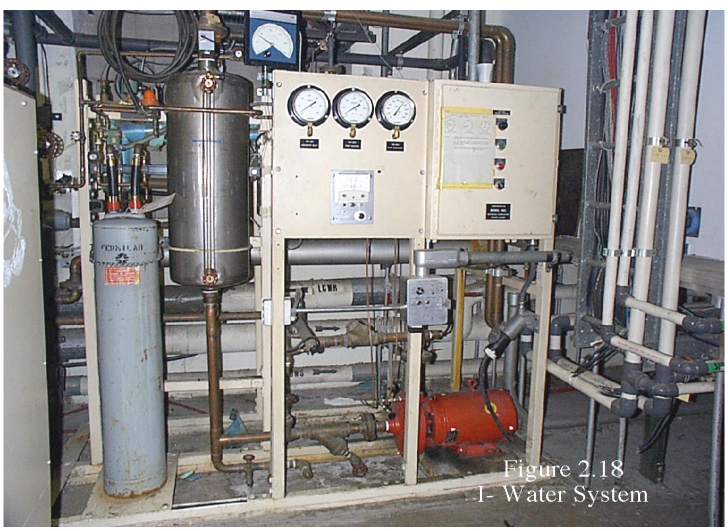


Figure 2.18
I- Water System

Schematics of the H- and I- 750 keV line water flows are shown in figure 2.19 and 2.20.

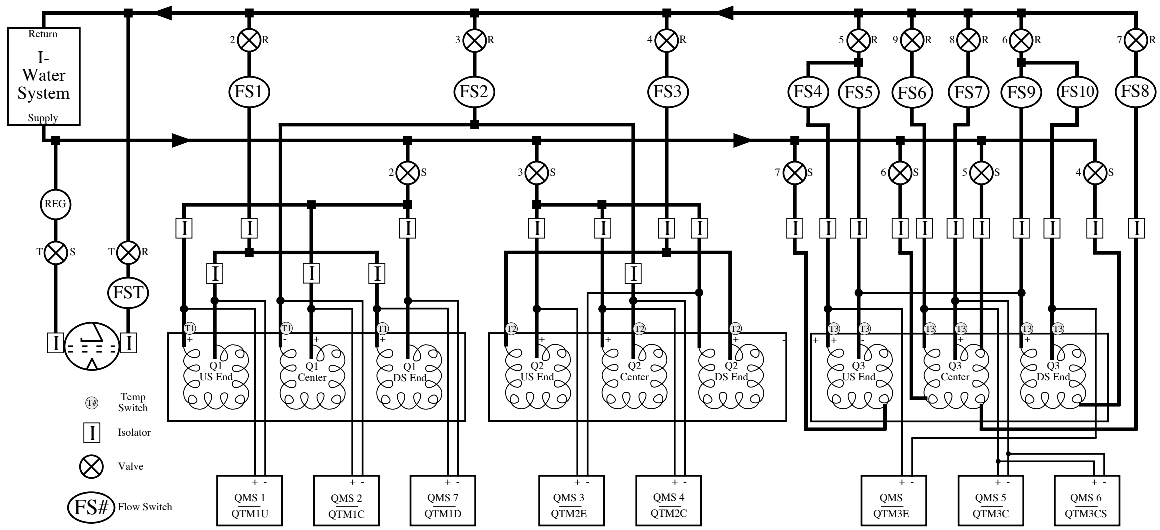


Figure 2.20, I- 750 KeV Line Water System

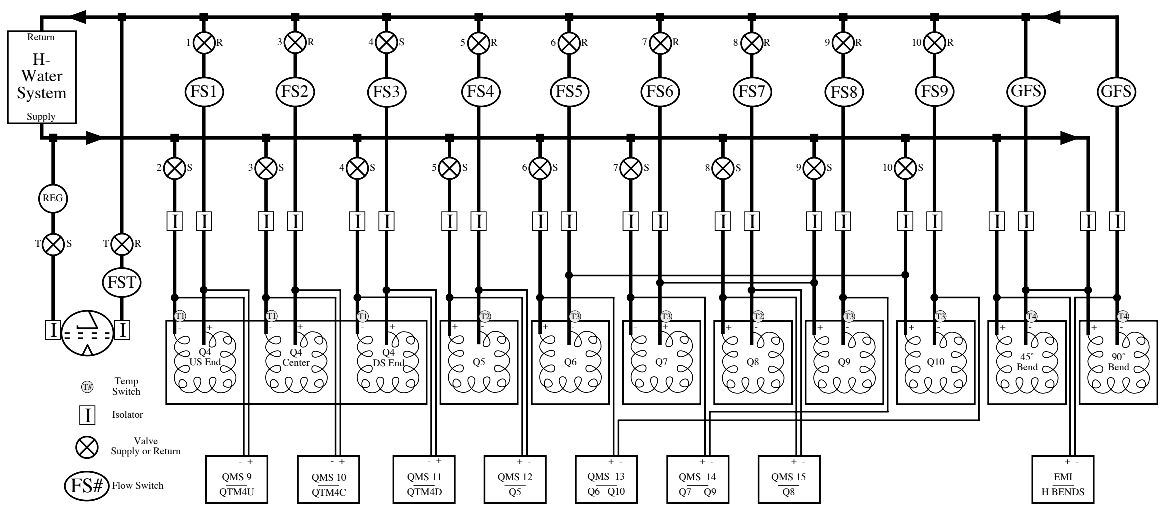


Figure 2.19, H- 750 KeV Line Water System

Chapter 3, 750 keV Transport Line

Each Preaccelerator has its own transport line up to the point where the lines merge and continue on to the Linac. The I- transport line is the simpler and shorter of the two, as seen in figure 3-1. Once the beam pulse has left the column, it passes through a quadrupole triplet Q1, which focuses the beam in both planes. The end elements each have there own power supply L:IQTM1U & IQTM1D, and the center element has its own supply L:IQTM1C. The beam current then is measured by the toroid T1 (L:ITOR1).

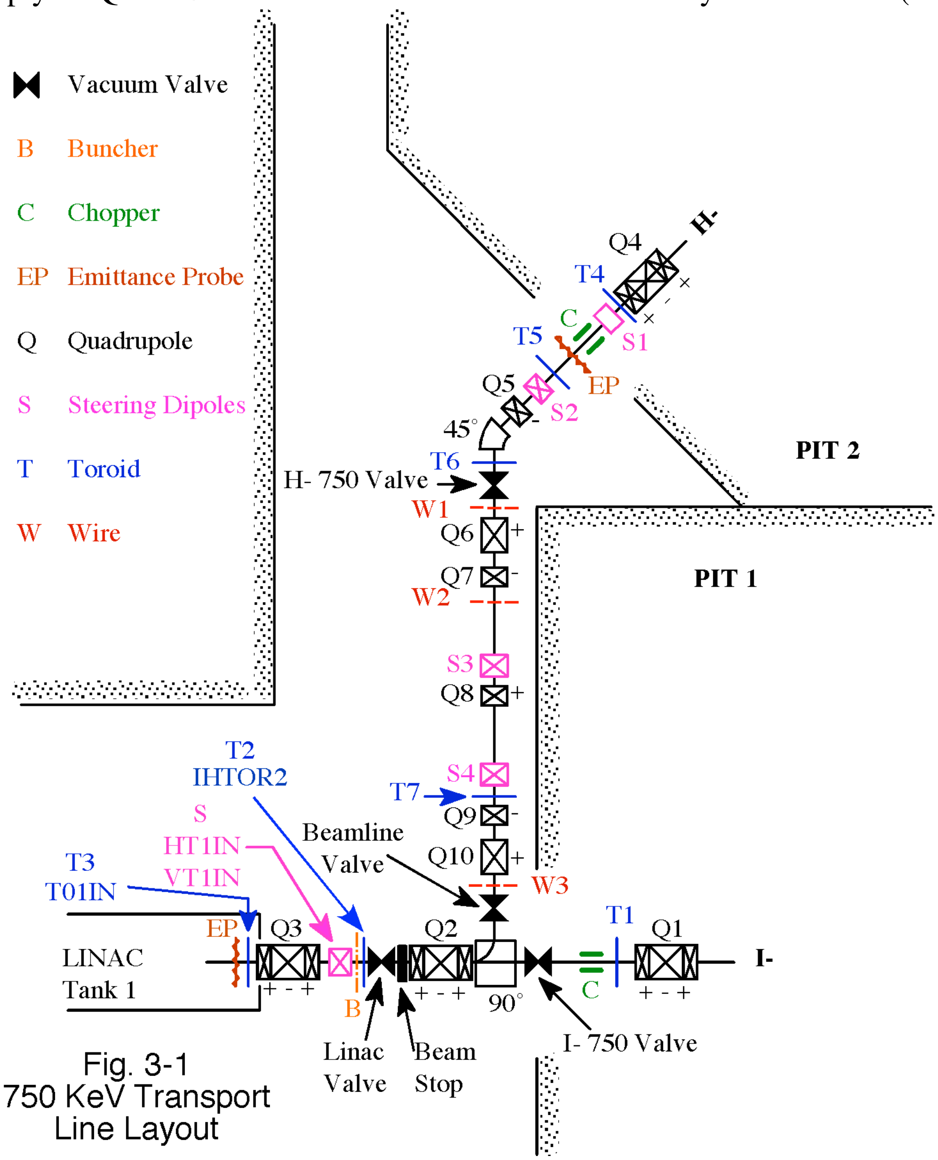


Fig. 3-1
750 KeV Transport
Line Layout

The beam then passes through an electrostatic chopper that selects a short portion of the beam pulse that is sent to the Linac. The unwanted beam is deflected into a carbon disk, while the selected beam (the chop) passes through undeflected. The 750 keV chopper is described in greater detail later.

The selected beam chop (40 μS or so for High-Energy Physics, HEP) then passes through a 90-degree bending magnet that is normally off for I- operations and on for H- operations. The beam travels a straight path through a second quadrupole triplet Q2 (power supplies L:QTM2C and L:QTM2E), the Buncher, toroid T2 (L:IHTOR2), a vertical and horizontal dipole (L:HT1IN and L:VT1IN), and a third quadrupole triplet Q3 (power supplies L:QTM3C and L:QTM3CS for the center element, and L:QTM3E for the end elements).

An emittance probe is the last device in the line. It's used to (figure 3.2) measure the angular divergence of the beam. But this is a destructive measurement and is done only under special conditions.

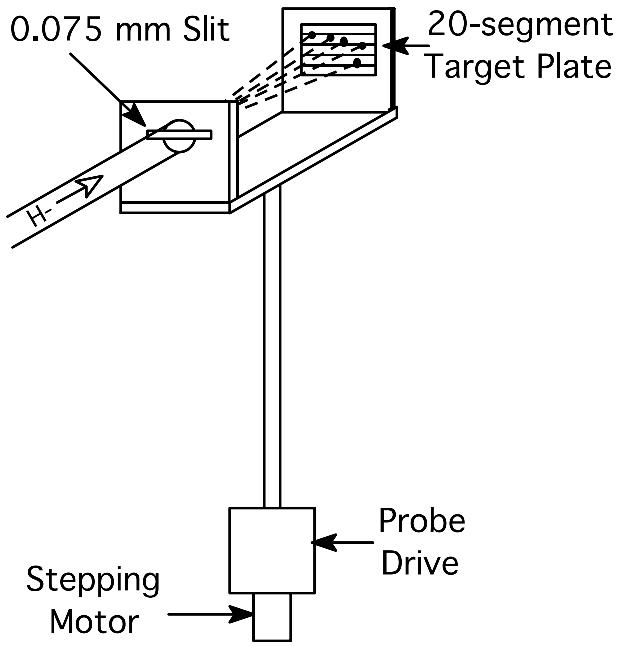


Figure 3.2, Emittance Probe

If you'll look back at figure 3.1, you'll see that the H- transport line is a bit more involved. The first element is a quadrupole triplet Q4, which controls all three elements individually (L:HQTM4U, L:HQTM4C, L:HQTM4D), although the last element (4U) usually runs at a fixed value. Toroid T4 (L:HTOR4) measures the beam coming out of the column and is followed by a vertical dipole trim S1 (L:HVT1). Then comes the H- chopper, an emittance probe, toroid T5 (L:HTOR5), horizontal and vertical dipole trims S2 (L:HHT2, L:HVT2), and a single quadrupole Q5 (L:HQ5).

The next element is a 45˚ bending magnet that runs in series with the 90˚ magnet mentioned earlier. These magnets have a bulk supply L:HBENDS and the 90˚ magnet also has a trim L:TRIM90. A gaussmeter in the aperture of the magnet measures the magnetic field, but is not used for regulation or tuning. L:HBENDS is off for I- operation, the beam extracted from the H- source at that time is sent straight through the 45˚-bending magnet to a carbon block.

Under very special conditions it may be desirable to run the 45˚ magnet without the 90˚ magnet. To do this, it is necessary to remove the 90˚ magnet from the circuit by rotating two rhomboidal plates (figure 3.3) located on the wall below Q9 in the H- 750 line. In normal operation, both magnets are left in the circuit, and the supply L:HBENDS is turned on or off depending on whether H- or I- beam is to be used.

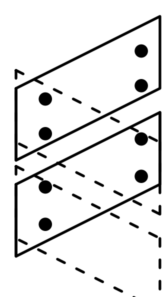


Figure 3-3
45˚ 90˚
Lead Switching

Next in the 750 keV line is toroid T6 (HTOR6), a beam profile monitor W1, and a number of single quadrupoles Q6-10. Q6 and Q10 are in series, as are Q7 and Q9. Proper operation of the line requires a specific relation between the current in Q7 and Q9 and the currents in Q8, Q6, and Q10.

S3 and S4 are dipole trim packages (L:HHT3, L:HVT3, and L:HHT4, L:HVT4).

The three monitors, W1-3, were used for the initial tune up of the line, but are no longer used. Present beam intensities destroyed the wires.

Toroid T7 (L:HTOR7) is used for rough tunes of the H- transport line.

The beam from the H- source is then bent 90˚ to travel through Q2 and on to the Linac, which becomes the same line for the I- beam from here on out.

All the quadrupole power supplies are the same, the Sorenson SCR20-250, except for L:QTM3E. All power supplies for the above quads and dipoles are in the Preacc control room, except for the two large EMHP supplies. One of these supplies (located below the stairs leading from the upper gallery to the Preacc control room) powers the 45˚ and 90˚ bending magnets, and the other, which powers L:QTM3E, is in the lower Linac gallery near the water system for RF station #1. Any of the above supplies will trip off if there is insufficient water flow for their loads.

There are four vacuum valves in the 750 keV transport lines (figure 3.1 again). Two of the lines are interlocked and two are controlled manually; the gate valve controller located in the Preacc control room handles the status and control of these valves. The H- and I- valves are interlocked to the vacuum systems; both valves will close if either Linac vacuum (monitored by a thermocouple in the transport line) goes bad. If the vacuum in either column goes bad (monitored by ion gauges) the valve for that system will close. These valves can also be closed manually from the gate valve controller. If the H- valve closes, the 45˚-90˚ supply L:HBENDS will trip off to keep beam from hitting the valve, The I- valve has a carbon block attached to its upstream face to protect it from beam if it closes.

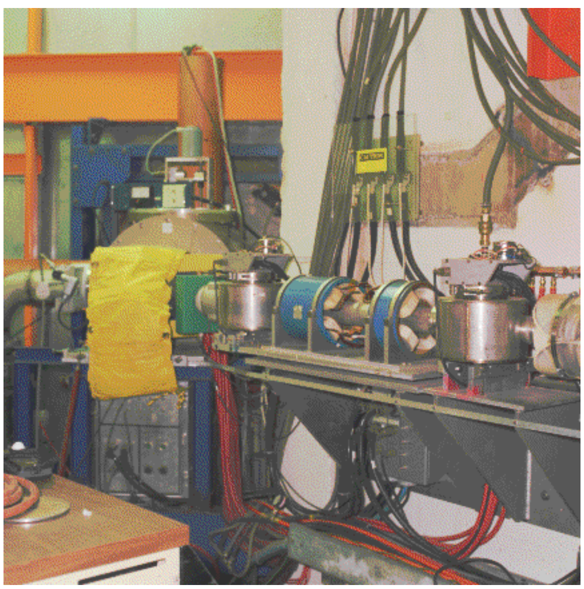
The beamline valve and the Linac valve are manually controlled from the gate valve controller. The Linac valve is also interlocked to the tank one vacuum pumps and will close if both pumps trip.

To the left (figure 3.4) is a side view of the 750 line. If you look from the blue Buncher cavity on the right and follow it to the left and the yellow 90˚ magnet, you'd be heading upstream toward the "I minus" source, which is located just beyond the yellow 90˚ magnet.

Just upstream from the Buncher, in between it and the 90˚ magnet is the Linac beam stop.

The line on the left is the H- beamline as it enters the yellow 90˚ magnet.

Figure 3.4



This is a view of the 750 KeV line (figure 3.5) looking, more or less, upstream toward the "H minus" source. The source is located beyond the yellow 45˚ magnet; the magnet is draped in yellow lead blankets.

The right side of this picture connects with the left side of the upper picture, splitting S3 (white), skipping Q8 (which is in between the two pictures and not shown), and then showing the very end of S4 on the upper picture. S3 and S4 are steering dipoles. (See figure 3.1.)

Figure 3.5

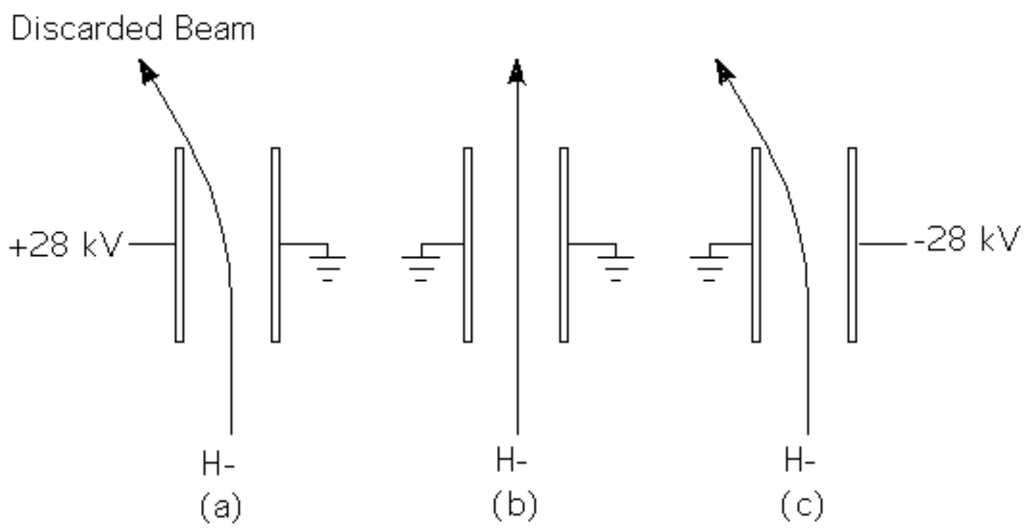
Between the quadrupole triplet Q2 and the Linac vacuum valve is the Linac safety system primary critical device: the beam stop. The beam stop is a block of metal that will drop into the beam path if the Linac safety system trips (to protect personnel), or if the pulse shifter fails to inhibit beam when it should. The block is pneumatically controlled, closing in the event of a power failure or the loss of gas pressure. If the beam stop is commanded to close and does not, both the H- and I- Haefely power supplies will trip off.

750 keV Chopper

The chopper, which consists of a pair of conducting plates that straddle the beam path (figure 3.6), determines the amount of beam allowed to pass from the source to the Linac. An initial potential difference (a) between the plates causes the beam to be bent off to one side and be lost in a carbon disk. The plates are then brought to the same potential for a controlled period of time (b), which allows the bean to pass through undeflected. The potential difference returns, bending the beam again (c).

The duration of the selected beam pulse (the chop) varies depending on the beam pulse use: HEP, neutron therapy, or standby (the “do nothing” chop).

Figure 3.6: 750 keV Chopper Operation



The 750 keV chopper power supply (figure 3.7) consists of two Thyratrons connected through a 4 MΩ resistor to a common anode supply that runs at about 28 kV. One Thyratron (the on tube) has its anode connected through 90Ω resistor to one of its plates. The other Thyratron (the off tube) has its anode coupled to the second plate through a 90Ω resistor and a series capacitor. The second plate is also connected to ground through a 100-kΩ resistor. Initially, then, the first plate is at 28 kV and the second plate is at ground. Incoming beam is deflected by the electric field between the plates. When the “on” tube fires, the tube anode (and thus the first plate) is grounded. With both plates at ground, extracted beam from the column passes through the plates unperturbed. When the “off” tube fires, the series capacitor, which initially had one side at ground and the other at 28 kV, suddenly has the high-potential side clamped to ground. The voltage change (the AC component) is coupled across the capacitor, bringing the second plate to –28 kV; the extracted beam is again deflected into the carbon disk. The second plate then charges back up to ground (relatively slowly) through the 100-kΩ resistor. Likewise, the first plate charges up to 28 kV through the 4 MΩ resistor leading to the anode supply. Note that the 80 μS beam pulse (determined by the arc pulse width) ends long before the plates return to their initial conditions.

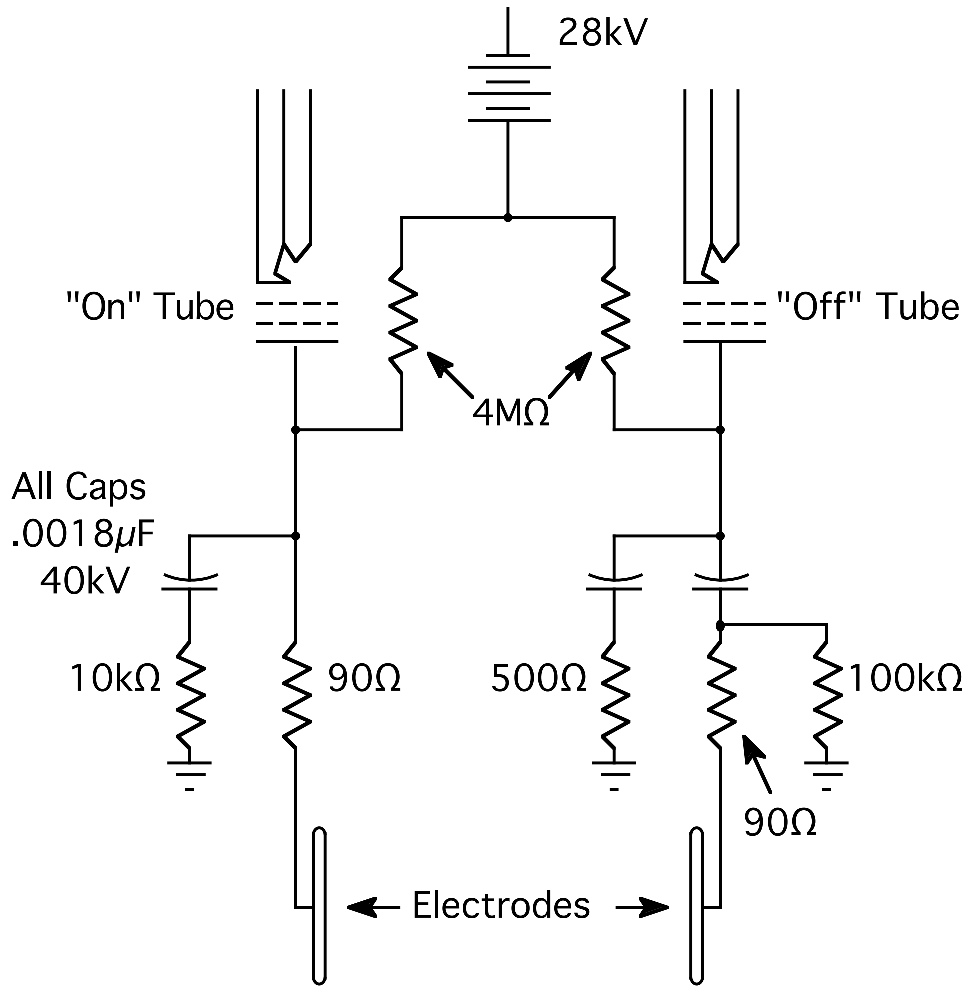


Figure 3.7: 750 keV Chopper Circuitry

The Chopper on and off times are determined by an IRM; there are on and off times for each of the four types of chop. The on off times are changed only with Crew Chief approval. The same chop pulse is sent to both H- and I- choppers. But if the source is down for an extended time, the chopper is also turned off. (The Booster Chopper trigger also fires the Chopper off pulse.)

The chopper power supply will trip off if the ion gauge that measures the column vacuum trips off. Once tripped, the supply voltage must be turned to zero before power it back on. The power supply will then require a local reset. The H- and I- chopper supplies are located in the upper Linac gallery by RF station #1.

750 keV Transport Line Operation

Tuning the I- 750 keV line is a matter of tuning the horizontal trim L:TRIM90, the vertical and horizontal trims (L:VT1IN & L:HT1IN), and the quads for maximum transmission into L:TO1IN (the beam current into tank one) and out of L:D7TOR, the downstream Toroid. Maximum intensity through both toroids may, with careful tuning, occur at the same time. You should conduct Linac steering after each iteration. Transmission of the beam through the I- 750 keV line should be almost 100%.

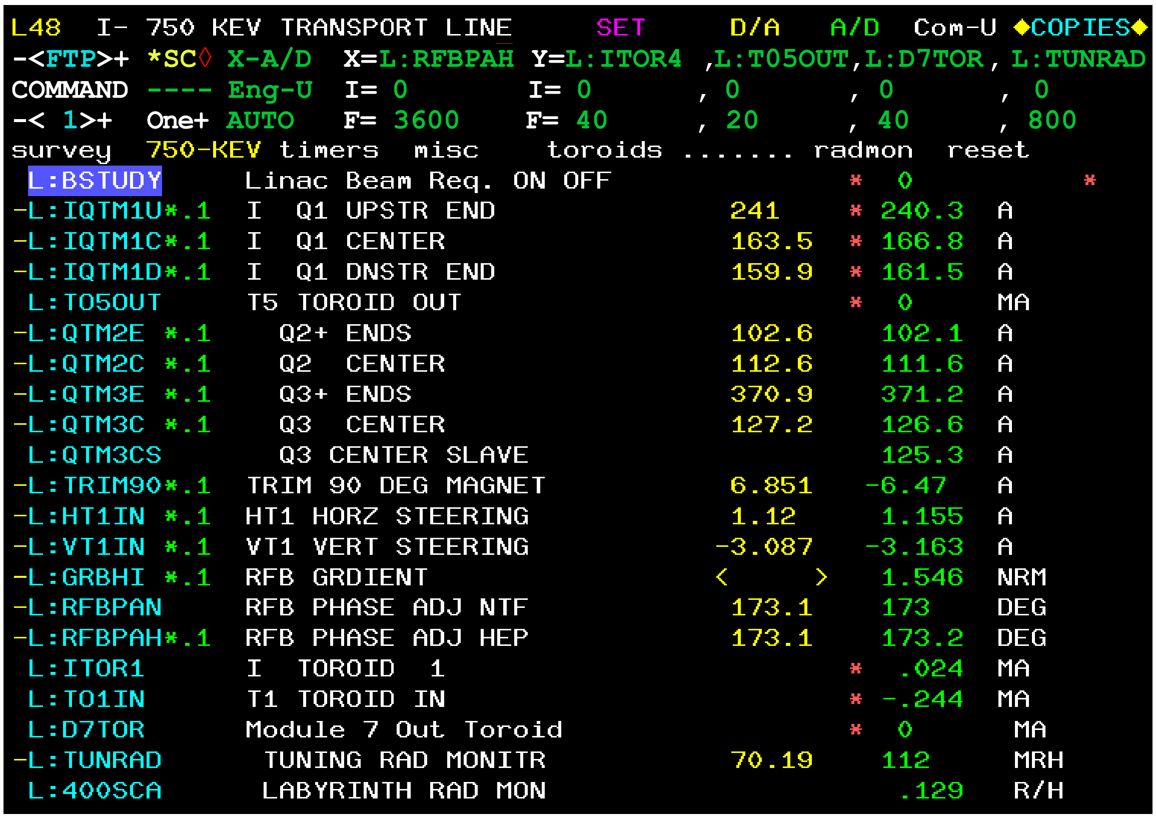
A Linac Tuning Guide

In all cases, you are tuning to achieve the best transmission rates along with the lowest losses.

I minus

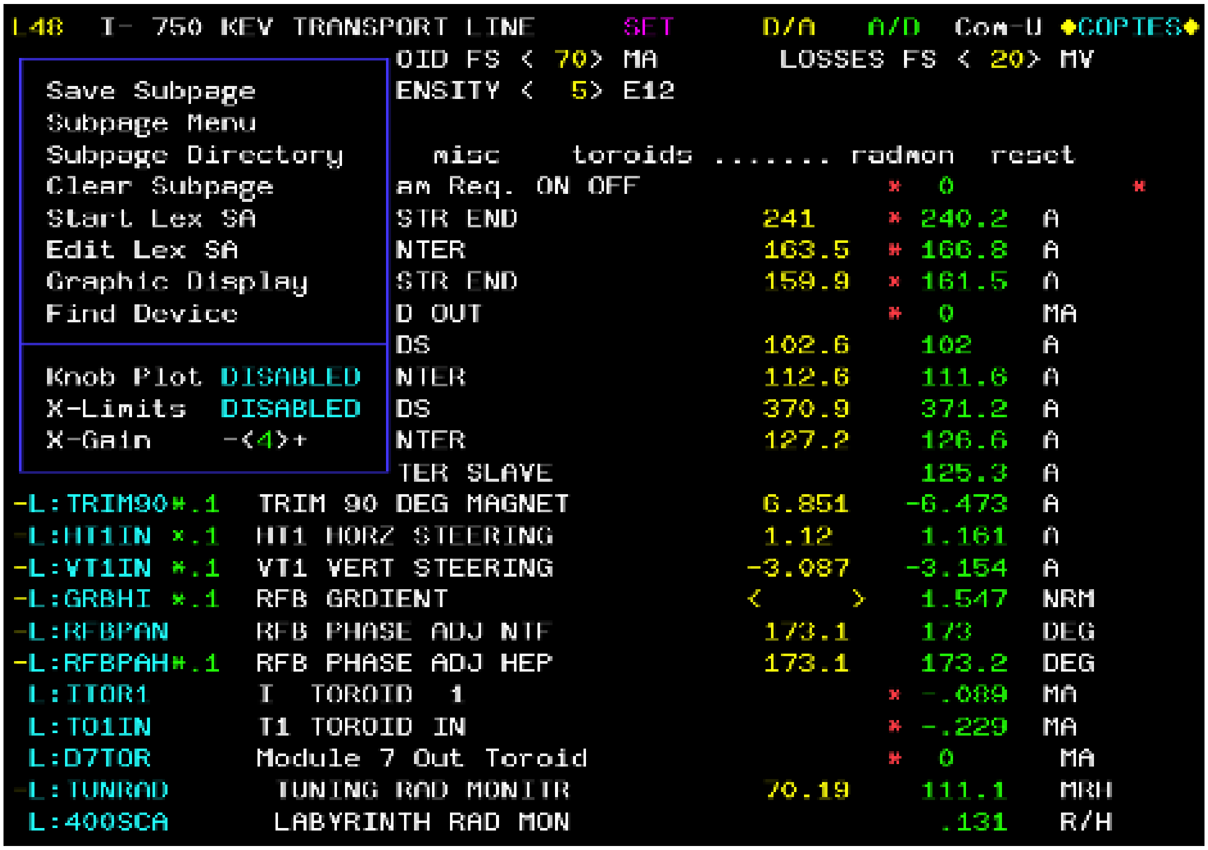
1) Check and write down the initial beamline conditions of the following devices.

Device	Reference	Location
L:ITOR1	I TOROID 1	End of I- Column
L:TO1IN	T1 TOROID IN	Beginning of Tank #1
L:D7TOR	Module 7 Out Toroid	Down Stream end of Mod #7
L:TUNRAD	Tuning Rad Monitor	East side of tanks



2) Select Linac and complete a D1 Save.

3) Set knob plot. (Remember to bypass the device you're knobbing and then to unbypass it when you've finished.)



4) Turn on the Rep rate generator to run Linac beam at a 3 Hz to 5 Hz range (see console MCRR#1).

- ♦ Using L32, complete a Linac Steer

5) Tune the Buncher phase.

- ♦ L:RFBPAH
- ♦ Bypass analog alarms when tuning, and unbypass and renominalize when finished. Also set L:RFBPAN = L:RFBPAH (RFBPAH is for HEP beam to Booster. RFBPAN is for NTF beam.)
- ♦ Complete a Linac Steer (L32)

6) Tune the Quads.

Device	Reference
L:IQTM1U	I Q1 UPSTR END
L:IQTM1C	I Q1 CENTER
L:IQTM1D	I Q1 DNSTR END
L:QTM2E	Q 2+ ENDS
L:QTM2C	Q 2 CENTER
L:QTM3E	Q 3+ ENDS
L:QTM3C	L:QTM3C (SLAVE)

- ♦ Complete a Linac Steer (L32)

7) Tune the Trims.

Device	Reference
L:HT1IN	HT1 Horizontal Steering
L:VT1IN	Vertical Steering

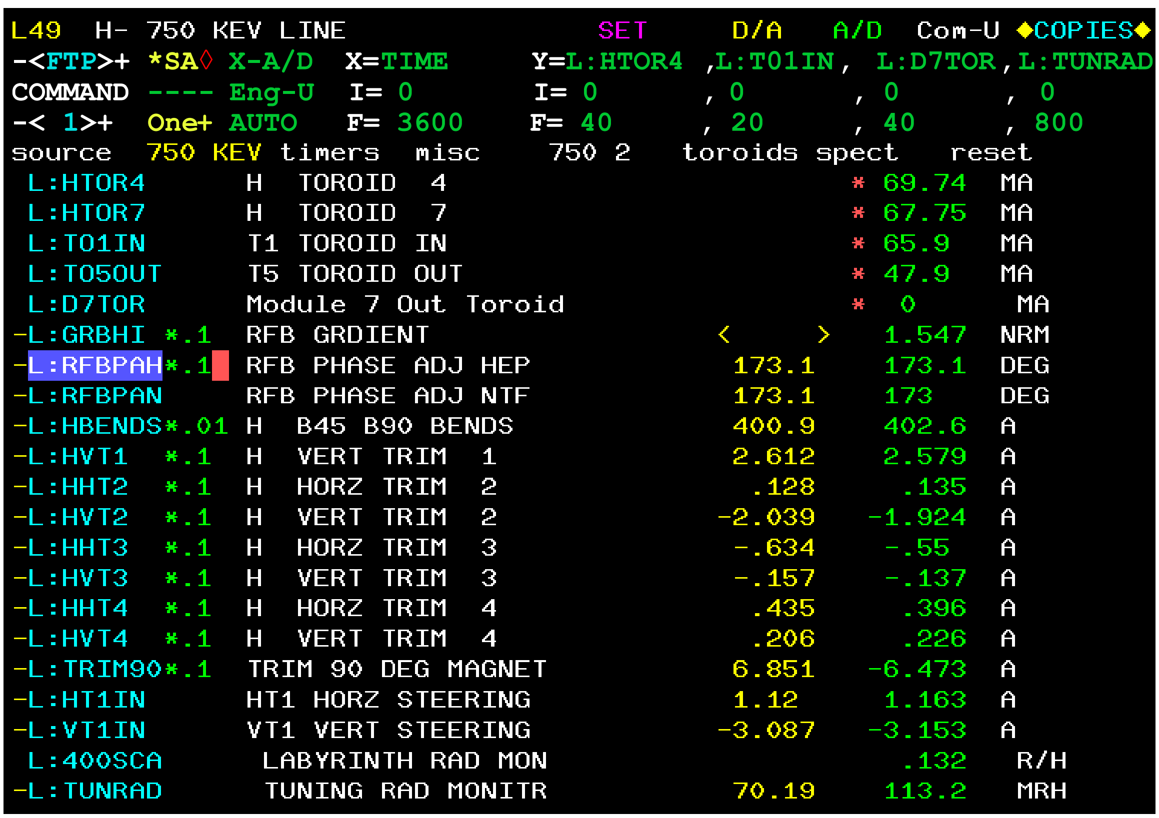
- ♦ Complete a Linac Steer (L32)

8) Compare present conditions with the initial conditions.

H minus

1) Check and write down the initial beamline conditions of the following devices.

Device	Reference
L:HTOR4	H TOROID 4
L:TO1IN	T1 TOROID IN
L:D7TOR	Module 7 Out Toroid
L:TUNRAD	Tuning Rad Monitor



2) Select Linac and complete a D1 Save.

3) Set knob plot. (Remember to bypass the device you're knobbing and then to unbypass it when you've finished.)

4) Turn on the Rep rate generator to run Linac beam at a 3 Hz to 5 Hz range (see console MCRR#1).

    - Using L32, complete a Linac Steer

5) Tune the Buncher phase.

    - L:RFBPAH
    - Bypass analog alarms when tuning, and unbypass and renominalize when finished. Also set L:RFBPAN = L:RFBPAH
    - Complete a Linac Steer (L32)

6) Tune the Quads.

Device	Reference
L:HQTM4U	H Q4+ UPSTR END
L:HQTM4C	H Q4 CENTER
L:HQTM4D	H Q4+ DBSTREBD
L:HQ5	H Q5 QUAD
L:HQ8	H Q8+ QUAD
L:HQ6Q10	H Q6 Q10 + QUADS
L:HQ7Q9	H Q7Q9 + QUADS
L:QTM2E	Q 2+ ENDS
L:QTM2C	Q 2 CENTER
L:QTM3E	Q 3 + ENDS
L:QTM3C	Q 3 CENTER
L:QTM3CS	Q 3 CENTER (Slave)

(Although only QT3C has a knob, the QT3CS output will change; this means that its alarm must also be bypassed.)

    - Complete a Linac Steer (L32)

7) Tune the Trims.

Device	Reference
LHVT1	H VERT TRIM 1
LHVT2	H VERT TRIM 2
LHVT2	H VERT TRIM 2
LHVT3	H VERT TRIM 3
LHVT3	H VERT TRIM 3
LHVT4	H VERT TRIM 4
LHVT4	H VERT TRIM 4
L:TRIM90	TRIM 90 DEG MAGNET
L:VT1IN	VT1 Vertical steering
L:HT1IN	HT1 Horizontal steering

    - Complete a Linac Steer (L32)

8) Compare present conditions with the initial conditions.

Changing Sources

As sources grow old, they diminish in output. Source pressure may be raised to maintain nominal arc current, but it is at best a temporary measure, since the extractor may start to spark and the beam current will likely diminish anyway, due to stripping of H- ions by gas molecules. Eventually, the source will slide off the deep end and it will be necessary to switch to the other source. (If the other source is already down you have a serious problem.)

Only Linac Preaccelerator experts change the sources.

750 keV Line Vacuum

The vacuum for the 750 keV area is maintained by the Ultek 2400 liter per second (5000 liter/sec for hydrogen gas) ion pumps at the head of each column, and by the Linac cavity pumping systems. The column ion pumps are large because they must handle the H_2 gas emission from the ion source. The ion pump power supplies are located in relay racks in the Preacc control room. Valve interlocks in this system are described elsewhere.

Column vacuum is read out in torr on an ionization gauge controller mounted in the rack above the ion pump supplies.

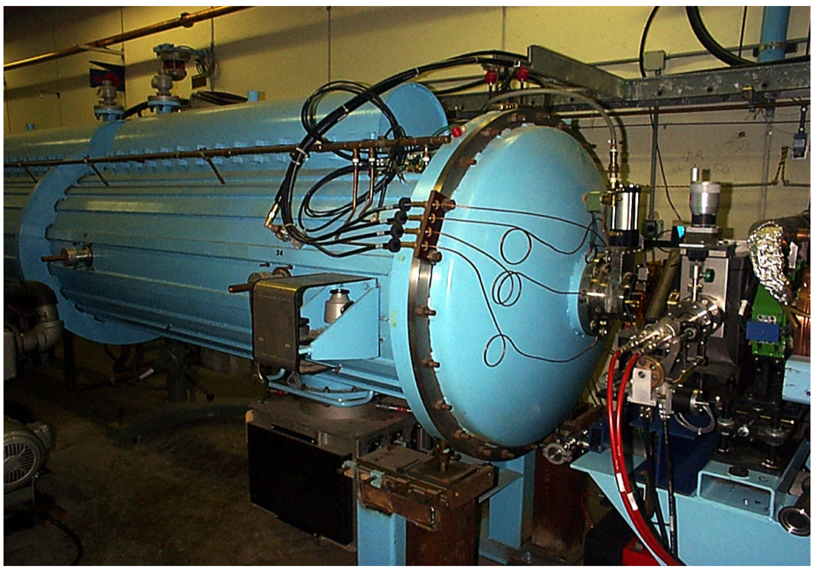
Notes:

Chapter 4, THE DRIFT TUBE LINAC

Introduction

Fermilab's original Linac was based on the Linear accelerator built by Luis Alvarez at Berkeley in 1947. Alvarez designed the first proton linear accelerator at the University of California at Berkeley where he was a Professor of Physics. He also provided the first published proposal for charge-exchange accelerators, discovered the K-capture process of He(3), received a Nobel Prize in 1968 for his work with liquid hydrogen bubble chambers (and working with his son Walter proposed the comet-impact origin of the extinction of species).

The FNAL Linac has two different sections:



The first section, figure 4.1, consists of five cylindrical, electrically-resonant, water-cooled steel tanks clad inside with OFHC (Oxygen Free, High Conductivity) copper. These Alvarez drift-tubes accelerate the beam from 750 keV to 116 MeV.

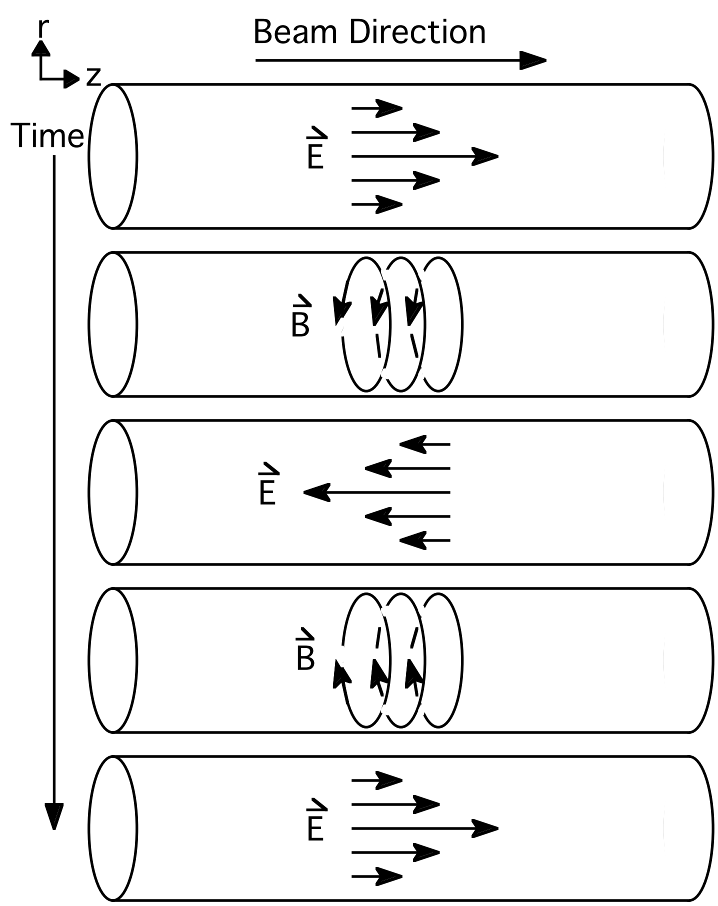
Figure 4.1

The second section, figure 4.2, has seven side-coupled cavity modules that operate at a frequency of 805 MHz. These modules are constructed of single cells brazed together in a structure capable of high vacuum. The side-coupled cavities can operate at higher accelerating gradients—7.5 MV/m. Seven 12 MW, 805 MHz Klystron RF power supplies drive the cavities and accelerates the beam to 400 MeV.

Electron versus Proton Linacs

It should be noted that there is an important difference between proton and electron Linacs. The $ß_s$ for electrons approaches unity at much lower energies than for protons. Thus $ß_s = c$ for an electron Linac. This implies that $ø_s$ can be designed to be zero, because it is not necessary to have a region of stable phase; an electron injected at any given phase will stay there. Setting ø = 0 for a proton Linac would maximize the energy gain for a very small number of particles, but the stable phase region would be so small that overall efficiency would be about zero. Electron Linacs can be made to run up to high energies. Above a few GeV, proton Linacs would more closely resemble electron Linacs because the velocity of the protons approaches c, but proton machines of that power would be neither inexpensive nor reliable. But higher energy proton Linacs do exist. Los Alamos operates an 800 MeV LAMPS facility that also uses a drift-tube and side-coupled cavity structure. Oak Ridge, Tennessee, is building a Spallation Neutron Source (SNS) that has an H- source, which can operate at 1 GeV.

Drift Tube Cavities



Fields

Figure 4.3 shows a simplified example of the field vector points for a drift-tube.

The magnitude of the electric field is constant along the length of each tank except for tank one. (The designed field in tank #1 slopes from 80% to 120% of the average gradient from upstream to downstream. This slope reduces coupling of beam energy into transverse directions.) The magnetic field component is circumferential in direction and is 90˚ in phase ahead of the electric field. Since the electromagnetic wave ψ function is not a product of free charge in the tank, the fields satisfy Laplaces's equation $\nabla^2\psi = 0$.

Figure 4.3

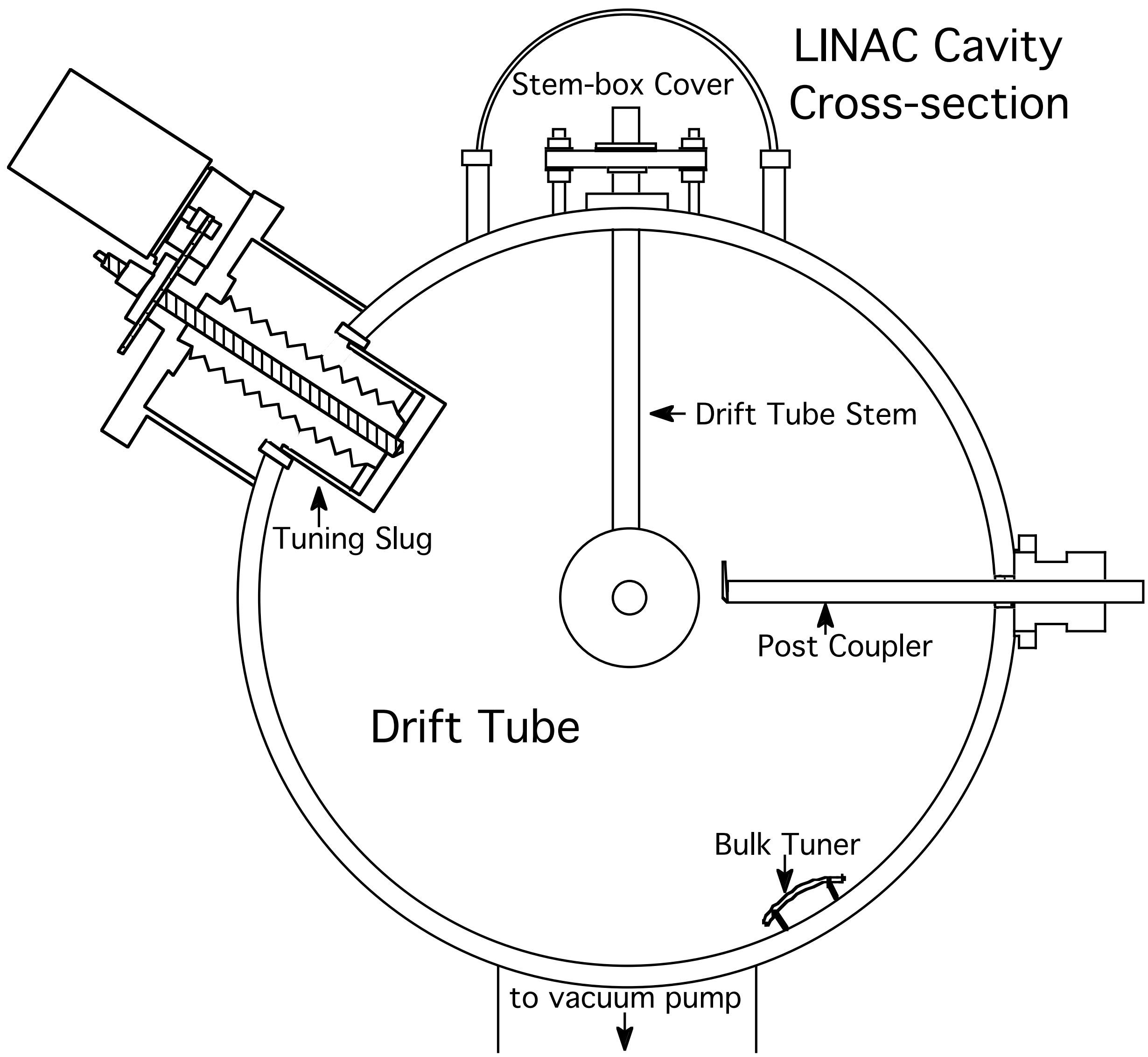


Figure 4.3.1

Accelerating Drift-Tube Cells

The interior of each drift-tube cavity actually consists of a number of resonant cells (figure 4.4); a cell runs from the middle of one drift tube to the middle of the next. The relative strengths of the electric fields in adjacent cells are controlled (in tanks 2-5) by the rotation of post couplers (figure 4.3.1). These posts stick out from the cavity walls at the cell boundaries. A small tab on the end of the post coupler biases the electric field toward one cell or the other, depending on the amount of rotation of the tab in that direction. The first drift-tube cavity has no post couplers. (Cell field levels are determined by the positions of the post couplers.)

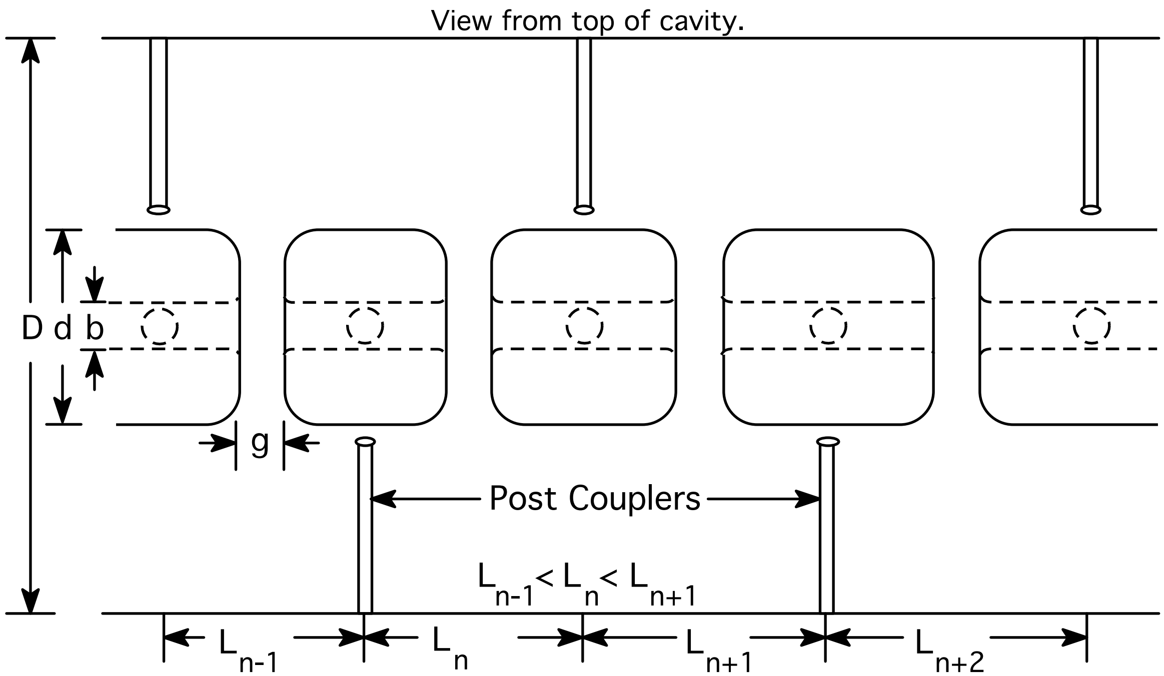


Figure 4.4

The length of the cells is such that particles traverse the gap between drift tubes when the electric field vector is pointing in the accelerating direction. When the electric field is pointing in the deceleration direction, the particles are shielded in the interior of the drift tubes ("drifting" in the absence of electric fields). The particles increase in energy and velocity with every gap crossed (figure 4.5).

The RF period should be equal to the transit time of the particles across the cell.

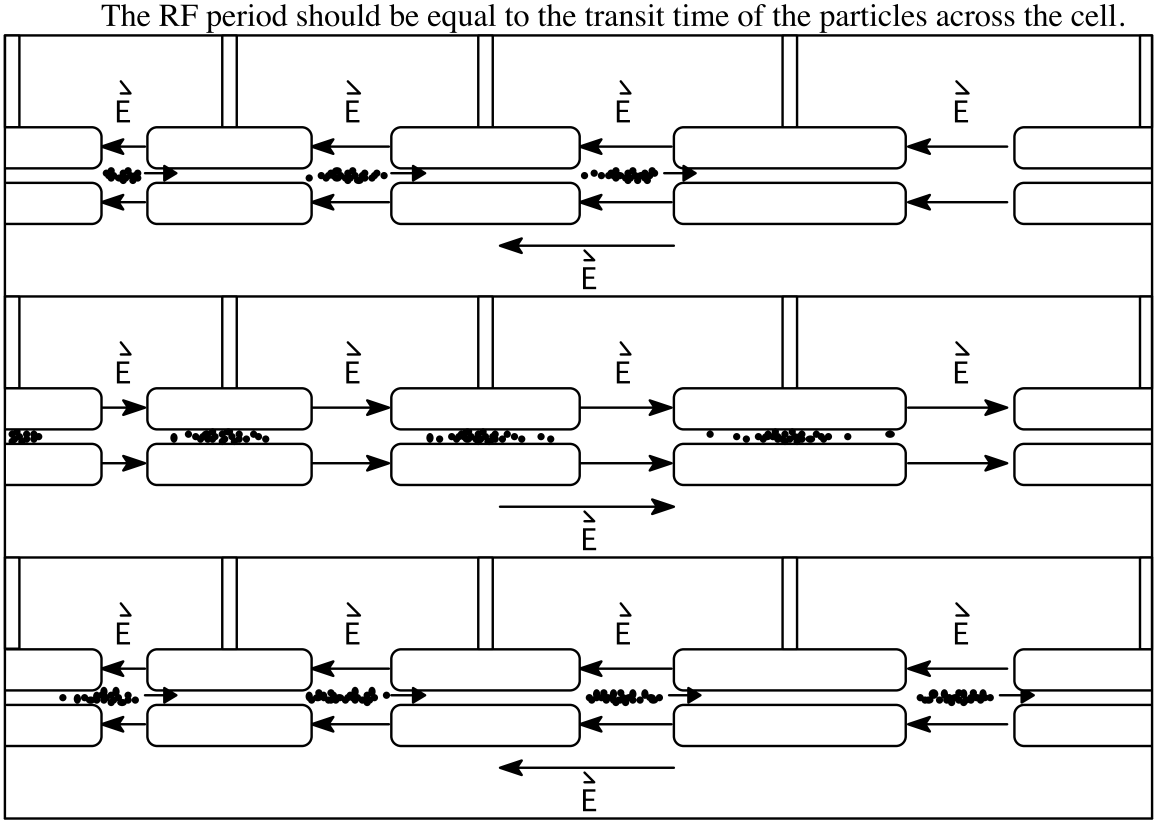


Figure 4.5

For a particle of charge e in an electric field E_0:

L = cell length

$$\text{Energy gain} = \Delta W_0 = e\int_{-L/2}^{L/2} E_0\,dz = eE_0\mathbf{L}$$

If E0 varies sinusoidally in time, the energy gain becomes:

$$\Delta W_{\sin} = e\int_{-L/2}^{L/2} E_0\cos\left(2\pi z/L\right)dz$$

which, of course, is zero. The drift tubes shield the particles at all times except when they traverse the narrow gap g, which takes a short amount of time with respect to the RF period, so the electric field doesn't vary much. This is equivalent to altering the limits of integration to get a nonzero value for $\Delta W_{\sin}$. The longitudinal transit time factor is defined by $T_1 = \Delta W_{\sin}/\Delta W_0$, which is determined by cell geometry $(T_1 < 1)$. Then:

$$\Delta W_{\sin} = \Delta W_0 T_1 = eE_0T_1L$$

If a particle is made to pass through the center of the cell at some phase ø before the maximum electric field, the energy gain becomes:

$$\Delta W_\phi = eE_0T_1L\cos\phi$$

There is one ø that will make the particle reach the center of the next cell just as the RF has gone through exactly 360°; this is the synchronous phase angle $ø_s$, with energy gain ΔW_s.

If a particle has a phase different from $ø_s$, it will have an energy gain different from ΔW_s; for a nonrelativistic particle, this will result in an incorrect average velocity through the cell with resultant phase shift with respect to the RF when the particle enters the next cell. In the case where $ø_s$ is before the RF peak, particles arriving early will gain less energy in the gap and slip back toward $ø_s$.

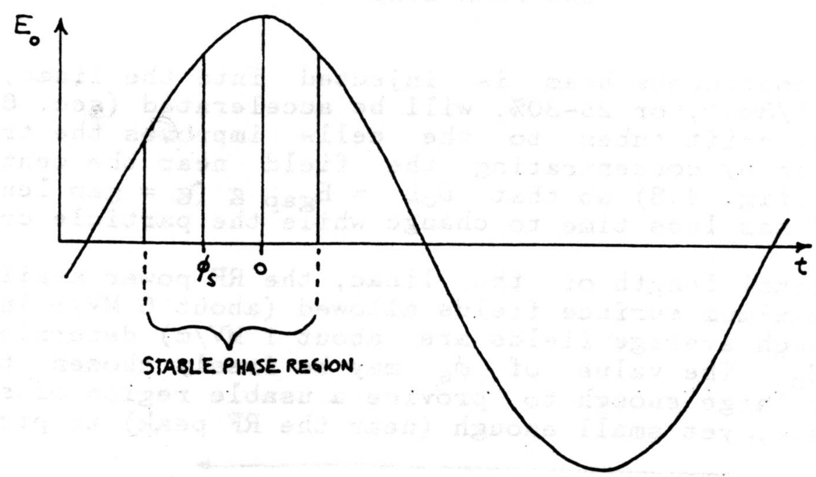


Figure 4.6

Particles arriving too late will gain more energy in the gap and catch up to $ø_s$. The particle with $\phi = \phi_s$ and $\Delta W = \Delta W_s$ is called a synchronous particle. The synchronous phase angle in the FNAL Linac is -32°. The stable phase region runs from about - $ø_s$ to $2ø_s$ (figure 4.6), about 105° (TM279). The synchronous phase angle in tank one is a little larger because the gradient is a bit higher.

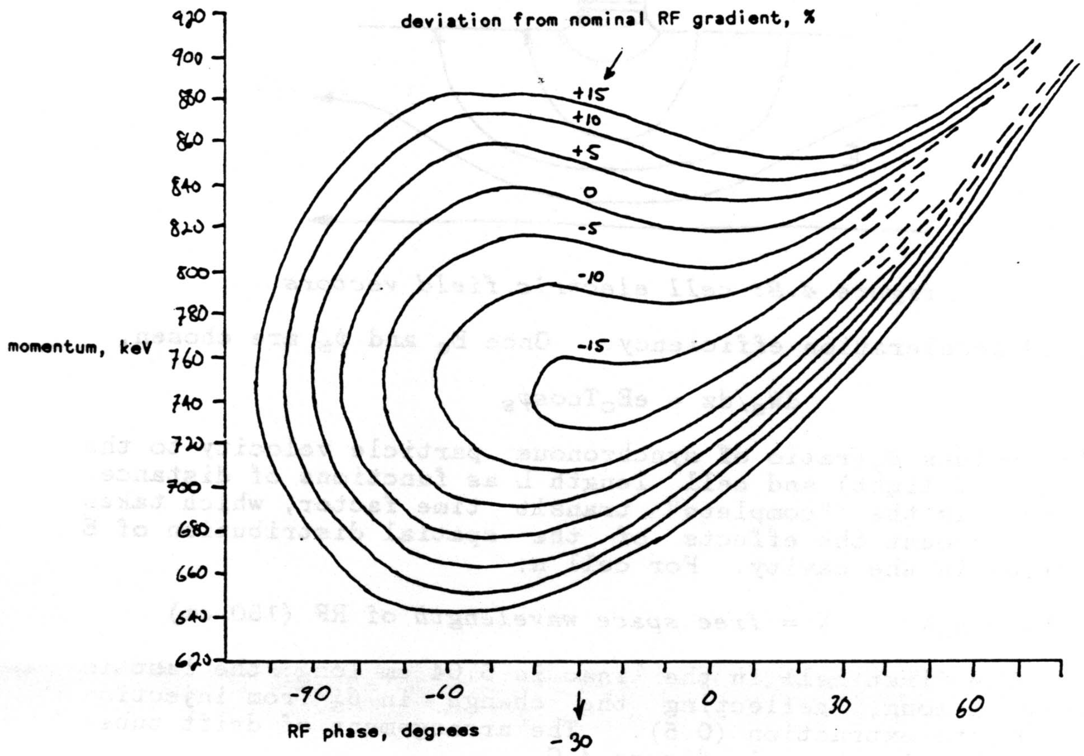


Figure 4.7

This stable phase region also defines the length of the RF bucket, outside of which particles are rapidly lost. A more conventional way to represent RF buckets is to draw them in phase space, where the horizontal axis represents particle position (or RF phase) and the vertical axis represents particle momentum (figure 4.7). The RF bucket is then a curve in phase space. (For an excellent discussion of this topic, read "Proton Synchrotron Accelerator Theory," by E. J. N. Wilson.)

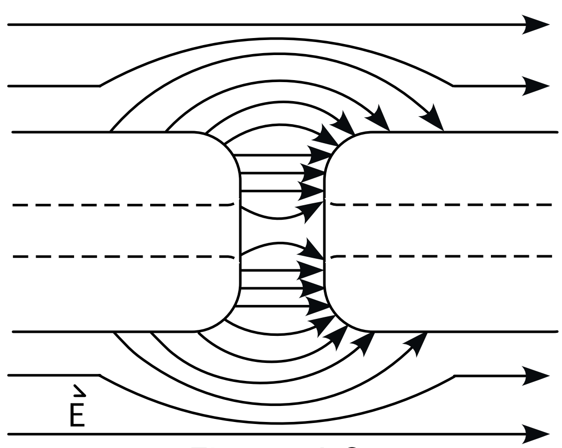


Figure 4.8

If a continuous beam is injected into the Linac, only 25 to 30% (105˚/360˚) is accelerated.

Drift tubes improves the transit time factor by concentrating the field near the center of the cell (figure 4.8) so that $E_0L = E_{gap}g$, where g = gap length. The field has less time to change while the particle crosses the gap.

The total length of the Linac, the RF power available, and the maximum surface fields allowed (about 6 MV/m in this case, though average fields are about 1 MV/m) determine the maximum E_0. The value of $ø_s$ may be freely chosen, but it should be large enough to provide a usable region of stable phase space, yet small enough (near the RF peak) to provide good acceleration efficiency. Once E_0 and $ø_s$ are chosen,

$$dW_s/dz = eE_0 T \cos\phi_s$$

determines ß$_s$ (the ratio of synchronous particle velocity to the speed of light) and cell length L as functions of distance. T is the "complete" transit time factor, which takes into account the effects of the spatial distribution of E fields in the cavity. For cell n,

$$L_n = \beta_s \lambda$$

where λ = the free space wavelength of the RF (200 MHz).

DTL Design Considerations

The RF power required to establish a field E_0 in a cell is:

$$P = (E_0 L)^2 / (ZL)$$

where Z = normal shunt impedance per unit length. The effective shunt impedance is defined as $R_s = ZT^2$ where T is the complete transit time factor. Then:

$$P = (E_0 L T^2) / (R_s L) \quad \alpha \quad (\Delta W_s)^2 / (R_s L)$$

R_s units $\quad M\Omega/m$

The major considerations in the design of the drift tube structure are:

- The determination of the drift tube and cavity geometry such that the structure will resonate at the design frequency.
- Obtaining the best electric field distribution near the axis (making divergence as small as possible).
- The determination of R_s and T. To minimize P we must maximize R_s and T.

It is desirable to use as high an RF frequency as possible, since R_s for a particular geometry varies as $\lambda^{-1/2}$, and the power required to maintain a particular field level varies as λ^{-2}. However, decreasing λ requires that the dimensions of the cell be made smaller; this creates a problem since the borehole diameter b has a minimum size (if it gets too small the beam won't fit through). Also, as the ratio of b to drift tube diameter d increases (figure 4.14), the effective radial variation of the field near the axis increases, introducing a large radial variation in the transit time factor that couples to radial and phase motions of the particles. Furthermore, it is necessary to incorporate radial focusing magnets (quadrupoles) in the drift tubes , which implies a minimum drift tube size. Finally, since $L = \beta_s \lambda$, there is a practical minimum injection energy for the Linac.

Cavity Number		**Units**	**1**	**2**	**3**	**4**	**5**
Proton Energy in		(MeV)	0.75	10.42	37.54	66.2	92.6
Proton Energy out		(MeV)	10.42	37.54	66.18	92.6	116.5
Cavity Length		(m)	7.44	19.02	16.53	16.68	15.58
Cavity Diameter		(cm)	94	90	88	88	84
Drift tube Diameter		(cm)	18	16	16	16	16
Borehole Diameter		(cm)	2.0-2.5	3.0	3.0	3.0	4.0
Cell Length L	(First Cell)	(cm)	6.04	12.2	41.1	53.3	61.8
	(Last Cell)	(cm)	21.8	40.8	53.0	61.5	67.9
Gap Length g	(First Cell)	(cm)	1.3	4.4	12.2	19.5	22.6
	(Last Cell)	(cm)	6.7	12.7	19.3	25.1	26.9
g/L	(First Cell)		0.21	0.2	0.3	0.37	0.37
	(Last Cell)		0.31	0.31	0.36	0.41	0.4
Axial Transit Time Factor	(First Cell)		0.64	0.86	0.82	0.75	0.73
	(Last Cell)		0.81	0.81	0.75	0.69	0.69
Effective Shunt Impedance	(First Cell)	(MΩ/m)	27	53.5	44.6	35	29.6
	(Last Cell)	(MΩ/m)	47.97	44.8	35.2	28.5	25
Drift Space Following Cavity		(m)	0.22	0.6	0.75	1.0	1.0
Number of Full Drift Tubes			55	59	34	28	23
Average Axial Field		(MV/m)	1.6-2.31	2.0	2.6	2.6	2.56
Average Gap Field	(First Cell)	(MV/m)	7.62	10	8.7	7.03	6.9
	(Last Cell)	(MV/m)	7.45	6.45	7.2	6.3	6.4
Peak Surface Field	(First Cell)	(MV/m)	8.9	12.6	13.1	12.9	14
	(Last Cell)	(MV/m)	10.2	9.7	12.9	13.2	14.1
Cavity Excitation Power		(MW)	0.61	1.5	2.34	2.44	2.5
Total Power per Cavity for 100 mA		(MW)	1.58	4.2	5.2	5.08	4.9

Figure 4. 9, Linac Specifications

Another trade off involves the ratio g/L. Making this ratio small optimizes T, but making the gap between two drift tubes very small increases the chances of sparking. Optimum values for g/L run from 0.2 to 0.4. Typically, D is fixed and g/L is juggled to obtain a maximum R_s.

Since each tank is made up of a series of resonant cells, the decision where to end the tanks is somewhat arbitrary. It is necessary for the E fields in the tanks to have a very strict phase relationship to one another, so it would be nice to have one cell per tank. But this would require an enormous and impractical (and very expensive) RF system. There is also a maximum practical limit for the length of a tank: about 20 free space wavelengths. This is because the separation of electromagnetic standing wave modes decreases as length^{-2}, and the effects of mechanical imperfections on local frequency errors increases as $(length/\lambda)^2$, resulting in difficulty maintaining the desired field distribution in the cavity.

Finally, there is a simple trade off between RF power required and overall length L of the Linac. Since:

$$PL\alpha \left(\Delta W_s\right)^2 / R_s = \text{construction (for a given geometry)}$$

one can use less powerful (cheaper) RF if the Linac is made longer. However, the costs of drift tubes and supporting structures usually make it most practical to obtain the largest reasonably priced RF systems available. (The RCA power amplifiers were originally developed for use in radar stations.)

Cavity Fields

Both the SCL Linac and the DTL operate in the TM_{010} Mode. This describes the field and its direction. The mode is generally in the form TM_{1mn} and TE_{1mn} where 1, m, n, are derived from Bessel functions that describe the field's zero crossing in a resonant cell.

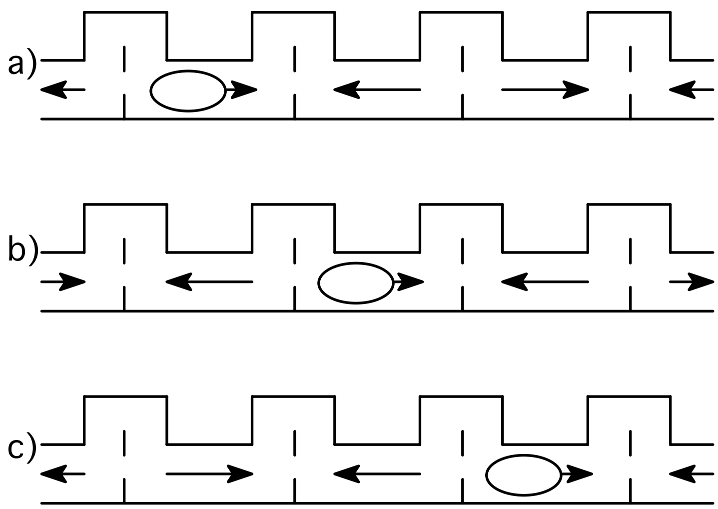


Figure 4.10

The phase shift describes the phase difference from one cell to a nearby cell. In the SCL, the phase shift from an accelerating cell to its nearest cell, a coupling cell, is $\pi/2$. The phase shift from one accelerating cell to the next is π, and the distance between the accelerating cells is $\beta\lambda/2$. (Where β equals the particle velocity divided by the speed of light, and λ is the wavelength of the electric field.) Therefore, since the phase shift between accelerating cells is π, the fields in adjacent accelerating cells are always in the opposite field. (See figure 4.10) When beam enters the first cell, the field is in the accelerating direction. As beam goes through the nose cone, the fields shift in the other direction. When beam enters the second cell, the field is now in the accelerating direction while the field in the first cell is in the decelerating direction. There is no beam in the first cell to see the field so nothing is actually decelerated. The beam continues to go through the cavities with accelerating fields, and beam is accelerated. The beam pulses from the DTL travel 8 cells apart in the SCL. (See figure 4.11) In contrast, the DTL phase shift is 0 between accelerating cells and the cells are separated by $\beta\lambda$. The $\pi/2$ mode has a great advantage over 0 and π modes in that it gives stability to the RF frequency phase.

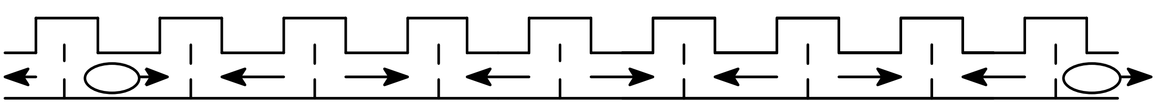


Figure 4.11

The above diagram shows the spacing between beam pulses during acceleration. There can be up to two pulses in a section and eight pulses in one module.

Linac RF Systems

There are 5 drift tube cavities (DTL) and 7 side coupled cavities (SCL) in Linac. The DTL makes up the first stage of the Linac and the SCL is the second stage. Each stage has its own RF systems that work on different frequencies. These systems drive their appropriate cavity fields to the gradient and phase necessary for suitable energy gain.

This is how it's accomplished. Every Linac cycle (66 msec) the RF systems provide a short pulse for the acceleration of beam. In between the RF pulses the cavity field collapses. Since the cavities are a highly resonant system, with a geometry that assumes a certain energy gain per cell, the failure of any RF system will strongly affect the transmission and output momentum of the Linac, making transmission of beam through the Linac impossible.

Each RF section consists of a low-level and high-level RF system. The low-level system provides a low power signal of the appropriate amplitude and phase for the high-level system, which is then amplified to about 5MW for the DTL and 7-9 MW for the SCL. This power is sent via a coaxial transmission line for the drift tubes cavities, and a rectangular wave-guide for the side coupled cavities to induce the electromagnetic fields in the cavity.

DTL RF System Operation

The cavity gradients and phases have a direct effect on the output momentum of the Linac. **You do NOT change the nominal values for these devices**. Any tuning of these parameters consists strictly of keeping them at their nominal values.

The second IPA, driver, and PA tubes are high Q tuned resonators that require occasional tuning, due to tube aging and fluctuations in supply voltages. The forward and reverse power of each stage (the power sent to and reflected from the load) is tuned by adjusting resonant input and output cavities on the tubes. Forward power is tuned to a specific level, while reverse power is tuned for a minimum, matching the impedance of one stage to the next. Reverse power of stage n is tuned by adjusting the input cavity of stage n+1, which affects the forward and reverse power of stage n+1, and so on.

Figure 4.12a

Each tube cavity has two adjustments, tuning and loading. The tuning adjustment actually changes the resonant frequency of the tube cavity, and the loading adjustment changes the coupling between the cavity and its load (the adjacent stage). On the left (figure 4.12a), you can see a picture of station one's driver racks. An overview of the driver racks, where most of this tuning is done, is shown in figure 4.12b.

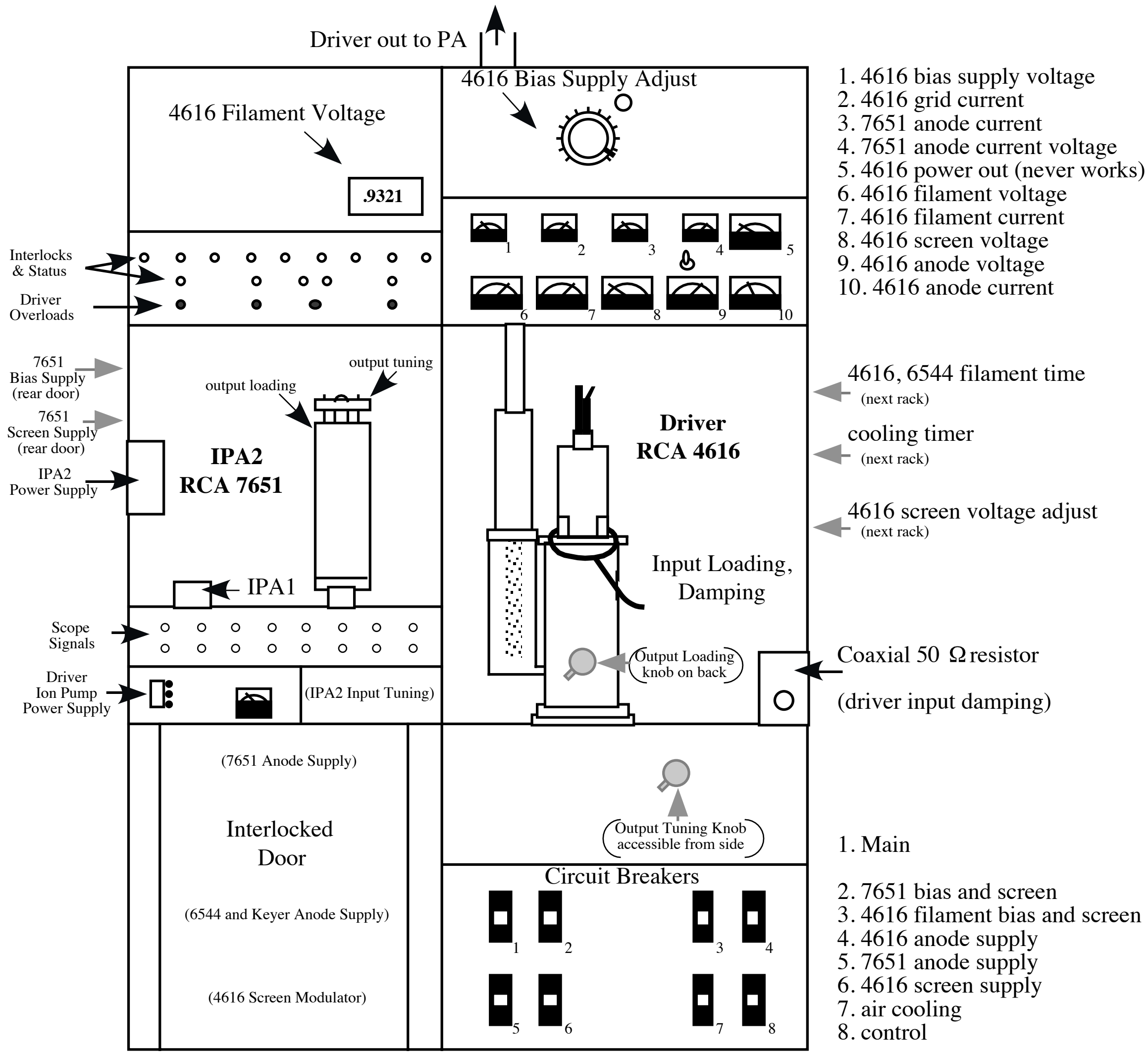


Figure 4.12b

Tuning an RF system is covered in OPBULL 1050. Please note that some of the adjustments are relatively insensitive, like the driver output tuning. However, others, like the **PA tuning**, **you are forbidden from adjusting**. Once all the stages have been tuned, the total phase shift across the amplifier chain will have changed. This will necessitate an adjustment of the fast feedback loop to zero phase lock input during beam time. The general layout of the RF system control panel is shown in figure 4.12b.

Once the procedure in OPBULL 1050 has been followed, connect the PHASE LOCK INPUT signal to the scope. It should be zero during beam time. If not, zero it using a small screwdriver to turn the PHASE REF ADJ pot on the front of the frequency control and phase lock module. PHASE LOCK OUTPUT should then be five volts at beam time.

The cavity represents a tuned L-C-R circuit that resonates at 201.24 MHz. The spaces between the drift tubes act like capacitors and the space between the drift tubes and the cavity wall acts like an inductor. When properly tuned, the capacitive and inductive reactances cancel and the cavity looks like a purely resistive 50 Ω load. If not properly tuned at full gradient, substantial power may be reflected back through the transmission line. This could damage the PA ceramic and the gas barrier by arcing across them, creating an effective electrical short.

To insure that the cavity is well tuned, the tuning slug tries to keep the PA reverse power at a minimum during beam time. An offset may work its way into the feedback loop, though, requiring some manual tweaking. Place the cavity tuner control into manual (figure 4.13b) and run the slug in and out to zero the PA reverse power during beam time. Then flip the tuner into auto and watch the reverse power. If all is well, it won't move. If it does, manually tune the slug for zero reverse power again and walk around to the back of the module. Using a very small screwdriver adjust the potentiometer on the back of the "frequency control and phase lock module" until the FREQ INC and FREQ DEC LEDs are both out. Then set the slug control back into auto. The reverse power during beam time should now stay at zero.

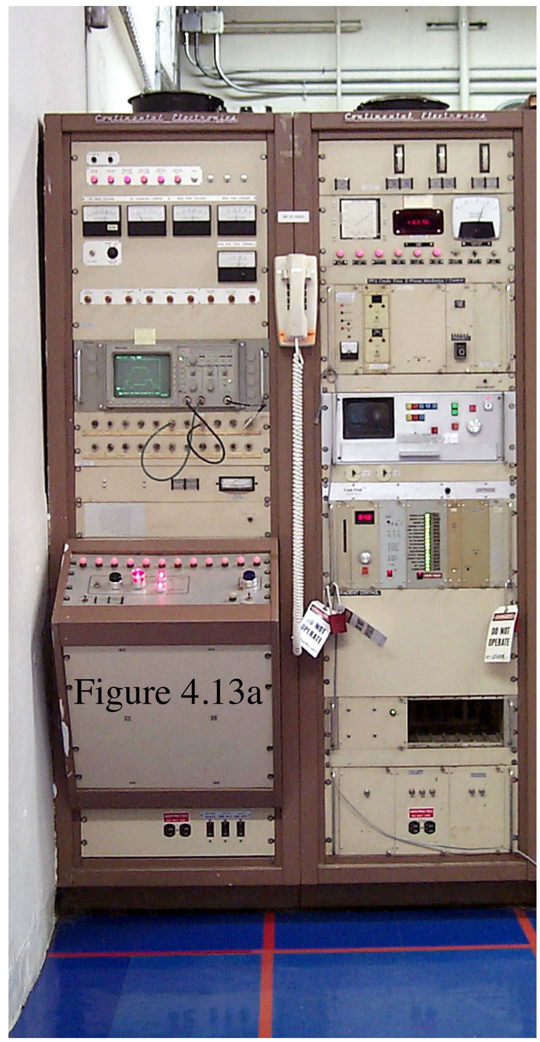


Figure 4.13a

Permanent inhibits are indicative of problems in the PA or transmission line. After a permanent inhibit, a local reset should be done and the gradient slowly turned back up while watching and listening for sparking in the PA and transmission line and looking for unusual vacuum activity in the form of high current flows in the cavity ion pumps. The operating impedance of the PA should be about 100 Ω, which can be calculated from the modulator peak voltage and peak current meters. A calculated value is also displayed on channel L:MDxLZ, where x is the system number. If the PA impedance is high, the filament current maybe raised to bring it into line (OPBULL 692). The filament current should not exceed 7000 amps without consulting a Linac specialist. Note that the current readback calibration is given by a graph posted next to the control switch.

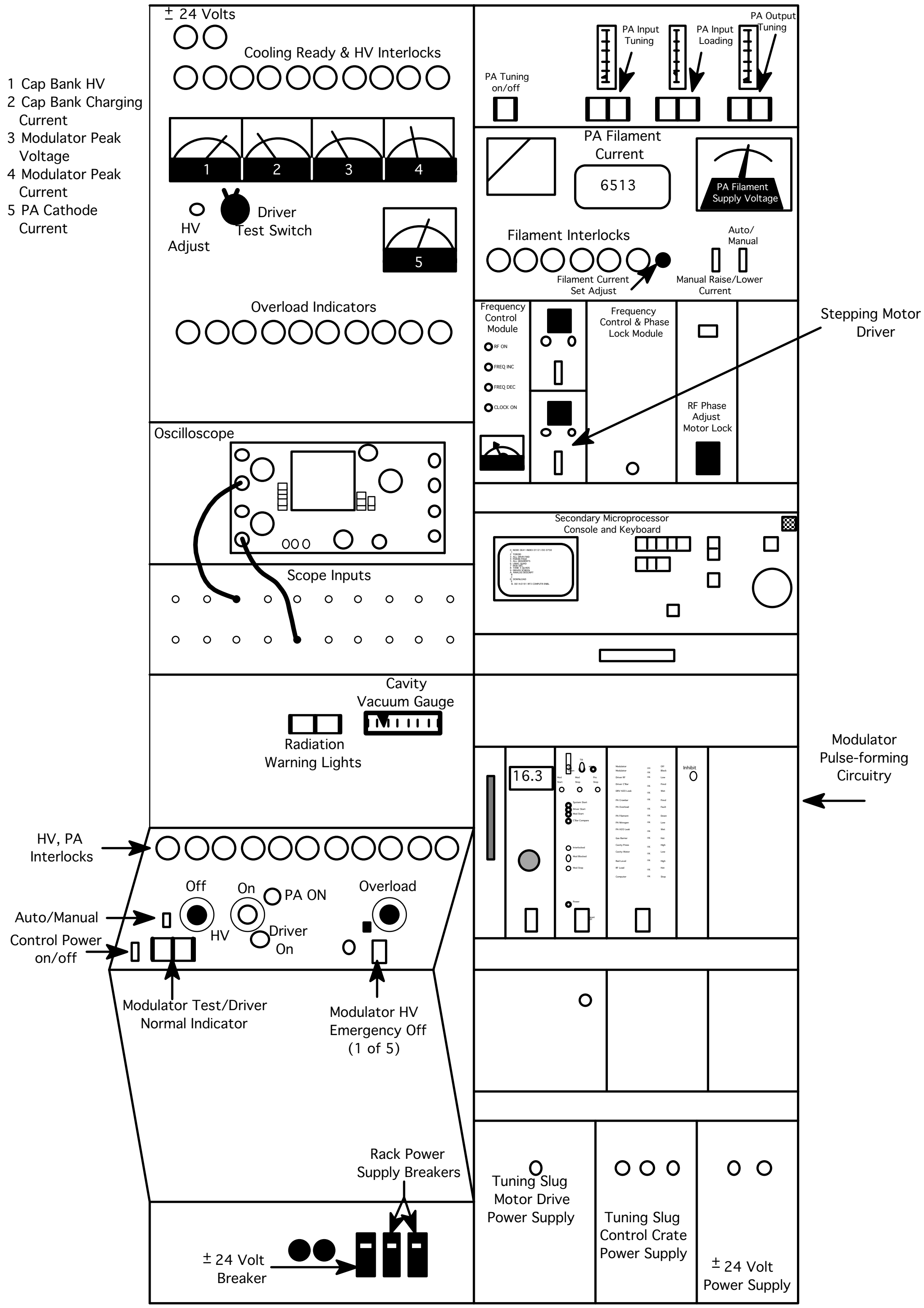

1 Cap Bank HV
2 Cap Bank Charging Current
3 Modulator Peak Voltage
4 Modulator Peak Current
5 PA Cathode Current
± 24 Volts
Cooling Ready & HV Interlocks
HV Adjust
Driver Test Switch
Overload Indicators
PA Tuning on/off
PA Input Tuning
PA Input Loading
PA Output Tuning
PA Filament Current
6513
PA Filament Supply Voltage
Filament Interlocks
Auto/ Manual
Filament Current Set Adjust
Manual Raise/Lower Current
Frequency Control Module
Frequency Control & Phase Lock Module
RF Phase Adjust Motor Lock
Stepping Motor Driver
Oscilloscope
Scope Inputs
Secondary Microprocessor Console and Keyboard
Cavity Vacuum Gauge
Radiation Warning Lights
Modulator Pulse-forming Circuitry
16.3
HV, PA Interlocks
Auto/Manual
Control Power on/off
Off
On
PA ON
HV
Driver On
Overload
Modulator Test/Driver Normal Indicator
Modulator HV Emergency Off (1 of 5)
Rack Power Supply Breakers
± 24 Volt Breaker
Tuning Slug Motor Drive Power Supply
Tuning Slug Control Crate Power Supply
± 24 Volt Power Supply

Figure 4.13b

If the RF at a station is off for several minutes, the cavity will cool down and be out of tune. When turning the station back on, the gradient should be raised slowly while watching PA reverse power (OPBULL 74, 596) and the position of the tuning slug (analog meter on front of the frequency control module).

An occasional PA crowbar from the RF systems is no cause for concern. If one particular station is crowbarring a lot, the usual solution is to turn down the modulator capacitor bank voltage a couple of kV. This voltage is controlled by a knob on the A5 rack cabinet (figure 4.13b) and read back on the PA HIGH VOLTAGE meter. Cap bank voltage should not be lowered below 35 kV because it will get so low that the switch tubes will "max out" during the pulse and lose output control. (Remember that the modulator regulator's job is to keep the modulator output the same.) The modulator voltage waveforms (figures 4.14a & b) will become distorted if this occurs, so watch the scope trace while lowering the cap bank voltage.

If problems with the station persist, leave the station off until an expert arrives. If you must turn off a station completely use the following procedure:

1) Turn gradient down (amplitude control module).
2) Turn modulator pulse off (waveform generator/sequencer).
3) Turn modulator high voltage off.
4) Turn EMERGENCY OFF switch to off position. This grounds the modulator's capacitor bank, first through a "soft" ground stick, then a direct short to ground.
5) Place PA filament control switch in MANUAL and lower filament current to zero with toggle switch.
6) Turn control power off.

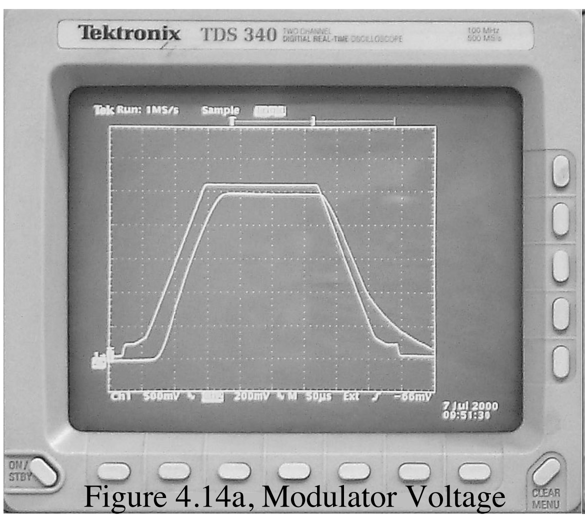


Figure 4.14a, Modulator Voltage

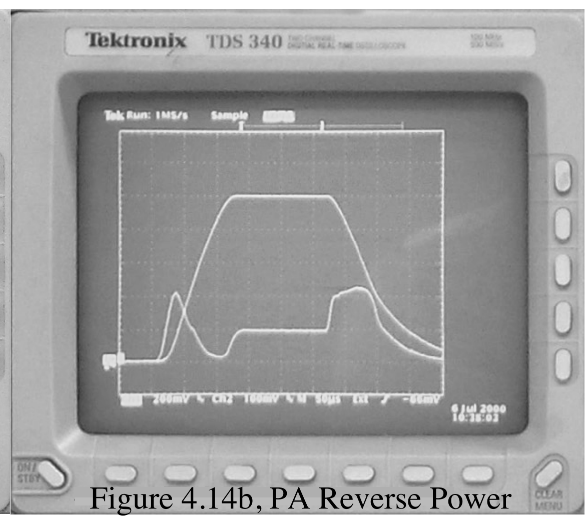


Figure 4.14b, PA Reverse Power

Cooling will remain on until the timers time out, unless the main breaker is shut off first. Only in an emergency should the main breaker be thrown before cooling shuts off. Note that this procedure is NOT sufficient for safety if the system is to be worked on. Linac specialists will supply further instructions if necessary.

Once repairs have been completed, the procedure for turning back on is as follows:

1) Turn control power on.
2) Place PA filament control switch in AUTO.
3) Wait for small red light next to blue OVERLOAD button to flash and then press the blue overload button. System overload status lights (top of A5 rack) should

go out PA filaments are brought up automatically if the switch is in the AUTO position, and modulator and driver will time out.

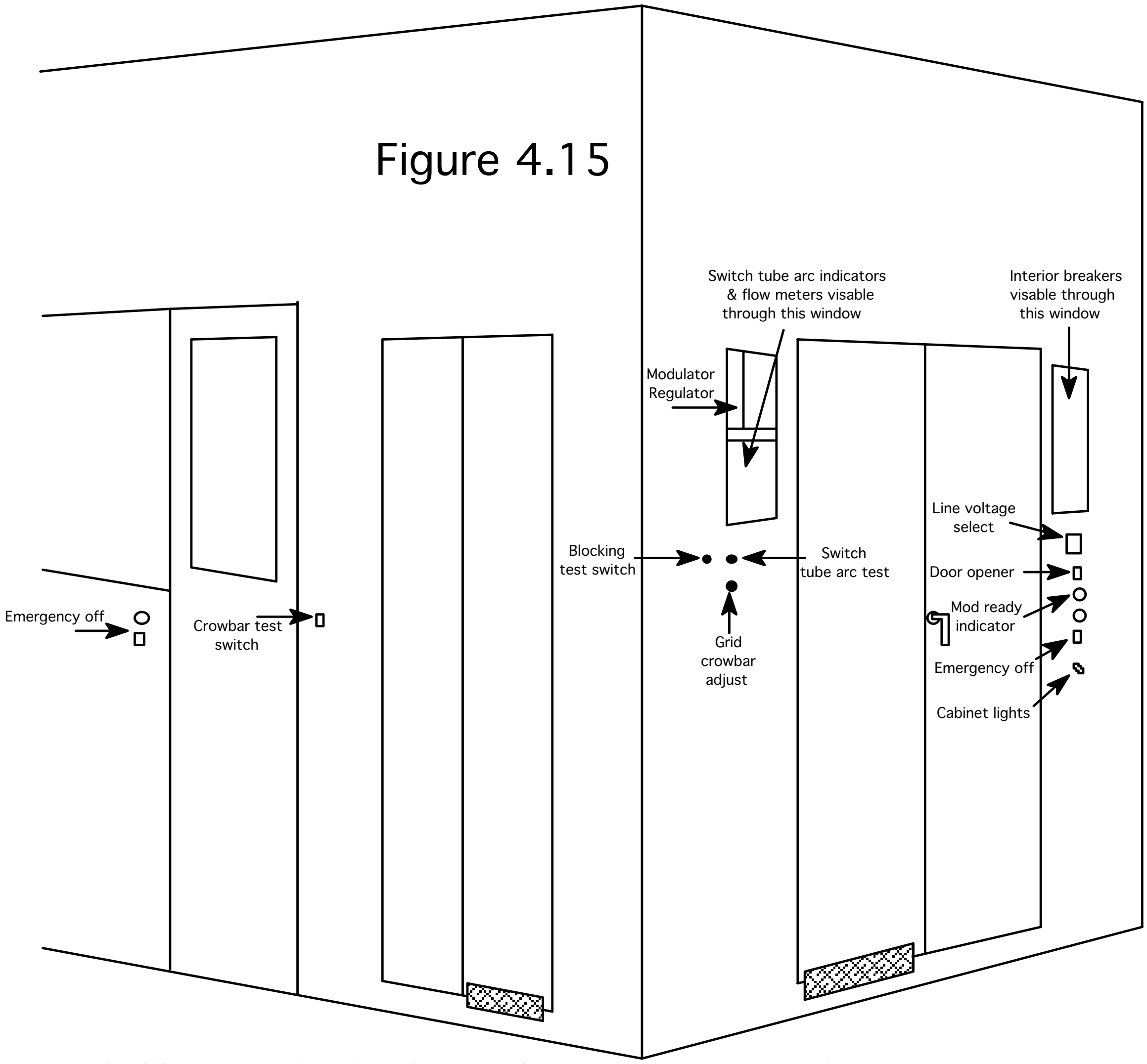
4) Turn EMERGENCY OFF switch to on position. There are actually five of these switches, and all must be on before modulator high voltage will come on. Switches are located on the A5 control panel, on the front of the modulator, on the left side of the modulator, on the crowbar rack on the right side of the modulator, and on the high voltage rectifier in the lower Linac gallery.
5) Turn modulator high voltage on. Driver high voltage comes on after second IPA screen bias comes on and driver anode supply is ungrounded.
6) Make sure gradient is set to zero.
7) Turn pulse on, check for nominal driver output.
8) Turn gradient up slowly, catching tuner penetration and PA reverse power. If RF has been off for some time, cavity will be cold and out of tune.

This procedure, which is a sign-off procedure, assumes that no difficulties are encountered in reviving the station. (You can find a description of the interlock lights in OPBULL 1049.) Consult a Linac specialist for difficult problems.

If the MOD READY interlock is lost, it usually means that a circuit breaker in the modulator had blown (figure 4.15). To access the modulator:

1) Turn down the gradient and shut off the pulse and the modulator high voltage.
2) Turn the EMERGENCY OFF switches on the control panel, and the front of the modulator off, and shut off the HV breaker.
3) Press the door open button and open the front door of the modulator. There is a ground stick mounted just inside the doorframe on the right hand edge.
4) While looking away (in case there's an arc), ground out the inner box. Hang the ground stick on the inner box.
5) Reset the breaker.
6) Return the ground stick to its stored position (this will close a microswitch to permit the high voltage to be turned on).
7) Close the door.
8) Turn the EMERGENCY OFF switches back on.
9) Turn the high voltage back on.
10) Turn on the pulse and raise the gradient back to nominal.

Although you are encouraged to troubleshoot problems, any modulator work more involved than resetting tripped breakers needs to be left to the experts. Modulators are dangerous!



If a life-threatening situation should ever arise when working on an RF system, throw the main breaker (figure 4.16) located in the A3 racks. This breaker is bordered in red and is easy to see. Throwing it will shut down everything in the system immediately. This is a rude shock for many components, so it should be done only in emergencies.

Spare modulator pulse forming network modules and power supplies are located in cabinets near station 5. Other spare items (aside from station 7) are located in a lock-up in the lower Linac gallery beneath system 1. A key is available from the key tree in the MCR.

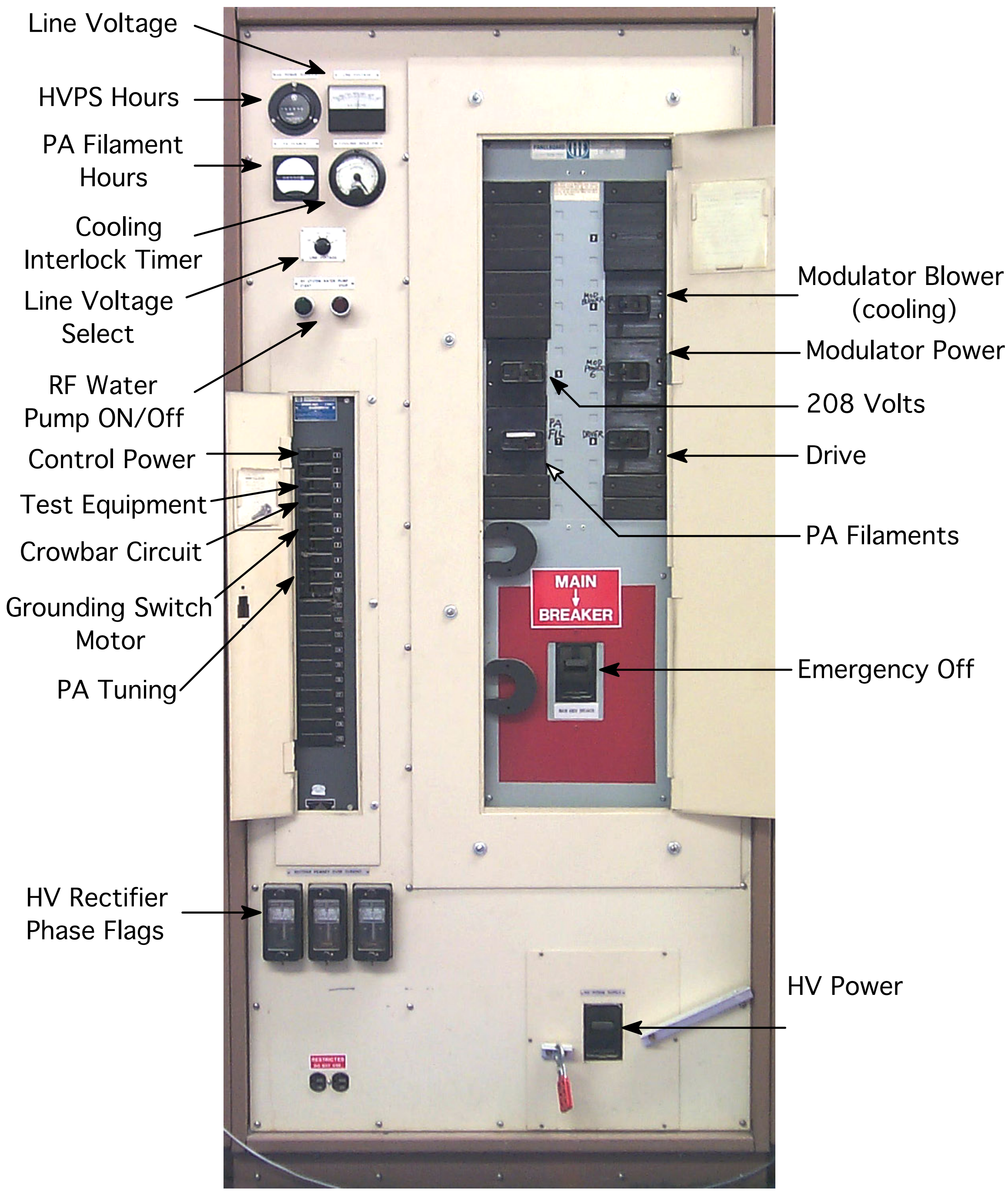

Line Voltage
HVPS Hours
PA Filament Hours
Cooling Interlock Timer
Line Voltage Select
RF Water Pump ON/Off
Control Power
Test Equipment
Crowbar Circuit
Grounding Switch Motor
PA Tuning
HV Rectifier Phase Flags
Modulator Blower (cooling)
Modulator Power
208 Volts
Drive
PA Filaments
MAIN BREAKER
Emergency Off
HV Power

Figure 4.16

Average values for RF system meter readings are shown here. All RF systems are slightly different, both in tune and temperament, so expect deviations from these numbers.

All racks:

4616 bias	200	VDC
4616 grid	30-50	mA
7651 anode	10-20	mA
7651 anode	3.5	kVDC
4616 filament	0.9	VAC
4616 filament	480	VAC
7651 bias	15	VDC
7651 screen	0.6	kVDC
4616 screen	20-50	mA
4616 screen	1.2	kV
4616 anode	17	kVDC*
4616 anode	110	mA
4616 filament	0.95	V

*Only works at system 1

A5 racks:

PA high voltage	40	kVDC
PA charging I	0.85	A
Modulator peak V	22-25	kVDC
Modulator peak I	250	A
PA cathode I	3.1	A
PA filament V	5.2	VDC
PA filament I	6700	A

Modulator:

6544 plate V	6.6	VDC
6544 plate I	0.23	A
Switch tube bias	2.8	kVDC
Switch tube bias	0.3	A

Drive Signal for RF

L:LLxF	4W
L:IPA1xF	350W
L:IPA2xF	4KW
L:DRxF	175W

Low Level RF

The LLRF drive signals—201.24 MHz for DTL and 804.96 for SCL—come from relay rack LT-5 located in the transition section on the far north side of the Klystron power supply gallery.

The LLRF system has the following task requirements:

- Provide the 1mW RF signal to the solid-state amplifier that drives the Klystron 12MW amplifiers (SCL) and a half-watt signal to the PAs (DTL).
- Provide an error signal to the water control loops that indicates the amount of cavity frequency error due to temperature detuning.
- Provide a station phase shifter and detector to use during phase scans and to set the final cavity phase.
- Provide an RF frequency that can track the cavity resonance frequency. This is the cold start system.
- Regulate the cavity gradient phase and amplitude to 1 degree and 1%. This is done with conventional feedback and with the help of a learning system that injects a signal into the loop in a feed-forward configuration.
- Terminate RF after the detection of cavity sparks on the nanosecond time scale.

In the lower section of the relay-rack LT-5 is a Mech-Tronics crate that houses the following modules:

- Reference Line Pressure Readout Module
- Reference Line 805 MHz ÷4 Module
- Phase Shifter Module
- Up Dn Control Module
- Phase Detector
- 201.2408/804.9632 MHz Frequency Reference

Directly above the Mech-Tronics crate is a Hewlett-Packard Computing Counter that displays the low-level signal sent to the DTL stations for reference. And above that is the VME bus crate electronics.

DTL LLRF

The Frequency Control and Phase Lock Module in the RF system control relay rack receives the LLRF signal. The module works like this (see figure 4.17): the signal first goes through the two-phase shifters (SH1 & SH2) that regulate the intertank phase. The output of the shifters is the desired RF phase for that station.

Power shifter PS1 sends the signal to phase shifter SH3, which in turn feeds a mixer that turns the continuous wave signal to pulses, as governed by the waveform generator/sequencer (not shown). Amplified by a series of two solid state and three tubes, the pulsed RF drive signal travels the transmission line to the cavity.

Pickup loops in the cavity measure the magnetic field in the center and at each end of the cavity. The output of the center pickup loop is compared with the "desired" RF phase at the phase comparator mixer PC1. The bipolar output of this circuit (phase lock input) is designed to be zero when the correct relation ship exists between the desired and actual RF phases. The signal is raised by five volts (phase lock output) and drives the phase shifter SH3. This counteracts the effects of cavity RF phase shifts caused by beam loading on the cavity (as the beam extracts energy from the cavity), the effects of PA tube and modulator aging, and the vagaries of tuning. This is sometimes known as the "fast" feedback loop.

A second loop acts to keep the cavity tuned to the correct frequency. When correctly tuned, the cavity looks like a purely resistive load; the cavity field is in phase with the applied voltage. Any phase difference due to a mistuned cavity can be observed by comparing the RF phase in the transmission line with the RF phase in the cavity. The "slow" loop does just this. A second output of the power splitter PS2 goes to phase shifter SH5 and to one output of the phase comparator mixer PC2. The other input comes from the forward power pickup loop in the transmission line. ("Forward" is specified because there is also a reverse power loop that measures power reflected from the cavity.) The output of PC2 is zero at the desired phase relationship between the inputs, which is set by the frequency adjust potentiometer. This is done after the power amplifier reverse power (for the transmission line reverse power pickup loop) has been tuned for a minimum.

If the output of PC2 is nonzero, the frequency control module will then tell the stepping motor driver to move the tuning slug, which alters the cavity resonant frequency.

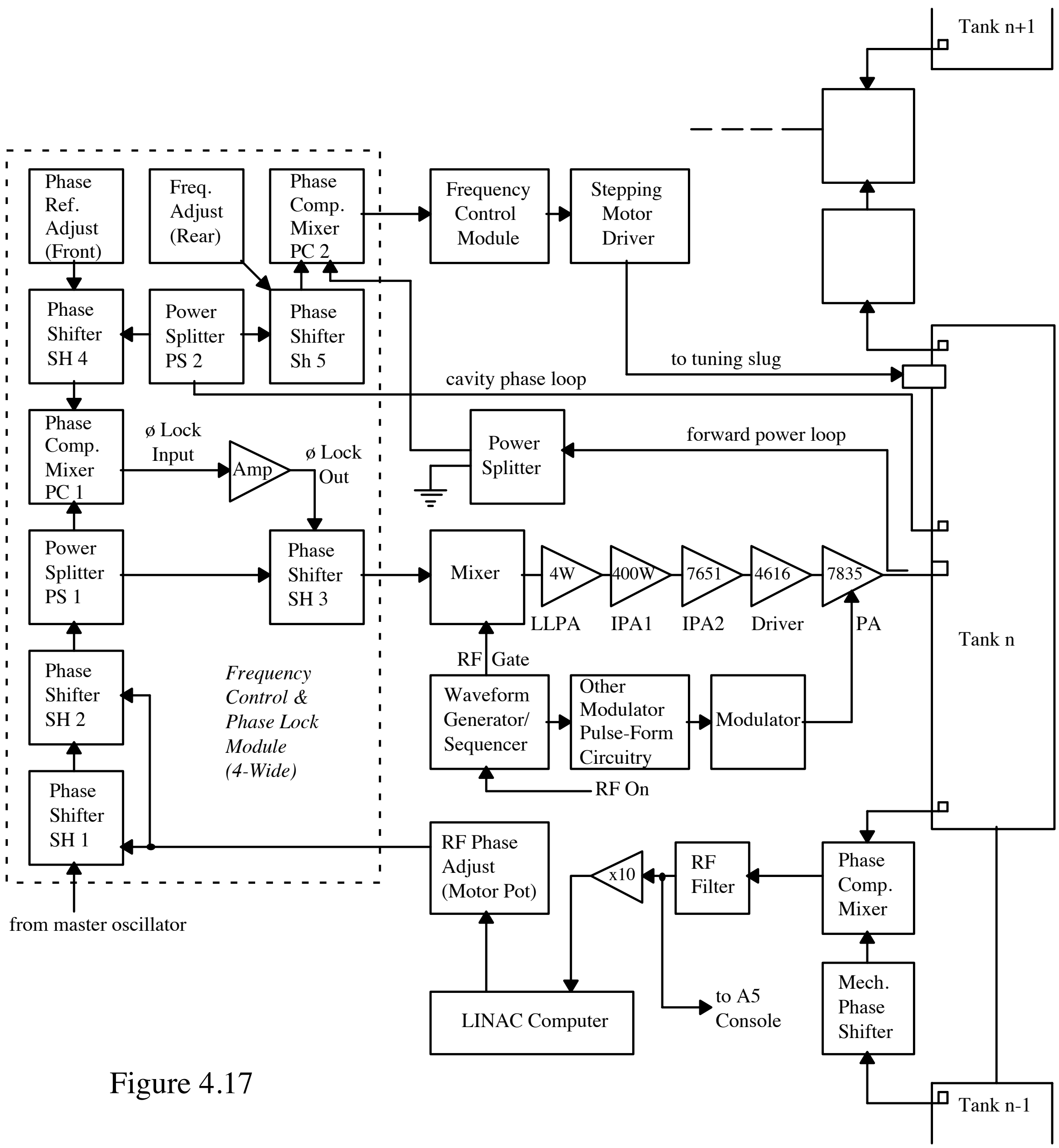


Figure 4.17

The last feedback loop maintains the desired phase relationship between cavities (the distance from one tank to the next may not be an integral number of cell lengths). The low-energy end pickup loop of cavity n is compared with the high-energy end pickup loop of cavity n-1. The signal from cavity n-1 is first fed through a mechanical phase shifter (mounted in a box strung between the cavities) that is set so that the output of the phase comparator mixer is zero at the desired phase. The mixer output is filtered, amplifies, and sent to the Linac computer as an intertank phase. The computer acts to keep the phase near zero by controlling a motor driven potentiometer in the RF phase adjust module. The180˚ phase shifters, SH1 and SH2, controls the phase that cavity "n" operates. The greatest phase difference between any two cavities should be less than 2˚.

The radial variation in the electric and magnetic fields are the Bessel functions $J_0(kr)$ and $J_1(kr)$, respectively. (See figure 4.18) The first zero of the electric field amplitude ($J_0(2.4048) = 0$) represents the wall of the RF cavity because the electric field at the wall must be zero. The actual frequency of 201 MHz is lower than what's possible for the given radius because the drift tubes' internal structure reduces the volume.

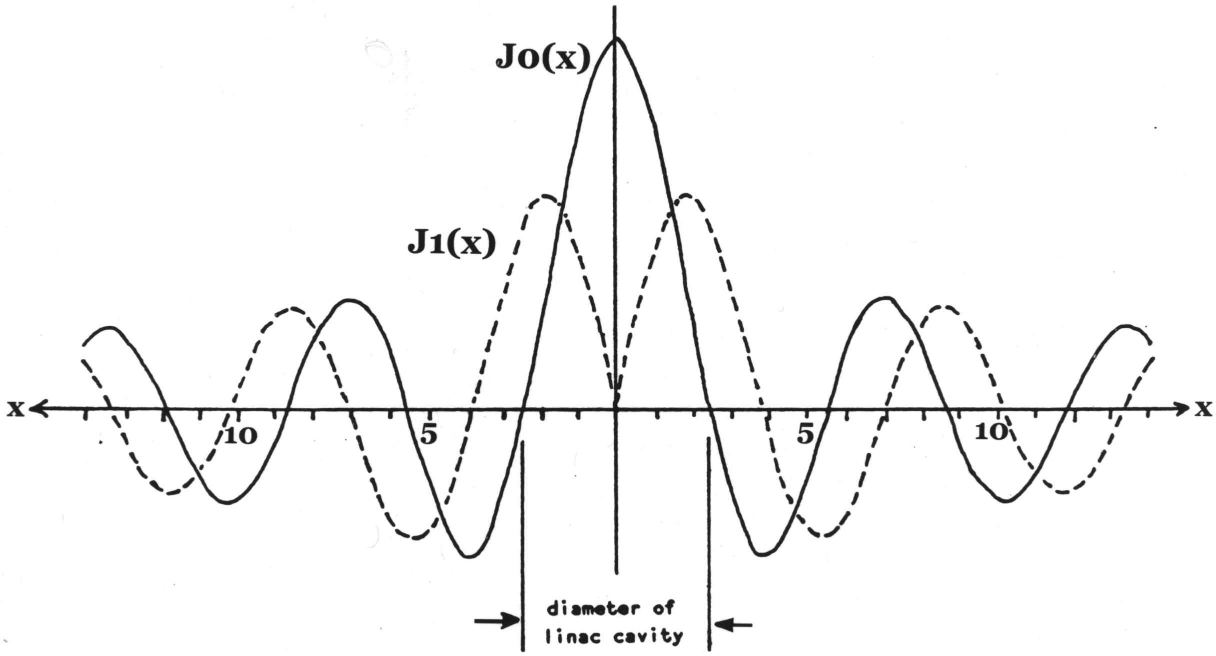


Figure 4.18: Bessel Functions $J_0(x)$ and $J_1(x)$

Note that the maximum of the magnetic field strength J_1 occurs just before the cavity wall and not at the wall. All the values for $J_0=0$ are possible wave modes in the cavity; getting the desired node is a matter of careful design and tuning.

Tuning a cavity to resonate at the correct frequency requires a very precise control of cavity volume. A bulk tuner runs along the length of each cavity, resembling a "D" in cross-section (see figure 4.19). The cavity and bulk tuner are both made oversized initially, resulting in an undersized cavity volume. The tuner is then trimmed (and the empty space in the cavity increased) until the correct frequency is approximated. Fine control is supplied by a series of copper pistons mounted in the tank wall that can be moved into or out of the tank to vary the volume. These tuning slugs are moved during initial set-up of a tank for frequency control and field measurements, and then set in place. One slug in each tank is motorized and is used in a servo loop to control cavity frequency during normal operation. Tanks 2-5 each have five fixed and one motorized tuning slugs. The slugs are six inches in diameter and have a five-inch range of travel. They also have post couplers that stabilize the RF fields. Tank #1 has twelve fixed slugs, with a thirteenth motorized. Tank #1 has the smallest tuning range in the Linac and is the most vulnerable to variations in the temperature of the cavity's cooling water. Tank #1 doesn't have a post coupler, which makes it very sensitive to dimensional errors.

It should be noted that although the active control of the cavity volume is through the tuning slug, this control is effective only if the temperature of the tank, as controlled by the water system, is constant to within a tenth of a degree Fahrenheit or so. If the water temperature takes off, the tuning slug ranges out very quickly and control of cavity volume is lost.

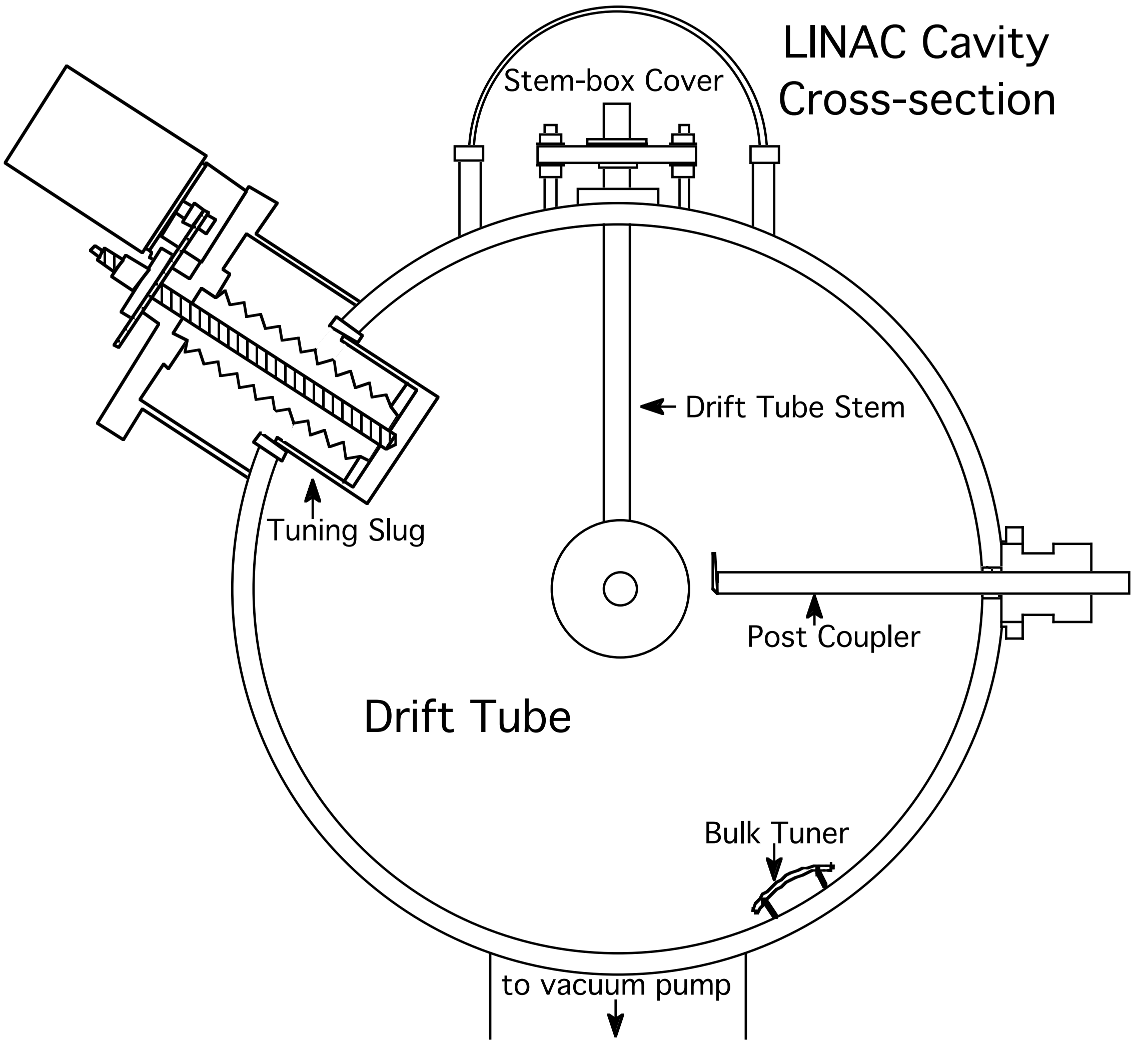
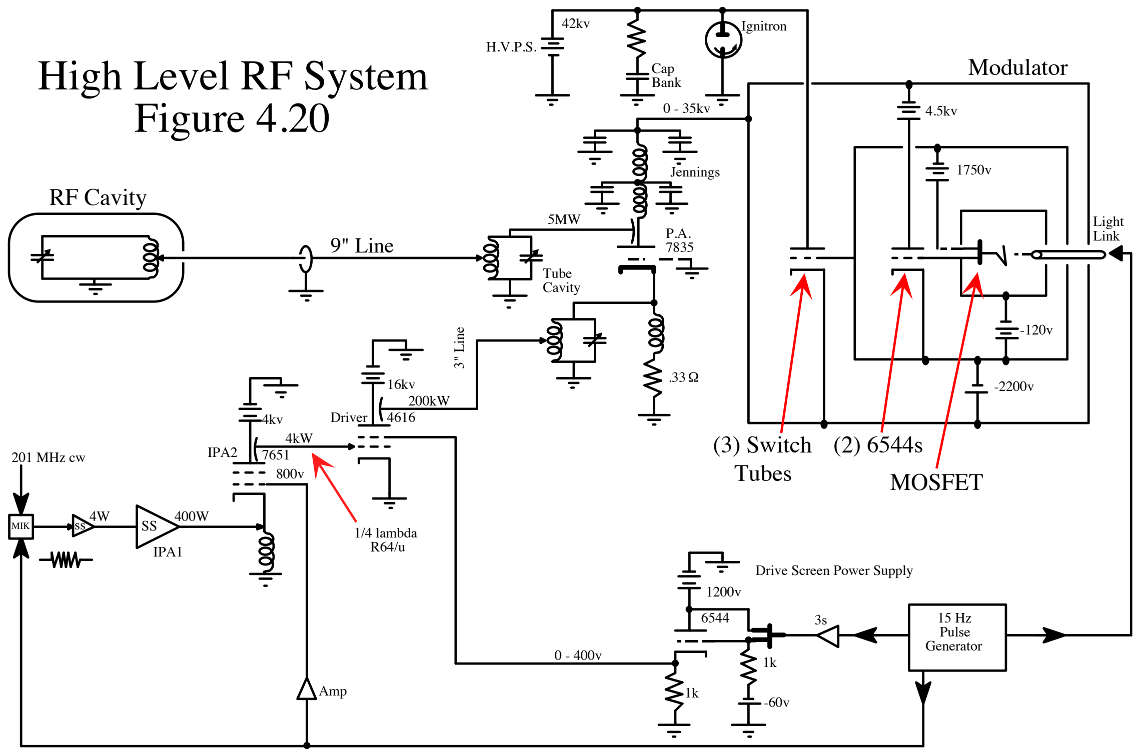

LINAC Cavity
Cross-section
Stem-box Cover
Drift Tube Stem
Tuning Slug
Post Coupler
Drift Tube
Bulk Tuner
to vacuum pump

Figure 4.19

DTL High Level RF

The output of the mixer in figure 4.17 ultimately will become the signal that drives the cavity, after being amplified by seven orders of magnitude. In figure 4.20, the signal first passes through a solid-state amplifier with an output of about four watts (sometimes referred to as the LLPA, Low Level Power Amplifier) located in the rear of the RF system control racks. The signal then travels to the driver racks (A11), where a second solid-state amplifier (called the first IPA, Intermediate Power Amplifier) boosts the signal to 400 watts (OPBULL 288). This then drives the cathode of the second IPA, and RCA 7651 tetrode with an output of 4 kW. Passing through a coupling capacitor, the signal drives the grid of the driver tube, an RCA 4616 tetrode with and output of 200 kW.



High Level RF System
Figure 4.20

Through another coupling capacitor, the output of the driver passes through a 3-1/8” diameter transmission line to the cathode of the power amplifier. The Burel 7835 triode has a peak power output of 5 MW with a duty factor of 0.0075; these powerful tubes cost from $40,000-$150,000 each.

The general layout of the RF system components is shown in figure 4.21.

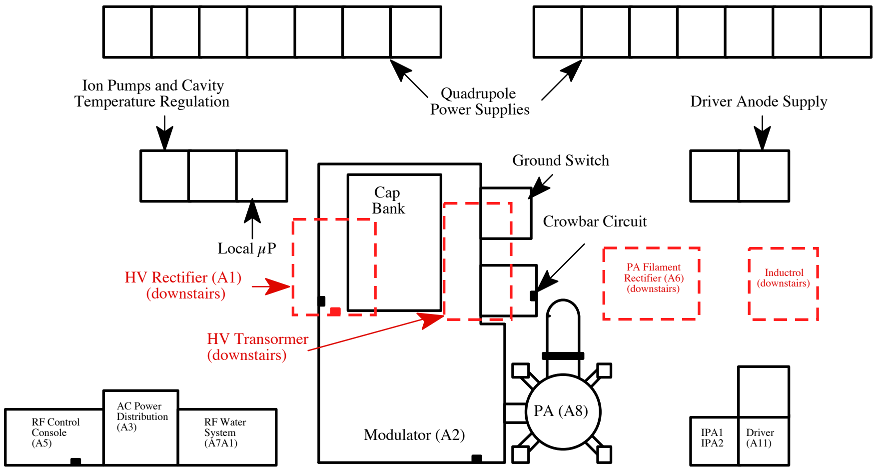


Figure 4.21

The RCA 7835 operates at a nominal filament current of 6600 amps at a potential of about 5 volts. This is supplied by two double-Y, full-wave bridge rectifiers. Control of the output current is obtained through a brushless motor driven induction regulator (*Inductrol*) connected to the input of the filament power supply. The power supply output current is regulated to a plus or minus 0.05% over a 6000-7000 amp operating range.

Back in the days of the Main Ring, the Inductrol varied the input voltage to the filament power supply to control the output current, compensating for variations in line voltage, which would sag. The auto voltage regulation loop has been disabled, but the Inductrol is still used manually for minor adjustments.

You can find the Inductrol and filament power supply located in the lower Linac gallery. Controls for the Inductrol voltage regulation loop are still on the front panel of the filament supply, but they've been disconnected at most stations.

The filament leads to the PA are water-cooled cables that pass up through the floor and connect to junction blocks at the bottom of the PA.

The capacitor-coupled 5 MW output of the PA drives the 9 3/16 inch diameter coaxial transmission line (TM94) that powers the cavity (see figure 4.22).

The transmission line and PA are pressurized with nitrogen at 1.5 - 2 atmospheres to reduce the chance of sparking. Passing from the rear of the PA, the line runs through the floor to the lower gallery. The line passes through a $\lambda/2$ range trombone (used to adjust the total length of the line, which must be an integral number of RF wavelengths long) and then runs horizontally through the wall into the Linac enclosure.

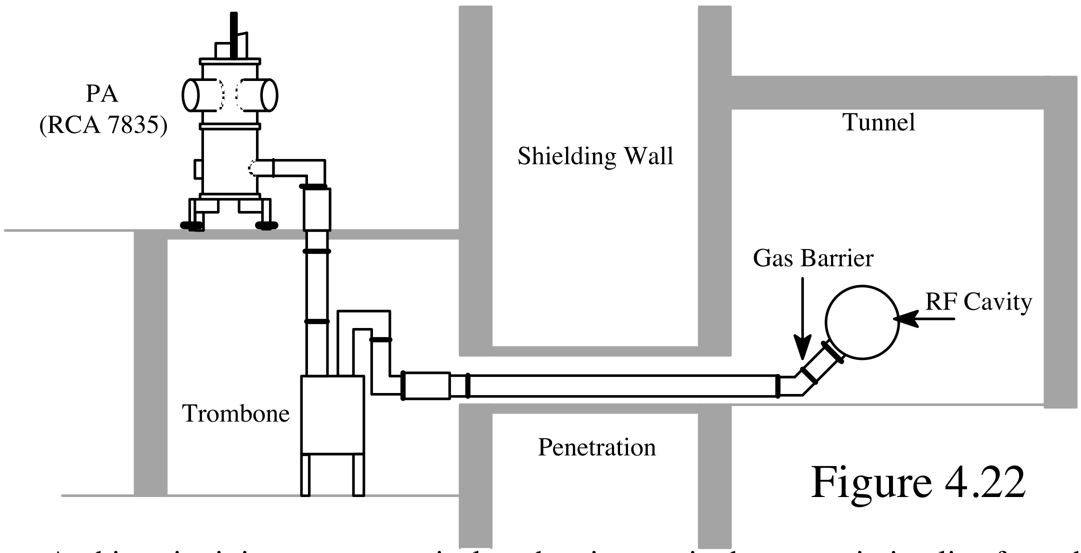


Figure 4.22

At this point it is necessary to isolate the nitrogen in the transmission line from the vacuum in the cavity. This is handled by a ceramic annulus called a gas barrier that fills the area between the conductors of the transmission line but is transparent to electromagnetic fields.

Once past the gas barrier, the transmission line runs into the cavity where it terminates in the drive loop. The center conductor of the transmission line runs unshielded for six inches, turns two right angles, and then is terminated to the outer conductor (see figure 4.23). The drive loop formed by the center conductor does not protrude into the cavity, but is recessed in the wall. The loop transmits the energy to the cavity as the magnetic fields produced by the alternating currents in the center conductor couples to the cavity's magnetic field.

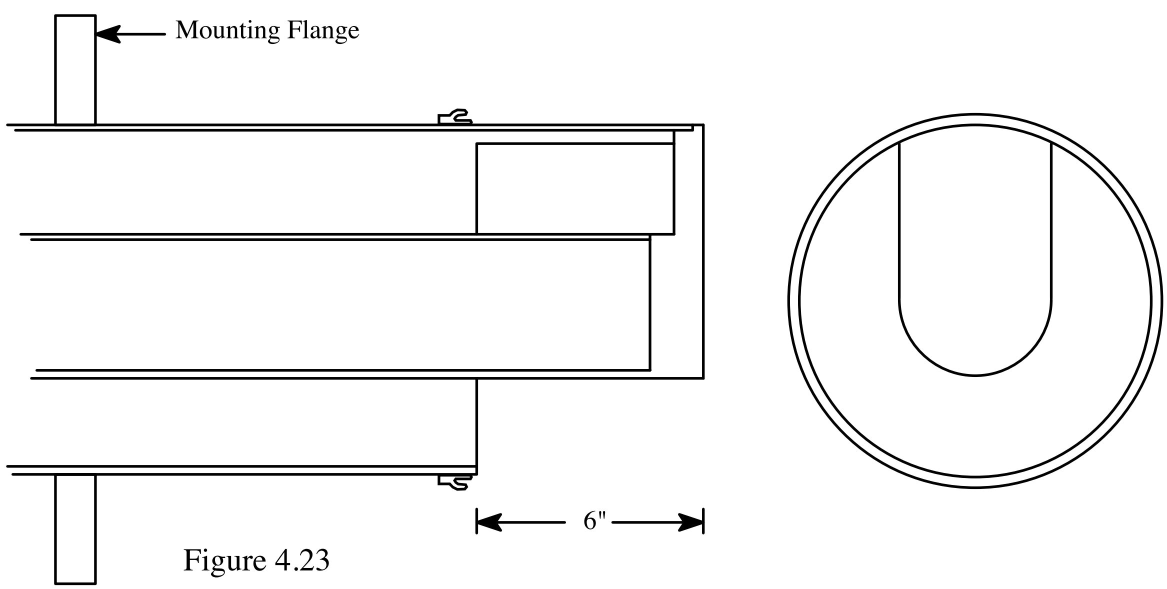


Figure 4.23

PA Modulator

Although the intermediate power amplifiers and driver delivers the RF waveform to the cathode of the power amplifier, the voltage on the anode controls the pulse duration and power output of the PA. The modulator, the large box to the left of the PA, provides the voltage. (The Linac modulators and PAs were custom built by the Continental Electronics Manufacturing Company of Dallas, Texas.)

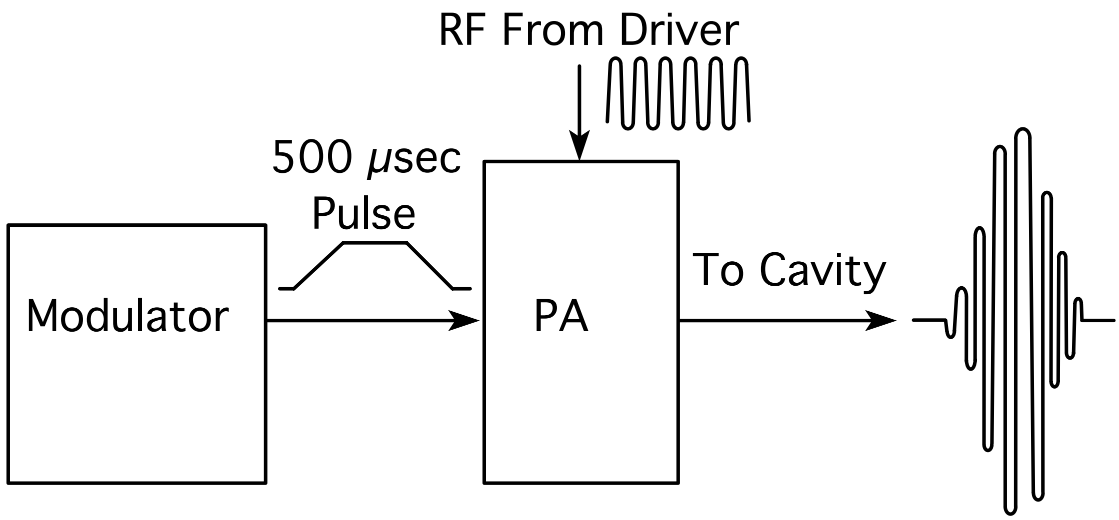


Figure 4.24

Two modules in the A5 racks define the modulator waveform, which in turn defines the outer envelope of the PA waveform (figure 4.24). Not only must the pulse be of correct amplitude and duration, but also the sequence of events that turns the RF station on and off must be carefully controlled to prevent damage to the components. For instance, if modulator voltage is applied to the PA's anode when there is no drive on the cathode, the PA could break into oscillation and destroy itself (OPBULL 75). If the modulator pulse starts or stops too suddenly, the resultant abrupt variation of RF drive to the cavity could result in a high voltage standing wave ratio (VSWR) and arcing across the gas barrier of the PA ceramic (a very, very bad thing).

When the Preaccelerator timing control sends a RFON timing pulse, the waveform generator/sequencer module (figures 4.25 & 4.26) first looks to see that an interlock enable from the pulse interlock module also exists. If so, after a 5 to 75-μsec delay (MOD START adjustment on the front panel of the waveform generator), a pulse is sent to the driver pulse controller to tell the driver to turn on. At the same time, a gate to the mixer goes high and permits the drive signal from the low-level system to reach the amplifier chain. The combination of these two signals will result in a 200 kW output of RF from the driver. After another 8.5 μsec, the pulse-interlock module looks to see that the driver output is indeed above 175 kW. If this is true, the interlock module sends a waveform enable to the waveform generator. However, if the signal doesn't appear, the modulator gradient will remain at zero and a driver stop pulse will occur 500 μsec later.

The modulator pulse begins with a 125 μsec linear ramp up to the three-volt level. The ramp down portion of the modulator pulse is also 125 μsec long. The total length of the modulator pulse (200-500 μsec) is set by the mod stop adjustment.

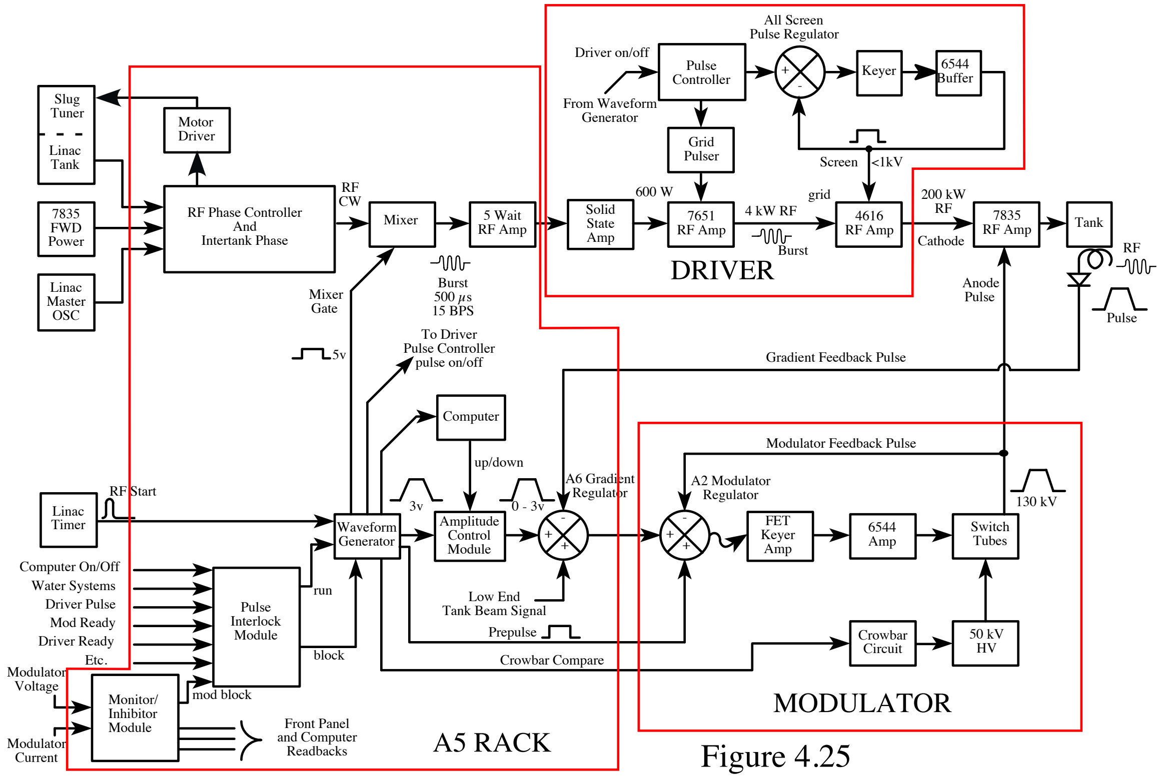


Figure 4.25

After a 5-75 μsec delay (Driver Stop Adjustment) relative to the end of the modulator pulse, the driver stop pulse turns the driver off. The mixer gate also goes low at this time, removing the low-level signal from the amplifier chain. A second driver off pulse occurs after a fixed 500-μsec delay relative to the driver start pulse.

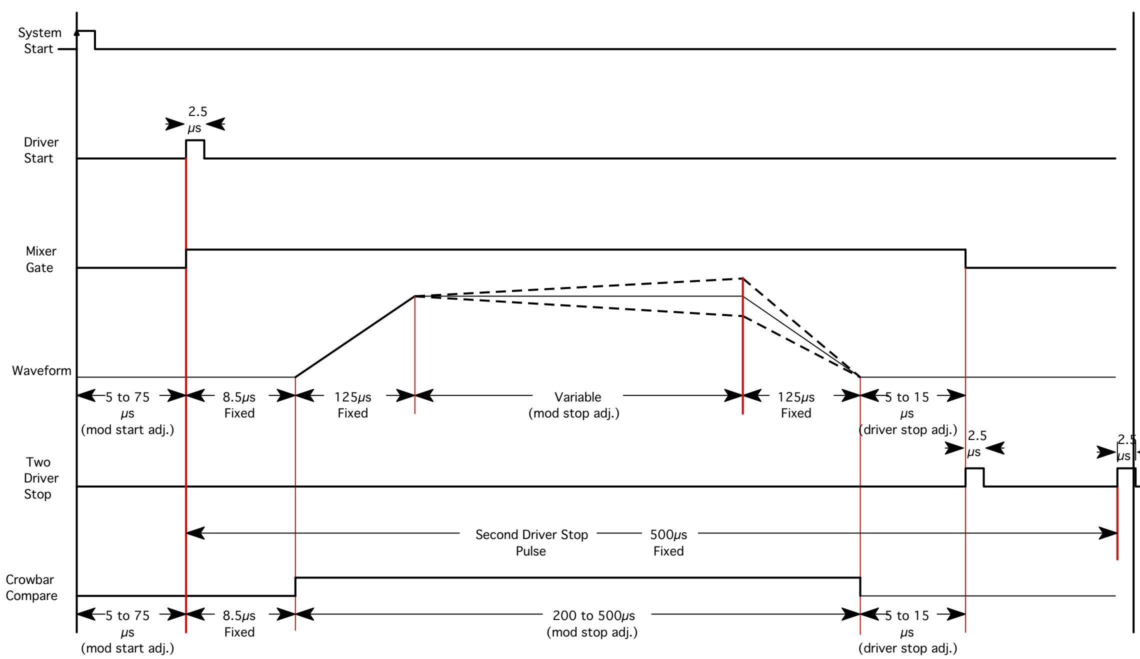


Figure 4.26 Modulator Pulse Timing

There are ten preprogrammed modulator waveforms available, selected through a rotary switch on the front of the waveform generator. A tilt switch effects the flattop portion, allowing it to slope up or down to compensate for any droop in the high-voltage power supply for the modulator, but this has not been needed. There is also a switch that will disable the output of the module to keep the RF system from pulsing.

The amplitude control module determines the size of the modulator input pulse and thereby the gradient level in the cavity. It is essentially a variable attenuator. The output of the waveform generator is fed into a digital to analog converter that is controlled by a counter. The counter looks at clockwise (increase D/A output) or counterclockwise (decrease D/A output) pulses that come either from the Linac computer of the local knob input. The output of the D/A then is buffered to remove glitches and is sent to the gradient regulator. An LED readout on the front of the amplitude control module shows the pulse amplitude in percent of maximum. A latching pushbutton below the knob zeroes the output of the module.

The gradient regulator loop keeps the cavity gradient within the specified 0.1% tolerance and compensates for beam loading. The gradient regulator module receives the output of the amplitude control module, as well as a gradient signal from the tank and a beam signal from the toroid mounted in the upstream end of the tank. An increase in the gradient signal lowers the output of the regulator while an increase in the beam signal raises it.

Figure 4.27a

A local microprocessor handles the second gradient control loop, which samples the A/D channel that represents the cavity gradient once per beam pulse or once every ten seconds in the absence of beam and adjusts the setting of the amplitude control module accordingly. This loop is inactive if the gradient's A/D readback falls below 0.8 volts.

The signal then passes from the crate in the A5 racks to the modulator regulator module mounted in the front of the modulator itself. The modulator regulator acts to keep the modulator current at the level needed to maintain the desired cavity gradient. It looks at the current flowing from the cap bank to the switch tubes and raises or lowers the input to the modulator to maintain the desired output. A pre-pulse from the waveform generator/sequencer gates the regulator on and off.

The signal is then ready for amplification by the modulator. It is converted to a 200 μW light pulse and sent through a fiber-optic cable to the first stage of the modulator, which is at a high potential.

Inside the modulator are three nested boxes each being the output of one stage of amplification. The three stages are thus shielded from one another, permitting a higher input capacity for each stage. The input waveform from the gradient regulator is sent inside the innermost box; there it is amplified and fed to a keyer (a solid-state pulser using a MOSFET power transistor) that results in a 1 kV pulse. The output of the keyer is tied to the innermost box, which pulses from -120 V to 1.2 kV.

The first box is joined to the grids of two Maclett 6544 tetrodes. The anodes of these tubes sit at 4.5 kV. The cathode outputs are connected to the second box, which pulses from -2.2 kV to 4 kV.

The second box is attached to the grids of three Westinghouse WL-23646 or ITT F-1123 triodes, known as the switch tubes. Their anodes are fixed to a 30-μF capacitor bank in the rear of the modulator that is charged by a 50 kV transformer. An SCR-controlled rectifier in turn drives the transformer. Transformer and rectifier are located in the lower gallery.

The capacitor bank stores about 24 kJ of energy at 40 kV. The cathodes of the switch tubes are connected to the third and outermost box and from there to the anode of the PA. The output of this stage pulses from zero to about 30 kV, turning on the PA to from the RF pulse.

Three toroids wrapped around the line that runs from the capacitor bank to the switch tube anodes, measures the current drawn by the modulator. (See figure 4.28) One toroid senses the modulator current for the gradient regulator circuit. A second toroid provides a signal for the modulator current readback and oscilloscope trace, and to trigger mod blocks; the monitor/inhibit module (figure 4.27b) watches the output of the toroid during the pulse. If the current exceeds 400 amps, the pulse is inhibited for the remainder of that cycle by sending a mod block, which is indicative of a spark in the PA of the transmission line (OPBULL 692), causing a permanent inhibit. A permanent inhibit both inhibits the pulse and turns off the SCR controller for the HV power supply for the cap bank until a manual reset is done; it also reduces the setting of the amplitude control module if the system is not reset within 30 seconds. This is done so that when the system turns back on, the reflected power from the cooler and out-of-tune cavity will not be so great.

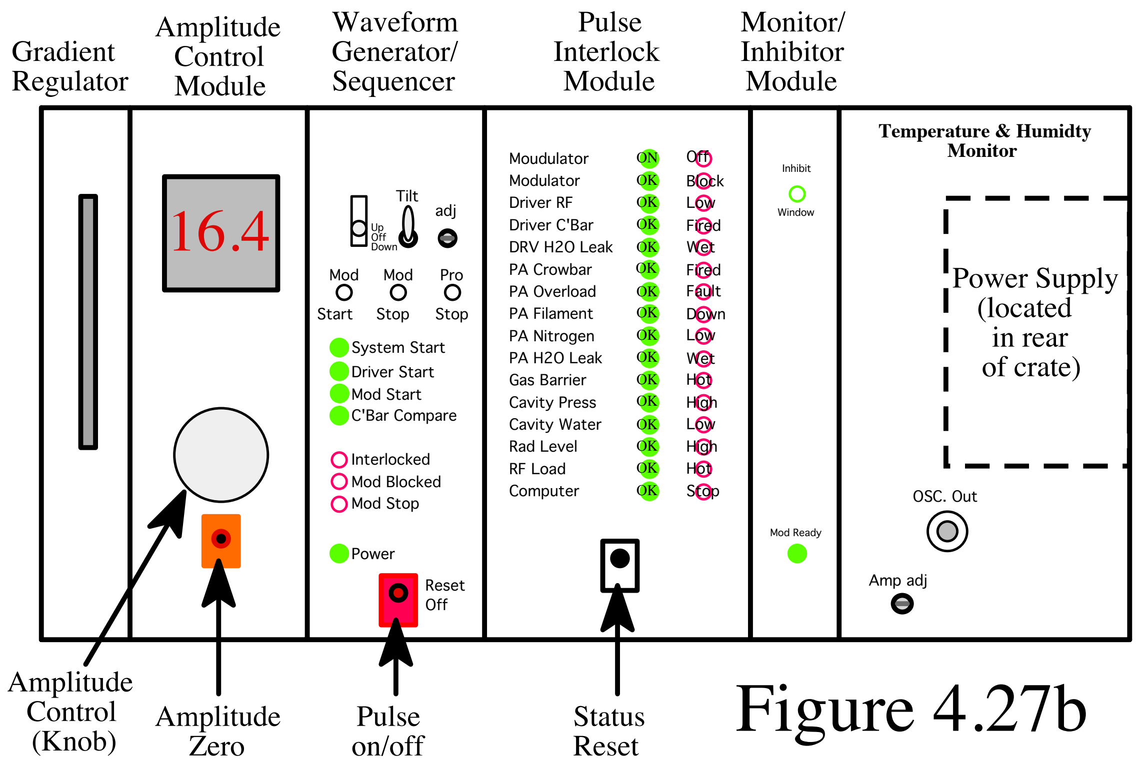


Figure 4.27b

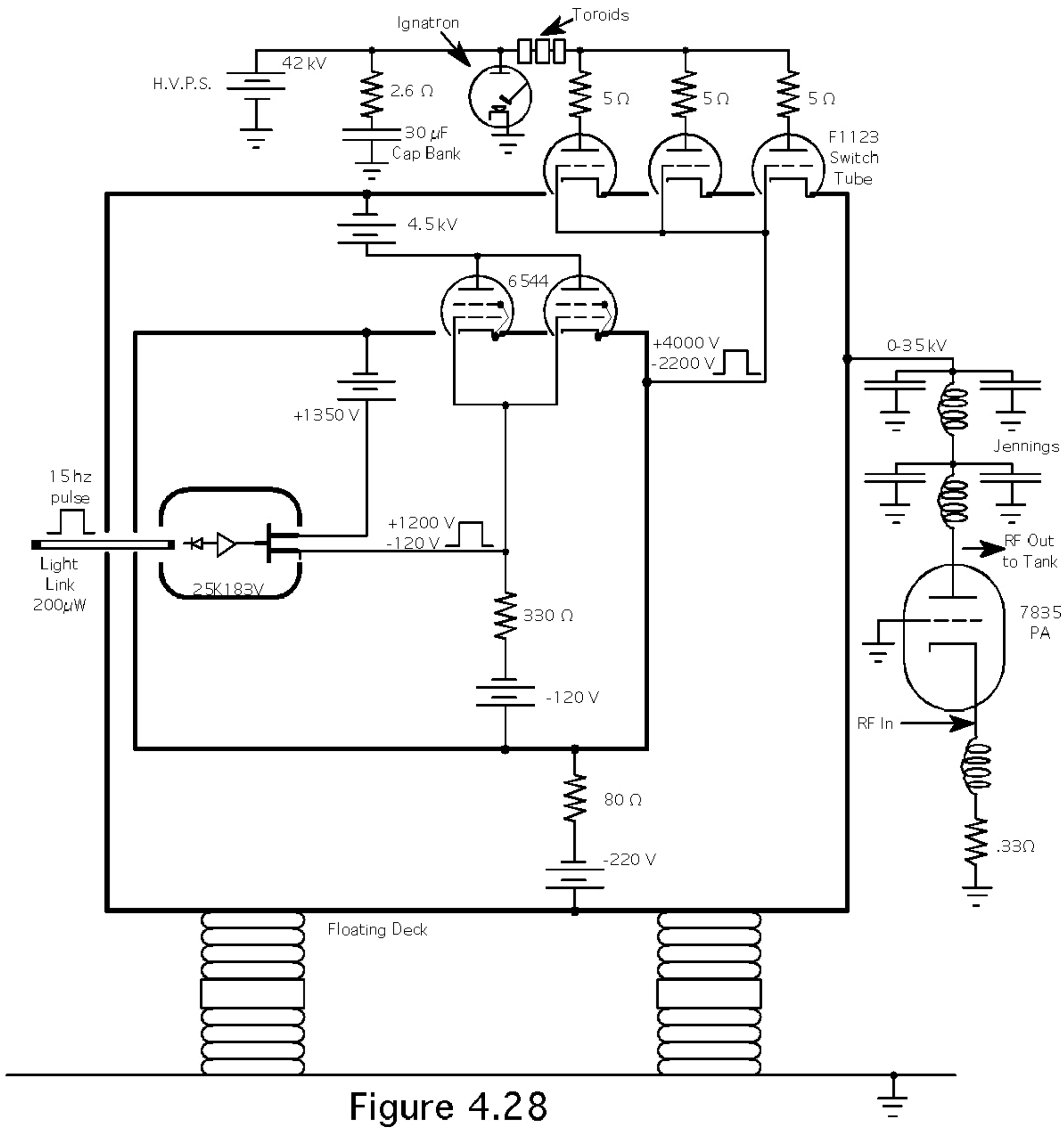


Figure 4.28

The third toroid is there to sense a PA crowbar. This requires a current of 600 amps during the pulse of 125 amps between pulses. The crowbar compare circuitry, located in a relay rack on the right side of the modulator (behind the PA) receives the crowbar compare level from the waveform generator so that it knows when the pulse occurs. This signal goes high at the start of the modulator pulse, telling the crowbar detector circuit in the modulator to change the crowbar level from 125 to 600 amps. At the end of the pulse, the signal goes low again, and the crowbar level returns to 125 amps.

A crowbar that occurs during the pulse is indicative of a sustained arc in the modulator, usually in the switch tubes. Indicators inside the modulator (left-hand window) will latch when a switch tube arc occurs. Exactly how serious a switch tube arc is depends upon the circumstances. Repeated arcs should be brought to the attention of a Linac RF specialist. A crowbar that occurs between pulses indicates that the modulator is coming on when there is no drive on the PA cathode, which is potentially lethal to the PA.

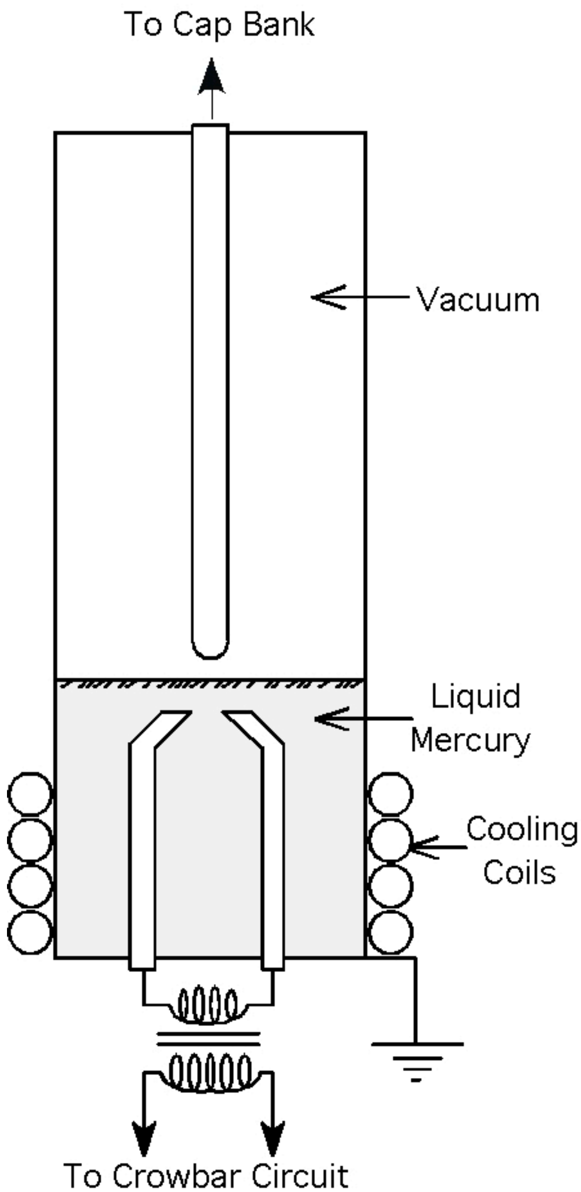


Figure 4.29 Ignitron

A PA crowbar fires the permanent inhibit and shorts the capacitor bank to ground through a device called an Ignitron. The Ignitron can pass large currents in a short amount of time. Inside the Ignitron (figure 4.29) the cap bank connects to an anode suspended above a pool of liquid mercury, which is at ground potential. The anode and the mercury are in close proximity but do not make electrical contact. Just under the surface of the mercury are two electrodes connected to a Thyratron in the crowbar cabinet. A crowbar fires the Thyratron, causing the mercury to vaporize. An arc forms in the vapor between the anode and the mercury pool as the current flows to ground. A thirty-second timer prevents the pulse from being reset until the Ignitron recovers. You can find the Ignitron located on the floor in front of the cap bank, toward the front of the modulator, which is right next to the toroids. It is warmed by two heat lamps and is thus hard to miss.

After the 30-second timeout an automatic reset occurs. The permanent inhibit reduces the gradient setting of the amplitude control module to half value. The computer then runs the gradient slowly back up to 0.8 volts (A/D). The regular gradient regulation loop then takes over if the auto-gradient for that station is enabled. If, after having sent 200 “increase gradient” pulses to the amplitude control module, the RF gradient is still less than 0.2 volts, the computer will stop trying to raise it. At this point an Operator will have to investigate.

DTL Permanent Inhibits

Modulator Block

A mod block occurs when the modulator current toroid reads more than 400 amps. The modulator is inhibited for the remainder of that pulse but allowed to resume pulsing with the next 15 Hz cycle. A mod block occurs due to a problem with the PA, the nine-inch coaxial line, or the cavity.

PA Crowbar

A PA crowbar happens when a separate modulator current toroid senses 600 amps for more than 2 microseconds during the pulse or 125 amps between the pulses. If this amperage is sensed, first the HV power supply is inhibited and next the Ignitron is fired, which grounds the capacitor bank. After 30 seconds, the computer will reset a PA crowbar and run the gradient back up. It will try to do this reset three times and then stop.

Permanent Inhibit

A permanent inhibit occurs when Mod Blocks occur on four consecutive pulses. It will inhibit the HV power supply and turn off the High Voltage SCR controller until it receives a reset. Our policy requires an operator visit and only a local reset.

The control system enables a remote reset from page L25. This remote reset has the same effect as pushing the blue button locally. However, a Perm Inhibit is indicative of problems sufficiently dangerous to the equipment that an operator needs to visit the station. The manual reset is initiated while an operator listens for sparking and being alert for any other problems.

The possible problems that could cause a Perm Inhibit include:

1) The Gas Barrier
2) Sparking in the Cavity
3) Vacuum problems in the Cavity
4) PA filament to low
5) Aging PA that needs to have its filament increased to lower the anode voltage
6) Sparking in the PA Cavity of in the Nine-Inch Line

The damage caused by sparking, which goes along with all of these problems, will be minimized by early detection. That is why a trained person watching for problems must reset Perm Inhibits locally.

When resetting a Perm Inhibit, look first at the PA filament reading and correct it if it is below the posted nominal reading. Check the ion pumps for bad vacuum. If these are good, reset the system and begin running up the gradient. If the station can be run up to full gradient, check the modulator voltage. The charging peak at the beginning of the waveform should be less than 30 kV. If it is and the station runs, your job is finished. If it's above 30 kV and you're on the evening or owl shift, try adding 50 amps to the filament current. If that brings the charging peak down you're done. If increasing the filament current doesn't help but the station is operating, bring the filament back down to the operating value. In either case leave a note in the MCR Elog and inform Linac experts. If the station continues to spark frequently run it down until it stops sparking and activate the Linac call list for further help. If this happens during the day shift, get a Linac technician.

A new 7835 costs $154,000, plus three hours of minimum downtime to replace. A gas barrier replacement requires is six to eight hours of downtime. Damage to the nine-inch line can cause three to four hours of downtime, not counting the time to diagnose it.

Damage to the interior of a cavity will take days to repair. These things do not often occur, but the program will suffer if they do. In any case, excessive sparking will shorten the lifetime of the equipment. This is the reason Perm Inhibits need to be reset locally.

DTL Buncher

The beam pulse coming out of the sources is, depending on the chop selected, anywhere from 10 to 57 μsec in length. As discussed previously, the synchronous phase angle of the Linac (-32°) determines the stable phase region (105°) of the RF bucket. Capturing 105/360^{ths} of the beam thus yields a capture efficiency of about 35%, which isn't very good.

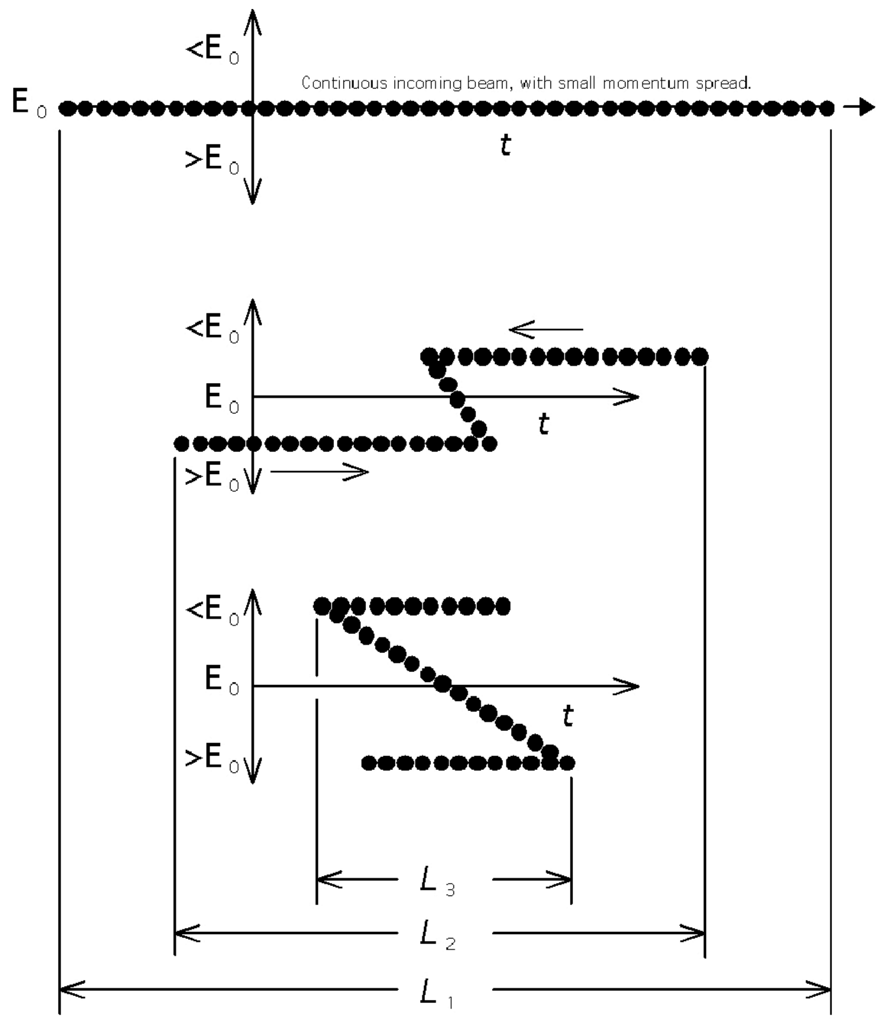


Figure 4.30

What is needed is a system that will stuff the particles into 201.24 MHz bunches so that more of them will fit into the RF buckets. This is the function of the Buncher. It is a single-gap RF cavity operating at the same frequency as the rest of the Linac, but phased so that particles arriving early in the RF cycle see a decelerating voltage and are slowed down. Those arriving later see an accelerating voltage and are speeded up (figure 4.30).

The ideal Buncher for injection would have a single slope sawtooth waveform that could bunch beam into arbitrarily small width bunches, which provides 100% capture efficiency (FN 277). This being the real world, sawtooths are difficult to produce at high powers, and so a sinusoidal waveform is used. This reduces the capture efficiency to about 70%. Still, this means the Linac Buncher can cram about 240˚ of beam into a 105˚ bucket.

DTL Buncher RF System

You can find the first Buncher RF system located next to station one. It is similar to the other Linac RF systems except that it lacks the driver and power amplifier stages of the amplifier chain. The cavity is driven off the second IPA (RCA 7651). The RF pulse itself is nearly square, since a smaller cavity can fill and empty of RF more quickly.

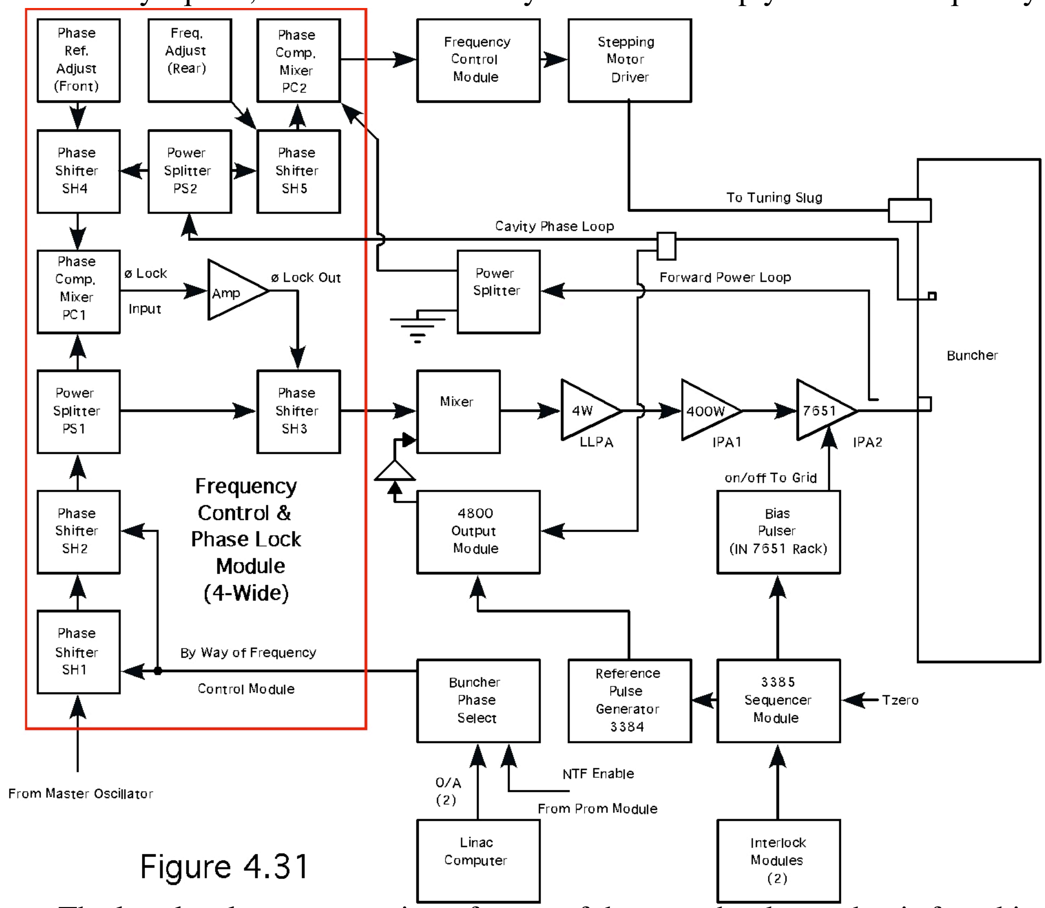


Figure 4.31

The low-level system consists of some of the same hardware that is found in the other RF systems, as well as some older hardware. Figure 4.31 shows a block diagram of the system. One difference is that there are no intertank phase loops. The Buncher phase is set to values commanded by the Linac computer.

Buncher Purpose

There are two RF phases associated with the Buncher: one is used for NTF operation, and the other for everything else. The Linac computer sends both desired phase settings to the Buncher phase select module. When the prom module in the Preacc control room sends out an NTF chop width, it also sends and NTF ENABLE pulse to the phase select module. This selects the NTF phase for a time determined by gate pulses from a CAMAC 178 card in the lower Linac gallery NTF racks. In the absence of the NTF enable signal it reverts to the HEP phase. The phase select module is the equivalent of the RF phase adjust modules in the other RF systems.

Note that in both cases the phase is referenced to tank 1, but the actual number that represents the phase is entirely arbitrary.

Another difference is in the circuitry that forms the pulse (OPBULL 1055). The 3383 sequencer module, when permitted by two interlock modules, generates all the system start and stop pulses, referenced to TZERO. The start and stop times sent to the bias pulser turns the 7651 tube on and off by controlling the grid voltage. The 3384 reference pulse generator produces a reference ramp for other start-stop times. The reference ramp is shaped and amplified by the 4800 output module. The output module also sums the ramp with the actual cavity field. The output is amplified and sent to the mixer, which both gates and modulates the RF signal passing to the 4-watt amplifier.

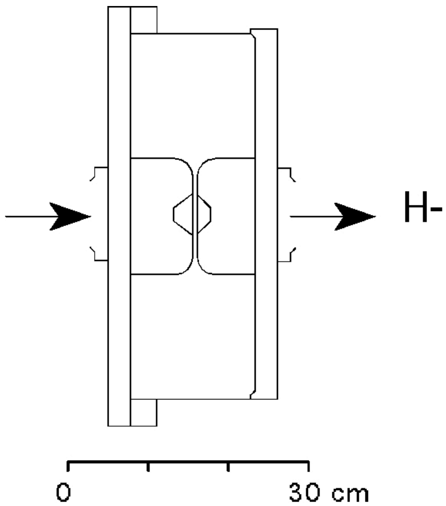


Figure 4.32

Unlike the other RF systems, you vary the amplitude of the Buncher RF by changing the size of the input to the amplifier chain, not by changing the cathode-to-anode voltage in the final amplifier.

The copper-plated steel cavity (figure 4.32), formerly used in the University of Minnesota Linac, contains two half drift tubes, drive loop, and slug tuner, all of OFHC copper. It is electrically analogous to a single cell in one of the Linac cavities.

DTL Buncher Operation

By the nature of its operation, the phase of the Buncher with respect to tank 0ne has a strong effect on Linac transmission. Not only can the Buncher increase the capture efficiency from 25% to 70%, but it can also decrease the efficiency to 15%.

The Buncher phase is a freely adjustable parameter not fixed in relation to any other system. Usually maximum transmission is desired and the Buncher phase is tuned to produce maximum current at the end of tank five. However, on rare occasions, it is desired to keep the injector below a certain intensity without removing a beam turn from the Booster. At these times the Linac is “phased back.”

It should be noted that changing the Buncher phase changes the position and momentum of the Linac beam, and thus the Linac steering should be done whenever the Buncher phase is changed. Usually the phase is reduced to lower the intensity, but it may also be raised past the peak transmission, albeit at the risk of causing strange momentum distributions in the Linac (seen as tails on the momentum wire profiles). Misphasing the Buncher by large amounts is discouraged because it can cause sparking and eventual failure of booster RF stations. DON’T FORGET! People have tuned Booster and Main Injector for hours on end to increase machine intensity only to discover that the Buncher had been misphased earlier and had not been set back.

The Buncher has two phase adjustments: one for the HEP (LRFBPAH) and another for the NTF pulses (L:RFBPAN). These are the D/As sent to the Buncher phase given to NTF so that their beam intensity could remain constant in the face of changing requirements for Linac/Booster intensity. In general, there is no reason to change the Buncher phase for NTF pulses unless requested to do so by the NTF staff. However, if the HEP phase (L:RFBPAH) is tuned (i.e., during a 750 keV tune up) for maximum intensity, the NTF phase (L:RFBPAN) should also be set to this new nominal value. This will give NTF maximum beam.

Vacuum Systems

Maintaining vacuum in the Linac transport lines, drift tube and side-coupled cavities allows the beam to travel through the machine without interference from gas molecules. Vacuum also acts as an electrical insulator, allowing high potentials between objects without arcing. Linac vacuum is typically 10^{-7} torr or better. Such low pressures require a sputter ion pump, which uses electrons to ionize gas molecules. Ions are captured on an anode and complete an electrical circuit. The rate that ions hit the anode is an indication of the absolute gas pressure. Ion gauges, which measure low pressures, work on the same principle. Potentials across the cathodes and anodes in ion pumps and gauges are in the range of several kV.

The ion pumps in the Linac are the diode type with titanium anodes. Titanium is good at catching gas molecules, although the anodes wear with time and may eventually have to be replaced, depending on vacuum conditions. Anodes may last anywhere from six months to indefinitely.

All the ion pumps in the Linac are made of a number of small modules ganged together. The Ultek pumps are made of 25 liter per second modules and the Varian pumps are made of 30 liter per second modules. When combined these pumps can move several hundred liters per second.

All the vacuum valves in the Linac are electrically controlled and pneumatically operated. Solenoids direct the flow of nitrogen gas that moves the valve actuators. The nitrogen comes from a header that runs the length of the Linac. This line also supplies gas to pressurize the PAs and transmission lines. The nitrogen comes from two LN_2 tanks located in the parking lot outside of the A0 service building. If the nitrogen supply runs out, all the vacuum valves in the Linac will close.

DTL Cavity Vacuum

Ion pumps maintain the vacuum inside the drift tube cavities. Each tank has two pump power supplies, one for the low-energy end and the other for the high-energy end. Each supply powers three Varian 1000 liters per sec ion pumps (mounted along the bottom of the tank) that pump directly on the cavity through slots in the floor of the cavity tank. The pumps on a common supply are wired in parallel, so the current being drawn by each pump is roughly the supply current divided by three. The ion pump power supplies are located in the racks behind the A5 control console at each station.

Tank #1 is an exception to the above. It has four ion pumps along the bottom of the cavity instead of six. Each power supply thus feeds only two pumps. Tank #5 has two Varian pumps and two Ultek pumps of the 1200-liter per second capacity, and the other two pump ports blanked off. Two Ultek pumps are available for these ports, but are usually held in reserve. The Varian and Ultek pumps have slightly different power supplies.

The drift tube cavities have vacuum valves located at each end except for tanks #1 and #2; they're so close together that there isn't room. Tanks #1 and #2 have a common vacuum system.

The upstream vacuum valve for tank #1 is the Linac valve mentioned in the 750 keV section. It is interlocked to the ion pump power supplies in tank #1 such that if both supplies trip off, the Linac valve will close. The high-energy end valve in tank #2 is likewise interlocked to the pump supplies for tank #2.

In all other tanks, the vacuum valves at each end of a tank will close off both of the pump power supplies for that tank trip off. Each power supply is set to trip if the combined pump current for that supply exceeds 200 mA.

The computer monitors status of the vacuum valves and the closing of any valve will inhibit beam. Remote control of the vacuum valves is available through the control system.

Each ion pump supply has a vacuum-monitoring gauge mounted in the rack next to it. This gauge uses the pump supply current to provide its vacuum reading, not an actual gauge (they're mounted in the cavities). Despite appearances, the gauge does not control the valves. The valve controller (figure 4.33) shows the status of the power supply interlock for each valve, the status of each valve, and provides local control. (This is also known as the gate valve controller.) This figure shown depicts the controller for cavities one and two, which have their vacuums tied together and is controlled from period #2. All the controllers look the same except for the marker to the left of the "Local - Remote" switch. Each marker is different.

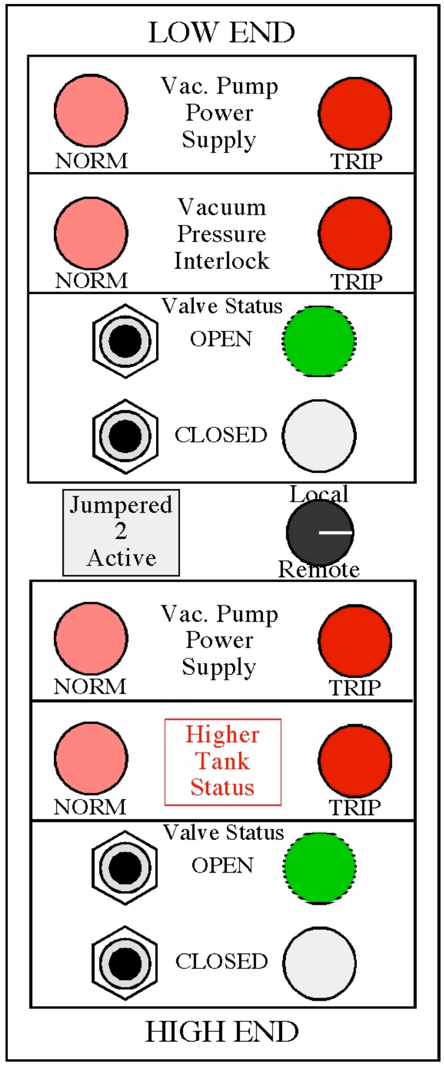


Figure 4.33
Cavity 1 & 2 Vacuum Valve Controller

The rear of the crate that holds the vacuum gauge and valve controller also is connected to the Linlock vacuum valve status line. This is simply a line coming from a 5-volt power supply in system 5 that is daisy-chained to all the valve controller crates. The line runs to the prom module in the Preacc control room, where it forms the Linac VACUUM VALVE input. When a valve closes, the appropriate valve controller drags this line to ground, inhibiting the BEAM ENABLE output of the prom module to the pulse shifter and thus inhibiting beam.

Jumpered 3 Active	Jumpered 4 Jumpered	Active 5 Active

The ion pump power supply provides the voltage (2-8 kV) necessary to produce the electrons that ionize gas molecules. The meter on the front panel of the supply can read pump current (usually given in milliamps), of the supply voltage. At normal operating pressures (10^{7} torr) the current and voltage have the usual inverse relation: as the pressure raises the current increases, and the voltage drops. In these ranges the current is the best indicator of the actual vacuum. At relatively high pressures (10^{-3} torr, or below 3 kV) the current stabilizes as the voltage decreases; voltage is then the best indicator of vacuum. There is a function of the meter to show the vacuum value directly, but it is of doubtful accuracy.

The most accurate method of determining the cavity vacuum is by reading the pump current, dividing it by the number of pumps it drives, and looking up the equivalent vacuum value on a chart posted on the side of the rack.

Water Systems

Conventional high-power electrical devices, like those found in the Linac, produce a good deal of waste heat. To keep components at operating temperatures many devices use cooling water that has been treated to reduce the number of free ions, which lower the conductivity. The LCW (Low Conductivity Water) systems are treated, temperature-regulated, and pressurized at the Central Utility Building (CUB).

Three separate LCW systems, the 95˚ system, the 55˚ system, and the chilled water system service all of the Linac.

1) The 55˚ system provides cooling for the low energy Linac, which includes the NTF power supplies. The 55˚ system indirectly provides cooling (through heat exchangers) for the Preaccelerator power tubes, 750 KeV trim and quadrupole magnets, NTF and target, RF stations, drift tube tank walls, Debuncher, and Drift Tube quadrupoles. These devices exchange heat with the 55˚ system to regulate temperatures, but do not draw water from the 55˚ system except, on occasion, to top off their stand-alone systems.
2) The chilled water system supplies cooling for the high energy Linac (Klystrons).
3) The 95˚ LCW system provides makeup for high energy Linac, the distribution skid, and the upper gallery RF station skids.

Linac uses different types of modular LCW pumping stations (water skids).

1) Two Preaccelerator pumping stations (figures 4.37a and b), which are similar in all aspects but looks, service the Haefely power amplifiers, and the 750 keV transport line elements. (The water resistors for H- and I- share a water skid.)
2) The RF water systems (figures 4.34a through d) provide cooling for the components of the RF systems
3) NTF (figure 4.38), which is the same as the low level system
4) The drift tube cavity water systems (figures 4.39 and 40) provide cooling and precise temperature control of the cavity walls and drift tubes.
5) The 400 MeV area and wave guide (figure 4.41)

The 55˚ LCW system typically runs at 48˚F (±4˚). The supply and return lines from CUB enter the lower Linac gallery near station #5. It is vital to proper Linac operation that the 55˚ system maintains temperature, supply and return pressure, and, to a lesser extent, conductivity (1.1 μohm/cm or less).

All the low level Linac cooling systems that use the 55˚ system are closed loop systems, exchanging only heat and never water. The Linac systems will top off their volume with 55˚ system water, but this is not the same as exchanging water. Each Linac system has its own heat exchanger, temperature regulator, pump, deionizer bottle, and reservoir. Temperature regulation is achieved by varying the 55˚ water flow through the heat exchanger to keep return water temperature constant. In order to operate, the systems must have primary cooling water present in the heat exchangers and sufficient reserve levels in the reservoirs. All types of systems are located in the lower Linac gallery.

Water System Operation

Linac is very sensitive to variations in water system temperature. Tank #1, with its small tuning slug, is particularly sensitive to temperature fluctuations. In fact, temperature problems are usually heralded by the tuning slug in tank #1 hitting its stops with the resultant alarm: SYSTEM 1 FREQ CCW LIMIT (although this may have another interesting cause).

To remedy this problem contact a Linac expert.

More often, however, the problem is with the temperature of the 55˚ system water temperature (L:LCWT) being set to alarm below 46˚ or above 52˚ F. Have the CUB personnel or the duty mechanic investigate all 55˚ system temperature alarms at once. If the temperature continues to rise above the set limit, shut off the beam. Then do the following:

1) Call a Linac expert
2) Shut off all quadrupole power supplies (this is done most efficiently by turning off all the wall-mounted breakers located behind systems 1 and 4 and the NTF quadrupole power supplies).
3) Run gradients down 50% initially. Only run them down all the way if absolutely necessary. In extreme cases turn off the pulse and modulator HV, and run PA filaments down to zero at all stations.
4) Shut off PA filament power, control power, and all other RF power supplies at all stations.
5) As a last resort, turn off the pumps for the RF and cavity water systems.

The above procedure is also used in the event of hose leaks in the modulator or the downstairs water system. A cavity water leak is cause for shutting down the system and calling Linac system experts **IMMEDIATELY**!

When the RF system shuts down due to a water interlock (or is shut down), it must be manually reset with the switch at the top of the RF System Water Monitoring & Control for each station rack. If the system is reluctant to come back on, check the thermal overload switch, the circuit breakers for motor contactors, and the system instrumentation breaker.

As was stated previously, occasionally it is necessary to make up volume in one of the water systems by filling the reservoir from the 55˚ LCW system. The procedure is as follows:

1) Set Auto/Manual switch on control panel to AUTO.
2) Open valve labeled 55˚ HEADER.
3) Water level on reservoir sight glass should rise and stabilize at correct level when automatic valve closed. Close 55˚ header valve and return system to MANUAL.
4) If the water level in reservoir falls, close 55˚ header valve. Locate flow gauge for the DI loop. Slowly close the DI valve until the flow gauge drops to zero. This reduces the system pressure below that of the 55˚ header so that the system may draw water from the header.
5) Open 55˚ header valve and fill reservoir to correct level.
6) Close 55˚ header valve, open the DI valve and return system to MANUAL.

Low Level RF Station Water Systems

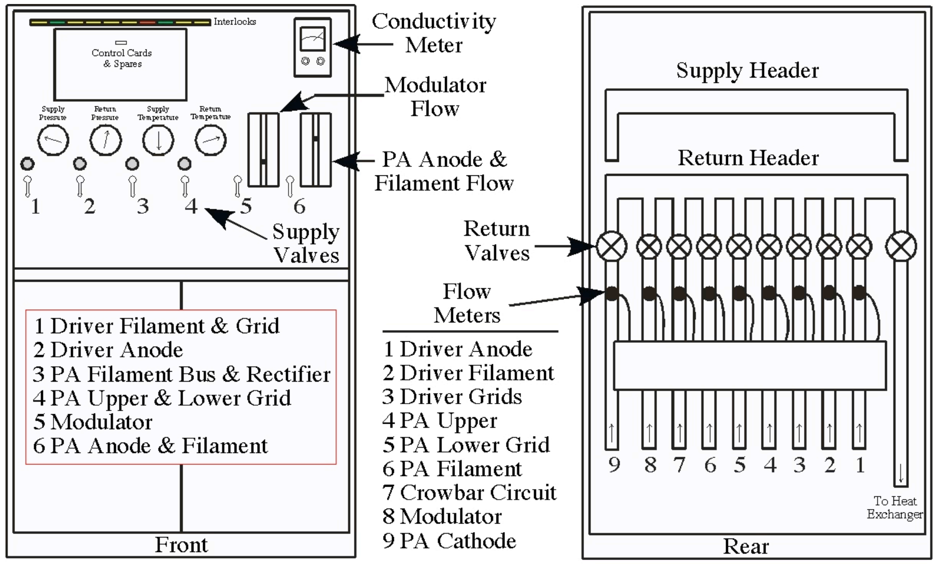


Figure 4.34a, A7 RF Water System Controls and Piping

The RF water systems for a given station have a common control panel with two sets of gauges. System pressures and temperatures can be read and the supply valves controlled from here (figure 4.34a). Note that if the lights above the first four supply valves are lit it indicates that the system's pump is off, not on. The RF Water system plumbing is immediately behind the control panel (figure 4.34d), and the cavity water system is on the lower level of the gallery. The controls for the RF water pumped are located in the A3 rack.

The RF water cooling system each removes about 150 kW of waste heat from the RF components. Water temperature is regulated at about 80˚F. If the temperature exceeds 120˚, the system automatically shuts off. The water control system, regulates, monitors, and interlocks the flow of water to the various components of the RF system (figures 4.34a-d).

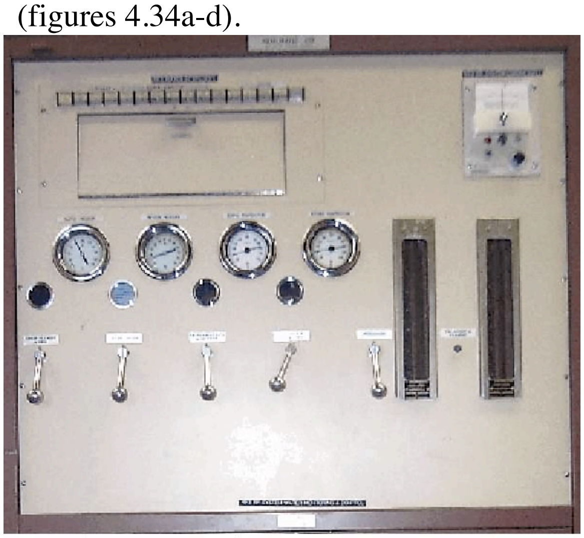


Figure 4.34b, RF Water System Control Panel—Front

Flow control is accomplished by using variable area valves for each circuit.

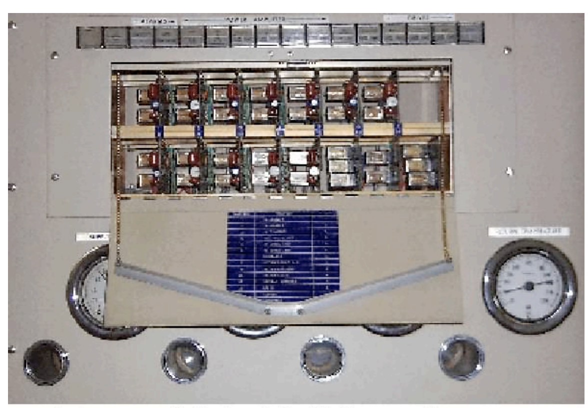


Figure 4.34c, RF Water System Control Panel, Control Cards

The supply valve for each circuit is on the front of the cabinet (figure 4.34b), and the return valves are in the rear (figure 4.34d);

some circuits have more than one return line. If you need to isolate a system, close the supply valve first, then the return. (Get this backwards and you're in for a shower, so be attentive.) Each individual circuit may be purged of water with nitrogen gas.

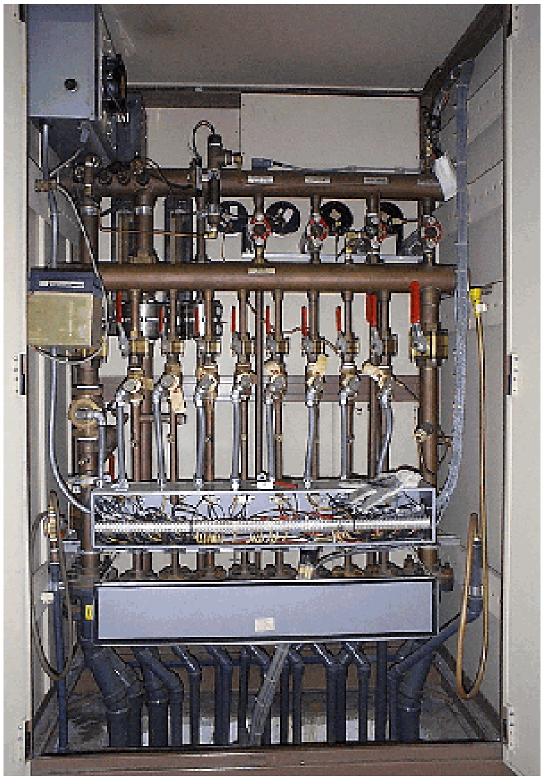


Figure 4.34d, RF Water System Control Panel, Back

All water-cooled RF components are interlocked to their power source by flow and thermal switches in the return lines from each circuit. The interlock cards are located behind a door at the top of the panel (figure 4.34c). Spare cards are located in this chassis, as well as the cage in the lower Linac gallery by system #1.

The power removed from each cavity by the cooling system (figure 4.36) is determined by the combination of RF losses and quadrupole power required by each cavity, which range from 10 kW for tank #1 to 25 kW for tank #5. To maintain a stable cavity resonant frequency (at least within the range where the tuning slug can maintain control), the supply temperatures for these systems are maintained to ±0.1 ˚F of a preset temperature between 72˚ and 78˚ F by the PLC controller located in the lower Linac Gallery. The loop set point and present value are displayed there. The closed servo loop regulates the flow of cold water to the primary side of the heat exchanger.

The new PLC control will enable the operator to control the cavity and RF cooling from both the basement and from any ACNET console. Don't get confused by the multiple "Manual and Auto Mode" buttons. The new control box buttons are only used to change the settings for the valve used to control the cooling water flow. They are not used to place the system in auto mode to fill the water tanks. The Manual/Auto switch located on the motor start box still controls filling the tanks. This switch is normally left in manual position.

If you discover a leak in any of these systems, immediately report it to Linac personnel.

The new PLC uses an operator interface to display the current station interlock trip information as well as other system temperature, pressure, and valve settings. When the system trips, the PLC latches the trip and displays them on the screen. The following chart shows a list of interlock trips and what may have happened to cause them to trip.

Description of Trip	Why System Tripped Off	What Do You Do
Circuit Breaker Trip	480 Contactor is Off	Turn Contactor On
Overload Relay Trip	Excess Motor Contactor Current	Contact Linac Expert
Gem Trap Fuse Blown	Blown Water Lever Fuse	Replace Fuse
Low Water Level	Tank Water Level Below Limit	Fill Water Tank
Manual Stop Trip	The Stop Button Was Pressed	Don't Press It
High Water Temp Trip	Klixon Detected Temp >110˚F	Let System Cool Down
No Water Flow Trip	Not Enough Water Flow In Sys	System Is Valved Off
Contact Relay Trip	The Motor Contactor Is Stuck	Contact Linac Expert

The PLC will work as a stand-alone system. You can change many device settings using this interface, but during normal operation only a few ever need changing.

Look at Figure 4.35. The first feature of the operation interface is the ability to view temperature and valve settings and readings. To view the temperatures and pressures, toggle the operator interface from Interlock to Device Settings by pressing the "esc" button in the upper right corner. You will notice that the light in the upper left corner labeled PLC Message will either be on or off. When on (lit) the LCD screen displays the interlock trip status. When off (not lit) the screen displays the various temperatures, pressures, and other settings. Use the up and down arrows to scroll through the list of valve settings and readbacks, and temperature setting and readbacks.

Figure 4.35, RF Cavity Temperature

To change the settings scroll to the desired device name, hit the enter button, type the new setting, and then hit the enter button again. This works for all devices that have a set point. If you make a mistake during this operation, press the "esc" button to cancel the value you typed in.

Here is a list of the annunciator lights and pushbuttons and their functions.

SYSTEM RUNNING
When lit this light means that the water system is running normally and all the interlocks are made up.

SYSTEM READY
When lit this light means that the water system was tripped off, but is ready to start. When the light is flashing it means that there is a wiring mistake and that Linac experts should be notified.

SYSTEM TRIPPED
When flashing, this light means that the water system has tripped off.

AUTO MODE
This pushbutton places the water system into automatic mode, which gives the PLC full control over valve settings. It used a P.I.D. (Proportion Integral Differential) Loop Algorithm to calculate the setting for the valve due to the difference between the temperature set point and read back. When in automatic mode, a small LED above the pushbutton will light up.

MANUAL MODE
This pushbutton places the water system into manual mode. When in manual mode, the PID Loop has no control over valve settings, thereby allowing the operator the change the valve set point by using the procedure described previously. When in manual mode, a small LED above the pushbutton will light up.

RESET TRIP LATCH
This push button is very useful in determining the current interlock trip status. For example, say that a low water level trip occurred, the PLC latched the interlock and displayed the "Low Water Level" trip on the LCD screen. The system is then filled with water, but doesn't start up when the operator presses the start button. This means that another interlock is preventing the water pump from starting. Pressing this button will re-check the status of the system and then re-display the interlock preventing the system from running. After pressing this button, the operator may still have to press the esc button to change the LCD screen to the interlock trip status mode. Though rarely used, this pushbutton is useful in trying to debug a problem in the system that may be intermittent.

FULLY OPEN VALVE
This pushbutton opens the valve for that system, either Cavity or RF, to the fully open position. Pressing this button does two things; it places the PLC into manual mode and then changes the valve opening/set point to 100%. This can be useful to quickly cool down the system without powering down each valve and cranking the valve open by hand. After the system has cooled down, you should place back into automatic mode by either pressing the AUTO MODE pushbutton or by using ACNET.
FULLY CLOSE VALVE
This pushbutton fully closes the valve for that system; its valve opening/set point is set to 0%.

The water system parameters can also be found on ACNET on page L2, subpages lcwrf & lcw_c, as well as the lower energy Linac consoles. If you have any questions about the system, please contact the Operations Specialist or a Linac expert.

Linac Cavity Temperature Control System

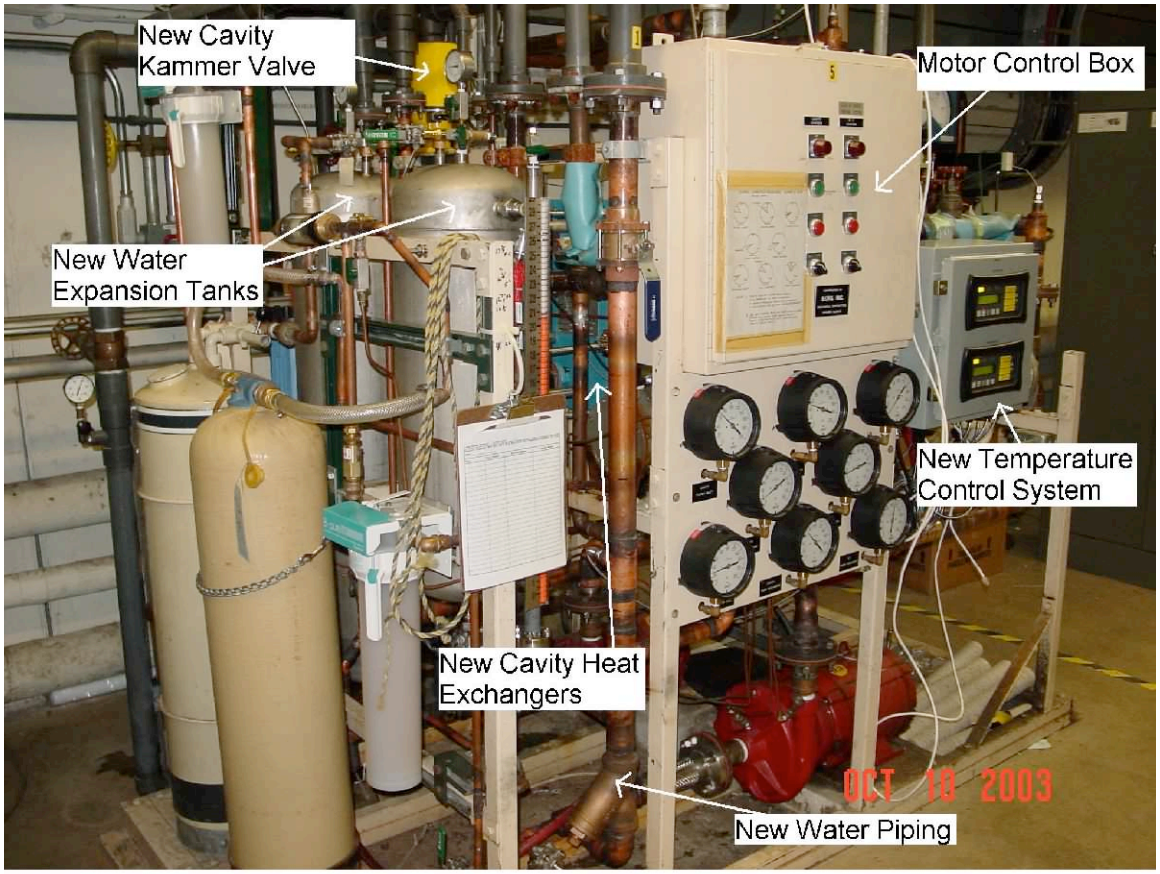


Figure 4.36, Low Energy Water Skids

A distribution skid located near the lower Linac gallery machine shop supplies the Cavity Water skids. The high-energy skid is a closed LCW system that heat exchanges with the CUB Chilled Water system to dissipate the approximately 100 kW of heat from the Cavity/Transition water skids. The water group can use the Booster's 95˚ F LCW system to manually fill the distribution skid's closed system. The distribution skid feeds about 59˚ F LCW into a header that has the cavity string cooling skids and the transition modules cooling skid attached in parallel. The chilled water supply temperature from CUB is approximately 44˚ Fahrenheit.

The seven cavity water skids and the transition module skid control the temperature by mixing heat exchanged LCW from the distribution skid with the LCW circulating between the cavity strings or transition modules and the cooling skids located in the Linac lower gallery. The Local Station computer controls the amount of water mixed. The main purpose of the Cavity cooling skids and the Transition module skid is to maintain a regulated LCW temperature of 80˚ F (27˚ C), which in turn will control the resonant frequency of the cavities. Each cavity string has its own LCW cooling skid. The transition module skid has three pumps on it. The bottom pump is a spare. The remaining top two pumps are for the two transition modules.

The Cavity/Transition cooling system exploits the temperature dependence of the copper cavities. For cavities constructed of a single metal, the percentage change in resonant frequency will equal the percentage change in dimension that is proportional to temperature. A full cavity string had a measured temperature dependence of -14.3 kHz/C, to a frequency change of 17.8 PPM/C at 805 MHz. Each accelerating cell has a half-inch cooling tube brazed in a groove that runs around the outside surface. The cooling channels are designed to have good flow rates at the inner surface of the tube to minimize thermal resistance between the LCW and the cooling tube. The supply and return lines are located on opposite sides of the cavities with one set of supply and return lines running across the top of the cavities. The orientation of the supply/return manifolds of the upper and lower set are opposite from one another. Connecting the cooling lines to alternate upper and lower supply/return lines will make the temperature drop, from supply to return line, small and give a more uniform temperature distribution in the cavity. This will also maintain the physical alignment of the Cavity/Transition sections during thermal cycling.

Fig. 4.37a H-Minus

Fig. 4.37b I-Minus

The H- and I- water skids are identical in function, even though their coloring is different. The only real difference between the two stations is the H- skid has the modern PLC control panel while the I- doesn't.

Fig. 4.38 NTF

Fig. 4.39 Station 3


Fig. 4.40 Station 5

Fig. 4.41 400 MeV

Chapter 5, Neutron Therapy Facility (NTF)

The Neutron Therapy Facility is no longer used as a therapy facility. When it did operate, it used high-energy neutrons for the treatment of malignant tumors. Linac produces neutrons by bombarding a beryllium target with 66 MeV H- ions. The NTF experts exposed a patient to the collimated neutron beam under tightly controlled conditions. The first Fermi facility was started in July1975. The facility was rebuilt and in September 1976 patient treatment began again with a more sophisticated setup and continues today.

The Linac operates at 15 hertz, that's 15 cycles per second of accelerator cycle. In the days before the Antiproton Source, the Linac was often idle and much of the beam could be devoted to NTF operation. More recently, rapid cycling of the Booster as an Accumulator/Debuncher injector has created a greater demand for Linac beam.

The beamline is now used, on occasion, for research.

Beamline

The Linac gallery floor plan determined the location of NTF, which required the use of an existing fright elevator at the junction of tanks 4 and 5 (figure 5.1). The beam energy is 92 MeV at this point, but the strongest conventional pulsed magnet that would fit in the 1-meter space between the tanks and still bend beam through the required angle can only bend beam of 65-70 MeV. The solution was to accelerate NTF beam pulses through the first three Linac cavities and then permit the ions to drift through tank 4 without additional acceleration. This is accomplished by delaying the timing of the RFON pulse for system 4 by 1 msec so that the RF pulse does not occur until after the beam has passed. The tank quadrupoles pulse at the regular time.

A pulsed C-type magnet (L:C58DEG) bends the extracted ion beam through 58˚ so it misses tank 5. The current in this magnet is ramped down when not sending beam to NTF to permit normal Linac operation. It takes about 66 milliseconds to change states. A Hall probe in the magnet aperture measures the magnetic field and may be read out through the control system. A 32˚ H- magnet, L:C32DEG, completes the 90˚ bend to send the beam through a transport line that passes through the wall of the Linac enclosure. This supply runs DC.

The transport line contains seven quadrupoles and two horizontal trims, and a toroid for monitoring beam intensity. The transmission efficiency of the line is typically 95%. Although the line is not achromatic, it is designed to have zero dispersion at the target. The effects of variations in beam momentum and focusing are minimized. Total length of the NTF transport line is about 20' with its power supplies located in the lower Linac Gallery below RF system 4.

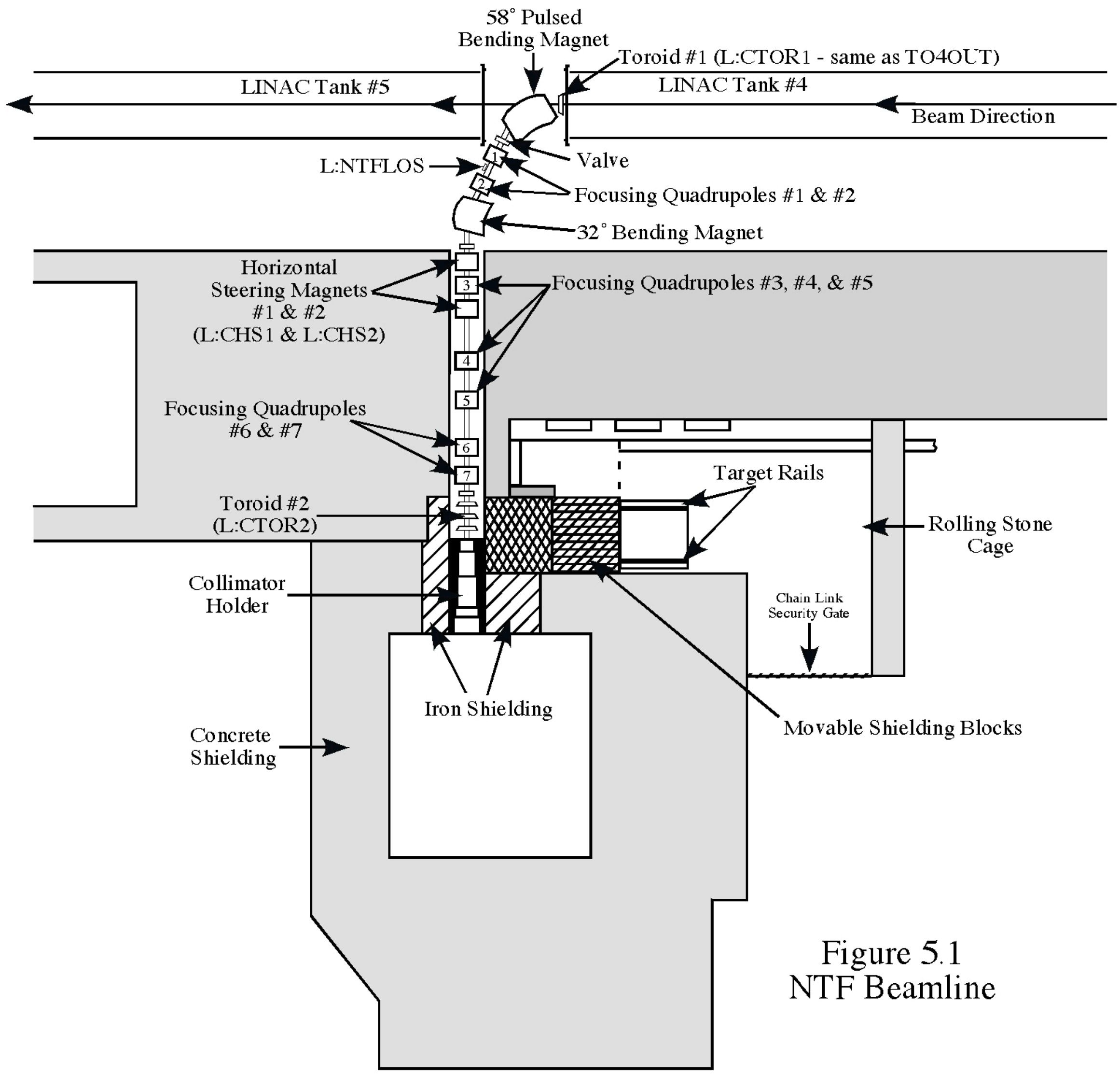


Figure 5.1
NTF Beamline

Target and Collimator

At the end of the transport line, the beam is focused to a 6 mm diameter spot; limited by the gradients available in the beamline quadrupoles. A tantalum collimator (figure 5.2) with a 15.9 mm bore prevents off-axis ions from striking the target. The target itself is a beryllium disk 25.4 mm in diameter and 22.1 mm thick. Beryllium is used due to its low atomic number (increases neutron production) and good mechanical properties (easier to work with than lithium).

The target removes 49 MeV from the incident ions, with the residual energy being spent in a gold disk that backs the beryllium block and improves thermal conductivity to the heat sink. The target assembly is housed in a water-cooled aluminum holder that is electrically grounded. Experience has shown that targets last at least five years before they must be replaced due to cumulative radiation damage.

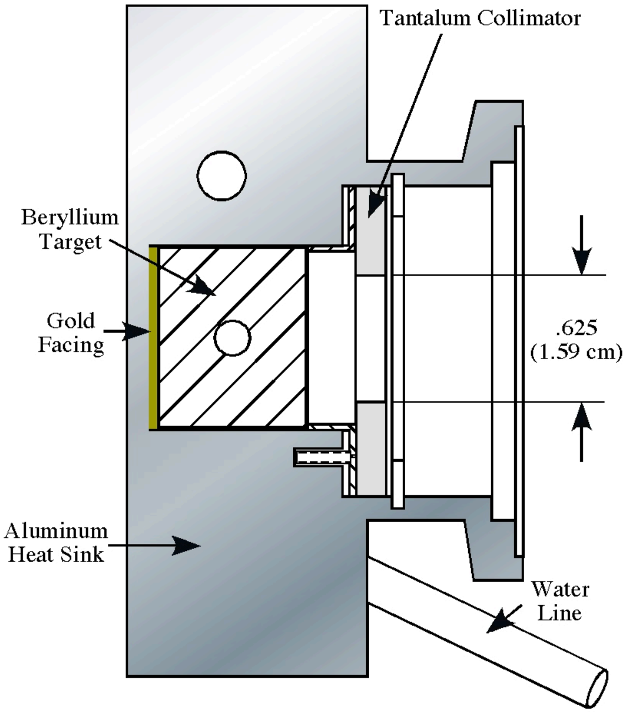


Figure 5.2 Target and Mounting Block

The neutrons pass through a primary collimator (figure 5.3) in the form of a steel cone 12.7 cm long. At the downstream end of this collimator, two air ionization chambers are used to monitor the neutron flux. These chambers consist of aluminum plates (alternating high-voltage and signal planes) separated by air. As the neutrons ionize the air, charge accumulates on the signal planes. When corrected for chamber temperature and barometric pressure (the interiors of the chambers are open to the atmosphere) the charge on the plates is proportional to the neutron intensity. During treatment, the ratio of the output charges between the two chambers and the ratio of the beam current (measured by the toroid in the transport line) to the output charge of the first chamber are monitored. If the ratios fall outside a narrow range, beam is inhibited.

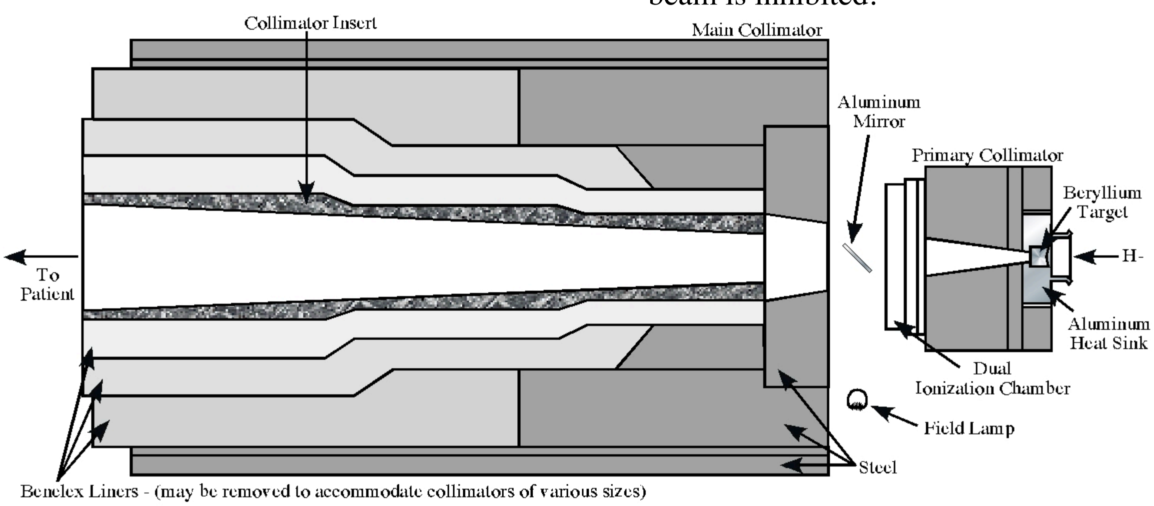


Figure 5.3 NTF Collimators

The output of the chambers is calibrated to the output of a tissue-equivalent ionization chamber that is itself calibrated using a cesiom-137 source in a fixture of known geometry. These two calibrations are performed at the beginning of every treatment day and output of the cesium-137 source is measured once a week using a chamber calibrated by the National Bureau of Standards on a yearly basis.

Downstream of the primary collimator, the 94 cm long main collimator shapes the neutron beam to the desired sized. A steel cylinder is fitted on the inside with a series of concentric Benelex liners (similar to G-10) that surrounds the collimator. Collimators are formed of a mixture of 1/8" polyethylene pellets, cement, and water. The Benelex liners can be removed to permit collimators with various size cross-sections to be used. Neutron beam cross sections, as measured in the plane of the area to be treated, can be up to 30 x 30 cm^2. The entire main collimator can be rotated about its long axis if a particular orientation is required. Teflon wedges may be attached to the downstream end of the main collimator to act as neutron attenuators or "prisms" to produce neutron flux gradients across the width of the subject.

Patient Setup

The treatment room was built on a freight elevator (figure 5.4). Entrance, simulation, and positioning took place on the upper level. For actual treatment, the room traveled to the lower level where the neutron beam entered from the wall-mounted collimator. Four orthogonal pairs of HeNe laser beams defined a geometric reference point at each level (isocenter) used in patient setup and alignment. The geometric relation of an X-ray source to the upper-level isocenter (or X-isocenter) was the same as the relation of the neutron source (assumed to be in the center of the target) to the lower-level isocenter (N-isocenter) with a 180˚ difference in orientation (figure 5.4). The Patient was usually positioned such that the tumor to be treated lied at the isocenter.

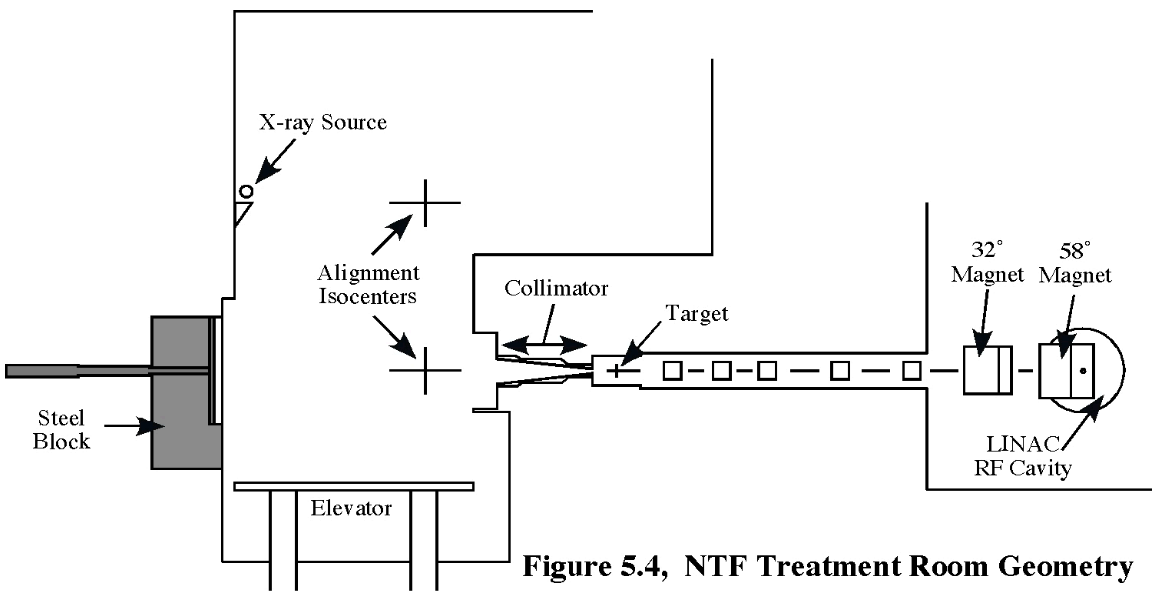


Figure 5.4, NTF Treatment Room Geometry

The patient was immobilized in the restraining chair usually by means of a custom-made cast. The areas where the neutron beam entered the patient ("portals") were determined by diagnostic radiographs (X-ray pictures), using the known geometry of the X-ray source and the X-isocenter. The positions of the restraining chair (adjustable in rotation, elevation, and two orthogonal directions) were adjusted to produce the desired field cross-section at the isoplane, the plane containing the isocenter and perpendicular to the neutron beam axis. In most cases, the transition from portal to portal was done by rotation only. The restraining chair coordinated at each portal was recorded so they could have been easily reproduced.

Reference points were drawn on the patient's skin (or cast) using the alignment laser beams in the upper level. The patient was then lowered to the neutron level, and the chair rotated through 180˚ and translated to the N-isocenter. The alignment laser beams at this level then duplicated the geometry of the lasers at the upper level, and the distance from the N-isocenter to the neutron target was the same as the distance from the X-isocenter to the X-ray source (190 cm). The lasers thus permit quick confirmation of proper alignment of the patient, in addition to the known coordinated of the restraining chair. Taking neutron radiographs and comparing them to the original diagnostic radiographs can further verify the position. As a final test, a small field lamp illuminates the patient through the main collimator by means of an aluminum mirror placed between the primary and main collimators at a 45˚ angle to the beam axis.

Once the correct collimator was in place, the air ionization chambers calibrated, the patient properly positioned, and the Linac and NTF transport line was ready, treatment would begin.

Individual neutron therapy programs averaged about four weeks in duration, with two to three treatments per week.

Control System

The treatment equipment is controlled by medical and beamline microcomputers. The beamline microcomputer monitors transport line dipole magnet currents, beam current, interlock status, commands the phase shifter for Linac RF system 4, and handles communication with Linac NODE 601C. It also measures barometric pressure and integrated ionization chamber voltages that are then used to calculate dosages (expressed in monitor units), given parameters loaded from the medical microcomputer. The beamline microcomputer monitors neutron dosages during patient treatment, automatically terminating exposure when the desired dosage is reached. The beamline microcomputer, beamline power supplies, measuring and integrating electronics, A/D converters, timers, and interlock systems are located in the lower Linac gallery near the water system for RF station #5.

The medical microcomputer in the NTF control room interfaces with the radiation therapy technologists via a console, and performs calculations for cesiom-137 source and air ionization chamber calibration. Auxiliary hardwired scalers and timers in the same racks will inhibit beam if the beamline microcomputer should fail to end the exposure when the correct number of monitoring units have accumulated.

Any unusual variation of the 32˚ or 58˚ magnet current or ionization chamber response during treatment will cause the beamline microcomputer to inhibit beam via the NTF interlock system. Quadrupole currents in the transport line are monitored by secondary #C and will also inhibit beam via the beam inhibit line if they wander out of tolerance. Once all the necessary conditions for a beam permit have been satisfied, actual exposure begins when two beam request switches on the NTF beam control module are pushed simultaneously.

NTF Interlocks

When a beam request and appropriate set of conditions exist, the pulse shifter will permit beam in the Linac. An elaborate system of interlocks allows an NTF beam request to occur only under proper conditions.

The task of collecting interlock data is allocated to the NTF Interlock Box. This box receives all kinds of hardwired information as well as information from the beamline microcomputer. This information is displayed on the front of the box and at two remote NTF status modules, one in the NTF control room and one in the MCR. Be forewarned that all three of these boxes are labeled differently—an interlock's name may change from box to box. The interlocks listed here follow the names on the module in the MCR.

There are three levels of interlocks in the NTF systems, each a superset of the previous level. The ANDed sum of the first level of interlocks is a ramp enable, which will permit the 58˚ bend magnet to ramp. All the inputs to the first two levels follow two separate and redundant electrical paths, labeled "A" and "B." Thus, there is an "A Ramp Enable" and a "B Ramp Enable" that look at the same interlocks. Both are required to permit the 58˚ supply to ramp.

Among the second-level interlocks is one called "Currents Nominal." This is an indication that the 58˚ and 32˚ supplies are on at the proper level, which means that the "A" and "B" ramp enables must exist. These enables act as inputs to the second level of interlocks, which are ANDed like the first level in two redundant electrical paths to produce system ready indications, "A System Ready" and "B System Ready." These are then ANDed together to form an input to the third level of interlocks.

If all three levels are made up, NTF will receive beam (if the Linac is operating).

The status in the MCR relay rack MCRR #1 shows the status of the NTF interlocks. An LED next to each input name will be out if the input is bad, indicating what is inhibiting the NTF beam. For an input diagram, see figure 5.5.

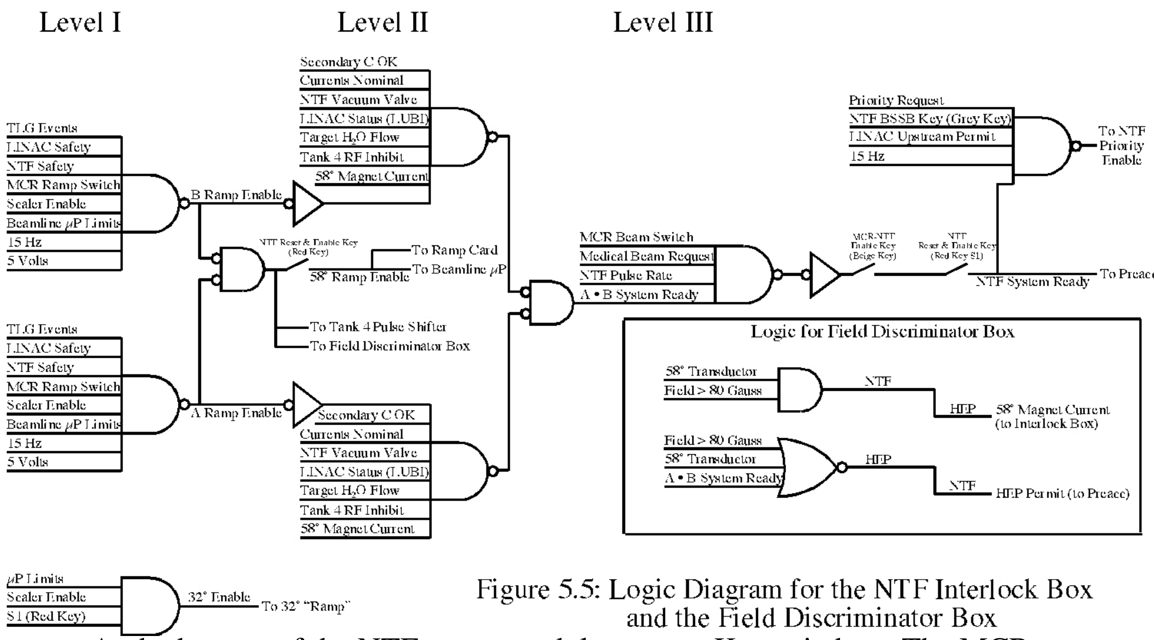


Figure 5.5: Logic Diagram for the NTF Interlock Box and the Field Discriminator Box

At the bottom of the NTF status module are two Keyswitches. The MCR Keyswitch must be in the "ON" position for NTF beam to occur. The tune-up Keyswitch allows beam when the key is turned and the tune-up beam switch is pressed. This is used when tuning up the transport line. The same key is turned in the medical Keyswitch in the beam control module during patient treatment.

RF4 Pulse Delay

When the 58° magnet is enabled, the beamline μP sends a signal to Linac RF system 4 to delay the LRF4 pulse. The delay system consists of two modules in the racks behind the A5 racks for LRF4.

At the normal LRF4 RFON time, the first module looks to see if an NTF enable exists at the input, from the NTF beamline microcomputer.

If the pulse exists, the enable output to the second module is latched, to prevent the system form changing its mind during the beam pulse. When the second module receives the NTF enable, it delays the incoming RFON timing pulse from the Preacc control room by 1 msec before passing it on to the LRF4 system, which turns on LRF4 later than normal.

When the NTF beam is enabled, the first module also sends a delayed S&H trigger signal to the A/D converters that are responsible for RF system readbacks. This assures that they sample at the correct time with respect to the RF pulse, which is proper tracking.

To verify that the RF from LRF4 is actually being shifted, the NTF interface modules, located at LRF3 and LRF4, look to see when the RFON pulse occurs at their respective systems. The LRF3 NTF interface sends its signal to the LRF4 NTF interface module.

If the two pulses occur at the same time, the output line to NTF goes LOW, which inhibits the NTF beam by removing the RF4 INHIBIT input from the interlock chain. This removes the NTF ENABLE output from the NTF status module in the MCR. The NTF interface modules are located in the crates containing the modulator pulse-forming circuitry at LRF3 and LRF4.

Another NTF ENABLE signal is sent to the low-level system, which allows the Buncher to select the RF phase used for NTF beam pulses.

NTF Operation

The responsibility for operating the Neutron Therapy Facility beamline lies with the NTF staff. Operation's responsibilities are to keep the Preaccelerator, 750 keV transport line, Buncher, RF systems 1-3, and the tank quadrupoles in systems 1-4 operating normally. During actual patient treatment, these items have top priority.

Daily operation of the NTF begins with issuing three keys from the MCR:

- The NTF beam enable key (brown tag)
- The NTF reset and enable key (red tag)
- The NTF BSSB key (grey tag)

The beam enable key is turned in the MCR Keyswitch on the NTF status module and is left there for the duration of NTF operation. The reset and enable key is placed in the tune-up Keyswitch during tune-up of the transport line, and in the medical Keyswitch in the beam control module in the NTF control room during patient treatment.

Since NTF does not depend on RF system 4 or the Klystrons to operate, a beam inhibit from one of these areas may be bypassed in order to run NTF beam. However, HEP beam should never be run under these conditions. A prerequisite for bypassing an inhibit, for the benefit of NTF, is the removal of the HEP enable key from the abort interface. This key is the locked up in the Crew Chief's cabinet until the inhibit monitoring is restored.

NTF Vacuum

The NTF vacuum system is quite simple. There is a single vacuum valve in the beamline just after the 58˚ bending magnet. The vacuum is continuous all the way to the beryllium target. The valve is interlocked to an ion gauge in the beamline, but not to Linac vacuum. The gauge readout and valve controllers are found behind the A5 racks for RF system 4.

A fore line runs upstairs to a roughing and turbo pump station behind the rack that contains the valve controller. The turbo pump runs continuously. An ion pump has been mounted in the wall in back of LRF4.

NTF Beam Timing

The timing of NTF beam pulses had been referenced to a signal called T0. The start and stop times were set by means of thumb-wheel switches in the "Predet" located in an electronics rack near the Cockcroft-Walton. The timing of all equipment related to beam delivery in the accelerator complex has been referenced to 15 Hz signals designated Tevatron clock event OC.

In the process of replacing the thumbwheel switch system with computer-operated controls, it was found that there is a five-microsecond discrepancy between the Linac timing system and the Booster timing system. The correct time for the 57 microsecond NTF beam pulse in the new system is between 1953 and 2000 microseconds after OC.

The NTDATA pulse is the timing signal for triggering the readout of beam data in the detectors that monitor NTF beam. It occurs at 1980 microseconds after OC.

Actual settings for the start and stop times of NTF beam can be found on a parameter page using the names L:TCHNON and L:TCHNOF. The data strobe time is given in L:NTDATA. The Main Control Room crew chief's console, which needs a password to change the database, is the only console that can change the pulse width.

Chapter 6, THE SIDE COUPLED LINAC

Side Coupled Cavities

Figure 6.1 shows several side-coupled cavity modules and figure 6.2 is a general diagram. There are seven of these 805 MHz modules in Linac, with a combined length of 64 meters. They take the ~116 MeV beam from the 5 drift-tube cavities and accelerates the beam to 400 MeV. Each side-coupled cavity module consists of 4 sections with each section containing 16 accelerating cells and 15 coupling cells. The 4 sections are joined together on the module girder by 3 bridge couplers. An 804.96 MHz signal, amplified by a 12 MW Klystron, drives the module. The accelerating gradient for each side-couple cavity module is about 7.5 MV/m, which is three times that of the drift-tube Linac.

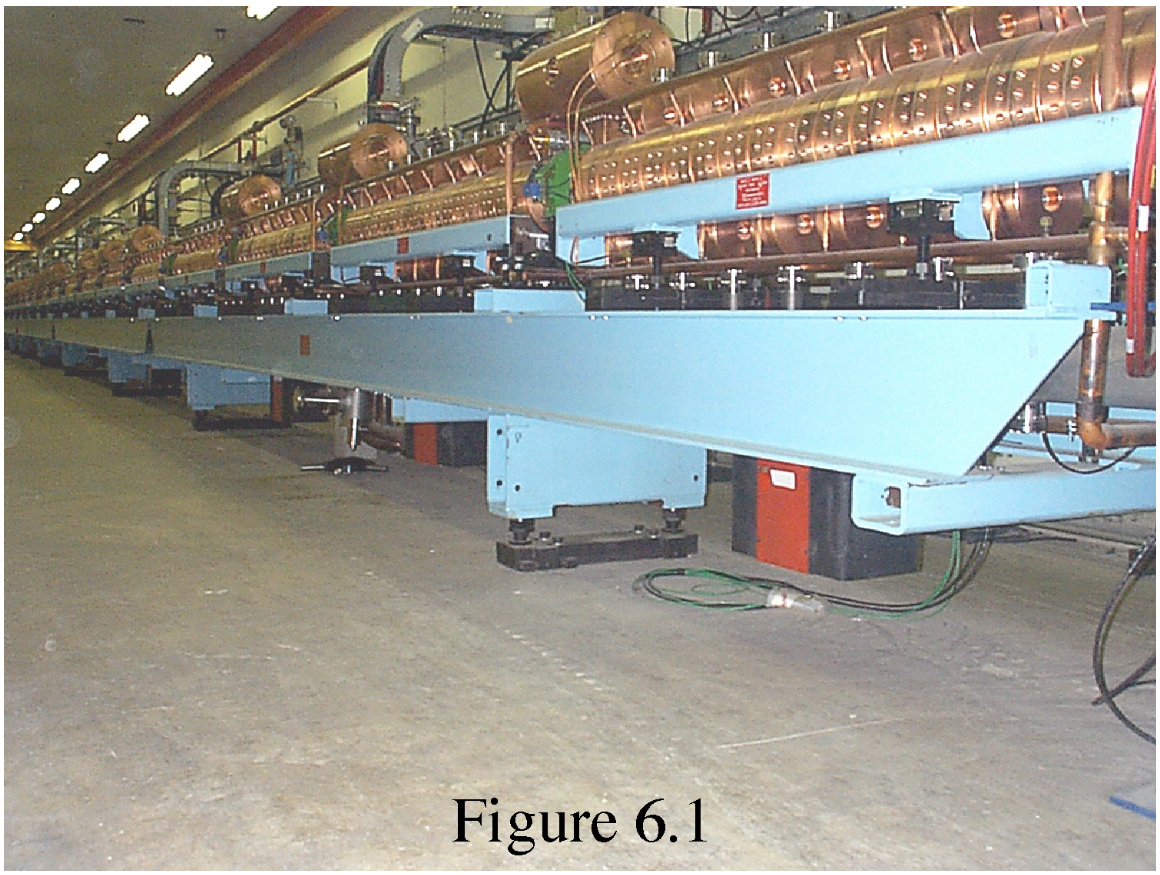


Figure 6.1

Accelerating Side-Coupled Cells

With side-coupled cavities, each individual cell is a separate accelerating cavity coupled to other cells in the module. The module is not one cavity with drift-tubes, but rather several separate cavities powered by the same RF source by coupling.

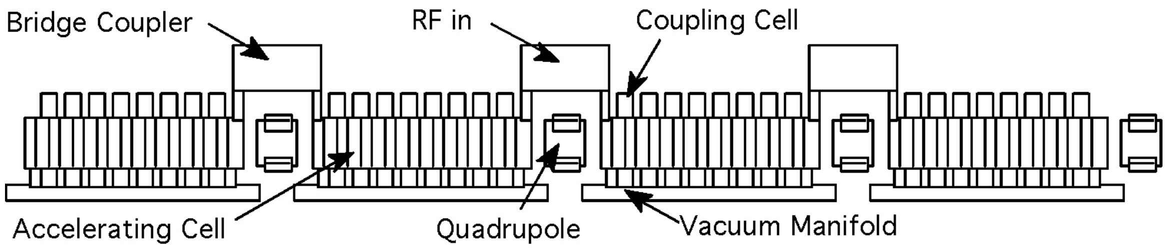


Figure 6.2

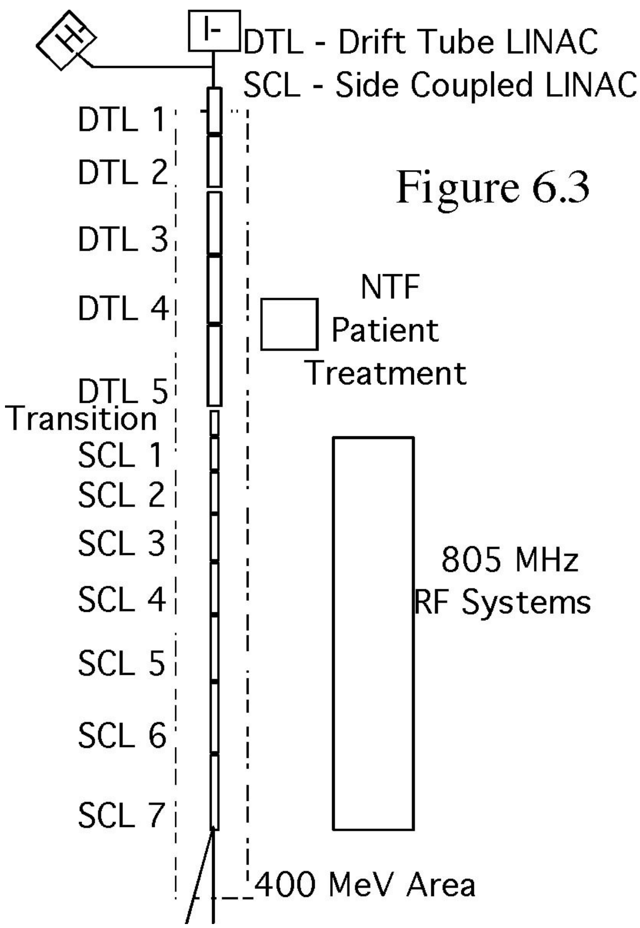


Figure 6.3

To synchronize the RF with the beam, the length of cell is $\beta\lambda/2$, where β equals the particle velocity divided by the speed of light, and λ is the wavelength of the electric field. As the particle velocity (β) of the beam increases from module to module the length of the accelerating cells increases within each module. This is the same as the 5 drift-tube tanks.

To the left, figure 6.3 shows the different tank sizes.

Another factor that went into the determination of the volume and shape of the cavities is a parameter called shunt impedance, denoted by Z. The shunt impedance can be defined by the following equation:

$$Z = \frac{(E_0)^2}{P/L}$$

where: E_0 = the average axial field (or gradient)

P/L = the RF power dissipated per unit length.

This is a good measure of efficiency. It is maximized during construction and tuning. The main parameter in determining the shunt impedance is the major cavity radius and the radius of the beam tube. The major cavity radius is the distance between the beampipe axis and the farthest cavity wall from the axis.

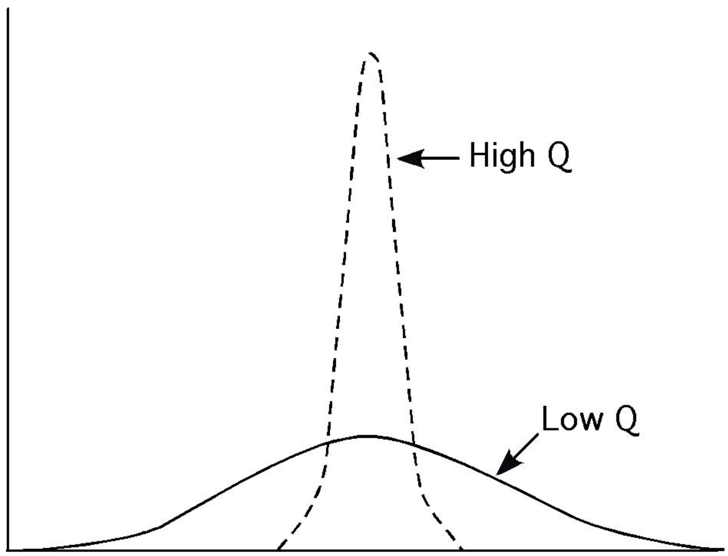


Figure 6.4

The quality factor, Q, is also important in determining the shape of a cell. This parameter describes the resonance of the cavity. (See figure 6.4) A cavity with a high Q will only resonate at frequencies that are very near the design resonant frequency. A cavity with a lower Q resonates over a larger range of frequencies. The quality factor is the ratio of the resonant frequency of the cell to $\Delta\omega$, the width of the resonance. An accelerator with a high Q needs to be very stable. It is difficult to maintain the resonant frequency of a high Q system because the width of the resonance is so small relative to the frequency. Several methods of automated tuning are necessary to keep the RF stable. Both the SCS Linac and the DTL have a high Q. This gives both structures a strong resonance. The quality factor can also be expressed by the following equation:

$$Q = \omega U / P$$

where: U = cavity stored energy
P = RF power.

Since the energy and power dissipation in the coupling cells is very small, the Q of the coupling cells is not an important design parameter in the design of the structure.

Study figure 6.5. The shape of the nose-cones plays an important part of the accelerating cell. The nose-cones concentrate the field toward the center of the accelerating gap, which creates a stronger field and better acceleration. (See figure 6.6)

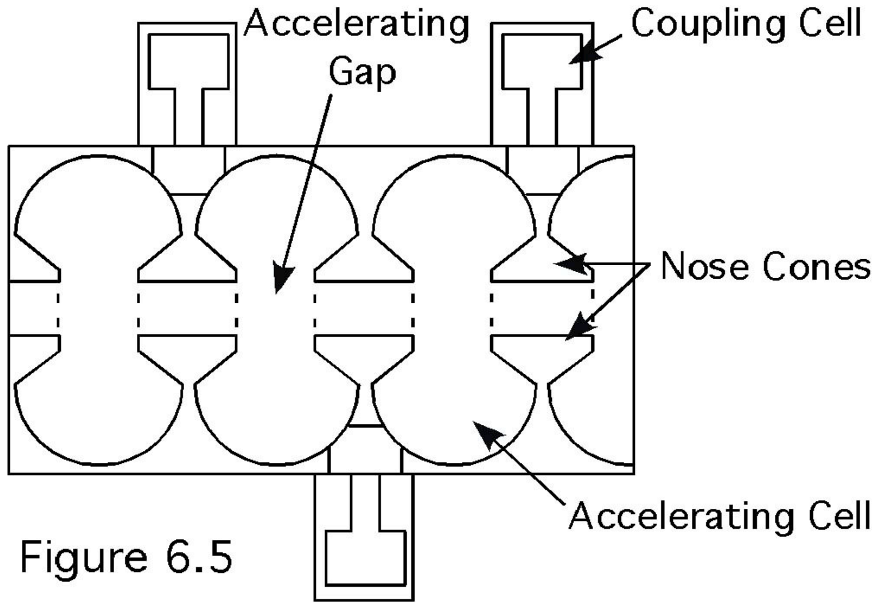


Figure 6.5

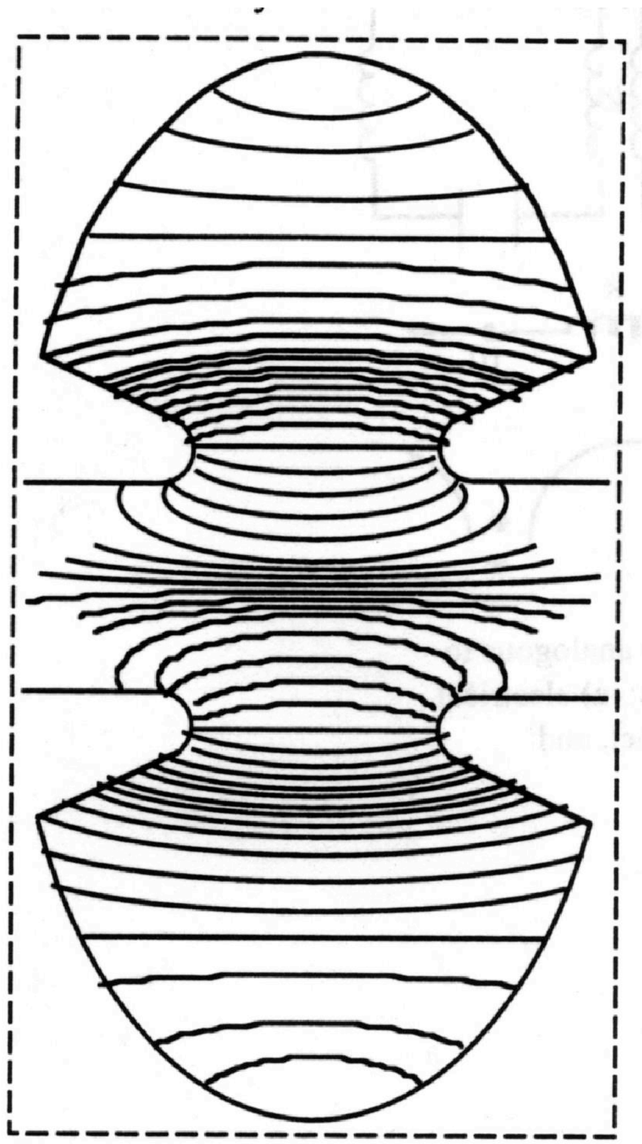


Figure 6.6 Nose Cone Field

This concentrated field accelerates the beam more efficiently than a uniform field across the whole gap. The shape of the nose-cones can also effect sparking depending on the peak surface fields, so a design to reduce sparking was chosen. The designed spark rate of the complete SCL is about 0.1% per RF pulse for 60 μs RF pulses (one station cycle) at a 15 Hz repetition rate. (In 2002, Linac experts measured the sparking rate at less than 0.01%.) This insures a long lifetime of the components with low voltage conditioning times. The nose-cone works somewhat like a drift-tube by shielding the beam from electric fields until they're in the direction of maximum acceleration, except that the drift-tubes shield the beam from decelerating fields. The fields in the SCS are optimized in the center of the cavity due to the nose-cones.

Coupling

A coupled accelerator is one that has independent resonant cavities that couples the energy between each cavity. The coupled cavities have a high efficiency while maintaining excellent shunt impedance. This shunt impedance allows coupled cavity Linacs to produce higher energy and higher current beams.

The stability of side coupled cavity modules comes from its ability to operate with a $\pi/2$ phase shift between the cells. Because of its $\pi/2$ structure, there are twice as many accelerating gaps per unit length. The coupling cavities absorb errors in the frequency for the accelerating cells. The following models can describe the coupling between cells: electric circuit, spring, and potential wells.

In the spring model, model b of figure 6.7, if the first mass is oscillating, the coupling through the spring forces oscillations on the second mass. The oscillation on the second mass will build until it has reached the same amplitude as the first. While mass one's oscillations are being coupled to mass two, mass two's oscillations are also being coupled to the third mass. This coupling could be extended to several masses. The other models have similar analogies.

Each coupling cavity carries the RF through the entire module to each accelerating cavity. During construction of the module, the cells are machined separately. The accelerating and coupling cavities are tuned to frequencies slightly different than 805 MHz (before the coupling slots are cut), but when coupled together the module resonates at 805 MHz.

Each of the models in figure 6.7 is analogous to the coupling in side-coupled cavities:

a) Electrical circuit model
b) Mechanical spring model
c) Potential well model.

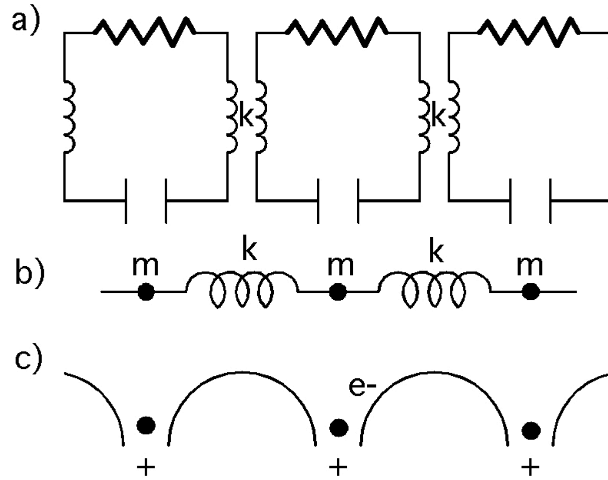


Figure 6.7

Cavity Fields

Both the SCL Linac and the DTL operate in the TM_{010} Mode. This describes the field and its direction. The mode is generally in the form TM_{1mn} and TE_{1mn} where 1, m, n, are derived from Bessel functions that describe the field's zero crossing in a resonant cell.

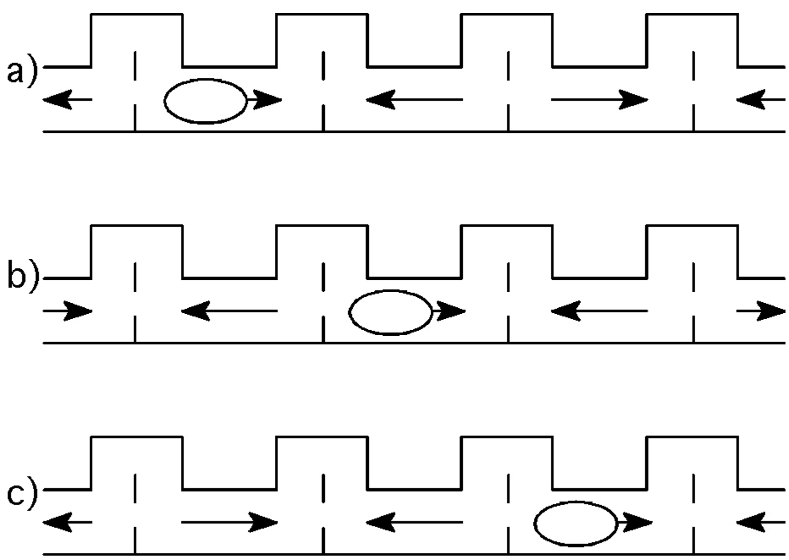


Figure 6.8

The phase shift describes the phase difference from one cell to a nearby cell. In the SCL, the phase shift from an accelerating cell to its nearest cell, a coupling cell, is $\pi/2$. The phase shift from one accelerating cell to the next is π, and the distance between the accelerating cells is $\beta\lambda/2$. (Where β equals the particle velocity divided by the speed of light, and λ is the wavelength of the electric field.) Therefore, since the phase shift between accelerating cells is π, the fields in adjacent accelerating cells are always in the opposite field. (See figure 6.8.) When beam enters the first cell, the field is in the accelerating direction. As beam goes through the nose cone, the fields shift in the other direction. When beam enters the second cell, the field is now in the accelerating direction while the field in the first cell is in the decelerating direction. There is no beam in the first cell to see the field so nothing is actually decelerated. The beam continues to go through the cavities with accelerating fields, and beam is accelerated. The beam pulses from the DTL travel 8 cells apart in the SCL. (See figure 6.9) In contrast, the DTL phase shift is 0 between accelerating cells and the cells are separated by $\beta\lambda$. The π/2 mode has a great advantage over 0 and π modes in that it gives stability to the RF frequency phase.

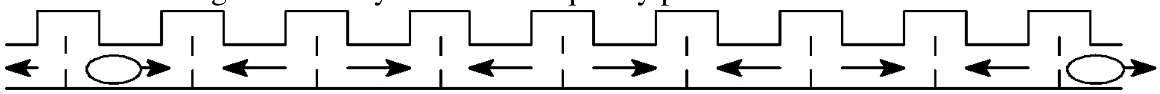


Figure 6.9

The above diagram shows the spacing between beam pulses during acceleration. There can be up to two pulses in a section and eight pulses in one module.

SCL Bridge Coupling

The bridge couplers are coupling cavities that are $3\beta\lambda/2$ long. This length keeps the beam and RF synchronous while being long enough to allow room for magnets and diagnostics. Figure 6.10 shows a picture of a Los Alamos bridge coupler, which is very similar to Fermilab's bridge coupler. The middle bridge coupler has a flanged iris coupled waveguide port to bring the RF into the module from the waveguide. The waveguide window is a ceramic window at the waveguide port that separates the waveguide air pressure from the cavity vacuum. The bridge coupler acts as a coupling cell to stabilize the RF before the RF goes to an accelerating cell where it interacts with beam.

The bridge coupler with the waveguide window is in the middle to equalize the RF power droop at both ends of the module. The other two bridge couplers are halfway between the middle bridge coupler and the ends of the module in order to accommodate the quads. (See figure 6.2)

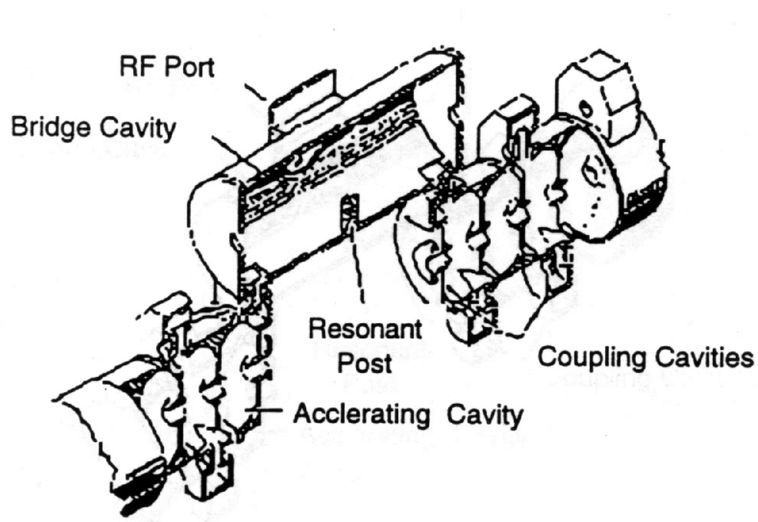


Figure 6.10 Bridge Coupler

Conserving space is important and that's what the bridge couplers do. Besides making room for the quads, the bridge couplers also provide room for trims and diagnostics like BPMs, crawling wires, and toroids. Another benefit is that all the quads and diagnostics are easily accessible. The two side-posts and two end-posts inside the bridge couplers control the fields; the posts are comparable in function to the post couplers of the DTL. The side-post and end-posts prevent mode-mixing. The bridge couplers resonate at TM_{010}, and the mode-mixing means that the cavity may resonate at another mode near TM_{010} causing beam to go unstable.

The end-posts tune the frequency of the TM_{010} mode. The bridge couplers are single cavity resonators with a long length and several modes can be close together in frequency. The side posts move these other frequency modes away from the 805 MHz frequency.

For the most part, the bridge couplers won't change the resonant behavior of the module. It should remain periodic in effect since the phase shift from the accelerating cells to the bridge coupler is $\pi/2$. The stability from this phase difference should compensate for any errors.

Linac RF Systems

There are 5 drift tube cavities (DTL) and 7 side coupled cavities (SCL) in Linac. The DTL makes up the first stage of the Linac and the SCL is the second stage. Each stage has its own RF systems that work on different frequencies. These systems drive their appropriate cavity fields to the gradient and phase necessary for suitable energy gain.

This is how it's accomplished. Every Linac cycle (66 msec) the RF systems provide a short pulse for the acceleration of beam. In between the RF pulses the cavity field collapses. Since the cavities are a highly resonant system, with a geometry that assumes a certain energy gain per cell, the failure of any RF system will strongly affect the transmission and output momentum of the Linac, making transmission of beam through the Linac impossible.

Each RF section consists of a low-level and high-level RF system. The low-level system provides a low power signal of the appropriate amplitude and phase for the high-level system, which is then amplified to about 5MW for the DTL and 7-9 MW for the SCL. This power is sent via a coaxial transmission line for the drift tubes cavities, and a rectangular wave guide for the side coupled cavities to induce the electromagnetic fields in the cavity.

Low Level RF

The LLRF drive signals—201.24 MHz for DTL and 804.96 for SCL—come from relay rack LT-5 located in the transition section on the far north side of the Klystron power supply gallery.

The LLRF system has the following task requirements:

- Provide the 1mW RF signal to the solid state amplifier that drives the Klystron 12MW amplifiers (SCL) and a half-watt signal to the PAs (DTL).
- Provide an error signal to the water control loops that indicates the amount of cavity frequency error due to temperature detuning.
- Provide a station phase shifter and detector to use during phase scans and to set the final cavity phase.
- Provide an RF frequency that can track the cavity resonance frequency. This is the cold start system.
- Regulate the cavity gradient phase and amplitude to 1 degree and 1%. This is done with conventional feedback and with the help of a learning system that injects a signal into the loop in a feed-forward configuration.
- Terminate RF after the detection of cavity sparks on the nanosecond time scale.

In the lower section of the relay-rack LT-5 is a Mech-Tronics crate that houses the following modules:

- Reference Line Pressure Readout Module
- Reference Line 805 MHz/4 Module
- Phase Shifter Module
- Up Dn Control Module

- Phase Detector
- 201.2408/804.9632 MHz Frequency Reference

Directly above the Mech-Tronics crate is a Hewlett-Packard Computing Counter that displays the low-level signal sent to the DTL stations for reference. And above that is the VME bus crate electronics.

SCL LLRF

A VXI bus crate and a control system interface, located in relay rack LK-0 for each Klystron station, receive the LLRF signals. The VXI bus crate electronics is an extended specification of the VME bus crate electronics with some added features for instrumentation. The control path begins with the Linac Control's Vertical Interconnect Card. The VIC maps the VXI memory into the memory space of the control VME crate. The VXI memory card has a common data pool for the control system and for the Motorola 133 CPU card in the VXI crate. The 133 handles all interface to the VXI modules and does the computation for the feedforward.

The RF signal is patched to three modules in the VXI crate: the Linac ø Det./Shifter, the Linac LLRF 805 MHz, and the Linac Phase/VXCO.

The VCXO (please note the name discrepancy) module can switch between the reference RF and a variable oscillator. The local oscillator is used for cold start when the cavities are not resonant at the reference frequency.

The Linac ø Det./Shifter receives the selected RF from the VCXO. The phase shifter controls the phase of the reference to the rest of the low-level system. This module allows you to shift a single cavity phase independent of the rest of the Linac over a 360-degree range (which is primarily used for phase scan measurements). The phase detector portion of the module reads the cavity to reference line phase over a 360-degree range. There is also a biased diode detector on the card that measures cavity gradient.

The LLRF module does the bulk of the work. It takes the phase adjusted signal from the Phase Shifter/Detector module as both signal source and reference. The module is really two separate controllers, one of amplitude and one of phase. Amplitude control starts with a circuit that creates a signal that is the desired envelope of RF in the cavity. The return signal (fanback) from the cavity goes to a diode detector to produce the cavity RF envelope. This signal is subtracted from the desired response to produce an error signal. The error signal then modulates the RF reference signal on its way to the Klystron. The phase controller works in the same way.

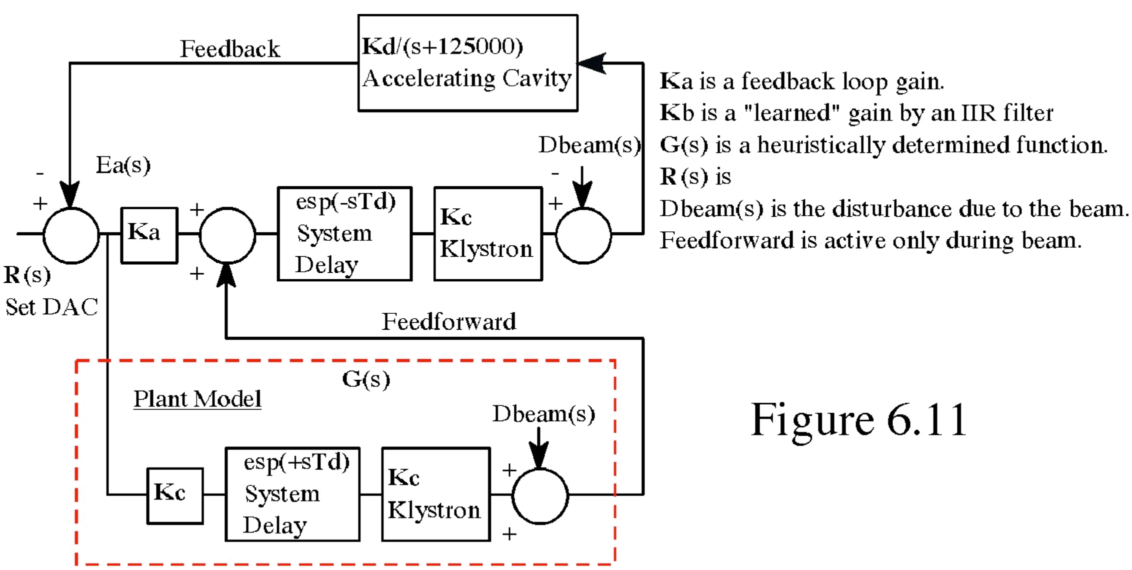


Figure 6.11

These feedback systems aren't fast or strong enough to handle the beam loading in the cavity. This is where the learning system comes into play. While the feedback system can deal only with the error caused by beam loading, we know when the beam is coming and we know the shape of the beam envelope. We also know the effects are quite repetitive. Armed with this knowledge we can pass a signal equal in magnitude and opposite in phase of the beam loading to the drive signal. This is done by digitizing the error waveforms and comparing the signals from before beam to those during beam. This new error signal is low pass filtered over many beam cycles and then used to produce a waveform that is played out on a DAC. This feedforward signal is added to the RF modulator drive signal. With the feedforward properly adjusted, the feedback system hardly knows that beam is present.

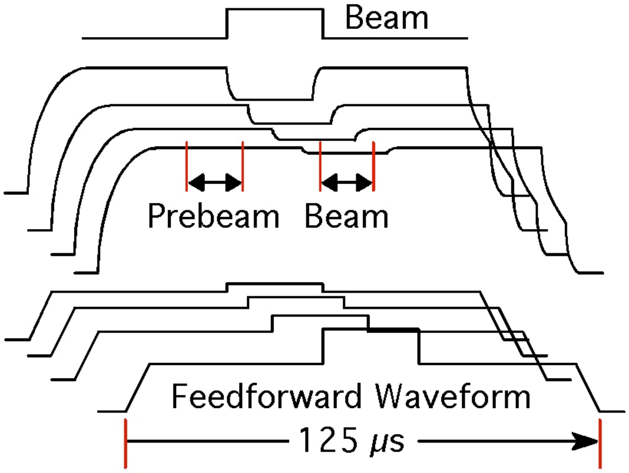


Figure 6.12

When the cavity waveforms don't look right it might not be the fault of the LLRF system. This system seldom suffers hardware failure. What usually happens is that there is a loss of gain somewhere in the loop or a request is made of the RF it can't perform. Some past troubles have been traced to the cavity temperature being off from its set point. This lowers the "gain" of the cavity and also gives a large phase shift. The solid state drive amps can fail in a low gain state. Also, the Klystrons have been known to run at a low gain for a variety of reasons.

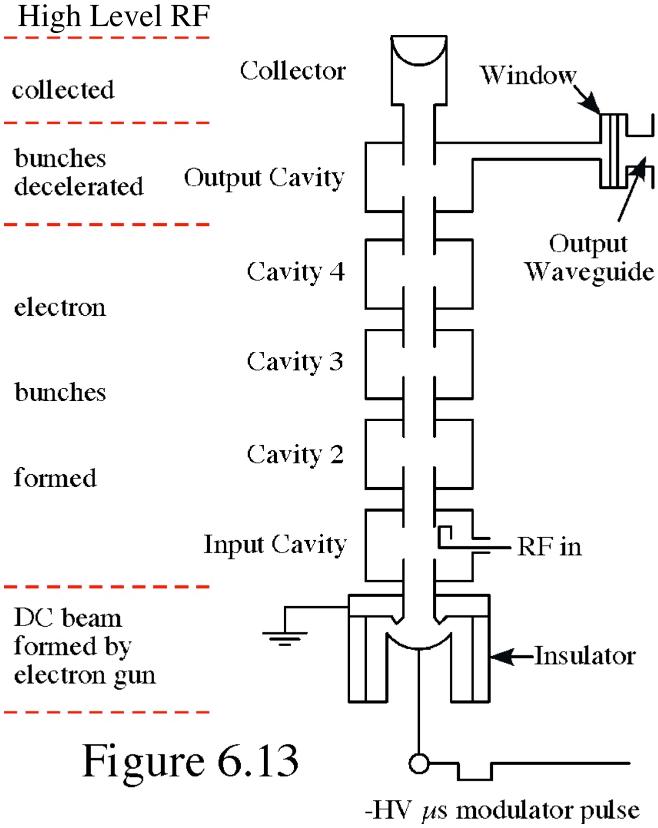


Figure 6.13

Klystron

The heart of the high level 805 MHz RF system is the Litton Klystron amplifier. A 500 W solid state amplifier initially amplifies the LLRF signal. The klystron takes this signal and, by using velocity modulation, drives the signal to oscillate at a higher amplitude before sending it to the side coupled cavities in the tunnel.

The High Energy Linac (HEL) Klystron consists of 5 cavities tuned to a resonant frequency of 805 MHz, which is actually a microwave frequency (See figure 6.13). These cavities each provide about 10 dB gain for a total of 52 dB gain. The maximum output of the Litton Klystron is 12 MW although they are usually operated at 7 to 8 MW.

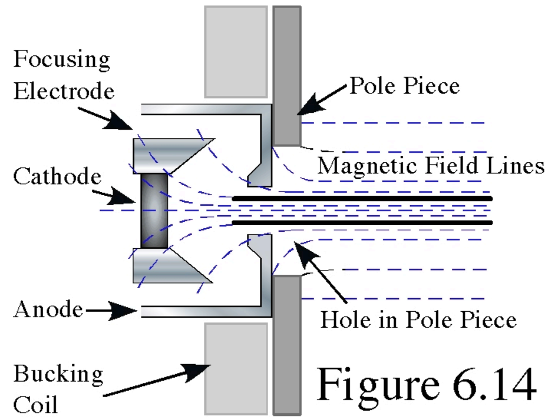


Figure 6.14

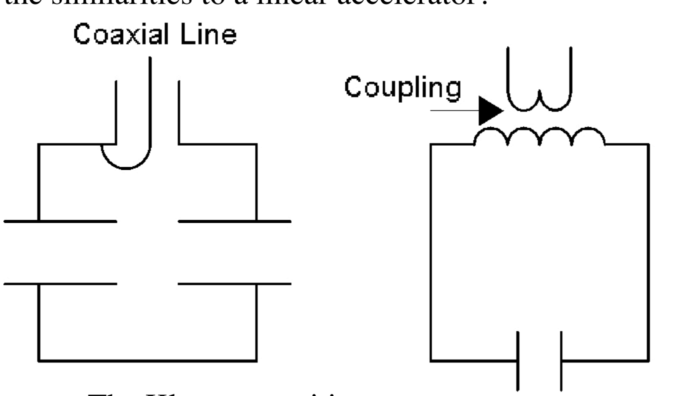
The bottom of the klystron tube contains the cathode, anode, filament, focusing electrode, bucking coil, and pole piece. (See figure 6.14) This is commonly referred to as the electron gun. The modulator produces a maximum current of 160 amps of electrons at a voltage of 170 kV on the cathode. The cathode is dish-shaped, which creates a large surface area for emitting electrons while aiming the electrons toward a focal point. These electrons are produced by thermionic emissions. A filament heats the cathode. The extracted flux of electrons accelerates from the cathode towards the anode. The cathode is covered with a barium strontium oxide coating to aid in the emission of electrons by lowering the work function of the cathode. (This is similar to the cathode in the Preaccelerator, except the oxide for the klystron cathode is solid at room temperature and is baked onto the cathode. The Preaccelerator, on the other hand, used a vaporized cesium.)

Three important parameters regarding the cathode are the temperature, voltage, and the current of the electron beam produced. The filament keeps the cathode at an optimum operating temperature. If the cathode is too hot, the oxide emitting material will melt off, if too cold it won't emit.

As the klystron gets older, its voltage is increased in order to keep its current constant. If the klystron is running well, the temperature and voltage should run at half the saturation values.

Klystron Body

The Buncher is the first of the five klystron cavities. The RF drive is coupled to the Buncher to provide the bunch structure for the beam (figure 6.15). The RF provides an alternating electric field in the form of a sine wave. The RF bunches the electrons in the Klystron tube by accelerating late particles and decelerating early particles. The average velocity of the bunch remains the same in the Buncher. The Buncher is the first step in converting DC beam into beam with a bunch structure. Some of the beam is not captured in the bunch and continues through the Klystron as DC beam. Do you recognize the similarities to a linear accelerator?



The coupling between the coaxial line and the cavity can be compared to coupling in electrical circuits.

Figure 6.15

The Klystron cavities are resonant structures that resonate at 805 MHz. The accelerating gap and drift-tubes work like a capacitor, and the volume and cavity walls act as an inductor (figure 6.16). The cavities are tuned with a tuning slug that controls the volume. This is controllable from holes in the tube. There is also a paddle on the end of the tuning slug that acts like a post coupler to control the electric field. The Klystron comes tuned from the factory and should require minimal tuning.

Coupling from the beam in the Klystron tube (figures 6.15 and 6.16) provides the velocity modulation in the last four cavities. There is no RF input into these cavities. The gaps by the nose cones at the ends of the drift tubes concentrate the electric field. As beam leaves a cavity, electrons are pushed to the other side because the cavity walls act as inductors. This distribution of charge creates an electric field in the cavity that will accelerate the DC electrons, the beam between the bunches. The DC beam is in the cavity when this electric field is present. So the DC beam is accelerated and some of the electrons catch up to and become part of the existing bunches. Since the cavity is a resonant structure, the negative charge will oscillate back to the other side to redistribute the charge.

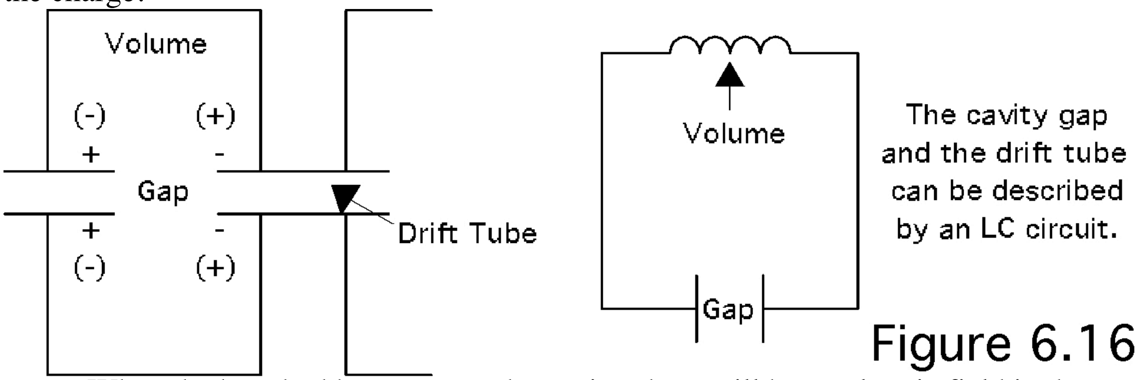


Figure 6.16

When the bunched beam enters the cavity, there will be an electric field in the other direction. The bunched beam will be decelerated, and more DC electrons will catch up to and join the bunch. This velocity modulation occurs in each of the cavities, and increases the amplitude of the oscillation at each step. Each cavity acts like a driver for the next step (figure 6.17). This explanation describes a steady state condition.

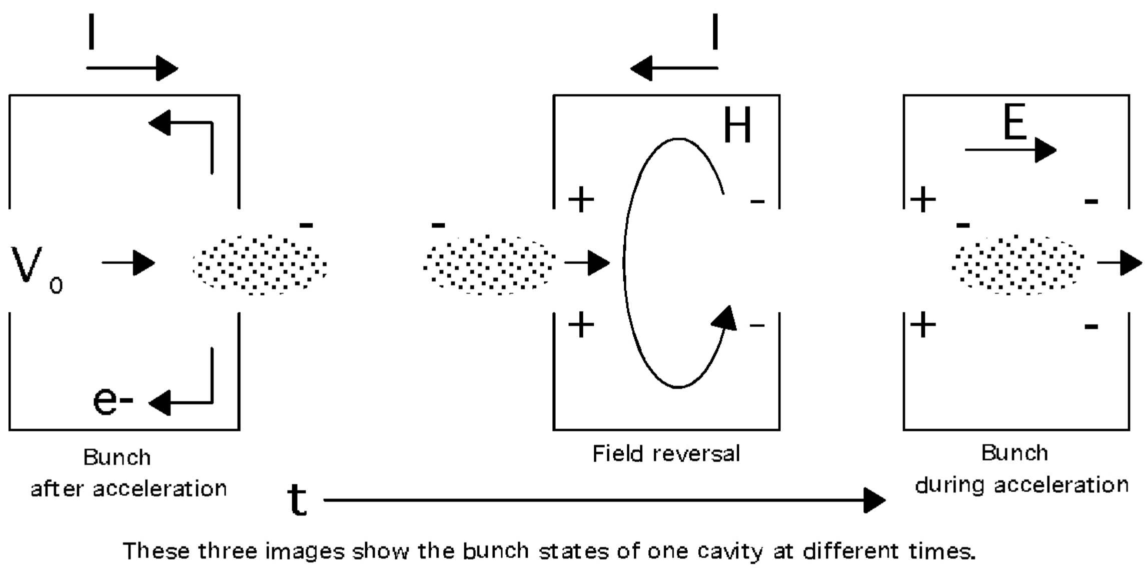


Figure 6.17

When a Klystron first starts up, it takes ~10 μsec to build up to a steady state oscillation. This velocity modulation is much like the RF acceleration process in an accelerator. The differences are that bunched beam is actually decelerated instead of accelerated and the velocity modulation is produced by beam loading rather than RF power from outside the cavity.

The last cavity in the Klystron tube is the output cavity. It decelerates the bunches more than the other cavities because the waveguide imposes a load on the cavity. The amplitude of oscillation is very large at this point; the total gain being 52 dB. The beam oscillations produce RF power. The RF energy is extracted through a coupling iris to the waveguide.

The Klystron tube is a tall black cylinder that isn't visible because there is a solenoid around the tube. The solenoid has six coils that go around each of the drift-tubes. Separate power supplies control the coils for individual tuning. These coils focus the beam to compensate for the divergence (due to space-charge effects). There are pole pieces to block the magnetic field from the electron gun and the collector. The bucking coil is the first of the six coils. Although the bucking coil is part of the solenoid it's located under the first pole piece. It compensates for the magnetic field that leaks through the anode.

Klystron Waveguide and Collector

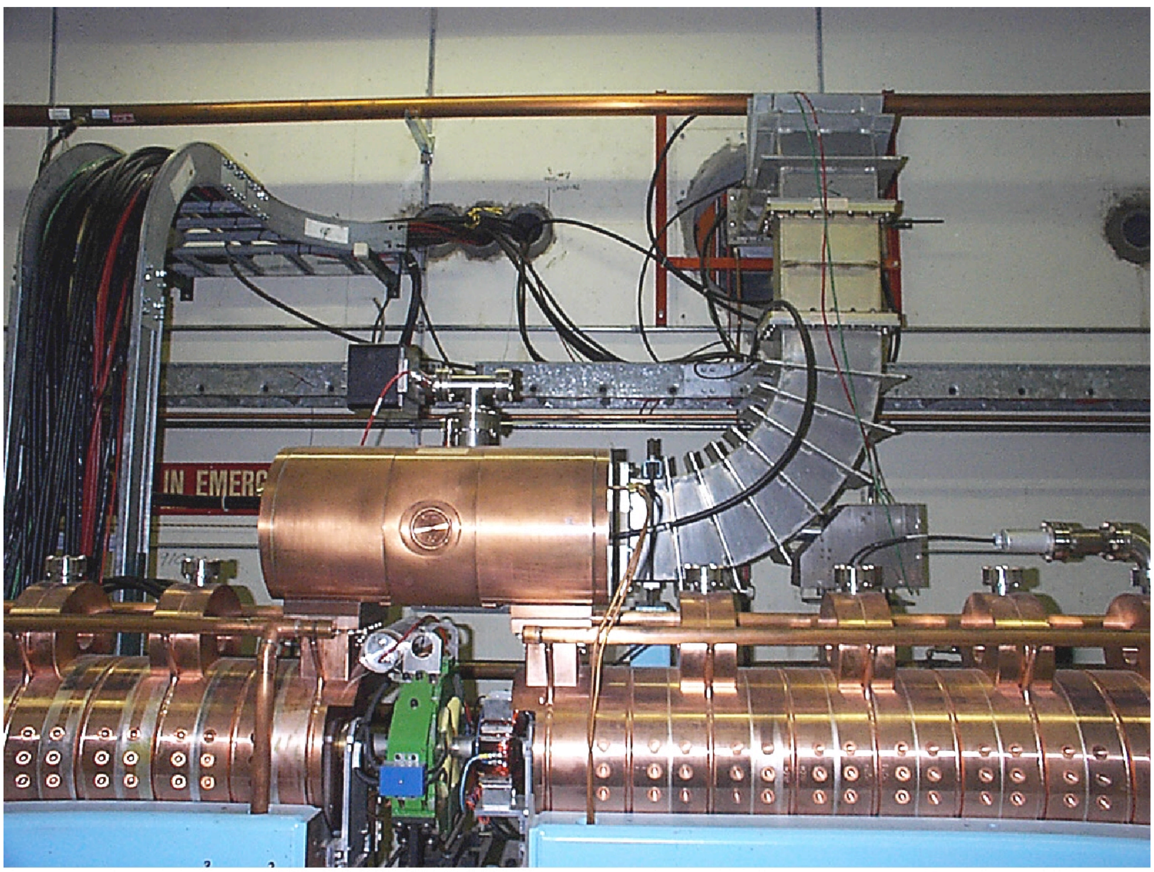


Figure 6.18

The waveguide carries the RF energy from the output cavity of the Klystron to the side-coupled-cavities (figure 6.18). This waveguide is connected to the Klystron body by a ceramic window used to separate the vacuum and air pressure. Pressurized air inhibits sparking in the waveguide. Photo multiplier tubes, located at the bends of the side-coupled-cavity, monitor for possible sparking. A Veeder-Root driver counts the light pulses that the photo multiplier tubes sees if a spark occurs. A Stan's Box (station interlock box) receives this information. If three sparks are counted, the Stan's box sends a signal to the Nanosecond Fault Box that tells the RF to shut off. **If the phototubes**

turn off the station, an operator must reset the station. If the station continues to trip off, you must call an expert from the Linac group.

After the output cavity extracts all the RF energy, the leftover DC beam hits a collector. Due to the excessive amount of DC beam hitting the collector, there is a hazard of RF leaking out of the collector. There is a RF Leak Detector above the collector to detect any RF. There is also a module in one of the NIM crates to control the sensitivity of the RF Leak Detector. This collector is at the top of the Klystron tube and is visible on a spare. Figure 6.19 shows the cross section of a three-cavity Klystron amplifier. The collector is separated from the solenoid by a pole piece to block the magnetic field.

Near the collector, there is a red plug that is the ion pump high voltage cable. The bent pipes coming off the collector provides cooling water for the collector. The DC beam gives off a lot of heat. These pipes circulate 35 gallons of LCW per minute through the collector. The other straight pipes provide cooling water for the rest of the Klystron.

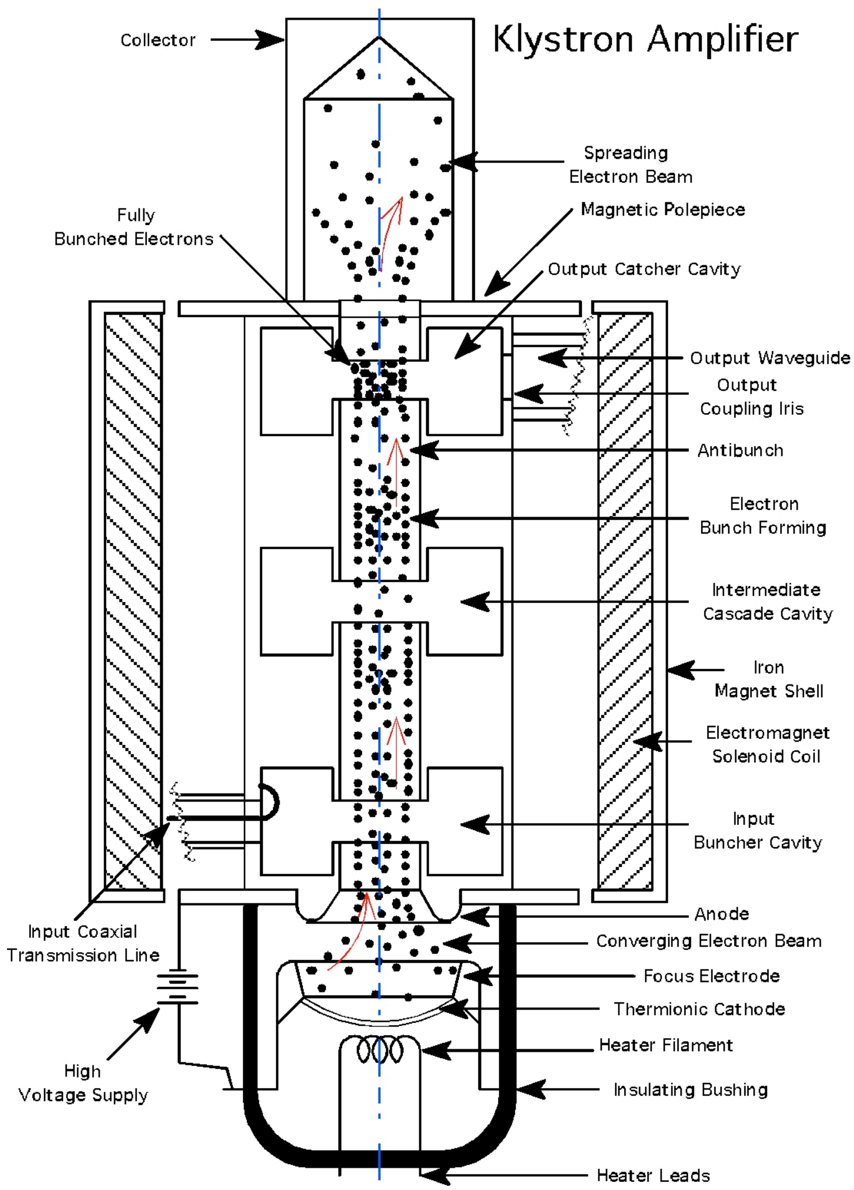


Figure 6.19

Figure 6.20 pictures a collector without its x-ray protective hood and the flange for connecting the waveguide.

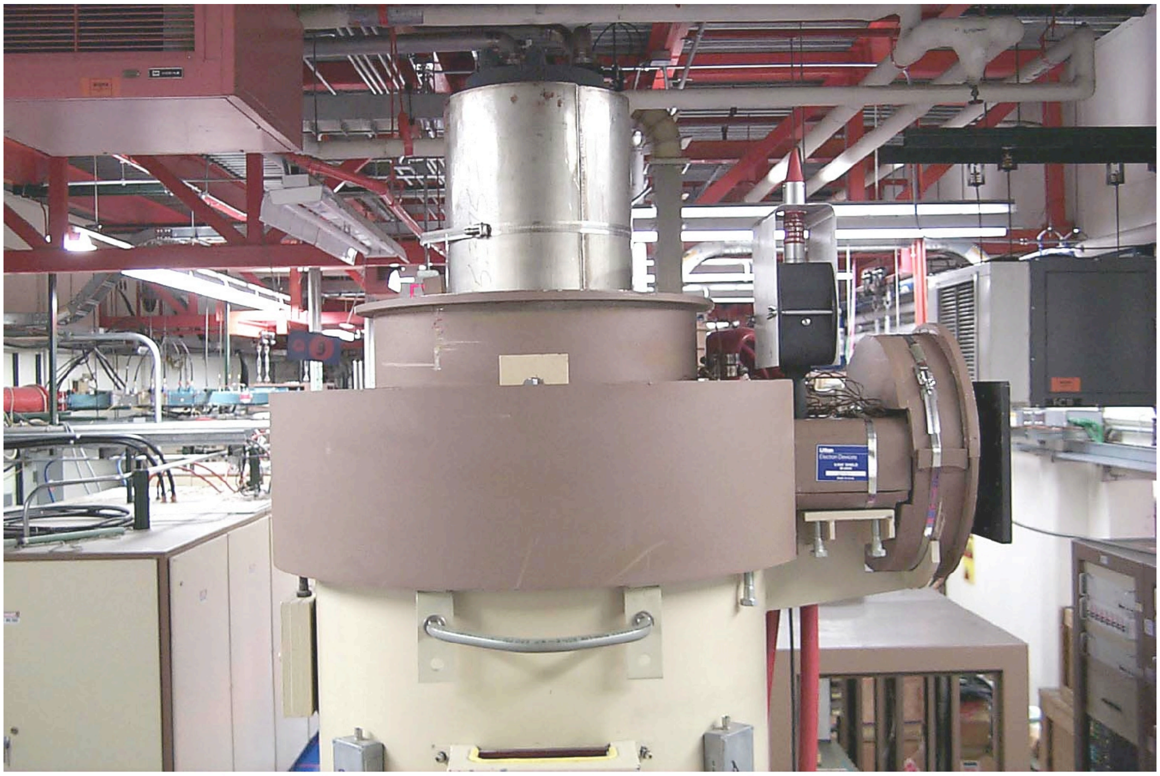


Figure 6.20, Collector

Transition Section Klystrons

The transition section Klystrons have a maximum output of 200 kW and are made by Varian (figure 6.21). The RF signal input into the transition Klystrons comes from a 100 Watt solid state amplifier. The 200 kW Klystrons work the same way as the Litton Klystrons. The transition section does not have a waveguide. Instead, it uses a smaller 3-inch coaxial transmission line. A waveguide is not necessary since these Klystrons have a lower output power. The distance of the transmission line must be an integer number of half wavelengths. The Vernier uses short pieces of cable and a phase shifter in the transmission line to match the line to the cavity. The Buncher user a trombone like the transmission lines in the LEL end. Since the Buncher is very critical to

Figure 6.21

operation, it has a trombone so that any future change to the transmission line can be done quickly.

The transition racks are located just east of Klystron station 1 racks. There are a total of ten racks for transition. The first four are for the Buncher. The middle two are for LLRF devices. The last four racks are for the Vernier.

SCL Tuning and Construction

The first step in construction and tuning of the FNAL cavities was deciding on rough dimensions for the cavities. The values used at the Los Alamos SCL were used as a starting point. However, the big problem was finding the cavity volumes and the coupling constants that determine these volumes. (See figure 4.13) Two programs, Superfish and Mafia, crunched the numbers and found the constants. Then, several aluminum models were built to test the frequencies of different volumes and shapes of cells.

The 805 MHz frequency is an average over an entire module, while the coupling and accelerating cavities are actually tuned at higher frequencies. The coupling cell operates about 10 MHz higher than the accelerating cell. The accelerating cells have slots built into its sides for connecting to the coupling cells. As the depth of the slot increases, the frequencies of both cells decrease to just below 805 MHz. Also, there are dents on the outside of the cell that were dinged inward to raise each cell's frequency until the module's average frequency was 805 MHz. This was the final physical change made to the cavities.

After many levels of coarse tuning, cooling water accomplishes the fine tuning of the bridge couplers and accelerating cells by regulating the cavity volume, which in turn controls the resonant frequencies.

There are three tuning adjustments in any accelerator: the beam energy or ß, the RF phase, and RF amplitude. A procedure called "Phase Scan Signature Matching" (page L23) finely tunes these adjustments. But this method of tuning is primarily for use during commissioning since it involves turning off the klystron stations and inhibiting beam to the downstream accelerators. The procedure determines the tank field's amplitude and phase, and the input and output betas of the beam. A stripline detector, which measures phase, is placed one position beyond the tank being measured with all other downstream tanks off. By using an externally generated phase varied over 360˚, the first phase measurement is taken with the tank off and the second with the tank on. This data is plotted against theoretical curves. A detailed fit of the data determines each tank's phase, amplitude, and betas.

Klystron Modulator

The klystron modulator circuits consist of three main units. Stations 1-7 have a 100kW charging supply, a 25 cell PFN and a 20:1 step-up transformer. The transition section has a 36 kV charging supply a 20 cell PFN and a 21.5:1 step-up pulse transformer. Figure 6.22 shows the modulator circuit for stations 1-7.

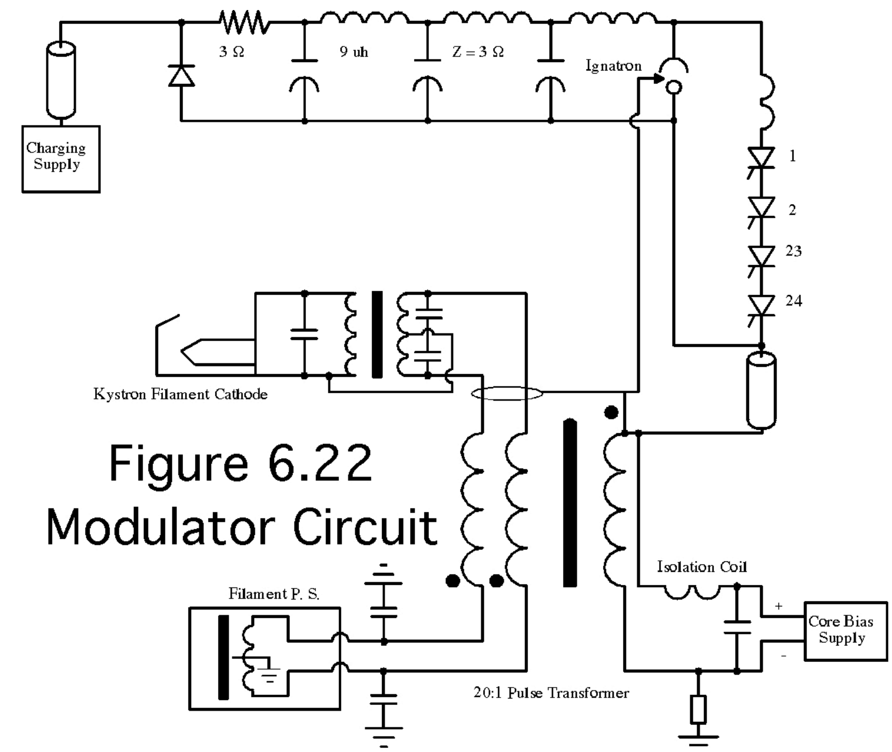


Figure 6.22
Modulator Circuit

	12 MW System Modulator	200 kW System Modulator
Output Power	12 MW	200 kW
Current	151 A	14 A
Voltage Pulse Length	125 microsecond	125 microsecond
Rep Rate	15 pulse per second	15 pulse per second
Flatness	+/- 0.1%	+/- 0.1%
Regulation	+/- 0.05%	+/- 0.05%

The modulator systems get their name from the RF power generated by the Klystron tube. Because the Klystron tubes used are 50% efficient, the modulators deliver twice as much power to the Klystrons cathode. The primary difference between the large and small Klystron modulator systems is the lower power requirements for the transition Klystron tubes. Two other differences are the step-up pulse transformer ratios and the absence of the de'Q'ing regulation loop on the 200 kW system due to the lower voltage requirements of this system, thus a commercial charging supply could be used.

Please note that most of the HEL systems have specific LOTO procedures. You can find the LOTOs in a filing cabinet against the wall near to the KRF1 modulator. Linac experts should always be involved when using one of these procedures.

The 12 MW Modulator Circuit

The charging supply maintains a 9 kV output voltage on the filter bank. When the charging supply SCR switch is fired, the 2.4 Henry charging choke resonates with the PFN capacitors and charges them to 18 kV. After a small delay, the PFN SCR switch is fired to discharge the PFN into the pulse transformer primary. The reflected load of the Klystron matches the 3 ohm characteristic impedance of the PFN and the primary sees a 9 kV/3kA square wave pulse. The charge/discharge cycle repeats at a 15 Hz rate. A series SCR switch is used to discharge the PFN.

The benefits of a SCR switch versus a Thyratron is that the SCR switch has a longer lifetime, its turn-on is slower, and it is less likely to produce noise interference at the RF station. Finally, the specified modulator pulse rise time is slow enough that the dI/dt limitations of the SCRs are not prohibitive. To enhance the SCR turn on capability, a saturating series choke will limit the dI/dt to 100 A per microsecond. The charging supply has no dI/dt problems, so it is built with 12 small power block dual SCR modules and associated circuitry.

Modulator Safety Interlocks

The charging supply and PFN cabinets are interlocked with redundant door interlock circuits. Any open doors will close four shorting relays in the charging supply and three in the PFN. One viewing window on the charging supply and three viewing windows on the PFN allow inspection of the shorting relays. The shorting relays discharge all hazardous stored energy in the system. It also grounds the circuit common to chassis ground in case the ground at the pulse transformer should be missing. The 480 VAC contactor is also opened. To inter either modulator cabinet, the door key must first be removed from a specially designed capture lock. It will release the key only if a 480 VAC switch feeding power to the charging supply is locked off first. The shorting relays within the modulator also derive their control from the 480 VAC power, and must therefore always be closed upon cabinet entry. In addition to the interlocks, a comprehensive lockout tagout procedure is required.

PFN Circuit

The PFN's coils and capacitor terminals are located inside a copper box those functions as a return bus and circuit common for the PFN circuit. The transient signals that occur during the PFN discharge are contained within this box and do not cause ground signals that could be picked up as noise elsewhere. The entire PFN and charging supply circuit float except for a single point ground located at the pulse transformer primary input. The coils are arranged in the form of a U-shape. The curvature was made as large as possible to fit in the 14 x 16 foot cabinet to minimize the variations in stray magnetic coupling that causes tuning problems. The PFN capacitors are placed in order of ascending capacitance to smooth out the square wave. With this arrangement, the pulse flatness meets specifications even before tuning the coils. The PFN SCR switch consists of 24 series C712PNs with associated snubber networks, self-firing circuits, and high voltage gate transformers.

Core Bias for the Pulse Transformer

The core bias supply is located in rack LKx-3, the modulator control rack. The supply puts a positive bias on the transformer core during the modulator pulse (the modulator pulse is negative) and a negative bias on the transformer core when the modulator is not pulsing. This is done so the pulse length can be longer without saturating the core. A saturated transformer core essentially behaves like a shorted primary. This supply is one of the interlocks for the modulator. It is grouped with the PFN interlocks in the modulator control rack.

Modulator Controls

You can find the modulator controls located in rack LKx-2. They perform three specific tasks: modulator operations, signal transient recording, and controlling the modulator regulation. This rack has a "crash button" for emergency shut off of the modulator system at the top of the rack. The control system took several steps to provide noise immunity and high voltage isolation.

Analog signal transmission between racks is done using current drivers, through twinax cable for shielding, terminated in 75 ohm impedance at the receiver. Logic level signals, which include trigger pulses as well as status levels, are sent via plastic fiber type QUS-100. Other measures to minimize electrical noise include the use of inductive cores on signal cables connected to the top of the control rack. The rack itself is enclosed with copper panels: top, bottom, and sides. Anodized chassis are used to contain modules that hold the circuit cards used for buffering, amplifying, comparing, and latching the signals used in the control of the modulator. Finally, the electronic boards were designed using separate power and ground planes.

The hardware controller protects the modulator circuitry by taking selected actions in response to changes in the modulator status. These include readbacks of klixons, water flow meters, core bias supply status, and the detection of load overcurrents and circuit overvoltages. The actions range from inhibiting the charge of the PFN to crowbarring the modulator. Remote control of the modulator is done using a VME system with a Motorola MVME 133XT CPU board and associated A/D and D/A converter boards that sample the waveforms. The Linac control system allows remote users to set operating power levels, enable or disable status bits, and transfer waveforms and status bits. This allows the control and diagnosing of the modulator from the Linac consoles.

The signal transient recording system used all the signals that are monitored during a complete charge-fire cycle and stored by the VME system. A/D boards with enough on-board memory to store 4 charge-fire cycles deep in a circular buffer scheme digitizes the analog signals. If an error occurs, an interrupt-driven task is activated under the real time operating system MTOS. Plus, the waveforms are transferred from the buffer to main memory where the Linac console can display the four cycles of digitized signals. At the time of trip all digital status signals are captured and can be displayed on the console to indicate the cause of a trip. A trip summation bit is monitored in an analog channel of the A/D board. Therefore, the timing of the trip can be correlated with the analog signals. Analog signals associated with the charging portion of the cycle are digitized at 80 microseconds/sampling using a 12-bit A/D board designed and constructed by the Controls group.

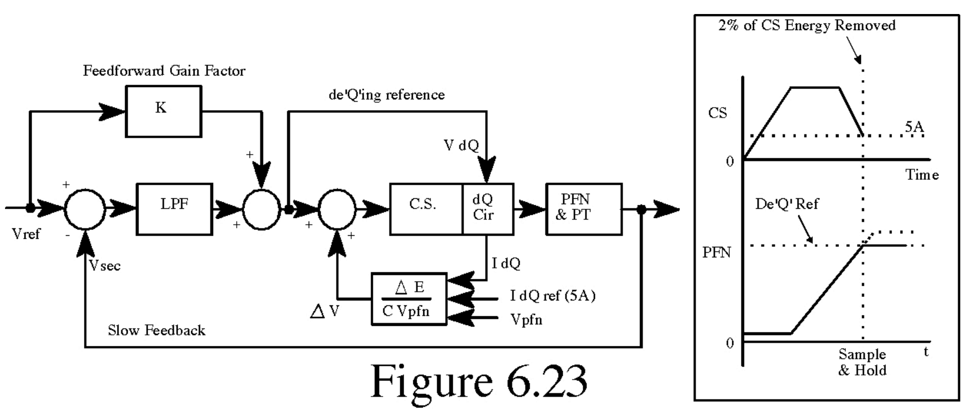


Figure 6.23

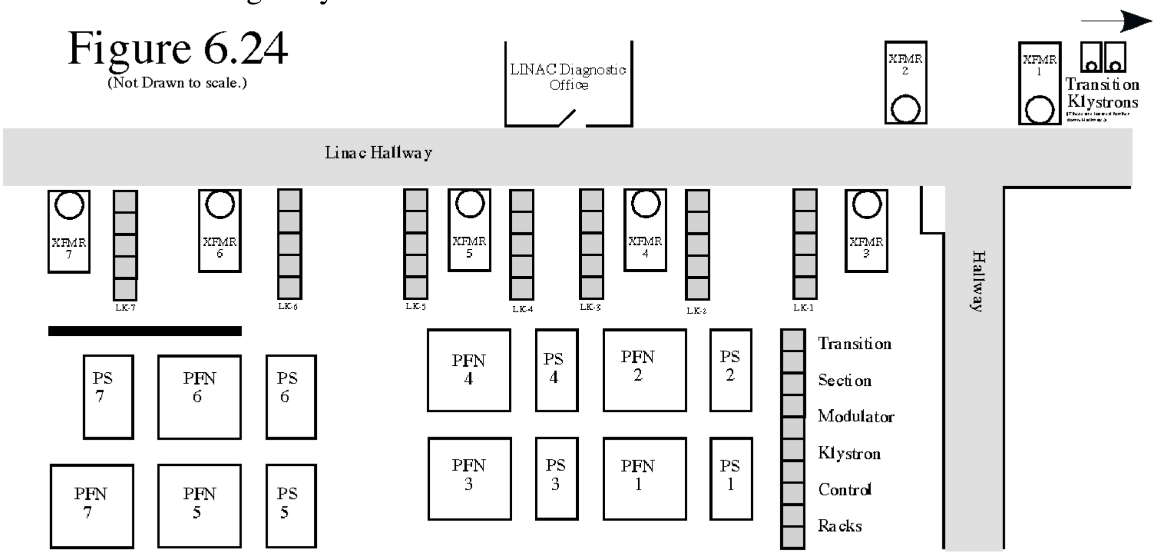
The modulator regulation loop (Figure 6.23) monitors the PFN output level using a standard de'Q'ing circuit. The coordination between the de'Q'ing level and the raw voltage in the charging supply is carried out by the VME system.

In the outer loop, the error between the sampled modulator output and the external reference voltage drives both the de'Q'ing set point and the charging supply voltage level. In the inner loop, the operating point of the de'Q'ing circuit is monitored and a correction signal derived to trim the charging supply voltage so the only 2% of the charging supply energy is removed.

Modulator Layout

You can find the three modulator units located on the east side of the Linac hallway on the high-energy end. The 20:1 step-up pulse transformer is under the Klystron tube near the hallway. The PFN and Charging Supply cabinets are in the Linac Power Supply Gallery. The PFN cabinet is larger (6'x6'x14') than the Charging Supply (6'x6'x6'). Figure 6.24 shows the arrangement of the modulator units. The units are well labeled in the gallery.

Figure 6.24
(Not Drawn to scale.)



The charging supply has local controls for turning the supply on and off. It also has a local reset for the three interlocks: overtemp trip, over current trip, and phase loss. The charging supply also has a breaker to switch off the 480 power used by the supply during charging. The PFN has no local controls on the unit.

Transition Section Modulator

The transition section modulator circuit and controls are contained in racks LT-0 through LT-9 located on the far north side of the Linac Power Supply Gallery. The first five racks are for one Buncher Cavity and the second set of five racks are used for the Vernier Cavity. Racks LT-0 and LT-9 contain the charging supply and PFN for both transition Klystrons. The step-up transformers are located under the Klystron tube as they are with stations 1-7. The core bias supplies for both transition step-up transformers are located in racks LT-2 and LT-7. The controls and functions discussed for the 12 MW system for station 1-7 are the same for the transition section.

Interlock Module Descriptions

<u>CS Signal Latch 1 Module (for modules 1-7 only)</u>

CS_KLIXON_5 - A signal derived from a 135 F Klixon contact closure located at the SCR switch in the charging supply. It is used to indicate excessive heat in the SCR switch. The signal is sent to the control rack via plastic optical link #27 and received at the light link interface chassis LL1 where it's converte3d to a signal. Then it's sent to the relay signal boards in the CS controller to be latched—LL29 to CS26.

I-DR-ST - This is a TTL active low signal that indicates the status of the current driver chassis located in the charging supply cabinet. It generates a U38 and U40 of the current driver where all the outputs of comparators are OR'ed. The signal it transmitted using plastic optical link #32 and received by the light link interface chassis LL8 where it is converted to a TTL level signal and sent to the signal latch1 board in the CS controller—LL28 to CS15.

DEQ_TR_ST - This is a TTL active low signal that indicates the status of the deQ trigger circuit located in the CS cabinet. Sensing the voltage of the power supply generates the signal. The signal is transmitted using plastic optical link #19 and received by the light link interface chassis LL7 where it is converted to a TTL level signal and sent to the signal latch1 board in the D\CS controller—LL27 to CS4.

PFN_CROWBAR - A TTL active low signal generated by the PFN system control board that indicates to the CS system control to trigger the crowbar in the CS. This action takes place when SW_B, I_DR, or FIRE_TR_ST signals are detected as error by the PFN system control board. This board generates an active low signal to indicate the CS controller to discharge the capacitor bank. It is sent from a PFN controller to the CS controller—PFN24 to CS38.

CH_I_ST - A TTL active low level generated in the SCR switch trigger circuit located in the CS. It is used to indicate the status of the trigger circuit. It is sent to the control rack via plastic optical link #29 and received at the light link interface chassis LL1 where it's converted to an active low TTL level signal. Then it's sent to the Signal latch 1 board in the CS controller to be latched—LL21 to CS27.

IGNT_I_ST - A TTL level signal generated in the Ignitron trigger circuit located in the CS. It indicates the status of the trigger circuit power supply. It is sent to the control rack via plastic optical link #17 and received at the light link interface chassis LL6 where it's converted to an active low TTL level signal. Then it's sent to the Signal latch1 board in the CS to be latched—LL36 to CS13.

RELAY_ERR - A TTL active low signal indicating that the MODULATOR SAFETY INTERLOCK has detected an error. The signal latch1 board in the CS controller and the CS system control board latch an error in the controller. The CS controller and the CS system control board fires the crowbar that inhibits the PHASE_CONTROLLER. The level is generated at the MODULATOR SAFETY CONTROLLER and sent to the CS controller—CS/PER to CS5.

PFN_AC_INH - A TTL active low signal generated by the PFN system control board that indicates to the CS system control to inhibit the AC CONTROLLER. This action takes place when any of the PFN signal or relay boards detect an error. It is sent from the PFN controller to the CS controller—PFN13 to CS39.

ST_OK - This is a signal that is active when the PAL in the signal or relay latch board of either CS or PFN controller has all input signals inactive high.

<u>CS SIGNAL LATCH2 MODULE (for modules 1-7 only)</u>

CS-WF - A latched TTL level status signal that indicates loss of water flow in the CS cabinet. The signal originates from a turbine flow meter monitored in a NIM chassis in

LKx_0. The light link interface chassis LL51 receives the status signal. From the light link chassis the status is transmitted to the signal latch2 board in the CS controller—LL52 to CS37.

CROWBAR_COND - A TTL active low level generated in the third channel of the comparator board in the CS controller. It is the result of CROWBAR_I exceeding the trip level set by R63 at U10. The output of U10-U9 is sent to signal latch2 where the level is latched.

EX_I - A TTL active low level generated in the first channel of the comparator board in the CS controller. It is the result of CS_I_CHARGE exceeding the trip level set by R61 at U5. The output of U1-U9 is sent to signal latch2 board where this level is latched.

EX_V - A TTL active low level generated in the second channel of the comparator board in the CS controller. It is the result of V_CAP exceeding the trip level set by R62 at U5. The out put of U5-U9 is sent to signal latch2 board where this level is latched.

SW_B - A TTL active low level indicating that the voltage ratio across the CS SCR switch (24:1) has changed. The ratio is determined by comparing CS_SWITCH_V and CS_SCR_V at the switch balance board U23-U24. The comparison is done by properly scaling the two signals by using the 10 K Ohm front panel knob pot R84. When the ratio changes at R24 and sent to the CS signal latch2 board where the transition is latched and the CS system control board (AC_INH and CROWBAR) takes appropriate action.

ST_OK - This is a signal that is active when the PAL in the signal or relay latch board of either CS or PFN controller has as all input signals inactive high.

<u>CS RELAY LATCH MODULE (for modules 1-7 only)</u>

CROWBAR_FIRE (not on transition module) - A TTL active low level generated by the CROWBAR FIRE momentary switch located on the panel above the MODULATOR SAFETY INTERLOCK chassis. Its main purpose is to provide a quick way of generating an event that the CS system control board uses to initiate a crowbar trigger.

I_DR_ST - This is a TTL active low signal that indicates the status of the current driver chassis located in the PFN cabinet. It generates at U38 and U40 of the current driver where all the outputs of the comparators are OR'ed. The signal is transmitted using plastic optical link #26 and received by the light link interface chassis LL11 where it's converted to a TTL level signal and sent to the signal latch1 board in the PFN controller—LL31 to PFN16.

FIRE_TR_ST - A TTL active low level generated in the SCR switch trigger circuit located in the PFN. It is used to indicate the status of the trigger circuit. It is sent to the control rack via plastic optical link #26 and received by the light link interface chassis LL11 where it's converted to a TTL level signal and sent to the signal latch1 board in the PFN controller—LL31 to PFN16.

PFN_WF - A latched TTL level status signal that indicates loss of water flow in the PFN. The signal originates form a turbine flow meter monitoring the water flow in the PFN, and processed in a NIM chassis in LKx_0. The light link interface chassis LL53 receives the status signal. From the light link chassis the status signal is transmitted to the signal latch2 board in the PFN controller—LL54 to PF39.

PFN_KLX2 (on transition section only) - A signal derived from a 135 F Klixon contact closure located at the SCR switch in the PFN. It is used to indicate excessive heat in the SCR switch. It is sent to the control rack via plastic optical link #23 and received at the light link interface chassis LL2 where it's converted to a TTL level signal. Then it's sent to the signal latch1 board in the PFN controller to be latched—LL22 to PF39. (Note: not connected.)

ST_OK - This is a signal that is active when the PAL in the signal or relay latch board of either CS or PFN controller has all input signals inactive high.

<u>PFN SIGNAL LATCH2 MODULE (for modules 1-7 and transitions)</u>

Q_SPARK - Not used.

SW_B - A TTL active low level indicating that the voltage ratio across the PFN SCR switch (24:1) has changed. The ratio is determined by comparing CS_SWITCH_V and CS_SCR_V at the switch balance board U23-U24. The comparison is done by properly scaling the two signals by using the 10 K ohm front panel knob pot R84. When the ratio changes at U24 and sent to the PFN signal latch2 board whew the transition is latched and the PFN system control board (AC_INH and CROWBAR_EN) takes appropriate action.

EX_V - A TTL active low level generated in the fourth channel of the comparator board in the PFN controller. It is the result of PRI_V exceeding the trip level set by R62 at U5. The output of U5-U9 is sent to signal latch2 board where this level is latched.

EV_V_SWITCH (not on transition section) - A TTL active low level generated in the first channel of the comparator board in the PFN controller. It is the result of PFN_SWITCH_V exceeding the trip level set by R61 at U1. The output of U1-U9 is sent to signal latch2 board where this level is latched.

EX_I - A TTL active low signal that is active when the number of spark counts and EX_I transitions are matched by the EOL-COUNTER board located in the PFN controller. Example: if the spark count=3, cycle count=0, and the output current pulse (PRI_I) exceeds the trip level set by R61 for U1 comparator on the comparator board for three different firings of the PFN, then EX_I counting PAL becomes active low and gets latched at the signal latch2 board as an error.

EOL - A TTL active low signal that is active when the number of sparks counts and EOL_I have matched in the EOL counter board located in the PFN controller.

ST_OK - This is a signal that is active when the PAL in the signal or relay latch board of either CS or PFN controller has all input signals inactive high.

<u>PFN RELAY LATCH MODULE (for modules 1-7 and transition)</u>

PTHI (not on transition section) - High oil level in the pulse transformer.

PTLO (not on transition section) - Low oil level in the pulse transformer to detect possible transformer oil leak.

BIAS_SUPPLY - A contact closure generated by a Gordo relay that senses whether voltage is present on the output of the bias supply that biases the core of the pulse transformer. This power supply is located at rack LKx_3 and the relay contact is connected through a twinax cable to the PFN relay latch Burndy GOB 16-19 SNE. In the PFN relay latch detects this contact.

TO_R_KLX - A relay contact indicating the temperature status of the resistor network used by the turn-off network in the PFN. This network absorbs the magnetization current of the pulse transformer immediately after pulsing. The resistor network is water cooled with 95˚ F water and a 135 F Klixon senses the rise in temperature. The relay contact signal is GOB 16-19 SNE at the PFN cabinet to the PFN controller relay latch board GOB 16-19 PNE.

EOL_R-KLX - A relay contact indicating the temperature status of the resistor network used by the end-of-line clipper network in the PFN. This network matches the load impedance of the PFN, limiting reflections due to a short on the output during pulsing. The resistor network is water cooled with 95 F water and 135 F Klixon senses the rise in temperature. The relay contact signal is GOB 16-19 SNE at the PFN cabinet to the PFN controller relay latch board GOB 16-19 PNE

X_RAY - Not used.

KLIXON_2 - No description.

ST_OK - This is a signal that is active when the PAL in the signal of relay latch board of either CS or PFN controller has all input signals inactive high.

SCL Transition and Buncher

The SCL operates with a stronger longitudinal focusing and weaker transverse focusing than the DTL. (See figure 6.26) The transition section changes the shape of the 201.24 MHz bunches to match the 805 MHz bunch structure. Beam is matched in six dimensions (x, y, z, p_x, p_y p_z) to conserve the phase space of the beam. The transition section is 4 meters long. All of the components, except four quads, are on the transition girder. The last three quads in DTL tank #5 and the first quad on module one of the SCL are available for the x-y matching of transition. This transition should not be confused with the synchrotron transition that we see in Booster and Main Injector. The transition is made up of the Buncher and Vernier.

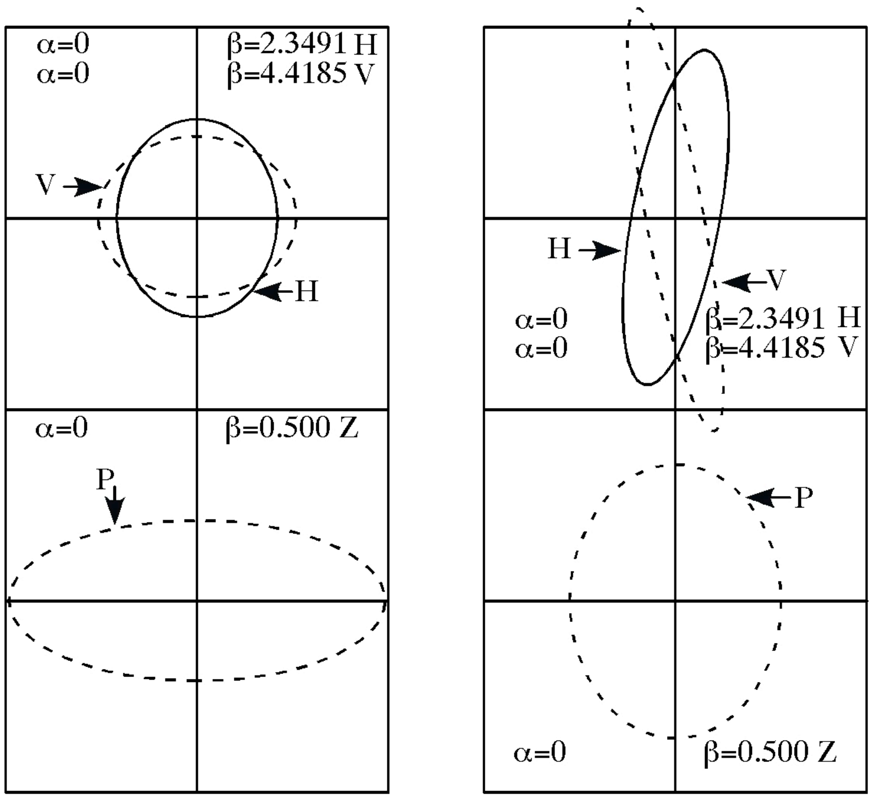


Figure 6.25

Figure 6.25 displays phase space diagrams of the bunch structure through transition. The left side displays the structure before transition and the right side shows the bunch after transition. Transverse diagrams are at the top and the momentum diagrams are at the bottom.

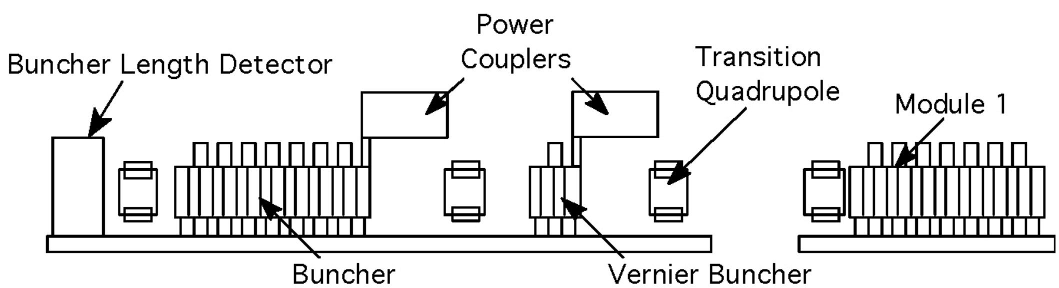


Figure 6.26

Two smaller side-coupled cavity sections accomplish the longitudinal matching. (See figure 6.26) After tank #5 in the DTL, there is a sixteen-cell, 805 MHz Buncher section. This Buncher works the same way as the DTL Buncher by introducing RF to the beam to begin an energy modulation but no net acceleration. The SCL Buncher runs at 2MV/m. It is used to adjust the beam longitudinally to fit it into an 805 MHz bunch.

Since the 805 MHz bunch structure is focused stronger longitudinally, the Buncher RF speeds up slow particles and slows down fast particles. This works the same way as the DTL Buncher. It can add to the effective length of the Buncher and it can be tuned separately from the Buncher. Both Bunchers have power couplers attached to them to let the RF in. The appearance and function of the power couplers is similar to the bridge couplers.

As figure 6.26 shows, the transition section consists of 4 quads, a Buncher, a Vernier Buncher (simply a second Buncher that improves efficiency), a bunch length detector, and several other diagnostics.

SCL Tuning and Construction

The first step in construction and tuning of the FNAL cavities was deciding on rough dimensions for the cavities. The values used at the Los Alamos SCL were used as a starting point. However, the big problem was finding the cavity volumes and the coupling constants that determine these volumes. Two programs, Superfish and Mafia, crunched the numbers and found the constants. Then, several aluminum models were built to test the frequencies of different volumes and shapes of cells.

The 805 MHz frequency is an average over an entire module, while the coupling and accelerating cavities are actually tuned at higher frequencies. The coupling cell operates about 10 MHz higher than the accelerating cell. The accelerating cells have slots built into its sides for connecting to the coupling cells. As the depth of the slot increases, the frequencies of both cells decrease to just below 805 MHz. Also, there are dents on the outside of the cell that were dinged inward to raise each cell's frequency until the module's average frequency was 805 MHz. This was the final physical change made to the cavities.

After many levels of coarse tuning, cooling water accomplishes the fine tuning of the bridge couplers and accelerating cells by regulating the cavity volume, which in turn controls the resonant frequencies.

There are three tuning adjustments in any accelerator: the beam energy or ß, the RF phase, and RF amplitude. A procedure called "Phase Scan Signature Matching" (page L23) finely tunes these adjustments. But this method of tuning is primarily for use during commissioning since it involves turning off the klystron stations and inhibiting beam to the downstream accelerators. The procedure determines the tank field's amplitude and phase, and the input and output betas of the beam. A stripline detector, which measures phase, is placed one position beyond the tank being measured with all other downstream tanks off. By using an externally generated phase varied over 360˚, the first phase measurement is taken with the tank off and the second with the tank on. This data is plotted against theoretical curves. A detailed fit of the data determines each tank's phase, amplitude, and betas.

Vacuum Systems

Maintaining vacuum in the Linac transport lines, drift tube and side-coupled cavities allows the beam to travel through the machine without interference from gas molecules. Vacuum also acts as an electrical insulator, allowing high potentials between objects without arcing. Linac vacuum is typically 10^{-7} torr or better. Such low pressures require a sputter ion pump, which uses electrons to ionize gas molecules. Ions are captured on an anode and complete an electrical circuit. The rate that ions hit the anode is an indication of the absolute gas pressure. Ion gauges, which measure low pressures, work on the same principle. Potentials across the cathodes and anodes in ion pumps and gauges are in the range of several kV.

The ion pumps in the Linac are the diode type with titanium anodes. Titanium is good at catching gas molecules, although the anodes wear with time and may eventually have to be replaced, depending on vacuum conditions. Anodes may last anywhere from six months to indefinitely.

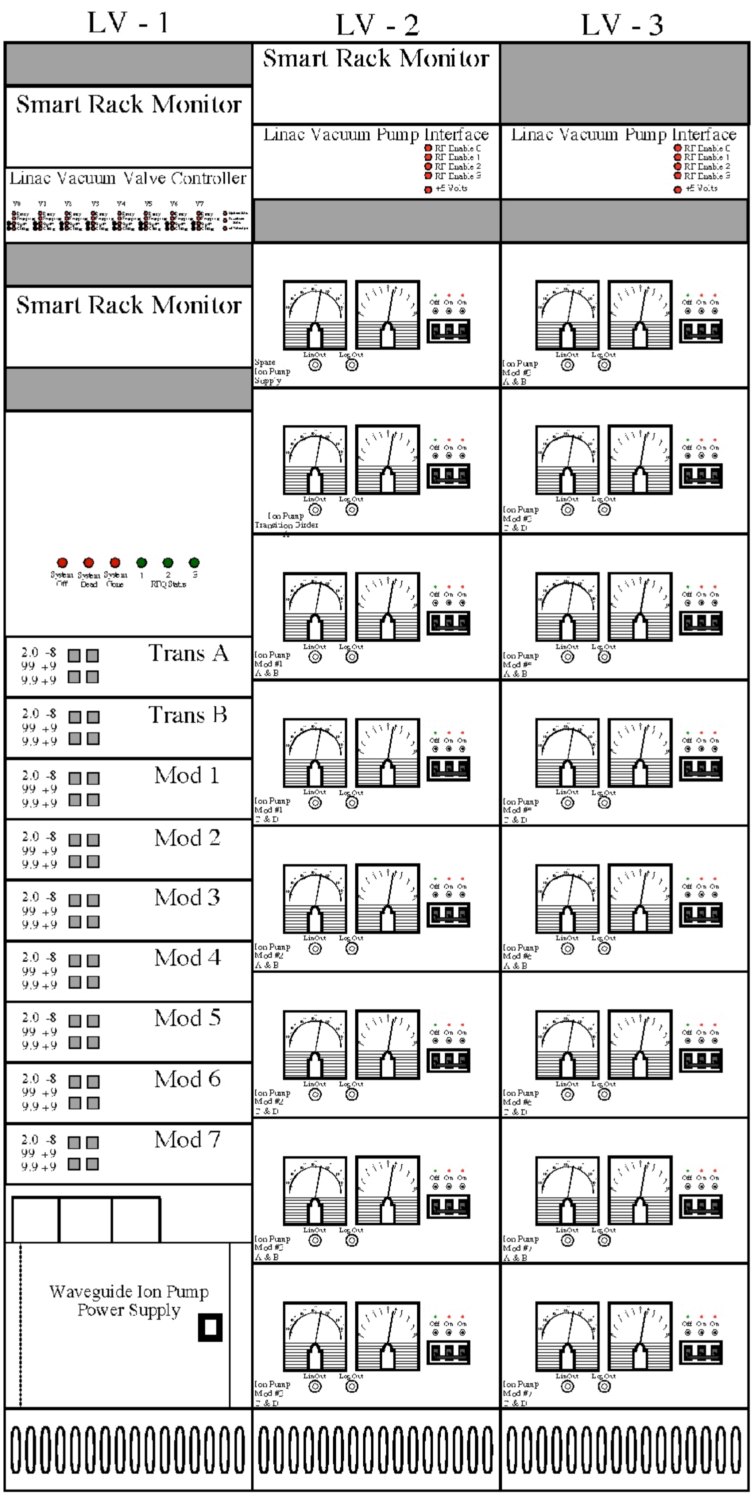


Figure 6.27
SCC Vacuum Valve Controllers

All the ion pumps in the Linac are made of a number of small modules ganged together. The Ultek pumps are made of 25 liter per second modules and the Varian pumps are made of 30 liter per second modules. When combined these pumps can move several hundred liters per second.

All the vacuum valves in the Linac are electrically controlled and pneumatically operated. Solenoids direct the flow of nitrogen gas that moves the valve actuators. The nitrogen comes from a header that runs the length of the Linac. This line also supplies gas to pressurize the PAs and transmission lines. The nitrogen comes from two LN_2 tanks located in the parking lot outside of the A0 service building. If the nitrogen supply runs out, all the vacuum valves in the Linac will close.

Side-Coupled Cavity Vacuum

Unlike the vacuum controls for the Drift Tube Linac, the vacuum controls for the Klystron system are located at the far high-energy end of the Linac gallery on the east side of the hall. The controls occupy three racks. (See figure 6.27.) Two racks contain the ion pump power supplies. Each power supply powers two of the four ion pumps per module. The other rack holds the ion gauge monitors, vacuum pump power supplies for the ion pumps on the seven central bridge couplers, and the vacuum valve controller.

The Vacuum Pump Power Supply Interface allows remote control of the eight vacuum pump power supplies in the rack. The interface chassis redistributes analog and digital signals from the eight pumps power supplies to the SRM chassis. The interface module receives control bits supplied from the SRM for the ON, OFF and ENABLE and pass it to the control card on the pump supplies. The interface chassis also passes the pump status information over to the valve controller where it will be used to determine if a vacuum valve should be closed or opened.

The high level RF systems also need information about the vacuum in a given module before power can be applied. To accomplish this the interlock chassis uses an analog discriminator to compare the Log/Lin pump signal to a potentiometer reference. The enable condition is satisfied if one of the two pumps power supplies for the module is ON and its Log/Lin signal is higher than the associated reference set point. If these conditions are met a high active TTL level signal will be generated and sent to the RF system. The LED status of the four RF enable signals is displayed on the interface module panel on the right hand side. When the LED is lit it indicates the RF enable is in a good state and the vacuum is good enough to apply the RF power.

The Vacuum Valve Control Chassis allows control of the eight vacuum valves and has status for the upstream and downstream vacuum permit on the right hand side of the control panel. The upstream vacuum permit LED shows the status of the permit generated by the Alvarez Standing-wave Linac. The downstream vacuum permit LED shows the status of the permit generated by the Booster 400 MeV line. At the time of this writing (March, 2003) the upstream/downstream permit LEDs were for information only and not interlocked to the Klystron vacuum system.

The vacuum valve controller chassis examines upstream and downstream pump status information passed by the interface module to determine if a valve is READY to open. When the READY LED is lit the valves can be opened or closed locally using the OPEN/CLOSE push buttons or remotely via the control system. The vacuum valves for that module and the vacuum valve just downstream are interlocked to the module's two ion pump power supplies. The status information shipped over from the interface chassis is evaluated to determine the on/off status and analog vacuum reading for the module ion pump power supplies. If both power supplies are off or have poor vacuum readings the valve and the valve just down stream will close. One vacuum pump power supply with good vacuum is all that is required to maintain and open vacuum valves.

Each module (sometimes called cavity string) has four 240 l/sec ion pumps attached to a six-inch vacuum header, which is connected to each section, by eight vacuum ports (one for every two accelerating cavities). The center bridge coupler has an ion pump attached to it. Section number three in each module also has an ion gauge attached to it to augment the vacuum readings ion pumps. Each module has one vacuum valve attached at the upstream end of the beampipe. The ends of the vacuum header where the ion pumps attach are sealed shut and are separate from the other module. Figure 6.28 illustrates the module layout.

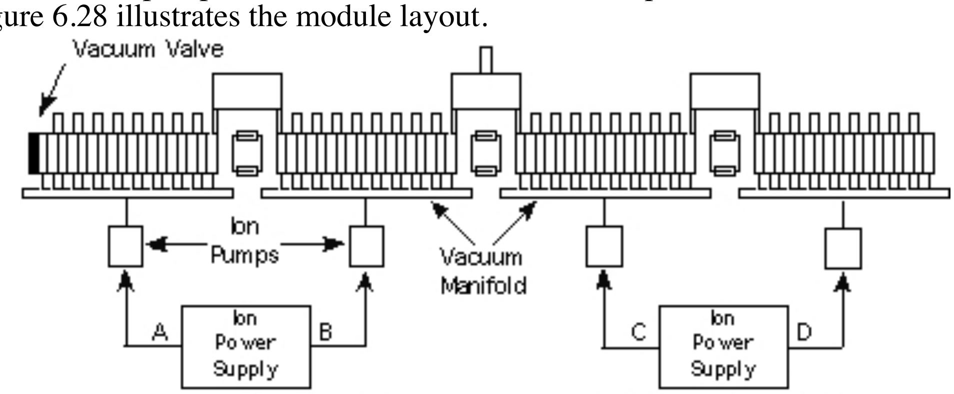


Figure 6.28, High Energy LINAC Module

Mobile roughing stations will rough pump the module vacuum. The operating vacuum level is 10 E-7 Torr.

Water Systems

Conventional high-power electrical devices, like those found in the Linac, produce a good deal of waste heat. To keep components at operating temperatures many devices use cooling water that has been treated to reduce the number of free ions, which lower the conductivity. The LCW (Low Conductivity Water) systems are treated, temperature-regulated, and pressurized at the Central Utility Building (CUB).

Three separate LCW systems, the 95˚ system, the 55˚ system, and the chilled water system services all of the Linac. Cooling for NTF power supplies, magnets, and target is provided by the 55˚ system. This system typically runs at 85˚ F, with supply and return pressures of 110 and 20 psi, respectively.

The side-coupled cavities get their cooling from the chilled water system. But cooling for the Preaccelerator, 750 keV, RF stations, drift tube tank walls, Debuncher, and quadrupoles is provided, indirectly, by the 55˚ system. For these devices a number of closed-loop pumping stations exchange heat with the 55˚ system to regulate temperatures, but do not draw water from the 55˚ system regularly.

The Klystron uses different water systems:

- Cavity Temperature Control System uses the chilled water system: ~43˚F.
- Klystron RF LCW also uses the chilled water system: ~43˚F.
- Cavity Water System also uses the chilled water system: ~43˚F.
- Debuncher RF uses the 55˚ LCW system.
- Waveguide Cooling System also uses the 55˚ LCW system.

Cavity Temperature Control System

A distribution skid located near the lower Linac gallery machine shop supplies the Cavity Water skids. The distribution skid is a closed LCW system that heat exchanges with the CUB chilled water system to dissipate the approximately 100 kW of heat from the Cavity/Transition water skids. The water group can manually fill the distribution skid's closed system by using the Booster's 95˚ LCW system. The distribution skid feeds about 15˚ C (60˚F) LCW into a header that has the cavity string cooling skids and the transition modules cooling skid attached in parallel.

The seven Cavity water skids and the two transition module skids control the temperature by mixing heat exchanged LCW from the distribution skid with the LCW circulating between the cavity strings or transition modules and the cooling skids located in the Linac lower gallery. The Local Station computer controls the amount of water mixed. The main purpose of the Cavity cooling skids and the Transition module skids is to maintain a well regulated LCW temperature of 80˚ F (27˚ C), which in turn will control the resonant frequency of the cavities. Each cavity string has its own LCW cooling skid. The transition module skid has three pumps on it. The bottom pump is a spare. The remaining top two pumps are for the two transition modules: the Buncher and Vernier.

The Cavity/Transition cooling system exploits the temperature dependence of the copper cavities. For cavities constructed of a single metal, the percentage change in resonant frequency will equal the percentage change in dimension that is proportional to temperature. A full cavity string had a measured temperature dependence of -14.3 kHz/C, to a frequency change of 17.8 PPM/C at 805 MHz. Each accelerating cell has a half-inch cooling tube brazed azimuthally in a groove on the outside surface. The cooling tubes are designed to have good flow rates at the inner surface of the tube to minimize thermal resistance between the LCW and the cooling tube. The supply and return lines are located on opposite sides of the cavities with one set of supply and return lines run across the top of the cavities. The orientation of the supply/return manifolds of the upper and lower set are opposite from one another. Connecting the cooling lines to alternate upper and lower supply/return lines will make the temperature drop from supply to return line small and give a more uniform temperature distribution in the cavity. This will also maintain the physical alignment of the Cavity/Transition sections during thermal cycling.

Klystron RF LCW System

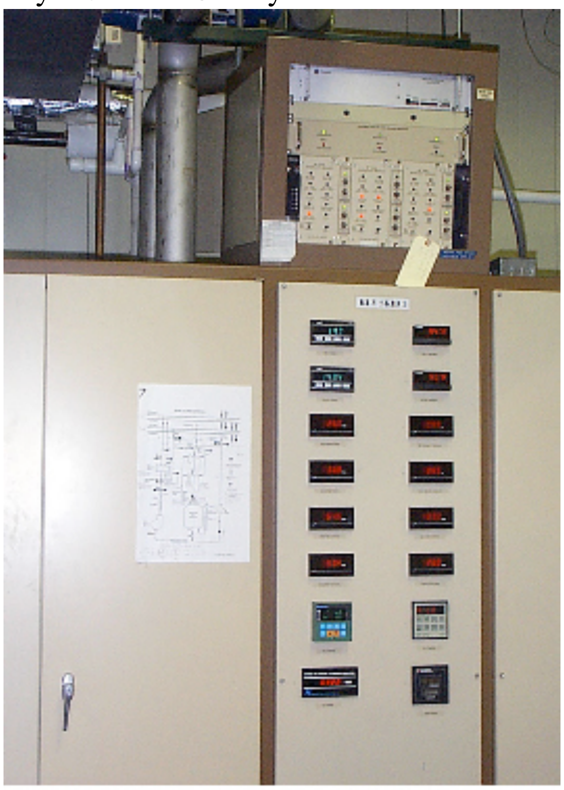


Fig. 6.29 Klystron Skid and Interlocks

The RF LCW System provides cooling for stations 1-7, Modulator (PFNs and charging supplies), and Klystron (Transformer Tanks, Solenoid, A/B, Body, and Collector). The RF LCW system is a closed system that is heat exchanged with CUB industrial chilled water (ICW).

Fig. 6.30 Klystron Tanks

There are three RF LCW skids that can provide heat exchanging with the industrial chilled water. Each RF LCW skid has an eighty-gallon expansion/reservoir tank to compensate for volume changes due to thermal expansion, a heat exchanger, and two deionization bottles. The closed RF LCW system can be filled manually by the water group using Booster's 95 LCW system if water loss occurs. I was discovered that the head pressure in the ICW water system was low at the water skids. Two water pumps were added to the ICW line to boost head pressure. The two water pumps, called CHW P1 and P2, and their pump breakers are located in the CUB utility tunnel. A status/alarm panel is located at the top of the ladder at the beginning of the tunnel heading towards the high-rise. Only two of the three skids are used during normal operation.

The RF LCW skids are located on the east wall in the LINAC Power Supply Gallery next to the garage door. Above Skid #1 is the interlock and status modules for all three skids. The pump motor panel for the three skids is located between skid #1 and the garage door. The skid's interlocks have three main groups:

1) Expansion/Reservoir tank level
2) Flow and resistivity in both the ICW and the RF LCW system
3) Temperature interlocks

An LED will indicate the status of the interlock. The interlock module's LED will light and latch, hence a local reset is required to clear the fault so the pumps can be turned back on. The Smart Rack Monitor (SRM) above the interlock modules monitors certain key parameters. These parameters can be plotted and setup to alarm in the MCR. The parameters that are monitored are the supply and return pressures and temperatures of the LCW system along with the flow rate of the ICW and LCW.

Fig. 6.31 Klystron Motor Panel

Fig. 6.32 Klystron Distribution Skid

Description of the Side Coupled Cavity Temperature Regulation (or Frequency) Control Loop

The temperature control loop is broken into three different cavity regulation loops:

1) Temperature Loop
2) Phase Loop
3) Frequency Loop

The purpose of these loops is to maintain the resonant frequency of the LLRF so it resonates at the frequency of the cavity. This will reduce the reverse power. Thereby minimizing the chance of damaging the ceramic vacuum window between the wave guide and the cavities.

The Temperature Loop adds the measured RF power fed into the cavity string to the power experimentally determined for the pumping motor. It then performs a calculation to determine how much flow from the chilled LCW (from the distribution skid) should be added to the circulating LCW. This keeps the temperature the same between the cavity skid and the cavity string. The calculation is based on the following two facts. First, the cavities are designed to work near room temperature (27˚ C) thereby rendering radiation and convection losses negligible. Second, since the radiation and convection losses are negligible, it can be assumed that if you take out the power you put into the system the temperature will remain constant (this is referred to as "feed forward"). Any imperfections to the system are added to the experimentally determined pumping motor heat load. However, keep in mind that no system is perfect and a slight drift upward or downward will eventually happen. To take care of this problem, the temperature loop takes the reading from temperature probes located inside bore holes on the upstream end of each cavity. The average temperature for the cavity string is computed. Because the temperature gradient is known for normal running conditions, the temperature inside the cavity can be inferred. The measured average temperature is compared to the temperature set point and an error signal is generated. This error signal then modifies the calculated temperature value that is fed to the flow calculation. After the flow calculation is performed, the three-way mixing valve adjusts the amount of chilled water that will mix with the cavity's LCW. Because the valve is nonlinear and can have hysteresis, a control loop has been placed around the valve. It will measure the flow rate, at the outlet and compare it to the set point given by the flow calculation. Any differences will be adjusted by this loop.

Regulation of temperature is fine, but the goal is to get the correct frequency and phase to accelerate beam. The Phase Loop does just this. When running beam, the measured cavity to wave guide phase difference is converted to a temperature change. This temperature change is clamped if is exceeds 1˚C. This is done to prevent the system from "running away" if the Phase Loop malfunctions. The temperature change is then fed into the loop that corrects the temperature's feed forward loop.

If no RF has been in a cavity, the temperature gradient between the outside cooling tubes and the cavity nose cone will change. The nose cone temperature will decrease by 1.84˚C since there is no RF heat load. This temperature change, at the nose cone will change the resonant frequency of the cavity by about 15 kHz. If power were turned on with this mismatch, the reverse power could damage the ceramic window between the wave guide and the cavities. Since the nose cone area accounts for only about one percent of the thermal mass of the system, it is easier to adjust the LLRF frequency to match the cavity's frequency than to quickly add heat to the water system to warm up the nose cone area. The Frequency Loop calculates a frequency from the cavity temperature probe readings and the RF power and feeds this to the LLRF VCO. The calculation takes into account how the frequency will change with time after power has been applied. After the RF is turned on it will take about 43 seconds before the resonant frequency is at nominal operating frequency, the Frequency Loop is disabled and the Phase Loop, which looks at the reference line, is enabled. The loops disabled are managed by the "Temp Loop pH Det/Stat up VCXO" in slot 9 of the VXI crate at each LKx-0 racks in the Linac gallery.

Debuncher RF and Cavity Water System

The Debuncher RF system is cooled by a closed LCW system that is filled and heat exchanged with the Linac 55˚ LCW system. The RF power supplies are kept at about 95˚F. It cools the Varian Klystron located in the room opposite the Debuncher water skids. The Debuncher Cavity water system is not a closed loop system. The Cavity water system mixes Linac's 55˚ LCW with the LCW circulating between the cavity and the Cavity water skid to maintain the proper temperature. Like the Cavity water system for the High Energy Linac, the Debuncher Cavity water system is used to control the resonant frequency of the Debuncher cavity. A local microcomputer is used to control the amount of LCW mixed. The Debuncher RF and Cavity water system skids are mounted on top of each other. The smaller Cavity LCW system is mounted on top of the Debuncher water cooling system.

You can find the Debuncher water system located in Booster west gallery just downstream of BRF station #16. The interlock and status module for the skid is located under the cavity water skid recirculation. The RF water skid has a heat exchanger with a forty gallon expansion/reservoir tank. The pump motor control panels are located just to the right of the RF water skid. The two large panels are for the primary and backup pumps for the RF water skid. The small panel is for the cavity water skid. The cavity and RF water skids have similar interlocks to the Klystron RF system, namely, expansion/reservoir tank level, resistivity and flow rate, and temperature interlocks. The Debuncher RF/Cavity water skid also has a Smart Rack Monitor that monitors certain key parameters. These parameters can be plotted and setup to alarm in the MCR.

Waveguide Cooling System

The RF cooling station in the lower Linac gallery for station #9 of the old drift tube Linac has been reworked to provide cooling to the 7 waveguides of the Klystron modules and upstream 400 MeV elements. The reworked station 9 system is a closed LCW system that is heat exchanged and filled with the Linac 55˚ LCW system. This system now feeds into the tunnel through penetration 9. Inside the tunnel the water header runs all the way down to the 400 MeV line area and then loops back. The header is dead headed by the new transition section. Water tubes are tapped off the header and run along the wall to the ceiling where the waveguide cooling tubes are located. The 400 MeV magnet elements tap off the header at various convenient locations.

Notes:

Chapter 7, 400 MeV Area

The 400 MeV beam can be steered at the end of the Linac enclosure into one of three beam transport lines (Figure 7.1).

First, Linac beam not deflected by the 400 MeV chopper (B:CHOP) enters one of the two dump lines. If the 40˚ spectrometer magnet is powered, the beam goes to dump #2, where a wire scanner generates a momentum spread. This displays the beamline's average momentum and its momentum spread. If the spectrometer magnet is off, beam goes to dump #1. This line measures the transverse emittances and is only used for studies.

The other line leads out of the Linac enclosure down to the booster injection girder.

400 MeV Transport Line to Booster

Along with the 750 KeV chopper, the 400 MeV chopper (a pulsed electrostatic deflector made up of a pair of charged plates) selects what portion of the beam goes to Booster. The width and the length of the chop determine the number of beam turns and the requested intensity. Adjusting the timing of the chop selects the best portion of the Linac pulse.

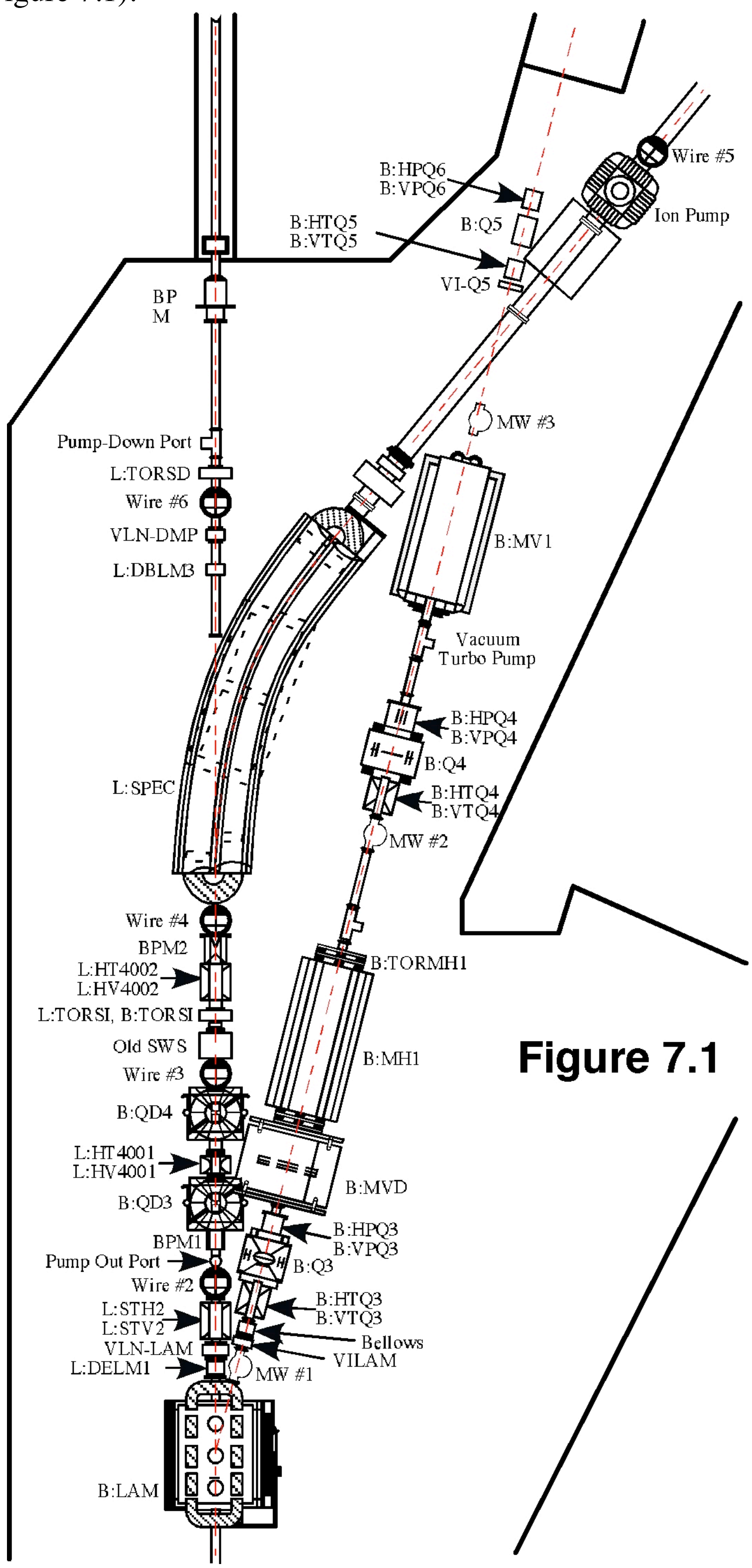


Figure 7.1

A power supply charges the chopper plates to approximately 60 kV between the Linac pulses. Figure 7.2 shows the relationships of the beam, the plates, B:Q2, and the Lambertson (B:LAM): 1) with both plates charged, the beam passes through to the dump. 2) With the “ON” plate grounded, the chopper deflects beam up into the field region of B:LAM. 3) The Booster beam viewed from the top. 4) With both plates grounded, the beam passes through to the dump. 5) A particle’s view of the Lambertson.

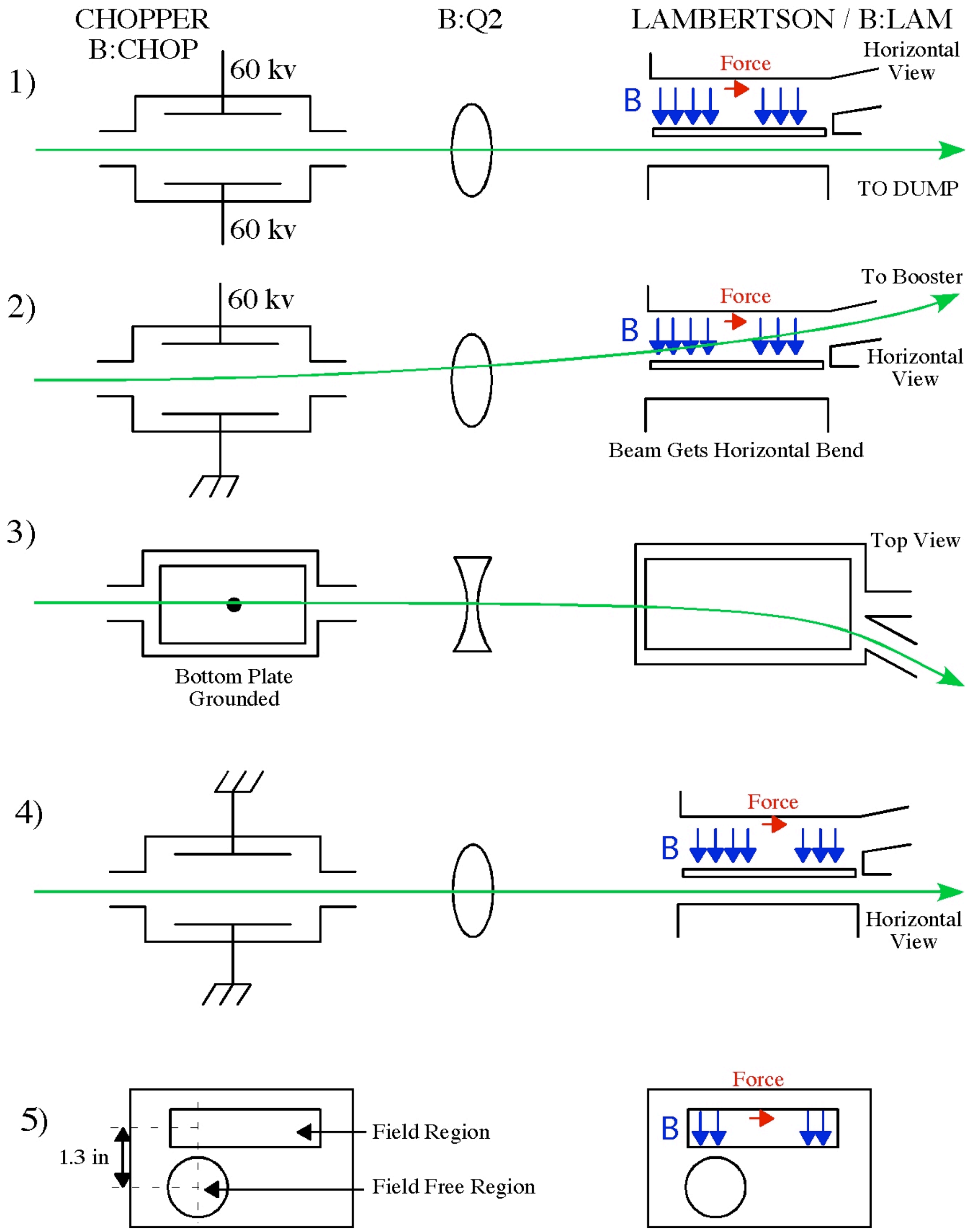


Figure 7.2

After the Lambertson, a vertical trim magnet (MV0) corrects an angle problem caused by the chopper and quad. Next, a horizontal bend magnet (MH1) moves the beam 4.82˚ to the west. Finally, another vertical trim (MV1) deflects the beam 12.51˚ down the chute into the Booster Ring. The angle of the shoot is 13˚. (For more information see the Injection section of the Booster Rookie Book.)

Momentum and Emittance Analysis Lines

Undeflected beam passes through the chopper and Lambertson to the momentum and emittance measuring system; the beam line ending at dump #2 measures momentum and dump #1 line measures emittance. How do you find momentum? You find it by tuning the quadruples QD3 and QD4 so that the beam fills the horizontal aperture of 40˚ spectrometer magnet, bending the beam through the magnet and measuring its width downstream with the horizontal wire scanner W5. This quadrupole tuning increases the resolution of the momentum measurement to a theoretical 0.1% by increasing the dispersion at W5.

Linac Steering and Momentum Analysis

Proper operation of the 400 MeV transport line assumes a specific beam position and angle at the entrance to the line. To this end the alignment of scanning wires W1 and W2 is such that the nominal beam position is at the center of the wires. Conducting a Linac steer will adjust the beam's center position using BPM positions (chapter three's Linac Tuning Guide).

Linac steering should be done before any 400 MeV line tuning, before any 750 keV line tuning, and once per shift just for the heck of it.

Momentum analysis is simply a matter of running wire W5 (horizontal) across the beam and observing the beam profile. A change in the peak width will correspond to a momentum spread change assuming no other focusing changes.

400 MeV Area Vacuum

Figure 7.3, located on the next page, shows a map of the 400 MeV vacuum system. Ion pumps, located by the chopper and in the line leading to dump #2, maintain the vacuum. Moore pumps exist downstream of this area in the Booster enclosure. The ion pump located near Q4 is separated from the beam pipe by a vacuum valve, but the other two are connected directly to the pipe. In addition to the ion pumps, turbo carts can be valved in to assist in pumpdown. Turbo carts contain a combination of roughing and turbo pumps that are manually operated.

Vacuum isolation valves provide the ability to work on a part of the transport line without having to let up the entire vacuum system to normal atmosphere. These valves, VLKLV7, VLNLAM, VLNDMP, VI-LAM, VI-Q5, VI-DEB, and VI-SEP can be remotely controlled from a rack in the Linac Gallery down at the high-energy end.

Pig gauges monitor the vacuum in the 400 MeV area. These gauges operate on the same principle as ion pumps. The readbacks for gauges PG-LAM, PG- Q5, and PG-MV2 are in the same rack as the isolation valve controllers. These provide vacuum reading to control the interlocked vacuum isolation valves. When the pressures measured by the gauge increase from the normal 10^{-6} torr to about $5x10^{-4}$ torr, the valves connected to that gauge will close. The Booster control system monitors the status of all the isolation valves, turbo cart valves, and pig gauge statue (OK/BAD).

In the event of a power outage, or any case where the vacuum is too poor to be able to use the ion pumps, it is necessary to use the turbo carts. Before using the following procedure, contact a vacuum technician. If you can't contact a vacuum tech, then use these instructions:

1) If the beampipe is up to air, open the valve between the beampipe and turbo cart. If the vacuum is only moderately bad, leave the valve closed. Start the roughing pump.

2) When the vacuum gets down to 30" (as indicated on cart) start the turbo pump. Wait five minutes.

3) Check the vacuum in the beampipe. Open the valve between the turbo cart and beampipe only when the pressures are nearly equal.

4) When the vacuum gets down to $5x10^{-4}$, start the ion pumps and turn on the pig gauges.

5) When the ion pump voltage gets above 4.5 to 5 kV, valve out the turbo cart. Turn off the turbo cart and wait five minutes. Then turn off the roughing pump.

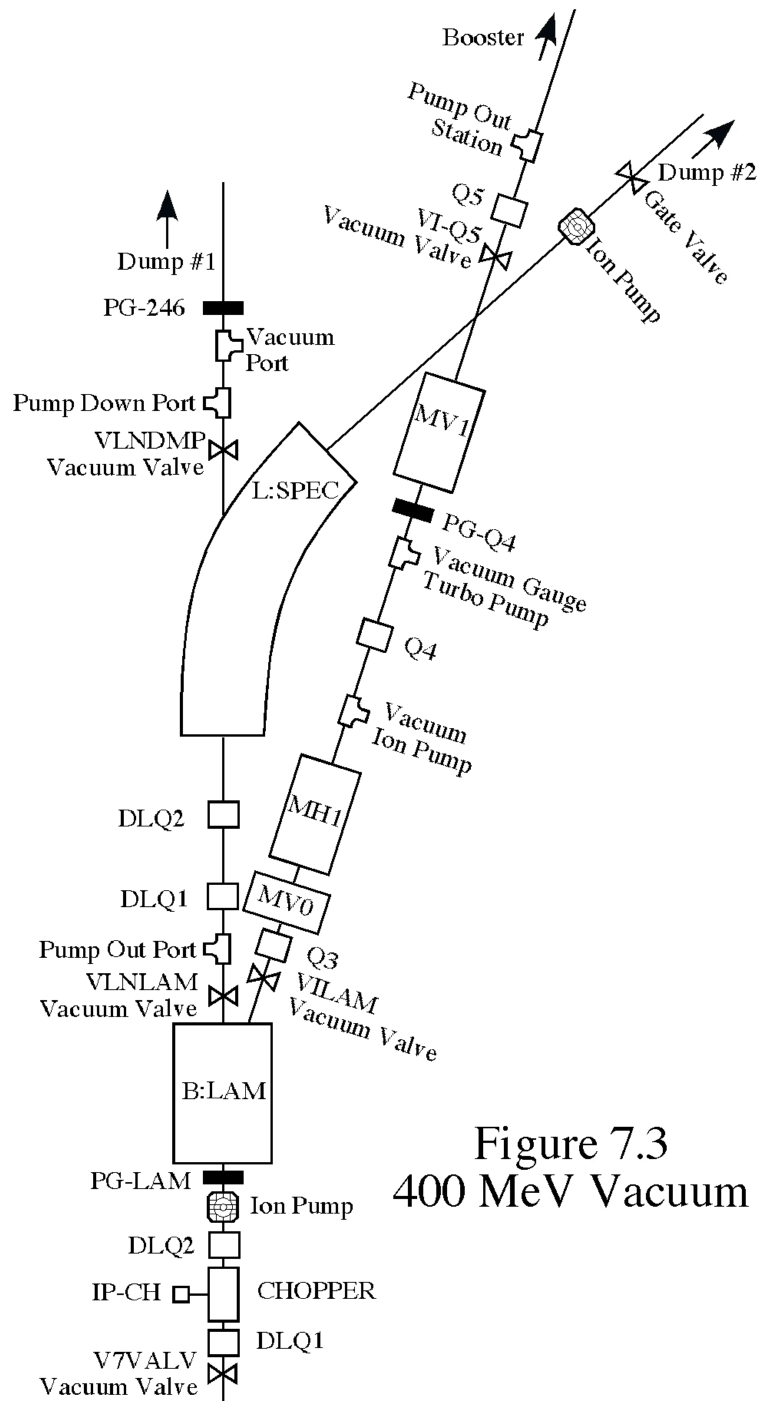


Figure 7.3
400 MeV Vacuum

Chapter 8, Quadrupoles

During acceleration of the beam through the Linac cavities, the beam tends to blow up due to space charge effects and to a phenomenon known as RF defocusing. This occurs because the field lines in the accelerating gap are not parallel, but converge in the first half of the gap and diverge in the second half. Since the synchronous phase angle is negative, the fields are increasing during the time of transit across the gap. Thus the diverging electric field has a greater effect than the converging one, and a net defocusing effect results.

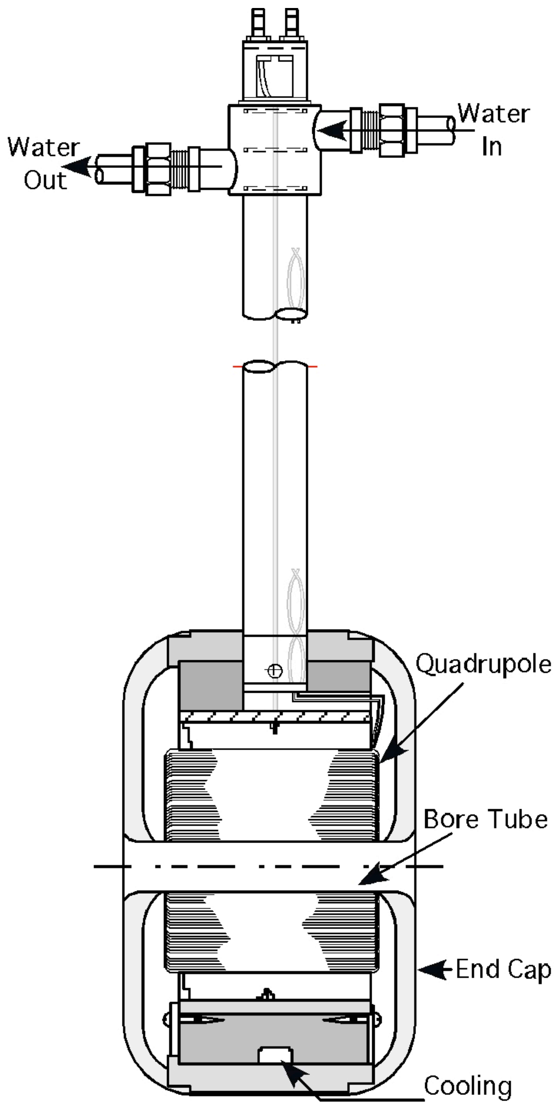


Figure 8.1

To keep the beam size at an acceptable value the beam must be focused in both horizontal and vertical planes during its passage through the cavities. To this end each drift tube in Linac contains a quadrupole magnet, alternating vertically focusing ("D" quad) and horizontally focusing ("F" quad). There is also a quadrupole built into each end of each cavity. Thus a cavity with n drift tubes and n+1 cells has n+2 quadrupoles. The first quadrupole in tank 1 is vertically focusing.

Quadrupole focusing is critical to the proper operation of the Linac, particularly in the first two cavities. If a quadrupole isn't at the correct value, the beam size downstream may become large enough to strike a drift tube and damage it. Therefore every quadrupole is monitored such that it inhibits beam if the current through the magnet is not within a 3-amp tolerance. It is NOT acceptable to run beam through the Linac if any quadrupoles are out of tolerance (OPBUL 212).

A cross-section of a typical drift tube and quadrupole is shown in figure 8.1. Both power leads and cooling water enter and exit through the drift tube stem that protrudes through the top of the Linac cavity. Power and cooling water feed through the stem-box covers located on top of all the drift tubes (figure 8.2). Some covers are evacuated to forestall vacuum leaks around the drift tube stems, and in the case of tank #1, to prevent cavity tune shifts due to changes in atmospheric pressure. This is because the drift tubes can, under the influence of air pressure, expand and contract like balloons, changing the gap width and thus the electrical characteristics of the cavity.

The quadrupoles are driven by Acme "Rectifier" supplies (OPBULL 779) located in the upper gallery. (Some of the supplies for tank 4 are in the lower gallery to make room for NTF equipment upstairs.) Each 200-amp supply drives one quad or two quads in series (one F and one D). (For DTL specifications, look at figure 4.9.) All the quad supplies are individually controllable.

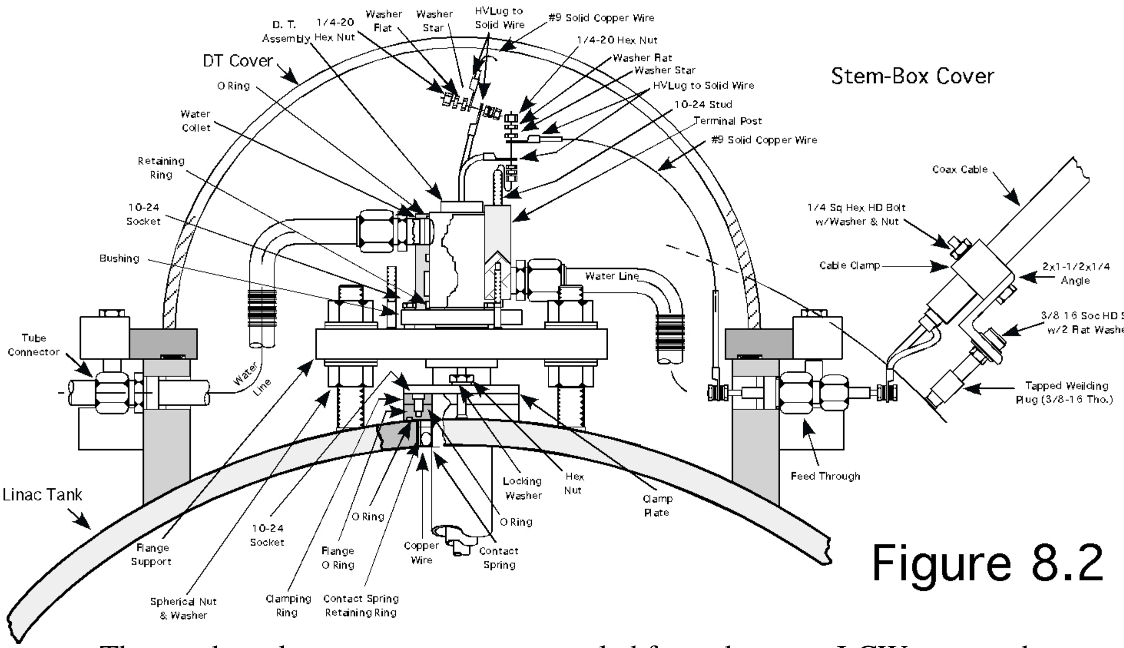


Figure 8.2

The quadrupole magnets are water-cooled from the same LCW system that controls the temperature of the cavity. Since the available cooling is limited, the power supplies for the quadrupoles are pulsed to reduce the duty factor. Since they are pulsed, they must be synchronized. This is done by the “QUADS ON” timing pulse from the Preacc control room. Every quadrupole power supply is transformer coupled to the cable carrying the pulse.

In each supply, an SCR-controlled bulk supply charges a capacitor bank. The timing pulse initiates a sequence of events resulting in the discharging of the cap bank into the load about 1 msec later. The current waveform resembles a sine wave; a current tolerance of 0.5% at maximum implies a usable pulse length of 100 μsec. The current pulse flows through the load back to the cap bank. Additional SCRs commute after the current peak to reroute the current, charging the cap bank in the original polarity. This way, about half of the energy from the cap bank is saved for the next pulse.

The current waveform of a quad power supply is shown in figure 8.3. The sharp discontinuity is the time of SCR commutation.

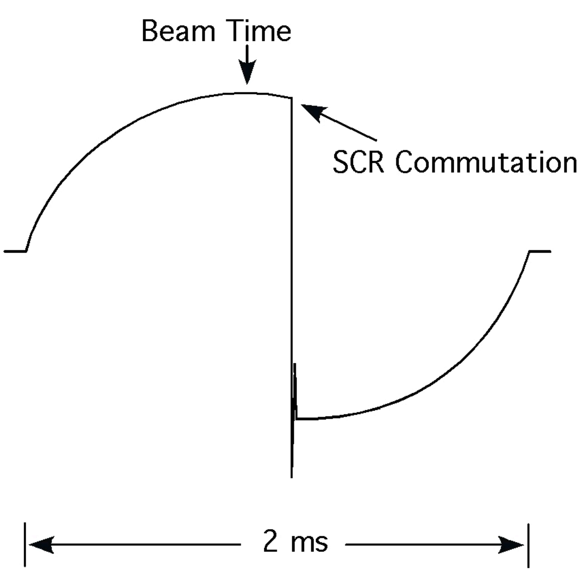


Figure 8.3

DTL Quadrupole Operation

Each Supply has eight control cards (OPBULL 779). One of these cards controls the timing of the current pulse relative to the QUADS ON timing pulse. If the pulse comes too early or too late, an overly large maximum current may be required to maintain the desired current at beam time.

When control cards for an entire supply are replaced, the supply should be “timed in” (OPBULL 780) by adjusting the lower potentiometer on the P5 control card while looking at the supply output on an oscilloscope. The output of the supply is sampled from a BNC spigot on the front.

You can see the quadrupole waveform in the control room by plotting the current versus L:DATA, which controls the time the current is sampled. If L:DATA is changed for such a plot, first disable all the auto-gradient and auto-phase loops in the RF systems and turn off the beam switch. Then change L:DATA back to its nominal value after doing such a plot, and re-enable the auto-gradient and auto-phase loops before turning on beam again.

The quadrupole currents are set and operators do not tune them. Any change in a quadrupole nominal value or tolerance should be noted in the logbook. Any change to a quadrupole setting should be referred to a Linac specialist.

If all the quadrupole power supplies in a cavity trip off, it is a sure sign that the cavity water system has tripped off. If the water system cannot be brought back on quickly, it is necessary to insure that all the quad power supplies are in fact off, since a quad without cooling can burn itself up quickly. This is most readily accomplished by turning off the 40-amp wall mounted breakers, which are labeled for easy identification.

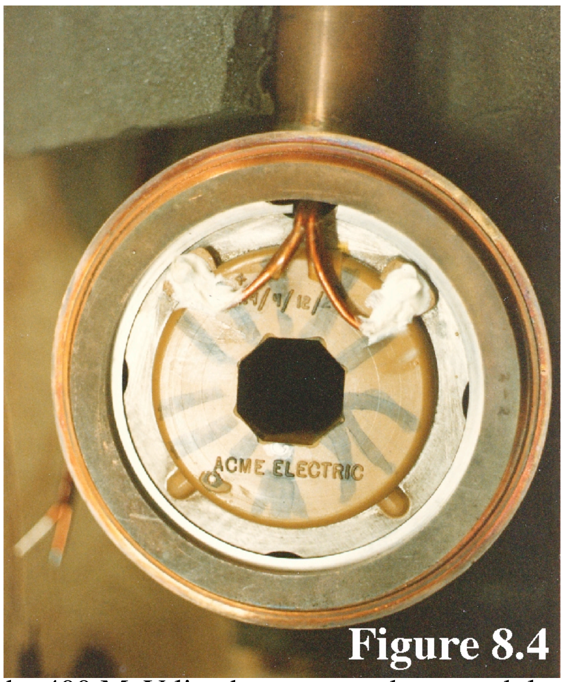


Figure 8.4


Figure 8.5

The panels containing these breakers are located behind systems 1and 4.

The main difference between the 200 and 400 MeV quadrupoles is how they are housed; in the 200 MeV line each cavity has many drift tubes with a quadrupole located inside each tube, while the 400 MeV line has one quad per module. See the figure 6.2.

Figure 8.4 shows one of the quadrupole magnets located in the drift-tube. Figure 8.5 shows an intact drift-tube. The quadrupole is located in the middle of the tube.

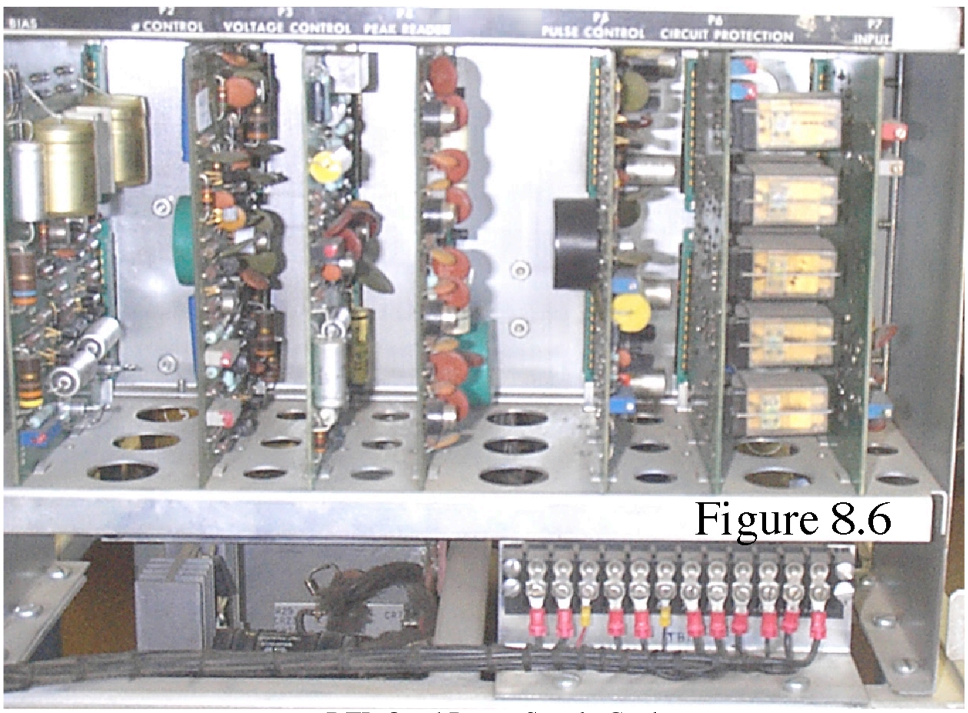
SCC Quadrupoles

Physically, the SCC quadrupoles are no different than the DTL quads; they simply aren't housed the same way.

The quads haven't shown any characteristic failures. If a quad misbehaves, it is simply changed. According to the Linac technicians, all the recent failure modes were esoteric component level things that had been "discovered" but not yet documented.

Troubleshooting

If you have a problem with the SCC quads, you will probably have to call in a Linac technician. They have to "feel" their way through the troubleshooting.



DTL Quad Power Supply Cards

If you do have an idea of what the problem is, with either the DTL or SCC quads, and you change cards, please be sure to do the following:

- Swap the control cards of the bad quad with cards from a quad that you know is operating properly.
- Swap the cards one at a time.
- WARNING - keep track of how the cards are plugged in. Their connectors are symmetrical. Potentially, the cards could be flipped and still fit in to their slot connector. Check another box for alignment if you're unsure of placement. See figure 8.6.

Chapter 9, Linac Timing (LCLK)

Linac uses the Tevatron clock (TCLK) to generate timing pulses for the Linac clock (LCLK). The TCLK signal begins in the Mac Room. From there it's transmitted to the Linac communications rack near the PFN for Klystron #1. The TCLK signal is then sent to Linac VME node 601 via fiber optic cable. The Linac DATA Server is node 600 and resides at the top of the rack above node 601. It's here in node 601 where TCLK is actually encoded into LCLK. (See figure 9.1)

From node 601 the newly converted LCLK signal fans out to the low energy Linac RF stations including the Preacc control room. LCLK is also transmitted back to the Communications Rack via the fiber optic cable and then on to the high-energy Klystron stations.

Linac Clock Distribution

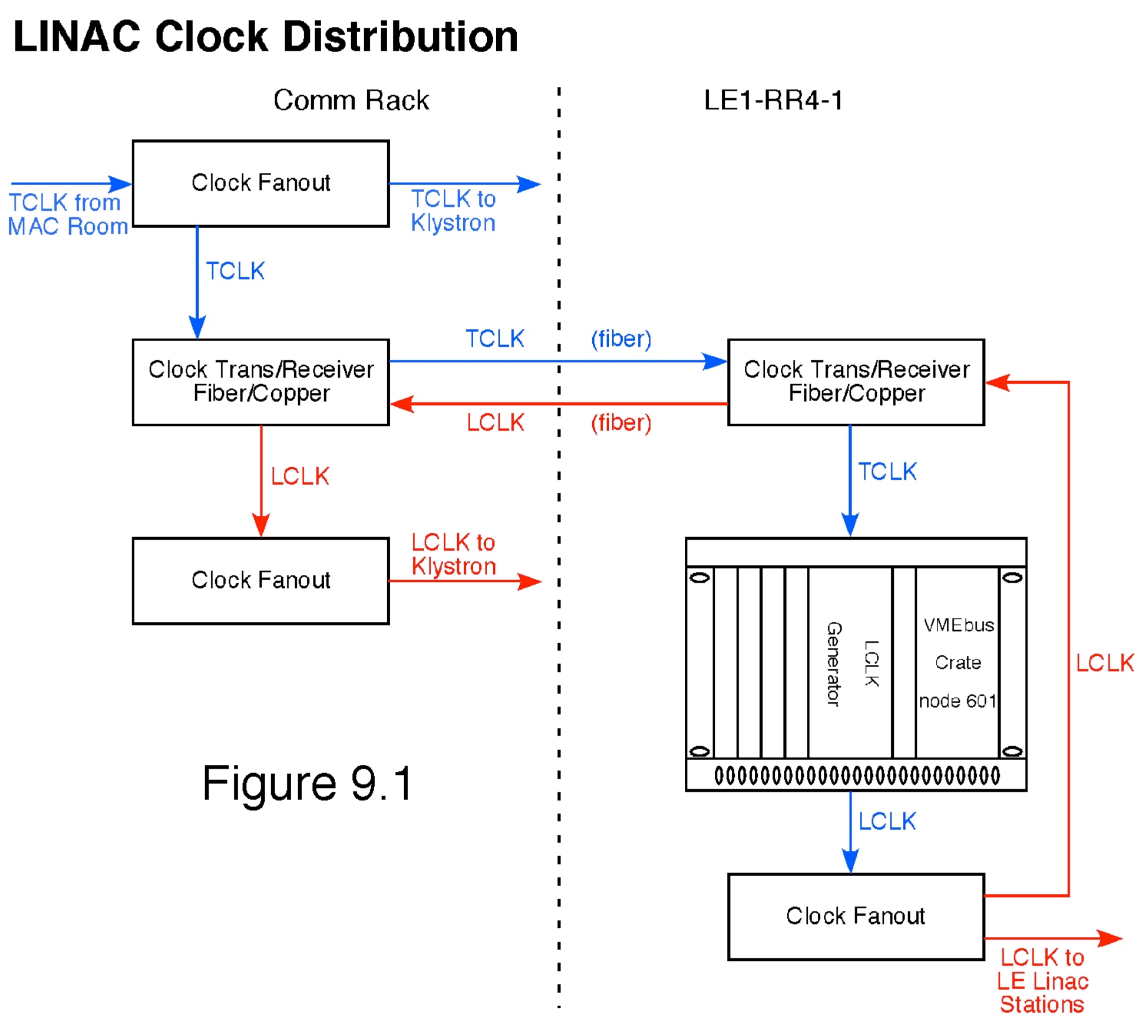


Figure 9.1

Linac Clock Events

LCLK distributes a clock signal that follows the same serial event encoding used for the Tevatron.

Linac Clock Events

Event	Assignment	Source
$AF	Booster Reset	TCLK from CommRack (fiber)
$AE	Trans Klystron System Delay	LOVDLY (601:B1)
$AD	Conditioned Beam Event	Hardware Module in node 611
$AC	Deb Klystron System Delay	KDDLY
$AB	Preacc Pulse Shifter	Preacc Pulse Shifter
$AA	HEP $52 or Linac Studies $0A	Timer PAL Output
$A9	none	none
$A8	none	none
$A7	Klystron 15 Hz Charge	CHARGE (601:A0)
$A6	Klystron Node μP Start	MPSTRT (601:A1)
$A5	Linac T-DATA	HEP/NTF Tdata switch module (LEI-RR2-10)
$A4	HE Quad PS Trigger	QTRIGX (601:B0)
$A3	HE Quad Sample Time	QSMAPL (601"A2)
$A2	Fast Time Plot Event $02	Timer PAL Output
$A1	LLRF Trigger	LLRFTR (601:A3)
$A0	none	none

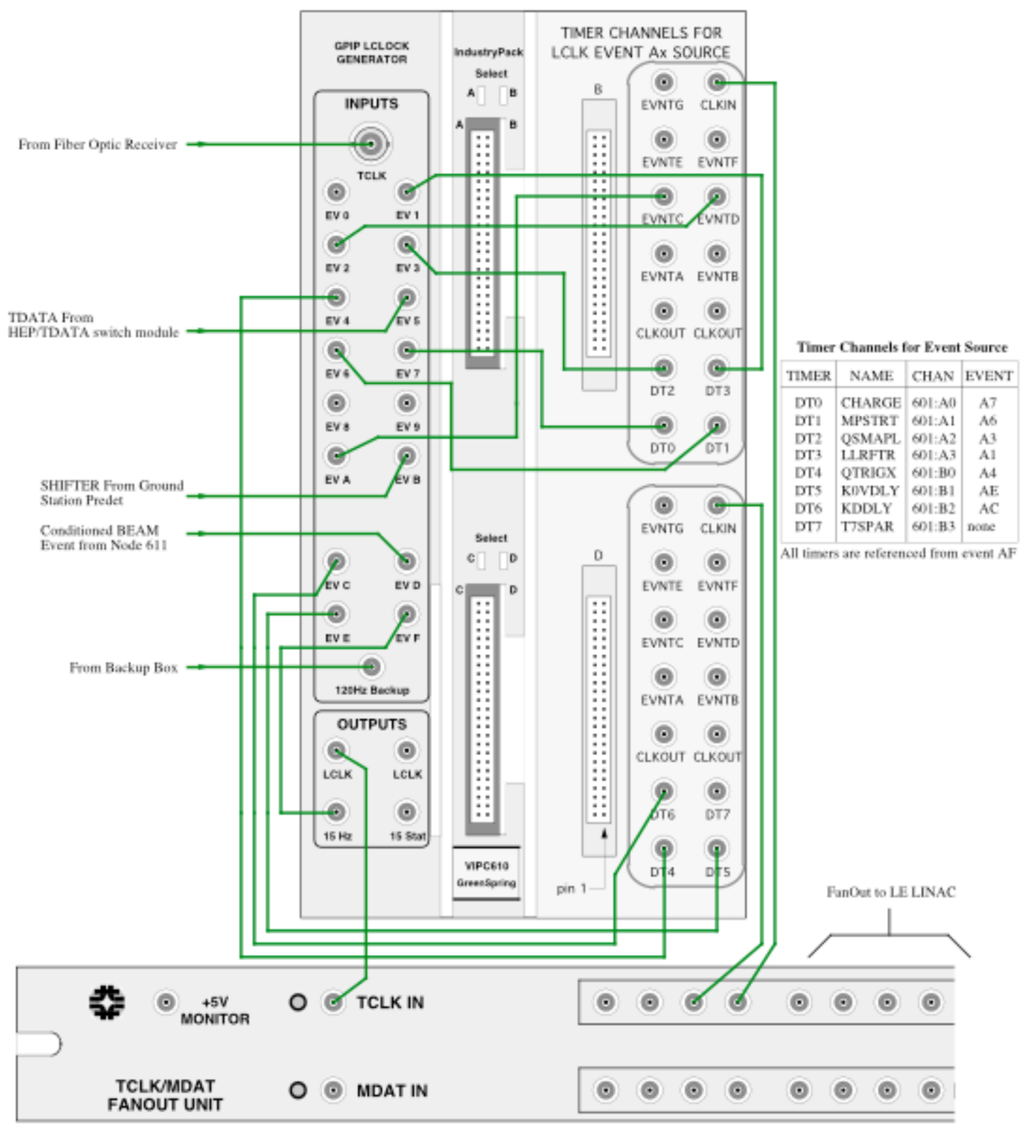
Figure 9.2

There are 15 inputs provided for timing trigger signals. When one of these inputs receives a pulse, it triggers an output of an associated LCLK event. The LCLK signal follows TCLK protocol and uses the same clock receivers and predet modules (V177 cards).

Linac and the LCLK generally continue operation, even when other parts of the accelerator complex are down for maintenance or due to problems.

Timing pulses are not locked to the TCLK signals while in the backup mode, but the LCLK generator will automatically lock to TCLK when its signal returns.

LCLK Generator System



Timer Channels for Event Source

TIMER	NAME	CHAN	EVENT
DT0	CHARGE	601:A0	A7
DT1	MPSTRT	601:A1	A6
DT2	QSMAPL	601:A2	A3
DT3	LLRFTR	601:A3	A1
DT4	QTRIGX	601:B0	A4
DT5	K0VDLY	601:B1	AE
DT6	KDDLY	601:B2	AC
DT7	T7SPAR	601:B3	none

All timers are referenced from event AF

Linac LCLK Generator System

NOTE: All clock generator inputs are 50Ω terminated.

mjk111500

Figure 9.3

Beam Chronology

It takes two msec for Linac to produce beam. In order to get beam to the Booster injection girder when its magnetic field is at its minimum, it must be produced and sent through Linac at the proper time. To do this Linac timing must issue a reset two msec before the field collapses. Booster uses that two msec to turn on and fire pulsed devices. This reset must be sent regardless of GMPS being off or running DC because intermittent pulsing could damage Linac. A backup reset keeps Linac going even if the Tevatron clock fails.

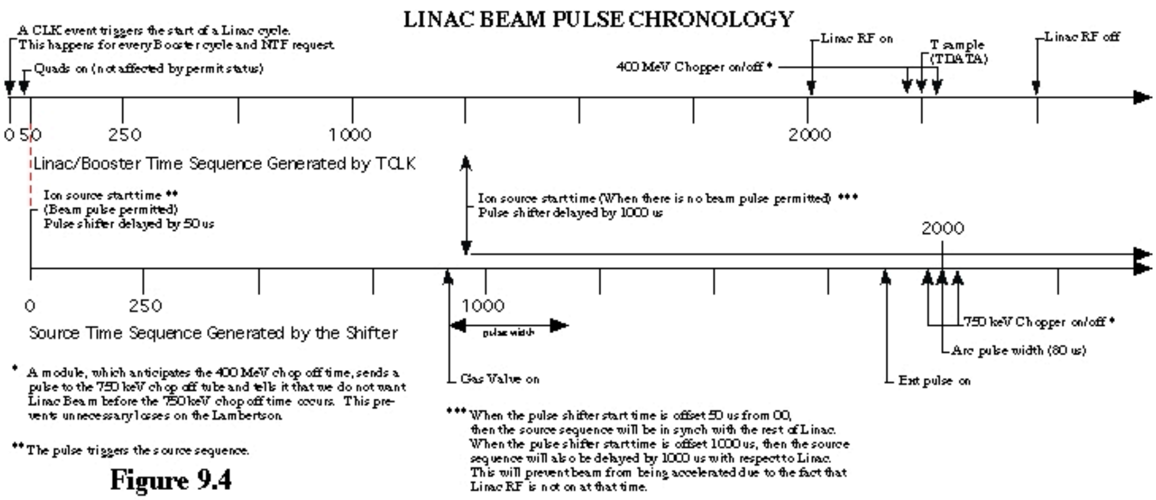


Figure 9.4

Enables and Interlocks

The Linac will not deliver beam to Booster unless it is asked to do so. This requires an enable for each particular type of beam pulse. Only one type of enable is allowed per pulse. There are presently four types of enables: HEP (for injection into Booster), NTF (for the Neutron Therapy Facility), a studies mode, and a standby mode. Whether or not a particular enable eventually generates a beam pulse depends on other interlocks, generated by accelerator hardware and by switches in the MCR.

Beam Inhibits and Alarms

Each Linac Control Station (LCS) is able to inhibit beam. This can happen during any 15 Hz cycle, but it should only happen when a device is out of tolerance or when a station trips off. The beam inhibit is accomplished via a common line wired into each of the VME back planes.

Linac Control Stations issue prompt Linac-type alarm messages.

The VME ground stations handle all H- and I- beam inhibit commands.

Chapter 10, Control System

The Linac Controls System is a modular, synchronous system that provides access to all the hardware in the 400 MeV line and its associated components. The primary observable function of this control system is to provide operators with information about the health and well being of Linac devices. This control system is unique because of the nature of a linear accelerator, such as synchronous operation, repeated system, and destructive RF and beam powers. To this end the controls system has the following fundamental features:

1) To inhibit beam before the occurrence of the next pulse of beam if there are any critical devices out of tolerance.
2) To allow the technician working on the equipment to see and modify the local parameters.
3) To provide modular control for the intrinsically modular Linac systems.

The 400 MeV control system consists of 21 VME crates that control the various sub-systems in that communicate directly with both the Linac Macintosh consoles in the gallery and with the PC consoles in the MCR. The Linac control system speaks with the MCR consoles using the ACNET protocol over Ethernet. Each VME local control station is a Front End. One Linac Control Station (LCS) acts as a server between the information in the various subsystems through Smart Rack Monitors (SRM) that are connected to an LCS by the Arcnet local area network.

The controls software in both the LCS and the SRM runs form information specific to that module obtained from tables in non-volatile random-access memory (NVRAM) at that module. There are two types of Linac control stations. Most of the stations use a VxWork operating system on Power-PC based VME crates. There are a few IRMs running Motorola 68040 CPUs under pSOS. The multitasking pSOS operating system directs a small number of tasks to perform the controls operations so that all activity is completed between beam pulses at 15 Hz (66.7 ms apart).

The Controls group hasn't finalized a topology drawing of the Linac control system. However, the known LCSs are distributed as follows:

1) One for the Preaccelerator and 750 keV lines
2) One for the Linac Clock systems (Node 601)
3) One for NTF
4) One for the MCR "Linac Alarm Screen"
5) One for the Linac Front End (Node 600)
6) Five for the 201 MHz RF systems
7) Nine for the 805 MHz RF systems
8) Three for the Linac diagnostics
9) One for the high-energy Linac quads.

These LCSs communicate with each other, with the Linac Macintosh consoles, and with the MCR via Ethernet. Each LCS is an equal partner on the network, able to obtain data from and reply to any other node on the network. All LCS hardware is interchangeable. The controls software is the same for each LCS.

The various Linac subsystems are referred to in the following manner:

Name	Node	Description
H	610	H- Ion source (H- dome or H- Haefely)
I	610	I- source (I- dome or I- Haefely)
G	610	Ground Station/750 keV Line
B	611	RF System for the Buncher and Emittance Probes
1	611	RF System for Tank 1
2	612	RF System for Tank 2
3	613	RF System for Tank 3
4	614	RF System for Tank 4
5	615	RF System for Tank 5
K0	620	RF System for Transition Section 0
kV	620	RF System for Transition Section Vernier
K1-K7	621-627	RF System for Klystrons #1-7
Diags	62C	Diagnostics
KD	62D	RF System for the Debuncher
Mags	62E	Quads
Diags	62F	High energy Linac Diagnostics
E	61E	400 MeV line devices
C	61C	NTF
A	61A	RF system for the test station

The node number is the last two bytes of the address of the LCS that controls that subsystem. This number is expressed in base 16 (hexadecimal). Each LEL system has its own LCS.

The VME stations and their little consoles are located as follows:

Node	Location (Little Console Location)
600	Linac data server
601	At RF station 1 (no little console)
610	At the Haefely Controls, ground station (G)
611	At RF station 1, above node 601 (RF1)
614	At RF station 4 (RF4)
616	At RF station 6 (RF6 & MCR)
620-62F	At Klystron RF stations 0-7 (at 0, 2, 4, 6, and 7)
62D	Booster Lab 7 Debuncher (Lab 7)
62E	Just South of the Linac Diags Room (the little console is right there)
62F	Linac Diagnostics Room (in Diags room)
61E	In the racks just beyond the Linac Gallery, 400 MeV line (E)
61A	At the test station (A)
61C	In the Linac basement at NTF, south side (C, basement)
62C	In the Diags Room

A VME Local Control Station

The VME local control stations, as listed above, each function as a full-fledged control system. They contain a CPU, two network adapters, non-volatile memory, and a catchall utility card in a 12-slot VME crate (figure 10.1). All cards except the utility card are commercially available.

In the left most slot of the VME crate is the card that contains the PowerPC, some volatile memory, a serial (RS232) port, and other functions. The other cards in the crate are (generally left-to-right in the crate):

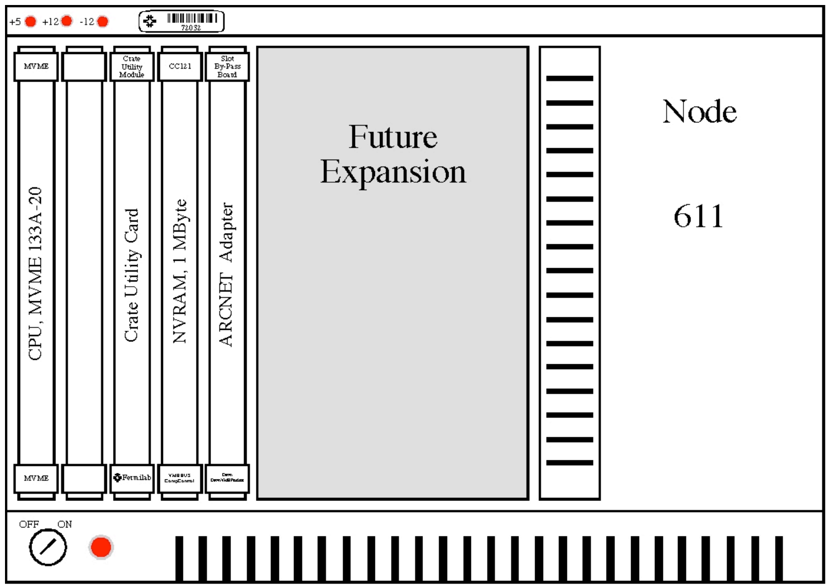


Figure 10.1, A Typical VME Crate Layout

1) An Ethernet adapter
2) A locally made Crate Utility Card
3) a 1 MB non-volatile (battery backed) RAM card
4) An Arcnet adapter
5) Other cards such as a 4-channel quick (2 MHz) digitizer.

The interface to the Linac hardware is via the Arcnet network to SRMs.

There are three local copies of the code that the local computer uses for the system:

1) One is running from volatile memory
2) A copy is in NVRAM, which it reads when the CPU is reset
3) A copy is in PROM, which it reads if the NVRAM copy fails.

If the system gets an unrecoverable error of if a watchdog timer (on the Crate Utility Card) expires, the system will try to reset itself. If the problem still exists when the system returns, then after 15 tries, the system will try no more. An expert would need to be called in this case.

The local computer is responsible for the following list of activities, which it performs within the 66.7 milliseconds between Linac beam pulses:

0 Receive an external interrupt saying that the 15 Hz clock has just ticked
1 Execute the Update Task

a Scan analog devices and binary status for alarms
b Service the PA running on the little console
2 Execute the Server Task (at 40 ms).

The Update Task is very important. It is not necessary to understand all of the details of its operation to understand its function, but some details are pertinent. Information in the LCS is stored in NVRAM in the form of various tables. One table, the RDATA table, contains the list of operations to be performed by the Update Task each cycle. The order of execution corresponds to the order of information in the table. In the Update Task, it takes a few ms to process the RDATA list. Typical RDATA table entries in a Linac LCS do the following:

1) Tell the SRMs via Arcnet that their data are needed
2) Recover the data from the SRMs and perform the next two steps with these data
3) Update reading for all analog devices
4) Update reading for all binary I/O data
5) Update the other, more obscure sorts of data kept by the system (e.g., data streams)
6) Perform zero data, linearization, derived channels, etc. as appropriate
7) Let all the Local Applications (LAs) run.

After RDATA processing in the Update Task, all currently active non-server data requests due this cycle are fulfilled for network requestors. In other words, if a console somewhere is expecting data from an LCS, then that information is sent over the network at this time.

A network request can cause the system to reply, asynchronously, at any time, although the system will not reply if it is busy. An LCS should always respond within 40 ms, even in a worst case, but it could reply as quickly as 5 ms. The systems generally have at least 45 ms of idle time per cycle.

Each LCS has a local database that describes the attributes of each analog device and of each bit of binary I/O. (You can locate this information in the ADESC and RDESC tables, respectively.) This database exists in parallel to the centralized ACNET database. It is possible for the technician in the field to modify the local database (e.g., she discovers that the conversion constants are not correct for the device). But usually changes are made to the ACNET database and this information is downloaded to the LCSs.

All of the information described here is stored in NVRAM on the separate 1 Mbyte NVRAM VME cards in the LCS. This information should survive a power failure. The Linac Controls experts have copies of the local database in a safe place where it can be restored in a catastrophe. This information is what makes the systems behave differently from one another. A complete list of the types of tables in an LCS is given in Table 13.1.

Linac Data Server and Interface to MCR Consoles

One of the VME LCSs, node 600, is responsible for consolidating the data flow between the LCSs and the MCR consoles. This LCS sometimes is called the Linac Front End and sometimes is called the Linac Data Server (LDS). It is needed because it has been observed that several remote systems trying to report data back to a console at 15 Hz will cause the console to fail. The LDS has no trouble performing this task for the consoles. (Since front ends have been typically thought of as a protocol-translating network computer, e.g., ACNET-to-CAMAC or ACNET-to-SCLC, then LDS is really not a front end.) The LDS gets a message directly from an MCR console and distributes the message, essentially unchanged, to the proper LCS.

Table 10.1, Linac Controls LCS System Tables

Table #	Name	Description	Size
0	ADATA	Analog Channel Dynamic Values	16
1	ADESC	Analog Descriptor	64
2	BALRM	Binary Alarm Flags	4
3	BDESC	Binary Descriptor	16
4	RDATA	Read Data Access Table	16
5	BBYTE	Binary Status Bytes (Binary Data)	1
6	PAGEP	Page Pointer (Local Software)	20
7	PAGEM	Page Memory (Private Memory)	128
8	LISTP	Active Data Request Ptr	8
9	CODES	For downloading software	32
10	CDATA	Comment Alarm Data (Sys Reset)	32
11	BADDR	Binary Byte Address	4
12	OUTPQ	Output Pointer Queue (Network)	8
13	PRNTQ	Serial Output Queue	4
14	LATBL	Local Applications	32
15	CPROQ	Coprocessor Queue Pointers	16
16	MMAPS	Memory-mapped template (D0)	8
17	Q1553	1553 Controller Queue Pointers	4
18	DSTRM	Data Streams	32
19	SERIQ	Serial Input Queue	1K
21	AADIB	Analog Alarm Device Info Blocks (D0)	32
22	BADIB	Binary Alarm Device Info Blocks (D0)	32
23	CADIB	Comment Alarm DIB (D0)	32
24	CSTAT	Combined Binary Status	32
28	IPARP	Internet Security	16
29	DIAGQ	Alloc, Liber Diagnostics	16

Special code has been added to each LCS to service the multi-purpose parameter page in the MCR. Each LCS averages 15 readings, paying attention to the presence of absence of beam, and reports a 1 Hz average back to the parameter page. The LDS passes this information unmodified.

All Linac LCSs understand the ACNET protocol, for example SETDAT, RETDAT, and FTPMAN.

Node 616 is a special node. It does no data acquisition. It performs two functions: it watches the network for prompt Linac-type alarms and places them on the Linac alarm screens, and it runs the little console in the MCR.

Node 610 listens to the short-wave radio station WWV and provides highly accurate time-of-day information to anyone on the network who cares to listen. All LCSs listen for this information and synchronize their internal clocks to it. The time field on the alarms screen and in the upper-right-hand corner of the screen on the little console reflects this accurate, synchronized time. This time stamp should be very close to the tune on the WWV receiver in the MCR.

Smart Rack Monitor

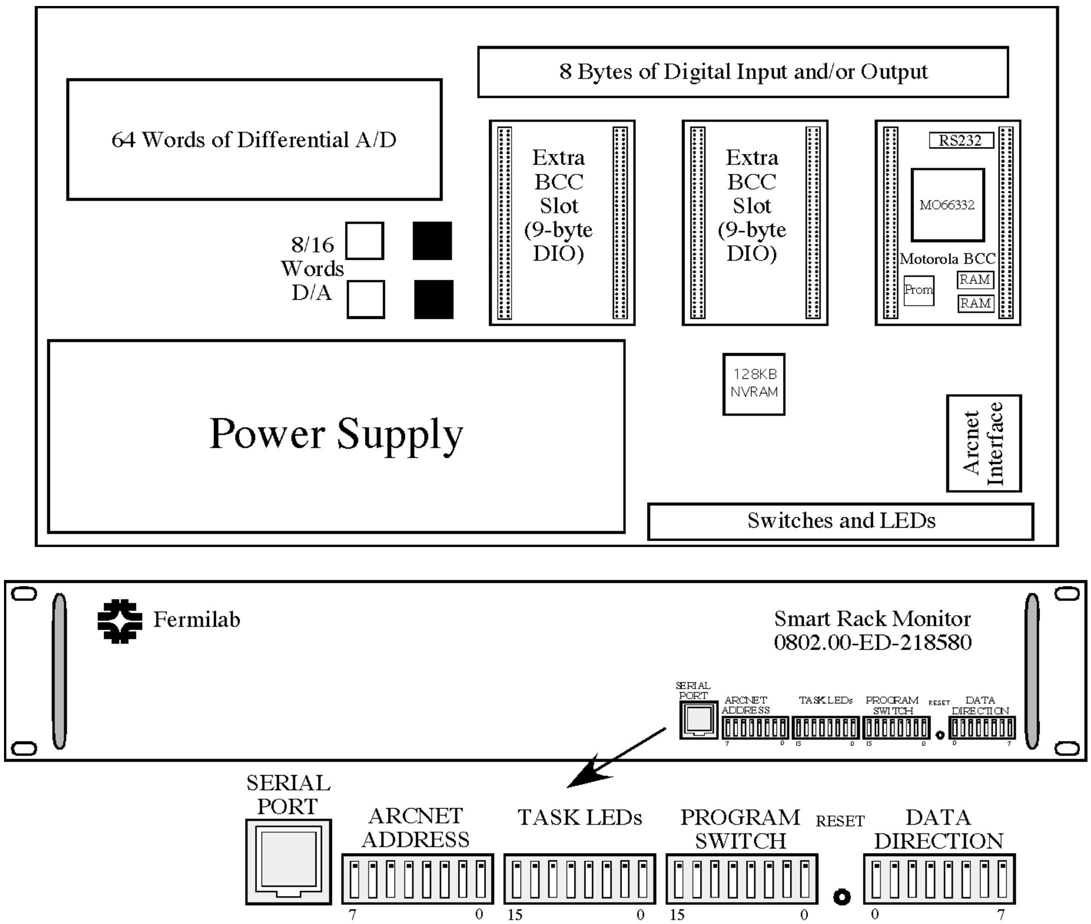


Figure 10.2, Smart Rack Monitor

Smart Rack Monitors (SRM) do the entire routine low-level data gathering. A block diagram for this device is shown in figure 10.2. An SRM is a 2U (3.5") 19" wide chassis that contains 64 16-bit differential A-D channels, 8 or 16 12-bit D-A channels, 8 bytes of digital I/O, 256k bytes of nonvolatile RAM, an ARCNET adapter and a processor. The processor is on a Motorola Business Card Computer (BCC) that includes an MC68332 processor, 64k bytes of RAM, 128k bytes of PROM and a serial port. There are three sockets on the SRM motherboard into which the BCC can be installed.

Several other boards have been designed and built at Fermilab to fit into the other BCC sockets. One of these cards allows the ERM to access the 16-channel A-D chassis, the 16-channel D-A chassis, and the Modulator Diagnostics at a Linac subsystem. This is the "red dot" board. The other 9-byte DIO card, the "blue dot" board, performs normal binary I/O. There is also a BCC-size Tevatron clock decoder in some SRMs that allows an LCS to be synchronized with the rest of Linac.

According to the type of hardware and data tables loaded into the SRM, we have 4 types of SRM in the Linac (the software is the same for each). These SRMs are distributed as follows in the Linac (the Arcnet column is the Arcnet address of the SRM, in HEX):

Node	Location	Arcnet	Type of SRM
610	G. Ground Station	A1	A/D, D/A & Binary
610	G Ground Station	A5	LCK Generator
610	G. Ground Station	A4	Timers, on-board D/As
610	I- Dome	A3	Fiber optic Arcnet: Timers, A/D, D/A, Binary, Old DIO
610	H- Dome	A2	Fiber optic Arcnet: Timers, A/D, D/A, Binary, Old DIO
611	RF for Buncher	A1	A/D, D/A, Binary, Old DIO
611	RF for Buncher	A4	Timers, A/D, D/A, Old DIO
612	RF Station #1	A2	A/D, D/A, & Old DIO
613	RF Station #2	A3	A/D, D/A, & Old DIO
613	RF Station #3	A1	A/D, D/A, & Old DIO
614	RF Station #4	A2	A/D, D/A, & Old DIO
614	RF Station #4	A4	Timers
615	RF Station #5	A3	A/D, D/A, & Old DIO
620	Transition Section	A1, A6	A/D, D/A, Binary, Timer
62n	Klystron 1-7	A1, A2	A/D, D/A, Binary, Timer
62n	Linac Basement	A3	Water Skid: A/D, D/A, Binary
624	C	A4	LCLK Generator
627	Klystron 7	A5	Ion Pump Interface
627	Klystron 7	A4	Valve Control Interface
62C 62E	Throughout Gallery	A1, A4	A/D, D/A, Binary, Timing
62F	Diags Room	A1, A7	A/D, D/A, Binary, Timing
62D	Debuncher		Same as Transition Section
61E	400 MeV Line	A2	A/D, D/A, Old & DIO
61E	400 MeV Line	A4	Timers, on-board D/As
61E	RE for Debuncher	A3	A/D, D/A, & Binary Interface

The controls program in the SRM has a list of tasks to perform modeled after the system software in the LCS. The information is stored in tables, including the information on what to do during the SRMs Update Task. A typical list of tasks performed by an SRM is as follows.

1. Wait for the parent LCS to ask for data
2. Direct the on-board digitizers to do their thing
3. Read the on-board digitizers
4. Direct the old A/D hardware to digitize
5. Read these data
6. Read the binary information (on-board and through 9-byte DIO card)
7. Place the data into the appropriate places in local memory
8. Reply to the parent LCA with the answers
9. Be prepared to reply to asynchronous setting messages.

The SRM has been measured to perform this set of tasks in about 10 ms.

The SRM also has three copies of its code, and tries to recover from unexpected problems by copying a backup copy of the code and resetting. After four attempts the SRM tries to execute the code from the PROM. If this fails, the SRM gives up and waits for help. Pressing the reset button on the front panel of the SRM causes it to retry one more time, but if the cause of the problem was not fixed, the SRM will give up again.

External Hardware

The external 16-channel, 12-bit, sample-and-hold A/D converters digitize analog signals in the old Linac subsystem (G, H, I, 1, 2, 3, 4, 5, and A). Each subsystem has one to six of these A/D converters. Usually, all the sample-and-holds in the Linac are triggered simultaneously by the L:TDATA timing pulse, which is generated at subsystem B. The analog range of these A/Ds is generally -10 to 10 volts. The subsystems that control RF stations (B, 1-9, and D) also have on A/D chassis with an input range of -2.5 to 2.5 volts for 4x increased resolution of RF signals. The Linac beam position monitors, located at 2-9 and E, are also digitized by 2.5 volt A/Ds.

All the old subsystems also have external 16-channel, 10-bit volt D/A converters of 0-10 volt outputs. These are used to control Linac quadrupoles and 750 keV line devices.

The upgraded Linac stations use the A/Ds and D/As on board the SRMs.

The dipole trim magnets and stepping motors are driven by the SRM on board D/As and DIO. Trim magnets are located at G, 3, E, and Mags. There are two types of trim magnet power supplies. 8 output power supplies are at 3 and at Mags, and are identified by two rows of BNC connectors on the front and a column of red LEDs on the right hand side of the chassis. These have a limit of +6 to -6 amps. The trim magnets controlled by this type of power supply are called L:xTyzzz where x is H or V, y is a digit 2 through 5 and zzz is IN or OUT. For example, L:HT4IN is the horizontal trim at the input to Tank 4. The other type of power supply has a range of +10 to -10 amps. This Power Supply is a 19" supply that controls a single trim magnet. These are located at G (L:TRIM90) and at E (L:HT2001 through L:VT2002).

Interface to the Upgrade Modulator and LLRF System

The modulator and low level RF systems in the upgraded Linac are controlled by the local VME and VXI systems. Communications with these systems is accomplished over a Vertical Interconnect (VI). This is a locally made VME device that maps 24 Mbytes of VME backplane memory form the slave VME/VXI crate to the master LCS in a transparent manner. The system code in each subsystem is organized in such a way that all the analog and digital reading and settings are with that 24 Mbyte window in a way that is well known to the LCS experts.

Each subsystem is responsible for incrementing a local counter that the LCS system software inspects at 15 Hz to be sure that counter is incrementing. If this counter is not incrementing, it is a reasonable guess that the low-level processor is not behaving properly. In this case, the device L:MnHB or L:LNHB (for Modulator or LLRF, respectively) will alarm. (HB stands for Heart Beast.)

Linac Timing

Linac uses the Tevatron clock, TCLK, to generate timing pulses for Linac. Two special SRMs exists to handle this function, one at the Ground Station and one at the COMM Rack near the PFN for Klystron #1. These SRMs contain a BCC with an ACTEL 1020 gate oscillator, on those occasions when TCLK is down. Thus, NTF can continue to run if TCLK is off. On the back of this SRM are lemo spigots that allow PREDET-type signals to be connected to generate clock events on the local clock. This local clock is referred to as LCLK. The events used are:

Event	Description
$AF	Booster Reset (regular 15 Hz)
$AE	Pulse Shifter (15 Hz for the ion source)
$A7	Klystron 15 Hz, Charge
$A6	Klystron 15 Hz, Fire
$A5	Klystron Reduced-rate, Charge

$A4	Klystron Reduced-rate, Fire
$A3	Upgrade Quad Sample Time
$A1	Low-Level RF Trigger

One of the SRMs at each LCS is dedicated to receiving LCLK. This SRM is loaded with a BCC similar to the one at the Ground Station. It also contains an ACTEL 1020 gate array, but this one is configures to accept LCLK (or TCLK) and to output properly timed pulses. Up to four delayed outputs, i.e., P start can be triggered form one event. Four clock events can be selected as outputs (determined by PALs). The timing SRM also serves as a clock (TCLK or LCLK) repeater, providing two copies of the clock.

The analog devices that describe these events are located in the LCS database beginning at channel number 0x080.

The devices are named as follows:

Name	Title	Description
L:RFnT0m	RFn TIMER m	Delay for this pulse
L:RFnEVm	RFn EVENT m	Event on LCLK that triggers this pulse
L:KnT0m	Kn TIMER m	Delay for this pulse
L:KnEVm	Kn EVENT m	Event on LCLK that triggers this pulse
L:KnCNm	Kn CONTROL m	Control word

The device L:DATA should be L:RF1T00 by the new system, but the old name has been retained.

ACNET Interface to Binary Status Information

The Linac subsystems each contain several dozen bits of digital status. These bits are read in groups in a manner similar to the way bits are read in other parts of the complex. These combined binary devices can be read on page S53 just like other binary information.

The combined binary devices can be set to alarm and to inhibit beam, as can the analog devices in the Linac Control system. They are reported on the Linac alarms screen in the normal manner, and they appear on the alarms screen as digital alarms. Do not ignore these alarms.

The nominal value for these devices is only pertinent when viewed as a raw hexadecimal value. This is the expected bit pattern for the bits in this device. The tolerance value, again viewed as a hexadecimal number, is considered to be a mask; the bits that are 1s are the bits that are observed in the alarm screen.

Note that this is the only way in which binary information produces an alarm in the Linac control system. It's important that operators understand how these bits produce alarm messages.

The combined binary devices in the 201 MHz subsystem at this time are:

- L:RnMISC
- L:RFnVAC
- L:RFnPA
- L:RFnDRV

The combined binary devices in the 805 MHz subsystems are:

- L:BnLCS
- L:BnILK1
- L:BnILK2

- L:BnDIS1
- L:BnDIS2
- L:BnSOL
- L:BnCOIL
- L:BnLLRF
- L:BnWATR
- L:BnMODR
- L:BnMOIL

Local Application

Each task has the ability to run customized closed-loop applications at the end of the Update task. These applications, called Local Applications or LAs, are independent programs written in Pascal or C, which can control anything at the LCS. The LAs currently in use are:

Name	Description
GRAD	Regulates gradient in the 201 MHz tanks
PHAS	Regulate inter-tank phase in the 201 MHz tanks
CROB	Recovery from PA crowbar
DRIV	Recovery from driver trips
PINH	Reduction of gradient after trip without recovery
QUAD	Recovery of DTL quad PS trip
PRES	Regulate ion source pressure
NETM	Lost network recovery
AERS	AEOLUS shepherding
FTPM	FTPMAN support
AAUX	ACNET AUX support
GATE	ACNET-header gateway support SRM
TEMP	Regulate water temperature in side-coupled cavities (SCC) modules
FREQ	Controls VCO to keep SCC resonant
EMIT	Emittance probe and wire scanner control
KRFG	Klystron gradient regulation
KRFP	Klystron phase regulation
PIDH	Haefely voltage regulation
COND	Klystron automatic reset
STAT	Klystron counting stats
ARTC	Phase difference via arc tangent
PERV	Klystron perveance
SCNT	Spark counting algorithm
BPMQ	BPM data collector

You may view these applications on page L23. These programs handle all routine failures of the hardware in the Linac subsystems. For example, the LA NETM watches the Ethernet activity at the LCS and tries to bring it back online if the network or the LVS should fail.

Alarms and Beam Inhibits

Each Linac Control Station (LCS) is able to inhibit beam. This can happen during any 15 Hz cycle, but it should only happen when a device is out of tolerance or when a station trips off. The beam inhibit is accomplished via a common line wired into each of the VME back planes.

Linac Control Stations issue prompt Linac-type alarm messages.

The VME ground stations handle all H- and I- beam inhibit commands.

Other Features

There are several more obscure features of the Linac control system. Each device can be made to wait for up to 15 consecutive bad readings before reporting an alarm. Many devices, most notably the BPMs, are read out through a 1 to 5 MHz Quick Digitizer.

Each LCS contains a binary datum at bit number 0x0A7, which controls whether or not that station reports alarms on the network. This bit should always be enabled! There is a special case in the alarms reporting algorithm that will report an alarm if this bit is turned off.

The beam enable line is split at Tank #4 into upstream and downstream halves. The downstream half is held high by a power supply at the ground station. The upstream end is held high at the location of the old Debuncher racks. Any LCS can pull it low to inhibit beam.

Checklist

An independent checklist program checks several aspects of the control system that never break but provides a logical loophole for catastrophe should they break. These items include the following questions:

- Are the expected stations answering to simple network requests?
- Would the local control stations report that "alarms reporting" is turned off?
- Is the system code in each station reasonably up-to-date?
- Are there any binary data that could inhibit beam silently?

This checklist program runs on the Unix workstation, called Garlic, in the Diagnostics room. It executes every day at 1600 hours and the output is sent to a Linac staff member. Other items are added and removed routinely.

Troubleshooting

Every LCS and every SRM have diagnostic LEDs on their front panels. The most interesting LEDs are on the VME crate utility card, which normally flash at 15 Hz. If there is no 15 Hz interrupts to the system, then they flash at 12.5 Hz. If you are standing in the Linac gallery you can hear the 15 Hz—it's easy to notice if the computer isn't synchronous to this sound.

A complete set of ACNET error codes, facility code 36, can be obtained from the Linac Controls Liaison.

The SRM LEDs should all be flashing at 15 Hz. If an SRM is disconnected from its LCS or if its LCS isn't getting 15 Hz interrupts, the SRM LEDs will flash at 12.5 Hz.

In general, it isn't appropriate for someone other than an expert to change an SRM because the software will need to be changed also. The module itself can be switched with one of the same type (number on a sticky label on the front panel of the SRM).

Before connecting the replacement to the network, the SRM dipswitches on the front panel must be changed to match the configuration of the removed SRM. If, after turning on the SRM, the LEDs flash at 15 Hz, then the SRM is okay, but it may still require some changes in its local tables. This is why it requires an expert.

The Linac timing system runs off of TCLK. If there's a glitch in TCLK, then Linac may miss a 15 Hz clock tick. The LCSs will not wait forever for the tick. After 80 milliseconds the software will generate an artificial tick. Since this tick is asynchronous, many devices like the quads will be out of tolerance at that particular time. Look for devices called L:nS15HZ for the 201 MHz Linac and L:ZnHZ15 for the 805 MHz Linac. This device measures the length of the cycle. If the cycle isn't 66 or 67 milliseconds, then it will alarm the system. The Linac alarms screen may not display the alarm. If TCLK is off, this system should kick in. This allows the RF system to continue to operate normally and NTF to run.

The Little Consoles

The device that is referred to here as "the little console" is a small 19" rack-mounted CRT/keyboard that the technician uses to view and modify parameters. They use the little console while working on the various Linac subsystems in the field. All of the Linac subsystems (G, 1, 2, 3, 4, 5, and E), Klystrons number 0, 2, 4, 6, 7, and D, the Diagnostics Room, and the MCR each have a little console. There are several others scattered around the Beams Division. Operators generally don’t need to use these consoles.

The parameter page is the most used application on the little console. The first line of the display contains a title, the date, and the time. The rest of the lines, excluding the last line, are available for parameter viewing. Enter the 6-character name of the device (without the L:) or the channel:node number: for example, GR1MID or 611:302. Use the red key labeled "INTR" on the face of the little console, or use the "ECS" key or any other key marked with "INTR" to perform the operation. The RETURN key does a carriage return, not an interrupt. Settings made on a little console are not logged in the ACNET setting logger. A device setting can be changed in one of three ways:

- Enter a new value and hit "INTR"
- Press the green up/down key on the face of the little console
- Use the knob

LCS Primary Applications

Name	Page	Description
PARM	VARIOUS	Local parameter page
EDAD	A	Analog descriptors, change local analog database
EDBD	B	Binary descriptors, change local binary database
LAPP	E	See parameters associated with the local applications
FRAM	F	See network frames (Does not appear on index page
CRTI	G	Little console image across the network (Page G)
SRMC	H	Copy memory to and from an SRM
MBLK	K	See pSOS-allocate VME memory
ACRQ	L	ACNET protocol data request test
MDMP	M, N	VME memory dump
SURV	Q	Roll-call on network of LCSs
TRNG	T	Ethernet initialization page

Some of the available applications are listed here, although they are not necessarily all loaded on each LCS.

> Note: If you need to use these programs, please consult an expert for a tutorial first. These applications interface with the Linac control system in a way that is subtly differently from the applications on an MCR console. Be especially careful with EDAD, EDBD, and MDMP.

All of the applications on the little console can be run from a Macintosh when the LCS is on the network. This is accomplished via the "VME Screen Image" application on the Mac.

Macintosh Consoles

Several Macintosh computers, i-Macs, have replaced some of the little consoles. Extensive controls software has been written for this platform. The applications available that can access Linac data are:

- ♦ Parameter page (note that "L:" is not part of the device name)
- ♦ Time plot, knob plot, and VME memory plot package
- ♦ VME memory dump page
- ♦ VME screen image (Page G)
- ♦ Lab View

These programs adhere scrupulously to the Macintosh "look and feel" and are quite easy to use. In order to make settings from one of these applications, one must enter the proper password. This is the "Enable Settings" option in the "Options" pull-down menu. You must use "Enable Settings" to do anything except look at the existing screen image. This program can be run even if the little console doesn't actually exist at the LCS.

Overview

This section is going to be a basic overview of how to use the Macintosh consoles located in the Linac upper gallery. The Mac consoles are used to interface with the controls of the Klystron systems and the rest of the Linac. The Macs are full-fledged consoles in regards to Linac devices, meaning that the Macintosh consoles have much the same facility as the MCR consoles.

If you walk down the Linac gallery, you will find five Macintosh consoles located among the Klystron stations. They are set up to look at the parameters of each station. For instance, the console between stations 3 and 4 looks at parameters of station 3 and 4. The Macintoshes can look at any parameter associated with Linac, but their primary use is dealing with the Klystrons.

There are two main applications on the consoles that operators should be aware of, one is the parameter pager and the other is the graphing package.

Parameter Page

As in the MCR, the parameter pages on the Macintosh consoles allow the viewing and adjusting of parameters. The basic parameter page layout is shown in figure 10.3.

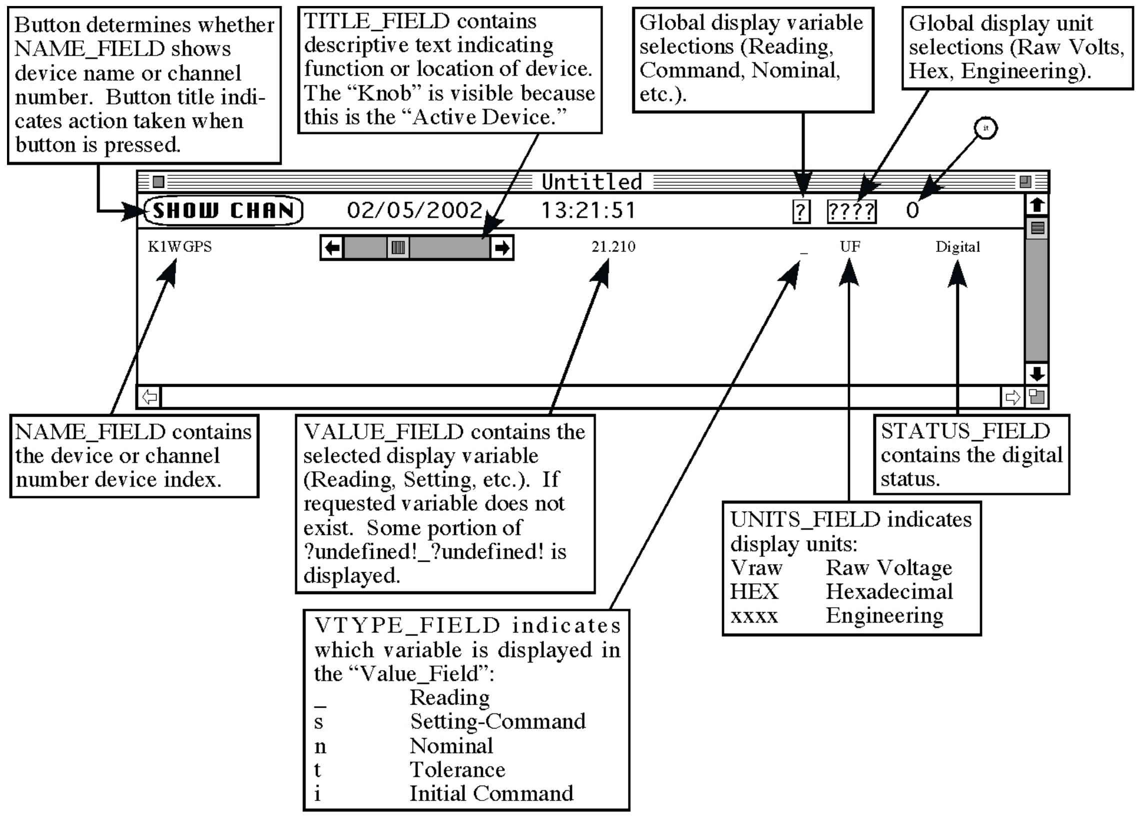
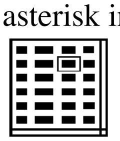


Figure 10.3

Here is a short description of the fields on the page. Just like a parameter page on an MCR console, the parameter name goes in the field on the far left.

Note: On the Linac Macintosh consoles it is not necessary to put an **L:** prefix on Linac devices. In fact you will not be able to display the parameter if an **L:** prefix is used.

In the next field over to the right is either the descriptive text or a scroll bar depending on the activity. The scroll bar is the "knob" for the device whose name appears in the field on the far left. The field to the right of the text field is one character wide. It will have an asterisk in it if the alarm has been bypassed and no asterisk if its alarm is enabled. The value field is the next field to the right and contains the value of the parameter. The setting field is to the right of the value field. The "units" field is the next field after the type field continuing to the right. And finally, the status field is on the far right of the page.



K1 General

Figure 10.4a

Parameter page icons look like figure 10.4.

If you would like to change a parameter you must first enable settings. To enable settings choose options and select settings.

If the menu as in figure 10.5 is not across the top of the screen you can make it appear by doing the following:

Figure 10.5

1. Open the 'File' menu.
2. Select 'New,' which opens another menu.
3. Select the 'Parameter' menu item. A new parameter page will open.

This new parameter page will have one parameter on it. The parameter is RF1SYN. RF1SYN is the syncing device to the first device and used primarily for diagnostics. You will notice that another window has opened at the bottom of the screen. This window was mentioned previously. It is called ERROR LOG and keeps track of errors and other system information. Your Macintosh screen looks something like figure 10.6.

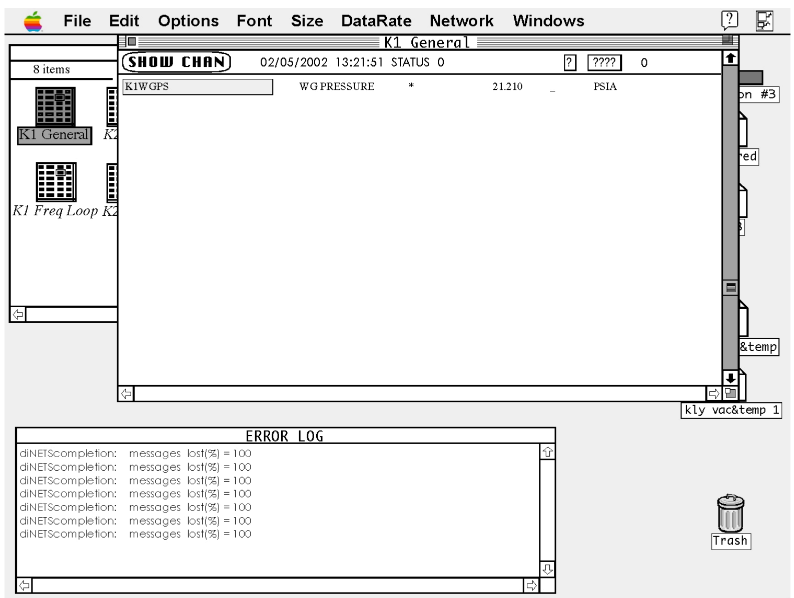


Figure 10.6

Now, to enable settings go to the 'Options' men item at the top of the page and open it. Then select 'Enable Settings.' Set the amount of time you would like console settings enable for. You should have a message in the ERROR LOG that reads "Settings are now enabled." Settings made on a Mac are sent to the ACNET settings logger.

Sometimes you will not want settings enabled. Disable settings go to the 'Options Menu' item at the top of the page and open it. Select 'Enable Setting.' Click on the 'OK' button. You should have a message in the 'ERROR LOG' window that reads "settings are now DISABLED." Setting will also become disables if no user activity occurs at the consoles for 30 minutes.

If a specific parameter is not on the parameter page you must type it in by highlighting the field on the far left of the page and then type the parameter without the **L:** prefix. Now to change its value, highlight the value field. If the value can be changed the field will highlight and the scroll bar appears in the place of the text field. If the value cannot be change nothing will happen when you click on the value field. Assuming the value can be changed you have a few ways to do it. You can 'knob' it (using the scroll bar) or type in the value. For this general overview it is recommended changing parameter values by typing then into the value field. You can try knobbing them but be aware that the knob/scroll bar can have its sensitivity set so that you may be making larger or smaller changes than what you want.

If you would like to try to adjust the 'knob' sensitivity for S8PWR go to the 'Options' field in the menu bar across the top of the screen and open it. Select 'Knob Response' as seen in figure 10.6b.

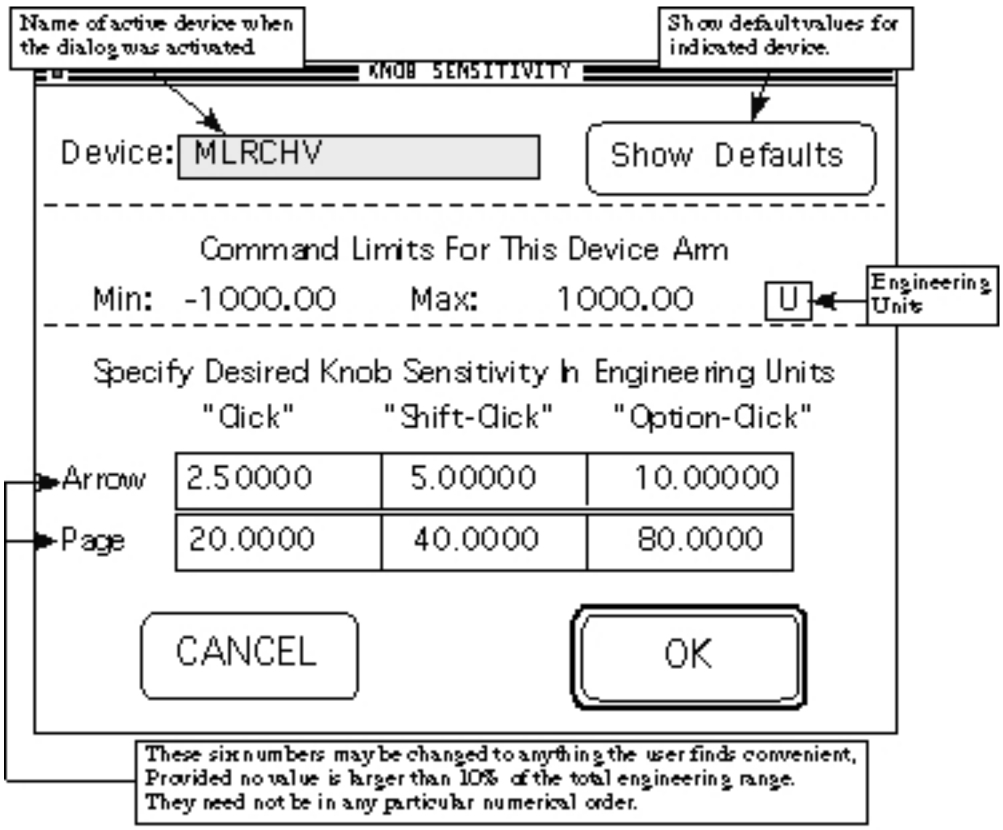


Figure 10.6b

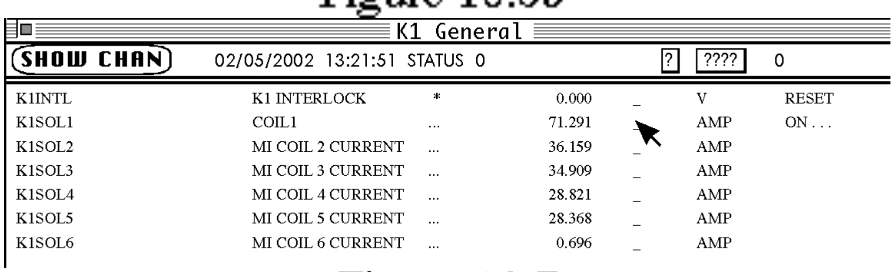


Figure 10.7

If after changing the parameter's value, you would like to change it back do the following:

- Open the field just after the value. (Refer to the arrow location on figure 10.7) A menu will open.
- Select the Initial menu item. If you have not closed the page you should get the original value back.

- ♦ **Note:** If you have multiple occurrences of the same parameter on the same page setting, its value back will only change the one parameter you currently have highlighted not all occurrences.

When closing a parameter page just close it the came way you normally close Macintosh windows. If you get a window asking to 'Save', 'Discard', or 'Cancel' the current parameter page it means you have made some changes to the parameter page. If you choose 'Save' then the current parameter page layout will be saved. If you choose 'Discard' then the default parameter page layout is saved. And finally, if you choose 'Cancel' then you will not leave the application.

Graphics Package

When a graphics window opens up it looks like figure 10.8a and has fields shown in figure 10.8b. The plotting package on the Macintosh consoles has several nice features: a zoom controlled by the mouse, histogram capabilities, and a buffer of data up

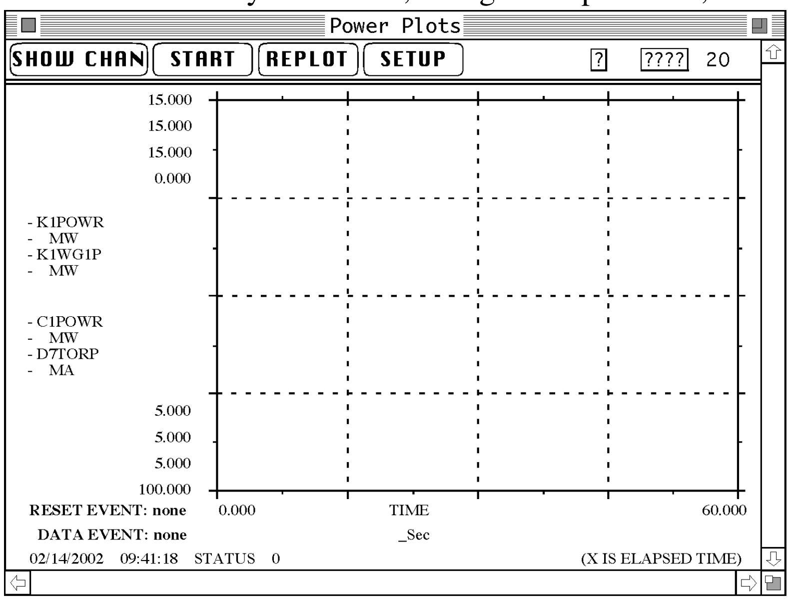


Figure 10.8a

to 10,000 points. It doesn't do once plus plots, or plot on time events.

Only the standard graphing capabilities will be discussed since operators will probably not make use of the features. If you want to plot something on a Macintosh console and there's already a plotting window open, take care that you don't wipe out someone else's plot.

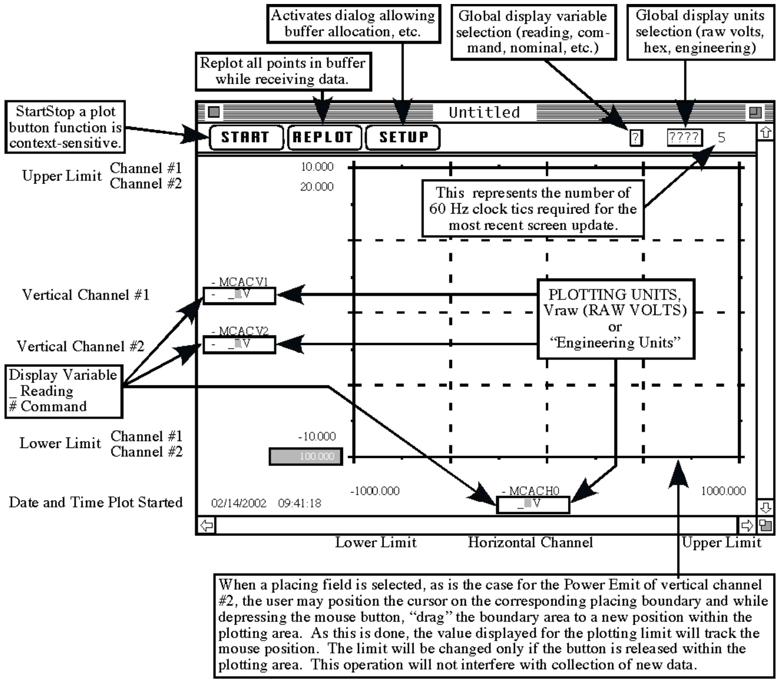


Figure 10.8b

To start a new plot, proceed as follows:

1. Go to the 'File' menu item bar that goes across the top of the screen and open the menu.
2. Select 'New.' This will open another menu.
3. Select 'Scatter Plot.'
4. A window will open containing the plotting grid with various fields.

Now highlight the various fields, like limits and parameter that you want to put values into. Then type in the devices and limits you want for plotting. Try using the dummy parameter mentioned in the Parameter Page section of this document (S8PWR) for the vertical axis and time for the horizontal taxes. Now click on the 'SETUP' button, which will open the window show in figure 10.9a.

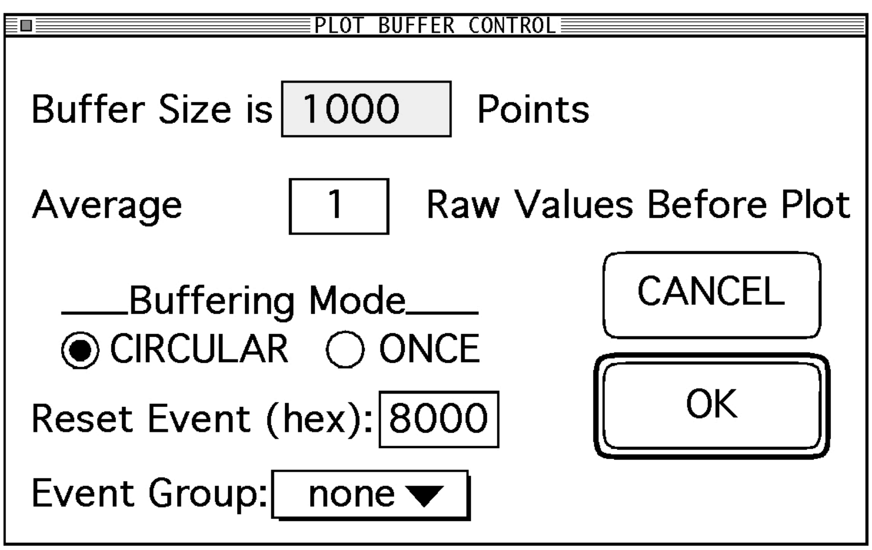


Figure 10.9a

The 'SETUP' is primarily for defining the number of points you want to save in the buffer, how often you want a point plotted, and if you want the buffer to continually update or to fill once and stop, figure 10.9b.

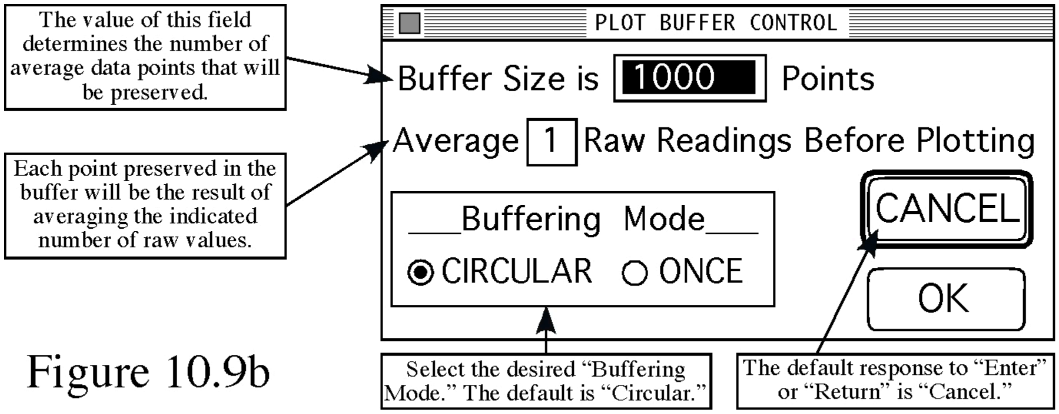


Figure 10.9b

Once you are done with the 'SETUP' click on 'OK' or ' 'CANCEL' depending on what you want. Next open the 'Plot Preferences' window by opening the 'Options' menu and selecting 'Plot Preferences.' A window as in figure 10.9c will appear. Choose you preference and click on 'OK.' Then finally, start your plot by clicking on the 'START' button.

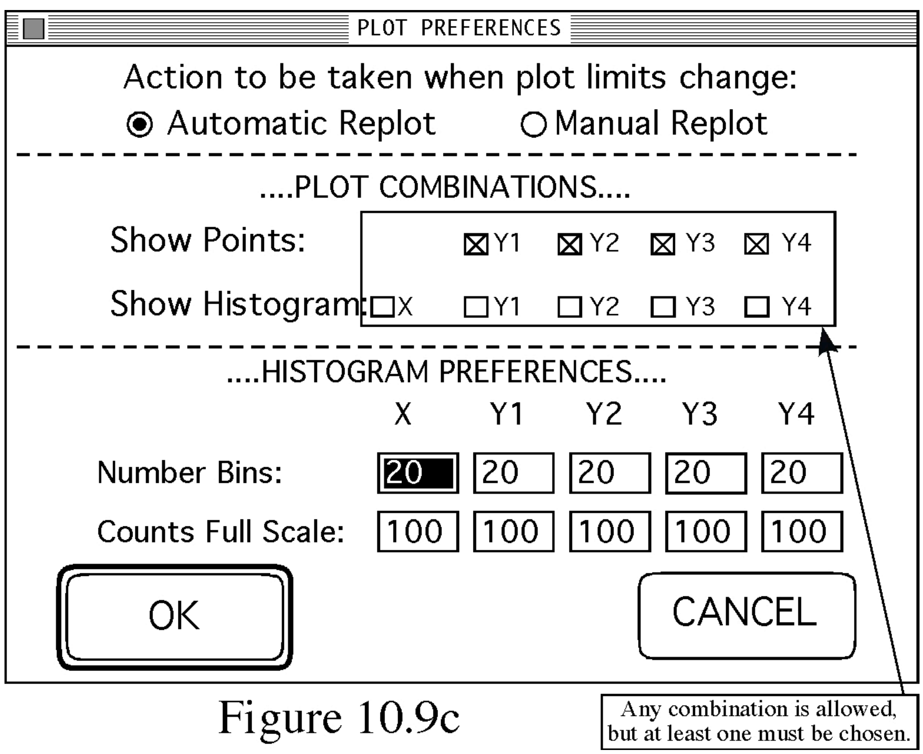


Figure 10.9c

You can save plots in the following ways:

1. When you close the plot window it will ask you whether you want to save your plot or not.
2. You can also choose save from the 'File' menu.
3. You can also send plots to various printers that are named in the 'chooser' menus.

Folder Overview

Operators should be aware of the following Macintosh folders located in the hard drive named 'Linac Controls' and the 'k#.' The #ik# represents the number of a klystron station. These folders, K#, are in the folders that contain parameter pages and plot setups specific to the klystron station in their label. For instance, folder k2 has parameter pages and plot specific to klystron 2.

The hard drive folder contains k# folders that are specific to klystron station near next to the Macintosh. The k# folders should contain a basic subset of folders and parameter pages. They are:

- k#
- General
- k#LLRF
- k# TempLoop
- k#FreqLoop
- k#(Mod folder)

See figure 10.10 in the 'k1' folder.

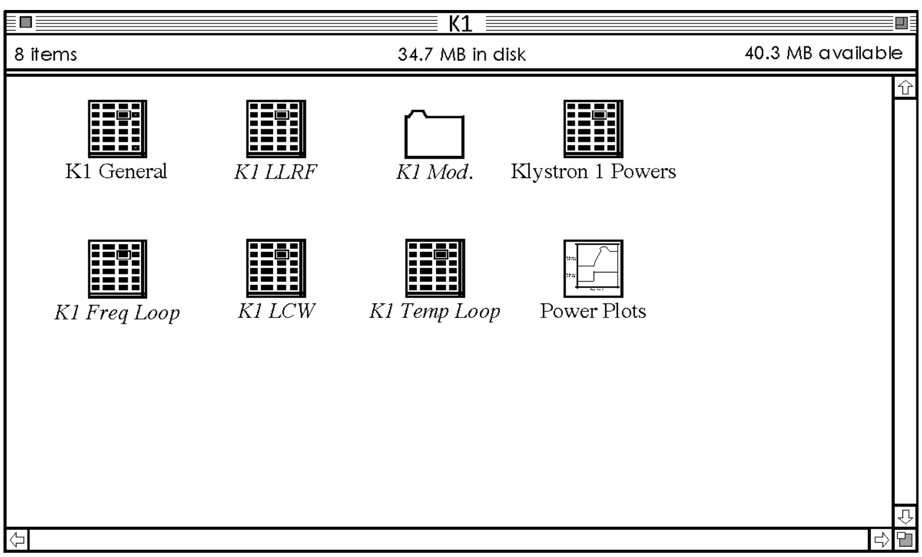


Figure 10.10

Other folders or parameter pages could exist, but the six named above should always be there. The titles of the folders are self-evident (figure 10.11).

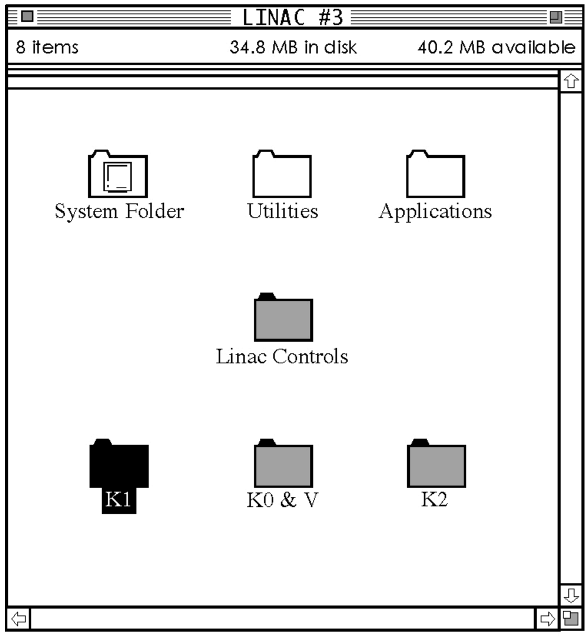


Figure 10.11

The 'Linac Controls' folder (figure 10.12) contains folders that have parameter page and plot setups to look at any of the Klystron station's system.

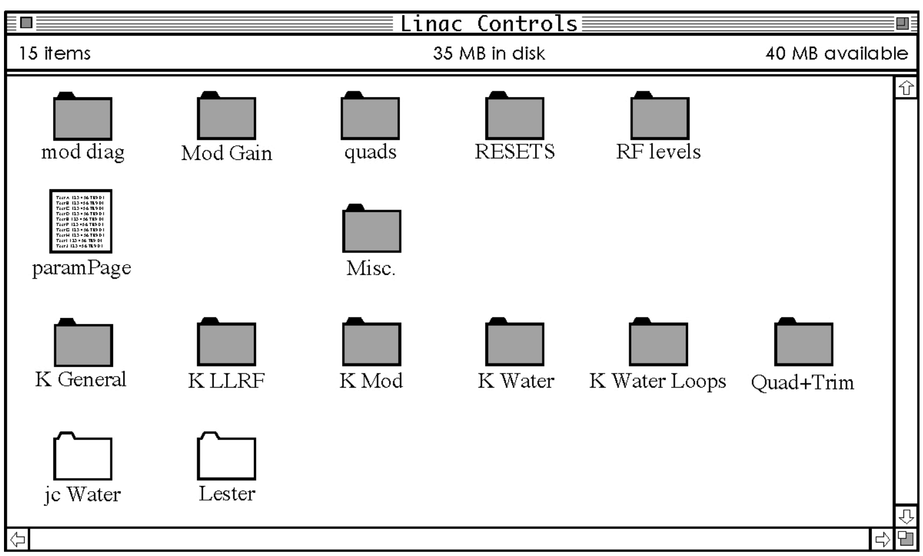


Figure 10.12

For instance, the K General folder (figure 10.13) contains saved parameter pages and plot setups for some of the more commonly monitored devices for Klystron stations 1-7.

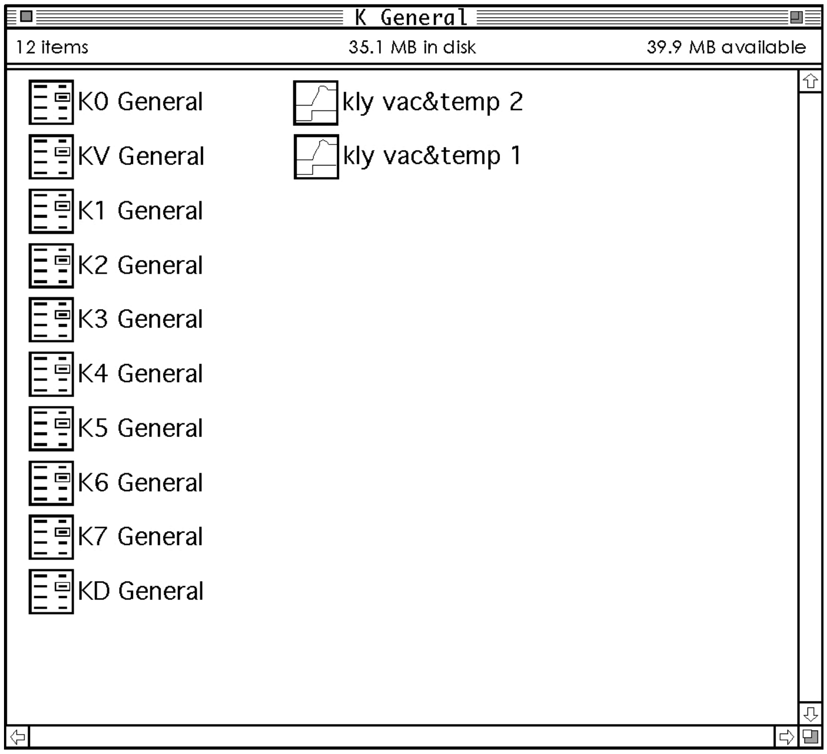


Figure 10.13

Little Consoles

The 'Little Consoles' are mentioned in the general overview of the Linac controls system. Also mentioned is the Macintosh consoles' ability to have the same functionality as the Little Consoles.

To start the Little Console applications there must be a parameter pager application running. You will be able to tell if one is running if there's an 'ERROR LOG' window at the bottom of the screen. If all of the previous conditions exist then doe the following:

1. Go to the 'File' menu at the top of the screen and open it.
2. Select the 'New' item and a new menu will appear.
3. Select 'VME Screen Image.' A window, as in figure 10.14, will appear.

To do settings and change pages you must have settings enabled. Keep in mind that when you change something through this interface you are actually changing things at the 'Little Consoles.' So if someone is standing at the little console and you are changing things on Linac station 1 using the Macintosh console, that person will see the changes as well.

Now that settings are enabled you can manipulate the little console, but first you must type in the node number and click on start. To change screens/pages use the enter key on the numeric keypad. Otherwise the console behaves the same as if you were actually standing at the little console itself.

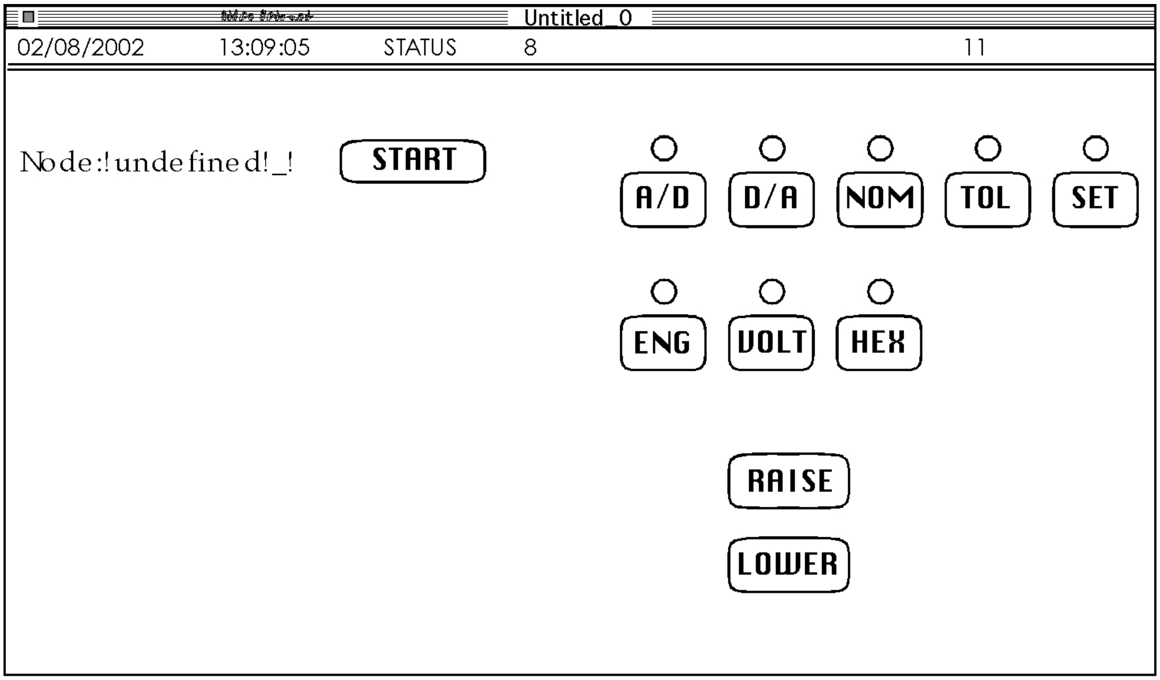

Untitled_0
02/08/2002
13:09:05
STATUS
8
11
Node:!undefined!_!
START
A/D
D/A
NOM
TOL
SET
ENG
VOLT
HEX
RAISE
LOWER

Figure 10.14

Chapter 11, Linac Application Programs

Most Linac tuning is done through ACNET, using consoles in the MCR. An index page, shown in figure 11.1, lists all the applications programs available in March of 2003. Aside from parameter pages, two programs, the LE RF system digital status page on L25 and the 400 MeV steering page on L32, are of the most interest and will be discussed here.

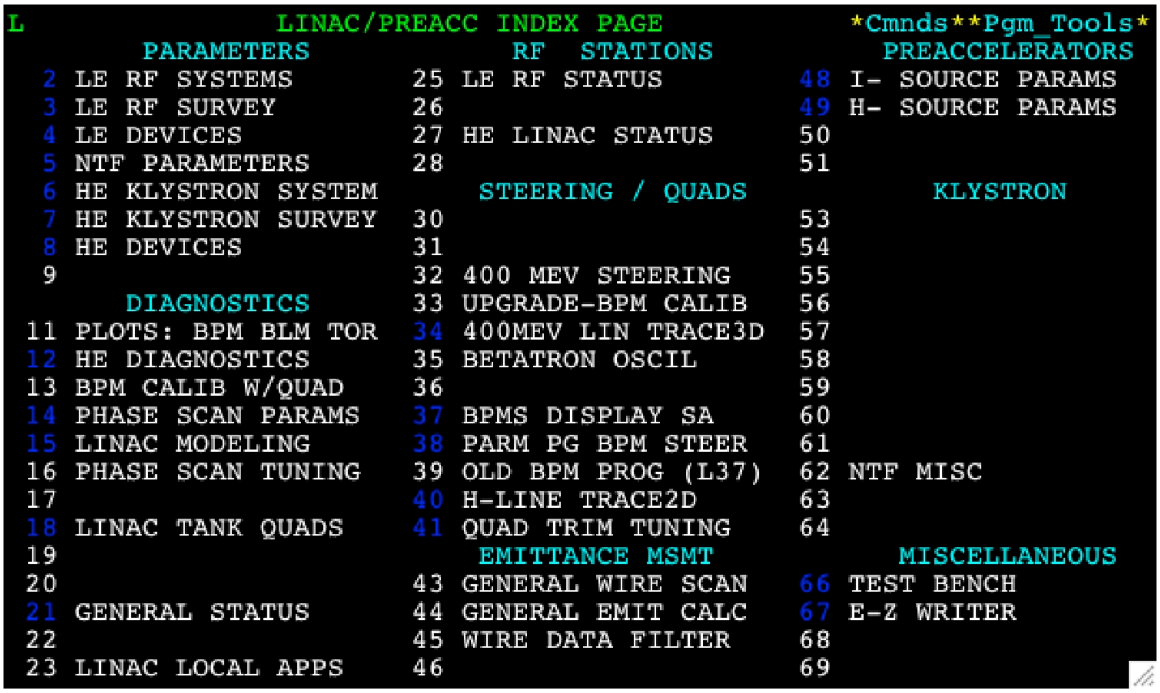


Figure 11.1 Linac Index Page

To display the Linac toroid outputs and losses, including all the beam currents along the Linac, go to Diagnostics, page L11, and display the plot (figure 11.2).

A toroid plot is useful in situations where the Linac beam has disappeared since it shows where beam was last seen. To view the analog readbacks choose parameter page L3 and click on TOROIDS.

L11 also displays the loss monitors from DTL 4 down to the end of the 400 MeV area. (It can also be launched by selecting the FTP of INJ.)

For Linac tuning please review the "Linac Tuning Guide" in chapter 3.

The loss monitors are useful when tuning the straight-ahead dump line for emittance measurements. The readouts for these monitors are available parameter page L3, subpage LOSSES.

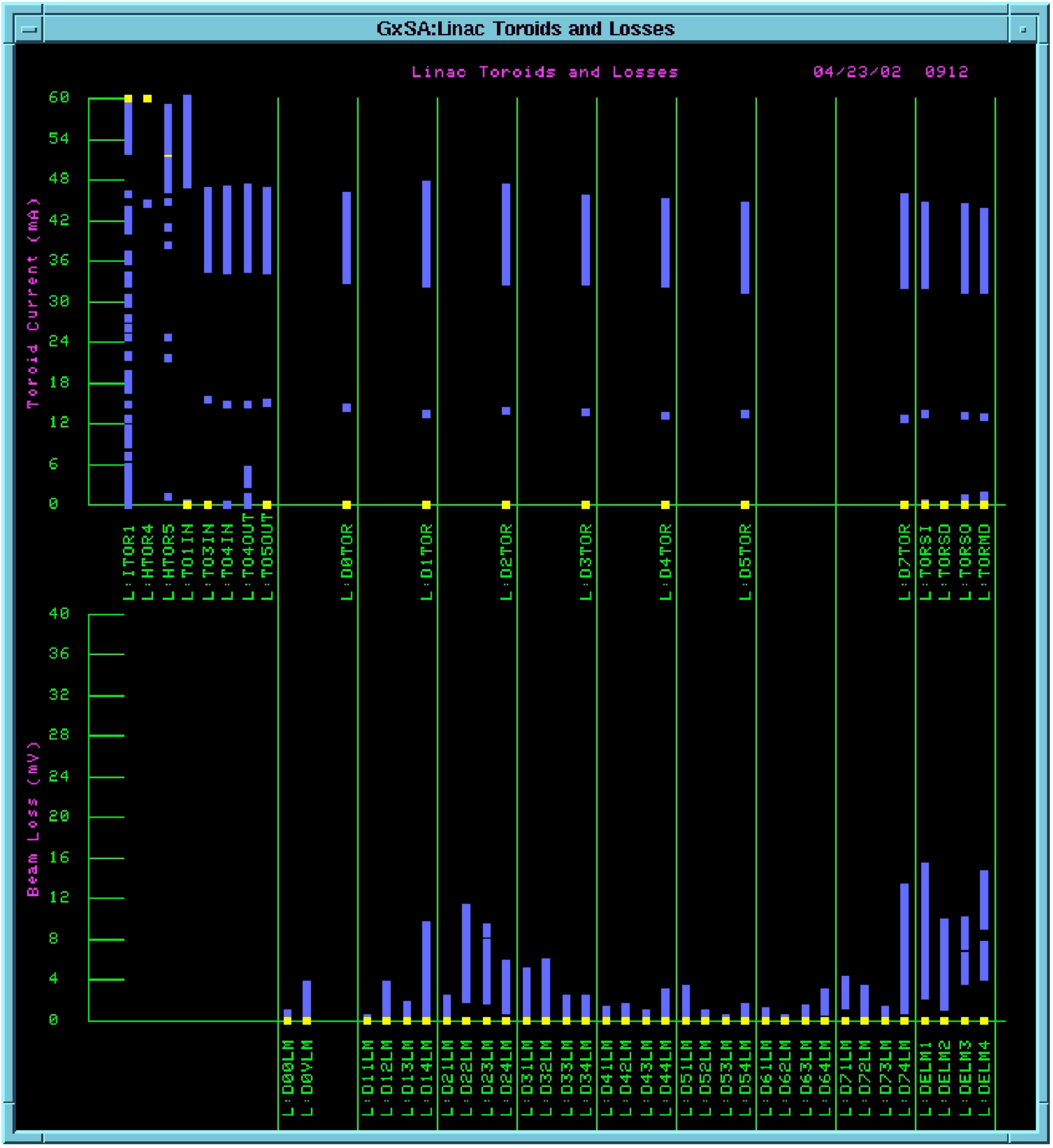


Figure 11.2 Linac Toroids and Losses

L25: Linac RF Status

Digital status bits from the Linac RF systems are displayed in figure 11.3. Good bits are represented as green dots, while the bad bits are red numbers, corresponding to the system cumber. Some bits are controllable through the computer system. These have yellow dashes after their names. These bits are displayed and explained on the next page.

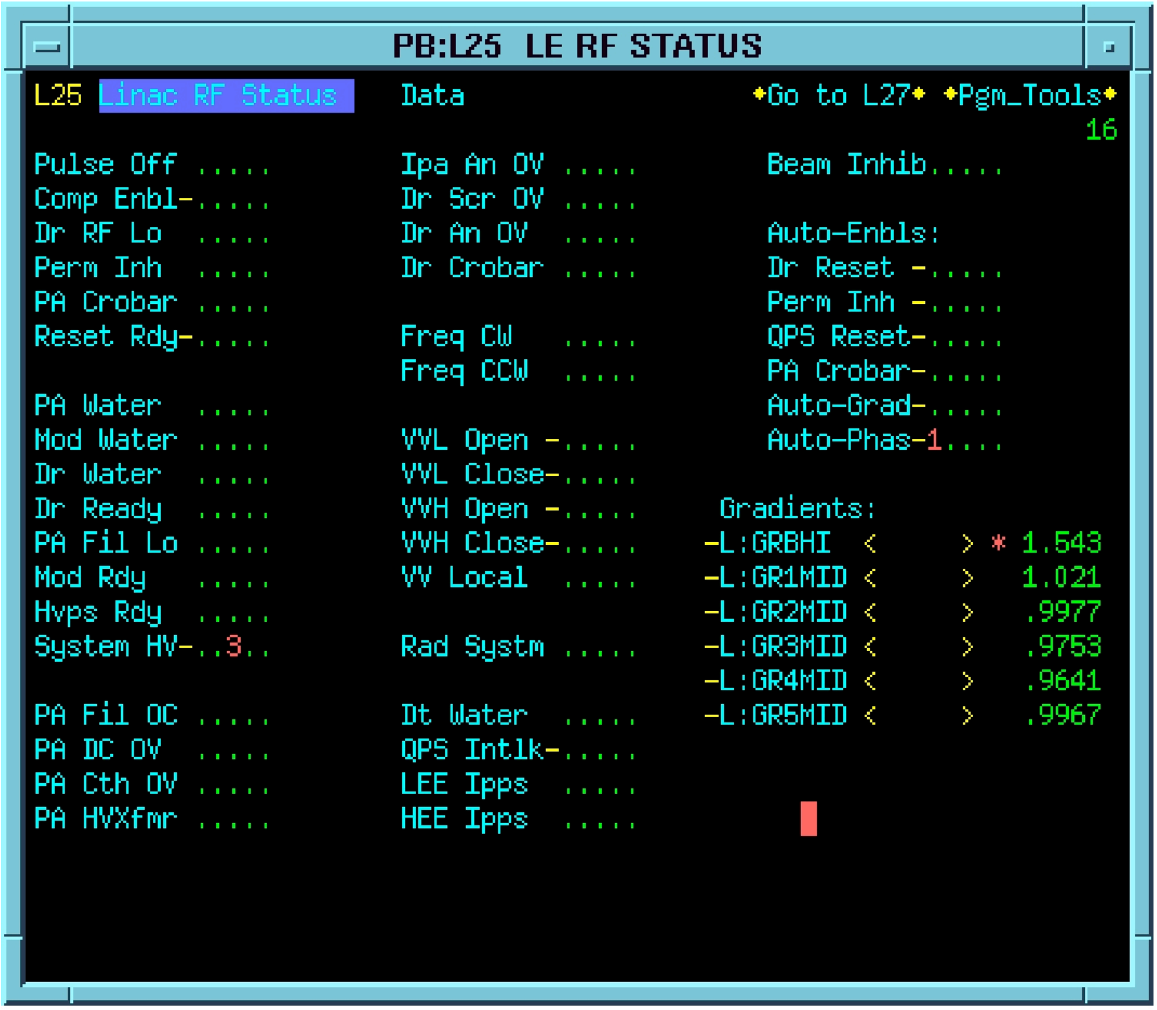


Figure 11.3 Linac RF Status

Comp Enbl	Computer enable. Setting this bit turns the modulator pulse off and inhibits the auto-reset function.
Reset Rdy	Reset Ready. Interrupting on this bit resets the RF station, the same as the blue OVERLOAD button on the A5 console.
System HV	This turns the modulator high-voltage on, the same as the big red button on the A5 console.
VVL Open VVL Close VVH Open VVH Close	Remote control of low- (VVL) and high- (VVH) energy vacuum valves.
QPS Intlk	Quadrupole power supply interlock. Interrupting under this bit sends a reset to all the quad power supplies in that system. This will not reset a blown breaker.

Dr Reset	Driver reset. Setting this bit inhibits the automatic reset of a driver overload.
Perm Inh	Permanent inhibit. The permanent inhibit function includes an automatic reduction of cavity gradient to half value if a reset is not performed within 30 seconds. This is done to keep the RF from being turned on too fast after the cavity has had a chance to cool down. Setting this bit inhibits the gradient reduction function.
QPS Reset	Quadrupole power supply reset. Setting this bit inhibits the automatic reset of quad power supplies in that system.
PA Crowbar	This bit inhibits the automatic reset of a PA crowbar, which includes running the gradient back up to 0.8 volts after the system had reset. For this reason this bit should be set when accesses to the Linac enclosure are made.
Auto-Grad	Automatic gradient regulation. Setting this bit inhibits computer control regulation of gradient levels above 0.8 volts.
Auto-Phas	Automatic intertank phase control. Setting this bit inhibits computer control of RF system phase used to regulate intertank phases to minimum levels. Always disabled for system #1.

An important note: the Auto-Grad and Auto-Phas controls should be inhibited whenever the timer L:DATA is changed from its nominal value of 2000 (or so) μsec. The software that regulates the gradients and phases sample these values at L:DATA time, and chaos will result in L:DATA is not occurring during the RF peak. NEVER change the nominal setting of L:DATA.

L32: Linac Steering

The Linac steering page provides automatic measurement of beam positions at the beginning of the 400 MeV transport line, as well as calculating corrections to the steering trim magnets that will center the beam.

The program has the option of operating under Novice or Expert Level. The program starts up in the Novice Level with the options available on the screen used most frequently. Clicking on the Novice Level will switch to the Expert Level. The Expert Level is not user friendly and (as far as I know) has no restore function. So, if you use it proceed with caution—better yet, leave this to the experts. However, you have two options at this level:

- Enter Calib:
  This allows you to enter calibration values by hand and save them to file.
- Redefine 0's:
  This sets the desired positions to steer to.

In the novice level there are five options you can initiate:

- Restore Dipoles:
  This will set all of the dipoles to the original values that existed before you entered the page.
- Read BPMs:
  This reads the horizontal and vertical beam positions at Q74 (L:D74BPH and L:D74BPV) and at Q2 after the chopper (B:HPQ2

and B:VPQ2). Use trim magnets L:D72TMH, L:D72TMV, and L:D74TMV to position the beam properly on the Lambertson.

- Pulses to Avg=6:
  This is where the user can input the number of pulses to take before displaying data. The current and suggested default is 6. This means the BPMs will average data for 6 *STUDIES* pulses. Set the 15 Hz box, or use the 15 Hz beam switch by each console, to 3 or 5 Hz and then turn on. Remember to turn it off when you are finished.
- Calculate New Dipole Settings:
  This command takes the collected BPM data and calculates trim values which you have the choice of sending or not. The offset value is the amount of the error (the desired position has been subtracted from the BPM reading). Under the heading *CHANGE* are the amounts in amps that the program wants to change the dipole settings. Under the heading *SET* is the value of the new dipole setting. The *Send New Settings* command will send out these settings. If no changes are to be made then the command won't even appear on the screen. The code will automatically change the nominal of the trims so beam is not inhibited. The program will warn the user if the trim setting(s) is/are out of tolerance.
- Check Calibration:
  Calibration numbers are the measured response at a particular BPM due to changing the current at a dipole. In essence, if you plot the BPM reading versus dipole setting and take the slope of this line (usually pretty linear) then you have the calibration number. This needs to be checked if the lattice has been changed in the region where steering is being done. Most likely this would be a change in the quadrupole values Q72, Q73, Q74, or B:Q2.

It should be noted that the trim supplies are small. D/A values of 10 or greater will probably not have the desired effect on the beam positions. If the program cannot center beam without turning a trim on that hard, the 750 keV line should probably be retuned.

Steering should be checked before and after any 750 keV line tuning, before any 400 MeV or Booster tuning, before any momentum scans, and once per shift. You should tune once per shift to forestall the natural tendencies of positions drifting.

Chapter 12, Linac Safety

Personnel hazards associated with the Linac fall into two categories: electrical and radiation. The main electrical hazards in Linac, RF systems and high-voltages, are common throughout the lab and won't be discussed here. However, the radiation hazards posed in Linac are unique due to the construction of the enclosure and the nature of its operation.

Radiation Hazards

Remnant radioactivity, caused by accelerated protons colliding with the Linac structure, is negligible below energies of 10 MeV. There are no significant hazards from radioactivity in the 750 keV line, which may be accessed during Linac operation.

The most active area in terms of remnant radioactivity is the 400 MeV area. The highest rates occur near equipment that intersects the ion beam. The bending magnets and wire scanners are good examples of this. The NTF beamline is also a "hot spot."

The Linac walls are composed of a concrete-soil-concrete sandwich ranging from three feet thick starting at the DTL area to twelve feet thick in the 400 MeV area. In addition, soil is piled on top of the enclosure to form a shielding berm several feet thick. During normal operation, rates outside the Linac enclosure are too small to be measured.

An exception to the above rates is the area downstream of the NTF treatment area in the lower Linac gallery. Dose rates as high as 50-100 mR/hr have been measured there, during NTF patient treatment. A Chipmunk style ionization chamber, permanently installed at this location, monitors the neutrons and γ -rays and warns personnel if rates exceed modest limits.

A second radiation hazard comes from the X-rays produced by the RF gradients in the accelerating cavities. Bremsstrahlung radiation is caused when high-energy electrons like those formed by Haefely power supplies and RF cavities are decelerated by the atomic nuclei in solid objects. RF cavities are particularly adept at producing this radiation, with dose rates as high as 2 R/hr measured at on foot from the cavity. Since most X-rays are formed at 70% of nominal gradient and above, turning the cavity gradients down to 50% of their nominal values and disabling the PA Crowbar bit and the auto gradient bits easily averts the problem. This is standard procedure before performing work near the cavities.

RF system modulators are also a source of X-rays. With proper shielding, normal rates around an operating modulator are less than 0.5 mR/hr. Since much activity occurs around these areas, radiation technicians survey the modulator exteriors every couple of months.

Linac Safety System

The status of the Linac radiation safety system (RSS) is generated and displayed in the Safety System terminal racks in the Main Control Room. The ten controlled access keys that open the gates to the enclosure are also kept in the control room. Removing any of these keys will inhibit the critical devices for the Linac and prevent beam from being accelerated. A critical device failure for any other accelerator enclosure will likewise inhibit Linac critical devices.

The critical devices for Linac are the beam stop (primary) and the gate valve (secondary). There is no electrical safety system, however the RF systems are interlocked. Flashing beacons mounted on the tunnel wall above each tank warn personnel in the tunnel when the gradient is above on and above a certain voltage.

The lack of an electrical safety system means that no electrical devices such as magnets, septa, or kickers get turned off automatically upon access (with two exceptions). Personnel accessing the tunnel must remain aware of its electrical hazards. They must turn off and lock off any device they intend to work on (LOTO). The 58° and 32° power supplies for the NTF line will trip off when the safety system drops, but the above rule still applies (LOTO).

The Linac enclosure had three entrances: two at the upstream end of DTL tank 1 and one in the 400 MeV area. There are 26 penetrations running from the lower Linac gallery into the enclosure, not counting NTF or a four foot by three foot block up hole at the beginning of the beamline. The penetrations are 30" in diameter and carry the transmission lines, power signal cables, and water pipes. Some are shielded with lead (depending on the local neutron flux) and all are covered with metal plates and padlocked.

If it becomes necessary to access a penetration, a single "penetration key" is available from the main safety system in a unique way. When the penetration key is removed, the Linac safety system for that enclosure drops, requiring a search and secure beginning with a special interlock at the downstream end of the lower gallery. This acts as a reminder to make sure all the penetrations are locked.

The special interlock only drops with the removal of a penetration key. A normal search and secure will begin in the usual manner (figure 12.1).

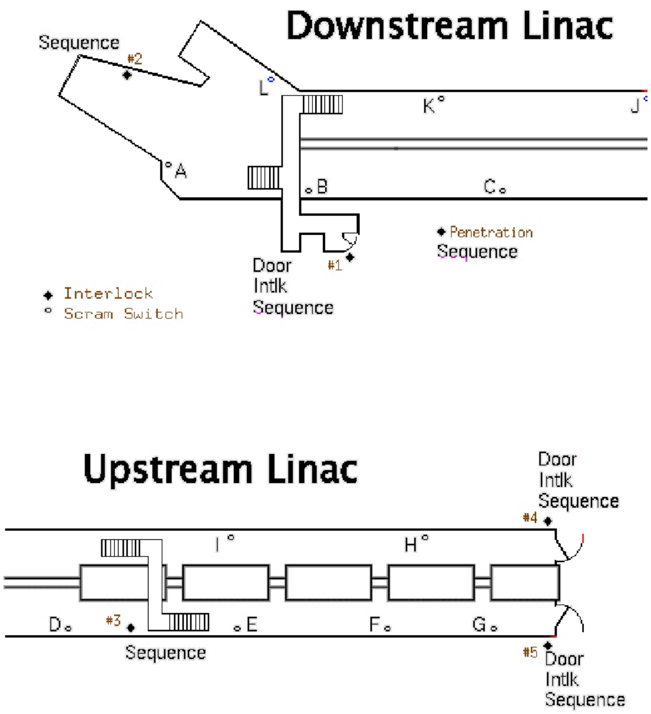


Figure 12.1

Chapter 13, Diagnostic Devices

The Fermilab 400 MeV Linac includes extensive beam diagnostics. These diagnostic devices insure the stability of the accelerator.

Diagnostic Device	Abbr.	Short Description
Beam Position Monitor	BPM	Transverse position of the Beam throughout the Linac
Dipole Trim Magnet	Trim	Correction of the transverse position
Resistive Wall-Current Monitor	RWCM	1. Beam Current Measurement 2. Time of flight, Dt 3. Crude (2 GHz) Bunch length measurements
Bunch Length Detector	BLD	Accurate (300 GHz BW) Bunch length measurement
Toroid	-	There is a single conventional Toroid in Module 7

Table: Beam Diagnostics for the 400 MeV Fermilab Linac

The space between the accelerating sections is consistently $3\beta\lambda/2$. ($3\beta\lambda/2$=55.9cm; $0.457 < \beta < 0.714$ for the Linac, which yields spacing from 25.6 to 39.9 cm.) This spacing is fairly restrictive, particularly in Module 1. The above mentioned diagnostic devices have been designed to take advantage of the limit space between accelerating sections.

Beam Position Monitors (BPM)

The Linac Beam Positions Monitors (BPMs) measure both vertical and horizontal beam positions by measuring the current induced on the pick up plates. Therefore as the beam gets closer to a given plate the amount of charge that is induced increases. Since the instantaneous beam current can also change, it is most accurate to determine the position from either the ratio of the two opposite plates, or the difference/sum of the opposite plates. The BPM RF module accomplishes this. The BPMs are read out through a fast (1 to 5 MHz) digitizer into a dynamic VME Memory. A single reading, representing either the central value of the position or the average value of the position, is the scalar value relayed to the observer in the Main Control Room. The conversion from voltage to an absolute position within the beam pipe is accomplished through linear scaling constants. This is possible because the electrical center is measured to be within a few mils (.001”) of the mechanical center for each of the BPMs. Typically the BPMs are located inside most of the Linac quadruples. The quads that don’t contain a BPM are in Q01, which is before the first transition section cavity (but there is a BPM at the end of the old Linac), Q14, which is the quad following module 1, and Q24.

Trim Magnets

Trims are located throughout the SCC area to correct the trajectory of the ion beam through the accelerator. These iron-core magnets are significantly stronger than air-core magnets of similar dimensions producing a 600 Gauss peak field from five amps of current. This translates to 2.3 milliradians of beam deflection. There are three types of trim magnets and they have been designed to entirely fit into the relevant spaces. The overall lengths are 48 mm, 64 mm, and 89 mm. The Smart Rack Monitor controls these trim magnets. Their analog input is calibrated such that a 10-volt input is equivalent to a 6-amp output.

Wire Scanners

Each wire scanner unit contains three measurement wires:

- A wire for measuring the X beam profile
- A wire for the Y beam profile
- A wire at 45 degrees with respect to X and Y (referred to as the U wire)

The X wire is vertical wire and moves horizontally through the beam. The information obtained from the U wire eliminates the mirror ambiguity from measuring only the orthogonal component of the beam at X and Y. A Paker Compumotor controls the motion of the wire. This motor moves a .004” tungsten wire through the ion beam, which induces a voltage on the wire (due to the loss of electrons from the molecular lattice of the wire). This voltage is brought out to the electronics by conventional RG58 cabling and plugged into the buffer box. The first element in the buffer box is a 15 MHz low-pass filter that removes the 200 MHz noise on the signal. Then the signal is amplified by 20 DB and driven into the sample and hold and digitizer in the control system. The voltage measured from each wire is proportional to the intensity of the beam passing through the wire. As the motor moves the wire through the beam, the amount of beam intercepting the wire changes in proportion to the shape of the beam, thus producing a profile of the beam. This motion is rather slow, about 1 cm per second.

Resistive Wall Current Monitor (RWCM)

A RWCM operates similarly to a BPM: converting the beam induced wall currents into a time sensitive voltage. The RWCM, however, has a ceramic gap directly in the beam pipe that entirely encircles the beam pipe. A series of small resistors line this gap and the voltage across these resistors is measured. The bandwidth of this signal is expected to be a few GHz. A containment vessel encloses the gap to prevent external RF fields from affecting the signal. The outside of the containment vessel has been surrounded by ferrite material. Wire is wound around this ferrite so that beam passing through the ferrite ring induces a magnetic field in the ferrite; the changing magnetic field induces a current in the coiled wire, which is measured to determine the beam current. A small winding of calibration wire is used to determine the absolute calibration of the coil. This toroid signal is patched into a NIM module that buffers and amplifies the toroid signal. Then the signal is fed into a sample and hold chassis, which is triggered at beam time. The fast signal comes out of the tunnel and into the Linac Utilities basement on a large helix type cable. There it is connected to the conventional temperature stabilized 3/8” helix that runs into the Diagnostics Room in the Linac Gallery. The signal from all of the RWCMs and some of the BPMs from the old part of the Linac are distributed among three 8-way switches so that any group of the three signals can be selected to make the Δt type measurement. The common conductor of the switch goes into a sample-and-hold chassis and is then digitized by SRM.

Bunch Length Detector

Because the velocity of the Linac beam is always substantially less than the speed of light, it is not possible to obtain an accurate or a detailed measurement of the bunch length from wall currents. So, you obtain the bunch length by using the secondary electrons liberated from a tungsten wire target in the beam. The negative high voltage on the wire accelerates these electrons, and some of them pass through an RF deflector-Einsel lens. The deflector, oscillating at 4th harmonic of the beam-bunching frequency, sweeps an image of the electron source (the wire) across the back plane of the device. A slit in the center of the back plane selects some of these electrons. An electron multiplier tube amplifies the electrons that pass through the slit. This generates a speedy signal, which is digitized by the control system. The density of the electrons that pass through the slit is therefore proportional to the density of the incident ion beam from a particular RF phase angle.

Notes: