Chapter 1

Ion source



1.1 **RIL Introduction and Overview**

Figure 1.1: Overview of the Pre-Accelerator

The Pre-Accelerator, also known as the RIL¹, consists of four major sections: the Ion source, Low Energy Beam Transport line (LEBT), Radio Frequency Quadrupole (RFQ), and Medium Energy Beam Transport (MEBT)². There are two ion sources, source A and source B, that are kept running; one acts as the operational source, and the other serves as a ready-to-go spare. The operational source can be swapped by closing isolation vacuum valves and turning off turbo vacuum pumps before sliding the source and most of the LEBT over to line up with the rest of the RIL. The overview of the RIL pictured in *Figure 1.1* shows in light blue the slide mechanism that allows for switching between A and B sources; notice that most of the LEBT slides with its respective source. Each source has its own solenoid, vacuum pumps and valves, and horizontal/vertical combination dipole trim packages. Beam leaves the ion source at an energy of

 $^{^1{\}rm RIL}$ stands for "Radio Frequency Quadrupole Injection Line", named as such because the Pre-Accelerator line uses a special RF cavity that also focuses beam transversely.

 $^{^{2}}$ LEBT is pronounced "lebbit" and MEBT is pronounced "mebbit".

35 keV. At the very end of the LEBT sits a pulsed Einzel lens chopper that pushes the low-energy (35 keV) beam back up the LEBT to control the pulse width of beam that enters the RFQ. Beam leaves the LEBT at 35 keV.

The RFQ is a special 201 MHz RF cavity that uses shaped electrodes to modulate the electromagnetic standing wave fields to accomplish transverse focusing, longitudinal focusing (bunching), and acceleration all in one device. Beam leaves the RFQ with a 201 MHz bunch structure and an energy of 750 keV. Finally, the MEBT uses a pair of quadrupole doublets to transversely focus and a small 201 MHz Buncher RF cavity to longitudinally focus the beam. Each MEBT quadrupole magnet also contains a horizontal and vertical trim dipole using extra built-in coils. The end of the MEBT feeds directly into the beginning of the Linac at the entrance to the LRF1 cavity.

1.2 Source body and plasma formation

The Proton source beam originates from a direct-extraction magnetron hydrogen ion source³. Each ion source resides in its own sealed cube. A high-voltage arc ionizes Hydrogen gas into a plasma contained by a uniform magnetic field, which is why it is named "magnetron". The high electric potential between the source body and a grounded electrode cone extracts and accelerates a beam of H⁻ (negative Hydrogen ions) away from the plasma volume. The resulting H⁻ beam continues on to the rest of the RIL. *Figure 1.3* illustrates the basic model of the ion source body.



Figure 1.3: Basic model of magnetron H⁻ source body

A 100-V, 250- μ s voltage pulse flexes a piezoelectric valve to fill with Hydrogen the space between anode and cathode, known as the "race track"; the entire source cube also fills with hydrogen. The arc power supply provides an approximate -250-V, 250- μ s pulse to the anode, striking an arc to the cathode that ionizes the Hydrogen gas and forms a plasma. The molybdenum cathode



Figure 1.2: Basic model of an H⁻ion

³The magnetron ion source was originally conceived at Novosibirsk in 1972 and later adapted for particle accelerators by Brookhaven and Fermi national laboratories.



Figure 1.4: Ion motion and formation in the source plasma

is covered in a 0.6-monolayer coating of cesium⁴ to reduce the energy needed to pull electrons from its surface and into the race track; this energy required to free ions from the cathode surface is known as the "work function". Figure 1.5 shows how the work function of molybdenum changes as a function of cesium coating thickness. The plasma creates energetic particles that strike the cathode surface, liberating surface atoms like H+ ions (i.e., protons) that join the plasma. Some of these protons capture two free electrons from the plasma and become H⁻ negative ions⁵. The external 1 kG magnetic field provided by permanent magnets facilitates ionization by causing electrons to curve through the plasma, increasing their path length from cathode to anode and thus improving the chance of ionizing other particles. This external magnetic field also contains the plasma within the race track. The cathode is dimpled near the circular extraction aperture to help focus the H⁻ beam that leaves the source. Figure 1.4 shows the motion of the different ions in the source plasma.

1.3 Extraction

 H^{-} beam is extracted from the plasma using a cone-shaped electrode, pictured in *Figure 1.6*. The titanium extractor cone is grounded and electrically isolated from the source body with high-voltage standoffs, and the tip of the extractor cone is solid tungsten to reduce the wear due to the impact of ions and damage due to sparking.

To extract H⁻ beam, the extractor power supply pulses both the anode and cathode of the source with a -35 kV 250 μ s pulse to create a high potential difference between the source and the grounded extractor cone. The extractor power supply for each source is located in the lower PreAcc pit. During extraction, there is still a -250 V potential difference between cathode and anode, but the extractor power supply provides a -35 kV offset to both. This situation is pictured in *Figure 1.7*. Thus the electric field formed from the high



Figure 1.5: Coating the molybdenum cathode with cesium reduces the work function, making it easier to generate plasma with the arc

 $^{^4\}mathrm{In}$ other words, about 60% of the cathode surface is covered in a one-atom-thick layer of cesium.

⁵This is only one of many mechanisms by which H⁻ ions are created in the source. This method involves surface interaction of ions, but H⁻ ions can also be formed in the bulk of the plasma. Since the source uses direct extraction to create the beam, it does not and cannot differentiate between ion formation mechanisms and extracts all negative ions.



Figure 1.6: Extraction cone and standoffs to attach to the source body



Figure 1.7: Extractor power supply providing 35 kV offset voltage to anode and cathode

potential difference from source body to grounded extractor cone pulls negative ions out of the plasma and accelerates them to 35 keV. Notice in *Figure 1.7* that the external magnetic field bends the trajectory of extracted electrons away from the rest of the H⁻ beam; this reduces the population of electrons in the extracted beam, as well as reducing the number of electrons that hit the extractor cone and cause a spark (electrostatic breakdown).

!		EXTRAC1	OR SUPPLY			-		
L:BEXTI	в	Source	Extractor	Curr		279.4	mA	
L:BEXTV	в	Source	Extractor	Volts		-35.06	KΥ	
-L:BEXTSV*10	в	Source	Extractor	PS V	35.64	37.81	KΜ	
-L:BEXTON	в	Source	Extractor	ON	1833	1833	uS	
-L:BEXTPW	В	Source	Extractor	Width	225	225	uS	

Figure 1.8: Extractor power supply parameters

1.4 Cesium delivery

The source plasma erodes the cesium coating on the cathode, so it must be continually replaced. cesium is delivered to the ion source cathode with an electrically-heated furnace that consists of a boiler, valve, and tube. The boiler consists of a copper tube that houses a 5-mg glass amuple of cesium; when a new ampule is installed, the boiler tube is closed up and crushed with a c-clamp to release the cesium. Heater tape wrapped around the boiler vaporizes the cesium, and the valve controls the flow of cesium vapor that passes into the source body via the tube. The source body, valve and tube are also wrapped in heater tape to facilitate vapor flow. The constituent parts of the cesium furnace are pictured in *Figure 1.9*.





Figure 1.9: The cesium boiler: a glass ampule of cesium that sits in a copper tube wrapped in heater tape

Figure 1.10: The cesium delivery system consists of a boiler filled with cesium, a needle valve to control flow, and a tube to carry the cesium to the source body

Pictured in *Figure 1.11* are the power supplies for the heater tape wrapped around the boiler, valve, and tube; each element has its own power supply. These supplies reside at the bottom of the source high-voltage rack in the PreAcc pit.



Figure 1.11: Power supplies to heat the cesium boiler, tube, and valve to facilitate delivering cesium vapor to the source

These power supplies do not have remote control ability, so any changes

to the heaters requires turning off the associated source's extractor supply and accessing the high-voltage cabinet. However, there are remote readback parameters for power supply output and temperatures, which are pictured in *Figure 1.12.* source and extractor sparking can cause these supplies to trip, leading to undesirable cooling of the associated component of the cesium delivery system. It is important to notice when one of the temperatures begins to fall and to quickly access the cabinet to reset the supply, typically by pushing the "OUT" button on the far right of the supply so the green output LED lights up. This will prevent the source plasma from suffering due to lack of cesium, which can take hours to properly recover.

!	50L	JRCE TEM	MPS AND HEATER SUPPLIES		
L:BCTEMP	в	Source	Cathode Temp	414.8	Deg
L:BSTEMP	в	Source	Source Temp	173.9	Deg
L:BTTEMP	в	Source	Tube Temp	235.6	Deg
L:BVTEMP	в	Source	Valve Temp	207.2	Deg
L:BBTEMP	в	Source	Cs Boiler Temp	127.2	Deg
L:BRACKT	в	Source	HV Rack Temp	31.69	Deg
L:BSRCI	в	Source	Source Heater	1,176	Ĥ
L:BBOILI	в	Source	Boiler Heater	.413	A
L:BTUBEI	в	Source	Tube Heater	29,53	Ĥ
L:BVLVI	в	Source	Valve Heater	1,791	Ĥ

Figure 1.12: Boiler, valve, tube, source heater parameters



Figure 1.13: Outline of vacuum equipment for source A; source B is identical

1.5 Source vacuum

The overall layout of the source A vacuum system is pictured in *Figure 1.13*, and source B is identical. Each source cube has its own 1200 L/s turbo-molecular vacuum pump to keep the cube pressure around 6-8 microTorr. Each turbo pump is connected to a scroll roughing pump by a roughing line and isolation valve, and the pressures at the turbo and scroll pumps are monitored by their own convection gauges. The source cube itself has a convection gauge for higher pressure measurement and an ion gauge for lower-pressure operational measurements; note that this is a measurement of the pressure in the entire cube that houses the source, and is thus only an estimate of the pressure in the extraction gap or between anode and cathode.

If the cube pressure becomes too high, the ion gauge will turn itself off, the turbo will spin down, and the turbo isolation valve will close. Manual recovery of the cube vacuum requires verification that the scroll pump is on and reading pressures in the μ Torr level. Then the turbo can be turned on and the isolation valve opened to allow the turbo to pump down while it accelerates to full speed (about 37000 RPM). At high pressure, only the source cube convection gauge will provide accurate pressure readback; when the cube pressure becomes low enough, the ion gauge will turn itself back on automatically and provide accurate readings.

1.6 Source operation and tuning

Each source has a high-voltage rack that contains its Hotlink Rack Monitor (HRM), arc supply and modulator, temperature readbacks, gas valve controller, arc oscilliscope, and heater power supplies. The entire rack and everything in it is pulsed to -35 kV by the extractor supply. *Figure 1.14* shows the cabinet for source B^6 . Both source cabinets are in the upstairs portion of the PreAcc pit next to the sources themselves. Access to these cabinets requires switching and locking off the extractor power supply and grounding out the rack.

The health of the source arc can be monitored via the source arc scope, which is located in the high-voltage rack but can be viewed remotely using either ACNET program D8 or CATV channels. Pictured at the top of *Figure 1.15*, the arc scope plots the arc current (dark blue) and the arc voltage (light blue) throughout the entire pulse. Excessive noise or upward/downward angles on the arc current indicate a problem that is likely related to too much or too little gas.

Pictured on the bottom of *Figure 1.15*, the extractor scope or "ground scope" shows the extraction of beam out of the source. The light blue trace is the extractor voltage, and the green trace is the extractor current. The dark blue trace shows the beam intensity on the source toroid (either *L:ATOR* or L:BTOR), and the purple trace is the beam intensity on the toroid L:TO1IN at the input of the Linac LRF1 tank.

Stable operation of the ion source requires a delicate balance between gas pressure, arc impedance (voltage/current) and the amount of cesium coating the cathode. Two main symptoms can occur if a source is operating improperly: either the source or extractor will repeatedly spark, or the arc current and beam output will deviate from operational values.

While there is no directly prescriptive method for tuning the ion source, operators can help with source stability by datalogging recent trends and comparing them to periods of stable operation. For example, if the arc current begins dropping, the operator could datalog the arc impedance and gas pressure; if the pressure on the ion gauge has recently changed along with the arc impedance, adjusting the gas pressure to reverse the trend may help bring the arc current back. Similarly, excessive noise or tilt on the arc current scope trace can indicate that the gas pressure needs to change. Occasionally, arc supply voltage changes need to occur as well, but the situations that warrant this require trial and error experience and consultation with PreAcc experts. Adjusting the cesium delivery to the cathode requires accessing the high-voltage cabinet to change the output settings for the heater supplies. This is only done by or in consultation with PreAcc experts. They can also adjust the cesium valve itself, which is necessary for much larger changes in cesium delivery.

To control the gas pressure in the source, operators and experts use parameters pictured in *Figure 1.16*: we change the gas pressure primarily by changing L:BGASOF, effectively changing the amount of time that the valve pulses to let gas into the source. L:BGASON determines when the pulse starts, but is not



Figure 1.14: The B source high-voltage cabinet



Figure 1.15: source arc scope (top) and extractor scope (left) showing normal operation

⁶The source A cabinet is nearly identical, but the HRM has been moved out of the cabinet to the PreAcc control room. In its place in the high-voltage cabinet are fiber-optic repeaters that communicate with the HRM; this was necessary to alleviate damage to the HRM from excessive extractor sparking, and may be a future upgrade for source B as well.

used when simply adjusting the gas pressure. L:BGASV is the voltage applied to the piezoelectric valve during the pulse. L:BGASO is the DC offset on the voltage pulse for the valve, and is occasionally set to a negative value to force a leaky valve to fully close when not pulsed. Two vacuum gauges measure the pressure as close to the source as possible, but keep in mind that they only provide an estimate: L:BIG is an ion gauge for low pressure readings, and L:BCG is a convection gauge for higher pressure readings.

!			GAS VAL	-VE -						
-L:E	BGASV	В	Source	Gas	Valve	Volts	109	140	\vee	
-L:E	BGASO	в	Source	Gas	Valve	Ofset	0	10	\vee	
-L:E	BGASON	в	Source	Gas	Valve	ON	800	800	uS	Ο.
-L:E	BGASOF	В	Source	Gas	Valve	OFF	897	897	uS	
L:E	BGASPW	Ĥ	Source	Gas	Pulse	Width		97	uS	
L:E	BIG	Sr	rcB Ion	Gauş	<u>i</u> e			6.919E-06	TOR	
L:E	BLCC	Sr	CB LEBT	r Col	ld Cat	Ga		3.614E-06	TOR	



Figure 1.17: The Paschen curve shows the relationship between breakdown potential and p*d, the gas pressure multiplied by the distance of the extraction gap

I	ARC SUPP	IY		
i papaou	070 5	057		
-L:BARCSV	-279.6	-257	V	
L:BARCV		180.1	V	
L:BARCI		17.78	Ĥ	
L:BARCZ		10.22	ohm	
-L:BARCON	1833	1833	uS	
-L:BARCPW	230	230	uS	

Figure 1.18: Arc supply parameters

Figure	1.16:	Gas	valve	parameters.
		~~~~		por orrection.

If the hydrogen pressure becomes too high in the source, it will increase the probability that H⁻ ions will interact with other ions in the plasma and lose their electrons. This is known as "H⁻ stripping" and both reduces the H⁻ yield and increases the population of free electrons in the plasma. These excess electrons can lead to extractor sparking if they hit the cone when leaving the plasma. Each source has a parameter that estimates the ratio of electrons to H⁻ ions: L:ARAT for source A and L:BRAT for source B.

If the gas pressure becomes too low, the source may spark from anode to extractor because the electrostatic breakdown potential changes as a function of pressure. This relationship between breakdown potential and gas pressure is known as the Paschen curve, and is pictured in *Figure 1.17*. Note that the breakdown potential changes depending on which side of the curve's dip the source is operating; sometimes a lower pressure may help with sparking, but otherwise it may increase sparking. For this reason, the distance between the anode and extractor and the gas pressure in the source must be carefully controlled.

Figure 1.18 shows the relevant parameters for controlling the source arc supply. Again, source B is shown, but the naming convention is identical for source A. The power supply voltage L:BARCSV can be adjusted to tune the source for stability, but is typically considered after adjustments to the gas pressure. Notice that the actual arc voltage is lower than the arc supply voltage; this is due to the intrinsic impedance of the plasma as measured by L:BARCZ. PreAcc experts typically advise operators on the amount of arc current a particular source needs to run, and adjustments to the act supply voltage and gas pressure serve to keep the arc current stable at the desired level. More arc current is not always better, as the source output beam tends to have higher emittance at higher arc currents. As with most of the ion source, careful balance of operating parameters is necessary for stable beam delivery.

Chapter 2

Low-Energy Beam Transport (LEBT)

2.1 LEBT Overview

The Low-Energy Beam Transport (LEBT) is a 1.2m-long beamline that connects the output of the ion source to the input of the RFQ. The LEBT focuses the high-emittance 35 keV beam to match the transverse characteristics of the beam required by the RFQ. A basic overview of the LEBT layout is pictured in *Figure 2.1*.

Each source has its own part of the LEBT that travels with it on the slide mechanism that includes two horizontal/vertical trim magnet packages, one solenoid, and a beam valve. So named after their constituent sources, the beam valves L:ALVV and L:BLVV isolate the movable upstream section of the LEBT when we need to switch operational sources. In the stationary portion of the LEBT downstream of ALVV or BLVV resides one of the Linac critical devices, a beam valve named L:LVV that both isolates the downstream RIL from the source sections and acts as a beam stop.

After the critical device is another horizontal/vertical trim magnet package, followed by the second solenoid L:LSOL. Finally, an Einzel lens chopper at the end of the LEBT either prevents beam transport to the RFQ by pushing it back upstream or allows beam through when the lens is grounded.

Because of the low-energy, high-intensity nature of the beam in the LEBT, the mutual electromagnetic repulsion between beam particles is the dominant cause of high emittance; this force is known as the "space charge force". The LEBT vacuum pressure is kept deliberately higher than the rest of the RIL, because partial de-ionization of the H⁻ beam reduces the effective space charge and thus helps prevent excessive emittance increase. Emittance control in the LEBT is vital to match the acceptance of the RFQ and provide high beam throughput to the Linac.



Figure 2.1: Basic overview of the LEBT



Figure 2.2: Optics simulation of LEBT solenoids showing X and Y beam envelopes

2.2 Solenoids

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The LEBT solenoid magnets generate a field of approximately 3000-4000 gauss from a current of about 400-500 A and have a focal length of about 20 cm. The fringe fields of the solenoids transversely focus the high-emittance beam from the ion source into the aperture of the RFQ at the end of the LEBT. These solenoids are shown before installation in *Figure 2.3*.



Figure 2.3: LEBT solenoids before installation

A simulation of the optics for the two-solenoid LEBT is pictured in *Figure 2.2* and shows how the transverse beam envelope changes throughout the LEBT: the horizontal and vertical beam envelopes are symmetrically-large through the LEBT, but focus down in both planes at the entrance of the RFQ.

Beam measurements have shown that there is a small horizontal offset in both position and angle at different solenoid currents, but this slight steering can be corrected by the corrector magnet packages in the LEBT. This gives some clue to a productive tuning strategy for the LEBT: adjust the two solenoid currents to maximize beam to the RFQ, then go back and adjust the corrector magnets to compensate for the steering effect of the solenoids and put the beam back in the center of the aperture.

2.3 Corrector magnets

The LEBT contains three horizontal/vertical corrector magnet packages. Each device contains coils for a horizontal and vertical dipole in the same space, as pictured in *Figure 2.4*. The trim packages are cooled by aluminium heat sinks with small fans to increase air flow.

The LEBT trims correct for steering deviations (position and angle) due to the solenoid fields. Therefore, it is a good idea when tuning the LEBT to adjust the focusing with the solenoids first, then go back and compensate with the trims to move the beam back into the center of the LEBT.



Figure 2.4: A LEBT corrector horizontal and vertical dipole corrector magnet package

2.4 Vacuum and space-charge neutralization

An overview of the LEBT vacuum system is shown in *Figure 2.5.* Each source line has its own vacuum valve, L:ALVV or L:BLVV, and there is a valve in the stationary end of the LEBT called L:LVV. L:LVV also acts as a beam stop and is one of the two critical devices for the Linac. The primary gas load in the LEBT is residual hydrogen from the source cube which is removed by uses two 470 L/S turbo vacuum pumps sharing the same roughing scroll pump with isolation valves for each turbo.

The operational vacuum pressure of the LEBT is around 5 μ Torr, which is roughly a factor of 10 higher than the RFQ and MEBT. This deliberate spoiling of the LEBT vacuum serves to partially cancel out the space charge of the beam, reducing emittance growth due to electromagnetic repulsion. This process is called "gas focusing" or "space-charge neutralization", and uses residual hydrogen gas in the LEBT to strip electrons from some of the H⁻ beam. By converting some H⁻ to H⁺, the net space charge is reduced, so the net repulsive force goes down as positive ions attract negative ions. While the amount of H- particles is reduced due to stripping, the emittance improvement from gas focusing improves the amount of beam through the RFQ enough to make up for it. Portrayed in *Figure 2.6*, this effect provides substantial benefits to beam efficiency and greatly increases the intensity that the RIL can provide.





Figure 2.6: Electron stripping from residual hydrogen gas partially reduces the space charge force



Figure 2.5: An overview of LEBT vacuum

2.5 Einzel lens chopper

The chopper for the LEBT controls the pulse width of beam sent into Linac, which is based on the requested intensity (i.e. number of Booster turns) for a particular HEP event. The LEBT uses an Einzel lens instead of a parallel-plate chopper, because the latter can reverse the effect of space-charge neutralization by sweeping ions out of the H⁻ beam. The Einzel lens, pictured in *Figure 2.7*, chops beam by pushing it back up the LEBT with a strong electric field. *Figure 2.8* shows the lens electric potential lines when blocking beam and when allowing beam through to the RFQ. Notice that when the Einzel lens allows beam through, it is focused at the RFQ entrance; this is due to the upstream LEBT solenoid optics.



Figure 2.7: The Einzel lens before installation in the LEBT

To block beam, the Einzel lens must be pulsed at a negative voltage higher than the beam kinetic energy; in practice, this ends up being about -38 kV. Some beam can leak through the lens if the voltage is not sufficiently higher than the extractor voltage (and therefore the beam kinetic energy). To allow beam through, the Einzel lens is simply grounded. A basic representation of the circuit for switching the Einzel lens on and off is shown in the left of *Figure 2.9.* The switches are banks of isolated-gate bipolar transistors (IGBTs) that change state to either power or ground the lens, and are pictured in the right of *Figure 2.9.* To chop beam by powering the lens, SW1 is closed and SW2 is open; to ground the lens and allow beam through, SW1 is open and SW2 is closed.



Figure 2.9: Einzel lens switching schematic left, actual IGBT switches on the right



Einzel lens ON at -38 kV



Figure 2.8: A simulation showing the electric potential lines when the lens is at high voltage, pushing beam back

Chapter 3

Controls and power supplies

Solenoid and Quad supplies here

The solenoid power supplies are controller by a PC-104 processor card that provides status, control and regulation for up to four DC power supplies over a single ethernet connection. The PC-104 controller also provides ACNET plotting data and has a built-in transient recorder for both analog and digital signals. The controller uses a PLC to manage control of the 480 VAC power supply contactors and shifting of 24 VDC power supply signals signal to TTL levels for use in the PC-104; these signals include power supply door switches, electrical safety system permit, klixons for temperature monitoring, and overcurrent monitoring. The PC-104 controllers communicate directly to ACNET via ethernet.



Figure 3.1: Solenoid power supply for LSOL (left), PC-104 controller and PLC for solenoids (right)

Re-take solenoid power supply picture to be more head-on and square.