Chapter 13. H^- Source and Linac Improvements

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13.1. Introduction

The present Linac configuration consists of two 750-keV Cockcroft-Walton preaccelerators connected to a Drift-Tube Linac (DTL) through a Low Energy Beam Transport (LEBT) system. The LEBT contains an rf buncher that enables about 70 percent of the dc beam pulse to be captured in the rf bucket of the Linac. The Drift-Tube Linac accelerates the beam to 116 MeV where it is transferred through a transition section into a Side-Coupled Linac (SCL). The SCL accelerates the beam to 400 MeV.

The Fermilab Linac achieved its first 200-MeV proton beam in 1970. Shortly thereafter it ran consistently at a 15-Hz repetition rate providing 100 mA of beam current at the optimum pulse length required for injection into the Booster. In 1976 the Linac began supplying protons for the Neutron Therapy Facility, and the beam pulse length was increased to about 60 μs.

In 1978 the Linac was converted to H^- operation with an additional Cockcroft-Walton preaccelerator to provide redundancy when H^- ion-source changes became necessary. Stripper-injection into the Booster Accelerator resulted in improved injection efficiency and permitted the beam pulse length to be adjusted to achieve maximum injected intensity. The reduced beam intensity in the Linac resulted in a higher quality beam and less beam loss along the Linac.

To reduce the beam emittance degradation in the Booster due to tune spread caused by space charge and small errors in the magnetic guide field, it was decided to increase the energy of the Linac. After the replacement of the last four Linac drift-tube tanks with more efficient side-coupled cavities operating at a higher gradient, the energy of the Linac was increased to 400 MeV. In 1993, 400-MeV beam was achieved. Presently the Linac produces an output intensity of about 47 mA with a 30 μs pulse length resulting in an intensity of 8.5×10^{12} protons per pulse. To achieve the required 3×10^{13} protons per pulse desired in the Proton Driver, beam current and pulse length must be increased.

In 1999 an experiment was performed to determine the high current capability of the side-coupled Linac structure that accelerates the beam from 116 to 400 MeV. [1] The ion-source, preaccelerator and drift-tube Linac sections were restored to the proton mode of acceleration. It was determined that a beam of 86 mA at a pulse length of 90 μs could be accelerated to 400 MeV thereby confirming the capability of the side-coupled structure to accelerate beams of the required magnitude. However, at the highest beam intensities difficulties arose with increased beam loss. An improvement in the beam quality at the highest intensities would be necessary to minimize the beam loss and the induced radioactivity in the accelerator components.

Table 13.1 shows a consistent set of measurements of the beam emittance as a function of energy along the Linac at a beam intensity of 30 mA. (At the nominal 47 mA intensity the emittances would be somewhat larger.) The data show that considerable emittance growth occurs below 10 MeV. This dilution has been studied and it is generally due to: i) non-linear space charge forces in the beam in the LEBT, ii) coupling of the betatron and longitudinal motion, iii) phase space mismatch to the input of Tank 1, and iv) quadrupole misalignments in Tank 1. Considerable effort has been expended in the last thirty years in the accelerator field in understanding the problems of emittance dilution and in producing H^- beams of higher brightness. It is proposed to improve the system below 10 MeV by rebuilding this section, taking full advantage of the latest technology.

Table 13.1. Emittance for H^- Beams

	Preacc Out	Linac In	Tank1 Out	Linac Out
Energy (MeV)	0.75	0.75	10	400
Intensity (mA)	54	49	33	30
Emittance / π (mm-mrad, 95%, norm.)	1.3	2.6	5.2	7.8

It is expected that by improving the Linac front end to achieve a brighter beam of greater intensity and smaller emittance, it will be possible to retune the rest of the Linac above 10 MeV to transmit the beam without increasing beam loss along the Linac. This improvement will have little impact on the passive shielding of the Linac. In fact, since the areas adjacent to the Linac enclosure are protected by interlocked detectors, increasing intensity even at a continuous 15 Hz rate would not present problems with regards to prompt radiation fields outside of the Linac enclosure. Thus it is expected that the Linac can deliver the requested intensity without increasing beam loss that would compromise the shielding or the maintenance of components in the Linac.

The possibility of increasing the Linac pulse length or the Linac repetition rate to achieve the desired intensity in the Proton Driver has been considered. The beam pulse length is primarily limited in the Side Coupled Linac to 90 μs by the cooling in the accelerating cavities and by increased sparking at longer pulse lengths. A redesign of the accelerating cavities and the klystron rf systems would be required to overcome this limit. To increase the repetition rate above 15 Hz would require the entire Linac to be rebuilt.

13.2. General Description of Linac Low Energy Improvements

It is proposed that the entire low energy end of the Linac be replaced incorporating the latest technology and new possibilities. This redesigned low energy section is based on two RFQ's [2] and a new Tank 1. With a new H^- source a more intense brighter beam is possible, reducing losses and producing a better beam for the Booster. The proposed system is shown in the isometric sketch in Figure 13.1.

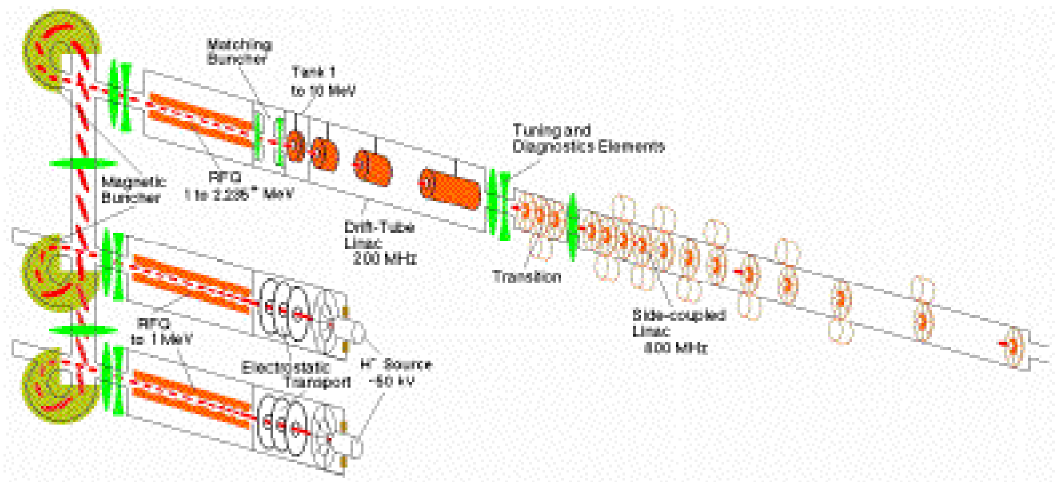

Figure 13.1. Sketch of the proposed low-energy improvements

13.2.1. Ion Source

Replacing the Cockcroft-Walton with an RFQ opens the possibility of improving the present H^- Magnetron ion source or considering other H^- sources to achieve the desired beam intensity and quality. Development of negative ion sources for accelerators has been reviewed by Peters [3-5] and in the book by Zhang.[6] First versions of the Surface-Plasma Sources (SPS) developed for charge-exchange injection of protons have operated at an intensity of approximately 50 mA in pulses of 0.05 - 1 ms with a repetition rate up to 50 Hz. H^- beam parameters of these SPS sources have been sufficient for normal operation of high-energy accelerator systems for the last twenty-five years without significant modernization of the ion sources. For the Proton Driver Project an increase in beam intensity and brightness is required. It is completely feasible to upgrade the SPS source for the required intensity, duty factor and beam quality without sacrificing the reliability and availability from its proven past performance.

The Fermilab Magnetron SPS has been operated since 1978. It produces a peak current of H^- ions, as measured at 750 keV, of 65 mA with an extraction voltage of 20 kV at a pulse length of 0.075 ms. 70 mA is possible at an extraction voltage of 25 kV. The emittance (brightness) of the source can be improved by optimizing the discharge geometry, gas injection extractor and plasma overneutralization. It is deemed possible to achieve a current of 85 mA of H^- beam with a reduction of the emittance by a factor of two, to 0.5 π mm-mrad (90%, norm.).

To significantly improve the brightness it is necessary to eliminate discharge noise. Development of noiseless Semi-Planotron sources and their adoption for injection into the RFQ will permit a beam of up to 110 mA of H^- with an emittance of 0.7 π mm-mrad (90%, norm.). For producing a beam of the highest brightness it is possible to use a

Surface-Plasma source with a Penning discharge, also known as the Dudnikov-type source. Fig. 13.2 demonstrates the production of a noiseless discharge by the small addition of N_2. A transition from a noiseless discharge to a noisy mode of operation decreased the brightness by 10 times or more.

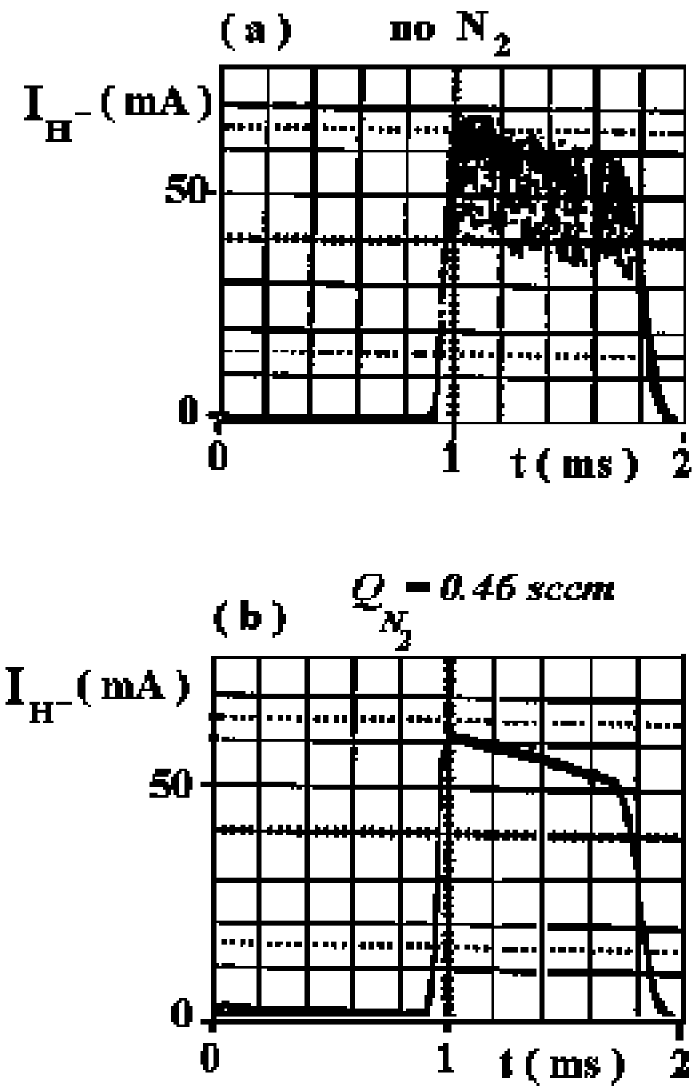

Figure 13.2. Production of noiseless discharge by a small admixture of nitrogen

The DESY rf type volume source is a possible alternative. It uses an rf coil outside a ceramic plasma chamber. Because of size it is not reasonable to fit this or many other types of H^- sources into the present pre-accelerator. The DESY ion source is reputed to have higher brightness, higher reliability and easier maintenance. A source of this type was run without cesium for 2800 hrs producing 40 mA with a duty factor of 0.05% and a pulse length of 100 μsec without any observed degradation in performance. A small injection of cesium and adjustment in the extraction system could well give the desired intensity of 115 mA. A 50 keV extraction voltage from the ion source is proposed for extracting sufficient current from the source and allowing for a short electrostatic focusing structure. This closely couples the source to the following RFQ. The increased energy of the H^- ions allows easier injection and greater transmission through the RFQ.

13.2.2. Radio-Frequency Quadrupole Accelerator (RFQ) and Medium Energy Beam Transport (MEBT)

A 201-MHz RFQ with an energy from 50 keV to 2.23 MeV could be proposed for the Linac pre-accelerator. However, there are good reasons to consider dividing the RFQ into two sections. Until recently dividing an RFQ into a number of sections was considered unreasonable due to the difficulty of matching the beam between the sections. In the PET Project [7] the difficulty was overcome by using a magnetic five-dimensional phase-space imaging system. In this system all particles take the same time to pass through the transport line, independent of energy or transverse size and angle, so the transverse and longitudinal motions are uncoupled at the entrance to the second RFQ section. It is proposed to use a similar system. This will be referred to as the double alpha system or the medium energy transport system (MEBT). An R&D program is proposed to insure the calculated performance of this system can be achieved.

13.2.3. RFQ-2

It is proposed to separate the RFQ so that the first section will have an input energy of 50 keV and an output energy of 1 MeV. This RFQ will be followed by the double alpha transport line consisting of two 270^o bending magnets and five quadrupoles. The isochronous line will transport the beam to a second RFQ. The second RFQ will accelerate the beam from 1 MeV to 2.235 MeV or higher. The question of the output energy of the first RFQ will be studied in greater detail as system design progresses.

Although the question of dividing the RFQ into two sections rather than a full length RFQ will be studied in more detail as design studies are undertaken, some of the virtues of a split RFQ are the following:

i) It is highly desirable to have a second ion source for standby operation. This is even more urgent when high intensity beams from a cesiated ion source are required. The second source could be a replica of the first source. It would include a second low energy RFQ section and the first part of an isochronous line to feed into the second part of the isochronous system with the addition of 4 quadrupoles and one additional 270^o bending magnet. (See Fig. 13.1).

ii) A single section RFQ operating at 201 MHz is long. This exacerbates the difficulty of achieving the required tolerances and results in a small separation of the dipole modes without the addition of coupling devices. Detailed design studies are required to assess the extra complication resulting from the extra length. The extra complication results in an increased cost for the structure.

iii) The double alpha system allows beam diagnostic and beam chopping devices to be added at an intermediate energy.

iv) The double alpha system can be tuned to accommodate different beam intensities.

v) The first short section of the RFQ can be readily replaced if contamination (cesium) or sparking cause difficulties or require vane replacement.

vi) A long RFQ requires a larger rf system to excite the structure. There is an advantage in designing a shorter length that can be powered by the same size rf system that is currently being used in the other Linac systems.

13.2.4. Matching Section

The beam from the RFQ must be matched to the DTL acceptance for the design current in all three planes. There are at least two ways to match the beam to the DTL. The first consists of three quadrupoles and one rf gap or buncher. The virtue of this arrangement is that the elements are tunable which is desirable to accommodate a range of beam intensities. It also allows space for the insertion of beam diagnostic equipment. A second method requires four more RFQ cells at the end of the RFQ and a half-length quadrupole in the DTL. It may be desirable to use a combination of these two methods.

13.2.5. Chopper

Separating the sections of the RFQ with the double alpha MEBT allows the insertion of a chopper in the system. The electrostatic Einzel lens following the source extraction gap can be segmented and excited with a pulsed voltage to deflect a portion of the beam pulse from the acceptance of the first RFQ. However, further chopping of the beam pulse will be required to: a) create a 7-bucket notch at the injection revolution frequency (300 kHz) for reducing beam loss at extraction, b) for antiproton production to create a 42-bucket gap at the injection revolution frequency in order to fit the bunch train to the circumference of the Accumulator (both for Stage 1 at h = 126), and c) reduce injection losses in the Booster by chopping 30% of the Linac beam at the injection rf frequency (5.4 MHz) for rf capture (Stage 2 at h = 18). Choppers that have been considered are:

(a) An rf cavity type using a Finemet wound core [8,9] placed close to the second RFQ section. Since the RFQ has a small energy acceptance, a $\pm 10\%$ energy error in a beam before it enters the RFQ can effectively cut the transmission efficiency down to zero. A prototype chopper with power supply has been designed and built. It is now installed in the transport line before the Linac at the HIMAC (Japan) for testing and is part of the US-Japan collaboration.

(b) Deflecting electrodes. If the last Einzel lens in the LEBT is segmented and a pulsed voltage is used to excite a pair of the segments, the beam from the source can be deflected enough to fall outside of the acceptance of the RFQ. LBL has designed and built a prototype chopper for the SNS using this technique. [10]

(c) Using strip deflecting electrodes. Deflecting electrodes excited by a traveling wave and positioned before the RFQ can be used as a chopper. This is a conventional design and is being used in the transport line before the linacs at BNL and LANL.

(d) Laser beam. Laser beam chopping of H^- beams has been demonstrated at Fermilab. [24] It works by flooding the beam with photons energetic enough to strip the first electron from the H^- ion. The neutral beam then falls out as the ion beam is guided in subsequent magnetic fields. At 1 MeV, a commercial 1064 nm Nd:Yag laser with photon energy 1.16 eV will photodissociate one electron (bonding energy 0.74 eV) from H^-.

13.2.6. The New 10-MeV Drift-Tube Tank

By raising the energy into the first tank of the Linac from 0.75 MeV to 2.235 MeV, the first 18 drift tubes which have a 2-cm bore diameter and quadrupole lengths of 1 inch and 1 1/4 inch will be eliminated. The new DTL then starts with drift tubes having a 2.5-cm bore and a quadrupole length of 1.75 inches. Thus the problem of misalignments will be significantly mitigated and the cell transit time improved to give a better acceleration rate. The capability of the structure to accelerate higher intensity and better quality beams will be enhanced.

A new Tank 1 will accelerate the beam to 10 MeV and match to the present Tank 2. This tank will be shorter than the present Tank 1 by ≥ 1.44 m and should incorporate a better drift tube alignment mechanism. It is optional whether a stabilized structure will be used because of the short length of the tank. Copper plating is common today and can probably be utilized. The old power supplies and rf system can remain in use.

13.2.7. Parameters and Performance Goals of this Configuration

Table 13.2 gives the expected goals for the low energy Linac improvements. In addition to providing a chopped beam of 3.3×10^{13} protons per pulse required for injection into the Proton Driver, the design beam emittance will be smaller by at least a factor of two. This will allow running at these higher intensities without additional beam loss.

Table 13.2. Parameters and goals for the performance of the new configuration of components for the low energy end of the Linac.

	Ion Source	LEBT/ Chopper	RFQ-1	MEBT	RFQ-2	Matching Section	DTL	CCL
Type	H^-	Electrostatic	Vane	Double Alpha 540^o	Vane	3 Quads 1Buncher	Drift-Tube	Coupled-Cavity
Output Energy (MeV)	0.05	0.05	1	1	2.23	2.23	116	400
Output Current (mA)	115	115	102	102	97	93	86	86
Output Chopped Current (mA)	115	80	72	72	68	65	60	60
EMITTANCE (π mm-mrad) (95%)		1.2	2	2.3	2.6		2.8	3
FREQUENCY (MHz)			201		201		201	805
Pulse Length (μs)	90		90		90		90	90

Other virtues of this new configuration are worthy of note:

i) H^- ion sources have been built and operated that approximate the brightness required in this proposal. Replacing the Cockcroft-Walton preaccelerators with radio frequency quadrupole structures will allow these sources to be used in this new configuration. Separating the RFQ sections will allow a spare source to be quickly brought on-line to provide the same redundancy that exists in the present system.

ii) Using RFQ technology for the Linac preaccelerator will eliminate the Cockcroft-Walton systems. DC accelerators require a special technology, unlike that used in the Linac itself. The RFQ systems are similar to those used in the Linac. Thus operation and maintenance will be simplified.

iii) The cost of these low energy improvements is modest when compared to the improvement goals.

iv) The physical space required for the proposed system will be considerably less than that used in the present Cockcroft-Walton system.

v) Improvements in the quality of the beam in the Linac allow studies to be conducted in systems downstream from the Linac to ascertain possible causes for beam deterioration. Although it is hard to predict what improvements in these downstream components are possible to prevent emittance dilution and beam loss, experience has shown that the dividends can be appreciable.

13.3. Description of the Ion Source and LEBT

13.3.1. General Remarks

High-brightness, intense H^- beams can be generated in Surface-Plasma Sources (SPS) by the interaction of a plasma with a surface to transfer electrons from an electrode to reflected or desorbed atoms, thus forming negative ions. The efficiency of negative-ion formation depends very much on surface properties, mainly the work-function. To enhance negative ion formation in the SPS, elements with a low ionization energy, such as the alkaline elements, are used. Most efficient of these is cesium. Still the work-function and catalytic properties of the surface for negative-ion formation depend very much on many parameters such as surface-cesium concentration, surface temperature and admixtures of other compounds, such as oxides, halides, nitrides, etc. Small changes in the surface condition dramatically change the efficiency of negative ion formation. It is a fine art to optimize the surface and plasma condition for high efficiency of negative ion formation. This condition is a strong reason for the variation in efficiency of negative ion production under apparently similar conditions. Small changes in the surface condition can increase or decrease the intensity of a negative ion beam by large factors. It is easier to have stable operation with relatively modest beam parameters such as I ~ 30 - 40 mA, J ~ 0.5 - 1 A/cm^2, Ti ~ 5 - 10 eV. Present day experience permits better optimization for long stable production of high-brightness, high-intensity beams of negative ions (I ~ 0.1 - 0.15 A, B ~ J/Ti > 1 A/cm^2 eV, N > 10^8 - 10^9 pulses).

13.3.2. Negative Ion Source for Charge-Exchange Injection

The first versions of the Surface-Plasma Sources developed for charge-exchange injection of protons had an operating intensity of about 50 mA with pulse widths of 0.05 - 1 ms and a repetition rate up to 50 Hz. H^- beam parameters of these sources were sufficient for normal operation of large proton accelerator complexes during the past 25 years without significant modernization of the ion sources. Now, new accelerator projects need an increase of the ion-beam intensity and brightness. Some upgrading of existing SPS could achieve the necessary increase of intensity, duty factor and beam quality without degradation of reliability.

The Fermilab Magnetron SPS pulse length could be increased significantly with a new discharge pulser and adjusted parameters. It is useful for stable operation to have a discharge power supply as a current source with a high impedance (Z = 5-10 Ohm, now Z = 1 Ohm) and a corresponding higher voltage. Optimization of the discharge electrode configuration should help increase the intensity up to 0.1 A without increasing the discharge power above acceptable levels. Gas delivery optimization should allow a longer pulse and higher intensity without an increase of the gas loading.

An optimized extraction system with a suppression electrode should improve the beam intensity, beam quality and beam space-charge neutralization with low gas pressure. A suppression of the positive ion extraction to the accelerating gap should suppress cathode and anode sputtering by accelerated positive ions, a main reason for the short ion-source lifetime. Improved cathode and anode cooling is necessary for increased discharge pulse length and intensity. The semi-Planotron version of the SPS would be better for operation at a higher duty factor.

From previous experience it is possible to have a reliable SPS with the following parameters: peak current after the extraction bending magnet of 0.12-0.15 A with a pulse duration of 1 ms, and a repetition rate of 15 Hz. A possible SPS with these parameters was tested in a relatively long run, although the adaptation of this source for extended operation in the Linac environment will need some effort. For ion source optimization and testing it will be necessary to resume operation of the ion source test stand and to upgrade the equipment. For prototyping of the equipment it will be possible to use previous developments from ANL, BINP, UMD, BNL, ISIS, and DESY.

Of interest is the rf ion source from DESY. It would be possible to test this source type using an rf proton source from NEC as a prototype. Relatively simple modifications could be made for testing this possibility.

13.3.3. Lifetime of Negative Ion Sources

1. The lifetime of ion sources with a cold electrode discharge is limited by electrode (cathode) sputtering and the formation of flakes. The flakes can create a short circuit of the discharge electrodes, close the emission aperture, or initiate a discharge instability and arcing. Deposition also changes the surface properties and efficiency of ion formation. Sputtering rates increase with energy of the bombarding ions (increase of discharge voltage), and with increase of the ion mass and charge. Different materials could have a very different sputtering rate.

2. A small admixture of cesium or other substances with a low ionization potential could be used to decrease voltage and significantly reduce the sputtering rate. These admixtures are used as catalysts of negative ion formation in the surface-plasma interaction in the Surface-Plasma Sources (SPS). In this application cesium is used as a thin (fraction of a monolayer) film on the surface to lower the work function from 4 eV to 1.6 eV. This increases the probability of secondary negative ion emission up to hundreds of times. It also decreases the number of sputtered atoms on the electrodes per emitted negative ion by many orders of magnitude.

3. Presently the SPS lifetime is limited through the sputtering of the cathode or anode due to back accelerated high-energy positive ions and flake formation from this deposit. The intensity of back accelerated positive ions could be suppressed using a 3-electrode extraction system with a suppression electrode, which reflects positive ions from the ion beam and improves the space charge neutralization. This improves the beam quality and stability of the ion source operation.

4. Optimized cesium film recycling (deposition-desorption) could be used for shielding of electrodes from the sputtering and can reduce the sputtering to a very low level. Cesium in a SPS acts as an oil in an engine increasing the operational lifetime. "Cold Start" of a discharge without cesium for a few minutes could be more destructive than many hours of low voltage operation. Emission current density of H^- up to $J \sim 1$ A/cm^2 has been observed in discharges without cesium. A fingerprint with a trace of Na or K could increase the efficiency of H^- production significantly. The power density in a discharge without cesium is very high and the sputtering rate is much higher.

13.3.4. Low Energy Beam Transport (LEBT)

An ion beam from a compact SPS has a very high current density ($J \sim 1$ - 3 A/cm^2) and perveance. For transport of these beams it is necessary to use a deep space-charge neutralization (compensation) or very strong continuous focusing by electrostatic forces as in the RFQ.

Partial compensation of space charge with magnetic focusing and noisy operation will create a strong variation of focusing and lead to an increase of emittance by ellipse oscillation. Still, this mode of transport is used in almost all injectors, and until recently it was acceptable. Space charge compensation by ions has some differences from the compensation by electrons. Ion oscillation in the potential of the beam is more coherent and can be a reason for very strong and fast beam-ion instability. Beam-ion instabilities have been observed recently in the electron beam of the Advanced Light Source (LBL) with increased residual gas density. In low energy negative ion beams this instability was observed many years ago (1976). Development of this instability along a 15 keV H^- beam at 70 mA is shown in Fig. 13.3. Coherent oscillations of positive ions in the beam potential excite quadrupole and dipole oscillations of the H^- beam and develop a decompensation and emittance growth.

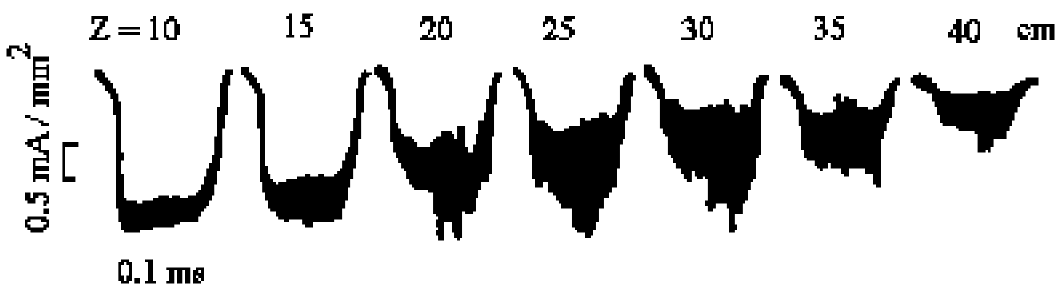

Figure 13.3. Beam current density evolution, p= 6×10^{-4} Torr

To eliminate this problem many versions of an electrostatic focusing-transport (ELEBT) have been proposed. Now under development is an ELEBT for SNS. The ELEBT developed at LBL [10] is shown in Fig. 13.4. Transport of a H^- beam of 65-keV energy with an intensity up to 42 mA has been demonstrated. Significant R&D for the development of an electrostatic LEBT operating at higher intensity is necessary.

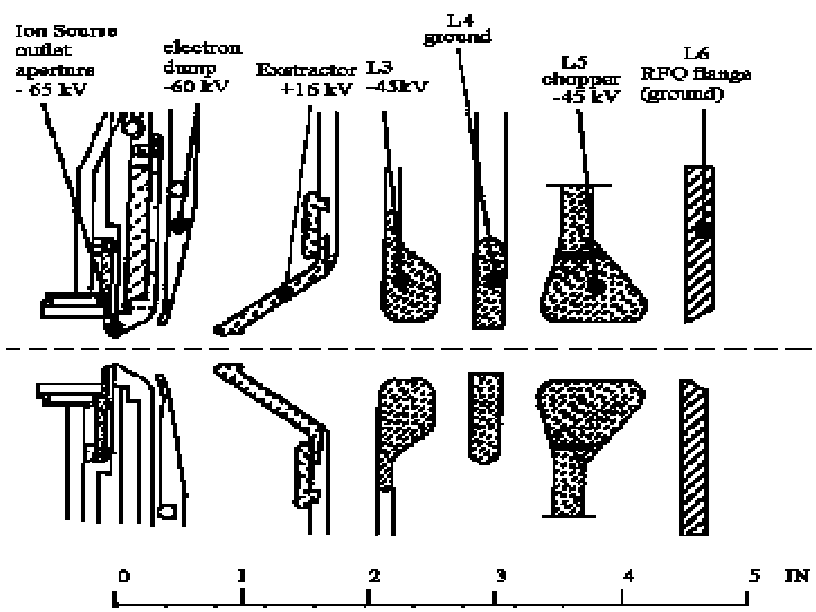

Figure 13.4. Cross section of the LEBT electrodes with ion source outlet aperture, electron dump, and RFQ endwall (LBL, for SNS)

The beam-ion instability could be damped by over-neutralization of the beam, changing the sign of the beam potential by an increase of the ion density in the beam. With increased ion and electron density, a stable beam transport could be reached with additional focusing by reversed space charge. This solution could be used for a short transport with acceptable levels of ion loss by stripping. This may be convenient because it is possible to locate a second (spare) ion source in front of one RFQ. Ion beam pulses from this ion source could be long enough for reaching a deep over-neutralization.

A good solution could be a LEBT with a fast beam over-neutralization by streams of noiseless plasma from a separate plasma source. With magnetic focusing, beams from two SPS could be steered to the entry of the RFQ. Close-coupled systems have been tested in ion implantation. Good neutralization decreases the beam emittance by approximately half.

13.4. Description of the Radio Frequency Quadrupole (RFQ) Structure

Using the design code PARMTEQ, RFQ's have been designed to accelerate a high intensity, low emittance beam to the entrance of Linac Tank 1. In the two section RFQ design, i.e. two RFQ's separated by the double alpha MEBT, the first RFQ is a "normal" design which accepts a 50 keV dc beam from the ion source, bunches it, and accelerates the beam to 1 MeV. The second RFQ accelerates the beam from 1 MeV to 2.23 MeV. The design allows a beam intensity of 115 mA to be accelerated with a transmission efficiency of better than 90%. To include the effect of possible emittance growth between the two RFQ's, the input emittance of the second RFQ is 20% larger than the emittance out of the first RFQ.

Table 13.3 shows the parameters of the first RFQ and Table 13.4 shows the parameters of the second RFQ. Note that in Table 13.4 the input emittance is 20% larger than the output emittance after the first section RFQ. Figure 13.5 shows the transmission as a function of input beam current for the first RFQ.

A one-section RFQ has been designed to transmit a 115 mA beam from 50 keV to 2.23 MeV. The transmission efficiency at this intensity is 98.8%. Table 13.5 shows the parameters of this RFQ.

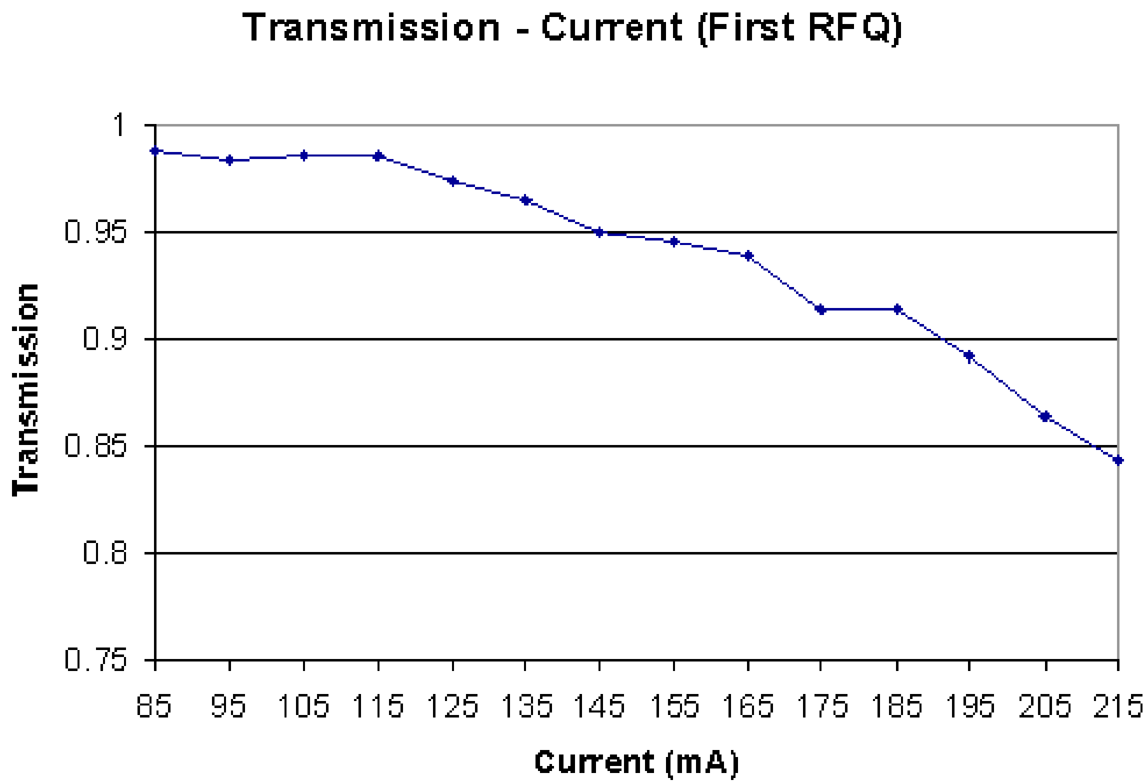

Figure 13.5. Transmission as a function of input beam current for the first RFQ

Table 13.3. First Section RFQ Parameters

Type	Conventional Four-Vane	
Frequency	201.25	MHz
Input Energy	50	keV
Output Energy	1.0	MeV
Input Current	115	mA
Aperture (r_o)(constant aperture design)	0.6	cm
Modulation	1.70	
Intervane Voltage	130	kV
Maximum E Field (2.06 Kilpatrick)	30.33	MV/m
Duty Factor (90 μsec, 15 Hz)	0.135	%
Peak Power	~313	kW
Length	~196.8	cm
Transmission	98.6	%
Input Emittance (X,Y), (normalized, rms)	0.25	π mm-mrad
Input Emittance (X,Y), (normalized, 5 rms)	1.25	π mm-mrad
Output Emittance (X), (normalized, rms)	0.377	π mm-mrad
Output Emittance (Y), (normalized, rms)	0.402	π mm-mrad
Output Emittance (X), (normalized, 5 rms)	1.885	π mm-mrad
Output Emittance (Y), (normalized, 5 rms)	2.010	π mm-mrad

Table 13.4. Second Section RFQ Parameters

Type (accelerator section only)	Conventional Four-Vane	
Frequency	201,25	MHz
Input Energy	1.0	MeV
Output Energy	2.23	MeV
Input Current	115	mA
Aperture (r_o), (constant aperture design)	0.6	cm
Modulation	1.70	
Intervane Voltage	127	kV
Maximum E Field (2.01 Kilpatrick)	29.63	MV/m
Duty Factor (90 μs, 15 Hz)	0.135	%
Peak Power	~294	kW
Length	~138.5	cm
Transmission	100	%
Input Emittance (X), (normalized, rms)	0.462	π mm-mrad
Input Emittance (Y), (normalized, rms)	0.489	π mm-mrad
Output Emittance (X), (normalized, rms)	0.525	π mm-mrad
Output Emittance (Y), (normalized, rms)	0.513	π mm-mrad
Output Emittance (X), (normalized, 5 rms)	2.625	π mm-mrad
Output Emittance (Y), (normalized, 5 rms)	2.565	π mm-mrad

Table 13.5. Single Section RFQ Parameters

Type	Conventional Four-Vane	
Frequency	201.25	MHz
Input Energy	50	keV
Output Energy	2.23	MeV
Input Current	115	mA
Aperture (r_o), (constant aperture design)	0.6	cm
Modulation	1.70	m
Intervane Voltage	129.3	kV
Maximum E Field (2.05 Kilpatrick)	30.17	MV/m
Duty Factor (90 μs, 15 Hz)	.135	%
Peak Power	~607	kW
Length	~341.27	cm
Transmission	98.8	%
Input Emittance (X), (normalized, rms)	0.25	π-mm-mrad
Input Emittance (Y), (normalized, rms)	0.25	π-mm-mrad
Output Emittance (X), (normalized, rms)	0.393	π-mm-mrad
Output Emittance (Y), (normalized, rms)	0.389	π-mm-mrad
Output Emittance (X), (normalized, 5 rms)	1.965	π-mm-mrad
Output Emittance (Y), (normalized, 5 rms)	1.945	π-mm-mrad

13.5. The Double Alpha Phase Space Imaging System (MEBT)

This section describes the design [23] of the double alpha phase-space imaging system or MEBT which transforms the beam from the match-point at the output of the first RFQ to the match point into the second RFQ. The design code TRACE 3D [22] was used. Table 13.6 shows the input parameters used in the computation. Table 13.7 shows the output beam parameters at the input match point to the second RFQ. Figure 13.6 shows the MEBT elements: two alpha dipoles and five quadrupoles. This arrangement is similar to that used in the PET project. The apertures of the dipole magnets have been increased a small amount over the PET magnets, but the edge angles have not been altered.

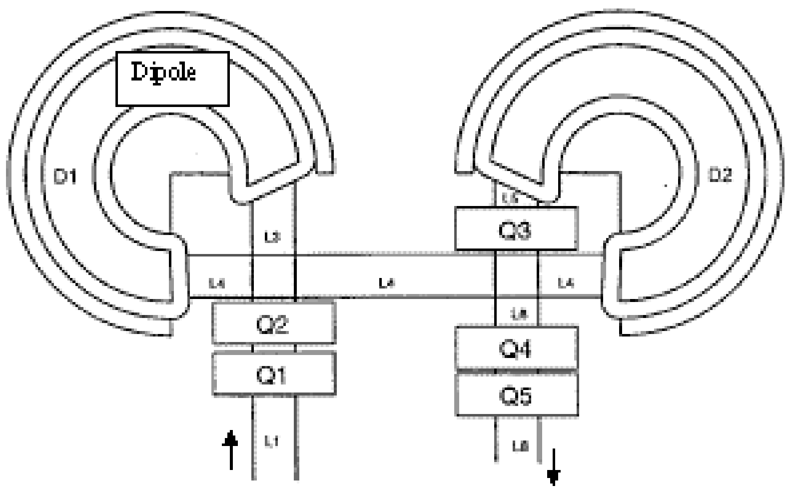

Figure 13.6. MEBT elements consisting of the two alpha dipoles and the five quadrupoles

Fig. 13.7 shows a good match into the second RFQ for a beam intensity of 80 mA. The small emittance mismatch is well within the acceptance of the RFQ, where an emittance growth of 20% has been allowed. Although this calculation demonstrates the feasibility of using such a system, as the PET project also demonstrated, an R&D effort will be required to validate the calculations and to derive the parameters for a physical design.

Table 13.6. 1.0 MeV RFQ Output

	α	β	ε	ε_n	
x	2.2788	0.1401	40.6163 π	0.5950 π	mm-mrad
y	-1.4541	0.0894	43.3576 π	0.6352 π	mm-mrad
z	0.1592	1.6562	739.582		deg-KeV

Table 13.7. 2.23 MeV RFQ Input

	α	β	ε	ε_n	
x	2.2456	0.1363	49.981 π	0.7322 π	mm-mrad
y	-1.412	0.0859	52.9293 π	0.7754 π	mm-mrad
z	0.1766	1.6606	885.1896		deg-KeV

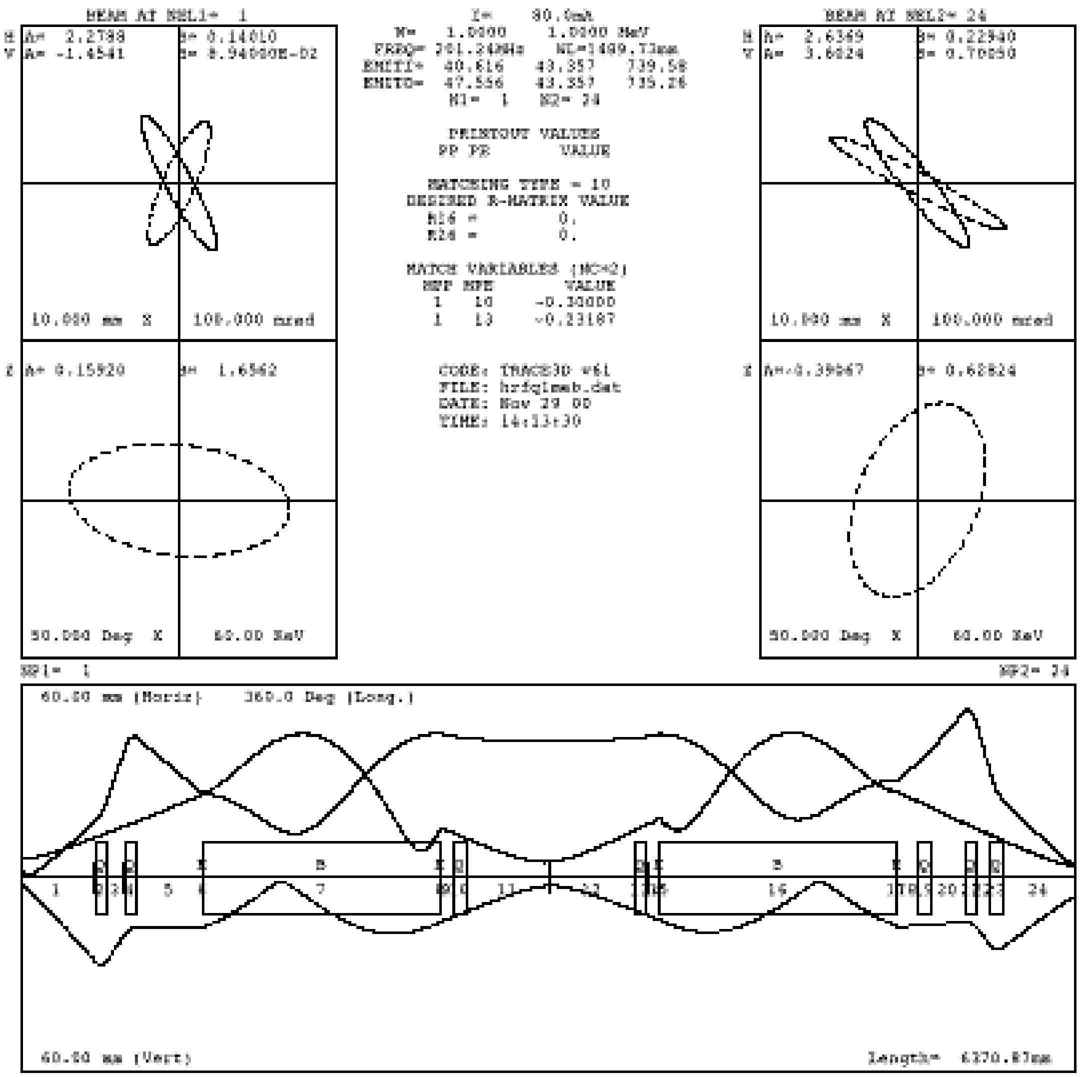

Figure 13.7. Trace calculation showing match to RFQ-2 for a beam intensity of 80 mA

13.6. Chopper

A beam chopper is necessary in the Proton Driver to reduce beam losses during injection from the Linac into the Booster and for creating a gap in the beam bunch train so that extraction loss due to kicker rise-time can be eliminated. Chopping of the beam is most conveniently done in the low energy part of the Linac system where the beam can be lost without causing induced radioactivity in the accelerator components. In this study various schemes have been investigated for providing the required chopping of the beam pulse.

The rf chopper will be used for creating 42-bucket gaps in Stage 1 and also for 30% beam chopping in Stage 2. Compared with the conventional traveling wave deflectors, its advantages are: i) simplicity, ii) fast rise- and fall-times (about 20 ns), and iii) short physical length (less than 10 cm). Laser chopping could be used to create the short extraction gap. It has very fast rise- and fall-time (several ns).

The rf chopper is similar to a beam transformer. It is based on the fact that the RFQ has a small energy window. A ±10% energy error in a beam at the entrance to an RFQ can effectively reduce the transmission efficiency to zero. The chopper consists of a pulsed power supply and a cavity. The cavity is loaded with Finemet-wound cores that serve as a beam transformer. The gap rf voltage is a waveform of square pulses with an amplitude of ±2.5 kV, or ±5% of the RFQ-1 injection energy of 50 keV. The spacing between two neighboring squares is equal to the chopped beam length. The extraction energy of the H^- ion source will be adjusted to 47.5 keV. After the chopper, the beam energy jumps between 50 keV and 45 keV. The beam portion with 45 keV is at the wrong energy for acceptance into the RFQ and will be chopped.

A prototype chopper cavity loaded with three 1 in. thick Finemet cores and driven with a power supply using a HTS 81-09 high-voltage transistor switch was built and installed in the LEBT before the RFQ in the Linac at the HIMAC in Japan. The preliminary results from the beam tests were encouraging. The Linac beam was successfully chopped and the beam with correct energy was captured in the rf bucket during injection into the synchrotron. Two issues need to be studied in greater detail: i) the tolerable voltage variation during the waveform peak, and ii) the effect of the low-energy (45 keV) H^- ion bombardment on the RFQ.

For laser chopping a 1.1 μs notch is to be created in a one-meter interaction region between the MEBT magnets. The one-meter notch is repeated 27 times by recirculating the laser pulse through the H^- beam as it streams into the interaction region. The laser pulse is routed to an external 20-meter delay line and reinjected when the interaction region refills with ions. The external cavity is a bowtie cavity with enough gain to make up for propagation losses. Judicious use of large aperture Q-switches, time of flight for clearing Q-switch rise times, and beam splitters will be used to shuttle the laser pulse in and out of the interaction region. Thus a 99% 1.1 μs notch will be created. H^0 beam will scatter on the MEBT magnet rather than the RFQ.

A 2.2 μs bow-tie cavity delay line will be required to accommodate multi-turn operation. It too requires some gain. The laser pulse is switched out of the 20-meter delay line to this one between turns.

13.7. The New 10-MeV Drift-Tube Cavity

The present 10-MeV drift-tube cavity was constructed at Fermilab as a prototype in 1968-69. The copper-clad steel for the tank walls was obtained from surplus materials at Lawrence Livermore Laboratory, and the welding was performed to develop the technique required for making copper-to-steel joints. Drift-tube fabrication as well as the drift-tube quadrupole alignment mechanism was experimental. The alignment of the drift tubes was unsatisfactory and failed to allow the required six-dimensional tolerances to be achieved. Alignment eventually depended upon controlled bending of the drift-tube support stems. Although the cavity accelerated beam to 10 MeV, beam quality was sacrificed by the poor quadrupole alignment. An attempt to realign the drift tubes after the tank was moved to its permanent building failed to improve the alignment. It was expected that a new tank could later be constructed to replace the prototype.

Considerable experience has been acquired since 1970 in the construction of drift-tube accelerating cavities. Copper plating of prefabricated tanks is the usual preferred fabrication technique. Better fabrication of drift tubes with cooling and quadrupole placement is available. Drift-tube alignment mechanisms have been improved. Stabilized rf structures allow better power transfer in the cavities, i.e. post couplers have been used in the higher-energy cavities of the drift-tube Linac, but the early construction of the 10-MeV cavity prevented their use in it. New types of rf structures for the acceleration of particles up to 10 MeV have been developed and are being promoted in the accelerator community. These issues will be studied before a final design is proposed.

Raising the input energy to the 10-MeV cavity allows a better phase-space match to be made to the drift-tube focusing system. In addition, it eliminates the first 18 drift tubes that contain quadrupoles with 2 cm. bore diameters and lengths of 1 and 1 1/4 inch. These quadrupoles were the most difficult to align and their fields were questionable. The accelerating gaps between these first drift tubes are short and the transit-time factor low, making acceleration inefficient. A new tank will be at least 1.4 m shorter than the present cavity and would start with drift tubes having a larger bore diameter and longer quadrupoles. The sparking problems associated with the low-energy drift tubes in the cavity would be ameliorated.

13.8. Linac Controls and Diagnostics

The Front End computers will run the same software used for the existing Linac. Data from these computers can be requested by consoles in the Main Control Room. The new additions to the Linac also operate at 15 Hz, and data will be collected synchronously with the 15 Hz repetition rate so that correlated readings from the entire Linac will be available.

The proposed low-energy Linac improvements are similar to the PET project done at Fermilab several years ago. The equipment to be controlled includes the ion source, two sections of RFQ Linac, the double alpha magnets, a new 10-Mev drift-tube Linac tank, the beam transport lines between these elements, and the beam instrumentation.

Although control system equipment tends to change rapidly over time, this write-up assumes that the control system will be built using today's technology and devices. The Front End computers consist of a single board computer, the Motorola MVME2400, mounted in VME bus crates, VXI crates, or IRM chassis. The IRM, Internet Rack Monitor, is a stand-alone chassis containing the computer and both analog and digital I/O. Additional I/O is added using commercially available VME bus boards and industrial PLC's, Programmable Logic Controllers. Table 13.8 is a list of the control system equipment and the devices controlled by each.

Table 13.8. Control Equipment for Linac additions

Chassis	Equipment	Comments
IRM-0	Ion Source	Ion Source potential, Fiber optic isolation
IRM-1	RFQ-1	Mounted in RF System Rack
IRM-2	RFQ-2	Mounted in RF System Rack
IRM-3	Power Supplies, PLC's	Transport and Alpha Magnets, Vacuum
IRM-4	Beam Instrumentation 1	See Table 13.9
IRM-5	Beam Instrumentation 2	See Table 13.9
VXI Crate	Phase control, cavity tuning	RF related signals and processing
IRM-6	Emittance Probes	May be needed only for commissioning

A variety of Beam instrumentation equipment will be needed to commission and monitor the operation of the RFQ part of the Linac. Table 13.9 is a list of needed devices.

Table 13.9. Beam Diagnostics Equipment

Quantity	Device
4	Emittance Probes, 32 channel, 2 horizontal and 2 vertical
4	Single wire Scanner beam Profile probes
5	BPM, Beam Position Monitors
4	Beam Current Toroids
1	Beam Phase Monitor Probe
4	Horizontal Trim Magnets
4	Vertical Trim Magnets.
4	Ion Profile Monitors, 2 Horizontal & 2 Vertical
1	Bunch Length Monitor

13.9. Retuning the Linac for Brighter Beam

After installing the new Tank 1, the five tanks of the drift-tube Linac will contain 191 quadrupoles excited from 118 power supplies, with most power supplies driving two quadrupoles. The transition section contains six quadrupoles, and the side-coupled Linac contains 28 quadrupoles. The quadrupoles will have been set from calculations assuming desired beam parameters, but little tuning will have been done to optimize the quadrupole settings for measured beam parameters due to the complexity of the focusing system. Measuring properties of this initial beam will allow a second calculation to better tune the focusing system. In addition, the matching between the cavities and the different Linac structures will be studied. By matching the output from each structure to the acceptance of the next structure, it is possible to eliminate emittance growth along the Linac as well as beam loss.

Currently the quadrupoles are tuned using a beam-loss criterion. The tuning should also include beam quality as one of the criteria.

13.10. Shielding Considerations

The 1991 Linac Shielding Assessment [11] is the current reference document governing radiation protection in the areas adjacent to the Linac enclosure at the low energy end (Tanks 1-5). The 1993 Linac Shielding Assessment1 [12] is the current reference document governing radiation protection in the areas adjacent to the Linac enclosure at the high-energy end (beyond Tank 5). The nature of the Linac operation and the complex shielding arrangements associated with the Linac enclosure make standard shielding calculation methods very difficult and somewhat unreliable.[13] Extensive radiation tests were performed prior to the completion of both the 1991 and 1993 Linac Shielding Assessments. [12,14,15] The results of the radiation tests performed for these shielding assessments show that relatively high dose rates could be achieved in very short periods of time; however, the dose delivered per pulse was relatively small and very manageable. (<<1 mR/pulse for locations outside of the Linac enclosure) [12,14,15]

Chapter 2 Articles 236 and 237 of the Fermilab Radiological Control Manual (FRCM) outline the posting requirements for beam-on radiation conditions for operating accelerators.[18] However, the posting requirements associated with Linac operation are governed only by Article 236. This is because it is highly unlikely that excessive beam loss could be sustained for a full hour in the Linac accelerator. [19] Table 13.10 is copied from the FRCM for the shielding requirements.

Table 13.10. (From the FRCM) Control of Accelerator/Beamline Areas for Prompt Radiation Under Normal Operating Conditions (refer to Article 236.2(b)(1))

Dose Rate (DR) Under Normal Operating Conditions	Controls
DR < 0.05 mrem/hr	No precautions needed.
0.05 < DR < 0.25 mrem/hr	Signs (CAUTION - Controlled Area). No occupancy limits imposed.
0.25 < DR < 5 mrem/hr	Signs (CAUTION - Controlled Area) and minimal occupancy.
5 < DR < 100 mrem/hr	Signs (CAUTION - Radiation Area) and rigid barriers (at least 4' high) with locked gates. For beam-on radiation, access restricted to authorized personnel.
100 < DR < 500 mrem/hr	Signs (DANGER - High Radiation Area) and 8 ft. high rigid barriers with interlocked gates or doors and visible flashing lights warning of the hazard. Rigid barriers with no gates or doors are a permitted alternate. No beam-on access permitted.
DR ≥ 500 mrem/hr	Prior approval of SRSO required.

Currently the areas adjacent to the Linac enclosure are posted as in Table 13.11.

Table 13.11. Posting of areas adjacent to the Linac enclosure

Adjacent Area	**Current Posting**
Upstream end (750 KeV) between the Linac enclosure and the Pre-Accelerator enclosure	Radiation Area
Linac Upper and Lower Level Galleries	Controlled Area
Downstream end located inside the Booster enclosure	Radiation Area
Outdoor berms and Utility Access area	Not posted

In order to comply with the limits established in Chapter 2 of the Fermilab Radiological Control Manual, interlocked radiation detectors are utilized throughout the Linac area. These interlocked detectors are positioned throughout the Linac enclosure and surrounding areas based on information provided in the 1991 and 1993 Linac Shielding Assessments. The information provided in these assessments shows that the detectors are positioned in the optimum locations to inhibit beam in the event of a multiple pulse beam loss scenario.

Prompt radiation levels outside of the Linac enclosure due to beam loss will increase approximately linearly as a function of increased intensity. Since the dose delivered per pulse is relatively small and very manageable to begin with, increasing the intensity by a factor of 5 would have very little impact. Since areas adjacent to the Linac enclosure are ultimately protected by interlocked detectors and not passive shielding, increasing intensity by any reasonable factor would not present problems with regards to prompt radiation fields outside of the enclosure.[16] The existing interlocked detector arrangement is adequate for an increase in intensity by a factor of 5.

Increasing Linac intensity without a concurrent upgrade of Linac control and diagnostic equipment will likely result in an increased number of interlocked radiation detector trips. Although upgrading Linac controls and diagnostics is planned (Section 13.8), it may still become necessary to upgrade the existing radiation detector cards from the somewhat over-reactive "rate" style card to the equally safe, yet more tolerant "integrating" style card. Other alternatives include the addition of more passive shielding to the Linac enclosure or imposing more restrictive occupancy limitations on the areas adjacent to the Linac enclosure and changing the radiological postings in accordance with the Fermilab Radiological Control Manual.

The radiation hazards associated with the operation of new rf producing equipment can be very significant. [17] The X-Ray production of the new H^- Source, RFQ's and associated power drivers will be addressed by a combination of enclosure interlocks, commissioning of equipment and periodic radiation surveys depending on their installed location.

Residual radiation levels and radiation damage to materials within the Linac enclosure are a function of beam intensity, beam loss and time of exposure. Work on activated components, regardless of the magnitude of activation, is handled in accordance with the procedures established by the Fermilab Radiological Control Manual. Minimizing beam loss and time of exposure are being addressed by upgrading the controls and diagnostics of this machine (Sec. 13.8).

13.11. Short Range Plans: The R & D Program

Although the technology for the low-energy Linac improvements have been generally accepted in the accelerator community and preliminary computational work done to verify the design parameters, the expertise for constructing a final system will have to be developed at Fermilab. An R & D program will be required to develop the hardware and verify its performance. The specific areas where R & D work will be required are:

1. Ion Source development and the electrostatic LEBT

2. The RFQ

3. The double alpha phase-space imaging system

4. The rf cavity with Finemet cores for beam chopping

5. Laser Beam chopping

13.11.1. Ion Source and Electrostatic LEBT

A short (one year) H^- source R&D program is proposed. The goal is to produce two new sources: (1) an improved magnetron, which would increase the H^- beam brightness by a factor of two; and (2) a noiseless semi-Planotron, which would increase the H^- current to 110 mA with high brightness.

1. Motivation:

   At the recent Proton Driver review, the committee recommended that the ion source *"should be an area of highest R&D priority"* for the ion source/Linac part of the Proton Driver Project. However, due to limited resources, we plan to reach the goal of an ion source required by the Proton Driver in several steps. This proposal represents the first step. It is a fairly short program (one year) and requires moderate investment. This effort may have an immediate impact on the improvement of the present Linac and Booster performance. These new sources can be mounted on the Cockcroft-Walton and provide an H^- beam with higher intensity and better quality *(i.e.,* a brighter beam).

2. R&D goals:

   (a) Improvement of the magnetron:
   The emittance (brightness) of the present magnetron can be improved by optimizing the discharge geometry, gas injection, extraction and plasma over-neutralization. The goal is to attain 85 mA of H^- with an emittance of 0.5 π mm-mrad (90% normalized, a factor of 2 smaller than the present beam emittance).

   (b) Development of a noiseless semi-planatron:
   The goal is to obtain up to 110 mA of H^- with an emittance of 0.7 π mm-mrad (90% normalized). This new source can be adapted for installation on the Cockcroft-Walton as a replacement of the magnetron.

As a future improvement of the H^- beam quality for the existing Linac and Proton Driver (after finishing the short R&D program), we propose to develop a H^- source giving a very high brightness, a Penning geometry Surface-Plasma Source, known as a Dudnikov type H^- source (DTS). Features of this source are: a noiseless discharge and beam formation, very high beam brightness, and the possibility of adapting it to the existing injector or the RFQ. The R&D goals are:

(a) Production of a H^- beam with an intensity of 120 mA and brightness 30-50 % better than the Semi-Planotron source.

(b) Adaptation of the DTS to the existing injector.

(c) Develop a source housing and a beam formation, transport, and focusing system for the RFQ.

It may be possible in this design to incorporate an optimized combination of the features of the DTS developed at BINP, ISIS, LANL, UMD, and INR. Developments at LBL and FU could be used in the LEBT. Suppression of fast ion instability is important for production of H^- beams with high brightness.

Space charge neutralization of H^- beams in the double-alpha line will be studied. Space-charge neutralization (compensation) by residual gas ionization is efficient for dc ion beams if an electron trap is created along the beam. For pulsed ion beams and for beams with intensity modulation, a higher gas density is needed for neutralization so beam loss by charge exchange or stripping of negative ions can be significant. Space charge neutralization by ions could result in fast ion instability. Over-neutralization is necessary for damping this instability. Space charge neutralization needs to have a plasma with a density close to the beam density, $n_p = n_b = 10^8 - 10^9$ cm^{-3}. But the gas density for production of this plasma by beam interaction with the gas should be much higher, $N_g = 10^{11} - 3 \times 10^{12}$ cm^{-3}. The corresponding level of gas ionization is very low. A plasma with a density $n_p = n_b = 10^8 - 10^9$ cm^{-3} could be produced with a very low gas density by plasma generation with a pulsed plasma gun where 50% of the injected gas could be ionized. The technology used for positive ion-beam neutralization could be used for negative beam neutralization (compensation) and over-compensation.

13.11.2. The RFQ

An RFQ using contoured circular rods exists at Fermilab and was provided by A. Schempp (IAP-Goethe University). [20] It is tuned to 201.5 MHz and has an input energy of 30 keV and an output energy of 750 keV with a transmission efficiency of 96 % at a beam current of 30 mA. It can be used to accelerate the H^- beam from the ion source and LEBT (a solenoid magnet exists from the PET Project that can initially serve as a LEBT) This will validate RFQ computations, assist in the characterization of the ion source output, and provide an input beam to the double-alpha magnet MEBT. This RFQ will also provide engineering and sparking level information.

13.11.3. The double alpha phase space imaging system

In the PET Project the RFQs were separated by two 270^o bending magnets and five quadrupoles to form a five dimensional phase-space imaging system to match the beam from one RFQ to the next RFQ. The system was used to match a 1-MeV beam of single charged $^3He^+$ beam from a 200-MHz RFQ to a 400-MHz RFQ after passing through a stripper to form a double-charged $^3He^{++}$ beam. The success of this system constituted a proof-of-principle experiment to ascertain the validity of separating sections of RFQ.

A TRACE3D [21] study was done to see if this equipment could be used for a 750-keV H^- beam from the Schempp RFQ. The result indicated that with minor changes in the magnet excitation currents this same equipment could be used to match the beam into the acceptance of the 10-MeV Linac tank. An H^- beam with a peak current of 65 mA will allow space charge effects to be investigated in this type of MEBT. It also will allow parameters to be investigated to verify computational codes and to acquire information preliminary to a final design of a system to upgrade the low-energy section of the Linac.

13.11.4. The rf cavity with Finemet cores for beam chopping

A prototype rf cavity with Finemet cores and a bipolar HTS 81-09 high voltage transistor switch in the power supply was built and installed on the Linac at the HIMAC in Japan. The preliminary results from the beam tests were encouraging, but additional issues need to be studied, such as:

a. Tolerable voltage variation during the peak of the waveform,

b. The effect of low-energy H^- ions bombarding the RFQ.

These issues with additional information necessary for a final design of such a chopper could be investigated in the proposed R&D program.

13.11.5. Laser Beam Chopping

The laser beam chopping scheme requires modification of the MEBT magnets to get the laser beam between them. This should be modeled in the design of these magnets. The scheme requires a commercial 15 Hz 500 mJ ND:YAG laser, two delay lines with large bore Q-switching, and two 15 Hz low-gain (disk) optical power amplifiers. For safety and pointing considerations, the entire system would be enclosed in rough vacuum.

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