Chapter 8. H^- Source and Linac Improvements and Upgrade

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A substantial upgrade of the existing Linac will be required to meet the needs of the Proton Driver specified here. In particular, it is required that we provide 600 MeV H^- ions to the Proton Driver at a rate of 10^{18} ions per hour. Thus, an upgraded Linac with higher energy and a smaller and brighter beam is required.

8.1 Introduction

8.1.1 Impact of Requirements on Linac

The synchrotron proposed in this report will require that the Linac produce a beam as specified in Table 8.1.*

Table 8.1. Linac Parameters - Present and Upgrade

Item	Present	PD2	Units	Increase
Ion species	H^-	H^-		
Kinetic energy	401.5	601.5	MeV	1.50
Emittance	7	3	π mm-mrad	0.43
Beam current	50	50	mA	1.00
Brightness	1.0	5.6	mA/(π mm-mrad)^2	5.44
Pulse length	64	90	μsec	1.41
Ions per pulse	2.00×10^{13}	2.81×10^{13}	per 15 Hz pulse	
Pulses per hour	19,000	54,000		2,84
Uptime	0.8	0.8		1.00
Ions per hour	3.04×10^{17}	1.21×10^{18}		4.00

Thus, the Linac will be required to (1) add extra acceleration at the end of the existing Linac, (b) increase the pulse length (c) increase the overall repetition rate (e.g., use more of the 15 Hz pulses) and (d) decrease the losses in the Linac enough to allow continued hands-on maintenance.

8.1.2 H^- Source and Linac Parameter Table

We propose to build this 600 MeV Linac with a new injection scheme and with an extra segment of 200 MeV acceleration in the transfer line to the new synchrotron. The injection will consist of a new ion source, a 2.5 MeV radio frequency quadrupole (RFQ)

* The number of pulses per hour in this table takes into account the measured average number of pulses per hour requested of the Linac since January 1, 2001 (~1000) and the imminent request for 5 Hz operation of MiniBoone (18,000 per hour). The actual uptime measured over this period is only about 40%.

and a new 10 MeV drift tube tank at 201.25 MHz. All of these components need to accelerate over 50 mA of beam for 90 µsec. Table 8.2 details these specifications.

Table 8.2. Parameter Table for 600 MeV Linac and Ion Source

	Ion Source	LEBT/ Chopper	RFQ	Match Section	New Tank 1	DTL	CCL	HEBT	New CCL
Type	H^-	Electro-static	Vane	*TBD*	RGDTL	Drift-Tube	Coupled -Cavity		Coupled -Cavity
Output Energy (MeV)	0.05	0.05	2.5	2.5	10	116	401	401	601
Output Current (mA)	66	66	55	55	52	50	50	50	50
Emittance (π mm-mr, 95%)	1.0	1.2	2.0	2.6	2.8	2.8	3	3	3
Frequency (MHz)			201	201	201	201	805	805	805
Pulse Length	90	90	90	90	90	90	90	90	90

8.1.3 Pulse Length Requirements

In order to achieve the desired number of ions per pulse, it will be necessary to establish a longer beam pulse than is currently produced. We currently have 64 µsec available for accelerating beam. With trivial adjustments in the timing of the RF pulse, we can increase this by 32 µsec, which meets the required pulse length of 90 µsec.

This 90 µsec pulse is achieved by using most of overhead built into the system. The high-voltage systems in the new section of the Linac must be able to produce this 90 µsec with an overhead factor of 20%.

8.1.4 Achieving Acceptable Losses

The following table outlines our target level for the losses in the new machine.

Table 8.3. Linac Particle Loss Budget

Item	Present	PD II	Units	Change
Losses (Meas & tolerable)	2%	0.23%		9
Instantaneous Losses	1.00	0.12	millamps	9
Ave Current Lost@ 15 Hz	1.44	0.23	microamps	6
Ave current Lost in 1 hour	0.019	0.19	microamps	0.1

In the Linac, presently operating for the Tevatron in collider mode at about 1000 pulses per hour, the losses are acceptable. These are approximately a factor of ten lower than the generally accepted criterion for hands-on maintenance, which is 100 mrem/hour at 1 foot. Thus, we can tolerate a factor of 10 increases in activation without impacting our ability to work on the machine. With this criterion and taking into account the difference in the beam requests, we can tolerate a fractional loss in the Linac beam of about 0.23%—a factor of ten improvements over present-day levels.

Decreasing the transverse emittance in the Linac will reduce losses. The largest fractional increase in the transverse emittance of the present Linac beam is through Tank 1—we see an increase of about a factor of five from the ion source to 10 MeV. A redesign of the Linac up to 10 MeV for optimum emittance is therefore necessary. We estimate that a new ion source, coupled tightly to a 2.5 MeV RFQ, which itself is coupled tightly to a new, shorter "Tank 1" would yield an emittance under 3 π mm mrad—a factor of two improvement in emittance, and a factor of 5 improvement in brightness.

A detailed study of losses in the present Linac will need to be conducted. Most of the losses we see now are due to a mismatch in the capture between the 201 MHz and the 805 MHz segments, but significant transverse mismatches also exist. Moreover, extensive studies have been published in recent years detailing the calculations necessary to predict emittance growth in ion linacs. It will be necessary to understand these calculations and how they relate to our situation.

8.2 Low-Energy Improvements

The redesigned low energy section utilizes a single exchangeable ion source coupled closely to a single RFQ via an electrostatic transport region, which will also serve as an electrostatic chopper. Based on the SNS design, a double valve system will facilitate ion source exchange removing the need for two RFQs. Replacing the Cockcroft-Walton with this system allows for the possibility of improving the present H^- Magnetron ion source as well as considering other H^- sources with higher brightness.

8.2.1 Ion Source

Details of the development of negative hydrogen ions sources can be found in Ref. [1]. A modest increase in beam intensity and brightness is required here. It should be feasible to upgrade the Fermilab Magnetron Surface Plasma Source (SPS) for the required intensity, duty factor and beam quality without sacrificing the reliability and availability from its proven past performance. For matching to an RFQ a circular extraction aperture is proposed following the Brookhaven design. [2] An optimized system, including a suppression electrode, should produce longer pulses with higher beam intensity, better beam quality and some beam space-charge neutralization. Source lifetime will be a key element in this system and improved cathode and anode cooling may be necessary to handle the increased discharge pulse length and intensity.

To produce beams of the highest brightness it would be possible to use a SPS with a Penning discharge, also known as the Dudnikov-type source. Transition from a noisy mode of operation to a noiseless discharge can increase the brightness by a factor of 10 or more. The DESY RF type volume source is also a viable alternative. [3] A small injection of cesium and adjustment in the extraction system should give the desired intensity of 66 mA. Further discussion can be found in Ref. [1].

A 50 keV extraction voltage from the ion source is proposed for extracting sufficient current from the source and to allow for a short electrostatic focusing structure closely coupling the source to an RFQ. The increased energy of the H^- ions allows easier injection and greater transmission through the RFQ.

For ion source optimization and testing it will be necessary to resume operation of the ion source test stand and to upgrade the equipment. In prototyping new source equipment it will be possible to use previous developments from ANL, BINP, UMD, BNL, ISIS, and DESY. Testing of the DESY type source is possible using an RF proton source from NEC as a prototype.

8.2.2 Low Energy Beam Transport (LEBT) and Chopper

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

A detailed description of a strongly focused electrostatic lens designed to couple the beam to the RFQ along with discussion of the need and possibilities for additional chopping can be found in PD1. [1] Briefly, The last Einzel lens in the LEBT will be segmented and a pulsed voltage applied in order to excite a pair of these segments such that the beam from the source deflects enough to fall outside the aperture of the RFQ. LBL has designed and built a prototype chopper for the SNS using this technique. [4] However further development will be required to achieve good focusing for the 66 mA current required. Laser beam chopping may be the best second choice as it allows for a very short LEBT section.

8.2.3 Description of Radio Frequency Quadrupole (RFQ) Structure

Using the design code PARMTEQ, a one-section RFQ has been designed to transmit a 66 mA beam from 50 keV to 2.23 MeV. The transmission efficiency at this intensity is 98.8%. Table 8.4 lists the parameters of this RFQ.

8.2.4 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.

Table 8.4. Single Section RFQ Parameters

Type	Conventional Four-Vane	
Frequency	201.25	MHz
Input Energy	0.050	MeV
Output Energy	2.23	MeV
Input Current	66	mA
Aperture (r_0), (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)	0.135	%
Peak Power	600	kW
Length	3.4	m
Transmission	98.8	%
Input Emittance (normalized, rms)	0.25	π-mm-mrad
Output Emittance (normalized, rms)	0.40	π-mm-mrad

8.3 Side-Coupled Cavity Modules From 400 MeV To 600 MeV

Additional acceleration to 600 MeV is required. Five new side-coupled cavity modules will be added to the transfer line to the new booster synchrotron, based on the design and techniques used for the Linac upgrade of 1993.

8.3.1. 400 MeV Beam Transport Line

The transfer line between the 400 MeV Linac and the additional 600 MeV modules has to satisfy several conditions:

- The line has to follow part of existing enclosure,
- The beam has to be cleanly extracted,
- The beam must be transported to the elevation of the new transfer tunnel and
- The beam must be matched to the accelerating structure.

It is assumed that beam is extracted using a DC magnet that fits between the 400 MeV Chopper and quadrupole Q2. The dipole magnet bends the beam by 20° and has a field of 7.4 kGauss with a bending radius of 4.25 meters. The extraction functionality of the present 400 MeV line is preserved. Two more horizontal bending magnets are needed to position beam next to the southern wall in the MuCool test area. The six quadrupoles in the line are used to control beam size as well dispersion in the horizontal plan.

To control the beam longitudinally, we will need two 3-cell bunching cavities. They will be positioned 22 meters away from the end of 400 MeV section and 5 meters before entrance to the new accelerating structure. To bring beam to the new elevation, two equal vertical magnets with opposite bends are used. The present design assumes that all bending magnet are the same, that quadrupoles are old "200 MeV quads" and that new accelerating modules will be copy of exiting design.

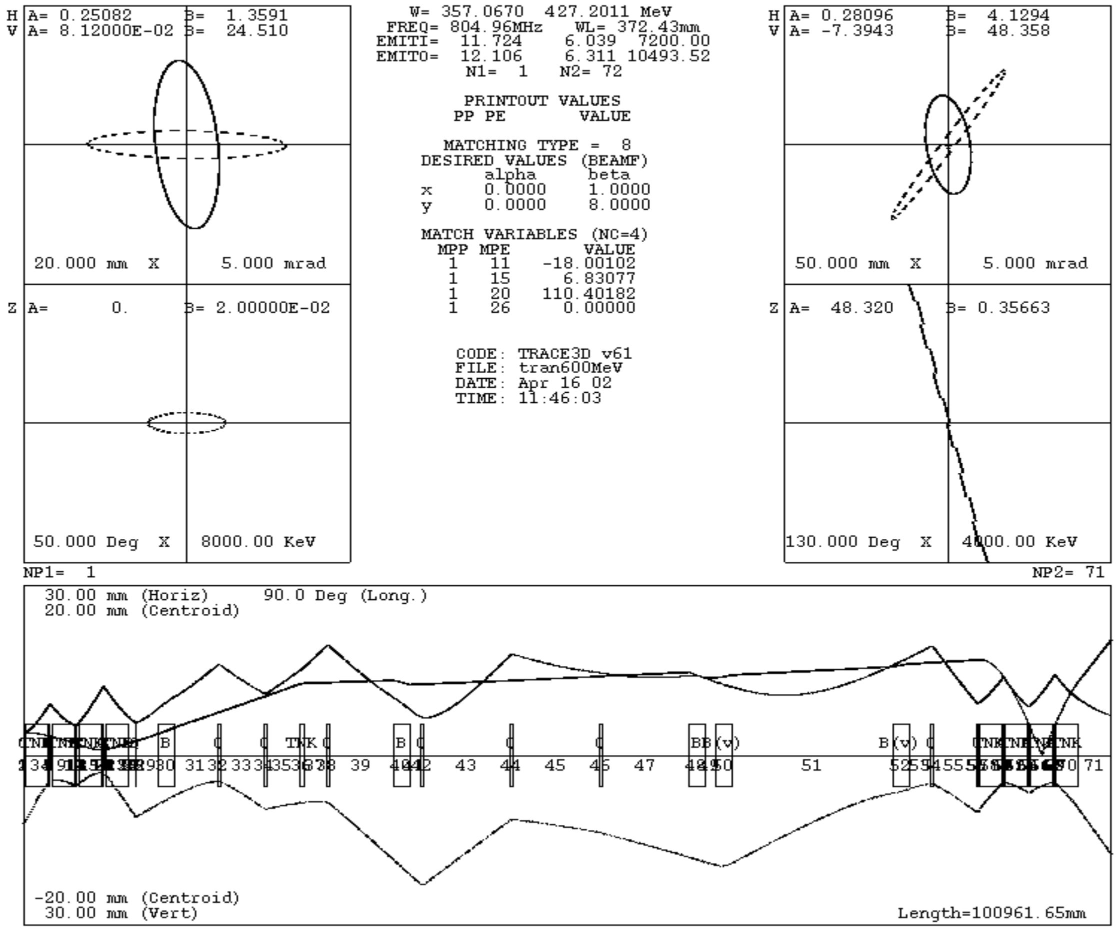

Figure 8.1. Trace-3D simulation of the 400 MeV beam transport line.

8.3.2 Options for Extending the Energy

The side-coupled structure and the Litton 12 MW klystrons used for the last ten years to extend the Linac energy from 116 MeV to 400 MeV have been satisfactory and reliable. Therefore, the choice of RF structure and power source to extend the Linac energy from 400 MeV to 600 MeV is to simply build more accelerating modules and use the same proven klystrons. The technology for constructing side-coupled cavities and building the RF systems was developed at Fermilab and the expertise exists to replicate the required systems for extending the Linac to this higher energy.

Using the more recent technology of superconducting accelerating cavities to extend the energy has been considered. If the long-range plan for the Linac were to ultimately extend the Linac energy beyond 1.0 GeV, then the development of superconducting accelerating cavities might be more favorably considered for the 200 MeV Linac extension. However the most cost-effective and simple solution is to replicate the existing Fermilab technology and this is what is proposed in this report.

8.3.3 Cavity Parameters

In order to extend the Linac energy by 200 MeV without exceeding the criteria for excessive sparking in the cavities, i.e. approximately 1.4 times the Kilpatrick limit of 26 MV/m at 805 MHz, 4 or 5 modules will be required. For this design a module is defined as four sections containing a fixed number of accelerating cells with the RF energy in the sections connected to each other via couplers of length 3/2 $\beta\lambda$. This space also allows the incorporation of quadrupole focusing elements within and between the modules. The RF power required for each module must not exceed the maximum RF power limit of the klystron used to excite the module. If these criteria are used in the design, then 5 modules of 40 MeV energy gain would be required. This segmentation of the structure results in a reduced peak surface voltage in the accelerating cavities, but this reduction would allow more stable operation (less sparking) for longer RF pulse-lengths and higher accelerated beam currents. Since these modules would be installed in a new enclosure containing the transport system to the synchrotron, the rigid sparking limits required in the old CCL modules would not be required.

At this stage of the design it is reasonable to use the same geometry of the accelerating cells that was developed for the lower energy side-coupled cavities. The program SUPERFISH was used to calculate the transit time factor T, the effective shunt impedance ZT^2 and the ratio of the maximum surface field and average accelerating field E_{max}/E_0 at several values of β corresponding to the energy range 116 to 400 MeV. Work was also done with the three-dimensional code MAFIA to confirm the results. Third order fits to the SUPERFISH results were made to derive the parameters necessary for the design of the accelerating sections. These data are used in the design of the modules from 400 to 600 MeV. These third order fits are:

$$ZT^2 = -34.700 + 266.92\,\beta - 247.07\,\beta^2 + 70.320\,\beta^3$$

$$T = 0.55963 + 1.2351\beta - 1.7236\,\beta^2 + 0.82560\,\beta^3$$

$$E_{max}/E_o = 1.5247 + 13.871\beta - 22.351\beta^2 + 13.507\beta^3$$

$$G/2 = -0.19017 + 4.1735\beta + 0.67878\,\beta^2$$

Using these parameters the design of the five modules to accelerate the beam from 400 to 600 MeV is shown in Table 8.5.

The grayed area displays the values for our existing Module 7, with the power numbers adjusted, through fudge factors on the shunt impedance and the total cavity power, to match the power measurements made on this operating cavity.

Table 8.5. CCL Module Parameters

Module #	Delta (KE)	KE(out)	Ave Beta	ZT**2	Lgth	E(max)	%E(k)	P(Cu)	P(cavity)	P(beam)	P(total)
7	44.4	401.5	0.70185	55.24	8.364	35.61	137%	7.6	7.6	2.22	9.79
8	40	441.5	0.72359	55.72	8.623	31.44	121%	5.9	5.9	2	7.91
9	40	481.5	0.74189	56.05	8.841	30.97	119%	5.7	5.7	2	7.73
10	40	521.5	0.75830	56.30	9.037	30.58	118%	5.6	5.6	2	7.58
11	40	561.5	0.77309	56.48	9.213	30.27	116%	5.5	5.5	2	7.46
12	40	601.5	0.78648	56.61	9.373	30.01	115%	5.4	5.4	2	7.35

Note that this table has very conservative values for the maximum electric field in the cavities: only about 20% over the Kilpatrick limit. The existing Linac was designed to a Kilpatrick factor of 140%, and the sparking rate is very acceptable. It is reasonable to redo this table with a more aggressive Kilpatrick factor and either (a) increase the energy out of this Linac segment (we estimate that an extra 5% of energy gain could be obtained in this way, to 630 MeV) or (b) reduce the number of cells in a section, thereby reducing the length of this addition.

8.3.4 RF Systems

The same Litton klystrons, locally built modulators/pulse-forming networks and computer controls will be used. The only change, other than modernization possibilities that may arise during the remanufacture of these items, would be a 20% increase in the pulse that the modulator/PFN can produce.

8.3.5 Maintenance Issues

The klystron gallery, containing the RF equipment, modulators, PFNs and controls for the five new 805 MHz cavities, should be built so that when the existing Booster is decommissioned, this new gallery may be connected to the exiting gallery. This will simplify the transfer of components between the galleries.

8.4 New Beam Diagnostics and Controls Requirements

The new Linac will need enhanced beam diagnostics and controls in order to measure the beam characteristics required to maintain the low losses specified in this proposal.

It will be necessary to include appropriate beam diagnostics in the 400 MeV transfer line to insure that the required bunching is maintained. Given the potential for a decrease by a factor of 10 in the losses in the existing Linac, it will be necessary to improve the character of the beam, our understanding of it and our ability to measure these losses.

The construction of this new accelerator will be an opportunity to upgrade and improve the Linac control system. For example, enhanced fast digitizers on all channels should be possible and would be desirable. Also, a simplified access to the data, possibly through the Web, should be considered.

8.5 Shielding Issues

The passive shielding that surrounds the existing Linac enclosure is, for the most part, inadequate for protecting adjacent areas from a sustained beam loss within the enclosure. A radiation safety system, utilizing 15 interlocked detectors, is installed to protect adjacent areas from excessive radiation levels. This same system will be sufficient for protecting the same areas for the proposed beam requirements, but modifications to the beam line component arrangement will likely require another shielding assessment to determine optimum interlocked detector locations. The 1991 and 1993 Linac Shielding Assessments can provide a description of the complex Linac passive shielding arrangement, and the associated interlocked detector arrangements.

Proposed modifications to the low energy end of the Linac may cause radiation levels near the existing 750 KeV end to increase. There is no passive shielding between the 750 KeV end of the Linac enclosure and the Pre-Accelerator enclosures. Depending on the positioning of the proposed RF cavities and RFQs, x-ray radiation levels in occupied areas may become excessive. In addition, it has been observed that varying amounts of backscattered radiation from the Linac enclosure finds its way into this area. This area is routinely monitored with an area film badge and these data show that doses in excess of 200 mrem/quarter, both for gamma and neutrons, are common.

The current proposal to have Linac beam re-directed at the south end of the existing Linac towards the new 600 MeV transport line will have to be done very cleanly to prevent beam from being inhibited by the 400 MeV labyrinth interlocked detector. The passive shielding above the existing, non-occupied utility portion of the Linac will be insufficient for the proposed transport line. Additions and modifications of the existing Linac Radiation safety system will have to be made.

The proposal for using 12.5 feet of passive earth shielding over the 600 MeV transport line will require a radiation safety system to limit beam loss within that enclosure. Consideration should be made to make the 600 MeV enclosure completely separate from the existing 400 MeV enclosure. This would require separate electrical and radiation safety systems, but would allow for the operation of the existing Linac while the 600 MeV portion is open for access.

8.6 Recent Measurements of the Losses in the Linac

Currently, we estimate losses in the high-energy segment of the existing Linac to be between 0 mA and 3 mA. The beam toroids do not measure any beam lost in the high-energy segment of the existing Linac. However, if we examine the loss monitors there carefully, there is possibility of a non-negligible loss in this segment. A measurement has been made recently to determine the correlation between the losses and the beam current lost. The sum of the loss monitors in the 805 MHz segment is correlated with the beam lost in this segment, as measured from the toroids, when we intentionally mistune an element at the beginning of the segment. We measure a correlation of about 20 “counts” on this sum per milliamp lost on the toroid. A constant reading of 54 “counts” on this channel, which is typical today, would correspond to 2.7 milliamps of beam lost in this segment of the Linac. This assumes that there is no offset in this loss reading. Naturally, the actual lost beam current is less than or equal to this value.

Assuming a constant loss throughout the 64 m 805 MHz segment of the Linac, then we observe at most 42 μA/meter of loss. At 116 MeV, this is a peak loss of about 5 kW; at 401 MeV, 16.8 kW. Normalizing to our beam-on duty factor of 0.09%, times our beam request duty factor of about 2% of the pulses actually being used, these losses become 0.1 to 0.3 W/m.

At this level of loss, we measure activation in the Linac to be as high as 12 mrem/hour at 1 foot, after 4 hours of cool down. The maximum activation measured in the 401 MeV transfer line to the Booster occurs at the Lambertson (which is scheduled for replacement in the summer of 2002) of 130 mrem/hour at one foot, after a 4-hour cool down. Thus, these levels are adequate for hands-on maintenance.

In conclusion, the upper limit for the beam lost in the 805 MHz segment of our existing Linac is 0.3 watts per meter. The peak activation is measured in the 805 MHz segment as 12 mrem/hr at 1 foot, measured at approximately 200 MeV, where the peak losses are less than 0.2 W/m.

Appendix 402 MHz Low-Energy Linac Replacement

Although not necessary for PD2, it would be highly desirable to consider the replacement of the entire drift-tube section of the Linac as part of the project for upgrade of the low-energy portion of the Linac. In the PD1 [1] arguments were made for the replacement of the Cockcroft-Walton preaccelerators by the more modern and accepted Radio-Frequency Quadrupole (RFQ) accelerating structure. Also it was pointed out that a large degradation in the quality of the accelerated beam occurs in the first drift-tube accelerating cavity, up to 10 MeV, as a result of the inferior alignment of the quadrupoles and the poor fabrication techniques used when this cavity served as a prototype for the fabrication of the other eight cavities in the Linac. The 200 MHz drift-tube section of the Linac is now over 30 years old and increasing operational demands are continually being requested.

The RF system for the DTL will soon require modifications to replace tubes that are no longer commercially available. The hard-tube modulators will require a redesign. The final power amplifier tubes are no longer available and rebuilding the failed tubes will be limited. For increased beam pulse-lengths, the power supplies for the pulsed quadrupoles will require replacement or extensive modification. Degradation of the elastomer seals on the drift-tube tanks will become a greater problem.

The technology of the design and fabrication of drift-tube accelerating structures has advanced considerably since the Fermilab Linac was constructed. Higher frequency structures powered by klystron-based RF systems are now the preferred choice. Permanent-magnet quadrupoles for radial focusing can be conveniently installed in the smaller drift-tubes. An example of a more modern DTL Linac was the one constructed for the Super-Conducting Super Collider Project. A commercial company fabricated this Linac. This company is routinely constructing DTL linacs that are mainly being sold for medical applications**.** [5,6] The technical specifications of one of their designs meet closely the requirements for a replacement for the Fermilab DTL. The budgetary cost estimate furnished at our request is considered a reliable estimate for the replacement cost of the Fermilab DTL.

The proposed system beyond the ion source and LEBT (Low Energy Beam Transport) consists of the following components:

- RFQ: A conventional four vane RFQ operating at 402.5 MHz to bunch and accelerate a 35 keV H^- ion beam up to 3.0 MeV is proposed. A matching section is built into the high-energy section of the RFQ to permit direct injection into the Ramped Gradient Drift Tube Linac (RGDTL) structure.

- RGDTL: The RFQ is close-coupled to a short section of a conventional DTL operating at 402.5 MHz. The fields in The RFQ are ramped to match the beam phase space from the RFQ at its input. The RGDTL accelerates the bunched 3 MeV beam from the RFQ up to 7 MeV for injection into the main DTL structure.

- DTL: A standard drift tube Linac operating at 402.5 MHz accelerates the H^- beam up to 70 MeV. This 20-meter length DTL consists of three tank sections with 102 drift tubes mounted in them. Each tank is made up of four sections and is driven by a 4 MW klystron RF system. RF power is fed to the tank through a waveguide window mounted on one of the tank sections.

- Matching Section: The Coupled Cavity Linac (CCL) structure used in the 400-MeV upgrade has a higher accelerating efficiency than the DTL above 70 MeV. The longitudinal phase of the bunched beam at 70 MeV in the 402.5 MHz DTL allows the beam to be matched into the 805 MHz CCL. And since the fabrication of CCL structure is well understood at Fermilab, it is a design choice to fabricate two CCL modules to extend the acceleration of the beam to 116 MeV where it would enter the existing CCL accelerating modules. The phase space of the 70 MeV H^- beam from the DTL is matched into the CCL using a 3.25 meter beam transport system containing two bunchers operating at 805 MHz and nine quadrupole magnets. The components used in the present system could be used in the lower energy matching system.

- Coupled Cavity Linac: The final stage of the system would be two side-coupled modules of conventional Fermilab design. This stage would consist of four sections of coupled cavities joined by 3/2 $\beta\lambda$ bridge couplers to accommodate the radial focusing quadrupoles and RF fed from the center-coupling cell of the module. These two modules would accelerate the beam to 116 MeV.

- Klystron/Modulator Systems: Three 4 MW, 402.5 MHz klystrons are used to power the constant gradient DTL tanks. The 10 MW RF systems for the CCL would be replicates of the existing 805 MHz RF systems in the Linac.

Table 8.6 lists the parameters of the proposed replacement DTL for the present Fermilab DTL.

Table 8.6. Parameters of the New 402 MHz Low-Energy Linac Section

			DTL				CCL		
		RFQ	**Tank 1**	**Tank 2**	**Tank 3**	**Tank 4**	**Match Section**	**Mod 1**	**Mod 2**
Input Energy	MeV	0.035	3	13.4	32.9	51.6	70.3	70.3	93.3
Output Energy	MeV	3	13.4	32.9	51.6	70.3	70.3	93.3	116.5
Delta E	MeV	2.965	10.4	19.5	18.7	18.7	0	23	23.2
Beam Current	mA	70	55	55	55	55	50	50	50
Frequency	MHz	402.5	402.5	402.5	402.5	402.5	805	805	805
Beam Pulse Length	usec	90	90	90	90	90	90	90	90
RF Pulse Length	usec	130	130	130	130	130	125	125	125
Rep Rate	Hz	15	15	15	15	15	15	15	15
RF Duty Factor		0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
Average Axial Field	MV/m		2.4 to 4.6	4.6	4.6	4.6	7.5 to 7.35	8	8
Length	m		4.5	6	6.1	6.2	3.25	4.8	4.9
Structure Power	MW		1	1.75	2	2		5.4	5.4
Beam Power	MW		0.63	1.07	1.02	1.02		1.38	1.39
Total Klystron Power	MW		2.5	3.8	4	4		8.5	8.5

The cost estimate of this 402 MHz low-energy system in 2002 dollars is as follows (in K$):

Components, including the RFQ, RGDTL, DTL, matching section, CCL, DTL rf systems, matching section rf systems, beam diagnostics, and the control systems	24,649
Installation and commissioning	2,500
Building modifications	500
TOTAL (K$)	27,649

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