Fermi National Accelerator Laboratory

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A Development Plan for the Fermilab Proton Source

Edited by S.D. Holmes
For the Proton Source Summer Study Group

Fermi National Accelerator Laboratory
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I. INTRODUCTION

The present Fermilab Proton Source is composed of a 750 KV ion source, a 400 MeV Linac, and an 8 GeV Booster synchrotron. This facility currently provides proton beams at intensities up to 5×10^{10} protons/bunch for injection into the Main Ring in support of the current Tevatron fixed target run. Following completion of the Main Injector project in 1999, the Proton Source is expected to provide protons to the Main Injector at an intensity of 6×10^{10} protons/bunch as required to meet established performance goals for Tevatron Collider Run II.

With the advent of the Main Injector the demand for protons in support of a diverse physics research program at Fermilab will grow. This is because the Main Injector creates a new capability for simultaneous operation of the collider and fixed target programs at 120 GeV. It has also been recently appreciated that a physics program based on the utilization of unallocated 8 GeV Booster cycles is potentially very attractive. A variety of experiments are either approved or under consideration including the Neutrinos at the Main Injector (NUMI) project, Kaons at the Main Injector (KAMI), and an rf separated K^+ beam for CPT tests, all utilizing 120 GeV protons, and a low energy neutrino (MiniBooNe) or muon program based on 8 GeV protons from the Booster. In addition significant effort is now being invested in defining paths to a factor of five improvement in Tevatron collider luminosity beyond those expected in Run II and in understanding the possible future siting of either a very large hadron collider or a modest energy "First Muon Collider" (FMC) at Fermilab. Support for these varied activities is beyond the capabilities of the current Proton Source--in the case of the FMC by about a factor of ten as measured in delivered protons per second.

The purpose of this document is to describe a possible evolution of the Fermilab Proton Source over the next ten years. The goal is to outline a staged plan, with significant enhancements to the Fermilab research program evident at each step, and with minimal disruption to the ongoing program from required construction activities. As will be described in the body of this document we believe that such a plan would be constructed of some, or all, of the following components:

- Relocation of the Booster
- Upgrading of the Linac energy
- Construction of a new Booster with higher energy and larger aperture
- Construction of a new intermediate energy Pre-Booster

An evolutionary implementation of these improvements is envisaged with benefits accruing to the Main Injector and Tevatron based program at each stage. The timing of these stages, and possible consolidation of multiple stages, will presumably be dictated by the availability of normally scheduled program interruptions in the Fermilab program and by the availability of funding. Upon completion of the final stage it is anticipated that the new Fermilab Proton Source would have the following capabilities:

- Support for proton targeting for antiproton production at a rate five times the Run II specification
- A factor of five increase in the number of protons available for Main Injector fixed target operations.
- A factor of five increase in the number of protons available for a low energy neutrino program.
- Support for muon production at a rate sufficient to achieve a luminosity of $\sim10^{33}$ cm^{-2}sec^{-1} in a 500 GeV (center-of-mass) muon collider.

This document describes a particular scenario that has been developed as part of the 1997 Beams Division summer study. This scenario is regarded as representative but not necessarily optimal. Impacts on the Fermilab program of each step are discussed, as are technical issues and areas of fruitful R&D, a cost envelope, and options for alternative implementations. It is expected that these options will be examined further as part of the natural development of a more concrete plan for proceeding.

I.1 Current Proton Source Performance

The performance of the Proton Source is characterized by the number of protons per bunch, the number of protons per second, the transverse emittance, and the longitudinal emittance. Under current operating conditions the number of protons per bunch is fundamentally limited by the space charge tune shift achievable at the 400 MeV injection energy and the aperture of the machine, the number of protons per second by the available shielding, the transverse emittance by the space charge forces at injection, and the longitudinal emittance by the momentum spread delivered from the linac and our ability to control longitudinal instabilities. Figures I.1 and I.2 characterize current performance.

Figure I.1 displays Booster performance, as measured by transverse beam emittance (95%, normalized), as a function of intensity. Two sets of points are included: the "200 MeV" points refer to pre-September 1993 operations when the injection energy was 200 MeV. The "400 MeV" points refer to current operations with a 400 MeV injection energy. Booster performance has long been believed to be limited by space-charge forces at injection. The straight lines through the points represent contours of constant space-charge tune shift (~0.4) as calculated at the injection energy. The data demonstrate that the improved performance attained by raising the injection energy is as anticipated based on a fixed space-charge tune shift limit. By way of reference the Booster and Main Injector apertures are approximately 20π and 40π mm-mr respectively. As can be seen from the figure an emittance of 15π mm-mr is expected at the nominal Main Injector operating intensity of 6×10^{10} protons/bunch.

Figure I.2 shows the performance of the Booster as measured in longitudinal emittance (95%, per bunch) during the period covered by operations with a 200 MeV and with a 400 MeV injection energy. Based on extrapolation of the 200 MeV points the Main Injector was designed with an acceptance of 0.6 eV-sec. As can be seen the achieved performance is dramatically better than had been assumed. This improvement is not directly related to increasing the injection energy, but has been achieved through the implementation of dampers to control several longitudinal coupled bunch modes. The improved performance has created options for increased Main Injector intensities based on slip stacking, a subject that is beyond the scope of this report.

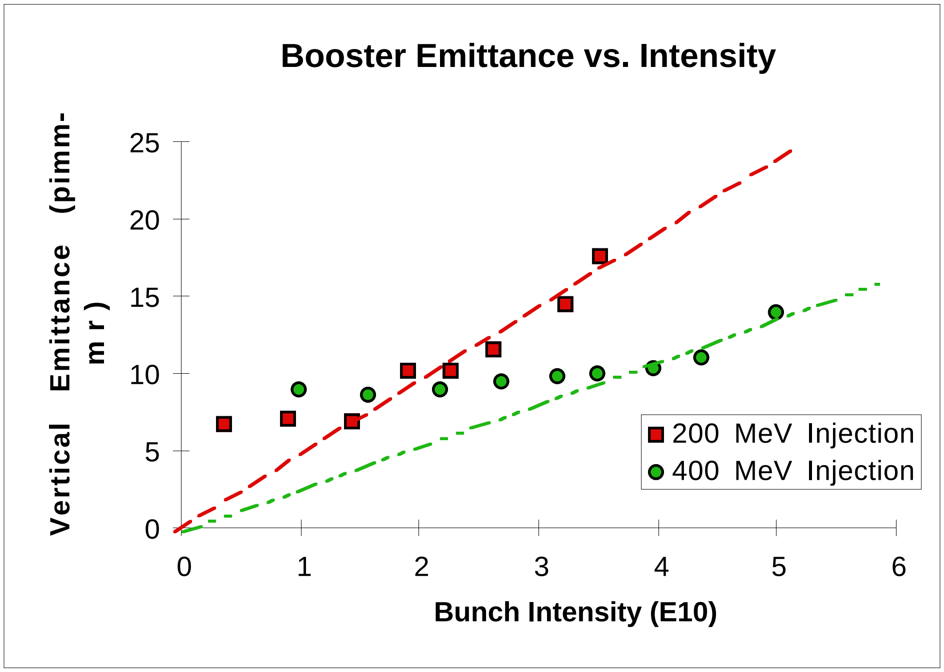


Figure I.1: Measured transverse beam emittance (95%, normalized) delivered from the 8 GeV Booster as a function of beam intensity. The "200 MeV" points were measured when the injection energy was 200 MeV. The "400 MeV" points correspond to the current 400 MeV injection energy. The straight lines represent contours of constant space-charge tune shift as calculated at the injection energy.

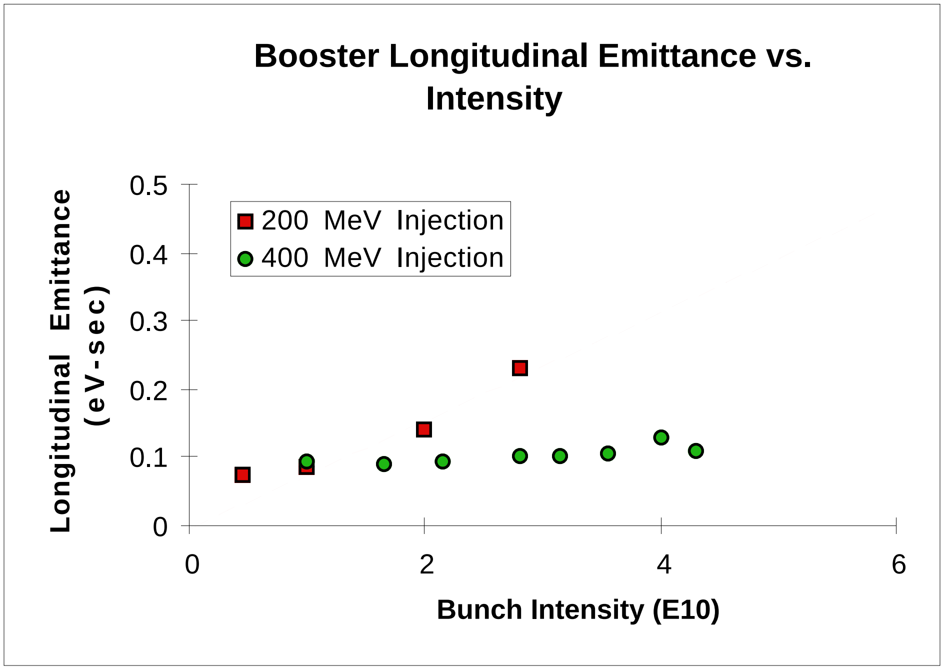


Figure I.2: Measured longitudinal beam emittance (95%) delivered from the 8 GeV Booster as a function of beam intensity. The "200 MeV" points were measured when the injection energy was 200 MeV. The "400 MeV" points correspond to the current 400 MeV injection energy.

I.2 Design Criteria

The anticipated performance of the Proton Source in 1999 (6×10^{10} protons/bunch with a transverse emittance of 15π mm-mr and a longitudinal emittance of 0.1 eV-sec/bunch) is sufficient to support the goals of antiproton production for Run II, NUMI or KAMI, and the fast extracted neutrino experiment MiniBooNe--assuming the implementation of an effective shielding solution in the Booster that will allow operations beyond the currently authorized level of 9×10^{15} protons per hour. Utilization of the Proton Source in support of a slow spill derived muon beam and a 500 GeV muon collider are both clearly beyond current capabilities. Support for an upgrade of the Tevatron collider luminosity or a proton-antiproton implementation of the VLHC injector may or may not be within current capability, depending on the antiproton production strategy implemented.

Support for the muon collider is by far the biggest challenge for a future Proton Source at Fermilab. The requirements include the capability of providing at 16 GeV:

- 5×10^{14} protons per second
- 5×10^{13} protons per bunch
- 2 nsec (rms) bunch length

In addition, the shielding requirements associated with delivering 1.8×10^{18} protons per hour are so far beyond the capabilities of the present Booster that a relocation of the Proton Source is probably unavoidable.

Design criteria have been established for an upgrade Proton Source based on the requirements of the 500 GeV FMC, with an auxiliary goal of defining a configuration that simultaneously enhances Fermilab's ability to support the broad scope of hadron-based capabilities described above. Design criteria thus derived, and serving as the basis for this study, are given in Table I.1.

Table I.1: Design criteria for an upgraded Proton Source at Fermilab.

	Muon Production	Main Injector Injection	Booster Fixed Target	
Energy	16	16	8-16	GeV
Repetition Rate	5	2	8	Hz
Number of bunches	2	12-84	12-84	
Protons per bunch	5×10^{13}	$21\text{-}3\times10^{11}$	$5\text{-}0.12\times10^{13}$	
Protons per pulse	1×10^{14}	2.5×10^{13}	1×10^{14}	
Transverse emittance (95%, normalized)	240π	50π	240π	mm-mr
Longitudinal emittance (95%, total)	2	20	20	eV-sec

The selection of parameters in this table is influenced by the following considerations:

<u>Energy</u> is selected to be near the optimum muon production energy as measured in muons per incident beam power.

<u>Total repetition rate</u> is defined as three times the muon collider requirement in order to provide flexibility in the balance of the Fermilab program.

Number of bunches is the FMC requirement for muon collider operations; or as consistent with the Main Injector rf system in the case of Main Injector or Booster stand-alone operation.

Protons per pulse is the FMC requirement at the selected energy and repetition rate; or maximum projected Main Injector capability (2.5×10^{13} protons per Booster pulse).

Transverse emittance is defined to keep space charge at injection within the range of experience at Fermilab, and to fit into the Main Injector aperture when required.

Longitudinal emittance is defined as the FMC requirement for muon collider operations. For Main Injector and Booster operations a factor of ten lower performance is acceptable.

I.3 Operating Scenarios and Proton Economics

An upgraded Proton Source with the performance characteristics given in Table I.1 would have the ability to support a varied program at Fermilab both before and in parallel with a muon collider facility. Full exploitation of the new Proton Source would require utilization of close to the full 15 Hz cycle rate available. Table I.2 describes a scenario for utilization of available Proton Source cycles during the period starting from the present to an era in which a muon collider is operating on the Fermilab site. Three eras are described in the table--"Near term hadron", encompassing Tevatron Collider Run II, 120 GeV Main Injector fixed target, and a Booster fixed target program; "Longer term hadron program", encompassing antiproton production enhancements in support of either Tevatron or higher energy collider operations, accompanied by significant enhancements in Main Injector and Booster fixed target capabilities; and finally "Muon Collider", encompassing a muon collider operations, possibly in parallel with continued Main Injector and Booster fixed target programs.

Table I.2: A possible allocation of Proton source cycles based on 15 Hz operations.

Near Term Hadron Program	Booster Intensity	Rate (Hz)	
Required upgrades: Booster shielding			
Booster supercycle: 28/15 sec			
Antiproton production	5×10^{12}	0.536	Run II goal
NUMI	5×10^{12}	2.678	NUMI request
MiniBooNe	5×10^{12}	4.821	MiniBooNe request
Booster Muons	5×10^{12}	6.964	
Booster supercycle: 43/15 sec.			
Antiproton production	5×10^{12}	0.349	Run II goal
KAMI	5×10^{12}	1.744	Available for slow spill
MiniBooNe	5×10^{12}	4.884	MiniBooNe request
Booster Muons		8.023	
Longer Term Hadron Program			
Required upgrades: Linac upgrade, new (relocated) Booster			
Booster supercycle: 28/15 sec.			
Antiproton production	2.5×10^{13}	0.536	Antiproton production $\times$ 5
MIST	2.5×10^{13}	2.678	MIST $\times$ 5
Booster Neutrinos	2.5×10^{13}	4.821	MiniBooNe $\times$ 5
Booster Muons	2.5×10^{13}	6.964	
Muon Collider Era			
Required upgrades: Pre-booster, linac rf upgrade, Booster rf upgrade			
Booster supercycle: 30/15 sec.			
Muon production	1×10^{14}	5.000	FMC requirement
Main Injector Fixed Target	2.5×10^{13}	2.000	MIST $\times$ 5
Booster Fixed Target	1×10^{14}	8.000	

II. DESIGN DESCRIPTION

II.1 Design Considerations

The Fermilab physics programs of the future need a reliable, high-performance proton source. A straightforward approach to meet the diverse and demanding needs of those programs is described. In particular, the considerations that lead to the choice of first-iteration values for major parameters for the synchrotron rings are presented.

The perfect proton source for Fermilab would be able to deliver beams having the ideal beam parameters for all possible future physics programs. Among the possibilities presently envisioned are beams for the Tevatron collider and for the VLHC, for antiproton production, for fixed-target physics based on the Main Injector, for experiments such as MiniBooNe that use beam from the source directly, and for muon production for a muon collider.

The muon collider makes such severe demands on the proton source that it tends to dominate design considerations. Over the last few years, various approaches to meet those needs have been explored. Within the last year a simple approach has been developed that not only satisfies the requirements of the muon collider but also can be adjusted, by appropriate parameter choices, to match the needs of the rest of the future program.

Muon Collider Requirements

Two short (2 nsec rms) bunches each containing 5×10^{13} protons at an energy around 16 GeV and a repetition rate of 5 Hz would meet the needs of a high-performance muon collider. (The proton source requirements are about the same over the whole range of final muon collider energies that have been considered, from 50×50 GeV up to 2×2 TeV.) These specifications deserve some elaboration.

A kinetic energy of 8 GeV rather than a higher energy would seem a natural choice for a proton source at Fermilab; 8 GeV is the energy of the present Booster and antiproton source as well as the design injection energy of the Main Injector. However, the performance of the Main Injector is likely to benefit from raising its injection energy. Not only would space-charge effects be alleviated, but the available normalized aperture would roughly double, scaling with momentum. (The ultimate benefit would derive from raising the injection energy above the Main Injector transition energy of about 20 GeV, or alternatively lowering the transition energy.) Furthermore, existing data and simulations suggest that to get the same pion yield about 70% more protons would be needed at 8 GeV than at 16 GeV for muon collider operations. Some uncertainties exist in the pion production cross sections at low secondary momenta ($p<0.3$GeV/c), and current data are insufficient to resolve them. An experiment is in progress at the Brookhaven AGS designed to shed light on this situation.

The design under study has an output kinetic energy of 16 GeV; that value results from constraining the circumference of the second ring to match that of the existing Booster. There are two main advantages of this choice. First, the second ring could occupy the same tunnel as a relocated Booster; secondly, the beam batch length from the second ring would match that of the present Booster, which would be ideal for antiproton production. Note, however, that the existing Booster magnets can not go beyond about 10 GeV.

The proton bunch structure for the muon collider is specified at the pion production target; it might be achieved by combining several bunches at the target via chicanes. However, the present design adopts the straightforward approach of accelerating only two bunches. Regarding the bunch length, an rms value of 1 nsec is preferable, especially if it is desired to enhance the natural muon polarization, but the muon collider designers are willing to settle for 2 nsec. It is worth noting that the combination of high bunch intensities and short bunch lengths makes it difficult to avoid space-charge problems in the rings.

This study adopts the 15-Hz repetition rate of the existing proton source at Fermilab. The factor of three over the muon collider specification of 5 Hz can be regarded either as a safety factor or as enabling operation of other physics programs at the same time as the muon collider.

Synchrotron Design Concepts for Muon Production

The present plan for achieving the muon collider performance specifications calls for two rapid-cycling synchrotrons in series, each of which accelerates two bunches at a time. Table II.1 presents major parameters of the two rings. The strategy for achieving the required short bunches at the target while alleviating space-charge effects in the rings is to start with two relatively long bunches occupying most of the circumference of a small ring, and to do a bunch-narrowing rotation in longitudinal phase space just before extraction from each stage. In order to simplify matching of the bucket contour in the second ring to the rotated bunch distribution emerging from the first ring, the rf frequency in the second ring is chosen to be a multiple of that of the first ring. The rf frequency ratio, herein sometimes called the compression ratio, is chosen to be four in the present design.

The Laslett incoherent space-charge tune shift limits the beam brightness at low energy. The limitation on beam intensity can be raised by increasing the injection energy and by making the transverse emittances larger. Of course physical and dynamic apertures must be large enough to accommodate the large emittances. A useful approximation for the space-charge tune shift $\Delta\nu_{sc}$ at the center of a round Gaussian beam is

$$\Delta\nu_{sc} = -\frac{3 r_p N_{tot}}{2\varepsilon_n \beta\gamma^2 B}$$

In this expression $r_p = 1.54\times10^{-18}$ m is the electromagnetic "radius" of the proton, N_{tot} is the total number of protons in the ring, ε_n is the 95% normalized transverse emittance, β and γ are the usual Lorentz kinematic factors, and B is the bunching factor, defined as the ratio of the average beam current to the peak current. Note that B is always less than or equal to one.

Both rings have peak dipole fields of 1.3 T in order to keep the ring circumferences relatively small while still allowing straightforward design of the conventional magnets. The magnet design is discussed elsewhere. Both rings employ separated-function lattices with flexible momentum compaction in order to raise transition above the extraction energy. This not only avoids accelerating through transition but also provides other advantages. Intense beams are not subject to certain instabilities such as the negative-mass instability below transition and empirically seem less susceptible to other instabilities such as microwave instability. Also, the negative natural chromaticity is beneficial for stabilizing the beam below transition, perhaps obviating the need for sextupole correctors, especially in the first ring. Having transition not too far above extraction also provides substantial bucket area in which to accomplish beam-shortening rf manipulations. In the present design the transition energy is chosen to make the synchrotron frequency in the final stationary bucket high enough to accomplish the bunch rotation in less than about half a millisecond.

Careful design of the beam pipes for both rings is required in order to manage eddy-current effects. Two approaches are under consideration. One is a thin metal pipe with water cooling and eddy-current coil corrections integrated on the pipe as in the AGS Booster. The other is ceramic beam pipe with some sort of interior cage to carry beam image currents as in ISIS.

The first ring operates at a harmonic number h=2. This allows the two bunches to be formed directly and accelerated with efficient use of the whole circumference in order to keep the bunching factor large. Space-charge effects are alleviated by a high injection energy (1 GeV kinetic) and large normalized transverse 95% emittances (200 π mm-mrad). This produces a Laslett incoherent space-charge tune shift of 0.4 for a bunching factor of 0.25. Large magnet apertures of order 12 cm are necessary to accommodate these emittances.

Table II.1: Parameter list for a Proton Source capable of supporting muon production requirements for a First Muon Collider

	Linac	Pre-Booster	Booster	
Injection Energy (Kinetic)	---	1.0	4.5	GeV
Extraction Energy (Kinetic)	1.0	4.5	16.0	GeV
Circumference	---	180.65	474.20	m
Current	65	---	---	mA
Pulse Length	328	---	---	µsec
Protons/bunch	---	5×10^{13}	5×10^{13}	
Bunches	---	2	2	
Total Protons	1×10^{14}	1×10^{14}	1×10^{14}	
Repetition rate	15	15	15	Hz
Transverse Beam Emittance (95%, normalized)	7π	200π	240π	mm-mr
Bunching Factor	---	0.25	0.25×2/21	
Space-charge tune shift (injection)	---	0.39	0.39	
Longitudinal Emittance (95%, per bunch)	---	1.8	2.0	eV-sec
RF Voltage		0.148	1.23	MV
RF Frequency (injection)	805	2.90	13.08	MHz
RF Frequency (extraction)	805	3.27	13.26	MHz
Harmonic number	---	2	21	
Transition Gamma	---	7	25	
Synchrotron Frequency	---	473	378	Hz
Bunch Length (injection, 95% half-width))		83	21	nsec
Bunch length (extraction, 95% half-width)		21	2.3	nsec
Momentum spread (Injection , 95% half-width)	---	0.1	0.5	%
Momentum spread (Extraction , 95% half-width)	0.1	0.5	1.2	%

The transfer energy of 4.5 GeV between the two rings is chosen to equalize the space-charge tune shift in the two rings. In the tune shift formula, there are two factors of γ. Roughly speaking, one factor of γ is used to make up for the larger circumference of the second ring; the other factor of γ is used to compensate for the shorter bunch length resulting from the bunch rotation. Both effects reduce the bunching factor in the second ring.

The design of the required 1-GeV linac is discussed elsewhere; here only a brief overview is given. H^- injection is used. It is assumed that the injected beam will be chopped and injected into pre-existing buckets to achieve high capture efficiency; the detailed optimization of this process is just beginning. In simulations, adiabatic capture does not work well at the low rf frequencies considered here. A debuncher is included to allow injection of small momentum spread, should this prove beneficial for creation of relatively small longitudinal emittance at injection into the first ring. The specified bunch rotations at extraction from each ring are expected to create momentum spreads of order 1% with longitudinal emittances of order 1 eV-sec per bunch. Such spreads would contribute a few centimeters in quadrature to the beam size for a short period before extraction from each machine. This is thought to be tolerable, given the large apertures required in any case.

The magnet/power supply circuit for each ring is assumed to be a 15-Hz resonant system like that of the existing Booster, with dipoles and quadrupoles electrically in series. This implies that the second ring can accelerate only one batch of two bunches at a time from the first ring in muon production mode. Adding about 15% of second harmonic to the magnet ramp reduces the required peak accelerating voltage by about 25%, which is probably worth doing, especially for the second ring with its large voltage requirement. Alternatively one might want to consider a programmable, non-resonant system.

Table II.1 shows a few rf parameters such as accelerating voltages (in the absence of second harmonic) and rf frequencies. One of the advantages of a two-ring system is that the two rings divide the work of accelerating the beam. ESME simulations of longitudinal motion are underway; results to date have conformed qualitatively with expectations. In particular, the simulated rms bunch length at output of the second stage is consistent with a simple back-of-the-envelope estimate of 2 nsec, as desired. Accelerator studies at the Fermilab Booster and the Brookhaven AGS have begun to test bunch-narrowing concepts. Further work is in order, both experimental and computational, to optimize the bunch-shortening strategy. Also, longitudinal space-charge effects are important in these simulations; significant but tolerable emittance growth is predicted. High injection energies help to alleviate these longitudinal effects, which result from space-charge voltages having the same $1/\beta\gamma^2$ kinematic dependence as the transverse tune shifts. Incorporation of tunable inductive inserts in the rings is under consideration to compensate the space-charge voltages below transition. An experimental program is underway in collaboration with Los Alamos to study the effects of inductive inserts on the beam in the PSR.

Meeting the Needs of the Rest of the Program

Within the general framework of multiple rings in series with bunch rotations before extraction from each stage, there is considerable flexibility in the choice of parameters (including the number of rings!). The parameters can be chosen in order to match the output beam to the needs of the rest of the physics program.

The design considered here starts with the choice of the circumference of the second ring to match that of the existing Booster. The output energy of about 16 GeV then results from an assumed dipole packing fraction of 0.575 and from the estimation that a dipole field of 1.3 T is about the highest reasonable choice that is consistent with straightforward design of magnets having thin silicon steel laminations. Driving such magnets into saturation would cause significant heating of the magnet yoke as well as potential problems with tracking of the dipoles and quadrupoles.

The harmonic numbers of the two rings (2 and 21) and their respective circumferences are chosen in such a way that the bucket spacing in both is an integral multiple of the canonical Fermilab bucket spacing of 5.645 m. In particular, the circumference of the first ring is 8/21 times that of the second ring. Thus the bucket spacing in the second ring is four times, and that of the first ring is sixteen times, that of the Tevatron and Main Injector. The bunch structure resulting from either machine will then fall into buckets of any of the existing Fermilab rings. Thus the existing rf systems in downstream machines need not be replaced.

An important design idea results from the realization that the Main Injector is fundamentally mismatched to the capabilities of the first ring. The Main Injector is incapable of handling the bunch intensities of 5×10^{13} that the muon collider requires, and the fill time would be excessive at the rate of two bunches every 66.6 msec. The normalized emittance of 200 π mm-mrad from the first ring, or 240π mm-mrad from the second ring, also greatly exceeds the normalized acceptance of the Main Injector, which is specified as 40 π mm-mrad at 8 GeV and hence would be about 80π mm-mrad at 16 GeV.

The mismatch between the first ring and the Main Injector can be circumvented by the simple expedient of bypassing the first ring when filling the Main Injector. All 21 buckets of the second ring would instead be filled directly from the linac using H^- injection. The Main Injector could then be filled with one or more Booster-length batches just as presently planned. However, since the rf bucket length of the second ring is four times that of the Main Injector, only every fourth bucket of the Main Injector would contain beam.

It is worth noting that the first ring could be omitted if the muon collider does not materialize. However, if the first ring exists and the muon collider is not running, the output of the first ring could be used directly to support low-energy physics programs while the second ring is used to feed the Main Injector.

The capabilities of the second ring at an injection energy of 1 GeV are well-matched to those of the Main Injector, as can be seen by the following scaling. A normalized acceptance of 240 π mm-mrad at 4.5 GeV scales with momentum to 76 π mm-mrad at 1 GeV, closely matching the 80 π mm-mrad acceptance of the Main Injector at 16 GeV. The bunch intensity of 5×10^{13} at the space-charge limit at 4.5 GeV scales as $\beta^2\gamma^3$ to 1.8×10^{12} per bunch, or 3.75×10^{13} per Booster-length batch, or 2.25×10^{14} per six Booster-length batches, at 1 GeV. This is 7.5 times the Main Injector design intensity. According to estimates the Main Injector seems capable, with upgrades, of accelerating five times its design intensity.

The strategy of sometimes bypassing the first ring has several ramifications. It suggests a layout that has both rings tangent to the line from the linac as in Figure II.1. The first ring should have a long straight section that supports both H^- injection and 4.5 GeV extraction. The second ring needs a long straight section that supports H^- injection at 1 GeV and proton injection at 4.5 GeV. Scaling from the Fermilab Booster implies that H^- injection at 1 GeV requires about a 12-meter straight section. This suggests a racetrack configuration for both rings.

If it is desired to interleave cycles, some of which go into the first ring and some directly into the second, on a short time scale, then either the linac or Booster must be capable of asynchronous operation. This requires further study.

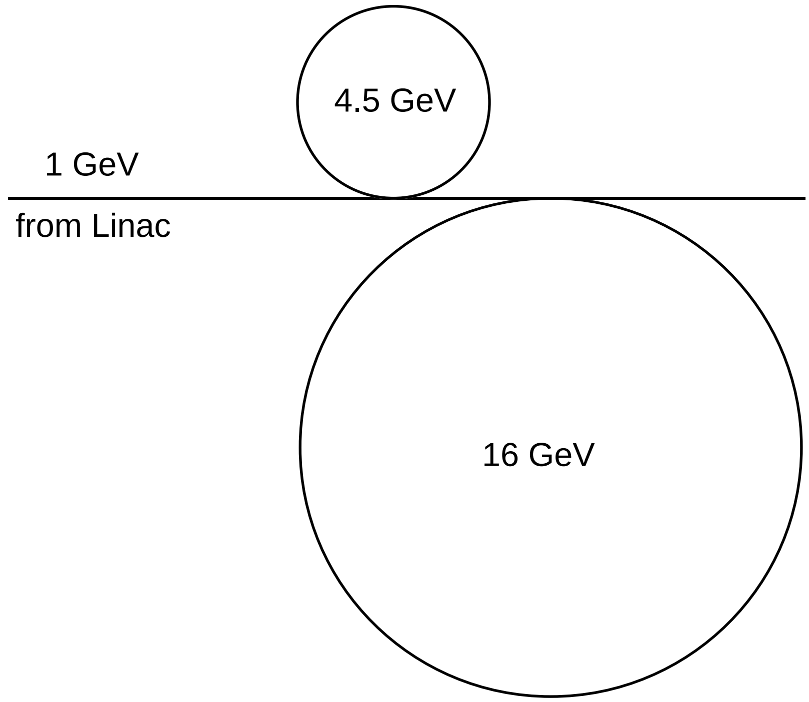


Figure II.1: Geometry of a new proton source. The 4.5 GeV pre-booster is situated to allow injection into the 16 GeV booster either directly from the linac or via the pre-booster.

II.2 Linac

At present the Linac delivers 1.6×10^{13} protons per pulse at a 15 Hz rate through the low energy linac for NTF treatment. This represents a pulse of 45 mA for 57 µs. This same current passes through the high energy linac to 400 MeV but with a pulse length seldom longer than 30 µs at 15 Hz. Since the high energy system runs continuously at 15 Hz with more than a 100 µs rf pulse length, operating at 1.6×10^{13} p/pulse at a 15 Hz rate for the full Linac is easily done.

The requirement for support of muon collider operations is 1×10^{14} protons per pulse at a 15 Hz at 1.0 GeV. The average current is a factor of six-to-ten beyond current capabilities, depending upon the extent of pre-bunching, while the energy is 600 MeV higher than the current facility. The upgrade strategy currently envisioned is a modest increase in the operating current, a significant increase in the pulse length, and construction of an additional 600 MeV of 805 MHz, side coupled linac identical in structure to the downstream end of the current linac. It is currently assumed that the linac would be relocated as part of this upgrade, although a plan to leave the existing structure where it is and extend through the to-be-abandoned Booster enclosure might be feasible.

Upgrading the existing linac

With a small effort it is likely that a pulse of 60 mA and 90 µs could be achieved. This represents a beam of 3.4×10^{13} protons, which at a 15 Hz rate provides 5×10^{14} p/sec. Increasing the ion source to reach this current has been studied and appears possible. The pulse length would at most need some correction for the voltage droop on the Pre-accelerator using a bouncer or Linac buncher correction. There appears to be no problem getting this pulse length with the present RF systems--50 mA has been accelerated through the high energy linac and 60 mA seems likely. At this level the Linac enclosure appears adequate.

Going to 1×10^{14} protons per pulse is significantly more difficult. This is probably best achieved by increasing the pulse length. We consider a pulse of 60 mA, ~270 μs long versus a 120 mA, ~135 μs pulse. Any increase exceeding $3\text{-}4\times10^{13}$ p/pulse from the Linac will require a new front end. This implies new sources, RFQs and a new Linac tank 1.

For 60 mA, 270 μs many changes will be needed to accommodate the longer pulse. The low energy linac will need an increase by a factor of three in the capacitance of the HV modulator capacitor bank or other HV compensation. The increased length will also require new or improved low level systems and possibly new pulsed quad supplies (which are presently being considered). In the high energy linac the RF power supplies, PFN modulators, klystron HV pulse transformers and oil tanks, RF low level controls, and the cavity water systems will need changing or upgrading. The RF water systems may also need upgrading.

For 120 mA, 135 μs the above modifications will still be needed but with slightly different considerations. In addition the peak RF power levels will exceed the low energy tube and the high energy klystron capabilities. The low energy 7835 power tube peaks at 5 MW which is equivalent in tanks 3 and 4 to the cavity power plus 90 mA. The high energy klystrons would also be well beyond their designed power limits requiring a peak of 15 MW from a 12 MW klystron. It may be possible to push the klystron to this level (actually more is needed for regulation) but a significant deterioration in performance is likely.

The high energy linac was designed for 50 mA with the bridge couplers considered for 35 mA. 35 mA was the Linac beam current at that time. The Linac now runs typically at 45 mA and a peak of 50 mA has been done. It is likely that the high energy linac will run at 60 mA but 120 mA is a significant extrapolation.

At the 1×10^{14} p/pulse, 15 Hz level the enclosure shielding, extrapolated from our present running, appears adequate except for a few areas that can be corrected. The exterior high energy berm may exceed the permissible limit for an open unmarked area but could be corrected with a fence and signs or by adding additional soil. The door at the 400 MeV labyrinth into the Linac tunnel and the 400 MeV cable penetrations may exceed their allowable limit. This may require closing off the labyrinth and sealing the cable penetrations. The labyrinth would need to be replaced with another entrance which could be located and better shielded on the other side of the Linac berm or in the Upgrade access-way. Depending on the mode of operation the beam to the Linac dump and that lost in the 400 MeV area could be significantly reduced thus lowering these radiation situations. With additional cavities to increase the Linac energy we would envision no beam to the dump and very low losses in the 400 MeV area except for a fault condition which, as at present, must be handled by detectors.

1000 MeV Linac Upgrade

The linac injector for a new proton Booster complex is assumed to have a kinetic energy of 1 GeV. An added 600 MeV of coupled cavity linac at 805 MHz could be joined to the end of the existing 400 MeV linac to achieve this energy. The new linac is sized to accelerate 75 mA of beam in a 340 μsec pulse at a 15 Hz repetition rate. This is adequate to produce 1.6×10^{14} protons per pulse, allowing for future improvements to the new Booster complex.

The average accelerating gradient E_0 is typically determined by some combination of sparking, power and length limitations. The 400 MeV linac was designed with a gradient of 7.5 MV/m since it needed to fit in the 60 m of available tunnel. The additional 600 MeV of linac is assumed to have a more conservative gradient of 6.5 MV/m for this cost estimate. The effective shunt impedance Z_{TT} is taken as 45 MΩ/m and varies slowly for side-coupled cavities above β = 0.7. The transit time factor T and cosine of the synchronous phase are taken as approximately

0.85. The accelerator packing fraction is 0.85, consistent with its value in the present 400 MeV linac. These values can be changed as a more detailed linac design evolves.

From these numbers, the peak cavity power is 0.678 MW/m, and the beam power is 0.353 MW/m. Including 10% extra power for reserve and control yields a total 1.13 MW/m of peak power. The total cavity length is 128 m, and the total accelerator length is 150 m. The total peak power capability is then 1.13 MW/m $\times$ 128 m = 145 MW, corresponding to about twelve rf stations if each is rated at 12 MW. The duty factor is 0.005 which determines the average power. Assuming 50% efficient klystrons, the modulators must supply 290 MW of peak power, and the average power dissipation in the rf gallery is 725 kW. The average power dissipated in the copper cavities is 434 kW, with 226 kW delivered to the beam.

II.3 Pre-Booster and Booster

The Booster currently delivers 4.2×10^{12} protons per batch at 8 GeV, at repetition rates of approximately 0.5 Hz, and with a total longitudinal emittance of about 8 eV-sec. The required performance in support of muon collider operations is 1×10^{14} protons per pulse at a 15 Hz at 16 GeV, divided into two bunches each with a longitudinal emittance of 4 eV-sec or less. The beam intensity required is a factor of twenty beyond current capabilities.

The upgrade strategy currently envisioned contains three primary components in addition to the previously discussed linac upgrade: 1)upgrading the Booster to 15 Hz operations; 2)construction of a new, larger aperture, 16 GeV Booster; and 3)construction of a new 4.5 GeV pre-booster.

Booster Extraction Upgrades

The largest impediment to 15 Hz operations at the current Booster intensity is the lack of sufficient shielding. The problems are both generic to the entire ring and specific to the L3 extraction area that resides underneath the Booster SW Towers. The short term goal is to identify improvements that will allow operations at 5×10^{12} protons per batch and 7.5 Hz. Effort is being directed towards minimizing losses and enhancing shielding to achieve this goal. Operations at a higher level are not consistent with the current Booster location and so will require relocation.

Three initiatives are underway to reduce extraction losses at L3. The first involves the relocation of kickers to provide the full complement of four kickers in the L2 straight section. This is expected to provide a cleaner extraction but the impact is hard to quantify prior to actual measurements. Second, the installation of new dogleg magnets into both Booster extraction areas is planned as a means of improving the extraction aperture. Installation will occur during the fall of 1997. The new doglegs will provide a 40π mm-mr circulating beam aperture as measured under the extraction septa in the Long 3 and Long 13 straight sections. They will also provide a 40π mm-mr 8 GeV extraction aperture. If needed the extraction aperture can be made larger, to as much as 60π. Finally, designs are in progress for rf hardware required to maintain a gap in the Booster beam that can be synchronized to the extraction kicker, thus minimizing losses on the extraction septum.

Studies of methods of enhancing Booster shielding are being conducted in parallel with this study and are not documented here.

Further improvements to the extraction systems will be required for proposed operation at higher beam repetition rates or with slow spill. The septum magnet cooling is presently inadequate to allow higher pulse repetition rates. The cooling for these magnets was designed to accommodate the resistive heating only, when in fact the dominant heating is due to eddy currents in the laminations. The MI-8 extraction septum cannot be operated above a 20% duty factor. It will be necessary at the same time to replace or upgrade the septum power supplies for the higher repetition rates. They were not designed for continuous high duty factor operation. Slow spill would require a complete re-design of the septum magnet and power supply as the existing system can operate in pulsed mode only.

Lattices

Lattice designs for both the pre-booster and the new booster have been initiated. Both lattices are of the "flexible momentum compaction" type, allowing for setting of the transition energy above the peak energy of the accelerator. This is particularly important in the case of the new Booster as it expedites the bunch rotation performed at the end of the acceleration cycle to produce the required 2 nsec bunches.

Lattice parameters are summarized in Table II.2. Lattice functions are shown in Figures II.2 and II.3. As shown the lattices incorporate sufficient straight section space for injection and rf. Yet to be incorporated are extraction areas and space for correction elements. Approximately 25/42 meters of circumference are available in the pre-booster/new booster lattices shown in Figure II.2/3 for incorporation of such space.

Table II.2: Pre-Booster and new Booster initial lattice parameters

	Pre-Booster	Booster	
Energy (kinetic)	4.5	16	GeV
Circumference	180.65	474.20	m
Straight sections	2×12	2×12	m
		14×6	m
Dipole Field	1.3	1.3	Tesla
Dipole length	1.5	1.25	m
Dipole gap (full height)	12.5	10.0	cm
Number of dipoles	60	112	
Quadrupole length	0.5	0.25-0.5	m
Number of Quadrupoles	56	120	
Tune			
Transition gamma	7.5	48	
Maximum beta function	31	37	m
Maximum dispersion	3.8	1.65	m
Natural Chromaticity	-5	-12	

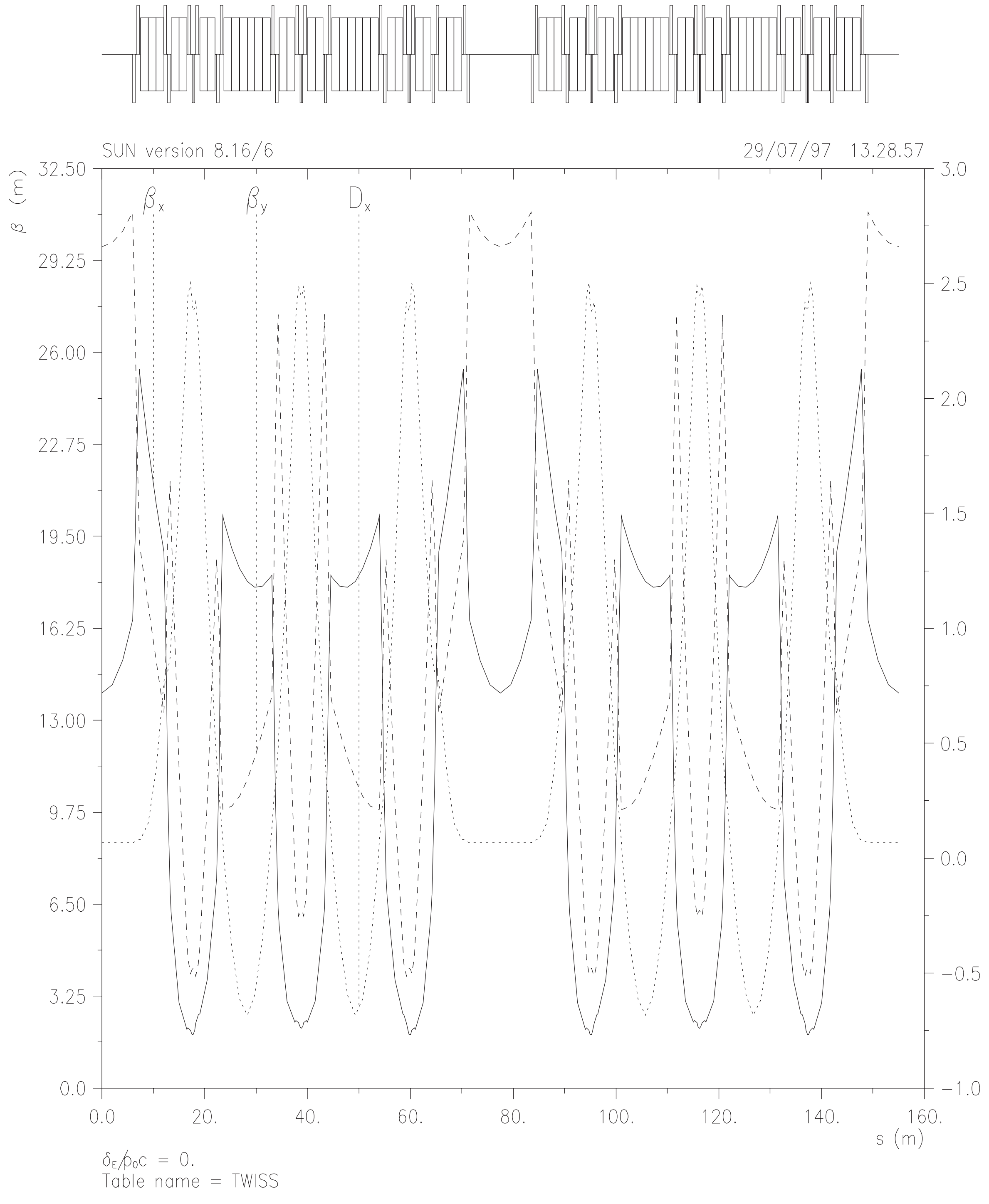


Figure II.2: Pre-booster lattice functions.

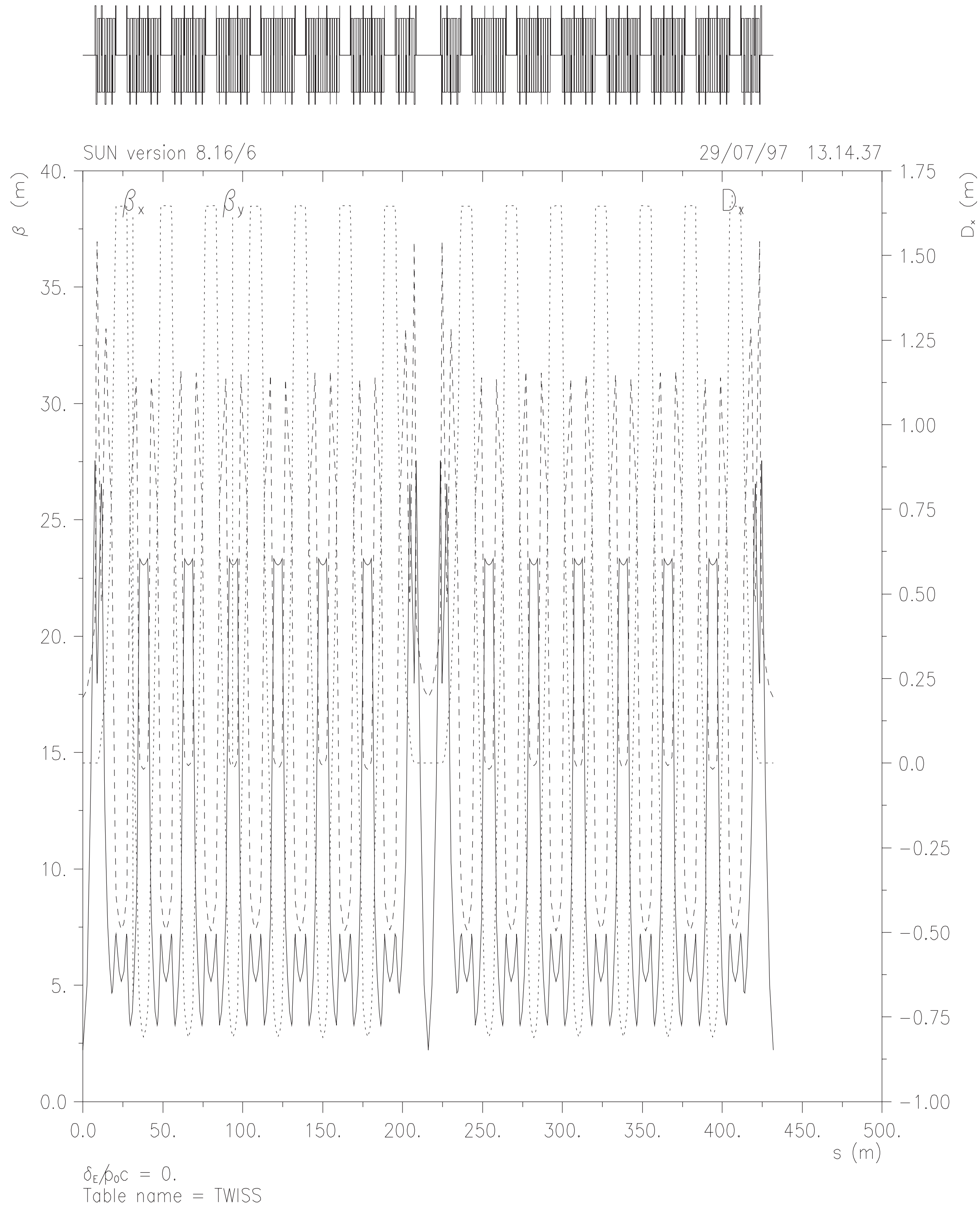


Figure II.3: New booster lattice functions.

Magnets

Dipole magnet requirements for the pre-booster and new booster are given in Table II.2. These requirements are challenging--operation at 1.3 Tesla and 15 Hz, with a substantial pole gap. A preliminary design has been developed that addresses issues relating to core power losses, operating current and voltage, and the affect of high frequency operation on magnetic field quality.

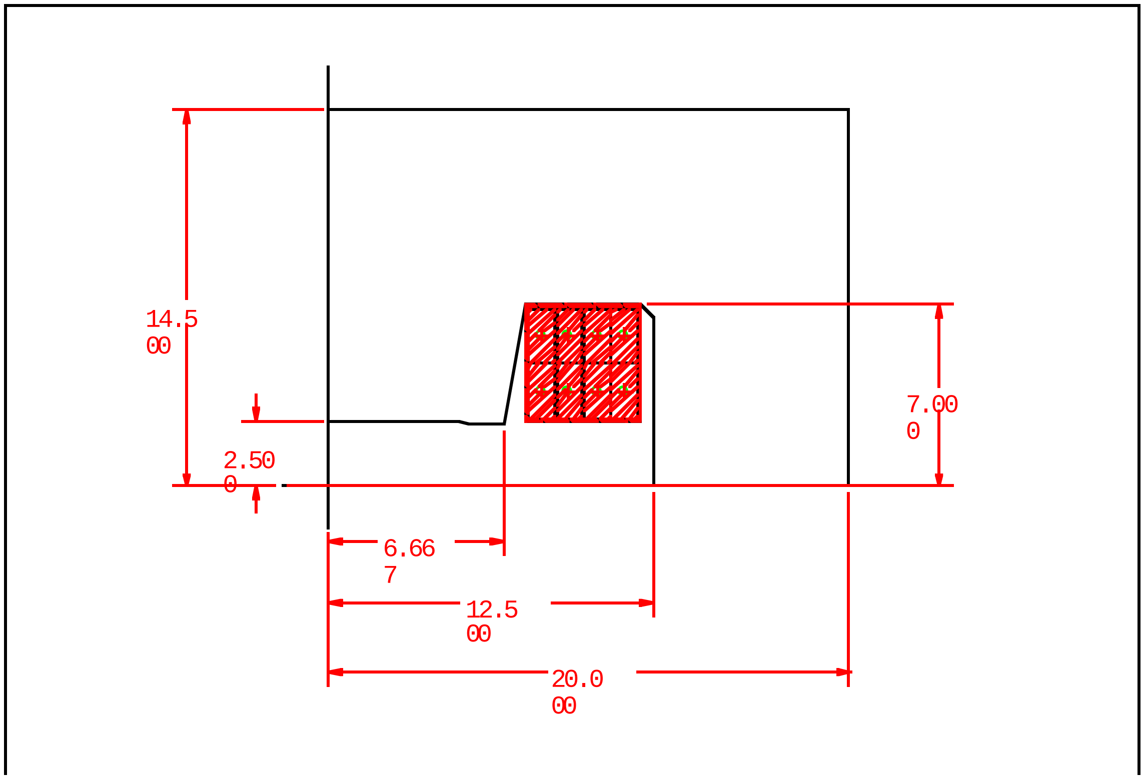
Preliminary dipole magnet design parameters are listed in Table II.3. The magnet core is constructed of 0.014" laminations of ARMCO M15 silicon steel. The calculated power dissipation in the core due to hysteresis and eddy current are approximately 12 KW for the Pre-booster and 6.4 KW for the New Booster dipole. In addition heating of the ends, assuming square ends, contributes an additional 8 KW to each magnet. Hysteresis and eddy current losses are included in the average power indicated in the table. End losses are not under the assumption that a suitable end profile can be identified that minimizes the problem (see for example FN-184-0320, S. C. Snowdon, 1969). Heat radiation calculations indicate that it will likely be necessary to cool the magnet core.

The coil is formed from eight turns per pole of 1"×2" copper conductor. This configuration is chosen to minimize the voltage drop across the magnet, but results in a relatively high peak current. A coil with sixteen turns per pole, running at half the current but twice the voltage, is another possibility. In either case there is not much to be gained by using a conductor wider than about an inch since the skin depth at 15 Hz is about 0.67".

Figures II.4 and II.5 show cross sections for the dipole magnets described above. Computer models indicate a field flatness of ±0.1% over a 6 inch (horizontal) aperture in the case of the Pre-booster dipole and a 5 inch aperture in the case of the New Booster.

Table II.3: Dipole magnet parameters for the Pre-booster and New Booster

	Pre-booster	New Booster	
Field	1.3	1.3	Tesla
Magnet Length	1.5	1.25	m
Gap	5	4	inches
Good Field aperture (@10^{-3})	±3.0	±2.5	inches
Current	16,500	13,200	A
Inductance	0.44	0.36	mH
Resistance	225	230	μΩ
Peak voltage drop	700	450	Volts
Average Power	43	26	KW



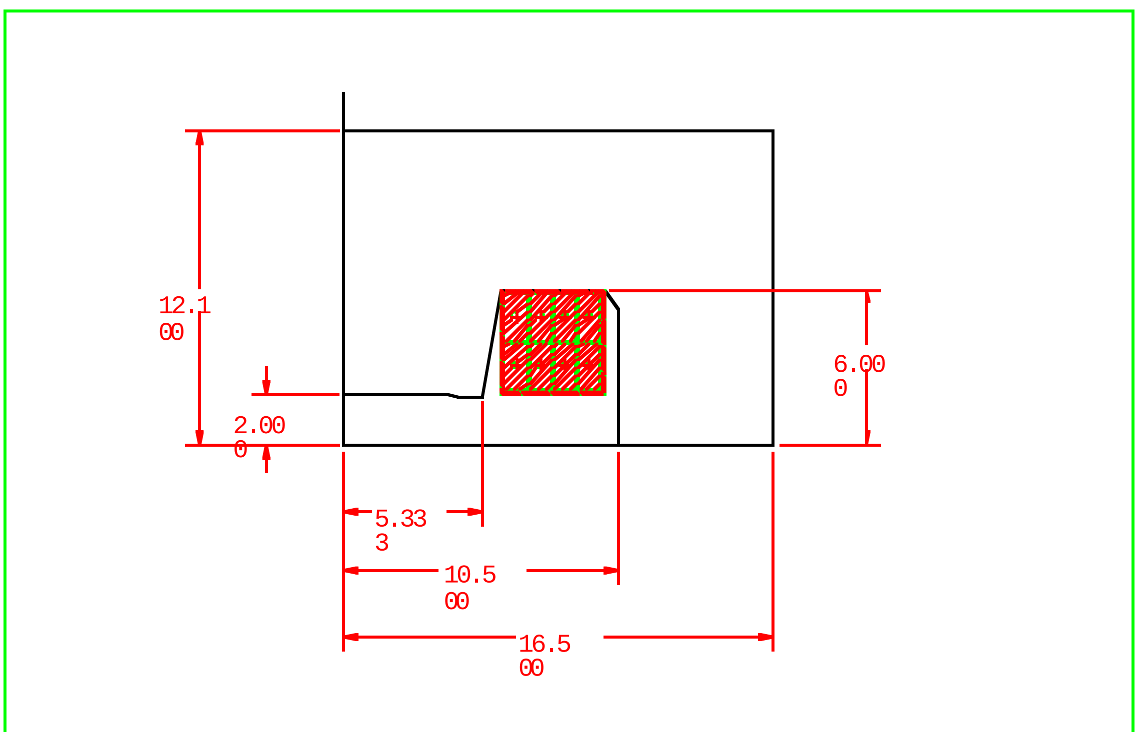


Figure II.4: Cross sections for the Pre-Booster (top) and New Booster (bottom) dipole magnets. One quadrant is shown. All units are in inches.

Radio Frequency Systems

Requirements for the Pre-booster and New Booster rf systems are given in Table II.4. The first and third columns reflect the muon collider design requirements contained in Table II.1 The middle column represents a possible operational mode of the Booster for injection into the Main Injector at an intensity one fourth that required for muon production targeting.

The parameters in the table assume that the magnet excitation curve is a sine wave at 15 Hz. Calculations show that the addition of a 15% second harmonic component to linearize the magnet excitation can lower the rf voltage and power requirements by 25-30% as compared to the numbers listed here. Study of such a system is probably warranted. In addition it may be valuable to consider operations of the New Booster at a somewhat lower rf frequency, for example 7.6 MHz. Operations at this frequency could relieve space charge during muon production operations by allowing longer bunch lengths at low energies, while simultaneously providing bunches for the Main Injector with the 132 nsec spacing that is expected to become standard for collider operations in the middle of the next decade.

Table II.4: RF system requirements

	Pre-Booster (1 GeV Injection)	Booster (1 GeV Injection)	Booster (4.5 GeV Injection)	
Harmonic Number	2	84	21	
RF Frequency (Injection)	2.90	46.48	13.08	MHz
RF Frequency (Extraction)	3.27	53.10	13.26	MHz
Peak Acceleration Rate	170	710	550	GeV/sec
Synchronous Phase	50	70	45	degrees
Accelerating Voltage (peak)	0.160	1.2	1.25	MV
γ_t	7	25	25	
Bucket Area	3	3	4	eV-sec
Number of rf stations	4	18	28	
Beam Current (dc)	26	2.5	10	A
Beam power (peak)	2.75	2.75	8.6	MW

Simulations of rf system performance have been initiated using the code ESME. Included are capture and acceleration in the Pre-booster and acceleration and bunch rotation in the New Booster. Results are summarized in Figures II.5-9. The simulations assume a multi-turn injection (300 turns or 0.21 msec) into the pre-booster of a chopped linac beam (±120°) with a 1.5 MeV momentum spread (95% FW). In the simulation program longitudinal space charge is turned on linearly from zero to the full value corresponding to 5×10^{13} protons per bunch during the 300 turn injection. No other impedance has been considered in the simulations to date.

The voltage program in the Pre-booster is shown in Figure II.5. The curve including space charge and a second harmonic component to the acceleration waveform was used in the simulation. The beam emittance grows from an initial 0.47 eV-sec to 1.8 eV-sec at extraction. Most of the emittance blowup occurs during the 300 turn injection and capture phase as can seen in Figure II.6. The voltage at extraction was kept at about 90 KV in order to achieve a distribution narrow enough to fit into the buckets of the booster ring. The extracted bunch length is 42 nsec (95% FW) and the momentum spread 50 MeV (95% FW).

The voltage program in the New Booster is shown in Figure II.7. In this case the longitudinal space charge contribution is insignificant because of the higher energy. With a sinusoidal magnet excitation the peak rf voltage is 1.25 MV and is reduced to 1.1 MV with the introduction of 15% of second harmonic. Simulations in the Booster start with a 2 eV-sec parabolic bunch matched to 200 KV (same bunch length and momentum spread as the distribution at the end of the Pre-Booster Ring). To reduce the final bunch length a bunch rotation is performed at the end of the ramp. The rf voltage is reduced from 800-200 KV, the bunch is left to rotate for a quarter of a synchrotron period, and then the voltage is raised again to 800 KV. After a quarter of a period at 800 KV the bunch length is reduced a factor of two as expected.

The rms theta distribution of the beam (proportional to the bunch length) throughout the Booster cycle is shown in Figure II.8. The final beam distribution at the end of the rotation is shown in Figure II.9. The final bunch length is 4.6 nsec (95% FW) and the momentum spread is 400 MeV (95 % FW).

An implementation of the Pre-booster rf system that has been examined is a ferrite core assembly with 50 cm outer diameter and 30 cm inner diameter. These are assembled into double ended ferrite tanks of length 1.3 m with a ceramic gap at the center. Each accelerating gap is calculated to generate 30 kV. Four such tanks are required. In this scheme the rf cavities are not tuned, but are operated below resonance for the entire acceleration cycle.

A possible implementation of the New Booster RF system would have two h=21 cavities in each of the 14 short straight sections. Each cavity would be a double gap, slow wave structure consisting of two quarter wave resonators. The cavities would use ferrite tuners to cover the 13.077 MHz to 13.256 MHz frequency range and provide detuning to compensate for the steady state beam loading. To minimize the transient beam loading, the R/Q of the cavity would be lowered to 20, The Q would also be lowered to 200 giving a cavity shunt impedance of 4 kΩ. Using these design values, each cavity would produce a peak accelerating RF voltage (V_{rf}) of 50 kV with 312 kW of RF input.

At the maximum acceleration rate and design current, with no fast feedback, the power amplifier must deliver a total output power of approximately 620kW with half of this going directly to the beam and the other half being dissipated in the cavity plus power amplifier. Two different tetrodes are possible candidates for the final stage of the power amplifier. Both the Eimac 8973 and the Thomson TH518 have rated anode dissipations of 1MW and are capable of delivering more than 1MW of output power. These tetrodes also have sufficient current output to provide fast transient beam loading compensation to help cancel the 13 kV/bunch per cavity induced voltage for a single passage of a 5×10^{13} proton bunch. The above design is conservative in that it does not rely on any fast feedback systems to stabilize the beam.

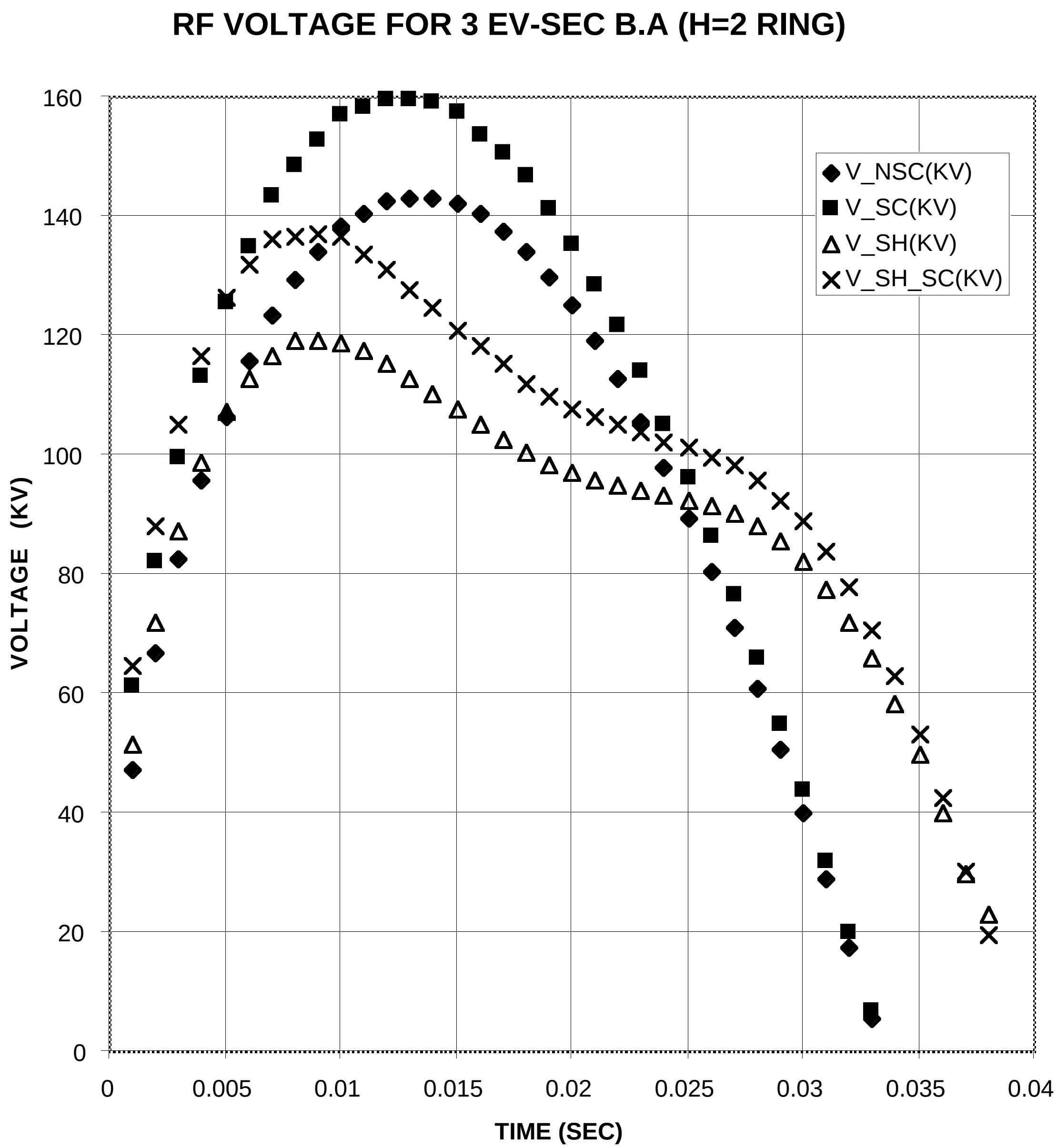


Figure II.5: RF Voltage curves for the Pre-Booster Ring and 3 eV-sec bucket area. The four curves represent the requirements with and without longitudinal space charge, and with and without the addition of a 15% second harmonic component to the magnet excitation ramp.

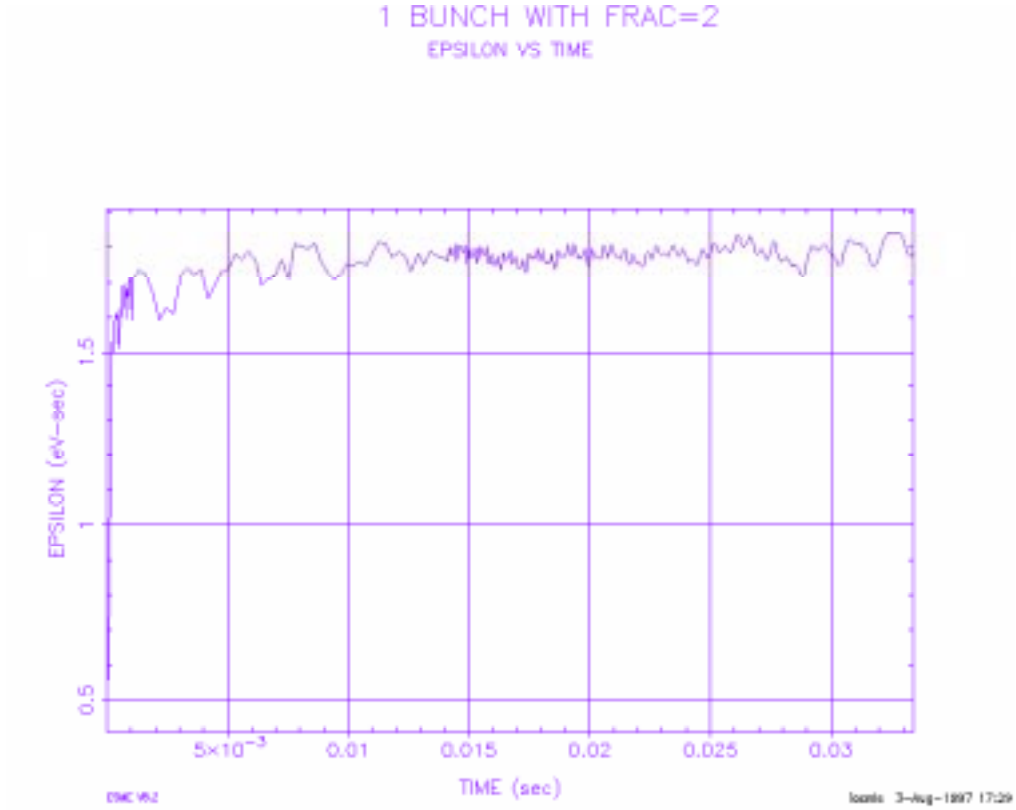


Figure II.6: Evolution of the bunch longitudinal emittance in the Pre-Booster Ring.

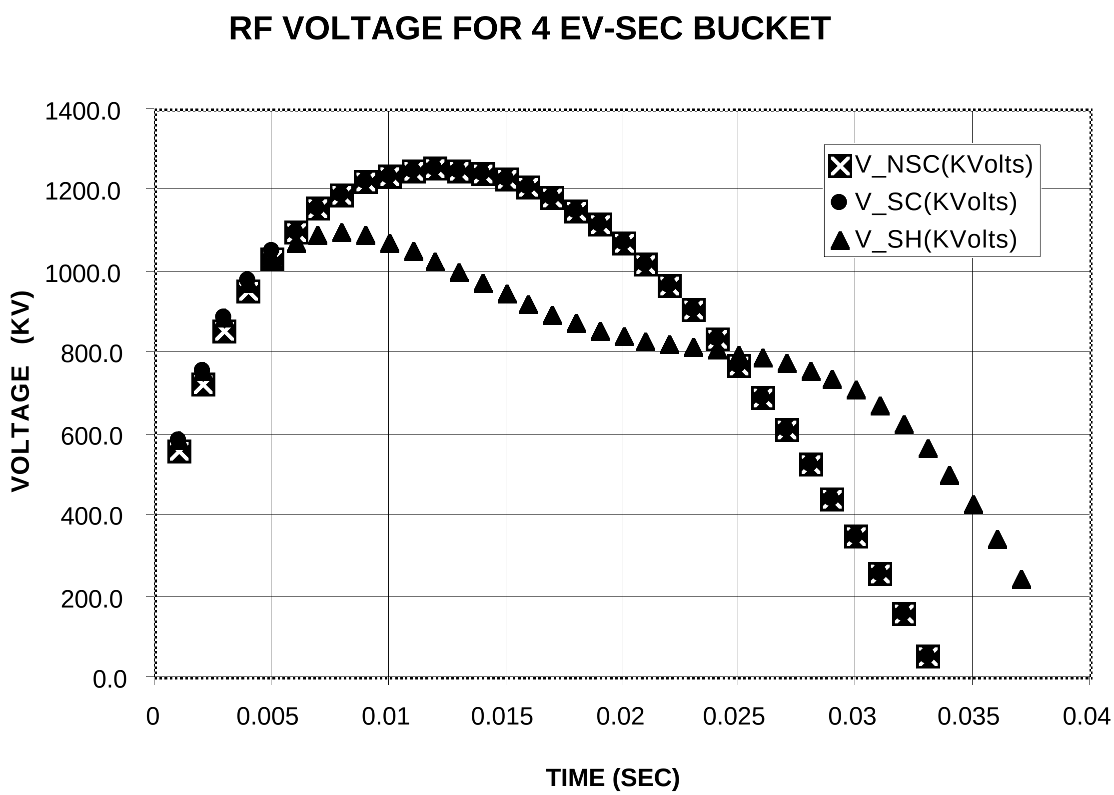


Figure II.7: RF Voltage curves for the Booster Ring and 4 eV-sec Buckets. The three curves represent the requirements with and without longitudinal space charge, and with and without the addition of a 15% second harmonic component to the magnet excitation ramp.

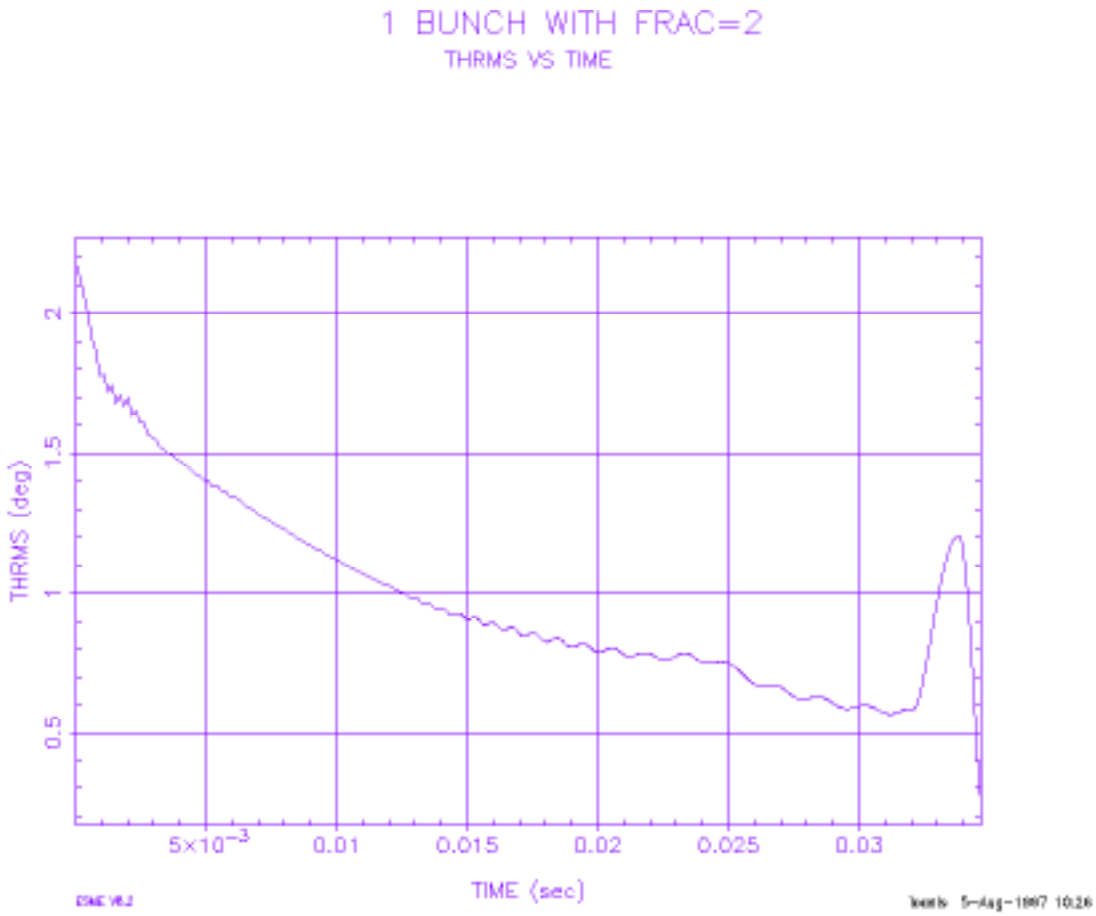


Fig. II.8: Rms bunch length in degrees during the ramp in the Booster Ring. The bunch rotation can be seen at the end of the plot, creating a 4.6 nsec (95%, half-width) bunch.

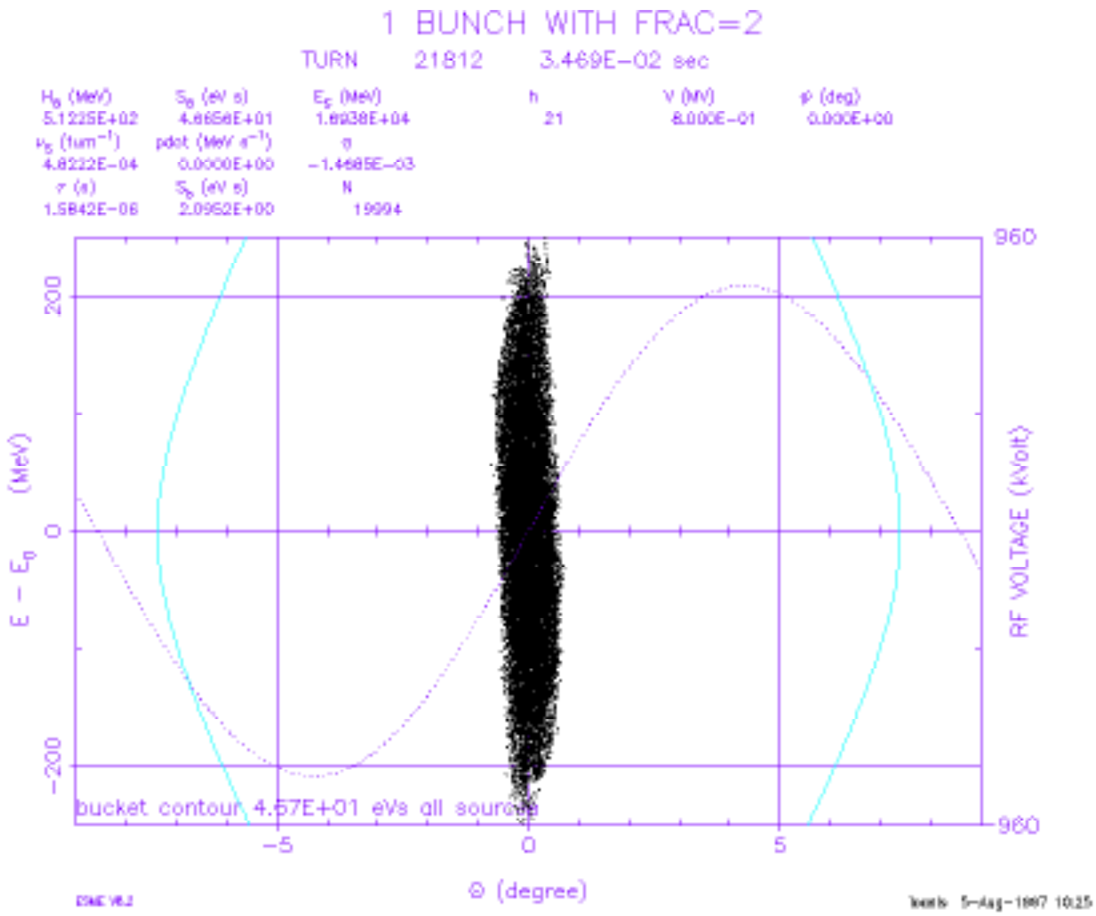


Figure II.9: Beam distribution at the end of bunch rotation in the Booster Ring.

Beam Loading

The current Booster RF cavities must ramp their resonant frequencies from 37 MHz to 53 MHz and provide 300 kW of power for the beam in order to maintain the orbit during the highest slope of the magnet ramp. The 18 cavities provide the beam with 800 kV/turn of RF to maintain the bucket area necessary to contain the entire longitudinal emittance of the beam.

One limitation of the current cavities is beam loading. When the voltage produced in the cavity by the beam becomes equal to or greater than the acceleration voltage, a beam instability could develop. The shunt impedance of the cavities at resonance is approximately 22 kΩ. With a beam intensity of about 1×10^{13} protons, the voltage produced by the beam is close to the acceleration voltage. If the cavities are to drive a more intense beam, the shunt impedance should be reduced, or the RF source impedance needs to be reduced.

With the current local feedback systems on the cavity voltage, any large increase in intensity will destabilize the beam because of Robinson instabilities. A rule of thumb used to avoid Robinson instabilities is to dump as much power into the cavity and amplifier as is dumped into the beam. At an intensity of 1×10^{13}, the beam begins to take a majority of the power from the system.

One way to get more power to the cavity is to add swamping resistors in parallel with the ferrite cavities. This will reduce the impedance of the cavity as seen by the beam, and raise the intensity threshold for Robinson instabilities. The drawback to this technique, however, is that it increases the power requirements of the power amplifier, because the impedance that the amplifier must drive is now lower. Another way to decrease the impedance seen by the beam is to add RF feedback to the amplifier. Although this decreases the impedance seen by the beam, it does not decrease the impedance seen by the power amplifier, so it does not increase the power requirements. The open loop delay of the feedback limits the amount of impedance reduction. Assuming a Q of about 100 and a feedback delay of about 60 ns with a linear amplifier, the effective resistance seen by the beam can be reduced by as much as a factor of 12. Only a factor of 5 is needed for the current cavities to operate without causing Robinson instabilities.

The simple RF feedback technique does not reduce the impedance of higher order modes, however. It may even increase the likelihood of producing an unstable coupled bunch mode because the deQing will increase the impedance of revolution harmonics close to the fundamental frequency. If higher order modes and coupled bunch modes become a problem in the design, the feedback can be improved to reduce the impedance for a wide bandwidth. Figure II.10 shows how this could be implemented. The tracking comb filter provides exactly one turn delay from pickup to cavity and lowers the beam impedance for the fundamental and all revolution harmonics. Tracking filters have already been designed for the Booster dampers and should not require much modification to use in the RF system.

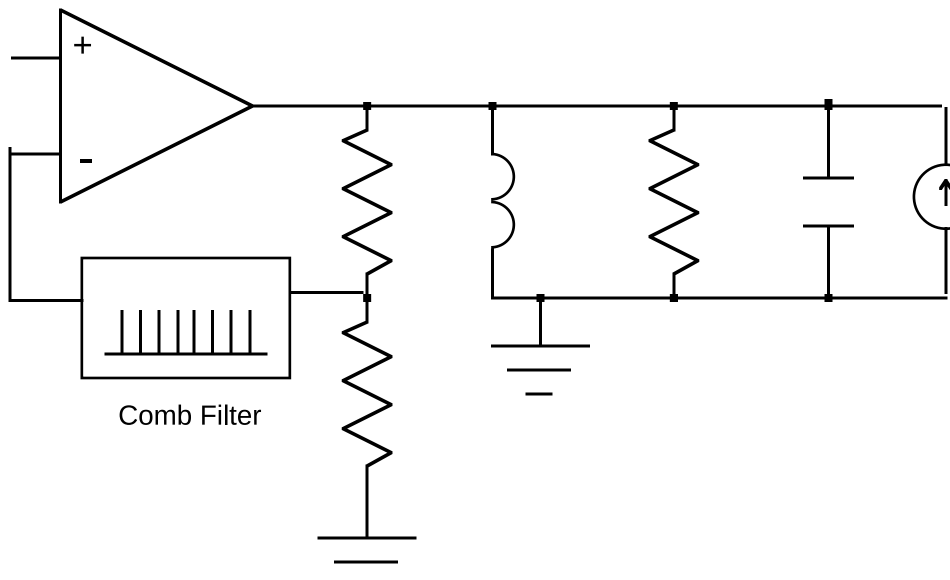


Figure II.10: Equivalent circuit using RF feedback with tracking comb filter.

Feedback performance is limited by the total delay in the feedback loop. If the gain required to control beam loading and instabilities exceeds the gain margin of the feedback loop, it will be necessary to construct a feed-forward compensation system. This system is equivalent to the longitudinal coupled bunch dampers already installed in the booster. The beam signal from a wall current monitor is delayed, filtered, and summed with the RF reference to cancel out the beam current in the cavity. If the delays and amplitudes are perfectly matched, the signal will completely cancel cavity impedances. It is very difficult to get the signals matched to the levels and bandwidth necessary, and a combination of feedback and feedforward may be required.

Finally, if something outside the bandwidth of the cavity drives a strong instability, separate cavities and power amplifiers must be constructed in order to keep control. This would be very costly due to the amount of gain, bandwidth, and power required to control longitudinal instabilities. Before making such a costly commitment, many tests should be performed on the current booster with the other techniques mentioned above to determine the source of the instability.

Power Supplies

It is currently assumed that the power supply/magnet system will be operated as a resonant circuit. Operating in a resonant mode provides great benefit in reducing the volt-ampere requirement of the power supply. At 15 Hz the magnet impedance is dominantly reactive. A resonant circuit permits the reactive energy to be exchanged between passive circuit elements without passing through the power supply each magnetic cycle. The power supply need then be sized to provide only the real power lost in the circuit elements. The present resonant Booster circuit operates with four 1000 volt supplies. To produce the same 15 Hz current in the magnets without the resonant circuit elements requires almost one such supply per magnet, a total of 96!

A second harmonic can be added to the magnet current waveform. In a passive circuit implementation, this requires additional chokes and capacitors to create a second transfer function pole at 30 Hz. In the present Booster, these components would increase the physical volume required for resonant elements by about 25-30%. An alternative approach requires actively switching elements in and out of the circuit each cycle to effectively change the resonant frequency between the magnet current up-swing and down-swing.

The downside of the resonant implementation is that there is little flexibility in the operations of the machine. In the case of the New Booster, with potential requirements for operational modes beyond muon production it might be worth investigating a non-resonant system.

Vacuum

Overall vacuum requirements for the Pre-booster and Booster are modest because of the rapid cycle time. However, the vacuum pipe will be located in a region of high and rapidly fluctuating fields. A calculation based on a 5"×6" rectangular beam pipe, constructed of 0.050" thick Inconel 718, yields a power loss due to eddy currents of 8 kW/m at 15 Hz. This is clearly unacceptable.

An alternative would be a ceramic vacuum pipe, perhaps with either a coating or other conducting internal structure to carry the beam image currents. In any event this topic needs further serious investigation.

Beam Stability

Beam stability considerations have been studied including space-charge, microwave instability, potential well distortion, beam loading, resistive wall, and coupled bunch effects. Overall impedance limits for the accelerator vacuum chambers are indicated. In addition concepts for beam loading compensation and active damping have been developed. The general conclusion is that beams can be stable for the parameter set given in Table II.1. However, care will be required in design of the vacuum chamber and it is highly likely that dampers will be required to control the resistive wall instability and longitudinal coupled bunch instabilities in the New Booster for operational modes that include more than two circulating bunches. A novel ingredient in these accelerators is the possible incorporation of an inductive element in the ring to cancel the capacitive longitudinal space charge impedance generated by the high intensity beam. Experiments into the feasibility of such techniques are currently underway at KEK and LANL.

Dampers

As the booster beam current is increased, the threshold of transverse instabilities will increase as well. The present booster already has a system for controlling coupled bunch instabilities, and it can be improved for higher intensities without considerable modification. First, the strength of the power amplifiers can be increased from 200W to 5000W with commercial "off-the-shelf" units. Second, the system can be transformed from a wideband, bunch-by-bunch system to a narrowband, all-mode system. The bunch-by-bunch system samples and processes the information for each bunch separately, while the all-mode system concentrates on particular modes of oscillation. This greatly reduces the amount of noise seen by the beam and the power amplifiers. Both the bunch-by-bunch and mode damping techniques have been successfully tested on the present booster.

III. STAGING AND SITING

The new Proton Source described in Chapter II is comprised of three primary components: 1)an upgraded 1 GeV linac; 2)a new 4.5 GeV Pre-booster; and 3)a new 16 GeV Booster, all situated in a new location to overcome shielding difficulties on the current site. An appropriate location for the new complex, in close proximity to the Main Injector, is indicated in Figure III.1. Also shown on the figure is a possible location and interconnections to a 500 GeV muon collider. Since the cost of the new Proton Source is likely to be on the order of $200M one can consider possible phased implementations that could provide maximum benefit to the Fermilab program at each step. Two such staging scenarios are considered here.

Scenario 1		Benefits
Step 1:	Relocate and upgrade linac Relocate booster	15 Hz Booster operation; 3×current booster performance
Step 2:	Construct new booster	5×current booster performance
Step 3:	Construct new pre-booster	Capability to support 500 GeV muon collider

Scenario 2		
Step 1:	Relocate linac Construct new booster	15 Hz Booster operation; 2×current booster performance; cheaper than Scenario 1/Step 1
Step 2:	Upgrade linac	5×current booster performance
Step 3:	Construct new pre-booster	Capability to support 500 GeV muon collider

It is assumed in both alternatives that complete underground civil construction for the entire complex would be completed in step 1. This would allow subsequent installations to proceed with a minimum of disruption to the Fermilab research program. As shown in Figure III.1 the underground enclosures and galleries for the new proton source are separated from the Main Injector and the 8 GeV transfer line by sufficient distance to allow civil construction and installation to proceed concurrent with Main Injector operations. The exception is the transfer line from the new Proton Source into the Main Injector which will require a dedicated shutdown.

In both scenarios the proton source has been improved by a factor of five in performance at the end of step two, and is upgraded to muon collider class in step three. However, it is not obvious at present what the correct ordering of steps 1 and 2 might be. This will presumably depend upon the availability of funding and of downtime in the Fermilab research program. It should be noted that Scenario 2 is probably cheaper in step 1 (since the new Booster is estimated to be less expensive than a new linac) and probably involves less integrated downtime to the Fermilab program (since the new booster could be largely constructed in place while the existing 8 GeV booster continues to run). On the other hand Scenario 1 has greater potential for improved performance at step 1 and has an associated step 0--relocation of the linac and booster without any upgrades, that is the least expensive first step of all.

Operational parameters for the proton source under each step of the above scenarios are listed in Table III.1

Table III.1: Operational parameters for the Proton Source at each implementation step.

	Step 1		Step 2	Step 3	
	Scenario 1	Scenario 2			
Linac					
Energy (Kinetic)	400.0	1000.0	1000.0	1000.0	MeV
Current	48.0	48.0	48.0	65.0	mA
Pulse Length	45.0	67.1	112.0	328.5	μsec
Chopping Fraction	0.75	0.75	0.75	0.75	
N_{TOT}	1.0E+13	1.5E+13	2.5E+13	1.0E+14	H-
Momentum Spread (95% FW)	1.0	1.0	1.0	1.0	MeV
Repetition Rate	15.0	15.0	15.0	15.0	Hz
Pre-Booster					
Bunches				2	
N/bunch				5.0E+13	protons
Circumference				180.6	m
Injected Turns				477	
Transverse Acceptance (normalized @ injection)				450π	mm-mr
Emittance (95%, normalized)				200π	mm-mr
Physical Aperture (Half-height)				61	mm
Bunching Factor				0.25	
Space-charge Tune Shift				0.40	
Longitudinal Emittance (95%, per bunch)				1.8	eV-sec
Extraction Energy (Kinetic)				4.50	GeV
Repetition Rate				15	Hz
Booster					
Bunches	84	84	84	2	
N/bunch	1.2E+11	1.8E+11	3.0E+11	5.0E+13	protons
Bunch Length (rms)	2.7	2.2	2.2	8.6	nsec
Circumference	474.2	474.2	474.2	474.2	m
Injected Turns	20	37	62	1	
Transverse Acceptance (normalized @ injection)	80π	68π	142π	450π	mm-mr
Emittance (95%, normalized)	50π	30π	50π	240π	mm-mr
Physical Aperture (Half-height)	49	27	49	49	mm
Bunching Factor	0.26	0.26	0.26	0.02	
Space-charge Tune Shift	0.40	0.39	0.39	0.39	
Longitudinal Emittance (95%, total)	2.2	1.8	1.8	4.0	eV-sec
Extraction Energy (Kinetic)	16.0	8.0	16.0	16.0	GeV
Bunch Length at Extraction (95%, HW)	4.9	4.9	4.9	2.3	nsec
Momentum Spread at Extraction (95%, HW)	0.0%	0.0%	0.0%	1.2%	
Repetition Rate	15	15	15	15	Hz
Main Injector (Booster Batch)					
Bunches	84	84	84		
N/bunch	1.2E+11	1.8E+11	3.0E+11		protons
Bunch Length (rms)	2.0	2.0	2.0		nsec
Circumference	3319.0	3319.0	3319.0		m
Trev	11.1	11.1	11.1		μsec
Transverse Acceptance (normalized @ injection)	76π	40π	76π		mm-mr
Emittance (95%, normalized)	50π	30π	50π		mm-mr
Space-charge tune shift	0.01	0.11	0.03		

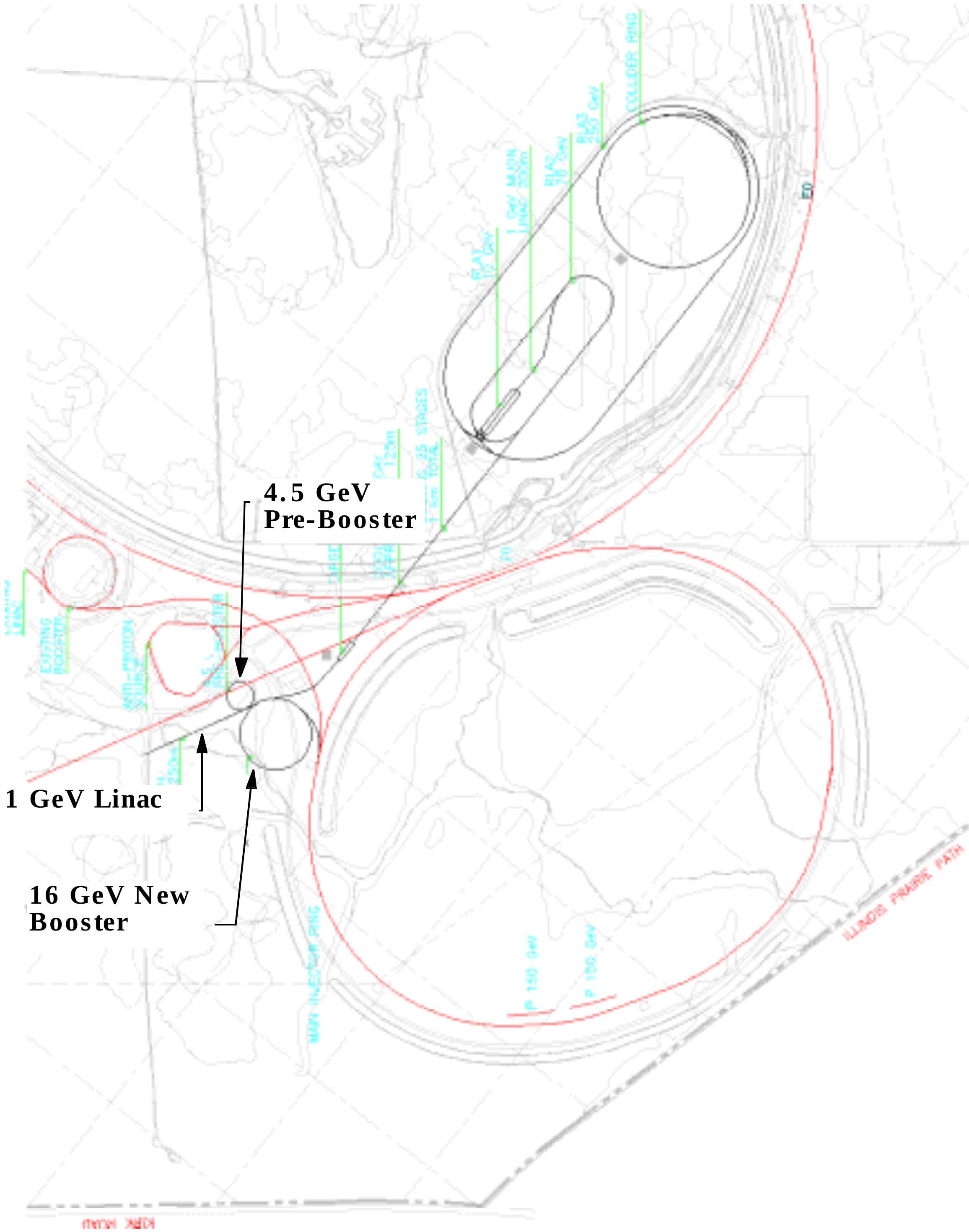


Figure III.1: A possible siting of a new Proton Source. Also indicated is a potential location for a 500 GeV muon collider utilizing the new Source.

IV. COST ENVELOPE

A very preliminary estimate of the total cost of the new Proton Source described above is given in Table IV.1. All dollar amounts are in thousands of FY1997 dollars. Estimates are based on design concepts in the case of magnets, rf, and civil construction, on scaling from the 400 MeV linac in the case of the linac upgrade, and on scaling from Main Injector costs in the case of other components. The estimate is intended to include labor and EDI&A costs. However, neither contingency nor indirect costs are included. Contingency is not regarded as a viable concept for an estimate that is not based on a well-defined design concept. The estimate could be significantly understated in areas of high technical uncertainty, such as the vacuum or power supply systems, and could overstate needs in areas such as rf where reutilization of some existing equipment might be possible. It is the editor's feeling that the estimate is likely to have an associated error of +40% -20%. This would leave the likely cost in the range $150-250M.

Table IV.1: Preliminary cost estimate for a new Proton Source. Dollar amounts are in thousands of FY1997 dollars.

	Relocate Linac Linac Front End Upgrade Relocate Booster MiniBooNe Beam/Target	Linac Upgrade	New Booster	Pre-booster	**TOTAL**
Technical Components					
Linac	$12,900	$58,700		$3,600	**$75,200**
Pre-Booster				$14,000	**$14,000**
Existing Booster	$4,300				**$4,300**
New Booster			$28,000	$19,900	**$47,900**
Transfer Lines	$500		$200	$200	**$900**
Target Station	$400				**$400**
Civil Construction	$34,100				**$34,100**
Project Management	$1,000	$1,000	$2,000	$1,800	**$5,800**
TOTAL	**$53,200**	**$59,700**	**$30,200**	**$39,500**	**$182,600**

V. NEXT STEPS

The design presented here is a first look at a possible evolution of the Fermilab Proton Source. Further development and optimization of this concept is required before a conceptual design report and more accurate associated cost estimate could be produced. During this study several features of the design were identified as worthy of further consideration over the course of developing a more complete concept. These are listed below along with identified areas that will require R&D before finalizing any design.

V.1 Design Issues

There are clearly a large number of design issues relating to the very demanding performance specifications of the proton source described in this report. The performance is well beyond current state-of-the-art and is comparable to accelerator based neutron spallation sources that are currently under design at a number of laboratories. Among the outstanding issues we would identify as requiring particular attention are:

1. The rf system. The system required is very high power and suffers from significant beam loading. Concepts for rf feedback need to be brought to maturity.
2. The vacuum system. A concept must be developed for a vacuum chamber that can satisfy the dual demands of surviving in a 15 Hz magnetic field while presenting a low impedance to the circulating beam.
3. The magnet system. A high field, large aperture, 15 Hz magnet is called for in this facility. The technology is challenging.
4. Residual activation and shielding. Little has been done on this, but it is a major issue in spallation sources and requires analysis.
5. Beam stability. Concepts for impedance minimization and development of innovative damper systems must be pursued.
6. The power supply system. In a resonant system addition of a second harmonic provides significant relief in the 16 GeV Booster rf system. It is probably also worth investigating a programmable power supply in the Booster if some of the more complicated operating modes involving mixed muon collider/Main Injector cycles are required.

V.2 Design Alternatives

A number of alternative implementations of the design concepts developed here were identified during our study as worthy of further consideration. These include:

7. Possible addition of a third ring. This has the potential benefit of allowing operation of the proton source at an energy above Main Injector transition.

8. Increasing the linac energy and eliminating the pre-booster. The feeling is that this is likely very expensive but it probably warrants a further look.

9. Lowering the rf frequency in the new Booster to 7.6MHz (h=12). This would allow longer bunches and reduce the space charge tune shift thereby allowing a reduction of the

pre-booster energy and/or reduction of the aperture. It would also provide bunches to the Main Injector with a spacing of 132 nsec, eliminating the need for coalescing during collider operations.

10. Possible use of chicanes to consolidate bunches for muon production targeting. This would allow the total charge in the pre-booster and the new booster to be distributed over a greater number of bunches.

11. Lowering the repetition rate, say to 10 Hz. This eases many problems in the rf, magnet, power supply, and vacuum systems. and is still twice the muon collider requirement. A cost-benefit analysis might be valuable.

12. A more detailed analysis of mixed operational modes is also called for. As presently envisioned the existence of the pre-booster does nothing to enhance Main Injector operations, and could actually be an impediment.

V.3 R&D Initiatives

A number of areas worthy of immediate R&D are derived from the above, and other, considerations identified during the course of our study:

- Linac ion source development program to address what the maximum H^- current that is likely to be available.

- Linac test station, including a prototype 350 μsec modulator, klystron, and cavity, to conduct investigations into utilization of long pulse lengths.

- Prototype pre-booster rf cavity to verify operational characteristics as described in this report.

- Prototype magnets to lead to an optimized design and matching between dipoles and quadrupoles.

- Prototype vacuum chamber to validate design concepts.

- Development of a direct feedback rf system.

APPENDIX: INDIVIDUAL CONTRIBUTIONS