Chapter 2. Machine Layout and Performance

R. Alber, C. Ankenbrandt and W. Chou

2.1. Overview

The Proton Driver (Phase I) design includes the following items:

1. A new 16 GeV rapid cycling synchrotron (the Proton Driver) in a new enclosure.
2. A new 400 MeV beam transport line in a new enclosure.
3. A new 12/16 GeV beam transport line, of which about one third is in a new enclosure; another two thirds is in the existing 8 GeV enclosure.
4. A modest improvement of the negative ion source and the low energy part of the existing 400 MeV Linac.

The layout of this new accelerator complex is shown in Figure 2.1.

The H^- beam will be extracted from the Linac to the 400 MeV transport line via the existing Linac access way. This beam is injected into the Proton Driver in the same way as in the present Booster, namely, through a charge exchange process, in which the electrons are stripped by a foil and dumped. The H^+ (proton) beam will then be accelerated to 16 GeV (or 12 GeV in Stage 1) in about 38 ms and extracted to the 12/16 GeV transport line. It is then injected into the MI-10 section of the Main Injector.

The 400 MeV beam line is about 320 m long. It has three sections: (i) a matching section between the existing Linac and the beam line, which includes a vertical drop; (ii) a linear section about 150 m long, which is reserved for a future 600 MeV Linac; (iii) another matching section between the beam line and the synchrotron, which includes another vertical drop as well as a debunching sector.

The Proton Driver has a circumference of 711.3 m, which is exactly 1.5 times the size of the present Booster (474.2 m). It is of a triangular shape and has 3-fold symmetry as shown in Figure 2.2. It has three arcs (P10, P30 and P50) and three long straight sections (P20, P40 and P60). Each arc is about 173 m long and each straight section about 64 m long. Of the three straight sections, P20 is dedicated to injection and beam collimation, P40 and half of P60 will be occupied by rf cavities; another half of P60 is for extraction. Details of the lattice structure will be described in Chapter 3.

The extraction beam line will be at 12 GeV in Stage 1 and 16 GeV in Stage 2. The total length is about 900 m. It consists of two sections. The upstream section, which is about 335 m long, connects the synchrotron to the present MI-8 enclosure. It is followed by a 564 m long section in the MI-8 enclosure. In this section, the lattice will remain the same as that in the present MI-8 line but the magnets will be replaced so that it can transport 12 or16 GeV beams.

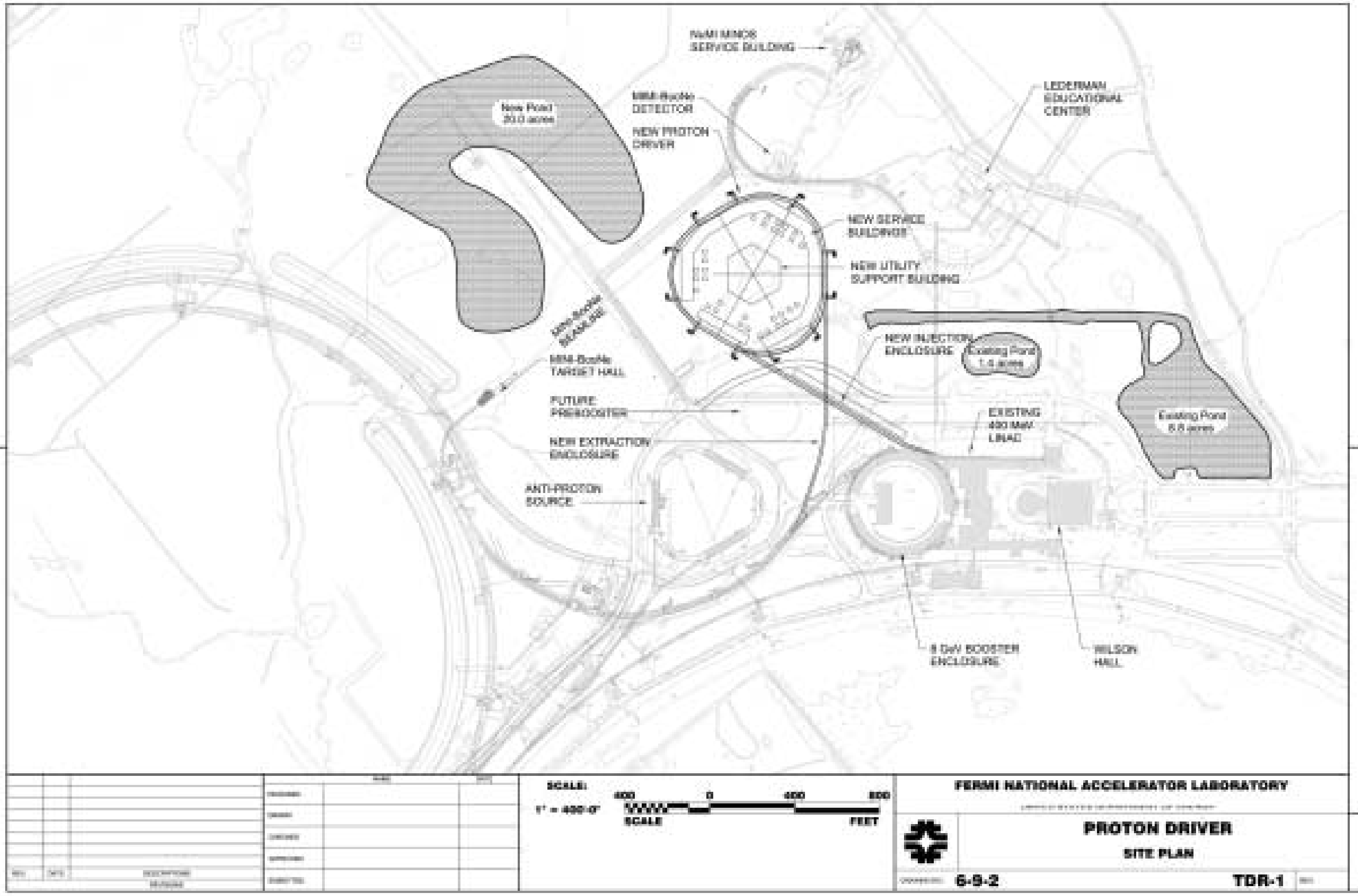

Figure 2.1. Layout of the Proton Driver Accelerator Complex

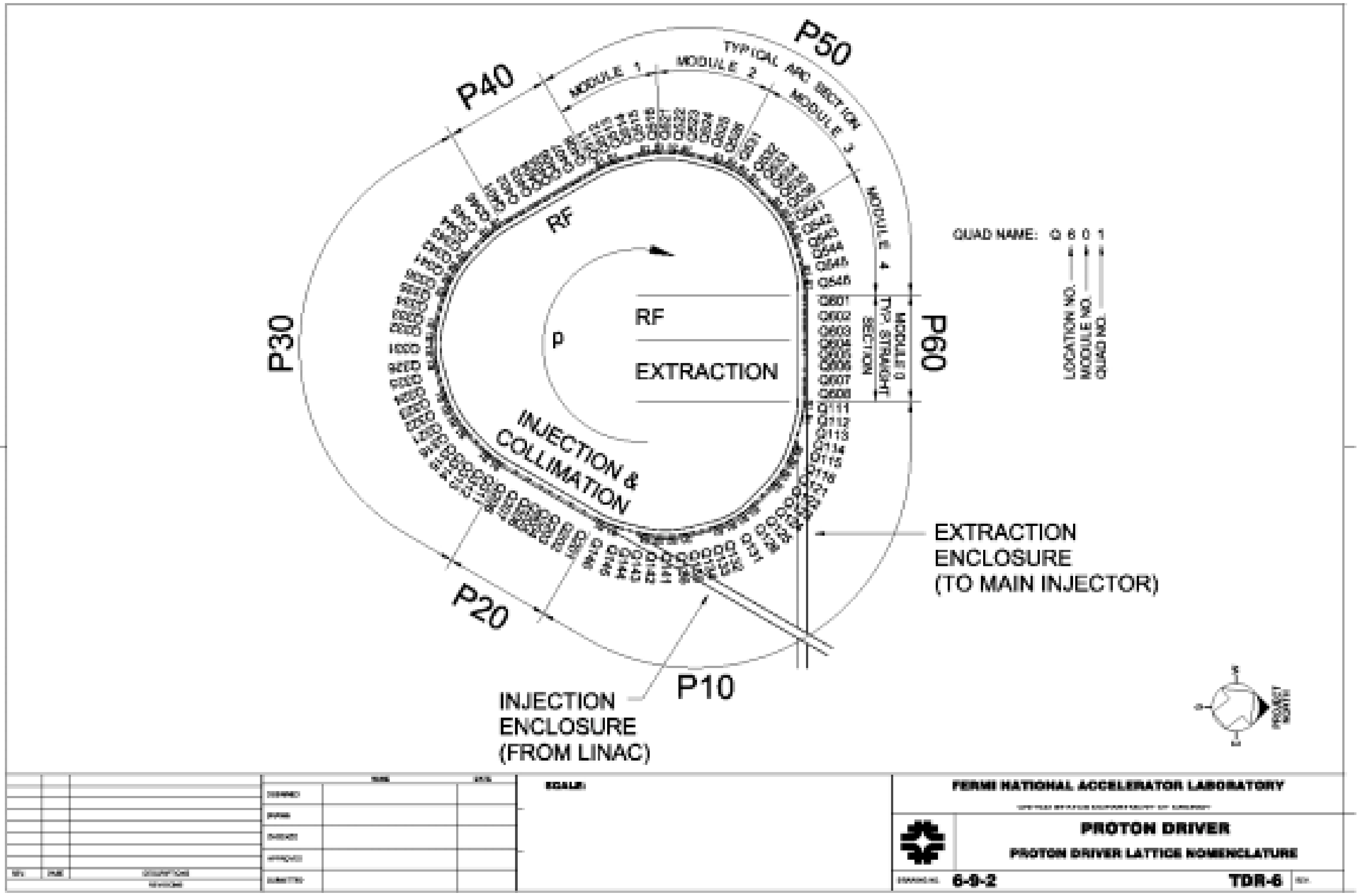

Figure 2.2. Layout of the Proton Driver Ring

2.2. Siting

The following criteria have been applied to the site selection:

- Minimize any possible interruption to the ongoing Fermilab HEP program, in particular, to Run II.
- Accommodate a triangular ring of 711.3 m, in which the injection and extraction are at two different straight sections.
- Leave enough space for a future upgrade (Phase II), i.e., space for addition of a 600 MeV Linac and for a 3 GeV pre-booster.
- Be in the vicinity of the present Linac and the Main Injector.
- Be able to reuse a large portion of the MI-8 enclosure.

Based on these considerations, the site of the Proton Driver is chosen at the west side of Kautz Road, see Figure 2.3. In this layout, the new 400 MeV beam line includes 150 m of free space for a future Linac upgrade. A future Pre-Booster can also easily fit in. The new 12/16 GeV beam line looks long, but about two thirds of it will be in the existing enclosure. The elevation of the Proton Driver is the same as that of the Main Injector. This ensures appropriate radiation shielding. The NuMI beam line is deeper. There will be no intersection between the NuMI line and the Proton Driver. Although the Proton Driver intersects the neutrino beam from the MiniBooNE target, this is not a problem.

The location of this site in a wetland area raises concerns. That will be addressed in Chapter 18.

2.3. Major Design Parameters

The Proton Driver has two distinct features:

1. It provides high beam power (about 1 MW).
2. It can produce short proton bunches (rms length about 1 ns).

While the former is a common feature of high intensity proton machines, the latter is a special feature of the Proton Driver, which could serve a future neutrino factory and/or a muon collider by generating intense short pion/muon bunches from a graphite or high Z target.

A major constraint in the design is to reuse the present Linac. The performance of this Linac has the following limits: maximum beam energy 400 MeV, maximum beam intensity 90 mA (or 60 mA after chopping), maximum usable pulse length 90 μsec and maximum repetition rate 15 Hz.

For a minimal neutrino factory, the required beam power from the Proton Driver is about 1 MW. The beam power is the product of beam energy E, number of protons per cycle N, and repetition rate f_{rep}:

$$P_{beam} = E \times N \times f_{rep} \qquad (2.1)$$

The repetition rate of the Linac is limited to 15 Hz. The number of protons per cycle from the Linac is limited to 90 mA $\times$ 90 μsec (or 60 mA $\times$ 90 μsec after chopping), equivalent to 5×10^{13} (or 3.4×10^{13} after chopping) protons. Because chopping is necessary in Stage 2, we pick 3.4×10^{13} the maximum available proton intensity at the injection from the Linac to the ring. Allowing reasonable beam losses during the cycle (10% at injection, 1% during ramp and at extraction), the design value of N is chosen to be 3×10^{13}. (This is the number of protons per cycle that will be delivered to the Main Injector or the muon production target.) At this repetition rate and beam intensity, a 12 GeV beam (Stage 1) would give 0.864 MW, and a 16 GeV beam (Stage 2) 1.152 MW.

We have studied the trade off between E and N for given beam power (1 MW) and repetition rate (15 Hz) in the energy range of 8 - 16 GeV. Generally speaking, a lower E would require a higher N. This implies significant changes in the present Linac, which we want to avoid because it would lead to a major interruption to Run II. Besides, a higher E (16 GeV) also has other virtues in producing short proton bunches, namely, making the bunch compression at the end of the cycle easier. This is because: (i) The longitudinal brightness N/ε_L would be lower; (ii) The space charge tune shift $\Delta\nu$ and momentum spread $\Delta p/p$ of the beam at top energy would be smaller, which mean the η-spread (η is the slip factor) during bunch compression would be smaller. A detailed study of the cost and performance impact for different energy choices can be found in Appendix B.

A caveat in choosing 16 GeV is that the beam in the Main Injector will still cross transition ($\gamma_t = 21.6$ in the MI). However, simulation shows no particle loss nor emittance dilution would occur during transition crossing when proper measures are taken. This will be discussed in Appendix D.

Another issue related to the beam energy E is the muon yield per unit proton beam power. When a high Z target is used, this yield is almost independent of E. When a graphite target is used, however, MARS simulations indicate that the yield could be 18% higher at E = 6 GeV than at 16 GeV for the same beam power. Because there are different opinions about these simulations, a HARP (Hadron Production) experiment is being conducted at the CERN PS to measure the muon yield at different proton beam energies on a variety of targets. We will revisit the energy issue when the HARP data are available.

The major design parameters of the Proton Driver in Stage 1 and 2 are listed in Table 2.1. As a comparison, the parameters of the present Linac and Booster are also listed.

Table 2.2. is a list of parameters of the 16 GeV synchrotron.

Table 2.1. Proton Driver Parameters of Present , Stage 1 and Stage 2

Parameters	Present	Stage 1 (MI)	Stage 2 (MI + ν-fact)
Linac (operating at 15 Hz)			
Kinetic energy (MeV)	400	400	400
Peak current (mA)	40	60	60
Pulse length (μs)	25	90	90
H^- per pulse	6.3×10^{12}	3.4×10^{13}	3.4×10^{13}
Average beam current (μA)	15	81	81
Beam power (kW)	6	32	32
Booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)	8	12	16
Protons per bunch	6×10^{10}	2.4×10^{11}	1.7×10^{12}
Number of bunches	84	126	18
Total number of protons	5×10^{12}	3×10^{13}	3×10^{13}
Normalized transverse emittance (mm-mrad)	15π	60π	60π
Longitudinal emittance (eV-s)	0.1	0.1	0.4
RF frequency (MHz)	53	53	7.5
Extracted bunch length σ_t (ns)	0.2	1	1
Average beam current (μA)	12	72	72
Target beam power (MW)	0.1	0.9	1.2

Note: Although originally designed for 15 Hz operation, the present Booster has never delivered beam at 15 Hz continuously. In the past it used to run at 2.5 Hz. In the near future it will run at 7.5 Hz for the MiniBooNE experiment.

Table 2.2. Parameters of the 16 GeV Synchrotron

Circumference (m)	711.3
Super-periodicity	3
Number of straight sections	3
Length of each arc (m)	173.2
Length of each straight section (m)	63.9
Injection kinetic energy (MeV)	400
Extraction kinetic energy (GeV)	16 (12 in Stage 1)
Injection dipole field (T)	0.08464
Peak dipole field (T)	1.5 (1.1445 in Stage 1)
Bending radius (m)	37.6
Maximum quad gradient (T/m)	8.7494 (6.6758 in Stage 1)
Number of dipoles	36 (long)
	12 (short)
Number of quads in the arcs	72
Number of quads in the straight sections	24
Max β_x, β_y (m)	35, 38
Min β_x, β_y (m)	1.3, 2.0
Max D_x in the arcs (m)	3.0
Min D_x in the arcs (m)	-3.0
Dispersion in the straight sections	0
Transition γ_t	-j 28
Horizontal, vertical tune ν_x , ν_y	12.428, 11.380
Natural chromaticity ξ_x , ξ_y	-19.0, -18.7
Revolution time at injection, extraction (μs)	3.3, 2.4
Injection time (μs)	90
Injection turns	27
Laslett tune shift at injection	0.2
Normalized transverse emittance (mm-mrad)	
Injection beam (95%)	3 π
Circulating beam (100%)	60 π
Longitudinal emittance (95%, eV-s)	
Injection beam	0.14 (0.03 in Stage 1)
Circulating beam	0.4 (0.1 in Stage 1)
Extraction bunch length σ_t (rms, ns)	1
Momentum acceptance	±2.5%
Dynamic aperture	> 100 π

2.4. Comparison with Other High Intensity Proton Machines

Table 2.3 lists the existing as well as the planned high intensity proton machines in the world. The ISIS at the Rutherford Appleton Lab in England provides the highest beam power (160 kW) at this moment. When the SNS at the Oak Ridge National Lab becomes operational in 2004, it will provide 2 MW beam power. The SNS is an accumulator ring, as is the European ESS. Probably the closest machine to the Fermilab Proton Driver is the JHF Project in Japan. It has a rapid cycling 3 GeV Booster and a slow ramp 50 GeV Main Ring. Both are capable of delivering about 1 MW of beam power. This similarity provides the foundation of the successful US-Japan collaboration on high intensity proton facilities, in progress now for three years.

Table 2.3. High Beam Power Proton Machines

Machine	Protons Per Cycle	Repetition Rate (Hz)	Protons Per Second	Beam Energy (GeV)	Beam Power (MW)
Existing:					
RAL ISIS	2.5×10^{13}	50	1.25×10^{15}	0.8	0.16
BNL AGS	7×10^{13}	0.5	3.5×10^{13}	24	0.13
LANL PSR	2.5×10^{13}	20	5×10^{14}	0.8	0.064
Planned:					
Fermilab MiniBooNE	5×10^{12}	7.5	3.8×10^{13}	8	0.05
Fermilab NuMI	3×10^{13}	0.5	1.5×10^{13}	120	0.3
Proton Driver Phase I	3×10^{13}	15	4.5×10^{14}	16	1.2
Proton Driver Phase II	1×10^{14}	15	1.5×10^{15}	16	4
ORNL SNS	2×10^{14}	60	1.2×10^{16}	1	2
Europe ESS	2.34×10^{14}	50	1.2×10^{16}	1.334	2.5
Japan JHF	3.2×10^{14}	0.3	1×10^{14}	50	0.8

2.5. Operation Modes

There are five possible operation modes of the Proton Driver.

1. *Main Injector 120 GeV fixed target experiments: (NuMI, KAMI, Meson, etc.)*
   The Main Injector will take four Proton Driver batches to fill its ring. Each batch gives 3×10^{13} protons. So the Main Injector will operate at 1.2×10^{14} protons per cycle, a factor of four higher than its present beam intensity (3×10^{13} protons per cycle). The necessary measures for the Main Injector intensity upgrade will be discussed in Appendix D. The cycle time of the Main Injector is 2 seconds. Therefore, it will take only 2/15 of the protons available from the Proton Driver. The other 13/15 can be used for other programs (see below).

2. *Proton Driver fixed target experiments:*
   These will be new physics programs based on the stand-alone capabilities of the Proton Driver and can be carried out in parallel to the Main Injector experiments. Thirteen out of every fifteen Proton Driver cycles can be dedicated to these experiments. This gives an average proton flux of 3.9×10^{14} per second. The beam energy is 12 GeV in Stage 1 and 16 GeV in Stage 2. Therefore, the beam power available to these experiments will be 0.75 MW and 1 MW in Stages 1 and 2, respectively. The high intensity secondary particle beams produced by the proton beams will enable a rich class of physics programs based on muon, kaon, neutron, and neutrino beams.

3. *Antiproton production:*
   In this operation mode, the Main Injector will take one Proton Driver batch every 1.5 seconds. In order to fit the size of the Accumulator, the batch size will be 84 bunches (at 53 MHz operation). In other words, the batch will only occupy 2/3 of the Proton Driver. The other 1/3 will be chopped in the front end of the Linac. Each Proton Driver batch would contain 2×10^{13} protons, which is four times more than the present Booster batch (5×10^{12}). This means the antiproton production rate would be increased by a factor of four, provided that the production target and the cooling systems in the Debuncher and Accumulator would be upgraded accordingly. This mode of operation can be performed simultaneously with operation mode 1.

4. *Protons for Tevatron Collider experiments:*
   The 7.5 MHz bunch structure in Stage 2 would provide a useful feature for the Tevatron Collider experiments, namely, a 132 ns bunch spacing in Run IIb. The coalescing process in the Main Injector would no longer be necessary.

5. *Neutrino factory:*
   In Stage 2, a neutrino factory could take all the protons that the Proton Driver can provide. So there will be a competition between the experiments in operation mode 2 and a neutrino factory. However, it is conceivable that operation modes 1 and 3 would continue because they only need a small portion of protons from the Proton Driver.

Figure 2.3. Proton Driver Site Plan