3. Proton Driver

3.1 Introduction

The proton driver under design at Fermilab is a high intensity rapid cycling proton synchrotron. Its function is to deliver intense short proton bunches to the target for muon production. These muons will be captured, phase rotated, bunched, cooled, accelerated and finally, injected into a storage ring for neutrino experiments. In this sense, the proton driver is *the front end* of a neutrino factory. In addition to serving a neutrino factory, the proton driver may serve other needs. For example, it would replace the present Fermilab Booster as a high intensity new booster. As such it could be the platform for providing 6 times as high proton flux and 12 times as high beam power to experiments. It could also increase the beam intensity in the Main Injector by a factor of 4, where it may begin to have intensity limitations. The antiproton production rate and Tevatron luminosity could be enhanced accordingly, after comparatively modest upgrades in other machines.

The first serious effort for designing a new proton driver at Fermilab started around 1995 and was summarized in 1997 [1]. That work has continued, and a complete design report for such a machine is being prepared for the end of 2000. It is not appropriate to include the details here, and in the following, we only discuss the interaction between the Booster design parameters and those of the Neutrino source.

There are two primary requirements of the proton driver:

1. High beam power: P_{beam} = 1.2 MW
This requirement is similar to other high intensity proton machines that are presently under design or construction, e.g. the SNS at the ORNL, the ESS in Europe and the Joint Project (formerly known as the JHF) in Japan. This similarity makes it possible to establish a worldwide collaboration for tackling various technical design issues in a coherent manner.

2. Short bunch length at exit: σ_b = 3 ns.
This requirement is particular to the proton driver. It brings up a number of interesting and challenging beam physics issues that must be solved. The bunch length is related to the longitudinal emittance ε_L and momentum spread Δp by:

$$\sigma_b \propto \frac{e_L}{\Delta p}$$

In order to get short bunch length, it is essential to have:

- small longitudinal emittance (emittance preservation during the cycle);
- large momentum acceptance (in the rf and as well as in the lattice);
- bunch compression at the end of the cycle.

3. Low beam loss during acceleration to keep the activation of machine components low enough to allow maintenance. The above requirements on the machine design make this a major challenge.

3.2 Choice of Major Design Parameters

The design goal of the neutrino factory at Fermilab is 2×10^{20} muons per year to the neutrino experiments. This requires 4.5×10^{14} protons per second (see chapter 2). At a repetition rate of 15 Hz, 3×10^{13} protons per cycle are required. The average beam current is 72 μA. At 16 GeV, this provides a beam power of about 1.2 MW.

The beam power is the product of three parameters – proton energy E_p, number of protons per cycle N_p and the repetition rate f_{rep}:

$$P_{beam} = E_p \times N_p \times f_{rep}$$

The rep rate is chosen to be 15 Hz for two reasons: (1) Fermilab has a 15 Hz linac. A repetition rate higher than 15 Hz would require a major change in the present linac set-up. (2) A repetition rate lower than 15 Hz would mean more protons per cycle, which will be difficult in the present linac.

A proton energy of 16 GeV was chosen for the proton driver study. The choice of beam energy is a compromise resulting from the following considerations:

1) All other things being equal, higher energy synchrotrons most probably require higher investment cost.

2) At the outset of this study, the calculations being made so far indicated that muon flux scales with beam power over a fairly wide range of proton energies. For a fixed repetition rate and a specified beam power, reducing the beam energy would require a proportional increase in beam intensity. Those changes in turn would cause the following undesirable parameter changes: higher longitudinal phase space density N_b/ε_L (in which N_b is the number of protons per bunch), higher space charge tune shift ΔQ at top energy (which would make bunch compression more difficult) and large momentum spread $\Delta p/p$.

3) The present Fermilab linac should be able to deliver the intensity required for a 16 GeV synchrotron, 3×10^{13} particles per cycle at 15 Hz, after upgrades of modest scope. More substantial upgrades would be necessary for higher intensities.

4) Higher intensities will exacerbate space-charge effects at low energy in the synchrotron, and it would probably be necessary to raise the linac energy to alleviate these effects, perhaps to 1 GeV.

5) For the present 400 MeV linac and a 16 GeV synchrotron, the ratio of input and output momenta for the synchrotron is about 18, which is a rather large but probably tolerable dynamic range for a rapid cycling synchrotron.

There are a number of open questions regarding the design energy for the booster that can only be answered by looking at the overall service that the Booster must provide in support of the laboratory physics programs. These broader questions were not addressed at this time, and the parameters shown in Table 1 below were determined to be adequate for the purposes of this study.

The proton driver for the neutrino factory is called Phase I. Details of Phase I design will be described in the following sections. A possible future upgrade of the proton driver to serve a muon collider is called Phase II. Table 1 lists the main parameters of the two phases. However, Phase II design will not be discussed in this report. For comparison, the present proton source parameters are also listed in Table 1.

3.3 Technical Systems

The central part of the proton driver is a new 16 GeV synchrotron that would be installed in a new tunnel. There are eleven main technical systems: a new linac front end, a chopper, 400 MeV line, 16 GeV lines, 16 GeV ring lattice, injection and extraction systems, RF systems, magnets, power supplies, vacuum and collimators. The design of each system has been worked out to some detail and will be briefly described below.

3.3.1 New Linac Front End

In order to use much of the present linac as an injector for the first stage of the proton driver, the linac must provide H^- ions in excess of 4800 mA-μs (60 mA and 80 μs). Although both the beam current and pulse length are within the capability of the system, the beam loss and induced radiation in the structure at high intensity operation would become an issue. The front end of the linac will be changed to increase the transverse brightness of the beam. The new front end consists of a brighter source (either a modified magnetron or a DESY rf type volume source), a short electrostatic focusing structure (LEBT) and a 201

MHz RFQ from 30 keV to 1 MeV. In addition, an isochronous transport line made of two 270° bending magnets (the α-magnets) and five quads, a second 201 MHz RFQ from 1 MeV to 2.235 MeV and a modified Drift Tube Linac (DTL) section, in which the first existing 18 drift tubes will be eliminated, are required. The rest of the linac (*i.e.*, Tank 2 to 5 of the DTL and the Coupled Cavity Linac) will remain the way it is now. With these modifications the transverse beam emittance ε_T at 400 MeV is expected to decrease from 8 π mm-mrad (present value) to 3 π mm-mrad. This would greatly reduce beam losses in the linac due to the aperture limitations in the system.

	PRESENT	(ν-FACTORY) PHASE I	UPGRADE PHASE II
Linac (operating at 15 Hz)			
Kinetic energy (MeV)	400	400	1000
Peak current (mA)	40	60	80
Pulse length (μs)	25	80	200
H^- per pulse	6.3×10^{12}	3×10^{13}	1×10^{14}
Average beam current (μA)	15	72	240
Beam power (kW)	6	29	240
Pre-booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)			3
Protons per bunch			2.5×10^{13}
Number of bunches			4
Total number of protons			1×10^{14}
Norm. transverse emittance (mm-mrad)			200π
Longitudinal emittance (eV-s)			2
RF frequency (MHz)			7.5
Average beam current (μA)			240
Beam power (kW)			720
Booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)	8	16	16
Protons per bunch	6×10^{10}	7.5×10^{12}	2.5×10^{13}
Number of bunches	84	4	4
Total number of protons	5×10^{12}	3×10^{13}	1×10^{14}
Norm. transverse emittance (mm-mrad)	15π	60π	200π
Longitudinal emittance (eV-s)	0.1	2	2
RF frequency (MHz)	53	1.7	7.5
Extracted bunch length σ_b (ns)	0.2	3	1
Average beam current (μA)	12	72	240
Target beam power (kW)	100	1200	4000

Table 1: Proton Driver Parameters of Present, Phase I and Phase II.

3.3.2 Chopper

A new type of chopper has been designed and built in collaboration with the KEK 2. This is a pulsed beam transformer made of three 1"-thick Finemet cores. It is driven by two HTS 81-09 transistors for bipolar operation. It is placed in front of the RFQ and modulates the injection beam energy by ± 10%. The rise- and fall-time of the chopper is about 30 ns. A prototype has been installed and successfully tested with beam on the linac at HIMAC, a medical center in Japan operating a high intensity accelerator.

3.3.3 400 MeV Line

The 400 MeV line connects the linac to the 16 GeV ring. It could be made of permanent magnets, similar to the present 8 GeV line used at Fermilab.

3.3.4 16 GeV Line

In the present layout, the 16 GeV transport line is about 2 km long and connects the driver to the target station. A major portion of it would be in the Tevatron tunnel. A preliminary design using FODO lattice has been worked out. One concern about transporting intense ($N_b = 7.5 \times 10^{12}$) short ($\sigma_b = 3$ ns) bunches in this long line is possible bunch lengthening due to space charge and lack of longitudinal focusing. However, simulation shows that the longitudinal emittance growth is negligible in this line [3].

3.3.5 16 GeV Ring Lattice

In order to minimize longitudinal emittance dilution a lattice design should be chosen which does not require to go through transition. This excludes the traditional FODO lattice for a 16 GeV ring. Flexible momentum compaction (FMC) type lattice have to be considered. Other requirements include: $B_{max} \leq 1.5$ T, large dynamic aperture (> 100π mm-mrad), large momentum acceptance ($\Delta p/p = \pm 2.5\%$), and dispersion free straight sections for rf. A collimation system is definitely required and the collimator design must be coupled to the lattice design.

There are presently two FMC lattices under study. One with a triangular shape is shown in Figure 1. The circumference is 711.3 m, which is 1.5 times the size of the present booster. Another lattice has a racetrack shape. Both provide a large or imaginary γ_t and use sextupoles to increase the momentum acceptance. A choice will be made after more careful comparisons between the two lattices.

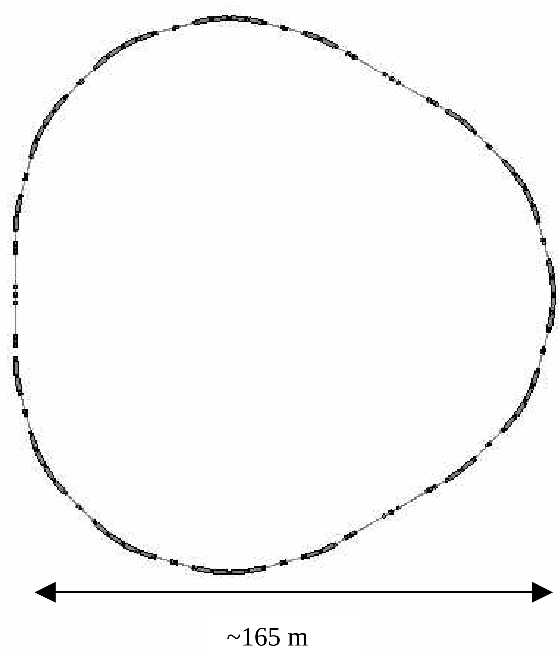

Figure 1: Footprint of the proton driver showing the triangular lattice.

3.3.6 Injection and Extraction

In order to reduce space charge effects, the injected beam will be painted in both transverse and longitudinal phase space. The horizontal injection system consists of 4 orbit bumpers and 2 fast kickers. The latter are used for painting and are located 90°apart (in phase) on each side of the foil. The foil temperature rise and beam emittance dilution during multiple passes through the foil have been calculated and seem tolerable.

Because this accelerator requires a resonant power supply, 1-turn fast extraction is considered. So far only one extraction point has been designed. A second extraction point is possible if placing the rf in dispersive regions (*i.e.*, in the arcs) turns out to be feasible.

3.3.7 The RF System

The required total rf voltage is about 1.4 MV. Due to the small circumference of this machine, the cavities must have a high gradient (30 kV/m). A study showed that Finemet cores (which is a new type of magnetic alloy) can withstand higher rf B-field than regular ferrite and thus provide higher gradient. The disadvantage is higher losses and lower Q. This can be partially compensated by cutting the core to two halves. In order to reduce eddy current heating, the sharp edges of the cut core should be shaped in order to minimize the radial B-field. A prototype 20 kV, 7.5 MHz Finemet cavity has been built at Fermilab in collaboration with the KEK and is shown in Figure 2. It will be tested in the Main Injector for 132 ns bunch spacing coalescing experiment.

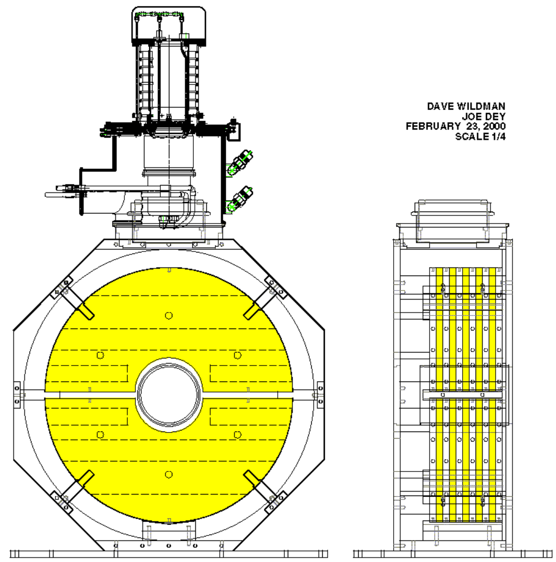

Figure 2: An rf cavity loaded with Finemet cores.

In addition to this acceleration rf system, a second rf system for bunch compression is considered 4. The main difference between the two systems is the duty factor. The one for acceleration will be used throughout the cycle. The second used for bunch compression is turned on for a few hundred microseconds in the cycle. Therefore, the latter could work at much higher gradient (0.5-1 MV/m).

3.3.8 Magnets

The main requirements are a large aperture (dipole: 12.7×31.8 cm^2, quad: 8.56 cm pole tip radius) and a large good field region (dipole: $\Delta B/B < 10^{-3}$ within ±10 cm). The lamination uses 0.014" silicon steel M17. The quadrupole design is similar to the large quadrupoles in the Fermilab Accumulator, except that it will use 4-piece laminations instead of 2-piece.

3.3.9 Power Supplies

A dual-resonance (15 Hz plus 12.5% 30 Hz component) is proposed. In addition to the main power supply, a second power supply for correcting the tracking error between dipole and quadrupole has also been designed. It drives the correction coils in the quadrupoles and uses a bucking choke in order to cancel the voltage and current induced by the main coils.

3.3.10 Vacuum System

In a rapid cycling machine, the eddy current in the beam pipe is a major problem. The ISIS solution, which is a ceramic pipe equipped with a metallic cage inside, works well. However, it requires additional vertical aperture within the magnet. The alternative is to use a thin metallic pipe. Three designs are being pursued: a 0.05" Inconel pipe with cooling tubes, a 0.005" Inconel pipe with ribs, and a composite material pipe with a thin Inconel (or Ti-Al) sheet inside. The pipe size is 5" × 9". The vacuum system design would give a vacuum of 10^{-8} Torr or lower. Such a vacuum would eliminate the concern about possible *e-p* instability as observed in the PSR at LANL.

3.3.11 Collimators

A 2-stage collimator system has been designed. Calculation shows that it can dump 99% of the lost particles in a controlled manner. With such a high efficiency, even for 10% loss at injection or 1% loss at ejection, the activation level in most of the tunnel would be around 1 W/m. Therefore, hands-on maintenance will be possible. The area near the collimators will require special local shielding.

3.4 Technical Design Issues

3.4.1 High Longitudinal Brightness

One of the most demanding issues in the proton driver design is the required longitudinal brightness. Table 2 is a comparison of the longitudinal brightness N_b/ε_L in existing as well as planned proton accelerators.

Machine	E_{max} (GeV)	N_{tot} (10^{12})	N_b (10^{12})	ε_L (eV-s)	N_b/ε_L (10^{12}/eV-s)
Existing:					
CERN SPS	450	46	0.012	0.5	0.024
FNAL MR	150	20	0.03	0.2	0.15
FNAL Booster	8	4	0.05	0.1	0.5
PETRA II	40	5	0.08	0.12	0.7
KEK PS	12	3.6	0.4	0.4	1
DESY III	7.5	1.2	0.11	0.09	1.2
FNAL Main Inj	150	60	0.12	0.1	1.2
CERN PS	14	25	1.25	0.7	1.8
BNL AGS	24	63	8	4	2
LANL PSR	0.797	23	23	1.25	18
RAL ISIS	0.8	25	12.5	0.6	21
Planned:					
Proton Driver Phase I	16	30	7.5	2	3.8
Proton Driver Phase II	16	100	25	2	12.5
Japan JHF	50	200	12.5	5	2.5
AGS for RHIC	25	0.4	0.4	0.3	1.3
PS for LHC	26	14	0.9	1.0	0.9
SPS for LHC	450	24	0.1	0.5	0.2

Table 2: Longitudinal Brightness of Proton Machines

The first phase for the proton driver (see Table 1) requires 3.8×10^{12} particles per eV-s, which is higher than most of the existing proton accelerators, with the exception of the PSR and ISIS. (The PSR is an 800 MeV accumulator ring. The ISIS, although an 800 MeV synchrotron, uses low field magnets, a small rf system, and has no sextupoles.)

In order to achieve high longitudinal brightness, one has to preserve ε_L, which is in contrast to the controlled blow-up of ε_L in many high intensity machines for keeping beam stable. The following measures are taken to preserve the longitudinal emittance ε_L:

1. Avoiding transition crossing in the lattice design. This eliminates a major source of emittance dilution.
2. Avoiding longitudinal microwave instability by keeping the beam below transition (The capacitive space charge impedance helps stabilize the beam below transition) and keeping the resistive impedance small (using a uniform metallic beam pipe).
3. Avoiding coupled bunch instability by using low Q rf cavity.
4. Applying inductive inserts for space charge compensation.
5. Applying longitudinal feedback system.

3.4.2 Bunch Compression

Bunch compression is required at the end of the cycle in order to shorten the bunch length to 3 ns. There are at least three possible methods to achieve this: (1) RF amplitude jump, (2) RF phase jump and, (3) the so called γt manipulation. The achieved compression ratio of either of these methods is about 3-5. Method (1) is the most common one. Although Fermilab has many years of experience with this operation, the high bunch intensity imposes new challenges:

1. During debunching, the beam momentum spread will decrease. This may give rise to excitation of the microwave instability.
2. During debunching, the rf voltage will decrease. This may exacerbate beam-loading effects.
3. In a regular bunch rotation simulation, the momentum compaction is assumed to be a constant α_0. However, the proton driver lattice is nearly isochronous ($\alpha_0 \approx 0$). The higher order terms (α_1, α_2,...) become important. Thus, particles with different $\Delta p/p$ have different path length ΔL. This complicates the bunch rotation process.
4. Due to short bunch length, the tune shift ΔQ from direct space charge and image charge remains large even at 16 GeV. This ΔQ also gives different path length ΔL. In other words, the path length of each particle depends not only on its longitudinal position but also on its transverse amplitude. This effect couples the longitudinal and transverse motion and is a new challenge to beam dynamics study.

Items 3 and 4 causes the so-called "η-spread" (η is the slip factor), which must be taken into account in theoretical modeling as well as in numerical simulations.

Several laboratories (Fermilab, BNL, KEK, CERN, GSI and Indiana Univ.) have decided to investigate methods to achieve the highest possible peak current, longitudinal brightness and compression ratio. An experiment in collaboration with BNL using the AGS has shown that bunches of σ_b = 2 ns can be produced for a bunch intensity of 4 X 10^{12} protons. The bunches were stable for the times measured during the experiment. [5]

3.4.3 Transient Beamloading

Transient beamloading can impose severe limitations on intense short bunch operation if not being compensated. A single bunch intensity of 7.5 X 10^{12} corresponds to a charge of q = 1.2 μC. With a gap capacitance of C = 300 pF, the single pass beamloading voltage q/C is 4 kV. Given the gap voltage of 20 kV the beamloading has to be compensated. However, because the bunch is very short (σ_b = 3 ns), it will be to difficult apply a short current pulse to perform direct compensation. This subject is a high priority R&D item in the proton driver study. RF feedforward systems for global compensation and an rf feedback system to reduce the bunch to bunch and turn by turn variation for a total reduction of 20-30 dB is required.

3.4.4 Space Charge and Instabilities

Space charge is a main limitation to achieve high intensity proton beams, in particular at injection. In order to reduce the Laslett tune shift, a large transverse emittance (60π mm-mrad, normalized, 95%) is used. Both the transverse and the longitudinal phase space will be diluted (painted) for a uniform particle distribution. Inductive inserts are foreseen to reduce the potential well distortion from space charge. An experiment is going on at the PSR/LANL using inductive insert modules provided by Fermilab. The results are encouraging. For a given rf voltage, the achievable beam intensity is increased when the inserts are in place. More measurements will be done to study the effects of the inserts on the beam.

There are two categories of instabilities in the proton driver which have been identified. One is the "conventional" type, for instance, impedance budget, resistive wall, slow head-tail, Robinson, coupled bunch, etc. These are by no means trivial. However, methods for compensation are well understood. Another type is "non-conventional," which is not well understood but is important for the proton driver.

For example, the longitudinal microwave instability below transition, fast head-tail instability (transverse mode coupling) in the presence of strong space charge, and synchro-betatron coupling when rf is placed in dispersive region. Both analytical and numerical studies are being carried out on these effects. Machine experiments are also being planned.

3.4.5 Particle Loss, Collimation Shielding

Here the main concern is the residual activity, which requires the residual dose to be below a certain level. Monte Carlo simulations using the code MARS show that, assuming an average particle loss rate of 1 W/m, the residual dose after 30 days irradiation and 4 hours cool down would be below 100 mrem/hr which is considered to be acceptable. This result agrees with other simulations done at LANL and ORNL. To meet these requirements, a collimation system has been designed with a capture efficiency better than 99% and would allow 10% particle loss at injection and 1% loss at extraction during normal operation. Shielding calculations have been performed as well. The needed berm thickness for shielding for a 1-hour accidental full beam loss is 29 feet.

3.5 Summary

Significant progress has been made to achieve the Phase I design goals. The proton driver consists of a modest improvement of the linac front end, a new 16 GeV synchrotron in a new tunnel and two new beam lines (400 MeV and 16 GeV). The synchrotron meets the needs of a neutrino factory and can provide a 1.2 MW proton beam with 3 ns bunch length. It also allows an upgrade path to a beam power of 4 MW and eventually a bunch length of 1 ns. The proton driver would also serve as a complete functional replacement for the Fermilab Booster, providing upgraded capabilities for the ongoing programs.

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