Proton Driver

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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. The first serious effort for designing a proton driver at Fermilab was during the summer of 1997 led by S. Holmes. The results were summarized in Ref. [1]. The present design study is a continuation of that effort. In particular, this design is tailored to meet the specific needs of a neutrino factory.

In addition to serve a neutrino factory, the proton driver may have other applications. For example, it would replace the present Fermilab Booster as a high intensity new booster. As such it could provide 6 times as high proton flux and 12 times as high beam power to the MiniBooNE experiment. It could also increase the beam intensity in the Main Injector by a factor of 4. The anti-proton production rate and Tevatron luminosity would be enhanced accordingly.

There are two primary requirements of the proton driver:

1. High beam power: $P_{\text{beam}} = 1.2$ 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 world-wide collaboration for tackling various technical design issues in a coherent manner.

2. Short bunch length at exit: $\sigma_b = 3$ ns.
   This requirement is *unique* for the proton driver. It brings up a number of interesting and challenging design issues that we must address in the study. The bunch length is related to the longitudinal emittance ε_L and momentum spread Δp by:

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

   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.

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It is interesting to compare the proton driver with the LHC or the former SSC. The LHC and SSC require proton beams very bright in the transverse plane. Transverse emittance (ε_T) preservation is of crucial importance in order to reach the design luminosity. In the longitudinal plane, however, ε_L would be blown up by two orders of magnitude in the injector chain in order to avoid instability and intrabeam scattering problem. The proton driver, on the contrary, requires high brightness in the longitudinal plane because of short bunch length, whereas ε_T would be diluted by painting during the injection from the linac to the ring in order to reduce the space charge effect.

2 CHOICE OF MAJOR DESIGN PARAMETERS

The design goal of the neutrino factory at Fermilab is 2×10^{20} useful muons per year to the neutrino experiments. Assuming one third of the muons in the storage ring is useful, it requires 6×10^{20} muons per year in the ring. Further assumptions are: one needs 15 protons (at 16 GeV) for every muon, and there are 2×10^7 seconds for experiments each year. These give 4.5×10^{14} protons per second. At a repetition rate (rep rate) of 15 Hz, 3×10^{13} protons per cycle is required. Therefore, the average beam current is 72 µA. At 16 GeV, this gives 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 rep rate f_{rep}:

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

The rep rate is chosen to be 15 Hz for three reasons: (1) Fermilab has a 15 Hz linac that can be used for the proton driver. Any rep rate higher than 15 Hz would require a major change in the present linac. (2) A rep rate lower than 15 Hz would mean more protons per cycle, which will be difficult in the present linac. (3) This proton driver is designed with an upgrade capability for a future multi-TeV muon collider. The life time of a 2 TeV muon is about 40 ms. The 15 Hz rep rate is comparable to the muon decay rate.

The proton energy of 16 GeV is chosen due to the following considerations: (1) Lower energy is not preferred. Because it would give 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 larger momentum spread $\frac{\Delta p}{p}$. (2) The present Fermilab linac can deliver 3×10^{13} particles at 15 Hz. If the proton energy is lower than 16 GeV, it would require more particles from the linac, which will be difficult. (3) The present linac is 400 MeV. For a 16 GeV ring, the dynamic range is about 18, which should be fine. If further raising the energy, the dynamic range would become too large and cause trouble to the magnets.

It is clear that the parameter choice made above are based on the proton driver design itself. However, when considering the downstream subsystems that the proton driver would serve, there are two issues that should be pointed out:

1. A recent MARS simulation of the muon yield *vs.* proton energy for a graphite target shows a peak around $E_p = 6$ GeV. If this result is confirmed by target experiments (*e.g.*, HARP at CERN and E951 at BNL) and by other simulations (*e.g.*, FLUKA at CERN), it will play a role in the choice of E_p in the final design.

   From the cost point of view, however, a lower energy ring does not necessarily translate into lower cost. For the same beam power, the cost of a 16 GeV ring using the existing 400 MeV linac could be comparable to that of a lower energy ring plus an upgraded linac. (A detailed cost comparison is yet to be done.)

2. A rough estimate of the power consumption of the downstream subsystems, which are mostly in burst mode operation, shows that it would be prohibitively expensive for high rep rates. Thus, a lower rep rate is preferred. However, the target would obviously prefer a higher rep rate. Therefore, a trade-off investigation is needed for rep rate optimization. But this is out of the scope of the current study.

In addition to P_{beam}, f_{rep}, E_p and N_p, there are two more important parameters to choose, namely, the bunch length σ_b and number of bunches in the ring.

- Bunch length: A shorter bunch is preferred by the muon decay channel (to capture more muons per proton) and by muon polarization. However, several quantitative calculations of muon yield *vs.* bunch length indicate that, when σ_b is increased from 1 ns to 3 ns, the decrease in muon yield is small ($< 10\%$). The polarization, on the other hand, has a stronger dependence on σ_b. But it is not required by the current study. For the proton driver, a 3 ns bunch is much easier to produce than a 1 ns bunch, because a longer bunch would give smaller space charge tune shift ΔQ, smaller momentum spread $\frac{\Delta p}{p}$, and smaller bunch compression ratio. Therefore, it is decided to choose $\sigma_b = 3$ ns.

- Number of bunches: For given total number of protons in the ring and the length of each bunch, it is preferred to have more bunches. However, the downstream induction linac, which is for muon phase rotation, can only deliver 4 pulses per cycle. This limits the bunch number to 4 in the present design. It should be pointed out that, there is a new US-Japan initiative (between Fermilab and the KEK) for developing low frequency (several MHz) high gradient (0.5-1 MV/m) rf system. This would open up the possibility of using rf phase rotation replacing the induction linac. In this case, the bunch number could be increased to 18 or higher.

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. As a comparison, the present proton source parameters are also listed in Table 1.

3 TECHNICAL SYSTEMS

The proton driver consists of a new 16 GeV synchrotron that would be installed in a new tunnel, a moderate Linac upgrade and two new transport lines (400 MeV and 16 GeV). The design of each technical system has been worked out to some detail and will be briefly described below.

3.1 New linac front end

In order to use much of the present linac as an injector for Phase I of the proton driver, the linac must provide H^- ions in excess of 5400 mA-µs (60 mA and 90 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 a problem so hands-on maintenance may suffer. Therefore, it is planned to change the front end for increasing 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), a 201 MHz RFQ from 30 keV to 1 MeV, 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 Tank 1 (DTL), in which the first 18 drift tubes will be eliminated. The rest of the linac (*i.e.*, Tank 2 to 5 and the CCL) will remain as it is now. With these modifications, it is expected that the transverse beam emittance ε_T at 400 MeV would be decreased from 8 π mm-mrad (present value) to 3 π mm-mrad. This would greatly reduce beam losses in the linac, which is believed to be mainly due to the aperture limit in the system.

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 a 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 on the linac of the HIMAC, a medical accelerator center in Japan. The beam test was successful [3].

3.3 400 MeV line

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

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 ma-

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

	Present	Phase I (ν-factory)	Phase II ($\mu\mu$-collider)
Linac (operating at 15 Hz)			
Kinetic energy (MeV)	400	400	1000
Peak current (mA)	40	60	80
Pulse length (μs)	25	90	200
H^- per pulse	6.3×10^{12}	3.4×10^{13}	1×10^{14}
Average beam current (μA)	15	81	240
Beam power (kW)	6	32	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}
Normalized 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}
Normalized 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_t (ns)	0.2	3	1
Average beam current (μA)	12	72	240
Target beam power (kW)	100	1200	4000

jor 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, PARMILA simulation shows that the beam longitudinal emittance growth is negligible in this line.

3.5 16 GeV ring lattice

In order to minimize longitudinal emittance dilution, a principal requirement in the lattice design is that it should be transition free. This excludes the traditional FODO lattice for a 16 GeV ring. One must consider the flexible momentum compaction (FMC) type lattice. Other requirements include: $B_{max} \leq 1.5$ T, large dynamic aperture ($> 100\pi$ mm-mrad), large momentum acceptance ($\frac{\Delta p}{p} = \pm 2.5\%$), and dispersion free straight sections for rf. Due to the importance of a collimation system in this high intensity machine, the collimator design must be coupled to the lattice design.

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

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) from the foil on each side of the foil. The foil temperature rise and beam emittance dilution during multiple passes through the foil have been calculated and should not be a problem.

Because this machine uses a resonant power supply, only 1-turn fast extraction is considered. At this moment, only one extraction point has been designed. A second extraction point is possible if one could demonstrate that it would be safe to place rf in dispersive region (*i.e.,* in the arcs).

3.7 RF system

The required total rf voltage is about 1.2 MV. Due to the compact size of this machine, the cavity must have high gradient (30 kV/m). Study shows 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 problem about Finemet is that it has low Q and is lossy. But this can be partially solved by cutting the core to two halves. In order to reduce eddy current heating, the sharp edges of the cut core should be shaped such that the radial B-field is minimized. A prototype 14 kV, 7.5 MHz Finemet cavity has been built at Fermilab in collaboration with the KEK. It will be tested in the Main Injector for 132 ns bunch spacing coalescing experiment.

In addition to this acceleration rf system, another rf system for bunch compression is also under investigation. [4] The main difference between the two systems is the duty factor. The one for acceleration will be used for 50% of the cycle, whereas that for bunch compression is put to use for just hundreds μs in a cycle. Therefore, the latter could work at mush higher gradient (0.5-1 MV/m).

3.8 Magnets

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

3.9 Power supplies

Four proposals have been considered: (1) programmable IGBT (as the MI sextupole power supply), (2) single 15 Hz resonance circuit (as in the present booster), (3) dual-resonance (15 Hz plus 12.5% 30 Hz component), and (4) dual-frequency (up-ramp 10 Hz, down-ramp 30 Hz). After a careful comparison, (3) is chosen. The reasons are the following. It is cheaper (by a factor of 2) than (1); it can save 25% rf power compared with (2); and it has no ripple problem at injection, which is a main concern of (4).

In addition to the main power supply, a second power supply for correcting the tracking error between dipole and quad has also been designed. It drives the trim coils in the quads and uses bucking choke for cancelling the transformer effect between the main and trim coils.

3.10 Vacuum system

In a rapid cycling machine, the eddy current in the beam pipe is a major problem. The ISIS solution, which uses ceramic pipe equipped with a metallic cage inside, works well. However, it requires additional vertical aperture of the magnet. The alternative is to use 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" $\times$ 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.

3.11 Collimators

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

4 TECHNICAL DESIGN ISSUES

4.1 High longitudinal brightness

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

The proton driver Phase I requires 3.8×10^{12} particles per eV-s, which is higher than most of the existing machines, 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 for ε_L preservation:

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

4.2 Bunch compression

A bunch compression is needed at the end of the cycle in order to shorten the bunch to 3 ns. There are at least three possible ways to do this gymnastics: (1) RF amplitude jump, (2) RF phase jump and, (3) γ_t manipulation. The achieved compression ratio of either method is in the range of 3-5.

Table 2: Longitudinal Brightness of Proton Machines

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

Method (1) is most common among the labs. Although Fermilab has many years of experience with this operation, the high bunch intensity poses new problems:

1. During debunching, the beam momentum spread will decrease. This may give rise to microwave instability.
2. Also during debunching, the rf voltage will decrease. This may cause severe beamloading 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 become important. Thus, particles with different $\frac{\Delta p}{p}$ 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 modelling as well as in numerical simulations.

These problems have got the attention of beam physicists. Several labs (Fermilab, BNL, KEK, CERN, GSI and Indiana Univ.) have decided to carry out experimental studies in a "contest" — to see who can get the highest peak current, longitudinal brightness and compression ratio.

4.3 *Transient beamloading*

This problem is crucial to the intense short bunch operation. The single bunch intensity (7.5×10^{12}) gives a charge $q = 1.2$ μC. For a 14 kV cavity and a gap capacitance $C = 300$ pF, the single pass beamloading voltage q/C would reach 3 kV, which has to be compensated. However, because the bunch is very short ($\sigma_b = 3$ ns), how to inject a short current pulse to do the compensation is challenging. This is a high priority item in the proton driver study. The plan is to use an rf feedforward system for global compensation and an rf feedback system for reducing bunch-to-bunch and turn-by-turn variations for a total reduction of 20-30 dB.

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 transverse and longitudinal phase spaces will be painted for a uniform particle distribution. It is also planned to use inductive inserts to reduce the potential well distortion from the space charge. An experiment is going on at the PSR/LANL using inductive modules provided by Fermilab. The results are encouraging. For given rf voltage, the achievable beam intensity is increased when the inserts are applied. More measurements will be done to study the effects of the inserts to the beam.

There are two categories of instability problems in the proton driver. 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, one knows how to deal with them. Another type is "non-conventional," which is not well understood but is important to the proton driver. For example:

- Longitudinal microwave instability below transition. In theory, the capacitive space charge impedance helps to make beam stable when it is below transition. However, a recent SPS experiment showed that, even below transition, a coasting beam can be unstable. It is not clear if the same would be true for a bunched beam. More experiments are needed.

- Fast head-tail (transverse mode-coupling) in the presence of strong space charge. This type of instability is clearly observed in electron machines. However, it has never been observed in any proton machine. There are two possible explanations:

  1. If the betatron tune spread ΔQ_β in a proton machine is many times larger than the synchrotron tune Q_s, then the mode lines ($m = 0, \pm 1, ...$) would get smeared and there won't be any coupling.
  2. In low- and medium-energy proton machines, the space charge force is significant. It would shift $m = -1$ mode downward as the beam intensity increases. Meanwhile, the inductive broadband wall impedance would shift this mode upward. Thus, they intend to cancel each other. This makes the coupling between the mode $m = 0$ and $m = -1$ more difficult.

  These claims need support from more careful analytical and numerical study.

- Synchro-betatron resonance due to dispersion in rf section. Due to the compact size of the proton driver, some rf cavities may have to be installed in the dispersion region. The concern is about the synchro-betatron resonance $kQ_\beta \pm mQ_s = n$. In previous studies, the case $k = 1$ has been fully analyzed [5]. However, the cases of $k = 2, 3, ...$ remain open.

4.5 Particle loss, collimation and shielding

Here the main concern is the hands-on maintenance, which requires the residual dose below certain level before one may proceed to do any repair work. Monte Carlo simulations using the code MARS show that, at 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. This result agrees with that obtained at LANL and ORNL. To meet this requirement, a collimation system has been designed. It has a capture efficiency better than 99% and would allow 10% particle loss at injection and 1% loss at extraction during normal operation.

The MARS code was also used for radiation shielding calculation. The needed dirt thickness for shielding 1-hour accidental full beam loss is 29 feet. It is close to the result obtained from the simplified scaling formula (the Dugan criterion), which gives 32 feet.

4.6 Other issues

A number of other design issues are also under investigation, including FMC lattice design for large momentum and dynamic aperture, beam injection when magnet current has a second harmonic (*i.e.*, $\dot{B}$ has a large non-zero value), injection painting, tracking error correction, cooling and induced field error correction of thin metallic pipes, high intensity high brightness H^- source design, fringe field correction of large aperture dipoles and quads, etc.

5 SUMMARY

Over the past year a team in the Beams Division has been working on the proton driver for Fermilab. Significant progresses have been made to reach the Phase I design goals. A Phase I 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). It 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 bunch length of 1 ns, which will be required by a future muon collider. In addition to serve a neutrino factory and/or a muon collider, the system would also serve as a complete functional replacement for the Fermilab Booster, providing upgraded capabilities in the future for the programs that the Booster would otherwise have served. New physics programs based on the stand-alone capabilities of the proton driver as an intense source of proton beams would also be enabled.

The Fermilab management has scheduled an internal technical review of the proton driver design study on April 17-19, 2000. A complete design report will be due early 2001.

6 REFERENCES

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