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Abstract. Fermilab has started the design work of a high intensity proton source called the proton driver. It would provide a 4 MW proton beam to the target for muon production. This paper discusses the basic features of this machine and the associated accelerator physics and design issues.

INTRODUCTION

Since about 1996, a Muon Collider Collaboration has been formed within the high energy physics (HEP) community to study the feasibility of a future collider using muon beams. Recently, this collaboration has turned its attention to a relatively cheaper and easier muon storage ring called the neutrino factory. Either a collider or a storage ring, it requires muon beams whose intensity is several orders of magnitude higher than that in any existing muon source. In order to produce such intense muon beams, a high intensity proton source, called the proton driver, is needed.

The proton driver is a high intensity rapid cycling proton synchrotron. Its primary function is to deliver intense short proton bunches to the target for muon production. These muons will be captured, phase rotated, cooled, accelerated and finally, injected into either a storage ring for neutrino experiment (a ν-Factory) or a collider for $\mu\mu$ collision. In this sense, the proton driver is *the front end* of a muon facility.

There are two primary requirements of the proton driver:

1. High beam power: $P_{\text{beam}} = 4$ MW.
   This requirement is similar to other high intensity proton machines that are presently under design, *e.g.,* the SNS, ESS and JHF.

2. Short bunch length at exit: $\sigma_b = 1$-2 ns.
   This requirement is *unique* for the proton driver. It brings up a number of interesting and challenging beam physics issues that we will discuss in this paper.

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[1] Fermilab is operated by Universities Research Association, Inc. under contract with the US Department of Energy.

The bunch length is related to the longitudinal emittance ϵ_L and momentum spread Δp by:

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

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

- longitudinal emittance preservation (no intentional blow-up);
- large momentum acceptance (in both rf and lattice);
- bunch rotation at the end of the cycle.

It is interesting to compare the proton driver with the former SSC. The SSC required proton beams very bright in the transverse plane. In order to reach the design luminosity, the design value of the transverse emittance ϵ_T was 1 μm, which was several times smaller than that in any existing high energy proton colliders. 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.

CHOICE OF THE PRIMARY PARAMETERS

The beam energy is the product of three parameters: proton energy E_p, number of protons per cycle N_p and the repetition rate (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. There are two reasons: (1) Muons decay quickly. So the collider needs to get re-fill quickly. The life time of a 2 TeV muon is about 40 ms. The rep rate should be comparable to the muon decay rate. (2) Fermilab is experienced in operating 15 Hz linac and booster.

Given the beam power and rep rate, the product $E_p \times N_p$ is determined. At this time, we choose 16 GeV and 1×10^{14} protons per pulse (ppp). This is based on the following trade-off considerations: (1) Higher E_p would give lower longitudinal phase space density N_b/ϵ_L, lower space charge tune shift ΔQ at top energy, and would give smaller momentum spread $\frac{\Delta p}{p}$. (2) However, higher E_p would also mean higher cost (*e.g.,* $V_{rf} \propto E_p^2$) and higher radiation power to the environment. The choice of 16 GeV is a reasonable compromise. There are two other important issues related to the choice of E_p:

- The muon yield per proton N_μ/N_p at the beginning of the decay channel is believed to be proportional to E_p. However, the effective muon yield (*i.e.,* N_μ/N_p at the exit of the decay channel) as a function of E_p is yet to be studied.

- For given $P_{\rm beam}$, the total energy deposition on the target is a constant (about 10%) in the range of E_p from 8 GeV to 30 GeV. However, the deposited energy is not distributed uniformly. A crucial parameter in the target design is the maximum density of energy deposition on the target. It needs to be simulated as a function of E_p.

Table 1 is a comparison of these parameters in high beam power proton machines.

TABLE 1. High Beam Power Proton Machines

Machine	Protons per Cycle	Repetition Rate (Hz)	Protons per Second	Beam Energy (GeV)	Beam Power (MW)
Existing:					
BNL AGS	8×10^{13}	0.5	4×10^{13}	30	0.2
FNAL Booster	5×10^{12}	15	7.5×10^{13}	8	0.1
RAL ISIS	2.5×10^{13}	50	1.25×10^{15}	0.8	0.16
LANL PSR	2.5×10^{13}	20	5×10^{14}	0.8	0.064
Planned:					
Proton Driver	1×10^{14}	15	1.5×10^{15}	16	4
Japan JHF	2×10^{14}	0.3	0.6×10^{14}	50	0.5
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

The layout of the proton driver was described in Ref. [1]. It consists of three accelerators: a 1 GeV linac, a 3 GeV pre-booster and a 16 GeV booster. At present, Fermilab has a 400 MeV linac and a 8 GeV booster. The proton driver would increase the beam intensity by a factor of 20 and beam power a factor of 40.

The proton driver would be built in two phases. In Phase I, a 16 GeV new booster will be built in a new tunnel, using the present 400 MeV linac as its injector. The beam intensity will be increased by a factor of 5. In Phase II, a 1 GeV linac and a 3 GeV pre-booster will be added, bringing up the beam intensity by another factor of 4. The parameters in these stages are listed in Table 2.

BEAM PHYSICS

Longitudinal beam dynamics

1. High longitudinal phase space density – Keep ϵ_L small:
   Table 3 is a comparison of the longitudinal brightness N_b/ϵ_L in existing as well as planned proton machines. The proton driver requires 12.5×10^{12} particles per eV-s, which is almost an order of magnitude (or more) higher than most

TABLE 2. Parameters of Present, Phase I and Phase II

	Present	Phase I	Phase II
Linac (operating at 15 Hz)			
Kinetic energy (MeV)	400	400	1000
Peak current (mA)	40	45	80
Pulse length (μs)	25	90	200
H^- per pulse	6.3×10^{12}	2.5×10^{13}	1×10^{14}
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
Booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)	8	16	16
Protons per bunch	6×10^{10}	3×10^{11}	2.5×10^{13}
Number of bunches	84	84	4
Total number of protons	5×10^{12}	2.5×10^{13}	1×10^{14}
Norm. transverse emittance (mm-mrad)	15π	50π	200π
Longitudinal emittance (eV-s)	0.1	0.1	2
RF frequency (MHz)	53	53	7.5
Extracted bunch length σ_t (ns)	0.2	0.2	1
Target beam power (MW)	0.1	1	4

of the existing machines except the PSR and ISIS, which are low energy (800 MeV) machines.

In order to achieve such a high longitudinal brightness, one has to preserve ϵ_L, which is in contrast to the "conventional wisdom" of blowing up ϵ_L to keep beam stable. The following measures are taken for ϵ_L preservation:

- Avoid transition crossing in the lattice design. This would eliminate a major source of emittance dilution.
- Avoid longitudinal microwave instability by keeping the beam always below transition and keeping the resistive impedance small in the machine design. Experience shows that, below transition, the microwave instability is much less likely to occur when the large capacitive space charge impedance is dominant.
- Avoid coupled bunch instability by using low Q rf cavity.
- Apply inductive insert to compensate the potential well distortion due to the space charge.

TABLE 3. Longitudinal Brightness of Proton Machines

Machine	$E_{\max}$ (GeV)	$N_{\rm tot}$ (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
KEK PS	12	3.6	0.4	2	0.2
FNAL Booster	8	4	0.05	0.1	0.5
PETRA II	40	5	0.08	0.12	0.7
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	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

2. Bunch rotation:
A bunch rotation is needed at the end of the cycle in order to shorten the bunch to 1-2 ns. There are three possible ways to do this gymnastics:

- RF amplitude jump
- RF phase jump
- γ_t manipulation

The first two methods have been in use for many years. The third one is a new idea first suggested by J. Norem and has been partially demonstrated at an experiment at the AGS. In either of these methods, the bunch length compression ratio is about 3-4.

Our simulation study is focused on the rf amplitude jump. Although Fermilab has years of experience with this operation, the high bunch intensity poses new problems:

(a) During the debunching process, how low can the rf voltage be?
Lower V_{rf} means lower $\frac{\Delta p}{p}$, which in turn gives larger compression ratio. At a high intensity bunch rotation experiment at the AGS, it was found that the minimum V_{rf} is limited by the beamloading effect rather than beam instabilities.

(b) What is the effect of the higher order terms of the momentum compaction factor α_1 and α_2 in bunch rotation?
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 become important. In other words, particles with different $\frac{\Delta p}{p}$ would have different path length ΔL. We are still in the process to understand this effect. Preliminary simulations show that, if α_1 is not properly chosen, the bunch rotation could fail.

(c) What is the effect of the transverse tune shift in bunch rotation?
This is an effect similar to the above but from the transverse plane. 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, which would affect bunch rotation. In other words, the path length of each particle depends not only on its longitudinal position but also on its transverse amplitude. One difficulty in studying this problem is how to mimic this space charge effect. Is it conceptually correct simply changing the lattice quad strength to estimate ΔL? Is a 6D simulation necessary to study this complicated transverse-longitudinal coupling problem? It will take a while for us to fully understand this problem.

At this workshop, it was proposed to have a 5-lab "contest." Namely, the machines in the five labs – BNL-AGS, FNAL-MI, KEK-PS, CERN-PS and SPS, and Indiana University-IUCF – would carry out two experiments: (1) bunch rotation, and (2) longitudinal microwave instability below transition. The competing items are: i. maximum peak current I_{peak}; ii. maximum longitudinal phase space density N_b/ϵ_L; and iii. maximum compression ratio.

Space charge and instabilities

As in all other high intensity machines, the following measures are taken to reduce the Laslett tune shift ΔQ at injection: high injection energy (3 GeV), large transverse emittance (200π mm-mrad, normalized), painting and a 2nd harmonic rf.

In addition to these, it is also planned to use inductive inserts to reduce the potential well distortion from the space charge. Although this idea was proposed many years ago, nobody ever tried it on a real machine until recently. There are two on-going experiments: one at the LANL-PSR using ferrite inserts, another at the KEK-PS using Finemet inserts. The data are being analyzed. A third experiment at the ANL-IPNS is also being discussed. Simulations show that inductive compensation helps during injection, acceleration and bunch rotation. However, because these inserts also introduce additional resistive impedance, one needs to be careful so that it would not cause any instability problem.

The "conventional" type of instabilities, namely, those we have studied for decades, include the impedance budget, resistive wall, slow head-tail, Robinson, coupled bunch, *etc.* These are by no means trivial. However, it is believed that one knows how to deal with them.

More difficult is another type of problems, the "non-conventional" ones, which become important because of the special requirements of the proton driver. They are yet to be understood.

- Longitudinal microwave instability below transition:
  Below transition, the validity of the Keil-Schnell criterion is questionable. There are a number of cases in which this criterion is violated. For example, the beam intensity in the RAL-ISIS is 10 times higher than the calculated threshold.

  In fact, there is no report on observation of microwave instability in any existing proton machines when they operate below transition. Only in some special machine experiments, which introduce large resistive impedance on purpose, self-bunching and perhaps also instability were seen in a coasting beam.

  More theoretical, simulation and experimental studies are needed on this subject.

- Fast head-tail (transverse mode-coupling) in the presence of strong space charge:
  This type of instability is clearly observed in electron machines. Moreover, the calculated threshold and growth rate agree well with the measurements. 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. Would this be a problem? 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. [2] However, the cases of $k = 2, 3, ...$ remain open. It is not clear at this moment if this would be a problem, although experiences tell us that betatron resonances up to the 3rd order could still be important even in a rapid cycling synchrotron.

Particle loss, collimation and shielding

The tolerable particle loss is an important issue in high intensity proton machine design. One main concern is the hands-on maintenance, which requires the residual dose below certain level before one may proceed to do any repair work. Using the preliminary lattice and magnet design of the proton driver, 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.

In the meantime, a collimation system has been incorporated into the lattice. Even with an assumed 10% loss at 3 GeV (which gives 72 kW), simulation shows that this system would confine more than 99% of the losses in a local section, leaving most of the ring (the so-called "quiet" area) below 5 W/m.

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.

Transient beamloading

This problem is crucial to the intense short bunch operation. The single bunch intensity (2.5×10^{13}) gives a charge $q = 4$ μC. For a 20 kV cavity and a gap capacitance $C = 400$ pF, the single pass beamloading voltage q/C would reach 10 kV, which has to be compensated. However, because the bunch is very short ($\sigma_b =$ 1-2 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. At this moment, 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.

The multi-pass beamloading voltage has a rich Fourier spectrum when a low Q cavity is used. An rf feedback system would have to provide several harmonics for sufficient compensation.

Lattice

The constraints and requirements of the lattice design are:

- $B_{max} \leq 1.5$ Tesla
- No transition crossing (which excludes the FODO lattice)
- Large dynamic aperture ($\epsilon_N = 200\pi$ mm-mrad)
- Large momentum acceptance: $\frac{\Delta p}{p} = \pm 2.5\%$
- Dispersion free straight sections for rf, injection and extraction

- Suitable locations for a collimation system

There are two FMC (flexible momentum compaction) lattice candidates, one is triangular, another racetrack. Both give large or imaginary γ_t and use sextupoles to increase the momentum acceptance. The same sextupoles can also be used to control the slope (α_1) of the momentum compaction factor if a compromise in chromaticity control is acceptable.

It turns out to be impractical to design a 16 GeV lattice that meets all the above requirements while keeps the same size (474 m) of the present booster. The new booster would be larger.

TECHNICAL SYSTEMS

RF

The required rf voltage is about 1.2 MV. Due to small size of the machine, the cavity needs to have high gradient (> 20 kV/m). A new type of magnetic alloy called the Finemet will be used. Thanks to the US-Japan collaboration, a 7.5 MHz, 20 kV prototype cavity is under construction. After high power bench test, it will be installed in the Main Injector for beam test.

Magnets

These are big magnets. The dipole has an aperture of 5" $\times$ 13" and weighs about 10 tons per meter. The peak field is 1.5 Tesla. Simulation shows the field quality is good: $\frac{\Delta B}{B} < 10^{-3}$ within ± 4". One important parameter is the ac loss of these magnets. The data from vendors' catalogs are not applicable, because they are measured at 60 Hz and without dc bias. Our measurement shows that, at 15 Hz and with dc bias current, the as loss is about 1/15 of that in the catalog.

Power supply

There are two proposals. One is a programmable power supply using fast switching IGBT (about 7 kHz). The reactive power will be stored in a capacitor bank. Another is a resonant power supply. The latter has three variations: (1) single 15 Hz resonance circuit (as in the present booster), (2) dual-resonance circuit (15 Hz plus 12.5% 30 Hz component), and (3) dual-frequency circuit (up-ramp 10 Hz, down-ramp 30 Hz, using IGBT to switch the frequency). Both (2) and (3) can save significant rf power and rf voltage. One concern about (3) is the ripple effect during injection.

An attractive feature of the programmable power supply is its feasibility, namely, to allow different ramp rate, a flat top and a flat bottom. But it is more expensive.

Vacuum pipe

The present design is a thin Inconel pipe (5" $\times$ 9" $\times$ 50 mils) with water cooling. Compared with stainless steel, Inconel has high strength and high electric resistivity. Its eddy current is 4 times smaller than that in stainless steel. Compared with the ceramic pipe (as used in the ISIS), Inconel reduces the vertical magnet aperture by 1.5-2 inches. The main concerns about an Inconel pipe are:

- Large deflection under vacuum: $\Delta y = -1$", $\Delta x = 0.7$"
- Eddy current heating: ~ 3 kW/m
- Eddy current induced error field: At $\dot{B}_{max}$, 1" reference point, the harmonic components are $b_1 = 93$ unit, $b_3 = 2.6$ unit.

Several pieces of prototype pipes are being fabricated. The water cooling tubes are glued to the beam pipe by some special epoxy, which is electrically an insulator but has good thermal conductivity. The pipes will undergo vacuum and heating tests.

Another design using ultra thin (5 mils) Inconel or Ti-Al alloy is under investigation. It uses ribs for mechanical stability. Because the heat load would be reduced by a factor of 10, the cooling system could be eliminated.

RF chopper

A new type of chopper, which is a pulsed beam transformer using Finemet and can be placed in front of the RFQ in the linac, has been designed and built in collaboration with the KEK. The beam test will be performed at the HIMAC in Japan.

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