OVERVIEW OF THE PROTON DRIVER

W. Chou

Presented to the Proton Driver Internal Technical Review, April 17-19, 2000 at Fermilab

Contents

1 Introduction

1.1 What is the proton driver?

It's a new proton source for generating *intense short* proton bunches.

1.2 What will it do?

- To serve a ν-factory at Fermilab;
- To serve a future muon collider (with some straightforward upgrade);
- Replacement for the Fermilab Booster;
- New physics program based on high intensity proton beams.

1.3 Primary requirements

1. *High beam power:* $P_{\text{beam}} = 1.2$ MW. (Phase II: 4 MW)
   This is similar to other high intensity proton machines (*e.g.*, SNS, ESS, the Joint Project). It enables us to form a world-wide collaboration.

2. *Short bunch length at exit:* $\sigma_b = 3$ ns. (Phase II: 1 ns)
   This is *unique* for the proton driver. It brings up a number of interesting and challenging beam physics issues.

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

   It is essential to have:

   - small longitudinal emittance (ϵ_L preservation);
   - large momentum acceptance $\frac{\Delta p}{p}$ (in the rf and lattice);
   - bunch compression at the end of the cycle.

Table 1: High Beam Power Proton Machines

Machine	Protons per Cycle	Repetition Rate (Hz)	Protons per Second	Beam Energy (GeV)	Beam Power (kW)
Existing:					
RAL ISIS	2.5×10^{13}	50	1.25×10^{15}	0.8	160
BNL AGS	7×10^{13}	0.5	3.5×10^{13}	24	130
LANL PSR	2.5×10^{13}	20	5×10^{14}	0.8	64
Planned:					
Fermilab MiniBooNE	5×10^{12}	7.5	3.8×10^{13}	8	50
Fermilab NUMI	4×10^{13}	0.5	2×10^{13}	120	400
Proton Driver Phase I	3×10^{13}	15	4.5×10^{14}	16	1200
Proton Driver Phase II	1×10^{14}	15	1.5×10^{15}	16	4000
Europe ESS	2.34×10^{14}	50	1.2×10^{16}	1.334	2500
ORNL SNS	2×10^{14}	60	1.2×10^{16}	1	2000
Japan JHF	3.2×10^{14}	0.3	1×10^{14}	50	780

1.4 Why do we need a new booster?

Can we meet these requirements with an "improved" booster? – No.

- Problems of the present Booster:
  - Limited intensity:
    Run II, NuMI: 5×10^{12} ppp at 0.7 Hz
    MiniBooNE: 5×10^{12} ppp at 7.5 Hz.
  - Inadequate shielding
  - The pulsed magnets, rf, power supply cannot work at 15 Hz (only main magnets are for 15 Hz)
  - Aperture limit:
    horizontal – short straight (max β_x and D_x)
    vertical – long straight (rf, BPM)
  - Aging problem
  - Components activation problem
- Can we "improve" the present booster by reusing a large portion of the existing subsystems?
  - Main magnets? – No, because
    * aperture too small
    * field quality problem
    * existing lattice goes through transition
    * combined function magnets limits the feasibility in lattice design
    * low peak field (0.8 T)
    * no beam pipe
    * not enough energy (8 GeV)
  - Main power supply? – No, not enough power capacity.
  - RF? – Possible (in the pre-neutrino factory era). But need modifications (larger aperture and higher gap voltage, cf. M. Champion's talk).
  - Other subsystems? – Maybe.

- Can we have another linac energy upgrade or add a pre-booster to improve the booster performance?
  - No enough room for more linac structures.
  - Due to Booster's own limitations, possible improvement with a pre-booster is limited. Diminishing returns will not be able to justify the investment.
- Can we reuse the existing tunnel? – No, because
  - Shielding problem (only 14', not deep enough)
    - The losses in the present booster operation are already a serious problem;
    - The new booster will eventually accelerate a lot more beams:
      - 20 times the intensity per cycle
      - 100% duty cycle (about 3% now)
      - twice beam energy
  - Interruption to on-going HEP program (prolonged downtime)
  - Shape (circular) and size (474 m) of the existing tunnel limits possible choices of lattice and beam energy;
  - No room for linac energy upgrade in Phase II;
  - No obvious place for a pre-booster in Phase II;
  - Cost consideration:
    Modification, demolition and replacement of the existing structure (tunnel, booster towers, booster service buildings) will probably be more expensive than civil construction of a new tunnel and associated infrastructure at a green field site.
- Conclusion:
  Go for a new booster.

2 Machine layout and parameters

- The proton driver construction will be staged:
  - Phase I: 1.2 MW, 3 ns. It will serve the ν-factory as well as the Main Injector's intensity upgrade (by a factor of 4).
  - Phase II: 4 MW, 1 ns. It will serve a muon collider.

  This review will be focused on Phase I only.
- The Phase I proton driver consists of:
  - A moderate improvement of the existing 400 MeV linac (a new front end replacing the C-W and a modified Tank 1);
  - A new 16 GeV rapid cycling synchrotron in a new tunnel (site is yet to be determined);
  - Associated beam transport lines.
- A main decision in Phase I design is to reuse the existing 400 MeV linac. This has obvious advantages. But it also establishes boundary conditions in the choice of major design parameters.

Table 2: Proton Driver Parameters of Present, Phase I and Phase II (04/06/00)

	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}	$7.5\,(1.7) \times 10^{12}$	2.5×10^{13}
Number of bunches	84	4 (18)	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 (0.5)	2
RF frequency (MHz)	53	1.7 (7.5)	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

3 Choice of major design parameters

3.1 Required beam power by a ν-factory:

$$2 \times 10^{20}\ \mu/\text{year for experiments}$$

$$\Downarrow$$

$$1/3 \text{ useful muons} \longrightarrow 6 \times 10^{20}\ \mu/\text{year in the ring}$$

$$\Downarrow$$

$$1/15\ \mu/p(16\text{GeV}) \longrightarrow 9 \times 10^{21}\ p/\text{year}$$

$$\Downarrow$$

$$2 \times 10^{7} \text{ sec/year} \longrightarrow 4.5 \times 10^{14}\ p/\text{sec}$$

$$\Downarrow$$

$$15 \text{ Hz} \longrightarrow 3 \times 10^{13}\ p/\text{cycle}$$

$$\Downarrow$$

$$72\ \mu\text{A average current}$$

$$\Downarrow$$

$$16 \text{ GeV} \longrightarrow 1.2 \text{ MW beam power}$$

3.2 Repetition rate

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

We choose $f_{rep} = 15$ Hz. Reasons:

1. The linac is 15 Hz. A higher f_{rep} would require major changes in the existing linac.
2. A lower f_{rep} would mean more protons per cycle, which is difficult.
3. For a future muon collider, $\tau_\mu(2\ \text{TeV}) = 42$ ms, which is comparable to 15 Hz.

3.3 Beam energy

- We choose $E_p = 16$ GeV. Reasons:
  1. At 1.2 MW and 15 Hz, 16 GeV requires 3×10^{13} protons from the linac, which is achievable with modest improvement.
  2. Lower energy means higher beam intensity. This has two effects:
     - One would need substantial upgrades in the linac high energy section (110 MeV - 400 MeV).
     - Further raising the linac energy may also be necessary due to space charge at injection to the ring.
  3. Lower energy would also make bunch compression more difficult, because:
     - higher longitudinal brightness N_b/ϵ_L;
     - higher space charge tune shift ΔQ at top energy; (η-spread)
     - larger momentum spread $\frac{\Delta p}{p}$.
  4. Lower energy would make Phase II upgrade harder (may need another bigger ring);
  5. For 400 MeV injection and 16 GeV top energy, the dynamic range is about 18. This should be fine. $E_p > 16$ GeV would make this ratio higher, which is difficult.

- However, the choice of 16 GeV also has its concerns:
  - Main Injector:
    $\gamma_t = 21.8$. There will still be a transition crossing.
    * A γ_t-jump system has been designed for the MI. Simulation shows that, with this system, there will be little emittance growth and negligible particle loss during transition even with 4 times higher beam intensity. (cf. I. Kourbanis' talk)
    * If $E_p = 24$ GeV, a potential problem is the negative mass instability in the MI at injection. Calculation shows the threshold would be reduced to about 7% of its present value (at 8 GeV) due to a small η/E factor.
  - ν-factory:
    * Hg target:
      Simulation shows muon yield scales with beam power and is independent of beam energy in a wide range.
    * Carbon target:
      Simulation shows a peak in muon yield around $E_p = 6$ GeV. To get the same number of muons, 16 GeV requires 3×10^{13} ppp while 8 GeV needs 5×10^{13} ppp.
      · $E_p = 8$ GeV would reduce beam power on the target by 17%, which is preferred.
      · $E_p = 8$ GeV would also increase beam intensity by 67%, which requires a significant change in machine design.

  The target experiment E951 at the BNL is a major multi-million dollar R&D program of the muon collaboration. Results will help us choose which target to use.

- Our approach:
  1. Complete the 16 GeV synchrotron design;
  2. Carry out a cost comparison study of 8 GeV *vs.* 16 GeV;
  3. Welcome committee's comments and suggestions.

3.4 Bunch length

We choose $\sigma_b = 3$ ns in Phase I. Reasons:

1. A short bunch length is required by muon production and muon polarization.
2. Calculation at Fermilab shows muon yield reduction $< 10\%$ when σ_b increases from 1 ns to 3 ns. (BNL claims different results.)
3. Polarization has a stronger dependence on σ_b. But it is not required by ν-factory.
4. To get 3 ns bunch is much easier than 1 ns.

3.5 Number of bunches

Given N_{total} and σ_b, more bunches are preferred. We are considering two scenarios: $N = 4$ and $N = 18$.

- In the present design, an induction linac is used for muon phase rotation. It can only take 4 bunches in a pulse.
- There is a KEK-Fermilab joint R&D to develop low frequency (a few MHz) high gradient (0.5-1 MV/m) rf. (cf. A. Moretti's talk) If it will replace the induction linac, then the number of bunches can be 18.

4 Overview of sub-systems

4.1 New front end

- High brightness H^- source (115 mA, 90 μs, 1 π mm-mrad)
- Chopper (rise- and fall-time < 30 ns)
- RFQ (201.25 MHz, 100 mA, 50 keV – 2.235 MeV, 1 or 2 sections)
- Double-α magnet MEBT
- Modified Tank 1 (2.235 – 10 MeV)

4.2 Lattice

- Circumference 711.3 m (1-1/2 times the booster size)
- No transition crossing
- Acceptance $> 60\ \pi$ mm-mrad, momentum aperture $\geq \pm 2.5\%$
- Zero-dispersion straights
- Two designs are going on. One is triangular, another racetrack. Choice will be made after a detailed comparison.

4.3 Injection and extraction

- To reduce space charge, the injected beam will be painted in the transverse phase space. Simulation shows a near uniform distribution in the x-y plane is possible.
- (Transverse simulation with space charge has not been done due to lack of expertise and manpower.)
- Only one extraction point. An additional point, if needed, will have to use some space allocated to the rf.
- Only 1-turn fast extraction is considered. Slow spill, if needed, will require a change in the power supply design.

4.4 Collimation

- 2-stage system, embedded in the inj/extr straight.
- Designed for 10% loss at injection, 1% loss at top, efficiency $> 99\%$
- Average beam loss in “quiet area” < 1 W/m. Hands-on maintenance is allowed.

4.5 Magnets

- Dipole: 1.5 T, gap 5” $\times$ 13”, 14-mil Si-Fe lamination.
- Quad: 8.9 T/m, Accumulator LQA type, 4-piece lamination.

4.6 Power supplies

- Resonant circuit at 15 Hz, with 12.5% 30 Hz component
- Compared with a single frequency circuit, this design saves 25% peak rf power.
- Trim coil in quads for tracking error correction and tune control.

4.7 Vacuum system

- Vacuum will be 10^{-8} torr or better.
- R&D for thin metallic pipe. Three designs are being pursued. Main challenges are mechanical stability under vacuum and eddy current heating.
- Back-up solution is the ISIS pipe (ceramic plus metallic cage). The penalty is about 2” additional vertical aperture.

4.8 RF

- Different customers require different rf systems. Even the same customer may ask for different rf for different designs. This makes the proton driver rf interesting.
- Main rf system (for acceleration and bunch compression) – This will be in CW operation. There are two different types of cavities under study:
  1. Finemet loaded cavity:
     - Collaboration with the KEK (US-Japan Accord);
     - Advantages over ferrites:
       * higher B_{rf}, which means higher accelerating gradient (30 kV/m);
       * low Q, which allows multiple harmonics operation.
     - Concern: low Q gives high loss.
     - Two possible frequencies:
       * 7.5 MHz: for the MI as well as for ν-factory (if induction linac is replaced by rf for muon phase rotation);
       * 1.7 MHz: for ν-factory only, in case induction linac will be used.
  2. Modified existing booster cavity, ferrite tuned, 53 MHz – for the MI only. Modifications include:
     - larger aperture (from 2-1/4 in to 5 in);
     - higher accelerating voltage (from 55 kV to 66 kV per cavity).

     These modifications will meet the proton driver needs and also improve present booster performance.
- Special rf system (for bunch compression only) – This will be in burst mode operation (low duty factor).
  This is still in early R&D stage and also a collaboration with the KEK. The goal is 0.5 - 1 MV/m at several MHz. In addition to proton driver bunch compression, it may replace the induction linac in a ν-factory.

5 Technical design issues

5.1 High longitudinal brightness

- High N_b/ϵ_L due to:
  - High beam power, a few bunches $\longrightarrow$ large N_b
  - Short bunch length $\longrightarrow$ small ϵ_L
- Minimize ϵ_L dilution:
  - Avoid transition (lattice design)
  - Avoid microwave instability
    - Keep beam below transition
    - Keep resistive wall impedance small (uniform beam pipe)
  - Avoid coupled bunch instability (low Q cavity)
  - Inductive insert for compensating space charge
  - Minimize filamentation during early acceleration (rf parameters optimization)
  - Longitudinal damper

5.2 High intensity bunch rotation

- Microwave instability during debunching;
- Beamloading during debunching;
- η-spread (or α-spread) effect:
  - due to higher order momentum compaction factor α_1
  - due to space charge tune spread ΔQ

5.3 Other issues

- Beamloading compensation of intense short bunches (hundreds amperes peak current);
- FMC lattice for large momentum and dynamic aperture;
- Beam collimation and local shielding;
- Injection when the magnet current is dual harmonic;
- Painting;
- Tracking error correction;
- High gradient rf cavity design and testing;
- Thin metallic pipe design and testing;
- High brightness H^- source;
- RF chopper;
- End effects of large short magnets, *etc.*

6 R&D program

6.1 Hardware R&D

With limited resources, we have divided R&D into three categories:

1. Critical for the proton driver, also benefitting present machines:
   (a) High gradient Finemet rf cavity (will do 132 ns bunch spacing coalescing);
   (b) Beamloading compensation (will benefit the MI);
   (c) 53 MHz booster rf cavity modification (will benefit the booster);
   (d) Linac front end test station (will benefit the linac).
2. Critical for the proton driver:
   (a) Thin metallic beam pipe;
   (b) RF chopper
3. Important for the proton driver, but can wait:
   (a) High gradient, low frequency rf in burst mode operation;
   (b) High brightness H^- source;
   (c) High current RFQ;
   (d) Collimators (including bent crystal as the primary);
   (e) Tracking error correctors;
   (f) Power supply using new technology (dual-resonance, dual-frequency, IGBT, *etc.*);
   (g) Fast rise- and fall-time kicker;
   (h) Passive and active feedback systems;
   (i) Large aperture magnets (including end effects).

6.2 Machine experiments

1. Beam test of Finemet cavity (Fermilab/MI, BNL/AGS)
2. Inductive insert (LANL/PSR, ANL/IPNS)
3. Lab "contest" on intense short bunch production:
   - Six labs: BNL, KEK, Fermilab, CERN, Indiana U. and GSI.
   - Two experiments:
     - bunch compression;
     - μ-wave instability below γ_t.
   - Three competing items:
     - Max I_{peak}
     - Max N_b/eV-s
     - Max compression ratio

7 Collaboration

7.1 US-Japan Accord

There are two programs.

1. One is an on-going program on high intensity proton facility R&D, including:
   (a) Barrier bucket rf;
   (b) High gradient rf in CW operation;
   (c) Inductive inserts;
   (d) RF chopper;
   (e) Beam halo and scraping.
2. One is a new proposal on high intensity muon beam study, including:
   (a) High gradient rf in burst mode operation;
   (b) Other items.

7.2 Muon collider collaboration

The Executive Board and Technical Board have indicated that there will be money support to the proton driver R&D starting next fiscal year (FY01). A budget request has been sent to the boards.

7.3 ICFA

There is an ICFA working group in the Beam Dynamics Panel. It has sponsored a series of mini-workshops devoted to the theme of high intensity high brightness hadron beams.

8 Schedule

- April 17-19, 2000: Internal technical review.
- October 2-6, 2000, Fermilab: ICFA Workshop on High Intensity High Brightness Hadron Beams.
- End of 2000: Complete Technical Design Report.
- There will be a parallel physics study group led by S. Geer for physics programs based on the proton driver. The report is due about the same time (or earlier).

Table 3: New Booster Parameters (04/17/00)

Circumference (m)	711.3
Super-periodicity	3
Number of straight sections	3
Nominal length of straight section (m)	48
Injection kinetic energy (MeV)	400
Extraction kinetic energy (GeV)	16
Injection dipole field (T)	0.085
Peak dipole field (T)	1.5
Bending radius (m)	37.6
Maximum quad gradient (T/m)	8.9
Number of arc dipoles	48
Number of arc quads	102
Max β_x, β_y (m)	26, 33.7
Min β_x, β_y (m)	3.4, 3.9
Max D_x (m)	5.5
Min D_x (m)	-1.0
Transition γ_t	-j38
Horizontal, vertical tune	10.78, 10.51
Natural ξ_x, ξ_y	-13.8, -14.2
Revolution time at injection, extraction (μs)	3.3, 2.4
Injection time (μs)	90
Injection turns	27
Laslett tune shift at injection	0.36
Normalized transverse emittance (mm-mrad)	
Injection beam (95%)	$3\ \pi$
Circulating beam (100%)	60π
Longitudinal emittance (95%, eV-s)	
Injection beam	0.5
Extraction beam	2
Extracted bunch length σ_t (rms, ns)	3
Momentum spread at extraction (95%)	$\pm 0.8\%$
Momentum acceptance	$\pm 2.5\%$
Dynamic aperture	$> 100\ \pi$

Table 4: Proton Driver RF Systems

<table>
<tr><th colspan="3">Main rf
(acceleration & bunch compression)</th><th rowspan="3">Special rf
(bunch compression)</th></tr>
<tr><th rowspan="2">Booster cavity
53 MHz</th><th colspan="2">Finemet cavity</th></tr>
<tr><th>7.5 MHz</th><th>1.7 MHz</th></tr>
<tr><td>MI</td><td>MI
ν-factory</td><td>ν-factory</td><td>ν-factory</td></tr>
</table>

Table 5: 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
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