AN 8-GEV SYNCHROTRON-BASED PROTON DRIVER*

W. Chou# for the Proton Driver Study Group, FNAL, Batavia, IL 60510, USA

Abstract

In January 2002, the Fermilab Director initiated a design study for a high average power, modest energy proton facility. Such a facility is a possible candidate for a construction project in the U.S. starting in the middle of this decade. The key technical element is a new machine, dubbed the "Proton Driver," as a replacement of the present Booster. The study of an 8-GeV synchrotron-based proton driver has been completed and published [1]. This paper will give a summary report, including machine layout and performance, optics, beam dynamics issues, technical systems design, civil construction, cost estimate and schedule.

INTRODUCTION

A Proton Driver, which is a high average power, modest energy proton facility, offers an interesting future physics program in the U.S. For example, neutrino physics (neutrino superbeam, off-axis neutrino experiments, and a neutrino factory), neutron electric dipole moment (EDM) measurement, neutron-antineutron oscillations, intense cold muon beams, a precision test of CPT, etc. [2]

There have been several iterations on machine studies at Fermilab. Following the completion of a 16-GeV proton driver design [3], the Fermilab Director issued a charge requesting Proton Driver Study II (PD2) on an 8-GeV proton driver. A major objective in the PD2 study is to reduce the up front construction cost.

PD2 explores two possible upgrade options: an 8-GeV high intensity proton synchrotron, or an 8-GeV proton linac. Both options are illustrated in Figure 1. This paper is a summary report of the synchrotron-based design. For details the readers are referred to Ref. [1].

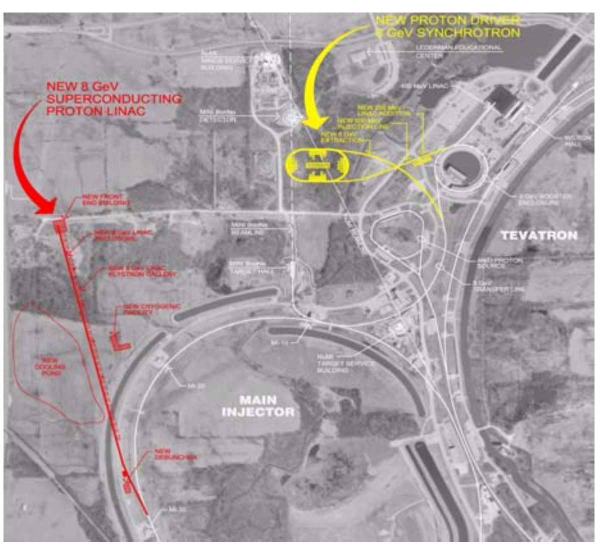

Figure 1: Layout of the two options of an 8-GeV Proton Driver: a synchrotron (yellow), or a linac (red).

LAYOUT AND PERFORMANCE

In Figure 1, the racetrack-shaped machine (in yellow) is a new 8-GeV synchrotron, or the Proton Driver. Also shown (in yellow) are the injection line (from the existing linac) and extraction line (to the existing Main Injector). The Proton Driver has a circumference of 474.2-m, the same as the present Booster.

The main parameters are listed in Table 1. The linac maximum beam energy is increased from 400 MeV to 600 MeV. The required beam intensity is 50 mA, usable pulse length 90 μsec, and repetition rate 15 Hz, all achievable in the present Linac. These numbers correspond to 2.8×10^{13} protons per pulse injected into the Proton Driver. Allowing reasonable beam losses during the cycle (10% at injection, 1% during ramp and at extraction), the design value is 2.5×10^{13} protons per pulse extracted from the Proton Driver. At 15 Hz and 8 GeV, the beam power is about 0.5 MW. With a Proton Driver, the present Main Injector can also be readily upgraded to 2 MW, a would-be most powerful machine in the world [4].

Table 1: Parameters of the Proton Driver

Linac (operating at 15 Hz)	
Kinetic energy (MeV)	600
Peak current (mA)	50
Pulse length (μs)	90
H^- per pulse	2.8×10^{13}
Average beam current (μA)	67
Beam power (kW)	40
Synchrotron (operating at 15 Hz)	
Extraction kinetic energy (GeV)	8
Protons per bunch	3×10^{11}
Number of bunches	84
Protons per cycle	2.5×10^{13}
Protons per hour	1.35×10^{18}
Norm transverse emittance (mm-mrad)	40π
Longitudinal emittance (eV-s)	0.2
RF frequency (MHz)	53
Average beam current (μA)	60
Beam power (MW)	0.5

Compared with the present Booster, the Proton Driver would deliver 5 times more protons per cycle and 10 times more beam power. In order to achieve such an improvement in performance, the following measures are adopted in the PD2 design:

- The linac energy is increased from 400 MeV to 600 MeV. (The space charge scaling factor $\beta\gamma^2$ is increased by ~50%).
- The tunnel is twice as deep (27 ft.).
- The magnets have large aperture. The good field region is 4 in × 6 in.

- The lattice has no transition crossing ($\gamma_t = 13.8$).
- The lattice has smaller beta-functions and dispersion (max $\beta_x = 15.1$ m, max $\beta_y = 20.3$ m, max $D_x = 2.5$ m).
- The RF cavity aperture is increased to 5 inches.
- The lattice has zero-dispersion long straight sections for the RF.
- The injected beam will be painted in transverse phase space to reduce space charge effects.
- The resonant power supply system is dual-harmonic (15 Hz plus a 12.5% 30 Hz component). This reduces the required peak RF power by 25%.
- A carefully designed 2-stage collimator system that will collect 99% of the uncontrolled beam loss.
- There is a perforated metal liner shielding the beam from the magnet laminations.
- The correctors (steering magnets and trim quads) are ac powered and have sufficient strength to make corrections through the full acceleration cycle.
- Space has also been reserved between the linac and the ring for a future linac energy upgrade up to 1.9 GeV. (The 600-MeV beam transport line is 254-m long.)

With these measures, it is believed that the Proton Driver can reach the required beam intensity while keeping the beam loss under control.

OPTICS AND BEAM DYNAMICS

Lattice

Lattice is the foundation of a synchrotron. It is worth making every effort to investigate all possible lattice candidates and choose the best one.

There are two basic requirements on the design: a transition-free lattice, and several dispersion-free straight sections. For high intensity operation in proton synchrotrons, transition crossing is often a major cause of beam loss and emittance blowup. One should avoid it in the first place. Dispersion in the RF, which is placed in one or more straight sections, may lead to synchro-betatron coupling resonance and should also be avoided. Other requirements include small beta and dispersion functions, large dynamic aperture, and ample free space for correctors and diagnostics.

A total of about a dozen lattices have been studied. The chosen one is a doublet 3-cell modular structure with a short dipole in the mid-cell, as shown in Figure 2. It meets all the requirements. The lattice consists of two arcs and two straight sections and has 2-fold symmetry. The details can be found in Ref. [5].

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#chou@fnal.gov

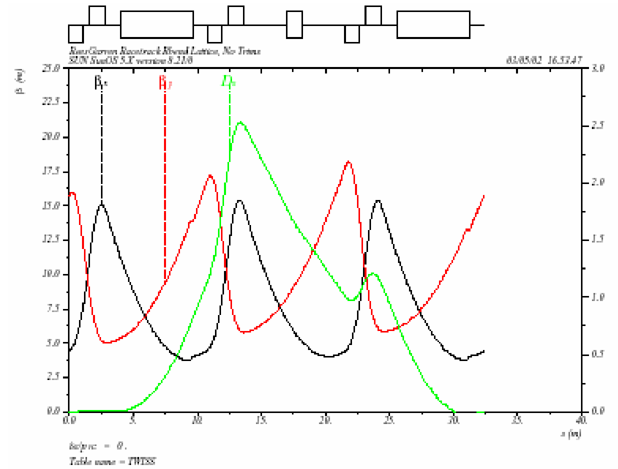

Figure 2: Lattice module of the Proton Driver. Each module has three doublet cells. The dipole in the mid-cell is short. The phase advance per module is 0.8 and 0.6 in the h- and v-plane, respectively. There are five modules in each arc.

Space Charge

Amongst various beam physics issues, the space charge is a major concern. It is often the bottleneck limiting the beam intensity in an intense proton source, in particular, in a synchrotron, because the injection energy is low.

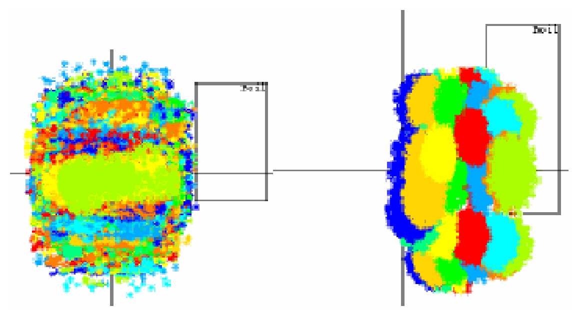

Figure 3: Space charge simulation using Track2D (by C. Prior). It shows the particle distribution after 45 turns injection in the Proton Driver with (left) and without (right) the space charge effect.

Numerical simulation codes Track2D and ORBIT are used in the design. They are particularly useful in helping determine the working point and painting method so that one may avoid resonance and minimize emittance dilution. Figure 3 illustrates how space charge dilutes the beam during multi-turn injection.

TECHNICAL SYSTEMS

All technical systems have been designed. Here is a summary of each system. The details can be seen in the corresponding chapters in Refs. [1] and [3].

RF

The RF system in the present Booster will be reused. Thanks to a dual harmonic magnet power supply (see below), the peak RF power is reduced from 1.4 MW to 1.06 MW, which the present system can deliver. But the RF cavity bore will be enlarged from 2-1/4 inch to 5 inch.

Magnets

The magnets have a good field region of 4 in × 6 in. The dipole peak field is 1.5 Tesla. The lamination uses M17 silicon steel. There are 12 turns per pole. The copper conductor contains a cooling hole. In order to have a balance between low ac losses and a tolerable voltage-to-ground, three conductors and top/bottom coils are connected in parallel. An ac field measurement facility has been set up at the E4R area for measuring the field at 15 Hz.

Power Supplies

A main feature of the power supplies is that it is a dual harmonic resonant system. On top of 15 Hz there is a 12.5% 30 Hz component in the magnet current. This reduces the peak RF power by 25% and increases the up-ramp time by 14%. A bench test of this system will be performed by using the Booster magnets at the E4R.

Vacuum

The original design uses an external vacuum skin for the magnets and metallic perforated liners to shield the beam from the lamination. However, a new design, which employs a thin metallic pipe reinforced by spiral ribs, looks promising and would be a better choice [6].

Beam Loss and Collimation

The beam loss budget is 10% at injection and 1% during acceleration and at extraction. Among these losses, most would be collected by a 2-stage collimation system, which has efficiency close to 99%, leaving the uncontrolled loss in the rest of the machine below 1 W/m.

Injection

One important advantage of a synchrotron-based Proton Driver is the low injection beam power. This makes the injection much easier compared with a linac-based approach. The stripping foil temperature rise is only about 800 K. A painting scheme has been worked out to obtain a uniformly distributed beam in the phase space with small emittance dilution caused by the space charge.

Extraction

This is an improved version of what is used in the present Booster. In particular, the orbit bumps (doglegs) are longer and weaker in order to minimize the so-called dogleg effect, which was recently found to have a significant impact on the Booster performance [7].

H^- Source and Linac

The H^- source and the linac front end will be upgraded. While the linac beam current will remain about the same (50 mA), the brightness will be increased by a factor of 3, the pulse length increased from 25 μs to 90 μs. The Cockcroft-Walton will be replaced by an RFQ. There will also be a linac extension from 400 MeV to 600 MeV.

Civil Construction and Shielding

The Proton Driver enclosure is 16 ft × 9 ft with 24.5 ft of equivalent earth radiation shielding. It is twice deeper than the Booster tunnel.

COST AND SCHEDULE

A cost estimate to build a Proton Driver at Fermilab has been done by a bottom-up method. Namely, the technical system designs were given to the engineers in each relevant department. They came up with a cost estimate based on their experiences building similar systems before. These costs were summed up, adding to it the EDIA (17%), lab overhead (13%) and contingency (30%). The total estimated cost (TEC) is $235 M in FY02 dollars.

Because this project is yet to be approved by the funding agency, there is an uncertainty on the starting date of construction. The construction would take about four years. In a most optimistic scenario, the groundbreaking could be in 2005. The machine operation would then start around 2009.

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