

# Chapter 1. Introduction

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## 1.1. Overview

The Proton Driver Study II (PD2) explores two possible upgrade options for the Fermilab accelerator chain: an 8-GeV high intensity proton synchrotron, or an 8-GeV proton linac. Part A of this report (Chapters 1 - 12) explores the synchrotron-based design.

The design study of the Proton Driver I (PD1) was completed in December 2000 and documented in Ref. [1]. The central part of that study was a 16-GeV rapid cycling synchrotron, generating 1.2 MW proton beams. The beam dynamics, technical systems design, civil construction and ES&H issues were described in detail in that document. In this PD2 report, we do not attempt to repeat all the work that has been done in the previous study. Rather, we will only highlight the differences in the two designs due to changes in major parameters. We recommend reading the PD1 and PD2 reports side-by-side in order to get a complete picture of the design.

A major objective in the PD2 study is to reduce the up front cost. In PD1, three major cost drivers were identified: the magnets, the power supplies, and the civil construction. (The rf is relatively cheap because the existing Booster rf system will be reused.) Each one of these three items represents about 1/4 of the total project cost. The cost of the magnets and power supplies scales with the stored magnetic energy and the number of magnets. The cost of civil construction scales with the machine size. Therefore, an effective way to reduce the cost is to lower the beam energy and reduce the machine size.

The charge from the Director (Appendix 3) clearly reflects this objective. The design goals for the synchrotron specified in the charge are: 8 GeV,  $2.5 \times 10^{13}$  protons per cycle, 0.5 MW. Table 1.1 compares the main parameters in PD1 and PD2.

**Table 1.1.** Comparison of PD1 and PD2 Parameters

Parameters	PD1	PD2
Ring circumference (m)	711.3	474.2
Linac energy (MeV)	400	600
Synchrotron peak energy (GeV)	16	8
Protons per cycle	$3 \times 10^{13}$	$2.5 \times 10^{13}$
Protons per bunch	$2.4 \times 10^{11}$	$3 \times 10^{11}$
Repetition rate (Hz)	15	15
RF frequency (MHz)	53	53
Normalized transverse emittance (mm-mrad)	$60\pi$	$40\pi$
Beam power (MW)	1.2	0.5

Because the acceptance of the Main Injector at 8 GeV is  $40\pi$ , the normalized transverse beam emittance is also chosen to be  $40\pi$  in PD2, smaller than the  $60\pi$  in PD1 (Note: PD1 could allow a larger emittance because its extraction energy is higher, either 12 or 16 GeV, which is also the MI injection energy.) In the meantime, the number of protons per bunch in PD2 is higher (see Table 1.1). In order to compensate the space charge effects, the linac energy is increased from 400 MeV to 600 MeV.

A logical choice for the size of an 8-GeV machine is 474.2-m, the same as the present Booster. This makes the circumference ratio between the Proton Driver and the Accumulator 1:1 and the ratio between the Proton Driver and the Main Injector 1:7. This simplifies beam transfers between machines.

## 1.2. PD2 vs. PD1

Based on differences between the PD2 and PD1 major parameters, the PD2 design includes the following changes:

1. A completely new lattice is designed. This lattice is transition-free ( $\gamma_t = 13.8$ ) and has zero-dispersion long straight sections. It is a racetrack with 2-fold symmetry. Although a triangle was the preferred shape in PD1, it is difficult to design a triangular lattice in PD2 with all the necessary features, in particular, enough usable straight section space and the desired phase advance per module. The PD2 lattice employs a doublet structure instead of a singlet one as in PD1. A main advantage of the doublet lattice is that it reduces the number of dipoles, of which the ends occupy a large portion of the drift space. It also reduces the number of quadrupole families and thus simplifies the lattice structure. This lattice is described in Chapter 3.
2. Transverse and longitudinal beam dynamics studies are redone using the PD2 parameters. (Chapter 4)
3. The designs of most technical systems are similar to PD1 and are consolidated into one chapter (Chapter 5). An exception is the magnet design, which includes significant changes. In particular, stranded conductor coils adopted in PD1 are replaced by solid conductor coils. This is possible because the eddy current loss in the coils is reduced thanks to smaller sizes of the magnets and the coils. To keep the voltage-to-ground under control, several coils are connected in parallel for reducing number of turns per pole.
4. The beam loss and shielding are recalculated and the collimators redesigned. (Chapter 6)
5. The injection and extraction systems are redesigned using the new lattice. (Chapter 7)
6. The linac new front-end design is simplified by using one RFQ and no alpha-magnets. (PD1 uses two RFQs and one alpha-magnet.) There is also a section describing the design of a new 200 MeV linac extension. (Chapter 8)
7. The two beam transport lines are redesigned. In PD1, they were 400-MeV and 12/16-GeV. In PD2, they are 600-MeV and 8-GeV, respectively. (Chapter 9)

8. The civil construction is revised using the PD2 footprint. Also a section on a 200 MeV linac extension gallery is added. (Chapter 10)
9. The ES&H considerations are reviewed. (Chapter 11)

### **1.3. PD2 vs. the Present Booster**

#### **1.3.1. Problems of the Present Booster**

There are three fundamental problems that prevent the present Booster from being a high intensity proton machine.

- a) The magnet aperture is too small (vertical 1.6/2.2 inches in the D/F magnet, respectively, horizontal good field region ~2 inches).
- b) The linac is too close to the ring (no room for a linac energy upgrade except by using higher gradient accelerating structures).
- c) The tunnel is not deep enough (13.5 ft.). Furthermore, there are office buildings on top of the tunnel. The radiation level on the surface from beam losses is a major concern.

These three limitations existed even during the design of the Booster more than 30 years ago. This was probably because Fermilab's main interest at that time was in high energy rather than high intensity. These problems make it virtually impossible to increase the Booster beam intensity by any significant amount, unless one replaced all the magnets, and/or relocated the linac, and/or moved the Booster deeper. Any of these measures would require building a new machine.

In addition to these problems, the present Booster has several other features that also make an intensity increase difficult:

- d) There is transition crossing during the cycle ( $\gamma_t = 5.45$ ).
- e) The lattice beta-function and dispersion are quite large (maximum at 33.7 m and 3.2 m, respectively), which lead to large beam sizes.
- f) The rf cavity has a small aperture (2-1/4 inches).
- g) The rf cavities are in the dispersive region.
- h) There is no rf shield inside the magnets.
- i) Orbit correction capability is limited.

Although actions are being taken to improve the situation (e.g., R&D effort to increase the rf cavity aperture, implementation of ac orbit correctors, addition of a gamma-t jump, etc.), room for improvement is limited.

#### **1.3.2. Design Considerations of the Proton Driver**

In the Proton Driver design, the three fundamental problems and other problems of the present Booster are addressed:

- a) The magnets have large aperture. The good field region is 4 in  $\times$  6 in.

- b) Space has been reserved between the linac and the ring for a future linac energy upgrade. (The 600-MeV beam transport line is 254-m long.)
- c) The tunnel is twice as deep (27 ft.).
- d) The lattice has no transition crossing ( $\gamma_t = 13.8$ ).
- e) 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).
- f) The rf cavity aperture is increased to 5 inches.
- g) The lattice has zero-dispersion long straight sections for the rf.
- h) There is a perforated metal liner shielding the beam from the magnet laminations.
- i) The correctors (steering magnets and trim quads) are ac powered and have sufficient strength to make corrections through the full acceleration cycle.

In addition, the following measures have been adopted in the PD2 design that will further help improve the performance:

- The linac energy is increased from 400 MeV to 600 MeV. (The space charge scaling factor  $\beta\gamma^2$  is increased by ~50%).
- 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.

With these measures, it is believed that the Proton Driver can have a factor of 5 more beam intensity than the present Booster (from  $5 \times 10^{12}$  to  $2.5 \times 10^{13}$  protons per cycle) while keeping the beam loss under control.

## References

- [1] "The Proton Driver Design Study," FERMILAB-TM-2136. (December 2000)