Chapter 13. Introduction

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13.1. Overview

In Proton Driver Study II (PD2), in addition to the study of both an 8 GeV synchrotron-based design and an 8 GeV linac-based design, the Director's charge (Appendix 3) also requests a study of necessary modifications and upgrades of the Main Injector and associated beam lines in order to take full advantages of either option for an 8 GeV Proton Driver. Specifically the charge sets the following goals:

- To increase the Main Injector beam intensity by a factor of 5 (from 3×10^{13} to 1.5×10^{14} protons per cycle);
- To reduce the Main Injector cycle time by 20% (from 1.867 s to 1.533 s);
- To increase the Main Injector beam power by a factor of 6 (from 0.3 MW to 1.9 MW).

Part B of this report (Chapters 13 - 21) presents a detailed discussion of the required system modifications and upgrades in order to reach these goals.

In the baseline design of the Main Injector, the beam intensity was rather moderate (3×10^{13} protons per cycle, about a factor of two higher than what was achieved in the previous Main Ring at Fermilab). [1] However, a previous study showed that, with appropriate modifications and upgrades, much higher beam intensity in the MI would be possible. [2] The present Booster can deliver 6 batches of protons to the MI at a maximum intensity of 5×10^{12} protons per batch. This matches the MI baseline design. When a Proton Driver replaces the Booster, however, the situation will change dramatically.

From Table 2.1 in Ch. 2, it is seen that a synchrotron-based Proton Driver will be able to deliver 2.5×10^{13} protons per batch to the Main Injector. The circumference ratio between the Proton Driver synchrotron and the MI is 1:7. Thus, the MI can take six Proton Driver batches for a total of 1.5×10^{14} protons, which meets the intensity goal. In the 6-batch operation, the present MI cycle time is 1.867 s (28 Booster cycles). In order to reach the 1.9 MW beam power goal, this cycle time needs to be reduced to 1.533 s (23 Proton Driver cycles). Table 13.1 lists the main parameters in the Main Injector upgrade.

An upgraded Main Injector will be a powerful machine. At present, the highest beam power from a synchrotron is at the ISIS/RAL, U.K., which provides 160 kW pulsed proton beams. The highest beam power from a cyclotron is at the PSI, Switzerland, which delivers a 1 MW dc beam. The nearly 2 MW beam power from an upgraded MI will be higher than any existing proton machine. It will also be comparable to the two large accelerator projects currently under construction, i.e., the SNS project in the U.S., a 1.4

MW machine, and the JHF project in Japan, which has both a 1 MW 3-GeV synchrotron and a 0.75 MW 50-GeV synchrotron.

Table 13.1. Main Injector Upgrade Parameters

Parameters	**Present**	**Upgrade**
Injection kinetic energy (GeV)	8	8
Extraction kinetic energy (GeV)	120	8 - 120
Protons per cycle	3×10^{13}	1.5×10^{14}
Cycle time at 120 GeV (s)	1.867	1.533
Average beam current (μA)	2.6	16
Beam power (MW)	0.3	1.9

Compared to these other high beam power proton machines, a unique feature of an upgraded Main Injector is that it can provide proton beams up to 120 GeV, an advantage for a number of important physics experiments. For example, the long baseline neutrino experiment, NuMI, requires high intensity proton beams with a tunable energy. As NuMI evolves to increase the precision and sensitivity of its measurements, more MI beam intensity will be needed. An upgraded MI can meet this requirement. The upgraded MI will provide about 2 MW at 120 GeV. When the beam energy is reduced, the cycle time will also decrease. The beam power will remain high over the extracted beam energy range of 8 - 120 GeV and only be slightly reduced due to the "overhead" in the cycle time (e.g. injection time, parabola in the ramp waveform, flat top, and overshoot for resetting the magnets).

In this study, two beam lines - NuMI and MiniBooNE - have been investigated in some detail. The former uses the MI 120-GeV beams, the latter the Booster 8-GeV beams. Both experiments benefit from PD2 because high beam intensities from the MI and the Proton Driver will be made available. Other beam lines, e.g., the antiproton transport lines, are not in the scope of this study. (Note: It is expected that the increase of the antiproton production will be proportional to the increase of the MI proton intensity provided that the target, beam lines and stochastic cooling system of the present antiproton source will be upgraded accordingly.)

13.2. Main Injector Modifications and Upgrades

At high intensities, beam instabilities and space charge become a major concern. Beam dynamics studies on these problems, employing both analytical and simulation methods, have been carried out and are described in Chapter 14.

In order for the Main Injector to operate at 2 MW, most of the technical systems need to be upgraded. Some of these upgrades are major, some moderate. Here is an overview:

- RF: To accelerate 5 times more particles in a shorter period, the rf system requires a major upgrade. The number of cavities needs to be increased from 18 to

20. The number of power amplifier of each cavity also needs to be doubled from one to two. (Chapter 15)

- Gamma-t jump system: Transition is crossed in the MI during the acceleration cycle. Presently there is no gamma-t jump system in the machine. But this system will be necessary in PD2 due to high intensity operation. A detailed design of the gamma-t jump system is given in Chapter 16. This system can provide a $\Delta\gamma_t$ from +1 to -1 within 0.5 ms. This gives a jump rate of 4000 s^{-1}, about 17 times faster than the normal ramp rate (240 GeV/s).

- Large aperture quadrupoles: In the baseline design of the Main Injector, it was known that a physical aperture bottleneck is at the quadrupoles upstream of the Lambertson magnets in several straight sections: MI-10, MI-30, MI-40, MI-52 and MI-62 (and also MI-60 when the NuMI extraction beam line is in place). In order to reduce beam losses at these locations, large aperture quadrupoles need to be installed replacing the regular quadrupoles. Their aperture will be increased from 83.48 mm in diameter to 102.24 mm, i.e., 4 inches. (Chapter 17)

- Passive damper and active feedback: To suppress coupled bunch instabilities, both a passive damper and active feedback are investigated in Chapter 18. The former places nonlinear lossy materials (e.g., a special ferrite of which the loss parameter μ'' is frequency dependent) in the rf cavity to damp the higher order modes (HOMs) while leaving the fundamental mode unaffected. The design of a longitudinal feedback system is also presented. A transverse feedback system exists in the MI but needs improvement.

- Radiation shielding and collimation: The shielding of the MI appears to be adequate for the upgrade. However, a collimation system is required in order to minimize the uncontrolled beam losses in the machine to reduce residual radioactivity so that hands-on maintenance can be performed. (Chapter 19)

- Other technical systems: (Chapter 20)
    - Magnets: The MI magnets will function adequately in the upgrade and modifications are unnecessary.
    - Power supplies: A shorter cycle requires an increase of the maximum ramp rate from 240 GeV/s to 305 GeV/s. A modest upgrade of power supplies is needed.
    - Mechanical and utility: The cooling capacity for magnets and power supplies appears to be sufficient in this upgrade. But the cooling system capacity for the rf system and cavities need to be doubled.
    - Kickers: A major upgrade is needed. The MI beam pipe has a vertical aperture of 2-inch everywhere except at the kickers, which is 1.3-inch. In order to eliminate this bottleneck, the kicker aperture needs to be enlarged.
    - Beam dump: With a modest upgrade, the present beam dump at MI-40 can absorb five times more protons.
    - Controls: Only minor changes are needed.

It is foreseen that several other systems will be required for the MI upgrade, e.g., a stop band correction system. The design of this system is not yet finished.

For the option of an 8-GeV superconducting proton linac, the MI needs a new 8-GeV H^- injection system. This will be discussed in Part C of this report.

13.3. Beam line Upgrades

In chapter 21 are discussed some details about the NuMI and MiniBooNE beam line upgrades. The major issues are shielding and cooling in the target halls, decay pipes and hadron absorbers. The ground water problem is a concern but there is a reasonable solution.

For the option of an 8-GeV superconducting proton linac, the present extraction system of the MiniBooNE cannot be used. Either the Main Injector or the Recycler will be used to transport beams from the 8-GeV linac to the MiniBooNE.

Finally, in chapter 21 there is a brief discussion on the 120-GeV beam lines in the old Meson experimental area. More shielding will be necessary but calculations have not yet been done.

13.4. Conclusion

The Main Injector and beam line upgrades can be implemented in two possible ways. They can be included in the Proton Driver project. Or these upgrades can be accomplished through a series of accelerator improvement projects (AIPs). The cost estimate (Appendix 1) shows that most of the systems upgrades cost around $1M or below, except the for the rf system. This makes them appropriate candidates for AIP funding.

These upgrades will not only meet the requirements on the MI with a new Proton Driver, but also greatly benefit the on-going physics program at Fermilab, including Run II and NuMI.

References

[1] "Fermilab Main Injector Technical Design Handbook," Fermilab (1994).

[2] W. Chou, "Intensity Limitations in Fermilab Main Injector," PAC 97 Proceedings, pp. 991-993; also see FERMILAB-Conf-97/199.