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Fermilab
Proton Improvement Plan: Preliminary Analysis of Scope and Funding

Fermilab

U.S. Department of Energy

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1. Introduction

Fermilab's Proton Source is the workhorse of the Accelerator Complex, providing 8 GeV proton beams for:

- the low-energy neutrino program (MiniBooNE and the planned MicroBooNE)
- and in the future Muon program (the mu2e and g-2 experiments)

and delivering protons to the 120 GeV Main Injector synchrotron to serve:

- the high-energy neutrino program (Minos at present and NOvA and LBNE in the future)
- the fixed target and test-beam program
- proton injection and antiproton production and acceleration for the Tevatron colliding-beam program (through FY11)

The Proton Source consists of a pair of Cockroft-Walton H- injector systems (CW), a drift tube linear accelerator (DTL), a coupled-cavity accelerator (CCL) and a 15 Hz, 8 GeV synchrotron (Booster). The CW, DTL and Booster were built from 1969 to 1970 and have been in continuous operation since. In the early 1990s, the Linac was upgraded with the installation of the high-energy CCL system. Most of the other Proton Source hardware is original; for example, several of the Linac low energy radio frequency tube amplifiers were developed in the late 1950's and early 1960's.

The location of the Proton Source within the larger Fermilab Accelerator Complex is shown in Figure 1. The Pre-Accelerator, at the north end of the chain, injects 750 keV beam into the Linac which accelerates the H- beam to 400 MeV. The injected H- beam is stripped to protons, which are then accelerated to 8 GeV in the Booster and extracted to the MI-8 transfer line. A scaled schematic diagram of the Fermilab accelerator complex is shown in Figure 2 below.

Until the Project-X linear accelerator is operational, the entire domestic accelerator-based high-energy physics program is powered by the 40+ year old Proton Source. Failure of any of the numerous components in the Proton Source brings the domestic accelerator-based program to a halt.

Many of the components in the Proton Source are now extremely difficult to maintain. The Proton Source has critical hardware components with no modern replacement options. Several key components are obsolete and require complicated rebuilding processes. One example is the F-1123 'Switch Tube' used in the Linac RF power system. Discontinued over 10 years ago, the repair of the F-1123 requires salvaging parts from other F-1123 tubes (or similar obsolete tubes). Failure of long-lead-time items, unavailable replacement components and aged hardware prone to failure in the Proton Source represent the largest risks associated with Fermilab's accelerator complex.

Figure 1: Location of Fermilab's 40 year old Proton Source

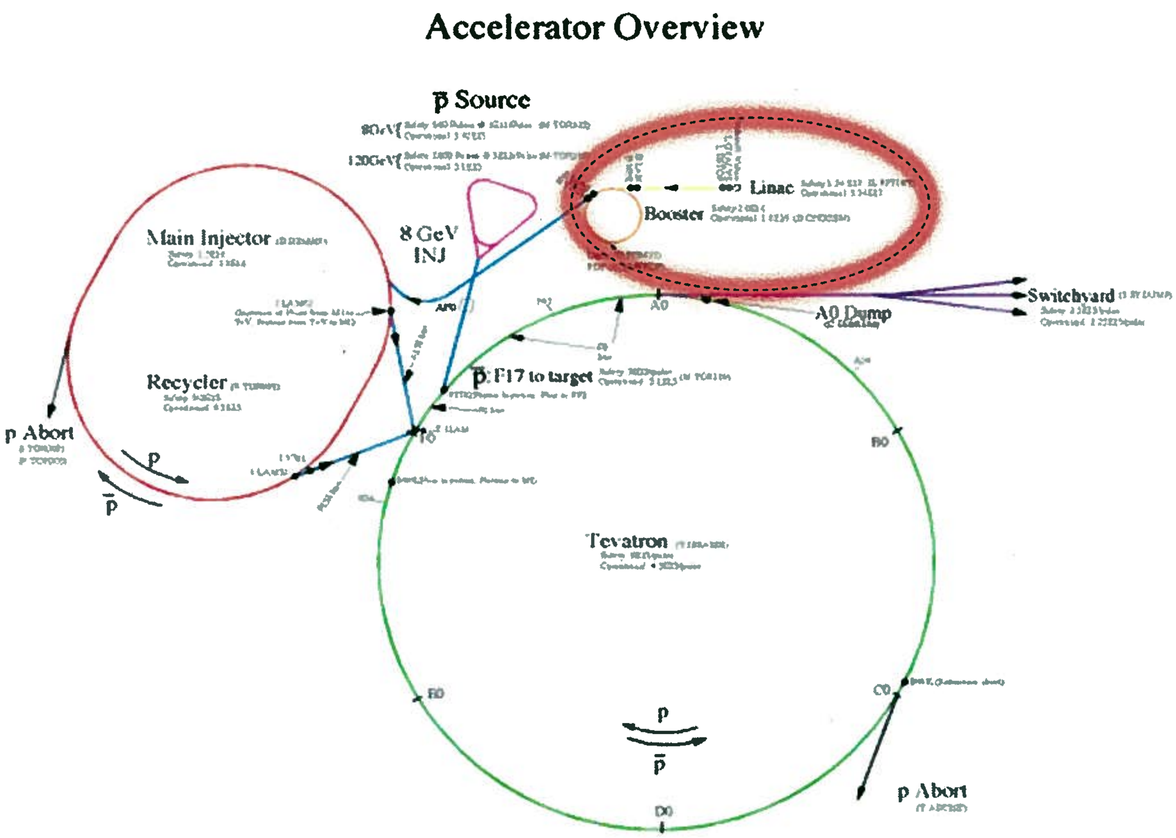

Figure 2: Schematic diagram of Fermilab's Accelerator Complex. The Proton Source is circled in the diagram.

In addition to the issue of reliability and availability of spare components, the demands for the performance of the Proton Source continue to increase. In fact, the demand for protons is projected to increase by a factor of two during the present decade, considering only those experiments which have received Fermilab PAC approval, and which are already in the DOE CD-process. Figure 3 shows the projected demand for proton throughput during the next decade.

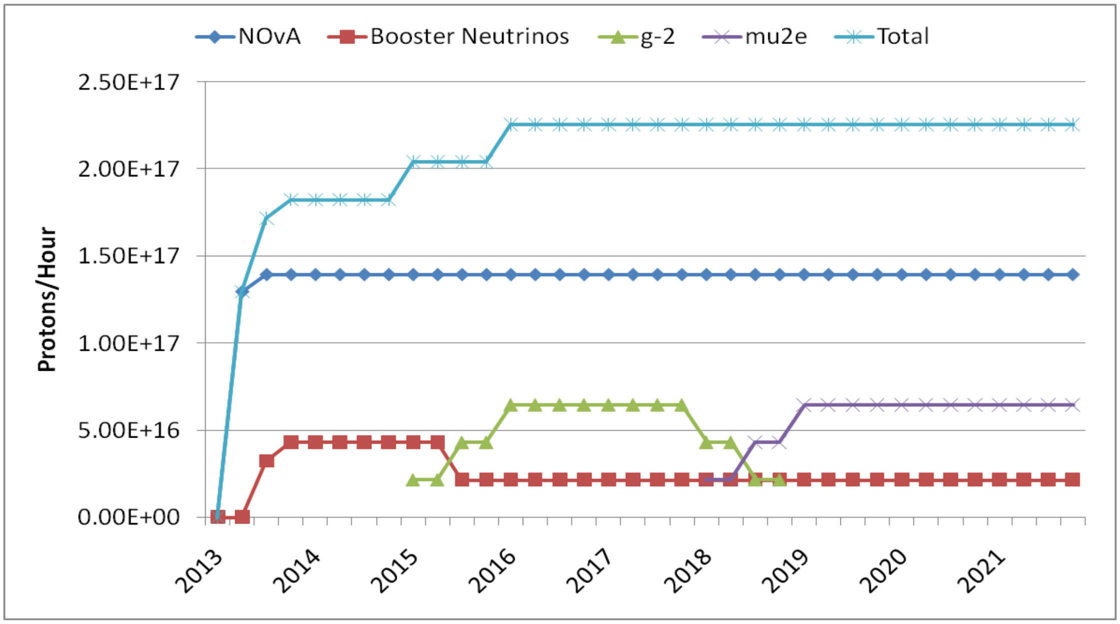

Figure 3: Proton source throughput goals for the next decade.

As the proton intensity per Booster batch is limited (magnet aperture and RF voltage), an increase in throughput can only be achieved by further increasing the Booster repetition rate, as shown in Figure 4. It must be emphasized that the Proton Source was never designed to deliver these performance levels. It was never designed to operate at the 15 pulses per second that is required for beam delivery. It was never designed to deliver the large proton throughput that it presently delivers. And it was never designed for a productive life which will be approaching 55 years by the time it may be retired once Project-X is complete. It should be noted that the staging of Project-X, which will delay the 8 GeV Linac portion, will require the Proton Source to operate beyond 2025.

Increasing the repetition rate requires modifying or replacing components that are limited to lower repetition rates due to thermal management issues at the higher average power levels. It should be emphasized that simply increasing the repetition rate by approximately a factor of two would double the beam loss and residual activation levels, thus making routine maintenance extremely difficult, time consuming and leading to increased collective doses for Fermilab's technical staff. Therefore, an important component of the Plan is the study, diagnosis and mitigation of losses in the Booster in order to maintain residual activation at present levels.

This document presents the goals for the Proton Improvement Plan, and a preliminary analysis of the required scope and associated funding and manpower needed to achieve those goals. The analysis presented is the result of a set of recent assessment and scoping activities which are documented in references 1-3.

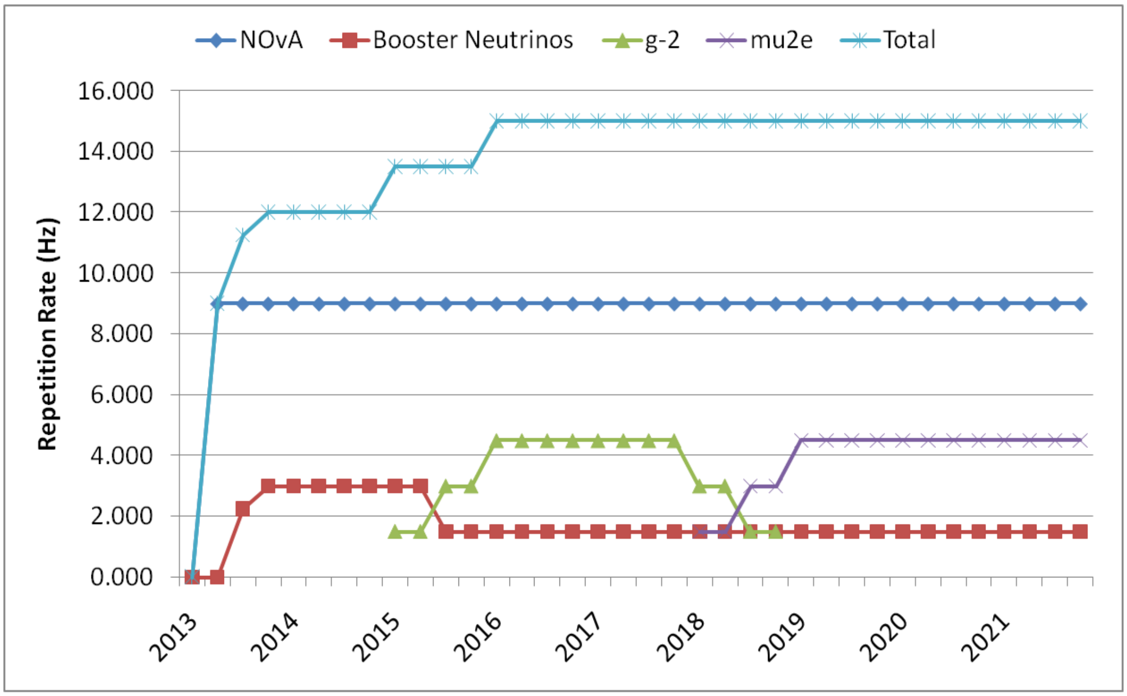

Figure 4: Beam repetition rate goals through the next decade.

2. Goals of the Plan

The goals of the Proton Improvement Plan are as follows:

- Increase the beam repetition rate from the present ~7 Hz to 15 Hz
- Eliminate major reliability vulnerabilities and maintain reliability at present levels (>85%) at the full repetition rate
- Eliminate major obsolescence issues
- Increase the proton source throughput, with a *goal* of reaching > 2E17 protons/hour
- Ensure a useful operating life of the proton source through at least 2025

The timeframe for realizing these goals will depend on the funding profile. In order to deliver the proton throughput displayed in Figure 3 it would require:

- Delivering 1.8E17 protons/hour (at 12 Hz) by May 1, 2013
- Delivering > 2.2E17 protons/hour (at 15 Hz) by January 1, 2016

In addition, within the planning activities, remaining vulnerabilities at the completion of the plan have been identified and backup plans formulated. Two critical remaining vulnerabilities, once this plan is completed, will be the Drift Tube Linac rf structures and the Booster gradient magnets. Full replacement of the DTL structures and Booster magnets would be a lengthy and expensive project. Retention of the original DTL structure is judged to be an acceptable risk while the risk associated with aging Booster magnets will be mitigated by the buildup of a small number of spare magnets.

3. Scope

The scope of the Proton Improvement Plan includes:

- Upgrading (or replacing) components to increase the Booster repetition rate
- Replacing components that have (or will have) poor reliability
- Replacing components that are (or will soon become) obsolete
- Studying beam dynamics to diagnose performance limitations and develop mitigation strategies
- Implementing operational changes to reduce beam loss

The Proton Improvement Plan scope is summarized as follows:

- **Linac Radiofrequency Quadrupole:** The Cockroft-Walton system will be replaced by a 750 keV RFQ, which increases the reliability of the injector system and improves linac output beam quality, which will improve beam loss and activation. This program is now underway, but requires the continued effort of key Accelerator Division personnel and funding at the planned FY11 and FY12 levels to be completed on schedule. Installation is planned for the long FY12/13 NOvA shutdown. Figure 5 shows the new FNAL RFQ injector design.

- **Drift Tube Linac RF Power Systems:** The high power RF drive system for the 201.25 MHz DTL systems is replaced with a new modulator design and a replacement for the 7835 high power RF amplifier hardware. This element addresses the long-standing vulnerability and the highest risk to the proton source by replacing obsolete and difficult to maintain equipment. This task will require significant engineering, technical and operational resources. The upgrade will be carried out over the full five-year duration of this plan.

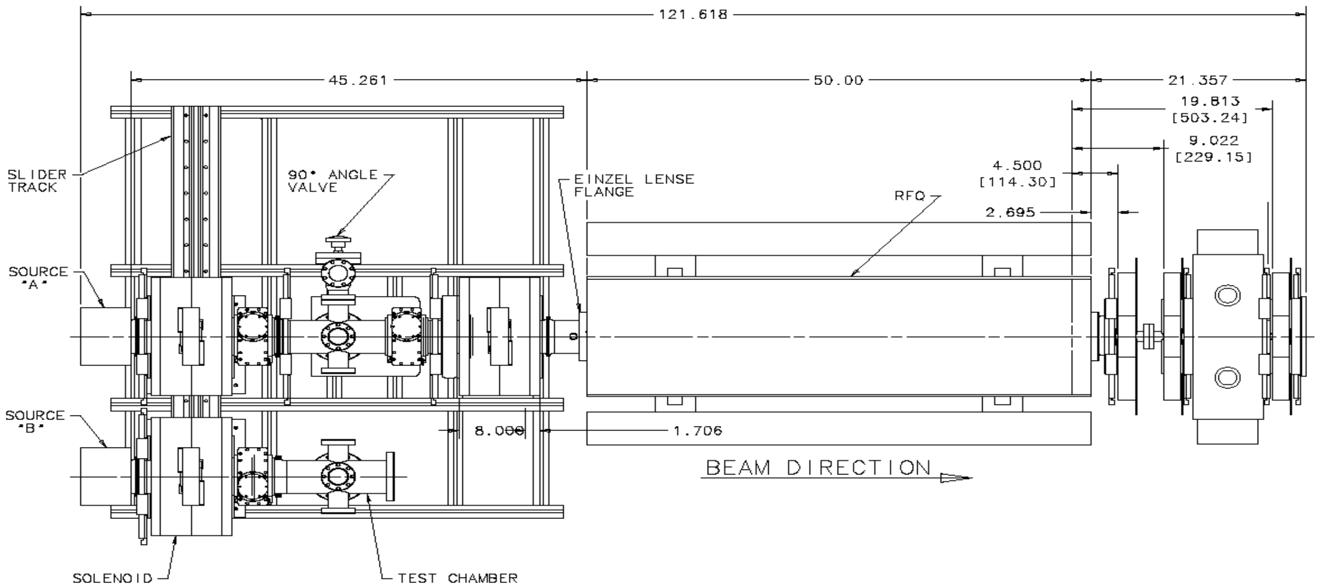

Figure 5: Pre-Accelerator RFQ Layout

- **Booster RF Solid State Program**. This completes the ongoing effort to replace the 40 year old power amplifier tubes inside the beam enclosure with new solid state amplifier components located outside the beam enclosure. To date, three have been replaced. The plan includes funding for replacing the remaining 16. This item is critical to meeting both the cycle repetition rate and the beam flux goals. Shown in Figure 6 are the two types of power amplifiers.

- **Booster RF Cavities, Tuners, Anode Supplies, and Bias Supplies**. Each of these elements requires immediate attention with dedicated engineering and technical resources to reach the 12 Hz operational goal in 2013 and the 15 Hz goal by 2016. The Booster RF cavity tuners will be refurbished (or upgraded) to increase reliability. The Booster RF cavity structures will be replaced with a new design capable of full 15 Hz repetition rate. The high-power RF anode supplies and cavity tuning bias supplies will also be replaced with updated units to handle the repetition rate increase and improve the overall system reliability. Each of these elements is a separate improvement which can be implemented independently of the others.

- **Doubling the 8 GeV Beam Flux:** This element includes all tasks needed to increase the proton throughput while maintaining beam loss at activation at acceptable levels. This includes efforts to study beam dynamics limitations due to space-charge, impedance and collimation systems, operational modifications such as a modified cogging scheme, implementation of injection painting and transverse feedback, measurement and correction booster optical parameters and improved alignment. Also included are upgraded shielding as necessary.

Figure 6. Forty year-old Power Tube Amplifier (left) and the replacement solid state unit (right)

- **Beam Instrumentation and Controls:** This element includes new and upgraded beam instrumentation in the linac and Booster to allow diagnosis of beam intensity and beam loss limitations and their mitigation. It also includes the replacement of obsolete control system components to improve reliability and mitigate risk due to parts unavailability.

- **Linac and Booster Conventional Systems:** This element includes improvements to water systems and AC power distribution for improved reliability.

- **Vacuum system upgrades:** This element includes improvements to the vacuum system for improved reliability and mitigation of obsolescence.

- **Booster Gradient Magnet Spares:** This element includes preparing and testing one of each of four types of booster magnets as ready spares.

4. Cost Estimate

The preliminary PIP funding and manpower estimates are shown in Table 1 below. This plan assumes that funding levels for proton source operations and maintenance will remain similar to current levels for the next several years. For example, if funds for necessary items such as Linac and Booster RF tubes are removed, it would be necessary to then insert them into the PIP budget request. Some scope elements will only be completely defined after a period of study and assessment. A best-effort to estimate costs based on experience has been performed. For the larger scope elements (the DTL high-power RF systems and Booster RF cavities) costs should be considered as appropriate at the conceptual level, not at the engineering design level. Further effort is required to refine the cost estimates presented in order to achieve a level of confidence suitable for "baselining" this plan. These larger scope elements have been phased in order to provide flexibility to accommodate funding availability different from the planning assumptions; and to allow for incorporation of "lessons learned" from earlier phases. Each of the phases is a standalone improvement to the Proton Source.

The plan presented herein can be carried out with an M&S funding profile as shown in Table 2. This funding profile is consistent with completion of the PIP by the end of FY16.

Table 1: Proton Improvement Plan – Tasks and associated cost estimates and manpower requirements

Task	Description	AIP M&S Costs (k$)	Capital Equipment M&S Costs (k$)	FTE-yrs
Project Management			0	9
DTL High Power RF System Phase 1	Design, fabrication, testing and installation of first unit	2,500		15
DTL High Power RF System Phase 2	Fabrication, testing and installation of additional 2 RF units	5,000		17
DTL High Power RF System Phase 3	Fabrication, testing and installation of additional 2 RF units	5,000		17
RFQ Completion	Complete acceptance, testing and installation of RFQ and disassembly of Cockroft-Walton		750	10
New Booster RF Cavities	Design, fabrication and testing of first article	1,500		9
Booster RF Cavity Upgrade Phase 1	Design, fabrication and testing of six units	5,500		10
Booster RF Cavity Upgrade Phase 2	Design, fabrication and testing of next six units, as required	5,500		10
Booster RF Cavity Upgrade Phase 3	Design, fabrication and testing of next six units, as required	5,500		10
Booster Tuner System Upgrade	Upgrade of existing tuners (as applicable) and purchase of new	2,000		5
Doubling beam throughput	Effort to study beam dynamics and implement operational improvements		0	8
Collimator system	Analysis of collimation system performance and upgrade	1,500		10
Instrumentation and Controls	Upgrade controls and instrumentation	1,500		15
BRF Anode and Bias supplies & test stand	Upgrade RF system components for reliability and obsolescence	1,700		5
Booster Solid state systems	Complete Booster RF solid-state system replacement		3,700	8
Conventional Systems Upgrades	Low-conductivity water system and power distribution system upgrades	2,300		4.5
Vacuum System Upgrades	Upgrade vacuum system components for reliability		400	6
Booster gradient magnets	Prepare a set of refurbished and tested booster magnets		80(ops funded)	1.5
TOTAL		**39,500**	**4,930**	170

Table 2: Assumed funding profile for the Proton Improvement Plan

Year	M&S Funding
FY12	6.2
FY13	6.2
FY14	13.3
FY15	12.3
FY16	6.4

5. Conclusion

The Proton Source has operated for over 40 years with unmatched success. Further demands for proton throughput, coupled with the need for continued reliable operation well beyond the design life of the facility, necessitates a dedicated program of improvements to secure the viable operation of the proton source for the next 15 years. The plan presented in this document requires approximately 45M$ of M&S funding over the next five fiscal years. Staffing at the level of approximately 34 FTEs each year are also required to carry out the plan. These resources are already on the Fermilab staff, so additional hiring is not required to carry out this plan.

6. References

[1] A Plan for Delivery of 8-GeV Protons through 2025, Beams-doc-3781, http://beamdocs.fnal.gov/ADpublic/DocDB/ShowDocument?docid=3781

[2] Proton Source Task Force Report, Beams-doc-3660, http://beamdocs.fnal.gov/ADpublic/DocDB/ShowDocument?docid=3660

[3] Proton Source December 2010 Workshop, http://beamdocs.fnal.gov/ADpublic/DocDB/DisplayMeeting?conferenceid=114