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FERMILAB – THE PROTON IMPROVEMENT PLAN (PIP)*

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Abstract

The Fermi National Accelerator Laboratory (FNAL) Proton Source is composed of three machines: an injector line, a normal conducting LINAC and a Booster synchrotron. The Proton Improvement Plan (PIP) [1] was proposed in 2011 to address the necessary accelerator upgrades and hardware modification to allow an increase in proton throughput, while maintaining acceptable activation levels, ensuring viable operation of the proton source to sustain the laboratory HEP program. The strategy for increasing the proton flux is achieved by doubling the Booster beam cycle while maintaining the same intensity per cycle. For the Linac, the focus within PIP is to address reliability. A summary of work performed, and respective results will be presented.

INTRODUCTION

Over the past decade, Fermilab has focused effort to increase the average beam power delivered to the neutrino and muon program. PIP was a campaign to perform numerous upgrades to the existing proton source machines. Prior PIP, Booster could provide 1.1E17 protons per hour, with protons per batch at 4.5E12 at 7.5Hz with 90% efficiency and 85% uptime. By the end of PIP, Booster can reliably provide 2.4 E17 protons per hour, with intensity per cycle at 4.5E12 protons per pulse and beam cycle rate at 15 Hz with 92% efficiency and 90% uptime.

The primary users of a high-intensity proton beam are the 8 GeV Booster Neutrino beamline (BNB), the 120 GeV Neutrino at Main Injector (NuMI) and the muon campus.

HIGH PROTON FLUX OPERATION

Achieving greater than 80 kW beam power from Booster required increasing the repetition rate from 7.5 Hz to 15 Hz while maintaining the same beam intensity per cycle. To accomplish the increase in repetition rate, the Booster RF power system underwent a significant upgrade. Figure 1 shows the proton delivered per day and the integrated protons delivered since 1994 up to 2018.

As can be seen, proton flux has seen a rapid increase with yearly output exceeding the previous.

RF Power System

Of the various contributors to limited repetition rates for the Booster Accelerator, the Booster RF system has often been cited as a primary factor. The reason for that is that the system has never been designed to accelerate beam at the sustained rates now being expected. The fundamental limitations have been due to RF hardware limitations. To improve the Booster RF reliability, the upgrade of the power amplifier is one of the main efforts inside PIP.

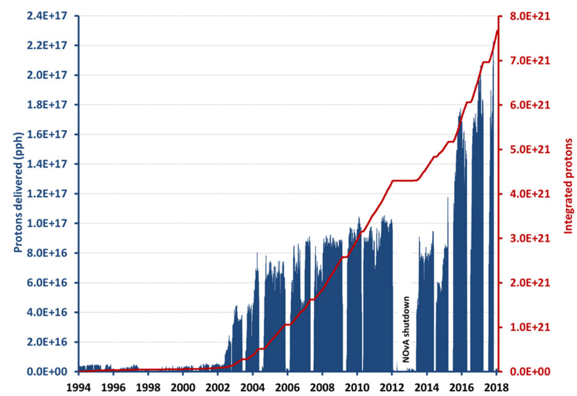

Figure 1: Booster integrated and per day protons delivery.

Cavity and tuner refurbishment The cavity and associated tuners, 3 per cavity, **require** cooling improvements to support higher repetition rates. Each cavity was removed from operation to be inspected, cleaned, tuners re-work, vacuum certified and tested at 15 Hz to certify operations prior to being installed in the tunnel again.

The ferrite tuner cone cooling path had been disconnected many years ago because of water leak history. As part of the refurbishment each tuner needed to be completely disassembled and the cooling channels reworked.

Solid State upgrade The Booster RF system, among its kindred Main **Injector** RF systems, has the oldest equipment and exhibits, not surprisingly, the least reliability. The driver amplifier tubes and the Cascode sections of the cavity mounted Power Amplifier (PA) was especially vulnerable to more frequent failures. The repair of the RF system was also compromised by the increased activation of components.

The greatest RF system reliability came with the complete installation of a solid-state RF driver and new Modulator in the equipment galleries and a new final stage amplifier at the enclosure cavity.

Notch and Cogging Upgrades

The Booster notch system is used to create a gap (aka "notch") in the beam for the extraction kickers. The phase I for this upgrade was to move the notch kickers and install a beam absorber for the notched beam. At 15 Hz the total beam power lost predicted in the tunnel is 270 W.

As a phase II of this upgrade, a new complement of 6 short kickers with respective new power supplies replaced the existing system. This allowed the relocation of the operational losses created by the notch into the absorber. Further efforts were pursued and successfully implemented

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which allowed the complete elimination of the notch creation in the Booster tunnel. This system is the Linac Laser Notch system, which will be described below. Nevertheless, this system is used as a secondary resource to clean the abort gap even further.

The cogging system was improved to reduce the manipulation of the radial orbit. The new scheme utilizes all of the 48 horizontal dipole correctors locations to change the magnetic field during the acceleration cycle. The gap creation was used to be at 700 MeV with the RF cogging system and it was moved to 400 MeV as shown in Fig. 2. Reducing the beam losses at the notch creation by 40% and the total cycle loss by 15%.

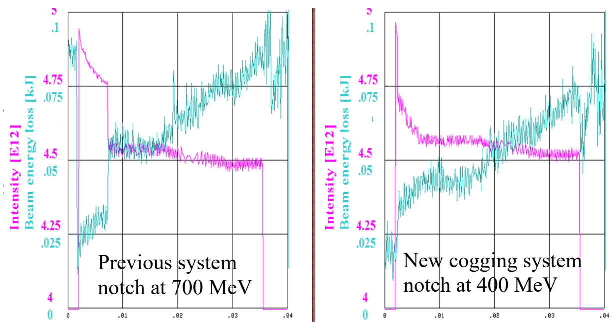

Figure 2: Magnetic Cogging system before (left) and after (right) update.

Laser Notch

A laser notch system [2] was built to create the notch within linac beam pulse at 750 keV, where activation issues are negligible. The laser system design has three stages of fiber and two stages of solid state amplification. This creates a burst of spatially a temporally uniform 200 MHz pulses, each with 2 mJ of energy to match ion bunch structure out of the RFQ to create a set of notches in the linac pulse at the Booster revolution period. Figure 3 shows the effect on the Booster beam losses when the linac laser notch system is OFF and ON.

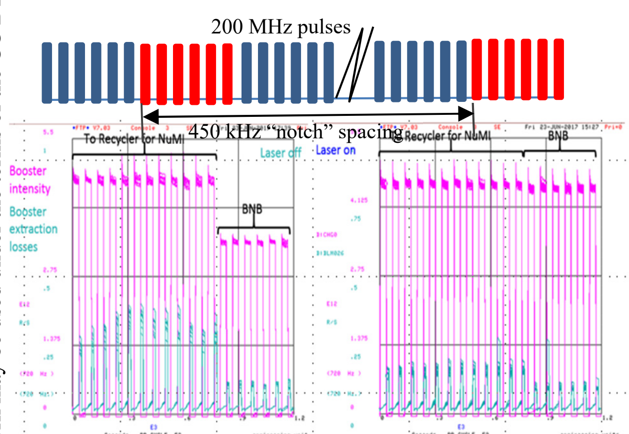

Figure 3: Linac Laser Notch system pulse pattern and impact on beam losses in Booster when the system is (OFF) and (ON).

Perpendicular Bias Second Harmonic Cavity

A perpendicular bias second harmonic RF cavity [3] (Fig. 4) is currently being constructed for use in the Fermilab Booster. The cavity will operate at ~76 - 106 MHz, twice the fundamental RF frequency, but will be turned on only during injection, and transition or extraction. Its main purpose is to reduce beam loss in Booster. After three years of optimization and study, the cavity design has been finalized and most of the parts are being manufactured and will be installed during the lab-wide summer 2018 shutdown.

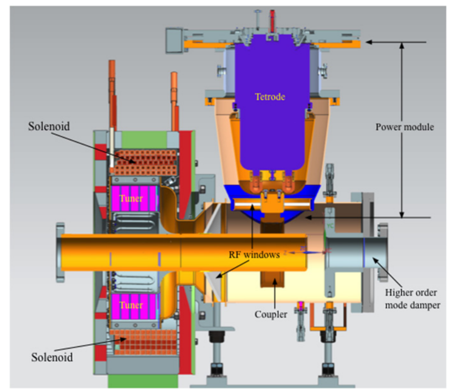

Figure 4: Cross sectional view of the 2nd harmonic cavity.

VIABILITY AND RELIABILITY

PIP strategy to address viability and reliability is to replace systems with obsolete parts and significant contributions to machine downtime. This front has been the focus for the pre-accelerator and the linac machines.

Injector Line

Since 1978, The Fermilab injector line consisted of two 750 keV Cockcroft-Walton accelerators and two magnetron H- sources. Based on the successful design at BNL (Brookhaven National Laboratory), under PIP, the injector was upgraded with a 200 MHz RFQ [4] (Radio Frequency Quadrupole) in 2012. The new design is divided into three parts: the ion source, the low energy beam transport (LEBT) and the medium energy beam transport (MEBT).

The ion source contains two H- magnetron at 35 keV and beam current around 60 mA with a power efficiency of about 60 mA/kV.

The LEBT optics is a standard one where two solenoids are separated by a short distance so that the beam at the source and at the entrance of the RFQ are at the focal points of each solenoid. In this region, an Einzel lens is installed near the entrance of the RFQ and will be used as a chopper system.

The MEBT lattice is composed of two quadrupole doublets and a buncher cavity.

With the new injector line, beam capture in the linac improved by nearly 30%.

Linac

The FNAL Linac accelerator accelerates H^- ions from 750 keV to 400 MeV. The low energy Linac section, built

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in 1969, uses 201.25 MHz Alvarez drift tube cavities powered by a 5 MW triode power tube (therein referred as 7835) accelerating beam up to 116 MeV, while the high energy section uses 805 MHz side coupled cavities powered by a klystron to boost the beam energy from to 400 MeV.

Solid State upgrade The Linac RF drive system consisted of variety of solid **state** amplifier, pentode, tetrode and triode vacuum tubes. The DTL system used over 75 tubes from 10 different vendors to operate. Under PIP, the tube consumption was reduced by 70% with upgrade to solid state technology.

200 MHz RF system The 201.25 MHz RF power system was a major concern for many years in regards long term operational reliability and viability. The issue is specialized maintenance required and extensive downtime generated by this system, specially the hard tube modulator. The risk is that power tubes could become unobtainable to support operations and additional vacuum tube could become obsolete. PIP strategy was to build-up a 4-year in-house inventory of the 7835, develop a workable plan to replace the final amplifier in case the tube line is discontinued and replaced the high voltage modulator with present day technology. For the former, a 200 MHz, 5 MW, 15 Hz klystron tube was developed as a viable solution for the replacement of the 7835 triode while a for the later, an in-house design of a 35 kV, Marx-topology modulator to drive the triode was developed. This will be discussed further below.

Marx Modulator The original high voltage modulator for the 7835 power amplifier (PA) was the major source of downtime, accounting for over 50% of the downtime in the last 15 years. The Linac modulator was built in the late 1960's, used vacuum switch **tubes**, discontinued in the early 2000s, to provide pulsed voltage to the anode of the 7835 PA. Furthermore, most of the relays, power supplies, diagnostics, and interlocks circuits, were obsolete and increasingly difficult to maintain. Within PIP, the strategy to mitigate the reliability issue was to replace the hard-tube modulator with a modern solid-state modulator which improves reliability, lower operational costs while maintaining the same waveform accuracy required to accelerate the beam.

The new modulator design topology was developed by the Fermilab Accelerator Division Electrical Engineering Department (AD/EE) [5]. A sub-set of the most critical Marx-Modulator parameters are shown in Table 1.

Table 1: Marx Modulator Main Parameters

Parameter	Value	Units
Maximum voltage	35	kV
Maximum current	375	A
Voltage regulation	±25	V
Pulse Repetition Rate	15	Hz
Maximum pulse width	460	µs
Minimum slew rate	15	kV/µs
Rise/Fall time	50-150	µs

Marx-modulator works by charging individual cells in parallel and discharging in series. The power is delivered to each cell via charging diodes and filter network. There is a total of 54 cells and they are divided into two categories: i) 42 switching cells which are used to create the basic waveform and produce the fast beam pulse rise/fall time and ii) 12 regulating cells which are sued to compensate for capacitor droop and provide the necessary beam top tilt. In Fig. 5, an illustration of the waveform is shown.

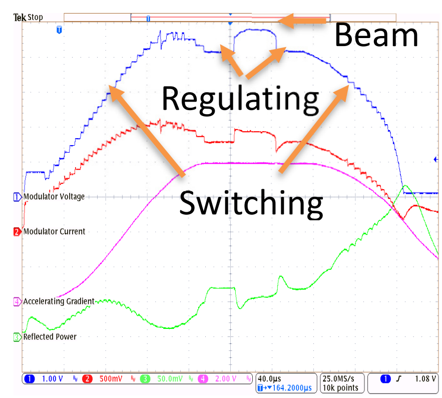

Figure 5: Linac Marx-Modulator typical waveform.

As of the date of this paper, 3 of the 5 DTL RF stations have been upgraded to Marx-Modulator. Figure 6 shows a comparison before and after of the beam pulse-by-pulse variation.

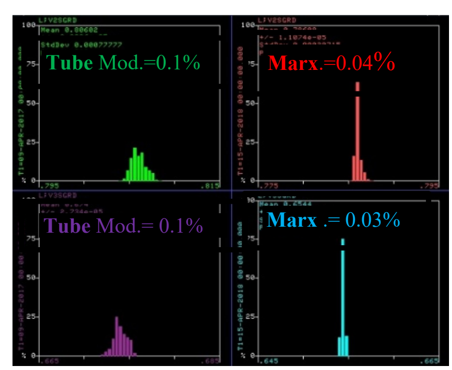

Figure 6: Gradient stability before (left) and after (right) Marx-Modulator upgrade.

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CONCLUSION

The Proton Source has been the workforce of the Fermilab experimental physics program. Injector and Linac is expected to continue be operational at least until middle 2020's when a new higher energy linac is supposed to be operational, but Booster is expected to continue be operational for at least 2 more decades. PIP successful reached all its original goals and is on track to be complete by the end of calendar year 2018.

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REFERENCES

[1] W. Pellico, *et al*., "The Proton Improvement Plan", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, p. 3409, paper THPME075.

[2] D. Johnson, "MEBT Laser 11Notcher (Chopper) for Booster Loss Reduction", presented at HB2018, Daejeon, Korea, paper THP1WC01, this conference.

[3] R. Madrak, "The FNAL Booster Second Harmonic RF Cavity", presented at HB2018, Daejeon, Korea, paper THP2WC01, this conference.

[4] C.Y. Tan, D.S. Bollinger, K.L. Duel, J.R. Lackey, W.A. Pellico, "The FNAL Injector Upgrade", FERMILAB-CONF-11-072-AD.

[5] T.A. Butler, F.G. Garcia, M.R. Kufer, H. Pfeffer, D. Wolff, "Design of a Marx-Topology Modulator for FNAL Linac", FERMILAB-CONF-15-094-AD, arXiv:1504.07589.