FNAL ACCELERATOR COMPLEX UPGRADE POSSIBILITIES

I. Kourbanis#, Fermilab*, Batavia, IL 60510, USA

Abstract

The Fermilab Accelerator Complex is ready to provide 700KW of beam power to the NuMI neutrino target for the first time. The current Accelerator performance will be discussed and then the possibilities for upgrading the beam power up to 4MW will be presented.

ACCELERATOR COMPLEX

The Fermilab Accelerator complex is shown in Figure 1. It has been re-configured for high power operation out of Main Injector and supports an 8 GeV neutrino program out of the Booster.

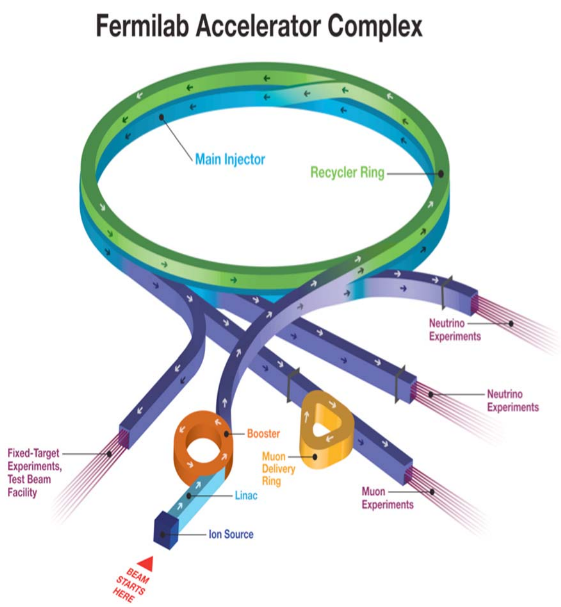

Figure 1: New configuration of the Fermilab Accelerator complex.

Proton Source

The protons source consists of the Pre-Accelerator (Pre-Acc), the 400 MeV Linac and the 8 GeV Booster synchrotron.

The 750 keV Cockcroft-Walton generator was replaced with an RFQ in 2012. The old part of the Linac (up to 116 MeV) uses Drift Tubes powered by RCA 7835 Triodes. The 1971 Booster [1] uses combined function dipoles with exposed laminations. The magnet aperture in the vertical plane is 1.6/2.2 inches in the D/F magnet respectively. It has a lattice with maximum beta functions of 34m and a dispersion of 3.2 m. It crosses transition without a gamma-t jump. The original RF cavities were recently refurbished to allow 15 Hz operations. The RF system was also upgraded with solid state drivers and new Anode Power supplies. Three additional RF cavities were installed in order to increase reliability. New Booster correctors were installed in 2008 for orbit, tune and chromaticity correction up the ramp. The Proton Source upgrades were part of the Proton Improvement Plan (PIP) [2].

Main Injector and Recycler

The Main Injector Accelerator (MI) [3] was commissioned in 1999. It is has seven times the circumference of the Booster. It has a designed admittance of 40 pi-mm-mrad (normalized at 8.0 GeV). It uses all new dipole magnets with sagitta. Most of the quadrupole magnets are recycled from the old Main Ring. It has zero dispersion straight sections, maximum beta of 58 m, and max horizontal dispersion of 1.9 m. It uses the old Main Ring cavities upgraded with solid state drivers. It accelerates protons from 8 GeV to 120 GeV with a maximum acceleration rate of 240 GeV/sec. It crosses transition without a gamma-t jump.

The Recycler [4] is a fixed energy storage Ring located in the Main Injector tunnel. It utilizes 344 combined function dipoles and 86 quadrupoles made out of permanent magnets. Two phase trombones provide tune corrections while Main Injector sextupoles are used for chromaticity correction. The Recycler was built to be a high reliability anti-proton storage Ring. The Recycler aperture is about 20% smaller than the MI aperture.

PRESENT HIGH POWER OPERATION

Slip stacking [5] is used to achieve high intensity. Up to 12 Booster batches can be slip stacked. Slip stacking has an efficiency of ~95% and the losses need to be controlled [6]. To achieve 700 KW we reconfigured the Recycler into a proton machine able to receive protons from the Booster and slip stack 12 Booster batches while the MI is ramping [7]. This reduced the MI cycle time from 2.2 sec to 1.33sec.The MI power and integrated beam to the NuMI target since 2013 when we finished the Recycler modifications are shown in Figure 2. The beam power is gradually increased as we slip stack more bunches. During the current summer shutdown we installing collimators in the Recycler [8] to control the lifetime losses during slip stacking. With the collimators in place we plan to increase the beam power to 700KW.

*Operated by Fermi Research Alliance, LLC under Contact No. DE-AC02-07CH11359 with the United States Department of Energy.
#ioanis@fnal.gov

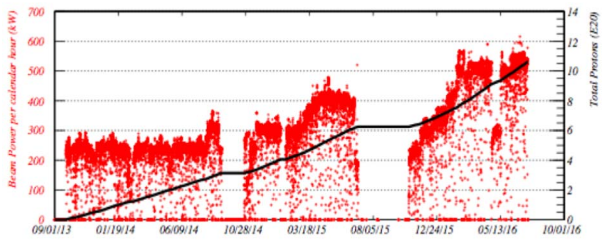

Figure 2: MI beam power and integrated beam from Aug. 2013 to July 2016. The points correspond to the average MI power over an hour.

REACHING 1.2 MW (PIP-II)

In order to further increase the Booster intensity Fermilab's plan is a series of upgrades called Proton Improvement Plan II (PIP-II) [9]. The main feature of PIP-II is the replacement of the current 400 MeV Linac with a new 800-MeV superconducting Linac with CW capability. The Linac energy is selected to support a 50% increase in Booster beam intensity, accompanied by a 30% reduction in space-charge tune shift compared to the current operations. The PIP II also includes upgrades to the Booster, Recycler and MI required to accelerate 50% more beam.

The new Linac (Figure 3) will have a new injection point in the Booster so a new injection girder with a new stripping foil system and new absorbers will be required. Because of the lower average current of the new Linac the number of injection turns will be an order of magnitude higher (300 instead of 20).

Booster improvements in RF capture at injection and transition crossing will continue under the Proton Plan. The use of a second harmonic cavity at injection and during transition crossing is going to be studied in the next couple of years. In addition studies are underway to develop a new Booster RF cavity. The new cavities will be built and tested under PIP with planned operations for PIP II and beyond.

In PIP-II the Booster repetition rate will be increased from 15 to 20 Hz. This will increase the beam separation during slip stacking in the Recycler reducing the slipping time and the beam losses. The higher Booster repetition rate will allow the option to deliver the full MI power from 60 to 120 GeV beam energy.

To slip stack at the higher energy separation in the Recycler will need new 53MHz cavities with higher voltage (140KV instead of 80 KV) capable of CW operation in order to be able run slip stacking at lower MI energies.

In order to accelerate 50% more beam intensity in MI we need more RF power than we have presently available. The MI cavities have a provision for adding a new PA essentially doubling the RF power. The option of using a more powerful PA will also be explored. With the new PA upgrades we will have enough RF power to accelerate up to 1.1E14p with 240 GeV/sec.

Slip stacking with larger separation will result in larger longitudinal emittance bunches in MI. In order to cross transition without losses will need a gamma-t jump. The design of a gamma-t jump for transition crossing in MI already exists [10]. The MI cycle time is expected to be reduced to 1.2 sec from 1.33 sec by optimizing the injection dwell time and speeding up the early parabola.

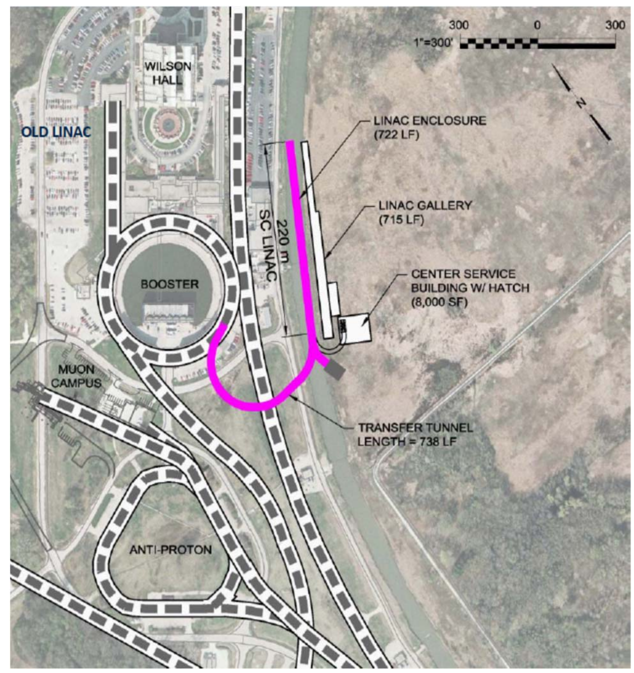

Figure 3: The new superconducting Linac and the injection line to the existing Booster in PIP II.The current Linac is on the left.

REACHING 2.5 MW (PIP III)

In order to reach the physics goals of LBNF/DUNE [11] it would necessary to increase the power from MI to at least 2.5 MW. Slip stacking cannot be supported anymore and the proton source will have to provide the full per bunch intensity to Main Injector.

The Recycler Ring cannot be used any more both because of the limiting aperture and the deteriorating field in the permanent magnets. In addition having Recycler in the same tunnel, limits the upgrade options for MI.

Since we cannot realistically increase the intensity from the current Booster, we need to replace it with either a new Rapid Cycling Synchrotron (RCS) or an 8GeV Linac [12] [13]. Both of these options have advantages and disadvantages that need to be carefully evaluated.

Table 1: MI and Proton Source Parameters for Present Performance, PIP-II, PIP-III and Faster MI with an RCS

	Present	**PIP-II**	**PIP-III (RCS)**	**Faster Main Injector (RCS)**
MI				
Beam Energy[GeV]	120	120	120	120
Cycle Time[s]	1.33	1.2	1.45	0.9
Protons per pulse[1e12]	49	75	190	190
Power[MW]	0.7	1.2	2.5	4.0
Proton Source				
Injection Energy[GeV]	0.4	0.8	0.8-2.0	0.8-2.0
Extraction Energy[GeV]	8	8	8	8
Protons per Pulse[1e12]	4.3	6.4	32	32
Beam Power to Recycler/MI[kW]	38	82	168	271
Maximum Beam Power to 8 GeV[kW]	25	82	645	401

The biggest issue with the Linac option is the ion stripping at 8 GeV. Since Recycler cannot be used and there is no available space in MI, a new Ring will be required for stripping and bunching. The advantage of the Linac is the amount of additional power available at 8 GeV and the capability to run at full power at lower MI energies.

The advantage of an RCS is that we can re-use most of the existing beam lines and hardware from the existing Booster including the new RF system. Among the disadvantages are the limiting power available at 8 GeV especially when running the MI at lower energies and the beam losses at injection energy that might require to increase the energy of the Linac above 0.8 GeV.

The MI RF will not have the power required to accelerate the additional beam intensity and a new RF system will be required. A preliminary design of a new MI RF system already exists [14]. It is based on a perpendicular biased cavity with an R/Q~50 Ohms driven by an 8973 power tetrode capable of delivering more than 1MW of output power.

There have been many RCS designs to date going back to 2000[15] [16]. The latest design (Proton driver II) is a 15 Hz 8 GeV synchrotron with large aperture and no transition crossing.

In order to minimize the injection time in MI a 20 Hz synchrotron will be needed. Without a proton stacker the total MI cycle will increase to from 1.2sec to 1.45 sec.

For this paper the upgrade scenarios with an RCS only are considered.

The parameters for a 20 Hz RCS with the same size as the current Booster are shown in Table 1.

FURTHER POWER UPGRADES

Since it is difficult to further increase the beam intensity we can increase the beam power by reducing the MI cycle time.

Increasing the acceleration rate in Main Injector a factor of 2.5 from 240 GeV/sec to 600 GeV/sec can reduce the Main Injector cycle time from 1.45 sec to 0.9 sec. This will increase the beam power at 120 GeV from 2.5 MW to 4.0 MW. The comparison between the two MI ramps is shown in Figure 4.Increasing the acceleration rate to 600 GeV/sec will require more power supply voltage and more RF (both voltage and power).

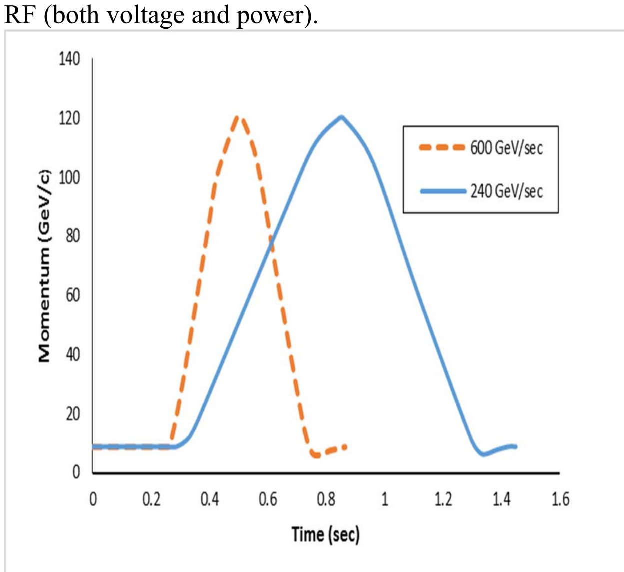

Figure 4: Comparison of MI ramps with 240 GeV/sec and 600 GeV/sec.

We will have to double the maximum power supply voltage by adding 2 bend power supplies and 1 Quad power supply in every Main Injector service building. The service buildings will have to be enlarged to accommodate the extra supplies. Power supply transformers, pads and additional feeder work needs to be added outside each building. Two additional transformers and harmonic filters will be also needed in the Power substation. The substation building will have to be expanded to accommodate additional breakers and equipment.

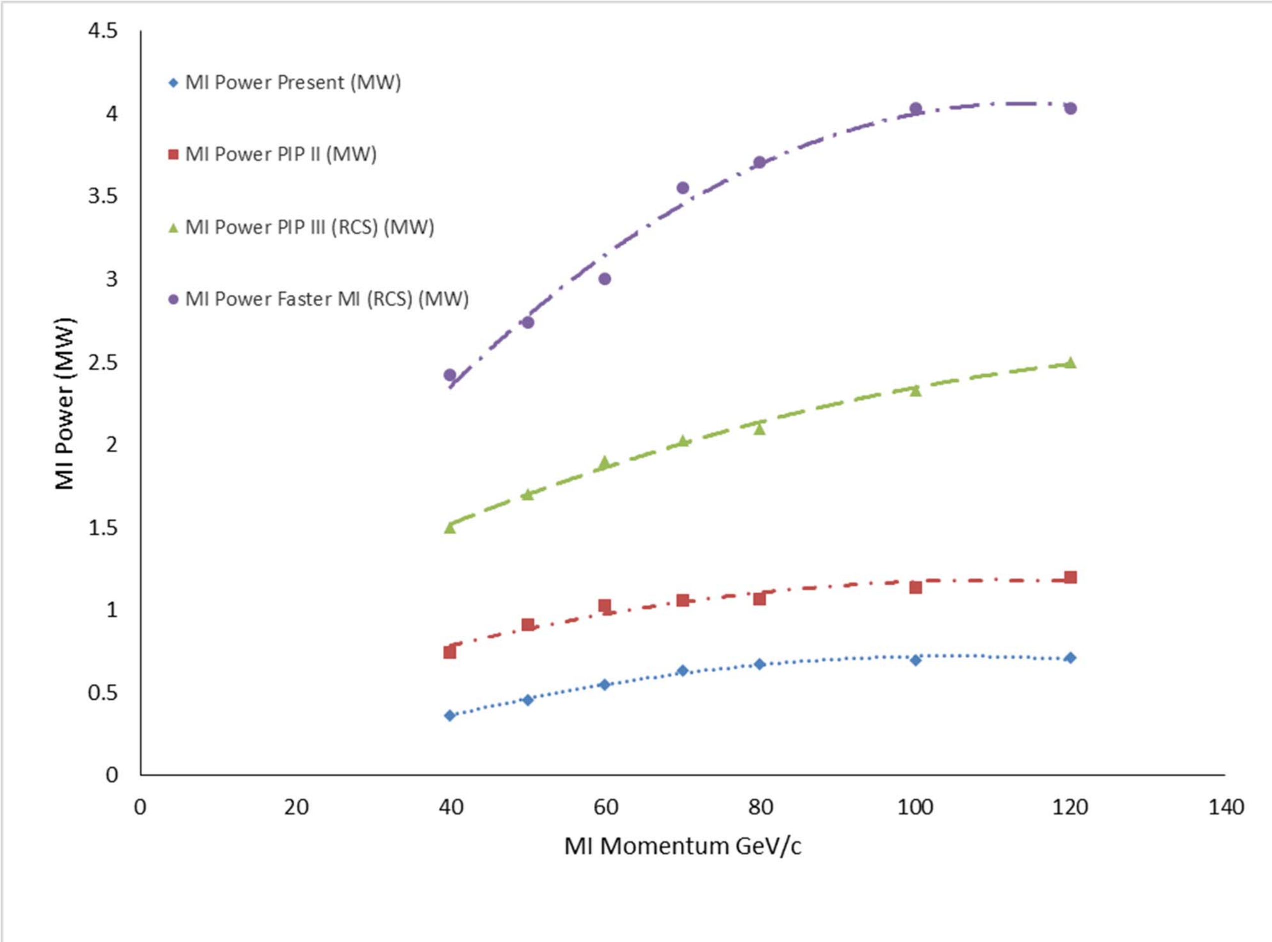

Figure 5: MI Beam Power vs MI momentum for the present and the upgrade scenarios outlined in Table 1.

The new RF stations will have the power required to accelerate 1.9E14 protons with 600 GeV/sec but additional voltage will be required. The minimum acceleration voltage is 6.75 MV and assuming a max bucket area of 0.65 eV-sec after transition a total of 7.5 MV of RF voltage will be required. Assuming 240 KV per cavity that will require at least 31 RF stations. Since the new cavity design is shorter that the current MI cavity we should be able to fit up to 33 cavities in the MI RF straight section.

The MI beam power vs momentum for the various cases considered is shown in Figure 5.

SUMMARY

By replacing the Proton Source and taking advantage of the fast ramping capabilities of MI we can increase the beam power from the Fermilab Accelerator Complex to ~4MW.

REFERENCES

[1] Fermilab Technical Memo TM-405 (1973).
[2] W. Pellico *et al.*, "FNAL-THE PROTON IMPROVEMENT PLAN (PIP)", in *Proc. IPAC2014*, Dresden, Germany.
[3] FERMILAB-DESIGN-1994-01. [9]
[4] Fermilab Technical Memo TM-1991.
[5] K. Seiya *et al*. FERMILAB-CONF-07-275-AD.
[6] B. Brown *et al.* "Fermilab Main injector: High intensity operation and beam loss control" *Phys. Rev. ST Beams* 16, 071001, 2013.
[7] I. Kourbanis, "Progress Towards Doubling the Beam Power at Fermilab's Accelerator Complex" in *Proc. IPAC2014*, Dresden, Germany.
[8] B. Brown *et al.* "Fermilab Recycler Collimation System Design" *NAPAC16,* Chicago, IL.
[9] http://pip2.fnal.gov/.
[10] W. Chou *et al*., "The Design of a gamma-t jump for Fermilab Main Injector", in *Proc. 1997 PAC*, Vancouver, BC., Canada.
[11] http://www.dunescience.org/.
[12] V. Shiltsev *et al*., in *Proc. IPAC2015*, Richmond, USA, p. 4019.
[13] E. Prebys *et al*., in *Proc. IPAC2016*, Busan, Korea, p. 1010.
[14] J. Dey, I. Kourbanis, "A New MI RF System for 2.3 MW Project X Operations". In *Proc.PAC2011*, New York, NY, p. 1079.
[15] "The Proton Driver Design Study", FERMILAB-TM-2136. (December 2000).
[16] "Proton Driver Study II part 1", FERMILAB-TM-2169, May 2002.