

Improvement Plans of Fermilab's Proton Accelerator Complex

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Abstract. The flagship of Fermilab's long term research program is the Deep Underground Neutrino Experiment (DUNE), located Sanford Underground Research Facility (SURF) in Lead, South Dakota, which will study neutrino oscillations with a baseline of 1300 km. The neutrinos will be produced in the Long Baseline Neutrino Facility (LBNF), a proposed new beam line from Fermilab's Main Injector. The physics goals of the DUNE require a proton beam with a power of some 2.4 MW at 120 GeV, which is roughly four times the current maximum power. Here I discuss current performance of the Fermilab proton accelerator complex, our plans for construction of the SRF proton linac as key part of the Proton Improvement Plan-II (PIP-II), outline the main challenges toward multi-MW beam power operation of the Fermilab accelerator complex and the staged plan to achieve the required performance over the next 15 years.

1. Introduction: Overview of the Fermilab accelerator complex

Fermilab accelerator complex – see figure 1 – is one of the largest in the world and consists of 16 km of accelerators and beamlines, two high power targets, several low power target stations, many experiment and service buildings, etc. It delivers beams of protons and secondary particles.

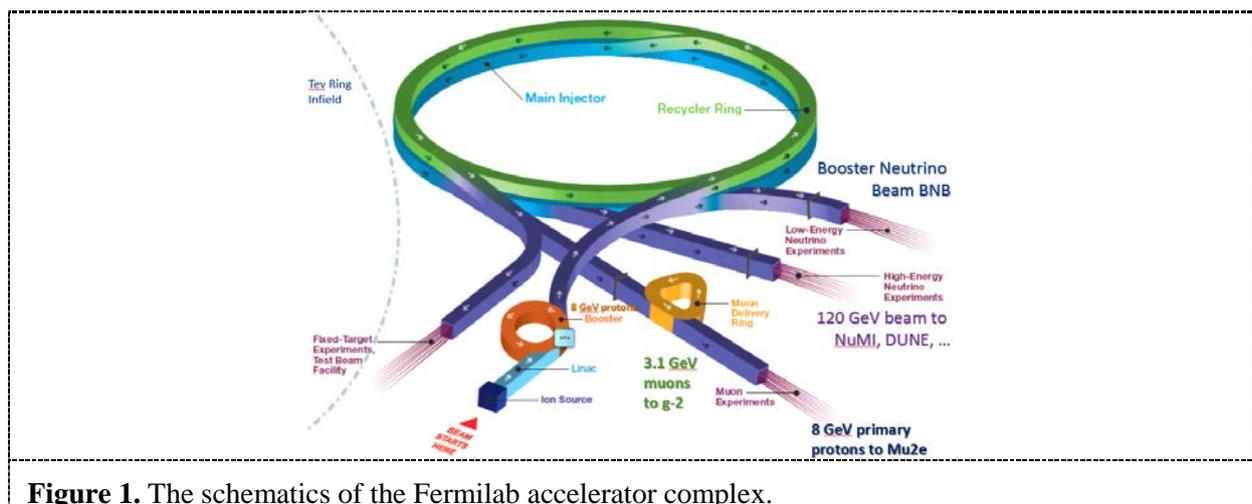


Figure 1. The schematics of the Fermilab accelerator complex.

All protons come from the 8 GeV proton source (400 MeV Linac injecting to 8 GeV rapid-cycling-synchrotron (RCS) Booster), which is largely original construction ca 1960's. The Booster combined function dipole magnets operate in a 15 Hz resonant circuit, which sets a fundamental clock for the complex; however, historically not all cycles could be loaded with protons due to imitations from

injection, extraction, and RF system and beam loss. Next machine downstream the complex is the Recycler, a 3.3 km 8 GeV storage ring made out of permanent magnets. Originally built for storage and accumulation of low intensity antiproton beams during the Tevatron Collider Run II (2001-2011) [1], the Recycler is now used to stack high intensity protons for loading into the 120 GeV Main Injector synchrotron which it shares the tunnel with. The Recycler circumference is sufficient to accommodate six batches of 84 Booster bunches each; however, this number is increased to 12 through the technique called “slip-stacking”, in which additional six batches are injected in the machine with slightly decelerated six original batches. The two kinds of batches travel at a slightly different velocity and “slip” with respect to each other until they overlap and at that moment they are transferred to the Main Injector and accelerated (more details can be found in [1]). The Fermilab complex supports a number of experiments – eg, 400 MeV Linac beam is sent to the Mucool Test Area, 8 GeV protons from the are supplied to 8 GeV Booster Neutrino Beam (BNB), ANNIE, MicroBooNE, MiniBooNE, MITPC, SciBath, ICARUS (future), and SBND (future), and to muon experiments of g-2 and Mu2e (future). 120 GeV proton beam from the Main Injector supports neutrino experiments at NuMI (MINOS+, MINERvA, NOvA) and LBNF/DUNE in the future, as well other fixed target experiments of SeaQuest, LArIAT and at the Test Beam Facility. See Ref.[2] for detailed information about these experiments.

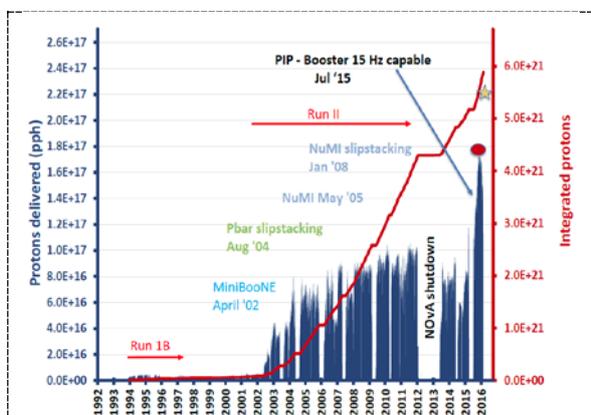


Figure 2. Historical production rate from the 8 GeV Booster (protons per hour) and its integral.

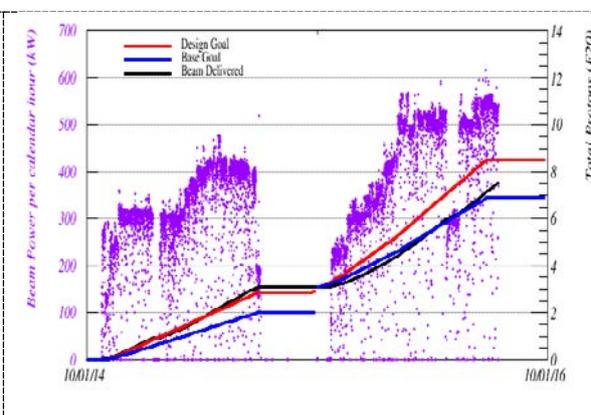


Figure 3. Two years record 2014-2016 of the hourly average 120 GeV proton beam from MI.

In May of 2014, the Particle Physics Project Prioritization Panel (P5) advisory to the Office of High Energy Physics in the US Department of Energy released a report [3], which identified the top priority of the domestic intensity frontier high-energy physics for the next 20-30 years to be a high energy neutrino program to determine the mass hierarchy and measure CP violation, based on the Fermilab accelerator complex which needs to be upgraded for increased proton intensity. Current long baseline neutrino program utilizes the Neutrinos from the Main Injector (NuMI) beam line that was built to provide protons for the MINOS experiment, located in the Soudan Mine in Minnesota, 725 km away. Later, the NOvA experiment was built 810 km away in Ash River, MN. It also uses the NuMI beam line, but it is built 14.6 mrad off axis, producing a narrower energy spread, resulting in an improved resolution for the CP violating phase and mass hierarchy. The physics goal set forth by the P5 Committee is: “...a mean sensitivity to CP violation of better than 3σ [...] over more than 75% of the range of possible values of the unknown CP-violating phase δ_{CP} ”. To this end, a new beam line and experiment are being planned. The beam line is the Long Baseline Neutrino Facility (LBNF) [4] and the new experiment is the Deep Underground Neutrino Experiment (DUNE) [5], located in the Sanford Underground Research Facility (SURF). This will be a truly international collaboration, including contributions from 150 institutions in 27 countries. The P5 physics goals require about 900 kt·MW·years of exposure (product of the neutrino detector mass, average proton beam power on the neutrino target and data taking period). Assuming a 40 kton Liquid Argon detector, this would take over 50 years at the 400 kW beam intensity which was typical when the program was first conceived. For

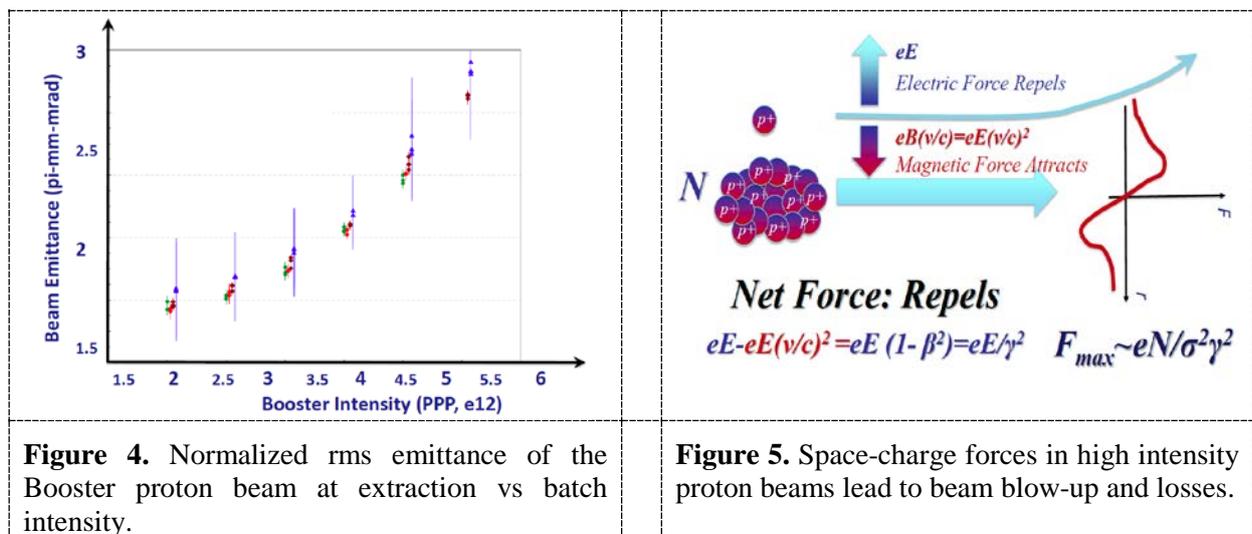
this reason, a series of accelerator upgrades toward the eventual goal of multi MW beam power have been undertaken and planned.

2. Current upgrade activities : Proton Improvement Plan (PIP)

The goal of the Proton Improvement Plan (PIP) campaign is to maximize the proton output from the existing complex with an ultimate goal of 700 kW power at 120 GeV in 2017. The key elements of PIP are reduction of losses and upgrades of the pulsed RF hardware in the Booster to allow beam to be accelerated on all 15 Hz cycles. This goal has recently been achieved and the total proton output from the Booster achieved some 1.8×10^{18} protons per hour - see figure 2. In addition, commissioning of the 6+6 batch slip-stacking in the Recycler allowed to reduce the Main Injector cycle time to 1.33s from 2.2s during the MINOS/Collider Run II era. Due to these improvements, in 2016 the Main Injector achieved world-record 615 kW average proton beam power over one hour to the NuMI beam line – see figure 3. On that way, the operations team increased number of batches slip-stacked in Recycler in steps (just 6 batches in late 2014, then 2+6, 4+6 and, finally, 6+6 batches in mid-2016). At each step, the increase intensity was followed by tuning for efficiency and minimization of losses. Finally, the peak power of 700 kW for one minute was demonstrated in June 2016. Sustainable routine operation at that level is expected in 2017 after an upgrade of the Recycler beam collimation system which is going to take place during the Summer 2016 shutdown.

3. Proton Improvement Plan – II (PIP-II)

In the current configuration, it's unlikely that significantly more beam could be injected into the Booster. The preceding machine, the Linac, can provide more than 6×10^{12} 400 MeV protons per pulse (PPP) but the efficiency of the Booster drops with the intensity increase and, hence, the operations team needs to keep the PPP at the level of about 4.3×10^{12} . At that level, the beam losses are tolerated and occur at the injection energy (some 3-4%) and at the “transition energy” of $\gamma=5.48$ (another 0.3-0.5%). At higher intensities both the beam emittance and beam losses grow beyond acceptable level – see figure 4. The reason for that is strong space-charge effect – illustrated in figure 5 – which is proportional to beam current (number of particles in the bunch N), and scales inversely with beam size σ and grows with time the beam spends at low energies (γ). From the latter argument, fast acceleration with gradient of about 5-20 MeV/m in RF Linacs is advantageous compared to that in the rapid cycling synchrotron (RCS) rings (effectively, some 0.002-0.01 MeV/m). Correspondingly, the maximum value of the RCS bunch intensity N increases as the $\beta\gamma^2$ of the injected beam (see, e.g., [6]).



The key feature of the proposed Proton Improvement Plan-II (PIP-II) project [7] - see figure 6 - is therefore to replace the existing 400 MeV linac with a new 800 MeV linac, capable of CW operation, which is being built in collaboration with India. This will increase the power available to the existing

NOvA beamline and to the new LBNF/DUNE line from 700 kW to 1.2 MW. In addition, the Booster rate will be increased from 15 to 20 Hz, allowing full MI beam power be achieved at the lower energy of 60 GeV (vs current 120 GeV), and 80 kW of beam for the 8 GeV neutrino program in addition to ~100 kW of available 800 MeV proton beam power with arbitrary bunch structure - see full list of the PIP-II key technical parameters in the Table 1.

Table 1. Beam parameters of PIP and PIP-II upgrades.

Performance Parameter	PIP	PIP-II	
Linac Beam Energy	400	800	MeV
Linac Beam Current	25	2	mA
Linac Beam Pulse Length	0.03	0.6	msec
Linac Pulse Repetition Rate	15	20	Hz
Linac Beam Power to Booster	4	18	kW
Booster Protons per Pulse	4.3×10^{12}	6.5×10^{12}	
Booster Pulse Repetition Rate	15	20	Hz
Booster Beam Power @ 8 GeV	80	160	kW
Beam Power to 8 GeV Program (max; MI @ 120 MeV)	32	80	kW
Main Injector Protons per Pulse	4.9×10^{13}	7.6×10^{13}	
Main Injector Cycle Time @ 60-120 GeV	1.33	0.7-1.2	sec
LBNF Beam Power @ 60-120 GeV	0.7	1.0-1.2	MW
LBNF Upgrade Potential @ 60-120 GeV	NA	>2	MW

The PIP-II project got CD-0 approval from the US DOE in 2015 and is scheduled for completion in 2025-2026. Currently, the project team carries out an extensive R&D program focused on reduction of the technical risk and the total project cost via development of the superconducting (SC) RF cavities, research towards significant improvement of the quality factor of the SRF cavities and construction and test of the PIP-II low-energy part (“front-end”). The PIP-II SC RF cavity development is multi-faceted as there are 5 different types of cavities needed which will operate at 3 different frequencies: the 162.5 MHz Half-Wave Resonators (HWRs) – their design is complete and the first cryomodule is in production; the 325 MHz Single-Spoke Resonators (SSR1) – their design is mostly complete and production started; and the design of the 650 MHz High-Beta resonators is also well advancing. All these developments involve collaboration with Indian institutions [8].

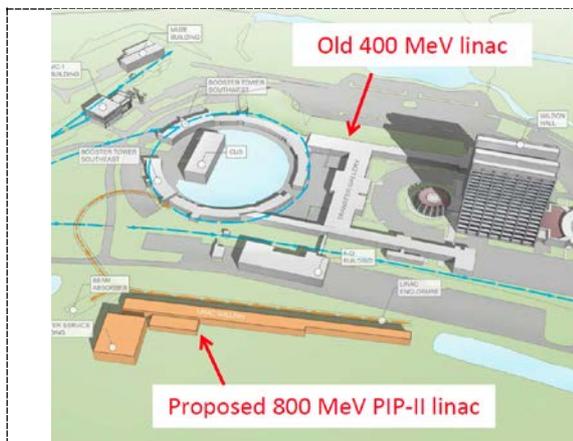


Figure 6. Schematics of the PIP-II proton linac and new injection line to the FNAL Booster.

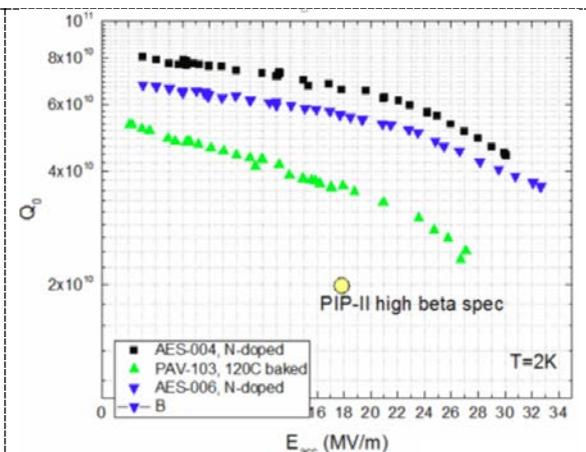


Figure 7. Quality factor of Nb SRF cavities doped with Nitrogen vs accelerating gradient.

The high- Q_0 SRF studies has recently discovered that Nitrogen doping during the Nb cavity surface processing [9] more than doubles the cavity's quality factor Q_0 – see figure 7 - and, thus, reduces needed cryoplant capacity. It was also found that fast cooling of the cavities (which operate at 2K) suppresses the magnetic flux penetration to SC cavity [10] and also improves Q_0 . The front-end Linac test facility [11] will demonstrate in practice two most challenging PIP-II design elements : “room-temperature” to “cold” SC RF transition at very low energy of 2.1 MeV and a 162.5 MHz CW beam chopper. The facility (see figure 8) is being built in collaboration with ANL, LBNL and SNS and two Indian institutions (BARC, IUAC) and has recently achieved beam acceleration through its 2.1 MeV CW RFQ.

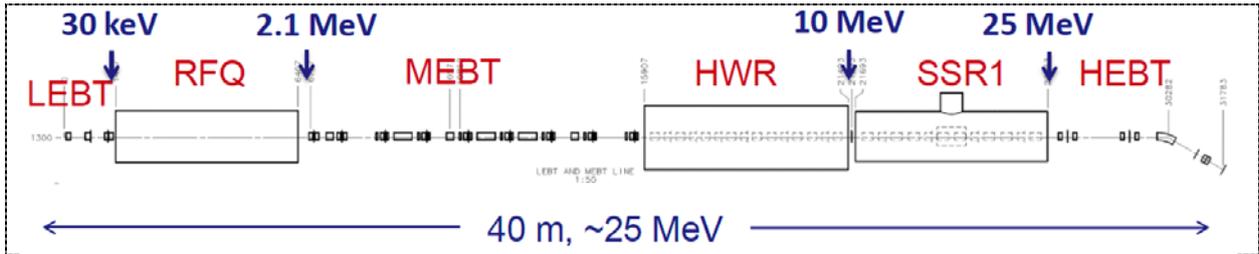


Figure 8. PIP-II injector experiment includes room-temperature CW RFQ and SC HWR and SSR1.

4. R&D towards future multi-Megawatt upgrade of the FNAL accelerator complex

Fermilab has recently started the conceptual development of the next upgrade of its accelerator complex to multi-Megawatt beam power levels after 2030 began corresponding R&D [12]. The key objectives of the upgrade are: i) attainment of more than 2.4 MW beam power for the LBNF/DUNE neutrino program (that is twice the PIP-II goal); ii) replacement of the Booster as a bottleneck toward higher intensities; iii) affordable cost of the upgrade; iv) usage of the PIP-II proton linac and the Main Injector synchrotron; v) development of multi-MW beam targets [13].

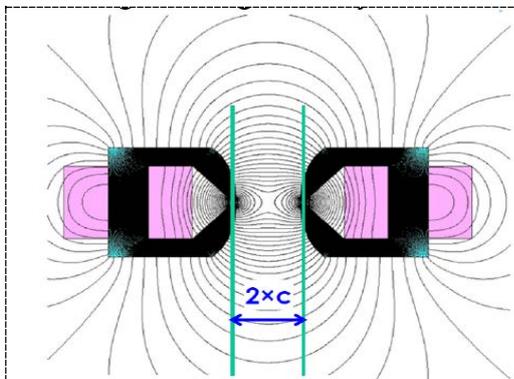


Figure 9. Field lines in the non-linear magnet for integrable optics.

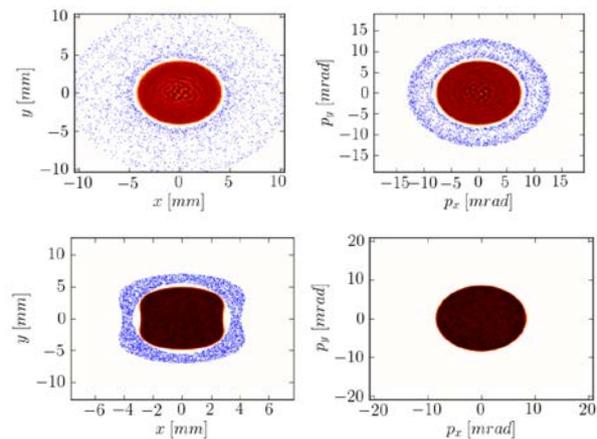


Figure 10. Halo particles (blue dots) under impact of strong space-charge forces of the core (red): top – linear optics, bottom – non-linear integrable optics.

The very first of conditions calls for either double PPP out of the Booster replacement machine in the case the Recycler ring is kept in operation with slip-stacking, or even quadruple it in the (expected) case of inability to operate the Recycler with the slip-stacking due to the process intrinsically lossy bunch manipulations. In general, the beam losses are the main obstacle to enable the multi-MW power upgrade. E.g., assuming usual tolerable radiation levels $\sim 1\text{W/m}$ in the accelerator enclosures, the total losses must be kept under 500 W in the new Booster which will be operating at the 320 kW extracted beam power level (i.e., the fractional beam loss should not exceed either $<0.15\%$ at the extraction energy or

~2% at injection); and be less than 3kW in the Main Injector with will deliver 2.4 MW beams (that corresponds to a fractional losses <0.12% at the top energy or ~2% at the injection energy). These numbers are extremely low and very challenging at the anticipated record high beam intensities – compare with the present level of the beam losses of about 3-5% in the Booster and MI under the conditions of 2-4 times lower PPP.

We plan to explore several approaches for such an upgrade: i) construction of a SRF linac which would extent the PIP-II energy to 8 GeV; ii) 8 GeV RCS which can handle $\times 4$ stronger space-charge forces; iii) a hybrid option of, e.g., 2 GeV Linac and 8 GeV RCS. The advantage of the linac option is that it would provide copious power at 8 GeV, both for ancillary program and so the high energy program could be run at full power at lower Main Injector energies; the major challenge the will be exploration of new techniques for significant reduction of the construction cost per GeV compared to that of the most recent SRF facility at SLAC (LCLS-II). Technical challenge of the H- ion injection into the Recycler or Main Injector at 8 GeV also needs careful evaluation. The advantage of the RCS is that the requisite minimal beam-loss performance has been demonstrated in the J-PARC 3 GeV RCS [14]. Disadvantageous would be limited proton beam power at 8 GeV. Even if a new RCS is built, the normalized emittance will continued to be limited by the acceptance of the Main Injector, so we would not benefit from a large physical aperture like that of the J-PARC RCS. This means that additional measures against the space-charge effects should be undertaken. One option would be to increase the energy of the linac and, therefore the RCS injection energy beyond the 800 MeV energy of the PIP-II linac, if that can be done in a cost efficient manner. Another option would be to mitigate the effect of the space charge use non-linear integrable optics or electron lenses.

It has been shown in [15] that contrary to conventional linear focusing accelerator optics lattices, the single particle dynamics exhibits significantly higher degree of stability in certain integrable nonlinear lattices that would permit mitigation of many of the space charge restrictions that limit beam intensity. Practical realization of such lattices is possible with, e.g., special type of nonlinear magnets similar to the one presented in figure 9. Numerical studies of space charge effects in such nonlinear lattices with intense bunches indicate strong suppression of beam halo formation – see fig.10 from [16]. Another opportunity to create such nonlinear element is to use high intensity magnetized electron beam of an electron lens [17].

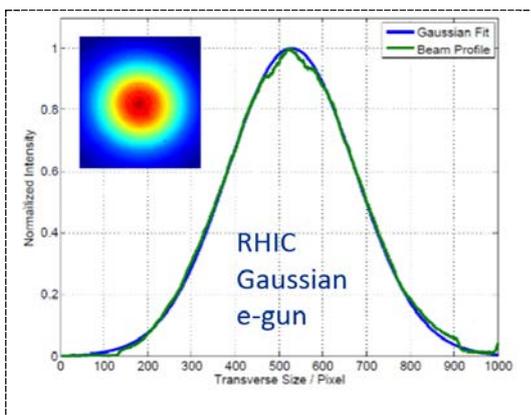


Figure 11. Gaussian electron beam current in the RHIC electron lens.

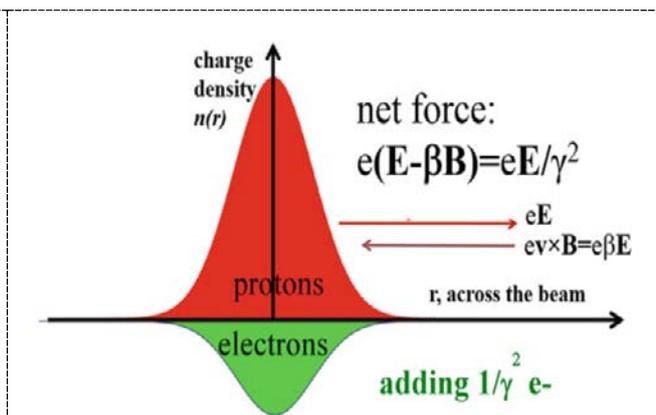


Figure 12. Compensation of the space charge forces of positively charge protons by addition negatively charged electrons.

Electron lenses with Gaussian transverse beam current distribution similar to that developed for the head-on beam-beam compensation in the Tevatron and RHIC [17] - see figure 11 – can be used for direct space-charge compensation (SCC) [18]. The method of SCC [19] calls for placement of stable negative charge of electrons on the orbit of high intensity proton beam, such that the transverse density profiles of both charges match and compensate each other as illustrated in figure 12. Besides electron

lenses, such configuration can be obtained via accumulation ionization electrons in strong magnetic traps, “electron columns” [20].

All these novel ideas will be experimentally tested at the Integrable Optics Test Accelerator (IOTA) ring at Fermilab Accelerator Science and Technology (FAST) facility [21] which besides the ring consists of its 150 MeV electron injector and 70 MeV/c (2.5 MeV kinetic energy) proton RFQ injector– see figure 13. The R&D program at the 40-m circumference IOTA ring (see figure 14) requires development and installation of the corresponding non-linear magnets and electron lens, and operation with either 150 MeV electrons for initial test of the integrable optics or 70 MeV/c high brightness proton beam for the space-charge mitigation with IO and/or with electron lens and with an electron column. The IOTA/FAST facility is under construction now, first circulating electrons in the IOTA are expected in 2017-18 and first protons in 2019. A major milestone of 2016 was commissioning of the 52 MeV electron beam out of the SRF photoinjector which allowed to start a series of beam tests and studies with it.

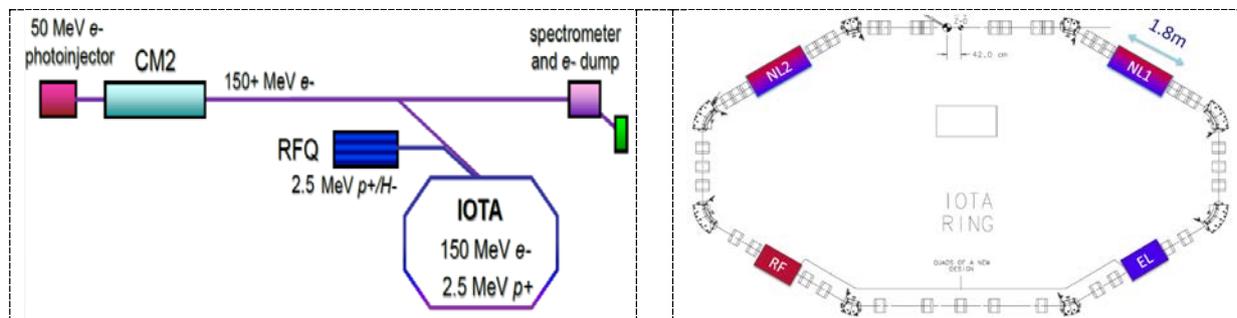


Figure 13. Schematic layout and main components of the IOTA facility.

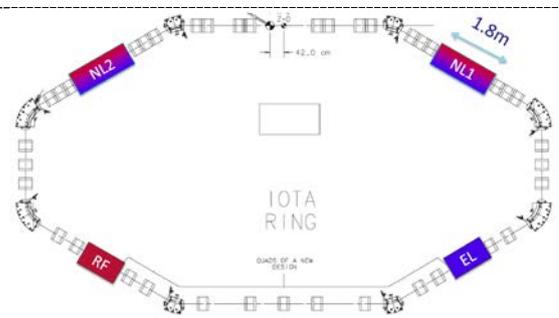


Figure 14. IOTA ring layout with two non-linear magnets and an electron lens for SCC.

5. Summary

Fermilab aspires leadership in the Intensity Frontier of high energy particle physics. Accelerator based neutrino research program relies on operation of 120 GeV proton beamline for NuMI at present and for the LBNF/DUNE in the middle of the next decade. Routine operation with world-record 600kW of average high-energy beam power on the neutrino target has been achieved in 2016 as the result of the Proton Improvement Plan (PIP) upgrade and further increase to 700kW after installation of additional collimators in the 8 GeV Recycler is expected in 2017 (PIP goal). The next upgrade of the FNAL accelerator complex (PIP-II) is under development, it aims at 1.2MW beam power on target at the start of the LBNF/DUNE experiment and assumes replacement of existing 400 MeV normal-conducting Linac with modern 800 MeV SRF Linac. Fermilab teams also explores several concepts to further double the beam power to >2.4MW after replacement of existing 8 GeV Booster. Extensive accelerator R&D program with sizeable international collaboration is launched to address cost and performance risks for these upgrades: the PIP-II Injector Test facility, development of cost-effective SRF cavities and experimental R&D program at the IOTA ring to demonstrate novel space-charge mitigation methods.

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