# LONG TERM PLANS TO INCREASE FERMILAB'S PROTON INTENSITY TO MEET THE NEEDS OF THE LONG BASELINE NEUTRINO PROGRAM*

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*Abstract*

The flagship of Fermilab's long term research program is the Deep Underground Neutrino Experiment (DUNE), located at the 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. This paper outlines the staged plan to achieve the multi-megawatt beam power required by the DUNE physics program.

## BACKGROUND

### *P5 Report*

The Particle Physics Project Prioritization Panel (P5) advises the Office of High Energy Physics in the US Department of Energy. The panel released a report in May, 2014 [1], which identified the top priorities for Fermilab as:

- Support the LHC and its planned luminosity upgrades.
- Pursue the g-2 and Mu2e muon programs
- Continue some level of R&D toward a future linear e+e- collider (ILC)
- Focus on a high energy neutrino program to determine the mass hierarchy and measure CP violation.

This final item will form the "flagship" activity for the lab for the next 20-30 years, and drives the need for increased proton intensity.

### *Fermilab Accelerator Complex*

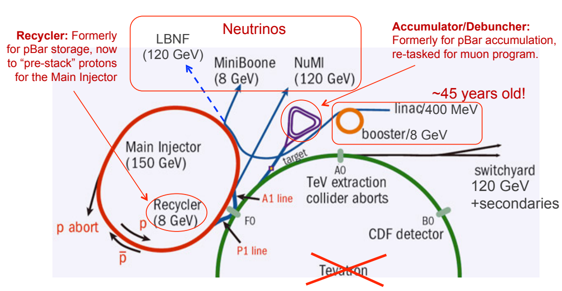


Figure 1: Fermilab accelerator complex, with recent changes indicated.

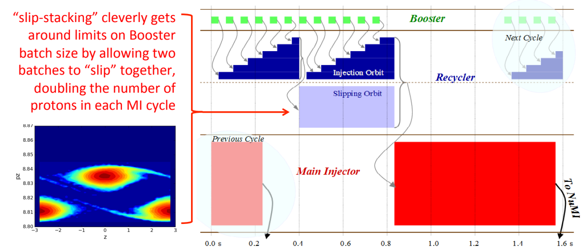


Figure 2: Accelerator cycle for high energy neutrino program. Twelve 8 GeV Booster batches are slip-stacked into the Recycler, then transfered to the Main Injector.

Figure 1 shows the Fermilab accelerator complex. Some components were re-tasked after the Tevatron was shut down. All protons come from the 8 GeV proton source, which is largely original construction. The Booster lattice elements operate in a 15 Hz resonant circuit, which sets a fundamental clock for the complex; however, beam loss and limitations from pulsed elements have historically meant that not all cycles could be loaded with protons.

Figure 2 shows the cycle of accelerator complex to provide 120 GeV protons to the high energy neutrino program. The Recycler, which shares the tunnel with the Main Injector, is an 8 GeV storage ring made out of permanent magnets. It was originally used to store antiprotons, but now is used to stack protons from the Booster for loading into the Main Injector. The Recycler circumference is sufficient to accommodate six Booster batches; however, this number is increased to 12 through the use of "slip-stacking" [2], in which six batches are injected, then slightly decelerated. Thus, subsequent batches will be traveling at a slightly different velocity, and will "slip" until they overlap with the original batches. Once the 12 batches have been loaded, they are transferred to the Main Injector and accelerated.

### *Long Baseline Neutrino Program*

The Neutrinos from the Main Injector (NuMI) beam line was built to provide protons for the MINOS [3] experiment, located in the Soudan Mine in Minnesota, 725 km away. Later, the NO$\nu$A 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 power to resolve the neutrino mass hierarchy.

The physics goal set forth by the P5 Committee is:

> "a mean sensitivity to CP violation of better than $3\sigma$ [...] over more than 75% of the range of pos-

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sible values of the unknown CP-violating phase $\delta$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 physics goals set forth by the P5 require 900 kt·MW·years of exposure [6]. 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.

## INCREASING PROTON INTENSITY TO THE HIGH ENERGY NEUTRINO PROGRAM

The lab has adopted a staged approach to increasing the proton intensity ot the high energy neutrino program.

### *Proton Improvement Plan (PIP)*

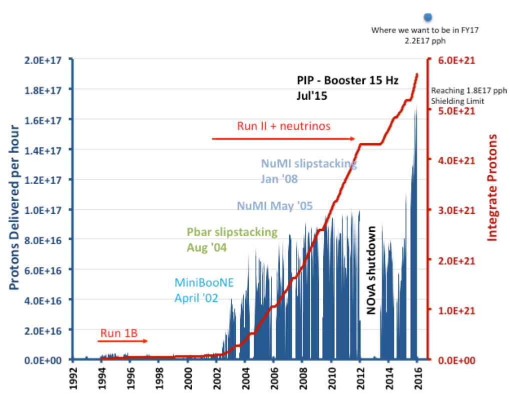


Figure 3: Evolution of proton delivery.

The Proton Improvement Plan (PIP) [7] is a campaign to maximize the proton output from the existing complex. The key component is to reduce losses and upgrade pulsed hardware in the Booster to allow beam to be accelerated on all 15 Hz cycles. This goal has recently been achieved. In addition, slip stacking has been commissioned in the Recycler, reducing the Main Injector cycle time relative to what it was in the MINOS era. Figure 3 shows the total proton output from the Booster. The goal of the PIP campaign is $2.2 \times 10^{17}$ protons per hour. This and other upgrades will allow the Main Injector to deliver 700 kW of beam to the NuMI line. Recently, an average of 615 kW of beam power were deliverd to NuMI for one hour.

### *Proton Improvement Plan-II (PIP-II)*

In the current configuration, it's unlikely that significantly more beam could be injected into the Booster. The maximum

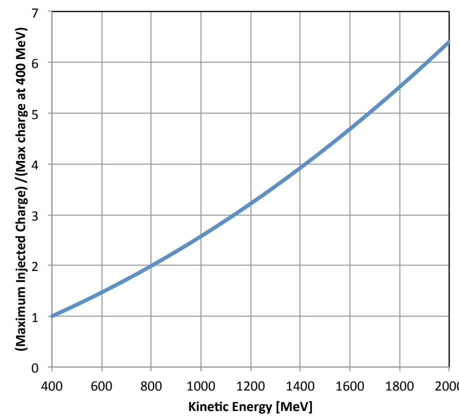


Figure 4: Maximum injected protons as a function of injection energy, relative to 400 MeV.

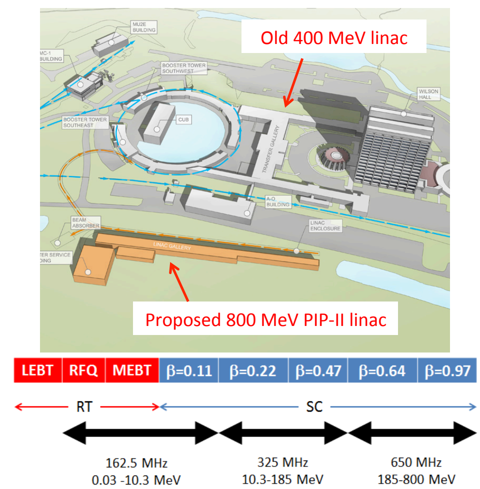


Figure 5: Proposed 800 MeV PIP-II accelerator.

protons that can be injected comes from limiting the space charge tune shift to avoid harmonic resonances, leading to the condition

$$\Delta\nu \approx \frac{N r_0}{2\pi\epsilon_N \beta\gamma^2} F B \lesssim .3$$

where $N$ is the total number of protons, $r_0$ is the classical proton radius, and $\epsilon_N$ is the normalized emittance. $F$ is a transverse form factor, which is 3 if $\epsilon_N$ is the 95% Gaussian emittance, and 1 if it is a uniform full emittance. $B$ is "bunching factor", defined as $B \equiv I_{max}/I_{ave}$. $\epsilon_N$ will continue to be limited by the Recycler and Main Injector to close to its current value. Therefore, if tune shift kept constant, the maximum value of $N$ iwill increase as the $\beta\gamma^2$ of the injected beam, as illustrated Figure 4.

The key feature of PIP-II [8] is therefore to replace the existing 400 MeV linac with a new 800 MeV linac, capable of CW operation, shown in Figure 5, which is being built in collaboration with India. This will increase the power available to NO$\nu$A and 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 power down 60 GeV, as




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Table 1: Proton Source Parameters for Current Best Performance, the Booster in PIP-II, and for Both the Linac and RCS Options for Future Upgrades. Challenging parameters are highlighted in red.

| | Current (best) | PIP-II (Existing Booster) | New 8 GeV Linac | New 8 GeV RCS |
|---|---|---|---|---|
| MI/Recycler | | | | |
| Beam Energy [GeV] | 120 | 120 | 120 | 120 |
| Cycle Time [s] | .615 | 1.2 | 1.2 | 1.45 |
| Protons per pulse [1e12] | 38 | 75 | 160 | 190 |
| Beam Power [MW] | 1.2 | 1.2 | 2.5 | 2.5 |
| Proton Source | | | | |
| Injection Energy [GeV] | 0.4 | 0.8 | 0.8 | 0.8-2.0 |
| Extraction Energy [GeV] | 8.0 | 8.0 | 8.0 | 8.0 |
| Protons per Pulse [1e12] | 3.3 | 6.4 | 160 | 32 |
| Beam Power to Recycler/MI [kW] | 38 | 82 | 168 | 168 |
| Maximum Beam Power to 8 GeV Program [kW] | 25 | 82 | 3872 | 645 |

Table 2: Comparison of Rapid Cycling Synchrotrons, including J-PARC. The current tune shift for the Booster is probably an overestimate.

| | Booster (Now) | Booster (PIP-II) | New RCS (800 MeV) | New RCS (2 GeV) | J-PARC RCS |
|---|---|---|---|---|---|
| Injection Energy [MeV] | 400 | 800 | 800 | 2000 | 400 |
| Extraction Energy [MeV] | 8000 | 8000 | 8000 | 8000 | 3000 |
| Emittance (normalized) [$\pi$-mm-mr] | 15 | 15 | 20 | 20 | 102 |
| Protons/batch [1e12] | 4.2 | 6.6 | 32 | 32 | 84 |
| Tune Shift Parameter | -0.43 | -0.11 | -0.41 | -0.13 | -0.28 |
| Frequency [Hz] | 15 | 20 | 20 | 20 | 25 |
| Output power, max [kW] | 81 | 169 | 819 | 819 | 1008 |

well and/or additional power to 8 GeV users. The parameters of the Booster and Main Injector during the PIP-II era are shown in the second column of Table 1, compared to the current best performance. The PIP-II project received CD-0 ("Mission Need") approval from the DOE in November, 2015.

The front-end design of the PIP-II linac is being validated in the PIP-II Injector Experiment (PXIE) at Fermilab [9].

### *Beyond PIP-II*

To reach the physics goals of LBNF/DUNE in a timely manner, it will be necessary to increase the power from the Main Injector into the multi-megawatt range. This cannot be realistically achieved with the existing Booster, so the plan is to replace it with either an 8 GeV linac or a Rapid Cycling Synchrotron (RCS) [10]. The parameters for both options are shown in Table 1.

The advantage of the linac is that it would have 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. One disadvantage is that ion injection into the Recycler or Main Injector at 8 GeV is *quite* challenging. Because of space contraints in the Main injector and other considerations, the linac option would also require injection into the Recycler or a new bunching ring.

One advantage of the RCS is that the requisite performance has been demonstrated in the J-PARC 3 GeV RCS [11]. Also, with more intense batches, slip-stacking in the Recycler could be abandoned. One disadvantage is that there would be limited protons at 8 GeV.

Even if a new RCS is built, the normalized emittance will continue to be limited by the Main Injector, so we would not benefit from a large physical aperture like that of the J-PARC RCS. This means injection energy will continue to be an issue. At the 800 MeV energy of the PIP-II linac, the tune shift would be unacceptable large. One option would be to increase the energy of the linac, which would be rather expensive. Another option would be to use non-linear optics [12] or electron lenses [13] [14] to mitigate the effect of the space charge. These ideas will be investigated in the Integrable Optics Test Accelerator (IOTA) [15] [16] [17] [18]. Table 2 shows the parameters of the existing Booster, the Booster in the PIP-II era, and the new RCS at both the 800 MeV and 2 GeV injection energies.

Over the next few years, we plan to produce conceptual proposals for both the linac and the RCS options, including the approximate cost range of each.

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[6] The integrated beam power specified by the P5 was 600 kt·MW·years; however, a more refined analysis yielded the 900 number. See, for example, G. Rameika's talk at the PIP-II project review (`http://tinyurl.com/PIP-II-Project-Review`)

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