ACCELERATORS FOR INTENSITY FRONTIER RESEARCH

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Abstract

In 2008, the Particle Physics Project Prioritization Panel identified three frontiers for research in high energy physics, the Energy Frontier, the Intensity Frontier, and the Cosmic Frontier. In this paper, I will describe how Fermilab is configuring and upgrading the accelerator complex, prior to the development of Project X, in support of the Intensity Frontier.

INTRODUCTION

In 2008, the Particle Physics Project Prioritization Panel (P5) was charged by the High Energy Physics Advisory Panel to the Office of High Energy Physics to develop a 10 year plan for US particle physics under various funding scenarios. The Panel identified three frontiers for research [1]:

- the Energy Frontier, using high-energy colliders to discover new particles and directly probe the properties of nature.
- the Intensity Frontier, using intense beams to uncover the elusive properties of neutrinos and observe rare processes that probe physics beyond the Standard Model.
- the Cosmic Frontier, revealing the natures of dark matter and dark energy and using high-energy particles from space to probe the architecture of the universe.

With the shutdown of the Fermilab Tevatron Collider, the Energy Frontier is being explored at the Large Hadron Collider at CERN [2]. The Cosmic Frontier makes use of terrestrial and space based experiments, but not terrestrial accelerators. The Intensity Frontier has a rich set of experiments involving neutrinos, muons, and kaons, with signals characterized by small variations from the standard model and requiring intense beams of particles for exploration.

There is a set of currently identified experiments at Fermilab investigating short and long baseline neutrino oscillations, rare decays and properties of muons, and rare decays of kaons. These experiments can currently be broken down into those which require proton beams at 8 GeV (peak energy of the Fermilab Booster) and those which require proton beams at 120 GeV (utilizing the Main Injector). In Figure 1, the requested proton flux to the various programs is shown as a function of time. To meet the demands in future years, there is a series of configuration changes and upgrades to the complex.

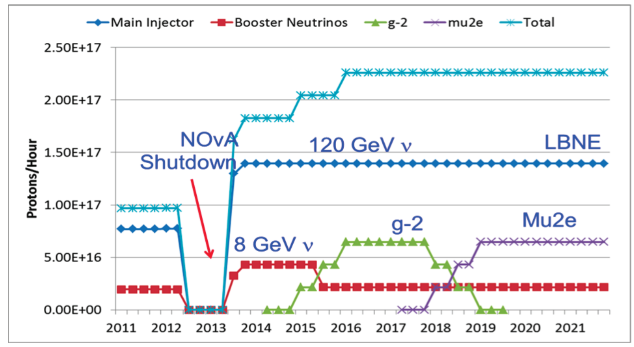

Figure 1: Past and Future proton requests.

FERMILAB'S CURRENT ACCELERATOR COMPLEX

For the near future Intensity Frontier program, the complex consists of an H^- Linac, a rapid cycling Booster, the Recycler and Main Injector synchrotrons, and the Pbar rings (see Figure 2). The Linac produces a 400 MeV ≈35 mA beam of H^- ions. With charge exchange injection into the Booster, multiple turns and higher intensity can be accomplished. The Booster, with a 15 Hz cycle, accelerates protons from 400 MeV to 8 GeV, with peak currents approaching 500 mA (5e12 per pulse). The Recycler is a permanent magnet (≈ fixed energy) synchrotron of 7x the Booster circumference in the Main Injector tunnel, previously used as a $\bar{p}$ accumulation and storage ring in the Tevatron Collider program. The Main Injector is a fast cycling synchrotron in the range of 8 GeV to 120 GeV, again at 7x the Booster circumference. The two Pbar rings (Debuncher and Accumulator) are 8 GeV rings with the same circumference as the Booster. They were used for $\bar{p}$ stacking in the Tevatron Collider program and will be repurposed for use in the future.

THE 8 GEV PROGRAM

The 8 GeV program focuses on short baseline neutrino oscillations and muon properties. The Booster Neutrino Beam (BNB) requests single pulses to the target at the highest rate possible, with no other specific beam requirements. As such, it takes beam directly from the Booster. The muon experiments (g-2 [3] and Mu2e [4]) do have specific additional beam requirements with regard to bunch spacing and intensity and the complex is tasked to meet them. Addi-

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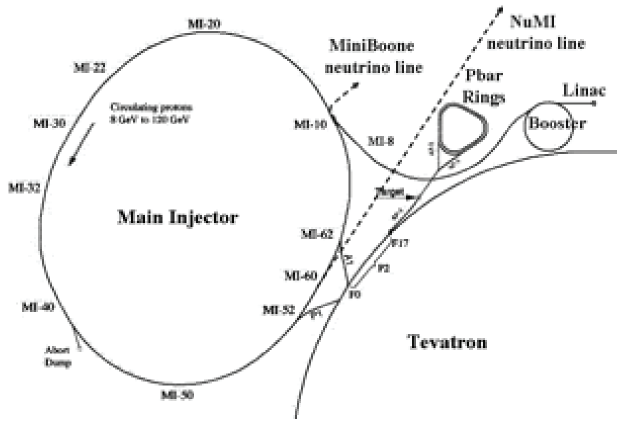

Figure 2: Layout of Fermilab Accelerator Complex.

tional functionality of the Recycler and Delivery rings are used to form the beams. In addition, the 120 GeV program also makes signficant demands on protons from the Booster.

Experimental Requirements BNB

The MicroBoone experiment [5] is a short baseline neutrino experiment and is the only planned user of the Booster Neutrino Beam. The proton request to satisfy the physics program is a total of 6e20 protons on target, which can be satisfied with 2 years of operation at 2 Hz with 5e12 protons per pulse. With the improvements associated with the Proton Improvement Plan (described below), this request is achievable on the timescale of 2015.

Experimental Requirements g-2

The g-2 experiment [3] measures the anomalous magnetic moment of the muon, with a precision goal of 0.14 parts per million. 3.09 GeV/c muons circulate in a 7.1 m radius storage and decay ring, with an RMS length less than 50 nsec to fit around the injection kicker. The experiment requires a several pion lifetime ($c\tau\beta\gamma = 173m$) beamline between target and the muon decay ring to maximize the muon purity. The experiment will use the existing $\bar{p}$ beamlines, target station, and rings (repurposed and renamed) to move the proton, pion, and muon beams around.

Protons will be injected from the Booster into the Recycler (using upgrades from the NOvA project, described below), debunched and recaptured in 4 2.5 MHz RF buckets, and extracted singly to the target through a new beamline from the Recycler to the existing beamline that was used to transport protons to the target station. Pions will be captured and transported to the former Debuncher (now Delivery) ring, operating at 3.09 GeV/c. Decay muons would be extracted and transported to the g-2 muon ring. The total trip is approximately 700 m, allowing for a signficant increase in the muon purity compared to previous experiments.

Experimental Requirements Mu2e

The Mu2e experiment [4] measures (or limits) the rare decay conversion of a muon into an electron. Low energy muons are produced and captured in the orbit of a nucleus, with a well defined lifetime due to standard muon to electron and two neutrino decays. Such decays have a maximum electron energy of 52.8 MeV. Conversion without the presence of the two neutrinos gives a electron with an energy of 105 MeV.

The experiment is done with a slow extracted beam over many milliseconds. To minimize backgrounds from pion decays, the experiment requires a bunch spacing of $\approx$ 1.5-2.0 μsec, an RMS width of less than 100 nsec, and an extinction between bunches of better than 10^{-10}. Using the same bunch formation methods in the Recycler as g-2, a single bunch of protons can be captured in a 2.4 MHz RF system in the Delivery ring (which has a 1.7 μsec period) and then slow extracted to the muon production target. Specialty hardware in the transfer line allow for the total extinction of protons outside of the RF buckets.

Current and Future Performance

The Booster currently runs at a maximum repetition rate of $\approx$7 Hz and 5e12 per pulse, corresponding to 1×10^{17} protons/hour. Intensity is limited by beam losses, while repetition rate is limited by cooling of the RF cavities. The BNB program and the 120 GeV neutrino program has pushed capacity to historic highs, as shown in Figure 3. However, the future demands on protons from the Booster require another doubling (or better) of the total throughput (as shown in Figure 1). A detailed plan has been developed to upgrade elements of the Linac and Booster to meet the experimental demands.

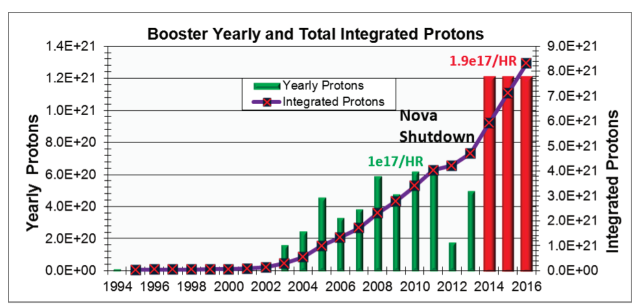

Figure 3: Historical Booster performance in protons/year and total integrated protons.

The Proton Improvement Plan (PIP) is currently underway with the following goals:

- Increase the beam repetition rate from the present $\approx$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

Throughput goals are to develop the capability of delivering 1.8E17 protons/hour (at 12 Hz) by May 1, 2013 and > 2.2E17 protons/hour (at 15 Hz) by January 1, 2016. PIP builds on the success of the Proton Plan upgrades [6] carried out in support of the BNB program over the last 8 years.

The highlights of the PIP come with a new H^- source and RFQ, replacing the existing magnetron source and Cockroft Walton, upgrades to the RF stations to allow for 15 Hz operation, and aperture increases, and general reliability improvements to utilities.

Based on the successful Brookhaven experience [7], the source and RFQ are planned for installation this summer. It is anticipated the improved emittance from the source/RFQ combination will help reduce beam losses.

Every Booster RF cavity will be removed from the accelerator, have all cooling lines and tuners refurbished, and re-installed. In addition, the power amplifiers are undergoing an upgrade to a solid state solution (identical to that used in the Main Injector) which will simplify maintenance and improve reliability as components are moved to the equipment galleries and away from the radiation environment of the tunnel. With these upgrades, the cavities are anticipated to run reliably at 15 Hz.

The Muon Ring Upgrades

In support of the muon program, the existing $\bar{p}$ rings will be used. The current plan repurposes the Debuncher ring as a Delivery ring for both g-2 and Mu2e. The Accumulator ring will not be used, though many magnets will be removed to repurpose existing beamlines. The Recycler will install a 2.5 MHz RF system and a new extraction system in the RR52 area, to take protons directly from the Recycler into the transfer line to the $\bar{p}$ target station.

All of the associated stochastic cooling hardware in the Delivery ring will be removed, as well as the existing RF systems. The g-2 experiment will use the Delivery ring as part of a beamline operating at 3.09 GeV, using the existing injection system and a new extraction system. The Mu2e experiment will use the Delivery ring for resonant extraction at 8 GeV, using the new injection system and the same extraction area as g-2. As they run at different energies and the Delivery ring is not designed to ramp, the experiments will run at different times.

For Mu2e, a new 2.4 MHz RF system will be installed in the Delivery ring, allowing for bucket to bucket transfers from the Recycler. This system must maintain the RMS width to be less than 100 nsec and reduce the out of bucket beam by a factor of 10^{-5}. A new beamline will be built to transfer the proton beam to the production target, with the inclusion of a 2.4 MHz AC dipole, phase locked to the RF system, to further reduce the out of bucket beam to meet the 10^{-10} extinction factor. Collimation and instrumentation are included to measure the performance.

THE MAIN INJECTOR PROGRAM

The Main Injector based program focuses on long baseline neutrino oscillations and future rare kaon decay experiments. For the neutrino experiments (MINERνA [8], Minos+ [9], NOvA [10]), a full turn pulse of beam from the Main Injector at 120 GeV is sent to the target. For the rare kaon decay experiment (ORKA [11]), a slow spill at 95 GeV is foreseen. This energy is chosen to optimize duty factor and beam power given limitations on RMS currents in the Main Injector.

Experimental Requirements MINERvA, Minos+, NOvA

The neutrino experiments all use the same extraction line, production target, and focusing. The NOvA experiment is the flagship experiment for the next 10 years, so the neutrino spectrum is being optimized in support of the NOvA requirements. NOvA is looking for the appearance of ν_e in a ν_μ beam. With a oscillation baseline of 810 km between the near site at Fermilab and the far site in Ash River MN and the value of Δm^2_{32}, the optimum ν_μ energy to observe $\nu_\mu \rightarrow \nu_e$ transitions is 1.6 GeV. Given the constraints of the existing NuMI target hall, the experiment sits 14.6 mrad off the beam axis. The kinematics of pion decay lead to a correlation between forward angle and energy. While it lowers the total number of neutrinos reaching the detector, it increases the flux in the energy range of interest as shown in Figure 4. The proton request to satisfy the physics program is 3.6e21 protons on target, which can be met with 6 years of operation and a doubling of the current power on target. A description of the upgrade program to meet these ambitious goals is described below.

Experimental Requirements ORKA

The ORKA experiment is looking for the rare decays $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ and $K^0 \rightarrow \pi^0 \nu\bar{\nu}$ using a stopped K beam produced by slow extracted proton beam. The 19 nsec bunch spacing is well matched to the K^+ lifetime (12.3 nsec) so no additional RF manipulations are needed. Production efficiencies are such that there is a broad maximum around 100 GeV in proton energy, so duty factor concerns dominate. Due to RMS current limitations in the Main Injector magnet power systems and the expectation that the 120 GeV neutrino program will be running simultaneously, the experimental optimization is a 4.4 second spill at 95 GeV every 10 seconds. A three year program with 9e19 protons/year is necessary to satisfy the physics program. As high intensity slow spill is being developed to support an existing experiment [12], there are no significant accelerator developments necessary to support ORKA.

Current Status

The Main Injector currently accelerates 3.7e13 protons per pulse with a cycle time of 2.07 seconds for the 120 GeV

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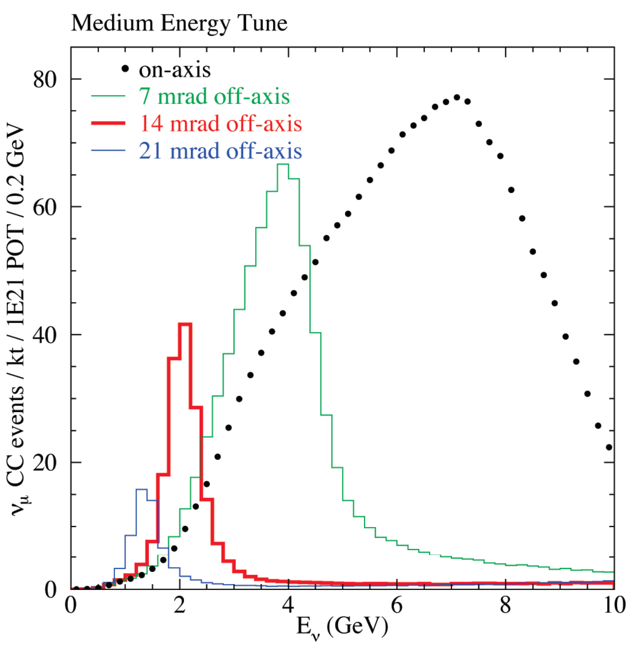

Figure 4: Muon neutrino charged current energy spectrum for the planned target hall configuration.

neutrino program. The intensity is limited by target performance. Peak performance is 4.5e13 protons per pulse every 2.2 seconds. Figure 5 shows the integral protons to the NuMI target since the beginning of the program in May 2005, delivering 1.6e21 protons in the 7 year period. A performance upgrade is needed to meet the physics program goals.

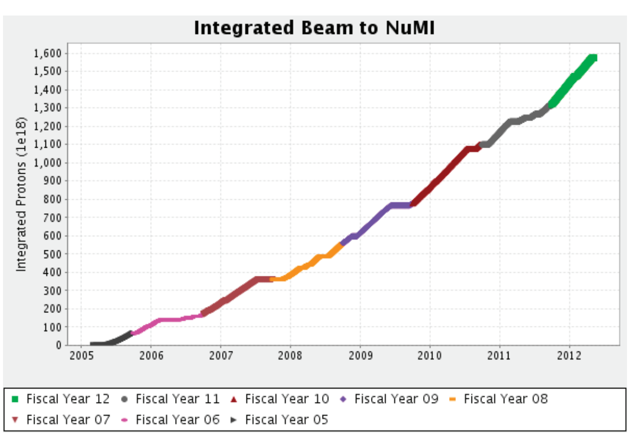

Figure 5: Integral protons to the NuMI target since the beginning of the program.

Upgrades in Support of NOvA

There are two ways to increase the integral protons to the target, more protons/pulse and more pulses. As Booster batch intensity is limited by losses, small gains are available from protons/pulse. The cycle time has two components: (1) the time for the Main Injector ramp from 8 GeV to 120 GeV (and back down) and (2) the time to inject 9 (or 11) batches at 15 Hz from the Booster. By moving accumulation of Booster batches from the Main Injector to the Recycler, we can shorten the injection time from 600 msec to 10 μsec. With the addition of 2 RF stations and upgrades to the main power systems, the cycle time will be reduced to 1.33 sec. The full set of operating parameters for the current and future 120 GeV neutrino program are shown in Table 1.

Moving the accumulation of Booster batches to the Recycler and doubling the power to the target does not come for free. New transfer lines are needed, including fast kickers to fit 12 Booster batches into the Recycler. New RF systems to handle slip stacking in the Recycler need to be installed. New targets and horns, to handle the increased beam power, need to be built. The configuration of the targets and focusing horns needs to be rearranged to provide the appropriate neutrino energy spectrum to support the experiment.

Table 1: 120 GeV Neutrino Program Parameters

	Current Operation	NOvA Operation
Protons/Batch	4.3e12	4.3e12
Booster Batches	9	12
Booster Repetition Rate	4.3 Hz	9 Hz
Number MI Injections	9	1
Cycle Time	2.07 sec	1.33 sec
MI Efficiency	95%	95%
Controlled Loss	3.5%	3.7%
Uncontrolled Loss	1.5%	1.3%
Beam Intensity (Extraction)	3.7e13	4.9e13
Beam Power on Target	323 kW	706 kW
Protons/hour	6.4e16	1.4e17

The Fermilab accelerator complex has turned off as of April 30 to begin the reconfiguration of the Recycler, the Main Injector, and the NuMI target station. After 12 months of installation work, there will be an accelerator complex capable of delivering 700 kW to the target. A six month commissioning period is anticipated, with a slow ramp to reach the full power.

FUTURE PROSPECTS

Given the recent directives from the Office of High Energy Physics, the accelerator requirements for the Long Baseline Neutrino Experiment are in flux. Leading up to this spring, the project team had made a set of decisions on the beamline and target design for a long baseline experiment with the far site at the Homestake mine in Lead SD. To accomodate the angle through the Earth and to minimize the civil construction (mainly underground work), the design initially brought the proton beam out from the Main Injector, up a hill and then back down to the target hall, located approximately at grade level. The beamline is designed to handle proton energies from 60 to 120 GeV, with adjustable final focus and minimal losses. The range in energy is to allow to maximize detected neutrino events over the 1300 km baseline and have sensitivity to both the first and second oscillation maxima. In Figure 6, the beam power is shown as a function of the Main Injector energy. It falls as the energy decreases because of the fixed time elements in the ramp (hysteresis reset at 8 GeV, parabola in/out of ramp, and flattop dwell time). Below 60 GeV, the power falls even faster as the cycle time goes below the 12/15 sec needed to fill the Recycler in between Main Injector cycles. Simulations are still ongoing to determine optimal energy, target, and focusing configuration.

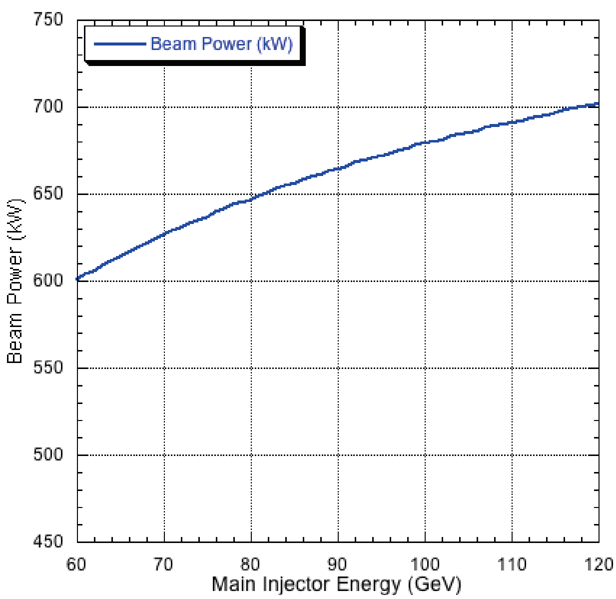

Figure 6: Beam power on target as a function of Main Injector flattop energy. It falls as the energy decreases due to the fixed time elements in the ramp.

Looking even further into the future, the Project X linac will truly drive the Intensity Frontier [13]. It will enable a 2 MW long baseline neutrino program, concurrent with significant increases in power for muon, kaon, and nuclear physics experiments. The Project X Injector Experiment (PXIE) is a program to research and develop the necessary components at the front end [14]. With many exciting new accelerator technologies, it will open windows for science.

CONCLUSIONS

Intensity Frontier experiments at Fermilab will explore the rich physics of neutrino oscillations, rare decays of kaons, and muon to electron conversion. All require intense proton beams, as provided by the Fermilab accelerator complex. To meet the various physics goals, a range of upgrades to existing accelerators (the Linac, Booster, and Main Injector) and reconfiguration and repurposing of $\bar{p}$ specific machines (the Recycler and the Debuncher) are either underway or being developed. The complex began a 1 year shutdown in May 2012 and will be coming out of the shutdown with the capability to deliver 700 kW to the NuMI target while simultaneously supporting the 8 GeV program. Looking further into the future, new beamlines in support of a long baseline neutrino experiment and new accelerators (the Project X CW linac) will enable the laboratory to further extend the reach into the physics of the Intensity Frontier.

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[9] The MINOS+ experiment at Fermilab (E-875/E-934/E-1016) http://www-numi.fnal.gov/index.html

[10] The NOvA experiment at Fermilab (E-929) http://www-nova.fnal.gov

[11] ORKA (the Golden Kaon) has Stage I approval from the Fermilab PAC. The proposal is available at: http://www.fnal.gov/directorate/program_planning/Dec2011PACPublic/ORKA_Proposal.pdf

[12] The SeaQuest experiment at Fermilab (E-906) http://www.phy.anl.gov/mep/SeaQuest/

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[14] S. Nagaitsev *et al.*, IPAC'12 New Orleans LA, THPPP058 http://www.JACoW.org. There are many additional posters covering specific technical aspects of PXIE submitted to this conference.

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