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Fermilab Accelerator Complex: Status and Improvement Plans

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Abstract

Fermilab carries out an extensive program of accelerator-based high-energy particle physics research, which relies on 8 GeV and 120 GeV proton accelerators. Routine operations with 700 kW, 120 GeV proton beam power on a neutrino target was achieved in 2017. There are plans to further increase the beam power to the 900 kW range. The next major upgrade of the Fermilab accelerator complex, the PIP-II project, is under development. Its goal is to deliver 1.2 MW of beam power on target at the start of the DUNE experiment in the middle of the next decade. PIP-II will replace the existing 40-year old 400 MeV normal-conducting Linac with a modern 800 MeV superconducting RF based linear accelerator. There are several concepts for future upgrades that will increase the beam power to >2.4 MW, after replacement of the existing 8 GeV Booster synchrotron. The Muon Campus provides 3.1 GeV polarized muons to the g-2 experiment and will provide 8 kW of 8 GeV protons to the Mu2e production target. The Fermilab Test Beam Facility provides a primary 120 GeV proton beam of moderate intensity, (1-300 kHz) and secondary particle beams of energies down to about 1 GeV, consisting of hadrons, muons and/or electrons/photons for detectors tests. In this article we discuss the current performance of the Fermilab accelerator complex, the upgrade plans for the next two decades, and the accelerator R&D program to address cost and performance risks for these upgrades.

Introduction: Overview of the Fermilab accelerator complex

The Fermilab accelerator complex (see Fig. 1) is one of the largest in the world, and consists of 16 km of accelerators and beamlines, three high power targets, several low power target stations, and many experimental and service buildings. It delivers beams of protons and secondary particles. The beam originates from a pulsed duoplasmatron H- ion source followed by a 750 keV RFQ and a 400 MeV normal-conducting pulsed linac that injects into an 8 GeV rapid-cycling-synchrotron (RCS) Booster, which is largely an 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. Historically, not all cycles could be loaded with protons due to limitations from injection, extraction, and RF system and beam loss. The next machine downstream in the complex is the Recycler, a 3.3 km 8 GeV storage ring made from 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 is located in the same tunnel. The circumference of the Recycler is sufficient to accommodate six batches of 84 Booster bunches each; however, through the technique called "slip-stacking", six more batches can be injected in the machine in addition to six slightly decelerated original batches, making the total of 12 batches. These batches travel at slightly different velocities and "slip" with respect to each other until they overlap and at that moment they are transferred to the Main Injector and accelerated to the maximum energy (more details on the "slip-stacking" method can be found in [1]). The Fermilab proton accelerator complex supports a number of experiments – e.g., the 400 MeV Linac beam is sent to the Mucool Test Area, 8 GeV protons from the Booster are supplied to the 8 GeV Booster Neutrino Beam (BNB), ANNIE, MicroBooNE, MiniBooNE, MITPC, ICARUS (near future), and SBND (future), and to the "muon g-2" and "Mu2e" (near future) muon experiments. The 120 GeV proton beam from the Main Injector supports neutrino experiments at NuMI (MINERvA, NOvA) and DUNE in the future, as well as the fixed target experiments SeaQuest and test beam facility. See Ref.[2] for detailed information on these experiments. The Fermilab accelerator complex has delivered neutrino beam with >85% uptime on average over the past 5 years.

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] that identified the top priority for the U.S.-hosted high-energy physics program to be a high energy neutrino program to determine the mass ordering and measure CP violation, based on the Fermilab accelerator complex, upgraded for increased proton intensity. The 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, Minnesota. It also uses the NuMI beam line, but it is built 14.6 mrad off axis, producing a narrower neutrino energy spread, resulting in an improved resolution for the CP violating phase and mass hierarchy. The physics goal of the future long baseline neutrino program set forth by the P5 report 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] at FNAL and the new experiment is the Deep Underground Neutrino Experiment (DUNE) [5], located in the Sanford Underground Research Facility (SURF) near Lead, South Dakota, 1300 km away from Fermilab. 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 proton beam power have been undertaken and planned.

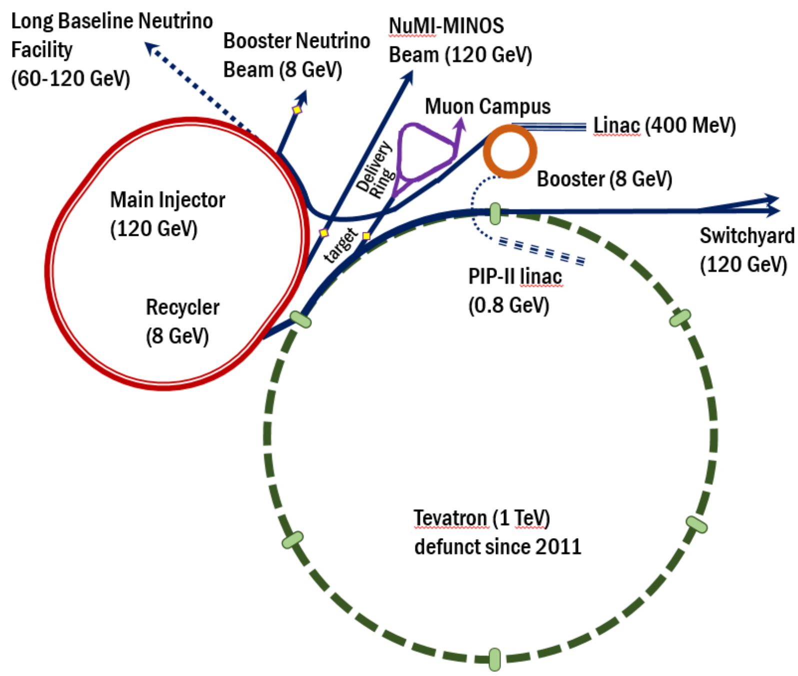

FIG.1: Fermilab accelerator complex includes 400 MeV H- pulsed normal-conducting RF linac, 8 GeV proton Booster synchrotron, 8 GeV Recycler storage ring that shares a tunnel with the 120 GeV proton Main Injector synchrotron, and a 3.1 GeV muon Delivery Ring. A number of beamlines connect the accelerators, bring the beams to fixed targets and to various high energy physics experiments. The most notable future additions (dotted lines) include the LBNF beam line for DUNE and 0.8 GeV CW-capable SRF PIP-II linac located inside the Tevatron ring and the corresponding beamline for injection into the Booster.

Current upgrade activities

In 2014-2018 the Fermilab accelerators underwent several upgrades to maximize the proton output from the existing complex, with an ultimate goal of delivery of 700 kW of 120 GeV beam power from the Main Injector. The key elements were the 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 $2.1 \cdot 10^{17}$

protons per hour. In addition, commissioning of the 6+6 batch slip-stacking in the Recycler reduced the Main Injector cycle time the from 2.2 s of the MINOS/Collider Run II era to 1.33 s. Due to these improvements, in early 2017 the Main Injector achieved a world-record of 716 kW average proton beam power over one hour to the NuMI beam line – see Fig.2. On the way, the operations team increased the number of batches slip-stacked in the 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 in intensity was followed by tuning for efficiency and minimization of beam losses. Installation of the Recycler beam collimation system and commissioning of a more efficient beam feedback system to control coherent instabilities during the slip-stacking process were the keys to the intensity increase.

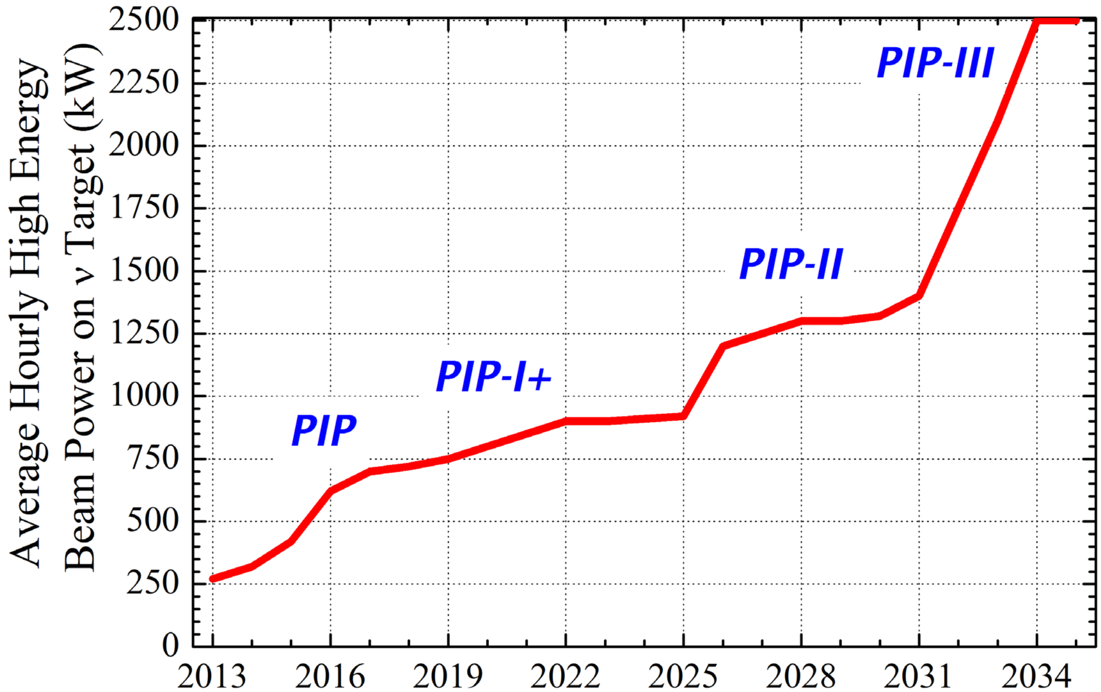

FIG.2: Average hourly average 120 GeV proton beam power from the Main Injector synchrotron on neutrino target – past accomplishments (2013-2018) and future plans (PIP-II) and concepts (PIP-III).

The Fermilab accelerator operations team is currently considering a campaign aimed at increasing the NuMI beam power to the 900 kW range, without major changes to the existing accelerator complex. The campaign needs to be finished prior to the construction of the PIP-II linac (see next chapter) and includes

1. Upgrades of the NuMI target station to be robust up to 1 MW.
2. Loss reduction in the Booster, and a 30% increase in protons per pulse – see Fig.3a.
3. Increasing the Booster rate from 15 Hz to 20Hz.

4. Modification of the Recycler slip-stacking RF system and the Main Injector ramp to allow faster 1.1 s cycle.

Proton Improvement Plan – II (PIP-II)

The key feature of the proposed Proton Improvement Plan-II (PIP-II) project [6] is to replace the existing 400 MeV normal-conducting RF pulsed linear accelerator with a new 800 MeV machine based on superconducting RF cavities, capable of CW operation. It will allow an increase of the 120 GeV proton beam power available to the new LBNF beamline to 1.2 MW. In addition, the Booster rate will be increased from 15 to 20 Hz, allowing full Main Injector beam power to be achieved at the lower energy of 60 GeV (vs current 120 GeV), and 80 kW of beam for the 8 GeV neutrino program - see full list of the PIP-II key technical parameters in the Table 1. PIP-II linac will be part of eventual extension of beam power to LBNF/DUNE to more than 2 MW (PIP-III) and will also provide a flexible platform for long-range development of the Fermilab complex; in particular, provide an upgrade path for a factor of 10 increase in beam power to the Mu2e experiment, and for extension of accelerator capabilities to include flexible high-bandwidth pulse formatting/high beam power operations.

Table 1. Beam parameters of the present Booster and PIP-II upgrades.

Performance Parameter	Present	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 GeV)	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/NuMI 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 received CD-1 approval from the U.S. Department of Energy in 2018 and is scheduled for completion in 2025-2026. The project has 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 SC RF cavities and construction and test of the PIP-II low-energy front-end. The PIP-II SC RF cavity development has five different types, operating at three different frequencies:

1. 162.5 MHz Half-Wave Resonators (HWRs).
2. 325 MHz Single-Spoke Resonators (SSR1 and SSR2).
3. 650 MHz Low and High-Beta resonators.

The high-Q_0 SC RF studies discovered that nitrogen doping during the Nb cavity surface processing [7] more than doubles the cavity's quality factor Q_0 and reduces the required cryogenic capacity. Fast cooling of the cavities (which operate at 2K) enhances the magnetic flux expulsion out of the SC cavity [8] and improves Q_0. The front-end Linac test facility [9] will demonstrate the two most challenging PIP-II design elements: very low energy transition from "room-temperature" RF acceleration to "cold" SC RF at 2.1 MeV, and a 162.5 MHz CW beam chopper. The PIP-II Injector Test facility has recently achieved beam acceleration through its 2.1 MeV CW RFQ.

The Muon Campus

The Muon Campus was constructed using infrastructure from the former Tevatron antiproton source. It is currently designed to operate in two modes, one for the Muon g-2 experiment, and the other for the future Mu2e experiment. In both modes, a bunch of 4×10^{12} 8 GeV protons from the Booster is re-bunched using 2.5 MHz RF in the Recycler into four bunches of 10^{12} protons with 95% of the beam contained in a 120 ns time window.

For the g-2 experiment, sixteen of these bunches are extracted to the g-2 target every 1.4 s for an average of 11.4 Hz, in bursts of 8 bunches at 100 Hz. The target and lithium lens used for focusing secondary particles are reused from the antiproton source. A pulsed dipole magnet selects a 3.1-GeV secondary beam, which is transported roughly 200m to the Delivery Ring. On the fourth turn around the 500m circumference Delivery Ring, the muons captured from forward pion decays are separated in time from the secondary protons, allowing a kicker with fast rise-time to remove the protons. For every 10^{12} protons on target, $O(10^5)$ muons with >95% polarization and momentum 3.094 GeV/c ± 2% are delivered to the g-2 muon storage ring. A similar number of positrons accompany the muons but do not interfere with the experiment. Full operation of g-2 experiment began in 2018.

In the Mu2e mode, 8 GeV protons will bypass the g-2 target station and will be transported to the Delivery Ring, from which they are resonantly extracted over a spill length of 43ms to the production target inside the Mu2e solenoid. An extinction system using an AC dipole will remove out-of-time protons on target at the level of 10^{-10} or better. Commissioning of beam to Mu2e experiment is expected to begin in 2020, with beam to the target in 2023.

Fermilab Test Beam Facility

The Main Injector accelerates the beam to 120 GeV at a frequency of 53 MHz, at which point a process called Resonance Extraction is started and a fraction of the beam is resonantly extracted to the Fermilab Test Beam Facility in a slow spill for each Main Injector rotation. The facility has two areas – MTest and MCentral. The primary beam consists of high-energy protons (120 GeV) at moderate intensities (1-300 kHz). This beam can also be targeted to create secondary particle beams in MTest areas of energies down to about 1 GeV, consisting of hadrons, muons and/or electrons/photons. Experiments in these areas typically turn over on a weekly (1-4 weeks) basis. The MCentral areas are purposed more towards long-term experiments with a turnover rate of months or even years. This beamline has the same secondary particle beams as MTest, but has the added capability of a tertiary beam line. The tertiary beam line can produce hadrons down to energies of 200 MeV.

FAST facility

The Fermilab Accelerator Science and Technology (FAST) facility's mission is to enable a broad range of beam-based experiments to study fundamental limitations to charged particle beam intensity and to develop transformative approaches to particle-beam generation, acceleration and manipulation [10]. It is fully-equipped to support R&D for the next generation of particle accelerators and incorporates a 40 m circumference Integrable Optics Test Accelerator (IOTA) storage ring with the capability of storing either electrons or protons with up to 150 MeV/c momentum. It has two injector accelerators: a 150-300 MeV photoinjector-based superconducting RF linear accelerator of electrons and 2.5 MeV RFQ accelerator of protons (H+) from a duo-plasmatron source. The electron injector employs one 1300 MHz ILC-type cryomodule powered by a 10 MW klystron, modulator, and an RF power distribution system that allows tests with up to 5 Hz repetition-rate. Both electron and proton injectors can be augmented with additional beam lines, dumps, and test areas to support user research and tests beyond those on the integrable optics and space-charge compensation envisioned in the IOTA ring.

The facility provides 20 MeV electron beams since 2015 and 50 MeV electrons since 2016. In 2017, the entire 300 MeV electron injector was fully commissioned to meet the IOTA beam specifications and demonstrated a world-record beam accelerating gradient of 31.5 MV/m in 1.3 GHz superconducting cavities. Starting in 2018, 100 MeV electron beams are being injected into and circulated in the IOTA ring. Proton injector beam commissioning is scheduled for 2019-2020. In 2018, the IOTA multi-year accelerator science research program began. It is focused on beam tests of novel ideas such as non-linear integrable optics, space-charge compensation with electron lenses, optical stochastic cooling and studies of beam instabilities and Landau damping that are needed for the next generation of multi-MW proton beams, including a potential PIP-III project [11 - 14]. Fermilab will also strive to establish a national user facility for accelerator science based on the FAST facility and its IOTA ring that will contribute to advances in all fields that use accelerators: light sources; free-electron lasers; very-high-energy colliders; electron-ion colliders, and high-intensity machines.

Summary

Fermilab's program is focused on supporting accelerator-based neutrino research as the top priority for the U.S.-hosted high-energy physics program. The accelerator-based neutrino research program relies on the operation of the 120 GeV proton beamlines for NuMI at present, and for the DUNE experiment when it starts, in the middle of the next decade. Routine operation with a world-record 700 kW of average high-energy beam power on the neutrino target has been achieved in 2017, and a further increase to the 900 kW range is anticipated after a series of continuing improvements to the existing accelerator complex in the coming years. The next major upgrade of the FNAL accelerator complex, the PIP-II project, aims at 1.2 MW beam power on the neutrino target at the start of the DUNE experiment. It will replace the existing 400 MeV pulsed normal-conducting Linac with a modern 800 MeV superconducting RF linear accelerator. The accelerator research program is exploring several concepts to replace the existing 8 GeV Booster and further double the beam power to >2.4 MW after the PIP-II project. An extensive accelerator R&D program with significant international contributions has been launched to address cost and performance risks for these upgrades: the PIP-II Injector Test facility, development of cost-effective SC RF cavities, and an experimental R&D program at the IOTA ring to demonstrate novel space-charge mitigation methods. Fermilab welcomes international contributions to the LBNF beamline design and construction, the PIP-II SRF linac and auxiliary systems, R&D on multi-megawatt targets and cost-effective SRF technology as well as actively develops collaboration on the fundamental high-brightness proton beams physics program at IOTA.

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