Fermilab Accelerator Complex Evolution (ACE)

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Outline

• Fermilab accelerator complex now
• PIP-II upgrade and LBNF/DUNE
• Accelerator Complex Evolution
  – Medium-term: Main Injector ramp rate and target system upgrade
  – Long-term: Booster replacement
• Accelerator R&D
Accelerator Complex priority - beam delivery to users

Protons-On-Target \(\propto\) Power \(\times\) Runtime \(\times\) Uptime

Multiple experiments operate concurrently
# Fermilab experiments plan

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Fermilab Accelerator Complex operation

18 Ticks: 12 to NOvA, 2 to g-2, 4 to BNB

1.2 sec

1.33s Main Injector cycle shown

$\frac{1}{15Hz} = 0.067 \, s$
# Beam power to NuMI – present

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<tr>
<th>Operation scenario</th>
<th>Nominal w. BNB/g-2</th>
<th>Reduced BNB/g-2</th>
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<td>10^{12} p</td>
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<tr>
<td>Booster ramp rate</td>
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<td>Hz</td>
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<td>Number of batches to NuMI</td>
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<td>MI power cycles for 8 GeV</td>
<td>0.81</td>
<td>0.9</td>
<td>0.96</td>
<td>1.01 MW</td>
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<td>Available 8 GeV power</td>
<td>36</td>
<td>30</td>
<td>27</td>
<td>23 kW</td>
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</table>

- Proton flux at 8GeV is limited by Linac/Booster performance
- MI cycle time variation balances NuMI/8GeV power

\[ P = \frac{eNE}{T} \]
Accelerator Complex in PIP-II / LBNF era

- New PIP-II SRF linac provides beam for injection into Booster at energy increased to 800 MeV from present 400 MeV
- Booster cycle rate is upgraded to 20 Hz from 15 Hz
- Proton flux at 8 GeV increases 2 times resulting in beam power from Main Injector up to 1.2 MW
- New LBNF beam line and target station for neutrino beam to DUNE
- Wide-reaching modernization campaign and series of upgrades will improve reliability
- Creates a platform for next-generation upgrades
**PIP-II Major Milestones**

- **Mar 2018**
  - Approve Alternative Selection (CD-1)

- **Dec 2020**
  - Approve Scope, Cost, Schedule (CD-2)

- **Mar 2019**
  - Linac Complex Ground-Breaking

- **Mar 2021**
  - Approve Long-Lead Procurements (CD-3a)

- **Jul 2020**
  - Cryoplant Bldg. Construction Approved

- **Apr 2022**
  - Approve Technical Construction (CD-3)

- **Sep 2024**
  - Linac Tunnel Occupancy*

- **Oct 2026**
  - Shutdown Complex Operations For Booster Connection

- **Jan 2027**
  - SRF Linac Comm. Begins

- **Dec 2028**
  - Project Completion Start of Operations (Early CD-4)
Accelerator Complex Evolution (ACE) plan – beyond 1.2MW

Our vision is centered on the ACE plan that has two components:

1. The Main Injector reliability improvements, cycle time shortening, and target systems upgrade to be carried out through the 2020’s called ACE-MIRT
   - Will accelerate the achievement of the DUNE science goals with respect to the original PIP-II plan
   - Improve reliability and safety of the key machines for the future of accelerator complex

Further, a Project would be established to build Booster Replacement. The implementation of ACE-BR would:

- Reliably deliver even more beam power to LBNF to ensure CP Violation measurement in DUNE Phase II
- Considerably enhance beam capabilities for a broader physics program
- Provide a robust and reliable platform for the future evolution of the Fermilab accelerator complex, possibly including a proton source for multi-TeV accelerator research
ACE-MIRT = Main Injector Ramp and Targets (now-2030)

This component of ACE plan aims to develop the Fermilab accelerator complex capabilities beyond PIP-II to *reach 2MW without new accelerator construction*.

Components offer independent (*) and incremental benefits

- **Overall efficiency and reliability of operations**
  - Implement improvements aiming to reduce losses, radioactive activation

  **Task 1)** Improve MI reliability by replacing quadrupole magnets with robust design

- **Machine capability: Maximum proton flux produced by the accelerator**

  **Task 2)** Upgrade MI ramp power system to enable faster cycle time (1.2→0.6s)

  **Task 3)** Upgrade MI RF acceleration system to allow for more beam flux

- **Ability of target station to convert protons to neutrinos**

  **Task 4)** Upgrade LBNF Target and Horns to reliable 2+ MW capability (*)
# Beam power in numbers – ACE-MIRT

<table>
<thead>
<tr>
<th>Operation scenario</th>
<th>Present</th>
<th>PIP-II</th>
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<td>Available 8 GeV power</td>
<td>30</td>
<td>83</td>
<td>56</td>
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Legend: **enabled by PIP-II** enabled by ACE-MIRT
NuMI power reaches 0.96 MW on May 22, 2023!

The power gain achieved without increase in beam intensity – important proof of concept for ACE
Top Priority: Complete LBNF/DUNE Phase I

DUNE Phase-I:

- Two 10 kt LArTPCs at Sanford Underground Research Facilities (SURF).

- A near detector facility, illuminated by the world’s brightest neutrino beam.

- The PIP-II accelerator upgrade under construction, which will enable a 1.2 MW proton beam.

- First goal? Mass ordering, with some sensitivity to the CP-violating phase.

- Also, sensitivity to electron neutrino component of a supernova burst!
Major Project this decade: A reimagined DUNE Phase II

- Include an early implementation of ACE-MIRT with the enhanced 2.1-MW beam.
- A third far detector at SURF.
- An upgraded near detector complex to aid in controlling systematics and search for BSM physics.

Science goals:
- Most precise measurement of the CP phase across a range of possible CP phase space
- Search for signatures of unexpected neutrino interactions.
- Study direct appearance of tau neutrinos.
## Fermilab experiments plan

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**Notes:**
- FY: Fiscal Year
- LBNF: Long Baseline Neutrino Facility
- PIP-II: Proton Infrastructure Program II
- NuMI: Near-Midpoint Module
- BNB: Booster Neutrino Beamline
- Muon Complex: Muon Neutrino Beam Complex
- SY 120: Superconducting Booster Neutrino Factory
- LINAC: Linear Accelerator
- ITA: Intense Triton Accelerator
- FTBF: Fast Triton Beam Facility
- SpinQ: Spin Quadrupole
- Open: Available for future planning
DUNE power and POT/Exposure implications

- Mu2e complete in 2033
- Booster replacement
- (Mu2e restarts 2029)
Overall ACE plan

1.2 MW
• PIP-II Project replaces Linac
• Modernization/upgrades of complex

2 MW
• Reliability upgrades
• Main Injector capabilities (cycle time)
• Target Systems capability improvements

2.4 MW
• Booster replacement
• New physics capabilities

ACE-MIRT Upgrades to existing machines
ACE-BR New machine
Path to ACE-BR – context

• In summer 2022 Fermilab commissioned a group to develop a strategy for upgrading the Fermilab accelerator complex
  – Primary focus on providing 2.4 MW to LBNF
  – Reduce the time for LBNF/DUNE to achieve first results
  – Sustain high-reliability operation
  – Potentially enable other science opportunities

• Input: the plan should consider
  – Extension of PIP-II linac to higher energy
  – Booster replacements
  – Improvements to existing accelerators
Potential ACE-BR options

• Extend SRF Linac to higher energy or construct new Rapid-Cycling Synchrotron
• Looked at 3 representative options of each type
• All six configurations require an extension of the SRF Linac to 2 GeV
  – The RCS option will benefit from the reduced space charge at the increased energy
  – The high-energy linac option will need the beam with an approximate energy of 2 GeV to take advantage of higher frequency, $\beta = 1$, high-gradient cavities that can be grouped and fed from a single, high-power klystron.
• Parameters can be re-optimized based on future experimental program.

Rapid-Cycling Synchrotron (RCS)
- **v1:** 10 Hz: Metallic vacuum chamber
- **v2:** 20 Hz: Ceramic vacuum chamber, larger aperture magnets, accumulator ring
- **v3:** 20 Hz: (C1b) with high-current linac, no accumulator ring

SRF Linac and Accumulator Ring
- **v1:** Basic: small increase in PIP-II current, using demonstrated XFEL RF
- **v2:** High current (5mA) and some RF R&D
- **v3:** High current and significant RF R&D
Example BR scenarios with siting

2GeV Linac + 2-8GeV RCS

8GeV Linac + 8GeV AR
Future path to ACE-BR

- The considered options were optimized to meet the 2.4 MW LBNF/DUNE requirement, while also enabling new capabilities
  - 2 GeV Continuous wave beam
  - 2 GeV pulsed beam (~ 1MW)
  - 8 GeV pulsed beam (~ 1MW)
- P5 reviewed the plan, some relevant recommendations

Rec 4g Develop plans for improving the Fermilab accelerator complex that are consistent with the long-term vision of this report including neutrinos, flavor, and a 10 TeV pCM collider (section 6.6).

Area Rec 12 Form a dedicated task force, to be led by Fermilab with broad community membership. This task force is to be charged with defining a roadmap for upgrade efforts and delivering a strategic 20-year plan for the Fermilab accelerator complex within the next five years for consideration (Recommendation 6). Direct task force funding of up to $10M should be provided.
ACE core technology R&D needs

• High-power target stations

• H- Foil Injection (RCS, Linac)
  – Foil overheating, particles scattering off foil, unstripped H
  – Greatest challenge for RCS and Linac scenarios
  – Laser H- stripping injection could be the way forward

• SRF Technology (Linac)
  – Improve accelerating gradient and Q-factors
  – Develop XFEL-style klystrons with 3ms long pulses

• Metallized Ceramic Beampipe (RCS)
  – Can metallized ceramic beampipe (like at J-PARC, ISIS) be deployed with a smaller aperture, reduced impedance, and greater replaceability?

• Space-Charge (RCS)
  – Bunch-lengthening RF and injection painting, but also electron-lenses?
Target materials R&D on critical path to 2+ MW target

- Identify **candidate materials**, grades, preparations, and conditions in operation
  - Develop the operation conditions for testing (radiation damage, static stresses, shock, temperature, fatigue cycles)

- **High-energy proton irradiation** of material specimens
  - Reach representative levels of radiation damage in characteristic conditions

- **Pulsed-beam Experiments** of irradiated specimens
  - Duplicate loading conditions of beam interactions

- **Non-beam PIE** (Post-Irradiation Examination) of irradiated specimens
  - Measure change of material properties (strength, CTE, density, hardness, ductility, thermal conductivity, …)
  - Material Science investigations of microscopic structural changes
  - High-cycle fatigue testing

**Five-years cycle** of design, irradiate, pulsed-beam, PIE (minimum from previous experience)

**Starting now** to inform 2.4 MW Target Design
Fermilab Muon Campus

• Repurposed and rebuilt former Tevatron Antiproton Source beam lines and rings in an optimal and cost-effective manner for use with Muon Campus experiments, including Muon g-2 and Mu2e
• Mu2e to run into 2030s
• g-2 completed data taking
  – Muon production target is operational
  – MC-1 (g-2) building becomes available
  – Opportunity for R&D with muon beams
Summary

• The Fermilab Accelerator Complex Evolution (ACE) plan capitalizes on the PIP-II investment and establishes a vision for the future of the accelerator complex.

• The ACE-MIRT (Main Injector Ramp and Targets) campaign to be realized over the next decade delivers higher number of protons to DUNE than PIP-II alone could provide, in a cost-effective manner without the construction of new accelerators.

• The future ACE-BR (Booster Replacement) will implement a modern and flexible Fermilab accelerator complex.
  – We strive to engage with the broad community to define a roadmap for this upgrade that will be compatible with the vision for a Muon Collider.
  – Several accelerator R&D areas critical for the success of ACE are synergistic with the Muon Collider effort.