# FNAL Accelerator Complex Enhancement (ACE)

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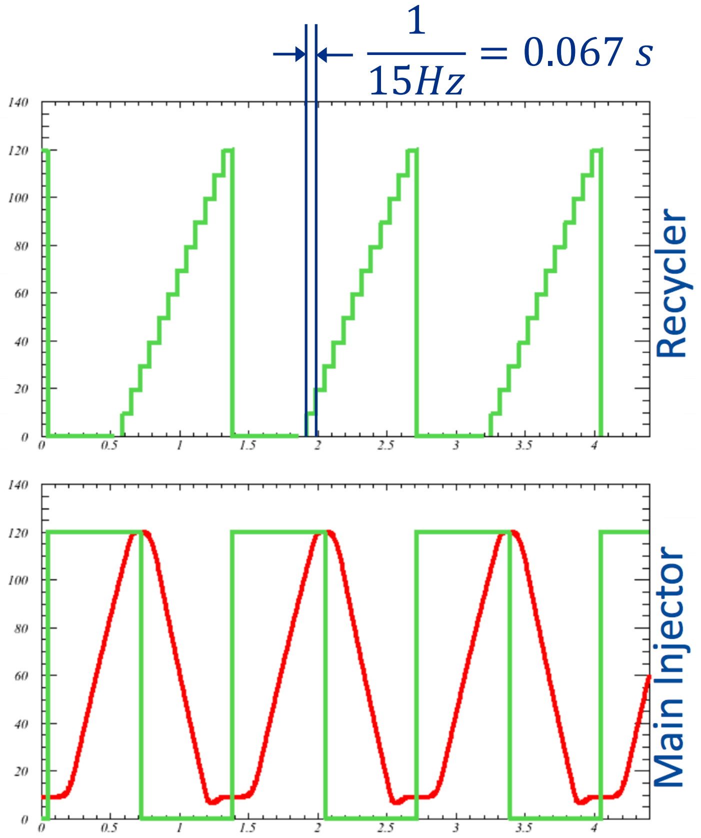
# Outline

- Fermilab Accelerator Complex now and in the PIP-II/LBNF era
- Accelerator Complex Evolution (ACE) plan
- Options for beam dump experiments under ACE plan

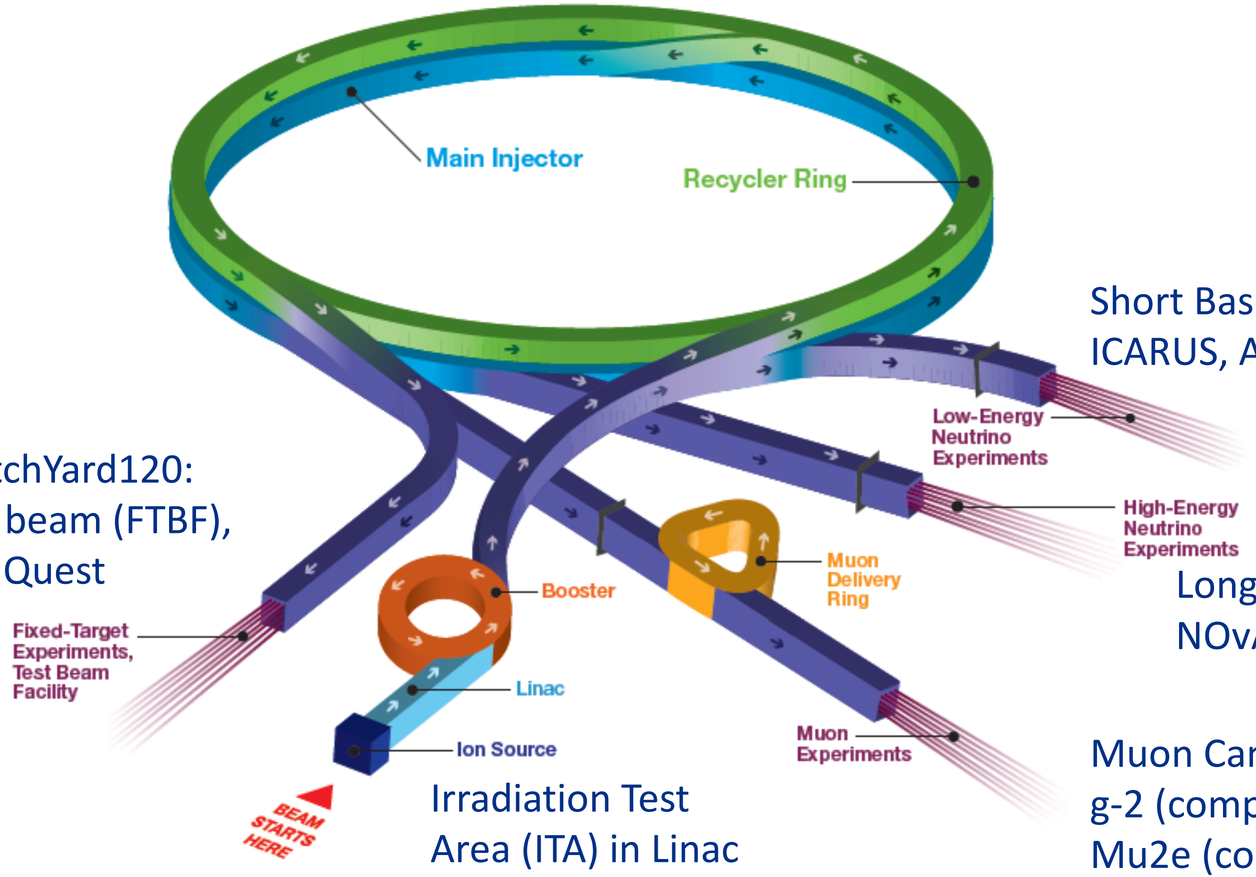
# Introduction to Fermilab accelerators

- $H^-$ linac (1970, 1993, 2012)
  400 MeV linac ~20mA
- Booster synchrotron (1970)
  $H^-$ stripping injection (1978)
    16 turns to ~4.7x10$^{12}$ p per pulse
  Ramp from 0.4 to 8 GeV at 15 Hz
- Recycler (1998)
  3.3 km permanent magnet 8 GeV ring
  Slip-stacking 12 Booster batches, ~56x10$^{12}$ p
  Also re-bunches beam for Muon Campus
- Main Injector (1998)
  8 to 120 GeV ramp, cycle time 1.2-1.4 s




1.33s cycle shown

# Accelerator Complex Now




Short Baseline Neutrino: ICARUS, ANNIE, SBND

SwitchYard120: test beam (FTBF), SpinQuest

Long Baseline Neutrino: NOvA

Irradiation Test Area (ITA) in Linac

Muon Campus: g-2 (completes this year), Mu2e (commissioning)

# Accelerator Complex in PIP-II / LBNF era

- PIP-II provides

  New SRF linac for injection into Booster at 800 MeV (present 400 MeV)

  Booster cycle rate upgraded to 20 Hz from 15 Hz

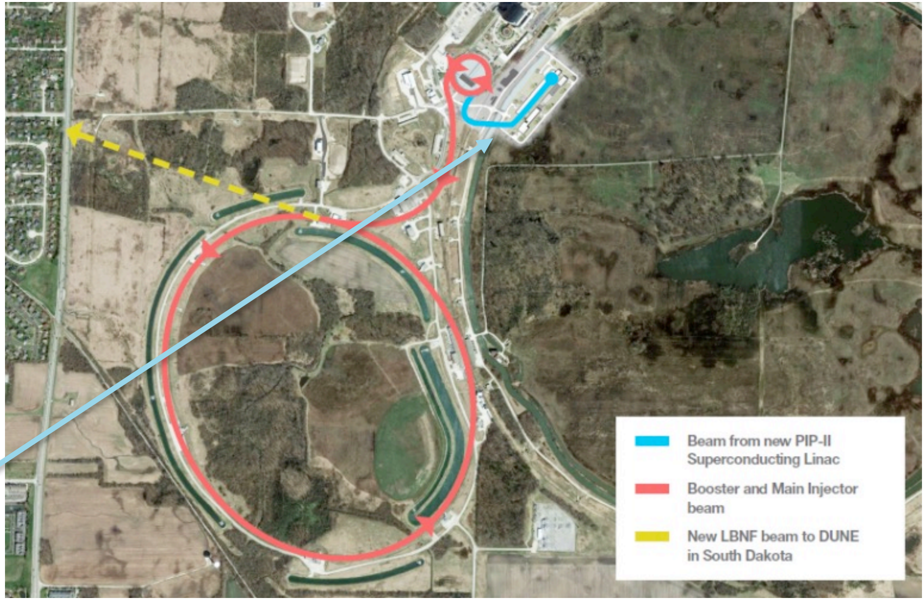
  Increased proton beam intensity at 8 GeV for 1.2 MW beam power from MI

- PIP-II Era begins in 2029, DUNE in 2031

  Mu2e (8 GeV)

  Fixed Target, Test beams (120 GeV)

  0.8 GeV Beam available for other exp. (e.g. with PAR, maybe other options for beam dump?)



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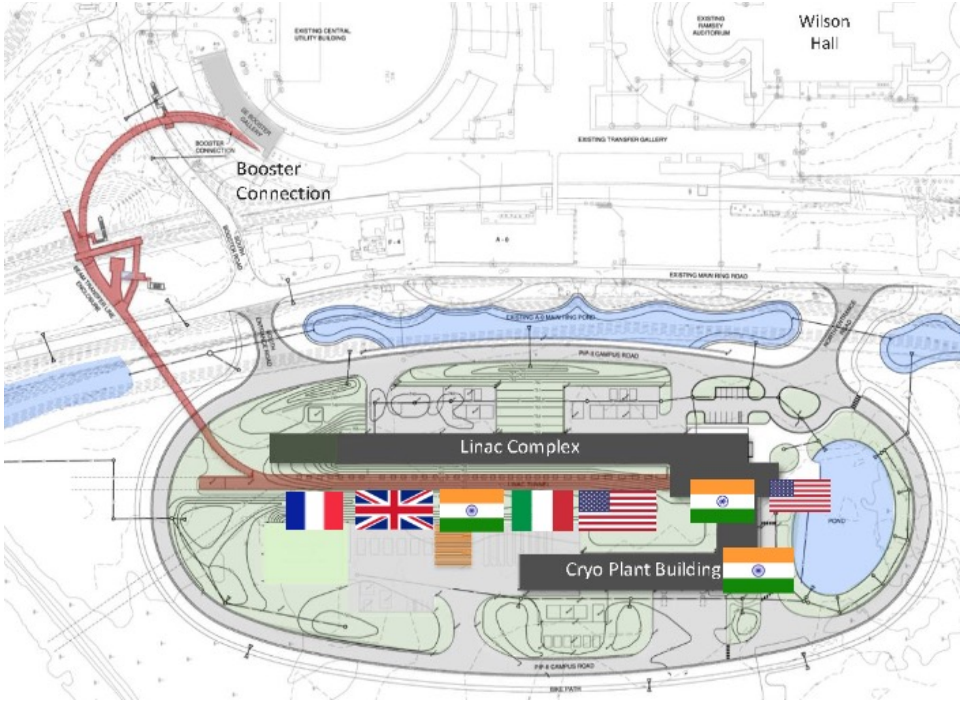
# PIP-II Layout

PIP-II Design includes

- Stub for continuation of Linac to higher energy
- Stub for Beamline to Muon campus



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# Fermilab Accelerator Complex Strategy

- In Summer 2022 Fermilab Director assembled a group to develop strategy for upgrading the Fermilab accelerator Complex

**Proton Intensity Upgrade**
**Central Design Group**

Robert Ainsworth, Giorgio Apollinari, Tug T. Arkan, Sergey Belomestnykh,
Pushpalatha C. Bhat, S.J. Brice, Brian Chase, Mary E. Convery, Steven J. Dixon,
Jeff Eldred, Grigory Eremeev, Brenna Flaugher, Jonathan D. Jarvis, Sergo Jiindariani,
David Johnson, Jonathan Lewis, Richard Marcum, Sergei Nagaitsev, David Neuffer,
Donato Passarelli, Frederique Pellemoine, William A. Pellico, Sam Posen,
Eduard Pozdeyev, Alexander Romanenko, Arun Saini, Kiyomi Seiya, Vladimir Shiltsev,
Nikolay Solyak, James M. Steimel, Diktys Stratakis, Alexander A. Valishev,
Mayling L. Wong-Squires, Slava Yakovlev, Katsuya Yonehara, Robert Zwaska

- Built on extensive prior work, whitepapers input to Snowmass, etc.
- Developed the Accelerator Complex Evolution (ACE) Plan
- Workshop Jan. 2023 focused on accelerator plan (https://indico.fnal.gov/event/57326/)
  - Particular relevance for this workshop: talk by Matt Toups on Beam Dump Experiments
- Presentations to P5 Townhalls (SLAC, Fermilab)
- Next Workshop (in series) June 14-15 on Science opportunities with ACE

# Accelerator Complex Evolution (ACE) plan

- Increase protons on target to DUNE Phase I detector by
  - Shortening the Main Injector cycle time to increase beam power
  - Upgrading target systems for up to 2.4 MW
  - Improving reliability of the Complex

  ~ 2030

- Establish a project to build a Booster Replacement to
  - Provide a robust and **reliable** platform for the future of the Accelerator Complex
  - Ensure high intensity for DUNE Phase II CP-Violation measurement
  - Enable the **capability** of the complex to serve precision experiments and searches for new physics with beams from 1-120 GeV
  - Create the **capacity** to adapt to new discoveries
  - Supply the high-intensity proton source necessary for future multi-TeV accelerator research

  ~ 2038

# Booster Replacement Options

- Provide
  - 2.4 MW to LBNF
  - 120 GeV beam available for other experiments
- Potential new science 'spigots':
  - Spigot 1: ~1-2 GeV Continuous Wave (CW), up to 4 MW, could be shared with AR
  - Spigot 2: ~1-2 GeV Pulsed Beam (0.4-2 MW) with accumulator ring
  - Spigot 3: 8 GeV Pulsed (0.16-1.2 MW) with accumulator ring
- Platform for future collider and detector R&D
- Front-end for future multi-TeV collider

- Specific Booster Replacement scenario will be developed with community input (like this workshop and in June) and informed by P5 and DOE decisions

# Booster Replacement Options: Two main Configurations

1) PIP-II SRF Linac extended to 8 GeV (3 options)
2) New Rapid Cycling Synchrotron (2-8 GeV) (3 options)

- All six configurations require an extension of the SRF Linac to 2 GeV and have goal to minimize shutdown time to connect.
- ACE Science workshop in June 14-15 will connect science opportunities to these potential configurations (https://indico.fnal.gov/event/59663/timetable/#20230614)

**RCS**

C1a) 10 Hz: Metallic vacuum chamber

C1b) 20 Hz: Ceramic vacuum chamber, larger aperture magnets, accumulator ring

C1c) 20 Hz: (C1b) with high-current linac, no accumulator ring

**SRF Linac and Accumulator Ring**

C2a) Basic: small increase in PIP-II current, using demonstrated XFEL RF

C2b) High current (5mA) and some RF R&D

C2c) High current and significant RF R&D



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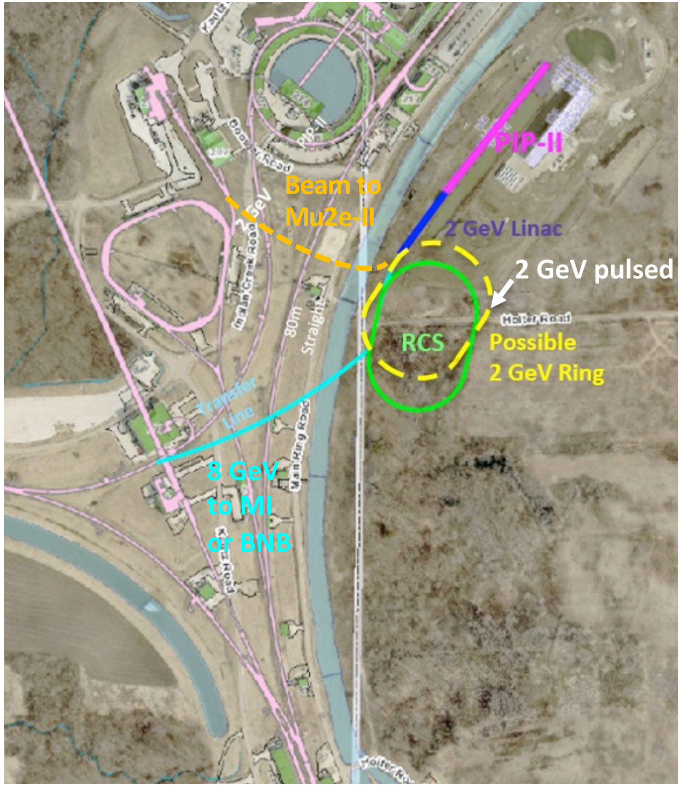
# Example Booster Replacement options and possible add-ons

C1b: 20Hz RCS + 2 GeV Accumulator ring

Main Elements:

- 1-2 GeV Linac
- 1-2 GeV Accumulator Ring
- 20 Hz 8 GeV RCS

Opportunities for Beam Dump Experiments: 1-2, 8, 120 GeV



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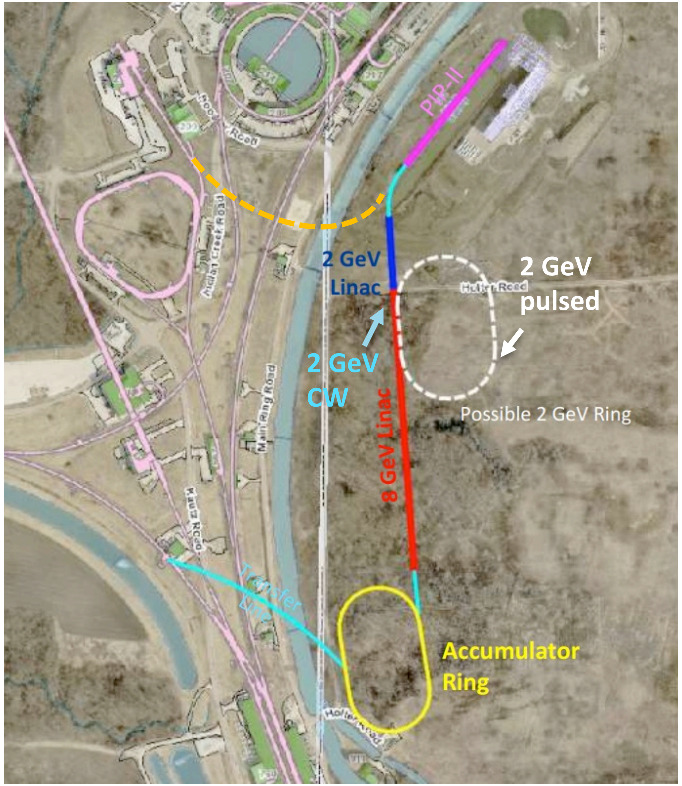
# Example Booster Replacement options and possible add-ons

C2a: SRF Linac + 8 GeV Accumulator ring

Main Elements:

- 1-2 GeV Linac
- Optional ~1-2 GeV Accumulator Ring
- 8 GeV Linac
- 8 GeV Accumulator Ring

Opportunities for Beam Dump Experiments: 1-2, 8, 120 GeV



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# Muon Collider

- Fermilab ACE program offers several synergies with Muon Collider R&D
- The ACE booster replacement plan may provide a path for a Muon Collider front-end
- Will be discussed at ACE Science workshop in June


| Muon Collider Proton Driver Parameters | |
|---|---|
| Energy | 5-15 GeV |
| Rep. rate | 5-10 Hz |
| Ave. Beam Power | 1-4 MW |
| Proton structure | 1-3 ns bunch with ~$10^{14}$ |

## Muon Collider synergies with ACE program

| ACE | Target | SRF | Proton Driver |
|---|---|---|---|
| Main injector upgrade | YES | | |
| Booster replacement | YES | YES | YES |

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# ACE Science Workshop June 14-15

Draft Agenda

- ACE
- Muon/Future Collider
- Neutrino Science beyond DUNE Phase 2
- Charged Lepton Flavor Violation
- Dark Matter Beam Dump experiments  (input from this workshop!)
- New Ideas
- Synergies: Physics, Science, Technology

# Summary

The Accelerator Complex Enhancement (ACE) plan capitalizes on the PIP-II investment and delivers

- More protons-on-target (POT) to LBNF than PIP-II alone could provide
- A Booster Replacement that will provide

  Even higher rates of POT accumulation

  A modern and flexible Fermilab Accelerator Complex

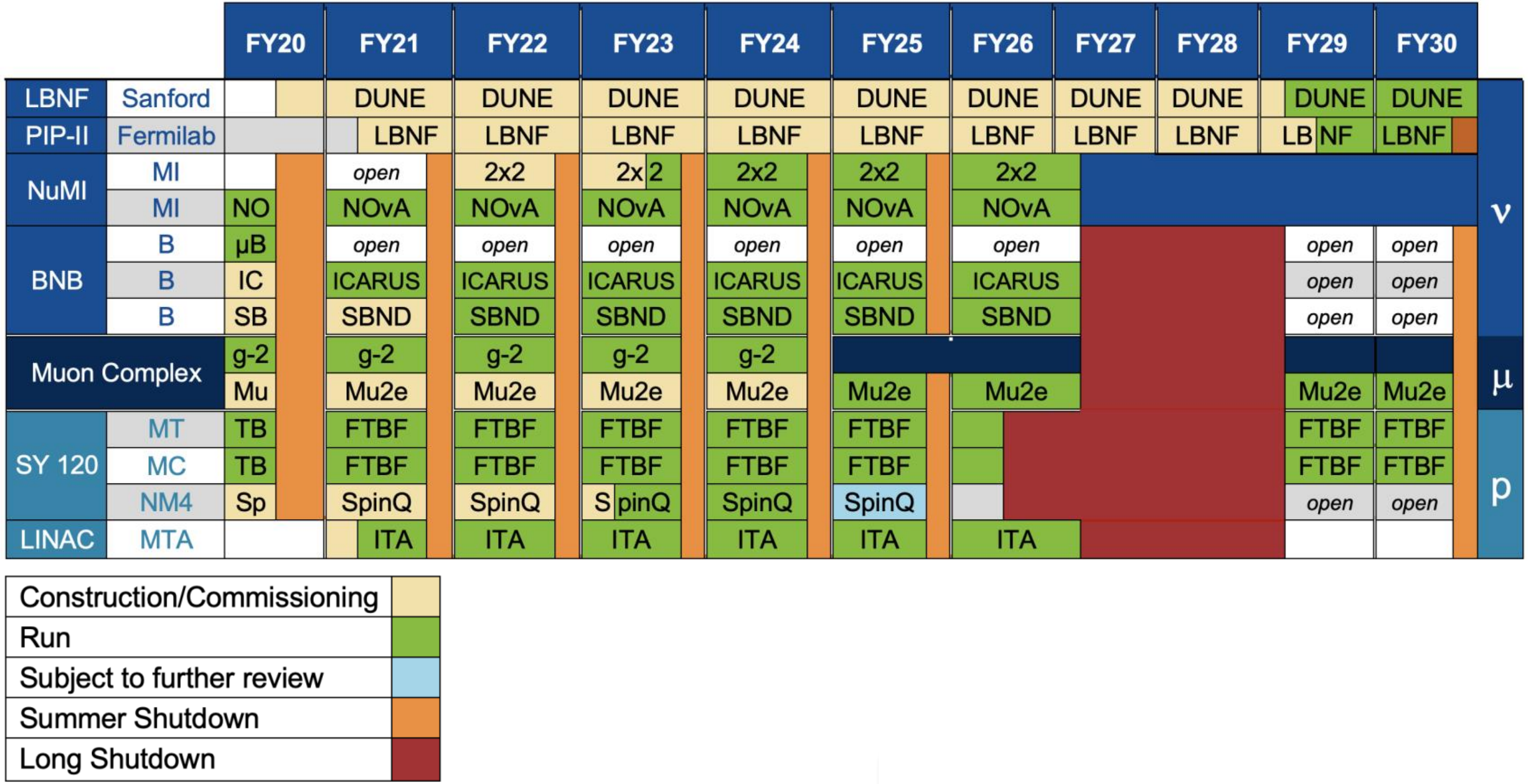
  Opportunities for Beam Dump experiments at a variety of energies (Jeff and Bill's talk will provide more details)

We look forward to the outcome of this workshop!

**Capability**
**Capacity**
**Reliability**

# Extra slides

# Beam delivery plan



# Impact of shortened cycle on other experiments

- In a nominal 1.2s cycle at 20Hz

  12 Booster batches slip-stacked together in the Recycler, accelerated to 120 GeV in the MI, extracted to LBNF (~0.65s in Recycler)

  2 Booster batches for Mu2e rebunched in the Recycler and extracted to the Delivery Ring one bunch at a time, as the bunch is resonantly extracted from the Delivery Ring in a 0.43ms slow spill to Mu2e (~0.55s in Recycler)

  10 Booster batches available to other experiments while Mu2e beam is in the Recycler

- In a 0.65s cycle

  Mu2e not supported

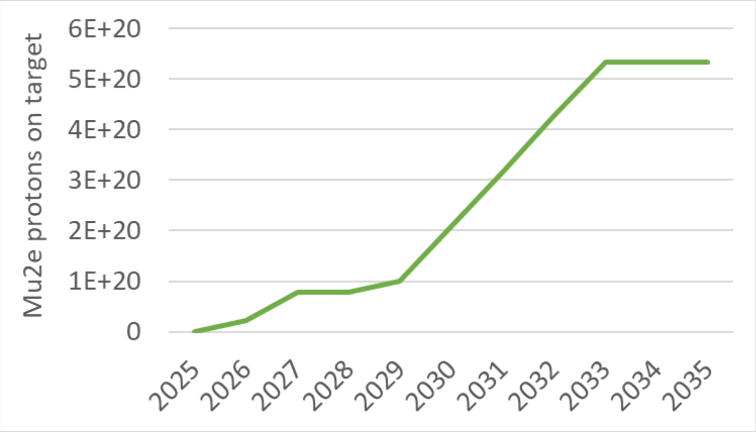
  1 Booster batch available to other experiments

# Options for beam sharing for DUNE / Mu2e

- Limit beam power to DUNE (1.2s cycle) until Mu2e complete (2033)

  Mu2e beam request is $3.6 \times 10^{20}$ POT physics data, total $4.7 \times 10^{20}$ including calibration

  May be consistent with LBNF/DUNE commissioning, high-power target/horn development

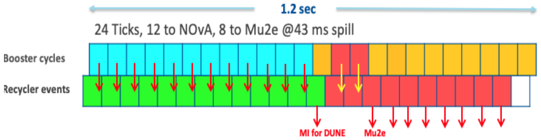



- Run shorter cycle time with shortened spill durations to Mu2e
  – Has some effect on Mu2e physics, working with experiment to quantify
- Run shorter cycle time with fewer spills to Mu2e
  – Extends duration needed to obtain requested Mu2e dataset
  – DUNE larger initial dataset but no overall gain
  – Less efficient use of Recycler

Fermilab is committed to delivering Mu2e

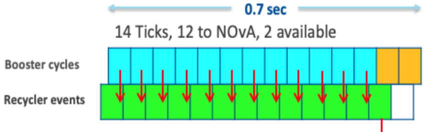
# Main Injector beam power in numbers

| | | PIP-II Booster | |
|---|---|---|---|
| **Operation scenario** | **Present** | **PIP-II** | **units** |
| **MI 120 GeV ramp rate** | **1.333** | **1.2** | s |
| **Booster intensity** | **4.5** | **6.5** | $10^{12}$ p |
| Booster ramp rate | 15 | **20** | Hz |
| Number of Booster batches | 12 | 12 | |
| MI power | 0.865 | **1.2** | MW |
| cycles for 8 GeV | 6 | 12 | |
| Available 8 GeV power | 29 | **83** | kW |



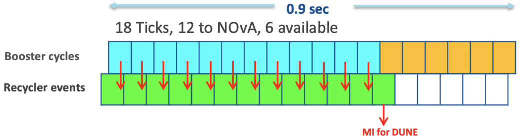

# Main Injector beam power in numbers – ACE

| | | PIP-II Booster | | | Booster Replacement | | | |
|---|---|---|---|---|---|---|---|---|
| **Operation scenario** | **Present** | **PIP-II** | **A** | **B** | **C** | **D** | **E** | **units** |
| **MI 120 GeV ramp rate** | **1.333** | **1.2** | 0.9 | **0.7** | **1.2** | **0.9** | **0.7** | s |
| **Booster intensity** | **4.5** | | | **6.5** | | **10** | | $10^{12}$ p |
| Booster ramp rate | 15 | | | **20** | | 20 | | Hz |
| Number of batches | 12 | | 12 | | 12 | 12 | 9 | |
| MI power | 0.865 | **1.2** | 1.7 | **2.14** | 1.9 | **2.5** | 2.4 | MW |
| cycles for 8 GeV | 6 | 12 | 6 | 2 | 12 | 6 | 5 | |
| Available 8 GeV power | 29 | **83** | 56 | **24** | 128 | **85** | 92 | kW |




# Main Injector beam power in numbers – ACE

| | | PIP-II Booster | | | Booster Replacement | | | |
|---|---|---|---|---|---|---|---|---|
| **Operation scenario** | **Present** | **PIP-II** | **A** | **B** | **C** | **D** | **E** | **units** |
| **MI 120 GeV ramp rate** | **1.333** | **1.2** | 0.9 | **0.7** | **1.2** | **0.9** | **0.7** | s |
| **Booster intensity** | **4.5** | | **6.5** | | | **10** | | $10^{12}$ p |
| Booster ramp rate | 15 | | **20** | | | 20 | | Hz |
| Number of batches | 12 | | 12 | | 12 | 12 | 9 | |
| MI power | 0.865 | **1.25** | 1.666 | **2.14** | 1.922 | **2.563** | 2.472 | MW |
| cycles for 8 GeV | 6 | 12 | 6 | 2 | 12 | 6 | 5 | |
| Available 8 GeV power | 29 | **83** | 56 | **24** | 128 | **85** | 92 | kW |

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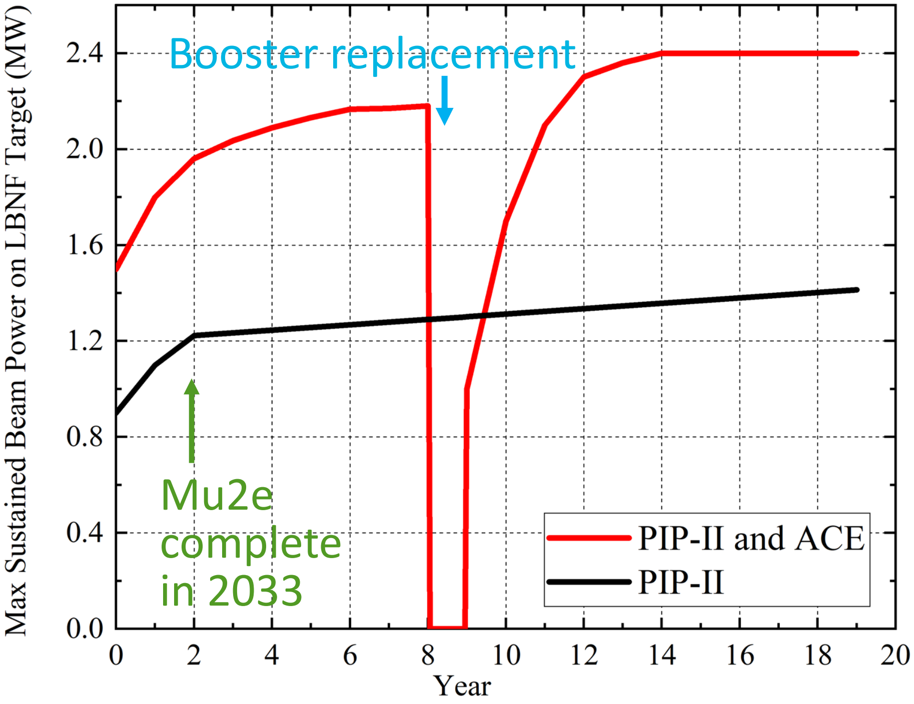
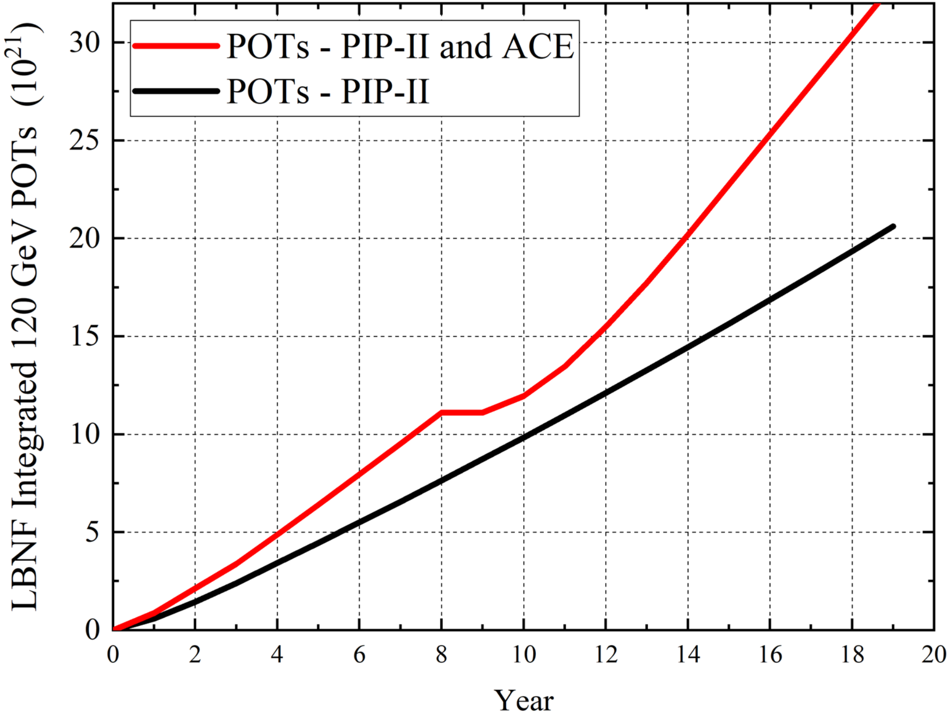
# DUNE power and POT implications



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# Main Injector

- 360 main dipole magnets
- 200 main quadrupole magnets originally used in the Main Ring (>50 years old)
- 108 sextupoles, 66 octupoles, corrector dipoles/ quads, specialty injection and extraction magnets
- Twenty 53-MHz RF cavities to accelerate beam, originally used in the Main Ring (>50 years old)
- 170 DC and 360 ramped magnet supplies with total of 140 MVA, 40 specialty pulsed magnet supplies
- The magnets, power supplies, and RF systems are cooled by low-conductivity water
- MI will be >30 years old when LBNF turns on