FNAL Accelerator Complex

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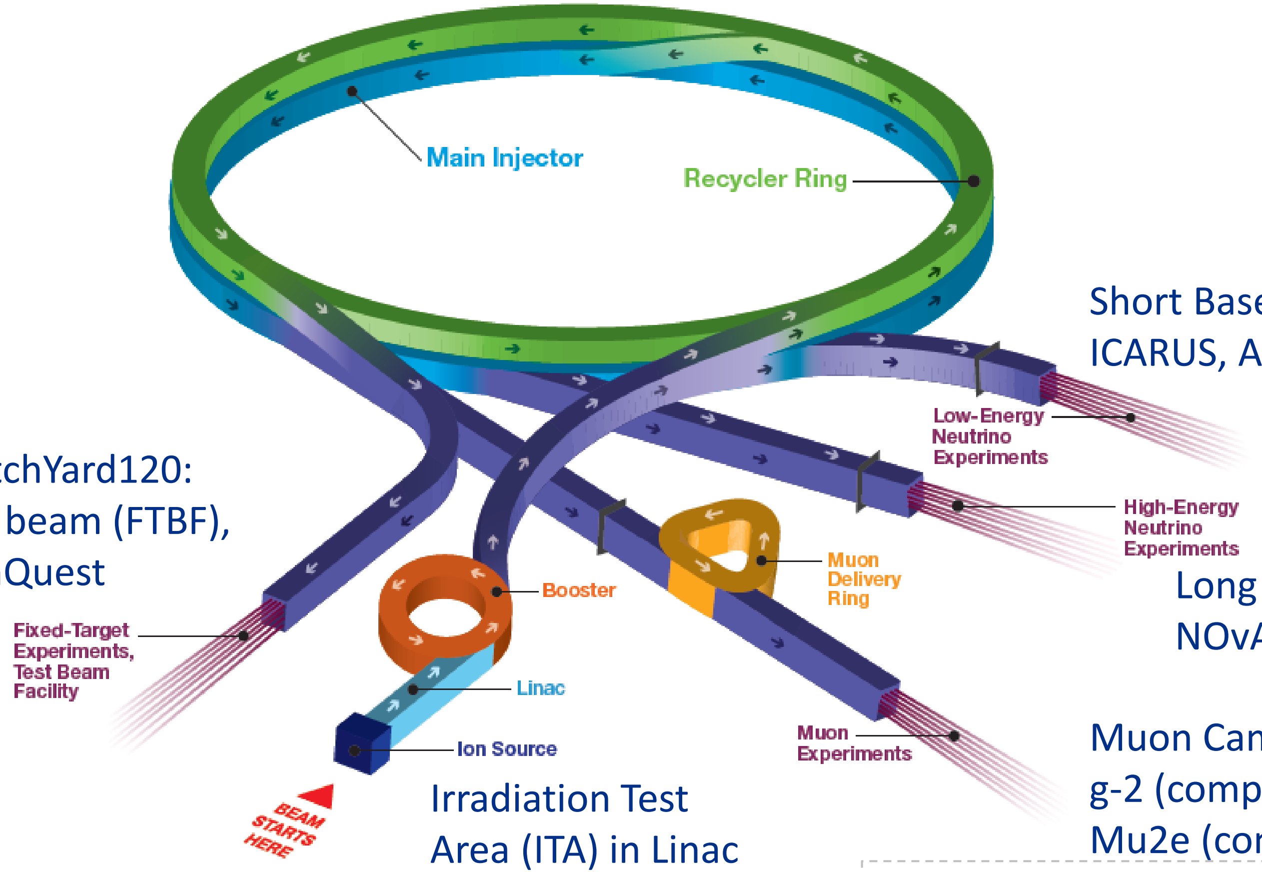
Outline

- Fermilab Accelerator Complex now and in the PIP-II/LBNF era
- Accelerator Complex Evolution (ACE) plan
- Beam to experiments under ACE plan

Caption

Accelerator Complex



Short Baseline Neutrino: ICARUS, ANNIE, SBND

SwitchYard120: test beam (FTBF), SpinQuest

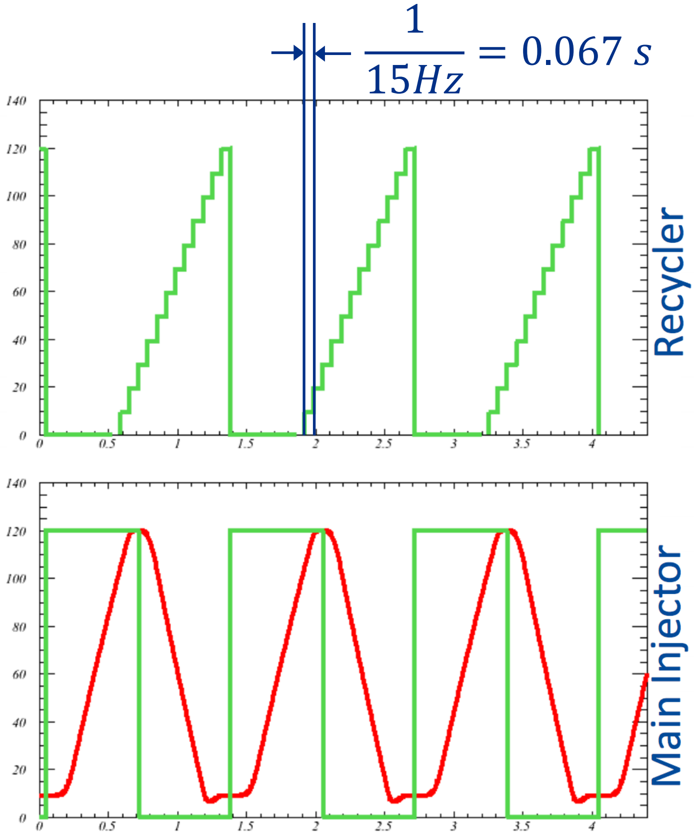
Long Baseline Neutrino: NOvA

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

Irradiation Test Area (ITA) in Linac

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



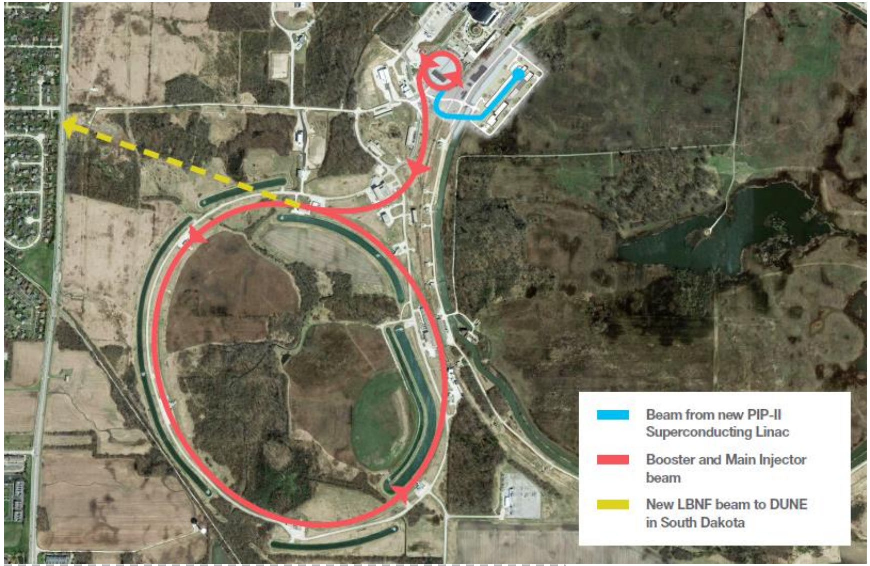
1.33s cycle shown

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

Accelerator Complex in PIP-II / LBNF era (pre ACE plan)

- PIP-II Project 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
- LBNF/DUNE-US Project provides
  - New proton beamline for up to 2.4 MW
  - Target systems for 1.2 MW
  - Shielding and absorber for up to 2.4 MW



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
- 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

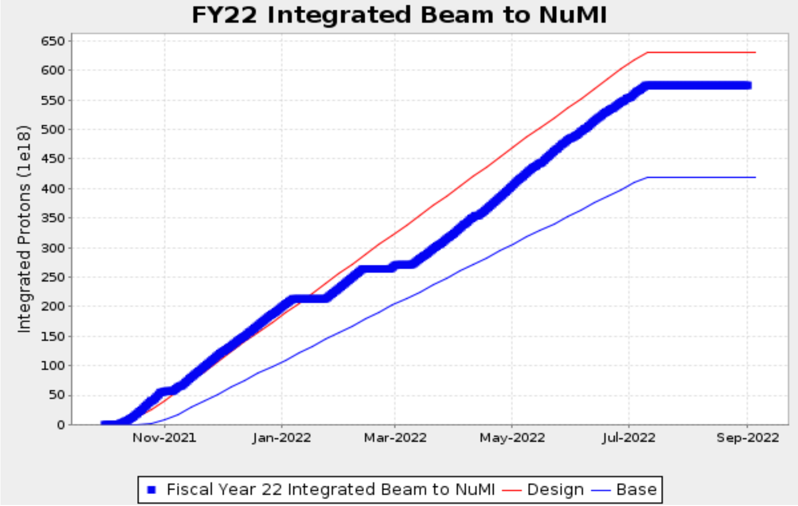
Previously referred to as PIP-III

Shortening the Main Injector cycle time

- Advantages over increasing the per-pulse intensity – reduces likelihood of space charge effects and instabilities, and reduces impact of limited aperture
- To shorten the MI cycle from 1.2-1.4s to 0.65s, the ramp needs to be ~twice as fast
- Requires more voltage and electrical power
  - Power supplies, transformers, feeders, service building size, additional tunnel penetrations, additional cooling
- RF accelerating system
  - Replace cavities with newer design (more volts per cavity) or add cavities of current design
- Regulation, control & instrumentation
  - New low-level RF, new power supply regulation/control system
- Beam dynamics, losses and shielding
  - Upgrade MI collimators, upgrade abort line

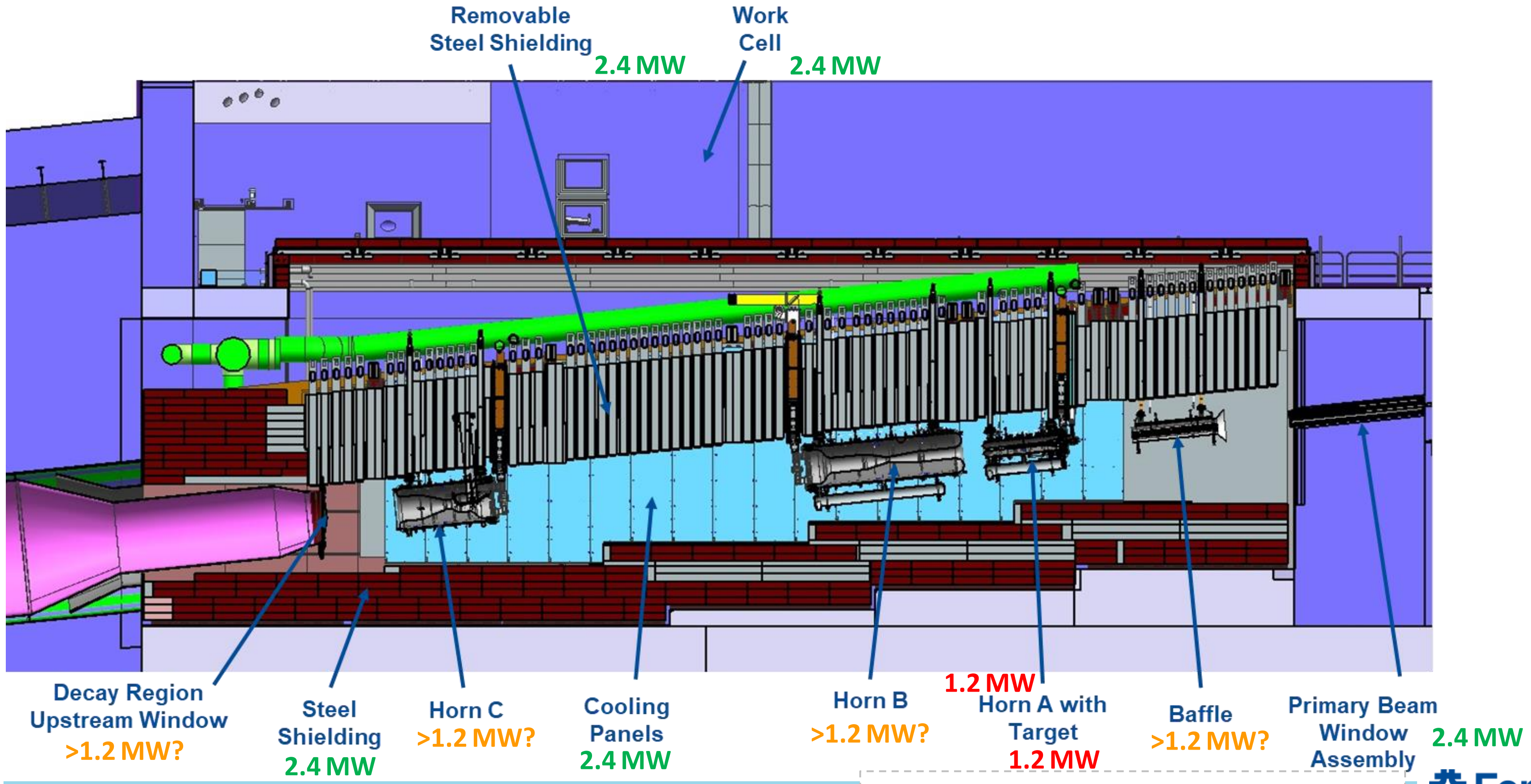
Improving reliability of the complex

- Maximize beam power
  - Minimize beam loss
- Maximize uptime during running periods
  - High reliability (replace aging equipment)
  - Ability to rapidly repair equipment that breaks
- Maximize length of running periods each year
  - Minimize duration of annual shutdown for maintenance
- ACE will
  - Invest in reliability, availability and stability
  - Reduce shutdown duration, improve work planning

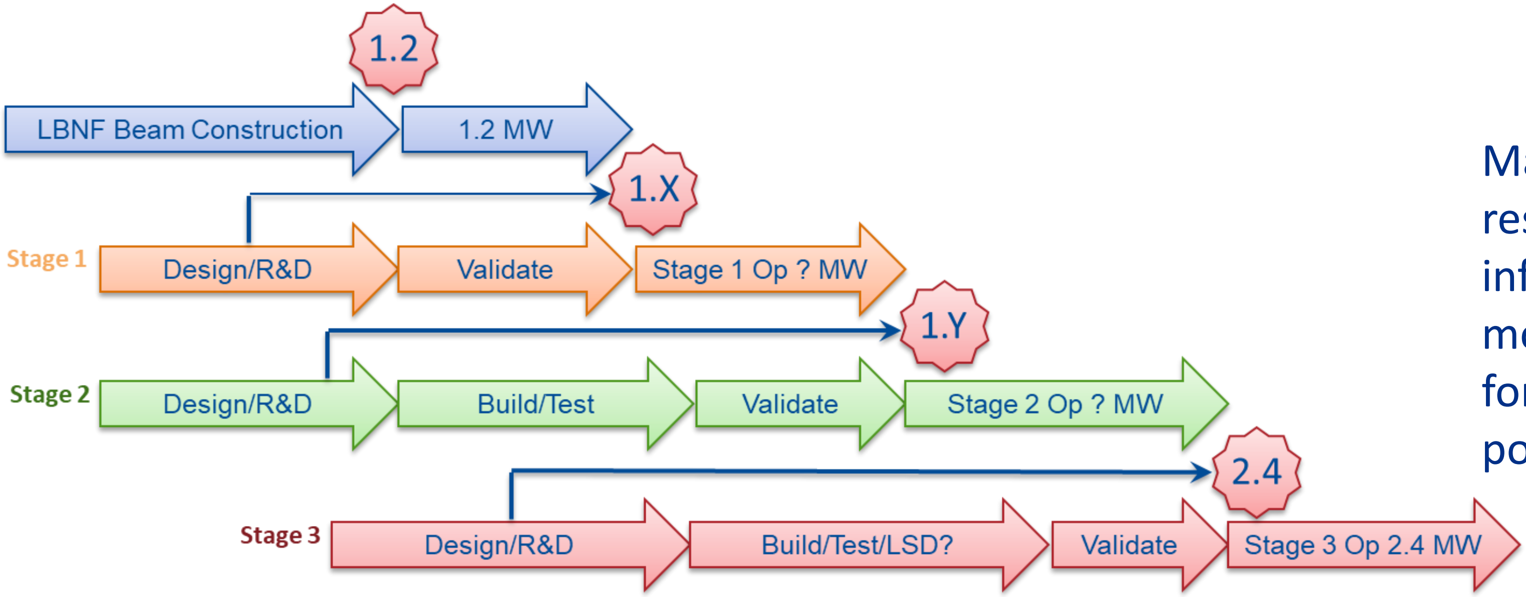


Overall FY22 efficiency 41%, DUNE/PIP-II goal 57%

LBNF target systems



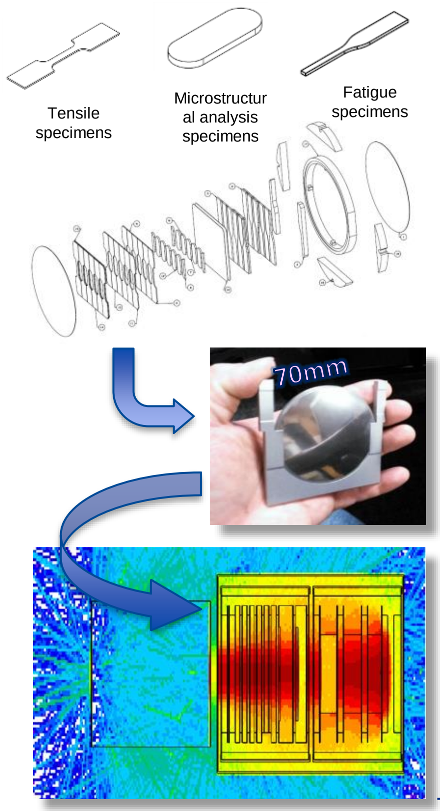
Target development staged approach



Materials R&D results needed to inform design modifications for higher beam power

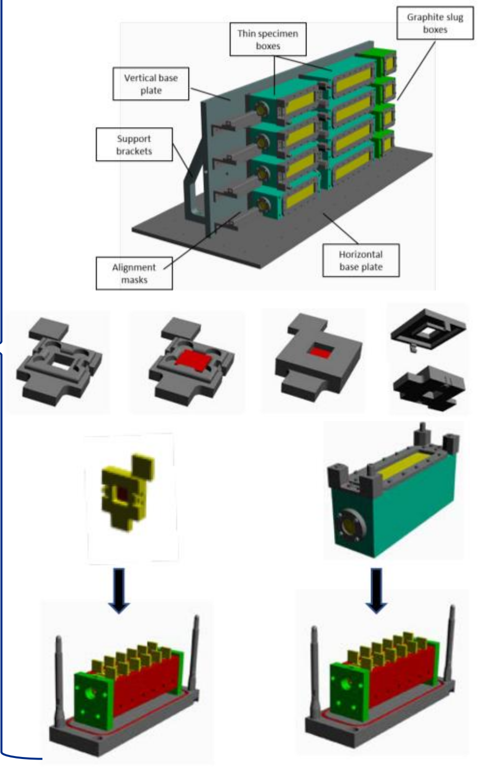
- **Stage 1** – Push current designs (1.2 MW) to validated limitations
- **Stage 2** – Design and build 2nd generation components with modifications to existing designs to raise limits while maintaining reasonable useful ν flux/POT
- **Stage 3** – Design and build fully optimized next generation systems to take full advantage of maximum POT from accelerator complex (may not be needed)

Target materials R&D on critical path to 2+ MW target



1. Identify candidate materials
2. High-energy proton irradiation of material specimens to reach expected radiation damage
3. Pulsed-beam experiments of irradiated specimens to duplicate loading conditions of beam interactions
4. Non-beam PIE (Post-Irradiation Examination) of specimens
   – Material properties
   – Microscopic structural changes
   – High-cycle fatigue testing

Five-year cycle needs to start ASAP



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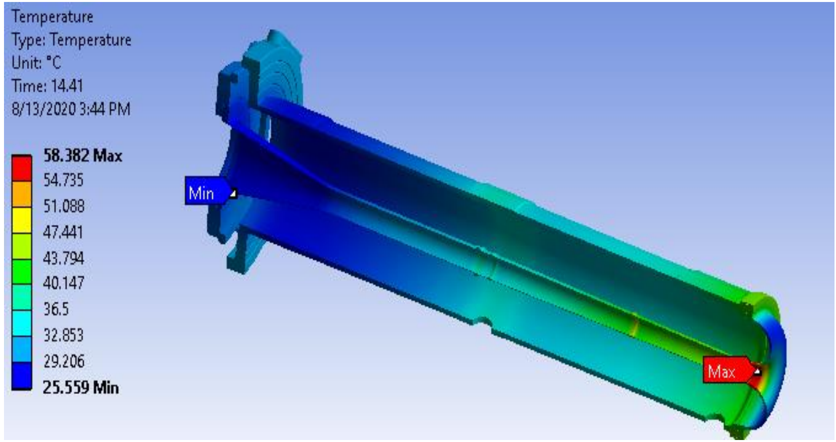
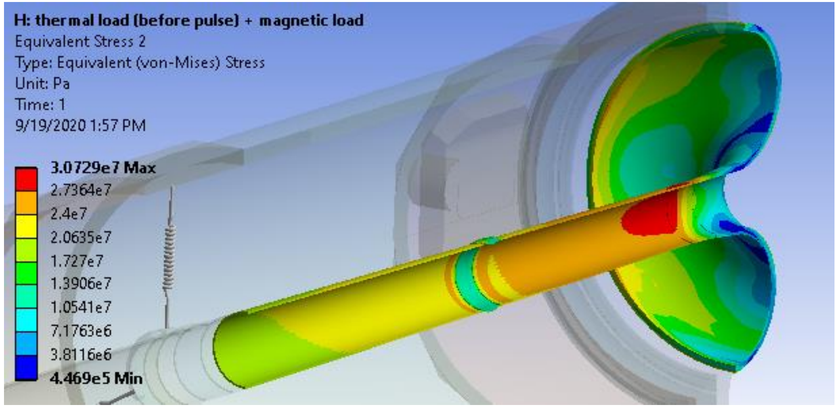
Horns for 2.4 MW performance

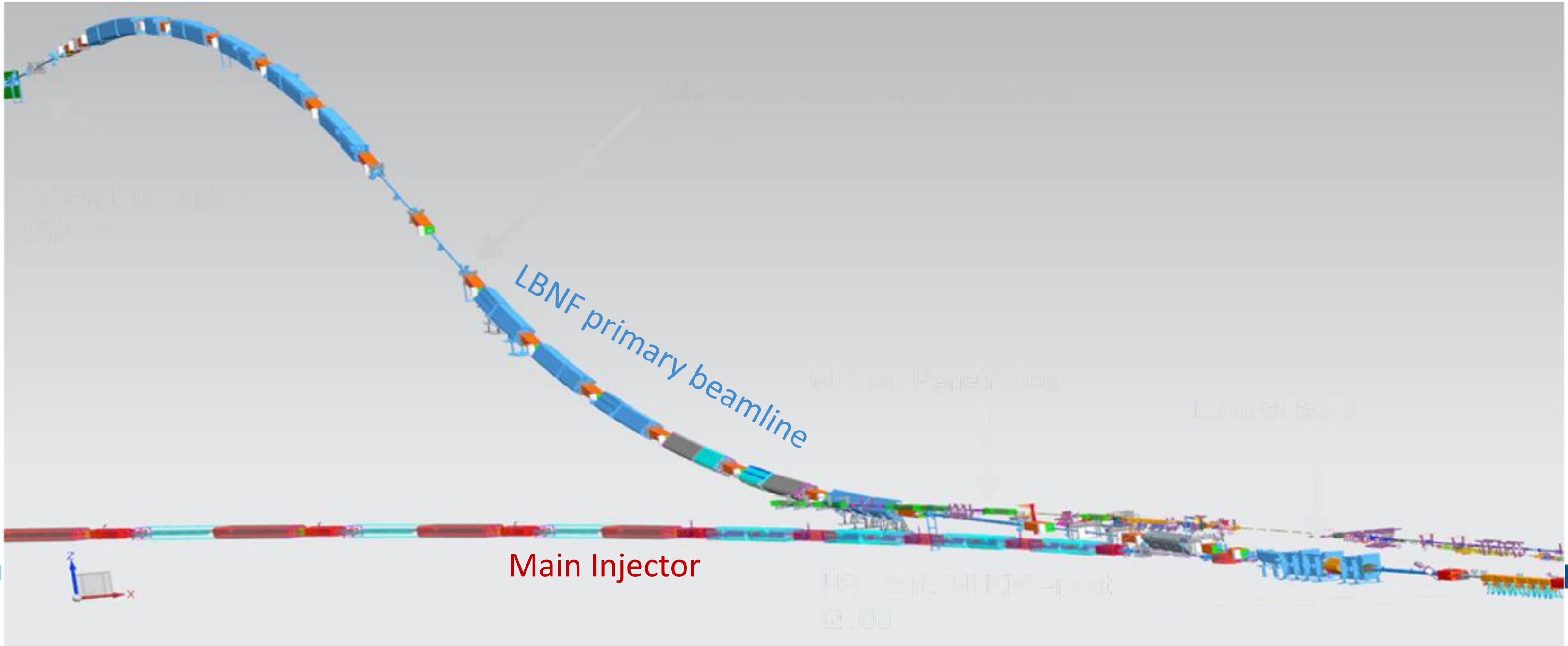
- Horn A requires reanalysis and likely redesign
  - 1.2 MW analysis indicates 2.7 safety factor on fatigue endurance limit
  - Likely redesign to:
    - Avoid beam heating in critical locations
    - Strengthen structure in critical locations
- Horns B&C see less beam heating
  - Safety factor: 7.3 for 1.2 MW operation
  - Require reanalysis, but less likely redesign





LBNF beamline

- Larger power supplies to ramp twice as fast, may need more building space
- Kicker power supply modifications to charge up faster
- Cooling water: additional pumps to remove and exhaust additional heat

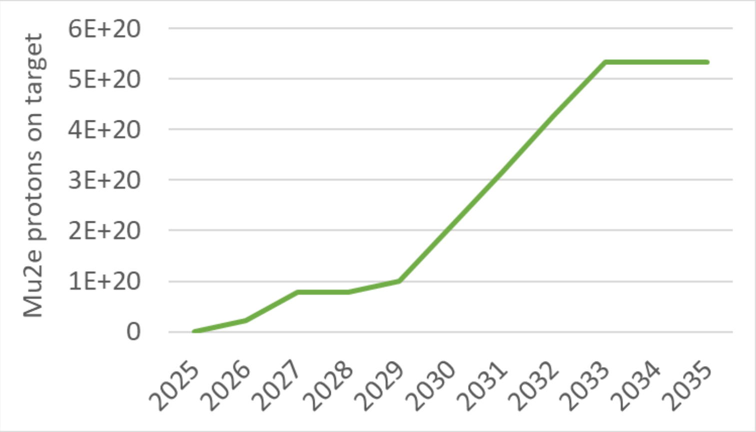


Impact of shortened cycle on other experiments

- 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 (pre Booster Replacement)
  - Recycler not available for Mu2e (finish Mu2e before reduce cycle time)
  - 1 Booster batch available to other experiments

Options for beam sharing for DUNE / Mu2e

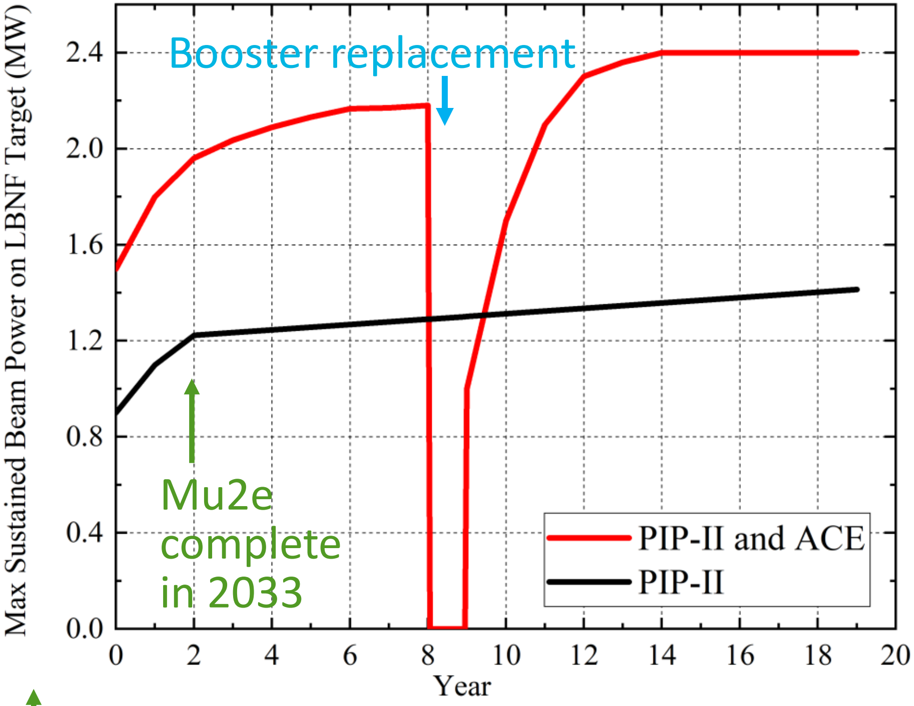
1. Limit beam power to DUNE (1.2s cycle) until Mu2e complete (2033)
   - Mu2e beam request is 3.6×10^{20} POT physics data, total 4.7×10^{20} including calibration
   - May be consistent with LBNF/DUNE commissioning, high-power target/horn development

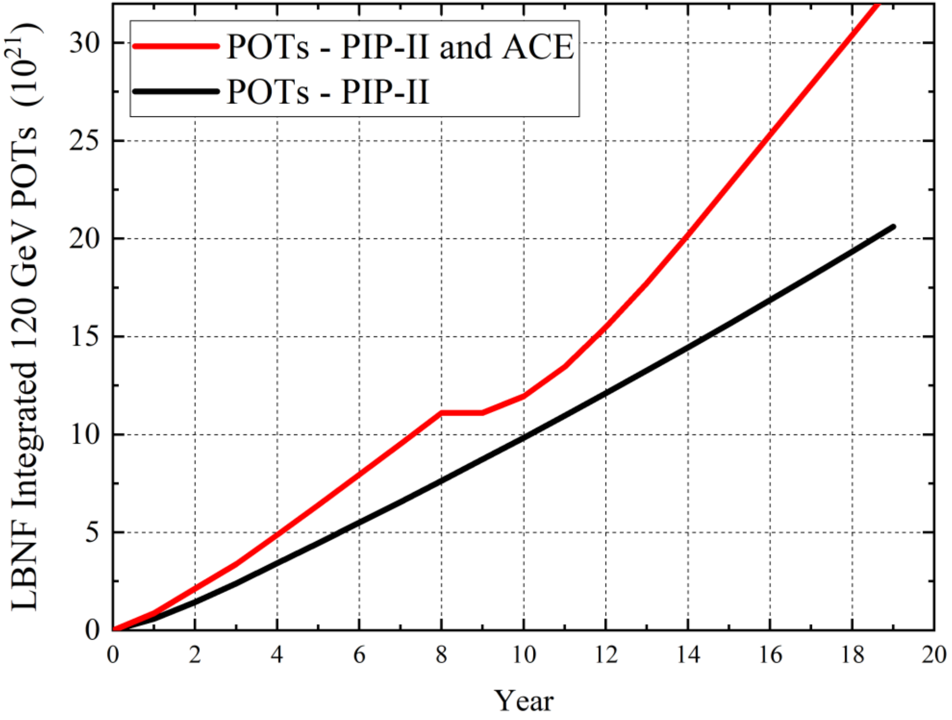


2. Run shorter cycle time with shortened spill durations to Mu2e
   - Has some effect on Mu2e physics, working with experiment to quantify
3. Run shorter cycle time with fewer spills to Mu2e
   - Extends duration needed to obtain requested Mu2e dataset
   - DUNE larger initial dataset but no overall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

Fermilab is committed to delivering Mu2e

DUNE power and POT implications





(Mu2e restarts 2029)

Booster replacement

- Extend SRF Linac to higher energy or construct new Rapid-Cycling Synchrotron
- Provides
  - 2.4 MW to LBNF
  - 120 GeV beam available for other experiments
- Potential new science ‘spigots’:
  - 2 GeV Continuous Wave (CW)
  - 2 GeV Pulsed Beam (~ 1MW)
  - 8 GeV Pulsed (~ 1MW)
- Platform for collider R&D
- Front-end for future multi-TeV collider

Booster replacement 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
- ACE Science workshop June 14-15 will optimize parameters

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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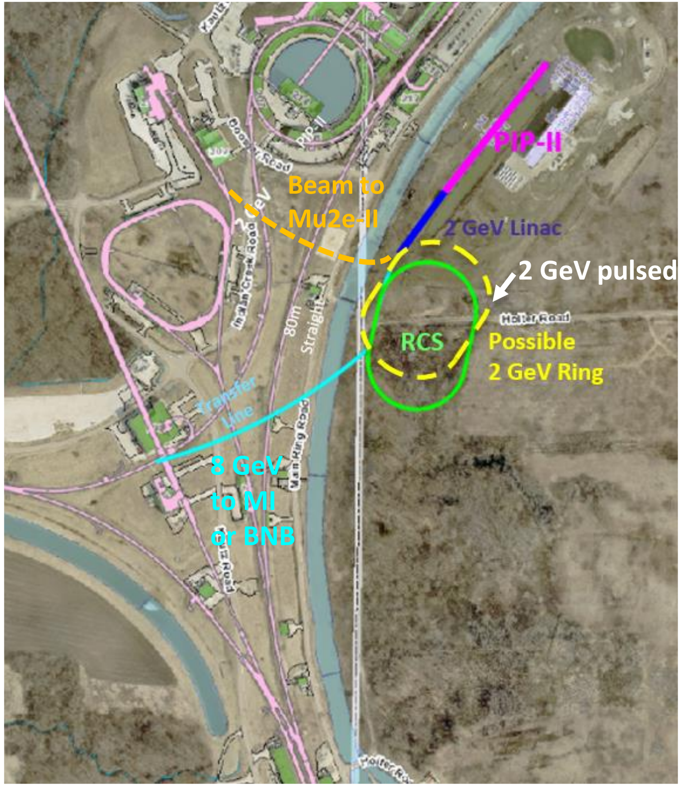
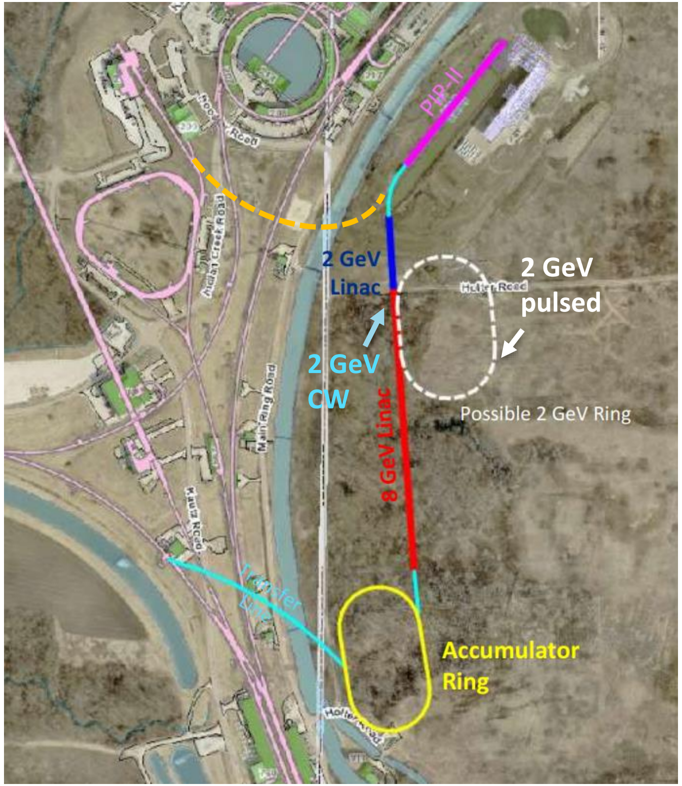
Example Booster replacement options and possible add-ons





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Muon Collider

See talk by Diktys Stratakis

- Fermilab ACE program offers several synergies with Muon Collider R&D
- The ACE Booster Replacement plan could provide a path for a Muon Collider front-end
- Will be discussed at ACE Science workshop June 14-15 at Fermilab

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 $\sim 10^{14}$

Muon Collider synergies with ACE program

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

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

Capability
Capacity
Reliability

Request to P5

We ask P5 to support the ACE plan that includes the following key components

1. Upgrades to Main Injector accelerator systems and infrastructure to enable beam power above 1.2MW through faster cycle time and efficient operations of the complex with the aim of achieving DUNE goals as fast as possible, performed as series of AIP and GPP between 2024 and 2032

2. Accelerated profile of high-power target system R&D to enable above 1.2MW operations in DUNE Phase I

3. Establishment of a Project for Booster Replacement with superior capacity, capability, and reliability to be tied to the accelerator complex at a time determined by the DUNE physics