ACE: Proton beam upgrade plan at Fermilab

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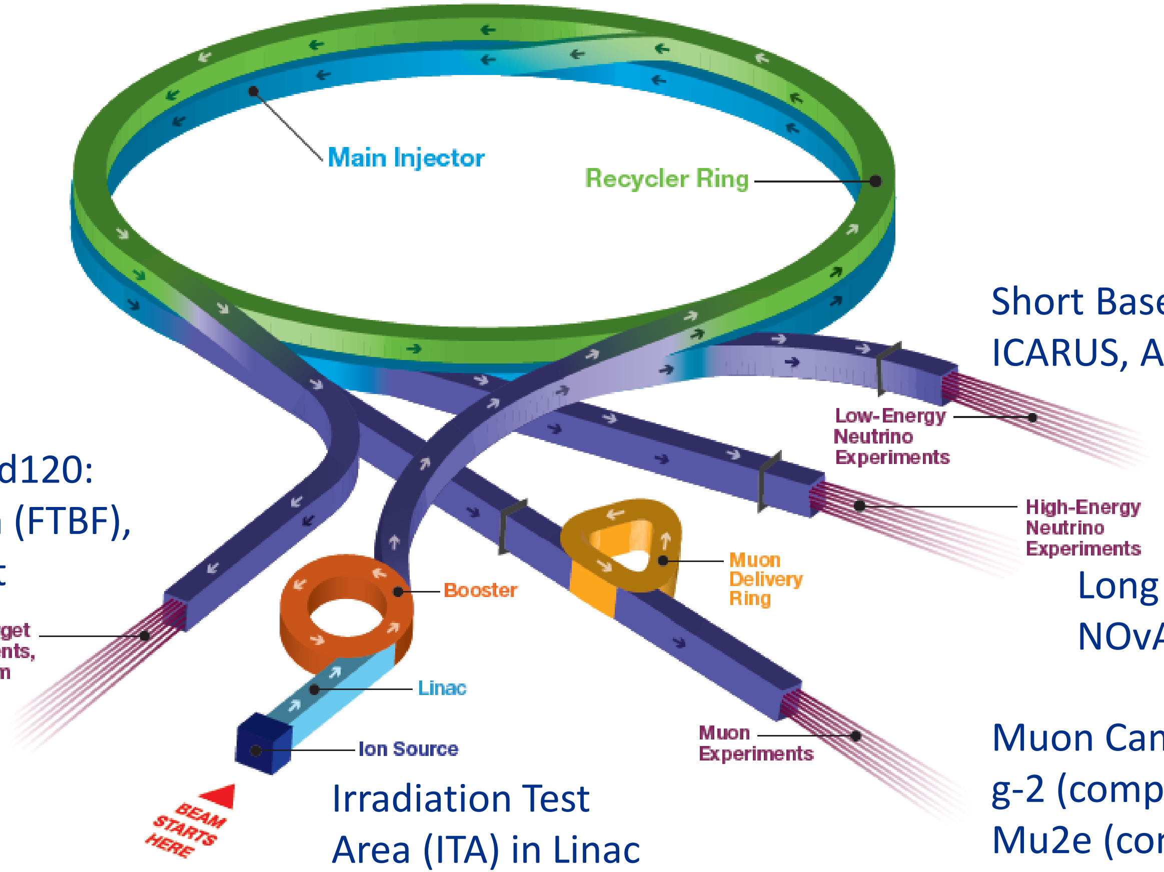
Acknowledgements

Thank you to Sasha Valishev and Mary Convery for slides.

Outline

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

Accelerator Complex



SwitchYard120: test beam (FTBF), SpinQuest

Short Baseline Neutrino: ICARUS, ANNIE, SBND

Long Baseline Neutrino: NOvA

Irradiation Test Area (ITA) in Linac

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

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Introduction to Fermilab accelerators

H^- linac (1970, 1993, 2012)

- 400 MeV linac ~20mA

Booster synchrotron (1970)

- H^- stripping injection (1978)

  16 turns to ~4.7×10^{12} p per pulse

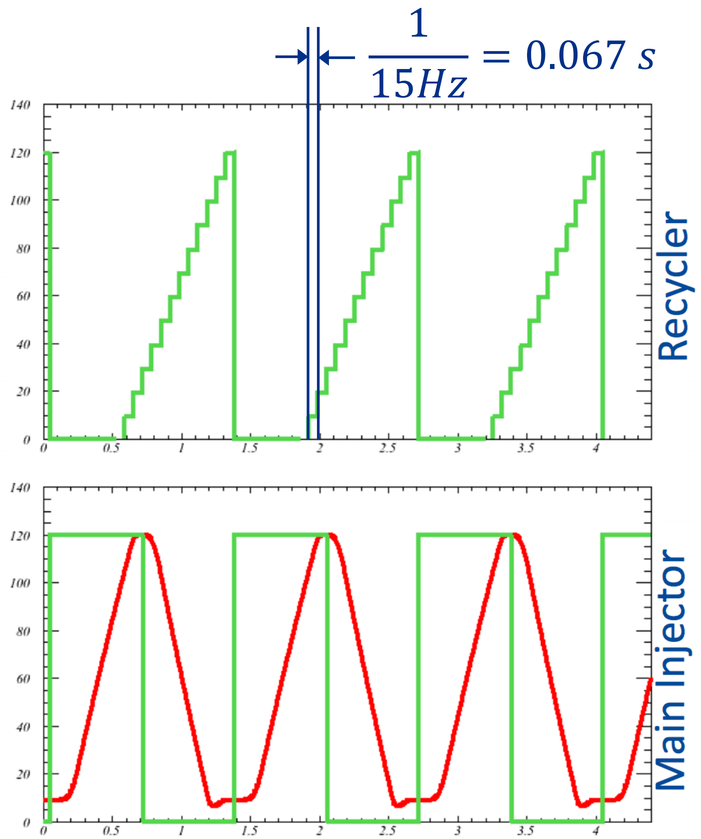
- Ramp from 0.4 to 8 GeV at 15 Hz

Recycler (1998)

- 3.3 km permanent magnet 8 GeV ring
- Slip-stacking 12 Booster batches, ~56×10^{12} p
- Also re-bunches beam for Muon Campus

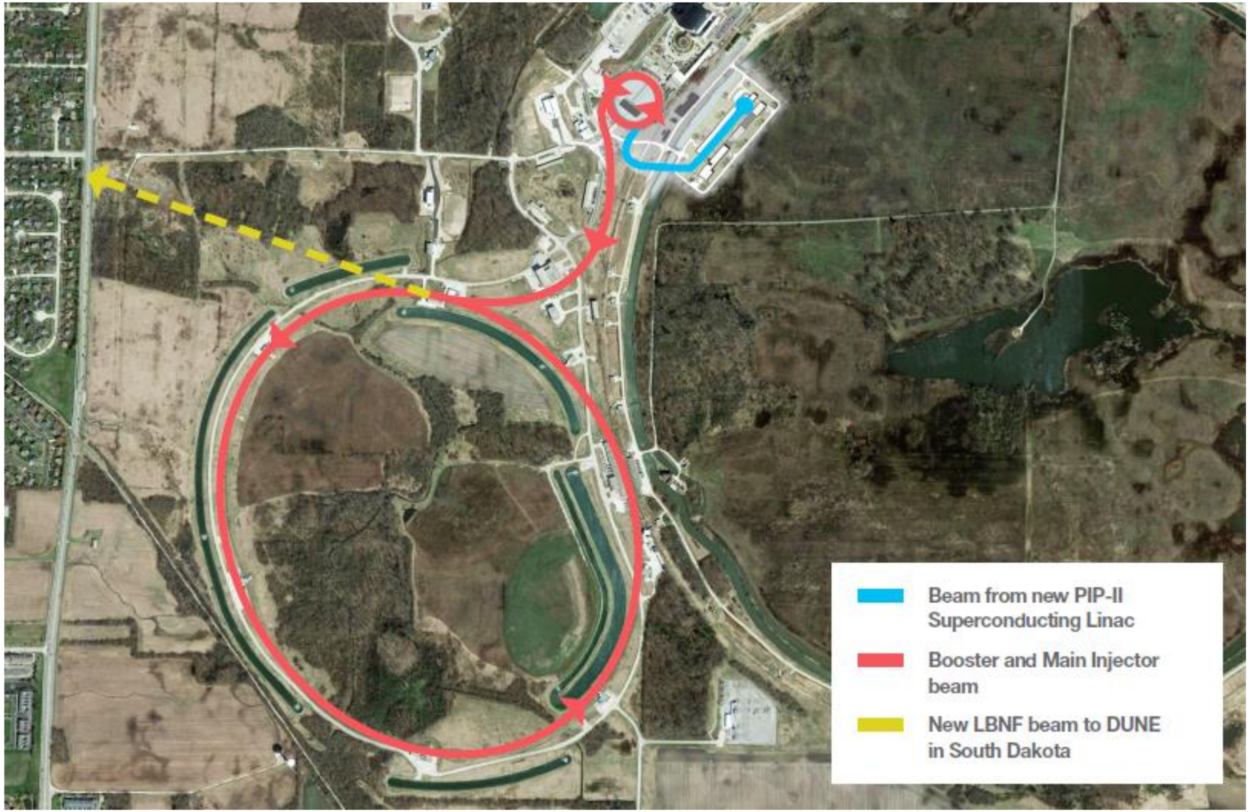
Main Injector (1998)

8 to 120 GeV ramp, cycle time 1.2-1.4 s



1.33s cycle shown

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



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

PIP-II Project provides

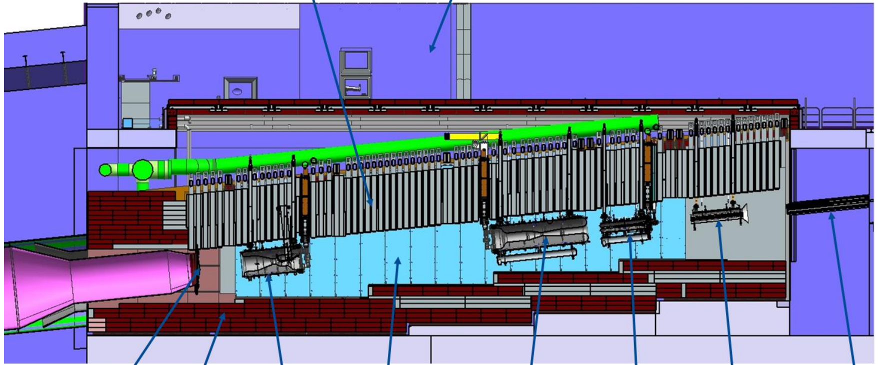
- New SRF linac for injection into Booster at 800 MeV (present 400 MeV).
- Booster cycle rate upgraded to 20 Hz from 15 Hz.
- Increased proton beam intensity for 1.2 MW beam power from MI.

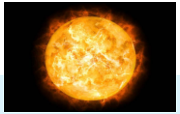
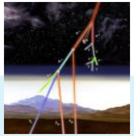
		PIP-II Booster	
Operation scenario	**Present**	**PIP-II**	**units**
MI 120 GeV ramp rate	**1.333**	**1.2**	s
Booster intensity	**4.5**	**6.5**	10^{12} p
Booster ramp rate	15	**20**	Hz
Number of Booster batches	12	12	
MI power	0.865	**1.2**	MW
cycles for 8 GeV	6	12	
Available 8 GeV power	29	**83**	kW

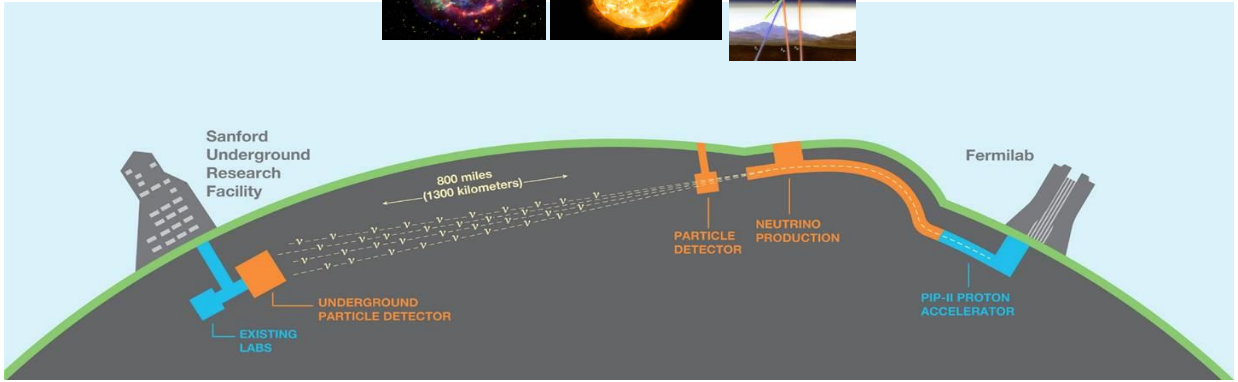
Accelerator Complex in PIP-II / LBNF era (pre ACE plan)

LBNF/DUNE-US Project provides

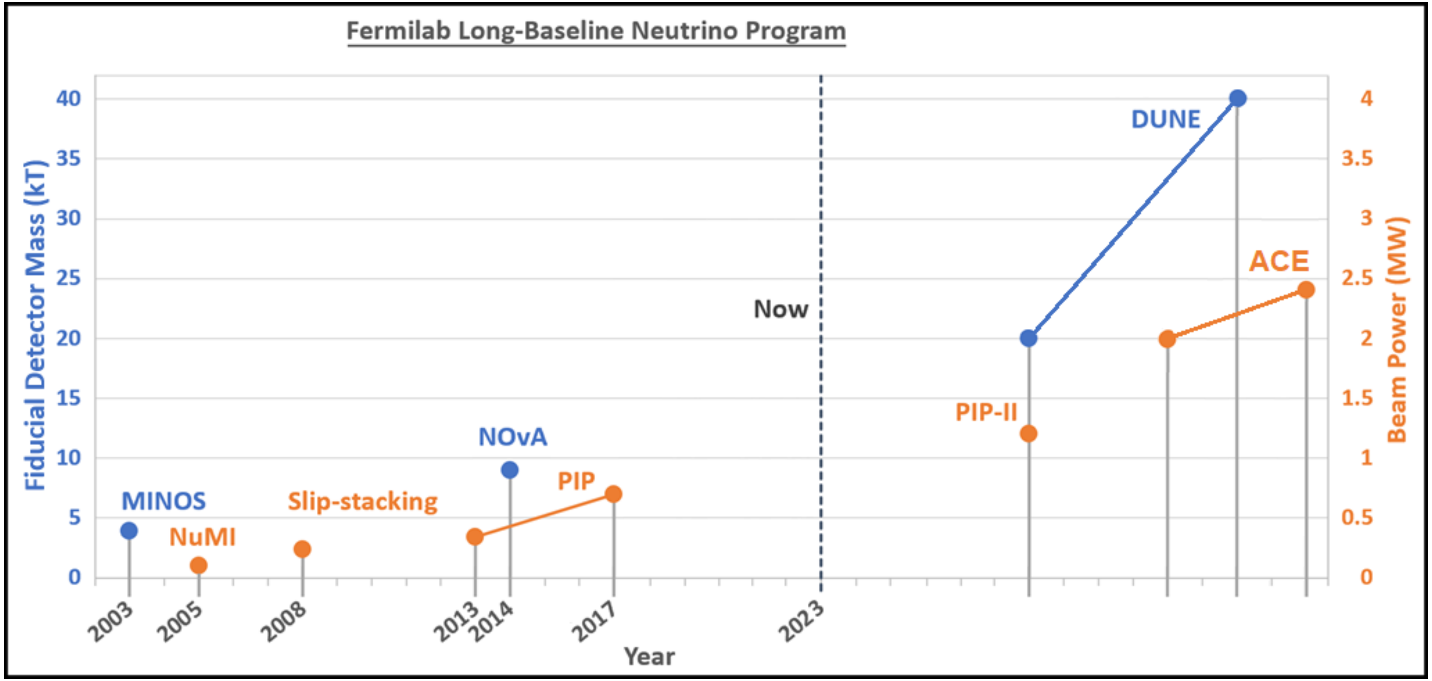
- New proton beamline for up to **2.4 MW**
- Target systems for **1.2 MW**
- Shielding and absorber for up to **2.4 MW**





Past & Future Long Baseline Neutrino Program



Updated from J. Eldred, JINST 2019

PIP-II upgrade will provide proton power of 1.2-1.35 MW;
ACE upgrade to 2.4 MW will make best use of the 40 kT DUNE detector.

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Accelerator Complex Evolution (ACE) plan

Previously referred to as PIP-III

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

Ongoing Projects and Operations

ACE

2 MW
- Reliability upgrades
- Main Injector capabilities (cycle time)

New Projects and addl. Ops

- Target Systems capability improvements

ACE-MIRT
Main Injector Ramp & Targetry

2.4 MW
- Booster replacement
  - PIP-II Linac extension to 2GeV
- New physics capabilities

Project to build new machine

ACE-BR
Booster Replacement

2.4 MW Upgrade with Reliability, Capability, Capacity

ACE MIRT – Main Injector Ramp & Targetry

PIP-II is 1.2 MW for DUNE/LBNF program with 1.2s Main Injector cycle

ACE-MIRT proposed to reduce Main Injector cycler to ~0.65s to increase beam power

		PIP-II Booster			
Operation scenario	**Present**	**PIP-II**	**A**	**B**	**units**
MI 120 GeV ramp rate	**1.333**	**1.2**	0.9	**0.7**	s
Booster intensity	**4.5**			**6.5**	10^{12} p
Booster ramp rate	15			**20**	Hz
Number of batches	12		12		
MI power	0.865	**1.2**	1.7	**2.14**	MW
cycles for 8 GeV	6	12	6	2	
Available 8 GeV power	29	**83**	56	**24**	kW

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ACE MIRT – Main Injector Ramp & Targetry

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

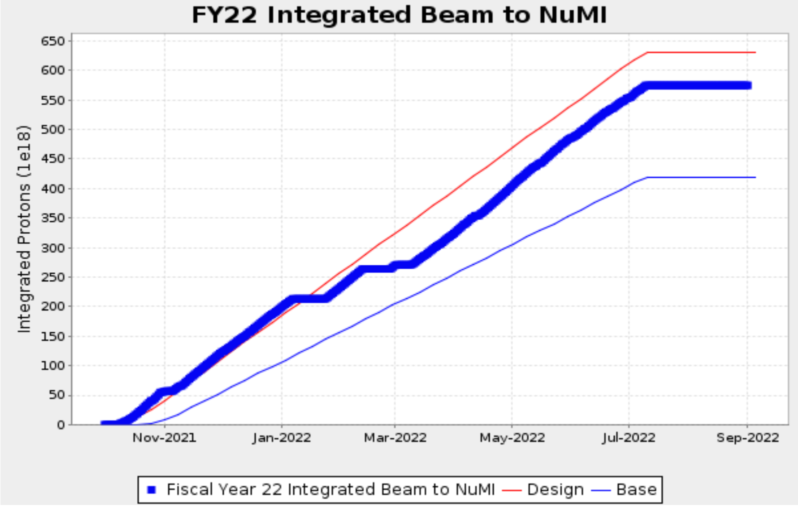
- New low-level RF, new power supply regulation/control system

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%

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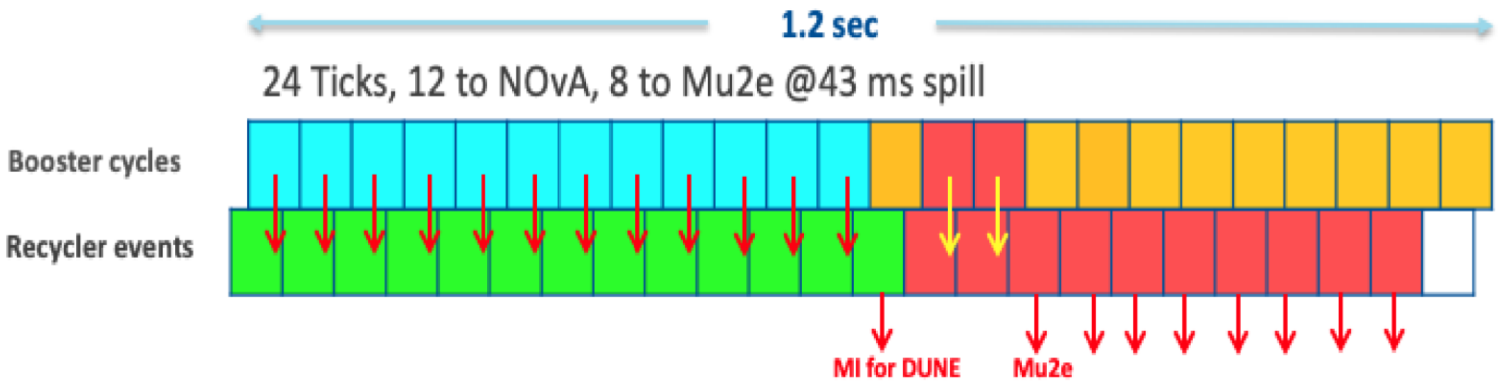
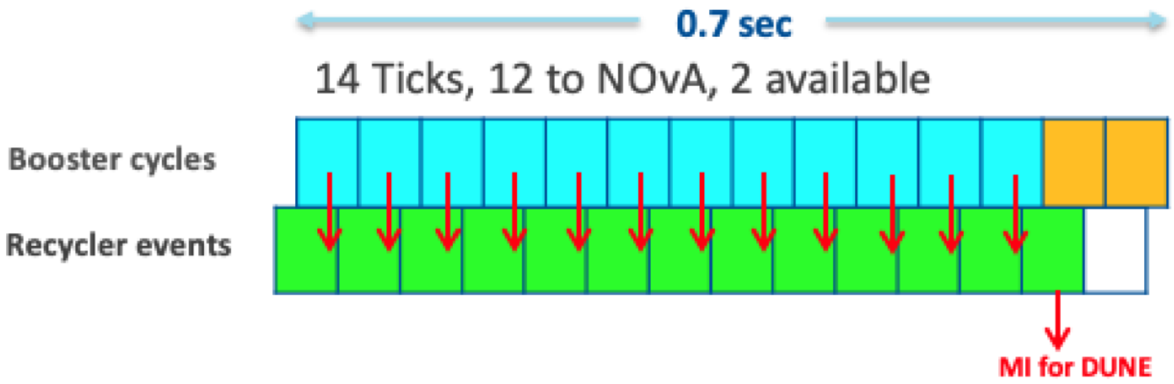
Impact of shortened cycle on other experiments

PIP-II Era MI Cycle:



ACE-MIRT MI Cycle:



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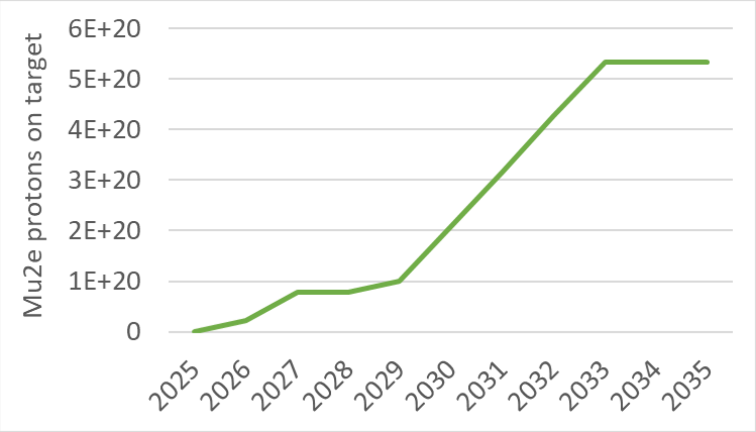
Impact of shortened cycle on other experiments

- 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

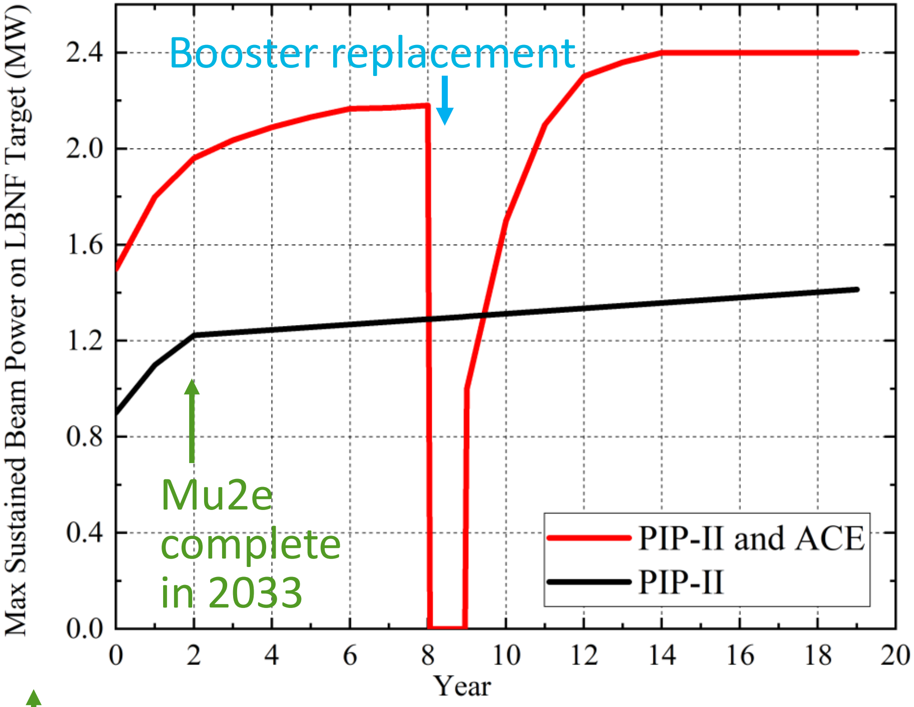
1. Limit beam power to DUNE (1.2s cycle) until Mu2e complete (2033)
   – Mu2e beam request is 3.6×10^{20} POT physics data, total 4.7×10^{20} including calibration
   – May be consistent with LBNF/DUNE commissioning, high-power target/horn development

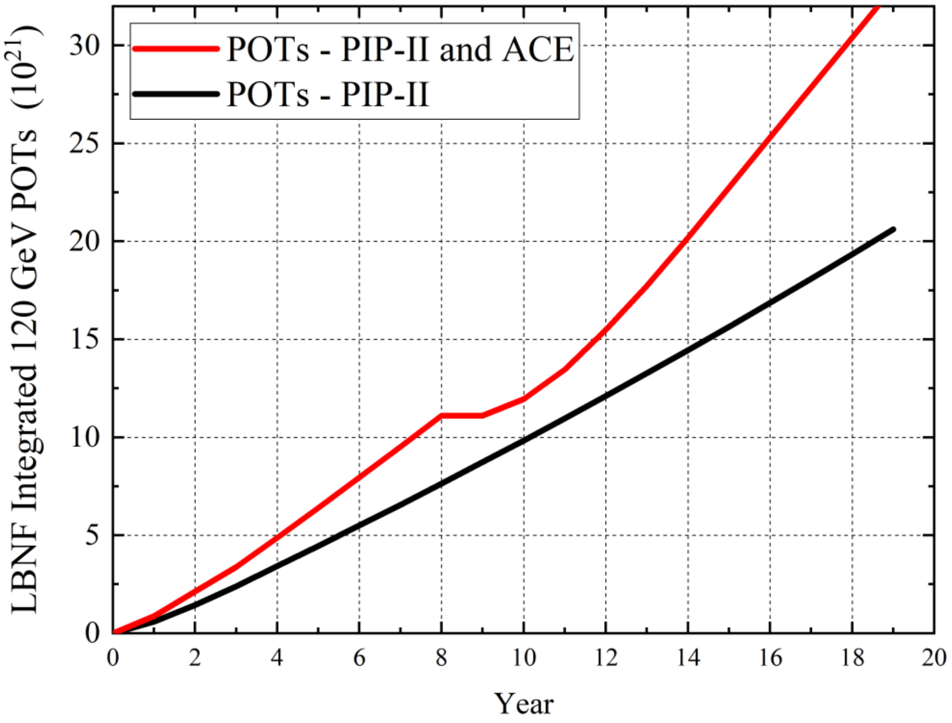


2. Run shorter cycle time with shortened spill durations to Mu2e
   – Has some effect on Mu2e physics, working with experiment to quantify
3. Run shorter cycle time with fewer spills to Mu2e
   – Extends duration needed to obtain requested Mu2e dataset
   – DUNE larger initial dataset but no overall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

Fermilab is committed to delivering Mu2e

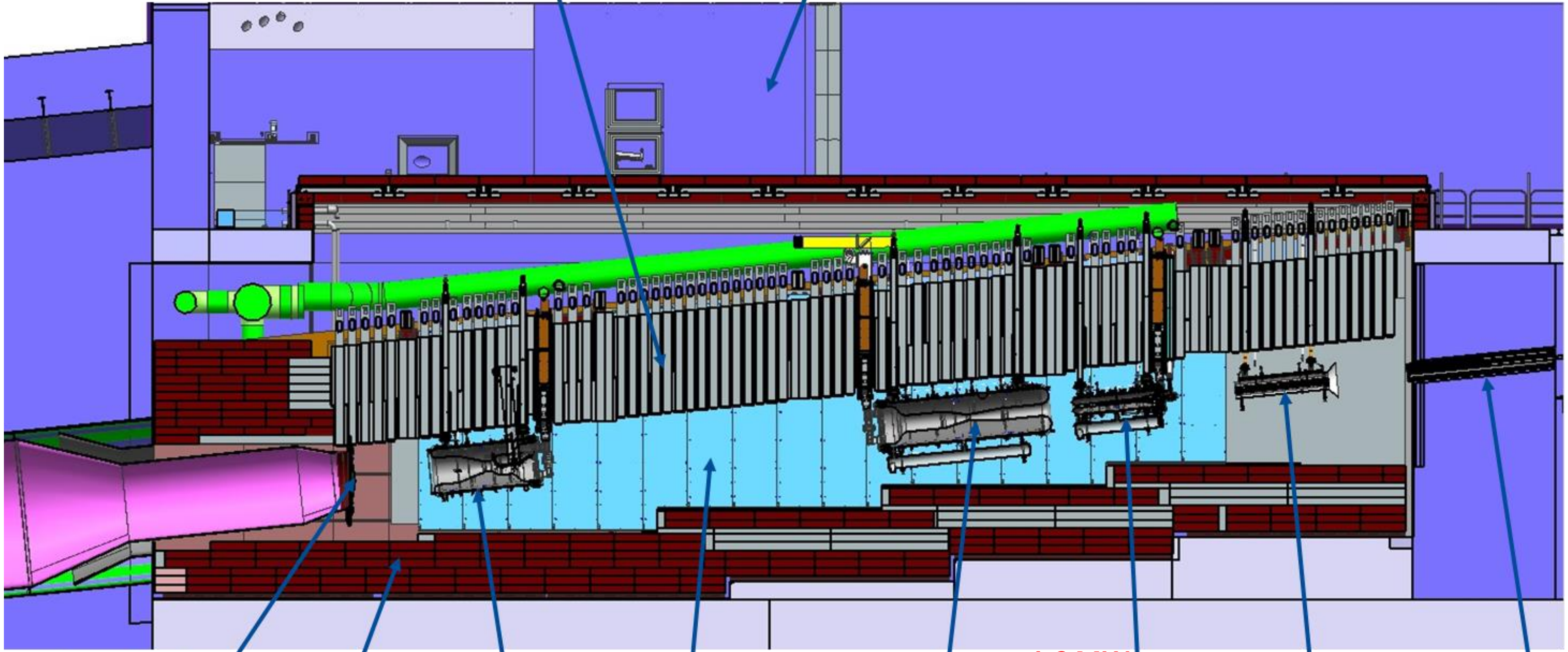
DUNE Power and Protons-on-Target (POTs)



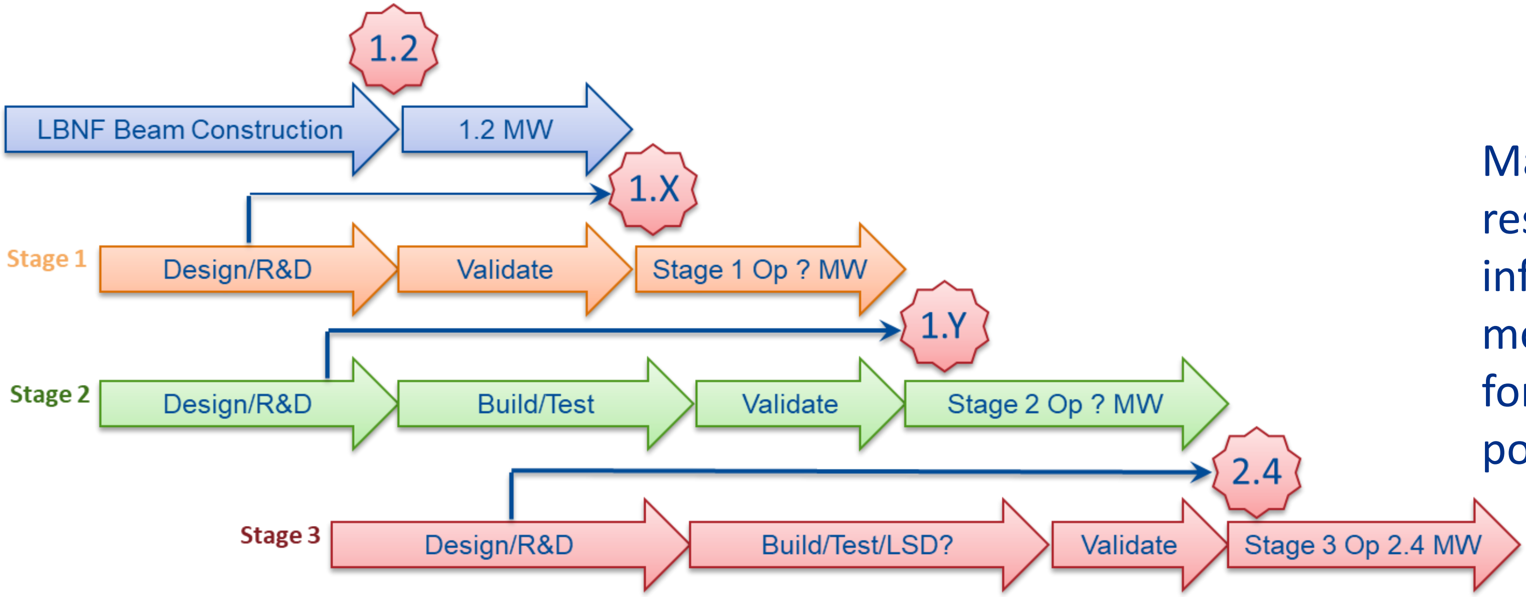


(Mu2e restarts 2029)

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)

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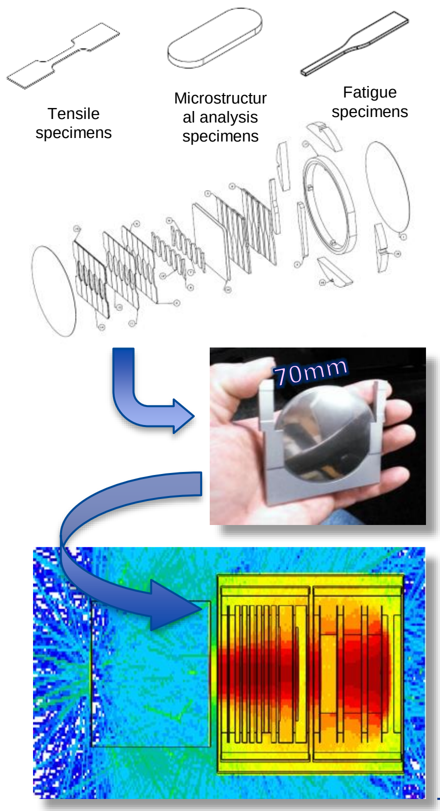
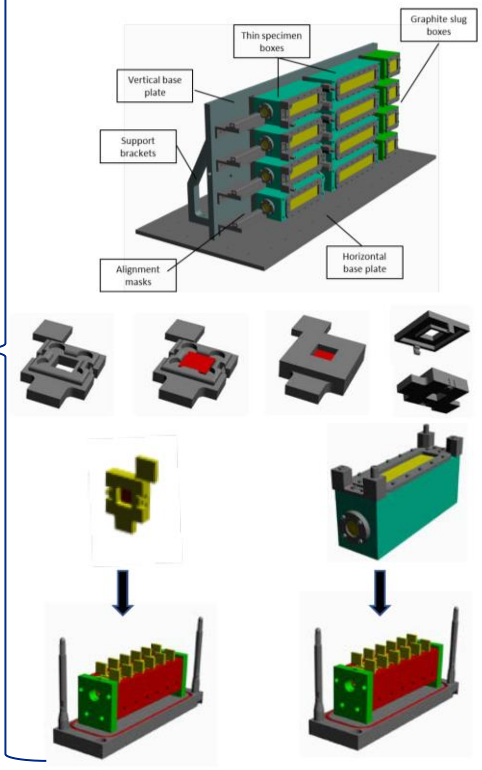
Target materials R&D on critical path to 2+ MW target



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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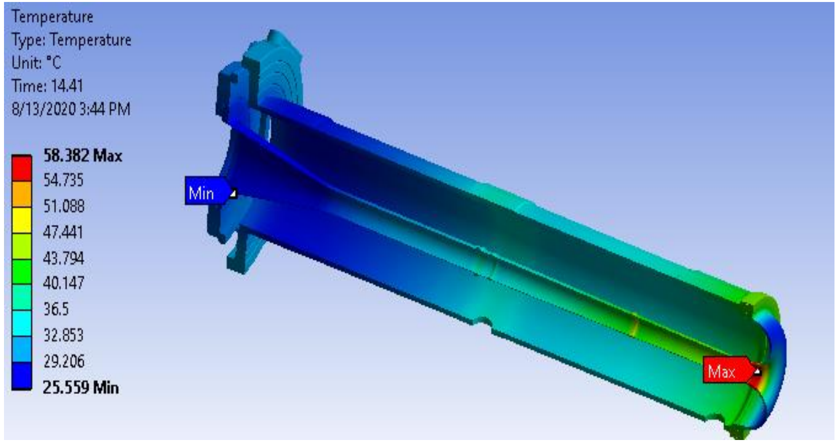
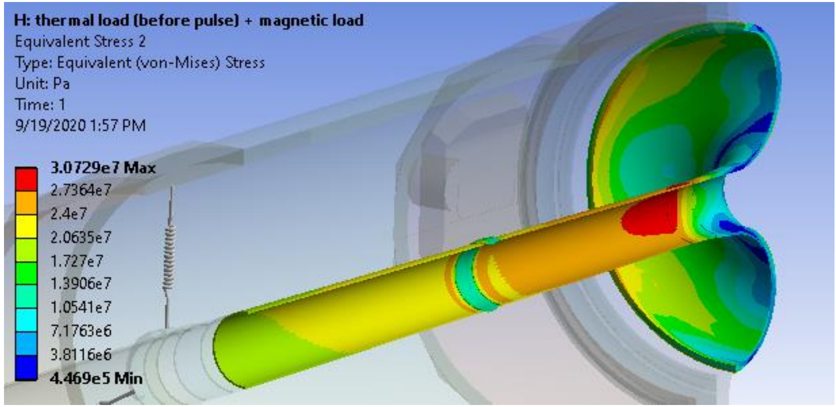
Horns for 2.4 MW performance

- 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



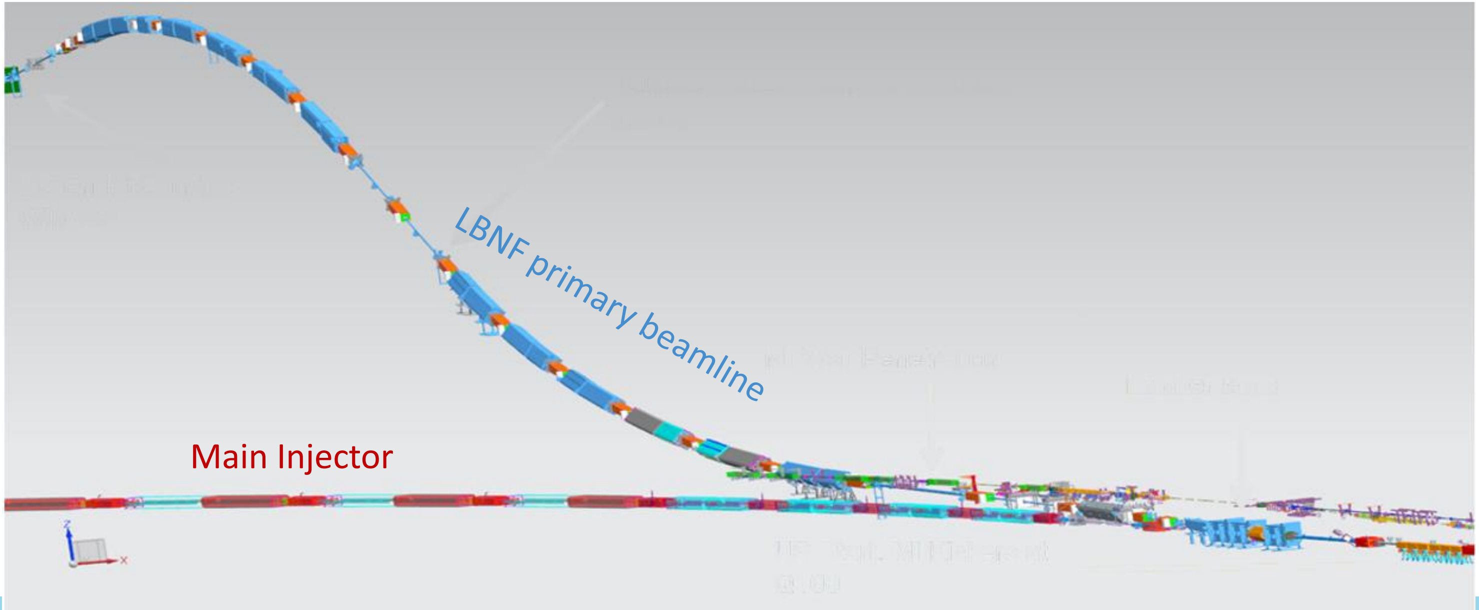


LBNF beamline

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



Accelerator Complex Evolution (ACE) plan

1.2 MW	• PIP-II Project replaces Linac • Modernization/upgrades of complex	*Ongoing* Projects and Operations
2 MW	• Reliability upgrades • Main Injector capabilities (cycle time) • Target Systems capability improvements	New Projects and addl. Ops
2.4 MW	• Booster replacement • PIP-II Linac extension to 2GeV • New physics capabilities	Project to build new machine

ACE

ACE-MIRT
Main Injector Ramp & Targetry

ACE-BR
Booster Replacement

2.4 MW Upgrade with Reliability, Capability, Capacity

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ACE BR – Booster Replacement

The Fermilab Booster will be over 60 years old.

- Booster intensity limited by the injection region and transition-crossing.

ACE BR is a new accelerator that will be greater reliability and intensity.

- Either a 2-GeV Linac + a 2-8 Rapid-Cycling Synchtron (RCS)
- Or an 8-GeV SRF Linac + an 8-GeV Accumulator Ring (AR)

ACE-BR will provide 2.4 MW to LBNF.

Potential new science beamlines ('spigots'):

2 GeV Continuous Wave (CW)

2 GeV Pulsed Beam (~ 1MW)

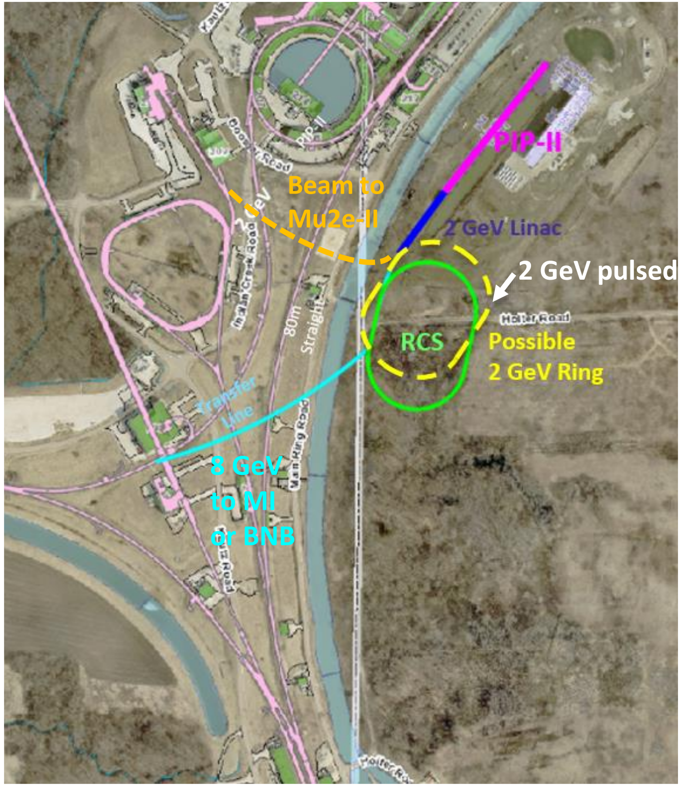
8 GeV Pulsed (~ 1MW)

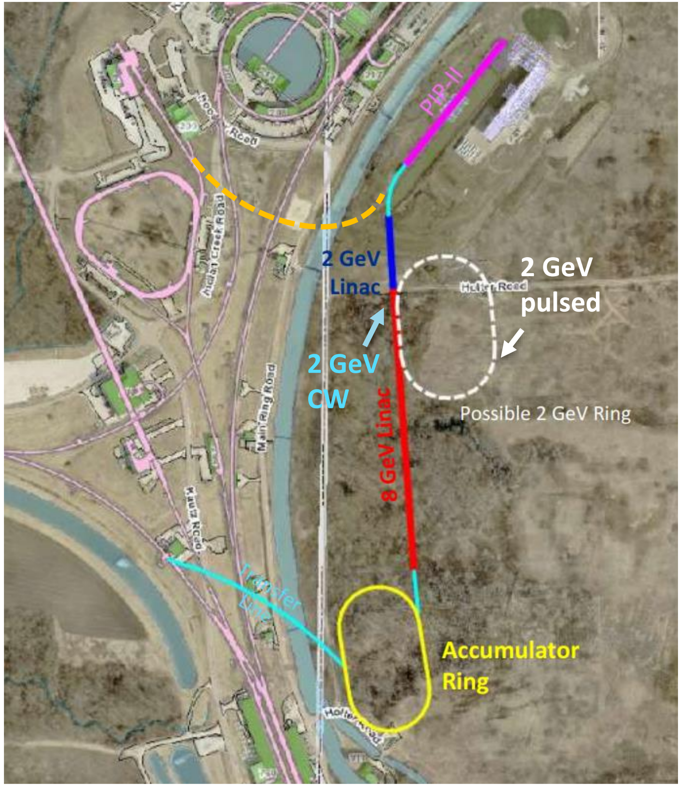
Platform for collider R&D; front-end for future Muon Collider.

Recent ACE Science Workshop in June 2023.

Example Booster replacement options and possible add-ons

2GeV Linac + 2-8GeV RCS **or** 8GeV Linac + 8GeV AR





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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
  - 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

Linac Beams with ACE-BR

Linac Beam at	0.0-0.8 GeV	0.8-2 GeV	2-8 GeV
PIP-II	2mA, CW	-	-
ACE RCS v1	2mA, CW	2mA, CW	-
ACE RCS v2	2mA, CW	2mA, CW	-
ACE RCS v3	5mA, 2ms, 20Hz	5mA, 2ms, 20Hz	-
ACE Linac v1	2.7mA, CW	2.7mA, 2ms, 20Hz	2.7, 1.5ms, 10Hz
ACE Linac v2	5mA, 2ms, 20Hz	5mA, 2ms, 20Hz	5mA, 2ms, 10Hz
ACE Linac v3	5mA, 2ms, 20Hz	5mA, 2ms, 20Hz	5mA, 2ms, 20Hz

RCS v1, RCS v2 extend CW linac out to 2 GeV

RCS v3, Linac v2, Linac v3 may lose CW capability for enhanced pulsed linac.

Linac v1 upgrades CW linac at 0.8 GeV, pulsed thereafter.

Pulsed Beam Power Available with ACE-BR

Pulsed Power at	0.8-2.0 GeV*	8 GeV
PIP-II	up to 2000 kW	80 kW
ACE RCS v1	up to 4000 kW	160 kW
ACE RCS v2	up to 2000 kW	720 kW
ACE RCS v3	400 kW	720 kW
ACE Linac v1	up to 2000 kW	160 kW
ACE Linac v2	400 kW	570 kW
ACE Linac v3	400 kW	1200 kW

0.8-2.0 GeV Power*: Pulsed power only if there is an accumulator ring, and only up to the capabilities of the accumulator ring.

8 GeV Power: What is available after serving DUNE/LBNF program.
ACE-BR has a major impact on the 8-GeV power!

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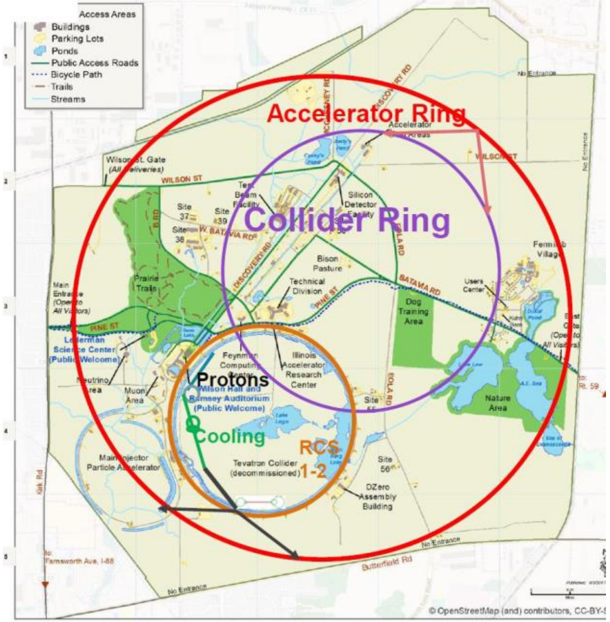
Muon Collider

Synergies with ACE program

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



Fermilab ACE program offers several synergies with Muon Collider R&D.

The ACE Booster Replacement plan could provide a path to a Muon Collider front-end.

Parameter	ACE-BR Scenarios	MuC-PD Scenarios
Energy	8 GeV	8-20 GeV
Rep. Rate	10-20 Hz	5-10 Hz
Power	0.3-1.6 MW	1-4 MW
Proton Structure	25-40 e12 over 2 μs ring	20-160 e12 in four 1-3 ns bunches

Example Path: ACE-Linac to Muon Collider (MuC)

Start with ACE-Linac v2 Configuration

That is **10 Hz x 5mA x 2ms x 8 GeV = 0.8 MW**

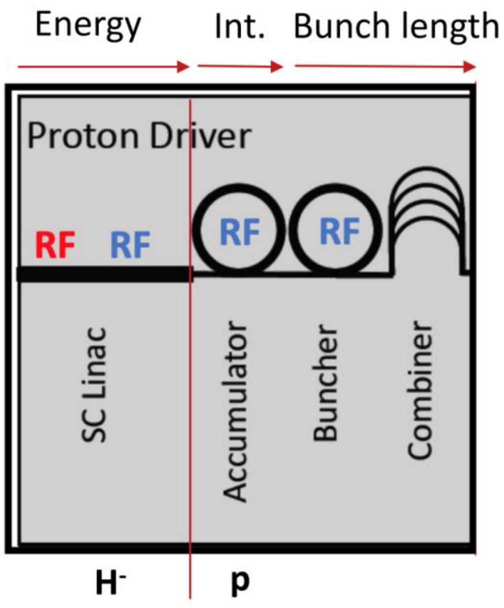
Upgrading to linac current **6-25mA**, we have **1-4 MW.**

Can we re-use the 8-GeV AR from ACE for MuC?

- MuC requirements are stricter than neutrino requirements.
  - Overdesign or re-build the 8-GeV AR?
- In the meantime any 8-GeV AR is useful for R&D.

MuC would also need an compressor ring, combiner, targetry.

- These upgrades could occur in stages in parallel with MuC R&D, construction, commissioning.



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Summary

- The ACE plan 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, upgrades 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
- The ACE plan capitalizes on the PIP-II investment and delivers
  – More protons-on-target 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 that enables new capabilities