Fermilab Proton Complex & Planning for Muon Collider Proton Driver

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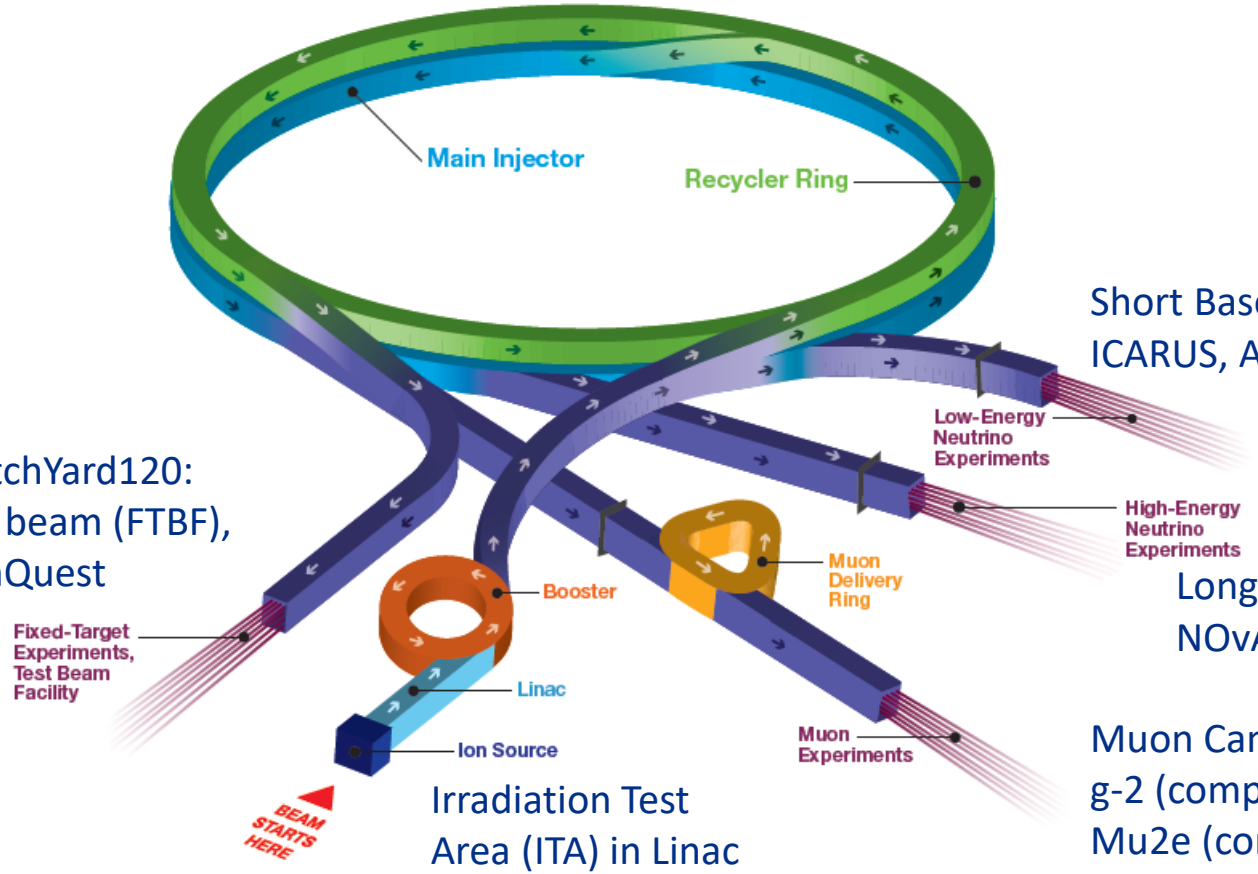
IMCC 2024 Annual Meeting

March 13rd 2024

Fermilab Proton Complex Plan through ~2033 (LBNF, PIP-II, and ACE-MIRT)

Accelerator Complex



Short Baseline Neutrino:
ICARUS, ANNIE, SBND

SwitchYard120:
test beam (FTBF),
SpinQuest

Long Baseline Neutrino:
NOvA

Muon Campus:
g-2 (completed),
Mu2e (commissioning)

Irradiation Test
Area (ITA) in Linac

Introduction to Fermilab accelerators

H^- linac (1970, 1993, 2012)

- 400 MeV linac ~20mA

Booster synchrotron (1970)

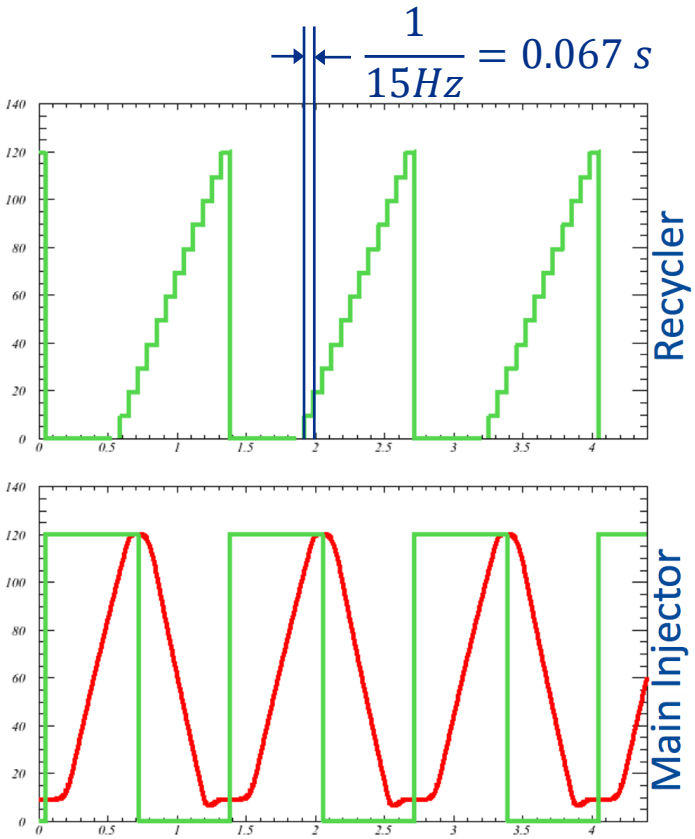
- H^- stripping injection (1978)
  16 turns to ~4.7×10^{12} p per pulse
- Ramp from 0.4 to 8 GeV at 15 Hz

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

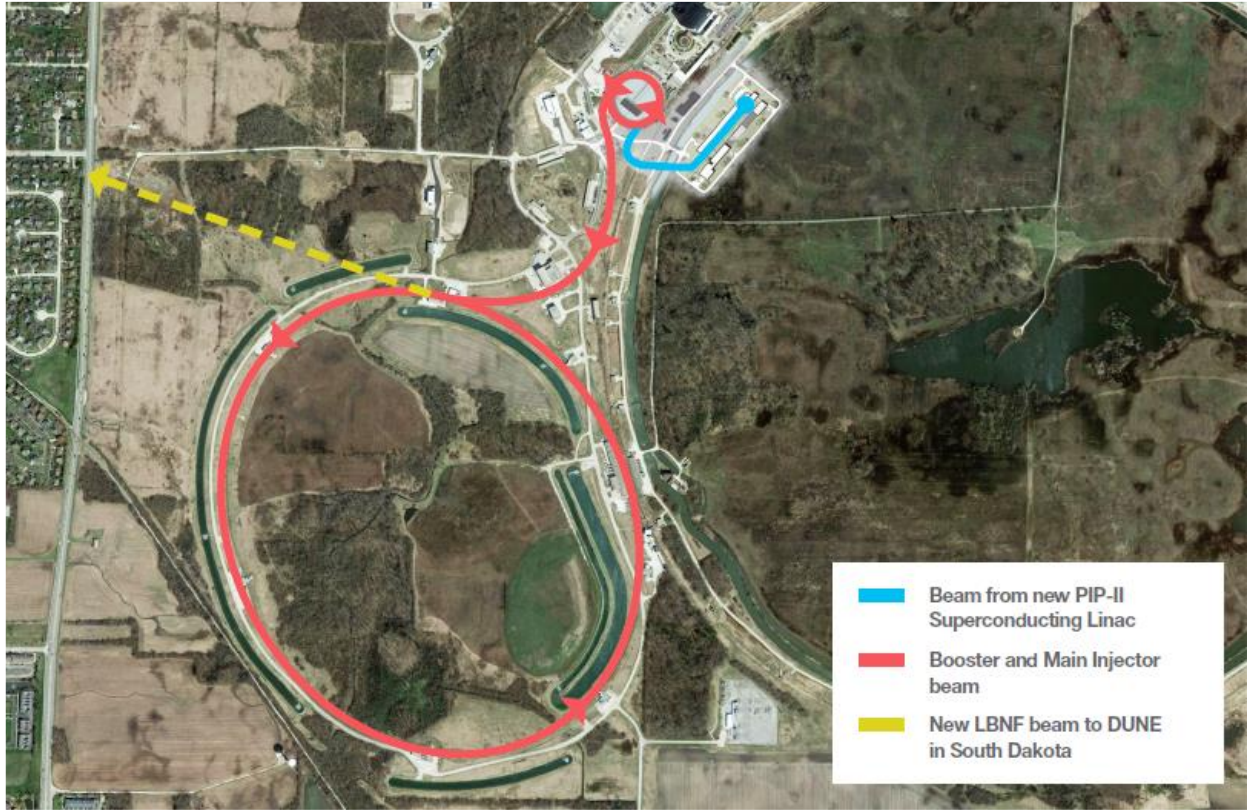
Main Injector (1998)

8 to 120 GeV ramp, cycle time 1.133s



1.33s cycle shown

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



Proton Complex

Booster, Recycler
Main Injector

PIP-II Linac

8-GeV, 2mA, CW

LBNF Beamline to DUNE experiment

120 GeV, 1.2-2.4 MW

PIP-II Major Milestones

Mar 2018
Approve Alternative Selection (CD-1)

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

Oct 2026
Shutdown Complex Operations For Booster Connection

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

Sep 2024
Linac Tunnel Occupancy

Jan 2027
SRF Linac Comm. Begins

2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028

Jul 2020
Cryoplant Bldg. Construction Approved

Apr 2022
Approve Technical Construction (CD-3)

Dec 2028
Project Completion
Start of Operations
(Early CD-4)

Mar 2019
Linac Complex Ground-Breaking

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

PIP-II Project provides

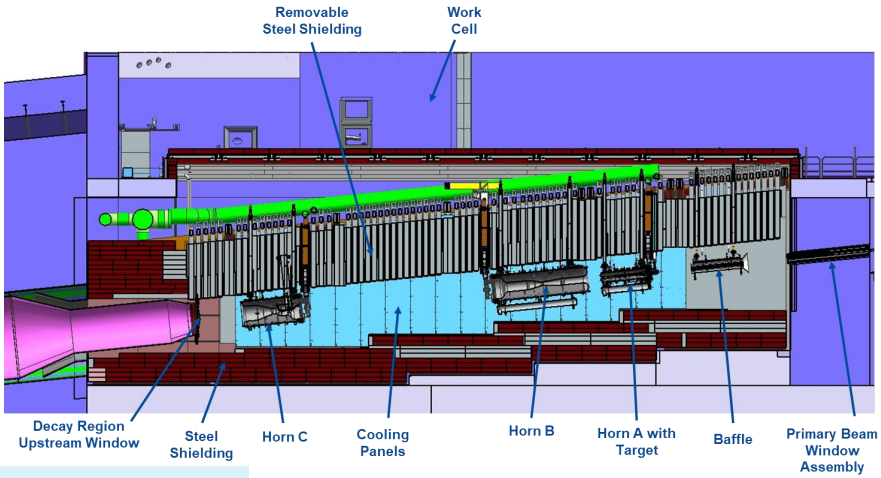
- New SRF linac for injection into Booster at 800 MeV (present 400 MeV).
- Booster cycle rate upgraded to 20 Hz from 15 Hz.
- Increased proton beam intensity for 1.2 MW beam power from MI.

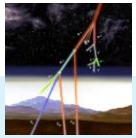
		PIP-II Booster		
Operation scenario	**Nominal**	**PIP-II**	**units**	**Demonstrated**
MI 120 GeV ramp rate	**1.333**	**1.2**	s	**1.133 s**
Booster intensity	**4.5**	**6.5**	10^{12} p	**4.7-4.9 e12**
Booster ramp rate	15	**20**	Hz	
Number of Booster batches	12	12		
MI power	0.75	**1.2**	MW	**0.96 MW**
cycles for 8 GeV	6	12		
Available 8 GeV power	29	**83**	kW	

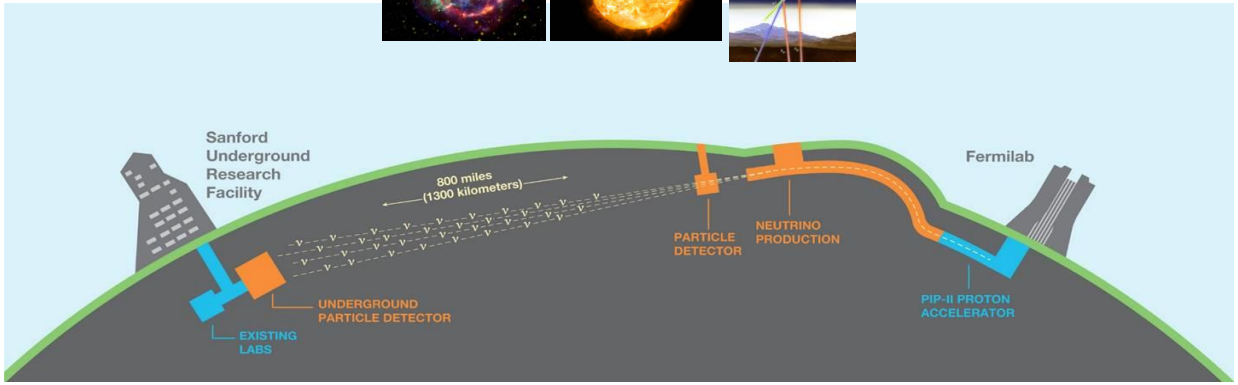
Accelerator Complex in PIP-II / LBNF era

LBNF/DUNE-US Project provides

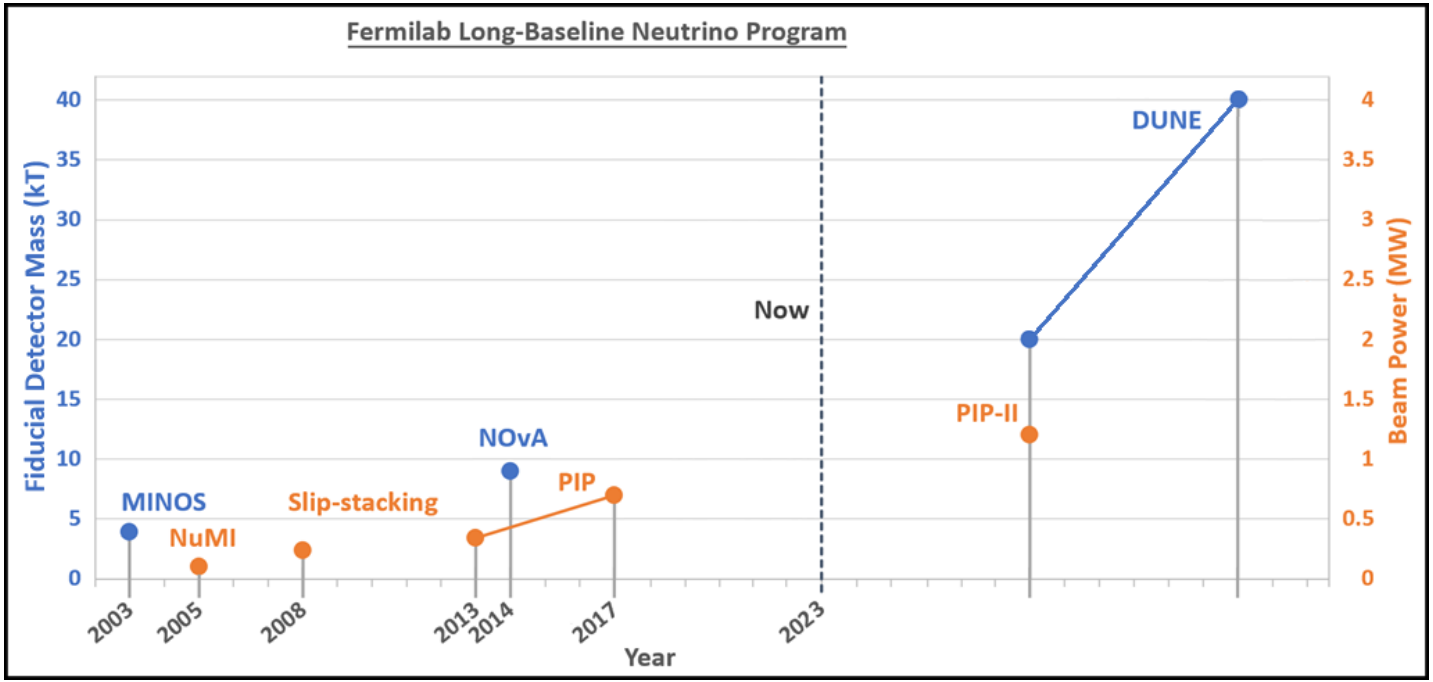
- New proton beamline for up to **2.4 MW**
- Target systems for **1.2 MW**
- Shielding and absorber for up to **2.4 MW**







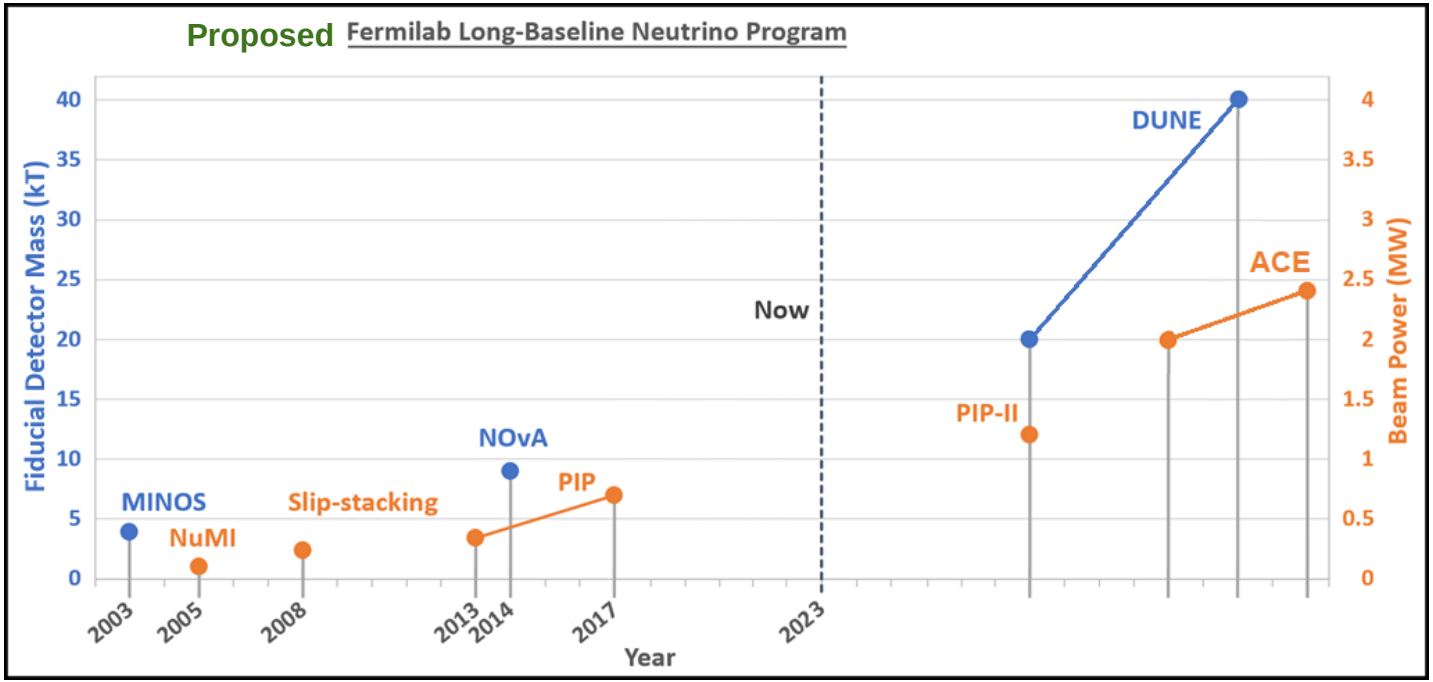
Past & Future Long Baseline Neutrino Program



Updated from J. Eldred, JINST 2019

PIP-II upgrade will provide proton power of 1.2 MW (at most 1.35 MW).

Past & Future Long Baseline Neutrino Program (with ACE)



Updated from J. Eldred, JINST 2019

PIP-II upgrade will provide proton power of 1.2 MW (at most 1.35 MW).

ACE upgrade to 2+ MW will make best use of the 40 kT DUNE detector.

Accelerator Complex Evolution (ACE) plan

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)
- Target Systems capability improvements

New Projects and addl. Ops

ACE-MIRT
Main Injector Ramp & Targetry

ACE MIRT – Main Injector Ramp & Targetry

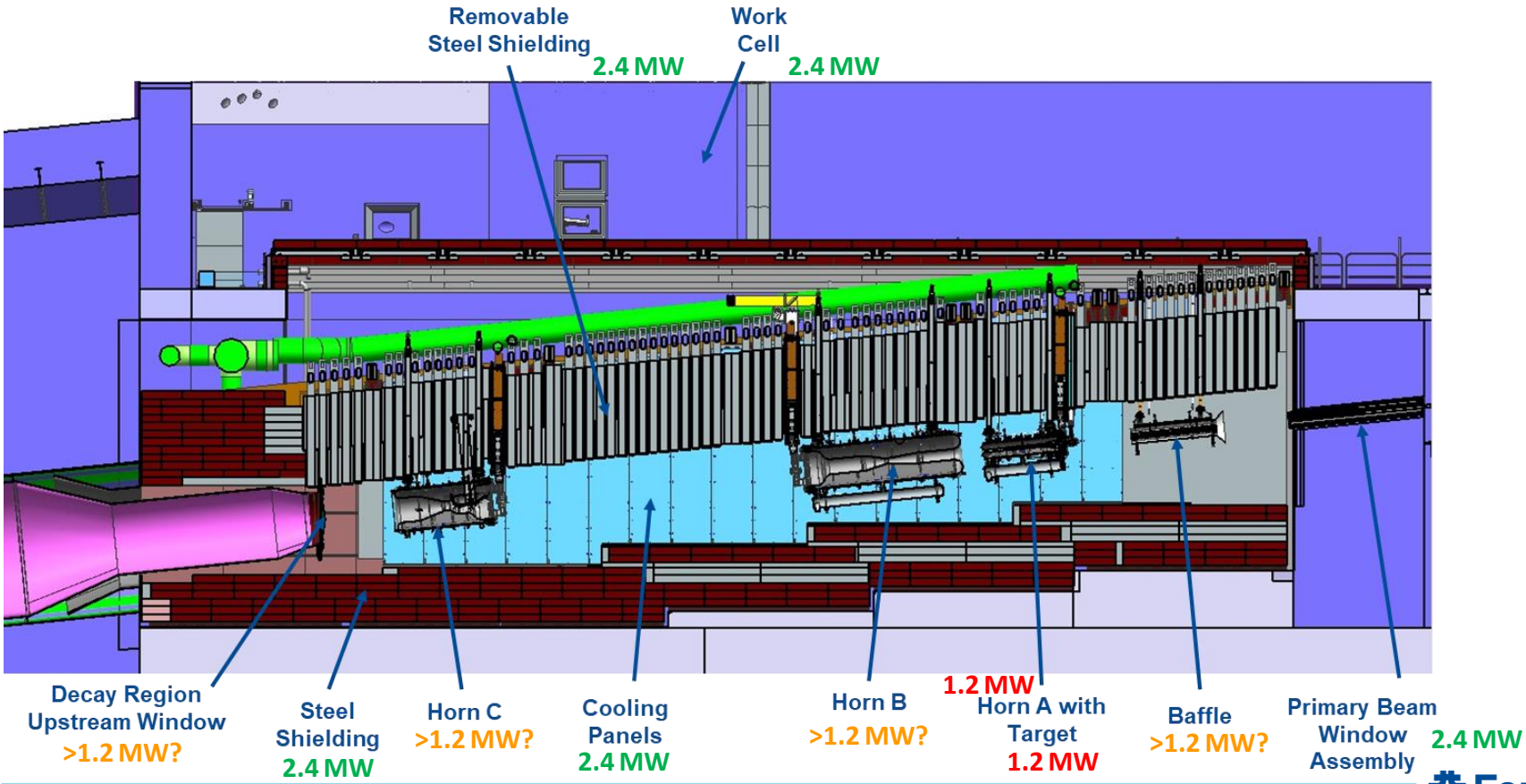
PIP-II is 1.2 MW for DUNE/LBNF program with 1.2s Main Injector cycle

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

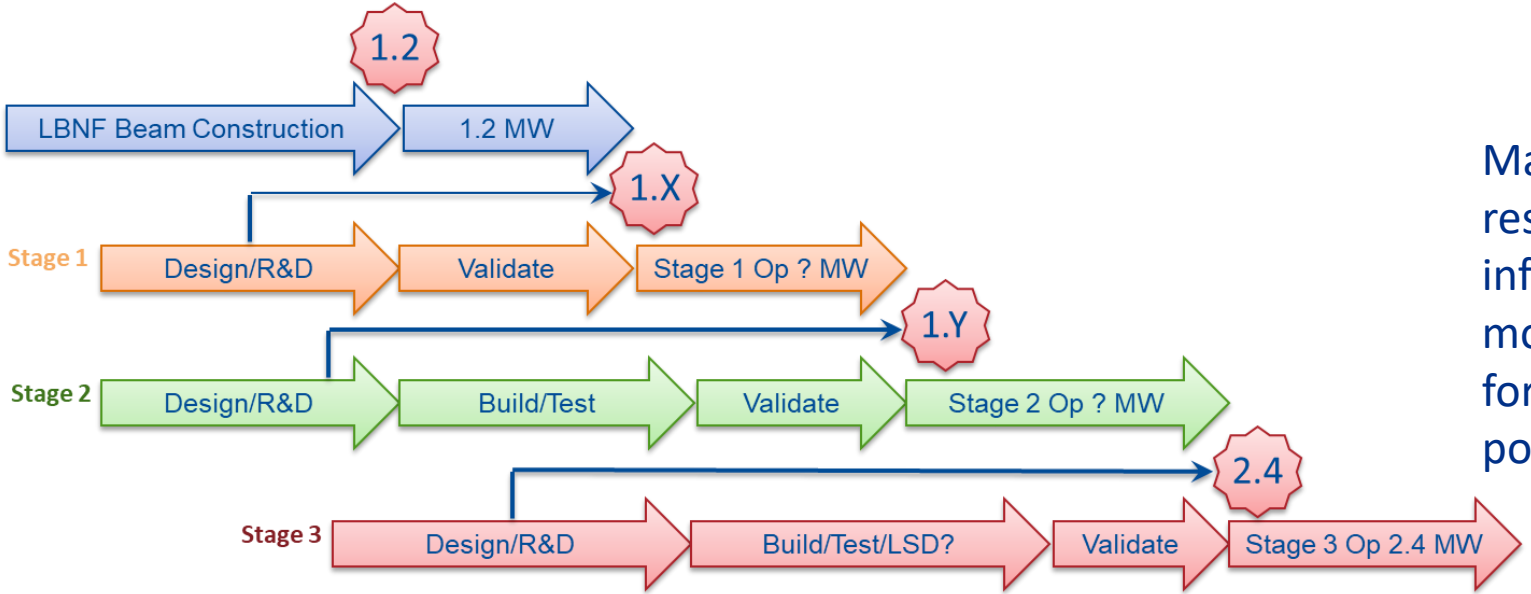
		PIP-II Booster			
Operation scenario	**Nominal**	**PIP-II**	**A**	**B**	**units**
MI 120 GeV ramp rate	**1.333**	**1.2**	0.9	**0.7**	s
Booster intensity	**4.5**			**6.5**	10^{12} p
Booster ramp rate	15			**20**	Hz
Number of batches	12		12		
MI power	0.75	**1.2**	1.7	**2.14**	MW
cycles for 8 GeV	6	12	6	2	
Available 8 GeV power	29	**83**	56	**24**	kW

Main Injector magnets and RF upgraded by factor of two.

LBNF target systems



Target development staged approach

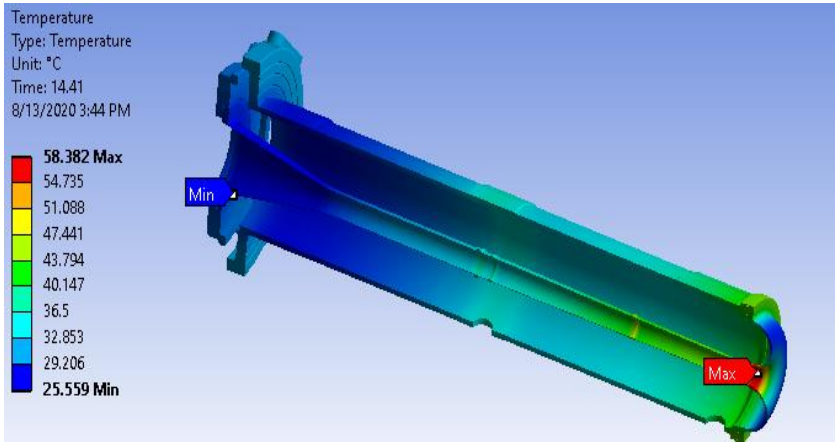


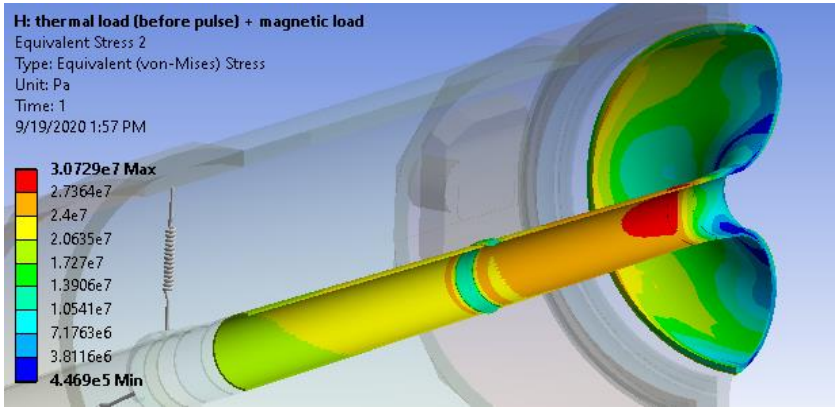
Materials R&D results needed to inform design modifications for higher beam power

- **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)

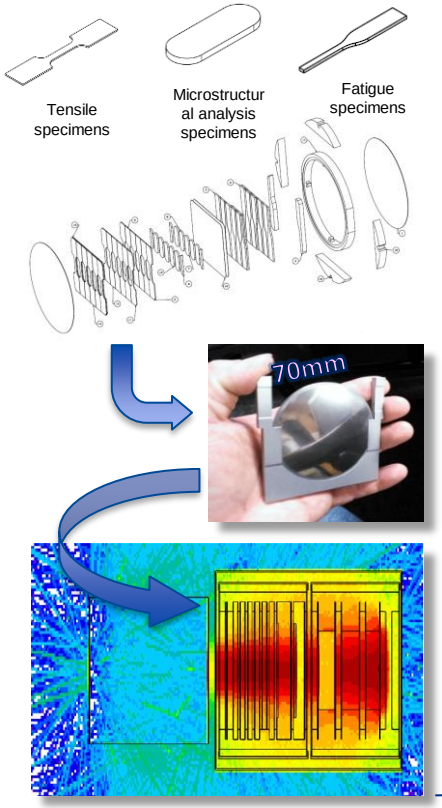
Horns for 2.4 MW performance

- 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





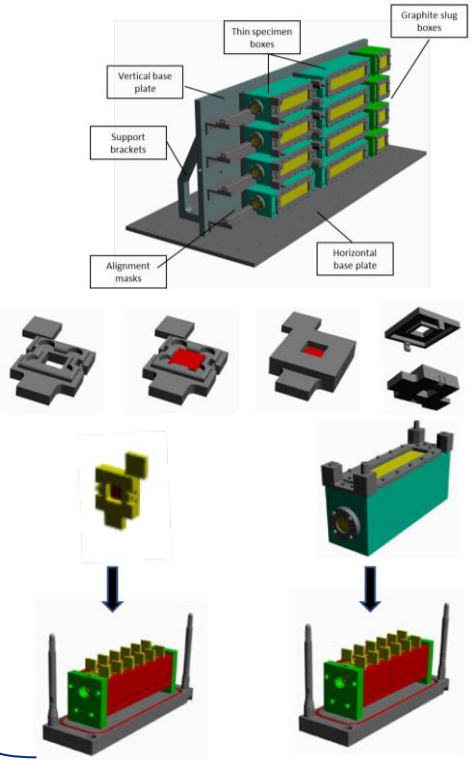
Target materials R&D on critical path to 2+ MW target



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

Five-year cycle needs to start ASAP

Scope not defined yet – can we integratate high-Z target R&D?



Recent Design Work on “Booster Replacement”

Accelerator Complex Evolution (ACE) plan

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

ACE-MIRT
Main Injector Ramp & Targetry

- Target Systems capability improvements

2.4 MW

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

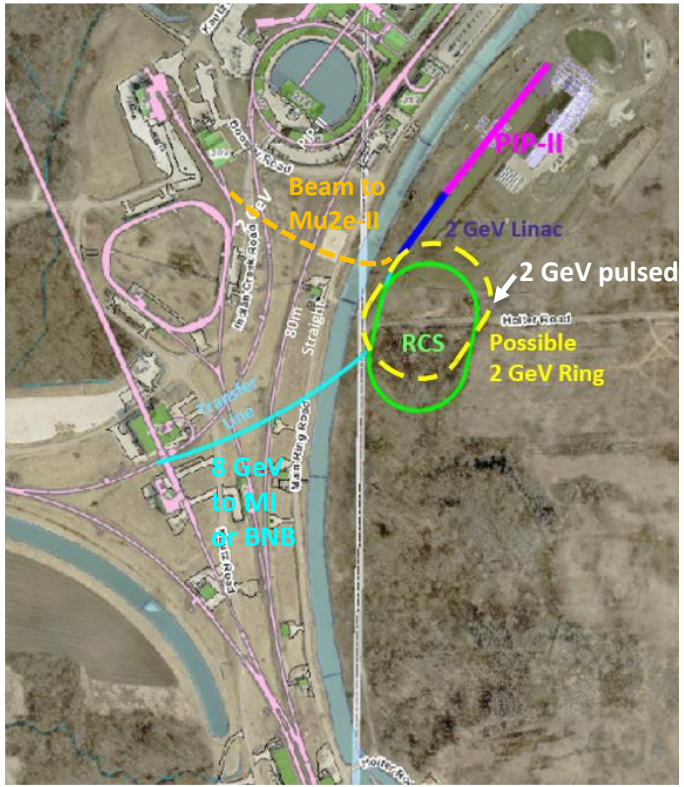
Project to build new machine

ACE-BR
Booster Replacement

Fermilab

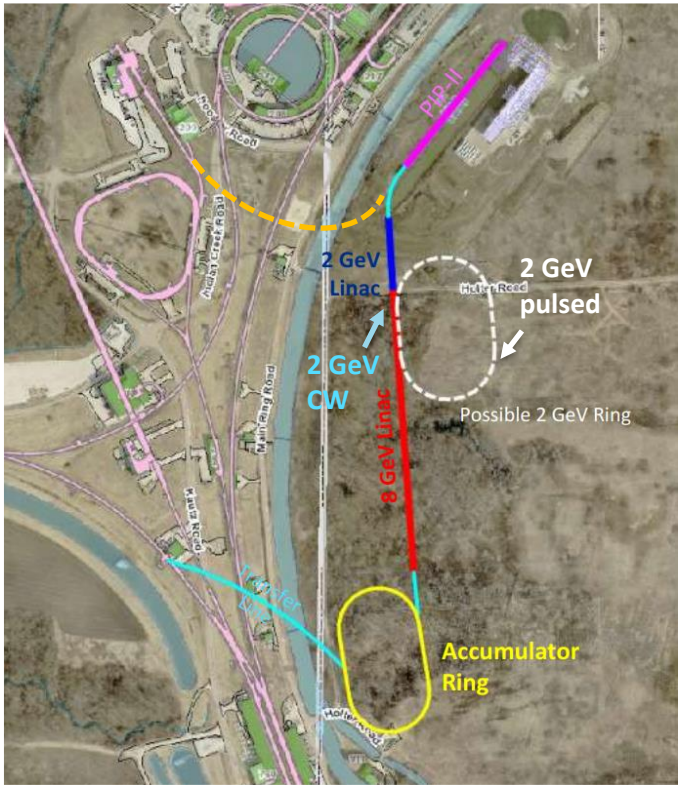
Example Booster replacement options and possible add-ons

2GeV Linac + 2-8GeV RCS



or

8GeV Linac + 8GeV AR



Path to Muon Collider

The ACE BR scenarios are mature accelerator designs

- Core focux on performance of neutrino program.
- Risk and cost analysis performed.

But, we need to develop new scenarios specifically oriented towards Muon Collider Proton Driver.

- Some of that prior design work will be instructive.

Parameter	ACE-BR Scenarios	MuC-PD Scenarios
Energy	8 GeV	5-12 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	60-320 e12 in four 1-3 ns bunches

2024 P5 Report Recommendations

P5 Recommendations

Affirms PIP-II, DUNE/LBNF, and ACE-MIRT:

Rec. 1 As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science. We **reaffirm the previous P5 recommendations** on major initiatives: **1b** **The first phase of DUNE and PIP-II** to determine the mass ordering among neutrinos, a fundamental property and a crucial input to cosmology and nuclear science.

Rec. 2: Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future. These projects have the potential to transcend and transform our current paradigms. They inspire collaboration and international cooperation in advancing the frontiers of human knowledge. **2b** **Re-envisioned second phase of DUNE with an early implementation of an enhanced 2.1 MW beam (ACE-MIRT), a third far detector, and an upgraded near-detector complex** as the definitive long-baseline neutrino oscillation experiment of its kind.

Area Rec. 13: Assess the **Booster synchrotron and related systems for reliability risks** through the first decade of DUNE operation, and take measures to preemptively address these risks.

P5 Recommendations

Calls for Accelerator R&D, especially for collider projects:

Rec. 4: Support a comprehensive effort to develop the resources—theoretical, computational and technological—essential to our 20-year vision for the field. This includes an **aggressive R&D program** that, while technologically challenging, could yield **revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.**

Area Rec. 8: Increase annual funding to the **General Accelerator R&D program** by $10M per year in 2023 dollars to ensure US leadership in key areas.

Area Rec. 9: **Support generic accelerator R&D** with the construction of small scale test facilities. Initiate construction of **larger test facilities based on project review**, and **informed by the collider R&D program.**

Area Rec. 10: **To enable targeted R&D before specific collider projects** are established in the US, an investment in collider detector R&D funding at the level of $20M per year and **collider accelerator R&D at the level of $35M per year in 2023 dollars is warranted.**

P5 Recommendations

Calls to Develop a New Vision for US Collider Program:

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**.

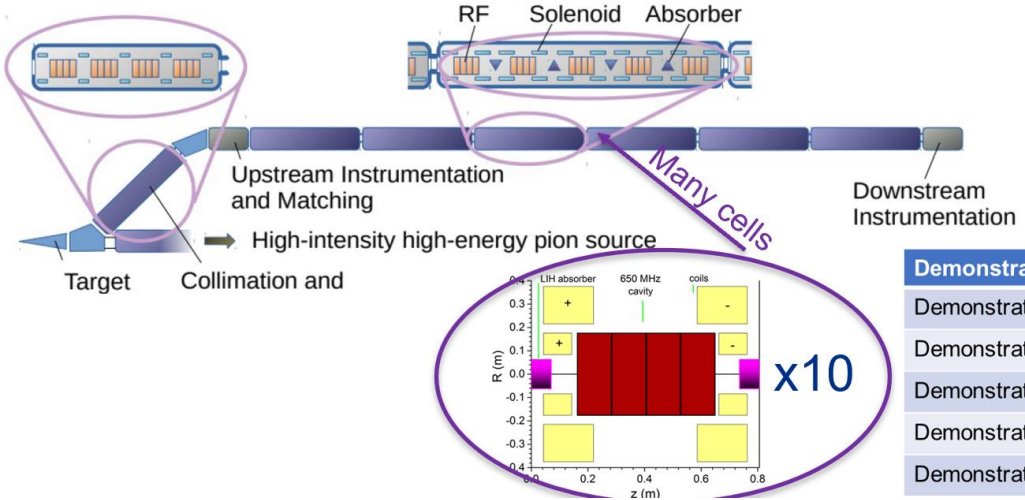
Rec. 6: Convene a targeted panel with broad membership across particle physics later this decade that makes **decisions on the US accelerator-based program** at the time when major decisions concerning an off-shore Higgs factory are expected, and/or significant adjustments within the acceleratorbased R&D portfolio are likely to be needed. A plan for the Fermilab accelerator complex consistent with the long-term vision in this report should also be reviewed. **4a** The level and **nature of US contribution in a specific Higgs factory** including an evaluation of the associated schedule, budget, and risks once crucial information becomes available. **4b** **Mid- and large-scale test** and demonstrator facilities in the accelerator and collider R&D portfolios. **4c** A plan for the **evolution of the Fermilab accelerator complex consistent** with the long-term vision in this report, which may commence construction in the event of a more favorable budget situation.

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**. Direct task force funding of up to $10M should be provided.

Some Recent Thinking on Fermilab Muon Collider

Muon Cooling Demonstrator Proposal

Next **5 years:** (1) A conceptual design of a demonstrator facility that allows testing the technology for cooling (2) Site exploration & cost estimate of a demo facility (3) Engineering design & start fabrication of a 1.5 prototype cooling cell



Credit: Yonehara (FNAL)

Demonstrator plan
Demonstrate operation of NC rf in B-field environment
Demonstrate forces between coils are manageable
Demonstrate performance of absorbers
Demonstrate performance of instrumentation system
Demonstrate 6D cooling with a realistic set-up

We are exploring Fermilab's Muon Campus (8-GeV protons / 3-GeV muons) as a possible site for this proposed muon cooling demonstrator.

Example FNAL MuC Proton Driver Scenario

Existing ACE design for an 8-GeV Linac

- **10 Hz x 5 mA x 2 ms x 8 GeV = 0.8 MW**
- ILC style cavity, LCLS-II style cryomodule, E-XFEL style RF power.
- Use higher linac current of **6-25mA**, that becomes **1-4 MW.**

H^- Injection in 8-GeV Accumulator Ring (AR)

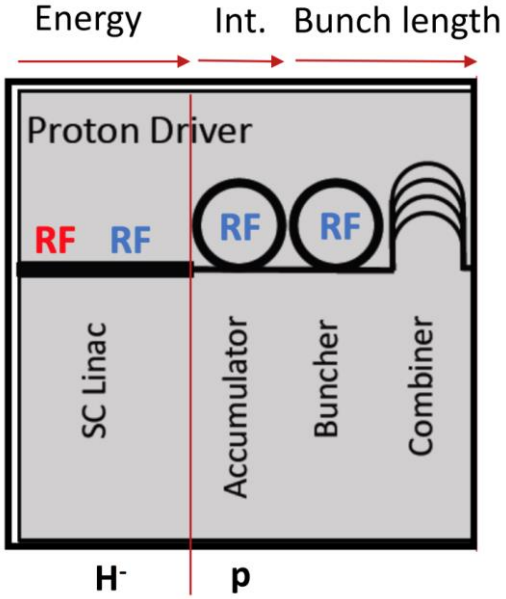
- Ideally, use laser-stripping H^- injection
    - Valuable R&D ongoing at SNS & J-PARC rings.

Transfer to Compressor Ring (CR)

- Four ~3-10ns bunches compressed into four ~1-3ns bunches.

Next to four bunch combiner, targetry, muon-side.

- What is the best staging towards ultimate performance?



Example FNAL Proton Driver Scenario

MuC Proton Driver (AR/CR):

Energy	8 GeV
Pulse Intensity	320 e12
Number of bunches	4
Pulse rate	10 Hz
Beam Power	4 MW
Bunch length (AR)	3-10 ns
Bunch length (CR)	1-3 ns
Ring Circumference	300-600 m
95% Norm. Emittance	120-216 π mm mrad
Laslett Space-Charge limit	0.2-0.6

Superconducting magnets may be necessary for 300m compact ring design.

Choose two of the four parameters:

1) shortest bunch (1 ns)
2) smallest emittance (120 π mm mrad)
3) moderate space-charge (0.2)
4) full beam power (4 MW)

Bunch compression at extreme space-charge limit as a valuable R&D topic for MuC

- Possible acc. R&D experiment at FAST/IOTA or another intense storage ring.
- Can we do any bunch compression in the four-bunch combiner line?

We are at the preliminary stages, this is only what I have proposed.

Bunch Compression at FAST/IOTA (Simulation)

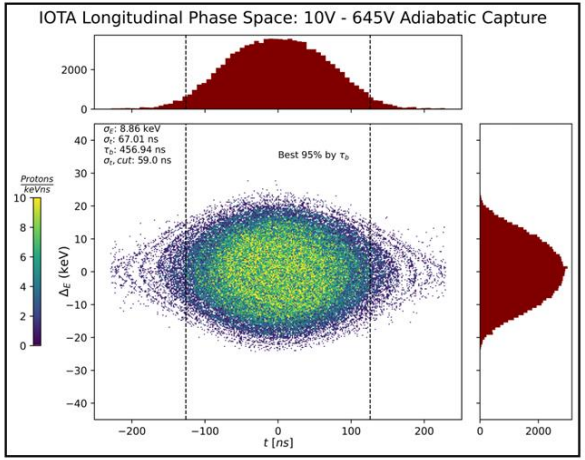
Proposed IOTA proton experiment

Snap bunch rotation with intense space-charge.

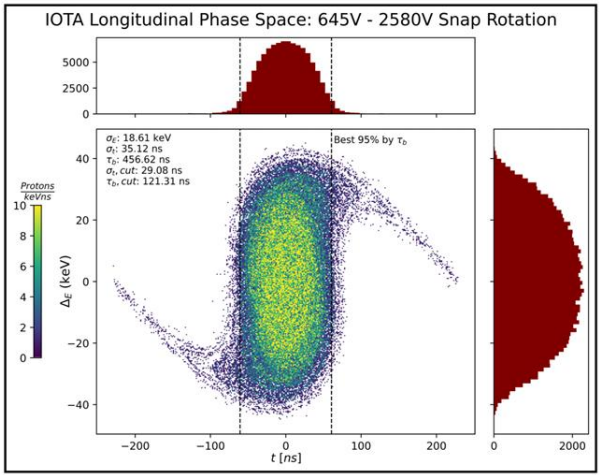
	IOTA (h=1)	IOTA (h=4)
$\Delta p/p$	0.001	0.001
$K.E.(MeV)$	2.5	2.5
h	1	4
β	0.07285	0.07285
η	-0.92568	-0.92568
$V_{cap}(3\sigma)$	$161.17V$	$644.7V$
$V_{compression}(3\sigma)$	$644.7V$	$2.58kV$
$Q_s(1\sigma)$	1.45×10^{-3}	5.81×10^{-3}
$Q_s(3\sigma)$	4.36×10^{-3}	1.74×10^{-2}

RF voltage requirements for a factor of two bunch compression ratio is shown for h=1 and h=4 case.

IOTA h=4, RF Capture:



IOTA h=4, RF Rotate:



Credit: Simons (NIU)

Summary

Fermilab Accelerator upgrades PIP-II / LBNF / ACE-MIRT through approx. 2033.

- New 0.8 GeV, 2 mA, CW SRF linac.
- 2+ MW beam power operation of the LBNF.
- Infrastructure upgrades, targetry R&D program.

New initiatives in accelerator R&D and demonstrators for future colliders.

- Proposal for Muon Cooling Demonstrator under development.
- Many other MuC R&D topics (fast-ramping magnets, high gradient RF, etc.)
- For proton driver R&D, H^- laser stripping & bunch compression under extreme space-charge.

New 20-year strategic plan for Fermilab to be developed in next five years.

- There should be significant design work on muon collider scenarios, look for IPAC24 papers.
- Other science opportunities and program synergies will be examined.

Backup Slides
(ACE-Era Experimental Program)

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)

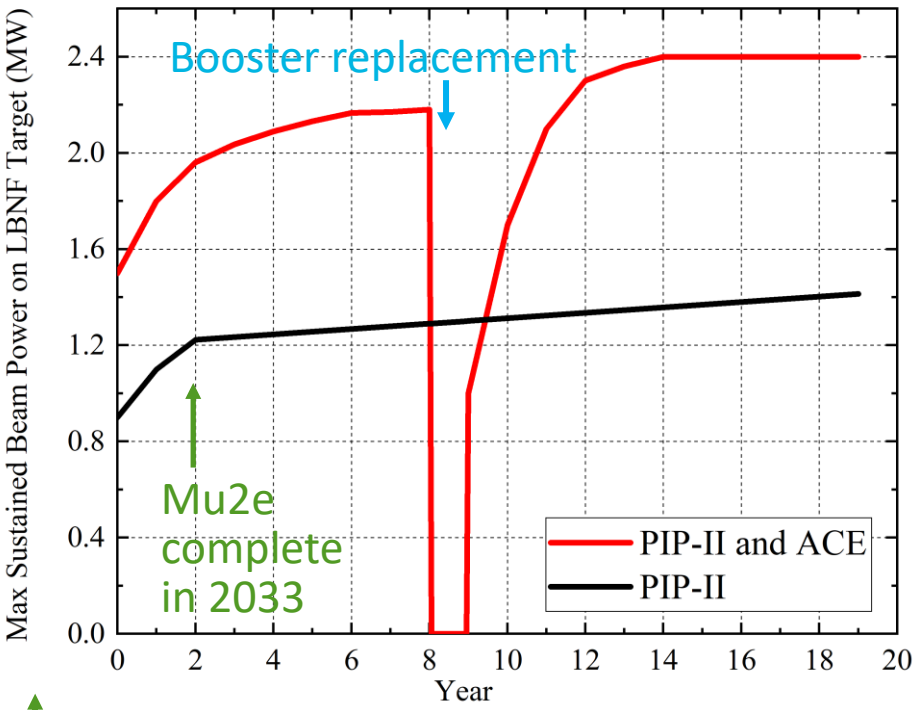
2 GeV Pulsed Beam (~ 1MW)

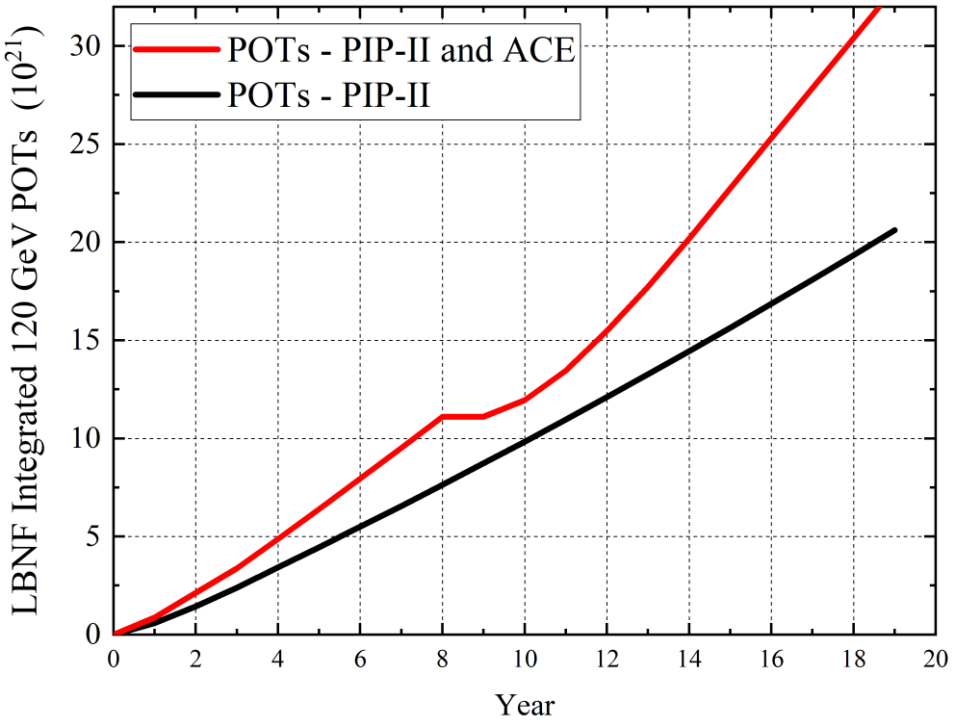
8 GeV Pulsed (~ 1MW)

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

Recent ACE-BR Science Workshop in June 2023.

DUNE Power and Protons-on-Target (POTs)





(Mu2e restarts 2029)

Fermilab

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!

Challenges and R&D Topics

H^- Foil Injection (RCS, Linac)

- Foil overheating, particles scattering off foil, unstripped H, overall chicane length.
- Greatest challenge for RCS and Linac scenarios (although not for PIP-II Booster).
- 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?

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
- Neutrino beam challenges and R&D areas
  - **Near-term:** high-power targetry, reliability, controls, ML.
  - **Next-gen:** H- injection, SRF gradients, machine impedance, space-charge.