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Fermilab Accelerator Complex Evolution (ACE)

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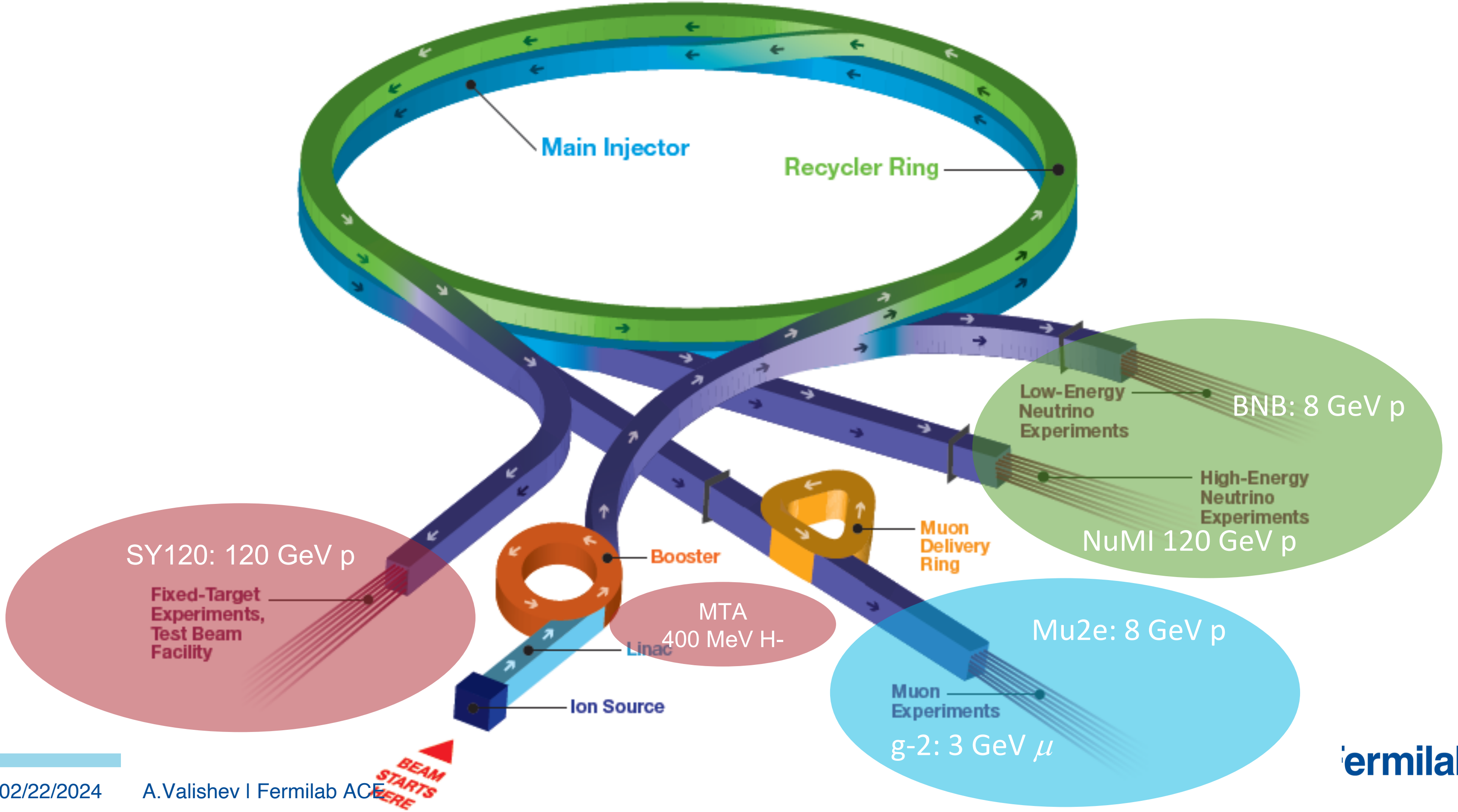
Princeton Muon Collider Organizational Workshop

22 February 2024

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

Fermilab Accelerator Complex – National Users Facility



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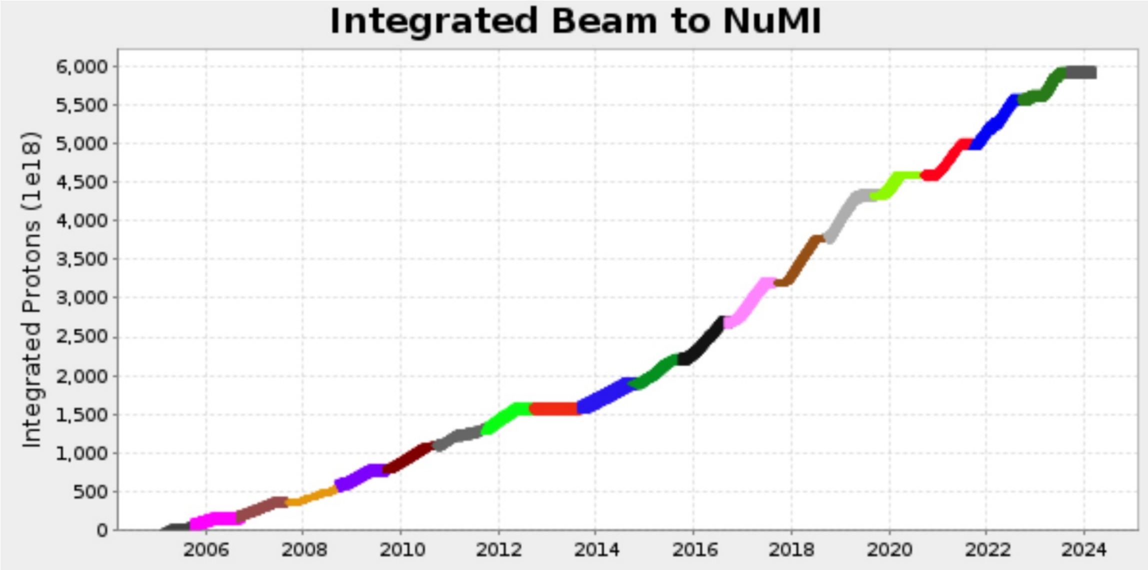
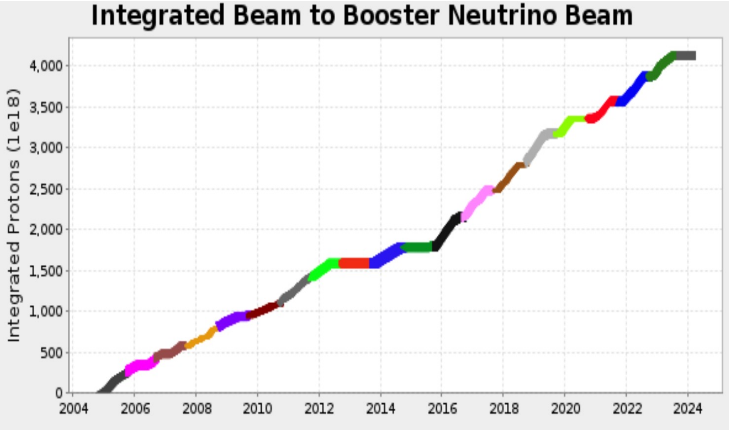
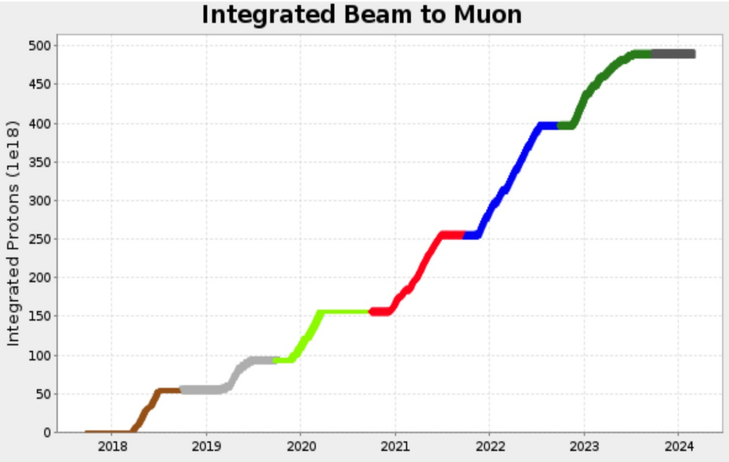
Accelerator Complex priority - beam delivery to users







Protons-On-Target ∝ Power × Runtime × Uptime

Multiple experiments operate concurrently

Fermilab experiments plan

		FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	
LBNF	Sanford		DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	ν
PIP-II	Fermilab		LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LB NF	LBNF	
NuMI	MI		*open*	2x2	2x2	2x2	2x2	2x2					
	MI	NO	NOvA	NOvA	NOvA	NOvA	NOvA	NOvA					
BNB	B	μB	*open*	*open*	*open*	*open*	*open*	*open*			*open*	*open*	
	B	IC	ICARUS	ICARUS	ICARUS	ICARUS	ICARUS	ICARUS			*open*	*open*	
	B	SB	SBND	SBND	SBND	SBND	SBND	SBND			*open*	*open*	
Muon Complex		g-2	g-2	g-2	g-2								μ
		Mu	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e			Mu2e	Mu2e	
SY 120	MT	TB	FTBF	FTBF	FTBF	FTBF	FTBF				FTBF	FTBF	p
	MC	TB	FTBF	FTBF	FTBF	FTBF	FTBF				FTBF	FTBF	
	NM4	Sp	SpinQ	SpinQ	SpinQ	SpinQ	SpinQ				*open*	*open*	
LINAC	MTA		ITA	ITA	ITA	ITA	ITA	ITA					

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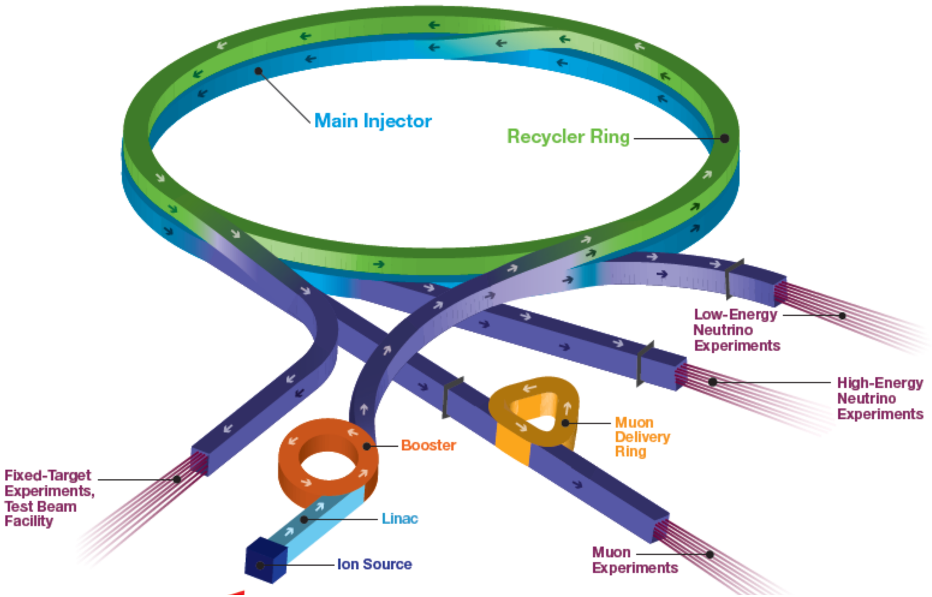
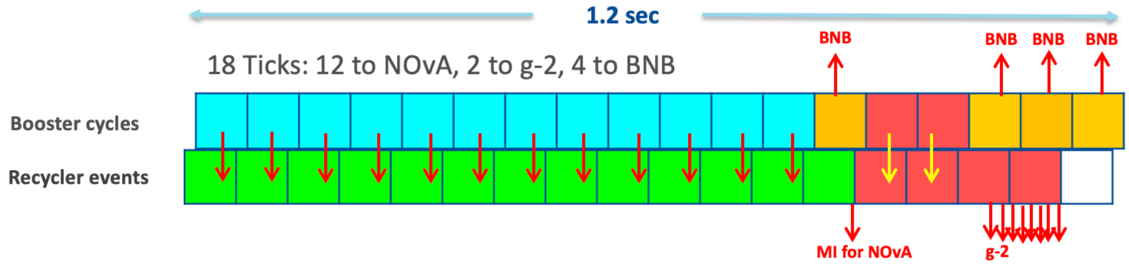
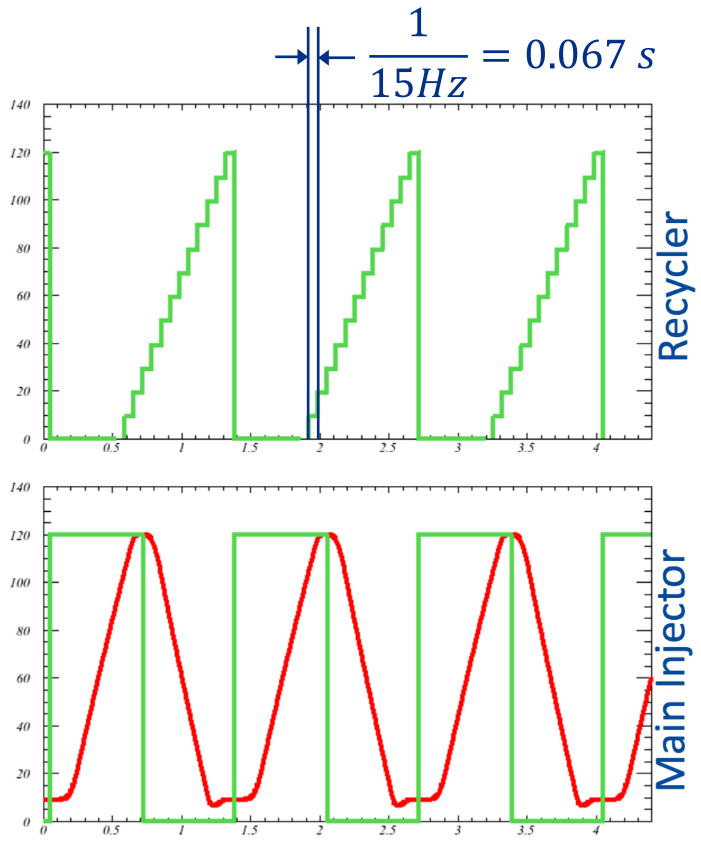
Fermilab Accelerator Complex operation







1.33s Main Injector cycle shown

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Beam power to NuMI – present

Operation scenario	Nominal w. BNB/g-2	Reduced BNB/g-2	5/22/23	Next step	units
MI 120 GeV cycle time	**1.333**	**1.2**	**1.133**	**1.067**	s
Booster intensity	**4.7**				10^{12} p
Booster ramp rate	**15**				Hz
Number of batches to NuMI	12				
MI power	**0.81**	**0.9**	**0.96**	**1.01**	**MW**
cycles for 8 GeV	8	6	5	4	
Available 8 GeV power	**36**	30	27	**23**	kW

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

$$P = \frac{eNE}{T}$$

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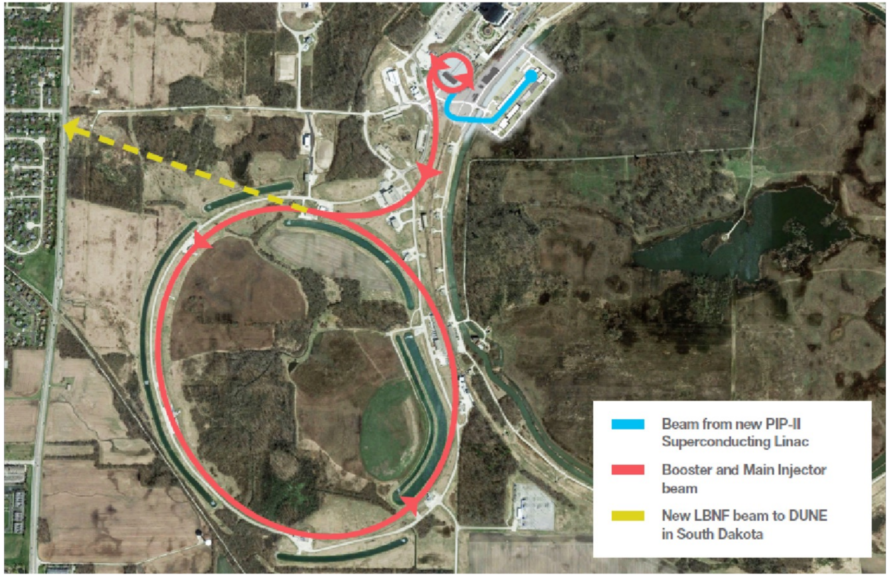
Accelerator Complex in PIP-II / LBNF era

- **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**

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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 Evolution (ACE) plan – beyond 1.2MW

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

2MW

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

2.4MW

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 (*)

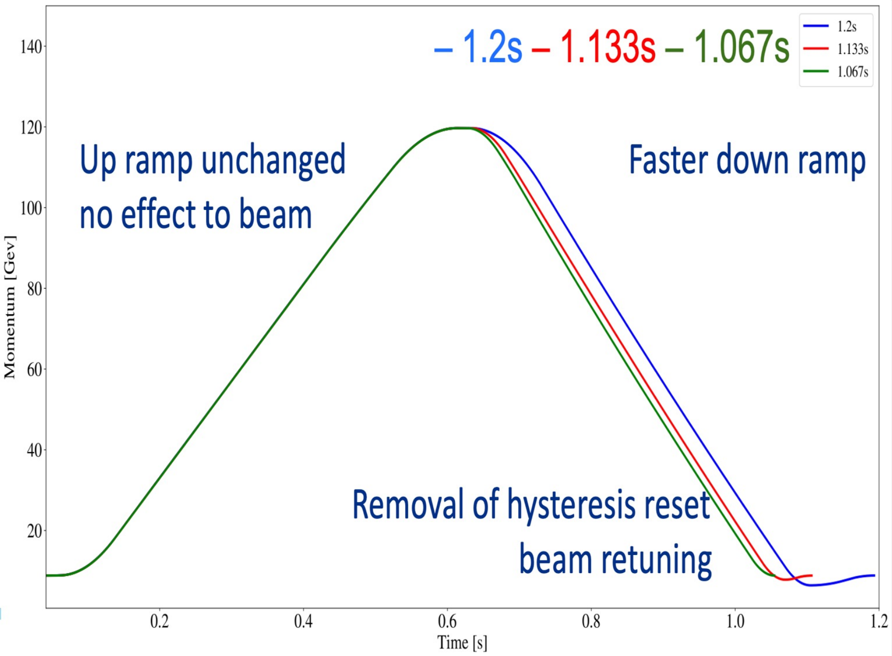
Beam power in numbers – ACE-MIRT

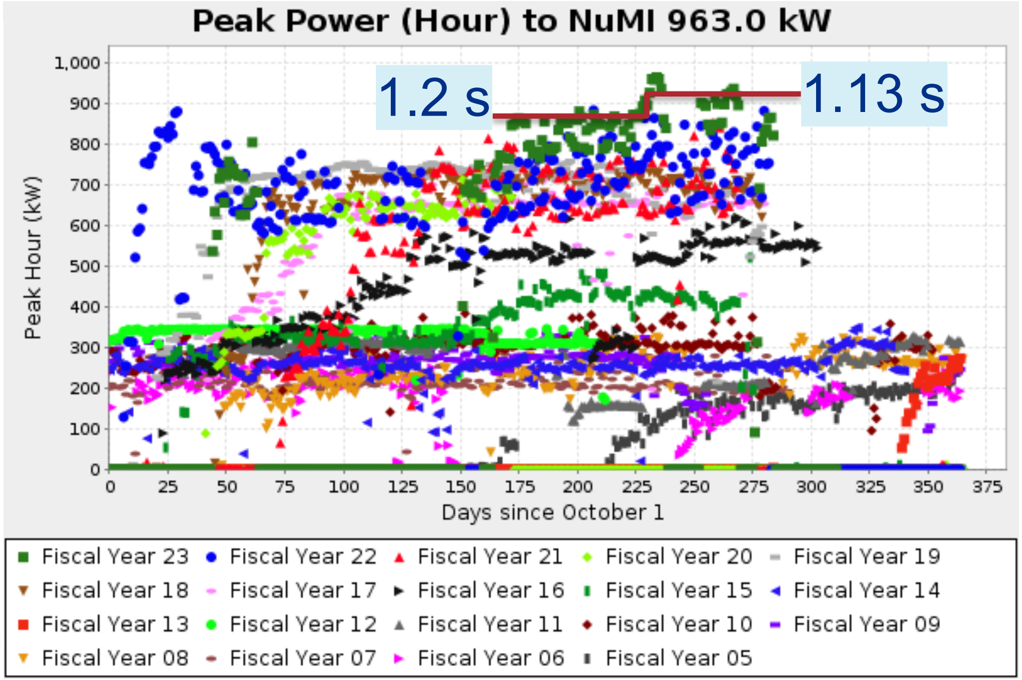
		PIP-II Booster			
Operation scenario	**Present**	**PIP-II**	**ACE (a)**	**ACE (b)**	**units**
MI 120 GeV cycle time	**1.13**	**1.2**	**0.9**	**0.7**	s
Booster intensity	**4.7**	**6.5**			10^{12} p
Booster ramp rate	15	**20**			Hz
MI power	**0.96**	**1.2**	**1.7**	**2.1**	MW
cycles for 8 GeV	**6**	**12**	**6**	**2**	
Available 8 GeV power	30	83	56	24	kW

8 GeV ⇦T⇨120 GeV

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

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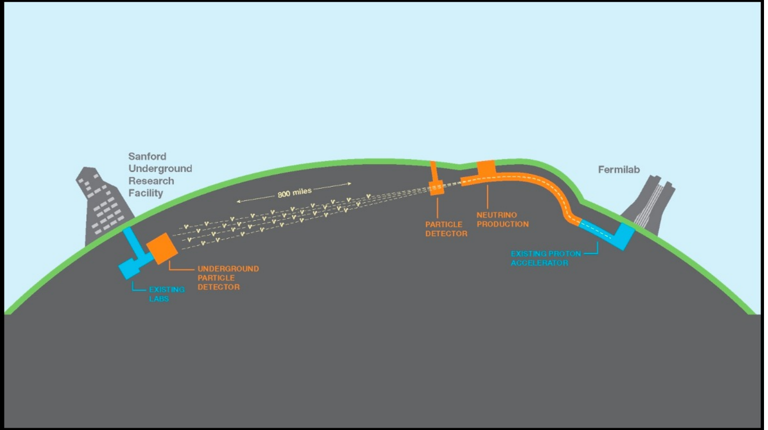
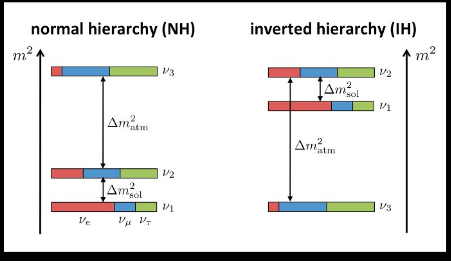
2023 P5

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**!





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2023 P5

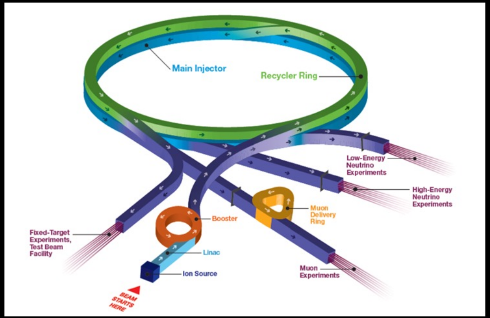
Major Project this decade: A reimagined DUNE Phase II

- 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.

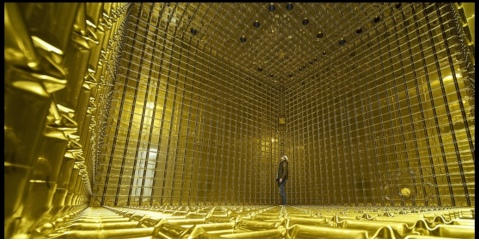
Science goals:

- 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 accelerator complex:



Inside an Liquid Argon TPC:



Fermilab experiments plan

		FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	
LBNF	Sanford		DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	ν
PIP-II	Fermilab		LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	
NuMI	MI		*open*	2x2	2x2	2x2	2x2	2x2					
	MI	NO	NOvA	NOvA	NOvA	NOvA	NOvA	NOvA					
BNB	B	μB	*open*	*open*	*open*	*open*	*open*	*open*			*open*	*open*	
	B	IC	ICARUS	ICARUS	ICARUS	ICARUS	ICARUS	ICARUS			*open*	*open*	
	B	SB	SBND	SBND	SBND	SBND	SBND	SBND			*open*	*open*	
Muon Complex		g-2	g-2	g-2	g-2								μ
		Mu	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e			Mu2e	Mu2e	
SY 120	MT	TB	FTBF	FTBF	FTBF	FTBF	FTBF				FTBF	FTBF	p
	MC	TB	FTBF	FTBF	FTBF	FTBF	FTBF				FTBF	FTBF	
	NM4	Sp	SpinQ	SpinQ	SpinQ	SpinQ	SpinQ				*open*	*open*	
LINAC	MTA		ITA	ITA	ITA	ITA	ITA	ITA					

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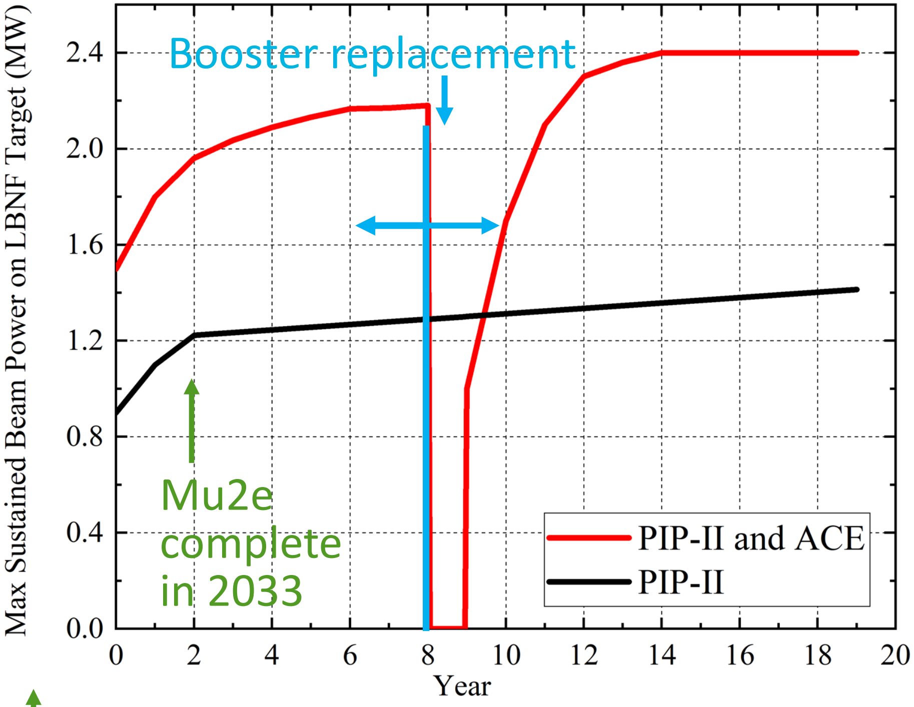
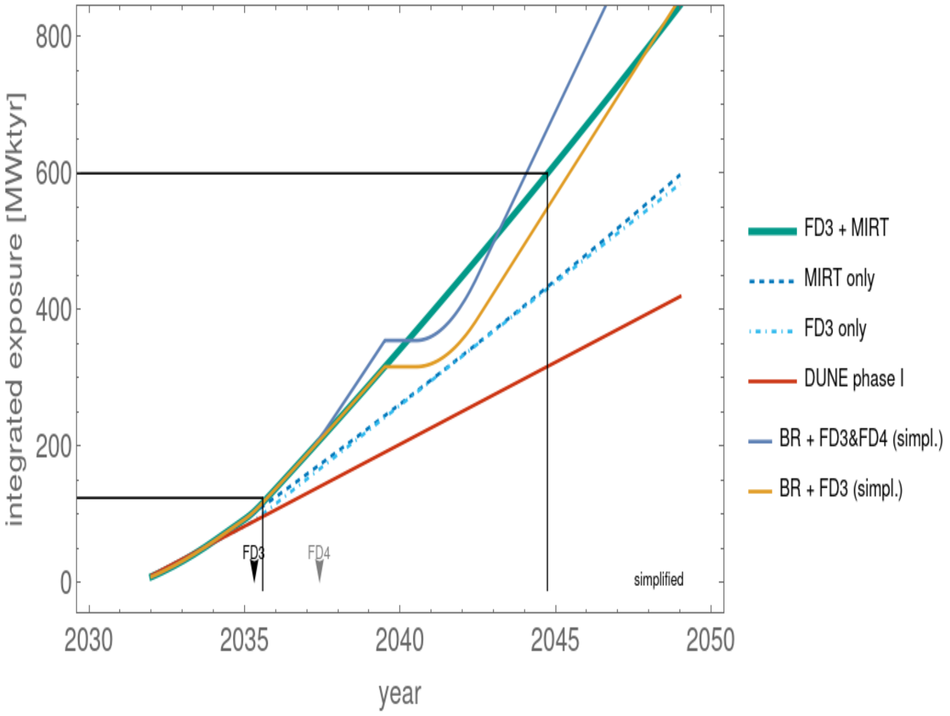
DUNE power and POT/Exposure implications





(Mu2e restarts 2029)

Overall ACE plan

ACE

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

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

ACE-MIRT
Upgrades to existing machines

- Target Systems capability improvements

2.4 MW
- Booster replacement
- New physics capabilities

ACE-BR
New machine

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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

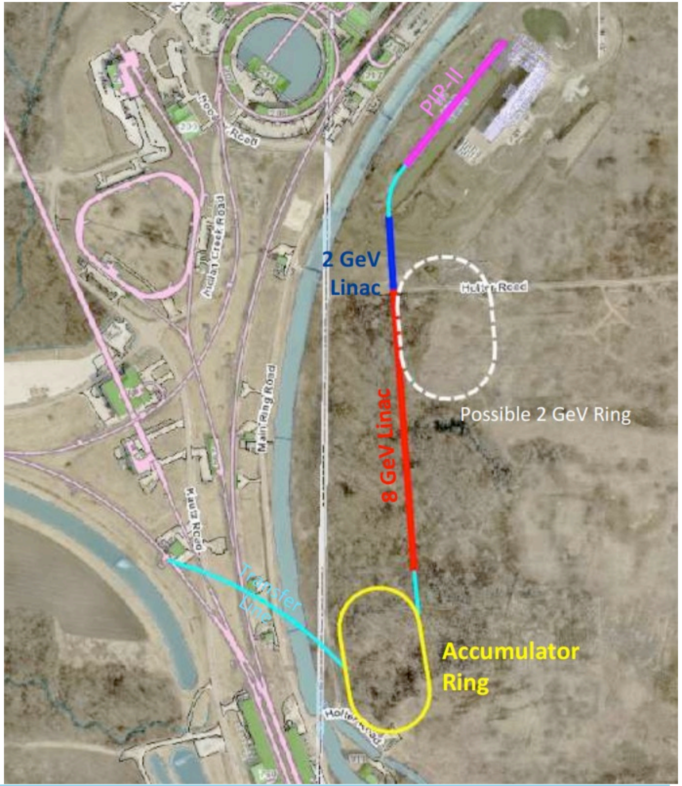
v2: High current (5mA) and some RF R&D

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

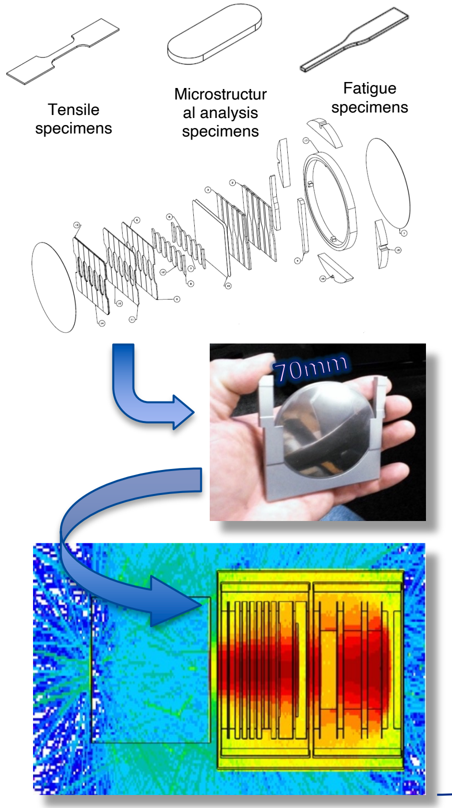
Rec 4g Develop plans for improving the Fermilab accelerator complex that are consistent with the long-term vision of this report including neutrinos, flavor, and a 10 TeV pCM collider (section 6.6).

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?

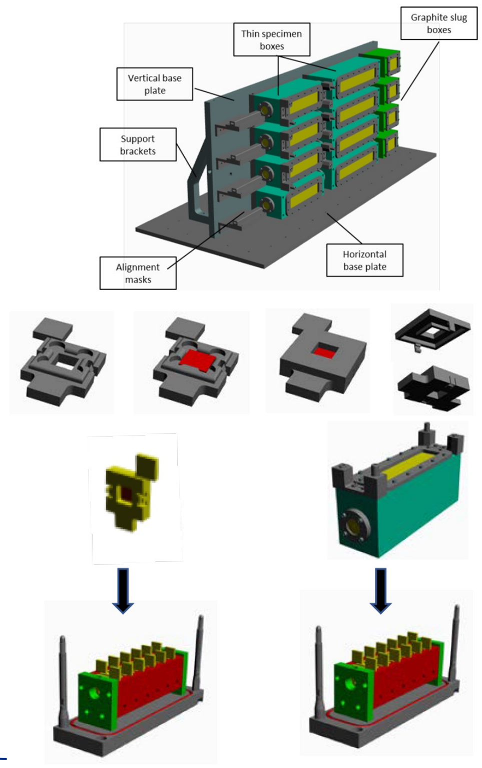
Target materials R&D on critical path to 2+ MW target



- 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



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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