



Fermilab Accelerator Complex Evolution (ACE)

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Princeton Muon Collider Organizational Workshop

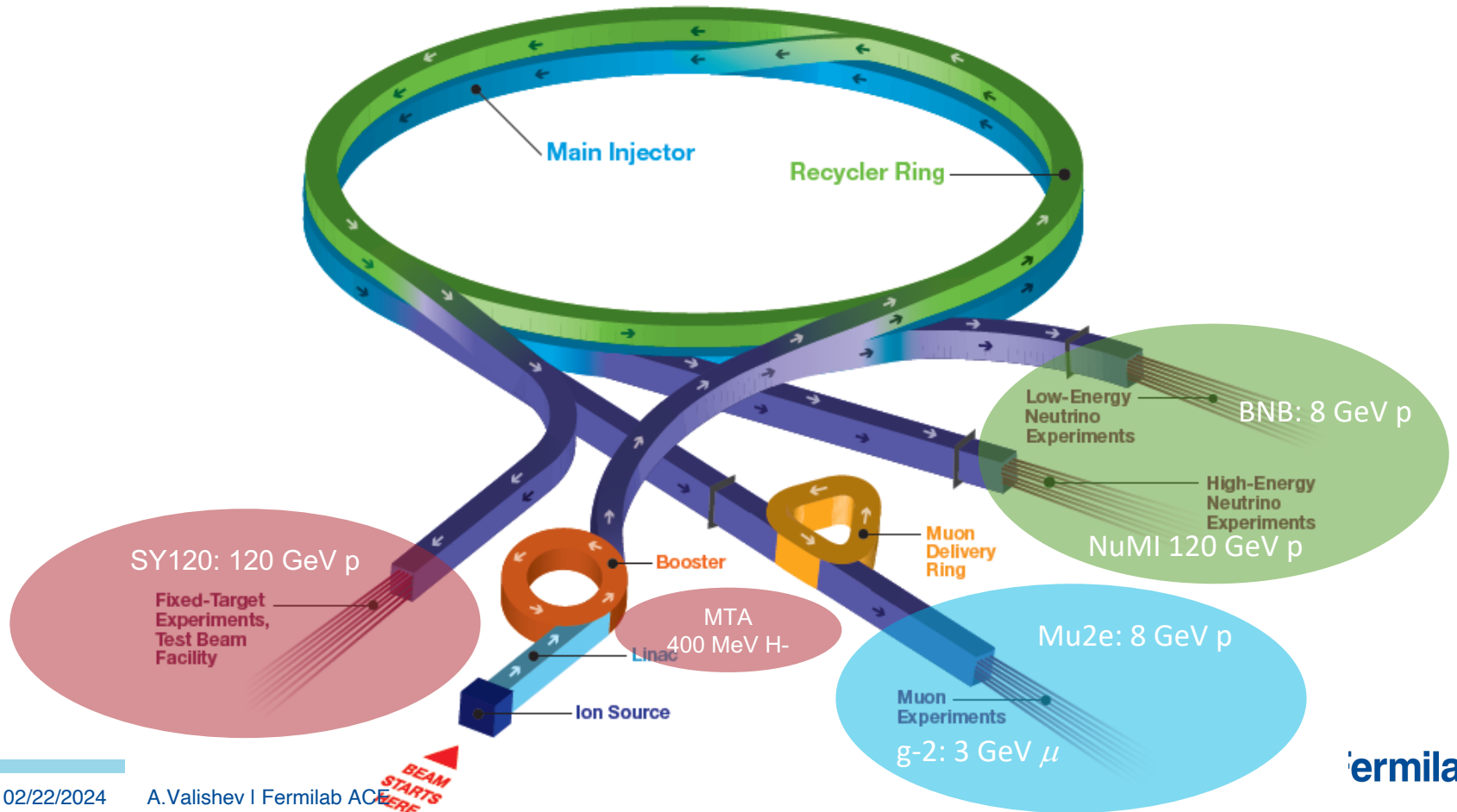
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Outline

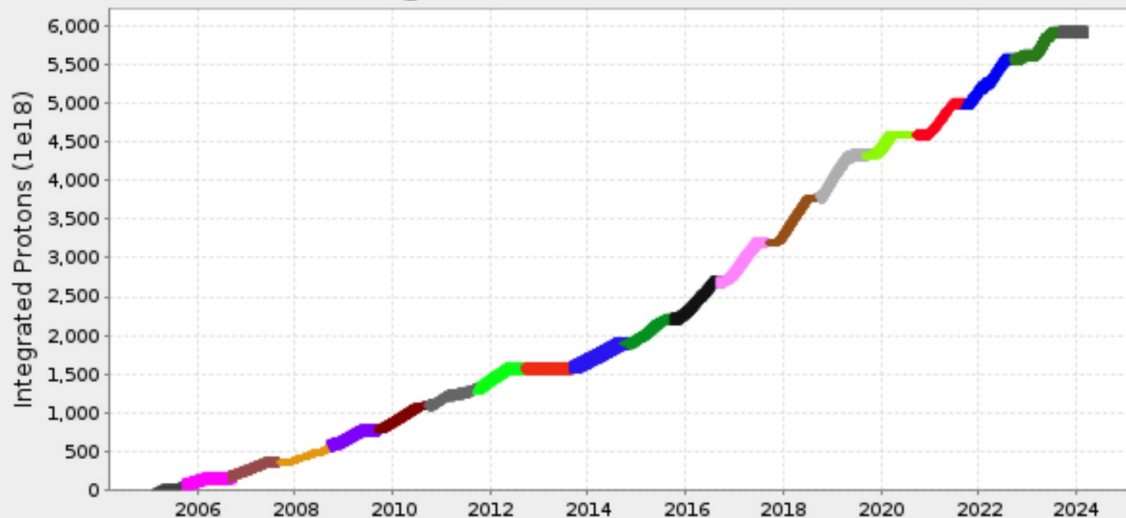
- Fermilab accelerator complex now
- PIP-II upgrade and LBNF/DUNE
- Accelerator Complex Evolution
 - Medium-term: Main Injector ramp rate and target system upgrade
 - Long-term: Booster replacement
- Accelerator R&D

Fermilab Accelerator Complex – National Users Facility

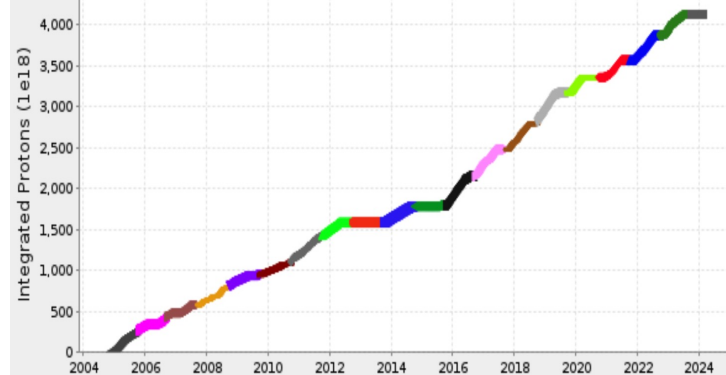


Accelerator Complex priority - beam delivery to users

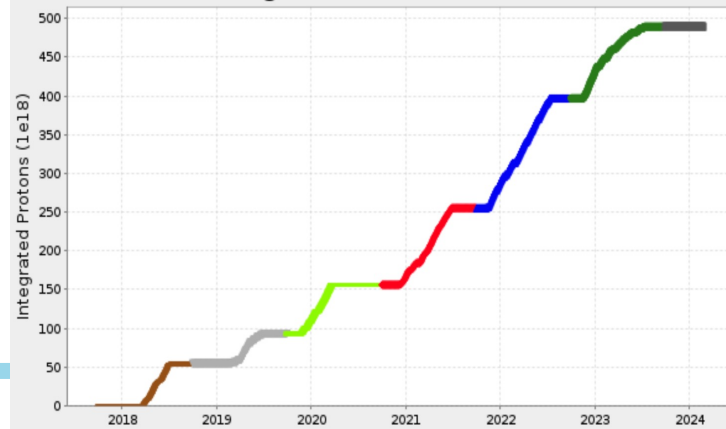
Integrated Beam to NuMI



Integrated Beam to Booster Neutrino Beam



Integrated Beam to Muon



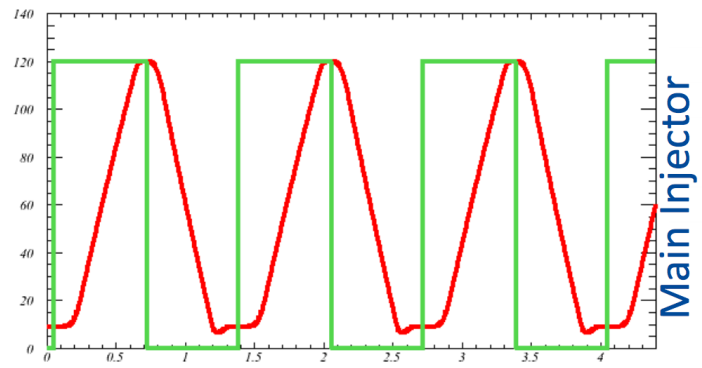
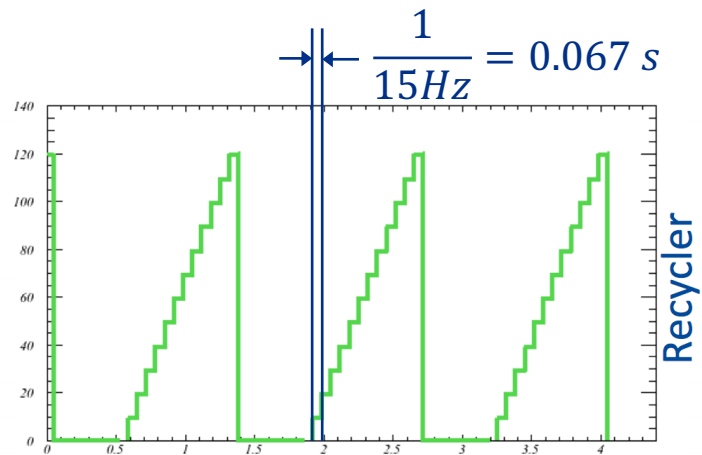
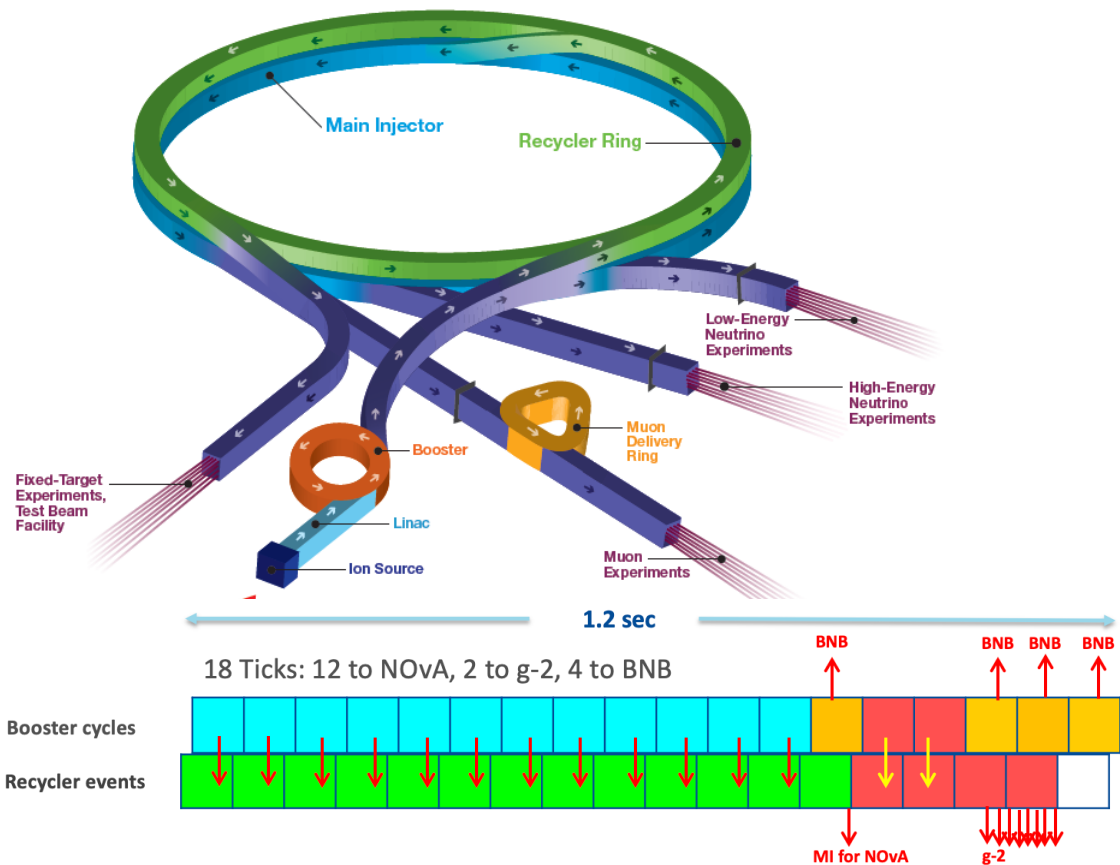
Protons-On-Target \propto Power \times Runtime \times Uptime

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					μ			
	MI	NO		NOvA	NOvA	NOvA	NOvA	NOvA	NOvA								
BNB	B	μB		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
SY 120	MT	TB		FTBF	FTBF	FTBF	FTBF	FTBF	FTBF						p		
	MC	TB		FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF						FTBF	
	NM4	Sp		SpinQ	SpinQ	SpinQ	SpinQ	SpinQ	SpinQ	open						open	
LINAC	MTA		ITA	ITA	ITA	ITA	ITA	ITA	ITA								

Fermilab Accelerator Complex operation



1.33s Main Injector cycle shown

Beam power to NuMI – present

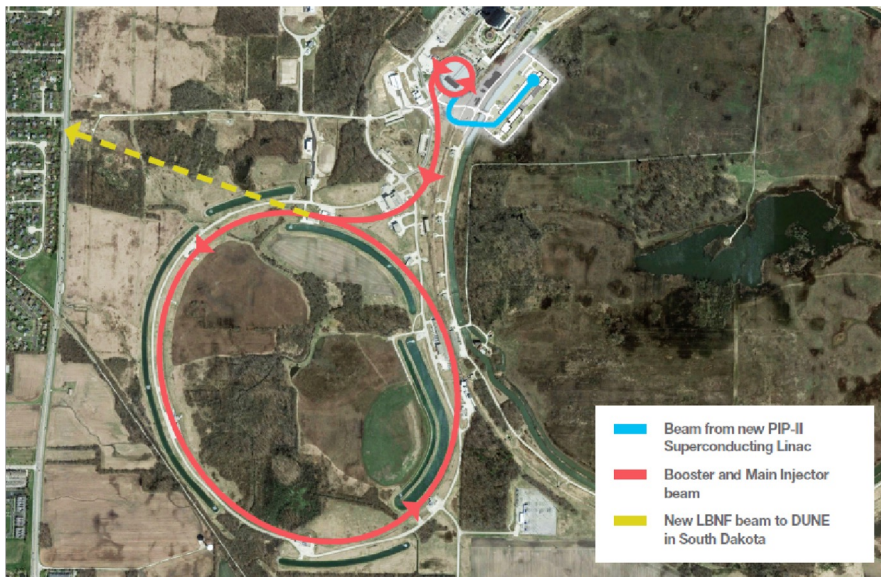
Operation scenario	Nominal w. BNB/g-2	Reduced BNB/g-2	5/22/23	Next step	units
MI 120 GeV cycle time	1.333	1.2	1.133	1.067	s
Booster intensity	4.7				10 ¹² p
Booster ramp rate	15				Hz
Number of batches to NuMI	12				
MI power	0.81	0.9	0.96	1.01	MW
cycles for 8 GeV	8	6	5	4	
Available 8 GeV power	36	30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

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

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

Accelerator Complex in PIP-II / LBNF era

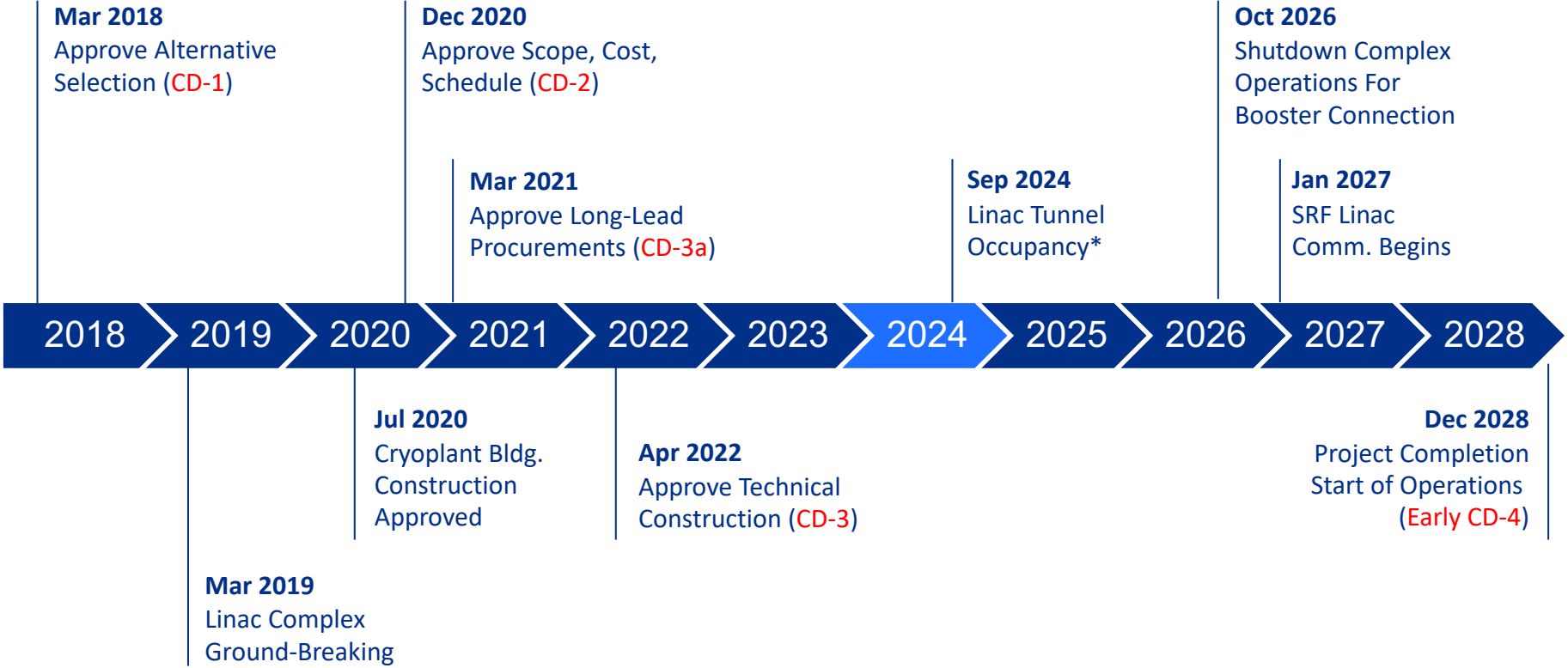
- **New PIP-II SRF linac** provides beam for injection into **Booster** at energy increased to 800 MeV from present 400 MeV
- **Booster cycle rate is upgraded to 20 Hz from 15 Hz**
- **Proton flux at 8 GeV increases 2 times** resulting in beam power from Main Injector up to 1.2 MW



- **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**



PIP-II Major Milestones



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

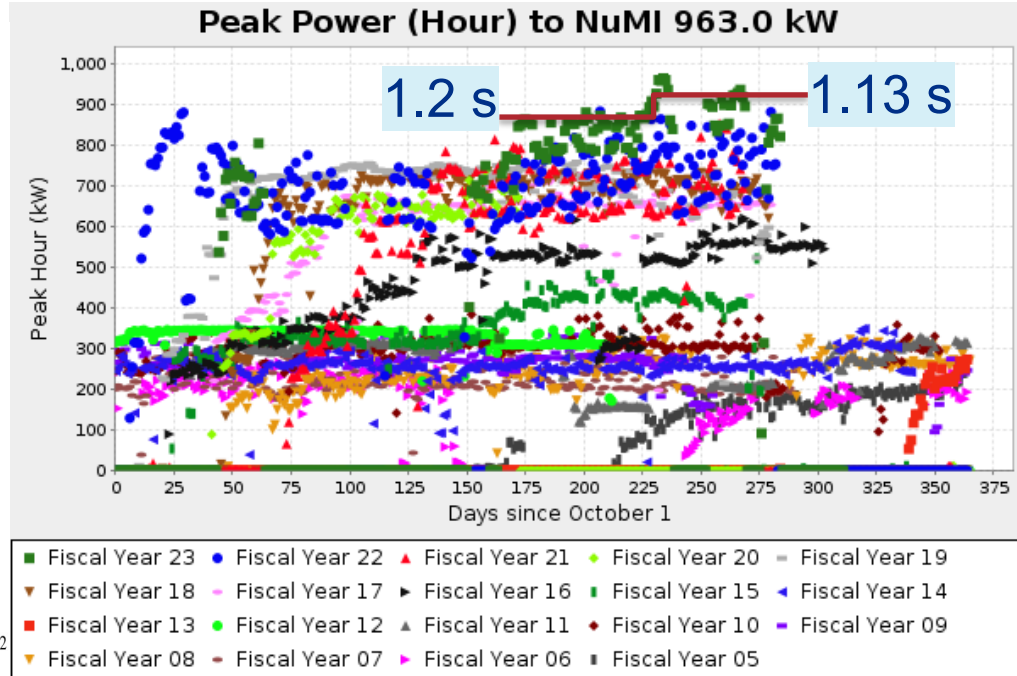
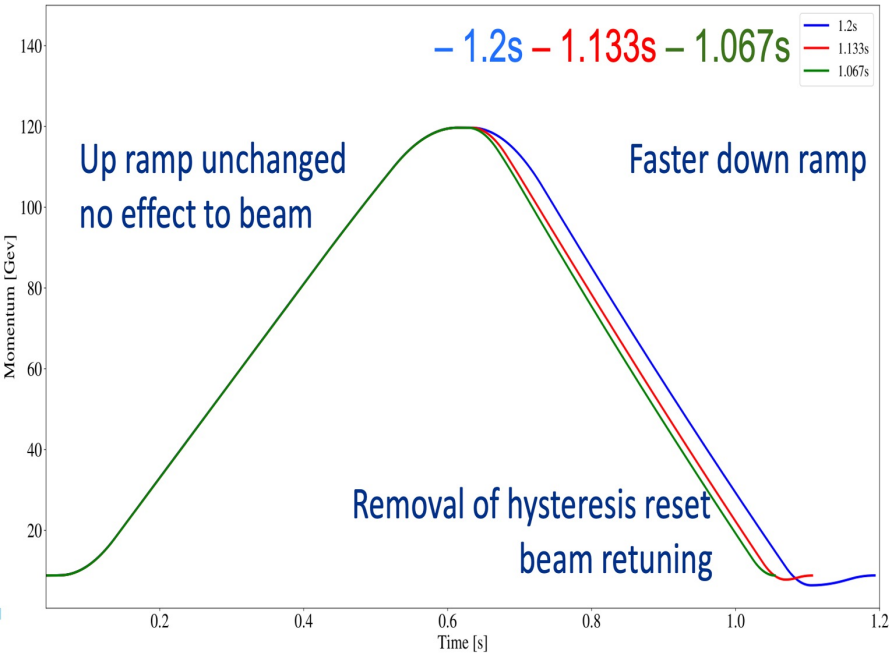


8 GeV ⇄ T ⇄ 120 GeV

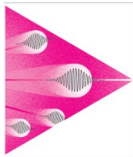
Legend: enabled by PIP-II enabled by ACE-MIRT



NuMI power reaches 0.96 MW on May 22, 2023 !



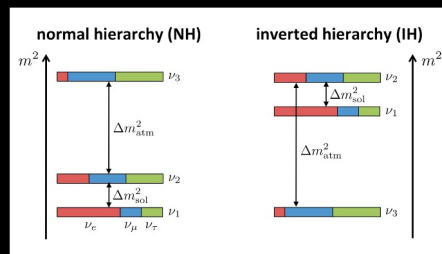
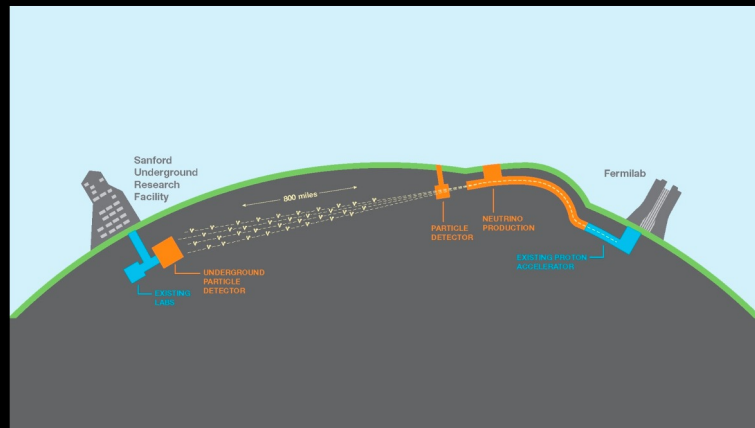
The power gain achieved without increase in beam intensity – important proof of concept for ACE



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!**



- 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**.

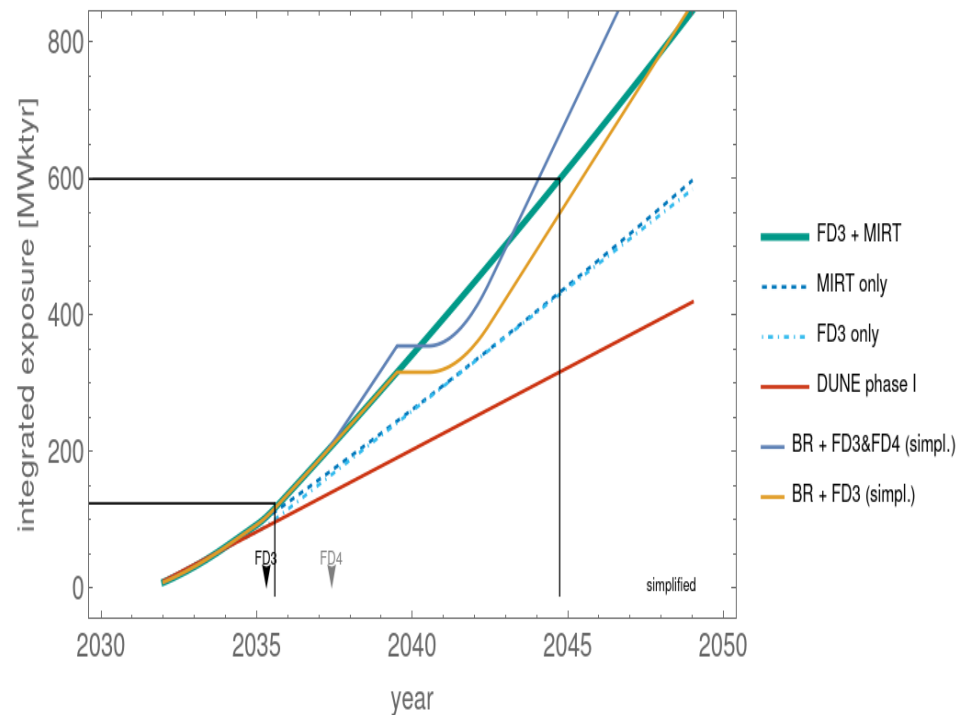
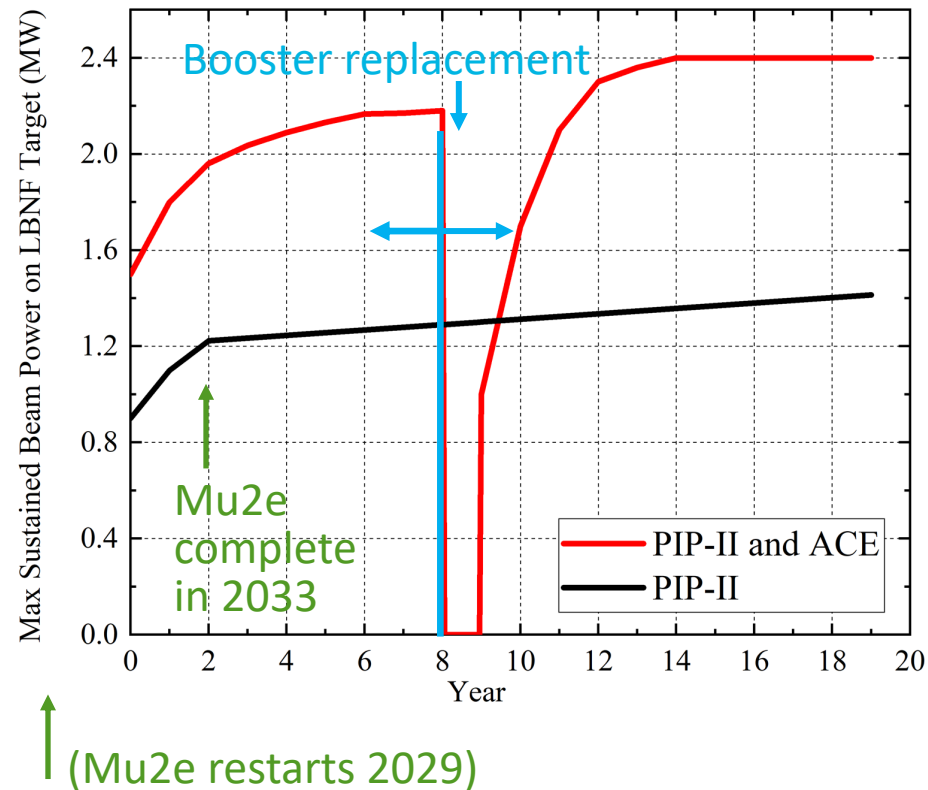
- **Most precise measurement of the CP phase across a range of possible CP phase space**
- **Search for signatures of unexpected neutrino interactions.**
- **Study direct appearance of tau neutrinos.**

A wide-angle shot of a vast, opulent interior space, possibly a temple or a palace. The walls and ceiling are covered in intricate, golden carvings and patterns. The floor is also highly decorated with golden motifs. A person is visible in the distance, providing a sense of scale to the massive room. The lighting is warm and golden, highlighting the rich textures and colors of the architecture.

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	DUNE				
PIP-II	Fermilab			LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF					
NuMI	MI			open	2x2	2x2	2x2	2x2	2x2						ν			
	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
SY 120	MT	TB		FTBF	FTBF	FTBF	FTBF	FTBF	FTBF							FTBF	FTBF	p
	MC	TB		FTBF	FTBF	FTBF	FTBF	FTBF	FTBF							FTBF	FTBF	
	NM4	Sp		SpinQ	SpinQ	SpinQ	SpinQ	SpinQ	SpinQ							open	open	
LINAC	MTA		ITA	ITA	ITA	ITA	ITA	ITA	ITA									

DUNE power and POT/Exposure implications



Overall ACE plan

1.2 MW

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

2 MW

- Reliability upgrades
- Main Injector capabilities (cycle time)
- Target Systems capability improvements

ACE-MIRT
Upgrades to
existing machines

2.4 MW

- Booster replacement
- New physics capabilities

ACE-BR
New machine

ACE

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

2GeV Linac + 2-8GeV RCS



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 (~ 1 MW)
 - 8 GeV pulsed beam (~ 1 MW)
- P5 reviewed the plan, some relevant recommendations

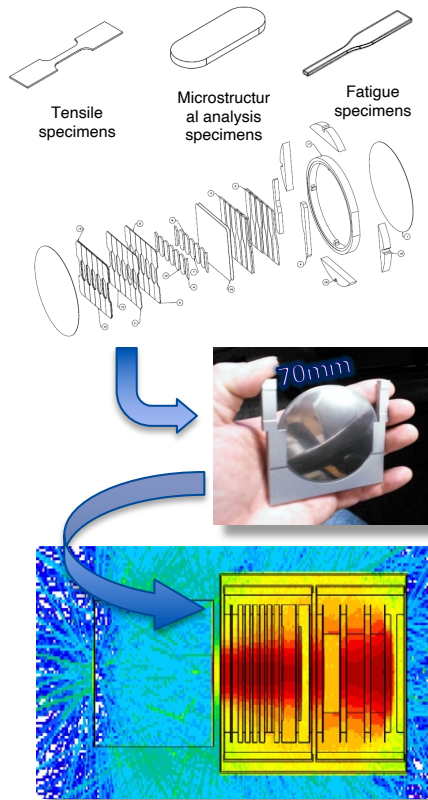
Rec 4g Develop plans for improving the Fermilab accelerator complex that are consistent with the long-term vision of this report including neutrinos, flavor, and a 10 TeV pCM collider (section 6.6).

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

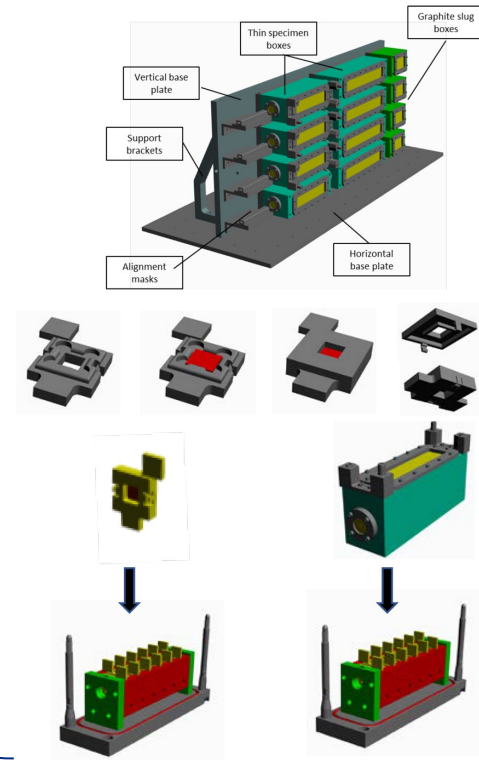
- High-power target stations
- H- Foil Injection (RCS, Linac)
 - Foil overheating, particles scattering off foil, unstripped H
 - Greatest challenge for RCS and Linac scenarios
 - Laser H- stripping injection could be the way forward
- SRF Technology (Linac)
 - Improve accelerating gradient and Q-factors
 - 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



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