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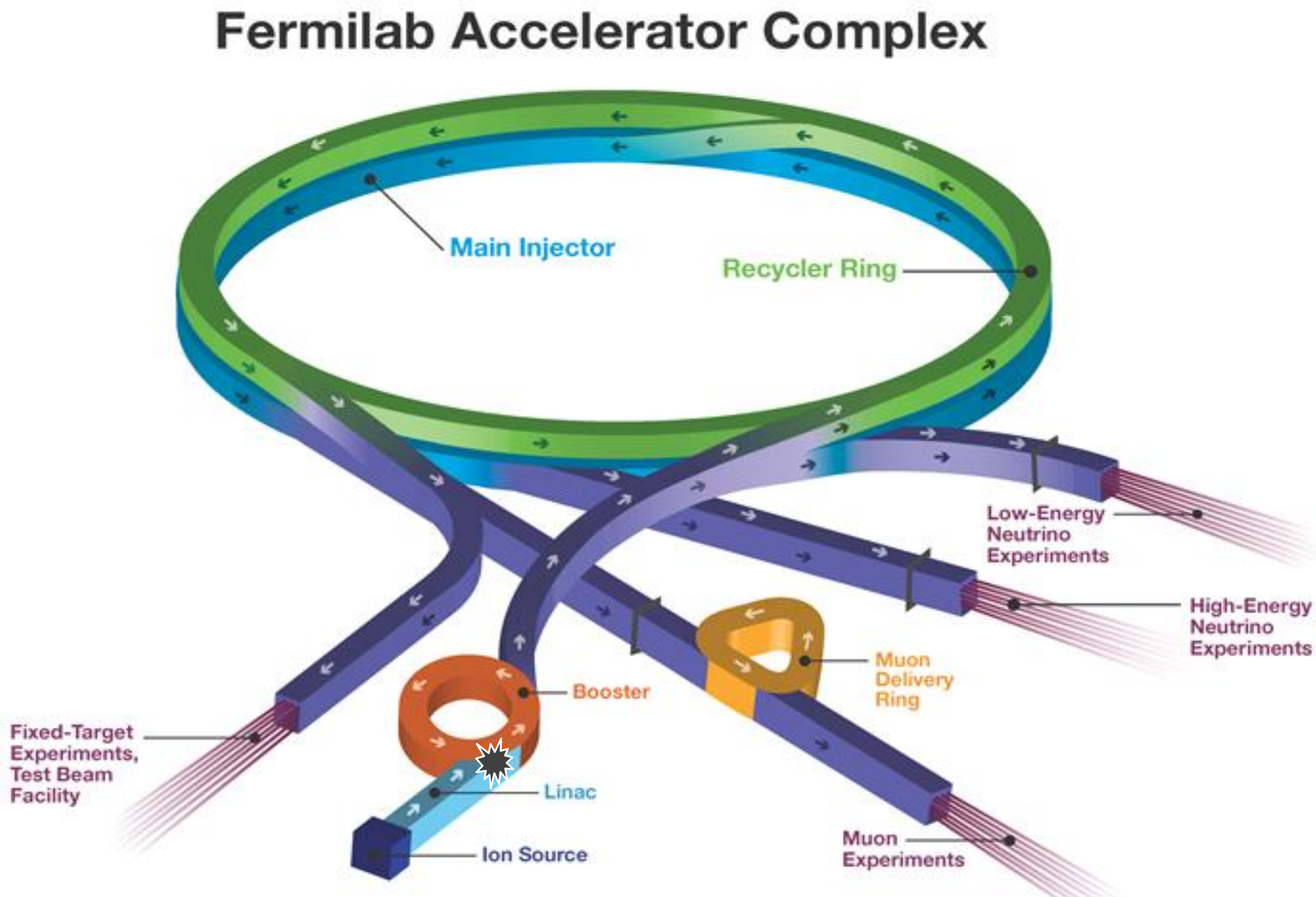
Future Accelerators for Fermilab Proton Complex

Jeffrey Eldred

Fermilab User's Meeting 2022

June 13, 2022

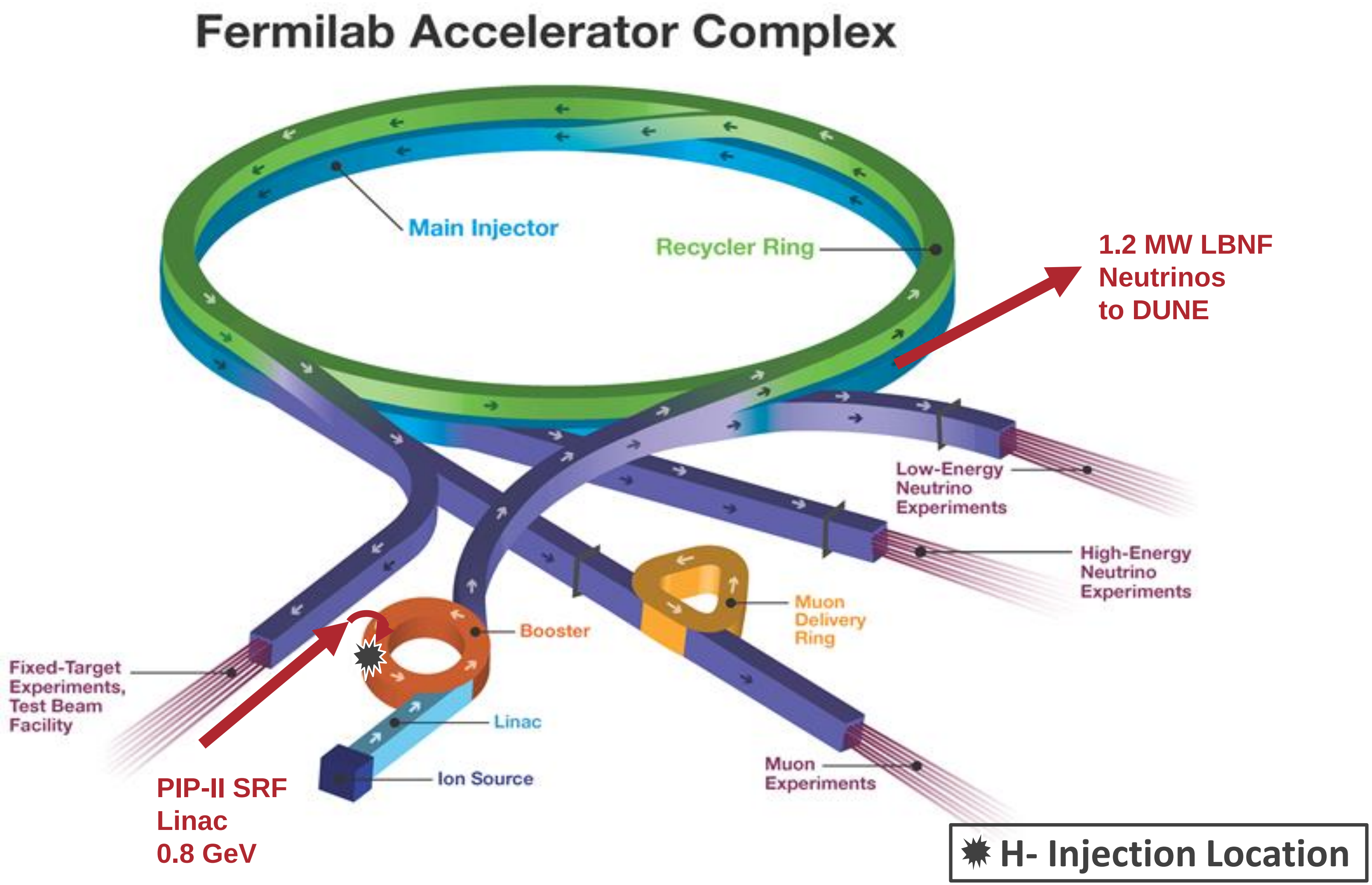
Fermilab Upcoming Upgrades PIP-II ~750kW



✸ H- Injection Location

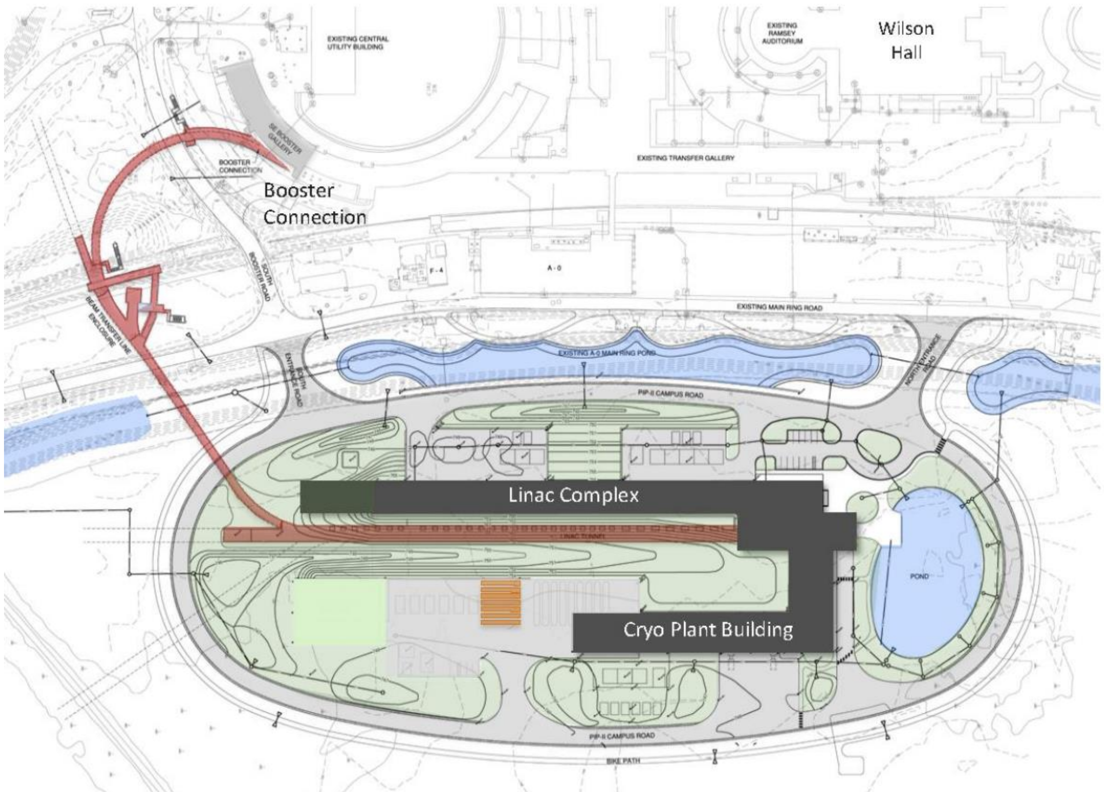
Record Main Injector power 893kW, Booster power 89 kW

Fermilab Upcoming Upgrades PIP-II 1.2MW



New SRF linac raises Booster injection energy, new LBNF beamline.

PIP-II Linac & Upgrade



800 MeV H− linac
- Warm Front End
- SRF section

Linac-to-Booster transfer line
- 3-way beam split

Upgraded Booster
- 20 Hz, 800 MeV injection
- New injection area

Upgraded Recycler & Main Injector
- RF in both rings

Conventional facilities
- Site preparation
- Cryoplant Building
- Linac Complex
- Booster Connection

E. Pozdeyev, SpaceCharge19

PIP-II project has received DOE CD-3 approval construction is already underway.

PIP-II Booster Power

	PIP	PIP-II
MI Beamline	NuMI	LBNF
RR/MI Intensity	$54 \cdot 10^{12}$ protons	$65 \cdot 10^{12}$ protons
RR/MI Rep. Time	1.333 s	1.2 s
MI Power	0.7 MW	1.2 MW
Booster Intensity	$4.5 \cdot 10^{12}$ protons	$6.5 \cdot 10^{12}$ protons
Booster Rep. Rate	15 Hz	20 Hz
Booster Ext. Power	85 kW	165 kW
Injection Energy	0.4 GeV	0.8 GeV
Efficiency	95%	98%

The primary purpose of the PIP-II is to inject into the Booster, and in turn power the high-energy proton complex including DUNE/LBNF program.

However, the PIP-II Linac is also designed to be CW-capable and the Booster only uses **~1.2% of the CW beam power!**

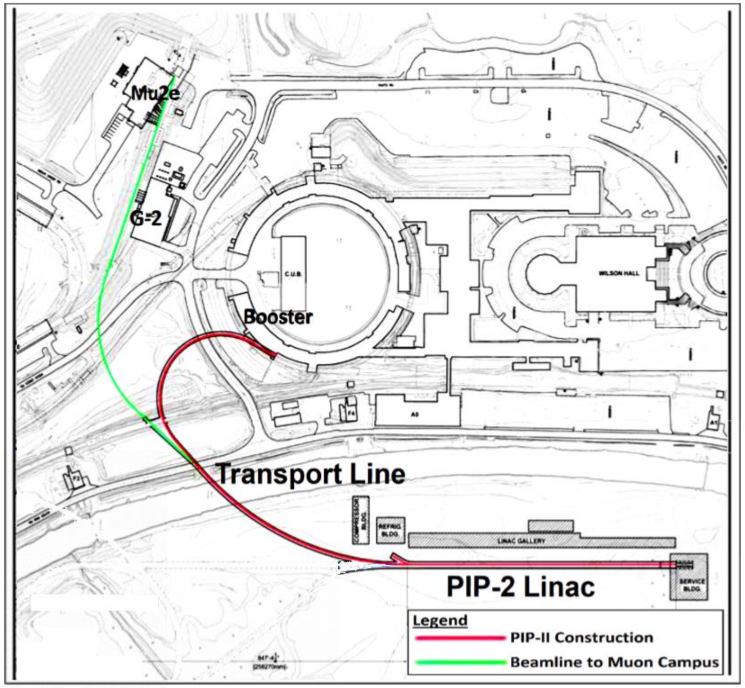
- Two proposed “near-term” programs are discussed.

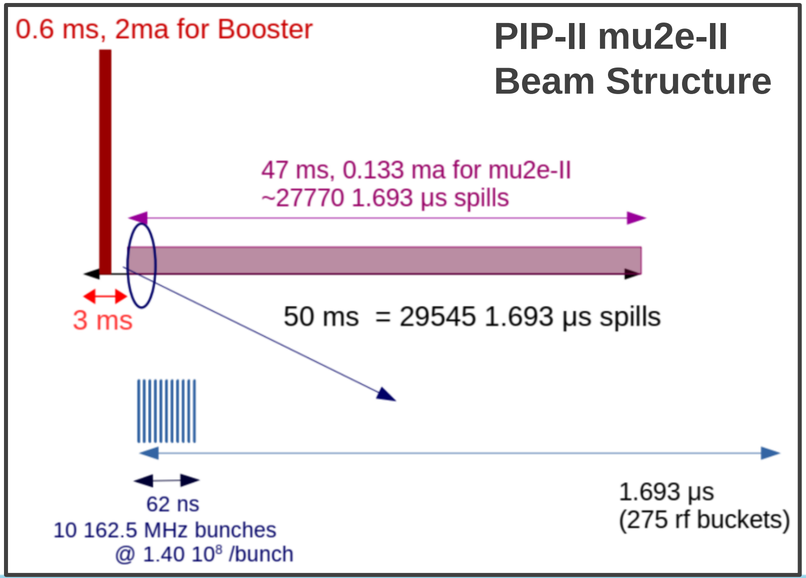
Proposed Mu2e-II Program

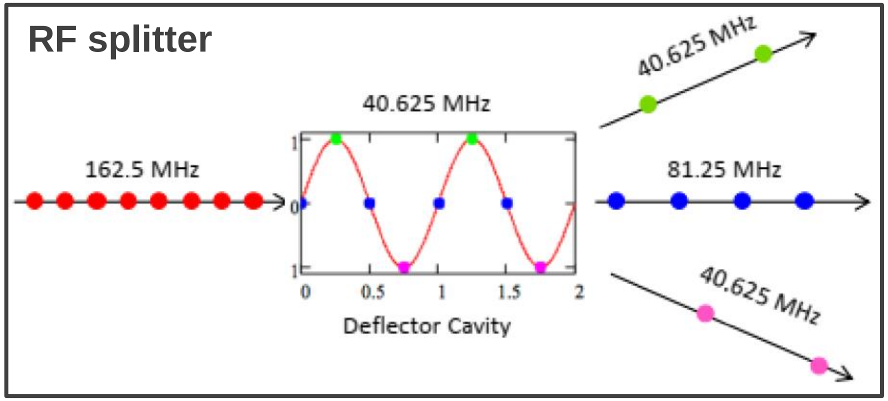
Mu2e-II proposed to send PIP-II linac beam to the mu2e experiment, ~100kW at 0.8 GeV.

Mu2e-II doing R&D on necessary changes for beam target, calorimetry, tracker, veto system, production solenoid, H- stripping etc.

Even with mu2e-II, with an RF splitter the vast majority of the PIP-II beam is still available!





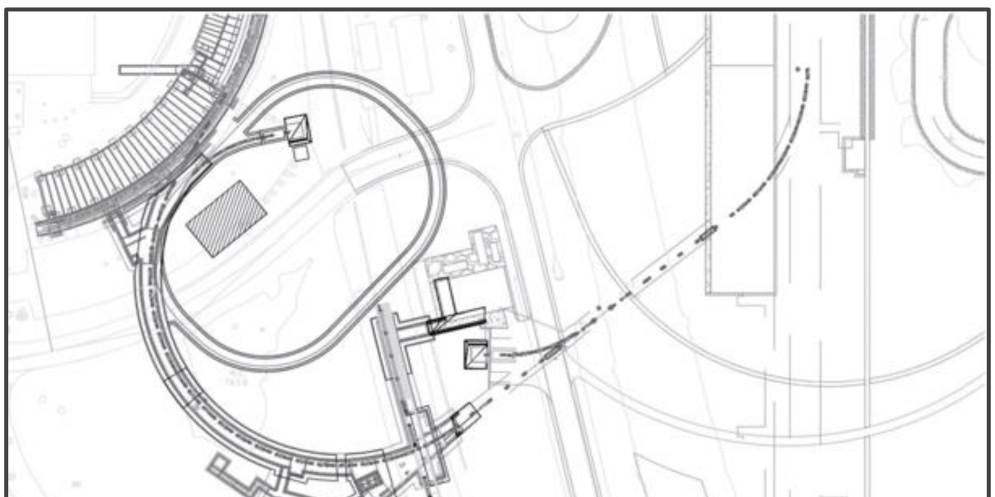


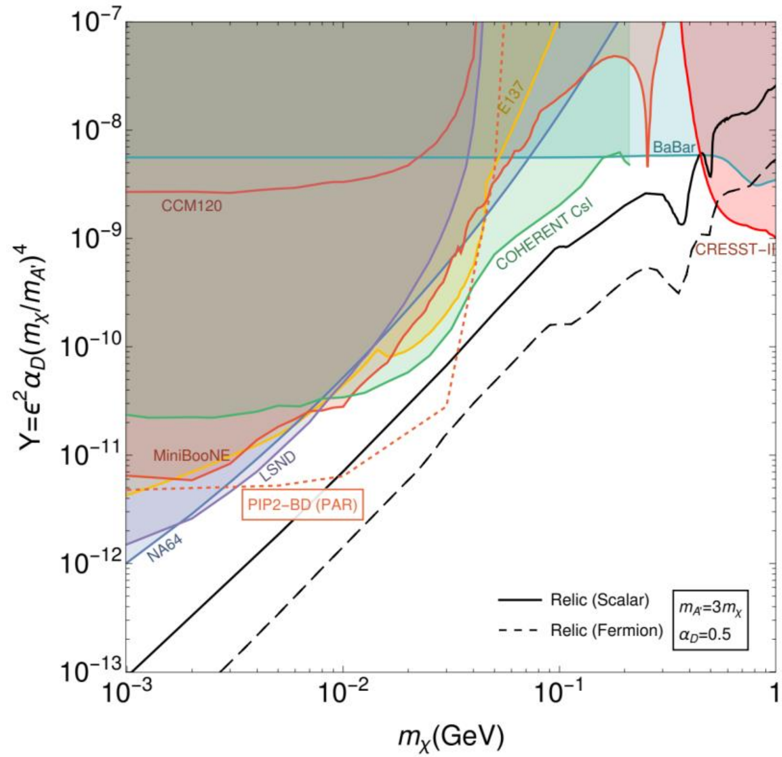
Proposed PIP-II Accumulator Ring (PAR)

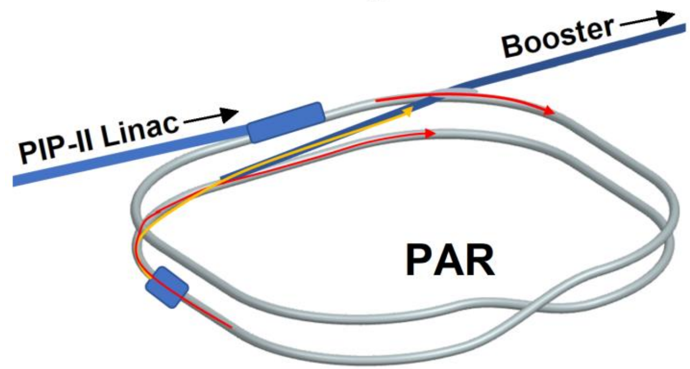
Features:
- Proposed 0.8-1.0 GeV proton storage ring.
- 474m in the form of a folded figure 8.

Benefits:
- 100 kW Dark Sector Program.
- Facilitates injection into PIP-II era Booster.
- Enables 1 GeV upgrade of Booster injection.

Snowmass white paper



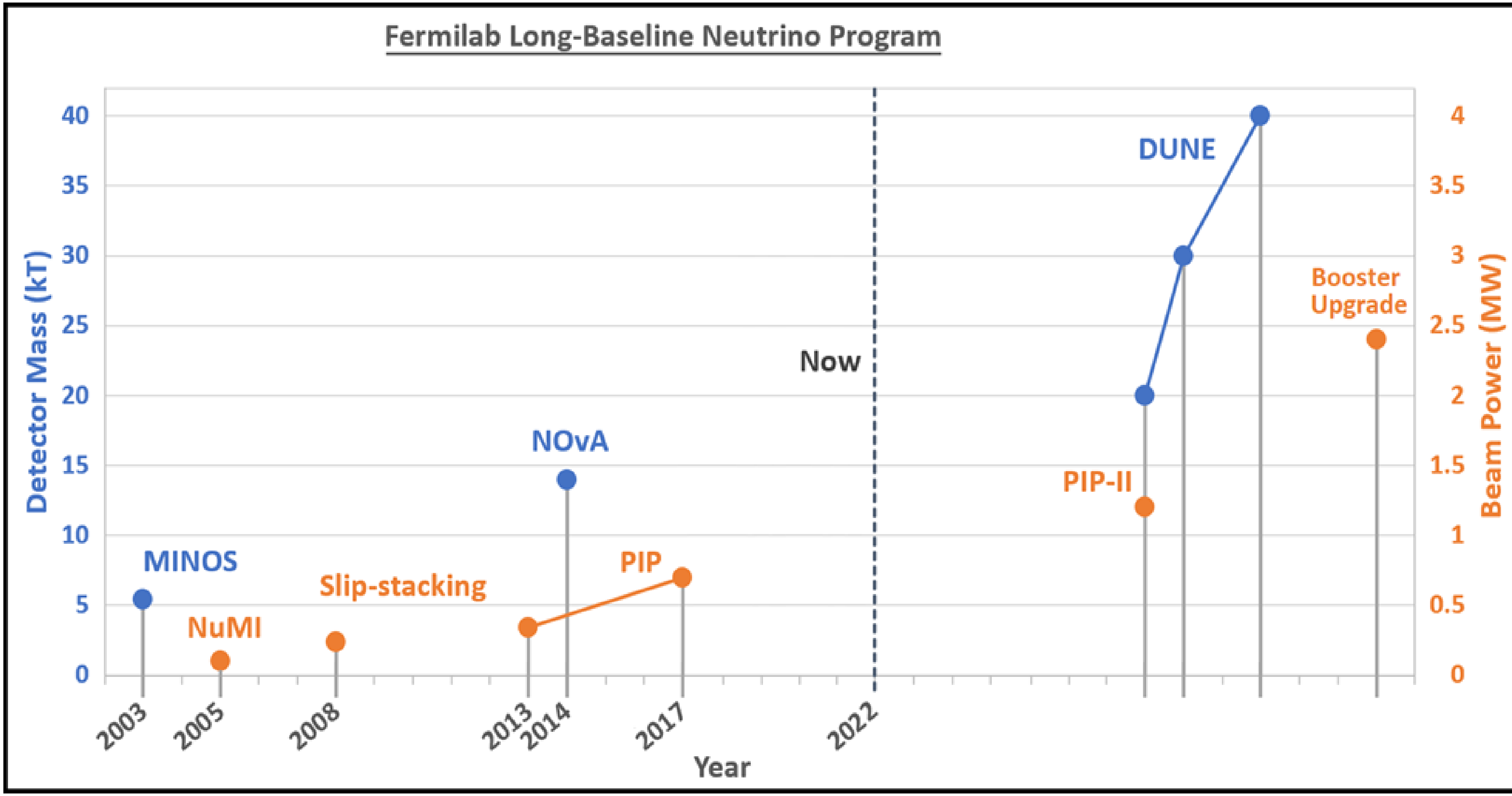




Proton Intensity Upgrade after PIP-II

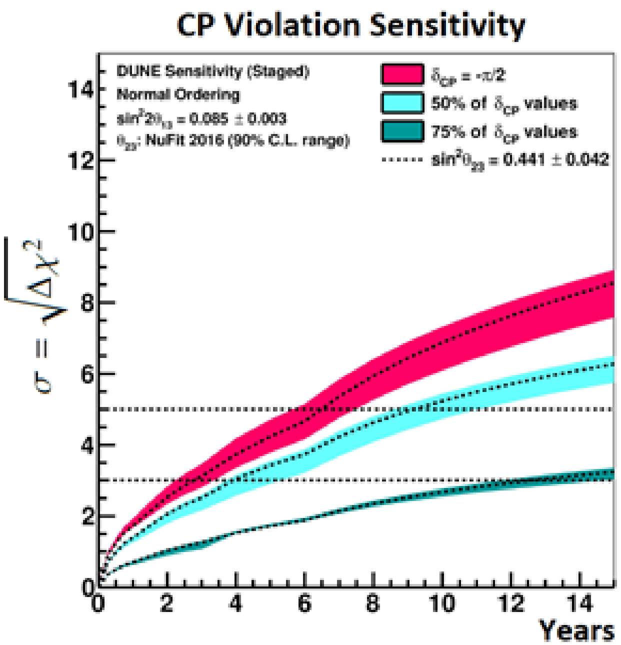
Beam Power and Detector Size

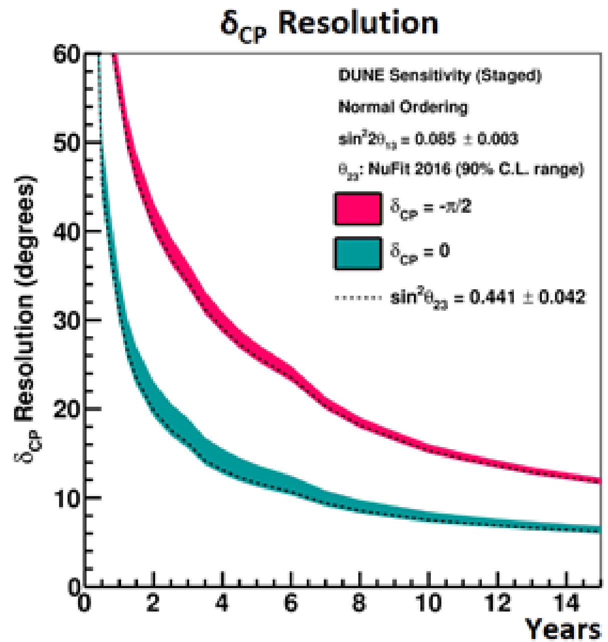
DUNE long-baseline neutrino program calls for **2.4 MW**



J. Eldred, JINST 2019

DUNE Physics, with 2.4 MW at 6 years

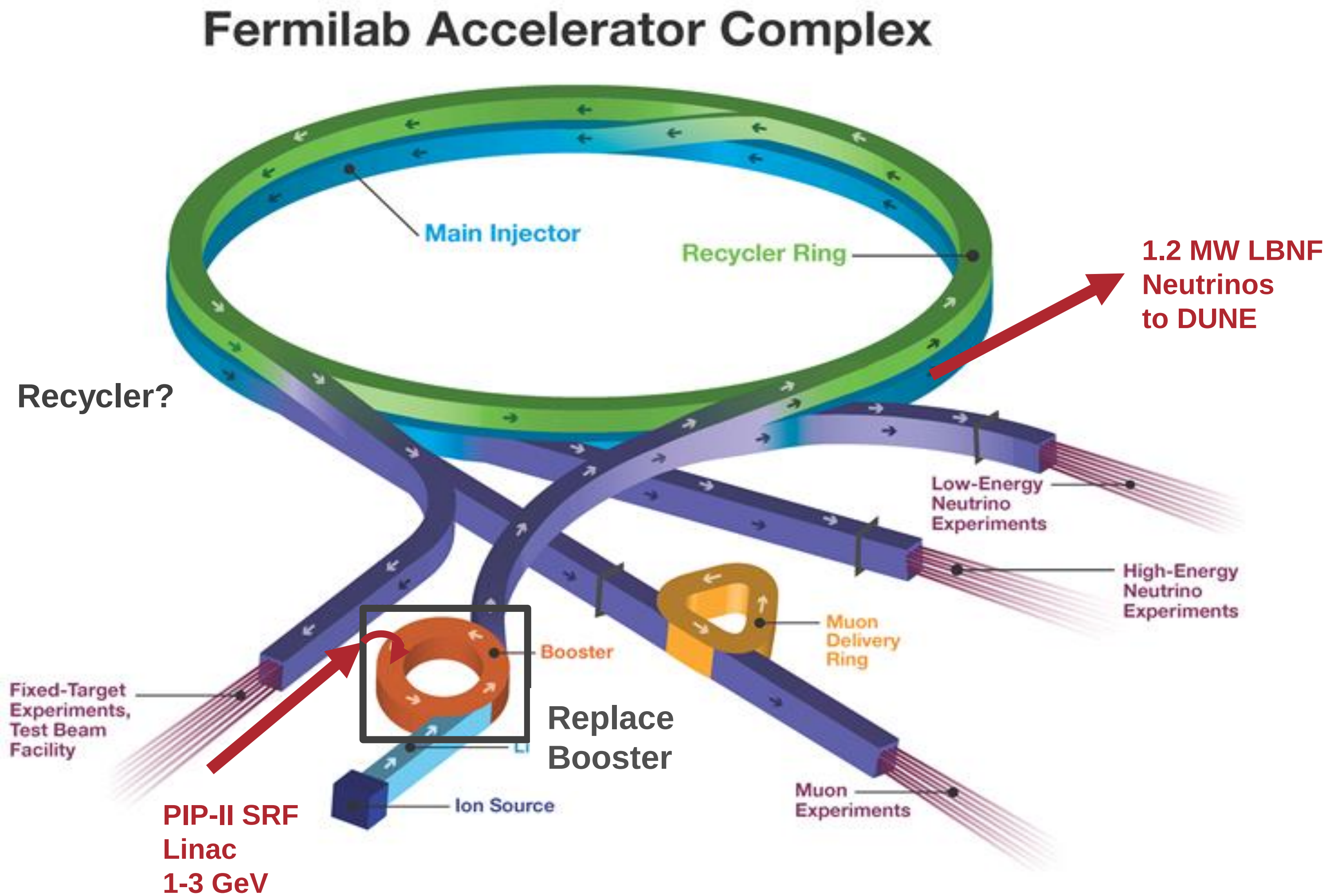




Physics Milestone	Exposure
5σ Mass Ordering ($\delta_{CP} = -\pi/2$)	1
5σ Mass Ordering (100% of δ_{CP} values)	2
3σ CP Violation ($\delta_{CP} = -\pi/2$)	3
3σ CP Violation (50% of δ_{CP} values)	5
5σ CP Violation ($\delta_{CP} = -\pi/2$)	7
5σ CP Violation (50% of δ_{CP} values)	10
3σ CP Violation (75% of δ_{CP} values)	13
δ_{CP} Resolution of 10 degrees ($\delta_{CP} = 0$)	8
δ_{CP} Resolution of 20 degrees ($\delta_{CP} = -\pi/2$)	12
$\sin^2 2\theta_{13}$ Resolution of 0.004	15

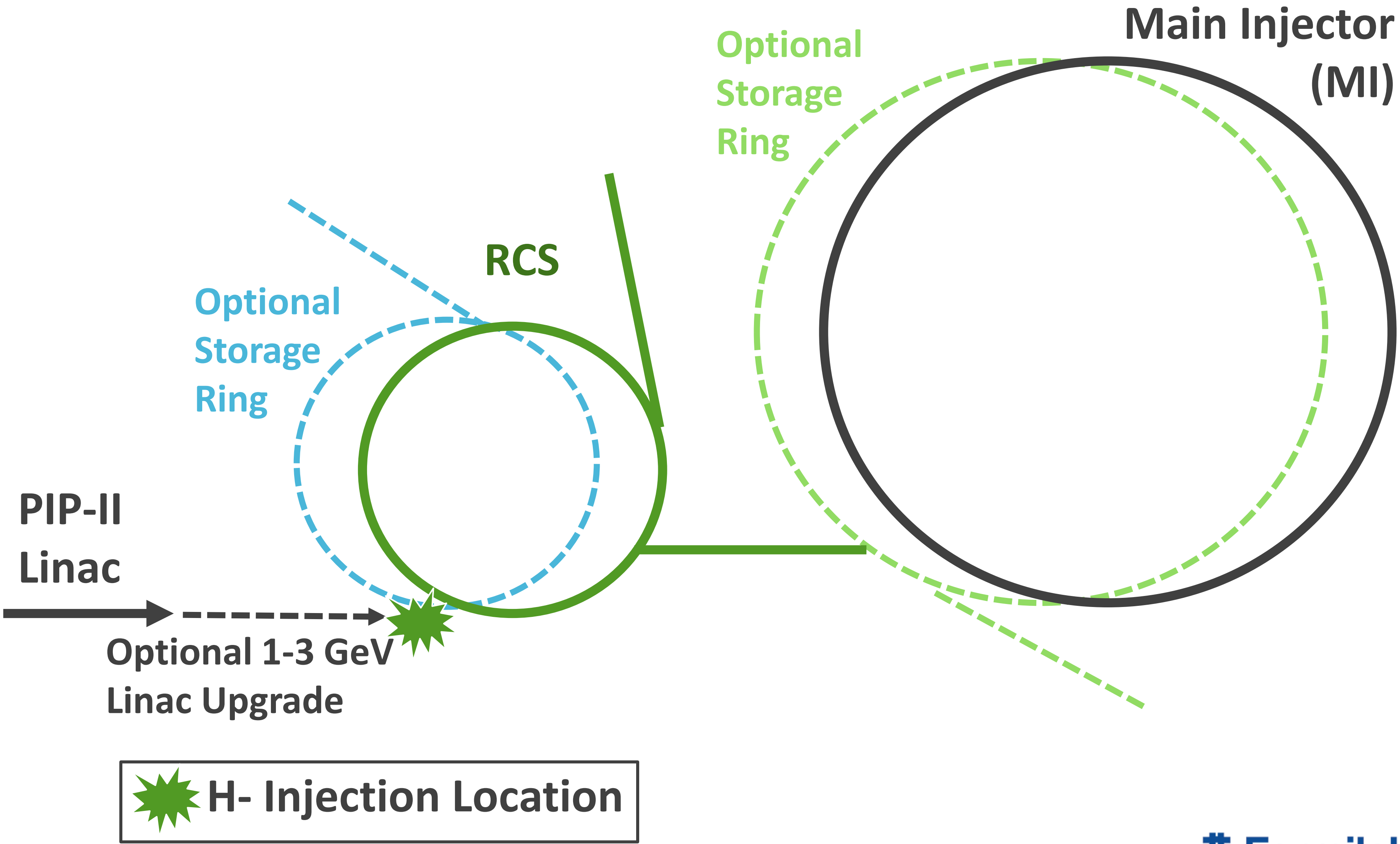
DUNE TDR, 2018

Fermilab Upcoming Upgrades Future 2.4MW

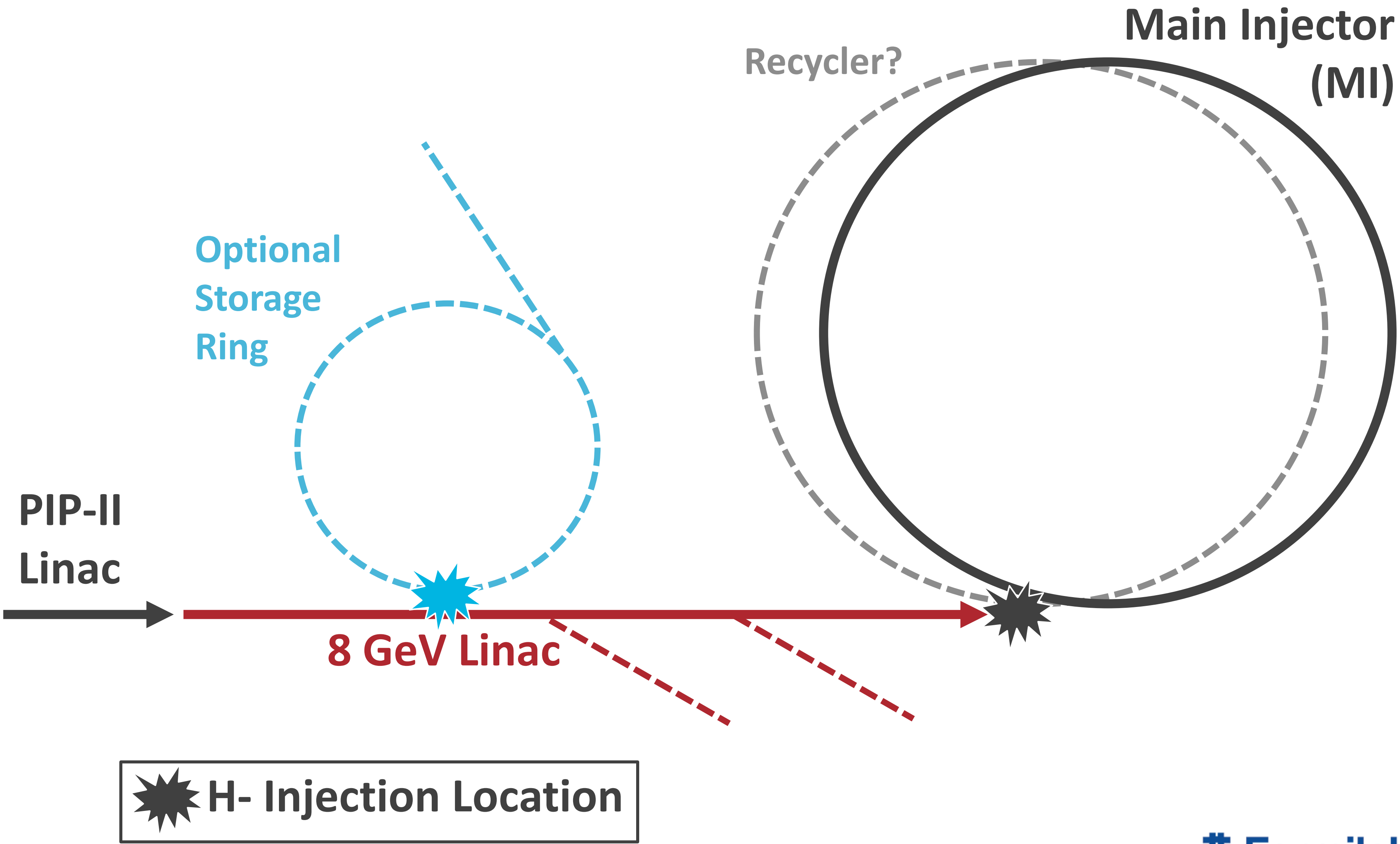


Booster prevents x2 PIP-II power, injection energy and transition-crossing limits

Rapid-Cycling Synchotron (RCS) Option



8 GeV Linac Option



Upgrade Design History & Process

In 2008, Project X: 8 GeV SRF Linac, directly into Main Injector.

In 2010, Project X ICD-2: 2 GeV Linac, New 2-8 GeV RCS.

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In 2021, Committee for Fermilab Booster Upgrade an integrated design effort:

Science Working Group chaired by R. Harnik
"Physics Opportunities for the Fermilab Booster Replacement"

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Next:
Snowmass & P5 Process

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Experiment	Dark Sectors	ν Physics	CLFV	Precision tests	R&D
Lepton flavor violation: μ-to-e conversion			■	■	
Lepton flavor violation: μ decay	■		■	■	
PIP2-BD: ~GeV Proton beam dump	■	■			
SBN-BD: ~10 GeV Proton beam dump	■	■			
High energy proton fixed target	■			■	
Electron missing momentum	■	■			
Nucleon form factor w/ lepton scattering		■		■	
Electron beam dumps	■				
Muon Missing Momentum	■			■	
Muon beam dump	■				
Physics with muonium	■			■	
Muon collider R&D and neutrino factory		■			■
Rare decays of light mesons	■			■	
Ultra-cold neutrons				■	
Proton storage ring for EDM and axions	■			■	
Tau neutrinos		■			
Proton irradiation facility					■
Test-beam facility					■

(electrons)

Physics Opportunities for the Fermilab Booster Replacement, 2021

‘Laundry List’ of Possible Experiments (RCS Scenario)

2 GeV CW-capable beam, 2mA

- mu2e-II type charged-lepton flavor violation experiment
- Low energy muon experiments (muonium, muon decay)
- REDTOP run-II/run-III program
- neutron-antineutron oscillation experiments
- EDM storage ring (with polarized proton source upgrade)

2 GeV pulsed beam from Storage Ring, ~1 MW

- PIP2-BD stopped pions, GeV-scale dark sector search
- AMF/PRISM charged-lepton flavor violation experiments

8 GeV RCS program, ~1 MW

- SBN-BD kaon decay-at-rest, intermediate energy dark sector search
- any successors to short-baseline neutrino program
- NuSTORM and muon-collider R&D
- proton irradiation facility
- muon beam dump experiment

120 GeV Slow-Extraction program, 8e12 over six second, once per min.

- DarkQuest dark matter spectrometer experiment
- M3 muon missing-momentum experiment
- test beam program

This is everything proposed at Snowmass! Not necessarily planned for Fermilab!

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8-GeV Linac Program (MI program)

Performance Parameter	PIP	PIP-II	BRL	Unit
Linac Beam Energy	400	800	8000	MeV
Linac Beam Current (chopped)	25	2	2	mA
Linac Pulse Length	0.03	0.54	2.2	ms
Linac Pulse Repetition Rate	15	20	20	Hz
Linac Upgrade Potential	N/A	CW	CW	
8 GeV Protons per Pulse (extracted)	4.2	6.5	27.5	10^{12}
8 GeV Pulse Repetition Rate	15	20	20	Hz
Beam Power @ 8 GeV	80	166	700	kW
8 GeV Beam Power to MI	50	83-142*	176-300	kW
Beam Power to 8 GeV Program (pulsed mode)	30	83-24*	500-375	kW
Main Injector Protons per Pulse (extracted)	4.9	7.5	15.6	10^{13}
Main Injector Cycle Time @ 120 GeV	1.33	1.2	1.2	s
Main Injector Cycle Time @ 60 GeV	N/A	0.7	0.7	s
Beam Power @ 60 GeV	N/A	1	2.15	MW
Beam Power @ 120 GeV	0.7	1.2	2.5	MW

*Total PIP-II with Booster 8 GeV power is 166 kW.

Injects at 20Hz into MI over six 2.2ms pulses

Section	Length	Bending field or RF frequency	Total bending angle or Linac mode	Cavities/magnets/ cryomodules	Cryomodule length
1 GeV transport	40 m	0.277 T	-45°		
1 → 3 GeV Linac	240 m	650 MHz	CW	120/20/20	9.92 m
3 GeV bend	200 m	0.13 T	105°		
3 → 8 GeV Linac	390 m	1300 MHz	Pulsed, 10 Hz	224/28/28	12.5 m
8 GeV injection		0.055 T			

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8-GeV pulsed
2μs -> 2ms

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RCS Scenarios

"Design Considerations for Fermilab Multi-MW Proton Facility" white paper

Parameter	PIP-II Booster	ICD-2	BSR
Linac Energy	0.8 GeV	2 GeV	2 GeV
Minimum Linac Current	2 mA	2 mA	2 mA
GeV-scale Accumulator Ring	Optional	Optional	Required
RCS Energy	8 GeV	8 GeV	8 GeV
RCS Intensity	6.5 e12	26 e12	37 e12
RCS Circumference	474.2 m	553.2 m	570 m
RCS Rep. Rate	20 Hz	10 Hz	20 Hz
Number of Batches	12	6	5
Accumulation Technique	Slip-stacking	Conventional	Conventional
8 GeV Accumulation	Recycler	Recycler	Main Injector
Available RCS Power	80 kW	170 kW	750 kW
Main Injector Intensity	80 e12	156 e12	185 e12
Main Injector Cycle Time	1.2 s	1.2 s	1.4 s
Main Injector Power (120 GeV)	1.2 MW	2.4 MW	2.4 MW
Upgraded Main Injector Power		3.3 MW	4.0 MW

RCS Scenarios (ramp rate and 8 GeV program)

"Design Considerations for Fermilab Multi-MW Proton Facility" **white paper**

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Upgraded Main Injector Power		3.3 MW	4.0 MW

ICD-2 RCS is more cost-effective, BSR is more ambitious

BSR delivers more for 8 GeV, compatible with a second LBNF target station

RCS Scenarios (required rings)

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ICD-2 scenario require Recycler (or similar), maintains RR experimental program.

BSR sceneario requires either an Accumator Ring or 5 mA linac upgrade.

RCS Scenarios (possible staging)

“Design Considerations for Fermilab Multi-MW Proton Facility” white paper

Parameter	PIP-II Booster	**Staging?**	ICD-2	BSR
Linac Energy	0.8 GeV	**~1.6 GeV**	2 GeV	2 GeV
Minimum Linac Current	2 mA	2 mA	2 mA	2 mA
GeV-scale Accumulator Ring	Optional	Optional	Optional	Required
RCS Energy	8 GeV	8 GeV	8 GeV	8 GeV
RCS Intensity	6.5 e12	~20 e12	26 e12	37 e12
RCS Circumference	474.2 m	~ 550 m	553.2 m	570 m
RCS Rep. Rate	20 Hz	**10 Hz**	10 Hz	20 Hz
Number of Batches	12	6	6	5
Accumulation Technique	Slip-stacking	Conventional	Conventional	Conventional
8 GeV Accumulation	Recycler	**Recycler**	Recycler	Main Injector
Available RCS Power	80 kW	~60 kW	170 kW	750 kW
Main Injector Intensity	80 e12	116 e12	156 e12	185 e12
Main Injector Cycle Time	1.2 s	1.2 s	1.2 s	1.4 s
Main Injector Power (120 GeV)	1.2 MW	**1.8 MW**	2.4 MW	2.4 MW
Upgraded Main Injector Power			3.3 MW	4.0 MW

Possible Staging with 1.8 MW, smaller Linac upgrade, PIP-II era Main Injector RF.

Optionally, could be designed to be upgradeable to either 2.4 MW scenario.

Summary

PIP-II upgrade, **massive potential for GeV-scale experimental program**
- Proposed ~100kW **mu2e-II program**.
- Proposed ~100kW **PAR / dark sector program**
- A lot of other ideas are out there – muons, neutrons, polarized protons.

Longterm planning for a subsequent **Proton Intensity Upgrade.**
- Engaging Snowmass and the wider physics community.
- Robust planning helps make wise decisions, maintain flexibility.

ICD-2 RCS: Well-developed proposal, focused on 2.4 MW for LBNF.
BSR RCS: More challenging injection/linac, much more 8-GeV power.
8-Gev Linac: R&D for 8-GeV injection, potential for high CW power.

What will be the **future 0.8-2 GeV** experimental program?
- power, beam structure, timeline.

What will be the **future 8 GeV** experimental program?
- power, beam structure, timeline.
- future role of Recycler Ring and Delivery Ring.