Accelerator Complex Evolution (ACE) at Fermilab

Nhan Tran
with credit to ACE Science workshop committee and discussion leads

Fermilab Users Meeting 2023
June 30, 2023

Outline

- **Prologue**
  - Evolution to the Accelerator Complex Evolution
  - ACE Science (Workshop)
- ACE overview and opportunities
- Physics vision and next steps

Fermilab

Lia's talk on Weds

The Fermilab Accelerator Complex Evolution (ACE)

ACE has two components

- **Upgrades to the Main Injector and target station** will allow DUNE to achieve world-leading results on an accelerated schedule
- **A Booster replacement** will
  - Provide a robust and **reliable** platform for the future of the Fermilab accelerator complex
  - Ensure high intensity for DUNE Phase II → CP Violation *measurement*
  - Enable the **capability** of the complex to serve precision experiments and searches for new physics with beams from 2-120 GeV
  - Create the **capacity** to adapt to new discoveries
  - Supply the high-intensity proton source necessary for future multi-TeV accelerator research

ACE Science Opportunities workshop

- Following on the 2019 booster science opportunities workshop
- Build on ACE concept and include: neutrinos, muons, dark sector, BSM, multi-TeV platform.

Vital that HEP Community drives this!

ACE Science Workshop
June 14 - 15, Fermilab
https://indico.fnal.gov/event/59663/

Leveraging PIP-II and ACE, the US is well positioned to host a world-leading energy frontier collider as the next major facility at Fermilab, conceived and executed as global endeavor.

Recent history

TM-2754-AD-APC-PIP2-TD

An Upgrade Path for the Fermilab Accelerator Complex*

R. Ainsworth, J. Dey, J. Eldred, R. Harnik, J. Jarvis, D.E. Johnson, I. Kourbanis, D. Neuffer, E. Pozdeyev, M.J. Syphers,† A. Valishev, V.P. Yakovlev, and R. Zwaska

Fermi National Accelerator Laboratory, Batavia, IL, 60510, USA

(Dated: May 19, 2021)

FERMILAB-FN-1145, LA-UR-22-21987

Physics Opportunities for the Fermilab Booster Replacement

John Arrington,[1] Joshua Barrow,[2,3] Brian Batell,[4] Robert Bernstein,[5] Nikita Blinov,[6] S. J. Brice,[5] Ray Culbertson,[5] Patrick deNiverville,[7] Vito Di Benedetto,[5] Jeff Eldred,[5] Angela Fava,[5] Laura Fields,[8] Alex Friedland,[9] Andrei Gaponenko,[5] Corrado Gatto,[10,11] Stefania Gori,[12] Roni Harnik,[5,*] Richard J. Hill,[5,13] Daniel M. Kaplan,[14] Kevin J. Kelly,[5,15] Mandy Kiburg,[5] Tom Kobilarcik,[5] Gordan Krnjaic,[5] Gabriel Lee,[16,17,18] B. R. Littlejohn,[14] W. C. Louis,[7] Pedro Machado,[5] Anna Mazzacane,[5] Petra Merkel,[5] William M. Morse,[19] David Neuffer,[5] Evan Niner,[5] Zarko Pavlovic,[5] William Pellico,[5] Ryan Plestid,[5,13] Maxim Pospelov,[20] Eric Prebys,[21] Yannis K. Semertzidis,[22,23] M. H. Shaevitz,[24] P. Snopok,[14] M.J. Syphers,[25] Rex Tayloe,[26] R. T. Thornton,[7] Oleksandr Tomalak,[5,7,13] M. Toups,[5] Nhan Tran,[5] Yu-Dai Tsai,[5,27] Richard Van de Water,[7] Katsuya Yonehara,[5] Jacob Zettlemoyer,[5] Yi-Ming Zhong,[28] and Robert Zwaska[5]

-ph] 8 Mar 2022

Report from the Fermilab Proton Intensity Upgrade Central Design Group

Robert Ainsworth, Giorgio Apollinari, Tug T. Arkan, Sergey Belomestnykh, Pushpalatha C. Bhat, S.J. Brice, Brian Chase, Mary E. Convery, Steven J. Dixon, Jeff Eldred, Grigory Eremeev, Brenna Flaugher, Jonathan D. Jarvis, Sergo Jiindariani, David Johnson, Jonathan Lewis, Richard Marcum, Sergei Nagaitsev, David Neuffer, Donato Passarelli, Frederique Pellemoine, William A. Pellico, Sam Posen, Eduard Pozdeyev, Alexander Romanenko, Arun Saini, Kiyomi Seiya, Vladimir Shiltsev, Nikolay Solyak, James M. Steimel, Diktys Stratakis, Alexander A. Valishev, Mayling L. Wong-Squires, Slava Yakovlev, Katsuya Yonehara, Robert Zwaska

Fermi National Accelerator Laboratory

May 31, 2023

***Posted* on ACE Science Workshop agenda**

https://arxiv.org/abs/2106.02133
https://arxiv.org/abs/2203.03925
+ many supplementary white papers

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Recent history

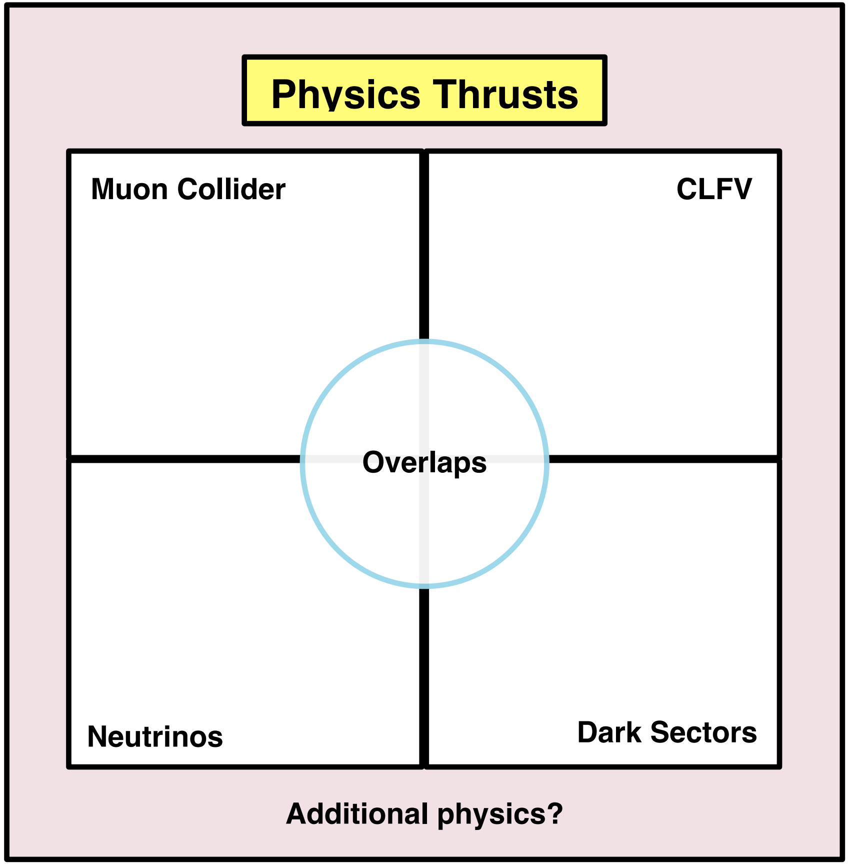
- **Muon collider** interest has increased through Snowmass process
- PIU-CDG study determined faster path to > 2MW to DUNE before Booster Replacement
  - Led to the broader Accelerator Complex Evolution (ACE) plan — **includes the MI fast ramp upgrade + Booster Replacement**

- ACE overview
  - **Part 1, ACE-MIRT**: **Reduce Main Injector Ramp time + Target R&D** to get to > 2 MW
  - **Part 2, ACE-BR**: **Booster Replacement**
    - Necessary for long-term facility reliability (Booster is 50 years old)
    - Deliver 2.4 MW to DUNE, enable world-leading accelerator physics program
      - Linac or RCS configurations for Booster Replacement

Recent-est History

- In light of PIU-CDG findings and Snowmass
  - Step back and re-evaluate ACE Science program and design
  - Collate community input and understand physics thrust complementarity

- **ACE Science Workshop (June 14-15)**
  - https://indico.fnal.gov/event/59663/
  - First in a series of workshops to co-design physics case and technical design
  - Physics cases largely developed orthogonally, need to understand synergies

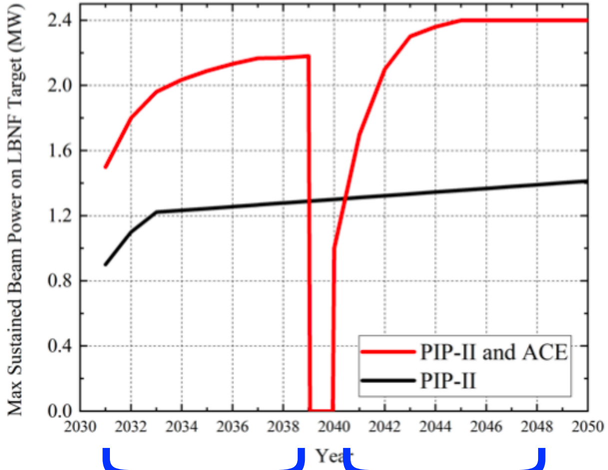


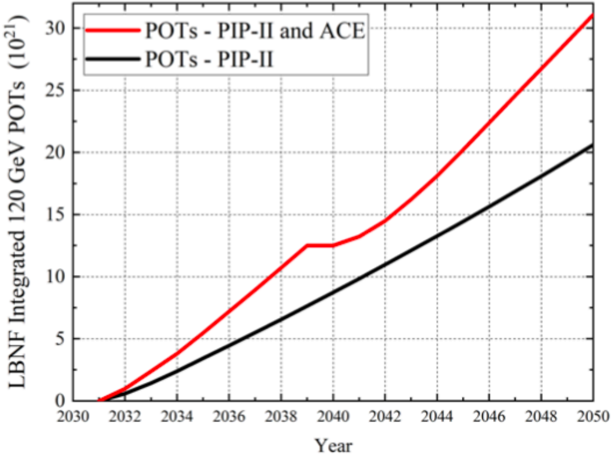
Outline

- Prologue
  - Evolution to the Accelerator Complex Evolution
  - ACE Science (Workshop)
- **ACE overview and opportunities**
- Physics vision and next steps

Mostly through pictures
(tables in backup)

DUNE plan



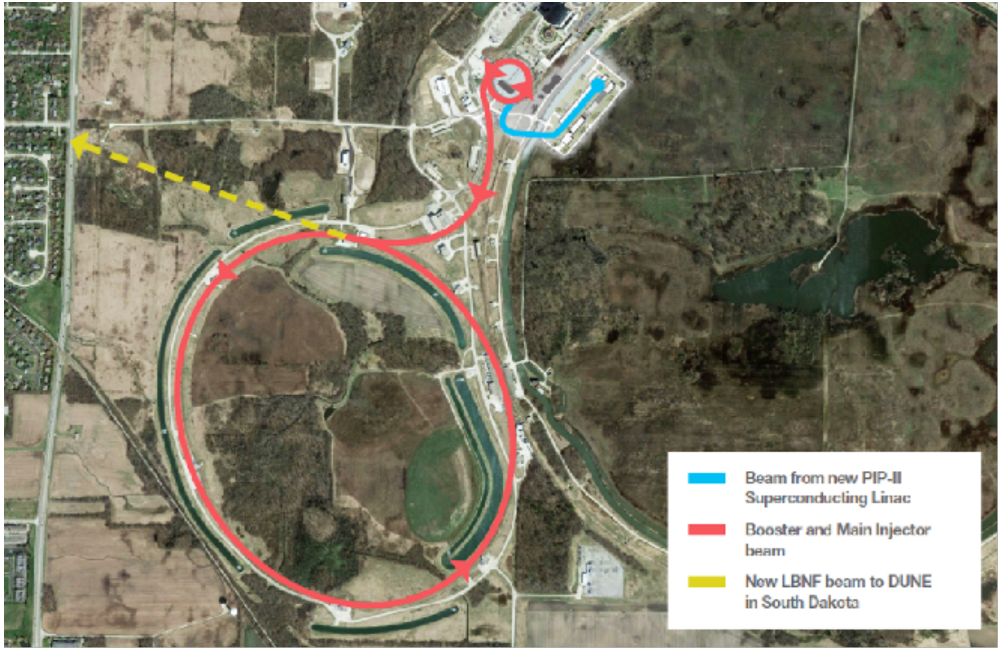


ACE-MIRT ACE-BR

ACE-MIRT: **Reduce Main Injector Ramp time + Target R&D** to get to > 2 MW

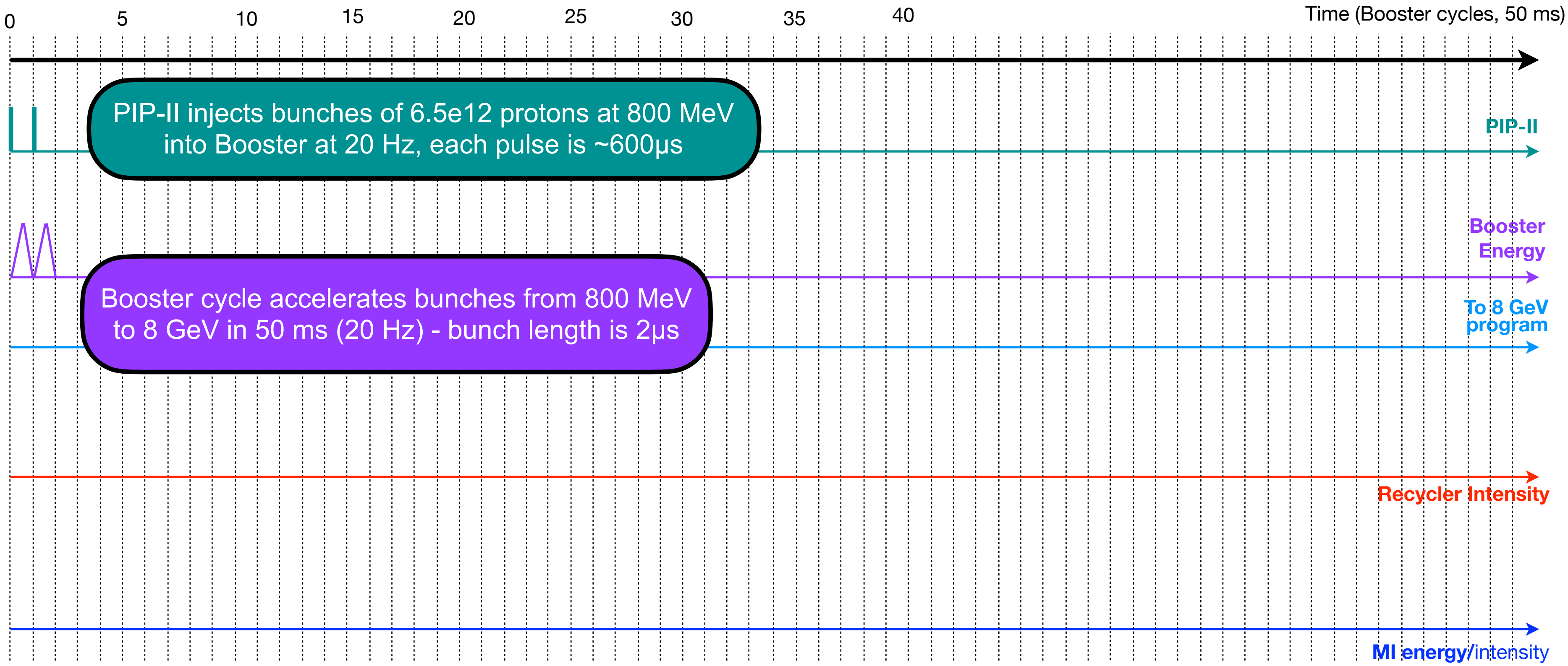
ACE-BR: **Booster Replacement**

PIP-II

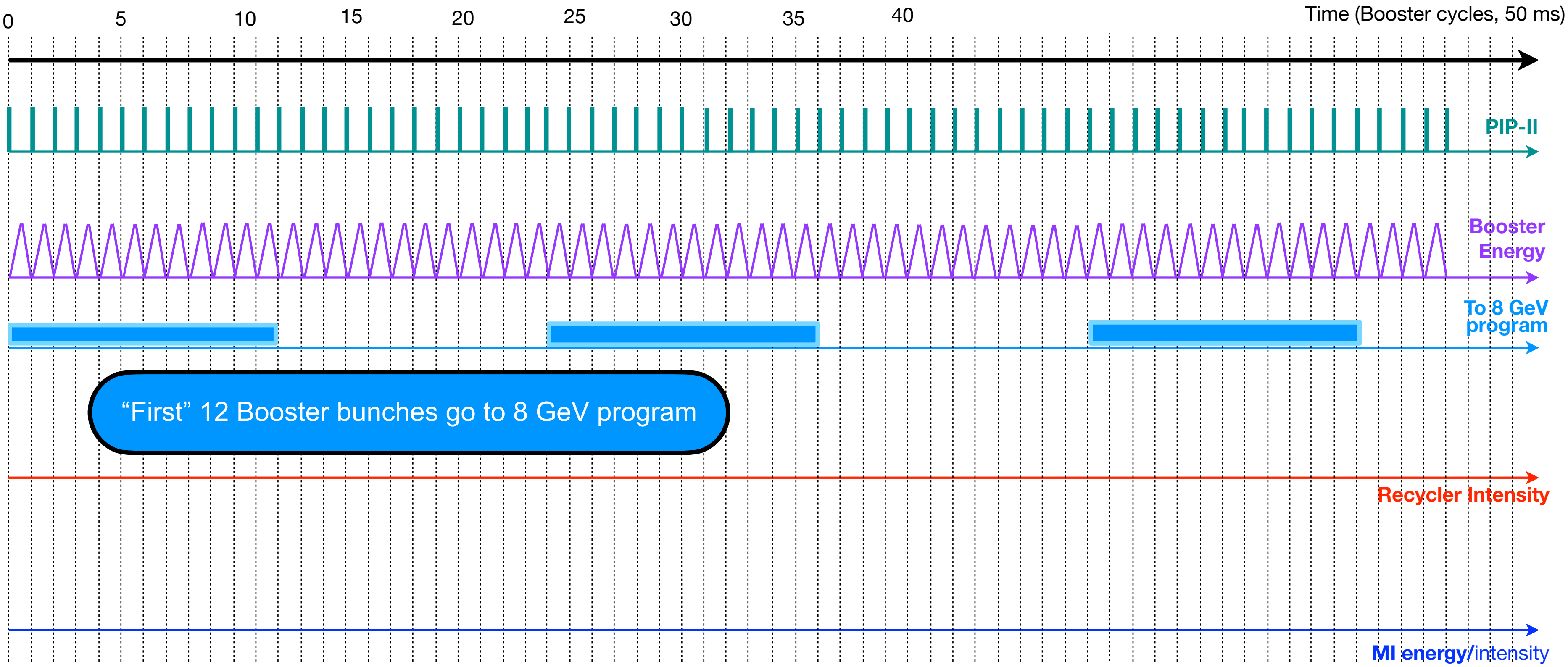


Scenario	Present	PIP-II
MI 120 GeV ramp time (s)	**1.333**	**1.2**
Booster Intensity (10^{12})	**4.5**	**6.5**
Booster ramp rate (Hz)	15	**20**
Number of batches	12	12
MI power at 120 GeV (MW)	0.865	**1.25**
Booster cycles for 8 GeV	8	12
Available 8 GeV power (kW)	29	83

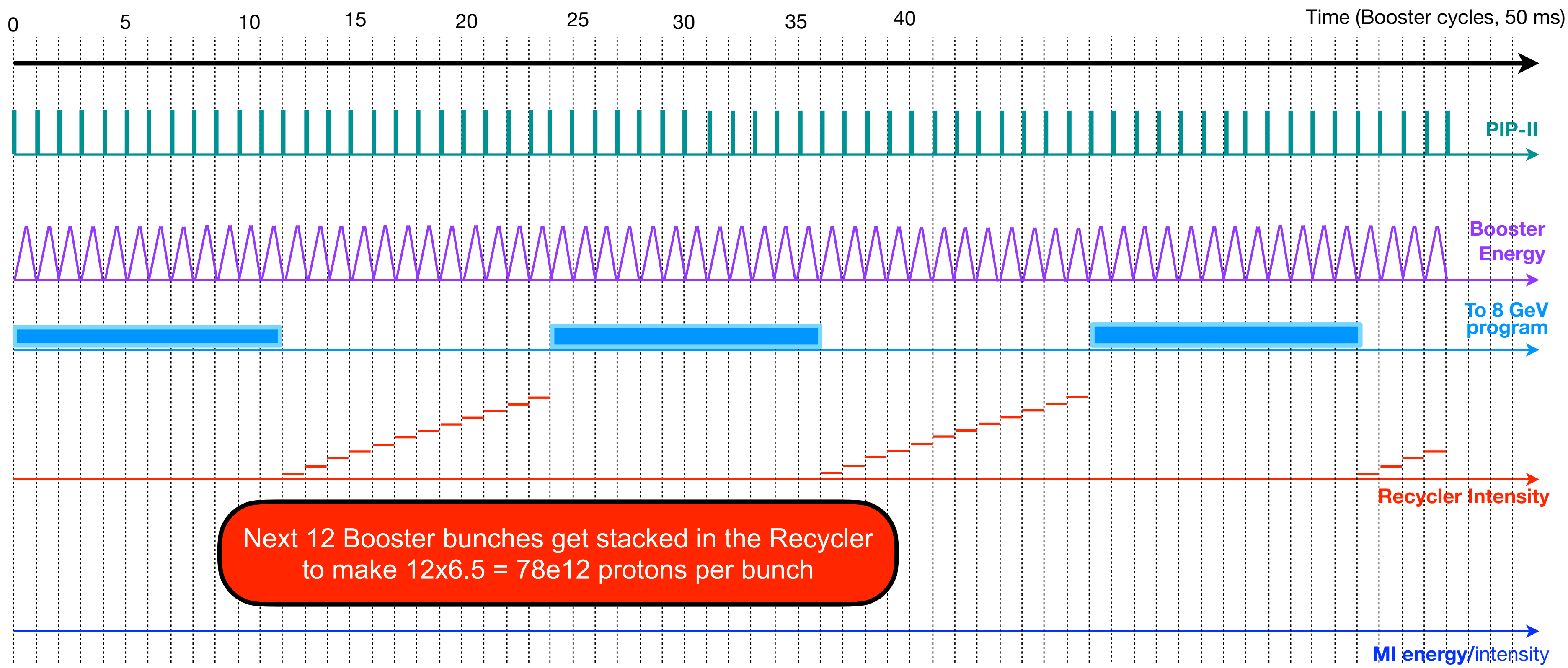
Accelerator Timeline - PIP-II Era



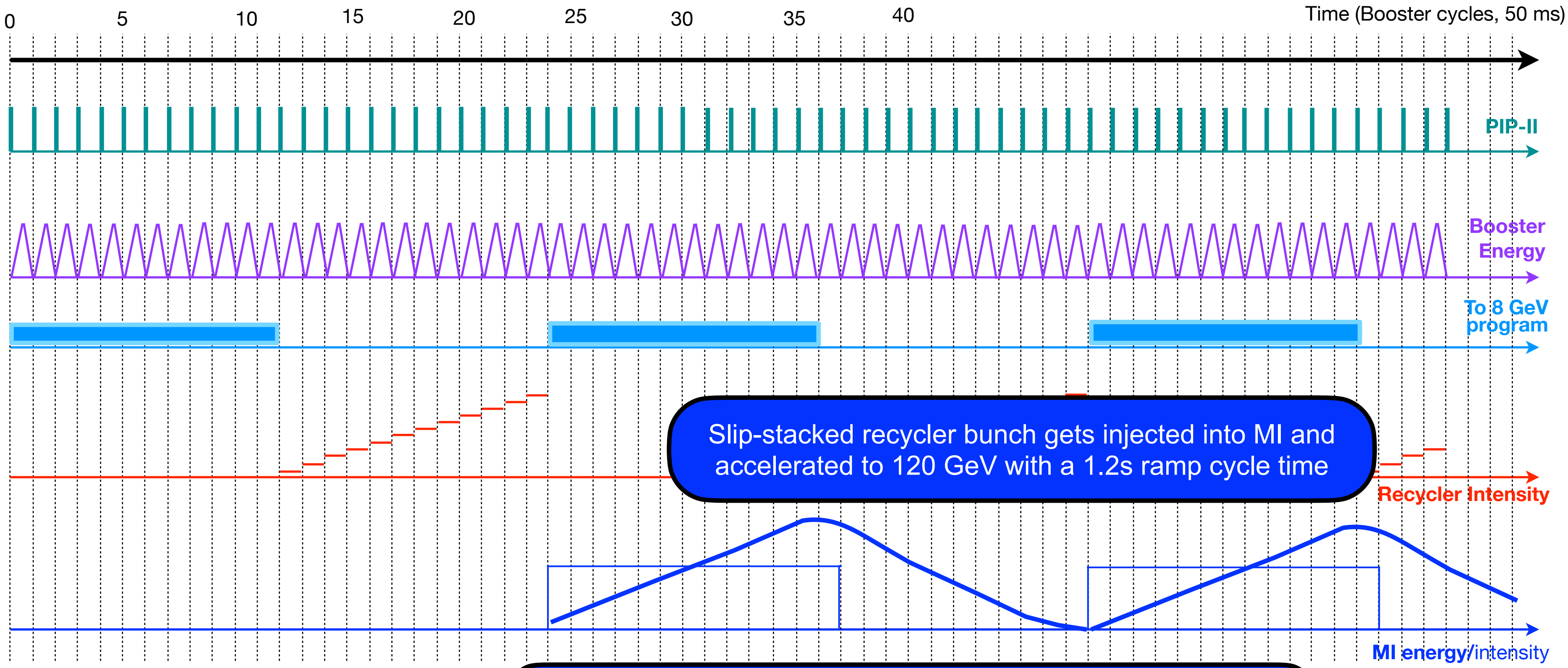
Accelerator Timeline - PIP-II Era



Accelerator Timeline - PIP-II Era



Accelerator Timeline - PIP-II Era



n.b. 1 out of 15 MI ramps go to Switchyard (e.g. Test Beam/SpinQuest)

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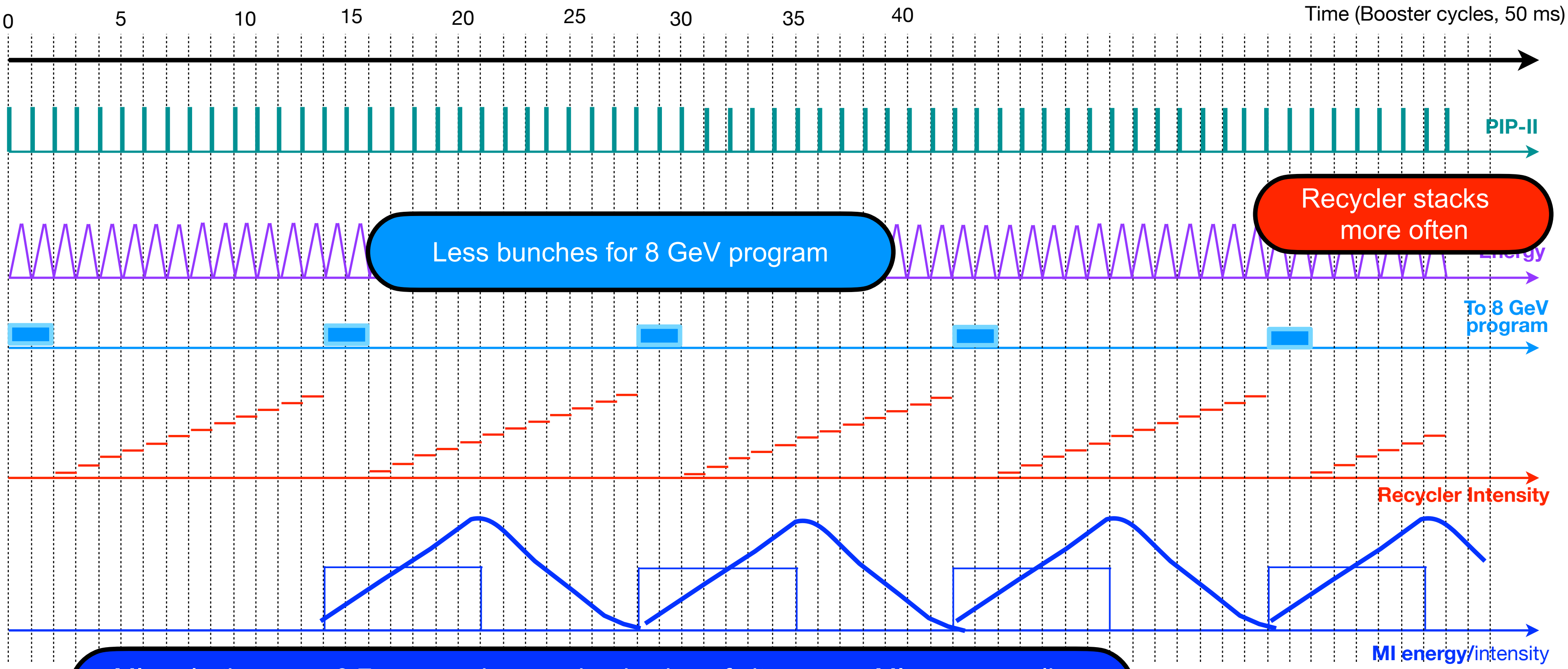
Accelerator Timeline - Main Injector Ramp Time (e.g. 0.7s)



MI cycle time now 0.7s — requires modernization of site power, MI power, cooling, controls, magnets, LLRF

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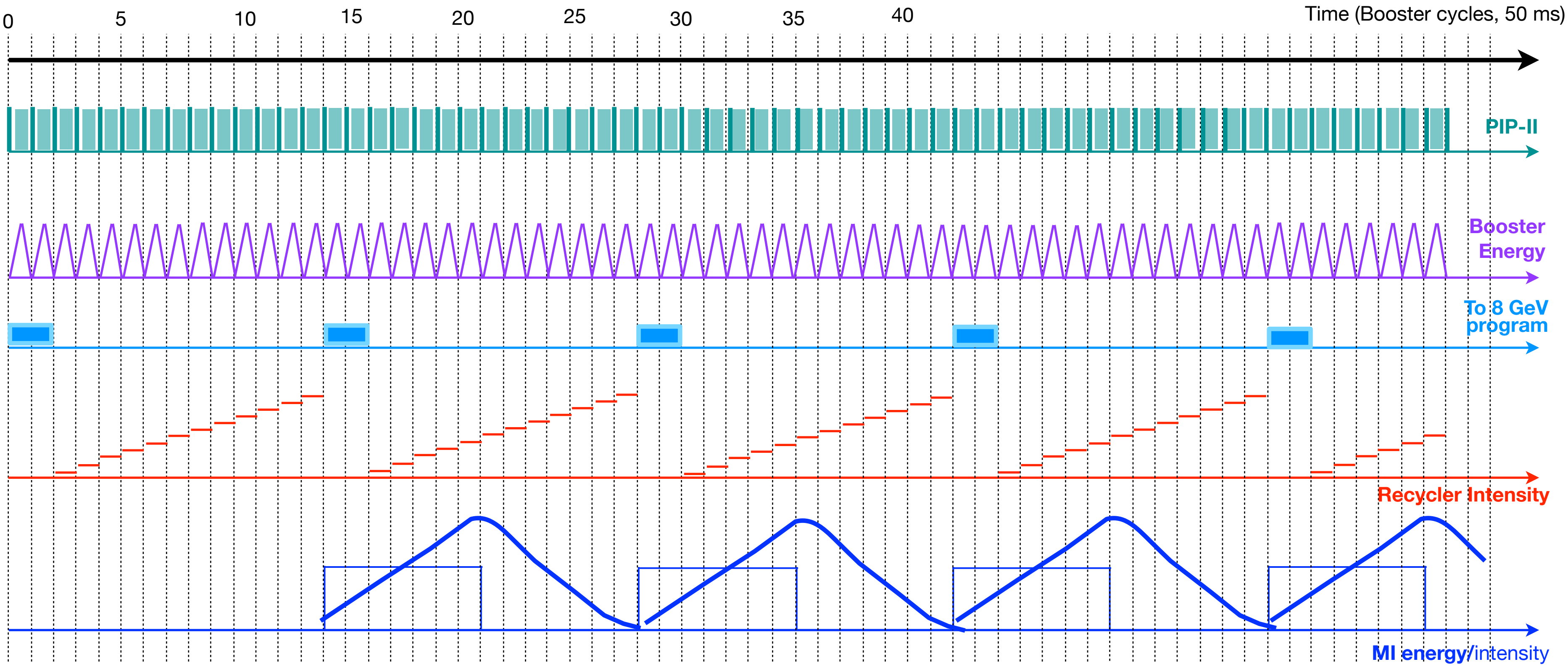
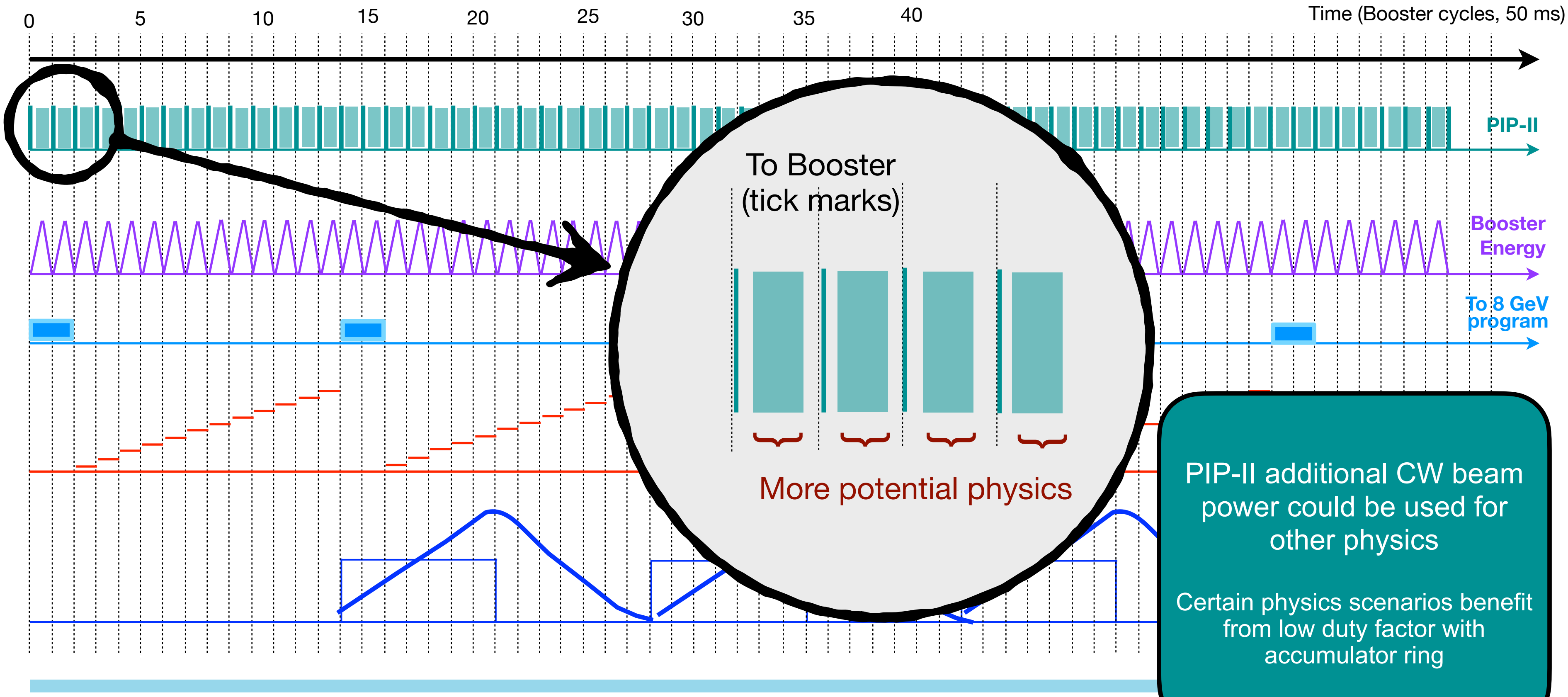
Accelerator Timeline - spigots from 0.8 - 2 GeV



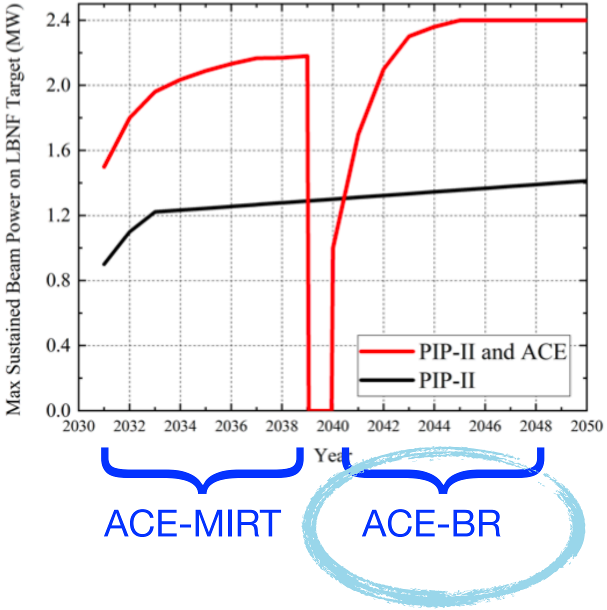
Accelerator Timeline - spigots from 0.8 - 2 GeV

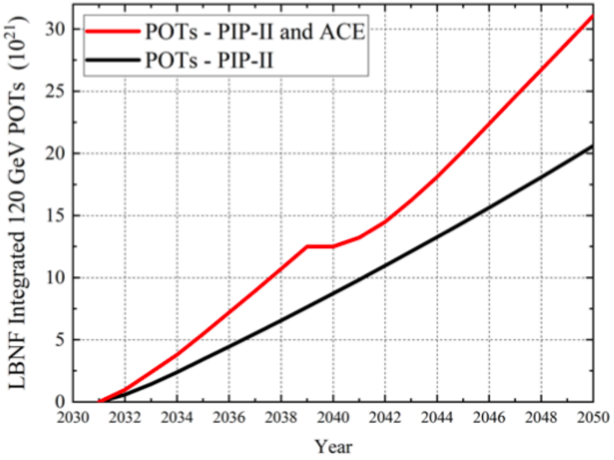


PIP-II additional CW beam power could be used for other physics

Certain physics scenarios benefit from low duty factor with accumulator ring

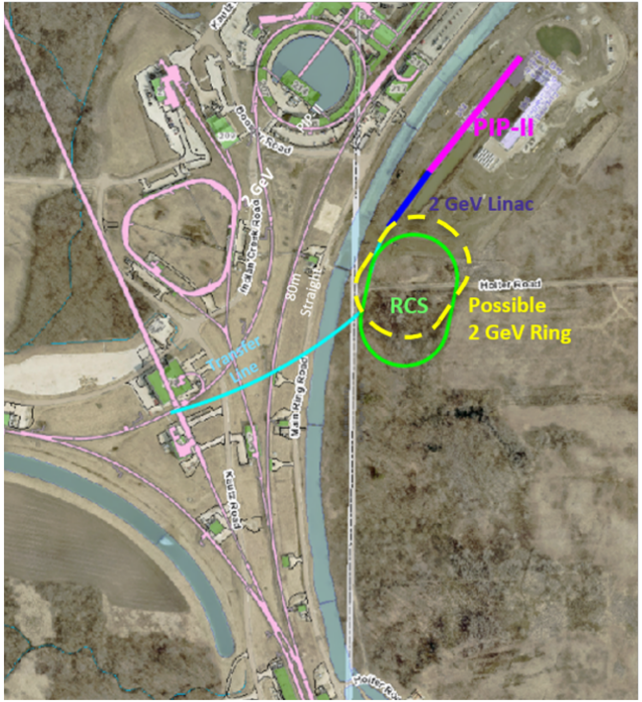
DUNE plan


Max Sustained Beam Power on LBNF Target (MW)
0.0
0.4
0.8
1.2
1.6
2.0
2.4
2030
2032
2034
2036
2038
2040
2042
2044
2046
2048
2050
Year
PIP-II and ACE
PIP-II
ACE-MIRT
ACE-BR


LBNF Integrated 120 GeV POTs (10^{21})
0
5
10
15
20
25
30
2030
2032
2034
2036
2038
2040
2042
2044
2046
2048
2050
Year
POTs - PIP-II and ACE
POTs - PIP-II

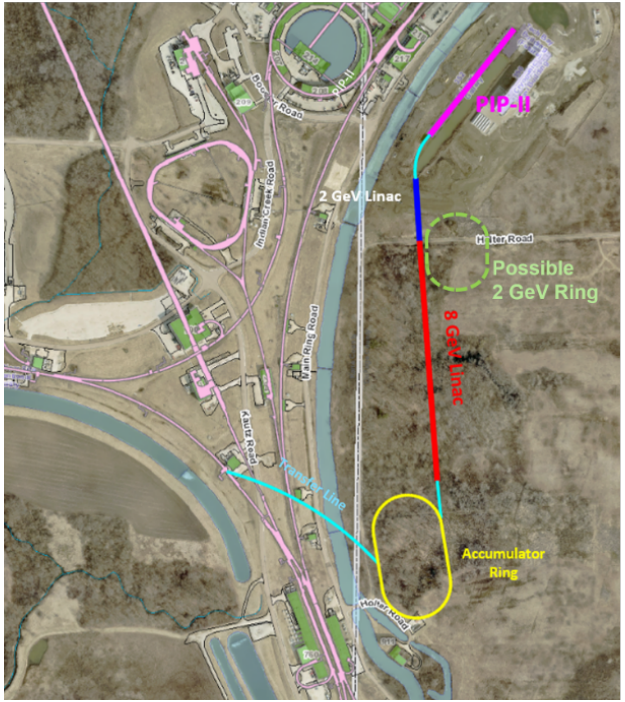
BR options: 800 MeV to 8 GeV

3 RCS options



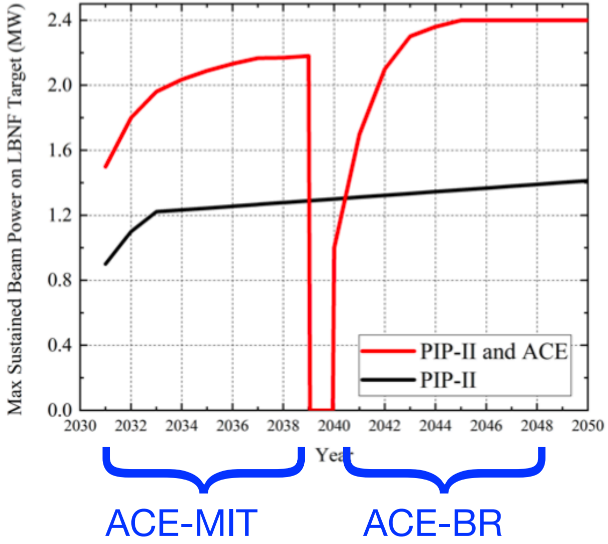
See backup for more details

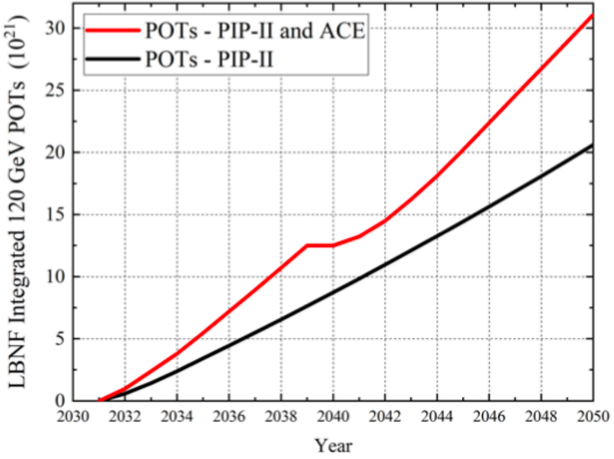
3 Linac options



** Estimate cost/schedule/ risk of basic ***elements*** of the accelerator (e.g. PIP-II upgrade to 2 GeV, target station, etc) in a large spreadsheet

Physics Spigots

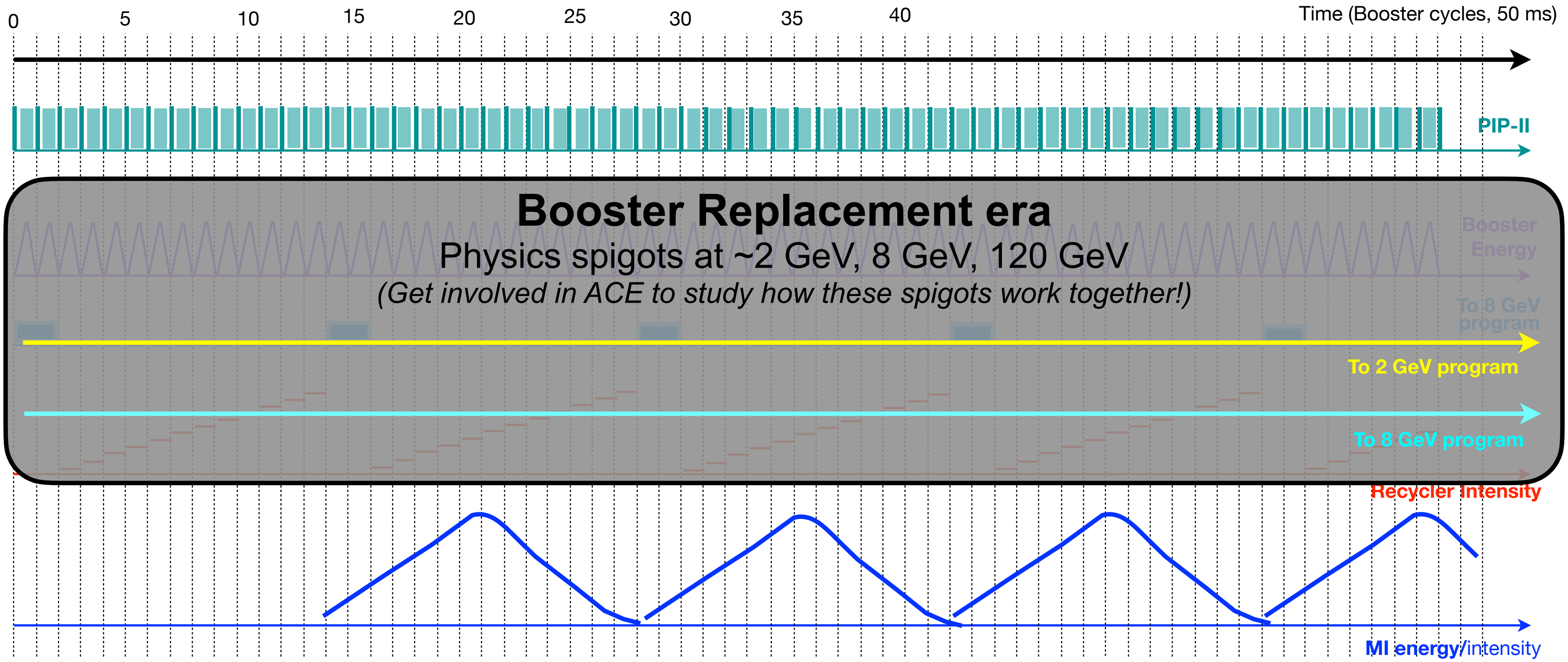




<u>During ACE-MIRT period:</u>
- significant beam available at 0.8 GeV,
- less so at 8 GeV (due to MI cycle time),
- 120 GeV slow extraction program could see more beam power

<u>During ACE-BR period,</u>
- significant beam available at 0.8-2 GeV,
- Potential for much more beam for 8 GeV program,
- 120 GeV slow extraction program even more beam

Accelerator Timeline - ACE-BR era



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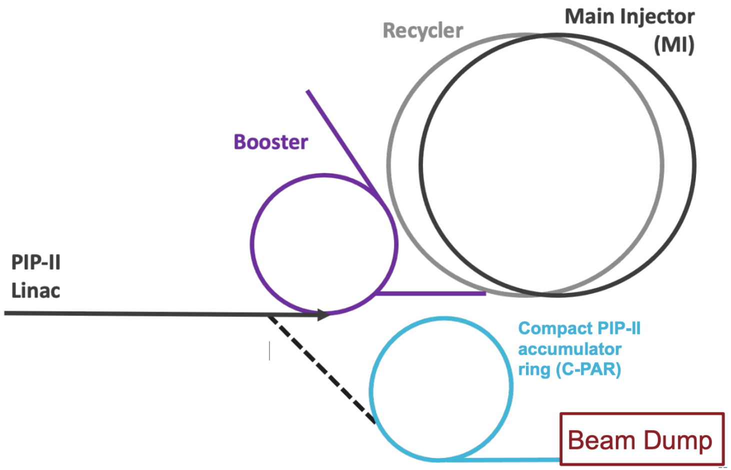
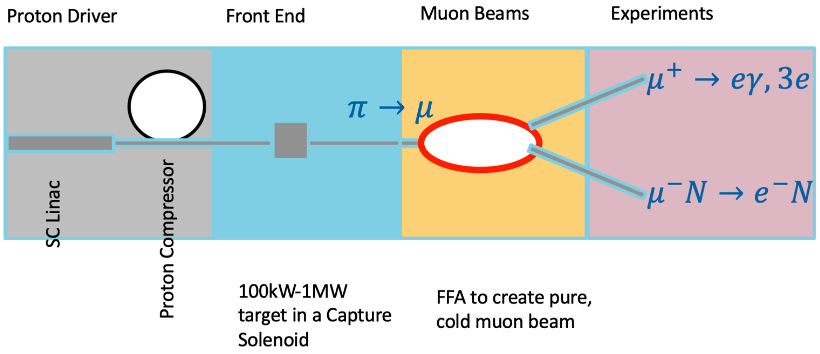
E.g. Physics from 0.8-2 GeV

Dark Sector Beam Dumps

See more, e.g. at
“Physics Opportunities at Beam Dump Facility in PIP-II and Beyond”
https://indico.fnal.gov/event/59430/





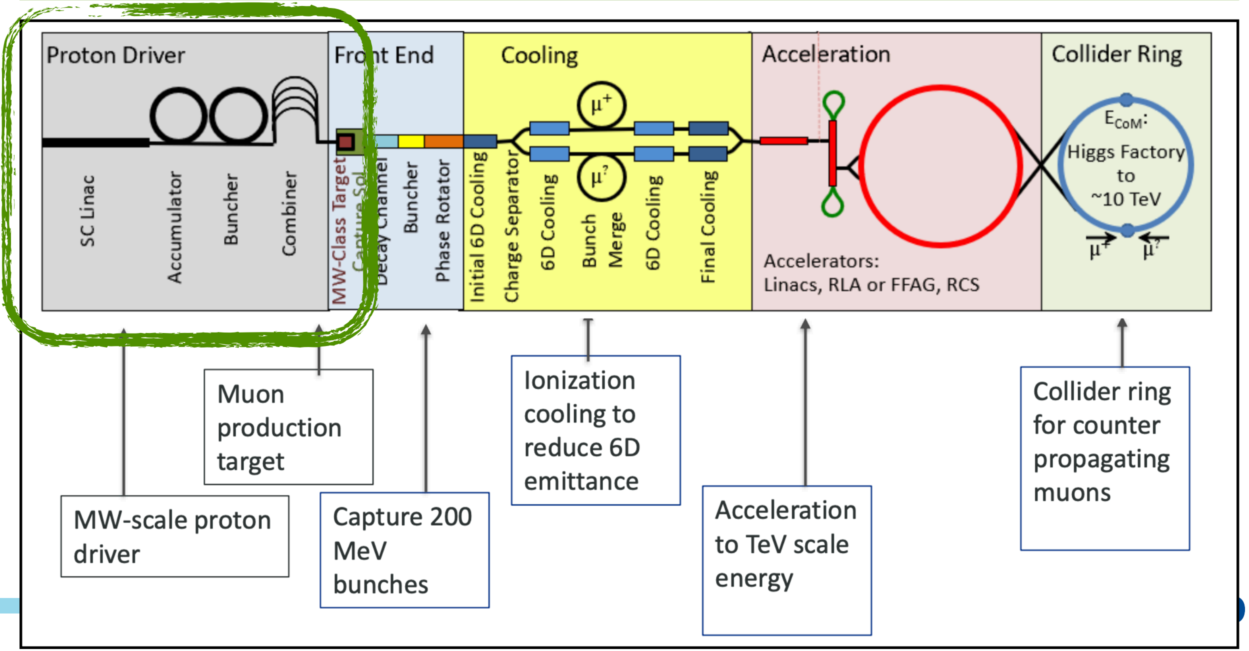
Advanced Muon Facility

See more, e.g. at
“Workshop on a future muon program at Fermilab”
https://indico.fnal.gov/event/57834/

Muon Collider Proton Driver: 8 GeV program

ACE-BR scenarios considered do not exactly map to Muon Collider requirements but not far off

Parameter	PIU scenarios	MuC-PD scenarios
Energy	8 GeV	8-16 GeV
Rep. rate	10-20 Hz	5-20 Hz
Avg. beam power	0.3-1.6 MW	1-4 MW
Proton structure	25-40 e12 over 2 μs ring	40-120 e12 in four 1-3 ns bunches



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- **Physics vision and next steps**

Science potential of ACE is broad, touches on energy, neutrino, rare/precision, cosmic, theory frontiers (and beyond!)

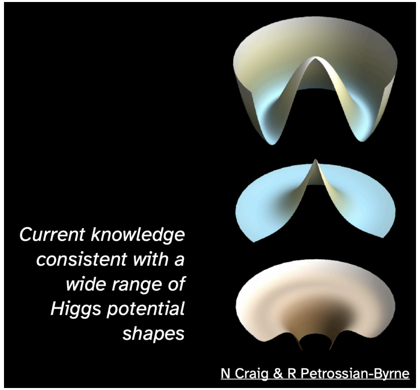
Just a few highlights, visit workshop agenda for much more information

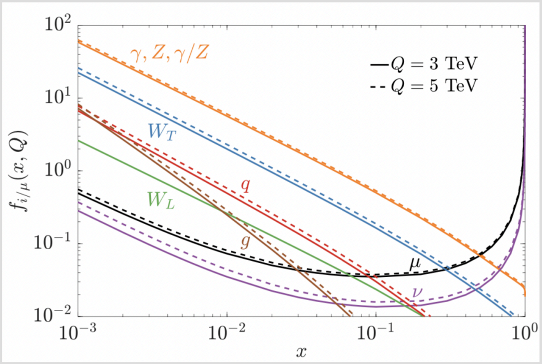
At the 10 TeV energy frontier

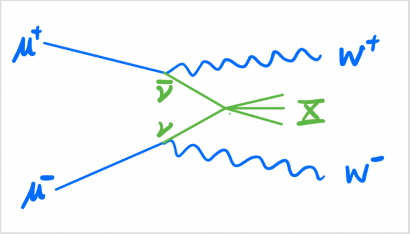
Ian Low, ACE workshop

A 10 TeV Muon Collider could:

- Study the microscopic nature of the Higgs boson as the most exotic state of matter in Nature.
- Testing unverified predictions of the SM.
- Explore the last vestiges of WIMP dark matter.
- Observe a new regime of quantum field theories.
- Strong synergies with the neutrino frontier.







https://indico.fnal.gov/e/aces2023

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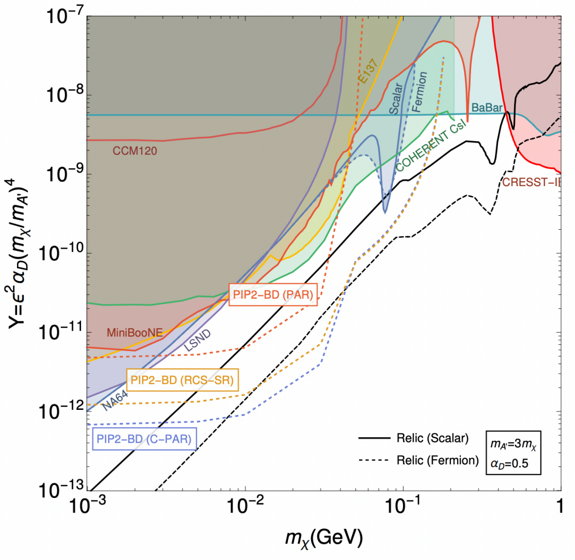
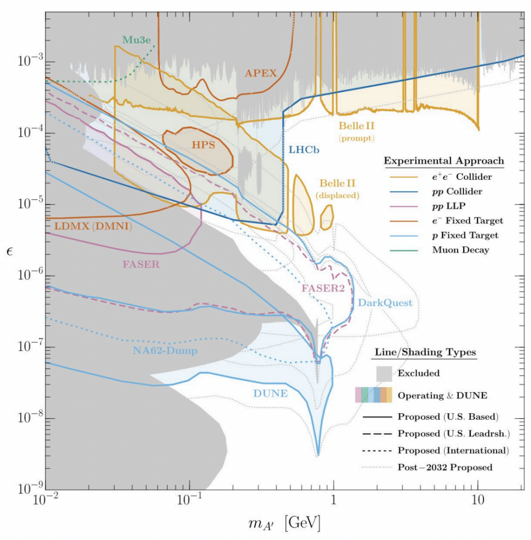
Dark sectors

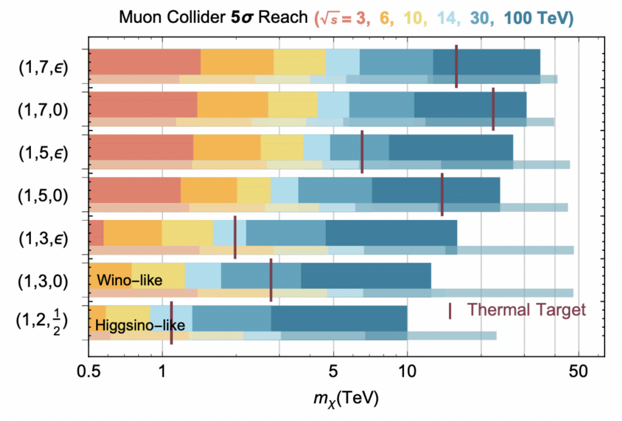
A powerful probe of open parameters space for Thermal Relic Freeze-out dark sectors from **MeV to TeV scale**



Sub-GeV thermal DM relics
PIP-II beam dump



Sub-GeV visible portals
DarkQuest, DUNE



TeV scale WIMP DM
Muon Collider

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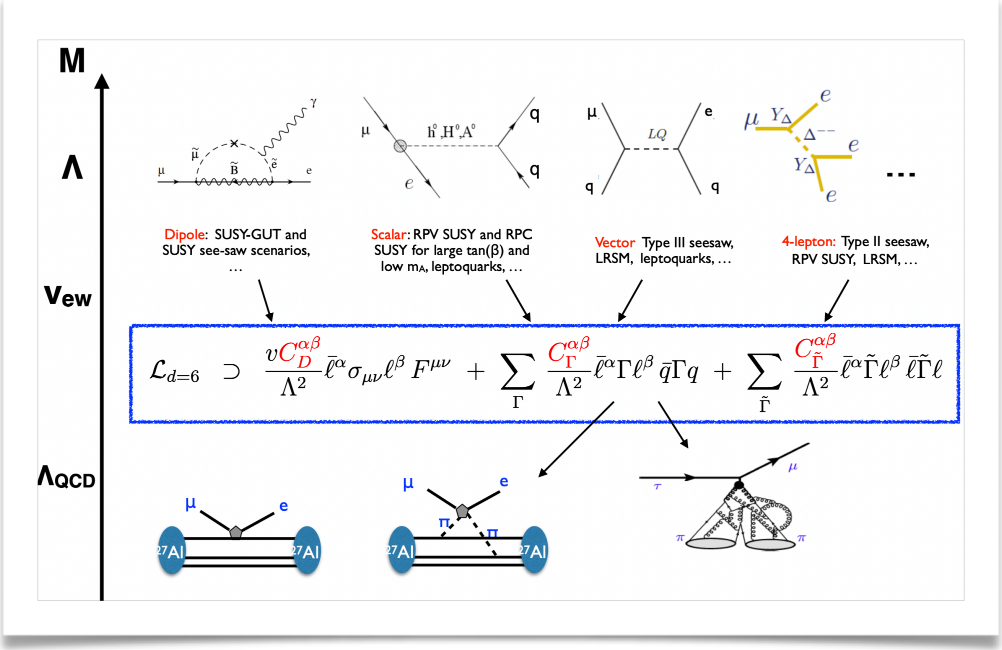
https://indico.fnal.gov/e/aces2023

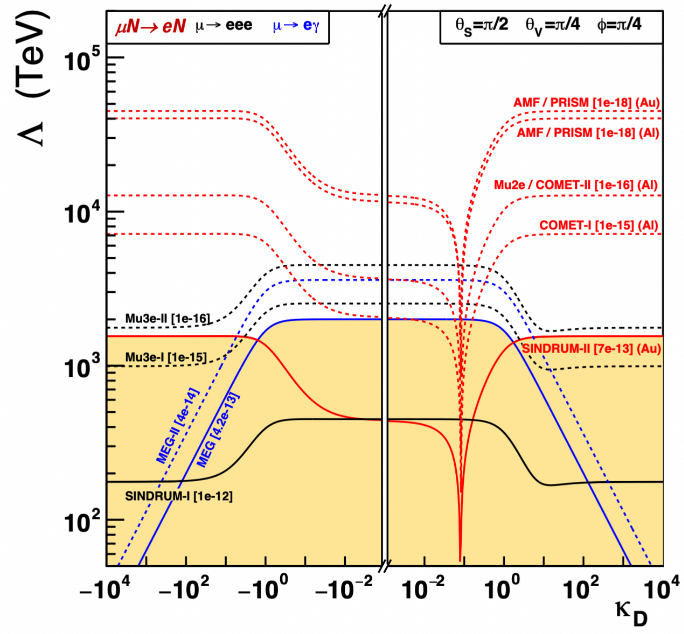
Indirect searches

Vincenzo Cirigliano, ACE workshop

Searches with rare muon decays can probe new physics scales up to ~10^5 TeV!



Davidson-Echenard 2204.00564



https://indico.fnal.gov/e/aces2023

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Neutrinos beyond DUNE

Future long baseline precision program

- Limitations of the super-beams:
  - $\pi^+ \to \mu^+ \nu_\mu$, charged-selected pions.
  - Dirty beam. Wrong-sign contamination, neutrinos from Kaons, muons lead to a beam ν_e background.
  - Systematics will kick in by (or before) the end of the DUNE and Hyper-K runs.
  - Only initial-state ν_μ: $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$.

Need more studies on neutrino factories in post DUNE world

$$\mu^- \to e^- \nu_\mu \bar{\nu}_e \quad \text{and} \quad \mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

- Muon energy and charge known very well $\to$ neutrino energy spectra known very well and neutrino beams very clean!
- Detectors with charge-ID allow one to kill the beam-background.
- High-energy ν_e and $\bar{\nu}_e$-beams allow for $\nu_e \to \nu_\mu$ and $\nu_e \to \nu_\tau$ oscillation measurements! **New oscillation channels provide priceless opportunity for more observables.**

Future short baseline program

Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactor	Gallium	
Flavor Conversion: Transitions	$3+N$ oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [103–106]
	$3+N$ w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[46, 47]
	$3+N$ w/ sterile decay	$\nu_4 \to \phi \nu_e$	✓	✓	✓ (orange)	✓ (orange)	[44, 45, 48–50]
Flavor Conversion: Matter Effects	$3+N$ w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	✗	✗	[38–42]
	$3+N$ w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓ (orange)	✓ (orange)	[43]
Flavor Conversion: Flavor Violation	lepton-flavor-violating μ decays	$\mu^+ \to e^+ \nu_\alpha \bar{\nu}_e$	✓	✗	✗	✗	[51–53]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to e \phi A$	✓	✓	✗	✗	[54]
Dark Sector: Decays in Flight	transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	✗	✗	[75]
	dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓	✗	✗	[73]
Dark Sector: Neutrino Scattering	neutrino-induced up-scattering	$\nu A \to N A$, $N \to \nu e^+ e^-$ or $N \to \nu\gamma\gamma$	✓ (orange)	✓	✗	✗	[63–72]
	neutrino dipole up-scattering	$\nu A \to N A$, $N \to \nu\gamma$	✓ (orange)	✓	✗	✗	[55–62]
Dark Sector: Dark Matter Scattering	dark particle-induced up-scattering	γ or e^+e^-	✗	✓	✗	✗	[74]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[74]

✓– the model can naturally explain the anomaly, ✓ (orange)– the model can partially explain the anomaly, ✗– the model cannot explain the anomaly.

- Requires additional potential modes of running such as anti-neutrino mode (Karagiorgi)
- Other ideas for short-baseline program too such as KDAR for mono-energetic neutrinos (KPIPE, Spitz)

https://indico.fnal.gov/e/aces2023

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ACE Science Workshop and next steps

- Discussion sessions — workshop included an afternoon dedicated to discussions among folks from different subfields
  - Identified many areas of priority and future study

- Examples of ACE design/R&D topics emerging from workshop:
  - **ACE-MIRT**: 8 GeV program beam power sharing across the CLFV, MuC R&D, and short-baseline neutrino program
  - **ACE-BR 0.8 → 2 GeV**: are accumulator ring pulsed beams compatible for dark sector and CLFV programs at both 0.8 and 2 GeV? Pros/cons of earlier 2 GeV Linac?
  - **ACE-BR 8 GeV**: is there a preferred design configuration to enable a Muon Collider proton driver? Is accumulator ring for MI compatible with MuC-PD

Looking forward

- Fermilab Accelerator Complex Evolution (ACE):
  - **ACE-MIRT**: upgrade Main Injector and Target R&D to **provide** > 2 MW to DUNE
  - **ACE-BR**: **deliver** full 2.4 MW to DUNE, **enable** next generation accelerator particle physics program, provide **reliable** beam to all its users

- Science potential is broad and significant with **4 physics thrusts**
  - Muon Collider, CLFV, Dark Sectors, Neutrinos beyond DUNE
  - Short remarks session highlighted additional exciting ideas

- ACE Workshop series initiated to
  - Gather **community input** and **understand complementarity** towards a conceptual design that enables a world-leading physics program

Supplemental material

ACE Science Workshop

- https://indico.fnal.gov/event/59663/
- First in a series of workshops to co-design physics case and technical design
  - Invite as much community input as possible - many community speakers
  - Involve early career folks as much as possible
- Organizers - experts across neutrino, collider, CLFV, dark sectors, accelerators

S. Gori
(Co-chair)

K. DiPetrillo

B. Echenard

J. Eldred

R. Harnik

P. Machado

M. Toups

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ACE Science Workshop

- Discussion leads

CLFV - Muon Collider


B. Bernstein


S. Jindariani


D. Stratakis

Dark Sectors - Muon Collider


C. Cesarotti


Y. Kahn

CLFV - Neutrinos


A. Thapa


I. Bigaran


R. Plestid

Neutrino - Dark Sectors


J. Zettlemoyer


A. Sousa


B. Dutta

CLFV - Dark Sectors


M. Solt

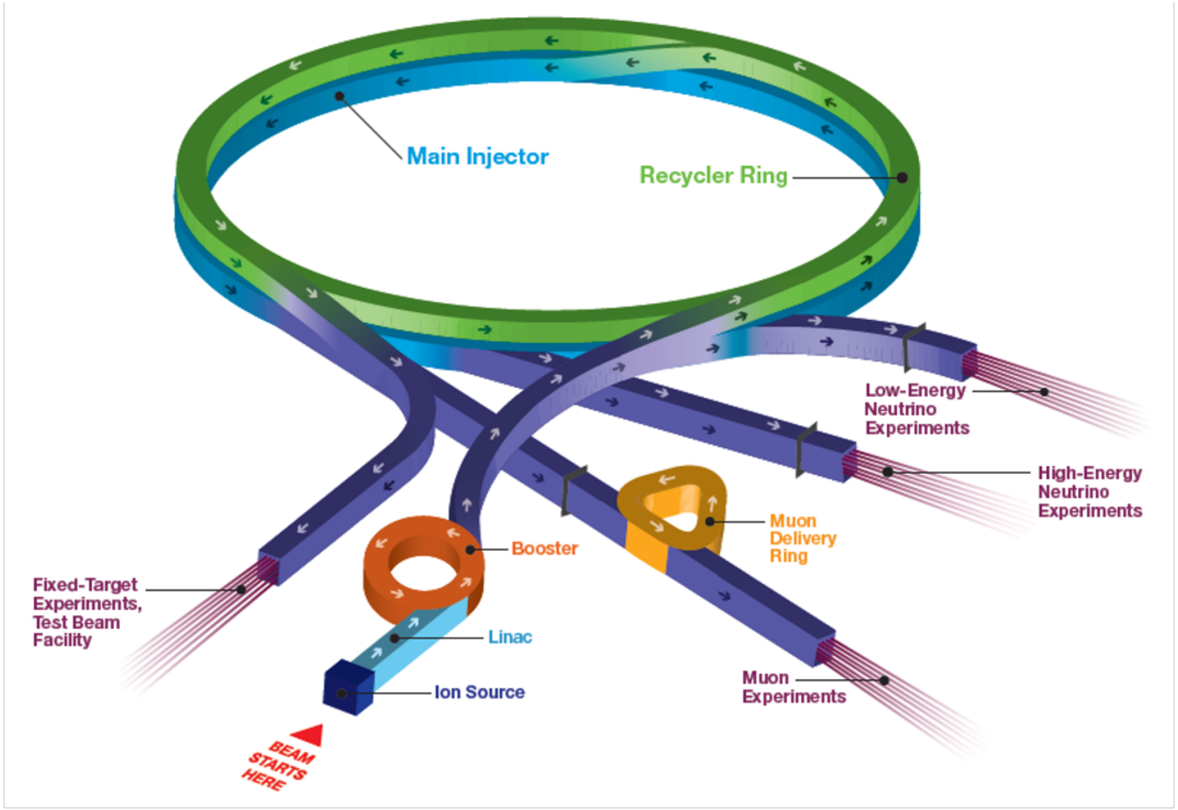

J. Zupan

Muon Collider - Neutrinos


Z. Tabrizi


C. Herwig

The Fermilab Accelerator Complex



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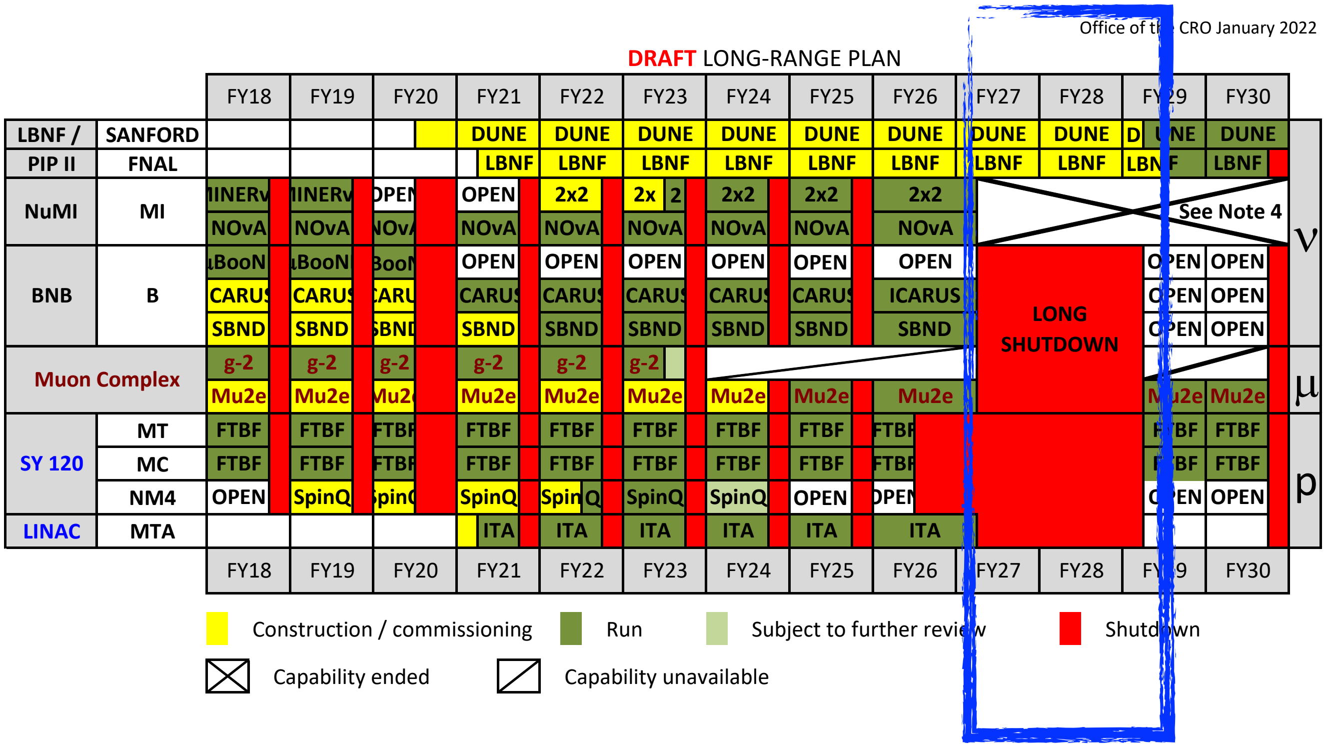
PIP-II



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Main Injector ramp time

		PIP-II Booster Intensity		
Scenario	**Present**	**PIP-II**	**A**	**B**
MI 120 GeV ramp time (s)	**1.333**	**1.2**	**0.9**	**0.7**
Booster intensity (10^{12})	**4.5**	**6.5**		
Booster ramp rate (Hz)	15	20		
Number of batches	12	12		
MI power at 120 GeV (MW)	0.865	1.25	1.666	**2.142**
Booster cycles for 8 GeV	8	12	6	2
Available 8 GeV power (kW)	29	83	56	24

Booster Replacement options w.r.t. DUNE

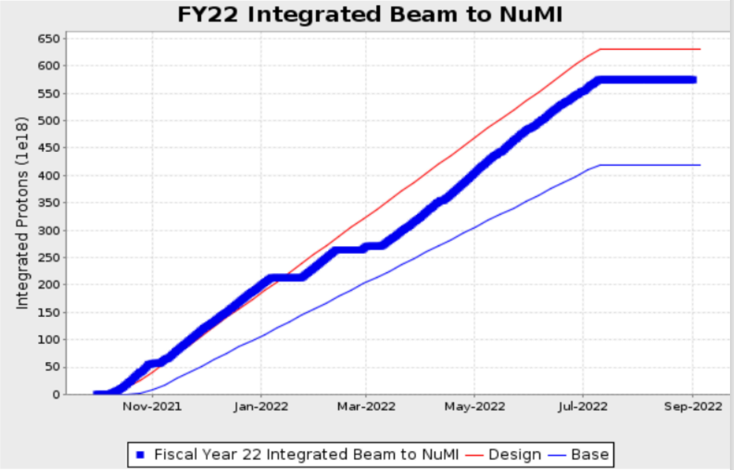
		PIP-II Booster			Beyond PIP-II Booster			
Scenario	**Present**	**PIP-II**	**A**	**B**	**C**	**D**	**E**	**units**
MI 120 GeV ramp rate	**1.333**	1.2	0.9	0.7	**1.2**	**0.9**	**0.7**	s
Booster intensity	**4.5**	6.5			**10**			10^{12} p
Booster ramp rate	15	20			20			Hz
Number of batches	12	12			12	12	9	
MI power	0.865	1.25	1.666	2.142	1.922	**2.563**	2.472	MW
Cycles for 8 GeV	6	12	6	2	12	6	5	
Available 8 GeV power	29	83	56	24	128	**85**	92	kW

n.b. a list of some of many potential scenarios!

Capability, Capacity, Reliability

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%

Example (non-comprehensive) list of physics

Experiment	Experiment type	Proton Beam: Energy [GeV]	Proton Beam: Power [kW]	Proton Beam: Time Structure	Uses existing or new beamline?	Spigot
Proton Storage Ring: EDM and Axion Searches	Precision tests Dark Matter	0.232	1e11 polarized protons per fill	Fill the ring every 1000s	new	S0B
Physics with Muonium	Precision tests	0.8	1e(13+/-1) POT per second	CW	new	S0B
REDTOP Run I	Precision tests	1.8 - 2.2	0.03-0.05	slow extraction	Muon Campus	S0E
REDTOP Run II	Precision tests	0.8 - 0.92	200	CW,	new	S0A, S0B
REDTOP Run III	Precision tests	1.7	>1,000	CW,	new	S1
Ultra-cold Neutron Source for Fundamental Physics Experiments, Including Neutron-Anti-Neutron Oscillations	Precision tests	0.8-2	1,000	quasi-continuous	new	S0A
CLFV with Muon Decays	CLFV	Not critical 0.8 to a few GeV	100 or more	continous beam on the timescale of the muon lifetime i.e. proton pulses separated by a microsecond or less. The more continuous the better	new	S0B
Mu2e II	CLFV	1 to 3	100	pulse width 10s of ns or better separated by 200 to 2000 ns. Flexible time structure and minimal pulse-to-pulse variation	new	S0A, S1
Fixed Target Searches for new physics with O(1 GeV) Proton Beam Dump	Dark Sector, Neutrino	0.8 to 1.5 GeV	100 or more	<O(1 micro s) pulse width for neutrino measurements, <O(30 ns) pulse width for dark matter searches, 10^{-5} or better duty factor	new	S0C, S2
PRISM-like Charged Lepton Flavor Violation	CLFV	1 -3 GeV	up to 2 MW	15ns pulses at a rep rate of about 1 kHz	new	S0C, S2
Proton Irradiation Facility	R&D	Energy is not very important	1e18 protons in a few hours	Pulsed beam (duty factor not specified)	new	S0B
SBN	Neutrino	8	32	20Hz	BNB	S0D & S3
Mu2e	CLFV	8	8	<10^{-10} extinction	Muon Campus	S0E
Fixed Target Searches for new physics with O(10 GeV) Proton Beam Dump	Dark Sector, Neutrino	8	up to 115	Beam spills less than a few microsec with separation between spills greater than 50 microsec	BNB	S0D & S3
Muon beam dump	Dark Sector	8 (producing 3 GeV muons)	3e14 muons in total on target for the whole run	CW	Muon Campus	S0E
Muon Collider R&D	R&D	8 - 16GeV	4e13 to 1.2e14 protons per bunch	5 - 20 Hz rep rate and bunch length 1-3 ns	new	S3
Muon Missing Momentum	Dark Sector	few 10s of GeV	10^{10} muons per experimental runtime	Pulsed beam (duty factor not specified)	new	S0F
High Energy Proton Fixed Target	Dark Sector, Neutrino	O(100 GeV)	1e12 POT/s therefore ~20 kW	CW via resonant extraction. "IF we could up the duty factor that woul dbe even better"(?)	Switchyard or new	S0F
Test-Beam Facility	R&D	120, lower energies would also be beneficial	10 to 100 kHz on the testing apparatus	Pulsed beam (duty factor not specified)	Switchyard or new	S0F
Tau Neutrinos	Neutrino	120	1200 or higher	MI time structure	LBNF	LBNF

Booster Replacement configurations

RCS Configurations:

C1a) 10 Hz metallic vac. chamber (~2GeV-8GeV): lower power at low energies, less physics opportunities, but could be made to be upgradabl

C1b) 20 Hz with ceramic vac. chamber (larger magnets) (~2 GeV-8 GeV), ~2 GeV Accumulation Ring (fixed energy, ideally separate from RCS tunnel)

C1c) 20 Hz with ceramic vac. chamber, high current linac (~2 GeV-8 GeV), no accumulation ring, need ~8mA current in PIP-II to quadruple the number of particles per injection compared to PIP-II

SRF Linac Configurations:

C2a) Basic: Slight increase in PIP-II current, demonstrated XFEL RF

- Meets LBNF/DUNE requirements without any major R&D on RF.
- Small amount of power for 8 GeV program
- Uses the recycler (options C2b & C2c don't)

C2b) High Duty factor RF source - Slight increase in PIP-II current, significant RF upgrade

- Needs longer pulses, higher rep rate, and significantly more power for 8 GeV program

C2c) Higher Current PIP-II - Significant upgrade (2.7mA to 5mA) , some RF R&D

- Combination of options 2 and 3 could provide MW-scale beam power at 8 GeV