Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Overview of proposed ACE at Fermilab

Nhan Tran with input from ACE Science Workshop committee, PIU-CDG team

PAC Meeting, June 2023

June 7, 2023

Outline

- **A brief timeline**
  - Booster Replacement studies and report, PIU-CDG report
  - ACE Executive Summary
- Fermilab accelerator complex & ACE (Accelerator Complex Evolution)
  - MI Cycle Time & Booster replacement options
- ACE Science Workshop and mid- to long-term planning process

"The PAC will be asked to review the process for community engagement, identification of the science goals, development of alternative concepts and functional requirements."

Booster Replacement studies and report

- Phase 1, previous PAC presentations:
  - **July 2020**: First report by Roni on status of Booster Replacement, including first workshop
  - **December 2020**: Report by Roni Harnik and Mike Syphers on progress
  - **June 2021**: Luciano Ristori report — White paper released; path to 2.4 MW for DUNE with Booster Replacement; options for broader physics program
    - PAC recommends formation of BR-CDG (Booster Replacement Central Design Group)

- Phase 2:
  - White papers and presentations at Snowmass 2022
  - PIU-CDG formed (was BR-CDG) - Proton Intensity Upgrade Central Design Group
    - Chaired by Steve Brice and Brenna Flaugher

Since June 2021 PAC meeting

- What has changed along the way?
  - **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-MIT**: **Reduce Main Injector cycle 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)
    - Configurations for Booster Replacement (Linac or RCS)

Status

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]

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

Outcomes and Physics Themes

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Physics Opportunities for the Fermilab Booster Replacement

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					■

Physics themes*:
1.1 Dark sectors
1.2 Muon-based searches
1.3 Muon collider R&D

n.b. report primary goal on DUNE 2.4 MW target

**includes additional physics ideas*

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Status and summary

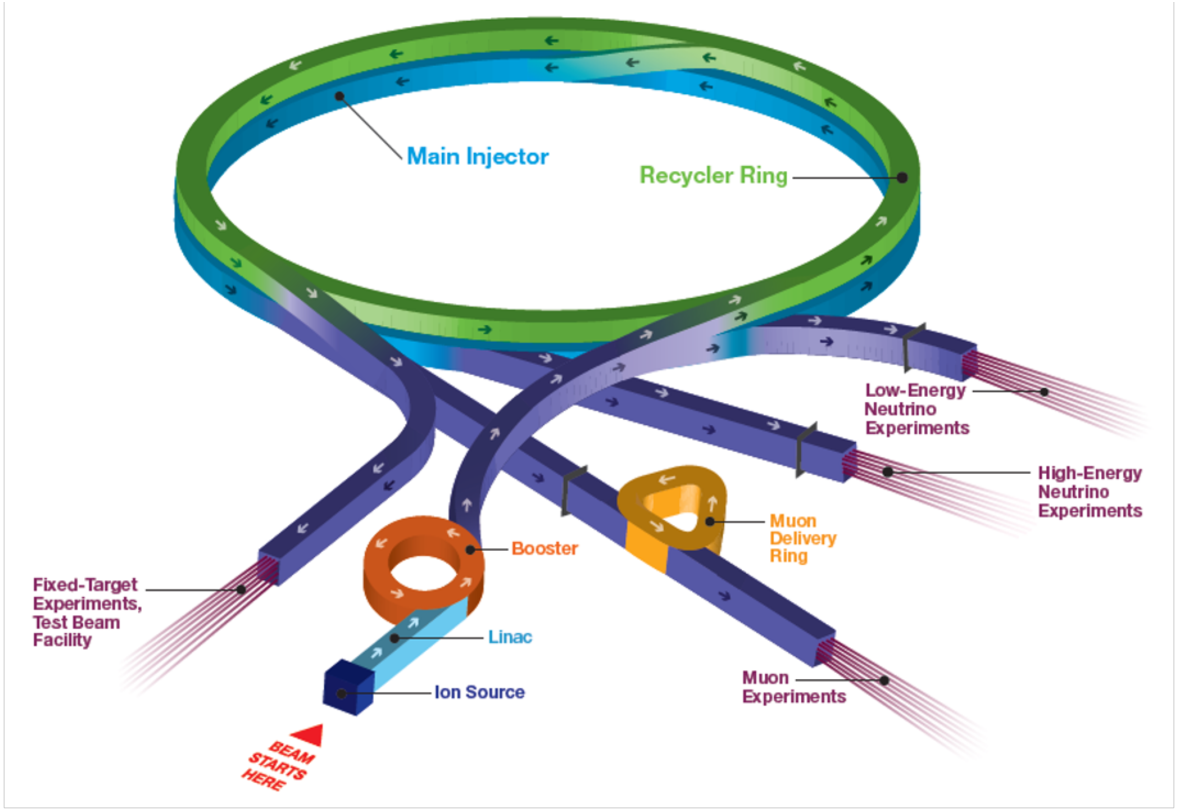
- In light of PIU-CDG findings and Snowmass community study…
  - Step back and re-evaluate ACE Science program and design
  - Assemble community input and understand physics thrust complementarity

- Next steps:
  - ACE Science Workshop next week (June 14-15)
    - https://indico.fnal.gov/event/59663/
    - First in a series of workshops to co-design physics case and technical design
      - Accelerator Design workshop planned for mid-July
  - Establish ACE Steering Committee to continue development of ACE towards CD-0 in ~2 year timescale

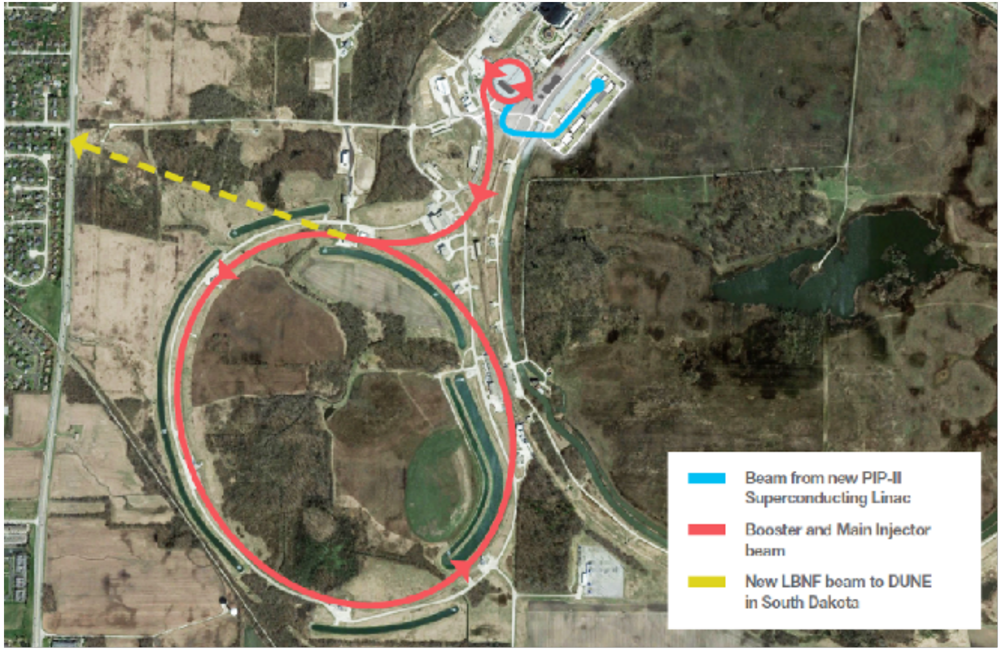
Outline

- A brief timeline
  - Booster Replacement studies and report, PIU-CDG report
  - ACE Executive Summary
- **Fermilab accelerator complex & ACE (Accelerator Complex Evolution)**
  - MI Ramp Time & Booster replacement options
- ACE Science Workshop and mid- to long-term coordination

The Fermilab Accelerator Complex



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

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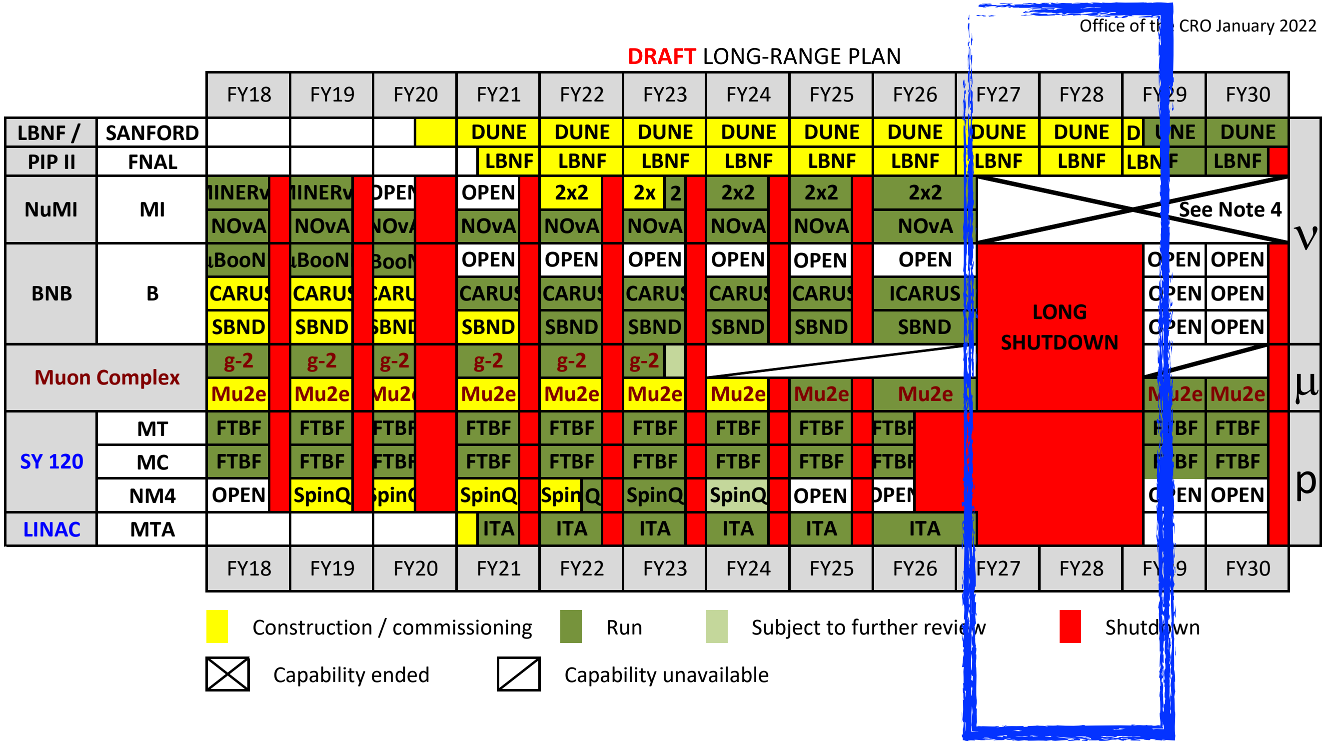
PIP-II



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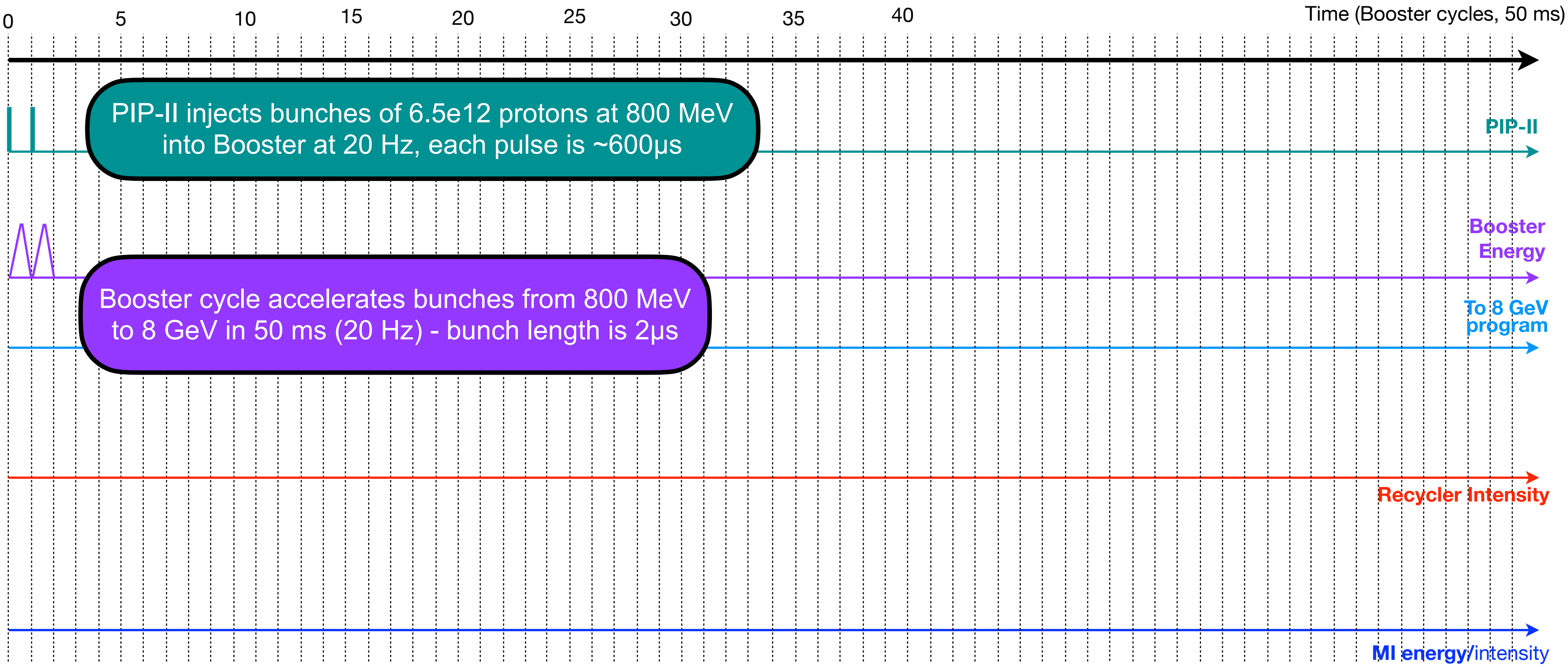
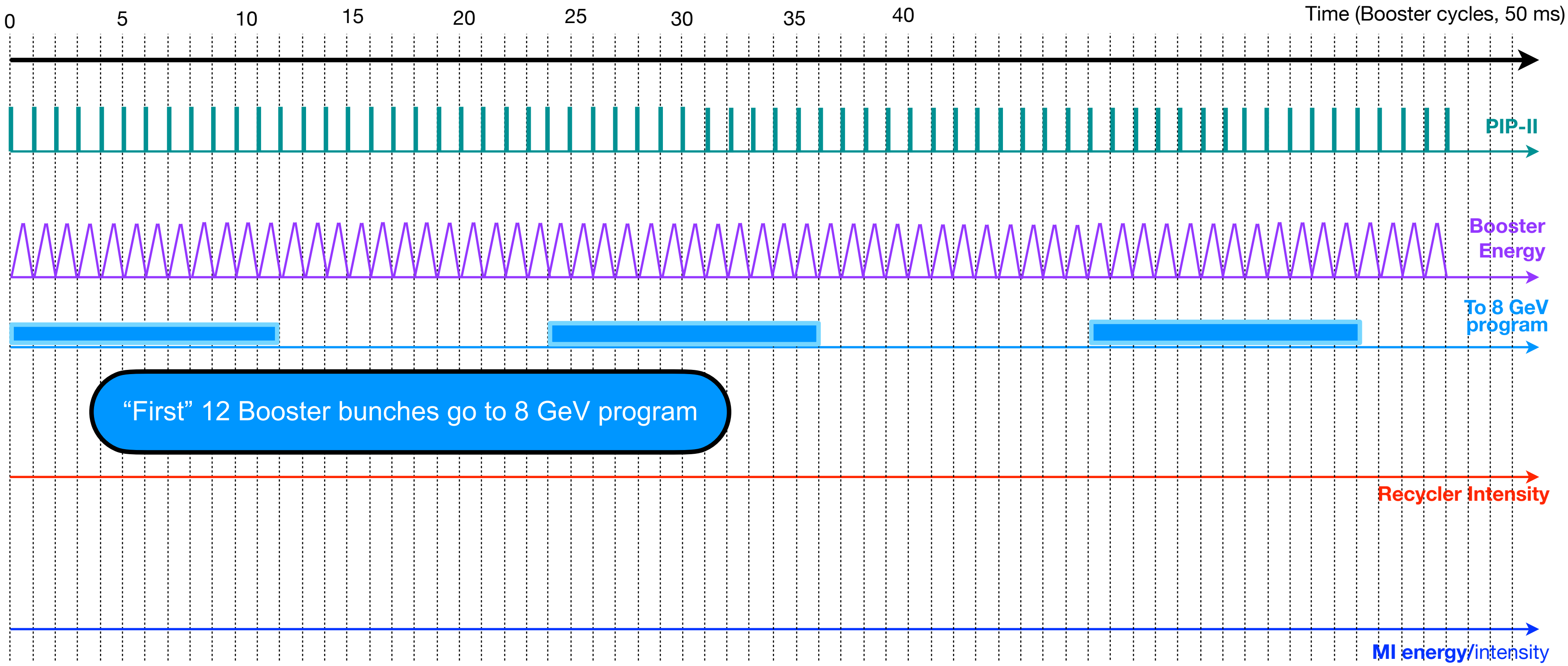
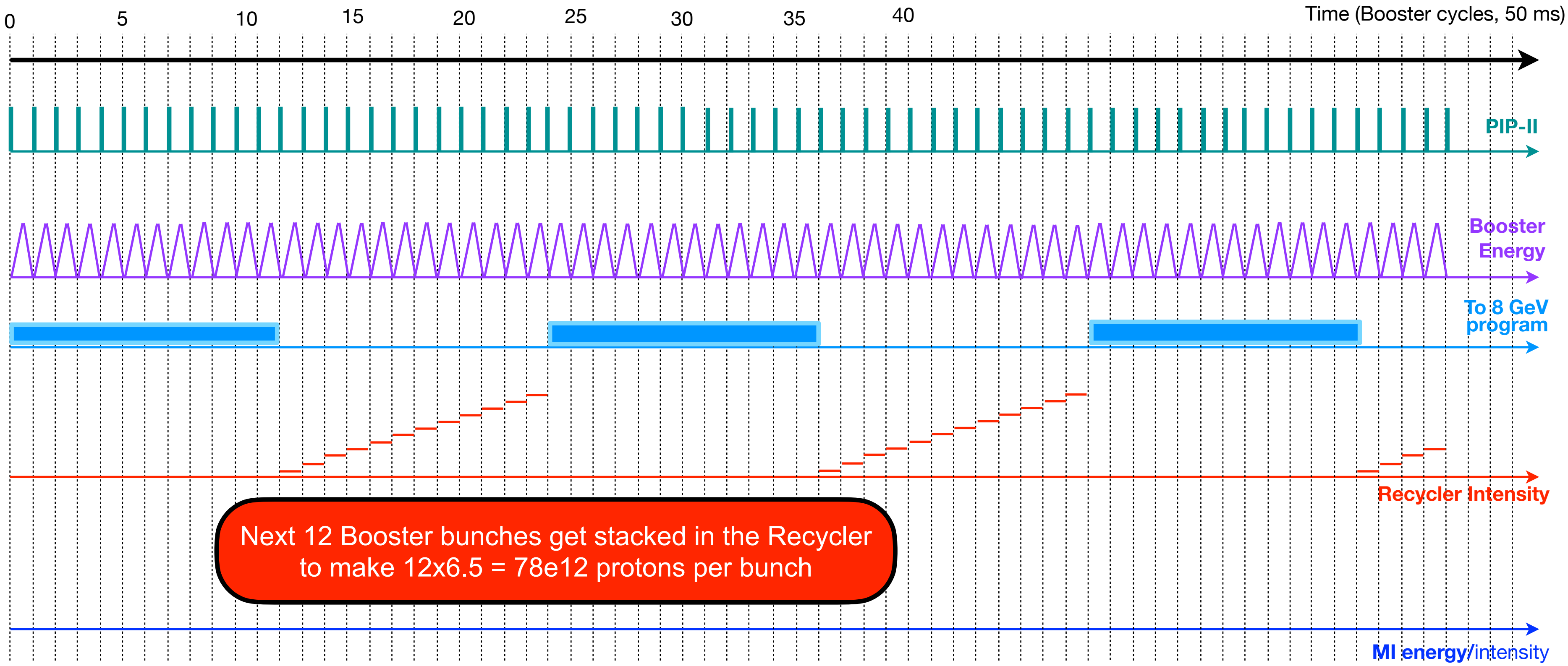
Accelerator Timeline - PIP-II Era



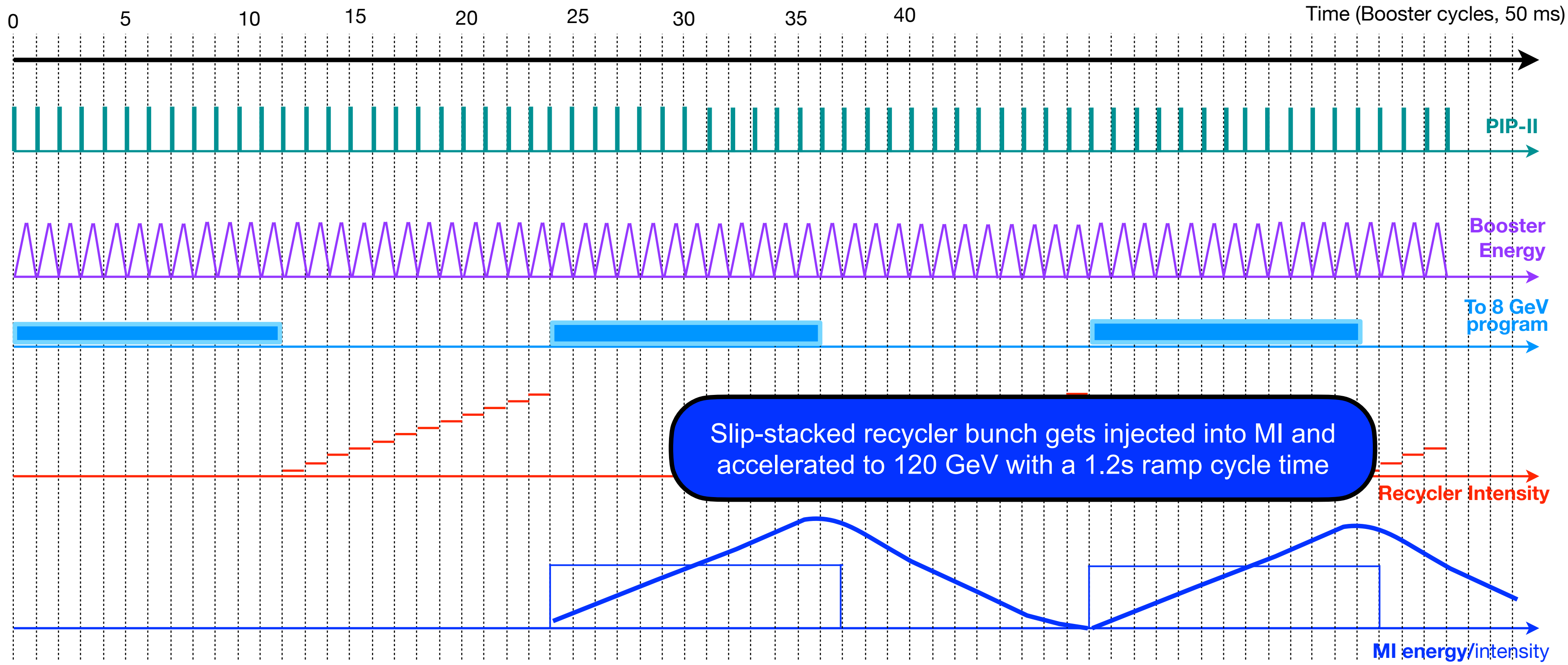
Accelerator Timeline - PIP-II Era



Accelerator Timeline - PIP-II Era



Accelerator Timeline - PIP-II Era



n.b. 1 out of 15 MI ramps go to Switchyard

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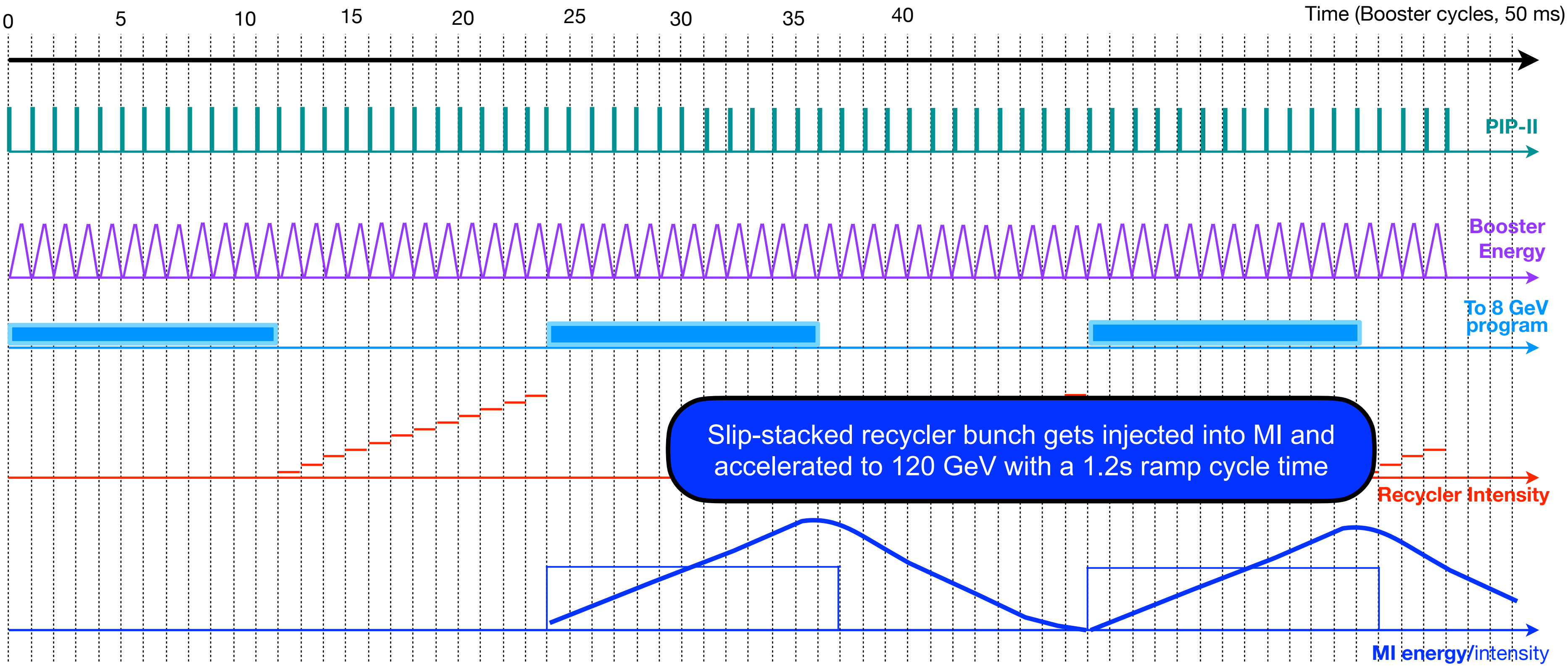
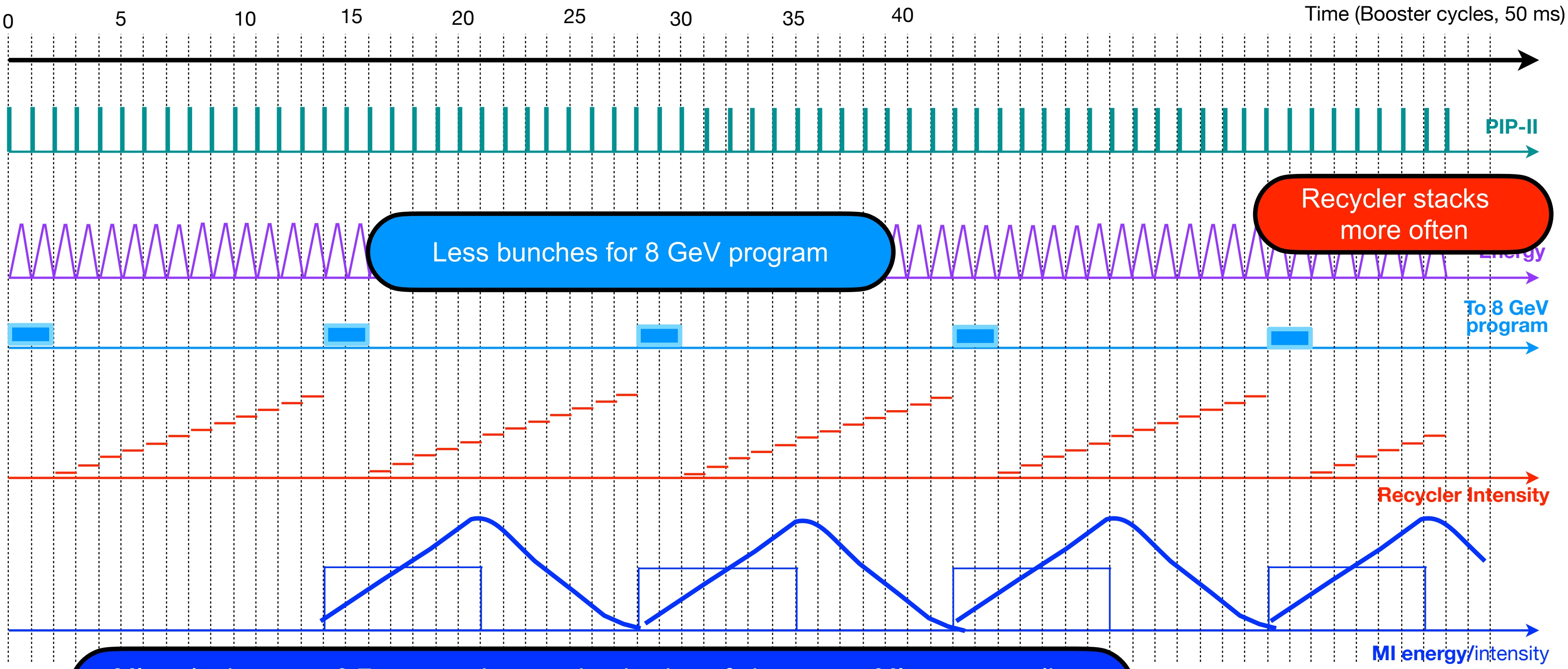
Main Injector ramp time

		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

Accelerator Timeline - Main Injector Ramp Time (e.g. 1.2s)



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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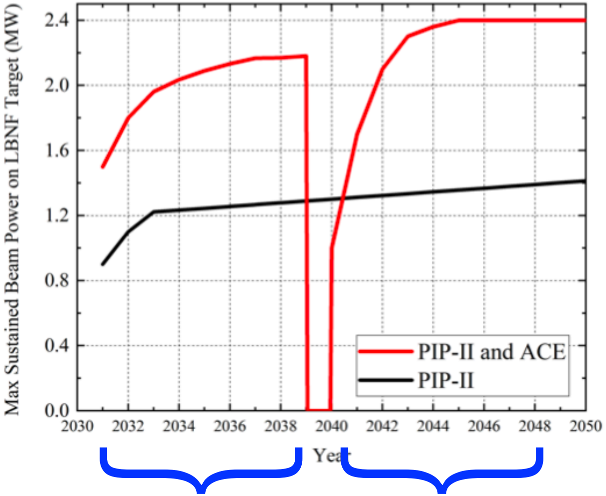
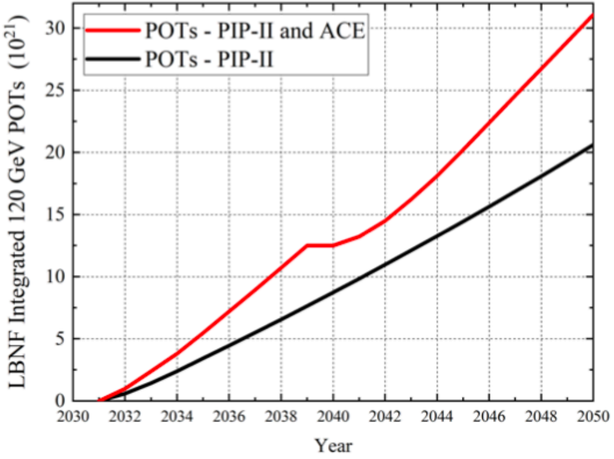
DUNE plan



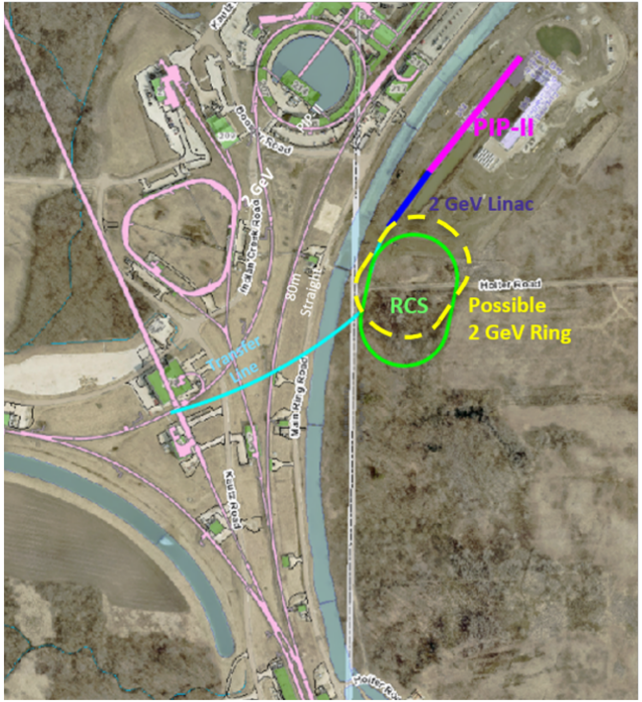
ACE-MIT ACE-BR

(Options depicted on the next slide)

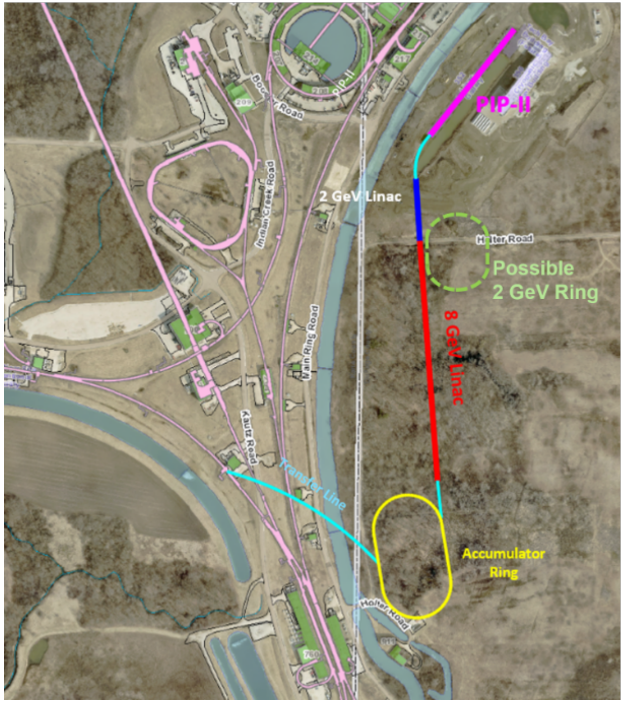


BR options: 800 MeV to 8 GeV

3 RCS options



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

See backup for more details

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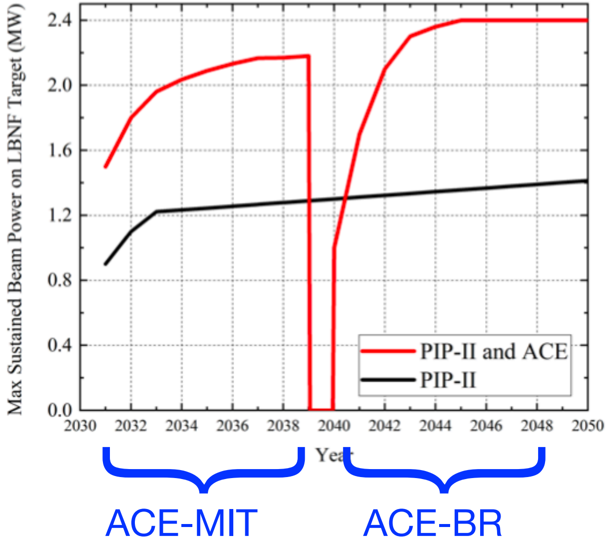
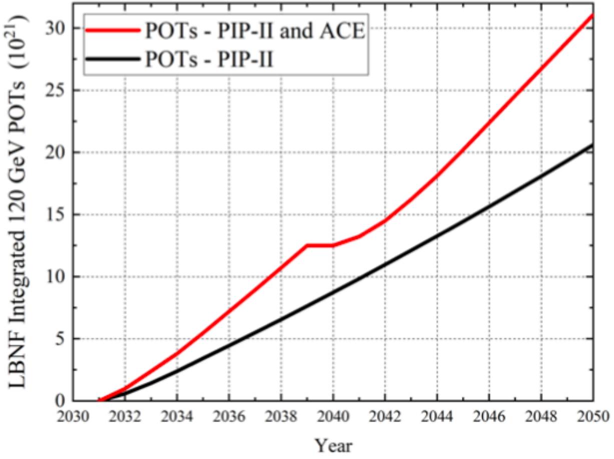
Physics Spigots





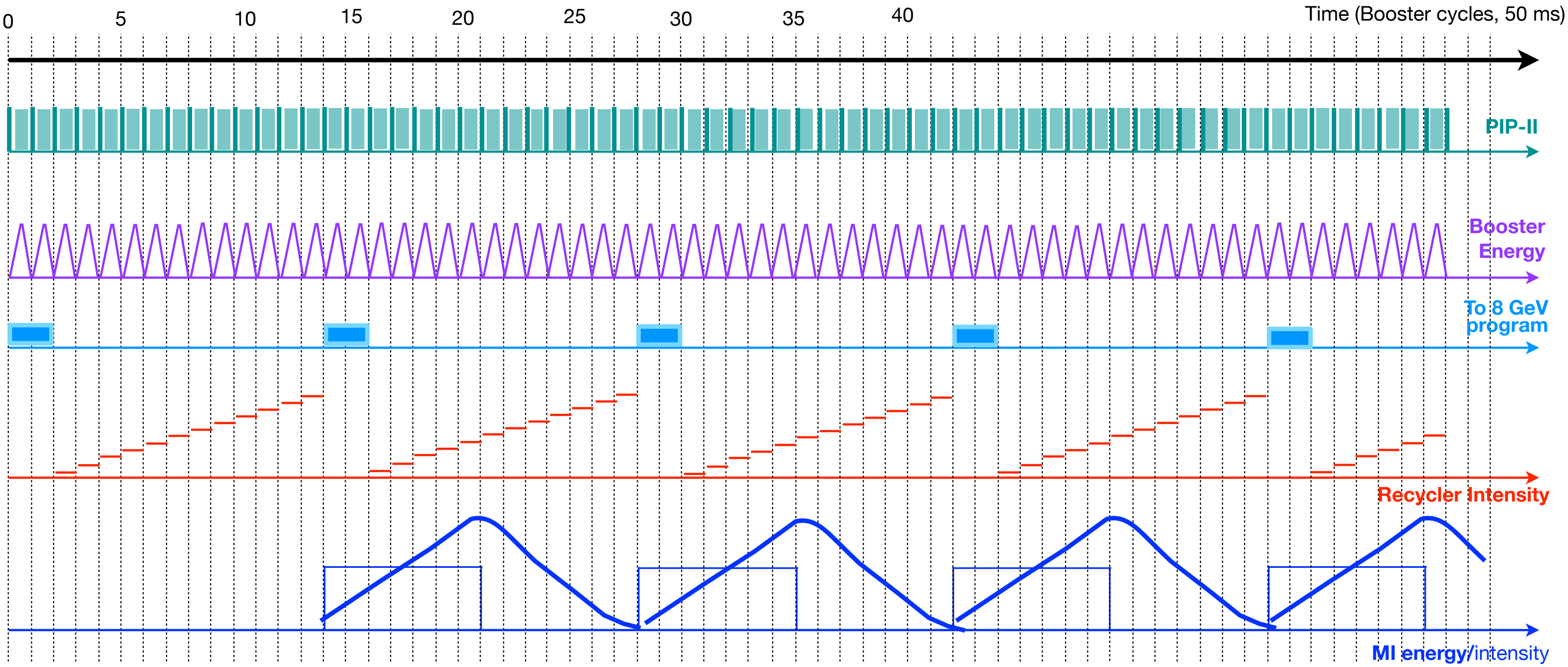
During ACE-MIT period:

- **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

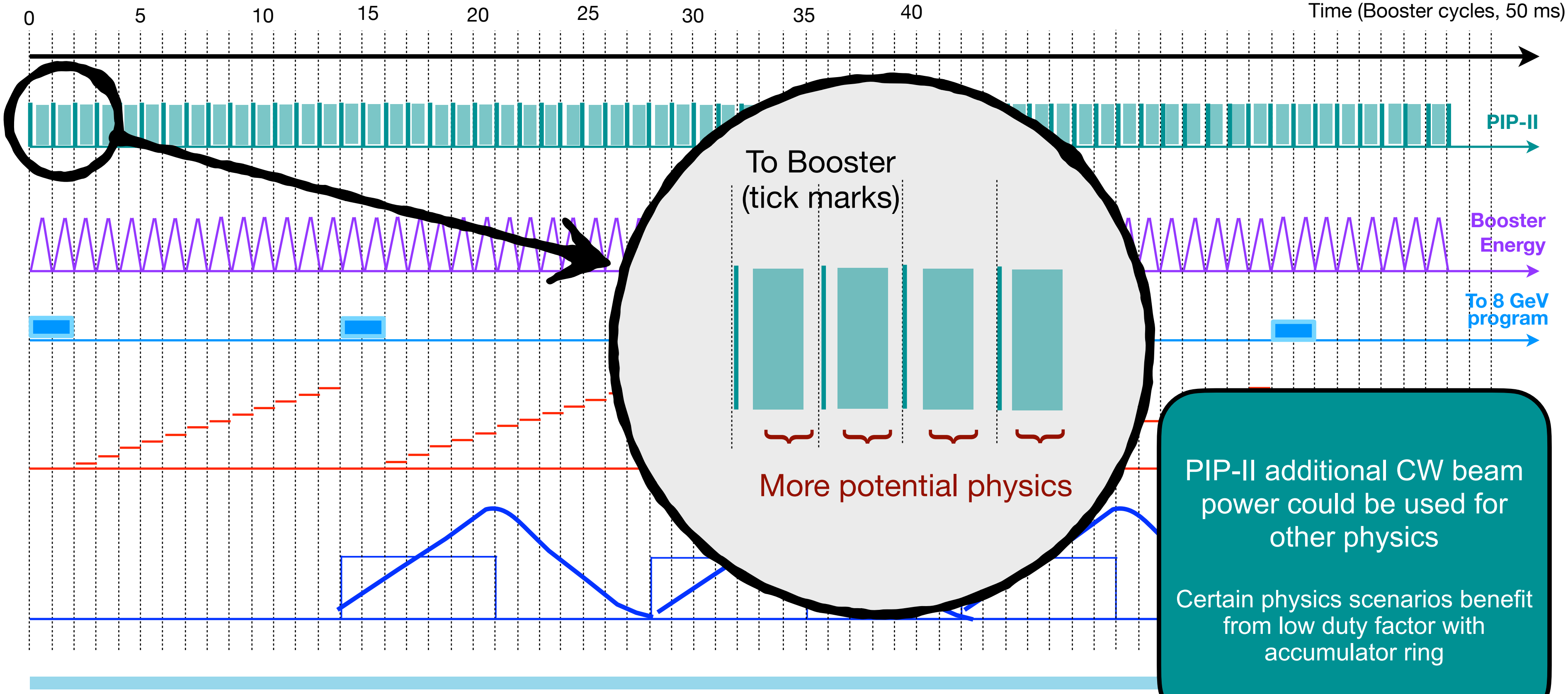
During ACE-BR period,

- **significant beam available at 0.8-2 GeV**,
- Potential for much more beam for 8 GeV program,
- 120 GeV slow extraction program even more (?)

Accelerator Timeline - spigots from 0.8 - 2 GeV



Accelerator Timeline - spigots from 0.8 - 2 GeV



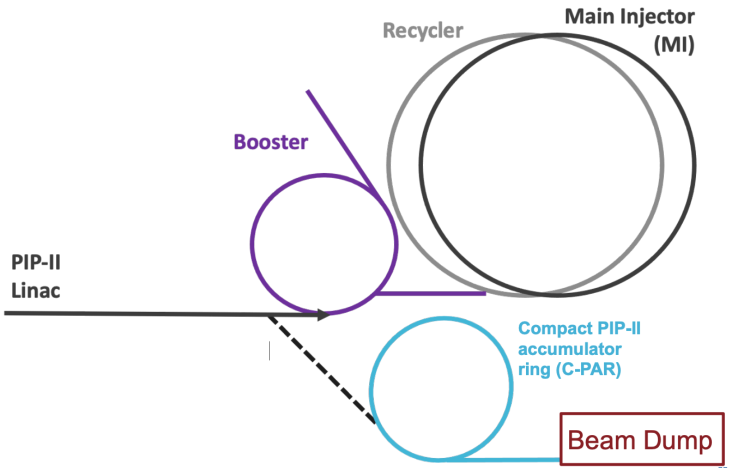
PIP-II additional CW beam power could be used for other physics

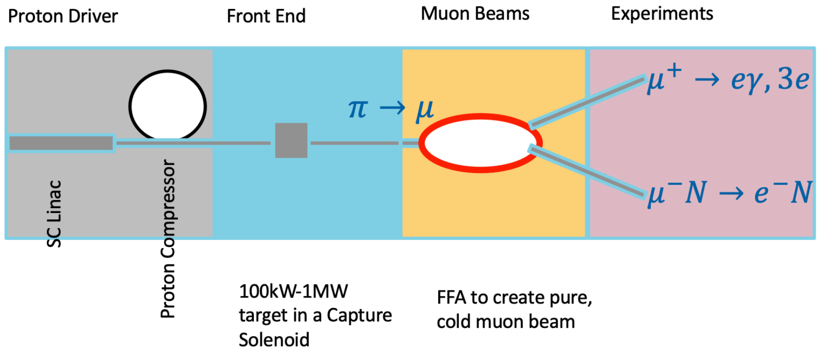
Certain physics scenarios benefit from low duty factor with accumulator ring

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/

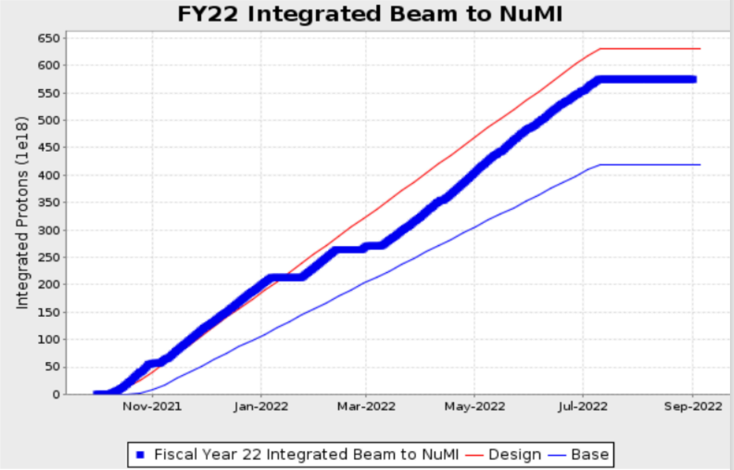
Booster Replacement options w.r.t. DUNE

		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!

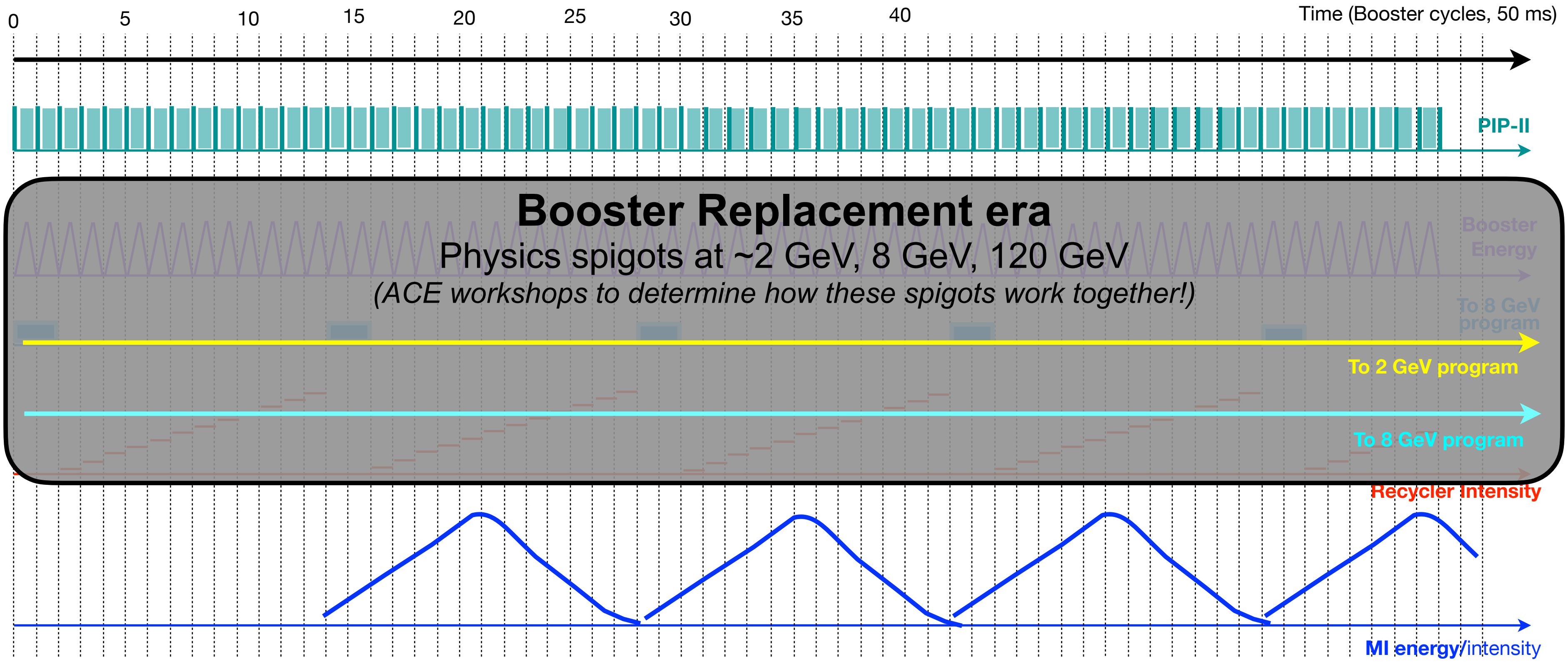
Improving reliability of the complex

- 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%

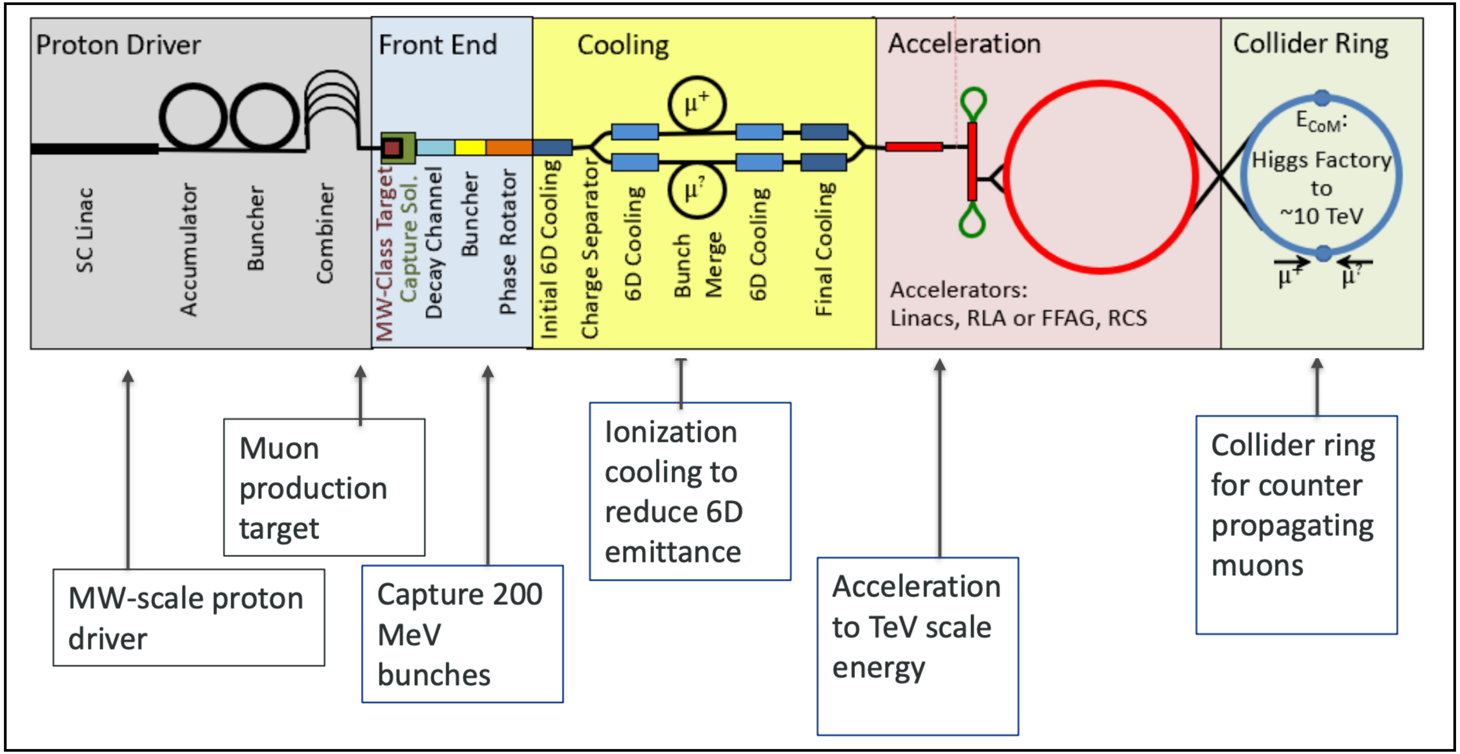
Accelerator Timeline - ACE-BR era



Example (non-comprehensive) list of physics

Experiment	Experiment type	Proton Beam			Uses existing or new beamline?	Spigot
		Energy [GeV]	Power [kW]	Time Structure		
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

Muon Collider

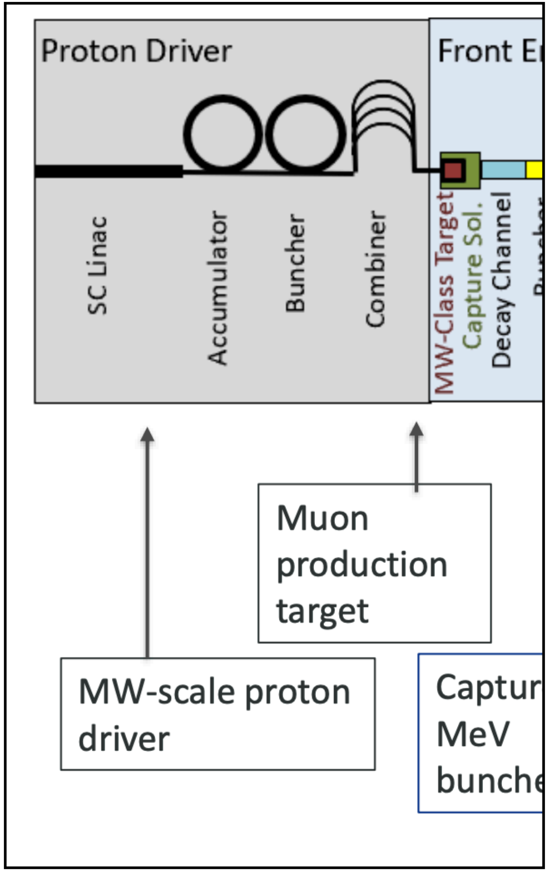


Muon Collider Proton Driver:
8 GeV program

ACE-BR scenarios considered do not exactly map to MuC scenarios but they are not that far off.

See the PIU-CDG report for more detailed scenarios (not a complete list)

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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  - MI Cycle Time & Booster replacement options
- **ACE Science Workshop and mid- to long-term coordination**

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

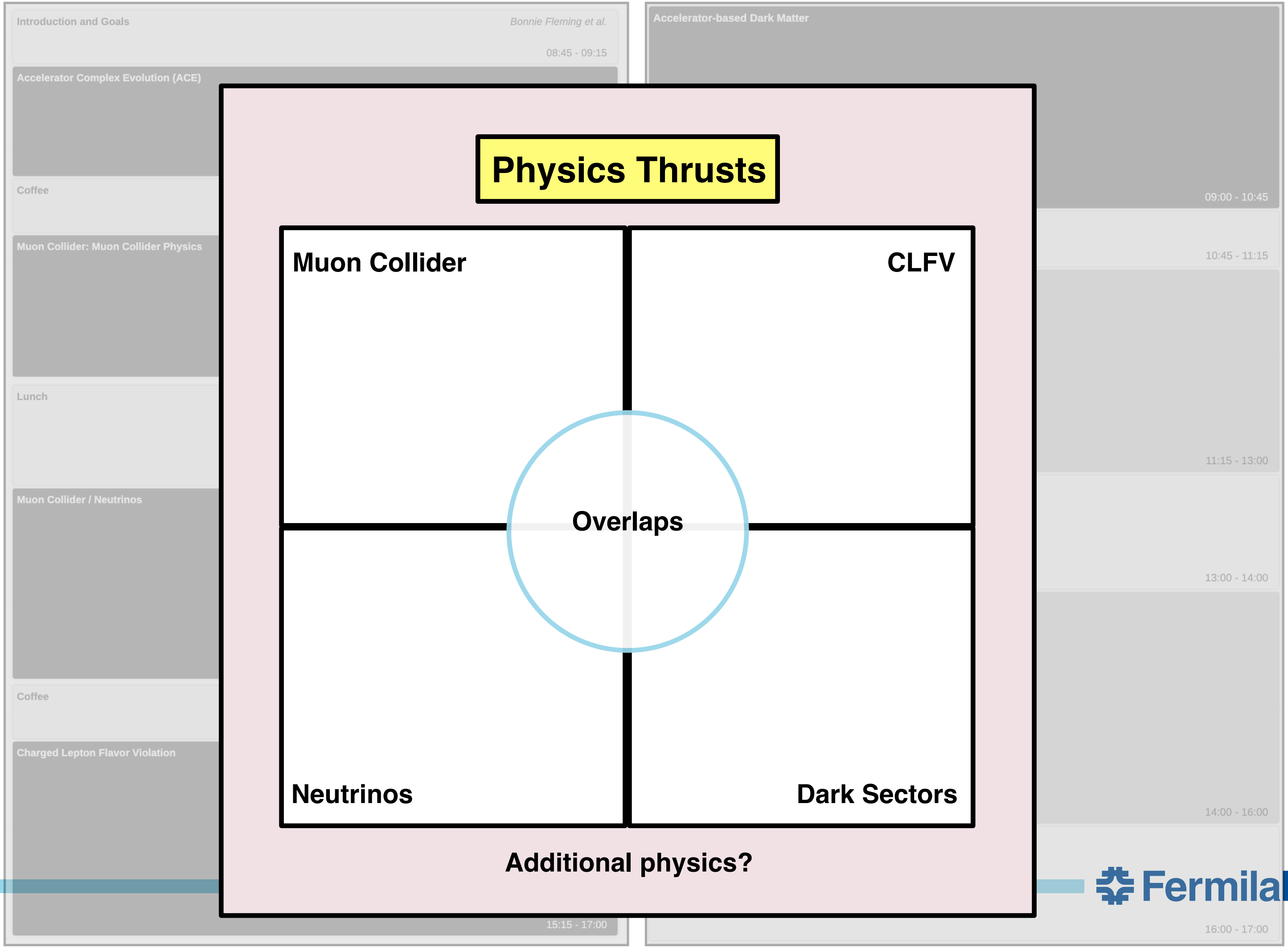
M. Toups

Agenda

Introduction and Goals — *Bonnie Fleming et al.*	08:45 - 09:15
Accelerator Complex Evolution (ACE)	09:15 - 10:15
Coffee	10:15 - 10:45
Muon Collider: Muon Collider Physics	10:45 - 12:02
Lunch	12:05 - 13:00
Muon Collider / Neutrinos	13:00 - 14:43
Coffee	14:45 - 15:15
Charged Lepton Flavor Violation	15:15 - 17:00

Accelerator-based Dark Matter	09:00 - 10:45
Coffee	10:45 - 11:15
Short remarks & Synergies intro	11:15 - 13:00
Lunch	13:00 - 14:00
Synergies: Parallel discussion	14:00 - 16:00
Summaries of parallels	16:00 - 17:00

Agenda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16:00 - 17:00
Physics Thrusts
Muon Collider
CLFV
Overlaps
Neutrinos
Dark Sectors
Additional physics?

Agenda

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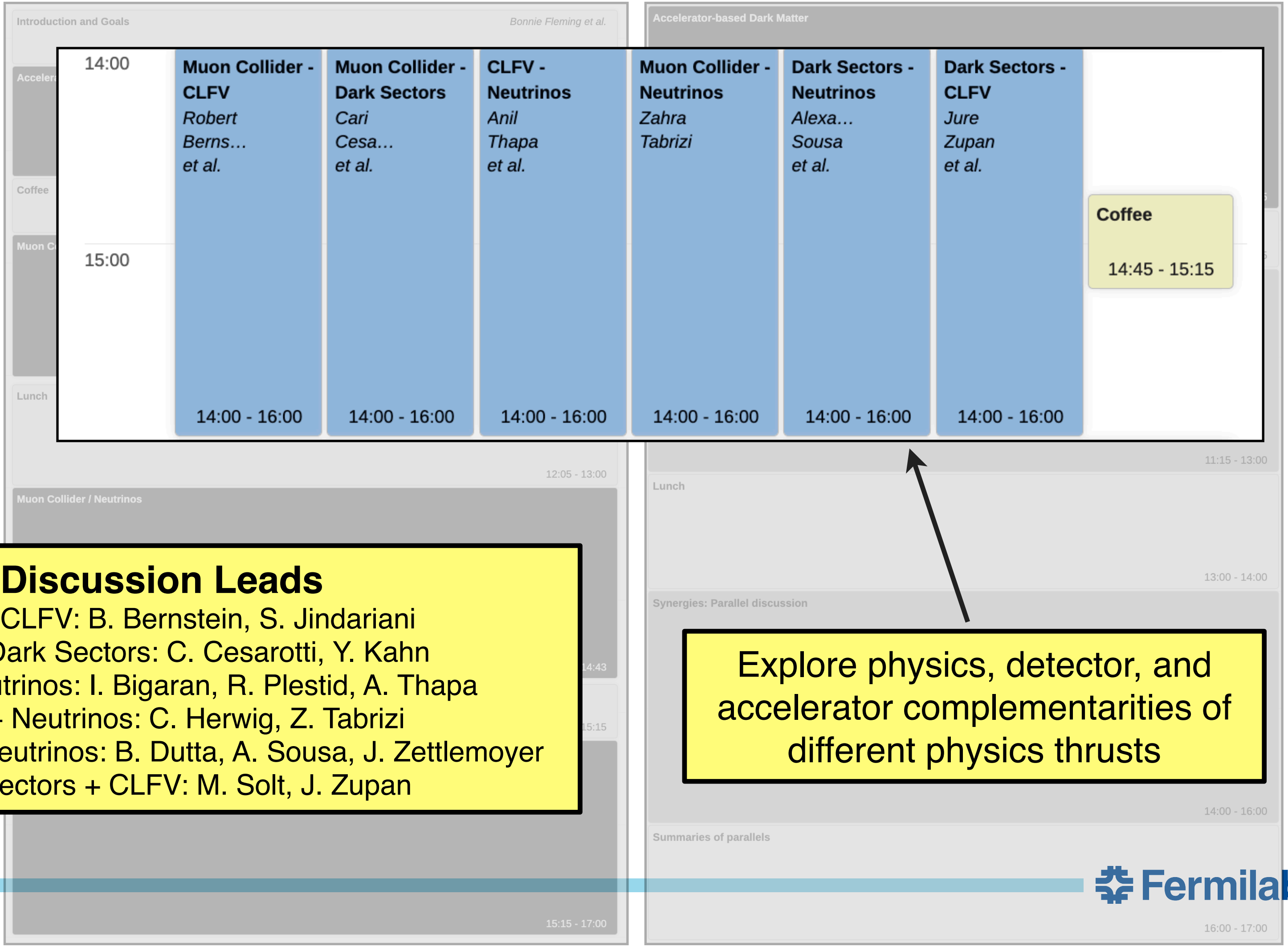
Short remarks session to collect or highlight new ideas

Agenda



Discussion Leads

MuC + CLFV: B. Bernstein, S. Jindariani
MuC + Dark Sectors: C. Cesarotti, Y. Kahn
CLFV + Neutrinos: I. Bigaran, R. Plestid, A. Thapa
MuC + Neutrinos: C. Herwig, Z. Tabrizi
Dark Sectors + Neutrinos: B. Dutta, A. Sousa, J. Zettlemoyer
Dark Sectors + CLFV: M. Solt, J. Zupan

Explore physics, detector, and accelerator complementarities of different physics thrusts

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Anticipated workshop outcomes

- Write a **brief report** on the content and summary of findings/discussion
  - Targeting ~few weeks after workshop

- Follow-up workshops to develop accelerator concepts based on discussions and report from 1st ACE Science workshop
  - Commission accelerator studies based science workshop findings
    - Define initial ACE configurations and R&D required
      - Based on elements defined in PIU-CDG report

ACE Coordination

BR Study
Harnik/Syphers/Ristori
w/HEP and Accelerator Working groups

→

PIU-CDG
Brice/Flaugher
(Chairs)
+ committee members

→

ACE Steering Committee
(Coordinate w/international organizations)

Goal: Organize meetings & workshops, collate materials, commission studies to prepare materials for CD-0 (Including workshop next week, June 14-15)

Work with lab management to define steering committee

Remarks from charge

"The PAC will be asked to review the process for community engagement, identification of the science goals, development of alternative concepts and functional requirements."

- A significant amount of work done to understand science capabilities at future Fermilab accelerator facility, **now with ACE (PIP-II and BR era)**
  - Process underway to understand how science capabilities are complementary
  - Science **priorities** set by **community engagement**, Snowmass + P5 processes
    - e.g. renewed community interest in Muon Collider
    - Develop in alignment with P5
  - This will set functional requirements and alternative concepts
    - Includes DUNE requirement of 2.4 MW
  - Develop ACE configurations satisfying requirements

Status and summary

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

- Next steps:
  - ACE Science Workshop next week (June 14-15)
    - https://indico.fnal.gov/event/59663/
    - First in a series of workshops to co-design physics case and technical design
      - Accelerator Design workshop planned for mid-July
  - Establish ACE Steering Committee to continue development of ACE towards CD-0 in ~2 year timescale

Backup

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