Status of the Booster Replacement

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Status of the Booster Replacement

Executive Summary

- **Delay by COVID**
  - Snowmass delayed
    - Explicit request to hold from organizers
- **White Papers completed by Task Force**
  - This completes Phase I
- **Now getting ready to go into Phase II**
  - Form BR-CDG committee
    - Booster Replacement Central Design Group
- **Aiming for CD0 early next year**

Why Booster Replacement?

- **Provide 2.4 MW to DUNE**
  - Our goal to satisfy P5 recommendation
  - Now ~ 800 KW max
  - Main bottleneck is Booster

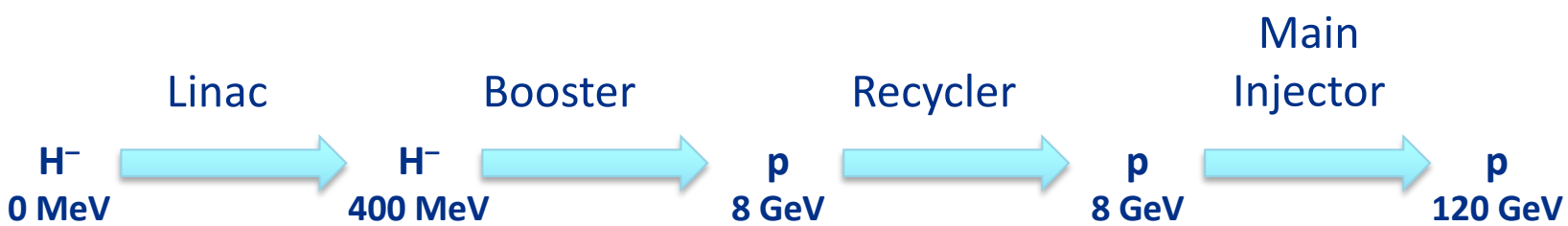
- **Booster intensity can be improved but not enough to reach 2.4 MW**

Need to replace Booster with something else

Present Scheme

- **Linac: H^- from 0 to 400 MeV**
- **Foil stripping: H^- to p 400 MeV**
- **Booster: p 400 MeV to 8 GeV**
  - 15 Hz 4.5 x 10^{12} p
- **Recycler: 12 Booster batches** (slip stacking)
  - 12 x 4.5 x 10^{12} = 5.4 x 10^{13} p
- **Main Injector: p 8 GeV to 120 GeV**
  - 120 GeV x 5.4 x 10^{13} x 1.6 10^{-19}C/1.2s = 0.86 MW

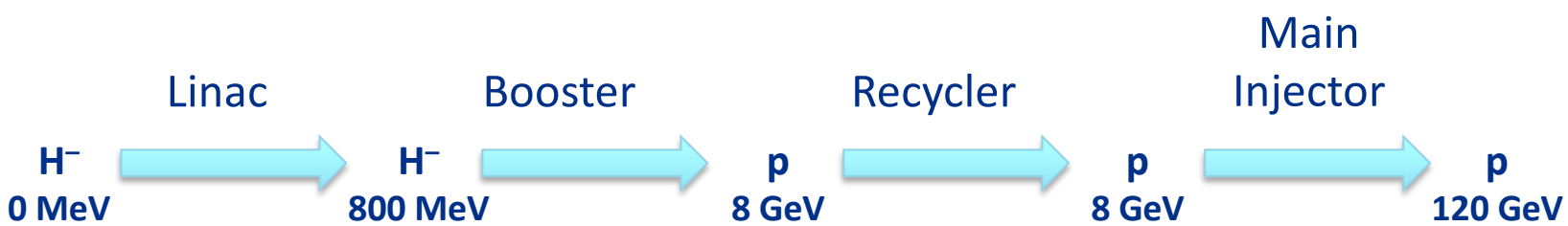
Booster ramping and MI ramping are overlapped in time using the Recycler.



PIP II Era

- **Linac: H^- from 0 to 800 MeV**
- **Foil stripping: H^- to p 800 MeV**
- **Booster: p 800 MeV to 8 GeV**
  - 20 Hz 6.5 x 10^{12} p
- **Recycler: 12 Booster batches** (slip stacking)
  - 12 x 6.5 x 10^{12} = 7.8 x 10^{13} p
- **Main Injector: p 8 GeV to 120 GeV**
  - 120 GeV x 7.8 x 10^{13} x 1.6 10^{-19}C/1.2s = 1.2 MW

Booster ramping and MI ramping are overlapped in time using the Recycler

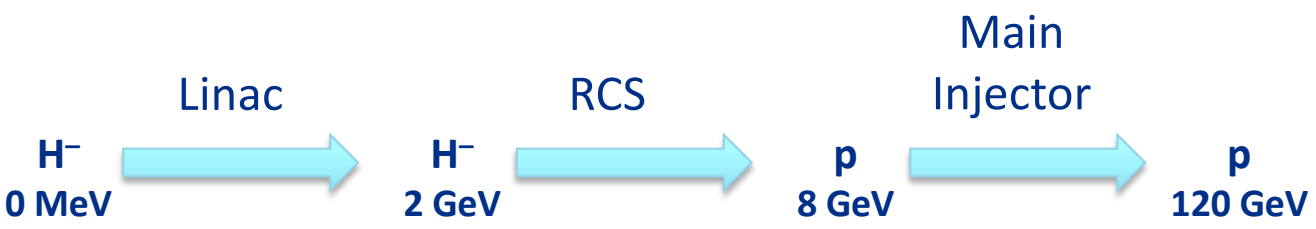


Upgrading the Accelerator Complex

- **A number of different scenarios have been proposed in recent years to replace the Booster**
  - [1] G. W. Foster et al., Proton Driver Study. II. (Part 1), FERMILAB-TM-2169C (2002)
  - [2] S. D. Holmes et al., Project X Initial Configuration Document - 2, Project X-DOC-230-v10 (2010)
  - [3] S. Nagaitsev and V. Lebedev, A Cost-Effective Rapid-Cycling Synchrotron, Reviews of Accelerator Science and Technology 10, 245(2019)
  - [4] J. Eldred, V. Lebedev, and A. Valishev, Rapid-Cycling Synchrotron for Multi-Megawatt Proton Facility at Fermilab, Journal of Instrumentation 14, P07021
  - [5] J. Eldred, Novel Approaches to High-Power Proton Beams, 1ST International Workshop on Neutrinos from Accelerators (NuFACT2019)
- **The scenario presented in this White Paper is not meant to be the unique solution but rather a good starting point for discussions and more detailed studies**
- **Central to the scheme is the construction of a new Rapid Cycling Synchrotron to accelerate protons from PIP II Linac**
- **It would bring 2.4 MW to DUNE as well as a possible new lower energy science program to Fermilab**

A new Rapid Cycling Synchrotron

- **Central to the scheme proposed in this White Paper is the construction of a new Rapid Cycling Synchrotron**
  - Input energy: 2 GeV
    - PIP II Linac extended from 0.8 to 2 GeV
    - Input from scientific community to maximize science opportunities at this lower energy
  - Output energy: 8 GeV
    - Minimize impact on existing injector complex
    - Could be fine tuned (10-12 GeV) for a compelling science case

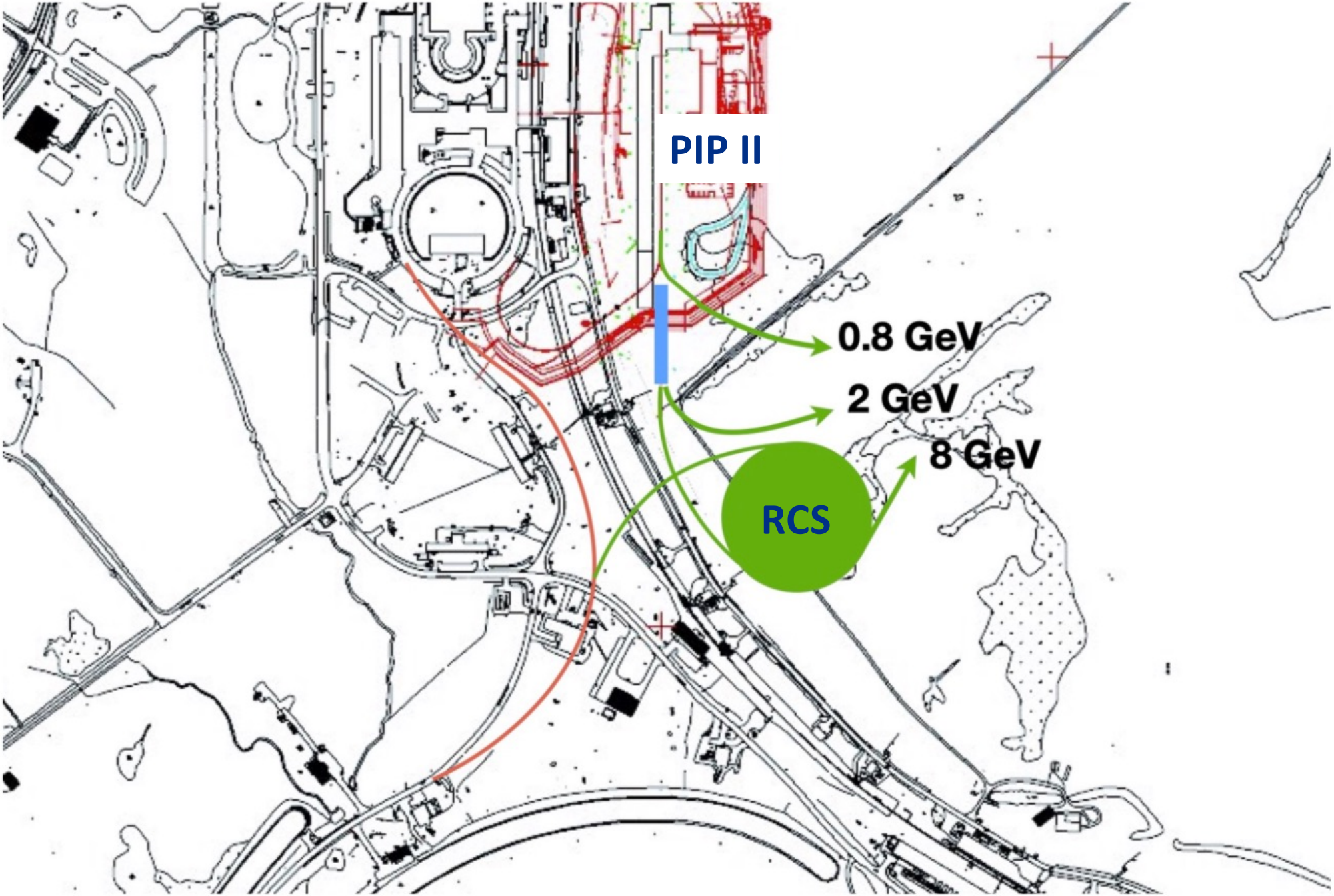


RCS Parameters

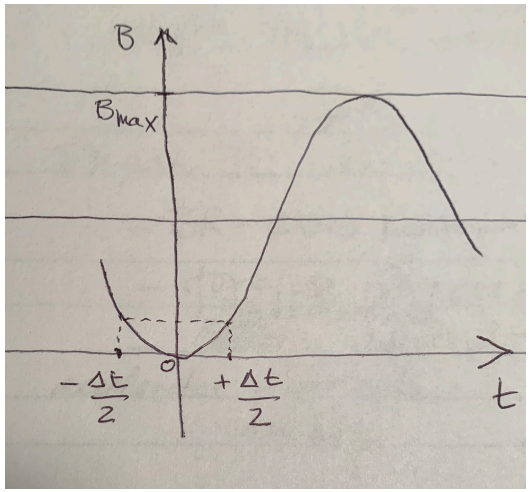
TABLE IV. RCS General Parameters.

Parameter	Value	Unit
RCS Intensity	35	10^{12}
RCS Injection Energy	2	GeV
RCS Extraction Energy	8	GeV
RCS Norm. Emittance (95%)	24	mm mrad
RCS Tune-Shift	0.20	
RCS Vertical Aperture	4.4-6.2	cm
RCS Circumference	≤ 570	m
Number of RCS batches	5	
RCS Ramp-Rate	20	Hz
Available RCS Power (60 GeV MI)	0.65	MW
Available RCS Power (120 GeV MI)	0.75	MW
MI Intensity	175	10^{12}
MI Power (60 Gev MI)	1.85	MW
MI Power (80 Gev MI)	2.00	MW
MI Power (120 Gev MI)	2.40	MW

- Main Injector cycle = 1.4 s
- (175 x 10^{12} p) x (120 GeV) / 1.4 s = 2.4 MW
- (35 x 10^{12}) x (5 RCS cycles) = 175 x 10^{12} p
- (5 RCS cycles) / 20 Hz = 0.25 s
- Number of RCS batches in one MI cycle = 28
- 23/28 batches available to be delivered to other users


PIP II
0.8 GeV
2 GeV
8 GeV
RCS

A 2 GeV Storage Ring?



- **To inject 35 x 10^{12} p from Linac at 2 mA takes ~3 ms**
- **Way too long! Compare with ~30 *μ*s now** (x100!)
  - B-Field ramp
  - Strip Foil scattering
  - Strip Foil heating
- **These problems alleviated by construction of a 2 GeV Storage Ring**
  - Accumulate p from Linac and form short bunches before injection into RCS
  - May be hosted in same tunnel as RCS
  - Permanent magnets?
  - May offer additional physics opportunities

Different Options

- **The proposed solution is not claimed to be unique or optimal**
- **Different options are available and the space of solutions may be degenerate**
- **We will need to consider the different opportunities offered for additional physics programs to break the degeneracy of otherwise nearly equivalent solutions**
  - **This will be one of the main goals of Phase II of the Booster Replacement process as carried forward by the Booster Replacement Central Design Group**

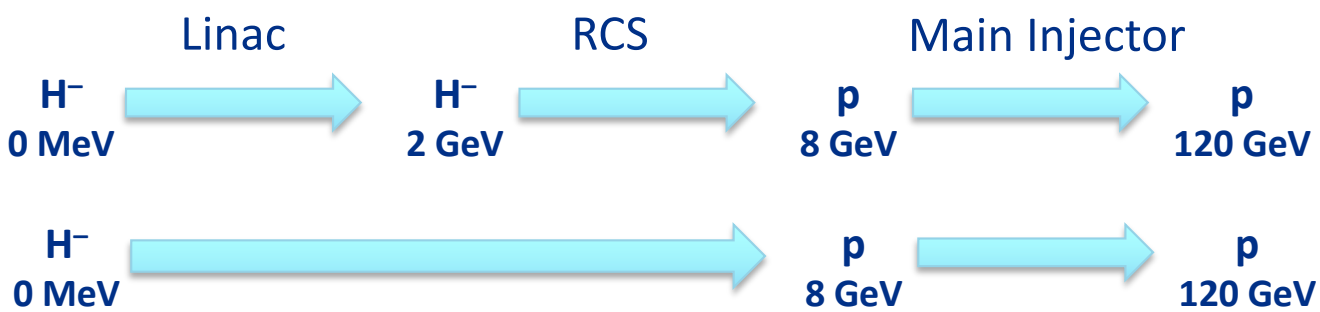
RCS vs LINAC

- 1. RCS
  - Linac H^- from 0 to 2 GeV
  - Foil strip H^- to p 2 GeV
  - RCS p from 2 to 8 GeV
  - MI p from 8 to 120 GeV

  - Straightforward replacement
  - Less expensive?
  - Pulsed beam
  - H– losses at lower energy

- 2. Linac
  - Linac H– from 0 to 8 GeV
  - Foil strip H– to p 8 GeV
  - MI p from 8 to 120 GeV

  - Mass produced cryomodules
  - More energy efficient?
  - Some experiments favor CW
  - Laser stripping easier at 8 GeV?
  - “Easy” intermediate energies



Recycler or not Recycler

- **In the proposed scheme RCS injects MI directly**
  - Recycler is eliminated
  - RCS and MI ramping not time-overlapped
  - 5 RCS batches at 20 Hz: 250 ms

- **Recycler not needed anymore?**
  - It would allow time-overlap of MI and RCS ramping
  - Shorten MI cycle time
  - Gain on average power output
  - Relax constraints on RCS repetition rate and bunch intensity

Demands serious consideration

Physics Topics

	Dark Sectors	ν Physics	CLFV	Precision tests	R&D
Charged lepton flavor violation: muon to electron conversion			■		
Charged lepton flavor violation with muon decays	■		■		
Stopped Pion Source	■	■			
Kaons Decay at Rest	■	■			
DM searches with Intermediate Energy Protons	■	■			
High Energy Proton Fixed Target	■			■	
Electron missing momentum	■	■			
Nucleon Electromagnetic Form Factors from Lepton Scattering		■		■	
Electron beam dumps	■				
Muon Missing Momentum	■	■			
N-Nbar oscillations				■	
Muon Collider R&D and Neutrino Factories		■			■
Tau Neutrinos		■			
Rare Decays of Light Mesons	■			■	
Proton Irradiation Facility					■
Proton Storage Ring: EDM and Axion Searches	■			■	
Test-beam Facility					■
Physics with Muonium	■			■	
Muon Beam Dump	■				

Beam Requirements

	protons					e	μ
	1 GeV	2 GeV	8 GeV	5-30 GeV	120 GeV		
	Storage Ring	CW		10-50 Hz			
Charged lepton flavor violation: muon to electron conversion		X					
Charged lepton flavor violation with muon decays		X					
Dark Sector Searches	X						
Sterile Neutrino Searches	X						
Dark Matter searches with Intermediate Energy Protons			X				
High Energy Proton Fixed Target					X		
Electron missing momentun						10 GeV CW	
Nucleon Electromagnetic Form Factors from Lepton Scattering						2 GeV	2 GeV
Electron beam dumps						1 GeV pulsed	
Muon Missing Momentum							30 GeV pulsed
N-Nbar oscillations		X					
Muon Collider R&D and Neutrino Factories				X			
Tau Neutrinos					X		
Rare Decays of Light Mesons		X					
Proton Irradiation Facility			X				
Test-beam Facility					X		
Physics with Muonium		X					
Muon Beam Dump							3 GeV CW

Tentative Timeline (1)

Spring 2021 (now) – December 2021

- **First Phase completed:**
  - Booster Replacement Task Force (BR-TF) White Papers delivered
- **Launch Second Phase:**
  - Booster Replacement Central Design Group (BR-CDG) being formed
    - Expand on present task force
    - Charge:
      - Propose priorities for Booster Replacement physics program
      - Identify and enumerate viable technical options to upgrade the accelerator complex and deliver 2.4 MW to DUNE
      - Understand how different options would impact Fermilab's future physics program beside LBNF/DUNE
      - Make recommendations
  - Review of accelerator plans by Accelerator Advisory Committee

Tentative Timeline (2)

Early 2022

- Possible down-selection of accelerator options
- Review by international "BR Definition Committee" (Formed by Nigel in 2019)
- Prepare for CD0
- Receive CD0 approval

Summer 2022

- Present at Snowmass
- Complete Conceptual Design Report
- Complete project plan
  - Preliminary cost/schedule
- Define R&D program
- Enlist partners, international and other DOE labs

Summary

- **Phase I complete**
  - White papers released
  - Options exist for upgrading the accelerator complex and deliver 2.4 MW to DUNE
  - The upgrade will open opportunities for a rich physics program at low and intermediate energies

- **Phase II is starting now**
  - BR-CDG group is being formed
  - Will propose physics program priorities and understand implications on technical choices for accelerator complex upgrade
  - Aim for CD0 after review by Booster Replacement Definition Committee in early 2022
  - Present at Snowmass in Summer 2022