Fermilab

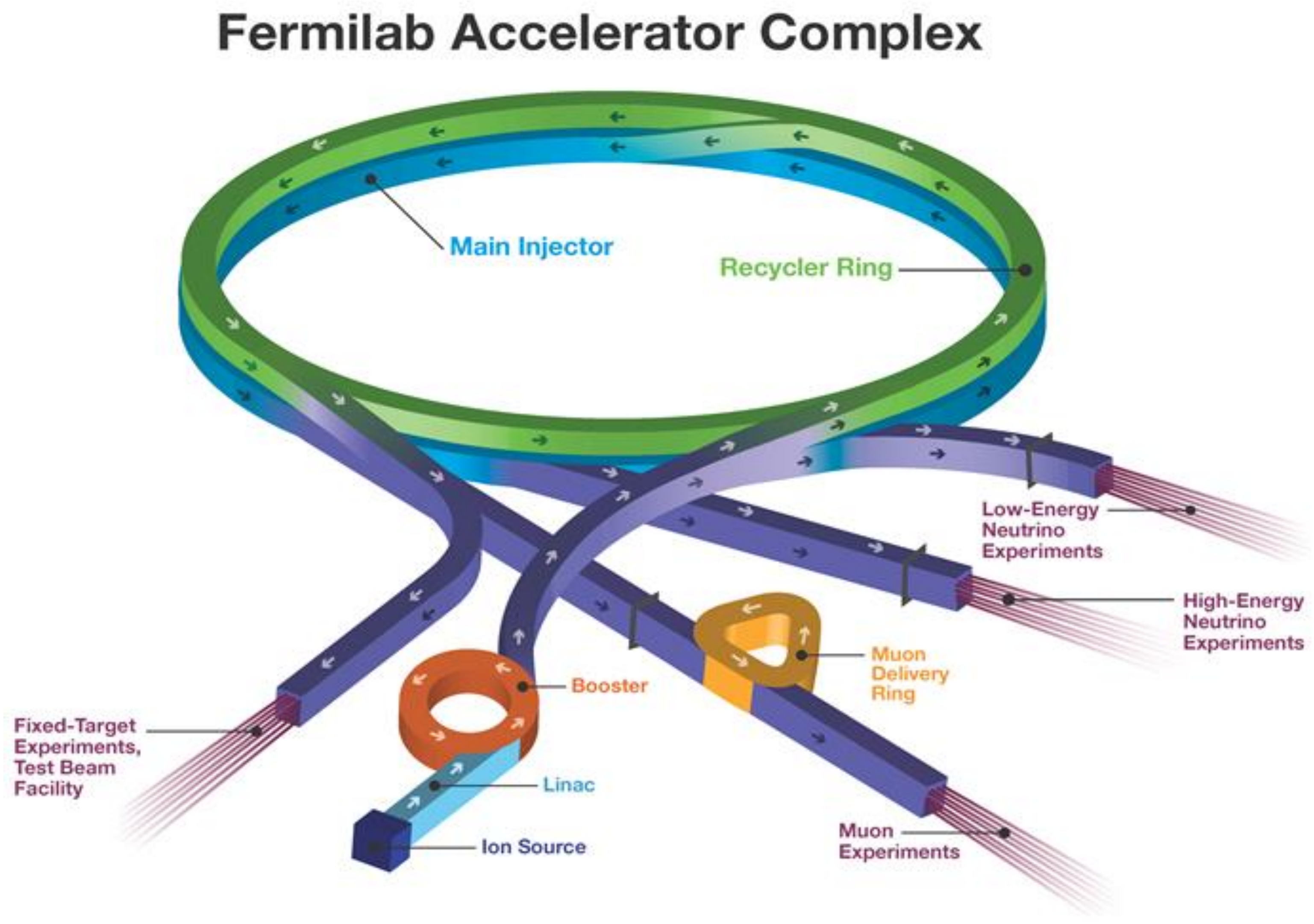
An Upgrade Path toward Multi-MW Beam Power at Fermilab

Jeffrey Eldred

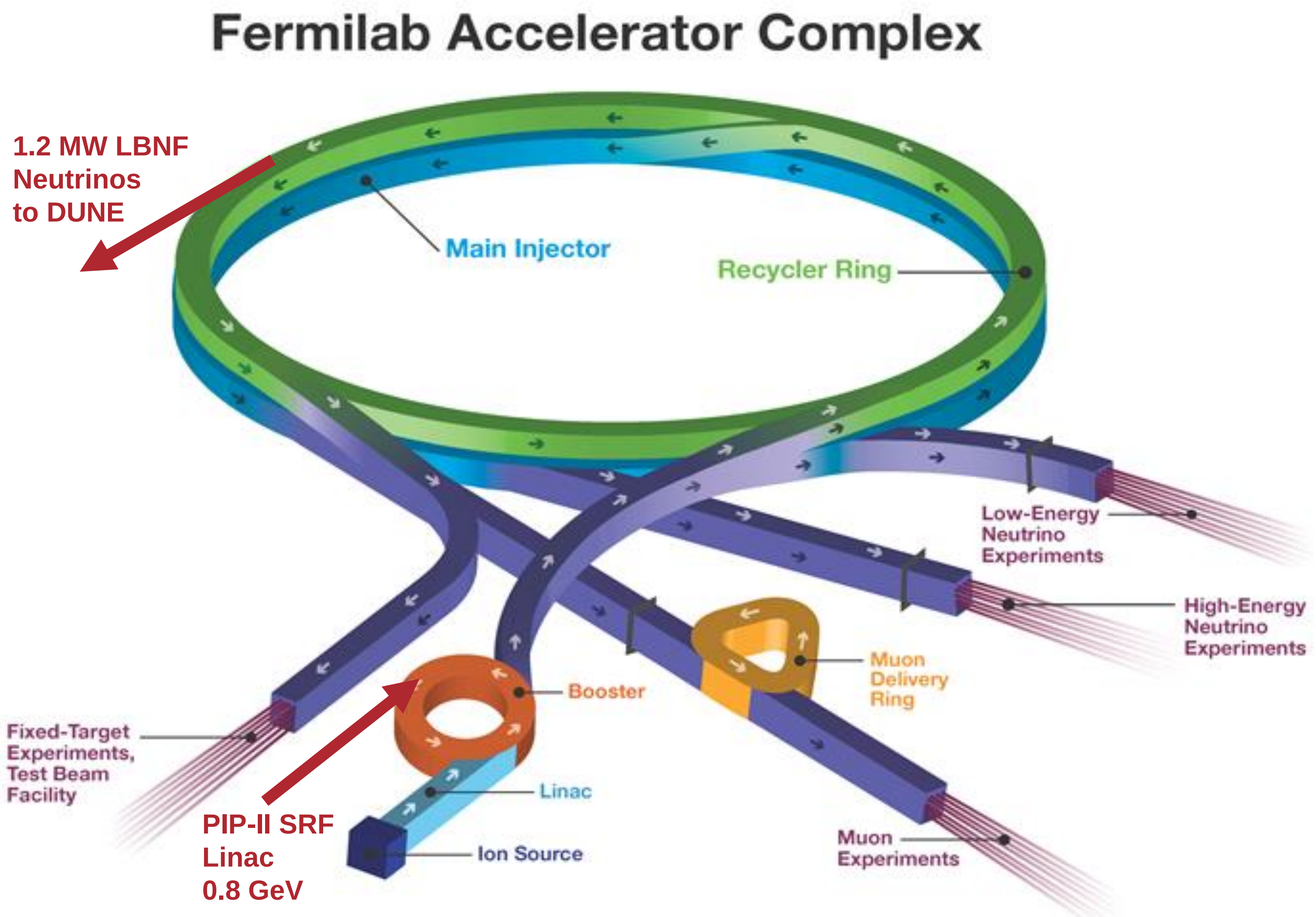
NuFACT 2021

September 6th 2021

Fermilab Upcoming Upgrades Now 750kW

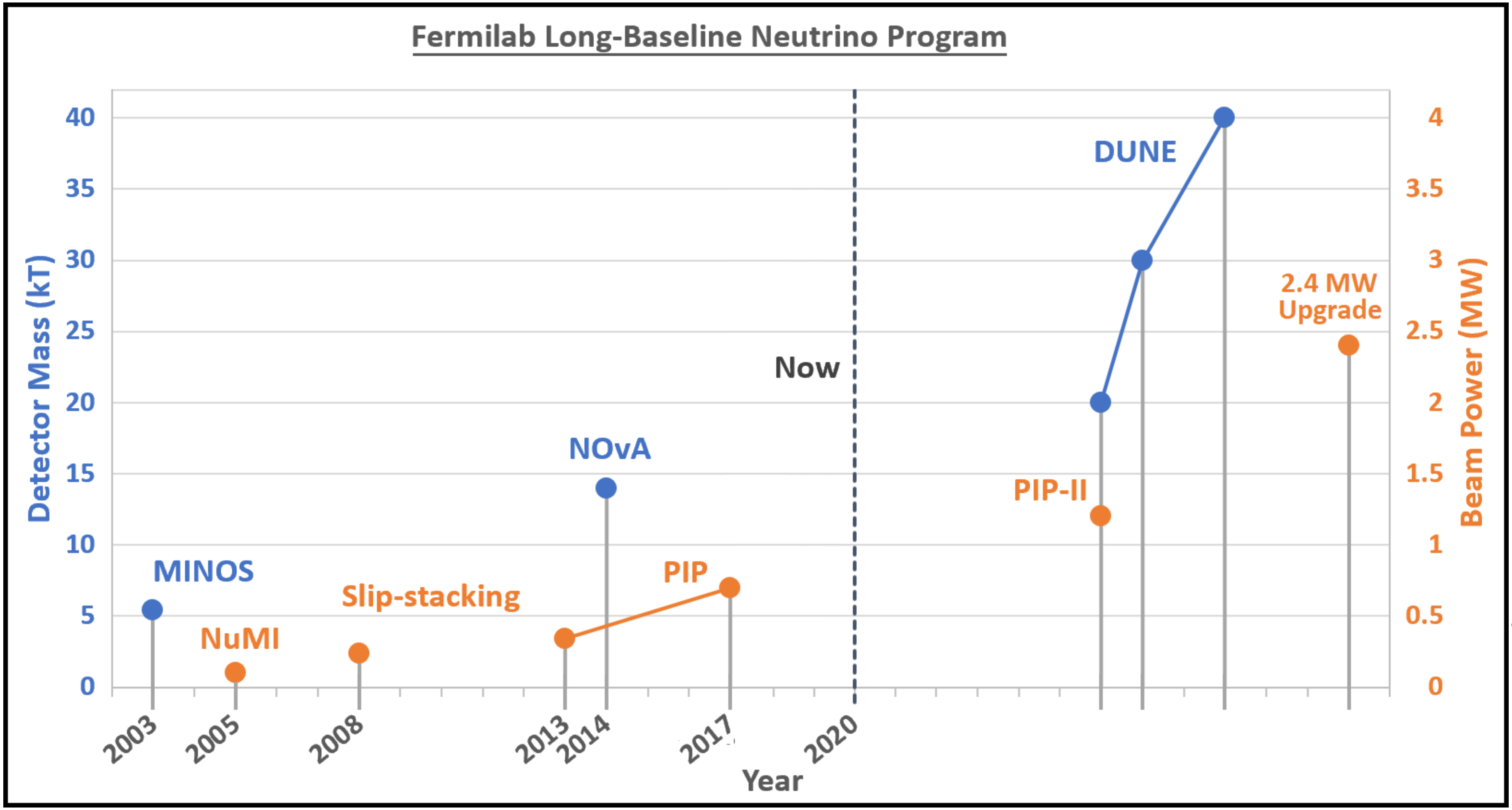


Fermilab Upcoming Upgrades PIP-II 1.2MW



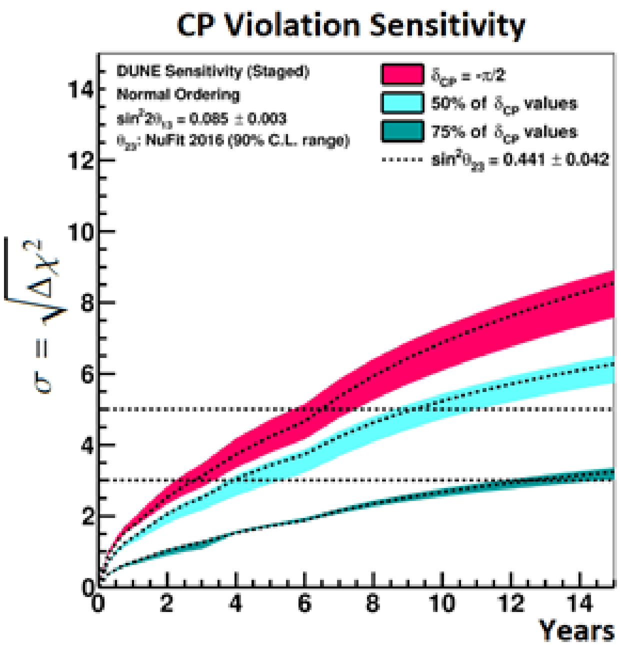
Beam Power and Detector Size

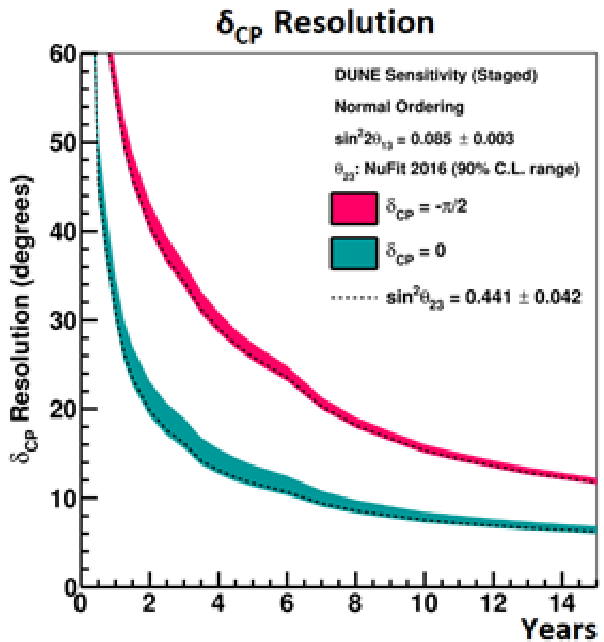
DUNE long-baseline neutrino program calls for **2.4 MW**



J. Eldred, JINST 2019

DUNE Physics, with 2.4 MW at 6 years

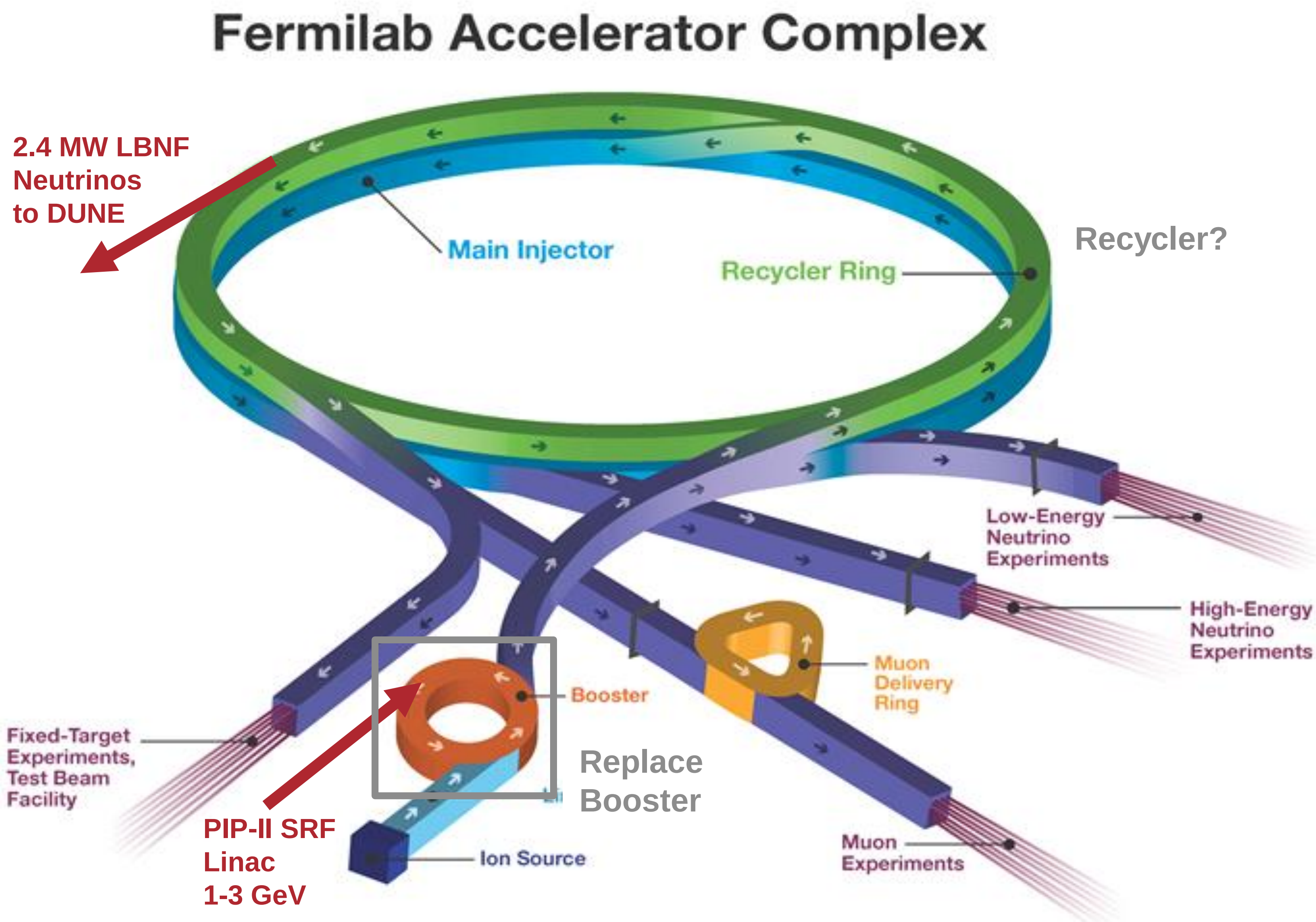




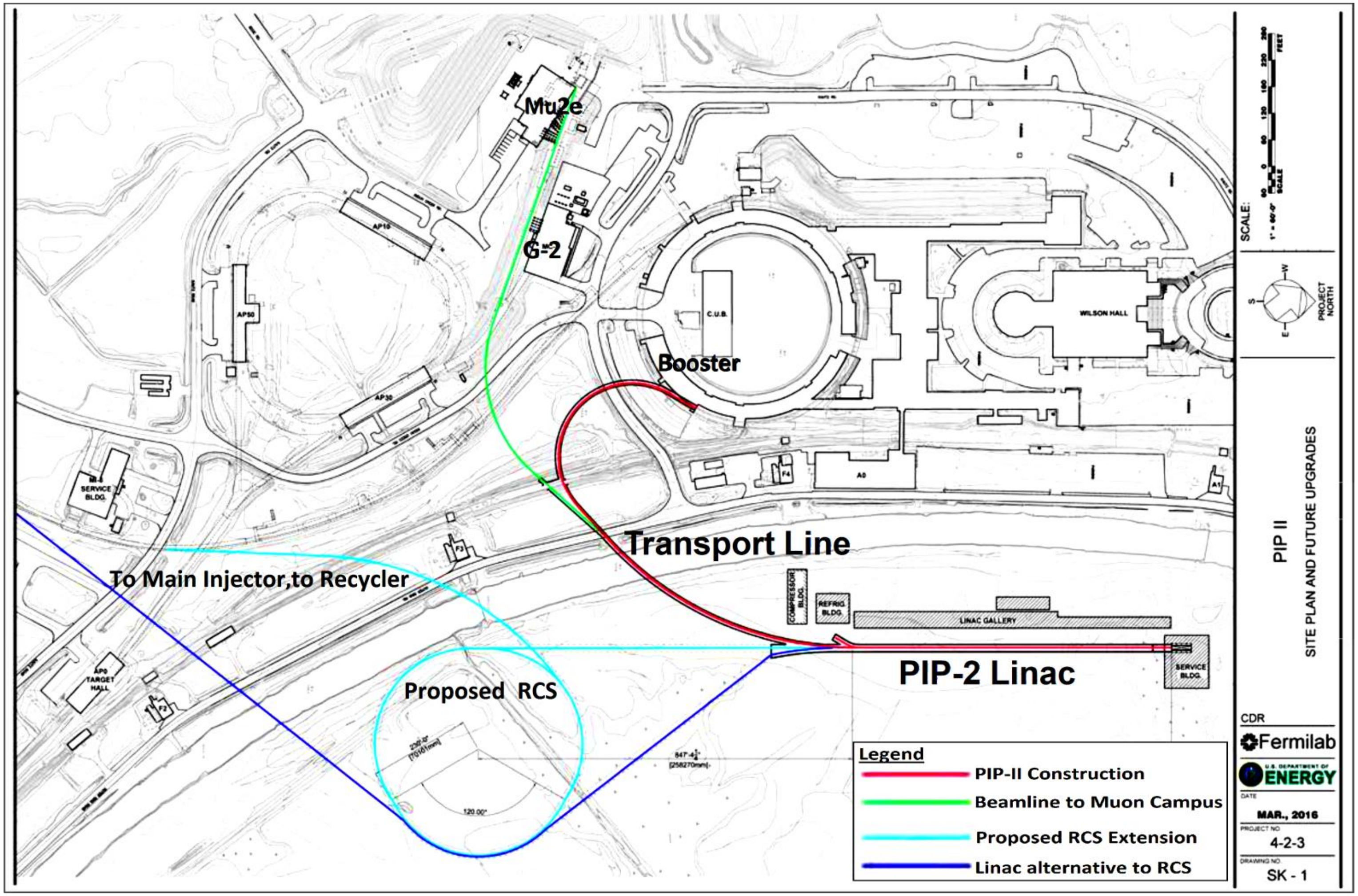
Physics Milestone	Exposure
5σ Mass Ordering ($\delta_{CP} = -\pi/2$)	1
5σ Mass Ordering (100% of δ_{CP} values)	2
3σ CP Violation ($\delta_{CP} = -\pi/2$)	3
3σ CP Violation (50% of δ_{CP} values)	5
5σ CP Violation ($\delta_{CP} = -\pi/2$)	7
5σ CP Violation (50% of δ_{CP} values)	10
3σ CP Violation (75% 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

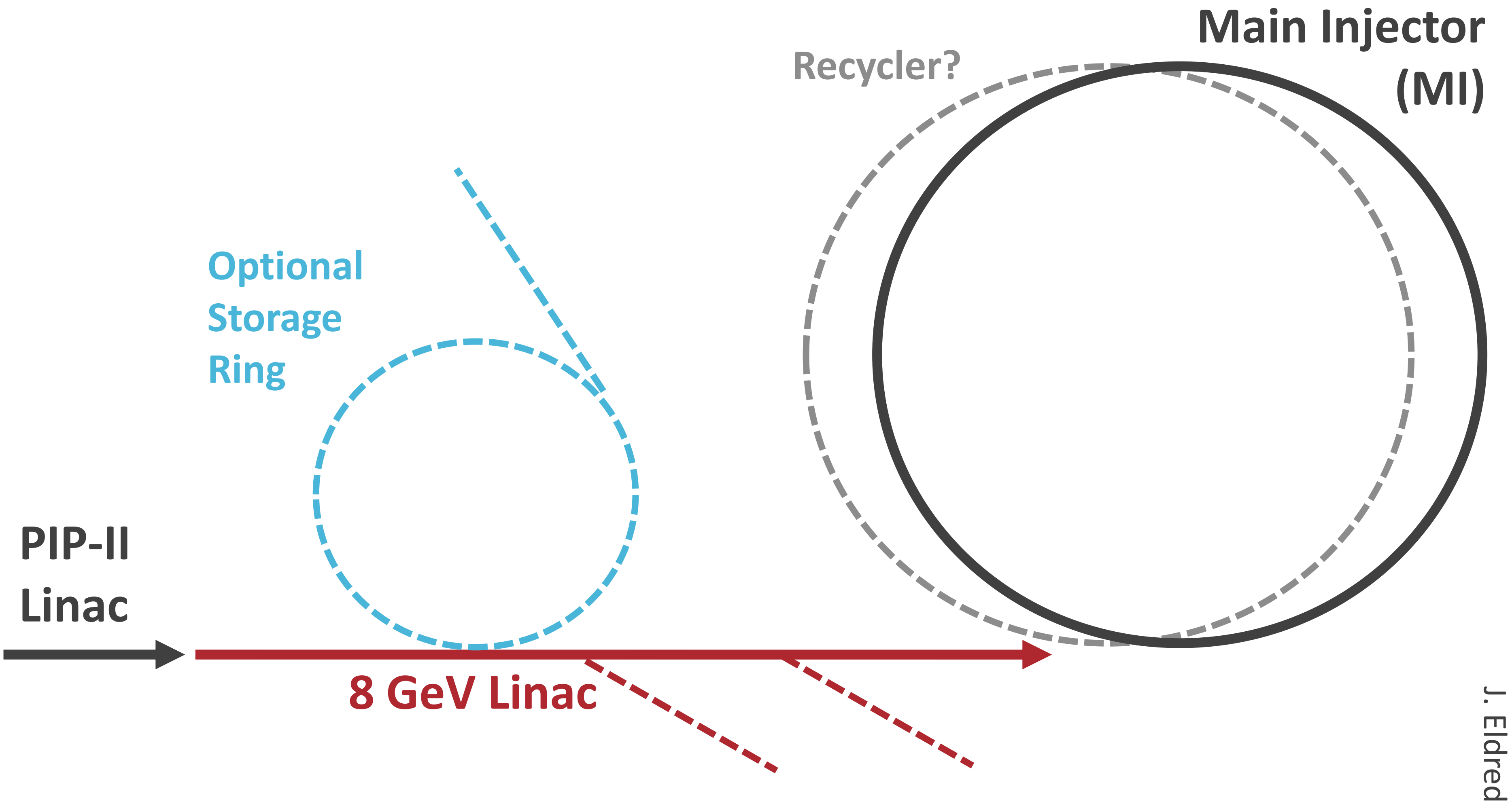


2.4 MW Upgrade: Build RCS and/or Linac to 8 GeV

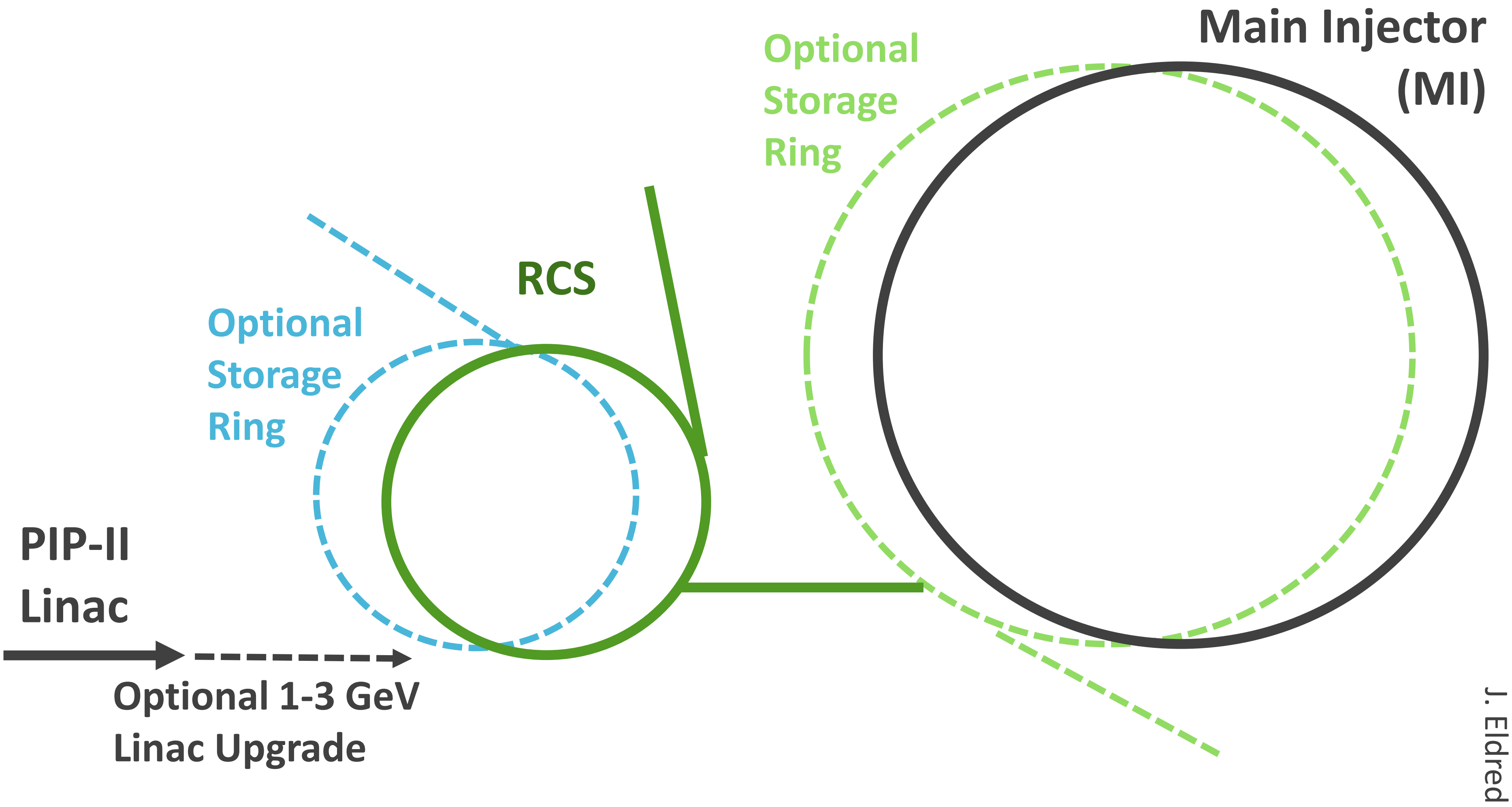


How we get to 2.4 MW will set the stage for the future of Fermilab!

8 GeV Linac Option



Rapid-Cycling Synchotron (RCS) 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.

In 2018, S. Nagaitsev and V. Lebedev: updated version of ICD-2.

In 2019, J. Eldred, V. Lebedev, A. Valishev: parametric study of RCS design.

The RCS path to multi-MW are well-considered, design requirements are needed.

In 2020, Committee for Fermilab Booster Upgrade an integrated design effort:
- Science Working Group (R. Harnik & about 25-75 people)
- Accelerator Working Group (M. Syphers & about 25 people)

We have been asked to develop a scenario to present to the Fermilab directorate and to present on Fermilab's behalf for Snowmass.

However, this design team does not represent any decision at higher levels.

2 GeV Linac + RCS Scenario:

- Accelerator Working Group paper - recent ArXiv paper.
- Science Working Group paper - mostly complete, still open.

Document Preview:

Physics Opportunities for the Fermilab Booster Replacement

Physics task force

November 27, 2020

Abstract

This is a menu of physics opportunities afforded by the Fermilab Booster Replacement and its various options. As in any self-respecting fancy restaurant, there are no prices in the menu.

overleaf.com/read/scgtzvbngfxr

Contents

R. Harnik, 2020

Fermilab

	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 exp.) Electron missing momentum	■	■			
(electron exp.) Nucleon Electromagnetic Form Factors from Lepton Scattering		■		■	
(electron exp.) 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	■				

R. Harnik, 2020

Proposed Experiments

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 (rare-decays)
- neutron-antineutron oscillation experiments

2 GeV pulsed beam from Storage Ring, ~1 MW

- stopped pion source experiments
- dark matter search at GeV-scale
- PRISM charged-lepton flavor violation experiments

8 GeV RCS program, ~1 MW

- kaon decay-at-rest program
- dark matter search from intermediate energy protons
- proton irradiation facility
- any successors to short-baseline neutrino program
- NuSTORM and muon-collider R&D
- muon beam dump, missing muon momentum

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

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

Accelerator Design Criteria

I) Assume PIP-II proceeds according to current plans.

II) Scenario should enable the Main Injector to achieve the 2.4 MW at 120 GeV for DUNE/LBNF in the near term.

- and for a 60 GeV MI cycle, at least 2 MW.

III) Scenario should allow a robust experimental program and enable future high-power upgrades.

IV) Identify topics which may require R&D.

Linac + RCS Scenario

At 2 GeV injection energy, space-charge is manageable for **~37e12 RCS**,

- For **20 Hz** rep. rate, the beam can be stacked directly into Main Injector.
- If we stack directly into MI, there will be extra cycles for 8 GeV program.
- **Sidebar:** Whether it would be possible/preferable to get to 2.4 MW with a Recycler-like 8-GeV storage ring is hotly debated.

At 2 mA linac injection current, long injection time becomes an issue for high-intensity, fast-ramping RCS.

Solution 1: Retrofit PIP-II linac for **5-10 mA pulses**, 0.6-1.2 ms injection.

- This strategy has strong precedents at other facilities (SNS, J-PARC)
- If that retrofit were to take place earlier, would benefit PIP-II Booster.

Solution 2: Create **2 GeV storage ring** for injection, transfer to RCS.

- Allows dedicated injection optics and longer accumulation time.
- With a subsequent laser stripping update, allows additional opportunity for MW-class pulsed 2 GeV proton program (capability overlaps with SNS).

Path to 4 MW Main Injector, by upgrade MI ramp rate & second target hall

High-Level Parameters of Possible Upgrade Scheme

Parameter	PIP-II	RCS
Linac Energy	0.8 GeV	2 GeV
Linac Current	2 mA	2 mA
RCS Energy	8 GeV	8 GeV
RCS Intensity	6.5 e12	37 e12
RCS Rep. Rate	20 Hz	20 Hz
Number of Batches	12	5
Available RCS Power	0.08 MW	0.8 MW
Main Injector Intensity	80 e12	185 e12
Main Injector Cycle Time	1.2 s	1.4 s
Main Injector Power (120 GeV)	1.2 MW	2.4 MW
Ultimate Main Injector Power	1.2 MW	4.0 MW

High-Level Parameters of Possible Upgrade Scheme

Parameter	PIP-II	RCS	ICD-2
Linac Energy	0.8 GeV	2 GeV	2 GeV
Linac Current	2 mA	2 mA	2 mA
RCS Energy	8 GeV	8 GeV	8 GeV
RCS Intensity	6.5 e12	37 e12	26 e12
RCS Rep. Rate	20 Hz	20 Hz	10 Hz
Number of Batches	12	5	5
Available RCS Power	0.08 MW	0.8 MW	0.2 MW
Main Injector Intensity	80 e12	185 e12	125 e12
Main Injector Cycle Time	1.2 s	1.4 s	1.2 s
Main Injector Power (120 GeV)	1.2 MW	2.4 MW	2.0 MW
Ultimate Main Injector Power	1.2 MW	4.0 MW	2.8 MW

Differs from ICD-2 scenario by:

- higher RCS intensity & Main Injector power
    - an updated 2.4 MW scenario is in the works.
- RCS does not use Recycler Ring for stacking.
- higher rep. rate and RCS power.

Facility Capabilties (2mA CW + 2 GeV SR scenario)

2 GeV CW-capable beam, 2mA
- upgradeable to 4 MW shared with any pulsed 2 GeV program.

2 GeV pulsed beam from Storage Ring, ~1 MW
- requires laser stripping and 2 GeV Storage Ring.
- 37 e12 at 60-120 Hz.
- investigating ~400ns pulse compression.

8 GeV RCS program, 0.8 MW
- 37e12 every 20 Hz.
- 0.8 MW concurrent with 120 GeV program.
- upgradeable to ~2 MW with RCS ramp-rate and optics improvement.

120 GeV DUNE/LBNF program, 2.4 MW
- upgradeable to 4 MW with Main Injector ramp-rate.

120 GeV Slow-Extraction program, 8e12 over six second, once per min
- loss-limited, may be upgradeable.

Proposed Experiments

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RCS Design Parameters

Rapid Cycling Synchrotron (RCS)

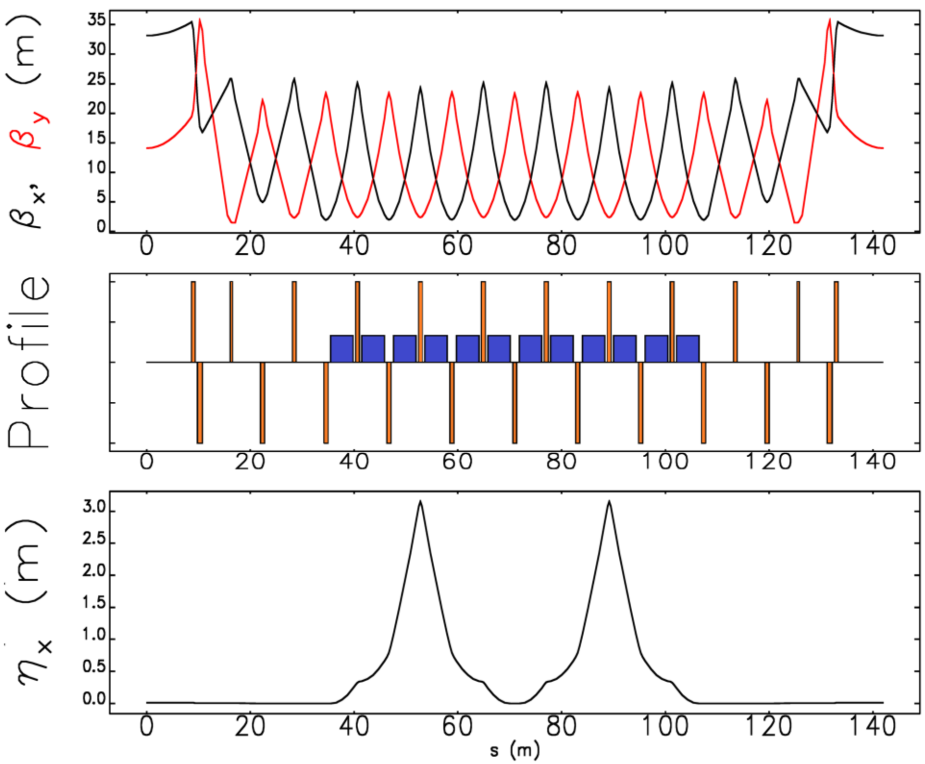
The RCS would operate at 20 Hz and accelerate from 2 to 8 GeV

A second ring operating at 2 GeV is proposed to be located above the RCS and used to accumulate charge from the upgraded linac.

Parameter	Value	
RCS Circumference	570 m	
RCS Rep. Rate	20 Hz	30 Hz
RCS Energy	8 GeV	
RCS Intensity	37 e12	
Number of Batches	5	
Average Current	3 A	
Available RCS Beam Power	0.8 MW	1.2 MW
Min/Max Dipole	0.31-1 T	
Min/Max Quadrupole Field	4.2-14 T/m	
RF Freq. Range	50.3-52.8 MHz	
Total RF Voltage	1.25 MV	1.9 MV
No. cavities (60 kV)	21	32

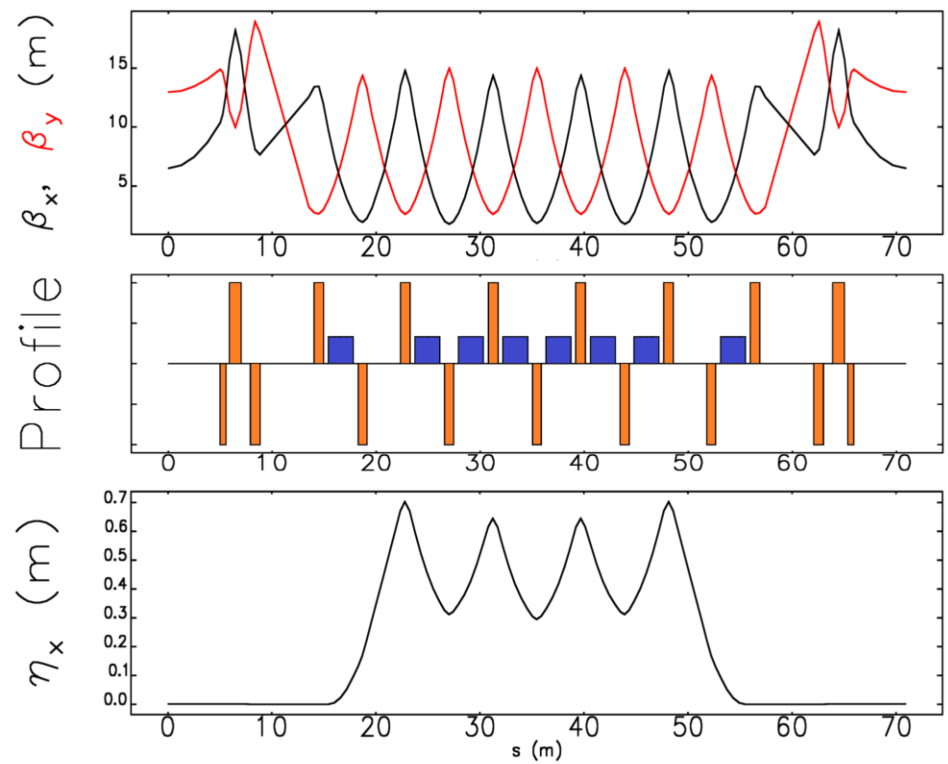
Preliminary RCS Lattice Configurations

2 GeV Injection Ring,
one of four periods



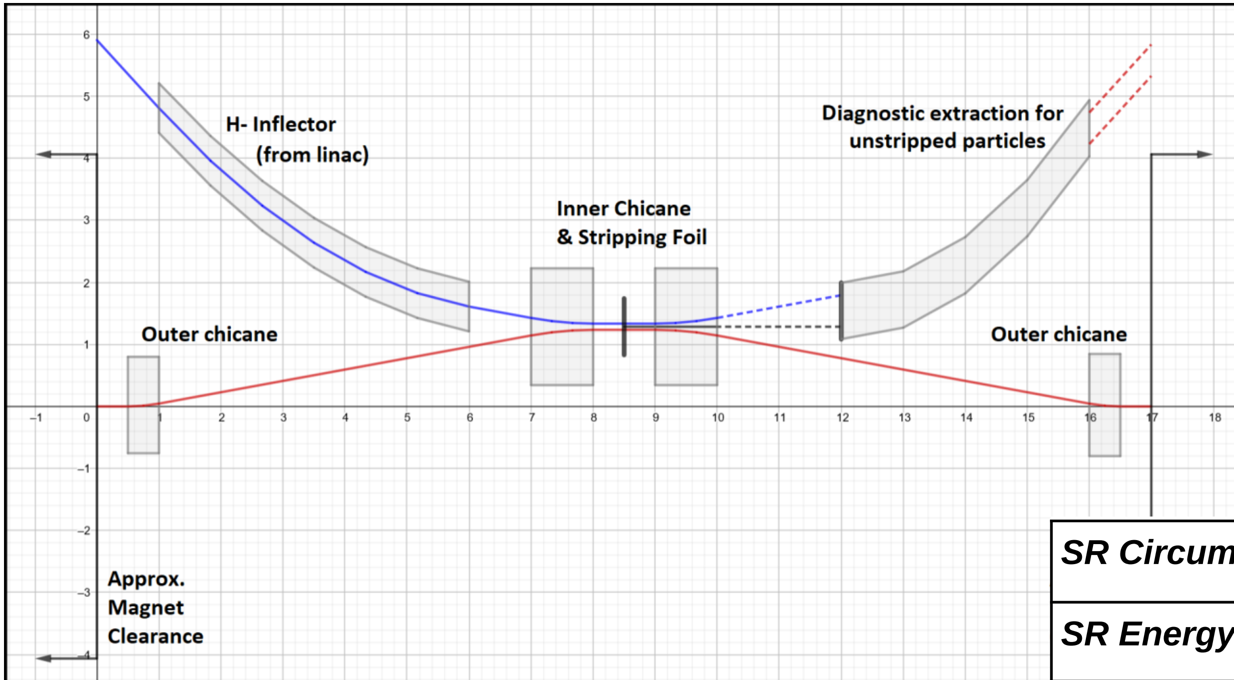
2 GeV Ring Optimized for Injection

2 - 8 GeV RCS Ring,
one of eight periods



8 GeV Ring Optimized for Acceleration

Beam Accumulation and H- Stripping in a Storage Ring



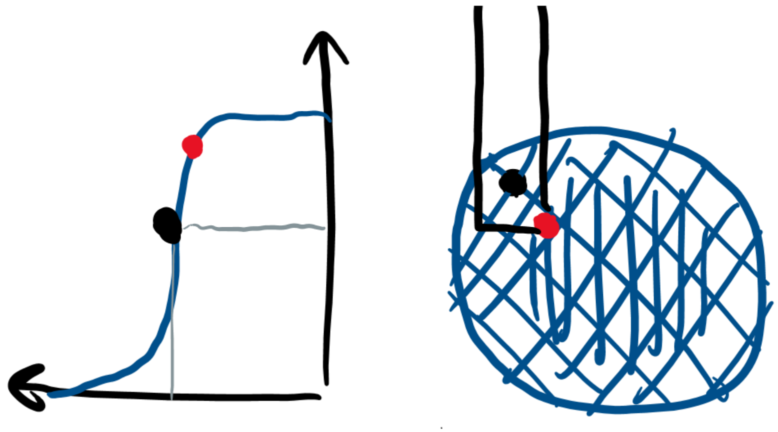
H- Foil Stripping Injection

17 m straight.

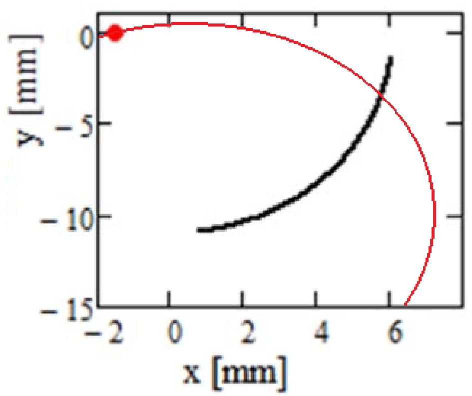
SR Circumference	*570*	*m*
SR Energy	*2*	*GeV*
Superperiodicity	*4*	
Injection Insertion Length	*12*	*m*
Dipoles per Superperiod	*12*	
Dipole Strength	*<0.4*	*T*

Anti-Correlated Painted Injection

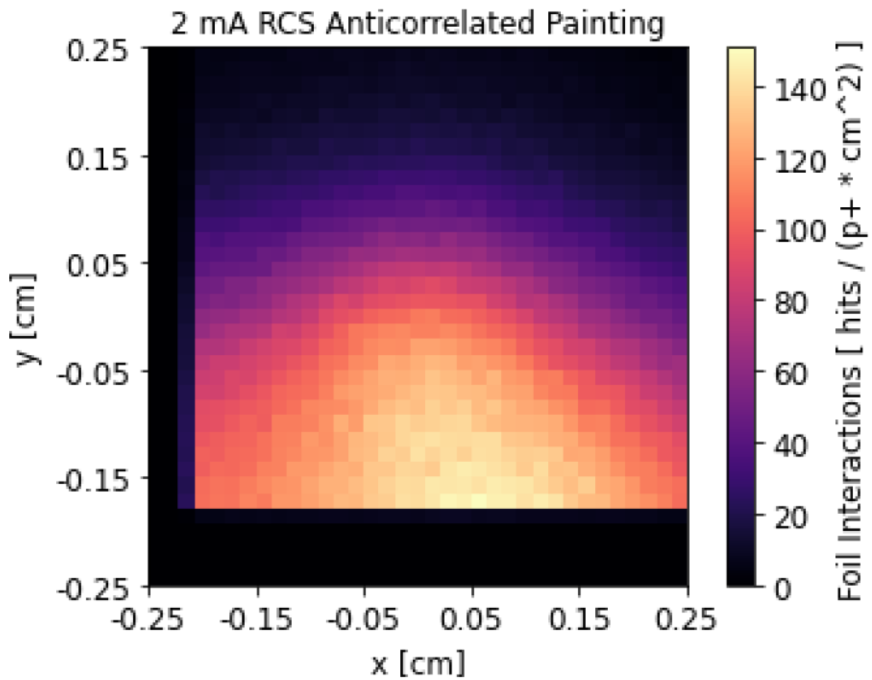
Beam Distribution during Injection



Anti-correlated Painting Injection



Hit Distribution



Matthew Hoppesch beams-9123

Injection painting scheme chosen to:

1) **Minimize foil hits from the circulating beam.**
2) **Optimize stability of the beam distribution.**

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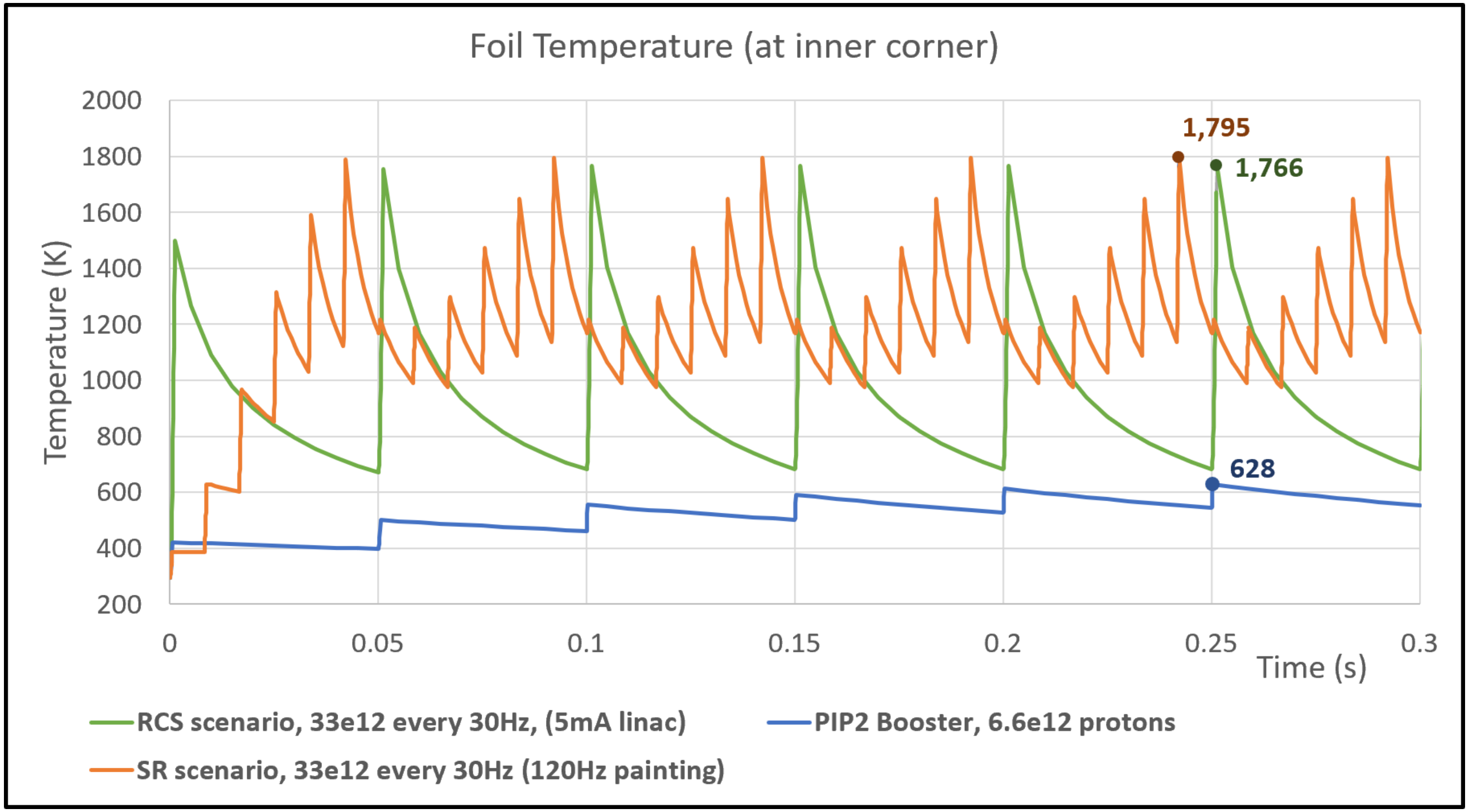
Beam Accumulation and H- Stripping in a Storage Ring



Scenario 1: Retrofit PIP-II linac to 5mA pulsed.

Scenario 2: Use six 120 Hz painting cycles to accumulate beam in storage ring every 20 Hz.

Summary

We have a self-consistent design for to 2.4 MW DUNE:

- 2 GeV upgrade of PIP-II + new 570m 8 GeV RCS.
- Upgrade is compatible with a wide range of proposed experiments.
- Accelerator design details are in paper and backup slides.

This specific scenario is unique for:

- does not require slip-stacking or Recycler.
- synergy with a 2 GeV accumulator ring.
- provides path to 4 MW upgrade of DUNE/LBNF.

The scenario also has options for being staged or scaled down.

- which beamlines should we plan to support?

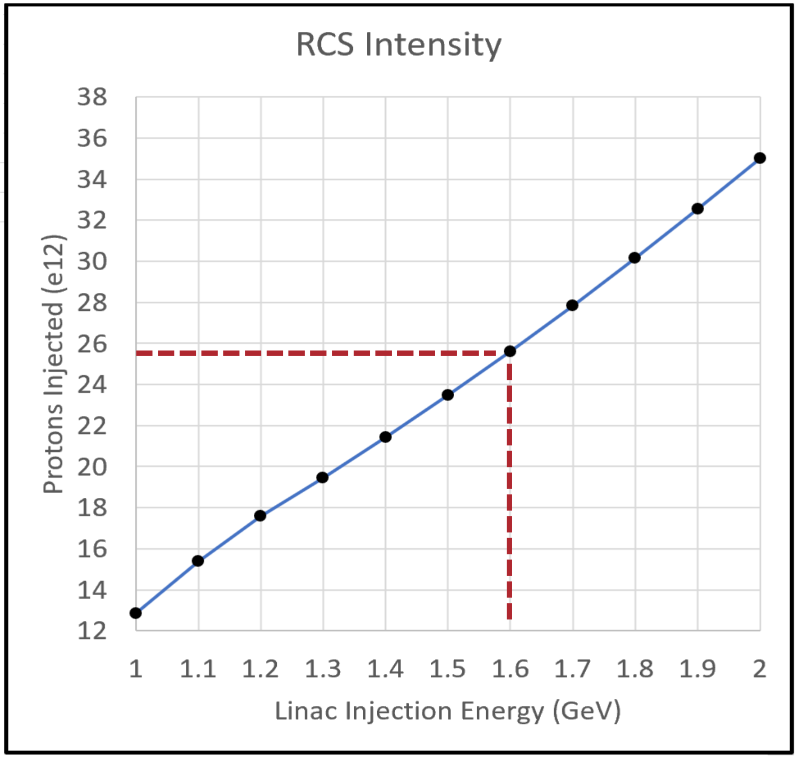
Next Steps

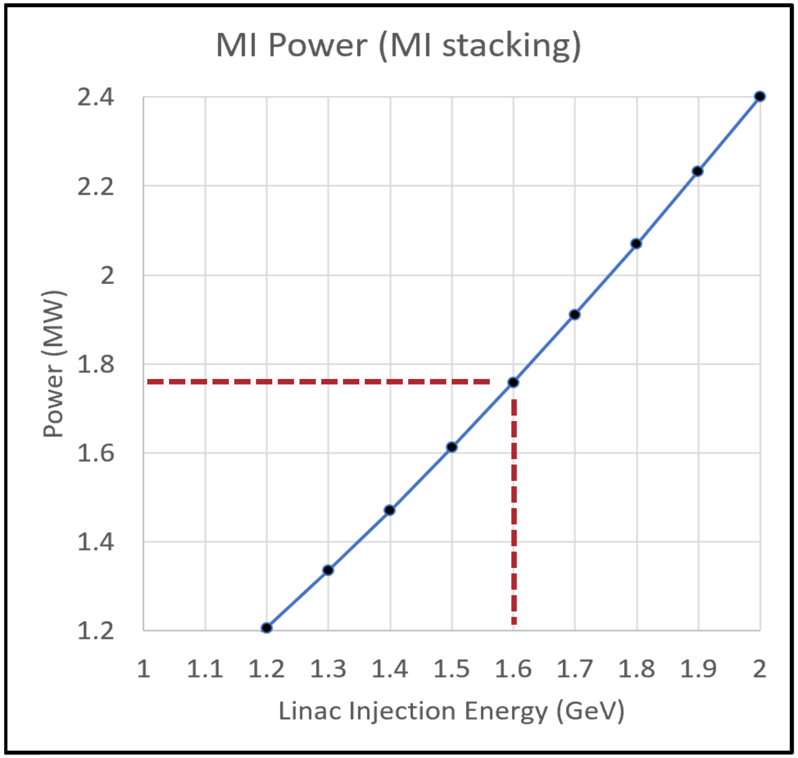
Feedback on physics prioritization and experiment siting from Snowmass.

Further and more in-depth design is possible after CD-0.

Backup

Staging RCS with partial upgrade of Linac & MI



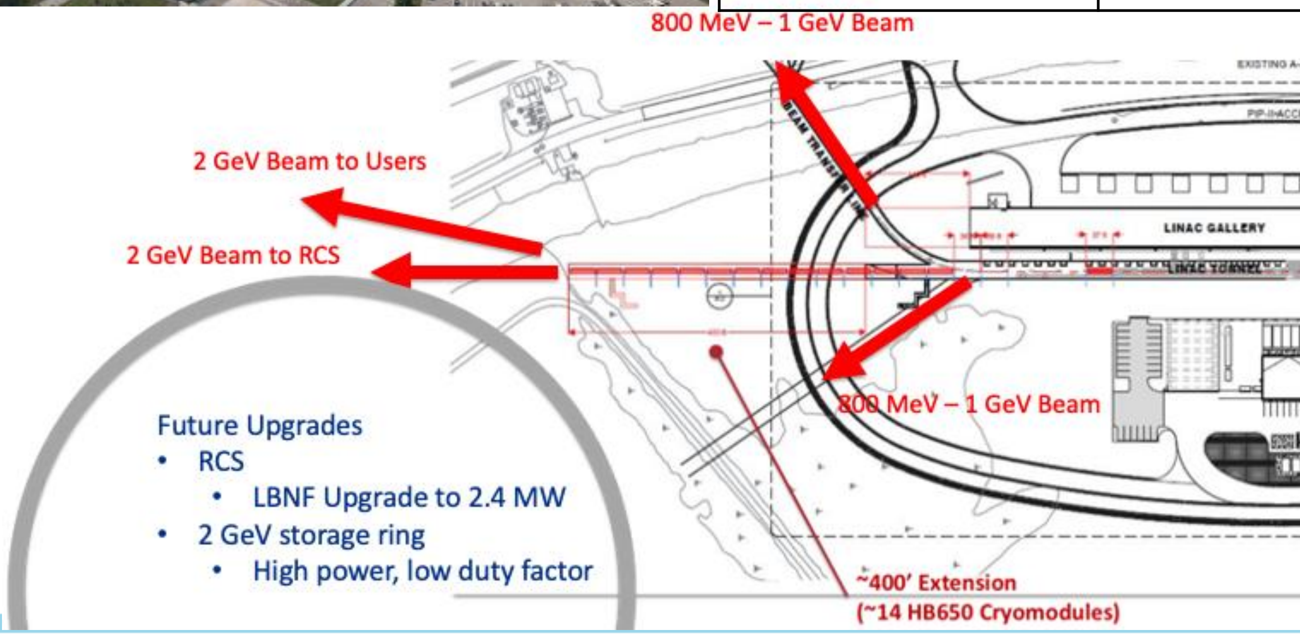


Linac can be commissioned concurrent with PIP-II operations, RCS can be commissioned at partial linac energy, etc.

At ~1.2 GeV, the PIP-II Booster **1.2 MW** benchmark is crossed.
At ~1.6 GeV, we have **1.8 MW** without Main Injector RF upgrade.
- If we can still use Recycler, RCS rep. rate only needs 10 Hz.

PIP-II Linac Upgrade to 2 GeV

Linac Parameters	*PIP-II Multi-users*	*with 2 GeV Upgrade*	
Beam Energy	*0.8*	*2.0*	*GeV*
Ave. Beam Current	*2*	*2*	*mA*
Bunch Length	*4*	*4*	*ps*
Min. Bunch Spacing	*6.2*	*6.2*	*ns*
Max. H- per bunch	*4*	*4*	10^8
Beam Power	*1.6*	*4*	*MW*

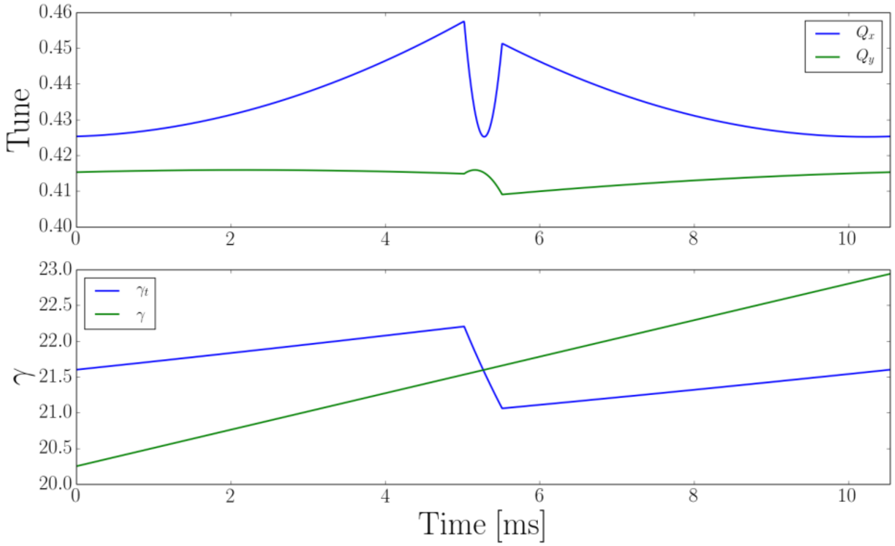


E. Pozdeyev, 2020

Main Injector Operations

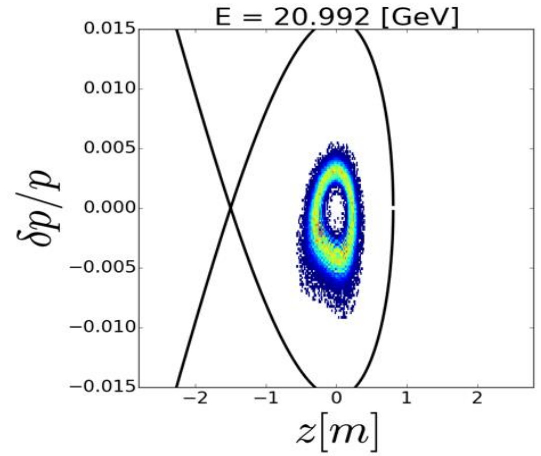
Keep 8 GeV injection into MI, re-using portions of Recycler as injection line

Removing slip stacking operation (Recycler) creates lower momentum spread in MI; helps to alleviate issues at crossing of transition energy



"Transition": energy where revolution frequency is independent of momentum

Special optics manipulation at the transition energy (left; part of PIP-II) and smaller momentum spread provide adequate phase space through transition:



transition energy in Main Injector (γ = 21.5)

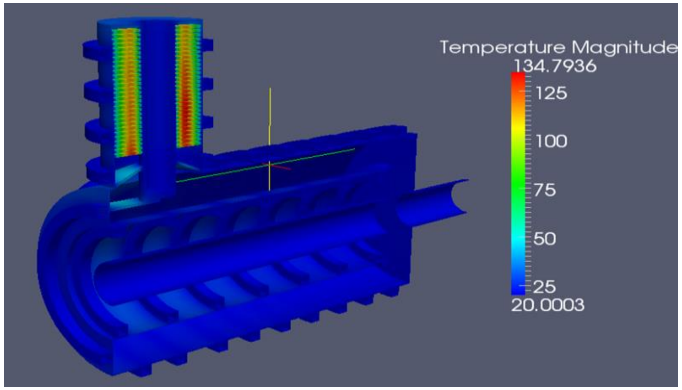
R. Ainsworth, I. Kourbanis

Main Injector RF System

MI RF system would be upgraded with new modern RF cavity system

- increases RF power to meet final intensity requirements
- also enables increased ramp rate to achieve higher overall beam power above 2.4 MW

RF System Specifications		
Frequency	*52.617 — 53.104*	*MHz*
Max. Acceleration Rate	*240*	*GeV/s*
Acceleration Voltage	*2.7*	*MV*
Peak Beam Power	*7.1*	*MW*
Average Beam Power	*3.6*	*MW*
Peak Voltage	*4.8*	*MV*
Average Beam Current	*2.7*	*A*
Fundamental RF Current	*4.6-5.2*	*A*
No. RF Stations required	*31*	

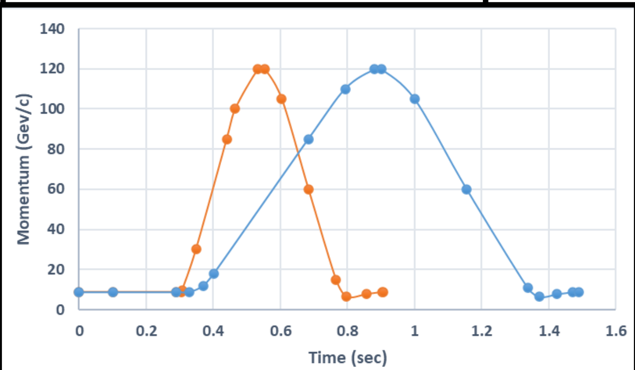


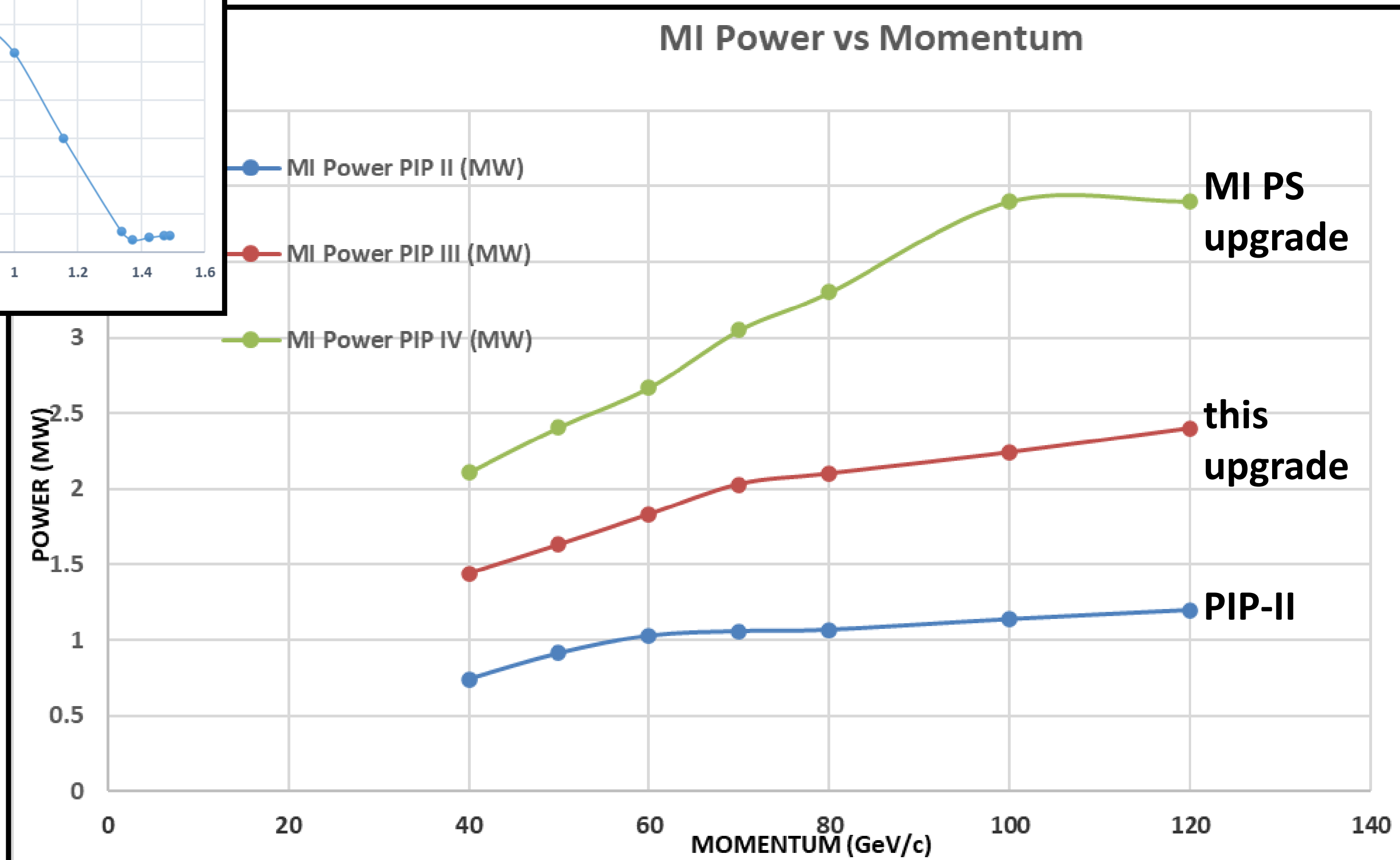
I. Kourbanis

Possible MI Upgrade for Higher Power Beyond 2.4 MW

Upgrade magnet power supply system to support higher ramp rate — reduce cycle time from ~1.5 s to about 0.9 s — factor of ~ 5/3

240 GeV/s —> 600 GeV/s





I. Kourbanis

Some R&D Areas

High-Power Targets:

- neutrino target for DUNE/LBNF, designs for other experiments.

H- Stripping Laser Technology:

- anticipating progress at SNS, J-PARC, FNAL.

Conventional RF design:

- large frequency sweep, significant beam-loading, high-gradient

IOTA Technology:

- innovations in electron lens and nonlinear optics.

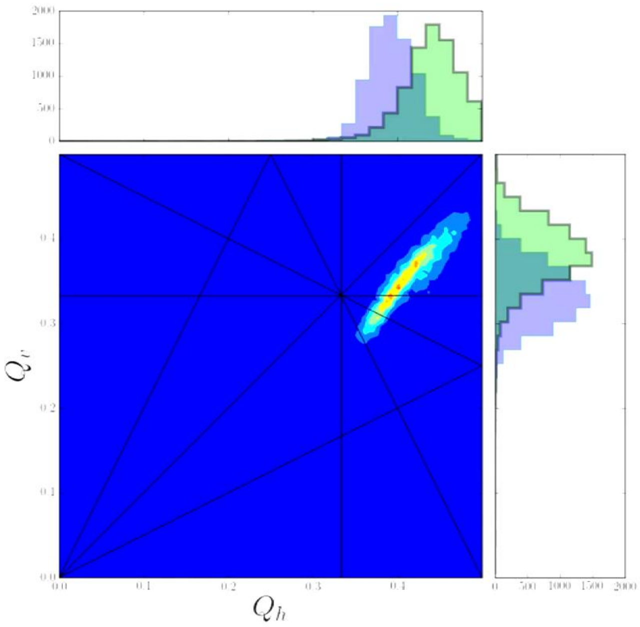
Ceramic beampipes:

- reliability and cost for ceramics, metallization, brazed-flanges.

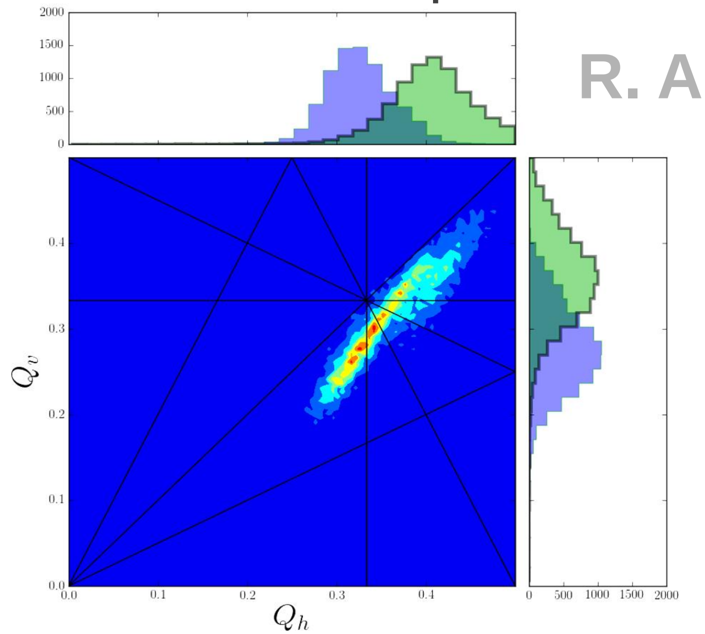
Recycler Intensity Challenges

Space-charge Tune-spread Losses:

Current Tune-Spread



PIP-II Tune-Spread



R. Ainsworth

If we go to higher than PIP-II intensity, but without a momentum separation between the beams, we will cross the same res. lines.

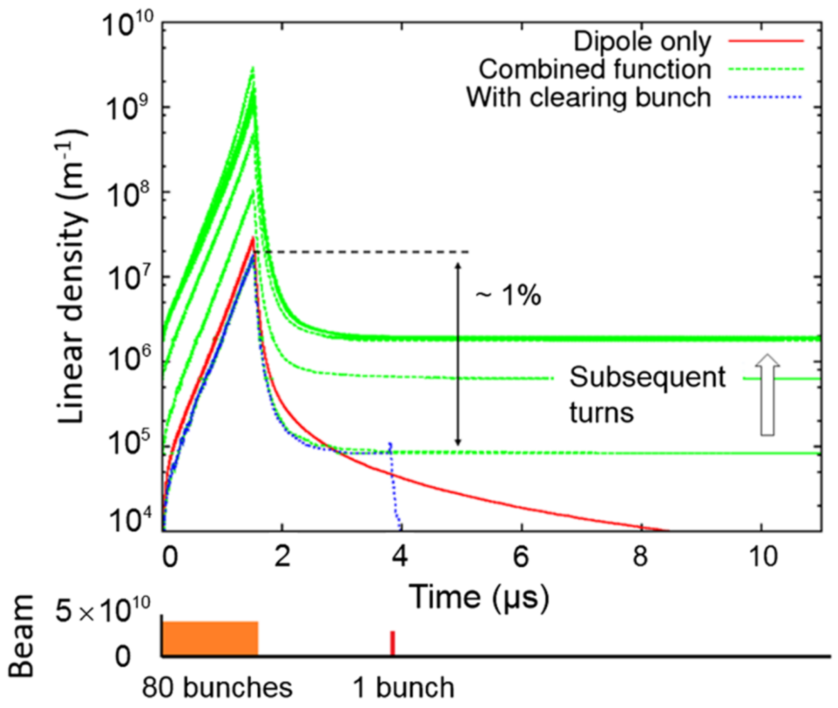
How well can we compensate the resonances lines?

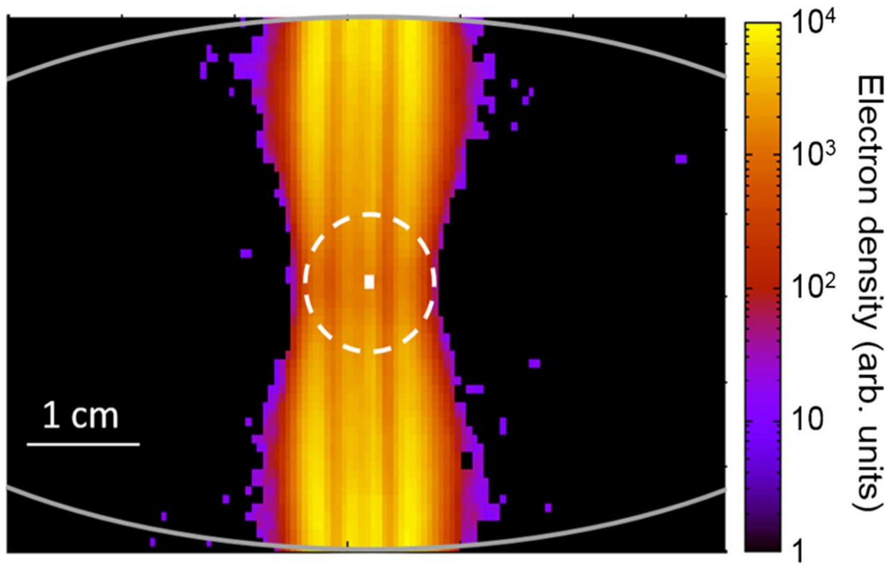
Recycler Intensity Challenges

Tight Aperture Losses:

Aperture limits RCS normalized emittance

Electron Cloud Instability:





S. Antipov et al. PRSTAB 2017

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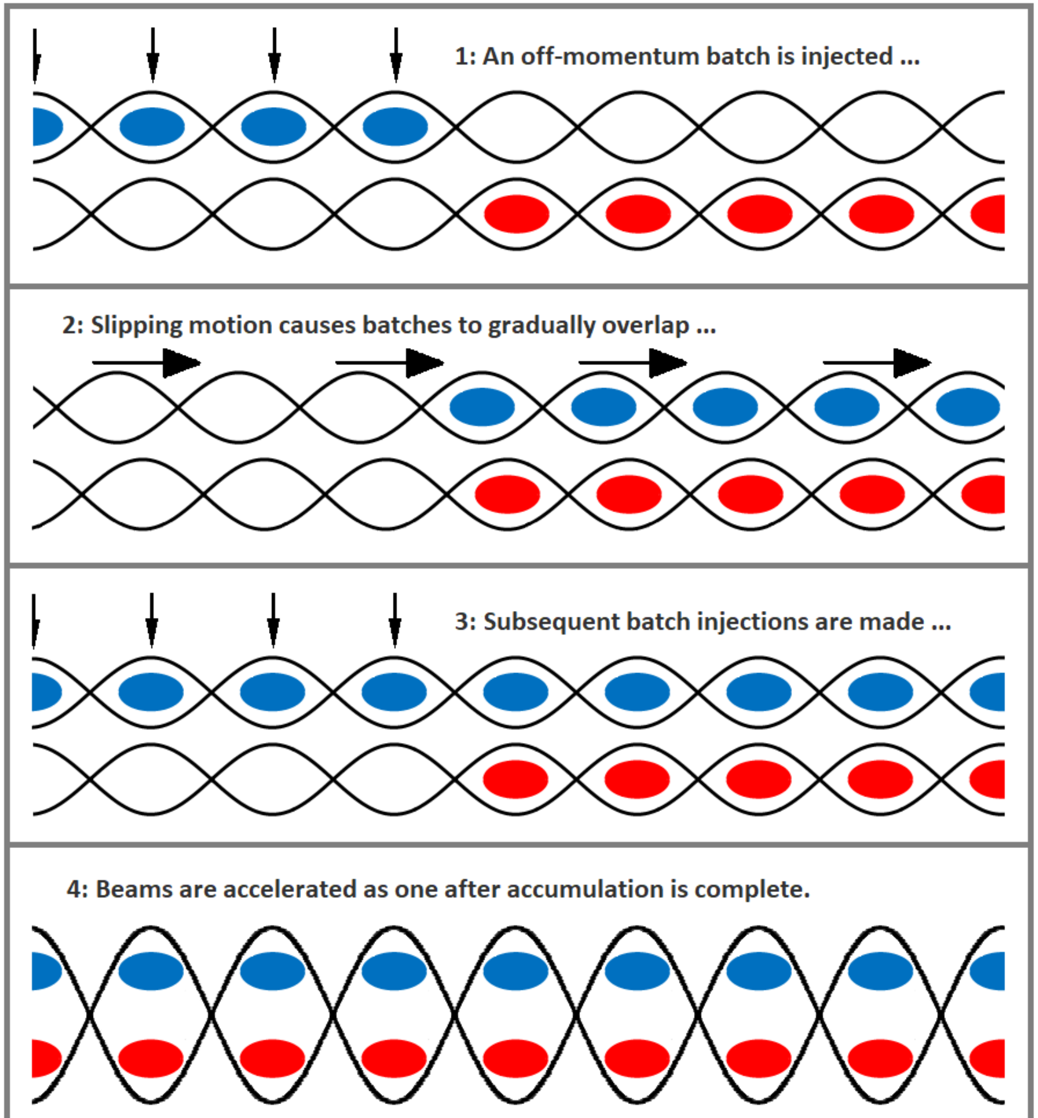
Slip-stacking Accumulation



RF frequency separation:

$$\Delta f = h_{\mathrm{RCS}} f_{\mathrm{RCS}}$$

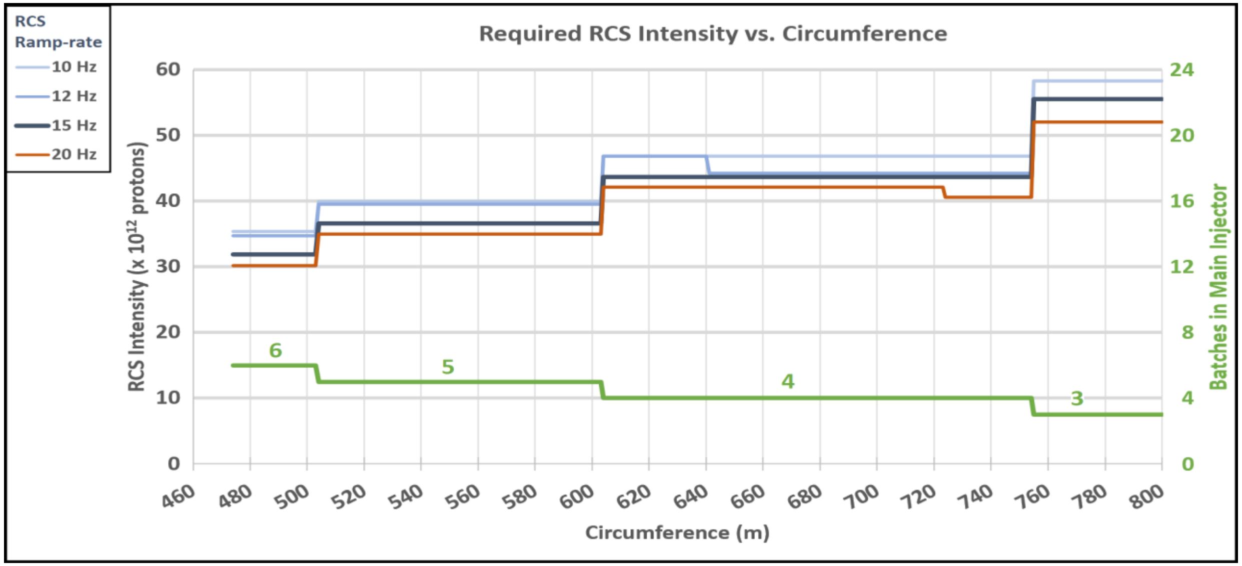
$$\Delta f = \left(h_{\mathrm{Booster}} \frac{C_{\mathrm{RCS}}}{C_{\mathrm{Booster}}} \right) f_{\mathrm{RCS}}$$

Momentum separation:

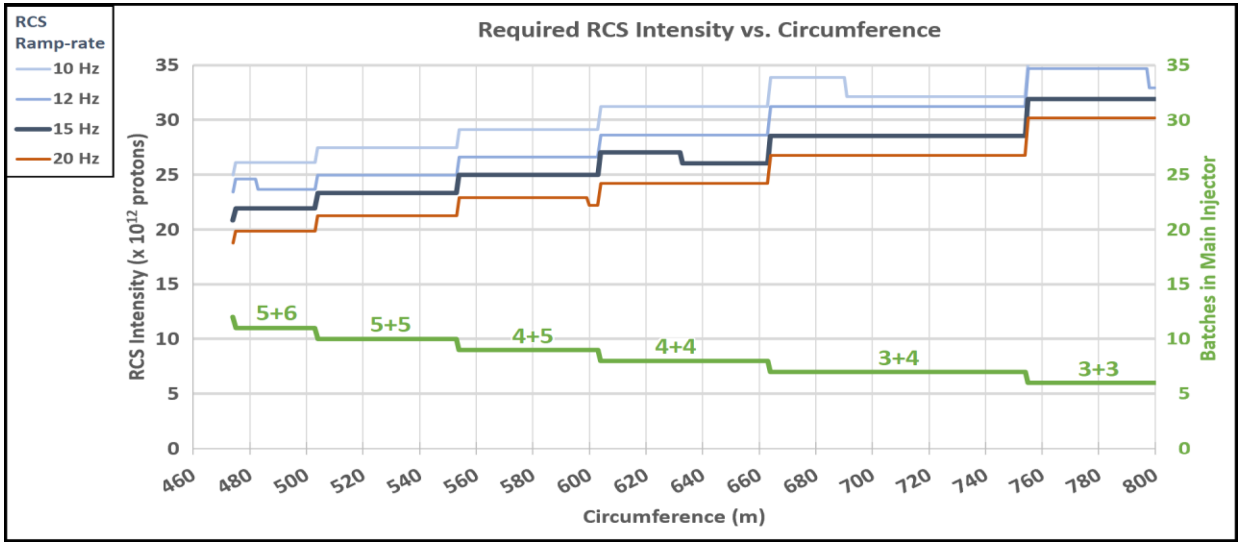
$$\Delta \delta = \frac{\Delta f}{f_{rev} h \eta}$$

2.4 MW with Slip-stacking

Conventional Stacking:



Slip-stacking:



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