Fermilab

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An Upgrade Path toward Multi-MW Beam Power at Fermilab

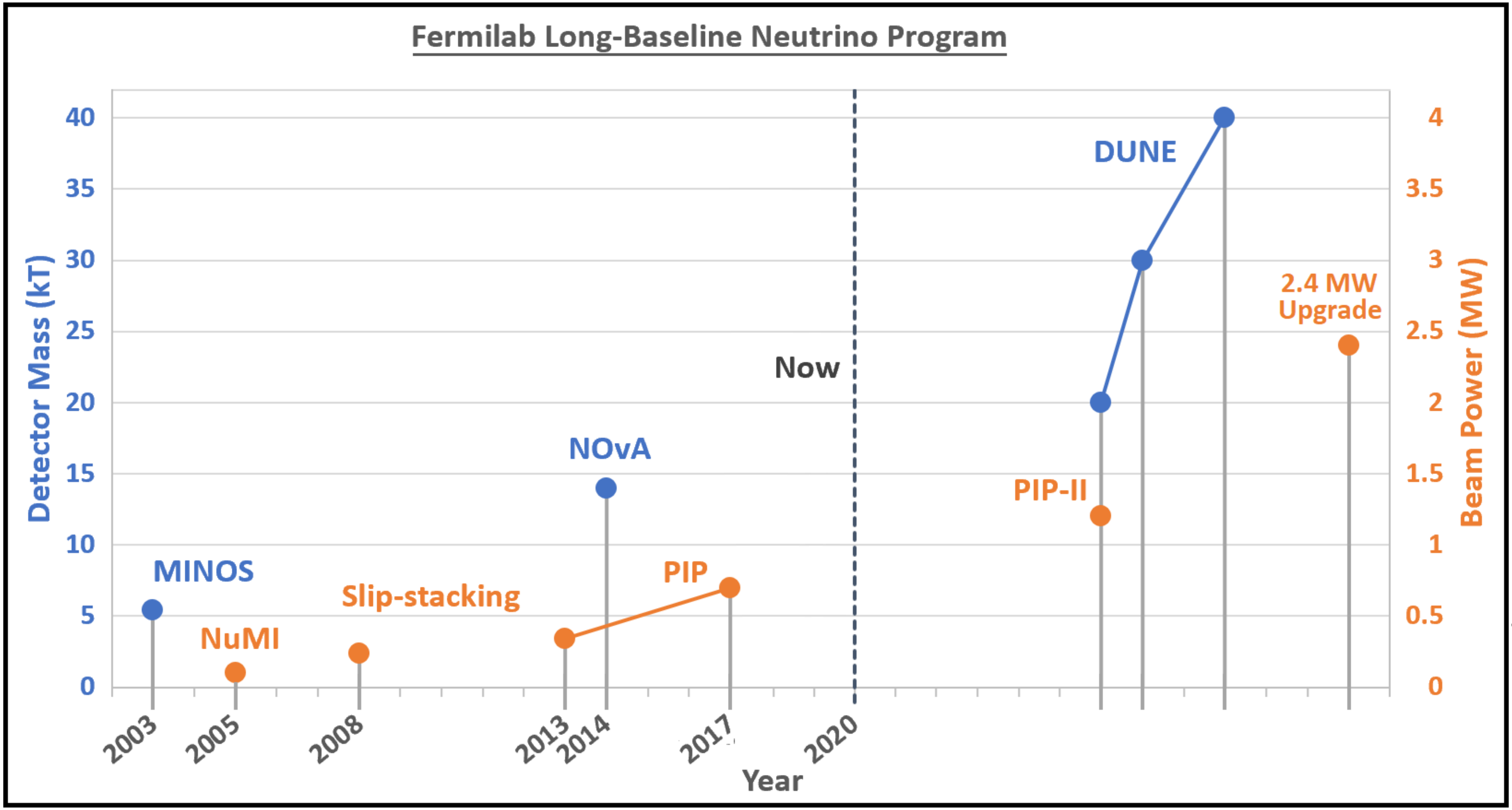
Jeffrey Eldred, for Accelerator Working Group

Scientists Advisory Committee

August 4th 2021

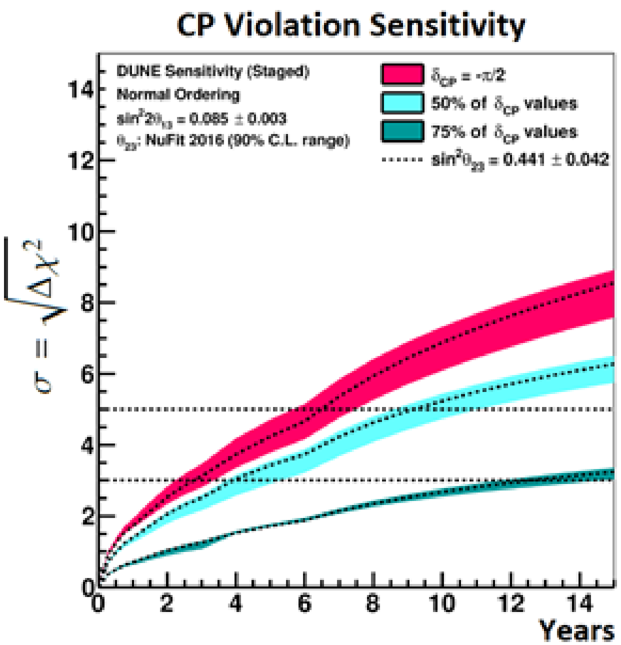
Beam Power and Detector Size

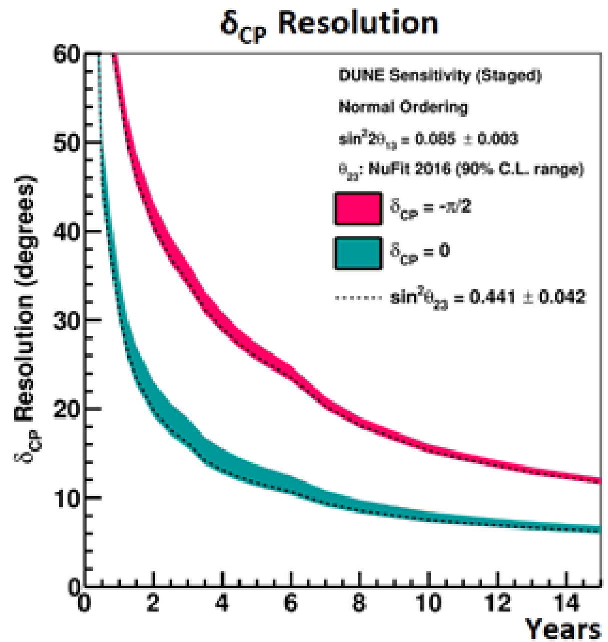
DUNE long-baseline neutrino program calls for **2.4 MW**



J. Eldred, JINST 2019

DUNE Physics, with 2.4 MW at 6 years

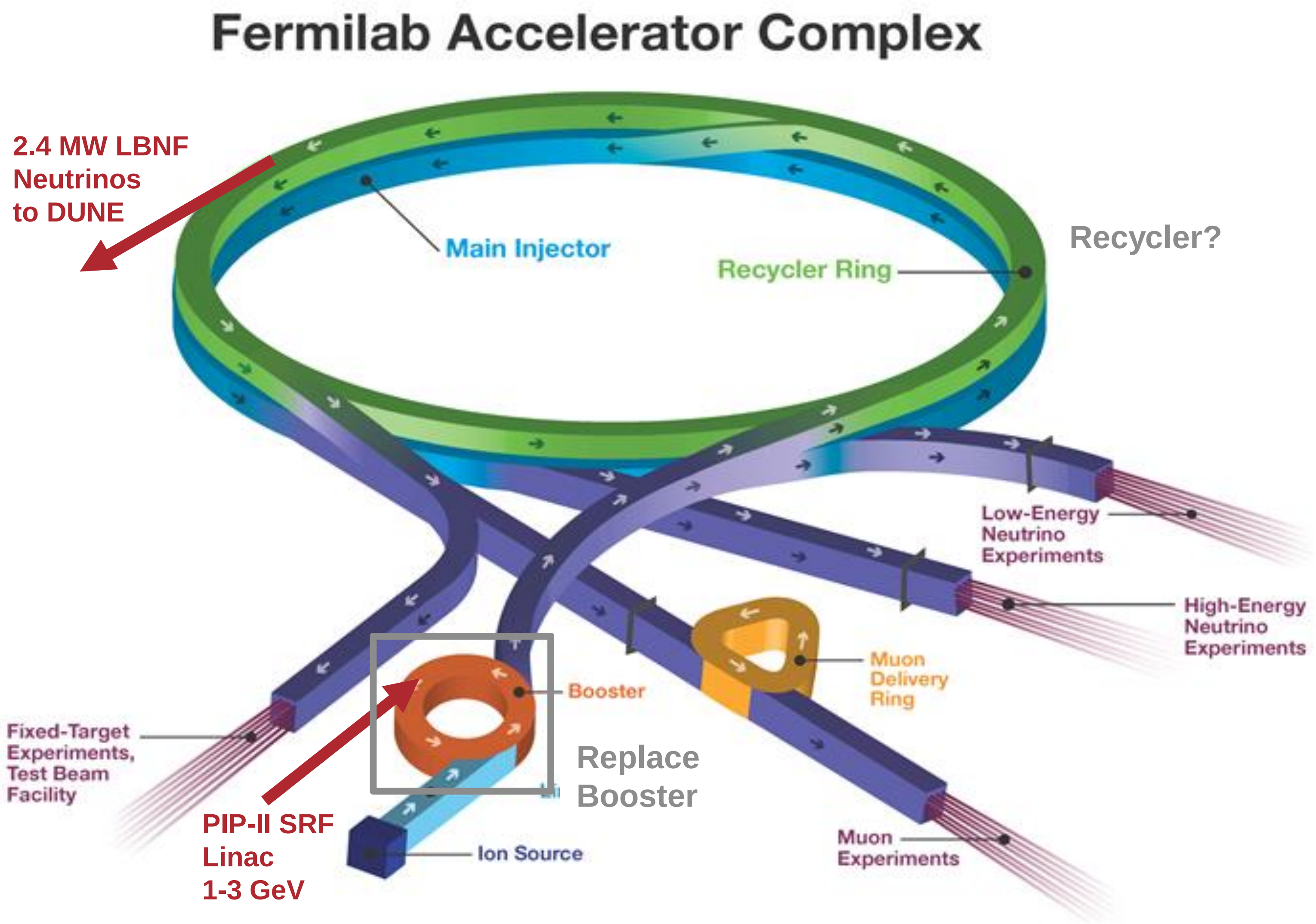




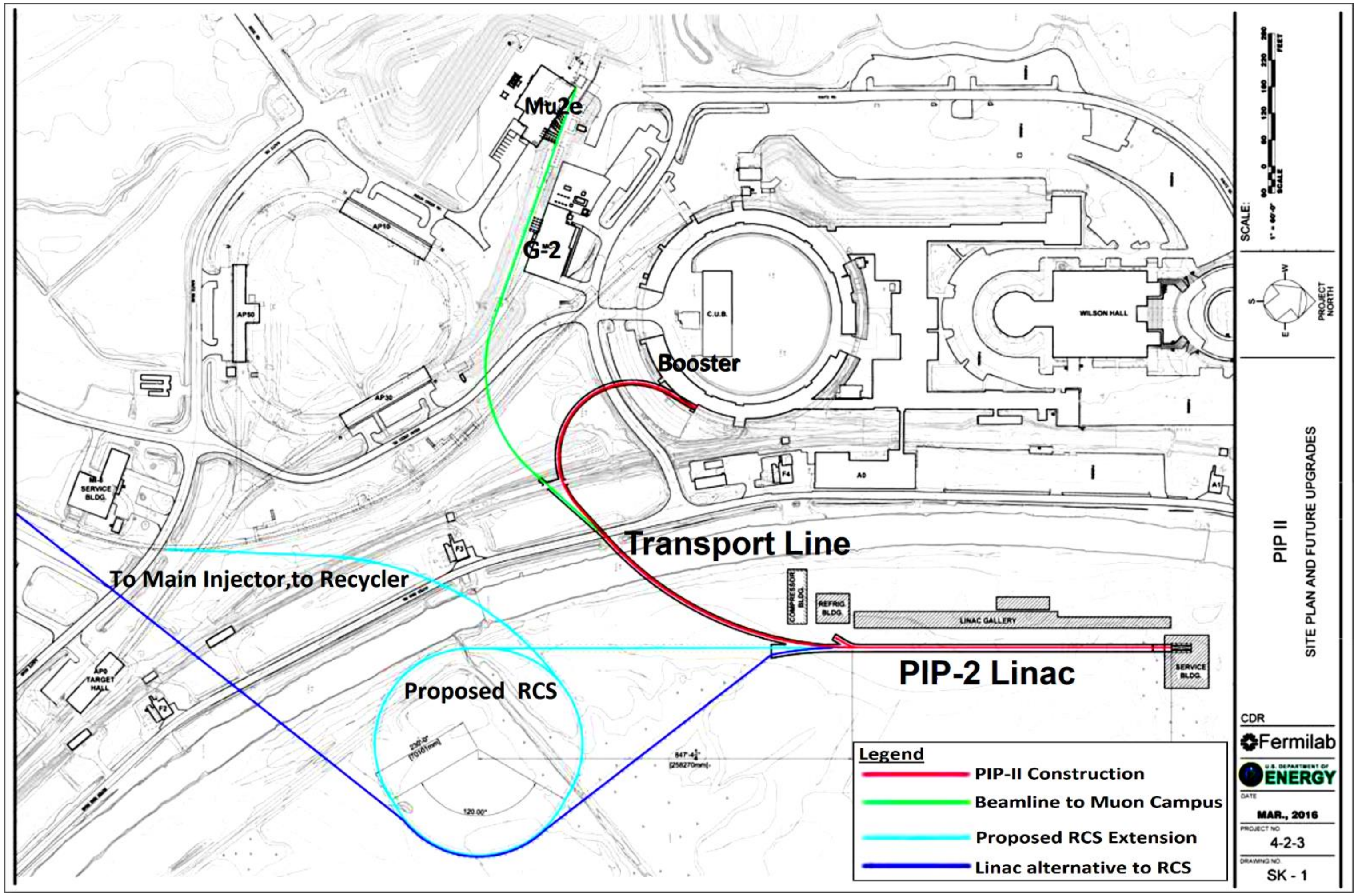
DUNE TDR, 2018

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

Fermilab Upcoming Upgrades Future 2.4MW

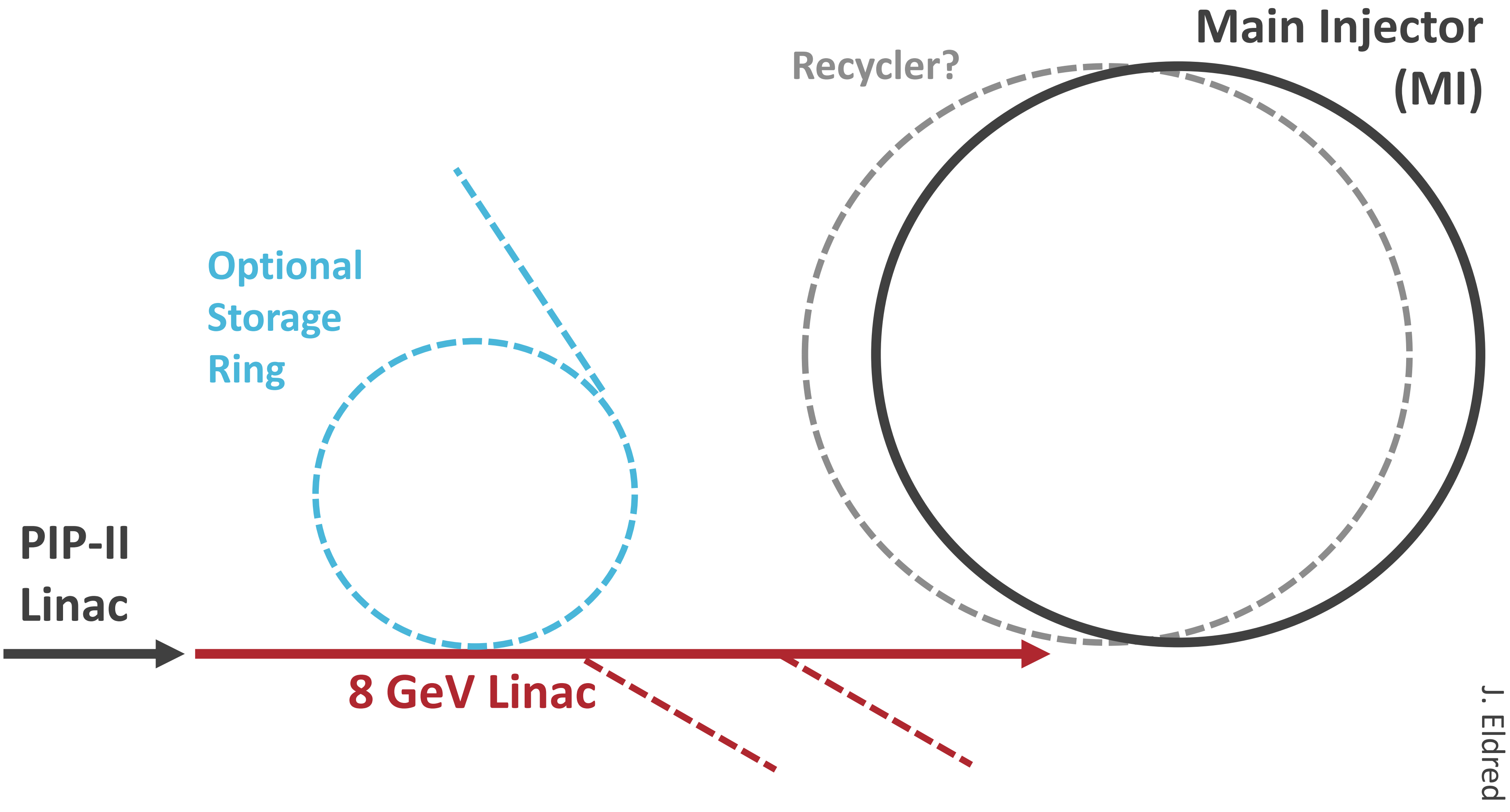


2.4 MW Upgrade: Build RCS and/or Linac to 8 GeV

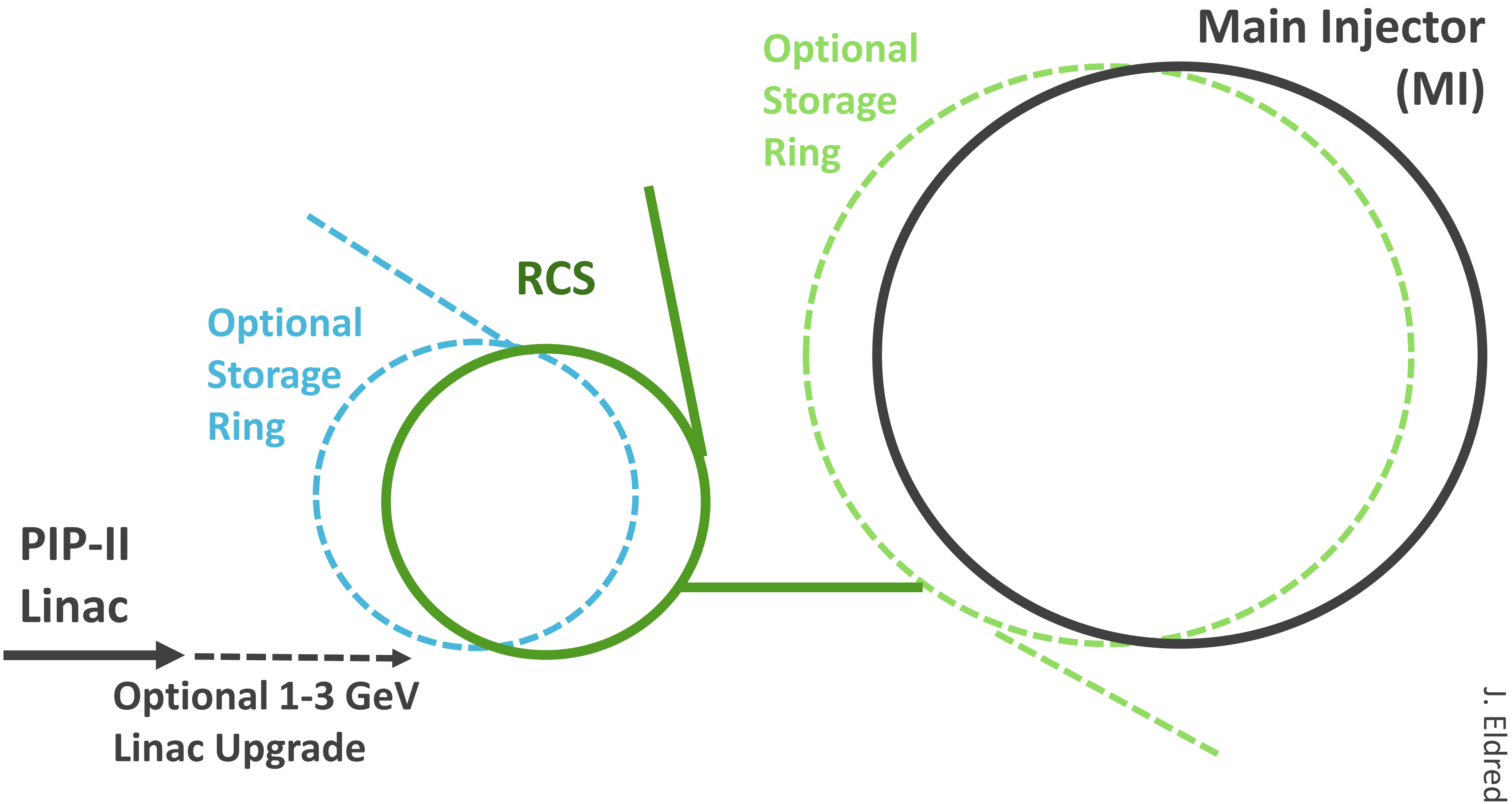


(Linac and RCS not to scale)

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

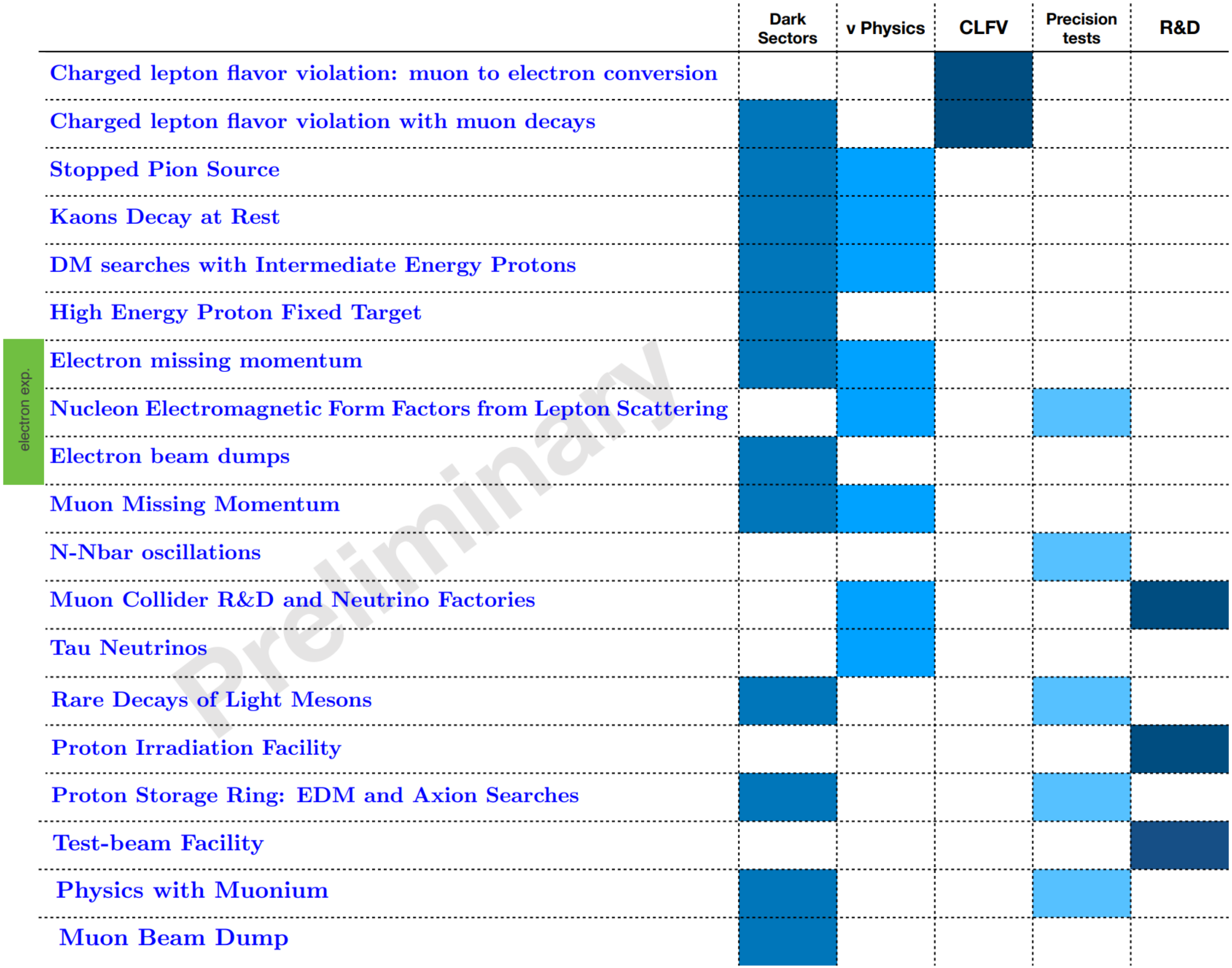
Abstract

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



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.

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

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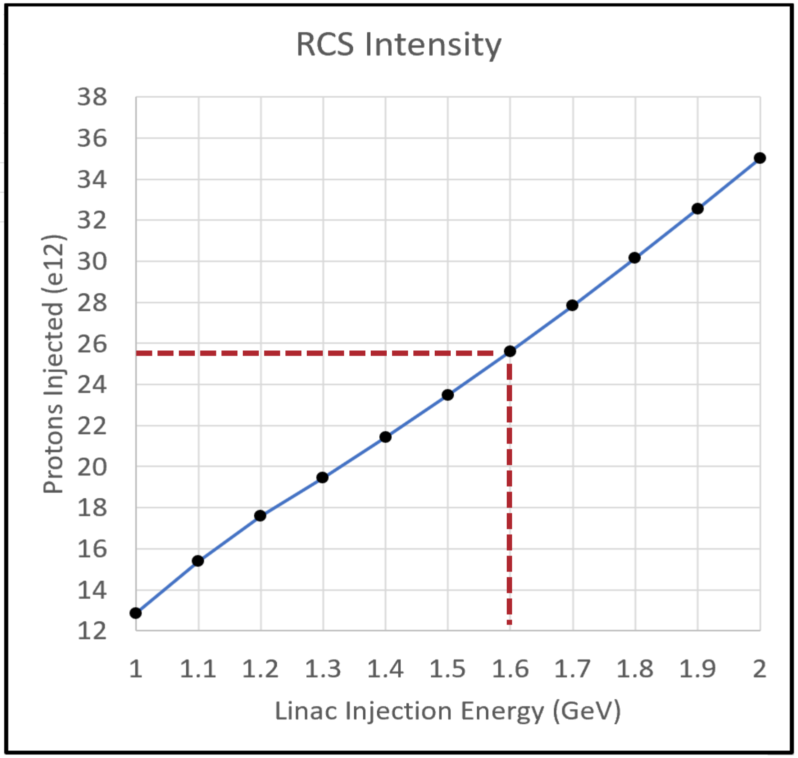
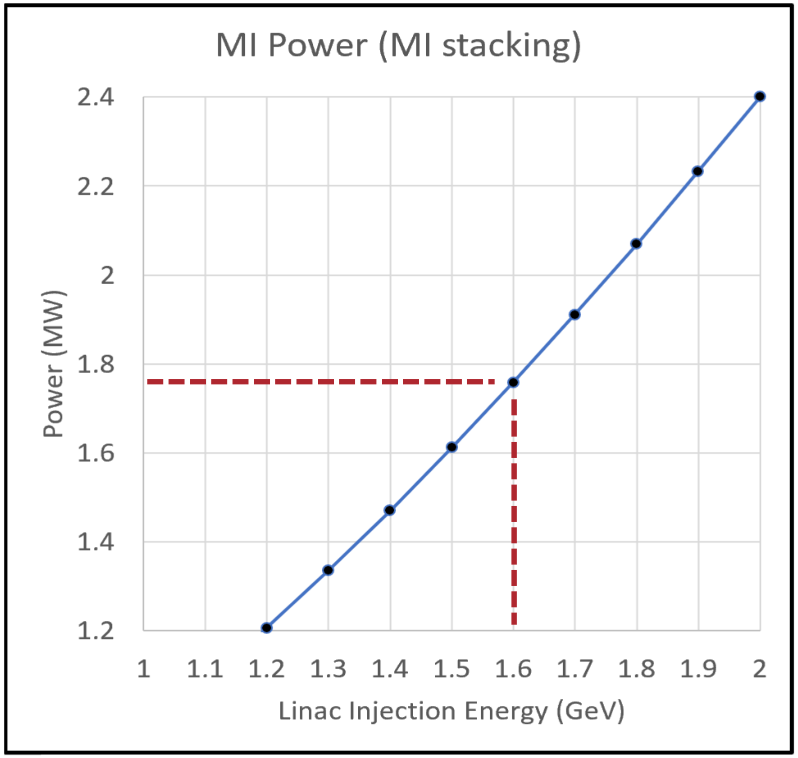
Staging RCS with partial upgrade of Linac & MI





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.

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.
- proposing a 2 GeV accumulator ring.
- provides path to 4 MW upgrade of DUNE/LBNF.
- these details can be revisited without changing the bottom line.

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

Next Steps

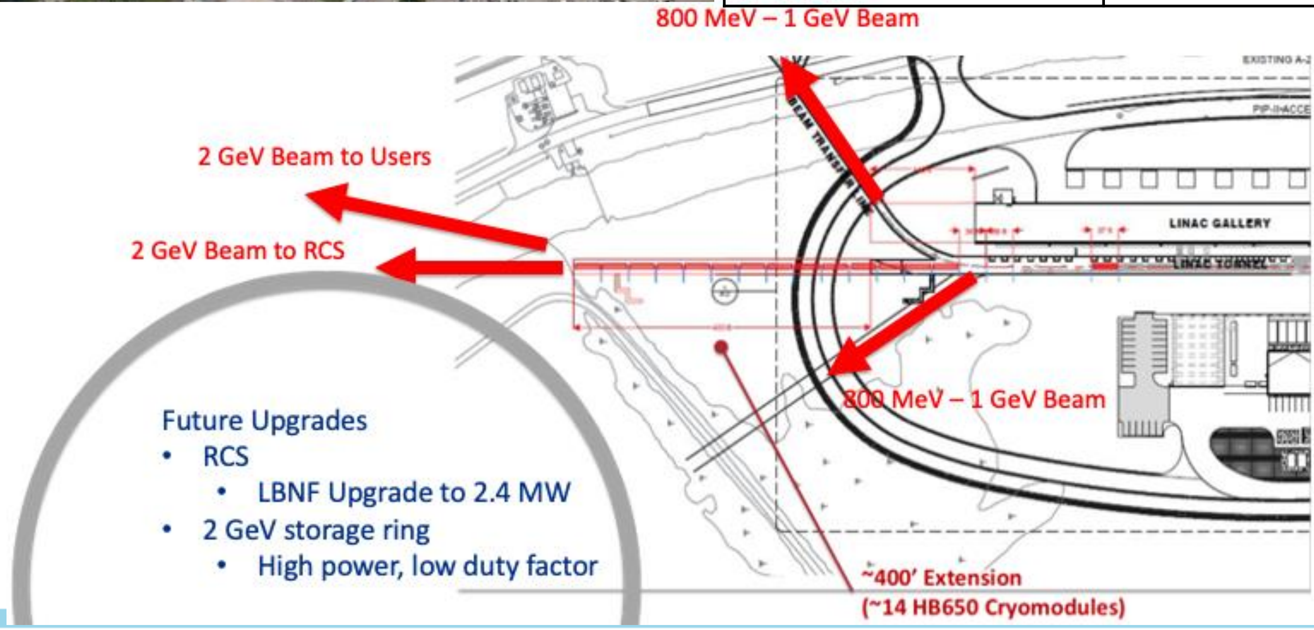
Feedback on physics prioritization and experiment siting from Snowmass.

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

Backup (Facility Design)

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

Rapid Cycling Synchrotron (RCS)

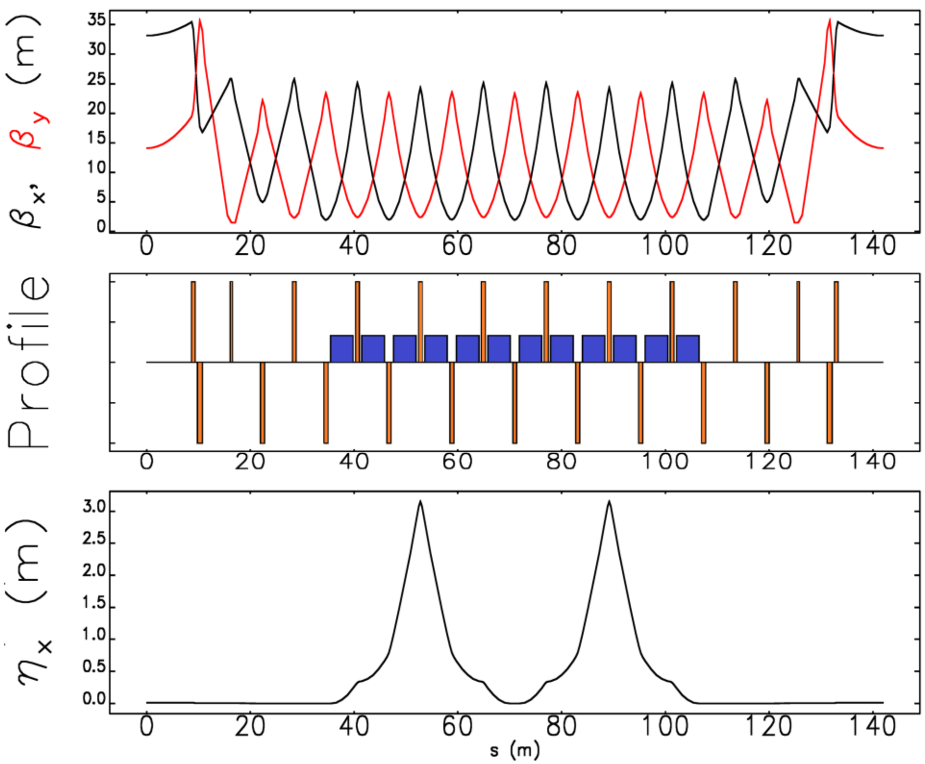
The RCS would operate at 20 Hz and accelerate from 2 to 8 GeV

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

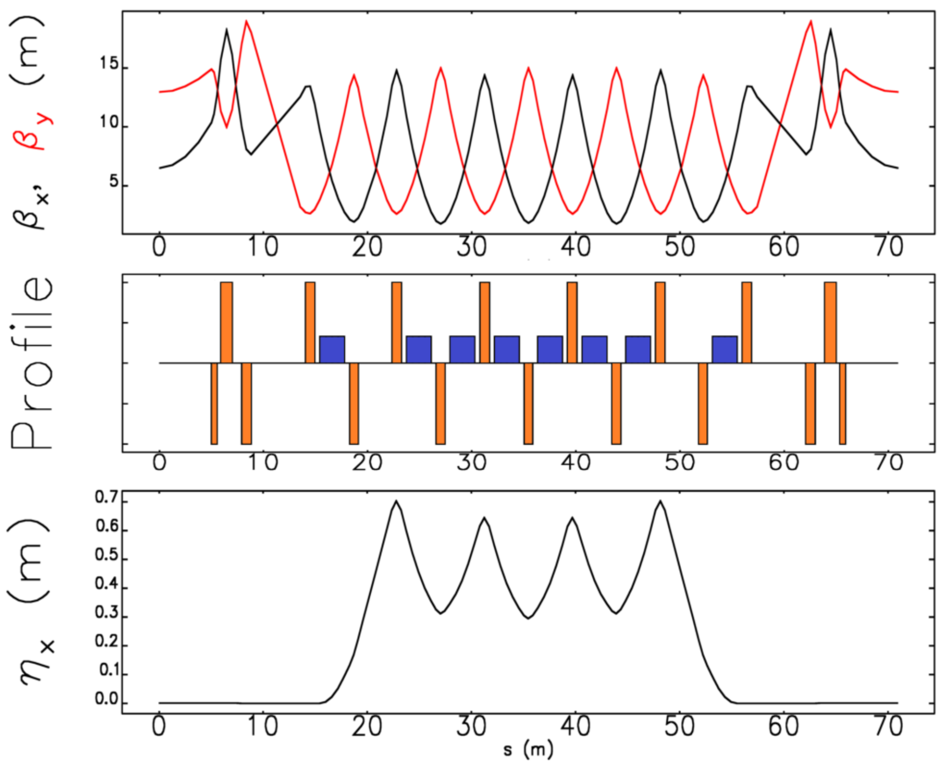
Preliminary RCS Lattice Configurations

2 GeV Injection Ring,
one of four periods



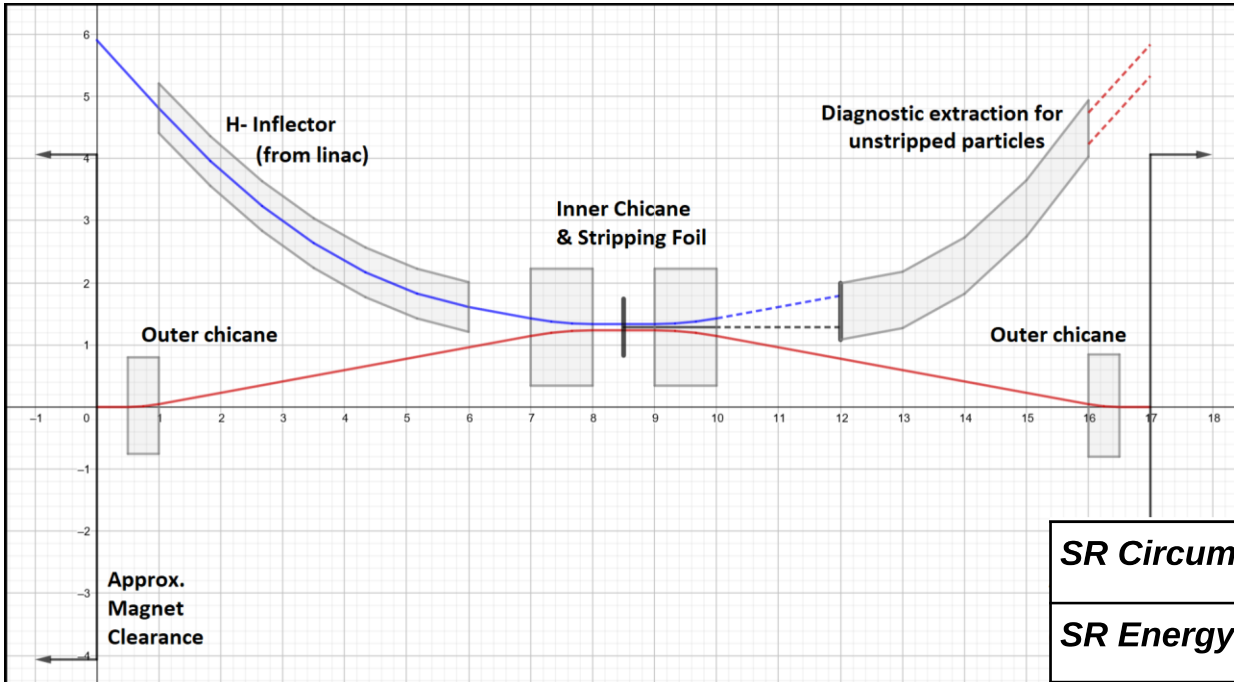
2 GeV Ring Optimized for Injection

2 - 8 GeV RCS Ring,
one of eight periods



8 GeV Ring Optimized for Acceleration

Beam Accumulation and H- Stripping in a Storage Ring



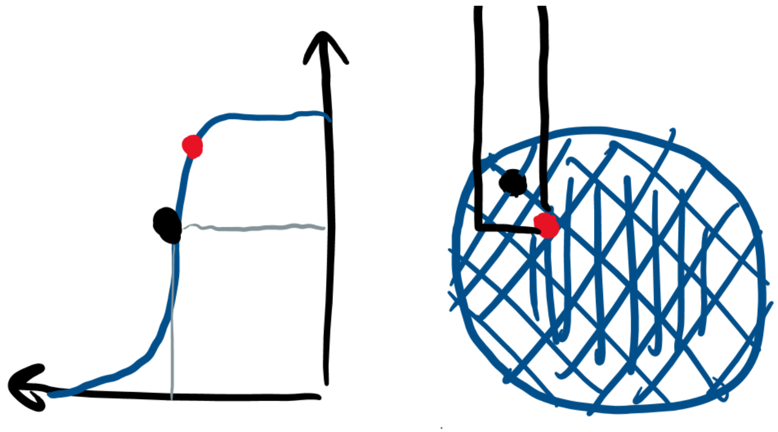
SR Circumference	***570***	***m***
SR Energy	***2***	***GeV***
Superperiodicity	***4***	
Injection Insertion Length	***12***	***m***
Dipoles per Superperiod	***12***	
Dipole Strength	***<0.4***	***T***

H- Foil Stripping Injection

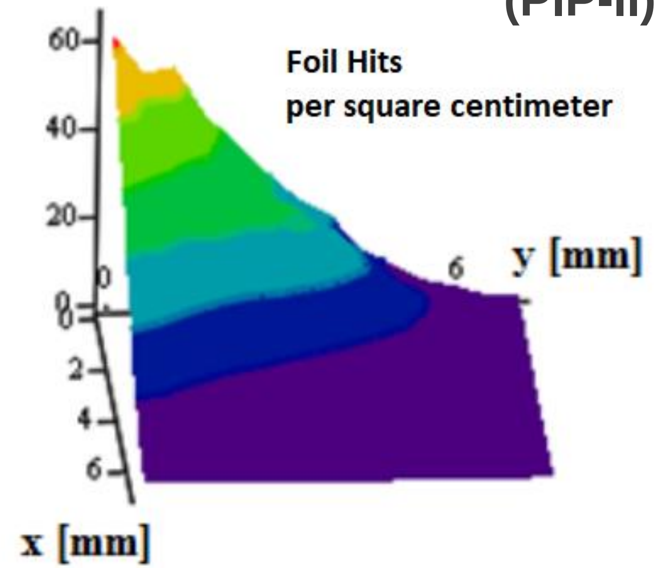
17 m straight.

Anti-Correlated Painted Injection

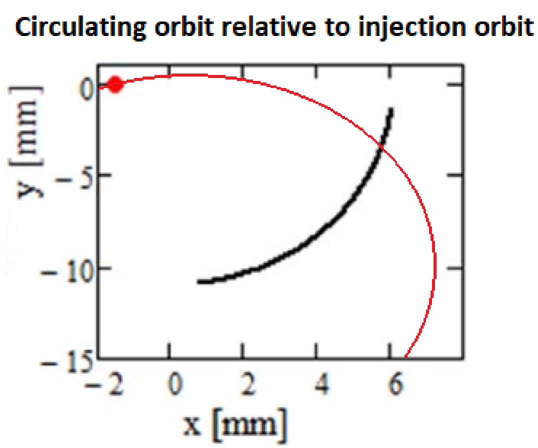
Beam Distribution during Injection



Peak Temperature on corner (PIP-II)



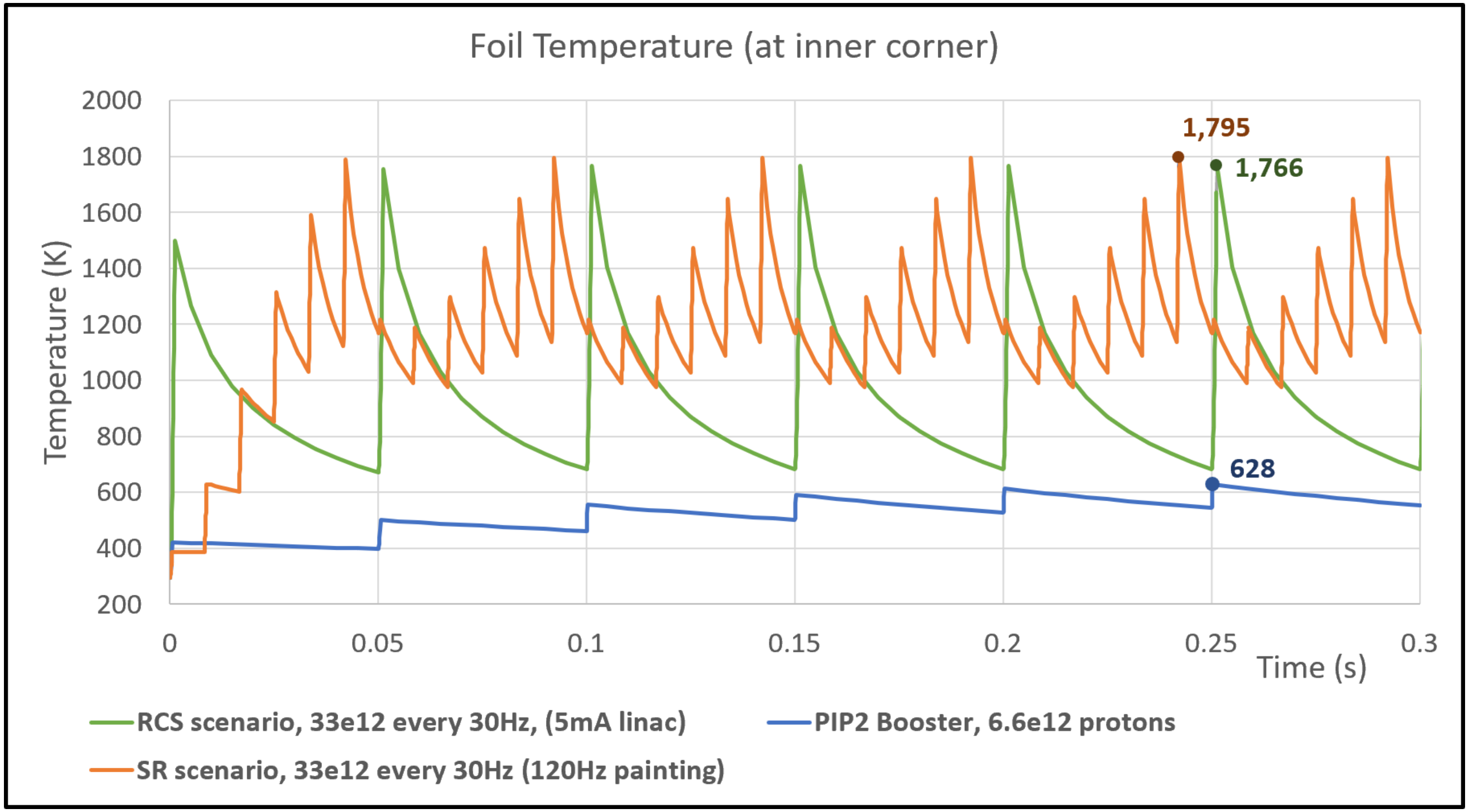
Anti-correlated Painting Injection



Injection painting scheme chosen to:

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

Beam Accumulation and H- Stripping in a Storage Ring



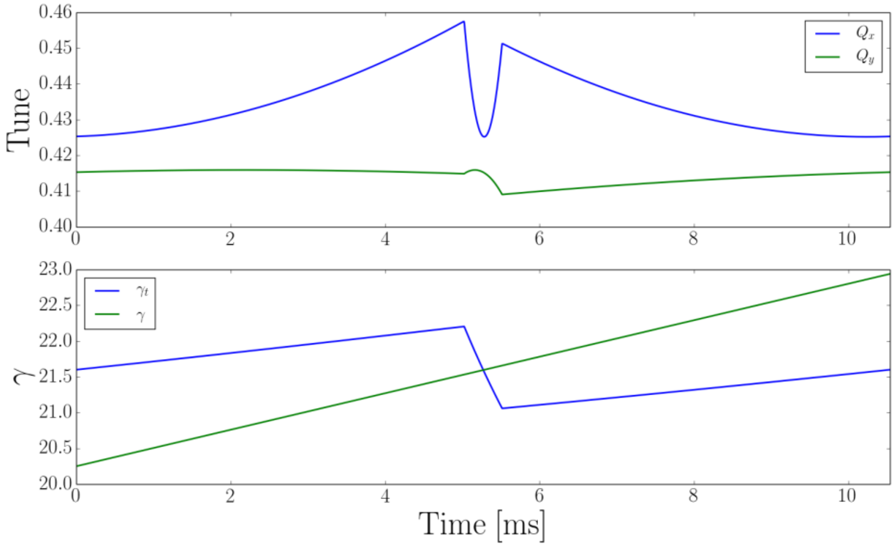
Scenario 1: Retrofit PIP-II linac to 5mA pulsed.

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

Main Injector Operations

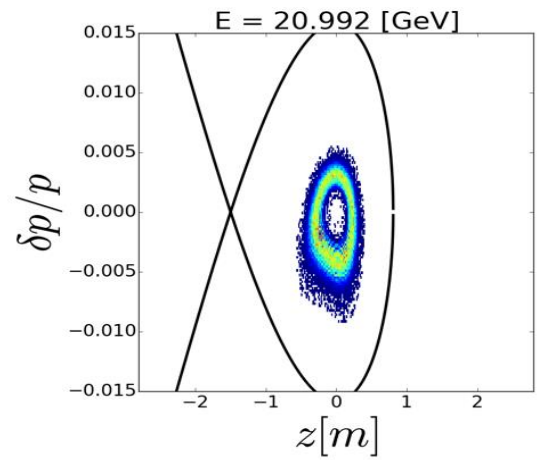
Keep 8 GeV injection into MI, re-using portions of Recycler as injection line

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)

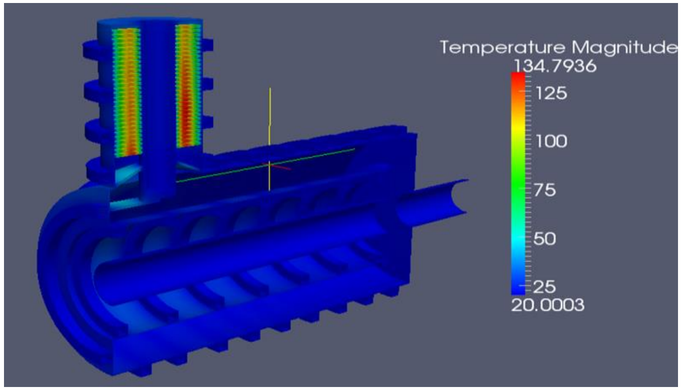
R. Ainsworth, I. Kourbanis

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*	

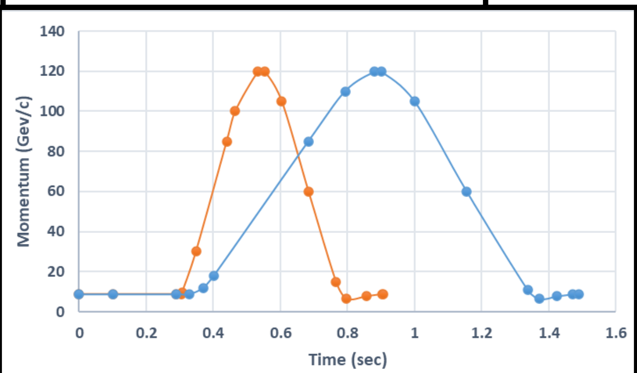


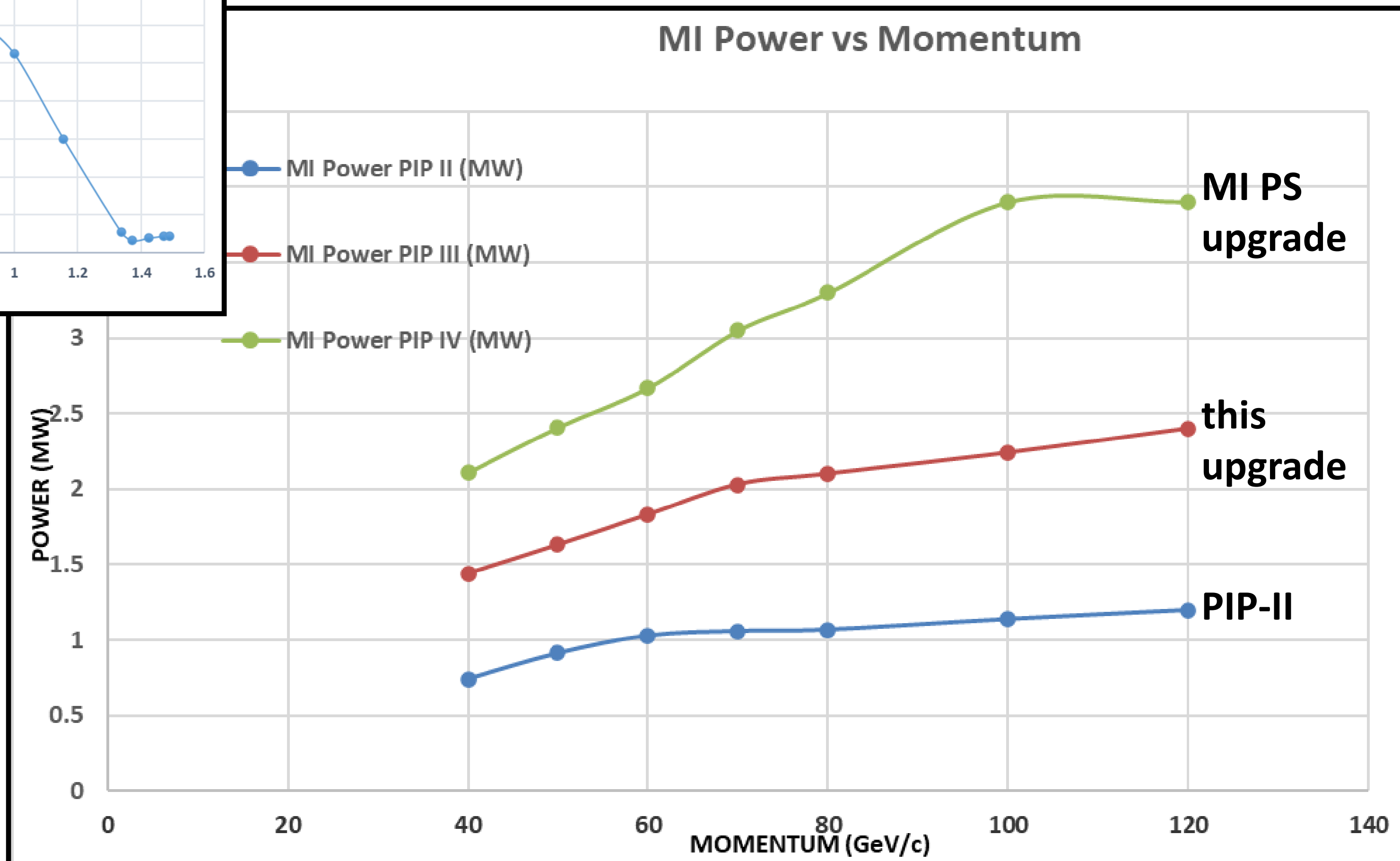
I. Kourbanis

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:

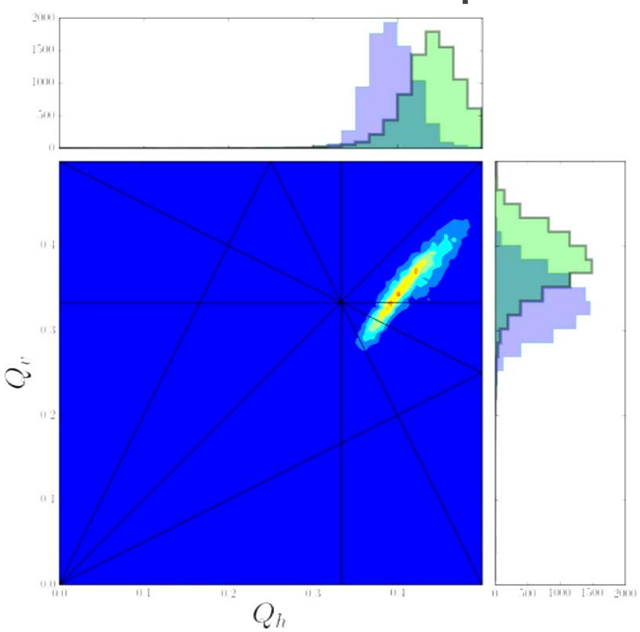
- reliability and cost for ceramics, metallization, brazed-flanges.

Backup

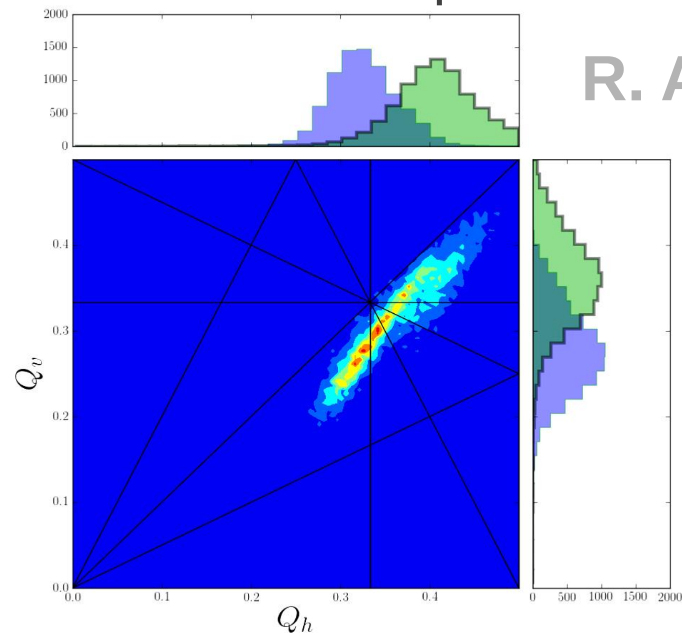
Recycler Intensity Challenges

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.

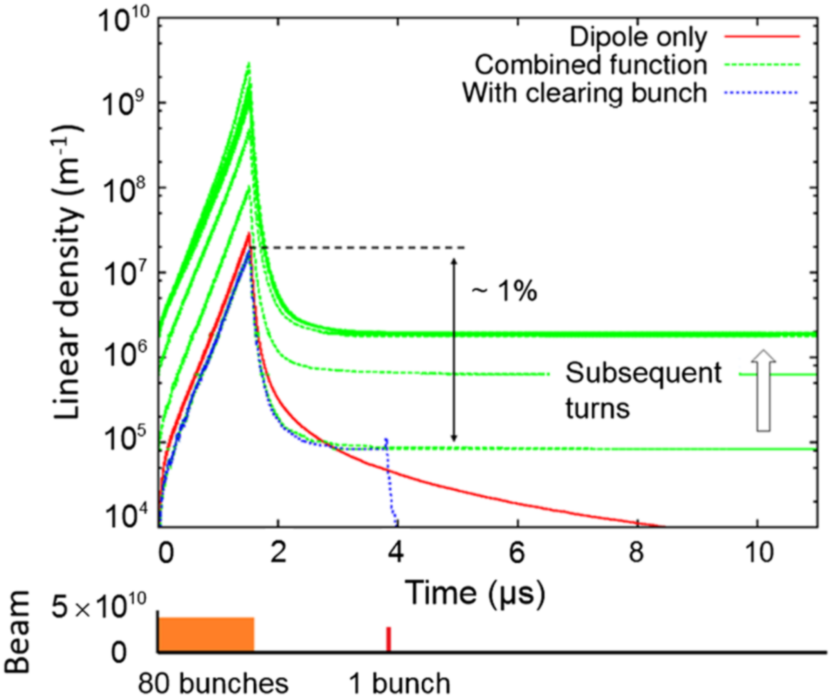
How well can we compensate the resonances lines?

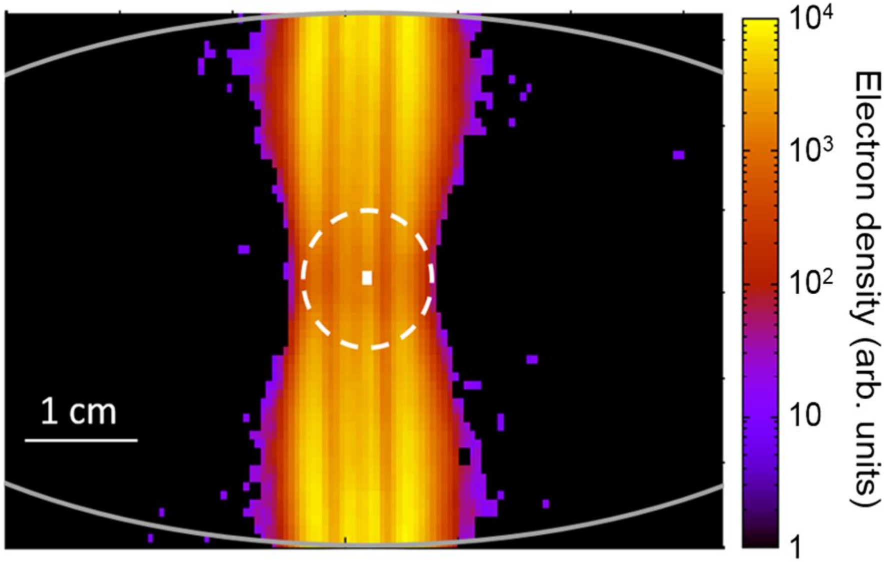
Recycler Intensity Challenges

Tight Aperture Losses:

Aperture limits RCS normalized emittance

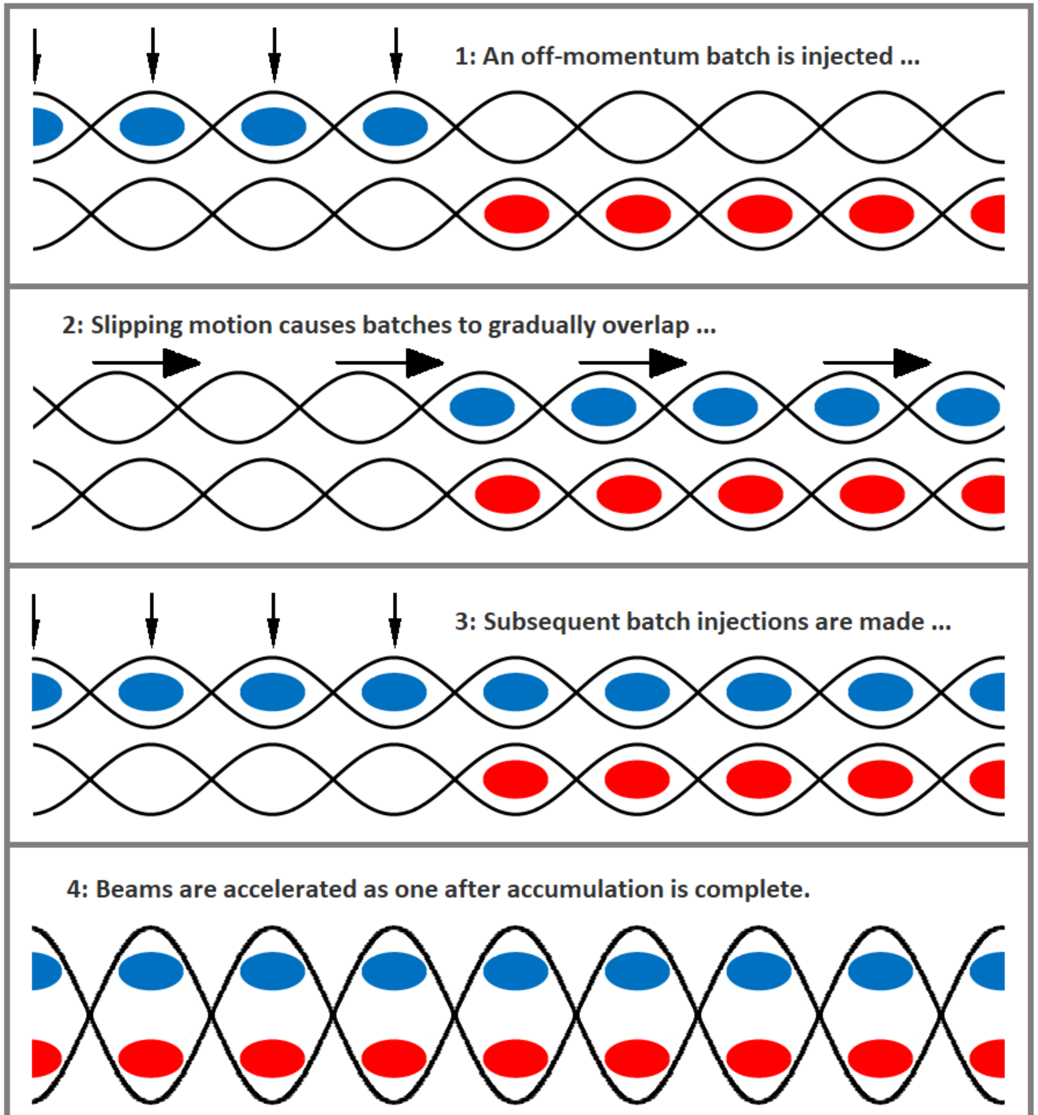
Electron Cloud Instability:





S. Antipov et al. PRSTAB 2017

Slip-stacking Accumulation



RF frequency separation:

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

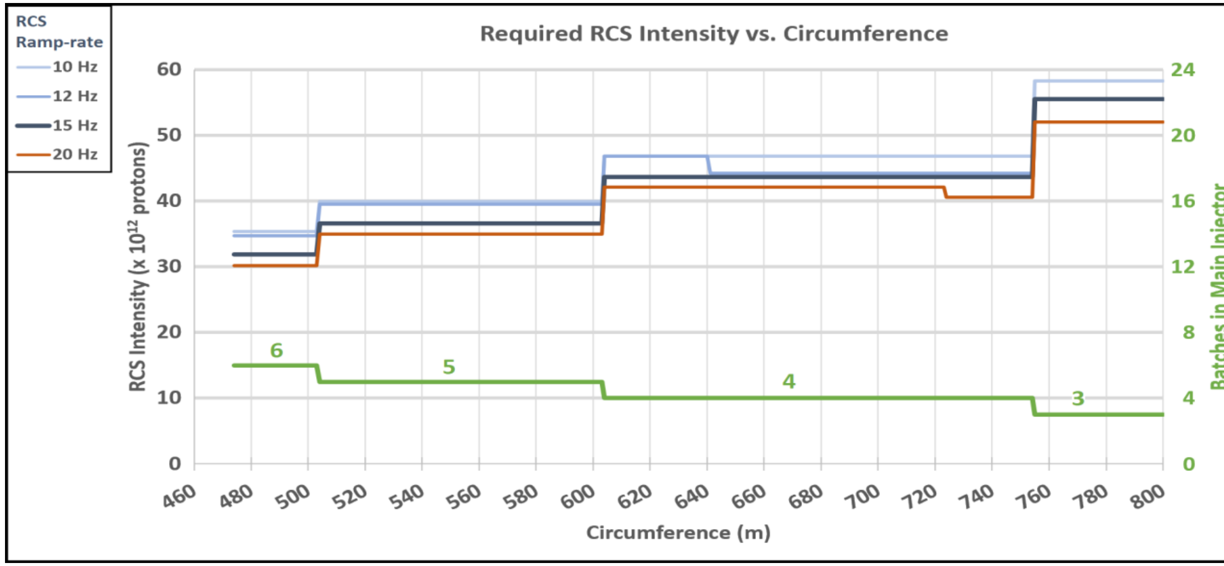
$$\Delta f = \left(h_{\mathrm{Booster}} \frac{C_{\mathrm{RCS}}}{C_{\mathrm{Booster}}} \right) f_{\mathrm{RCS}}$$

Momentum separation:

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

2.4 MW with Slip-stacking

Conventional Stacking:



Slip-stacking: