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High-Intensity Performance and Limits in the Fermilab ~~Main Injector and~~ Recycler

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U.S. DEPARTMENT of ENERGY

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Outline

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  - Recycler
- Slip-stacking
- Space charge
- PIP-II upgrades
- Resonance correction efforts
- Summary & Questions

Mitigation of third-order resonances in the Fermilab Recycler Ring

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Introduction

The FNAL Accelerator Complex delivers high intensity beam for Neutrino Experiments

Goal: As many protons as possible while keeping losses to acceptable levels

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Fermilab Accelerators

H- linac

- 35 kV source, 750 kV RFQ, 400 MeV linac ~20mA

Booster synchrotron

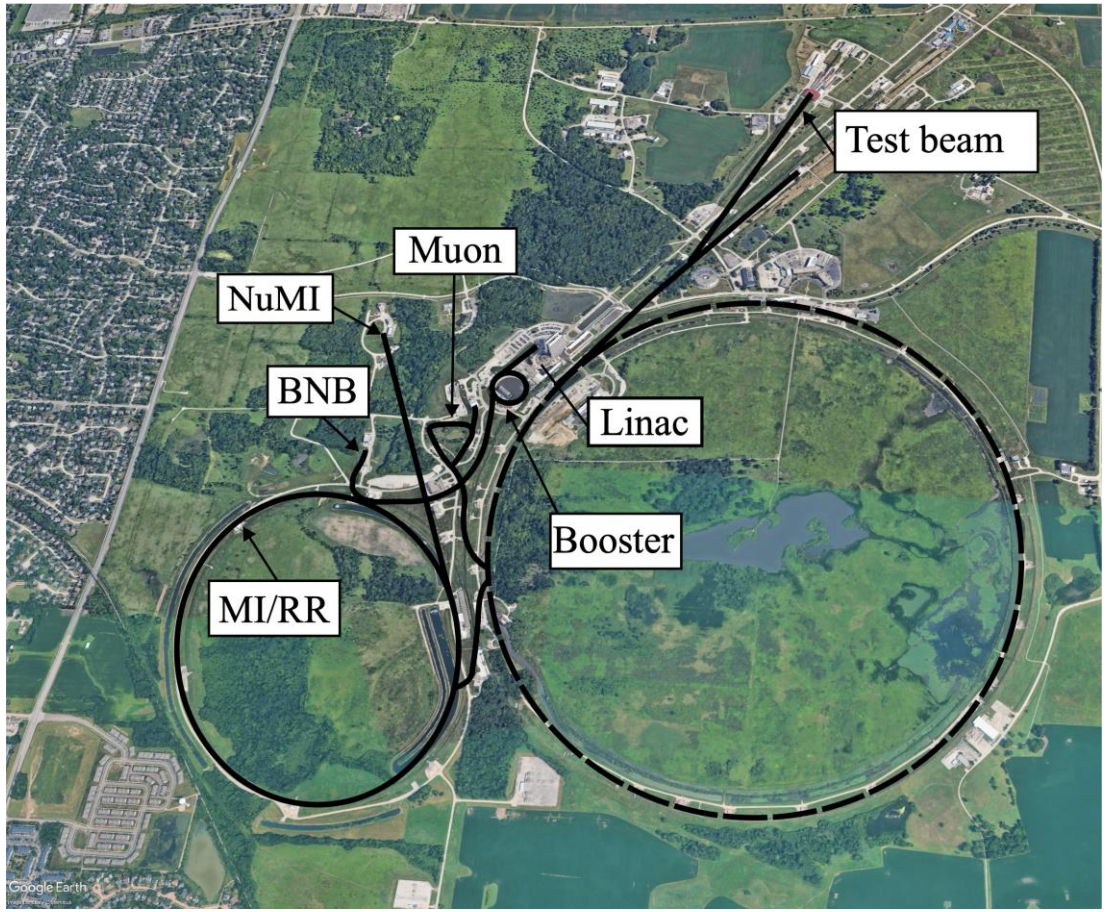
- H- stripping injection, ~16 turns to ~4.7E12 p
- 0.4 to 8 GeV at 15 Hz
- h=84

Recycler

- 3.3 km (h=588) permanent magnet 8 GeV ring
- Slip-stacking 12 Booster batches, ~56e12 p

Main Injector

- 8 to 120 GeV ramp in 1.067 s

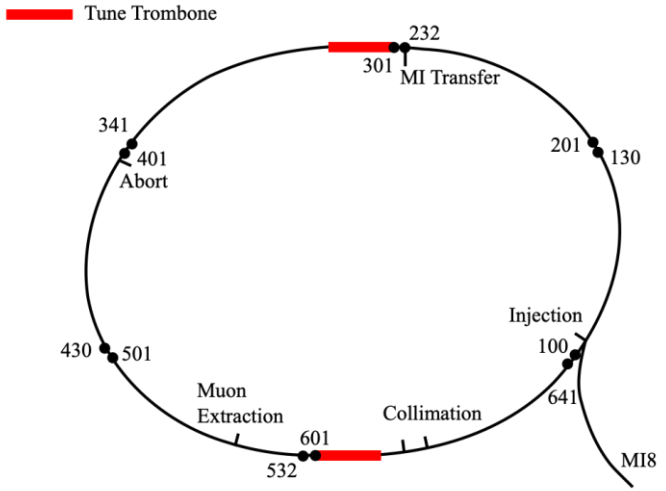


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Recycler

- Permanent magnet machine
- Shares enclosure with Main Injector
- Operates below transition
- Bare machine has super periodicity of 2

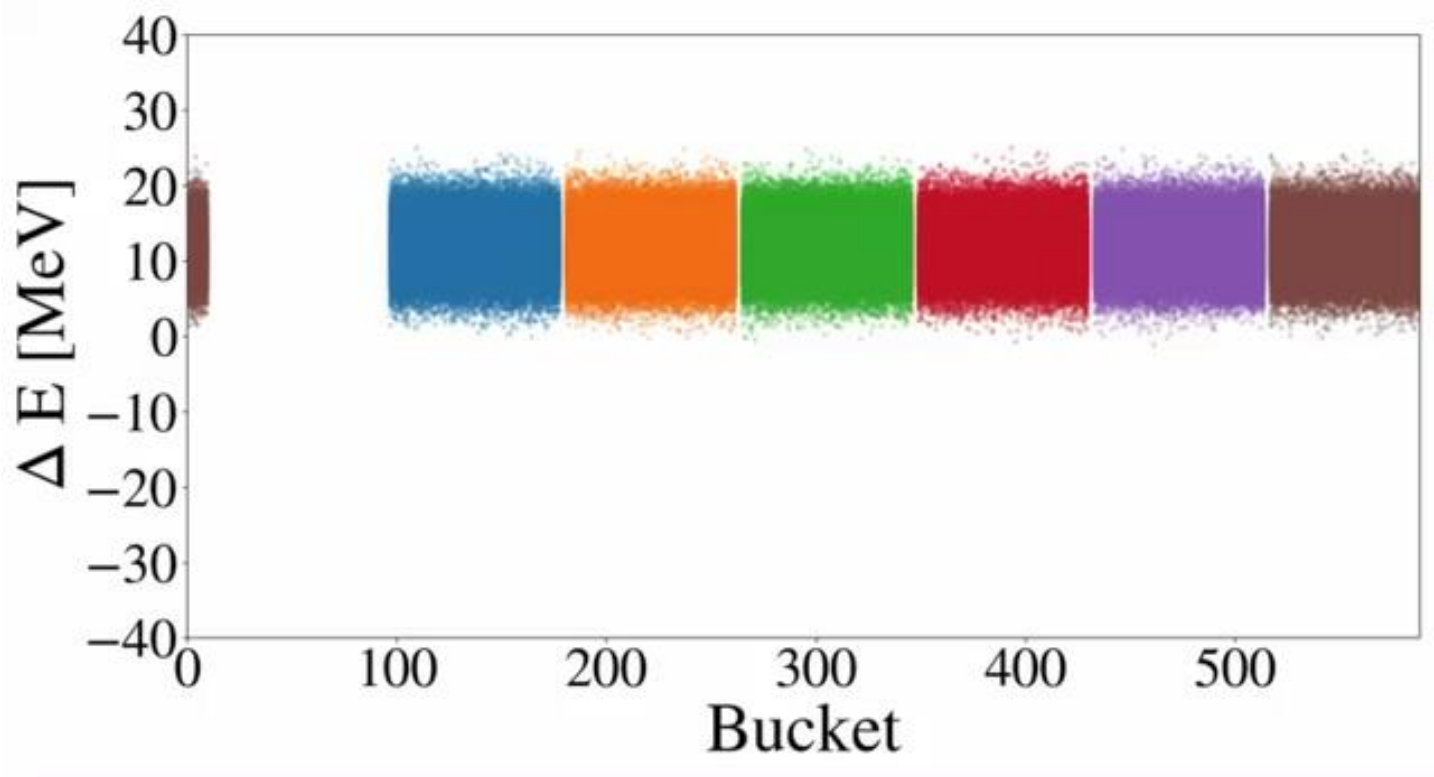




Parameter	Value	Unit
Circumference	3319.4	m
Momentum	8.835	GeV/c
Revolution period	11.1	μs
Revolution frequency	89.6	kHz
rf frequency	52.8	MHz
rf voltage	80	kV
	140 (PIP-II)	kV
Harmonic number	588	
Synchrotron tune	0.0028	
	0.0038 (PIP-II)	
Slip factor	-8.6×10^{-3}	
Superperiodicity	2	
Horizontal tune	25.43	
Vertical tune	24.445	
Horizontal chromaticity	−6	
Vertical chromaticity	−7	
Transverse acceptance	40	π mm mrad
95% normalized emittance	15	π mm mrad
95% longitudinal emittance	0.08	eV s
rms $\delta p/p$	0.0004	
Intensity	5×10^{10}	ppb
	8×10^{10} (PIP-II)	ppb
MI ramp time	1.2	s
	1.133	s
	1.067	s
Booster frequency	15	Hz
	20 (PIP-II)	Hz

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Slip-stacking

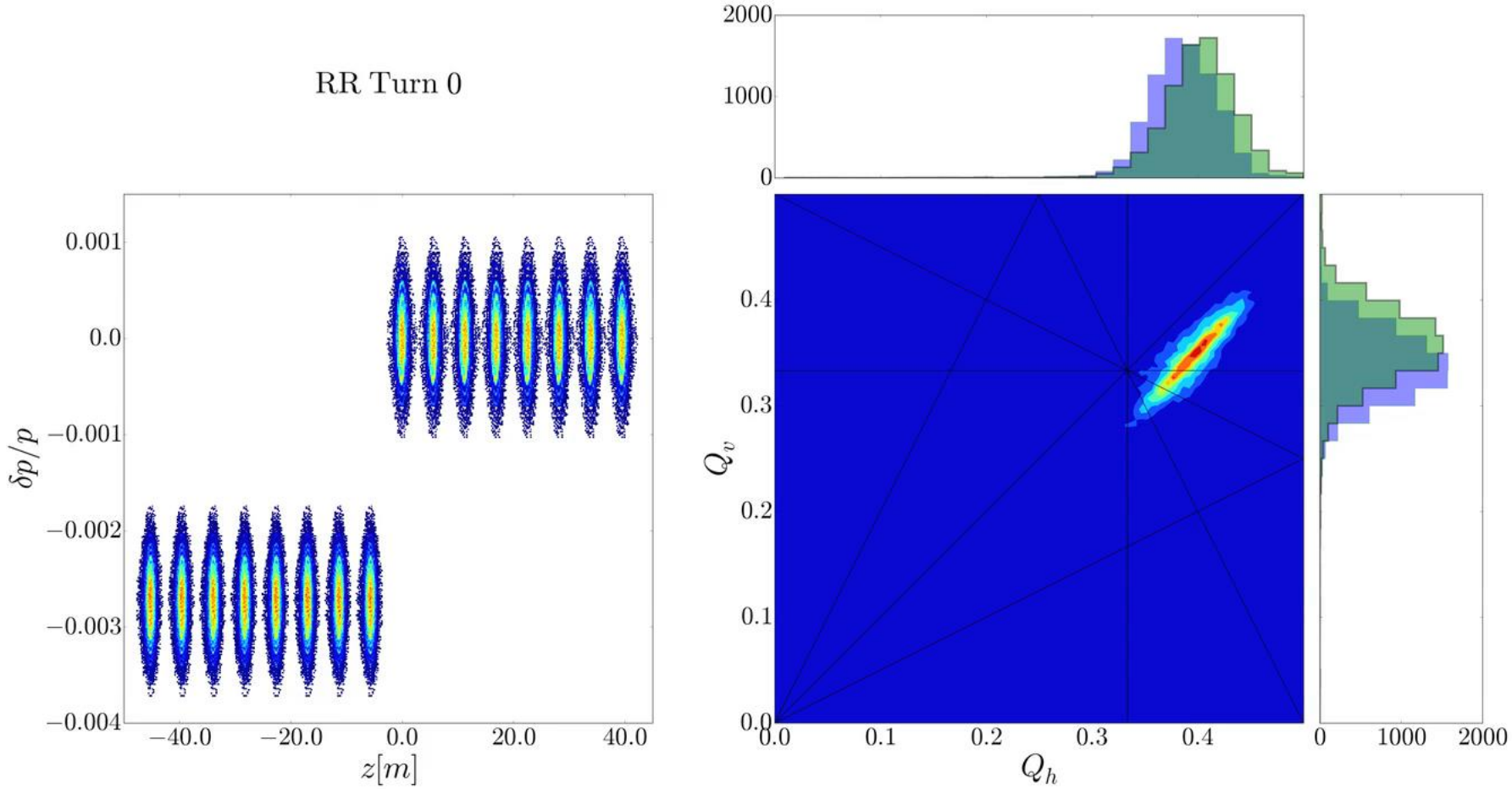


Separation between batches is set by Booster harmonic number 84 multiplied by Booster frequency

1260 Hz for 15 Hz -> 24 MeV

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Tune footprint during slip-stacking



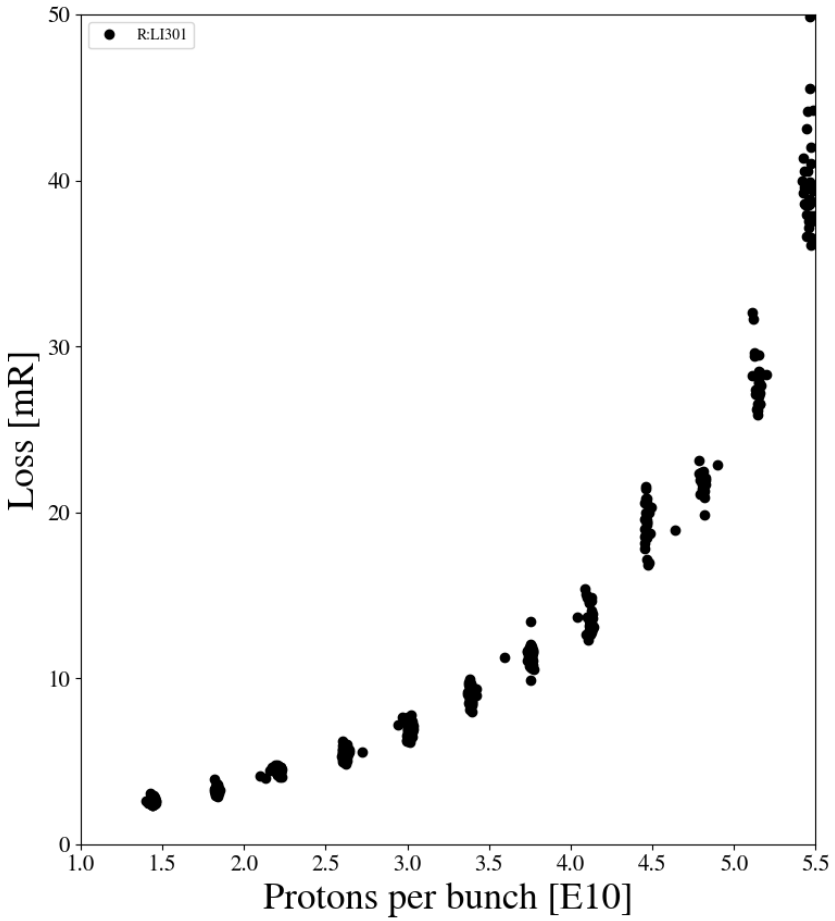
High intensity Slip-stacking operation

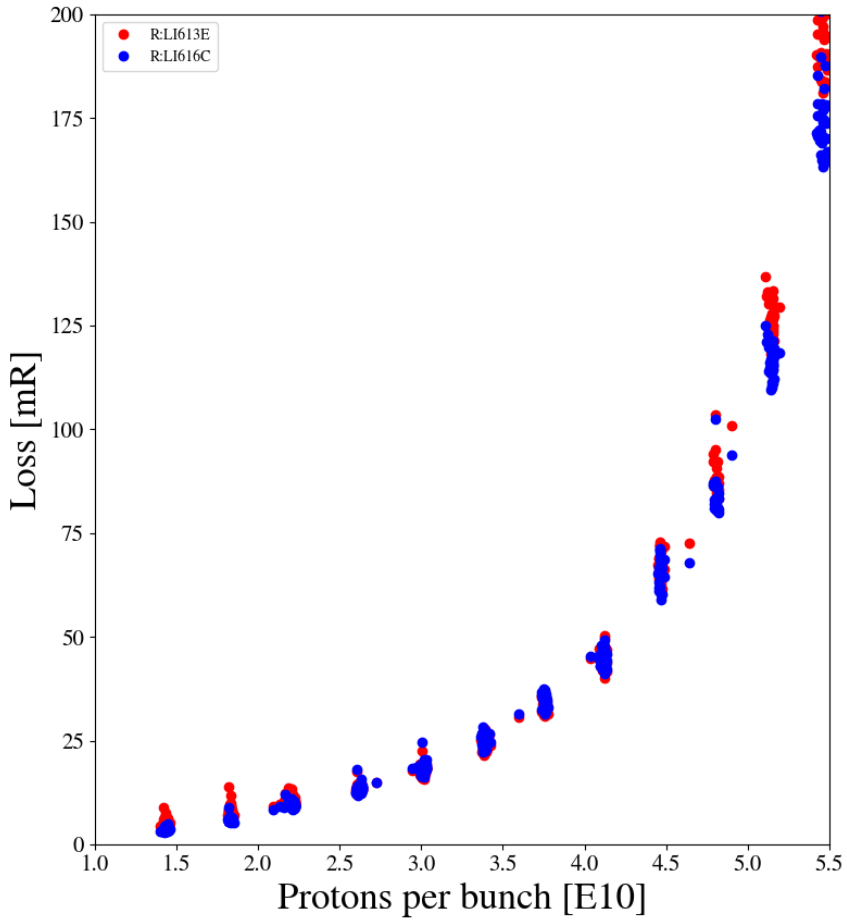
- Modulating tune shift as bunches overlap
- Two co-propagating beams means two footprints
  - Differing momenta means footprints separated by linear chromatic tune shift
    - Momenta are symmetric around 0 dp/p so quadratic terms cancels out
- Operating chromaticity is -6,-7
  - Footprints separated by ~0.02 Limited tune flexibility
  - Tune trombones used to change tune in permanent magnet machine

Is Space charge currently limiting Recycler operations?

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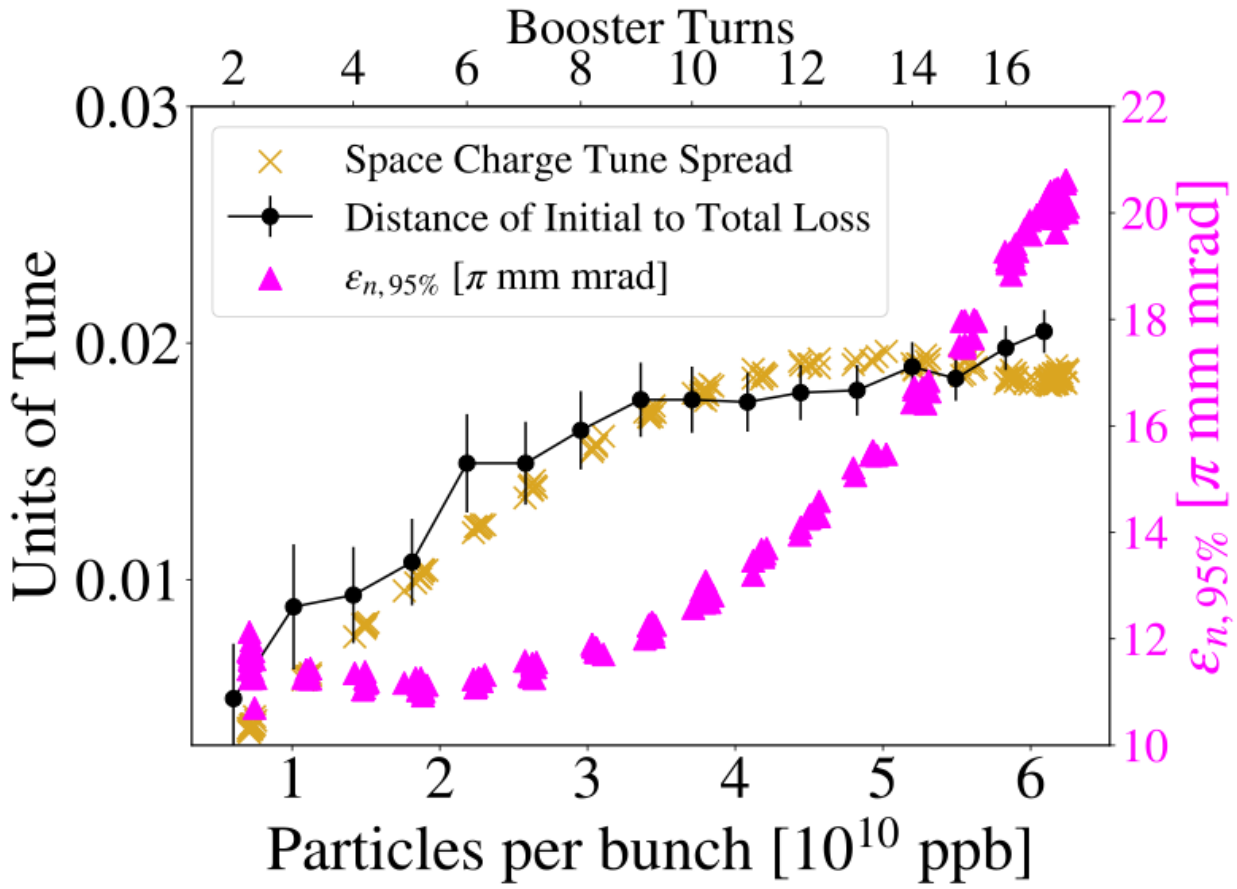
Beam loss is not linear

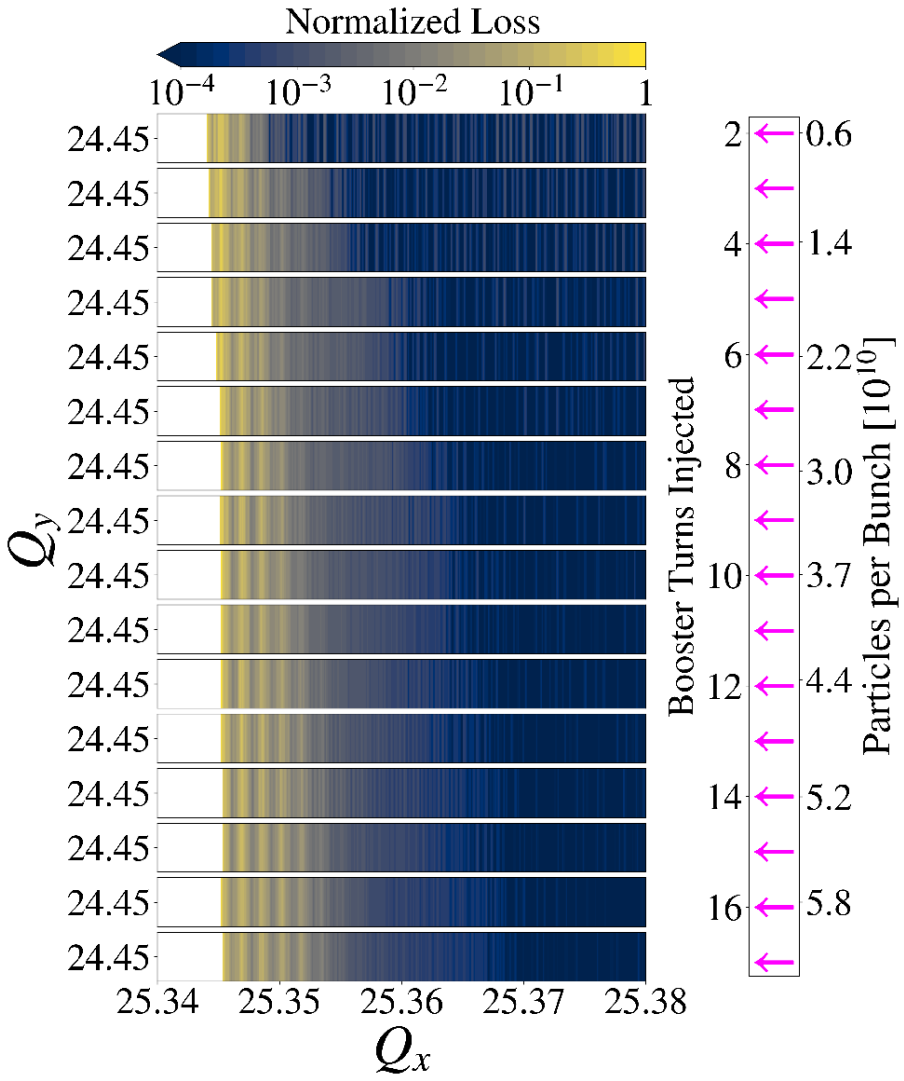




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Injected emittance with intensity

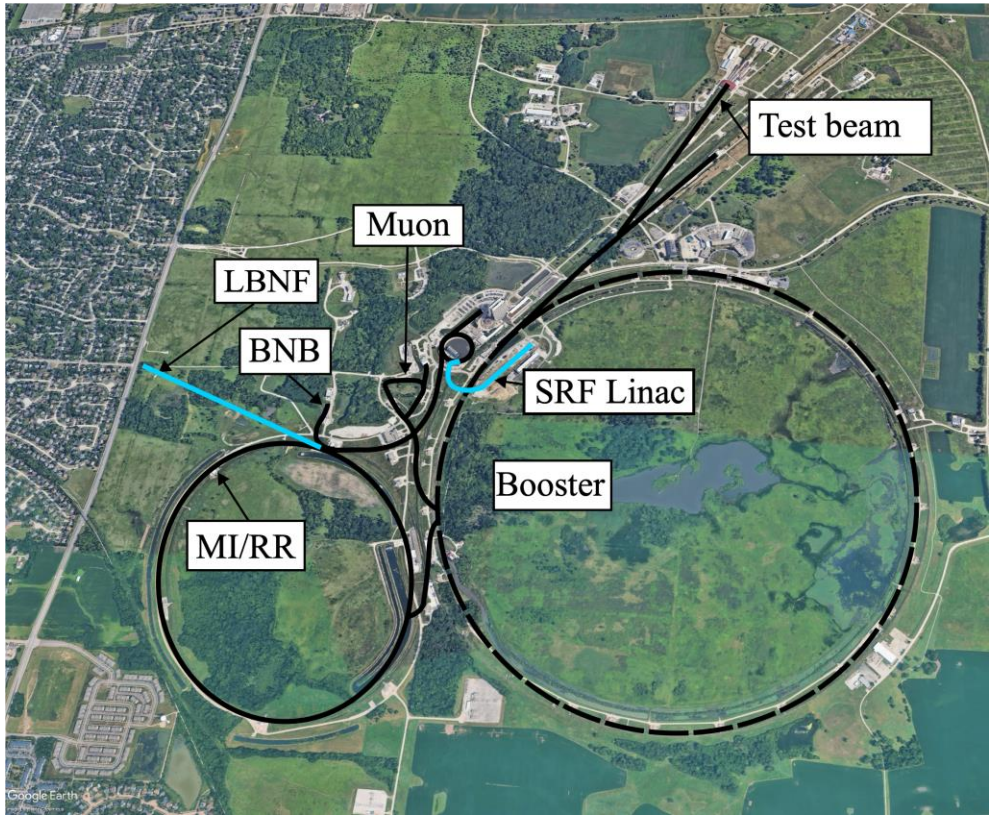




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PIP-II upgrades

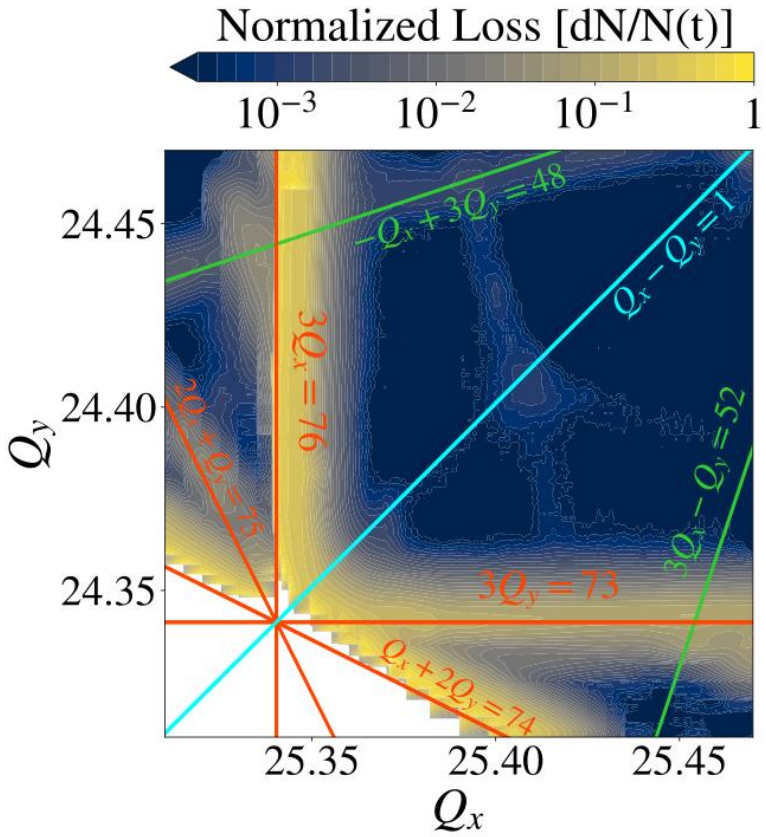
- We're beginning the last high intensity run before a long shutdown
  - PIP-II upgrades
- New SRF linac
- High injection energy into Booster (400 MeV -> 800 MeV)
- Booster 15 Hz -> 20 Hz
  - Bigger slip-stacking separation -> bigger footprint separation
- 50% more beam
- Minimal upgrades for Recycler & Main Injector

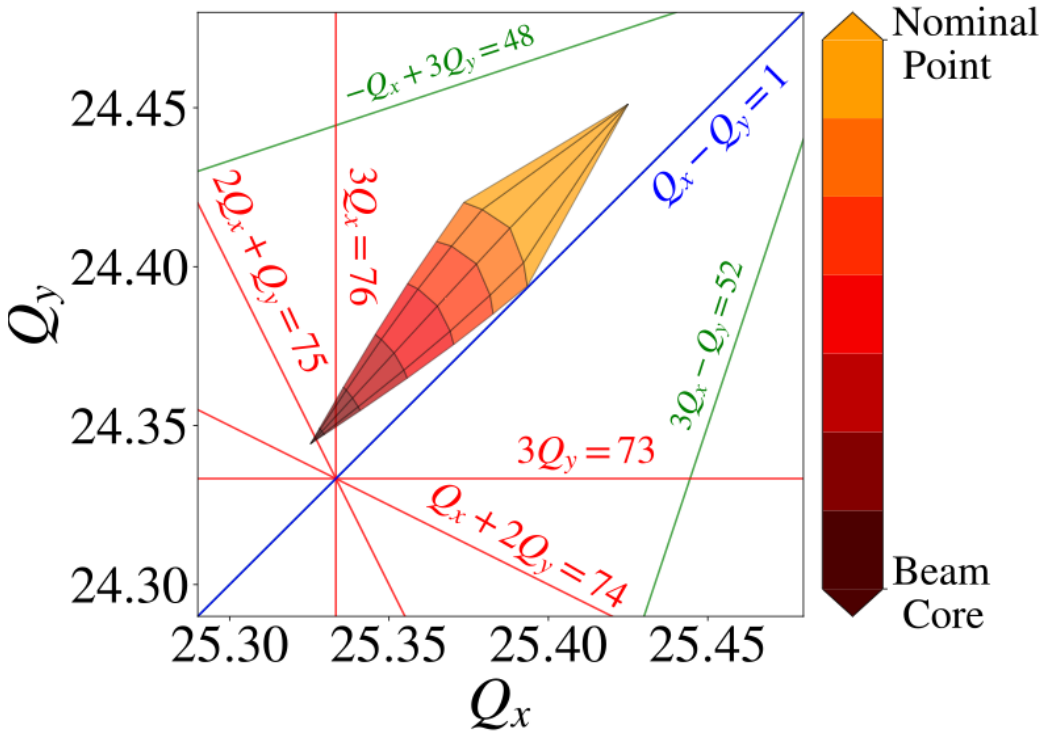


Post upgrades, injected emittance could be smaller, intensities will be higher

- Need to be ready

Space charge at PIP-II intensities



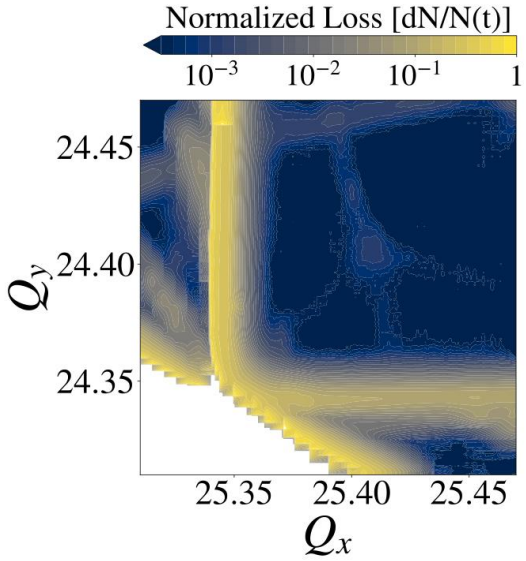


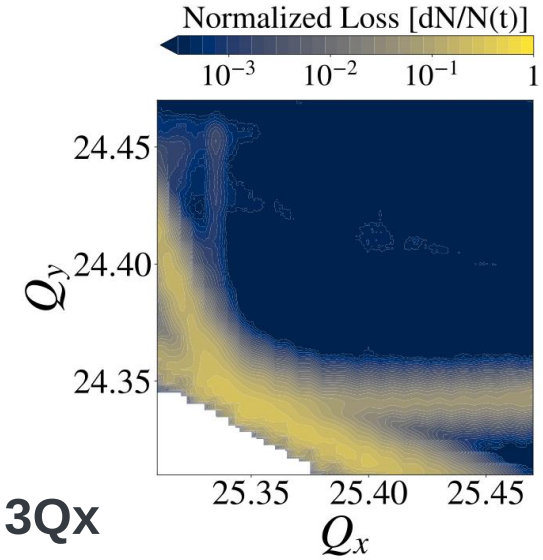
Resonance correction circuits

- The Recycler has 60 sextupole correctors for chromaticity correction
- We installed 8 sextupoles at 4 locations (0,90,180,270deg in phase advance) for 3Qx correction and 4 Skew sextupoles for 3Qy correction
  - Since added an additional two sextupoles although have not commissioned yet
  - Installed in straight sections to avoid chromatic effects
  - At each location, sextupoles were placed next to each other as one sextupole was not strong enough
- 4 Skew quadrupoles already installed for linear coupling correction

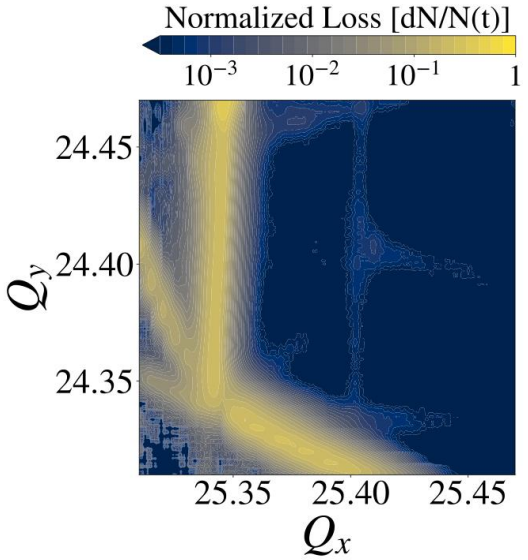
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Resonance correction – measured tune space

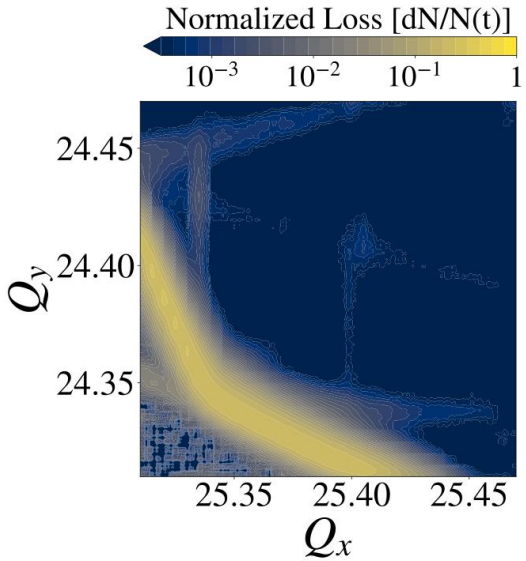




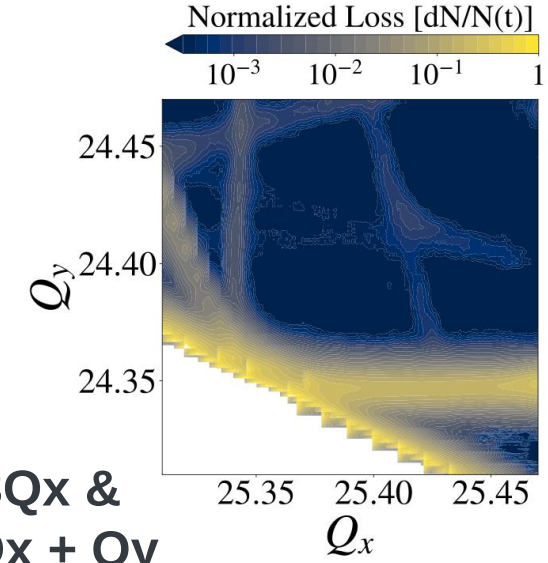
3Qx



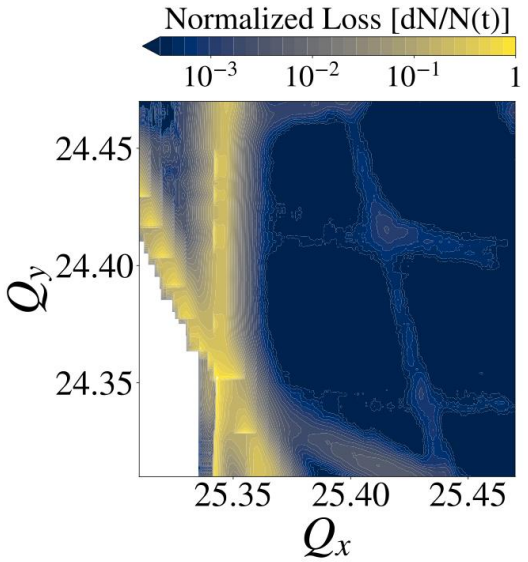
3Qy



3Qx &
3Qy



3Qx &
2Qx + Qy



3Qy &
Qx + 2Qy

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Summary & Open Questions

- The Recycler uses the slip-stacking process to double the beam intensity
  - Modulating tune shift where two footprints are separated by non-zero linear chromatic tune shift
- Space charge effects appear to saturate at current intensities/injected emittance
- Resonance correction systems in place for post upgrades

- Questions:
  - In the past, Resonance correction was tuned up by minimizing RDT at low intensity and leaving same corrections for high intensity. With the increased use of optimization algorithms, are there better optimums out there?
  - The 3rd Order correction circuit has sextupoles are 4 locations but doubled up, should we redistribute to 8 locations i.e. is it better to spread out the RDT corrections.

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Thank you!

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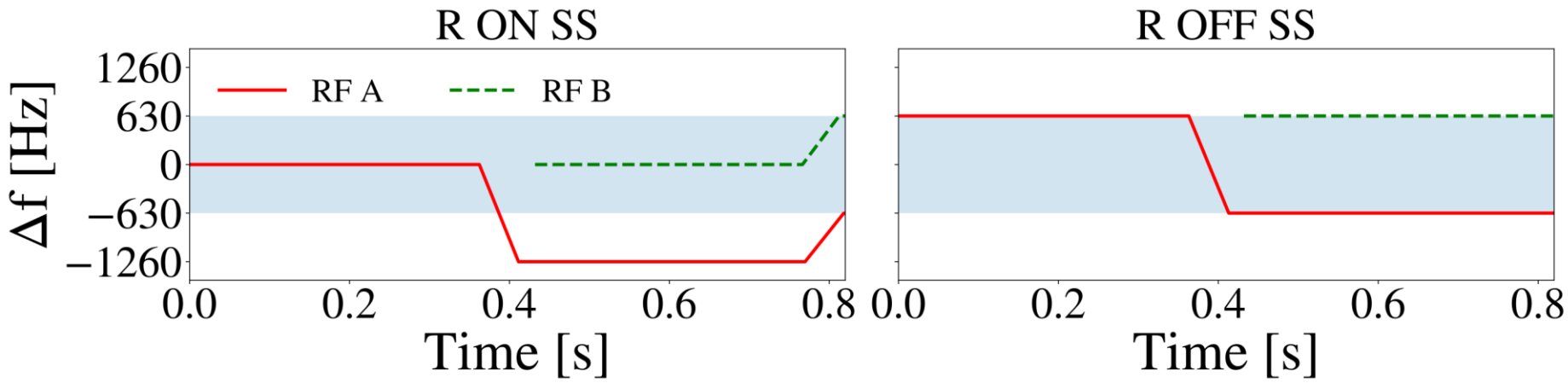
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Backup Slides

MI/RR challenges

Charge #4,6

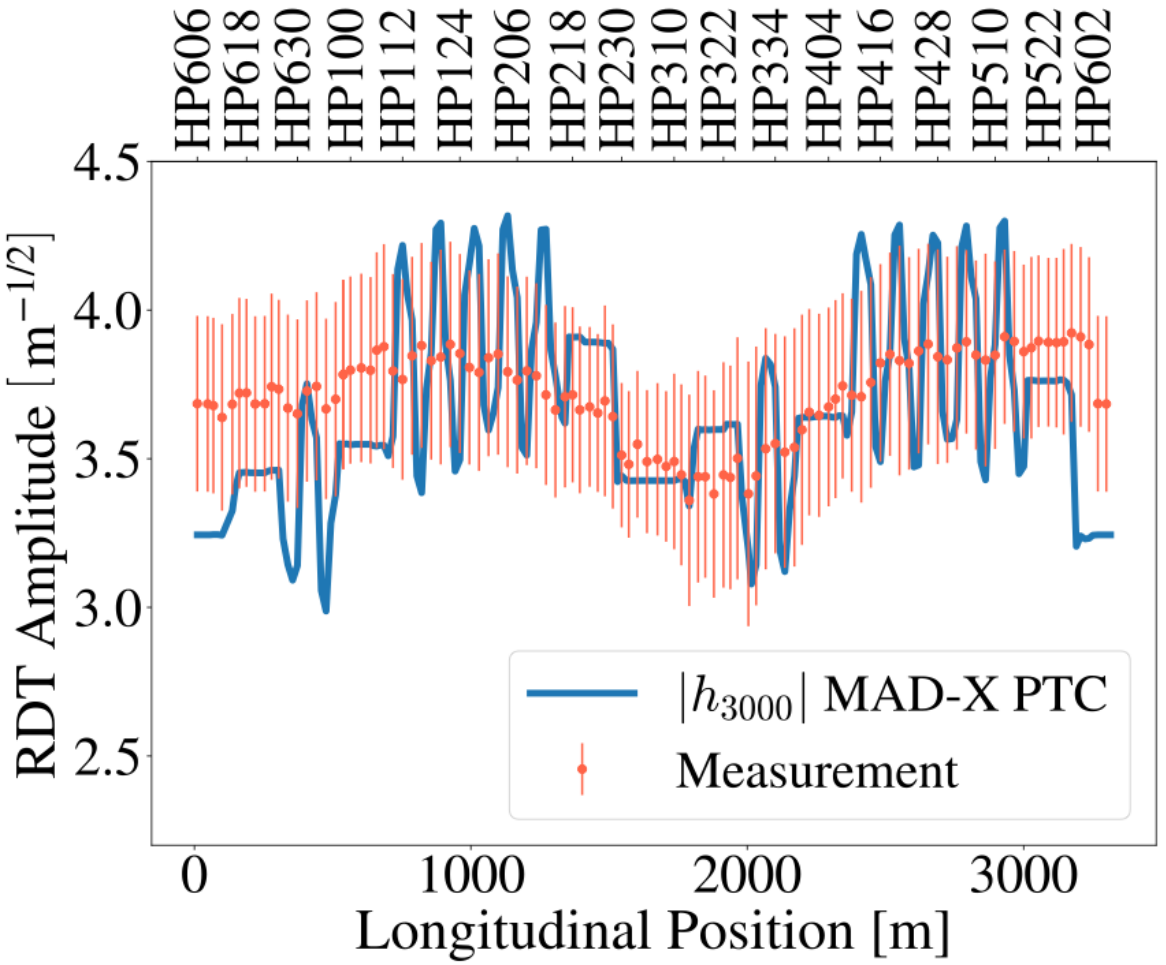
- To prepare for 20 Hz, Radial Offset slip-stacking implemented and operational since 2022
  - Reduced losses in MI by factor of 3



- PIP-II required a 1.2 s ramp in Main Injector
  - Implemented since 2019
  - Shortened further to 1.067 s allow 1 MW beam power record
- New Collimators in injection line to RR from Booster

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RDT measurement vs simulation



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