Fermilab

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The Recycler and Main Injector in the MW Era

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FRIB Seminar

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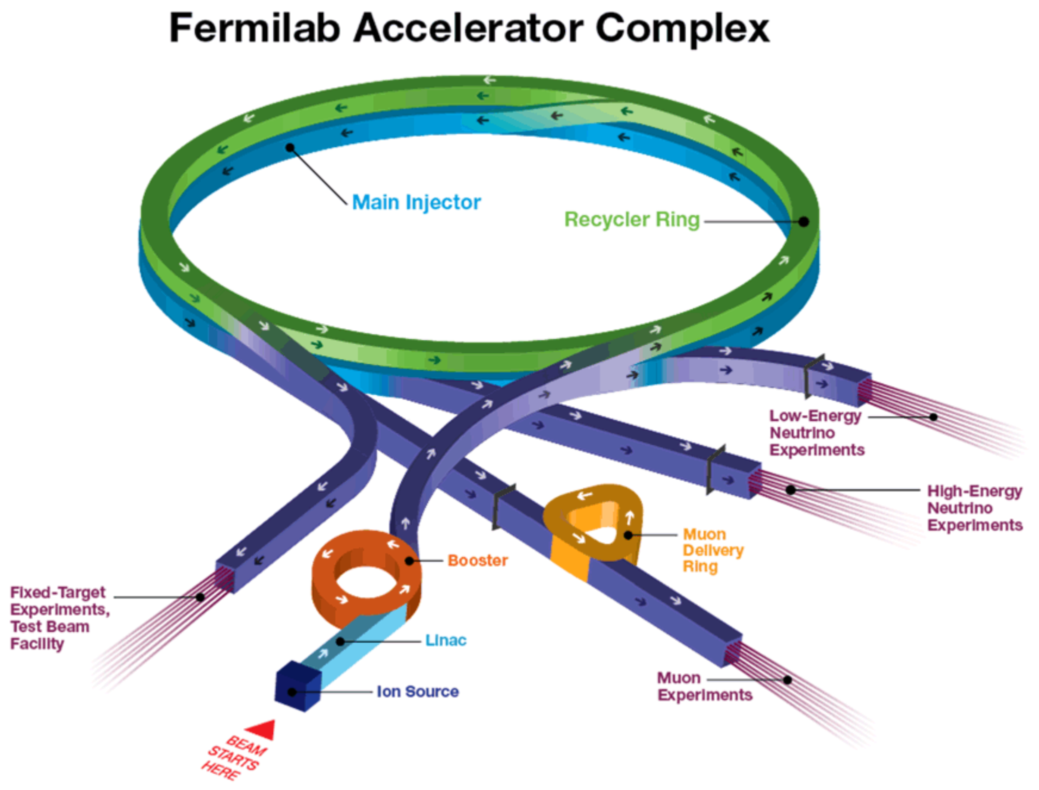
Outline

- Accelerator complex
  - Recycler and Main Injector
  - Slip-stacking
- Challenges for PIP-II
  - Space charge effects in the Recycler
  - Transition crossing in the Main Injector
- Instabilities
- Summary

Accelerator complex

- H^- linac
- Booster
  - h = 84
  - 15 Hz
  - 400 MeV -> 8 GeV
- Recycler
  - h = 588
  - Slip-stack 12 batches (double bunch intensity)
- Main Injector
  - 8 GeV -> 120 GeV



Repurposed Recycler

Recycler

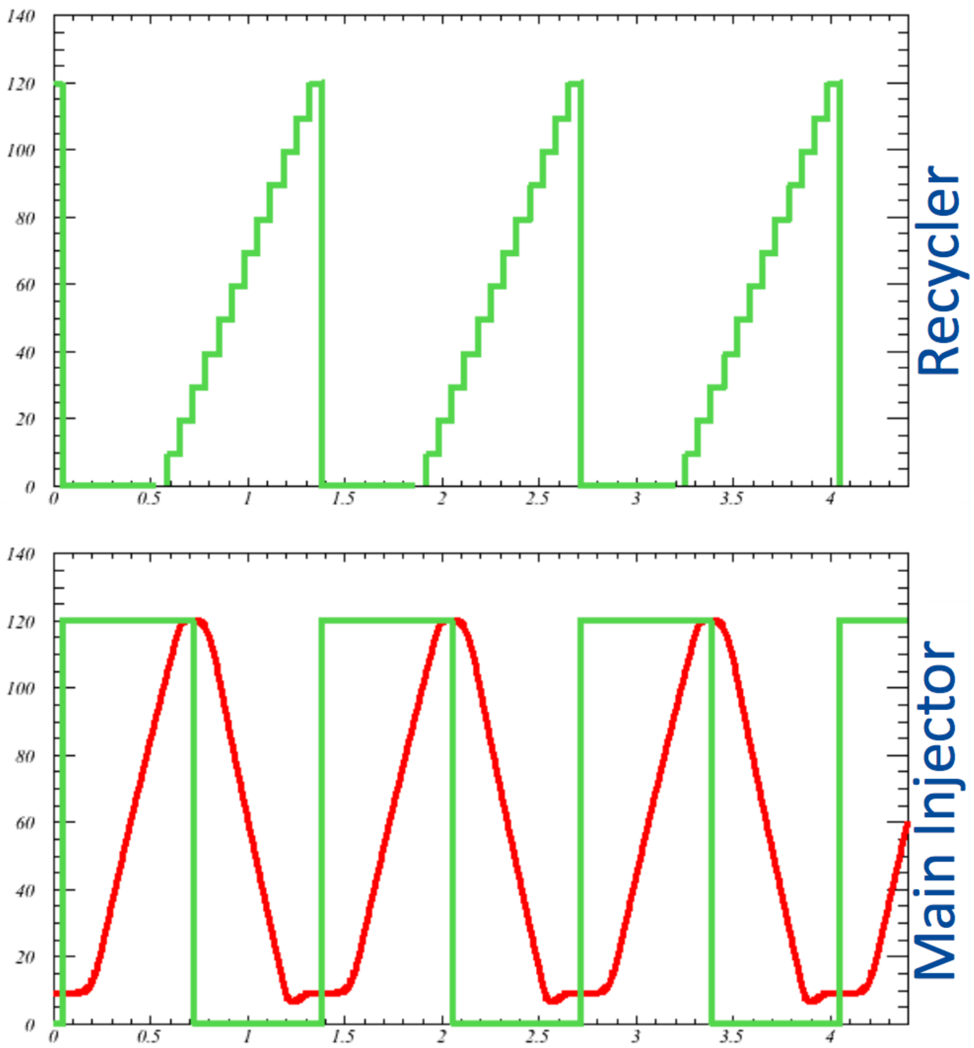
Main Injector

- Recycler is a permanent magnet storage ring
- Shares the tunnel with the Main Injector
- Originally named to recycle antiprotons from Tevatron which it never did!
- Eventually it stored and cooled antiprotons
- Contributed greatly towards increased Tevatron luminosity

Never designed for its current purpose

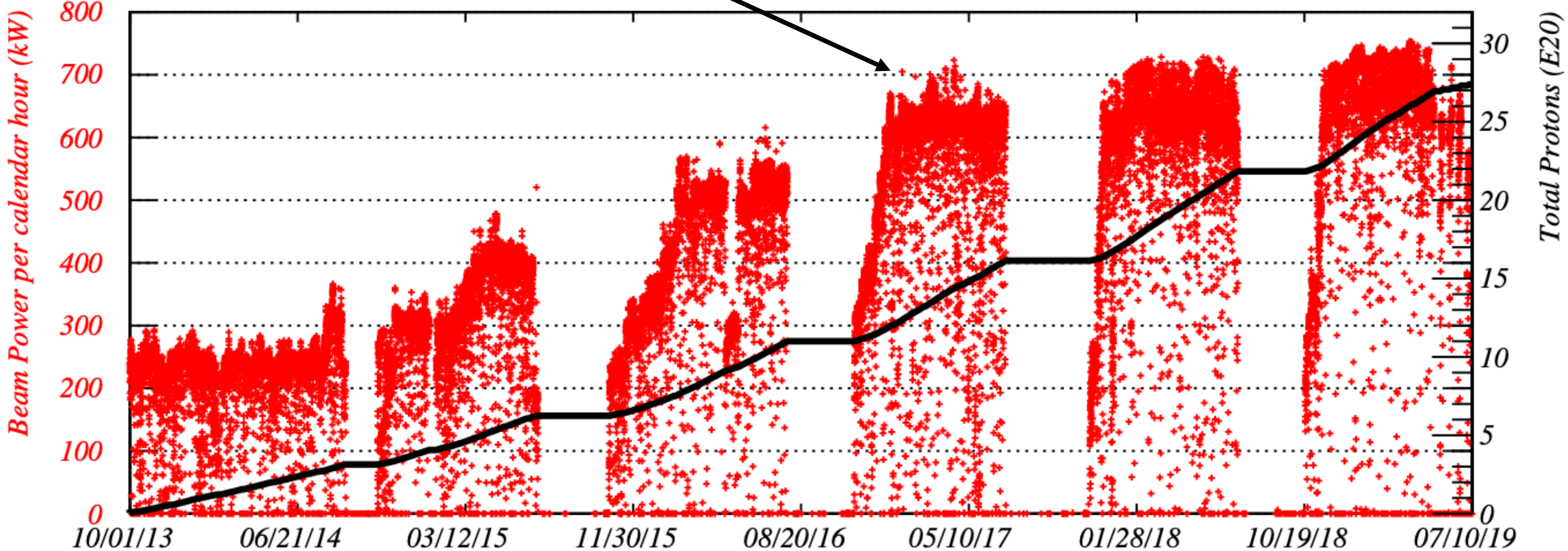
Scheme to increase beam power

- Slip-stack in the Recycler
- Increase the MI ramp rate (204 GeV/s to 240 GeV/s)
  - 2.2->1.33 s cycle time
- Achieve 700 kW with just a 10% increase in beam intensity from MI only



Power

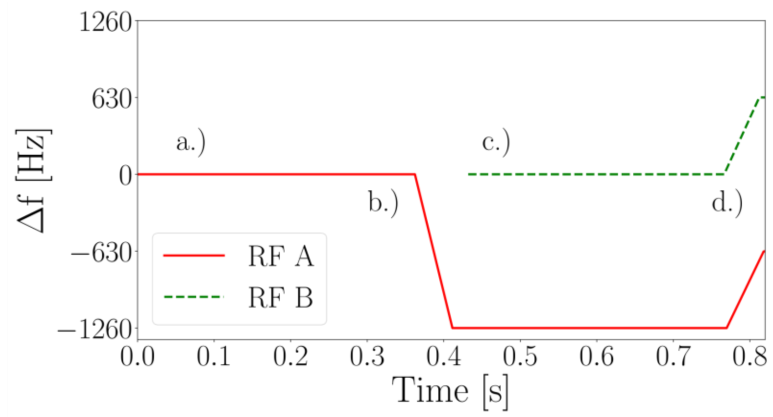
Running 700 kW consistently since Jan 2017



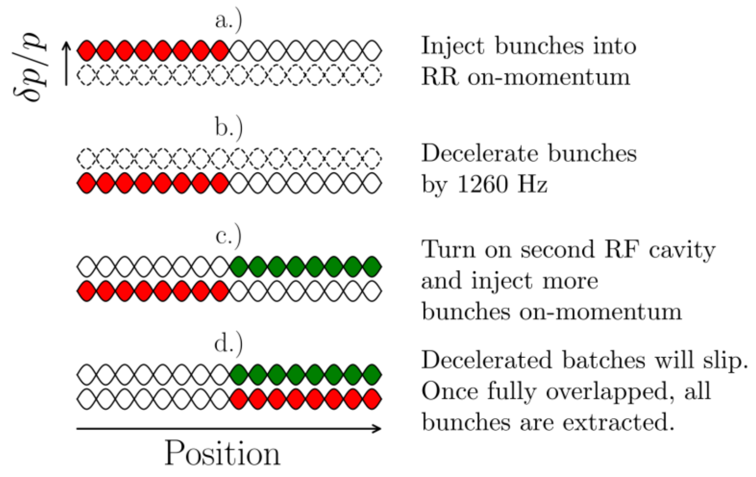
MI	RR	2+6	4+6	6+6
240kW	300kW	400kW	525kW	700kW

Slip-stacking

- Slip-stacking allows us to double the intensity of the bunches in the Recycler



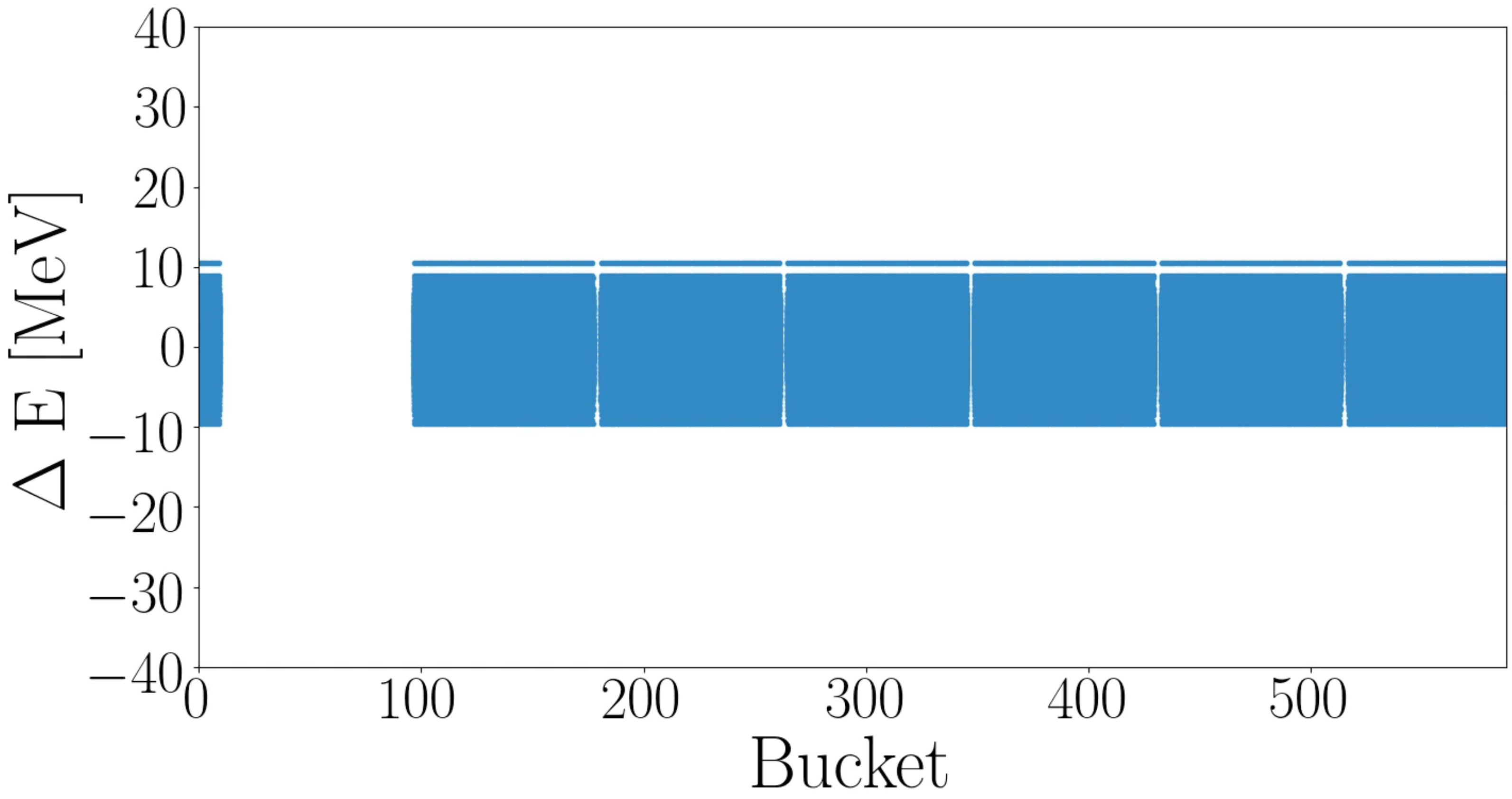
$$\Delta f = h_b f_b$$



$h_b = 84$

$f_b = 15\text{Hz}$

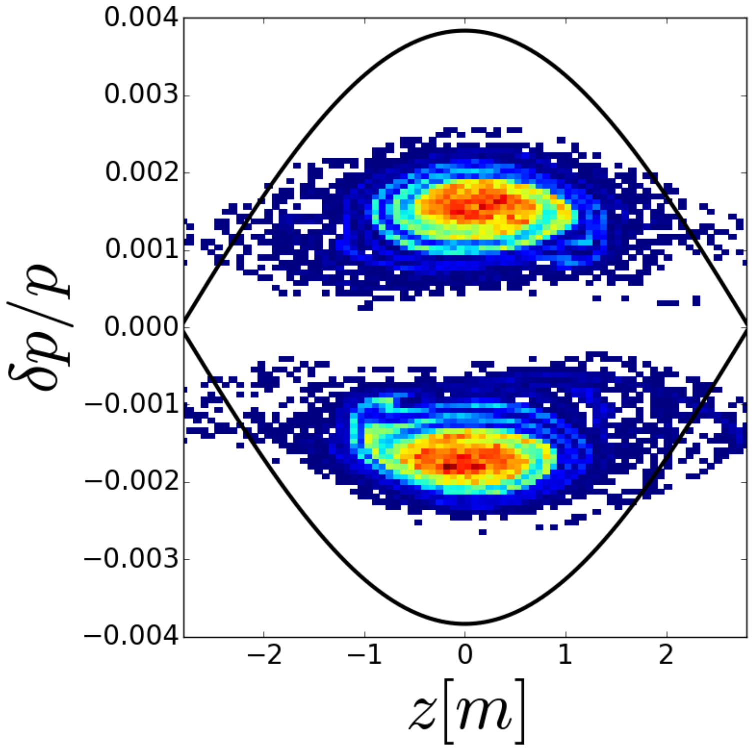
Slip-stacking



Gap clearing kickers fire before every injection sending beam to abort

Slip-stacked bunches extracted to MI

- This bunches are captured in the Main Injector and accelerated from 8 GeV to 120 GeV



Power evolution

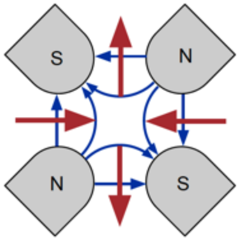
- PIP
  - 700 kW (~0.5 x 10^{11} ppb)
  - 80 kV RF for Recycler
  - 15 Hz Booster
    - 1260 Hz separation for slip-stacking
- PIP-II
  - 1.2 MW (~0.8 x 10^{11} ppb)
  - 140 kV RF for Recycler
  - 20 Hz Booster
    - 1680 Hz separation for slip-stacking
- PIP-III
  - 2.4 MW
  - No more slip-stacking, replace booster with new RCS or a new linac

Do space charge effects during slip stacking at high intensity cause problems?

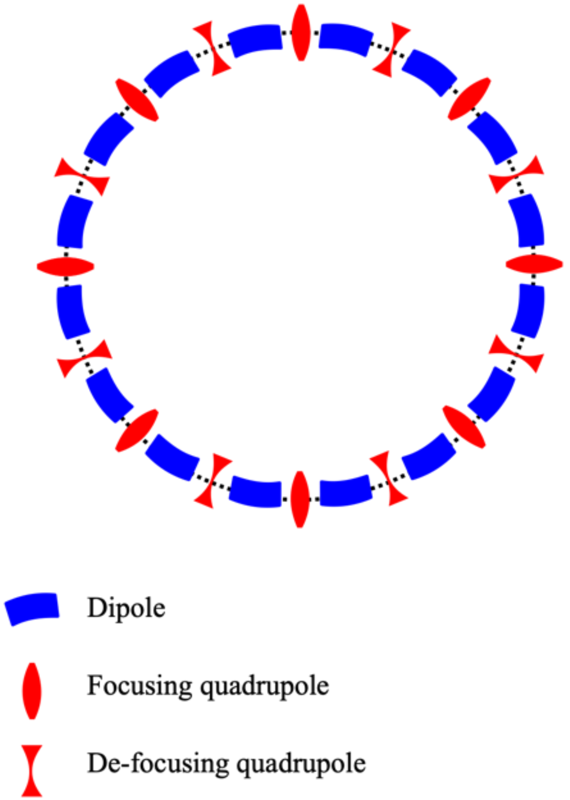
But first, a quick intro to space charge and betatron resonances

Linear focusing

- Dipole magnets to steer the beam
- Quadrupole magnets to focus the beam



- Quads focus in one plane and de-focus in the other



Betatron tune

- Alternating focusing means the beam oscillates as it goes around the ring

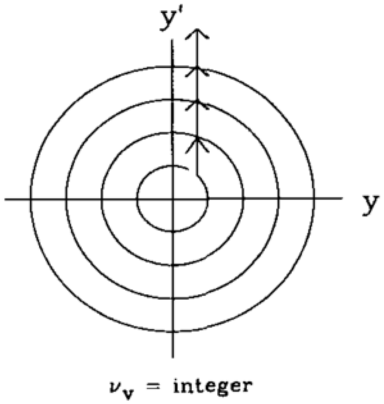
- Betatron tune - The number of oscillations the beam makes in one revolution

- For example, In the Fermilab Recycler, the horizontal tune is 25.44 and the vertical tune is 24.39

- The fractional part is very important!

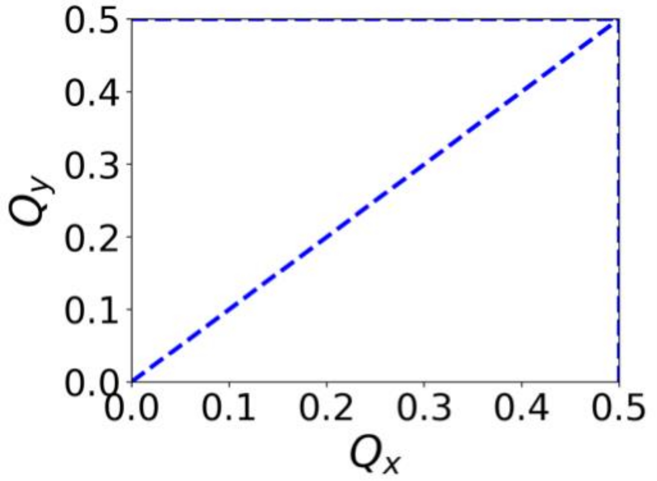
Integer resonance

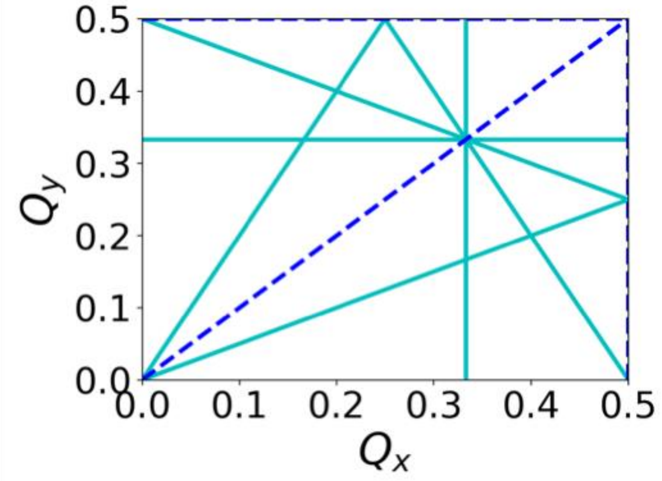
- Suppose the fractional part was zero i.e. the tune is an integer

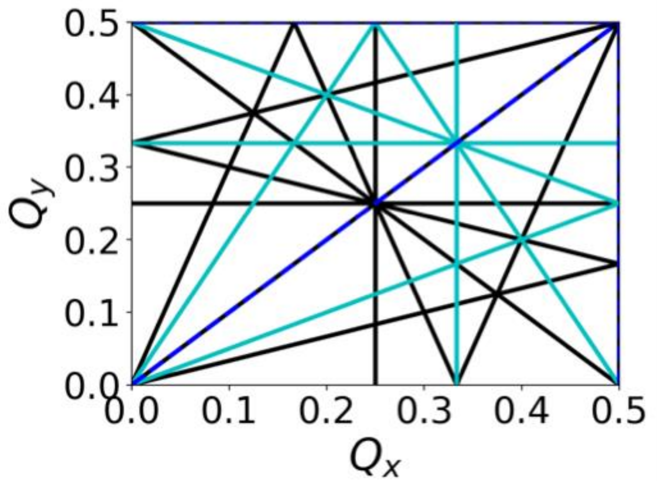


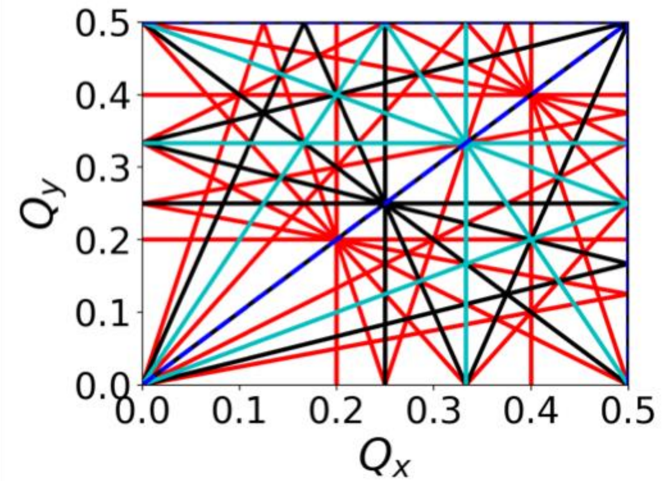
- If we have an error in a dipole magnet
- Particle would receive same kick every revolution
  - Eventually hit the beam pipe
  - Irradiate accelerator components

Resonances - many more possible



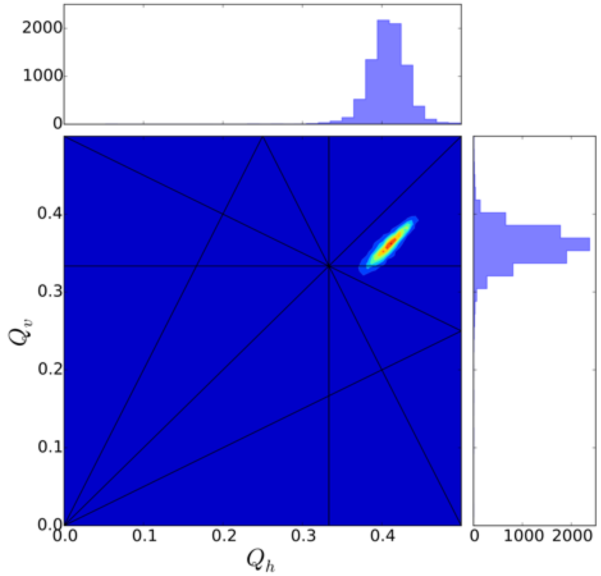






Space charge

- Inside a bunch, there is a spread of tunes
- Self field results in defocusing which leads to tune shift
- Space charge leads to tune shift
  - increases this spread with intensity
  - Worse at low energy
  - Depends on bunch length and beam size



$$\delta Q_{\mathrm{sc,V}} = -\frac{\beta_{\mathrm{V}} N r_0}{2\pi B_f \sigma_{\mathrm{V}}(\sigma_{\mathrm{H}} + \sigma_{\mathrm{V}})\beta^2\gamma^3}$$

Do space charge effects during slip stacking at high intensity cause problems?

If so, what are the sensitivities and how best to mitigate them?

Synergia

Self-consistent 3D Particle-in-cell accelerator simulation C++ code
- Specifically to simulate collective effects in accelerators
- Designed from the beginning to run on large parallel computing systems (but it doesn't have to)
- Library of Objects which are combined to create a simulation
  - Lattice, Bunch(es), Diagnostics (bunch measurements), Collectives, Propagation scheme, all under programmatic control
- **One or two co-propagating single bunch or multi-bunch beams**

Collective effects included with split-operator formalism:
- Space Charge (validated with GSI space charge benchmark, multiple models)
- Impedance (per-element) within bunch and bunch-to-bunch, $\gamma < \infty$ for boosters

Synergia contains an internal test suite that verifies the correct operation of most modules. Particle tracking is verified with MAD-X/PTC and analytic calculations. Space charge kicks are verified with analytic calculations. Particles are labeled.

Synergia is actively used to model all of our circular machines:
- Recycler, Main Injector, Booster, IOTA, Debuncher

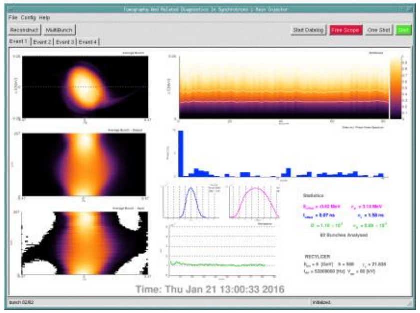
Synergia is developed by the Acceleration Simulations Group within Fermilab's Scientific Computing Division and is publicly available.

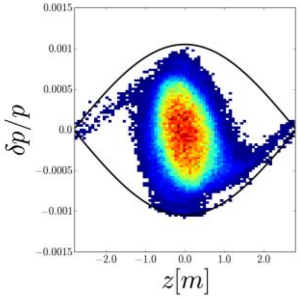
J. Amundson, P. Lebrun, Q. Lu, A. Macridin, L. Michelotti, C. S. Park, E. Stern, T. Zolkin.

https://web.fnal.gov/sites/synergia

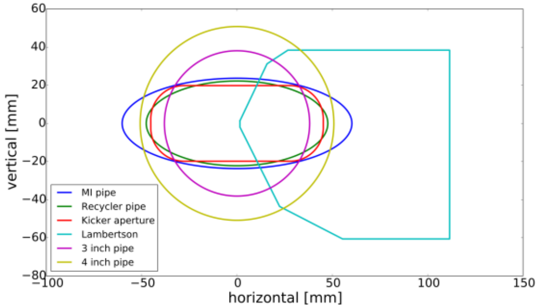
Recycler simulations - inputs

- Realistic longitudinal distribution from tomography





- Transverse distribution matched but using measured beam sizes (IPMs)
- MAD8 input file
- Using apertures, orbit bumps



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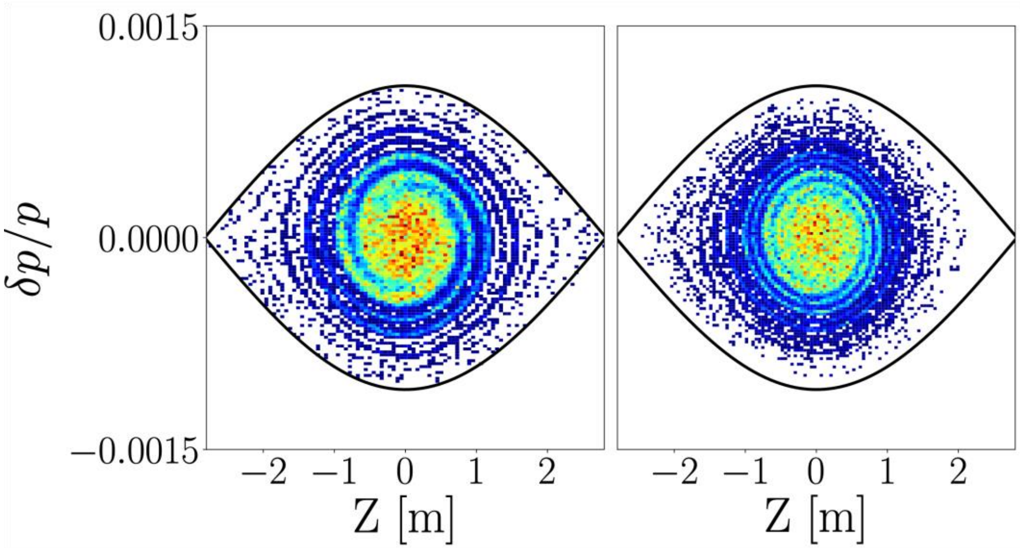
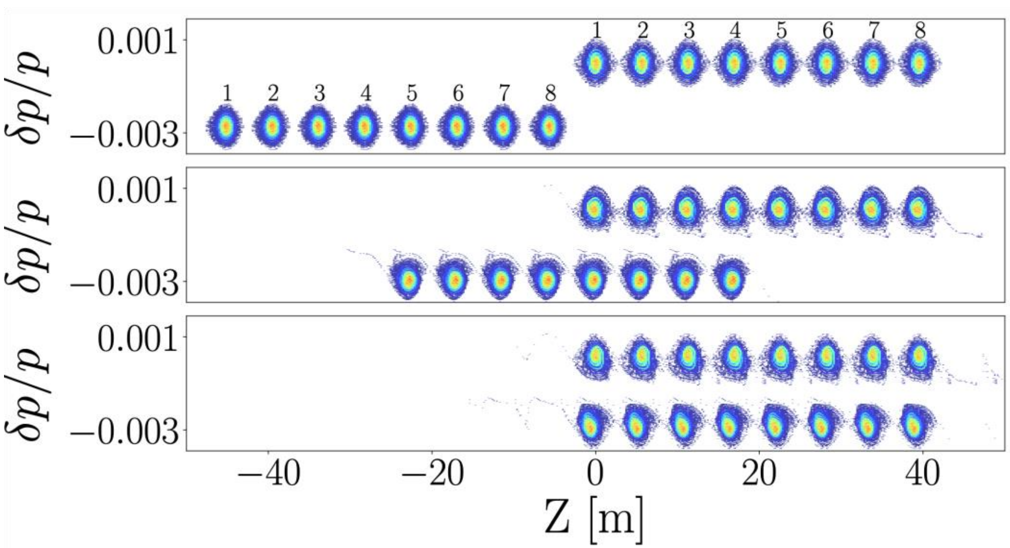
Recycler simulations - 1E11 ppb

Filament
50ms



Decelerate
1260Hz
50ms

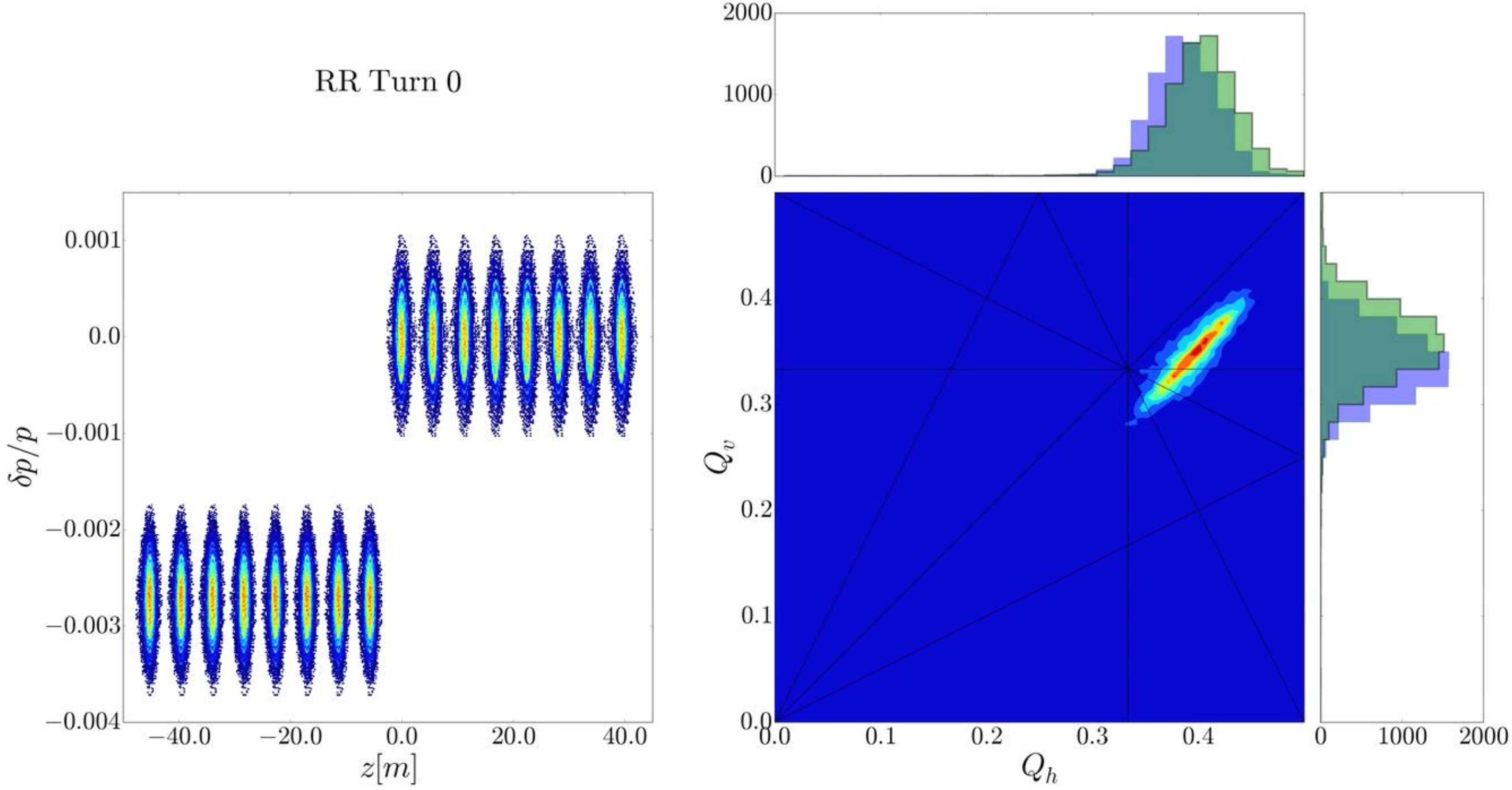


HMB
LMB

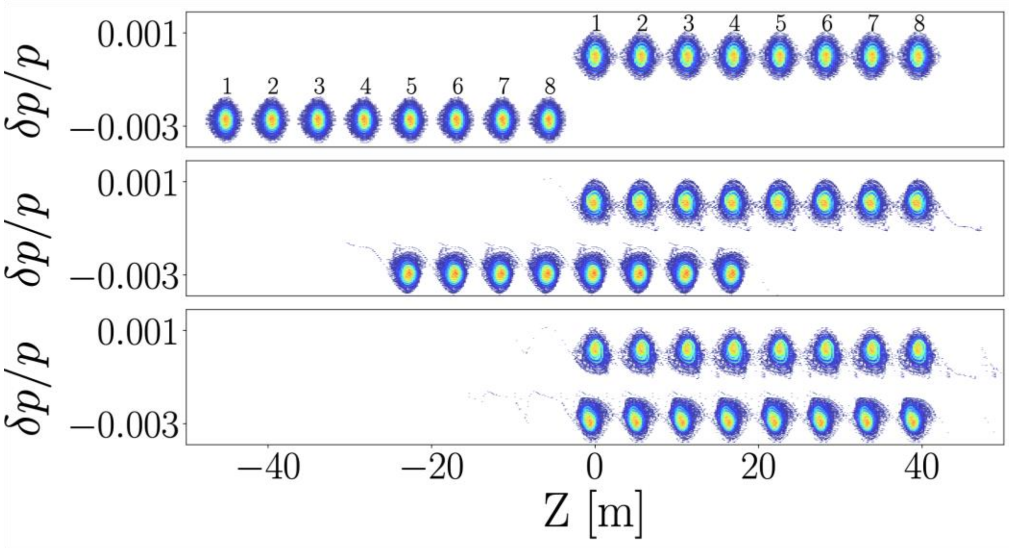
Parameter	Unit	RR
Macroparticles		65536
Q_h		0.39
Q_v		0.44
ξ_h		-5.8
ξ_v		-7.74
h		588
η		-8.6×10^{-3}
$\varepsilon_{n,95\%}$	[π mm mrad]	15
Intensity	[ppb]	1×10^{11}
f_{rev}	[kHz]	89.6
V_{rf}	[kV]	80

Space charge footprint

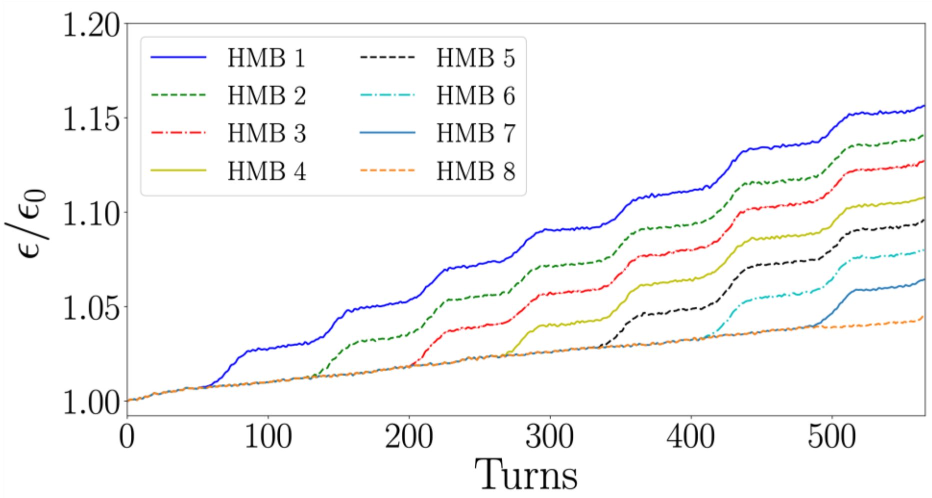
$\Delta Q_{sc} = 0.09$ for $1e11$

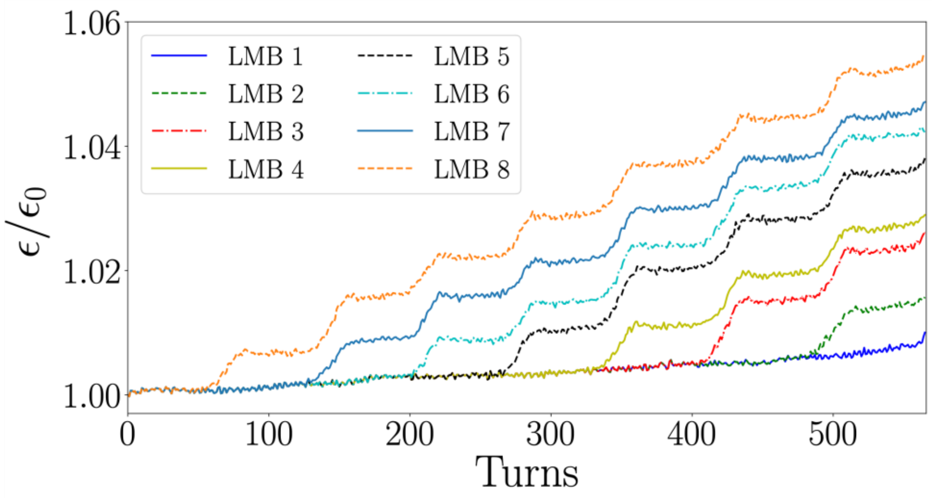


Effect on emittance

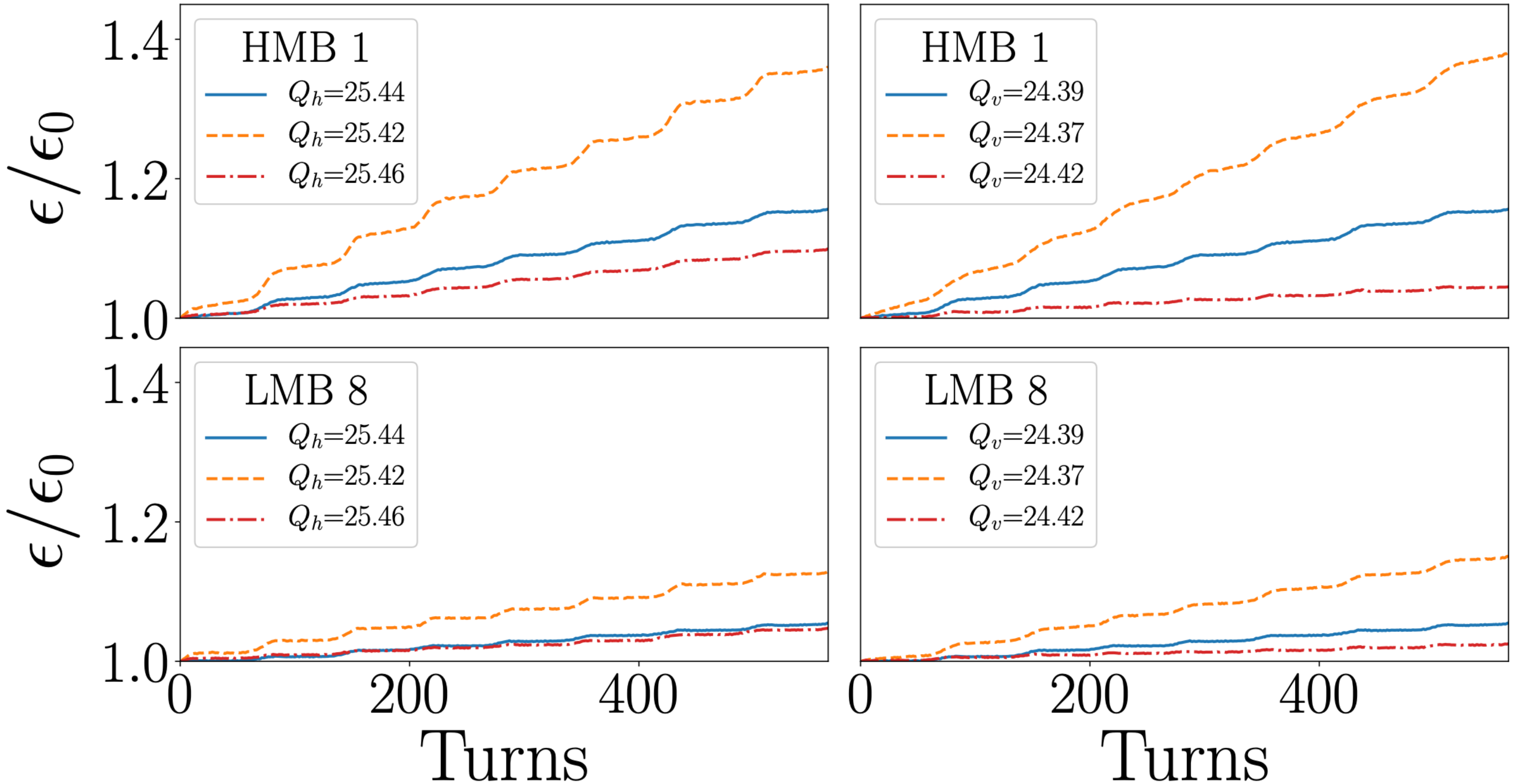


different scale!!!





Tunes

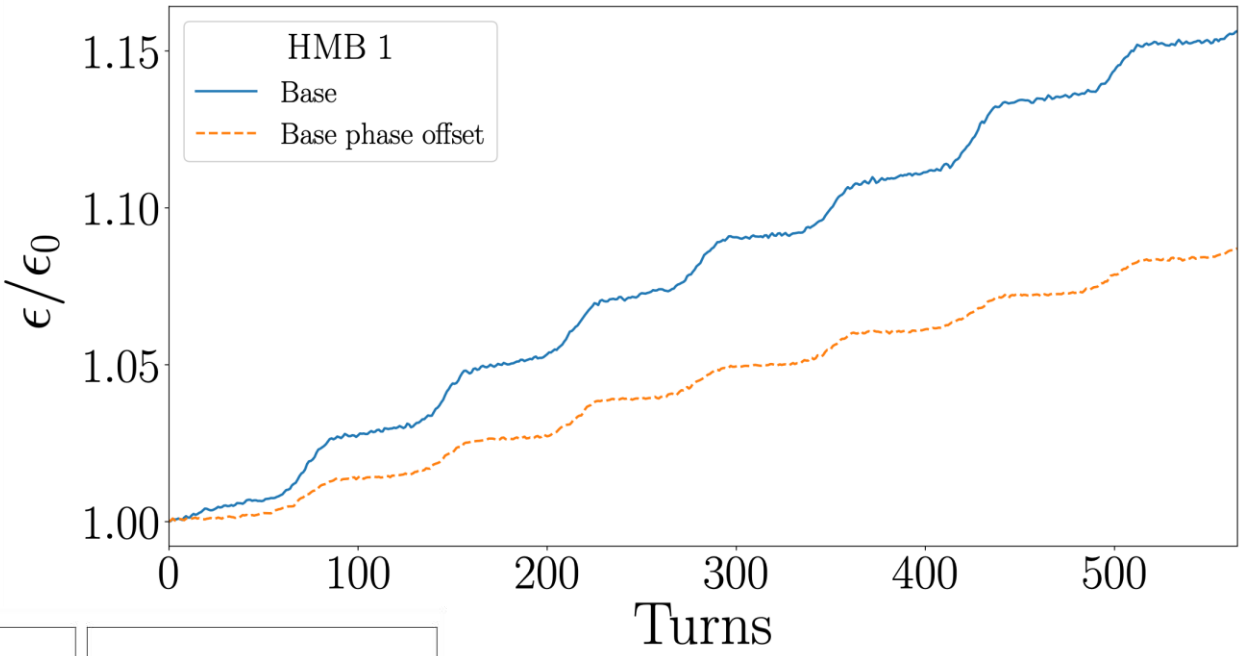


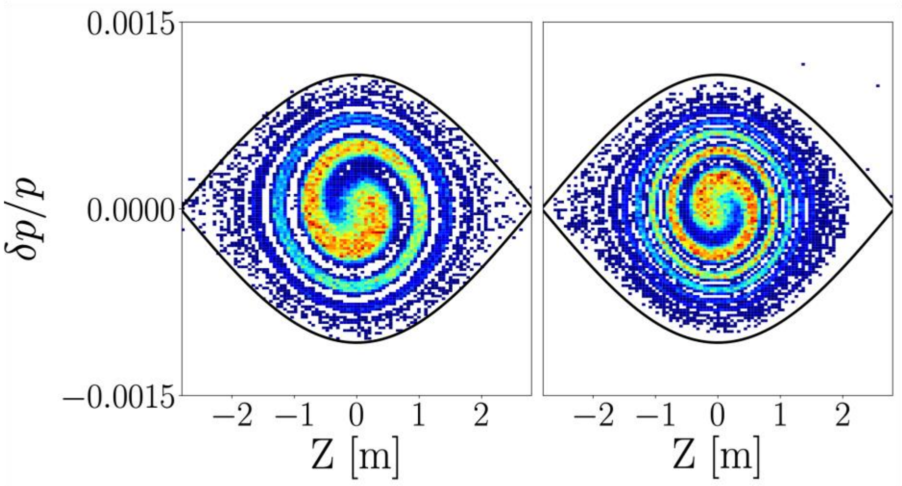
Lower tunes -> larger growth

Phase-offset

Base parameters, 1e11ppb (double 700kW)

Base case with 1.5ns injection offset





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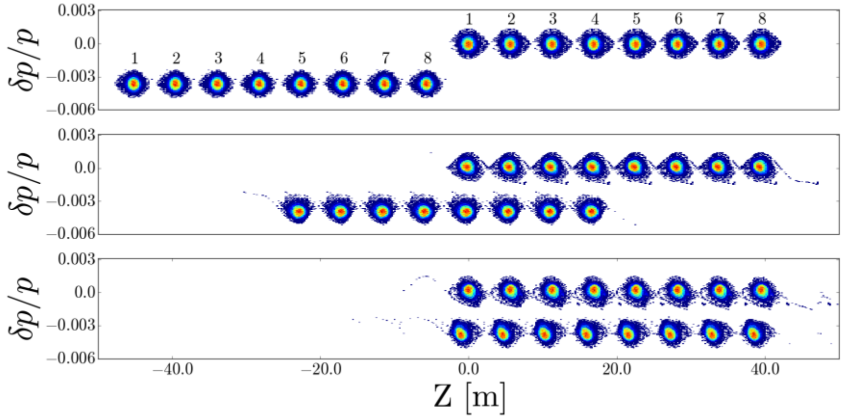
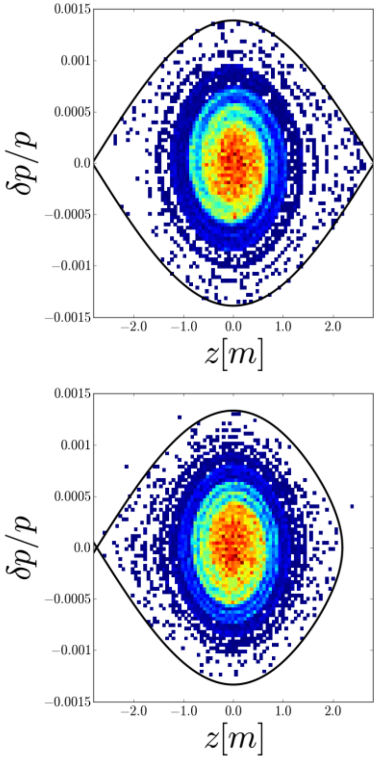
Base parameters, 1e11ppb (double 700kW)

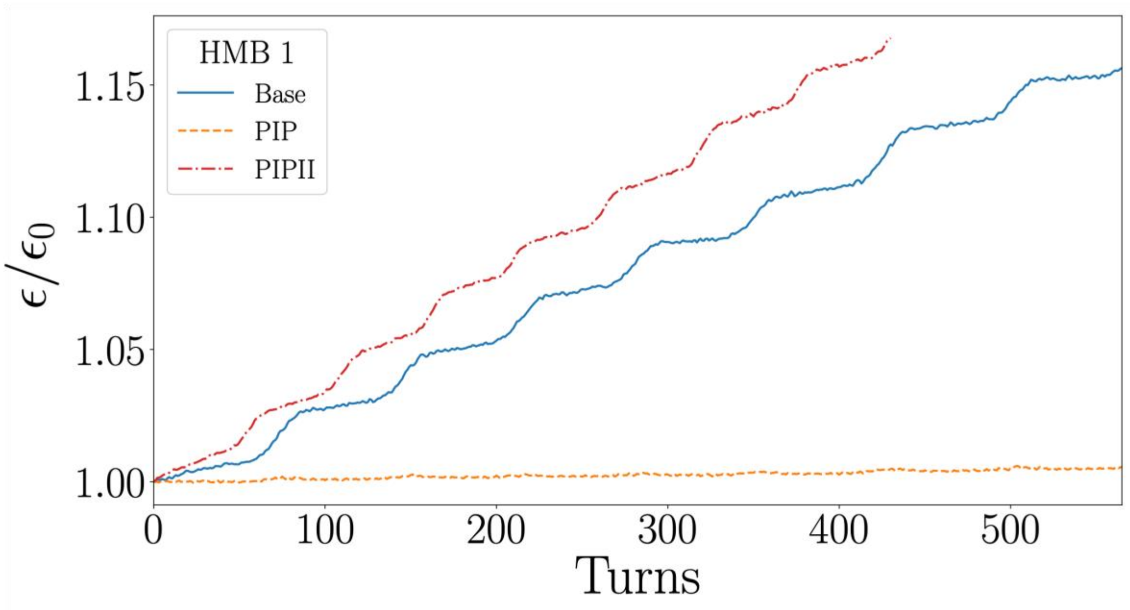
Separation increased from 1260 to 1680 Hz

80 to 140 kV

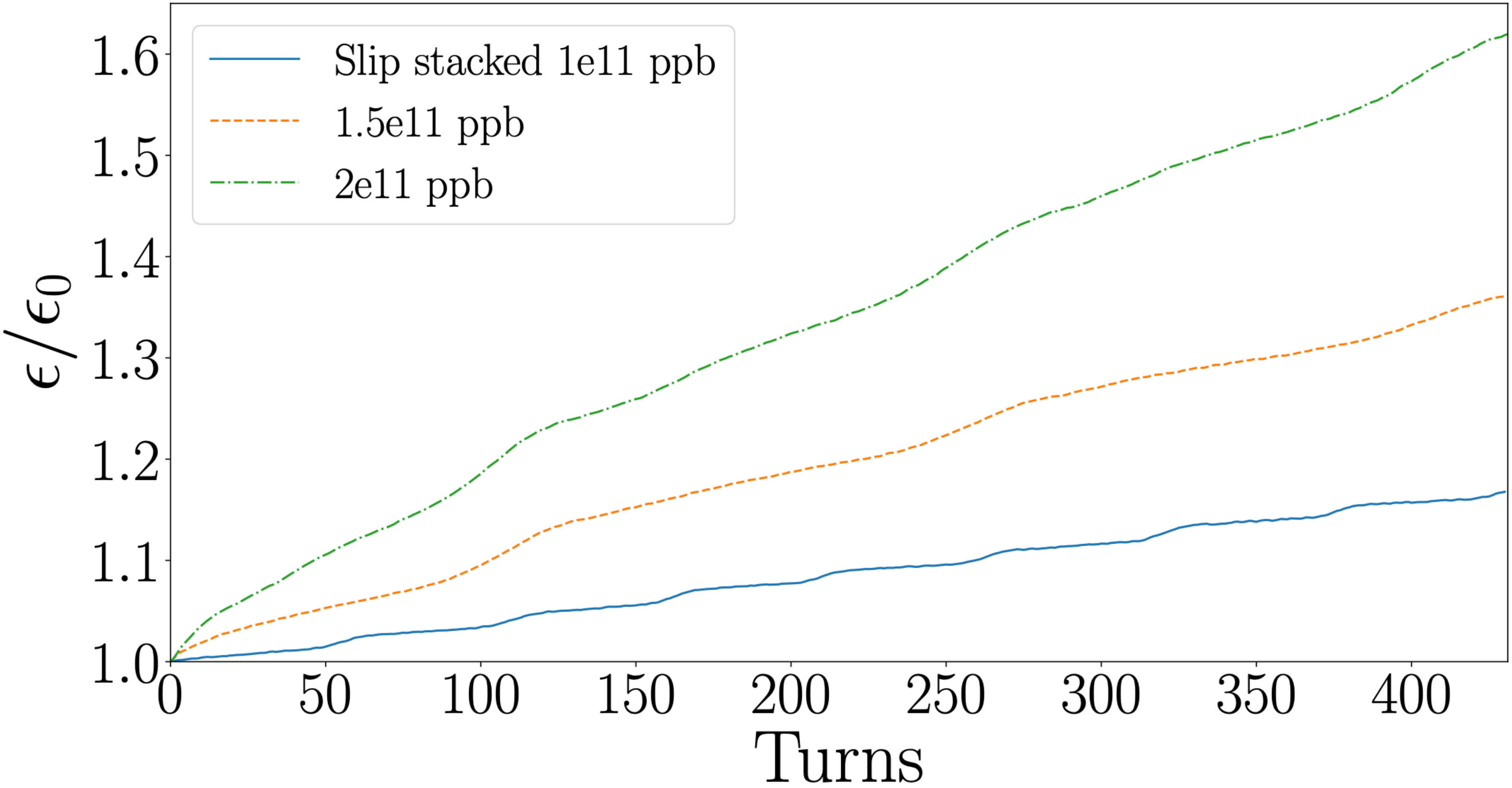
15 Hz to 20 Hz





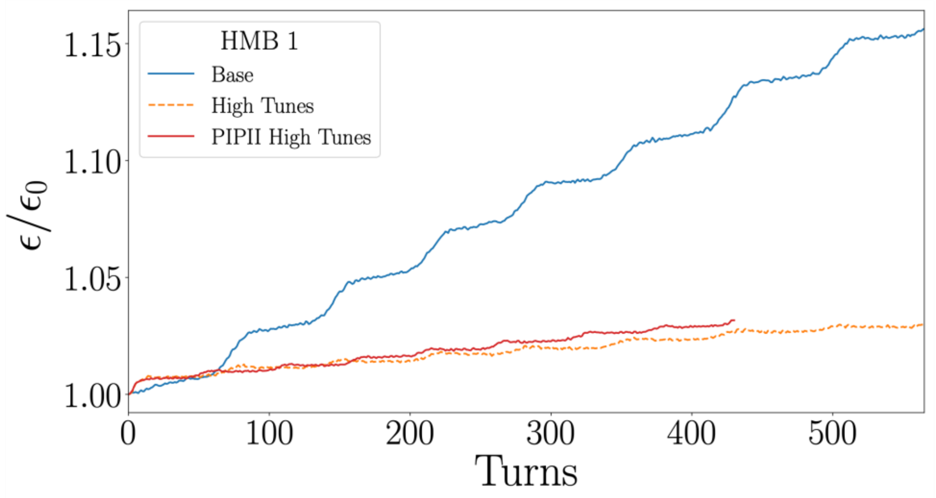


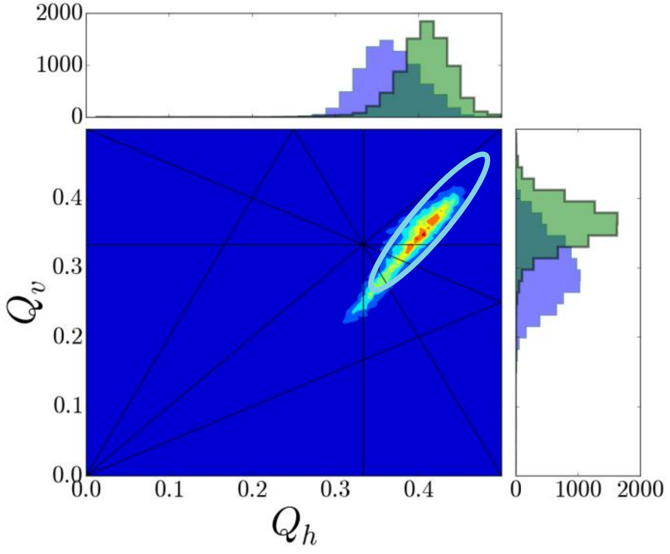
Single bunch vs slip-stacking



Slip stacking simulation conclusions

- As intensity increases, the space charge effects from slip-stacking result in emittance growth during the overlaps
- The effects can be minimized by optimizing the tunes and using an injection phase offset





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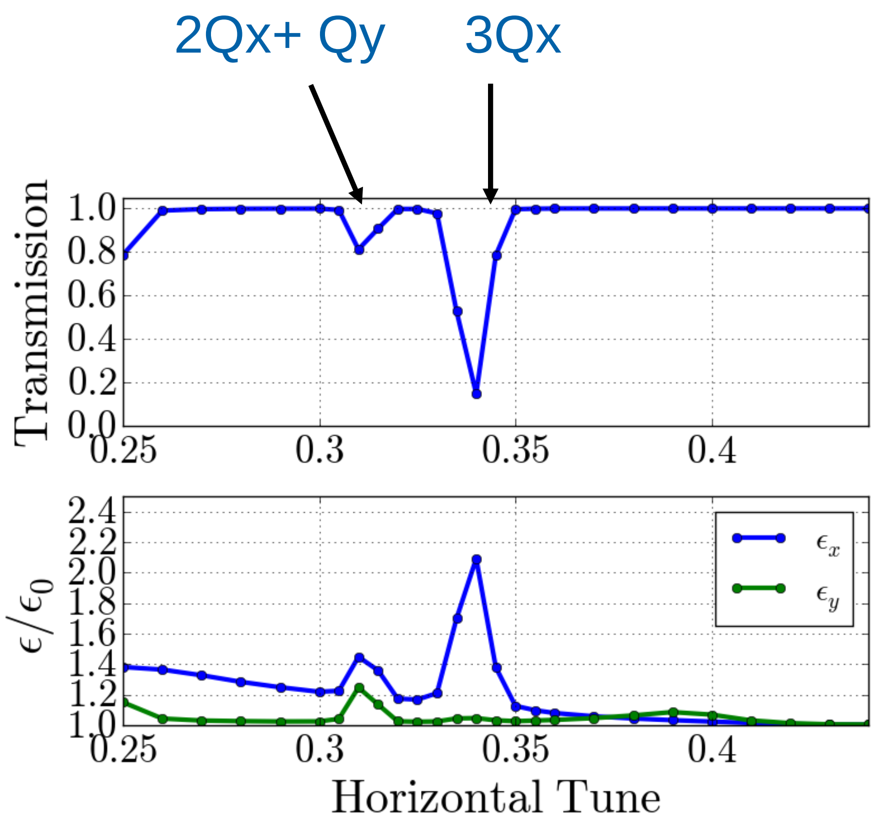
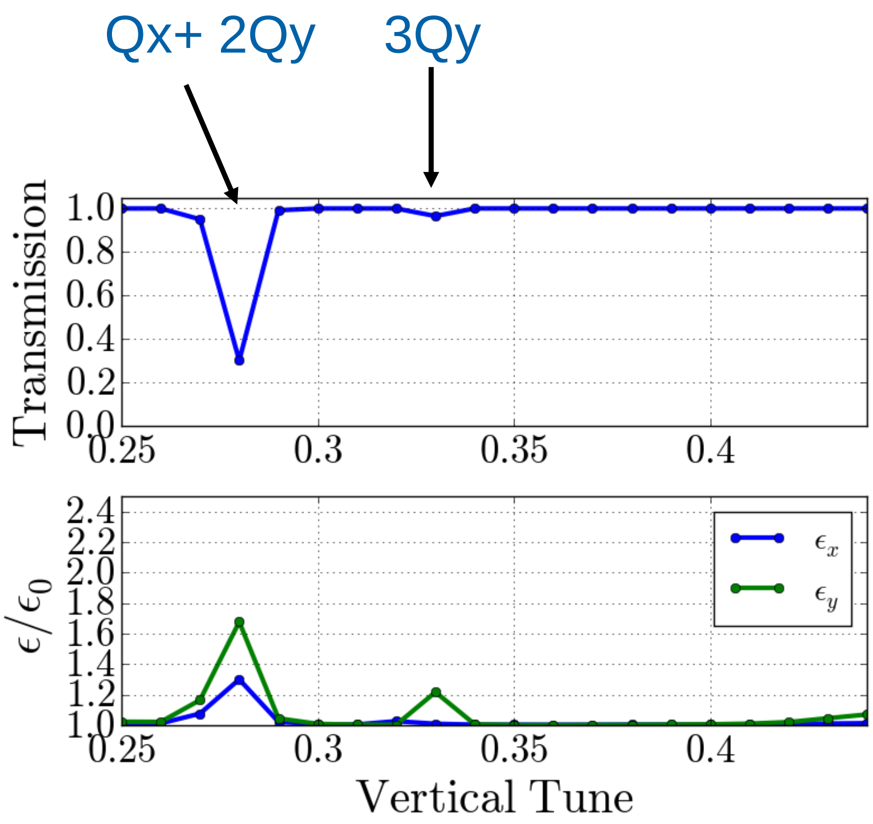
Tune space

If the emittance growth comes from hitting a resonance, can we compensate to widen the tune space?

1D tune scans - no space charge





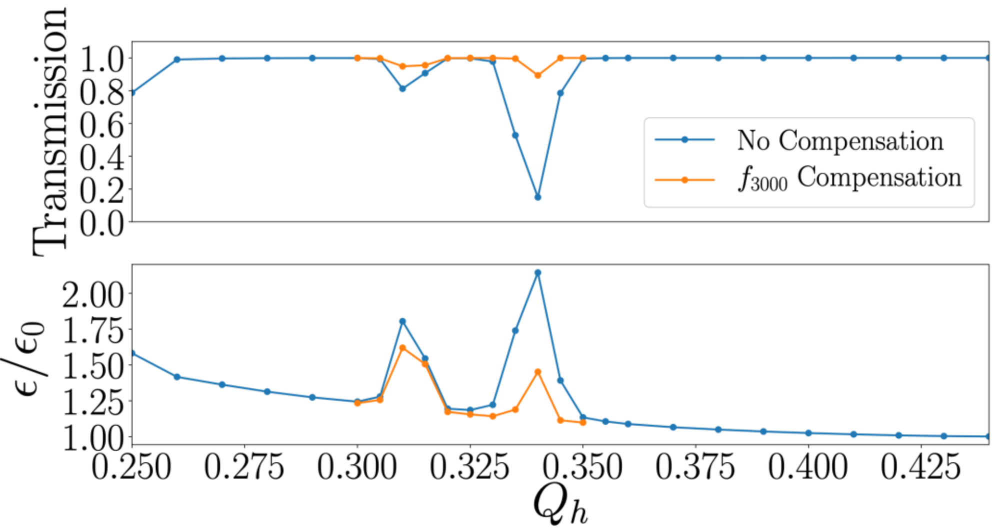
Third order resonance compensation

$$f_{3000} = -\frac{\sum_w K_{2,w} l_w \beta_{w,x}^{3/2} e^{i(3\Delta\phi_{w,x})}}{48[1 - e^{2\pi i(3Q_x)}]}$$

Use sextupoles to make the numerator zero

- Need two 90 degrees apart as f_{3000} is complex

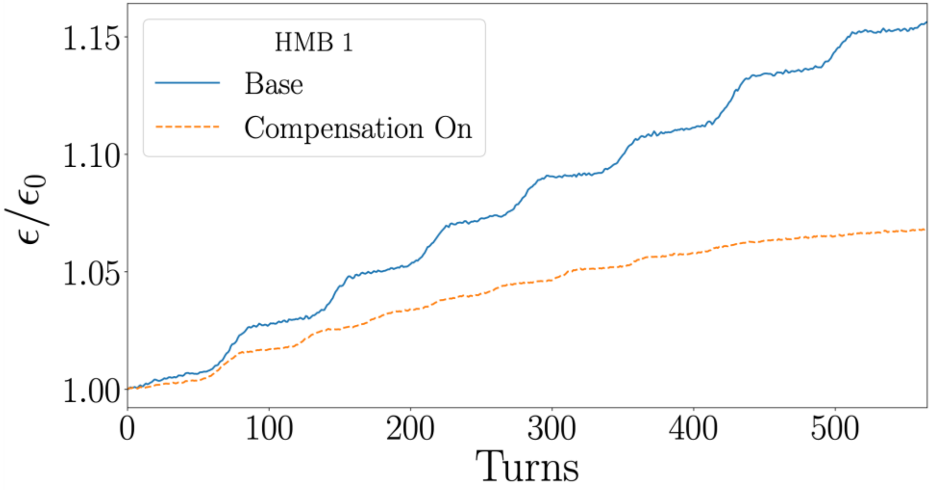
Resonance compensation



Transmission is improved!

Not 100%, higher order terms are not compensated

Slip-stacking case shows saturation within 8 overlaps



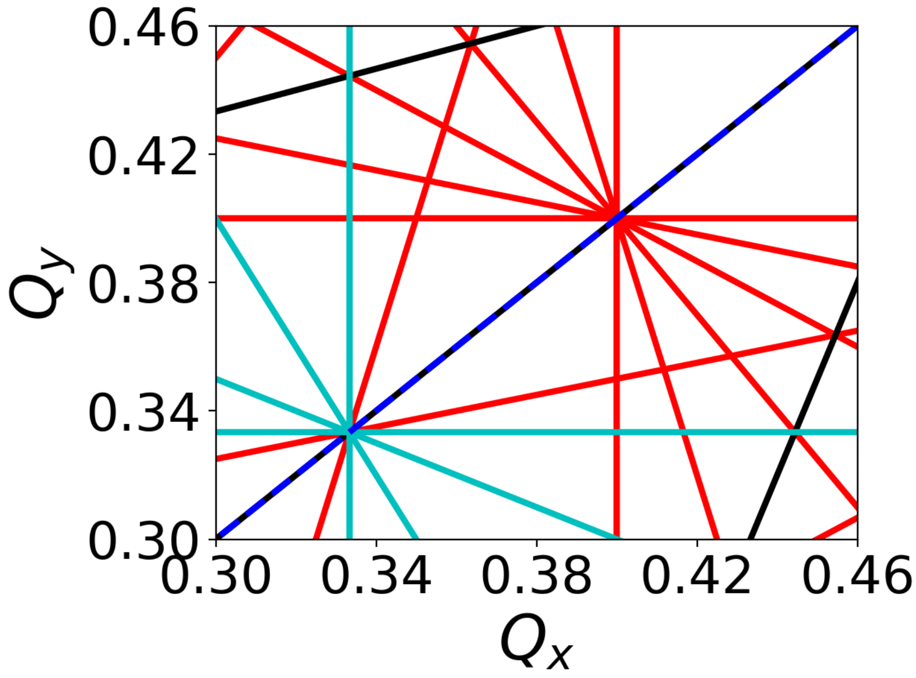
It worked for simulations

What about for the actual machine?

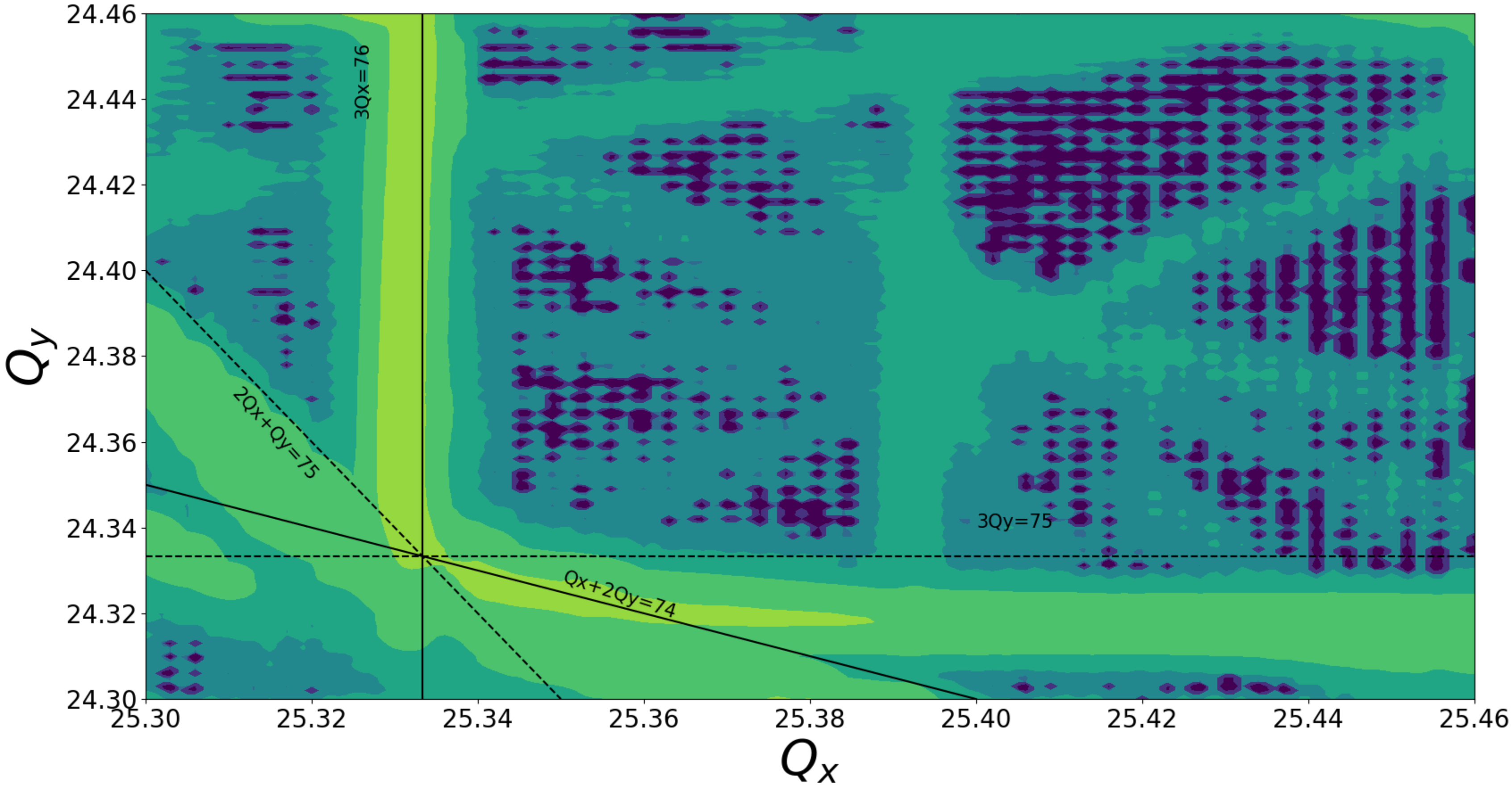
Tune space in Recycler

- The Recycler is a permanent magnet machine
  - Much less freedom to vary the tune
  - Typically constrained to between 0.3 and 0.46

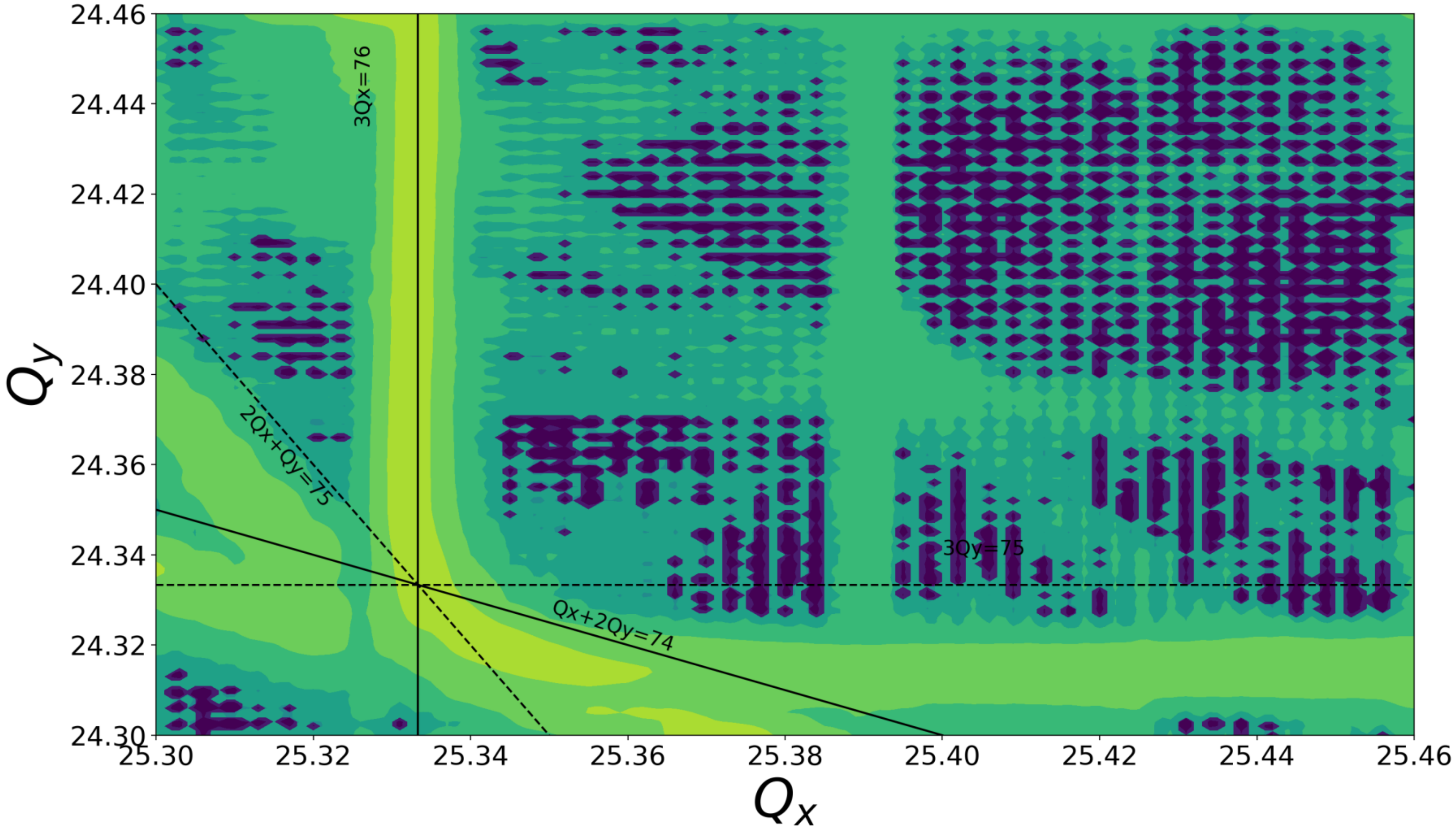
Possible lines



2D Tune scan - measured - low intensity



Skew quads on



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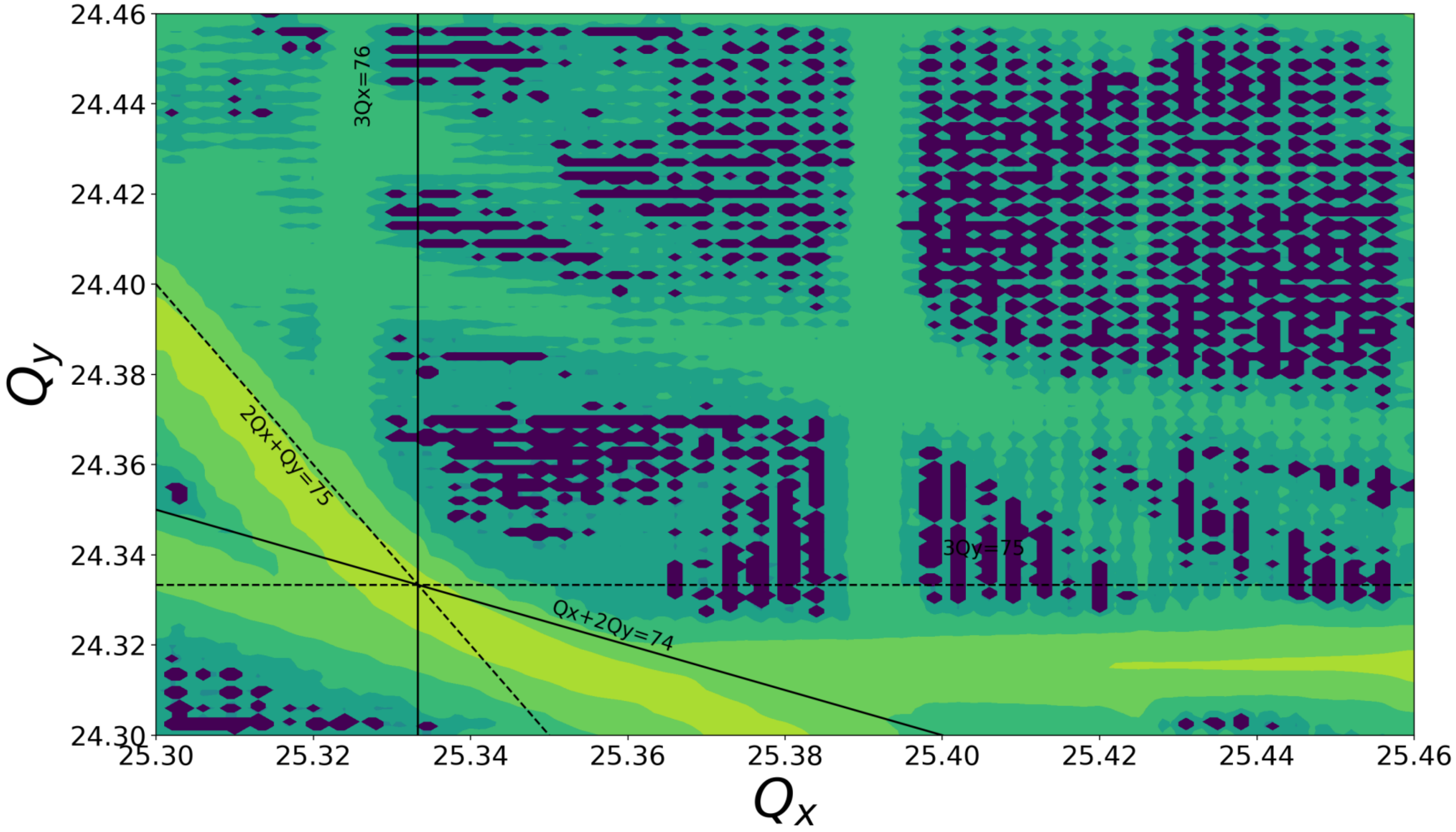
Skew quads on and compensation sextupoles on

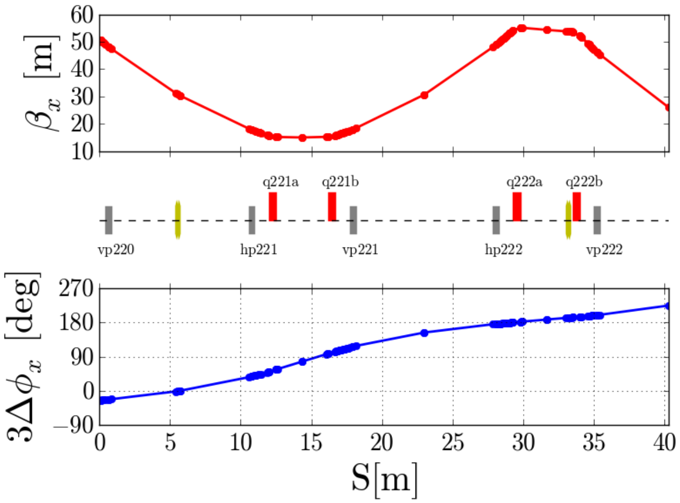


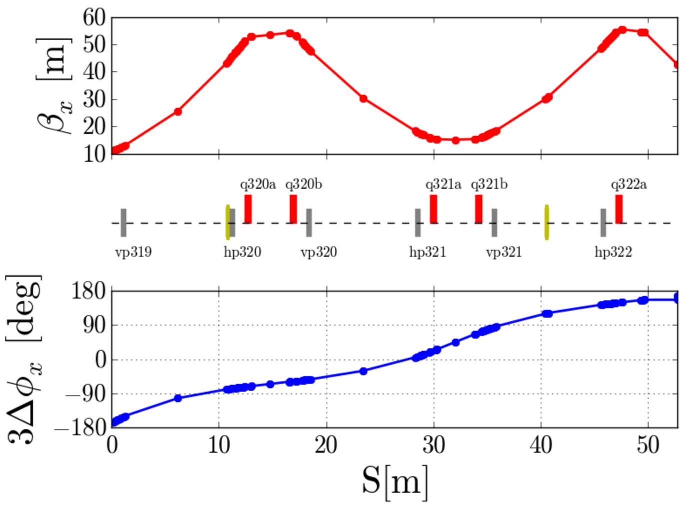
Dedicated scheme installed for 3Qx compensation

Install 8 sextupoles at 4 locations

- 2 at each location
- High beta
- Low dispersion
    - Less effect on chromaticity
    - Less orbit diff for slip-stacking
- Correct phase advance relationship

Skew sextupoles installed this summer to compensate 3Qy



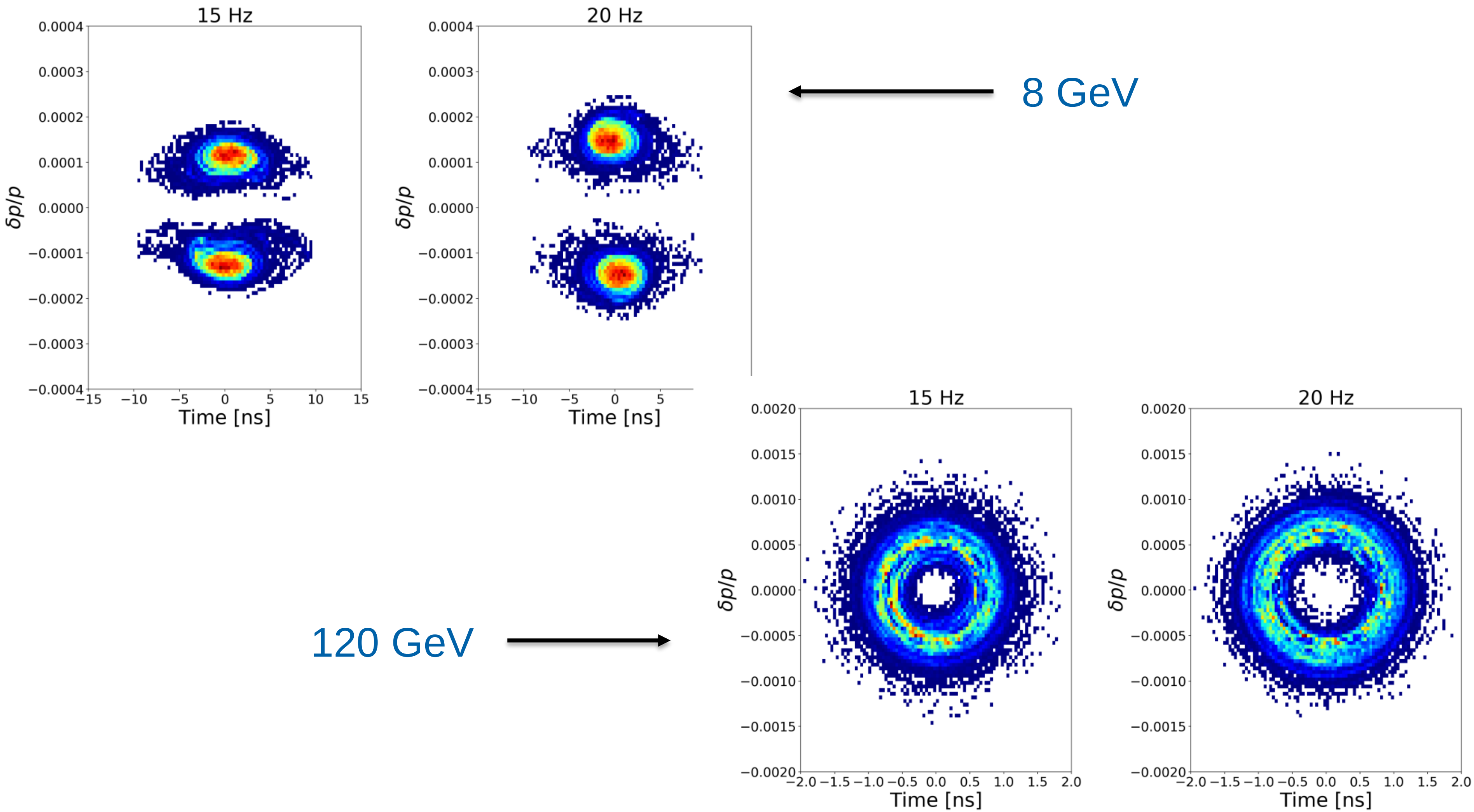


Transition crossing in Main Injector

Slip stacking leads to bunches with large longitudinal emittance

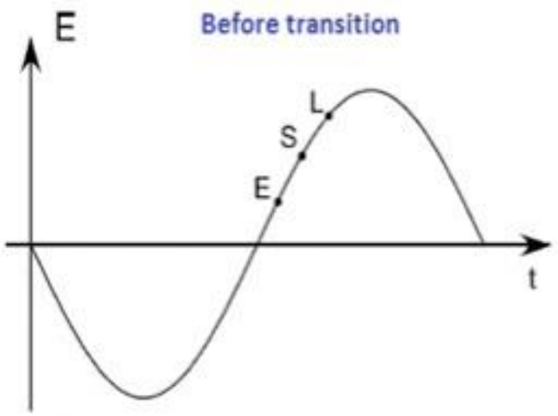
Leads to losses while crossing transition

Slip stacking leads to bunches with large longitudinal emittance

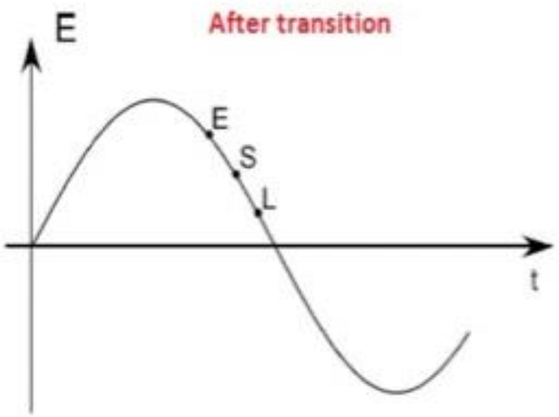


Transition crossing

- Transition occurs when the relative rate of of change of speed β equals the relative increase in path length



- Early (E), on time (S) and late (L) particles in a beam bunch before and after transition.



Transition crossing

- It can be characterized by the non-adiabatic time and the non-linear time
  - Both depend on $\dot{\gamma}$
  - The non-linear time depends on α_1

Non-adiabatic time

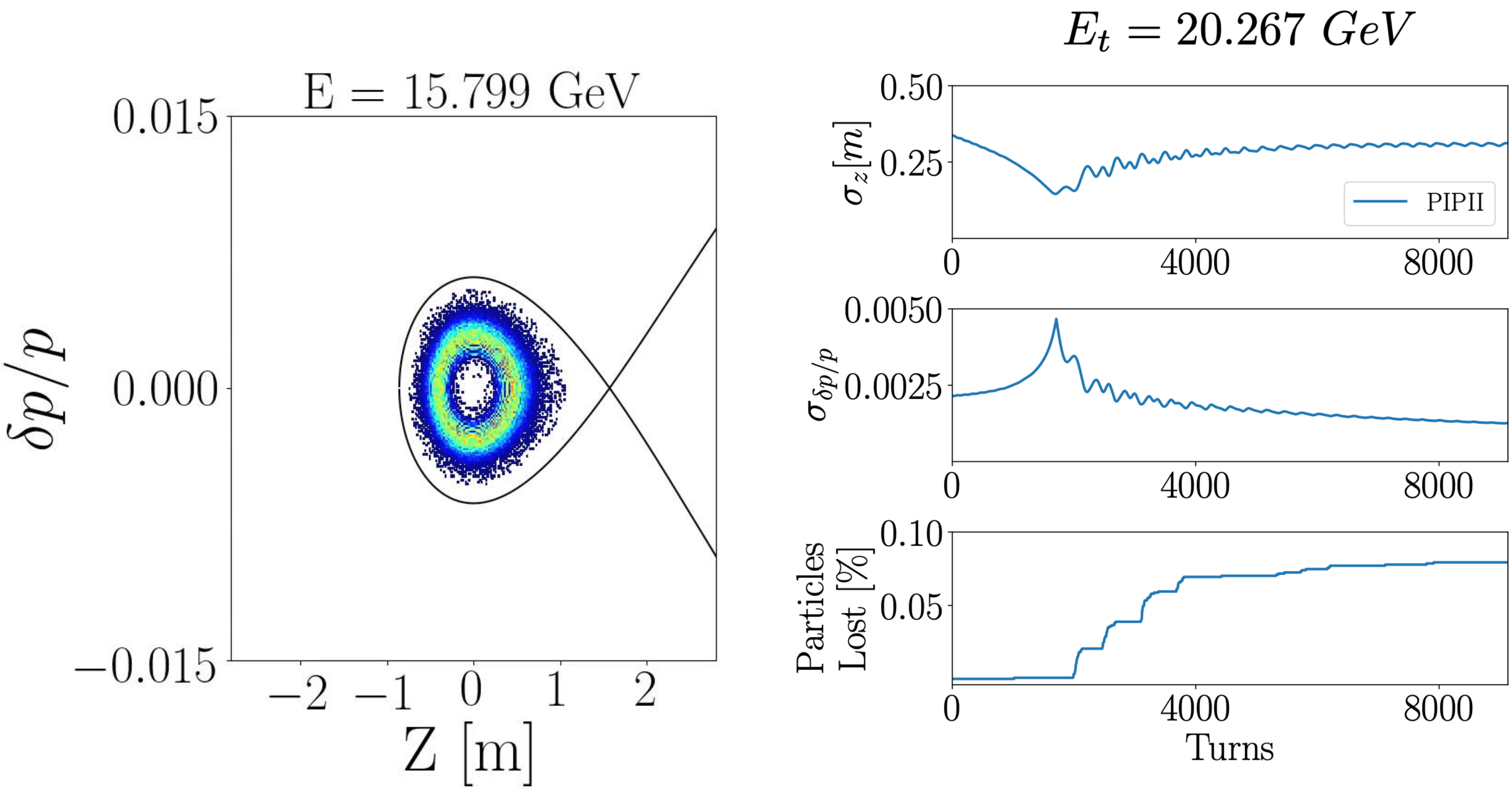
$$t_c = \left(\frac{E_t \gamma_t^3}{V |\cos\phi_s| h \dot{\gamma}} \frac{C_0^2}{4\pi c^2} \right)^{1/3}$$

Non-linear time

$$t_{nl} = \pm \frac{\gamma_t}{\dot{\gamma}} \left[\frac{3}{2} + \frac{\alpha_1}{\alpha_0} - \frac{\alpha_0}{2} \right] \delta p/p$$

$$C(\delta) = C_0[1 + \alpha_0\delta(1 + \alpha_1\delta + \alpha_2\delta^2 + ...)]$$

Transition crossing



Synergia simulation of transition crossing in Main Injector

Transition crossing

- How to reduce/prevent these losses?
  - Cross transition ‘faster’ to reduce t_c and t_{nl}
    - Gamma-t jump
  - Reduce effects from chromatic non-linearities
    - Modify α_1 using sextupoles to make non linear time very small

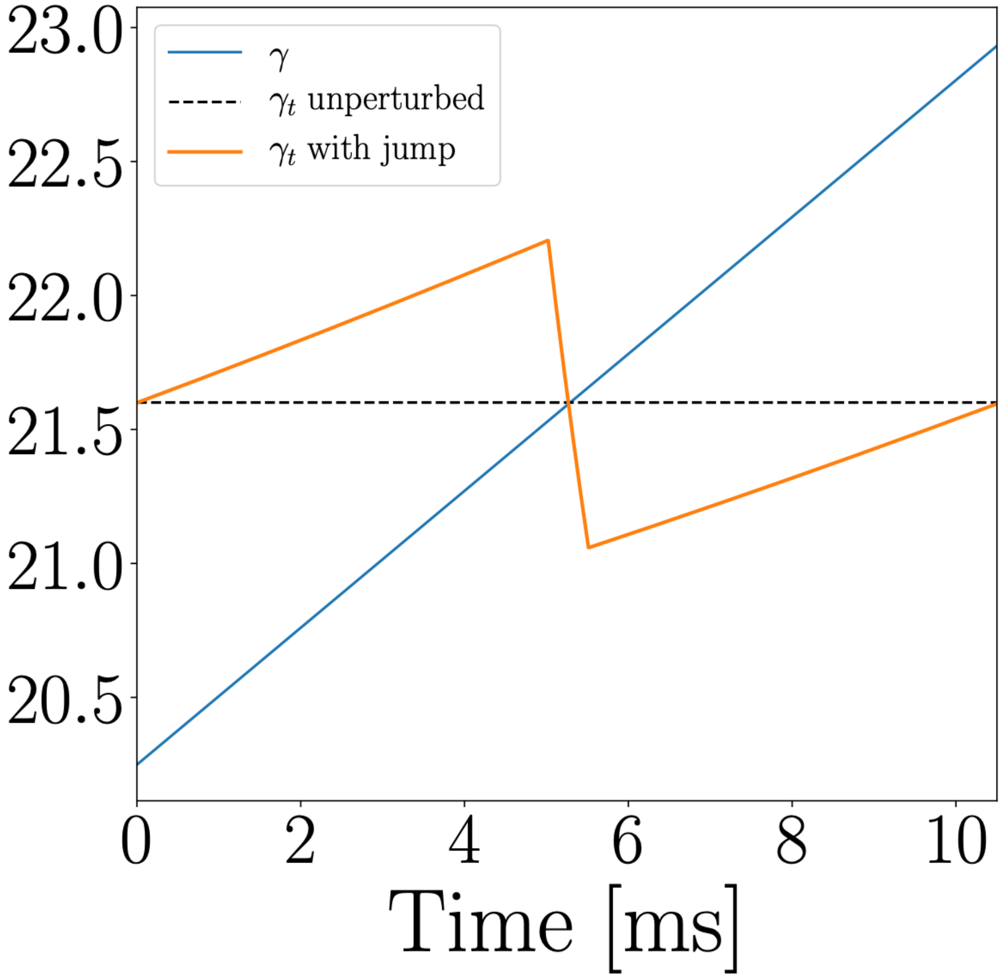
Non-adiabatic time

$$t_c = \left(\frac{E_t \gamma_t^3}{V|\cos\phi_s| h \dot{\gamma}} \frac{C_0^2}{4\pi c^2} \right)^{1/3}$$

Non-linear time

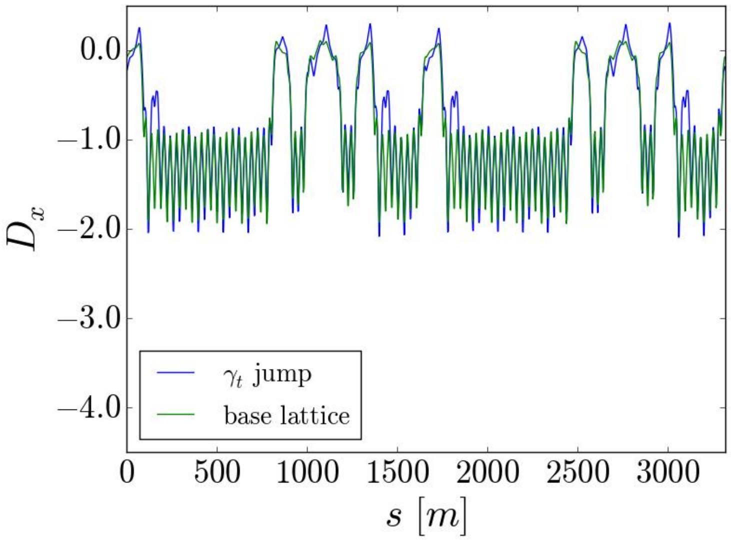
$$t_{nl} = \pm \frac{\gamma_t}{\dot{\gamma}} \left[\frac{3}{2} + \frac{\alpha_1}{\alpha_0} - \frac{\alpha_0}{2} \right] \delta p/p$$

Gamma-t jump



Effectively cross transition quicker using ramped quads

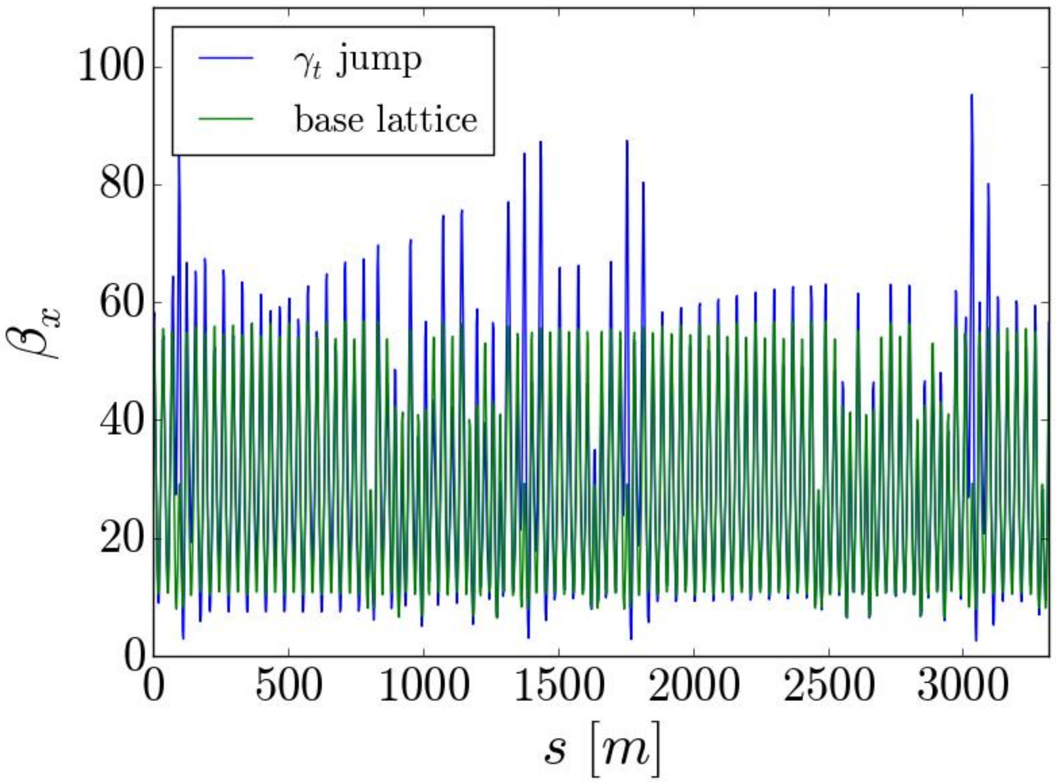
2 quads (0.85 T-m/m) in the arc
1 quad (1.7 T-m/m) in the straight section



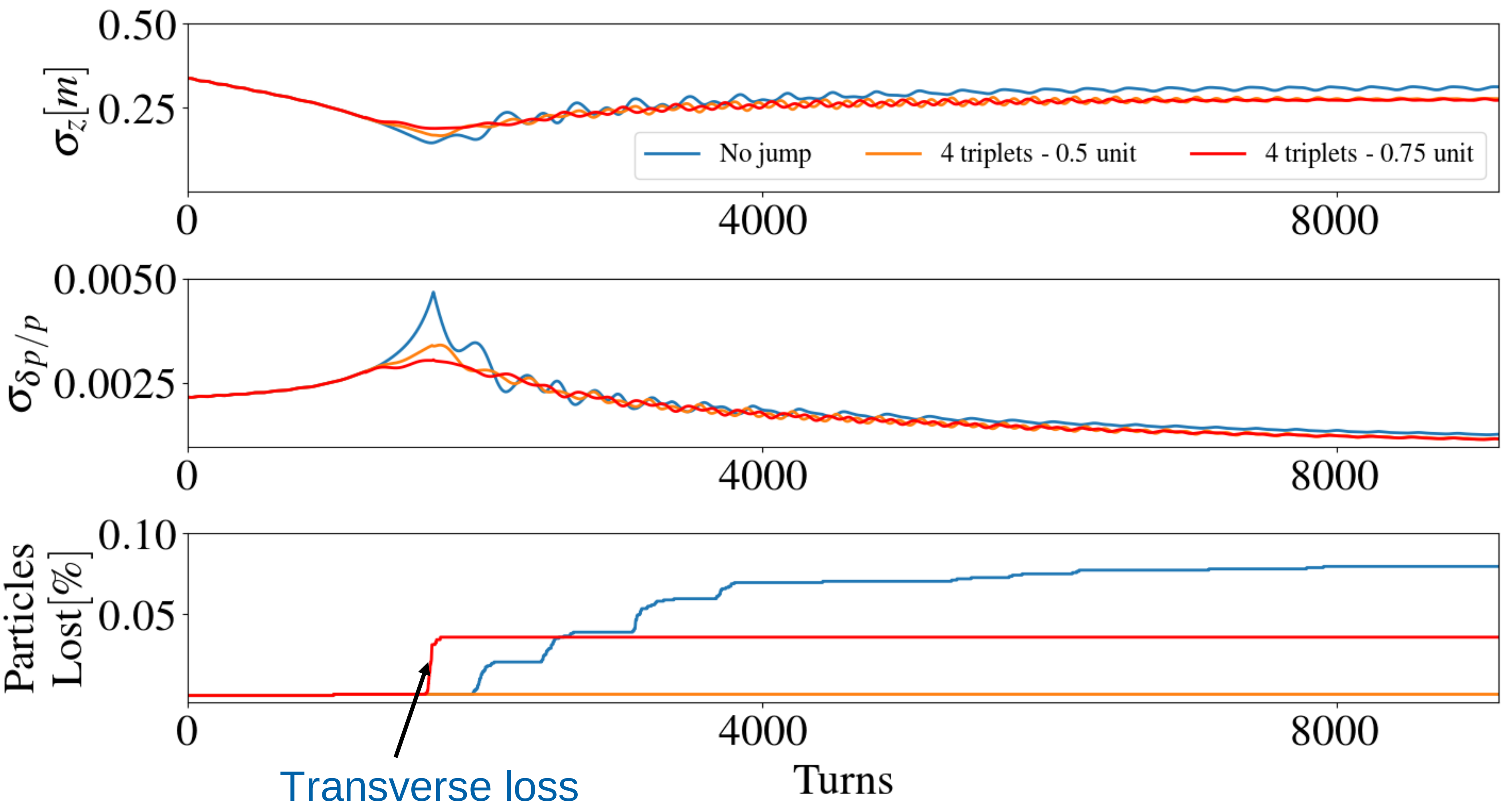
Gamma-t jump

At max of 0.5 unit jump

The quad triplets perturb the lattice
  - large beta-wave
- May have potentially adverse effects on transverse phase space



Gamma-t jump



Fermilab

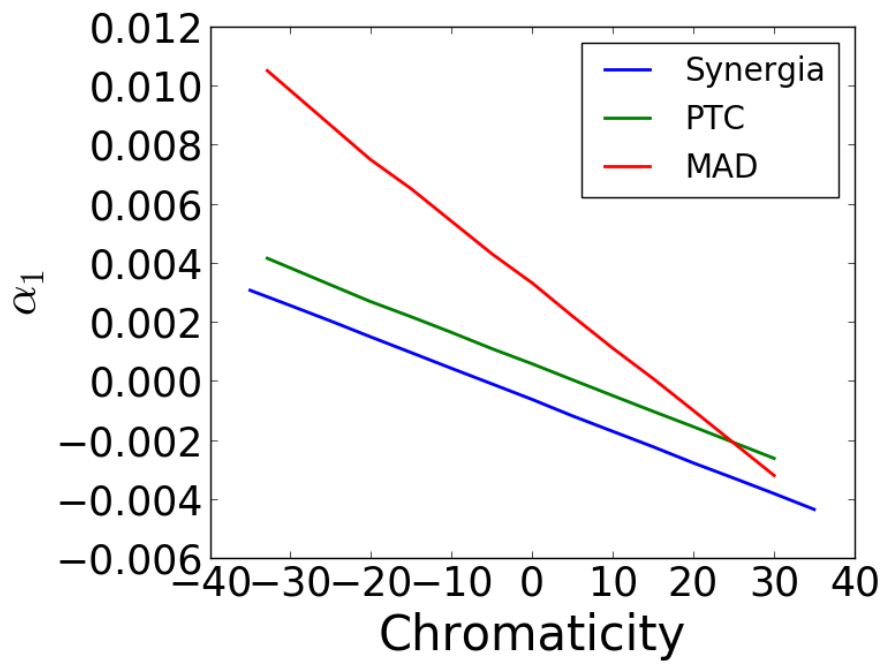
High chromaticity jump

Emittance growth caused by chromatic non-linearities (Johnsen effect) related to nonlinear time

$$t_{nl} = \pm \frac{\gamma_t}{\dot{\gamma}} \left[\frac{3}{2} + \frac{\alpha_1}{\alpha_0} - \frac{\alpha_0}{2} \right] \delta p / p$$

Attempt to make nonlinear time zero by modifying alpha_1 with sextupoles

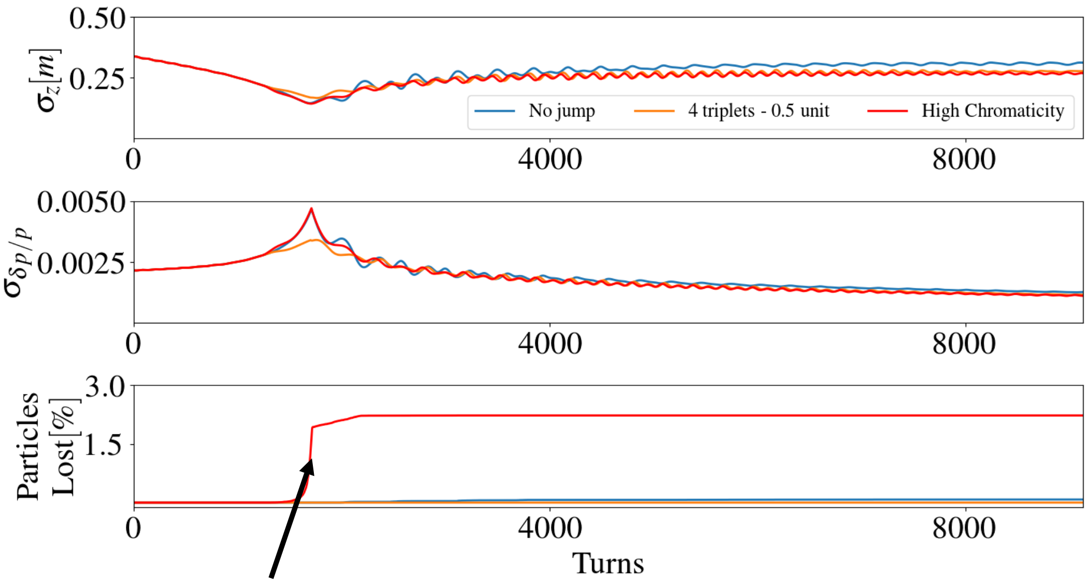
$$\alpha_1 = -\frac{3}{2}\alpha_0 + \frac{1}{2}\alpha_0^2$$
$$\sim -\frac{3}{2}\alpha_0$$



$\alpha_0 = 0.00214$

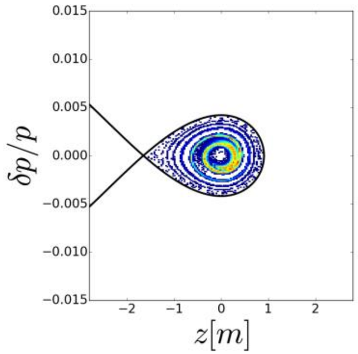
Set chromaticity to +36

High chromaticity jump

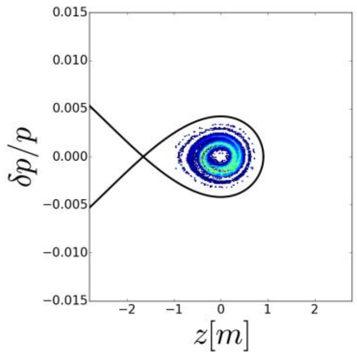


Transverse loss

PIPII

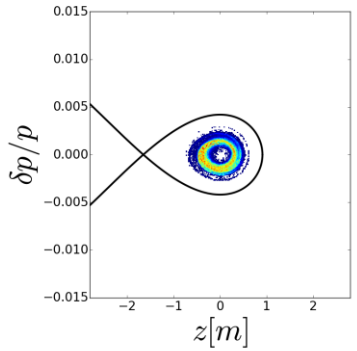


gamma-t



The positive chromaticity jump performs well longitudinally but results in huge transverse losses

high chrom



Fermilab

Instability Studies

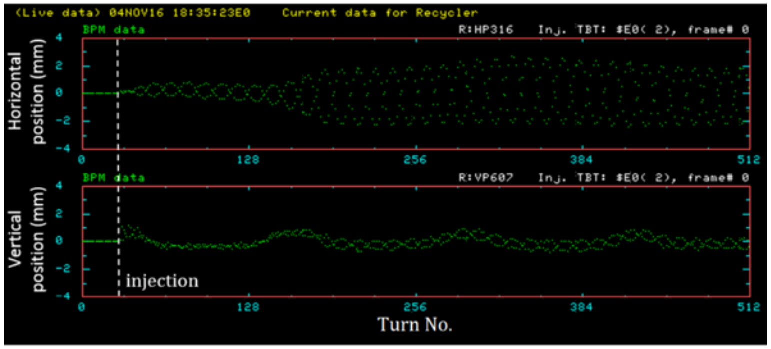
We see instabilities everyday operationally

Some are protected by feedback systems but not all

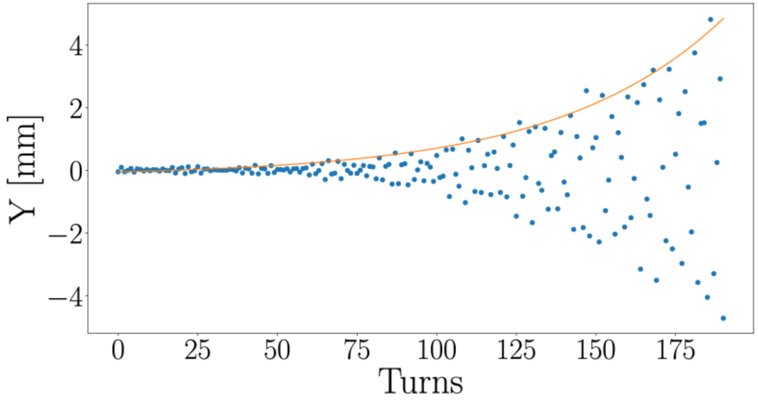
Important to study them to develop mitigation strategies

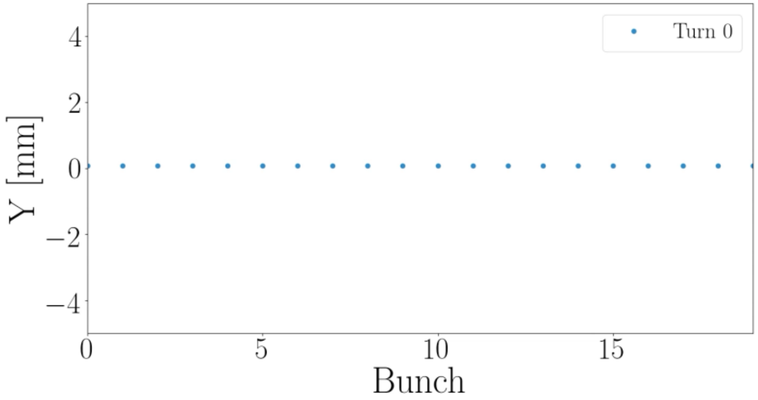
Instabilties

- Electron cloud instabilities
  - Proton bunch interacting with electrons inside the vacuum chamber
  - An issue during commissioning of Recycler



- Coupled bunch instabilities
  - Suppressed by damper system



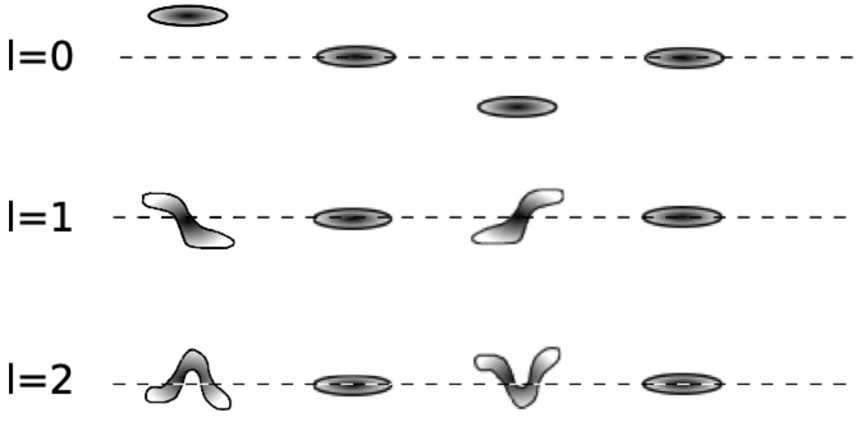


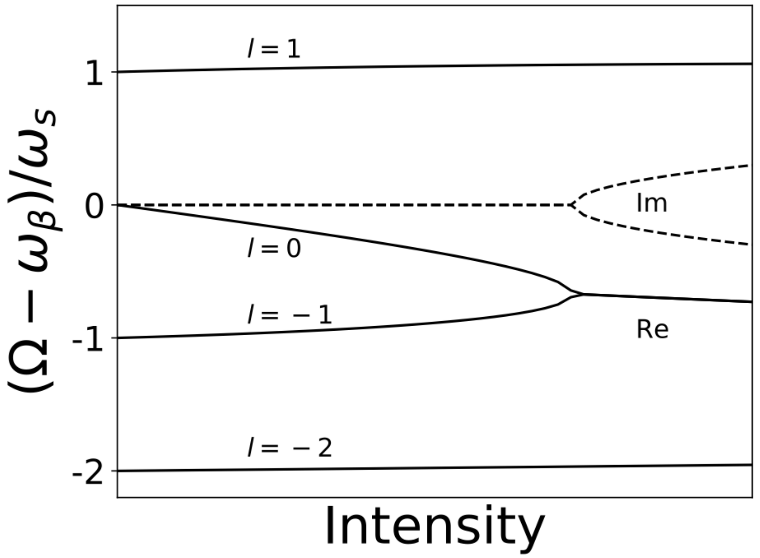
TMCI (Transverse Mode Coupling Instability)

- Bunches oscillate with different transverse modes

- Impedance in a machine can cause a detuning of these modes which scales with intensity

- If the detuning is large enough, the frequencies of two modes couple -> TMCI





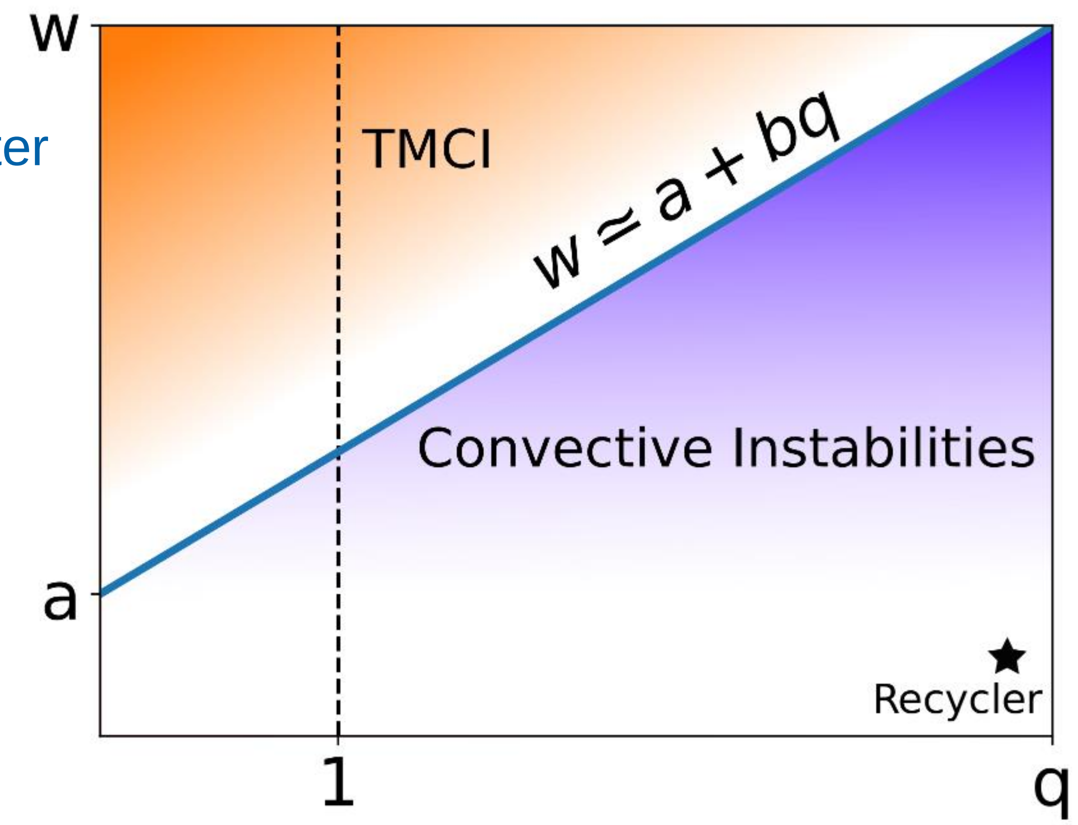
Space charge and TMCI

- For many years, space charge was thought to have a stabilizing effect on TMCI
  - Unusual, increasing intensity i.e. space charge normally makes things worse

- In 2018, Alexey Burov predicted a new kind of instability, convective instabilities
  - Occur in place of TMCI at strong space charge
  - Results in huge amplification from head to tail
  - Traditional dampers may make things worse

Space charge - wake plane

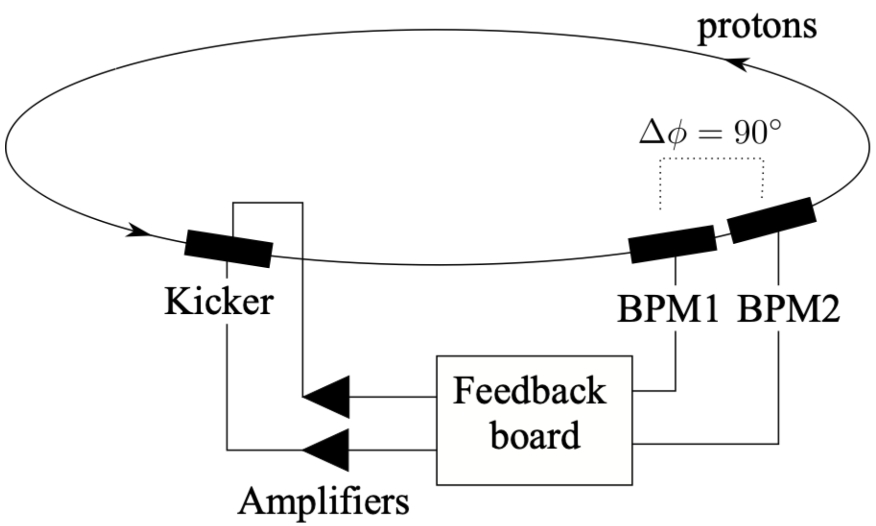
Wake parameter



Space charge parameter

Waker system

- New experimental program at FNAL studying instabilities
- High bandwidth anti-damper system to excite instabilities
- Test and verify theoretical predictions on instabilities
- First beam tests ~ Feb 2021



Post doc position at FNAL on instabilities

Job Description

Open Date: October 7, 2020

Close Date: November 4, 2020

Fermi National Accelerator Laboratory (known as Fermilab) seeks highly qualified candidates for a **Postdoctoral Research Associate** position focusing on instabilities in high power proton beams.

Fermilab is America's premier laboratory for particle physics and accelerator research, funded by tl U.S. Department of Energy. We support discovery science experiments in Illinois and South Dakot and at locations around the world, including Canada, mountaintops in Arizona and Chile, and the South Pole.

Successful delivery of intensity frontier science at Fermilab requires MW class particle beams. For these beams to be delivered reliably and with minimal losses, it is essential that the particle bunche remain stable.

Fermilab, an established world leader in research of beam instabilities, initiated a new dedicated research program investigating beam instabilities in rings. The research will characterize particle bunch instabilities in the presence of varying space charge and varying wake amplitudes. This will include an experimental program, which makes use of Fermilab's existing accelerator complex, along with a set of complementary simulations.

The position is for a period of up to three (3) years, with the potential for extension considered on a yearly basis thereafter.

You Will

- Perform accelerator studies focusing on beam instabilities.
- Contribute to development of hardware to excite, control and measure beam instabilities.
- Use Accelerator codes such as Synergia or PyHEADTAIL to simulate beam instabilities.
- Travel to conferences and present reports on your work.
- Abide by all environment, safety and health regulations.

Qualifications and Essential Job Functions

- Ph.D. in Experimental Physics or Engineering
- Knowledge of Accelerator and Computational Physics is preferred.
- Respect, understand, and value individual differences that embody the principles of diversi

Application Instructions

Interested candidates should submit via Academic Jobs Online:

- Cover letter
- Curriculum Vitae
- Research Statement
- Publication List
- Three Reference Letters (to be submitted by the reference writers at the AJO site)

https://academicjobsonline.org/ajo/jobs/17107

For general information about this position, please contact Rob Ainsworth at rainswor@fnal.gov

https://academicjobsonline.org/ajo/jobs/17107

Summary

- The Main Injector and Recycler currently support 700 kW operations

- Significant challenges to operate the Recycler and Main Injector at PIP-II intensities
  - Addressed some in this talk
    - Space charge tune shifts
    - Transition crossing
    - Instabilties

- Mitigation strategies also discussed
  - Resonance correction
  - Gamma-t jump

- Need to make sure the Recycler and Main Injector are ready to deliver 1.2 MW reliably

Back-up

Current limits

- Power limits
  - Current limit 54E12 (NuMI target limit). This corresponds to 777 KW with 1.33 sec cycle time.
  - MI is limited by the available RF power to 62E12 which corresponds to 892 KW with 1.33 sec

RR momentum aperture

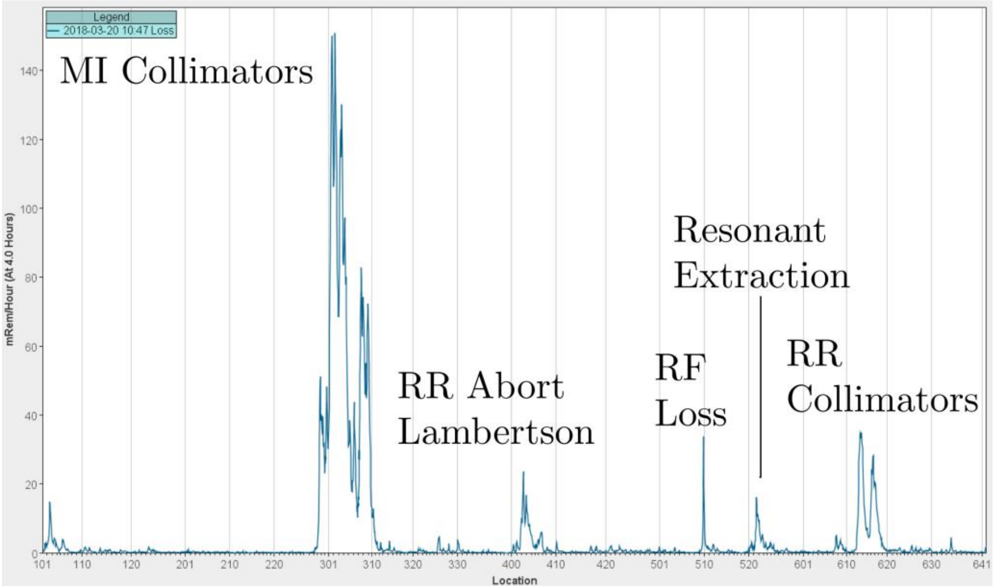
- -0.36 -> 0.23% aperture at 15 Hz
- inject off-momentum for 20 Hz
  - -+0.27%
- 0.45% momentum aperture

Uncaptured beam

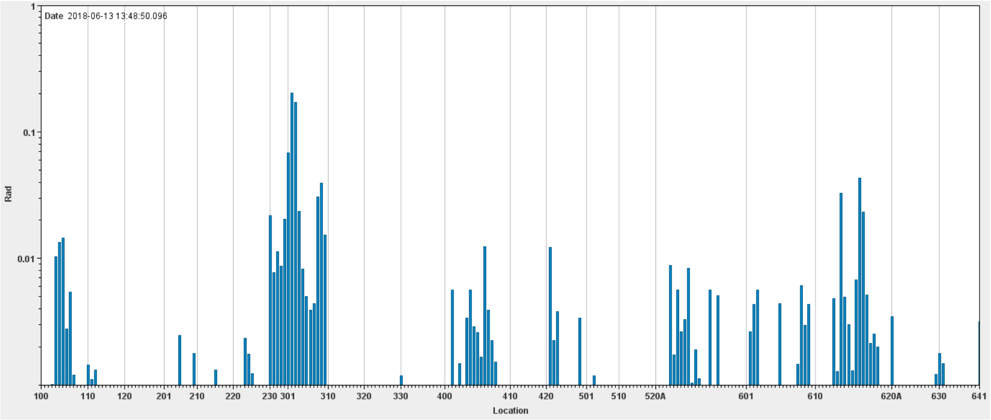
Case	σ_t [ns]	$\sigma_{\delta/p}$	Un-captured beam [%]
Base	1.9	0.0003	0.03
Base Phase Offset	2.3	0.00035	0.06
PIPII	1.57	0.00034	0.01
PIPII Phase Offset	2.02	0.00042	0.011

Radiation Survey around Ring

DALE survey

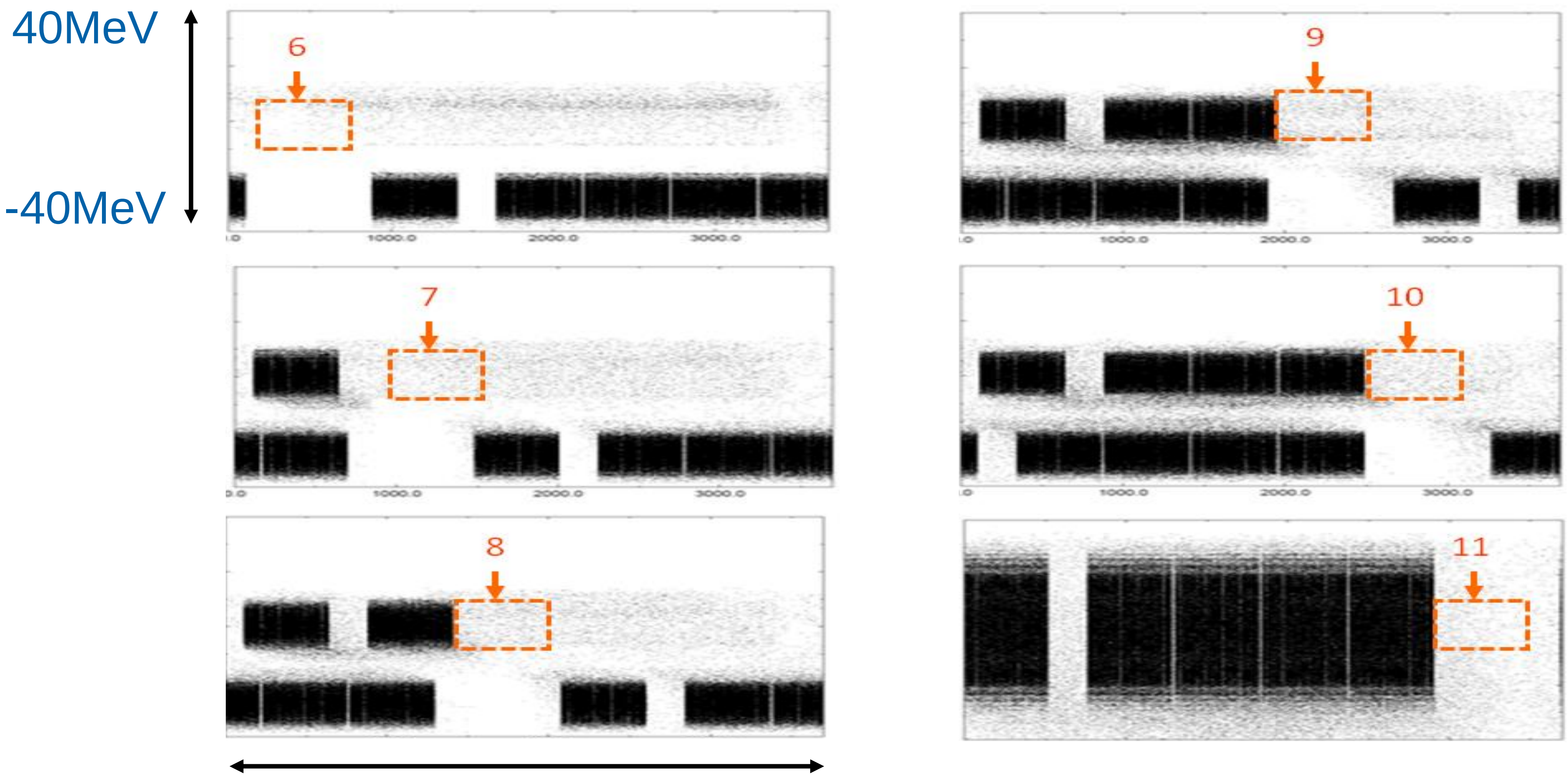


Loss monitors



Beam in the gap & un-captured beam

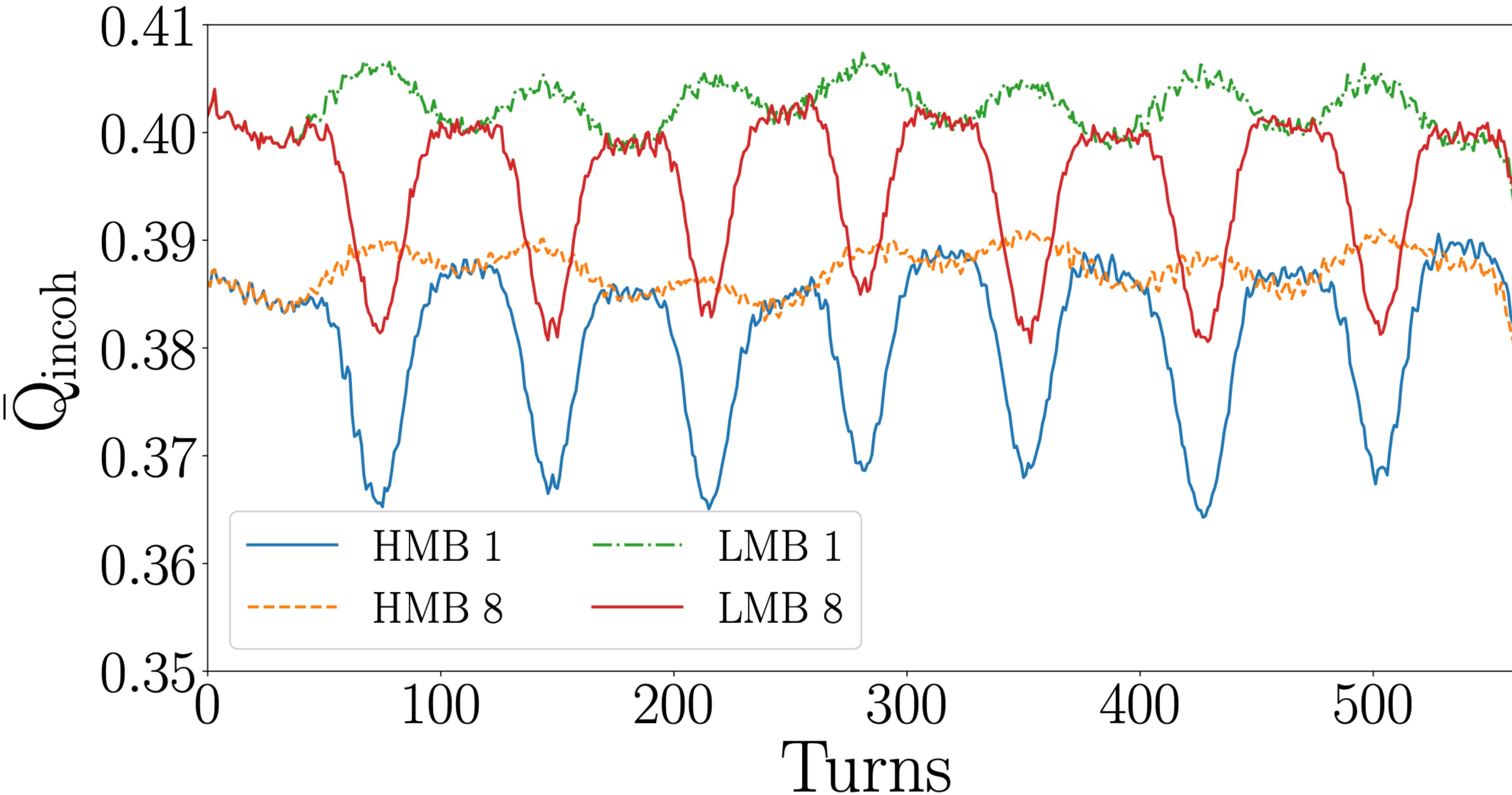
Simulation



588 buckets

Gap clearing kickers fire before every injection sending beam to abort

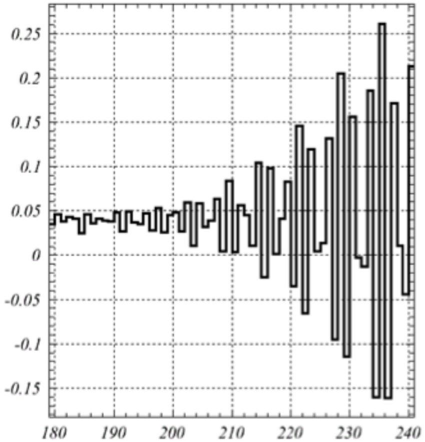
Footprint vs turn



Mean of horizontal tune distribution

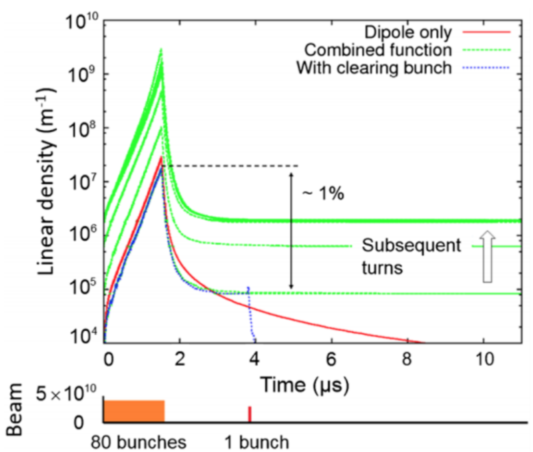
Fast instability

- A fast instability was observed in the Recycler but not in the Main Injector



Observed on BPMs, growth rate 10-15turns

S. Antipov

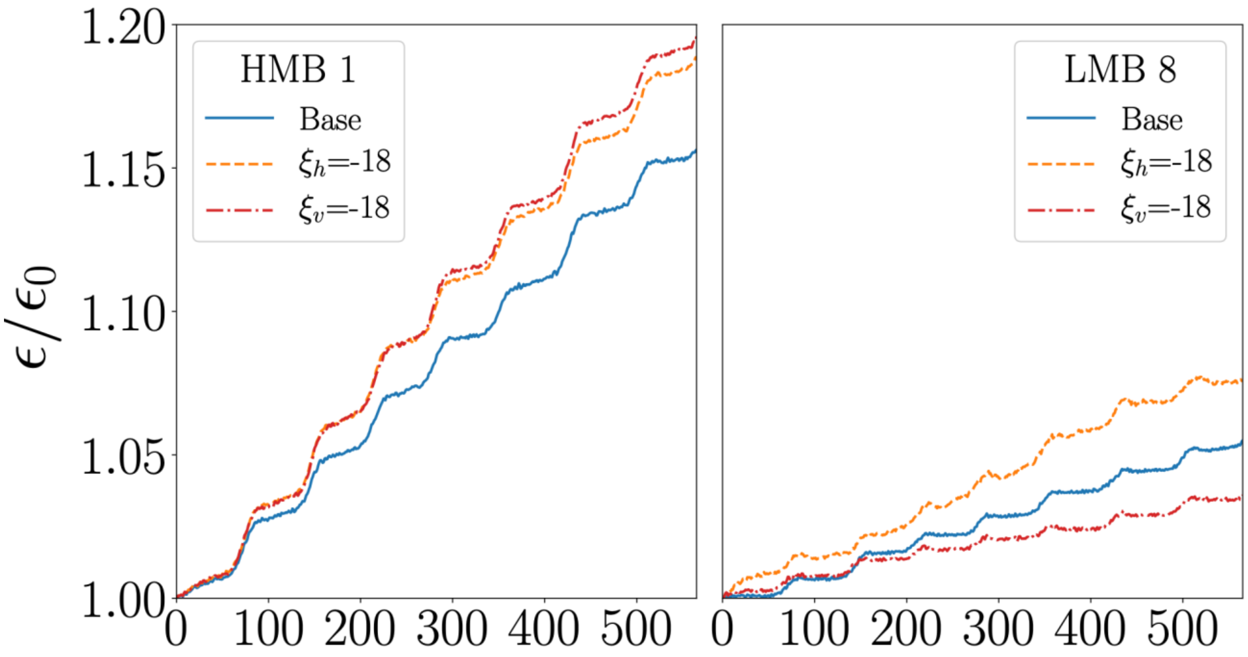


- Growth too fast to be stabilized by dampers

- Eventually, attributed to electron trapping in the combined function magnets

Chromaticity

Base parameters, 1e11ppb (double 700kW)



Higher Chromaticity also increases growth in general

Off-Momentum sees slight improvement due shift from chromaticity

1st order scheme