Fermilab

February 13, 2026

Integrated Diagnostic for Mode Coupling in the Fermilab Booster

Michael Balcewicz
Research Associate

U.S. DEPARTMENT of ENERGY
Fermi National Accelerator Laboratory is managed by FermiForward for the U.S. Department of Energy Office of Science

FERMI NATIONAL ACCELERATOR LABORATORY

Abstract

The interplay between longitudinal to transverse dimensions is an emerging challenge at the Fermilab Booster. Beyond an intensity threshold, mode coupling instabilities can be excited which cause catastrophic particle losses. By combining new longitudinal and transverse diagnostics over the entire ramp, it is possible to measure coupling and create online and offline diagnostics to characterize instabilities and minimize losses in the Booster.

Take Aways

Fermilab accelerator complex focused on PIP-II and LBNF/DUNE. To succeed we must solve anything that may slow or limit operations

1. PIP-II era Booster will operate at higher intensity with fewer losses
2. Mode coupling instability observed around beam transition at PIP-II intensities
3. Better instrumentation/tools needed to reliably dampen beam instabilities and better understand Booster
4. A combined integrated diagnostic that measures the entire Booster ramp longitudinally and transversely is needed to prepare us for PIP-II

01

PIP-II Era Booster

Booster at a Glance

For the sake of time, I won't go into detail about the Booster, but a few quick things to note

- 24 FOFDOOD sectors, each of same length
- 48 corrector packages
- GMPS gives sinusoidal energy ramp
- Cogging System provides synchronism with MI and Recycler
- Operational intensity 4.5e12 ppp

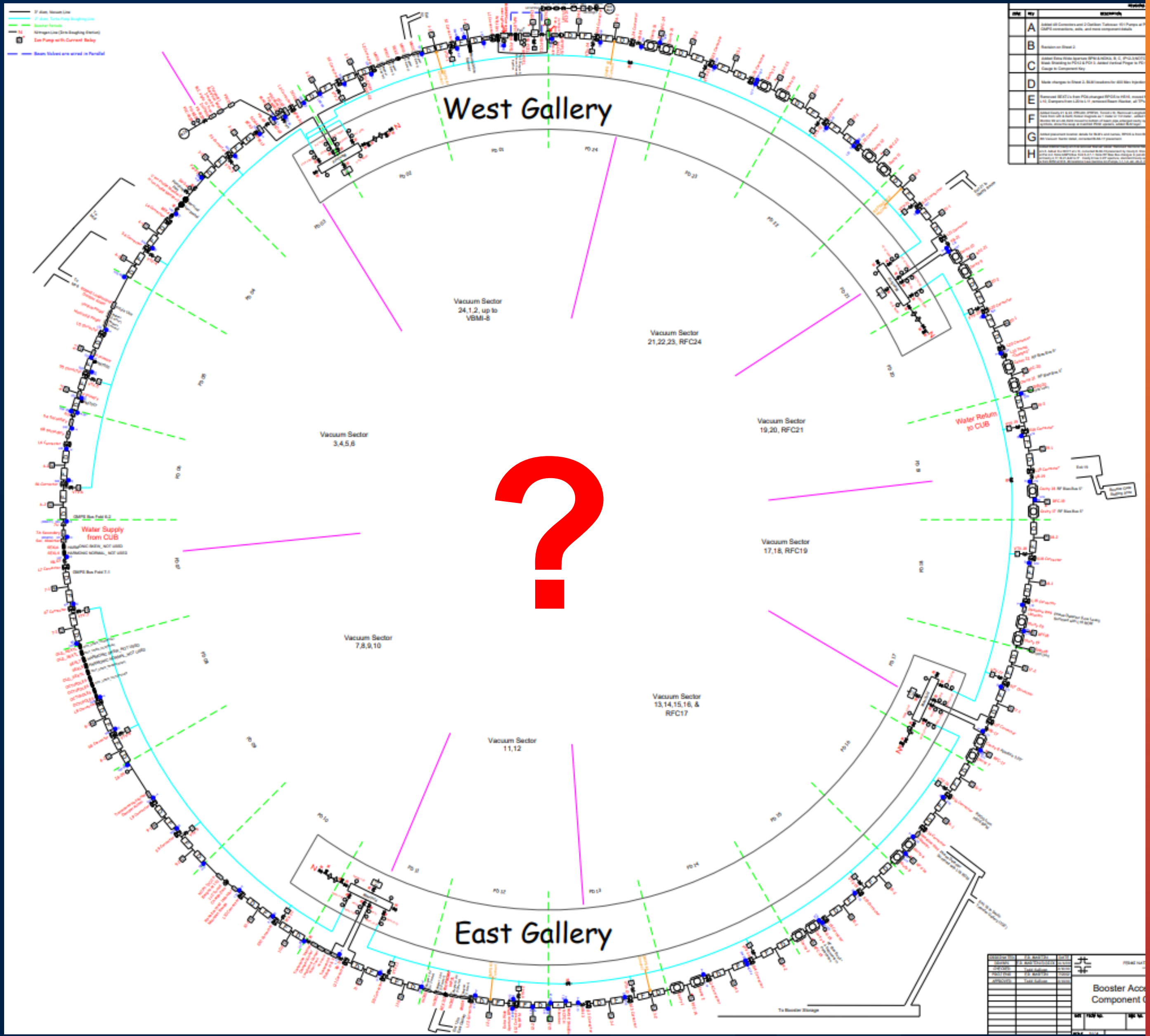
But the Booster Works, Right?

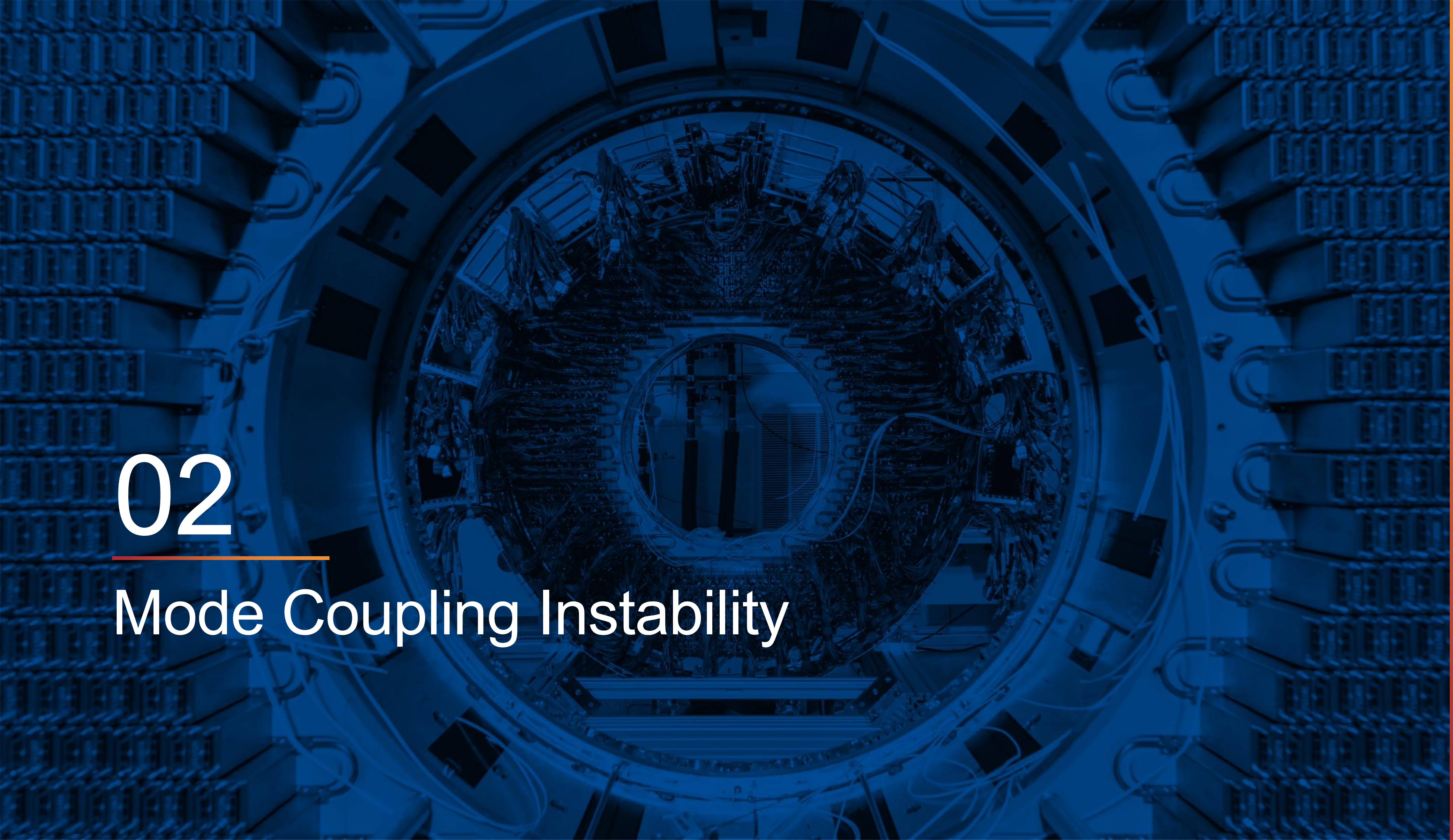
PIP-II really changes booster operations and expects more from Booster

- ~~24 FOFDOOD sectors, each of same length~~ Injection region shortened
- ~~48 corrector packages~~ Higher order correctors follow common* ramps
- GMPS gives sinusoidal energy ramp; GMPS has significant jitter, and must accommodate flat injection
- Cogging System and other feedback less effective at higher beam rigidity
- Operational intensity ~~4.5e12~~ 6.7e12 ppp, past instability threshold at γ_t transition

Central Issue

- Leaving a state with operational experience
- More importantly current operating conditions have subtle assumptions we are breaking
- All share a complicating factor, the contribution of coupling between dimensions*.





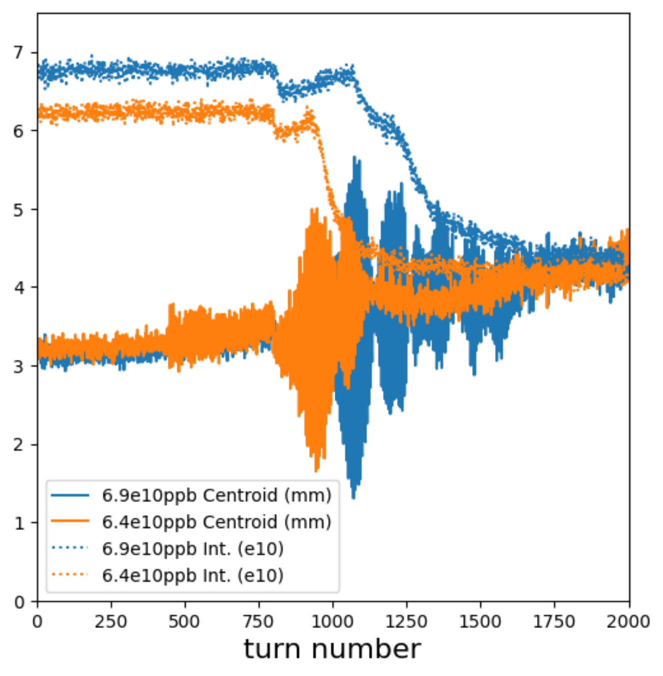
02

Mode Coupling Instability

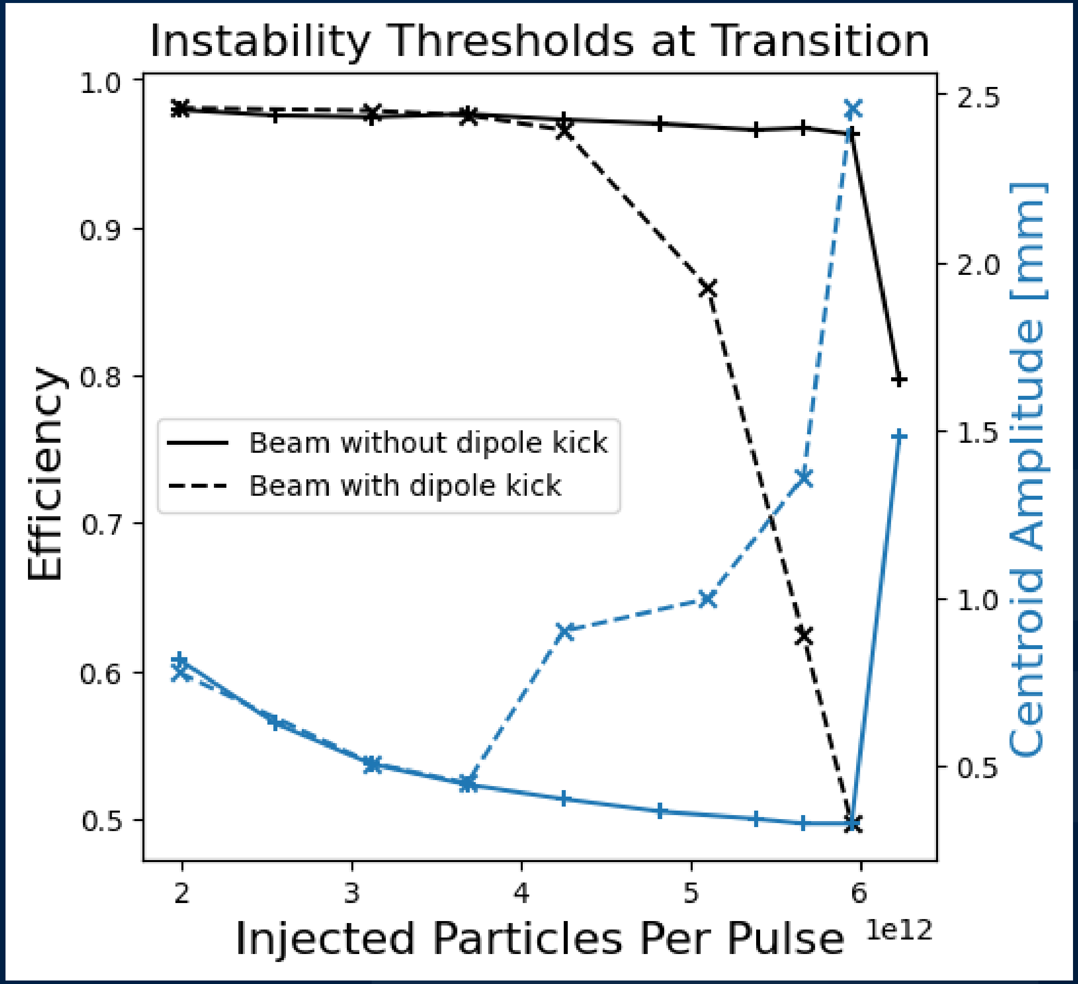
Transition Beam Loss

- Sudden beam loss observed in 2019, in depth study in 2023
- Past intensity threshold, some bunches generate large bunch tails and losses
- Could it be from phase jump?

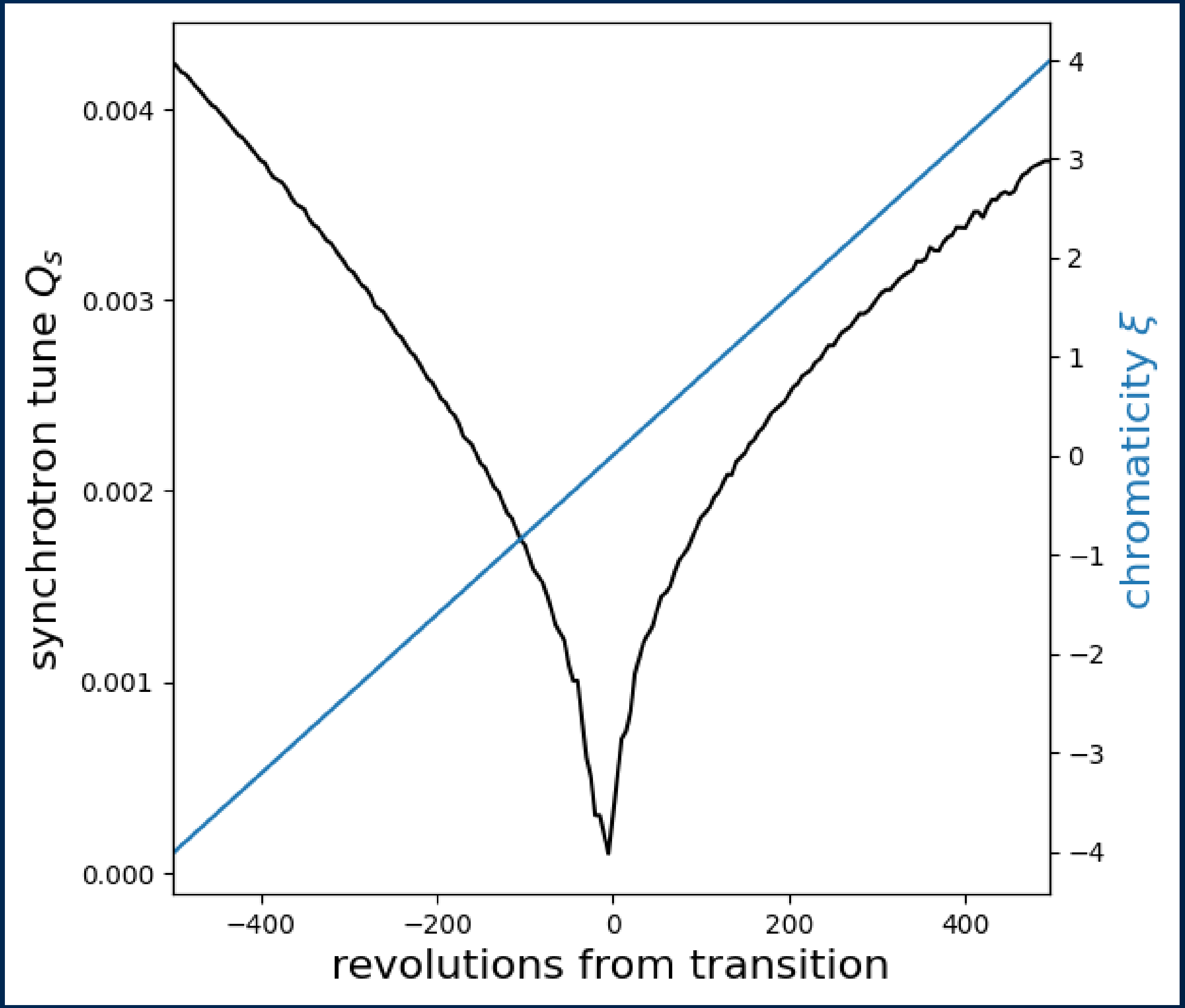
Dipole Motion Excited



Losses Occur Beyond Threshold

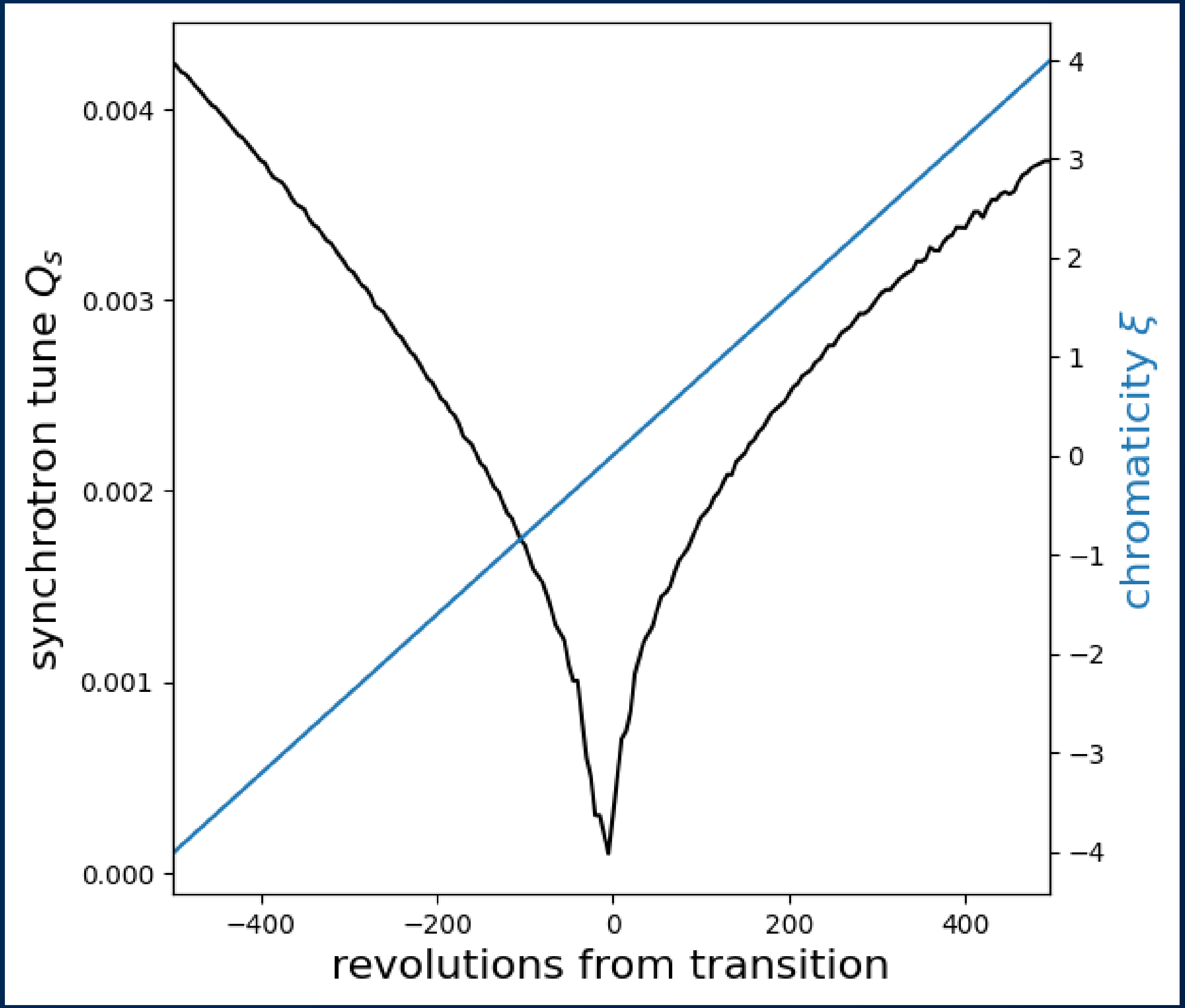


What's Special about γ_t Transition?



- Synchrotron oscillations temporarily stop
- Space charge and wakes become >> Q_s
- Chromaticity crosses 0
- Loss of Landau damping

What's Special about γ_t Transition?



- Synchrotron oscillations temporarily stop
- Space charge and wakes become >> Q_s
- Chromaticity crosses 0
- Loss of Landau damping

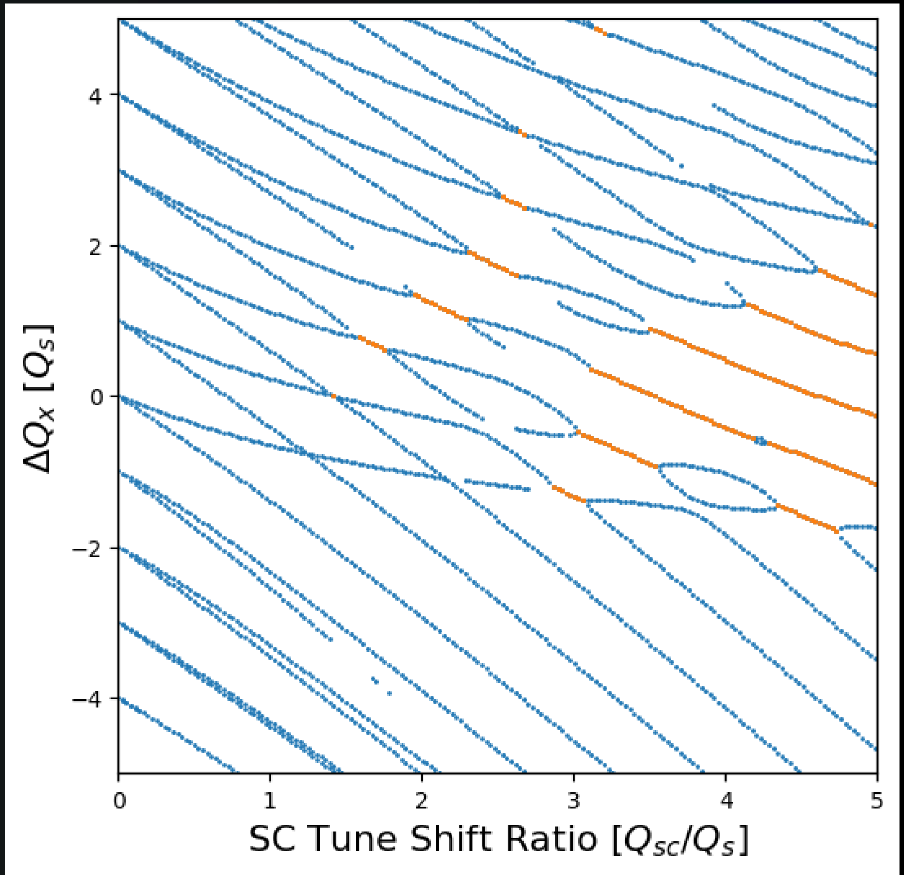
Unstable to Mode Coupling Instabilities!

Synchro Betatron Coupling: Modes

- Trans. motion with long. coupling can be represented synch sideband modes over length
- Combination of single particle and collective motion shift sideband modes ($\xi,\ \Delta Q_w,\ \Delta Q_{sc}$)
- Distance between modes synchrotron tune Q_s

- Developed semi-analytic model for these instabilities as part of graduate work
- Booster at transition is a mixture of three instabilities

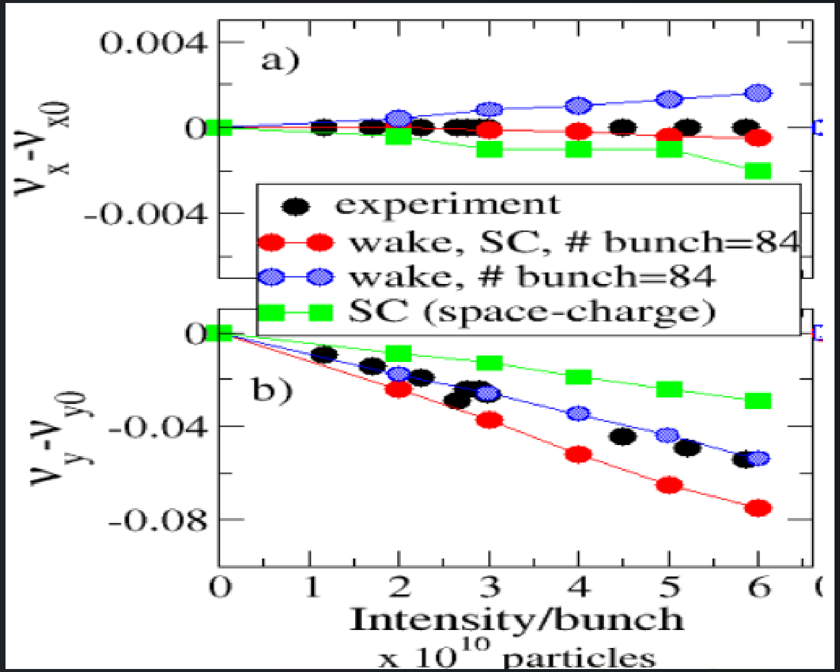
Mode Coupling Instability Diagram



Synchro Betatron Coupling: TMCI

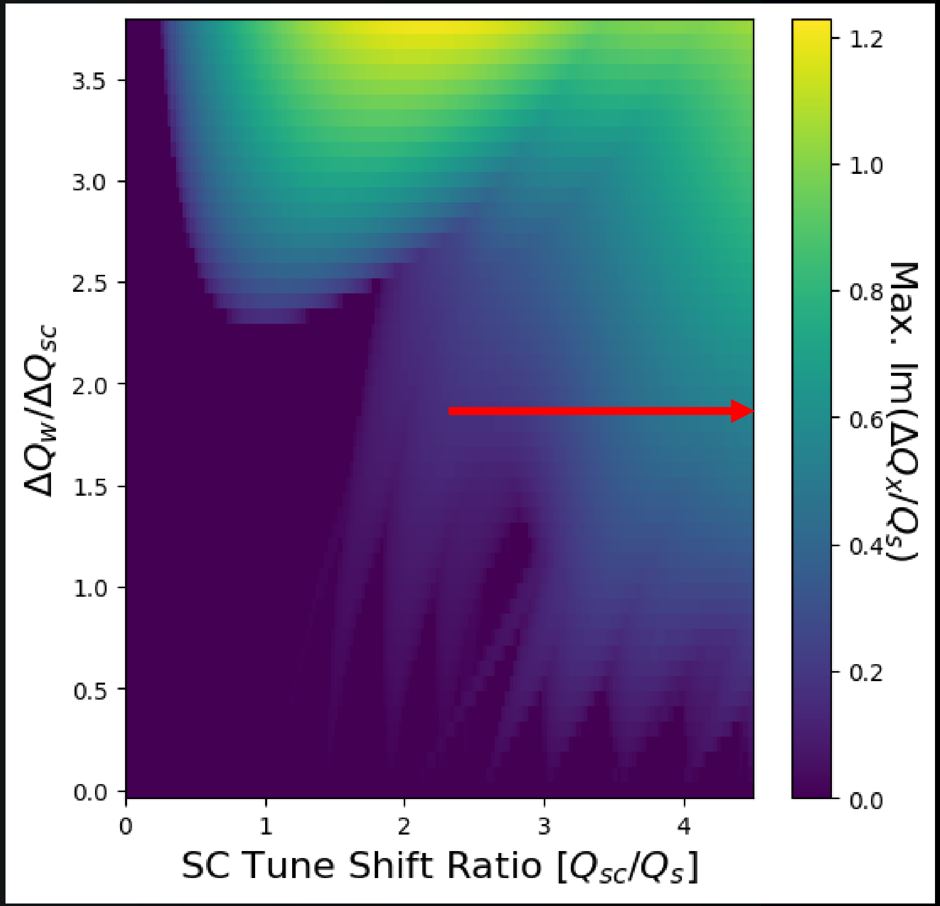
- Transverse Mode Coupling Instability (TMCI)
- Scales with wakes and (sometimes) damped by space charge
- Grows exponentially every revolution

Tune Shift: Simulations and Experiments



$$\frac{\Delta Q_w}{\Delta Q_{sc}} \approx \frac{11}{6}$$

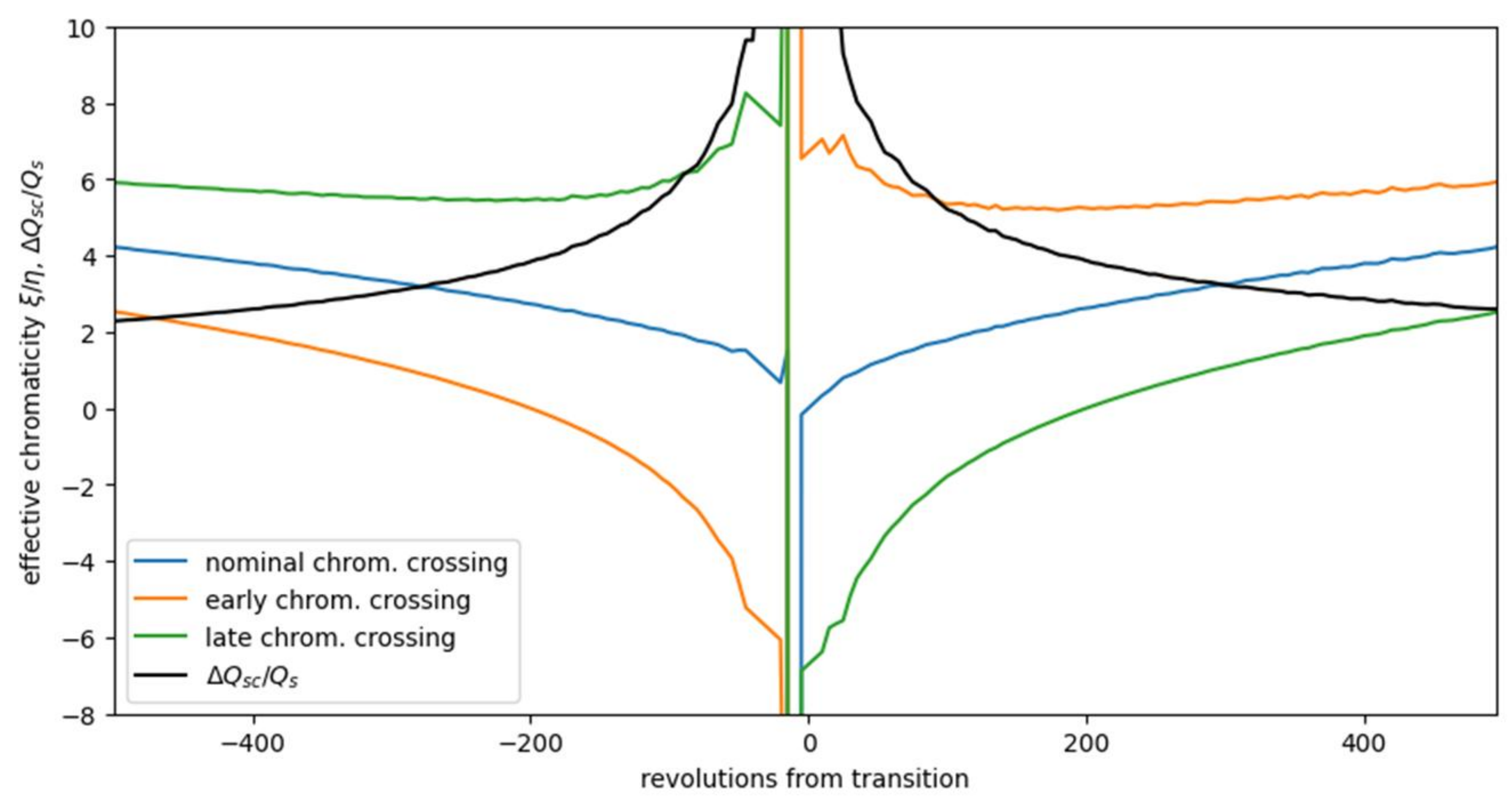
Growth rate of most unstable TMCI mode



$$\left.\frac{\Delta Q_{sc}}{Q_s}\right|_{\gamma\approx\gamma_t} \geq 2.25$$

Synchro Betatron Coupling: Head-Tail

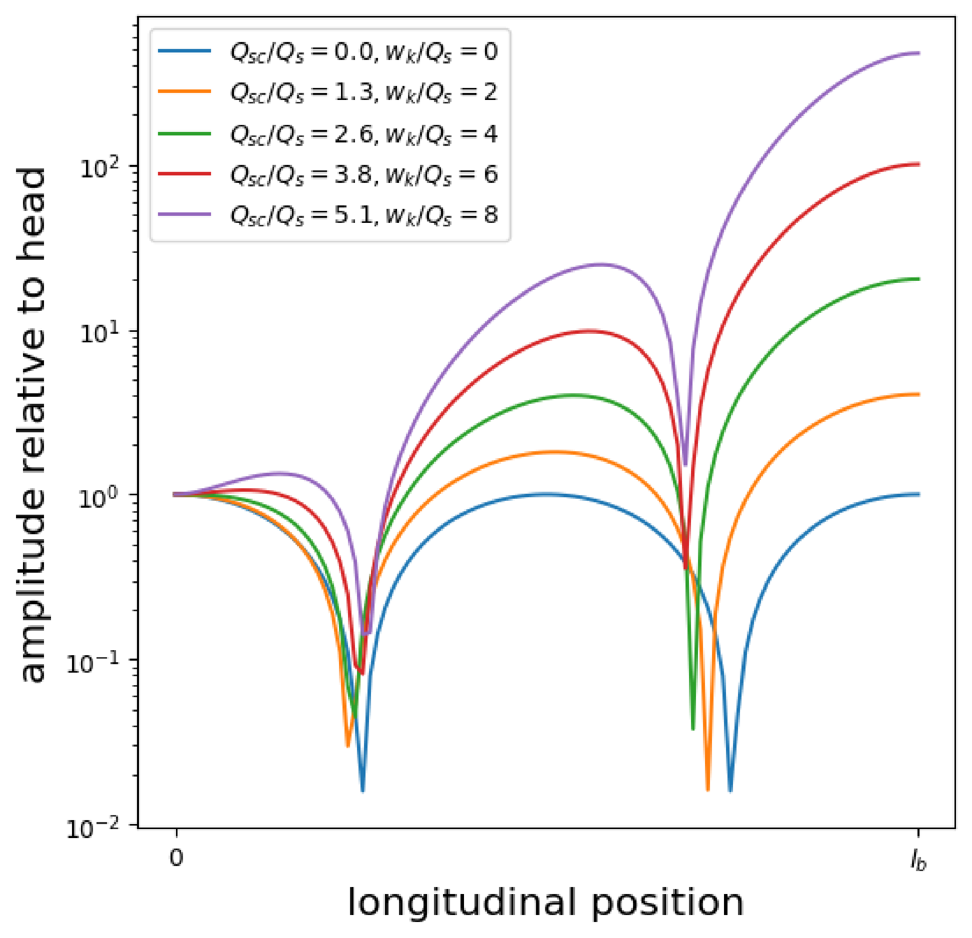
- Occurs when chromaticity is large, opposite sign as η
- Grows exponentially every revolution



- Scales with effective chromaticity ξ_{eff} where $\xi_{eff} = \xi/\eta$

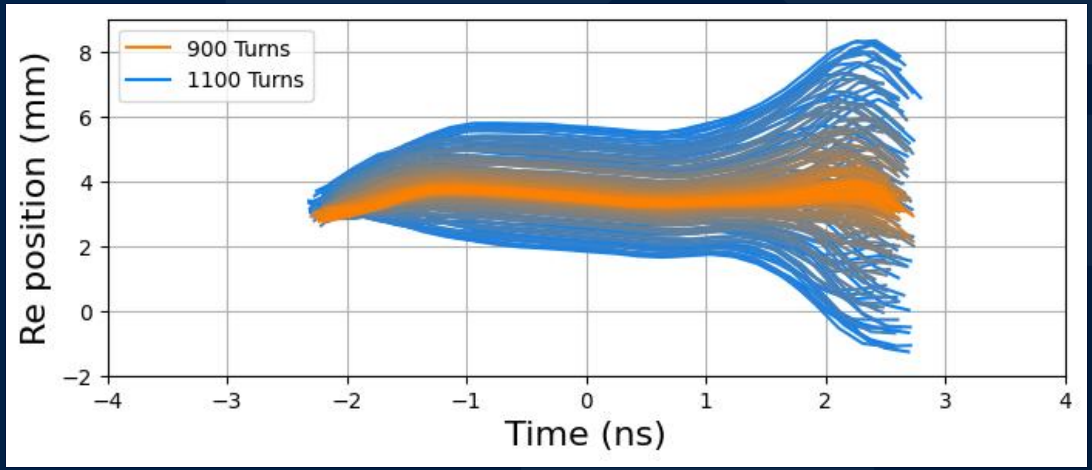
Synchro Betatron Coupling: Convective

Simulated Head Tail Amp.



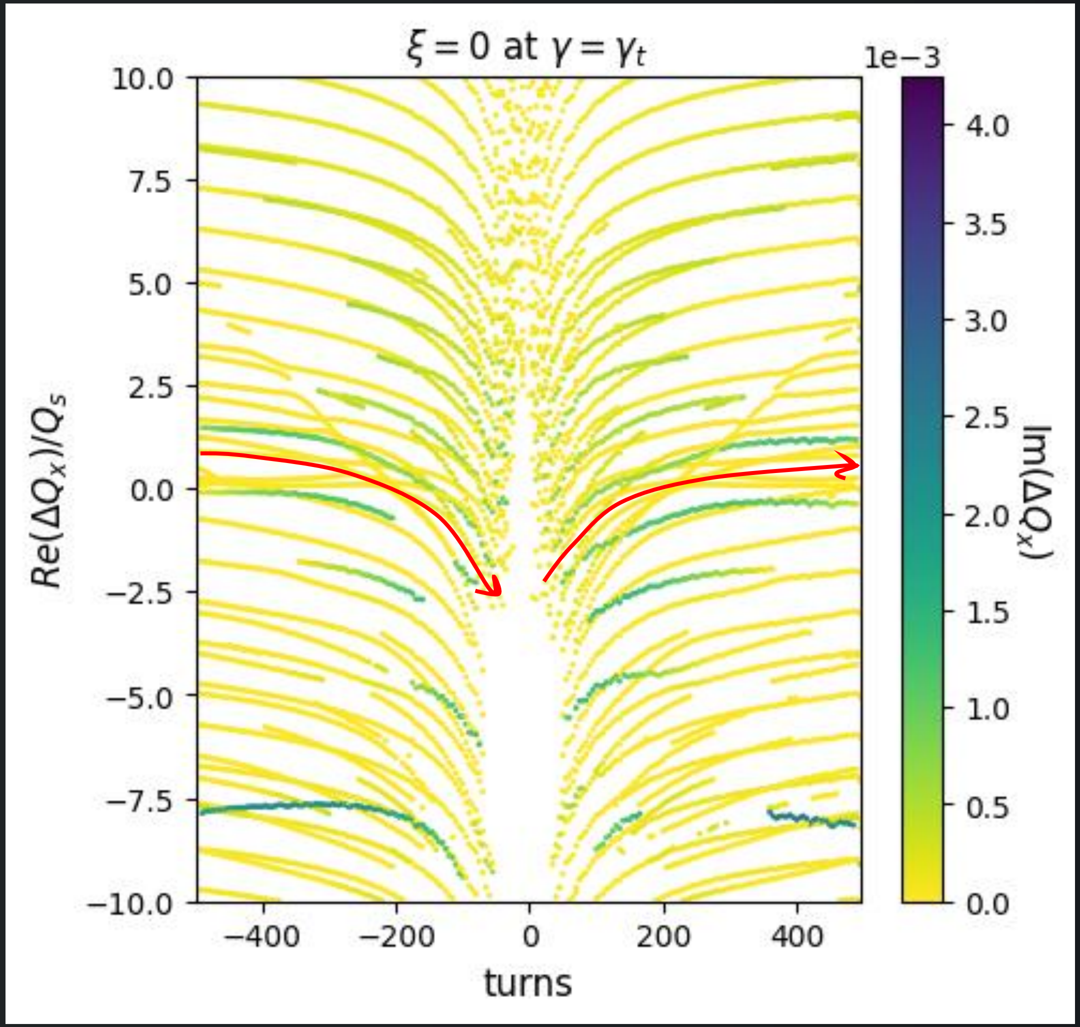
- Accumulating wakes and space charge creates large difference in amplitude at head and tail
- ‘Head tail amplification’
- Saturates at maximum amplitude

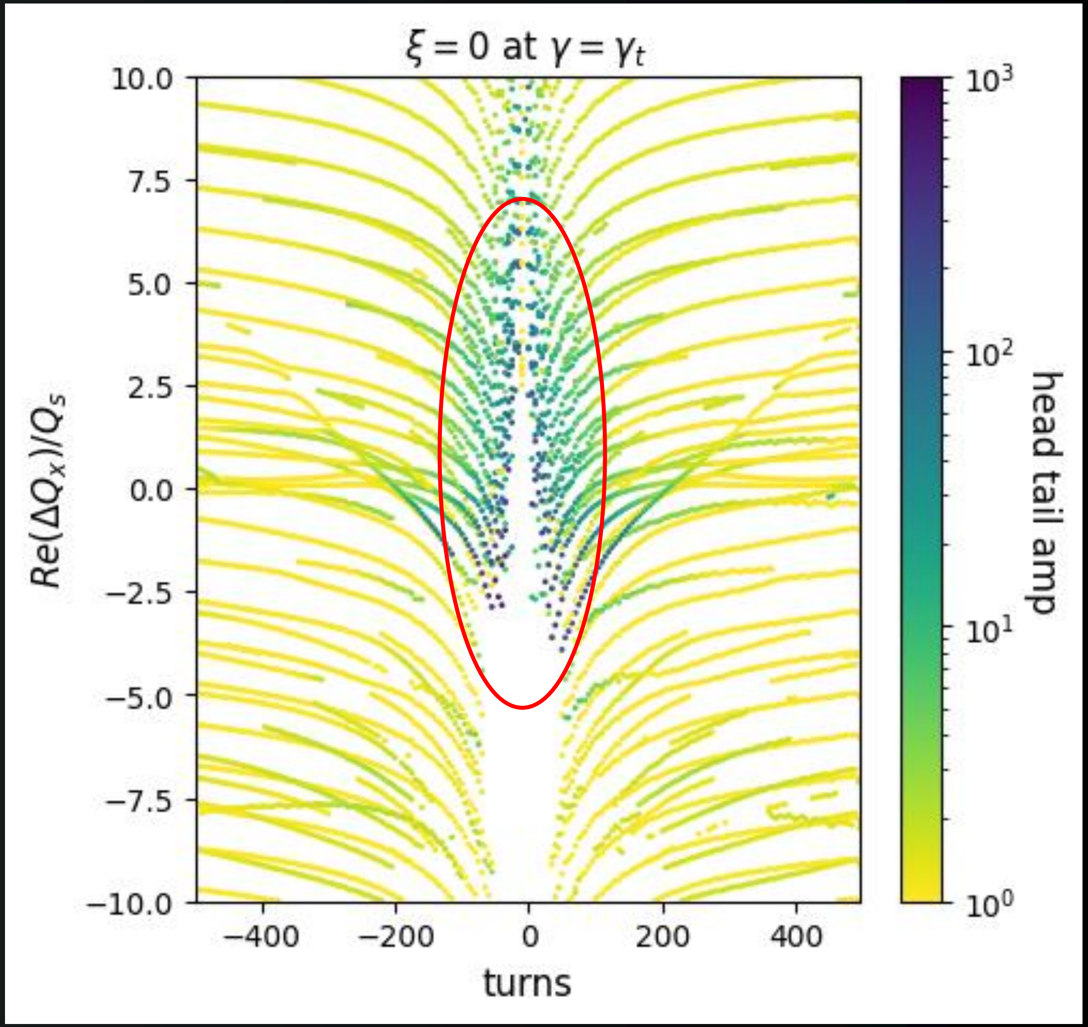
Measured Head Tail Amp.



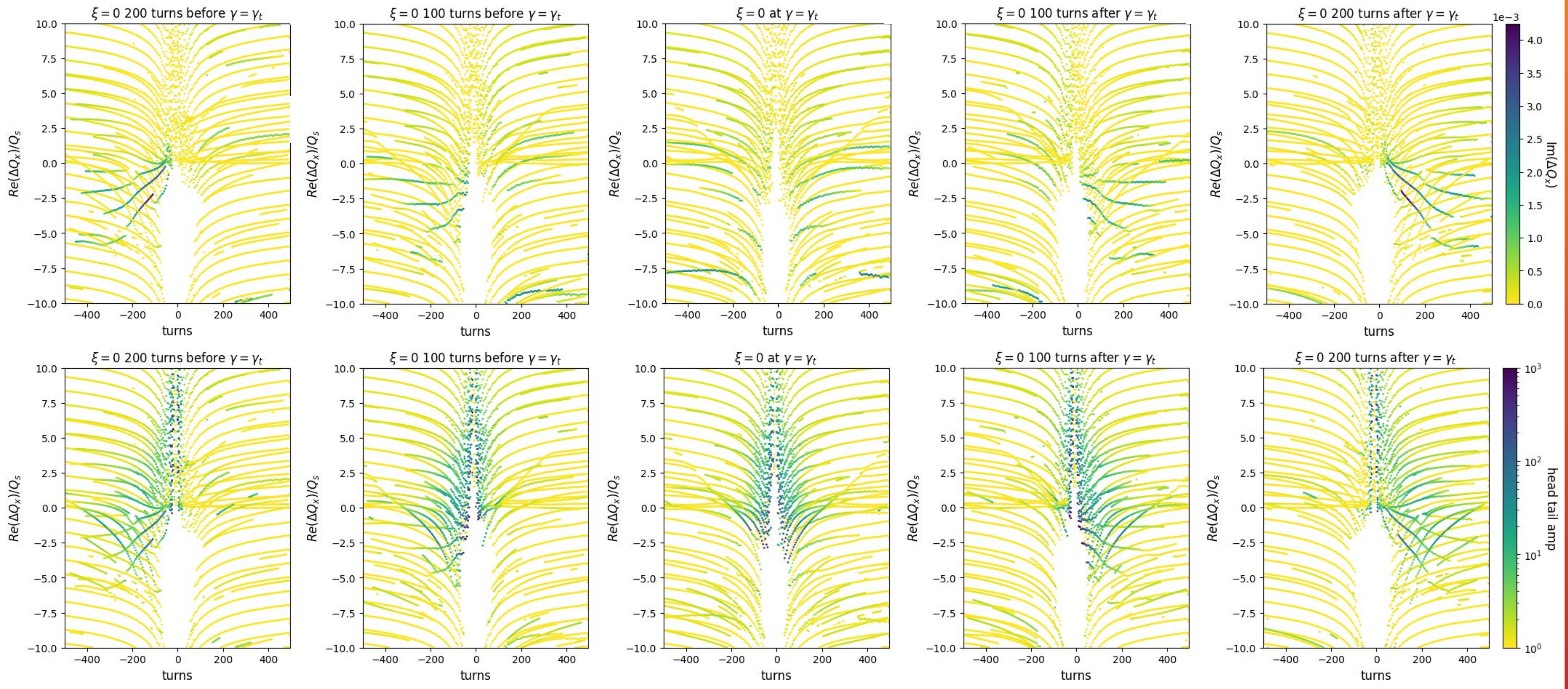
Instability Jungle

- Combination of instabilities
- Beam lost when both exponential growth and head tail amplification large

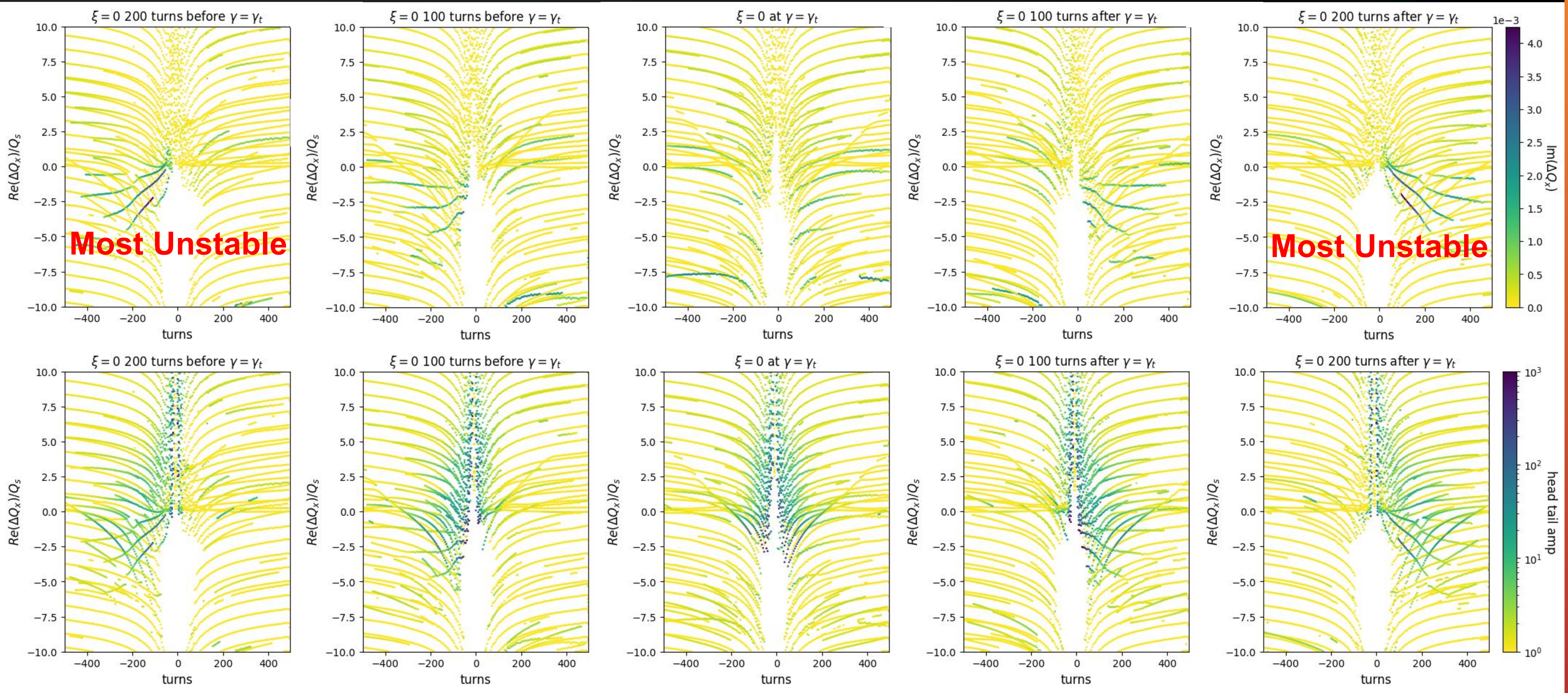




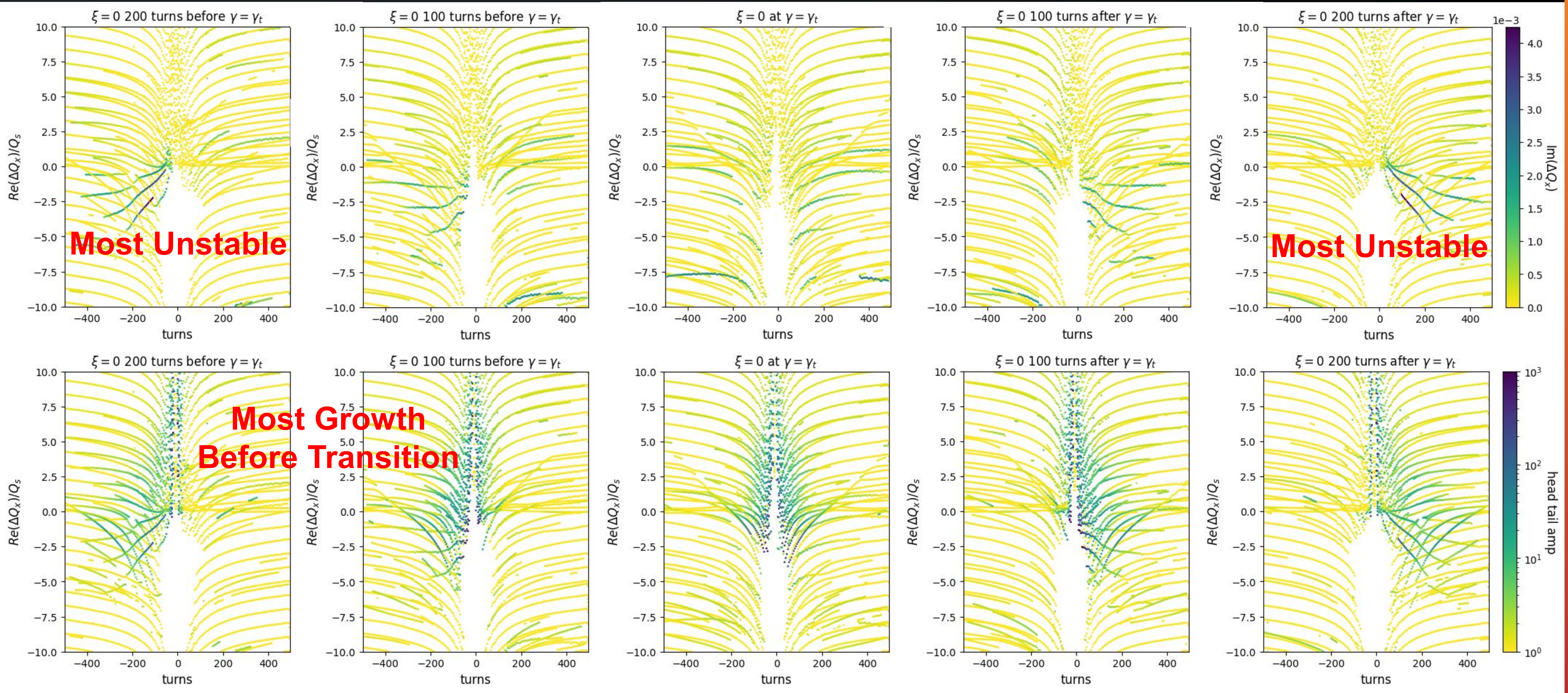
Instability Modeling



Instability Modeling

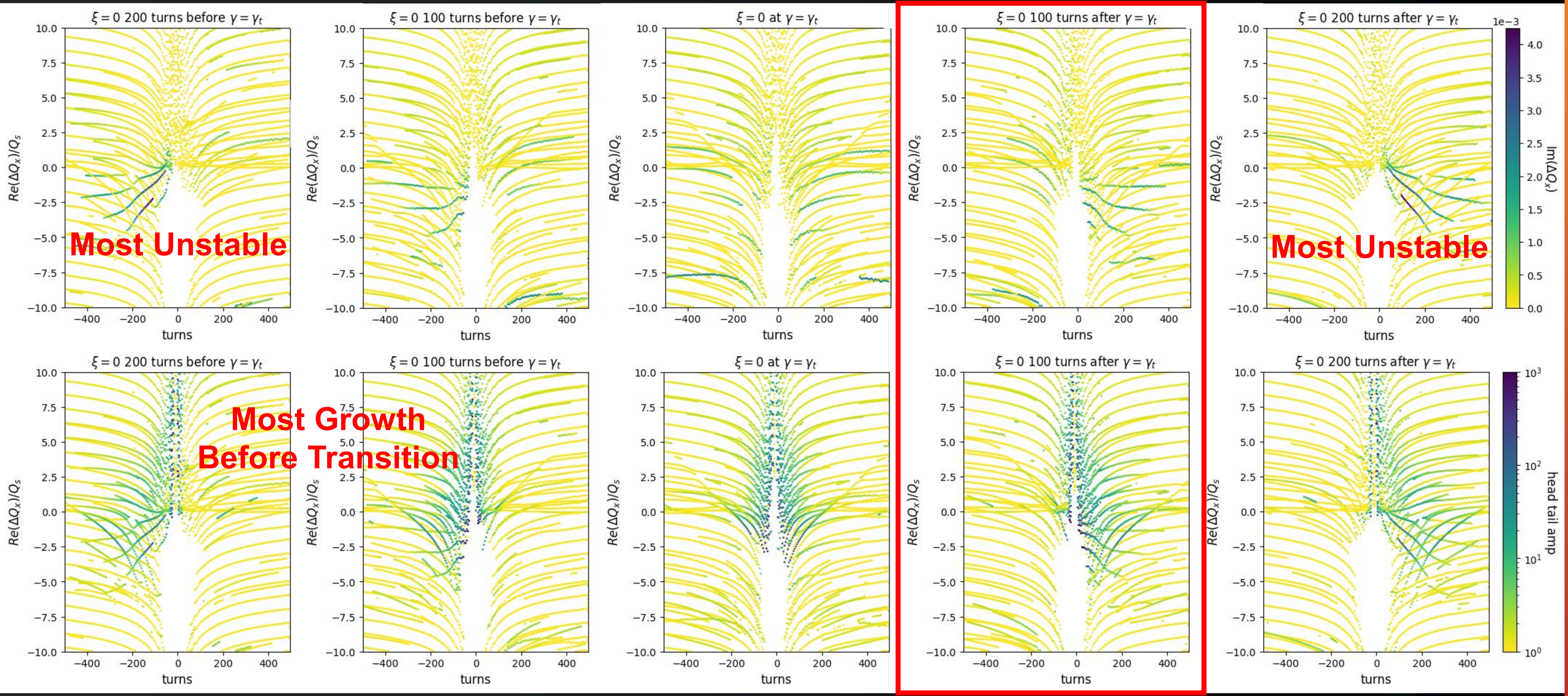


Instability Modeling

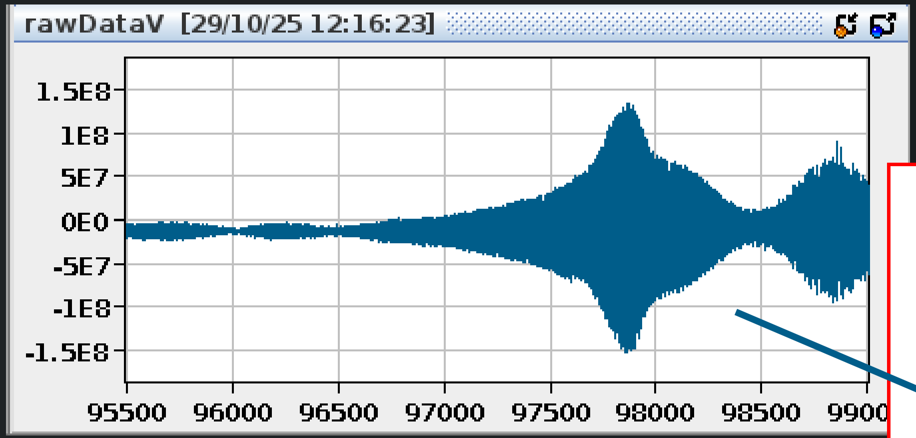


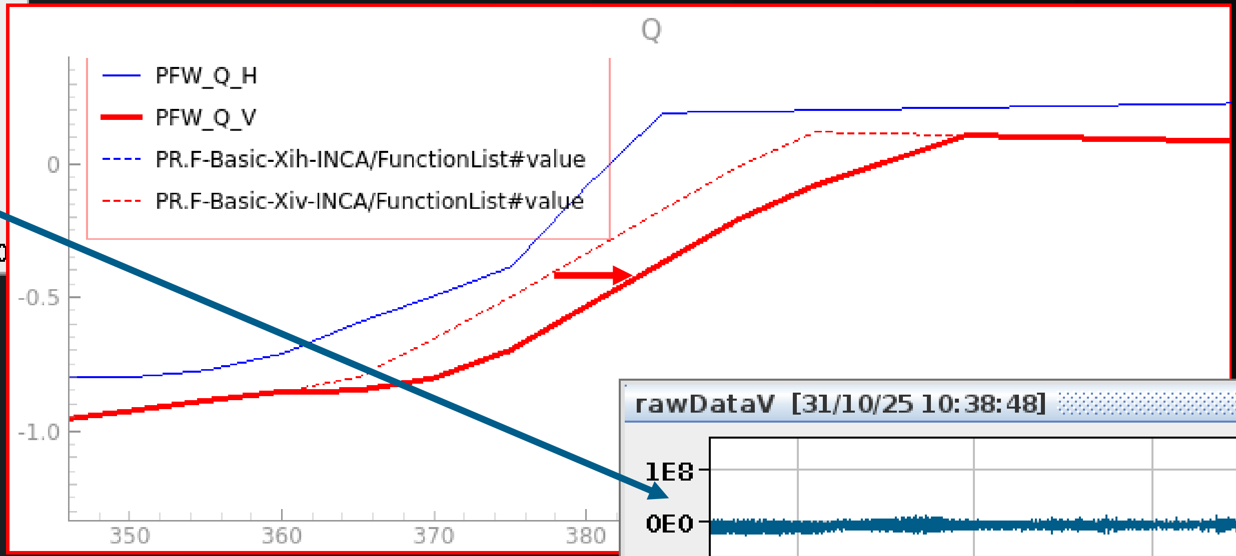
FERMI NATIONAL ACCELERATOR LABORATORY

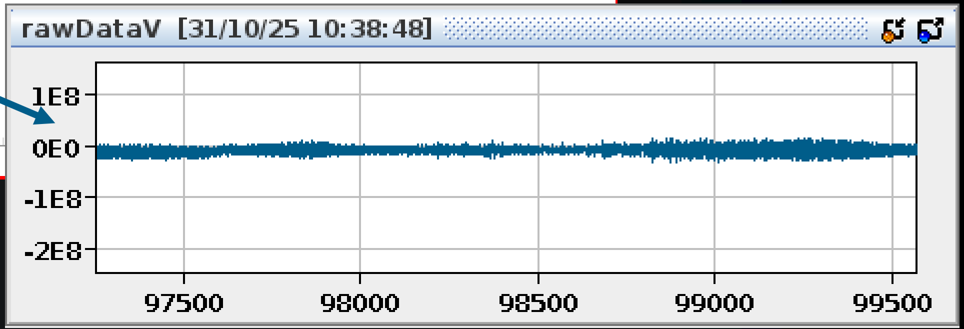
Instability Modeling



Works at CERN PS and Fermilab Booster







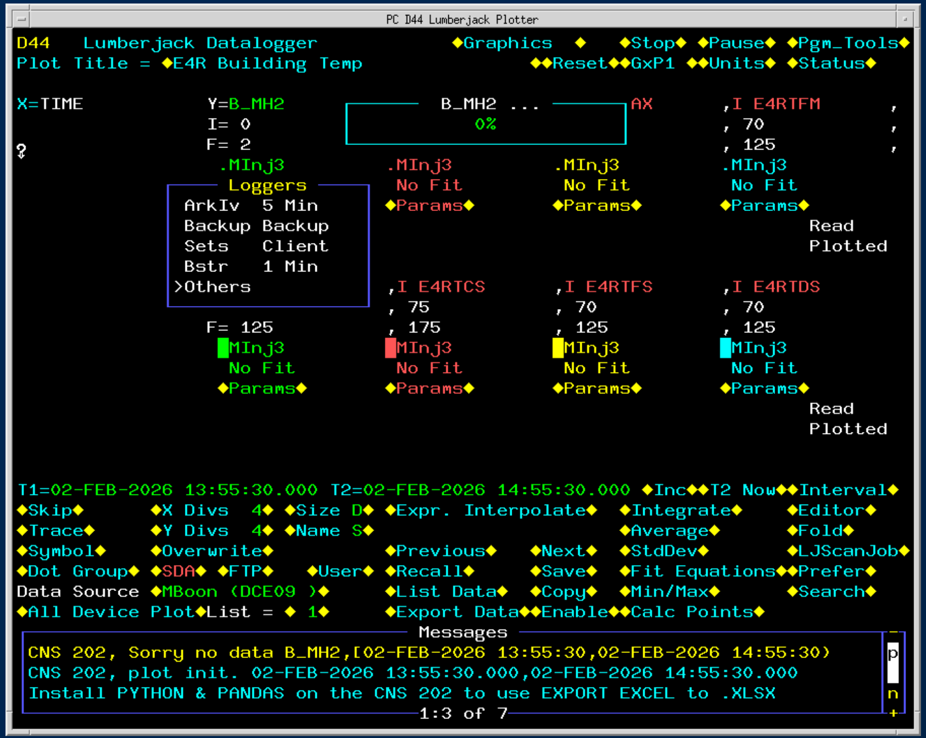
- Shifting the chrom. curve later in cycle suppresses instability at PS
- Significant increase in intensity
- Also works at Booster but less reliable

03

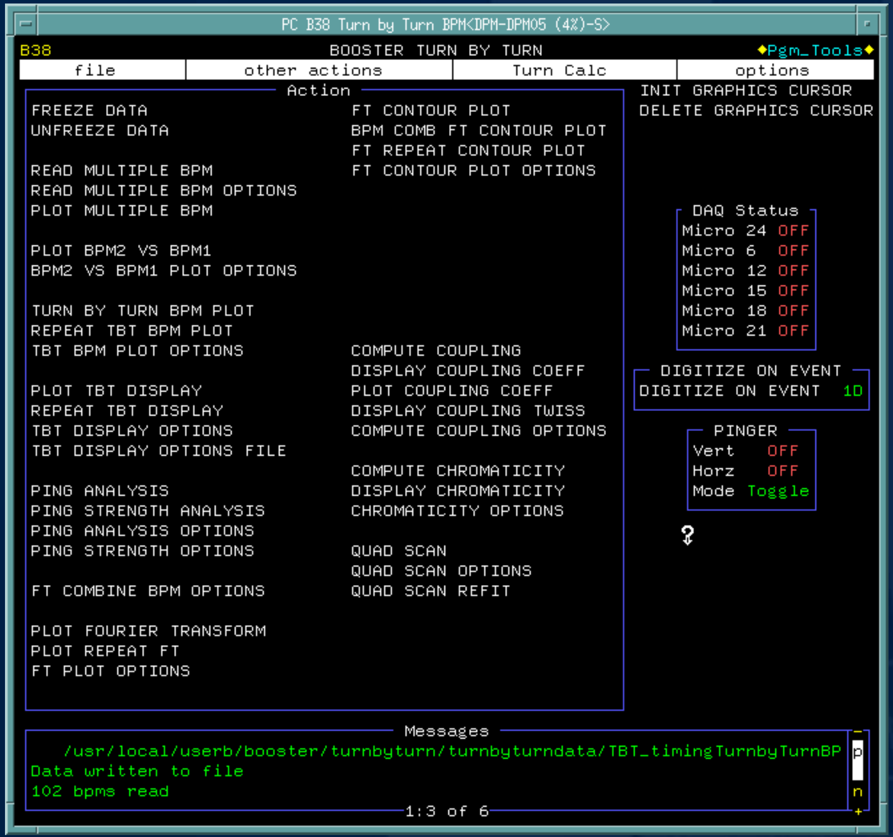
Need for Better Tools

Datalogger Lifecycle

- D44 data logger
- Limited circular buffer
- Max 8 inputs; takes arrays



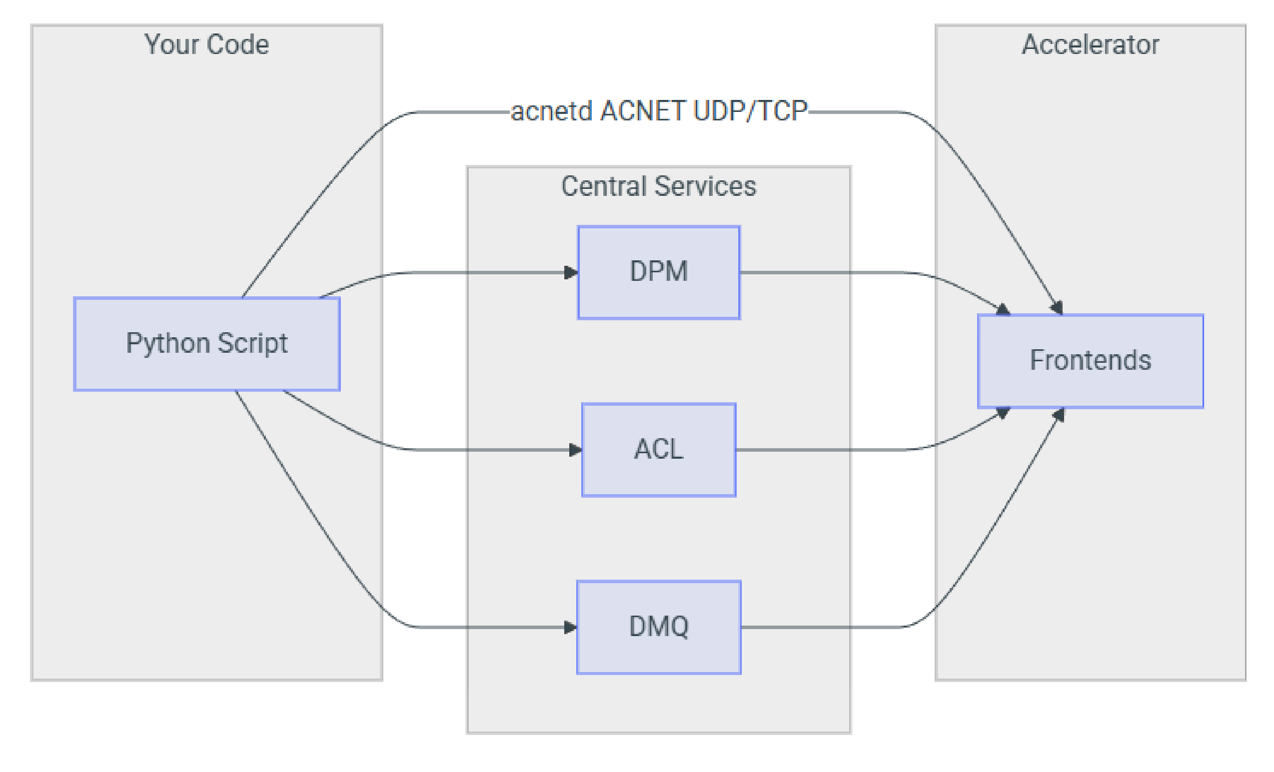
- BPM Tbt datalogger
- Only measures position
- Can take minutes to collect single dataset



- Neither are agile, or can support large datasets for PIP-II commissioning or AI

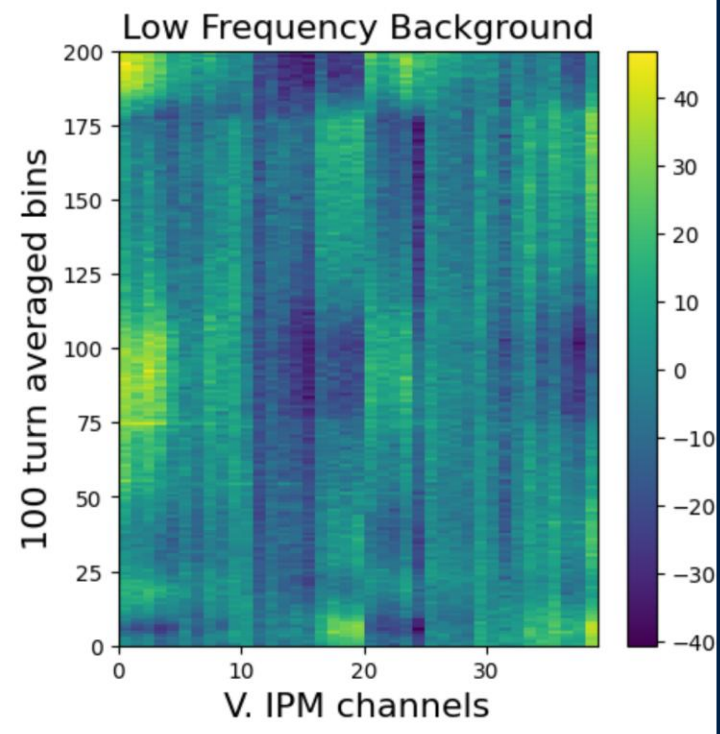
ACSys (or PACSys) Powers

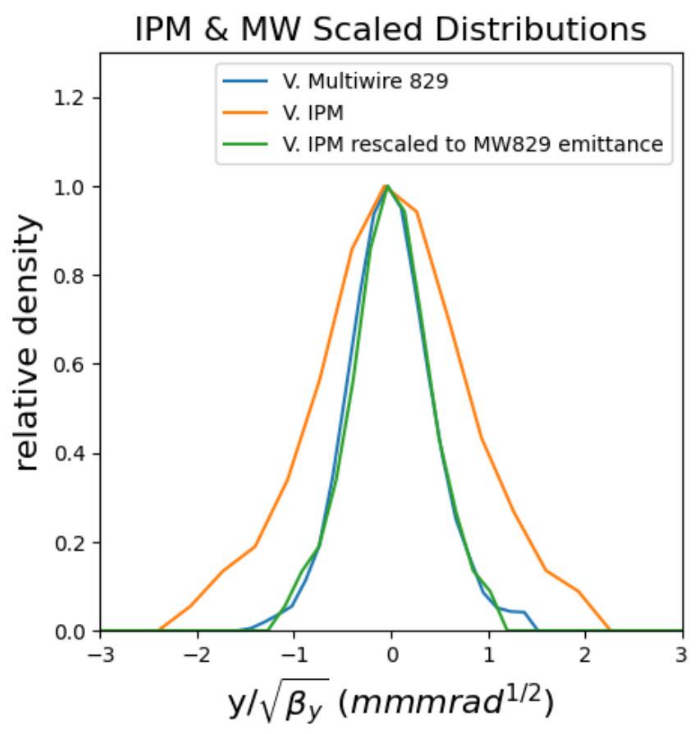
- Lots of amazing AI work being done
- Code must interface with instruments and controls
- Must work ‘out of the box’
- ACSys Python created by Fermilab
- PACSys out of IOTA
- Makes python possible
- Some data unavailable

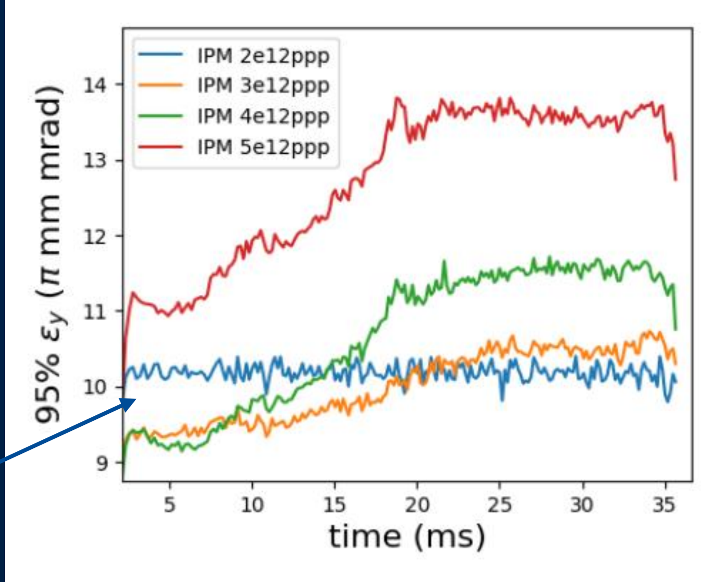


Horizontal IPM

- Work performed to calibrate IPM and understand noise profile
- Current optics model issue for both x and y
- Dispersion beam size only in x
- We don't have a (good) way to measure the full longitudinal ramp

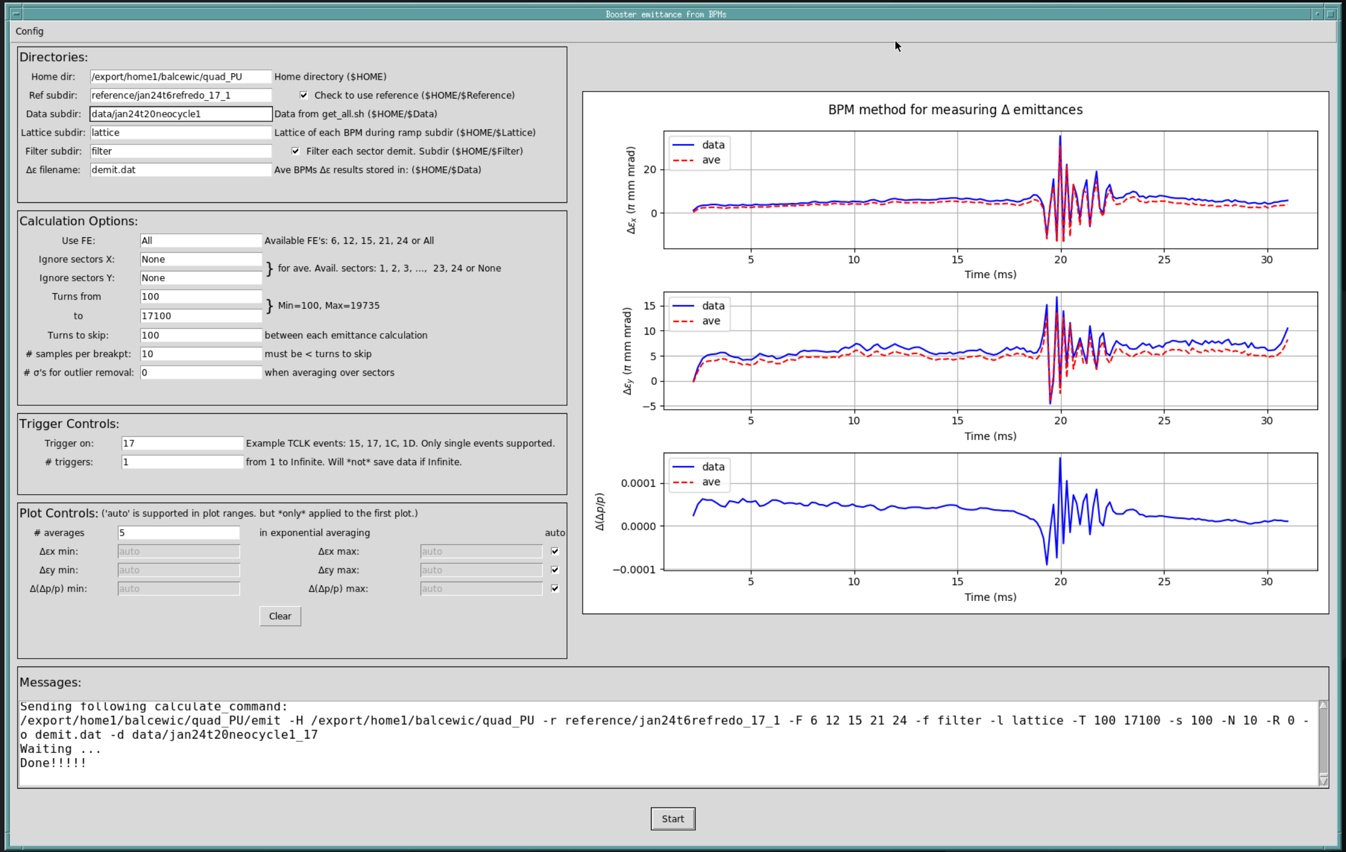






Less sensitive at low intensity

BPM Emittance Measurement



- Current FEs not reliable
- Upgraded BPM front ends coming
- Don’t want to overstress control system
- Longitudinal and transverse emittances coupled

04

Integrated Diagnostic

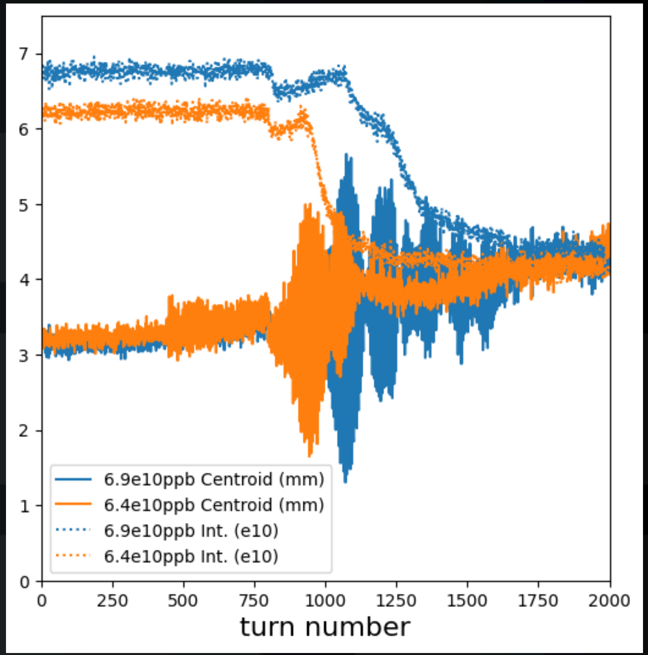
FERMI NATIONAL ACCELERATOR LABORATORY

Combined Injection to Extraction Diagnostic

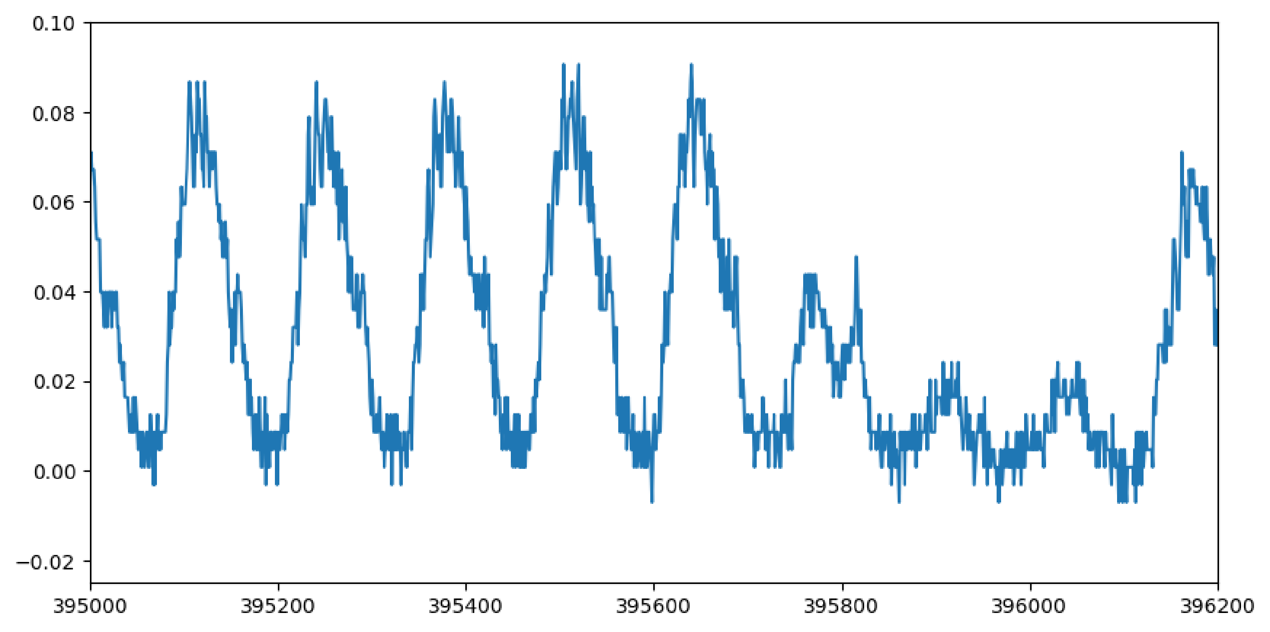
To my knowledge, we've never taken complete measurement of entire ramp

- Transverse Tbt for BPMs and longitudinal ≈ 0.2 ns samples
- Combines with other datasets
- Track machine state changes
- Combination of full & decimated datasets*
- Must avoid control system bottlenecks

Instability Near Transition



WCM Bunch By Bunch Profiles



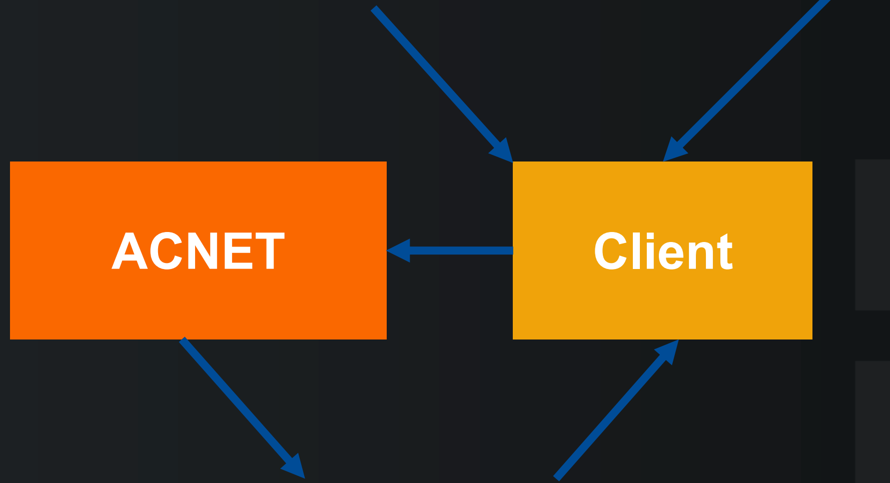
Not a ‘One-Off’

QICK board for longitudinal motion

- Want similar system to MI
- Not a ‘One-Off’
- Will install over summer shutdown

Transverse BPMs

- Being upgraded
- Can stream data out

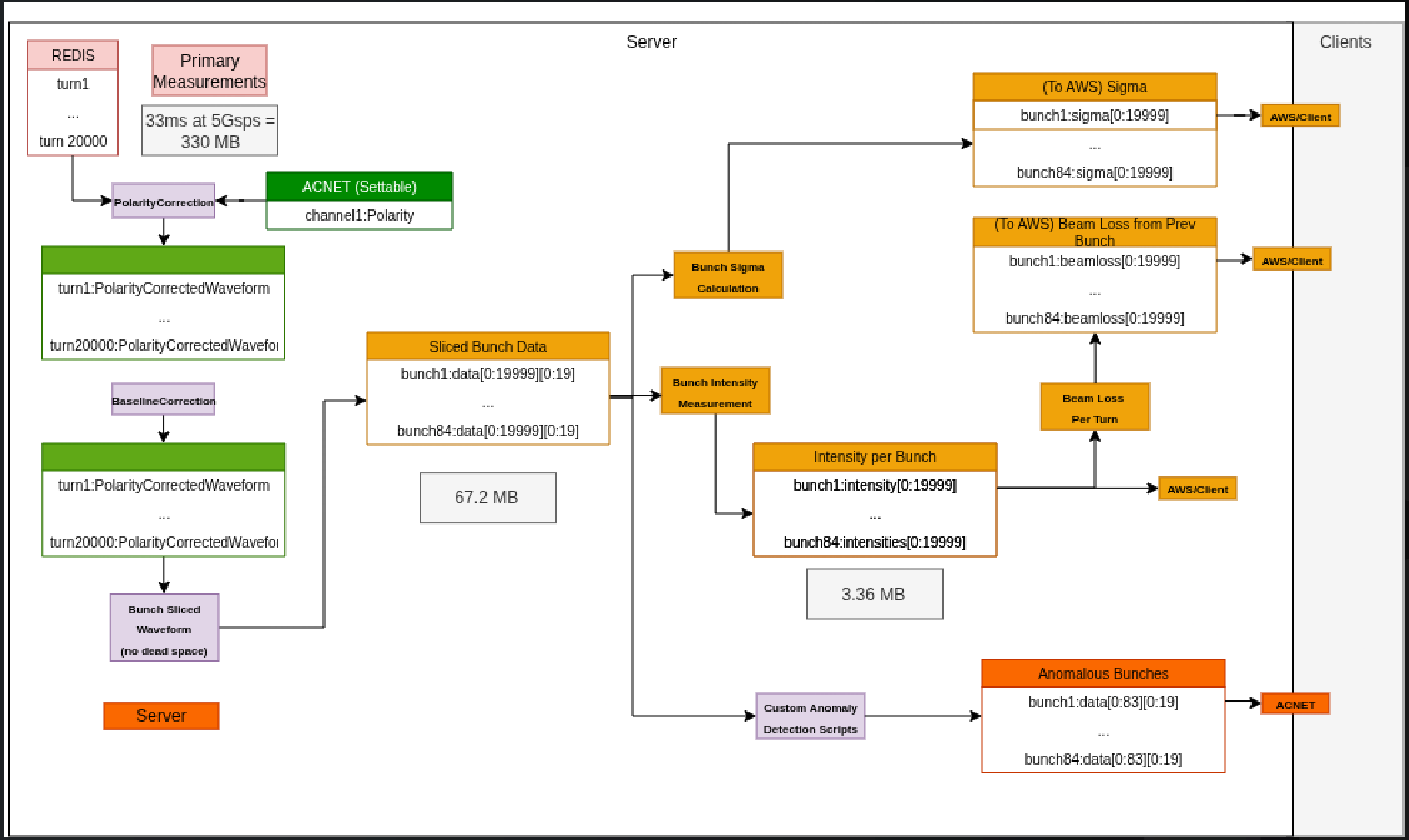


Reading Magnet Ramps

- Little data
- PACSys or ACSys

Data Collection and Processing

Mock-up of WCM for entire beam ramp

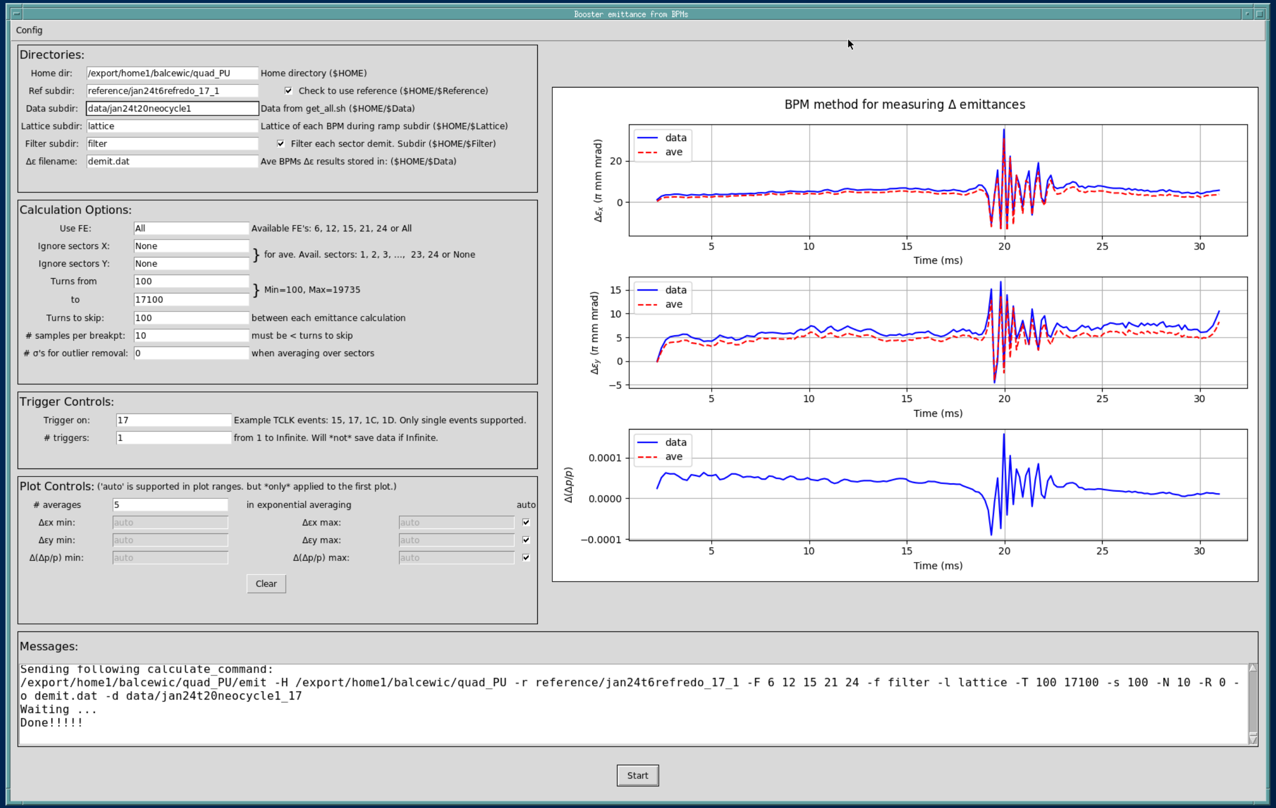


FERMI NATIONAL ACCELERATOR LABORATORY

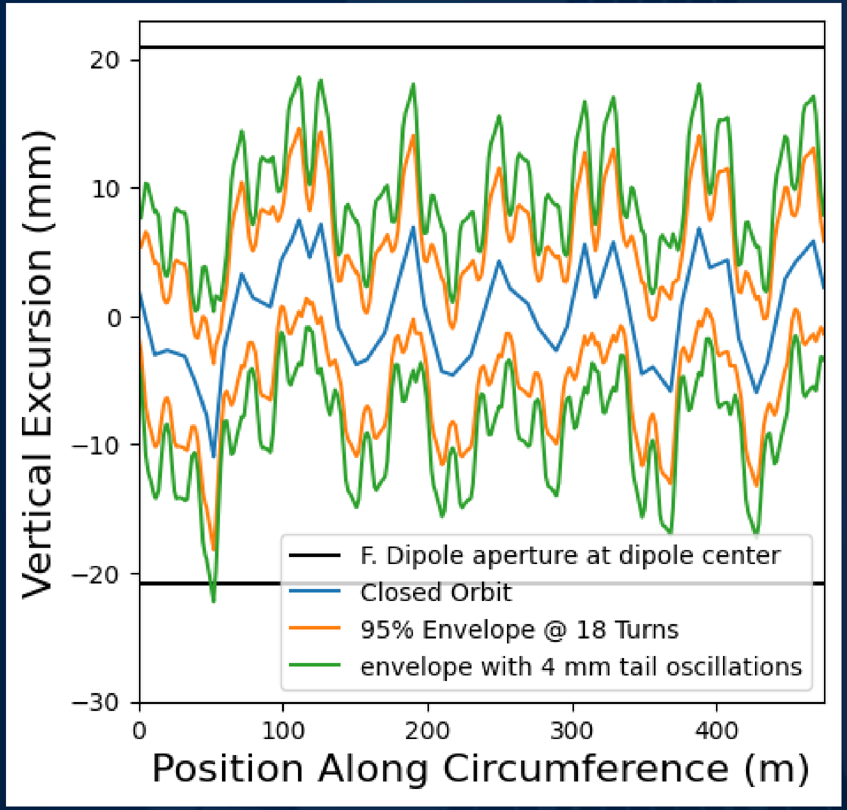
Online Beam Diagnostics

- Online measurements tell how dynamics change as parameters varied
- Passive measurement of beams
- Arbitrary analysis scripts, successful scripts deployed to operations

BPM Emittance Measurement



V. Beam Excursion

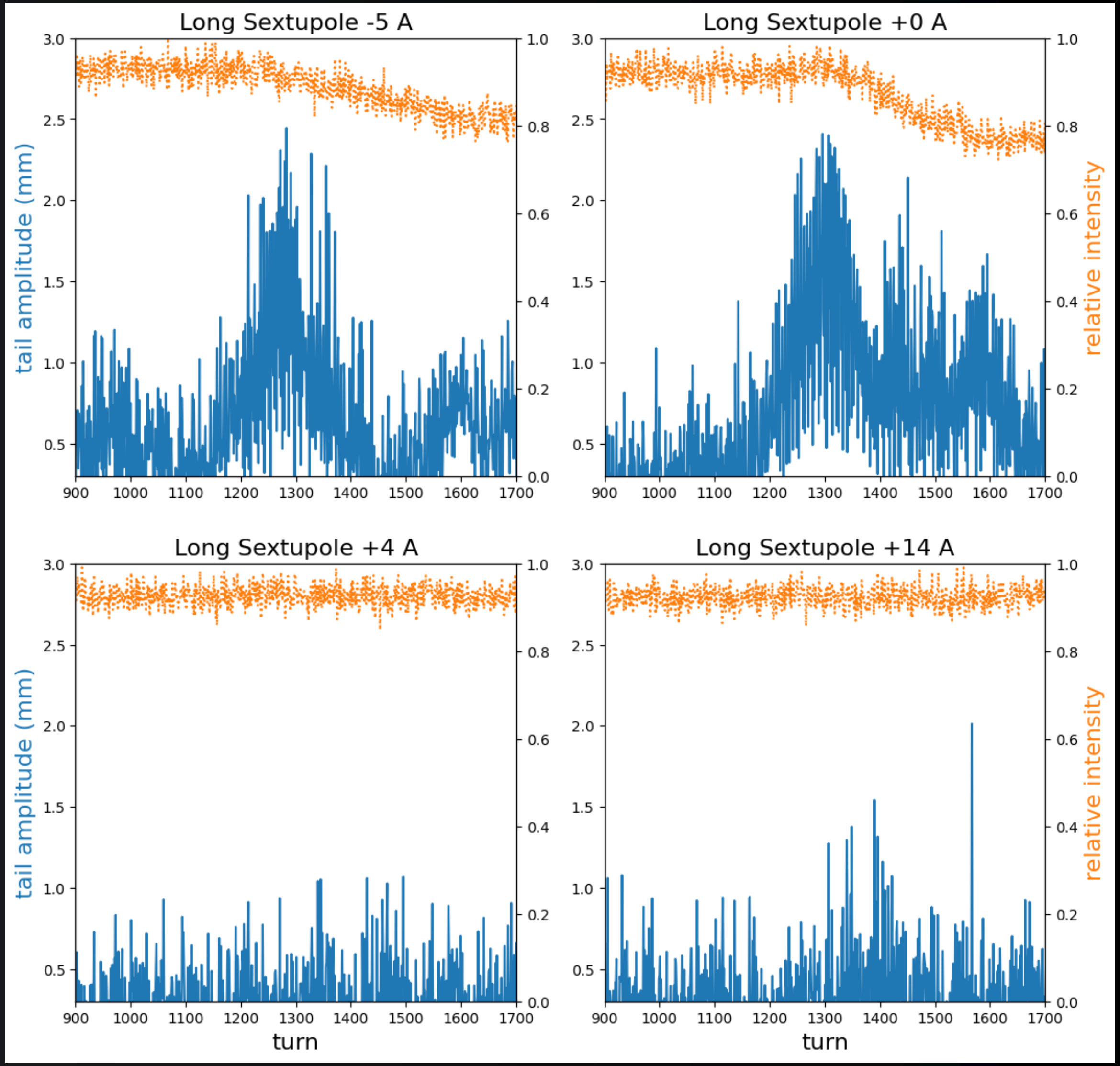


6D Beam Coupling

Coupling effects on Booster is an active area of research

- Must operationalize instability mitigation at γ_t transition
- GMPS power supply jitter equivalent to momentum offset*
- Longitudinal phase space tomography

Using Chrom. to Stop Transition Losses

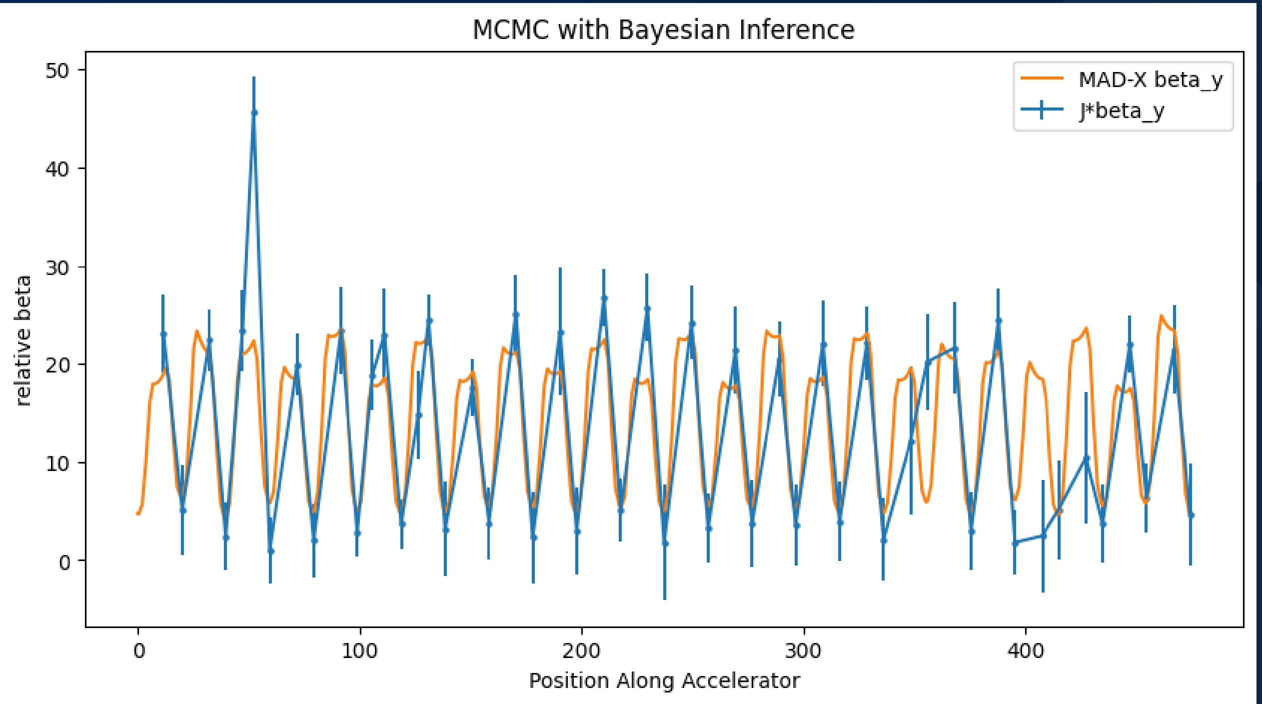


Physics Informed AI/ML

Long shutdown significant gulf without experiments

- Diagnostic provides perfect training sets for AI/ML
- Use AI/ML to infer beam parameters rather than treating as a black box
- Mock-up using MCMC to nondestructively measure linear optics
- We aren’t just building for today’s AI models*

Using MCMC to Estimate Beam Optics



Thank You

Any Questions?

LABORATORY


Fermilab
FermiFORWARD
U.S. DEPARTMENT of ENERGY
FERMI NATIONAL ACCELERATOR LABORATORY

Extra Slides

Career to Date

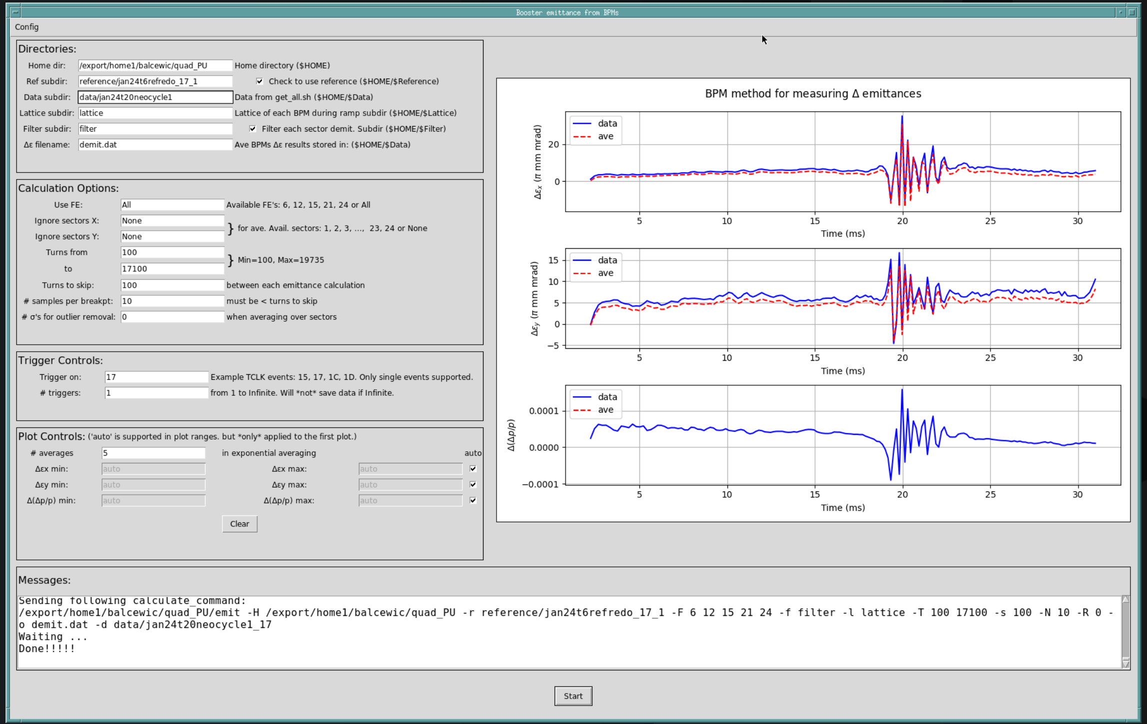
- Undergrad UCSB
- MSU for graduate school, joined Hao research group focused on theory/simulation
- As part of Accelerator Science and Engineering Traineeship (ASET) I did my thesis research at BNL's AGS*
- Postdoc at Fermilab Booster for past 2.5 years

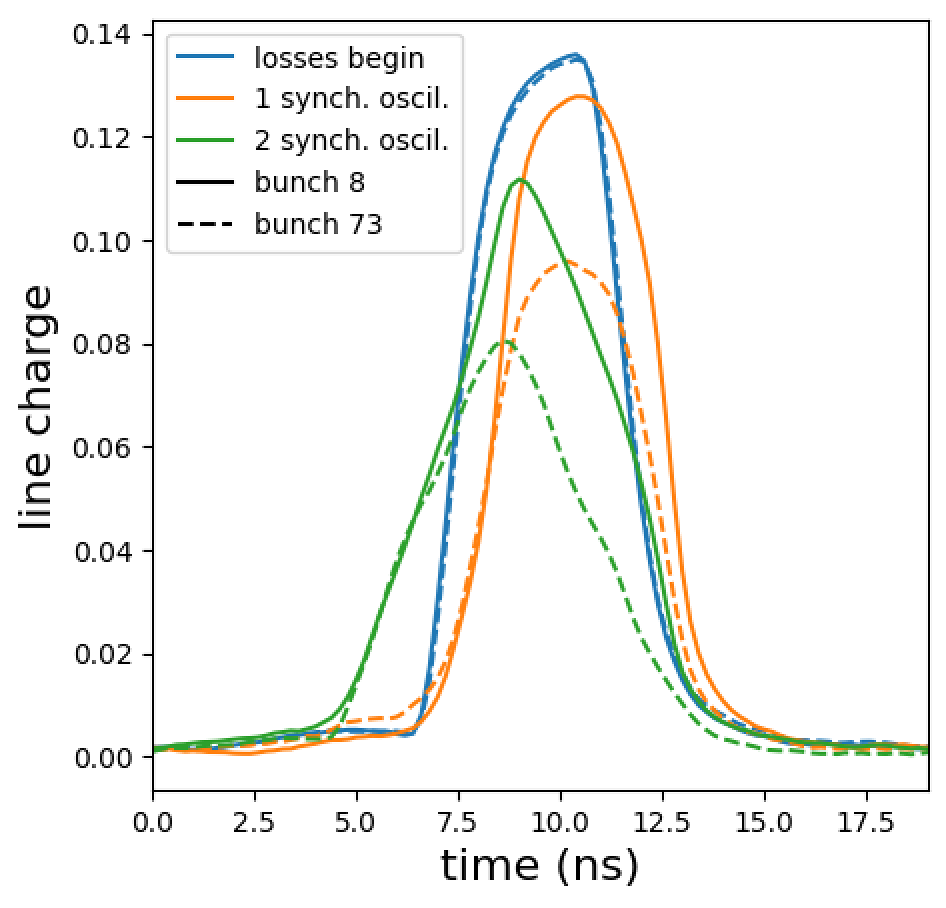
FERMI NATIONAL ACCELERATOR LABORATORY

Bottom Line: not all datasets can go through control system

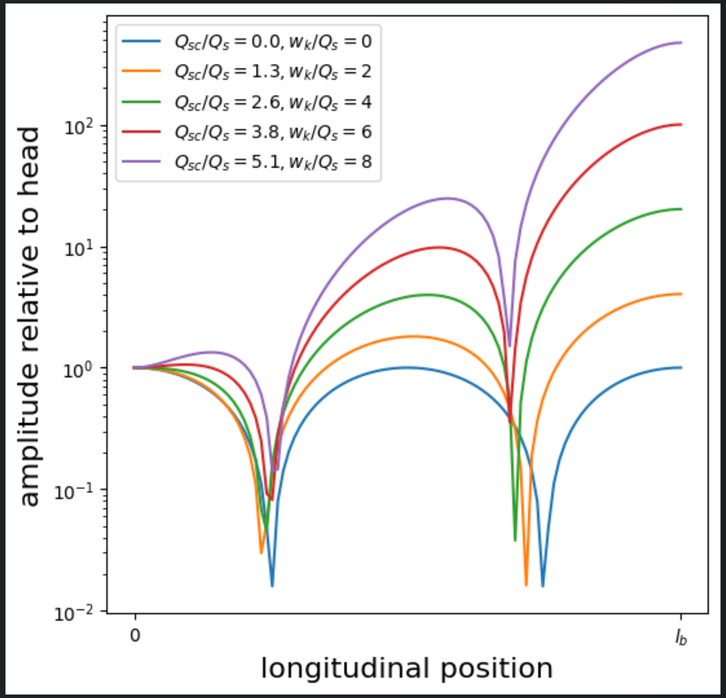
- Many transverse measurements are indirect longitudinal ones
- Bunch by bunch Longitudinal pickups could be >100,000,000 datapoints in a single pulse

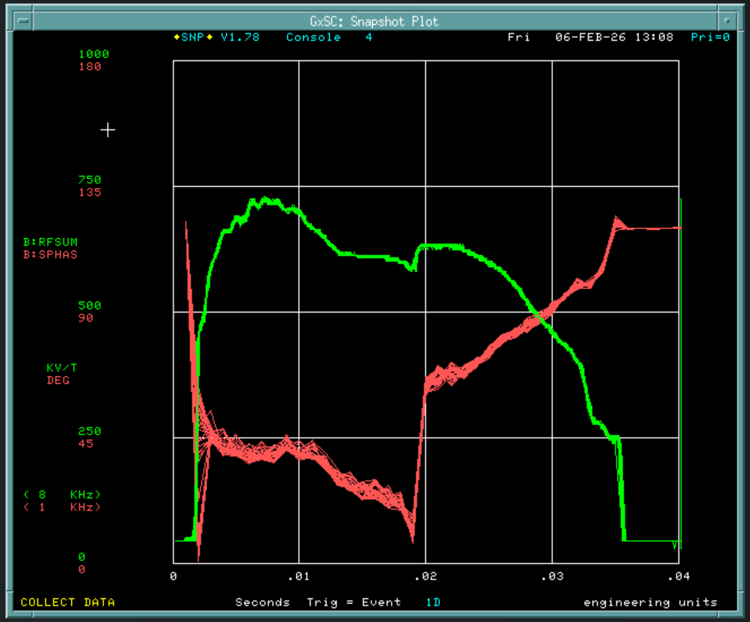
BPM Emittance Measurement*

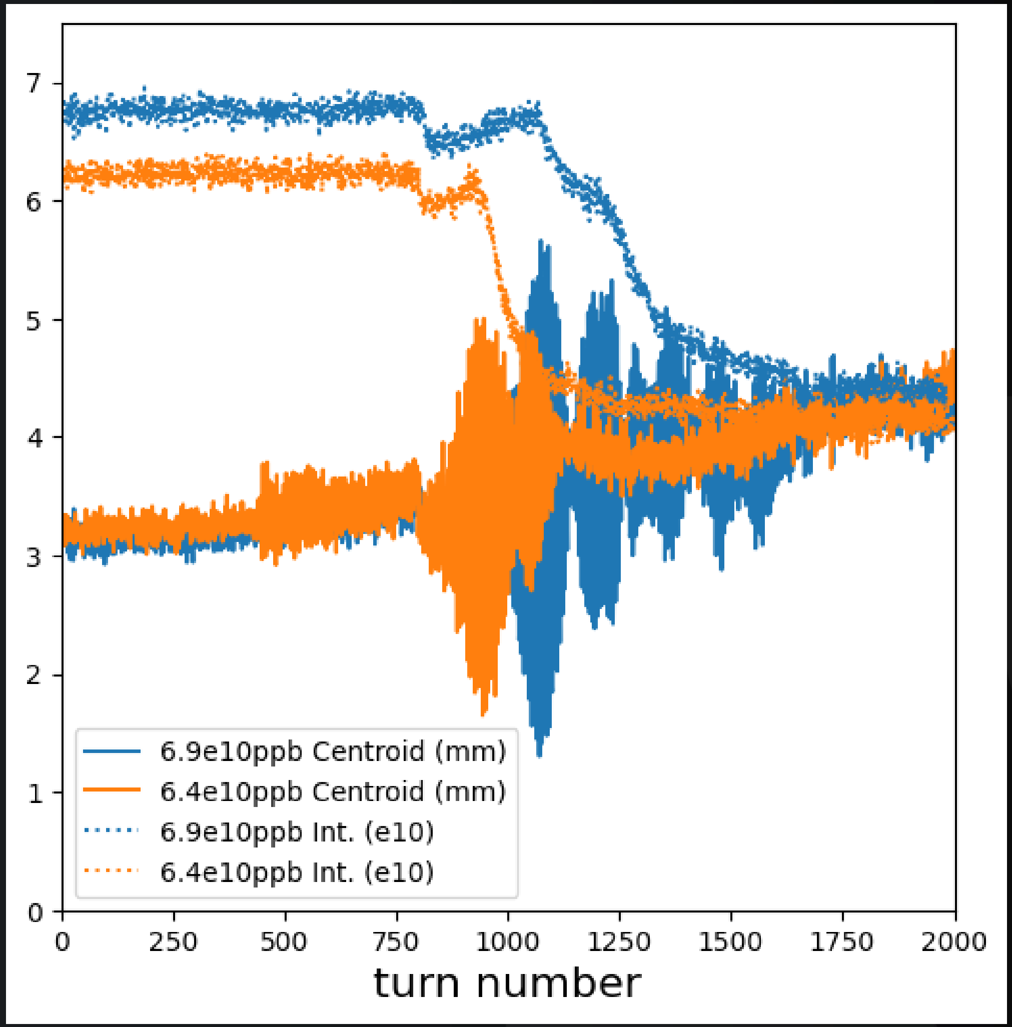




losses begin
1 synch. oscil.
2 synch. oscil.
bunch 8
bunch 73
line charge
time (ns)
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5





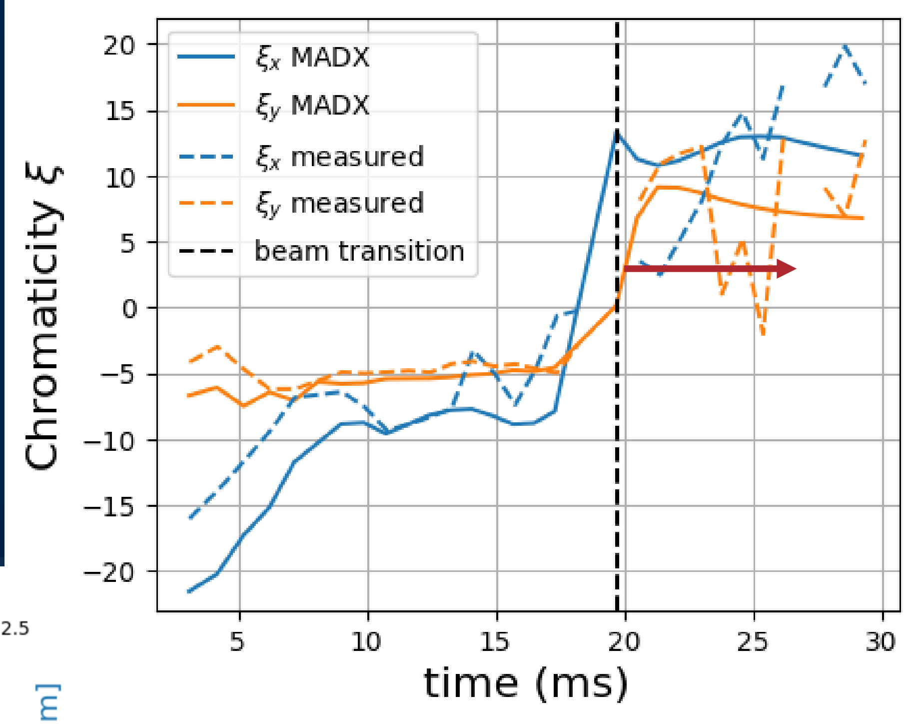


FERMI NATIONAL ACCELERATOR LABORATORY

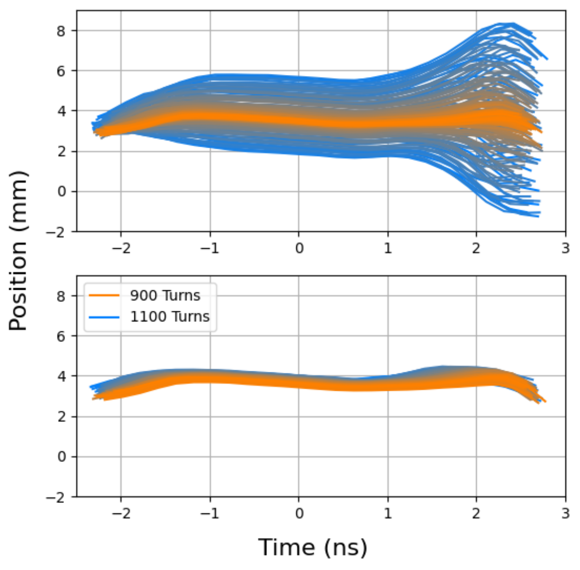
Mode Coupling in Booster

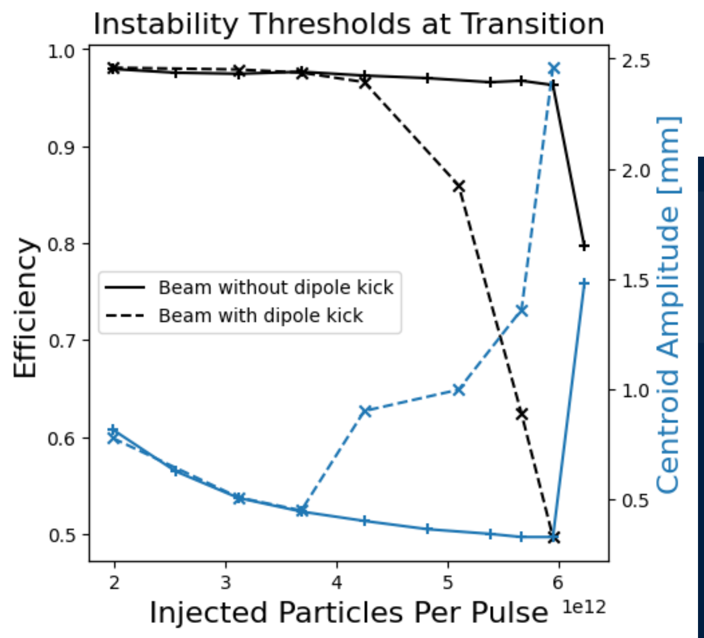
- Booster exhibits Mode Coupling Instability around transition
- Occurs in Booster Transition crossing
- Shifting chromaticity curve can suppress instability
- I've demonstrated in Fermi Booster and CERN PS

Shifting Chromaticity Suppresses Instability

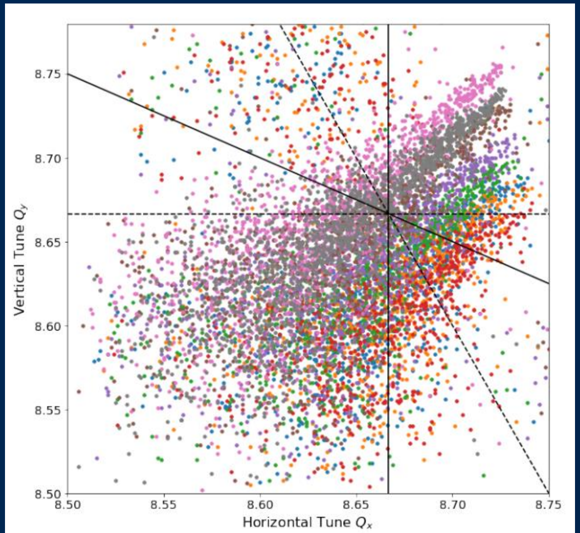


Inst. and Nom. Bunch

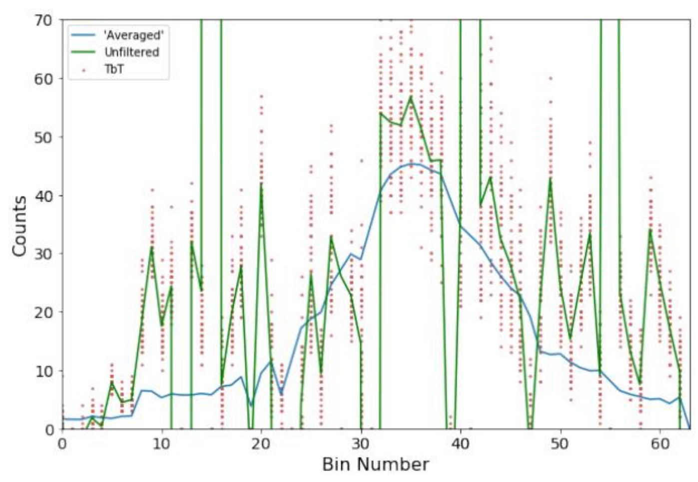




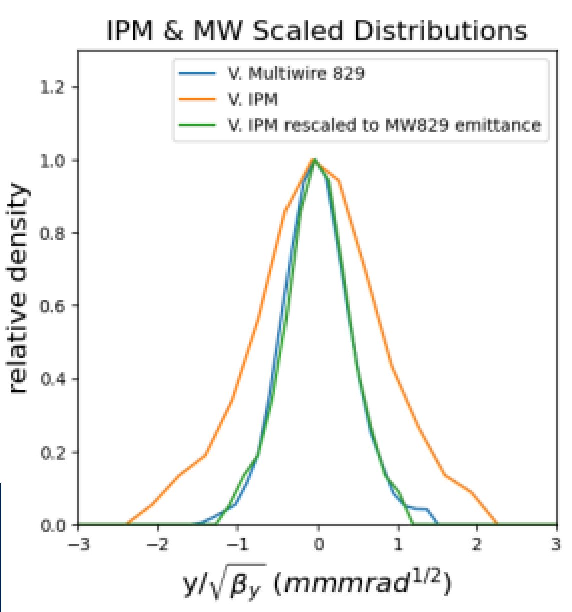
PIC Simulation of Space Charge Resonances



AGS eIPM



Booster IPM



FERMI NATIONAL ACCELERATOR LABORATORY