HSR Transition Related Experiments

Henry Lovelace III et al

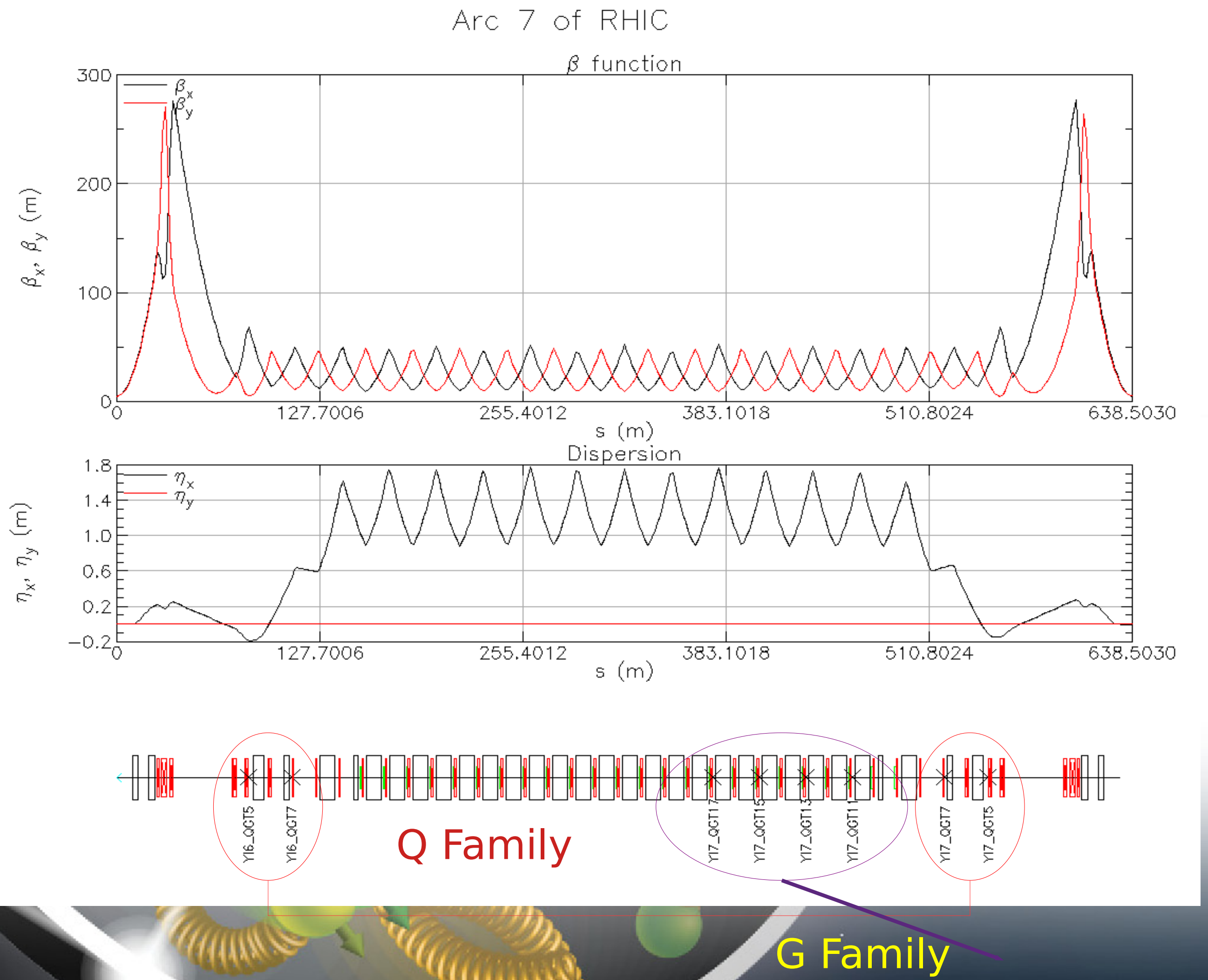
01/21/25

Outline

- Background
  - Transition crossing
  - EIC challenges
- APEX 23-10
  - Reduced Number Jump Quadrupoles
- APEX 25-07
  - Effect of Various Ramp Rates on Transition Crossing
- APEX 25-06
  - Resonance Island Jump (Phase II)

Typical RHIC Sextant

- For RHIC, a **First Order Matched** (FOM) correction system consisting of four families, Q inner (outer) and G inner (outer), of jump quadrupoles was implemented to correct the nonlinear effects of transition.



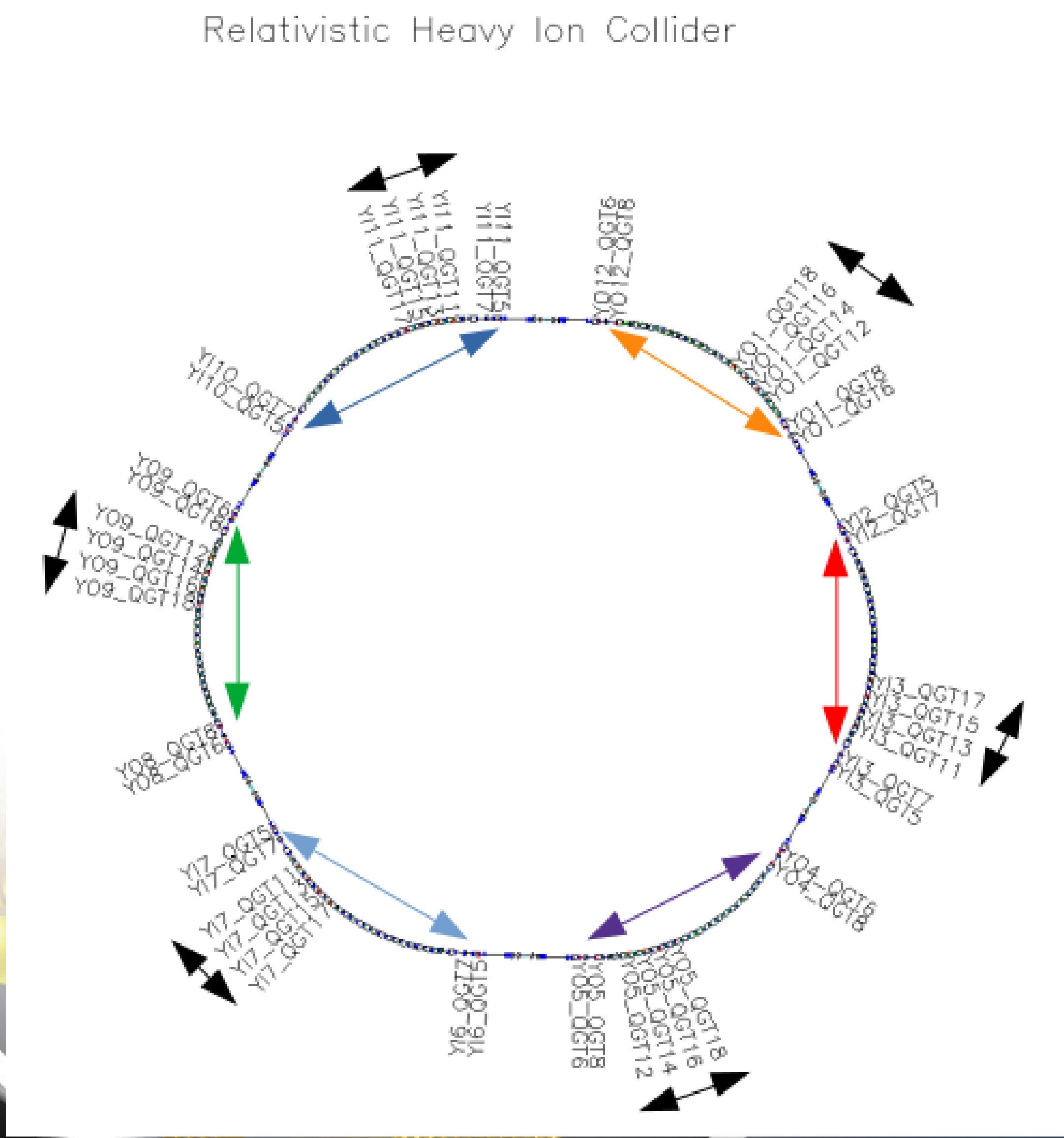
The First Order Matched correction, in the sense that $\Delta\gamma_T$ is linear to the integrated strength of the jump quadrupole, is:

$$\Delta\gamma_T = \frac{\gamma_T^3}{2C}\sum_i (k_1 l)_i \eta^2$$

Where η is dispersion

The FOM is a local (sextant) correction scheme

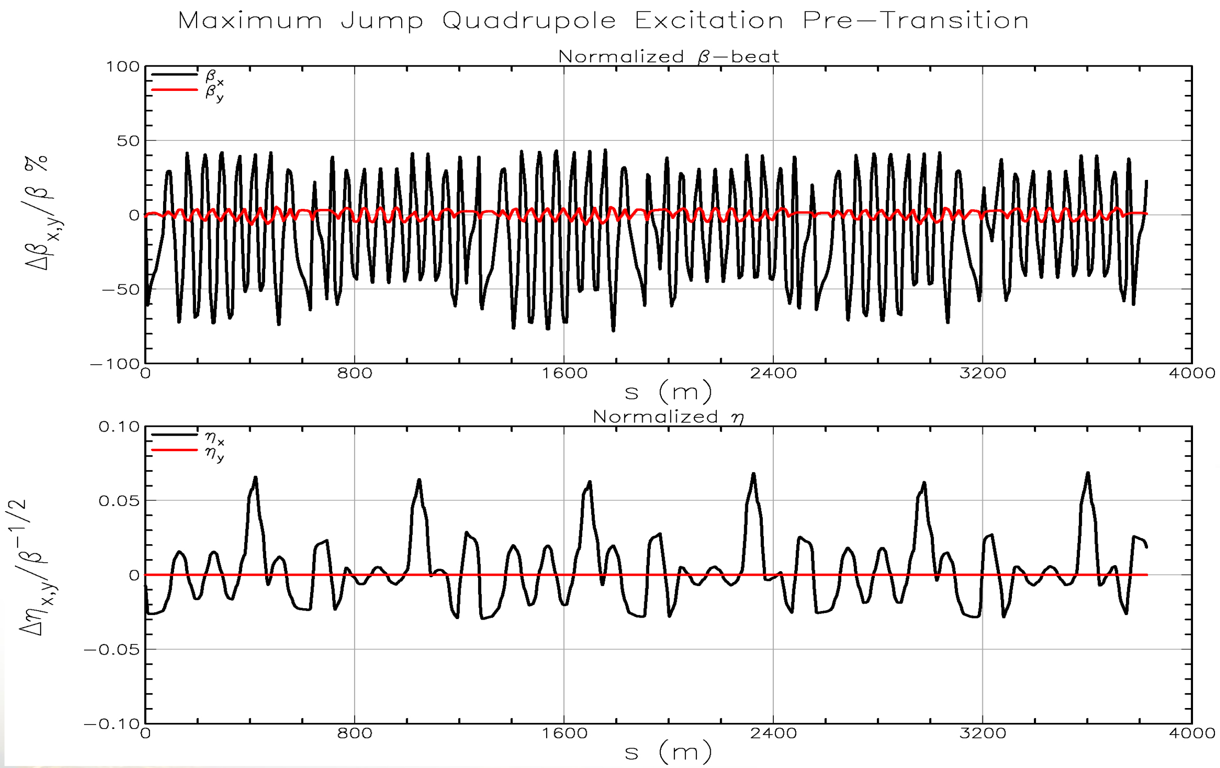
Reduced Number of Jump Quadrupoles

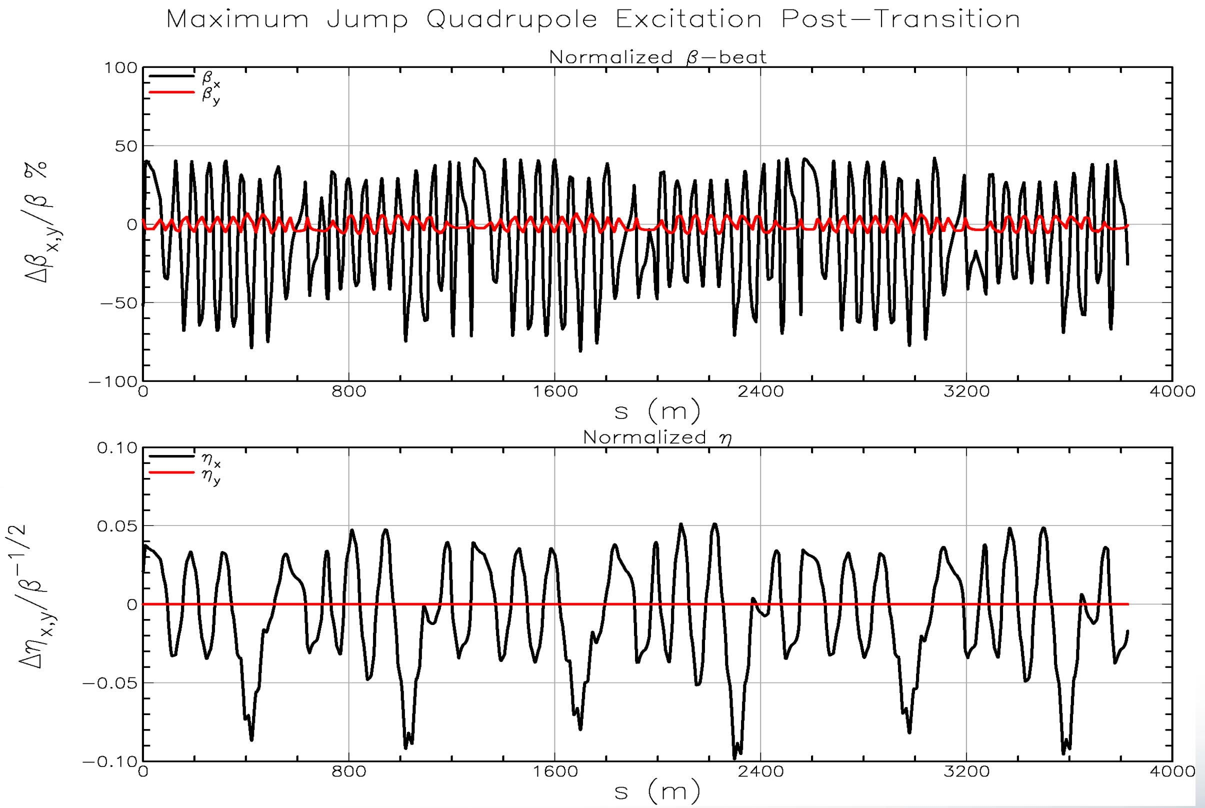


- Experiment Goal
  - Understanding the effect of the loss of compensation (Q) transition jump quadrupoles on transition crossing
  - Compare results to model
  - Subsidiary: Document RHIC transition crossing
- G family → Black arrows
- Q family → multicolor arrows

RHIC Maximum Optics Perturbation Pre- and Post- Transition

In RHIC, by design, the **$(k1l)_g \approx -(k1l)_q$** (6%difference)
Shown below are plots of the pre- and post-transition β(top)- and η(middle)- difference in baseline optics and jump quadrupole maximum excitation



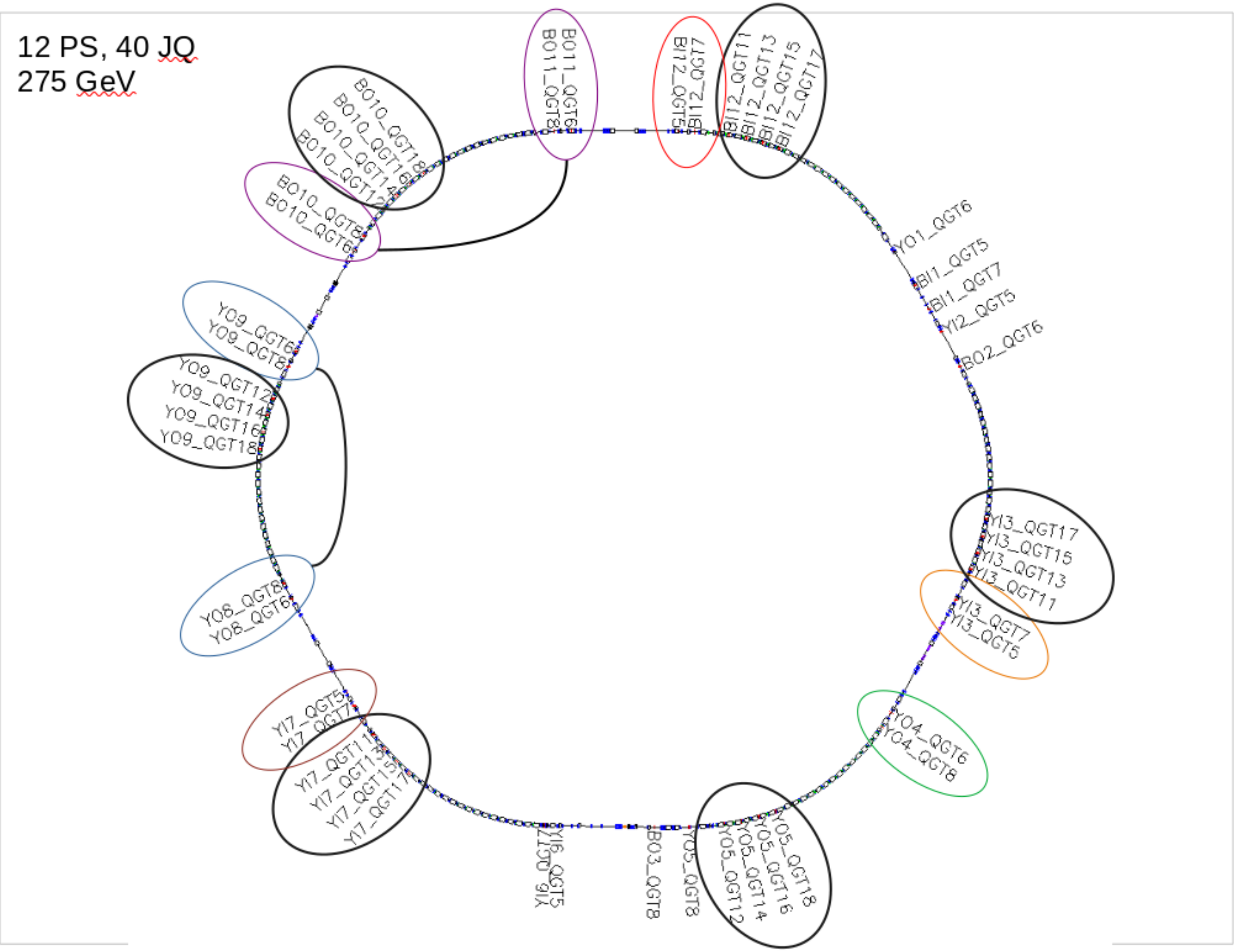


$$\frac{\Delta\beta_H}{\beta_H} = \frac{1}{2\sin(2\pi Q_H)} \sum_i (k_1 l)_i \beta_{Hi} \cos(2|\phi - \phi_i| - 2\pi Q_H)$$

$$\frac{\Delta\eta}{\sqrt{\beta}} = \frac{1}{2\sin(\pi Q_H)} \sum_i (k_1 l)_i \eta_i \sqrt{\beta_{Hi}} \cos(2|\phi - \phi_i| - \pi Q_H)$$

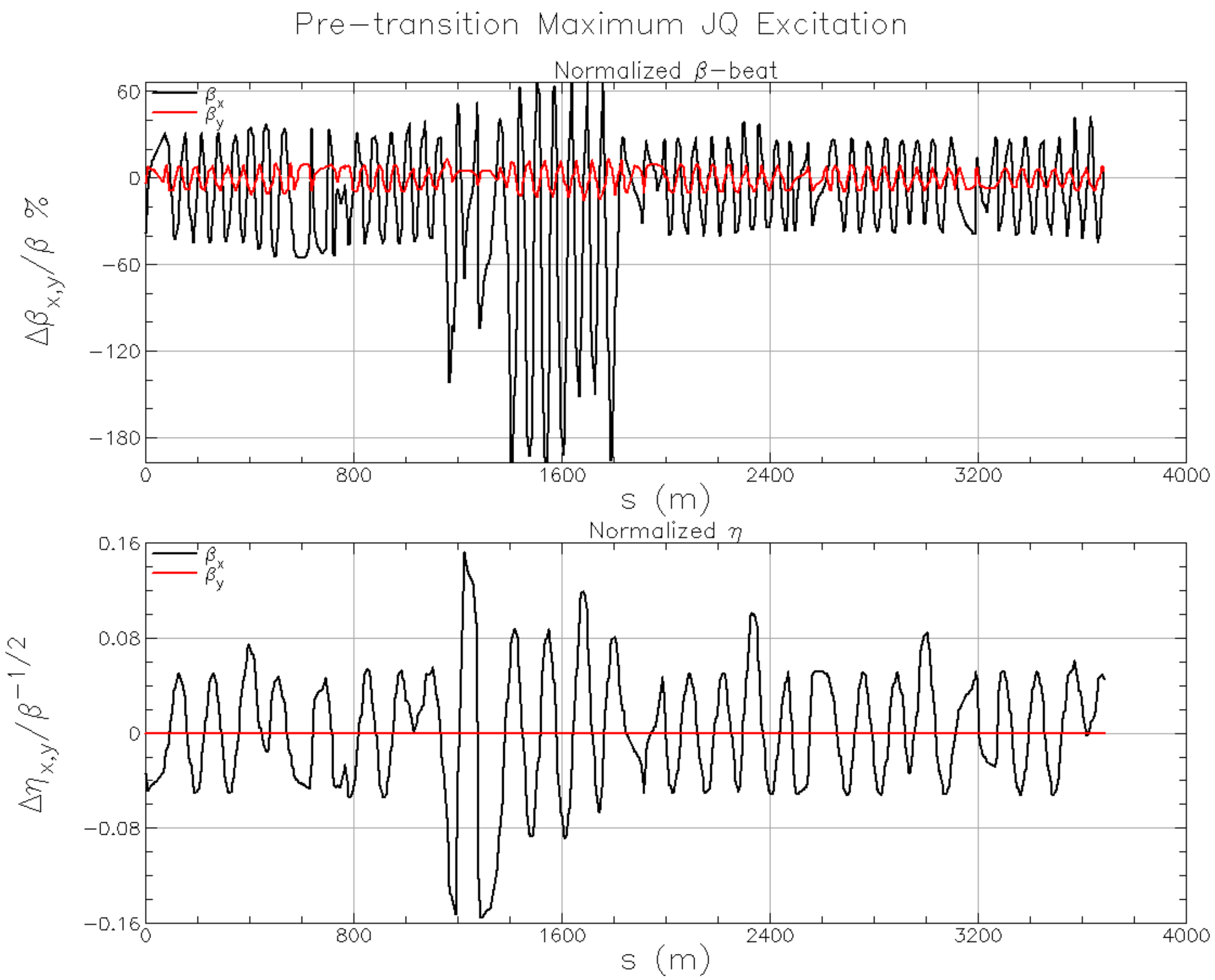
Electron-Ion Collider

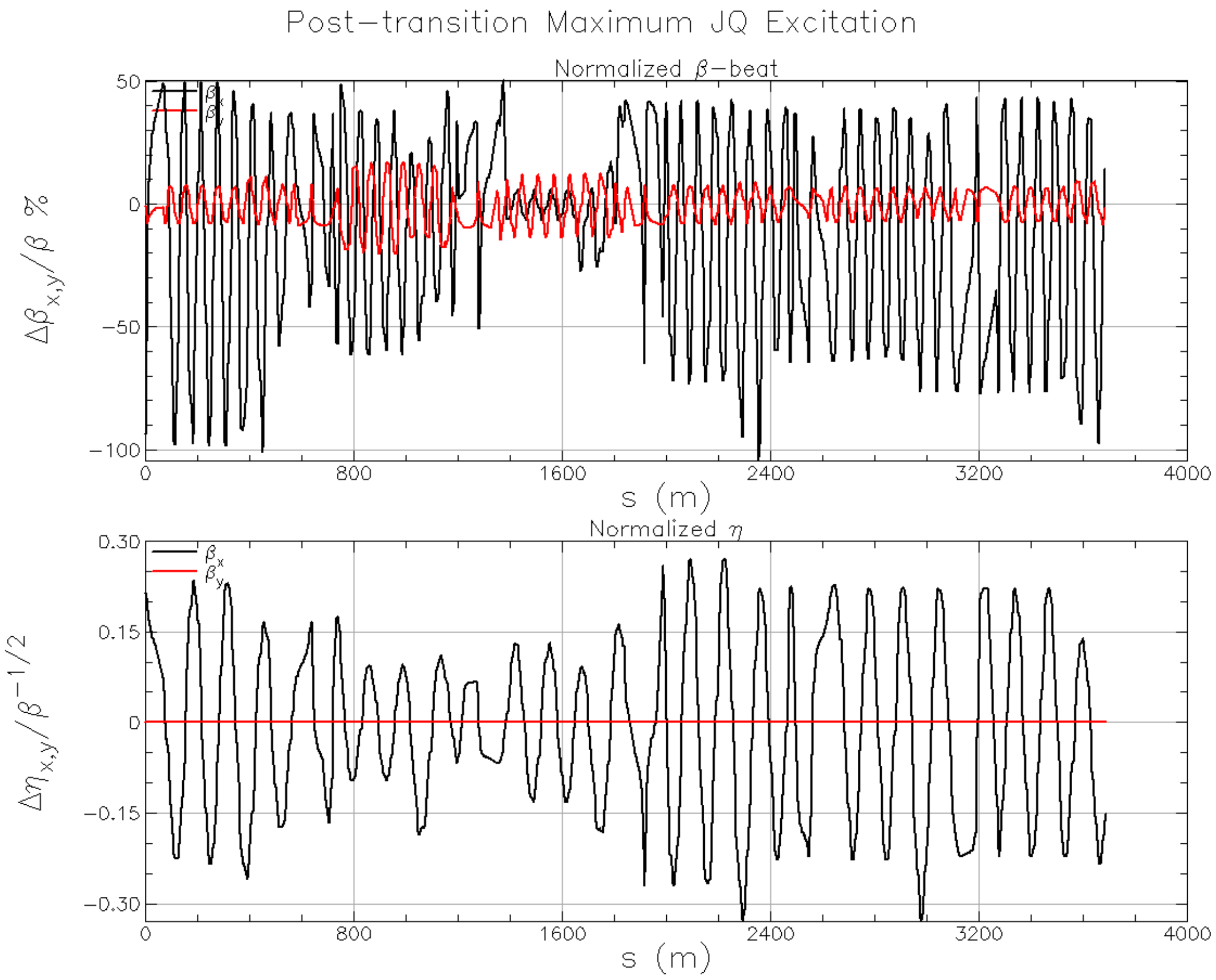
HSR Example



- The HSR:
  - 12 PS
  - 40 jump quadrupoles
  - IR2 missing/not used
  - IR6 missing/not used
  - Only 2 of the local compensation schemes remain intact

RHIC 8 PS Configuration





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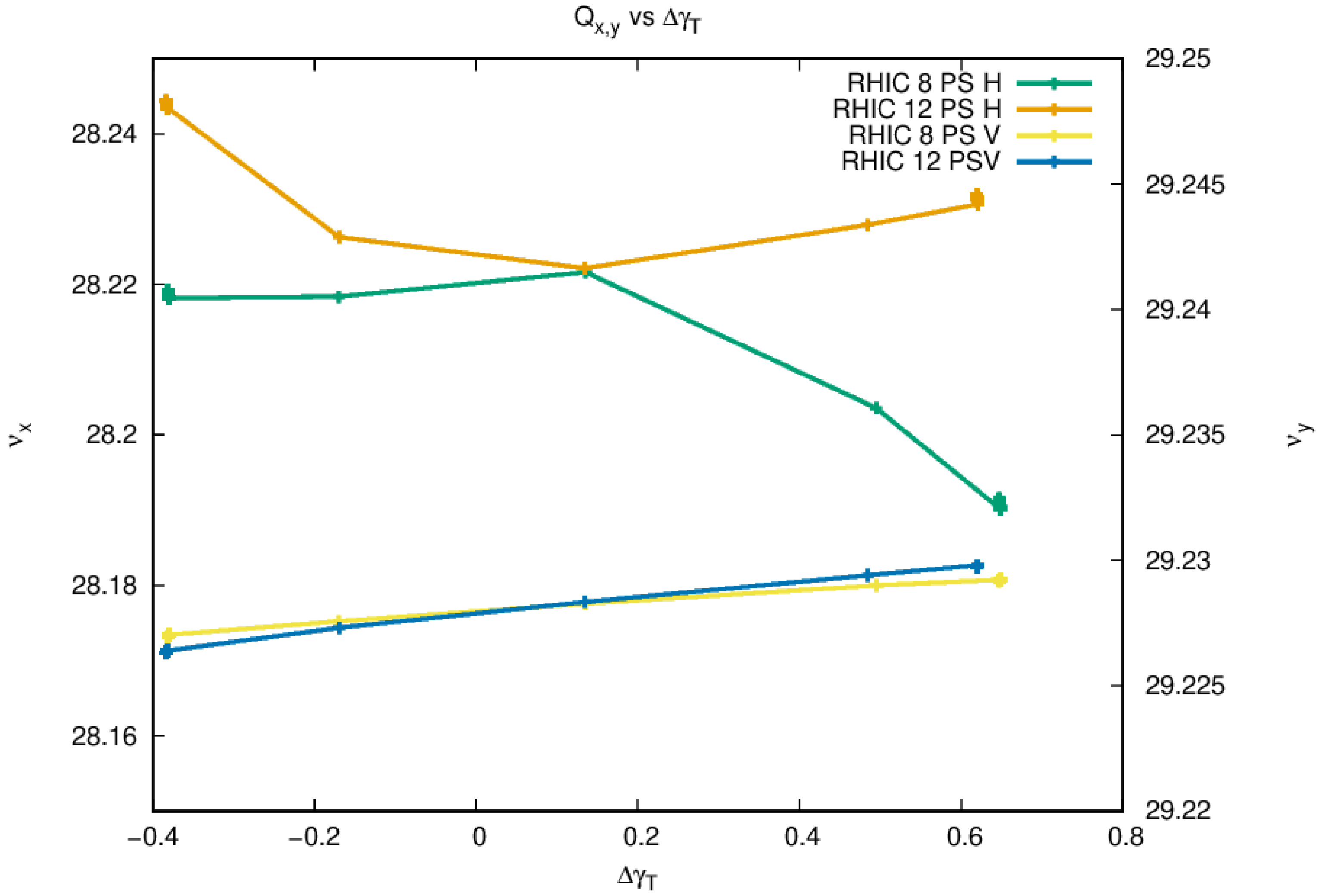
The **k factor** for this configuration is 2.7
β wave peak values are a factor of 4 times greater than standard RHIC

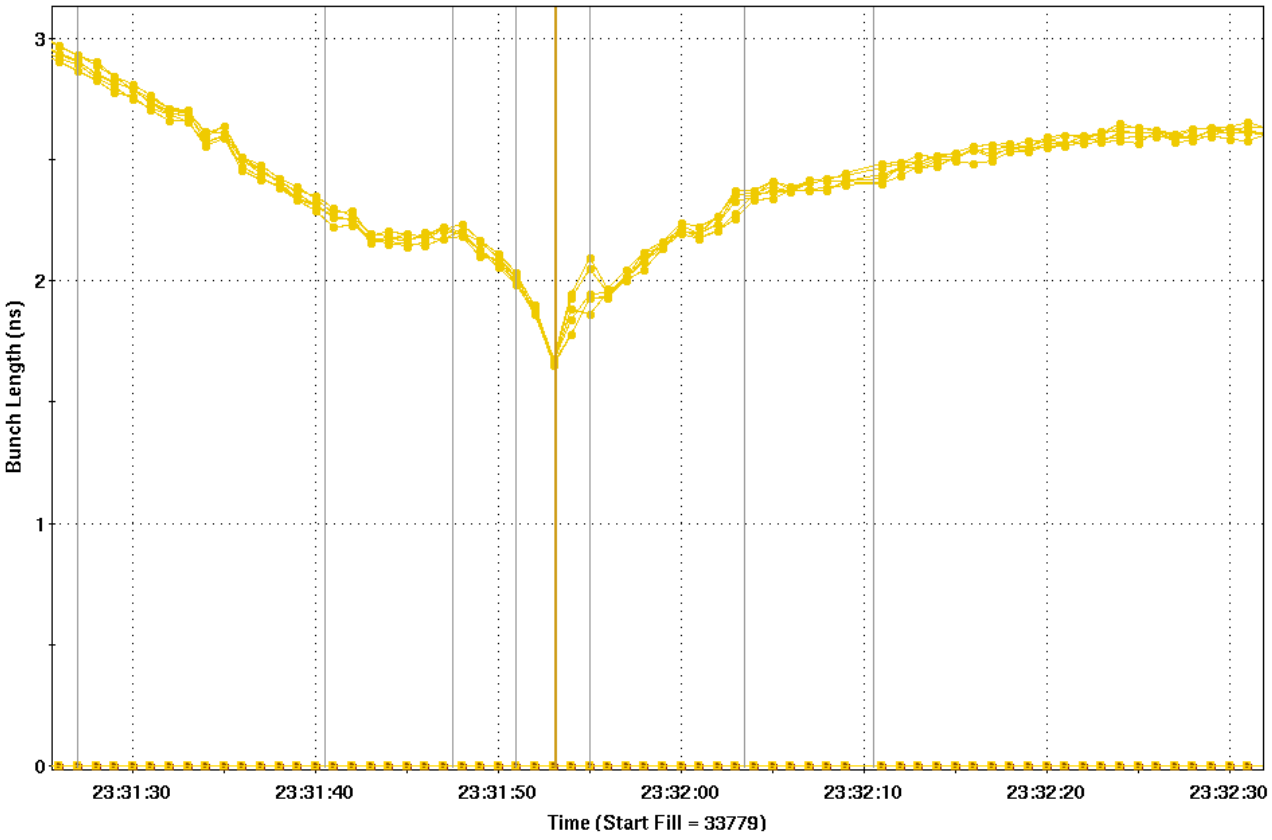
Tune evolution vs Transition γ



- Comparison between the 8 PS (Experimental) and 12 PS (Normal) configurations
  - 8 PS looks promising when tune evolution is modeled
    - Range is |k1l| < 0.008 1/m
    - 8 PS Q family
      - 0.013 1/m
        - Much too large!

Experiment 23-10

- Multiple jump quadrupole configurations
  - RHIC-48 (G, Q) = (24, 24) -baseline
  - HSR-40 has (G, Q) = (24, 16)
    - Local Compensation vs Global
  - Testing
    - (G, Q) = (24, 20)
    - (G, Q) = (24, 16)
    - (G, Q) = (24, 12)
    - (G, Q) = (24, 8)
- 12 bunches of nominal intensity
- Mis-tune injection to increase bunch length & momentum spread
- Observables
  - bunch length
  - current loss
  - emittances
  - orbit changes -- proxy for β waves



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Beam Experiment Proposal

Experiment Number:	23-10
Beam Experiment Title:	Transition Jump with Reduced Number of Jump Quadrupoles
Spokesperson(s):	Henry Lovelace III, Steve Peggs, Guillaume Robert-Demolaize
Status:	Running
Team:	Henry Lovelace III, Steve Peggs, Angelika Drees, Guillaume Robert-Demolaize
Experiment Goal:	Achieve a stable transition jump with minimal emittance blowup and beam loss using a reduced number of quadrupoles. The configuration of the jump quadrupoles implemented in the experiment will be similar to what is present in the current hadron storage ring design.
Benefits:	The experiment prove or disprove that transition can be adequately crossed using a reduced number of jump quadrupoles.
Experiment Description:	Using the WFG manager, a number of jump quadrupoles will be made to not ramp for transition crossing.
Hazard Analysis:	none
Approved By:	
Date Approved:	
Resources:	
Instrumentation:	loss monitor, ipm, bpms, and wall current monitor
Application:	WCM, Rhiclossmonitor, RHICIpm, orbitdisplay
Time:	8 hrs
Personnel:	Henry Lovelace III, Steve Peggs, Angelika Drees, Guillaume Robert-Demolaize, Matthieu Valette, Operators, OC, and possibly PS group
Intentional Beam Loss?	No
Plan for Data Analysis:	Ramp magnets, observe beam loss and emittance growth from transition crossing. Compare results of reduce quadrupole transition crossing to the normal RHIC configuration.
Results:	Expected results are that there will be significant longitudinal emittance growth. That beam loss will increase during and after transition.

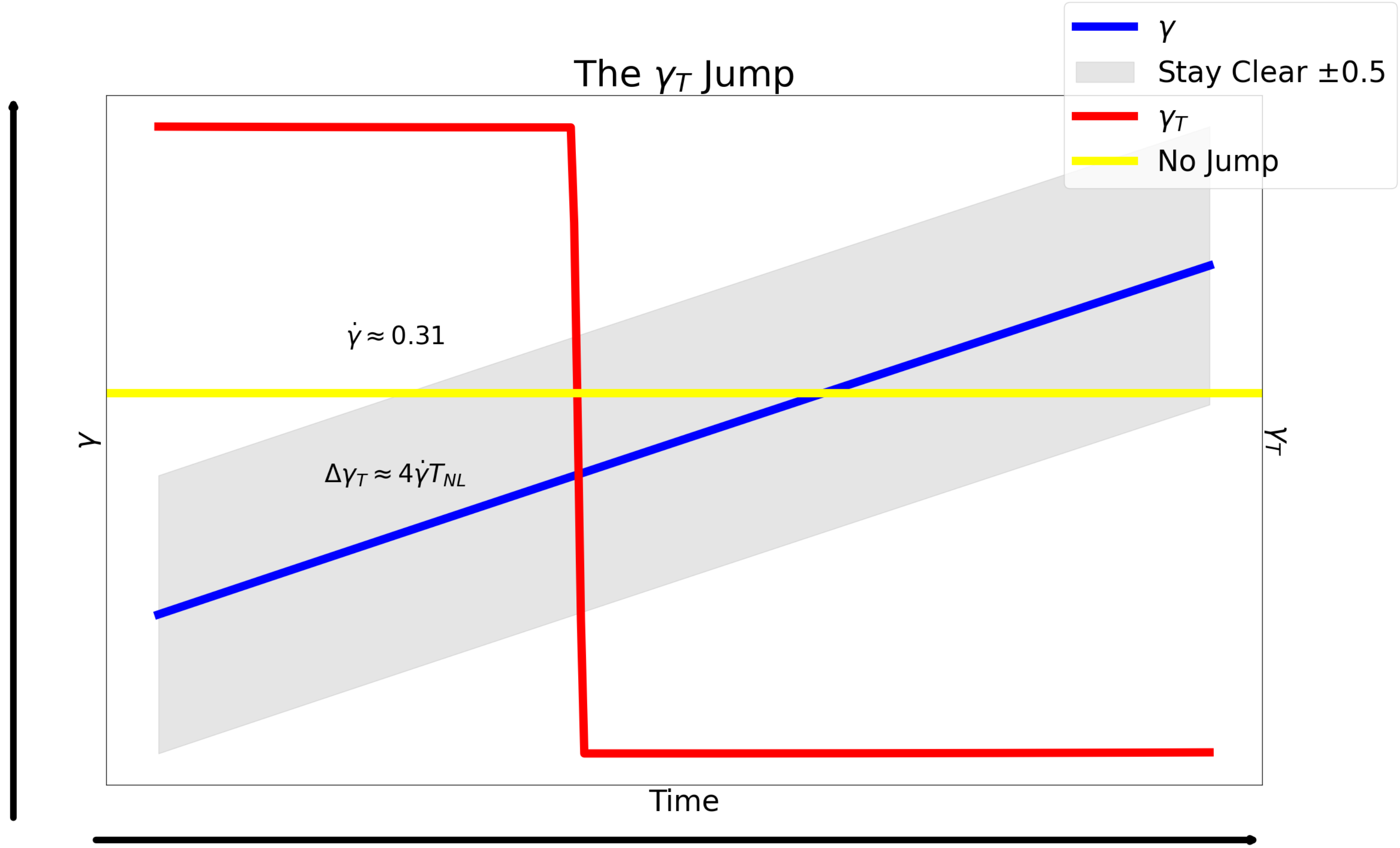
After meeting with OCs:

- Is it best to turn off jump quads or leave on?
- May require ramp development

Summary

- Experiment 23-10
  - Reduced Number of Jump Quadrupole
  - From tech note EIC-ADD-TN-41, two knob scheme has been established that will be used in the model for transition crossing
    - Due to the lattice symmetry breakage, the the efficiency of first order matched scheme will diminish
  - Multiple configurations where the number of Q families are reduced
    - The strength of the remaining Q family jump quadrupoles will be increase to compensate for the missing jump quadrupole families
    - Will give more understanding to the effect of less Q family jump quadrupoles in the EIC hadron storage ring
  - Normal beam diagnostics for transition crossing
  - 16 hrs
    - Changed from beam proposal request due to meeting with OCs
  -

Effect of Various Ramp Rates on Transition Crossing



- The nonadiabatic time, T_c, of the synchrotron motion where the bunches are shorter and may become unstable due to particles response to the change in the bucket can be formulated as:

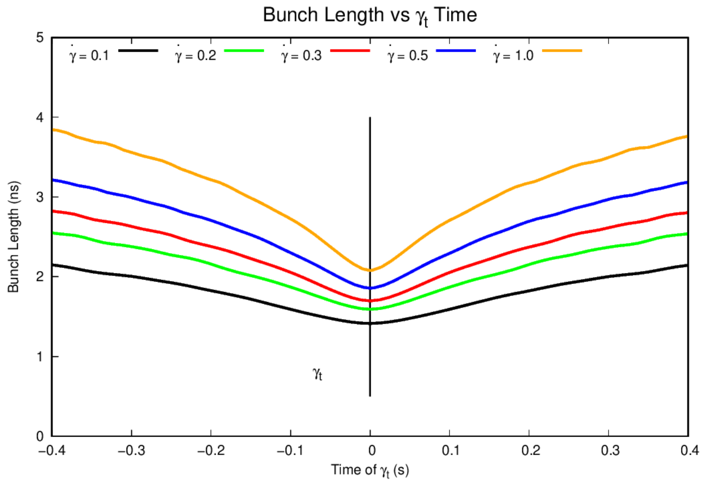
$$T_C = \left(\frac{AE_T}{ZeV|\cos(\phi_s)|} \times \frac{\gamma_T^3}{h\gamma'} \times \frac{C^2}{4\pi c^2} \right)^{1/3}$$

- Johnsen Effect

$$T_{NL} = \left(\alpha_1 + \frac{3}{2}\beta_T^2 \right) \frac{\gamma_T}{\gamma'} \delta_{max}$$

Longitudinal Model

- During transition, the bunch length shrinks which is a measurable quantity in RHIC
- The increasing of the ramp rate allows for increased bunch length during transition



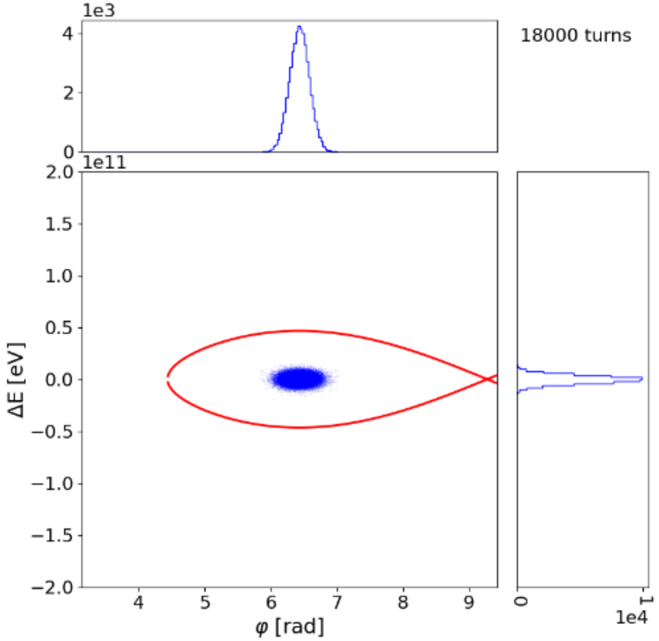


Figure 7: Pre-transition bunch and accelerating RF-bucket below transition. The red curve is the RF bucket and the points are the macroparticles. The horizontal and vertical axes are ϕ_s, the synchronous phase angle of the particle and ΔE, energy spread of the bunch. The beam profile of the phase (top) and the energy (right) amplitudes are in arbitrary units.

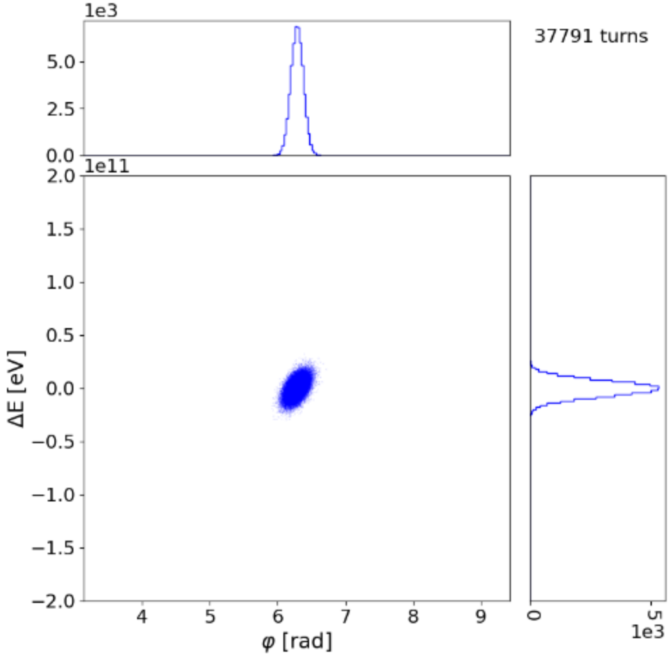


Figure 8: At transition, excluding the effects of the nonlinearities, the bunch is stretches and tilts. After transition, if well matched, the bunch returns to the pre-transition orientation. The points are the macroparticles with the axes ϕ_s the synchronous phase angle horizontal, and ΔE the energy spread vertical. The beam profile of the phase (top) and the energy (right) amplitudes are in arbitrary units.

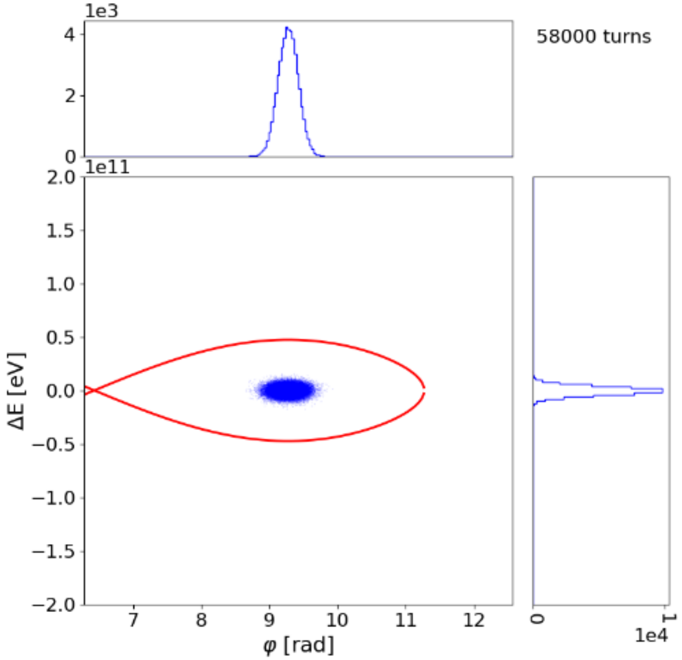


Figure 9: Post-transition bunch and accelerating RF-bucket below transition. The red curve is the RF bucket and the points are the macroparticles. The horizontal and vertical axes are ϕ_s, the synchronous phase angle of the particle and ΔE, energy spread of the bunch. The beam profile of the phase (top) and the energy (right) amplitudes are in arbitrary units.

Beam Experiment Proposal

Experiment Number:	25-07
Beam Experiment Title:	Effect of Various Ramp Rates on Transtion Crossing
Spokesperson(s):	Henry Lovelace III
Status:	Proposed
Team:	S. Peggs, G. Robert-Demolaize, K. Drees, B. Lepore, R. Seviour
Experiment Goal:	Prove that reducing the ramp rate of RHIC has an adverse effect on transition crossing
Benefits:	No benefit, only proof that reducing ramp rate will reduce the efficiency of the first order matched transition jump.
Experiment Description:	The main magnet ramp rates will be slowed using the slow factor in RHIC
Hazard Analysis:	none
Approved By:	
Date Approved:	
Resources:	
Instrumentation:	Instrumentation includes but is not limited to: BPMs IPMs WCM BLM Schottky Monitors ...
Application:	Applications includes but not limited to: RampEditor WFG Manager RFRamps ...
Time:	6
Personnel:	RF personnel MCR
Intentional Beam Loss?	No
Plan for Data Analysis:	Data from instrumentation mentioned will be compared to model
Results:	Unlike most experiment, the results of this experiment will show that decreasing the ramp rate will decrease the efficiency of transition crossing

After meeting with OCs:
- Multiple ramps will need to be generated
  - Feedback
  - Time dependent settings
    - Collimation
- Will require 12 hrs

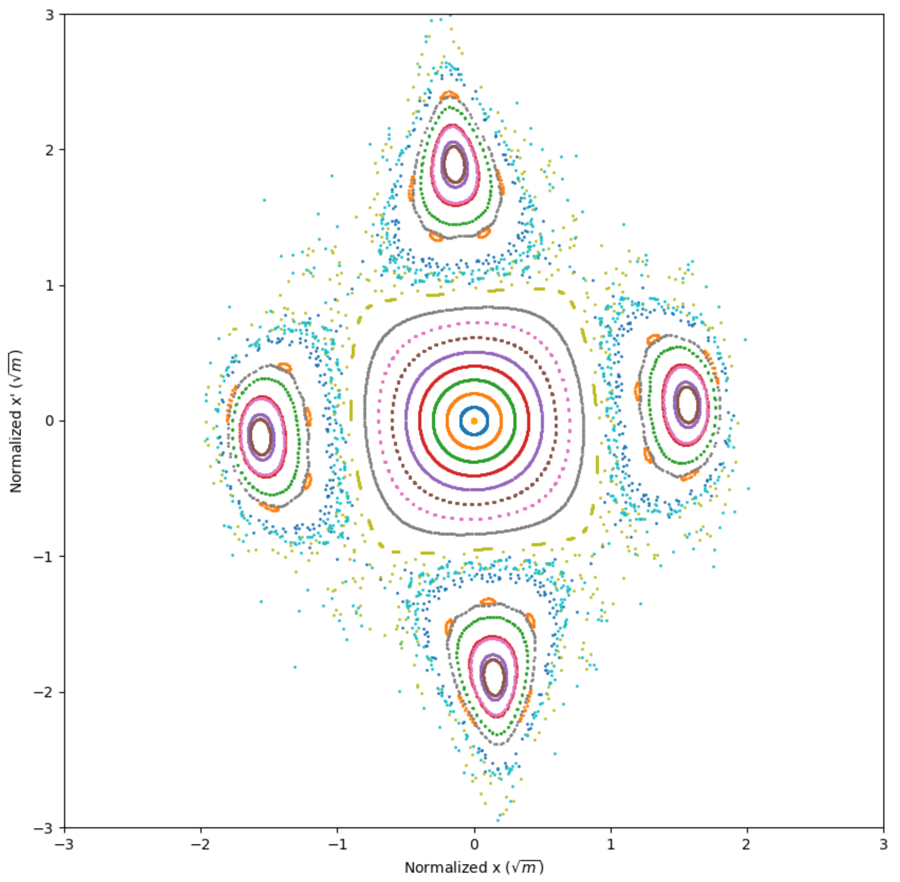
Summary

- Experiment 25-07
  - Effect of Various Ramp Rates on Transition Crossing
  - The experiment will give guidance on the effect of reducing ramp rate in the EIC hadron storage ring
    - Direct wind magnet may not ramp the rigidity at the same rate as the current RHIC rigidity ramp
  - As the ramp rate decreases, the bunch length at transition will also decrease which will lead to instabilities
  - Normal beam diagnostics for transition crossing
  - 12 hrs
    - Changed from beam proposal request due to meeting with OCs

Transition Crossing using Stable Resonance Islands Jump (RIJ)

The idea:

- Use nonlinear magnetic fields to produce stable resonance islands
  - $\boldsymbol{\alpha_{c,rij} > \alpha_{c,nom} \Rightarrow \gamma_{t,rij} < \gamma_{t,nom}}$
  - Dipole kicker deflects beam into stable island until $\gamma > \gamma_{t,nom}$
  - The beam is then kicked back on to the standard closed orbit by a dipole kicker

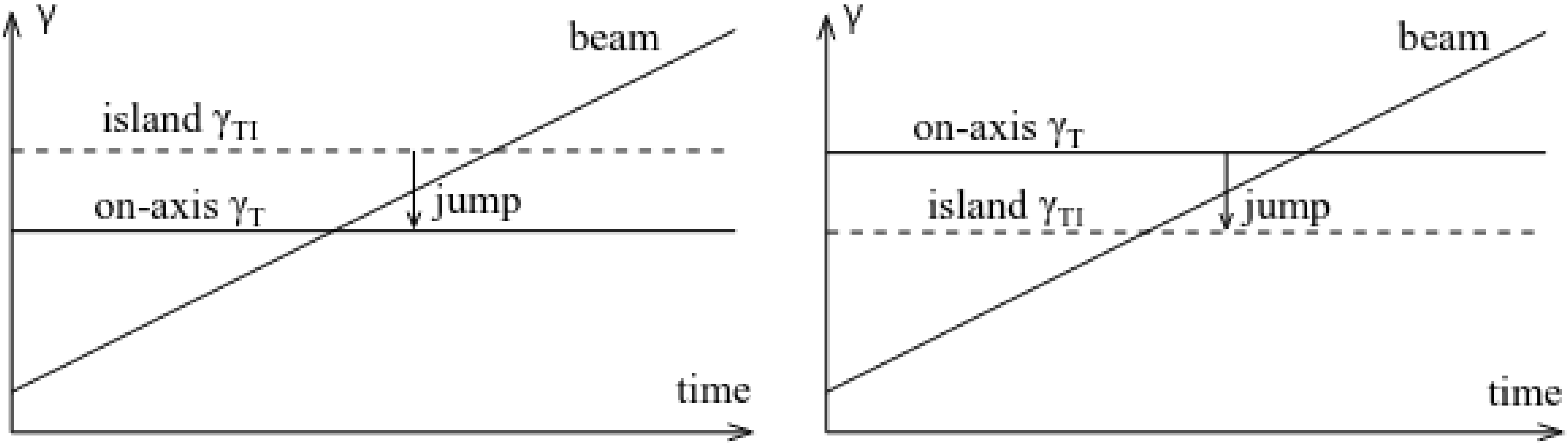


A novel non-adiabatic approach to transition crossing in a circular hadron accelerator

M. Giovannozzi[1,a], L. Huang[2], A. Huschauer[1], A. Franchi[3]

Transition Crossing using Stable Resonance Islands Jump (RIJ)

- Experiment Goal
  - Phase I: Establish stable resonance islands at injection and measure island tune, and Twiss parameters.



S. Peggs, H. Lovelace, III, G. Robert-Demolaize, and T. Satogata, "Resonance island jump theory for the hsr," 10 2023.

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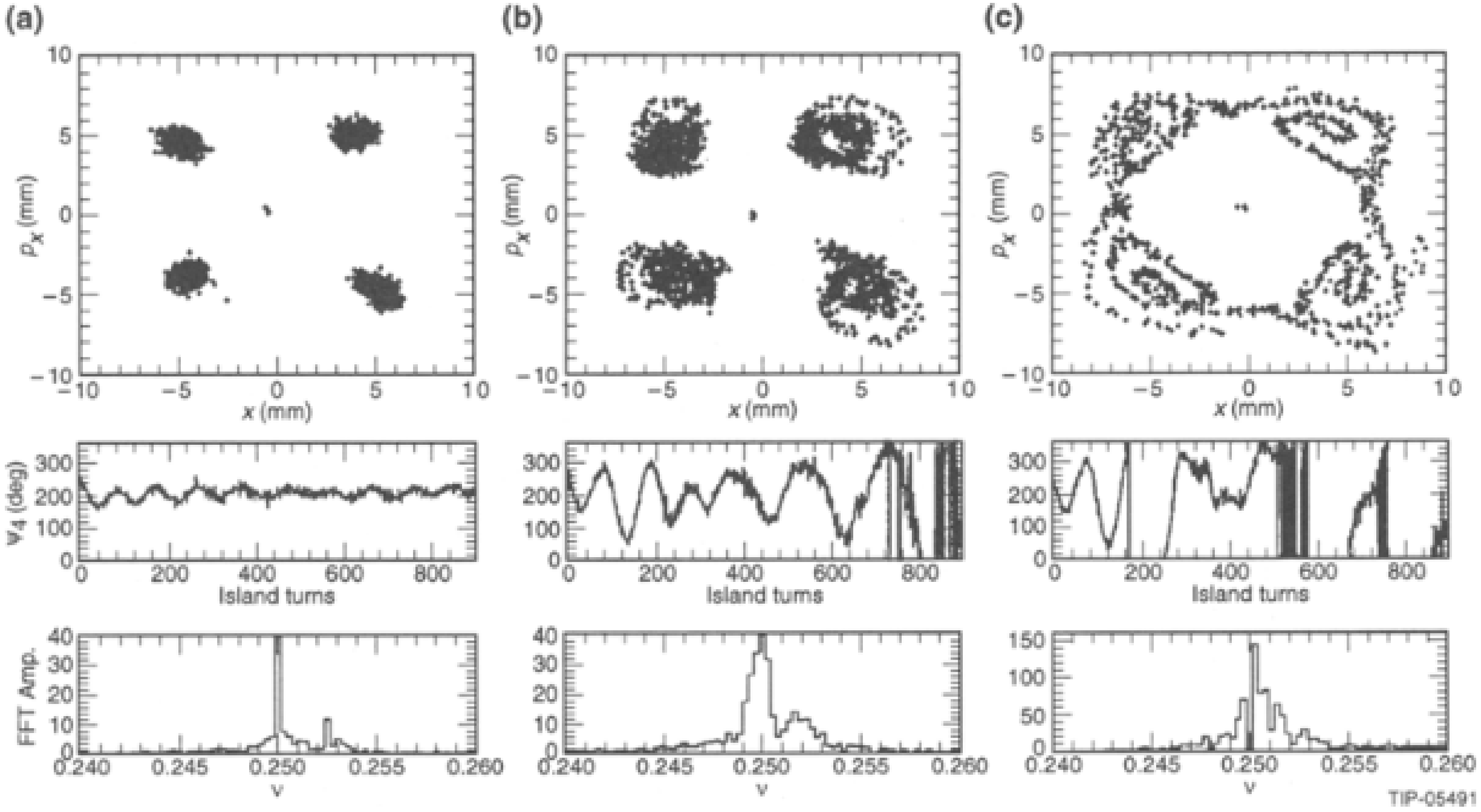
Experiment 25-06

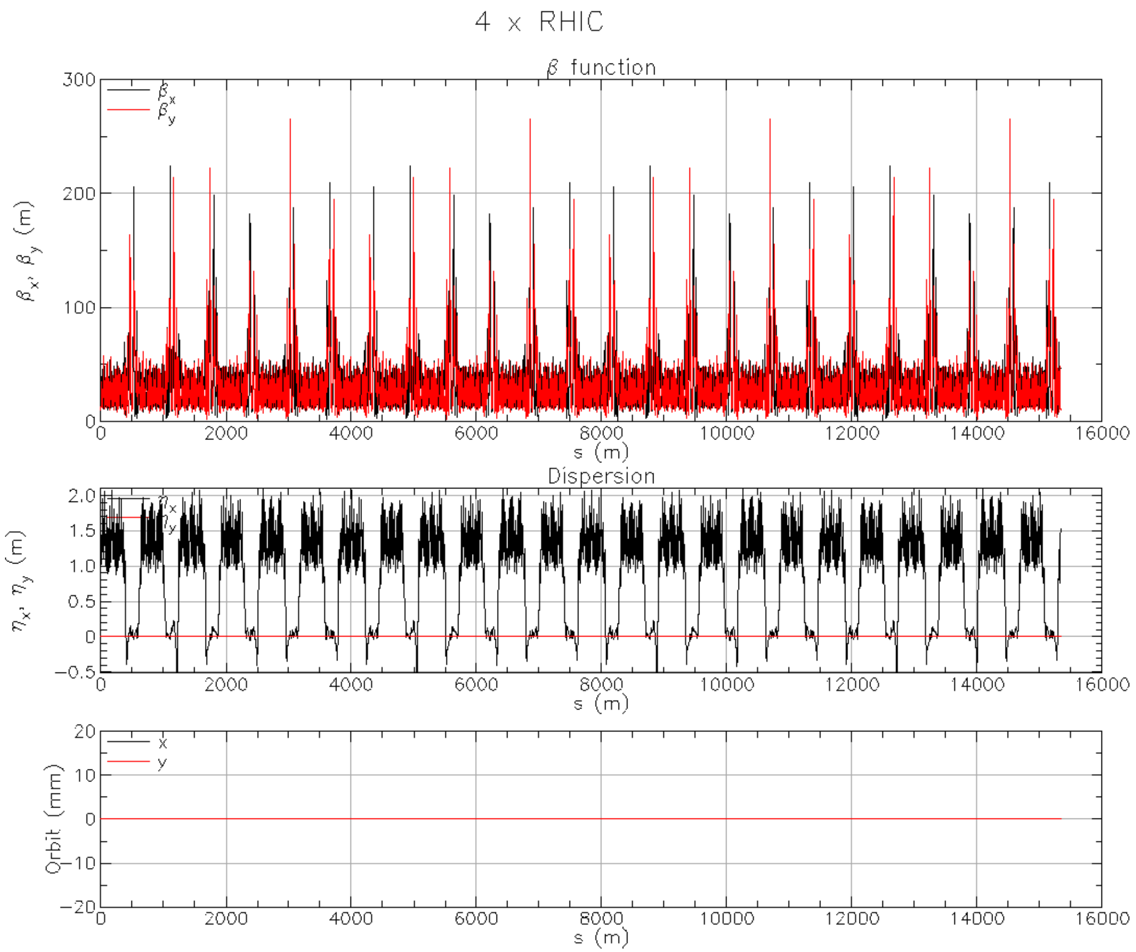


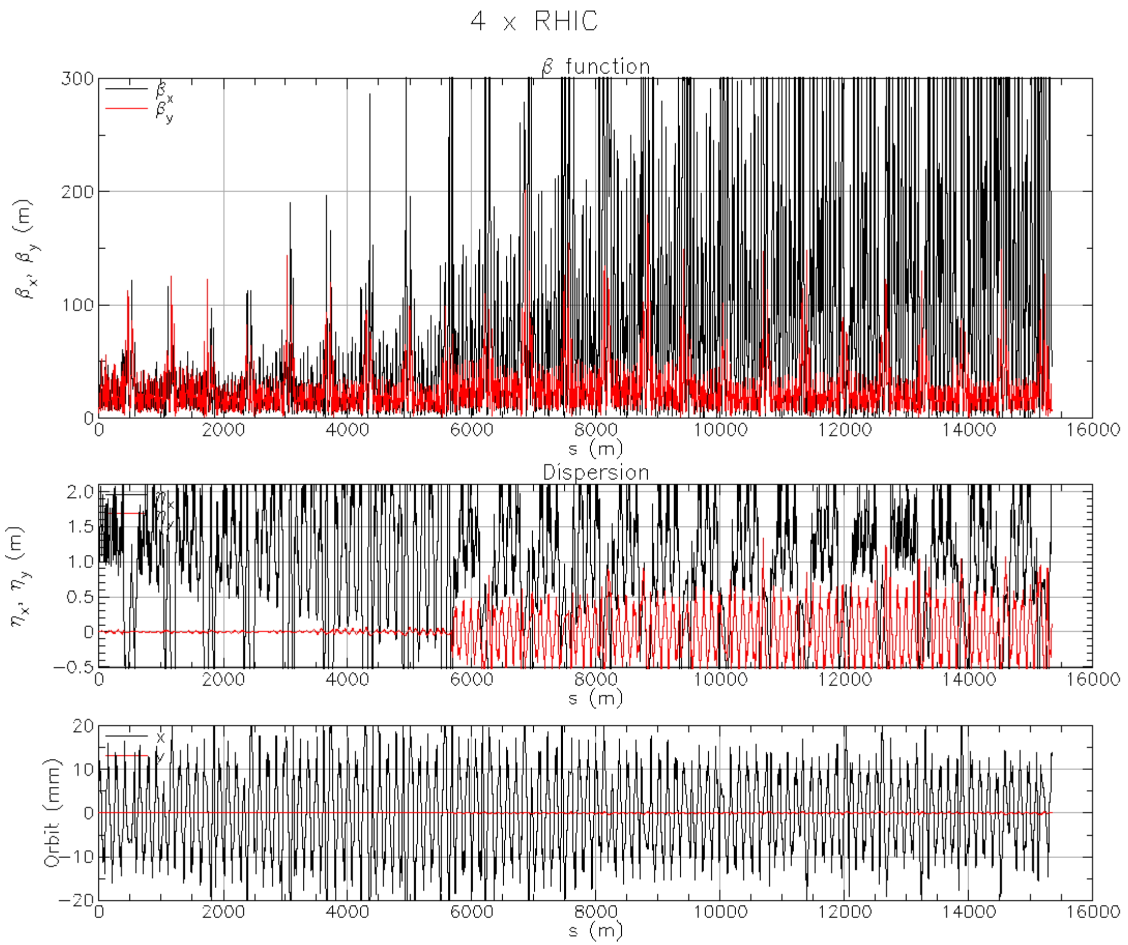
Lee, S.Y. (Feb 1995). Beam dynamics experiments at the IUCF cooler ring. AIP Conference Proceedings, 326(1), 12-51.

At injection, adjust tune to quarter integer stabilizing using octupoles

- Generate a system in which to measure the island tunes
- Calculate the $\Delta\gamma_T$ of the islands compared to the beam on axis
- Using the turn by turn analysis, the island tune will be calculated as well as the difference in gamma transition. The IPM will be used as a secondary method to verify trapping and separation during the island formation.

Beam Optics

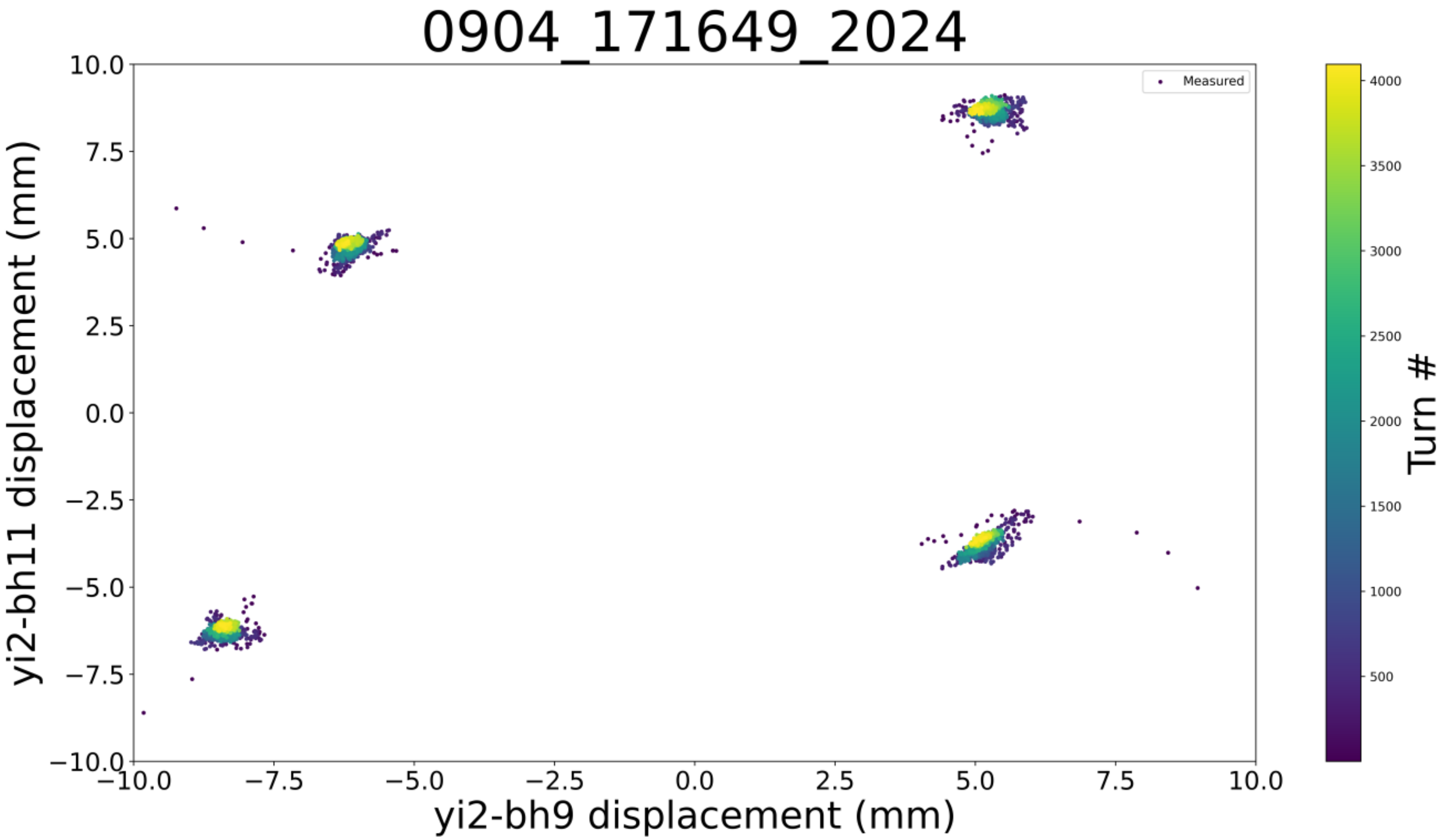




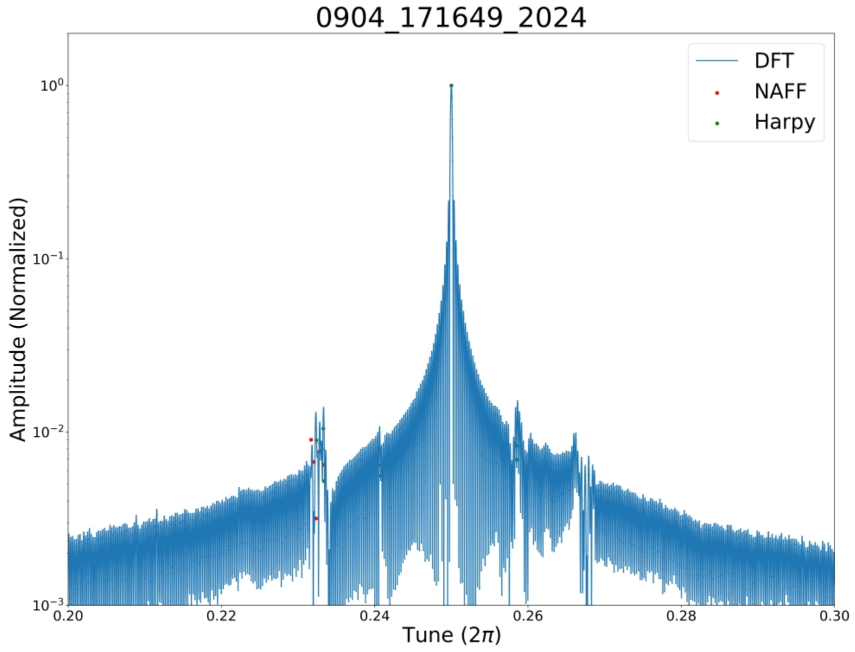
20-00-00 Configuration

$\Delta\gamma_T$ = 0.028 with 0.34 γ/s, t= 82 ms > T_c

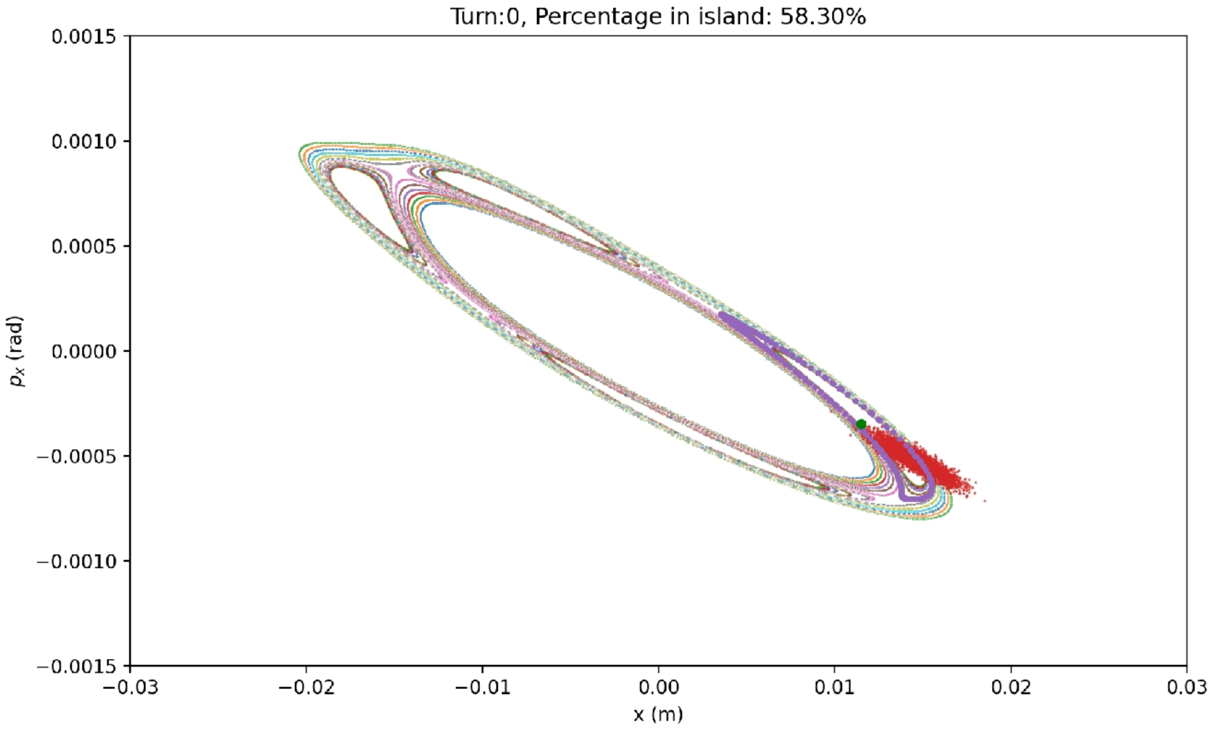
RIJ Phase I Measured Data

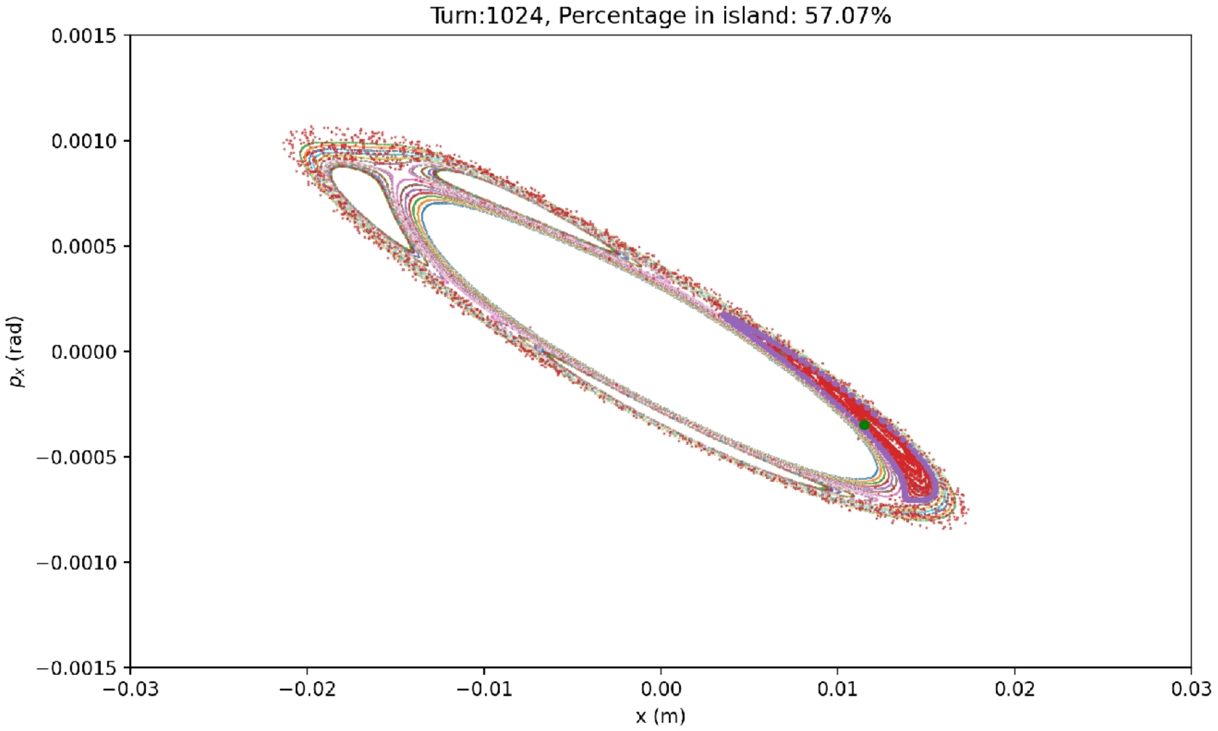


- Measured data from phase I
- Injected successfully into resonance islands
- Spiraling due to bunch filamentation



Bunch Filamentation





Simulated: After 1024 turns, the KAM theory holds true and no particle is trapped within any other island

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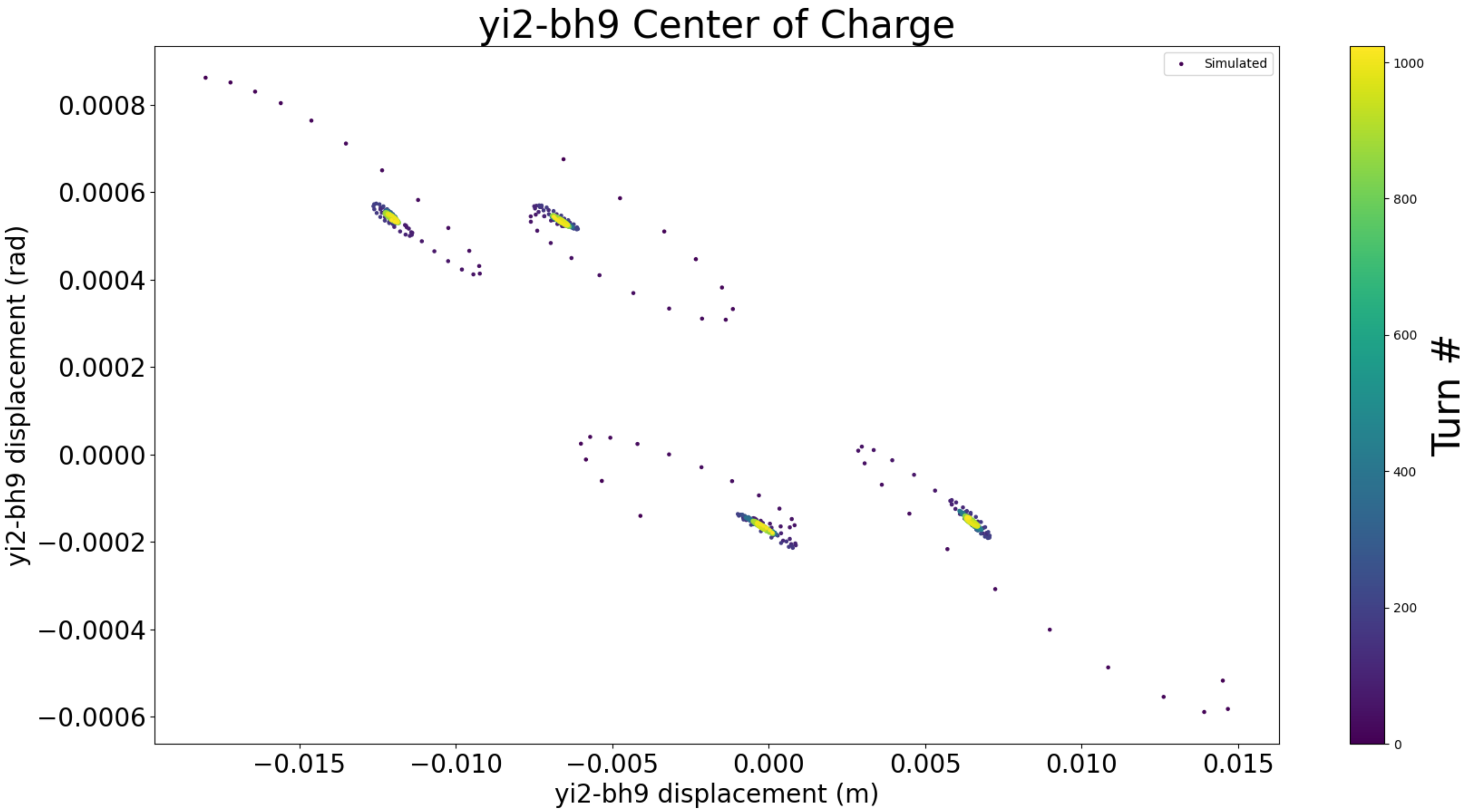
Bunch Filamentation

Simulated results of the spiraling effect due to bunch filamentation



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Beam Experiment Proposal

Experiment Number:	25-06
Beam Experiment Title:	Resonance Island Jump Phase II
Spokesperson(s):	Henry Lovelace III
Status:	Proposed
Team:	S. Peggs, G. Robert-Demolaize, K. Drees, B. Lepore, R. Seviour
Experiment Goal:	Ramp through transition with beam trapped in transverse resonance island. If one turn dipole kicker available, kick beam on-axis through transition.
Benefits:	Offer for the EIC HSR an alternative to the first order matched transition crossing scheme currently used in the RHIC. Also, to the wider accelerator physics community, demonstrate that resonance islands can be used to cross not only transition any unwanted resonance ie spin resonances
Experiment Description:	After injection into the 4th order resonance island is established, the beam will be ramped through transition to first understand transition within the new ramp, and then to cross transition if the dipole is available.
Hazard Analysis:	A single abort kicker module may be used which adds risk to the experiment. Low intensity will be used to mitigate any damage that may occur due to beam loss
Approved By:	
Date Approved:	
Resources:	
Instrumentation:	Instrumentation includes but is not limited to: BPMs IPMs WCM BLM Schottky Monitors ...
Application:	Applications includes but not limited to: RampEditor WFG Manager RFRamps ...
Time:	16-24 hrs uninterrupted if major failure occurs then more time will be needed due to setup time for experiment
Personnel:	RF personnel MCR Injection Expert
Intentional Beam Loss?	No
Plan for Data Analysis:	Data from instrumentation mentioned will be compared to model
Results:	A reasonable match of model to machine instrumentation for transition gamma and possibly transition crossing will be deemed successful

After meeting with OCs:

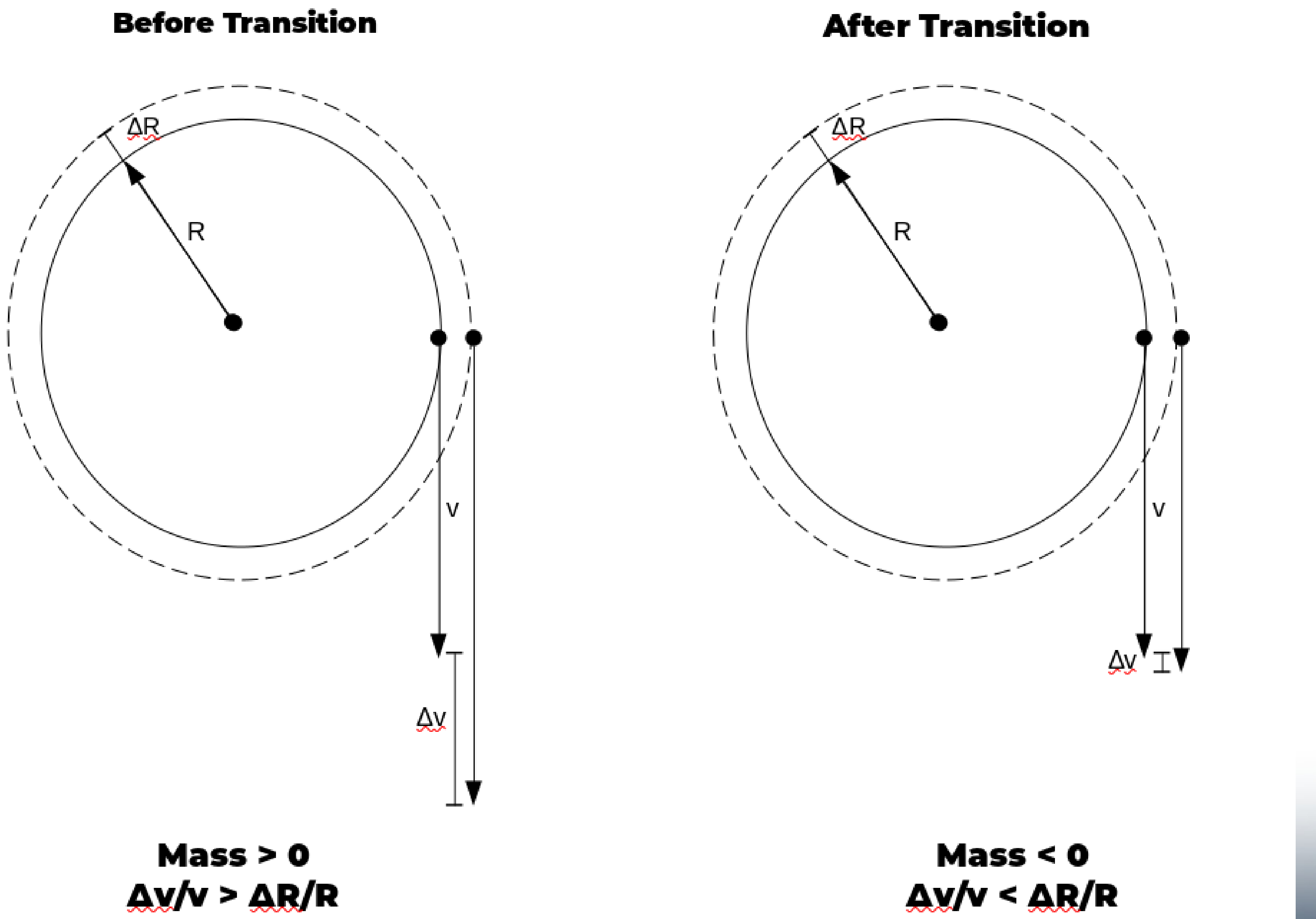
- Takes a great deal of coordination
  - Controls
    - RF radial loop
  - Pulse Power (For use of single abort kicker module)

Summary

- Experiment 25-07
  - Resonance Island Jump Phase II
  - The experiment offers a possible alternative to the first order matched scheme currently used in RHIC (Due to jump quadrupole reduction)
    - Give credence to future experiments of avoiding resonances by using non-adiabatic kicks in and out of islands
  - The first ever injection from transfer line into resonance island (after literature search), another first of energy ramp with transversely trapped beam is needed
    - Radial loop correction
      - Every fourth turn
  - Single turn kick
    - Possible use of abort kicker module (Require permit change ...)
    - ARTuS kicker not completely ruled out if island is rotated to a position that places the fixed point within kicker amplitude/angle
  - 16-24 hrs

Back up

What is Phase Transition?



- **Shown to the left is a schematic of two particles traveling in a circle about a central force. The more energetic particle travels with a greater radius, R and velocity, v. When Δv/v > ΔR/R, the particles are said to be <u>below</u> transition and if** Δv/v < ΔR/R, the particles are <u>above</u> transition.

What is Phase Transition?

- When accelerating a particle
  - We first will define the slippage $\eta = 1/\gamma_t^2 - 1/\gamma^2$
    - $\gamma < \gamma_t$ and $\eta < 0$, the particles that are more energetic than the synchronous will have a shorter revolution period
    - $\gamma > \gamma_t$ and $\eta > 0$, the particles that are more energetic than the synchronous will have a longer revolution period
    - The dependence on η causes the synchrotron tune to slow as the beam crosses transition
      - The adiabaticity condition not satisfied at transition

$$\frac{1}{\omega_s^2}\left|\frac{d\omega_s}{dt}\right| \ll 1$$

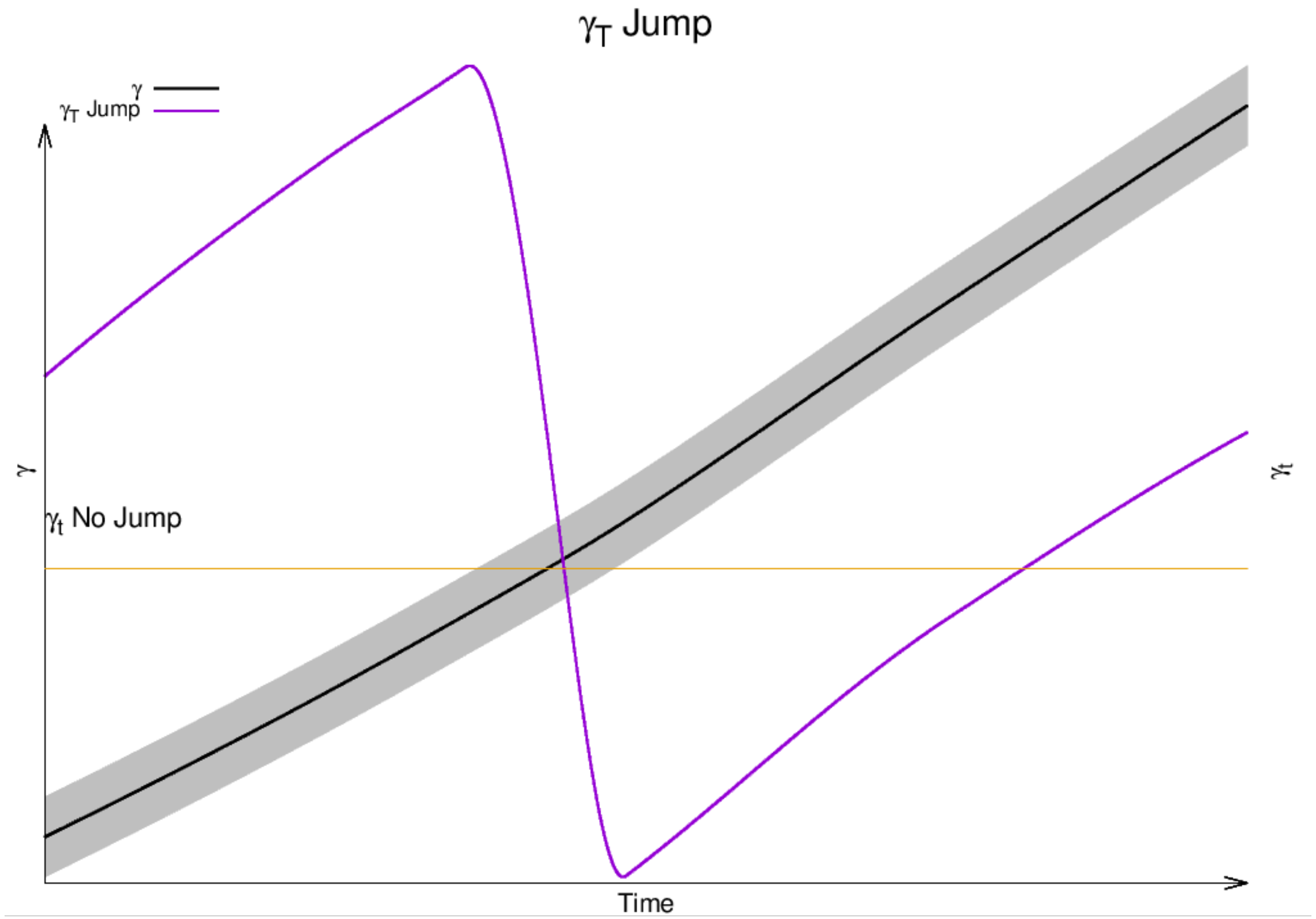
    - The revolution period of the particle is independent of the particles energy at $\gamma = \gamma_t$,
      - The nonadiabatic time, T_c, of the synchrotron motion where the bunches are shorter and may become unstable due to particles response to the change in the bucket can be formulated as:

$$T_C = \left(\frac{AE_T}{ZeV|\cos(\phi_s)|} \times \frac{\gamma_T^3}{h\gamma'} \times \frac{C^2}{4\pi c^2}\right)^{1/3}$$

- Johnsen Effect
  - Described as particles with various momenta crossing phase transition at different times
    - Unwanted emittance growth due to chromatic nonlinearities
  - The formulated analog to the time duration, nonlinear time T_{NL}, of the Johnsen effect is:

$$T_{NL} = \left(\alpha_1 + \frac{3}{2}\beta_T^2\right)\frac{\gamma_T}{\gamma'}\delta_{max}$$

The γ_T Jump



- **Allows the beam to cross transition faster.**
  - **The jump does not allow bunches the time to become *too* short, thus reducing space charge forces that are normally seen without the jump.**
- **γ_T is time-dependent**

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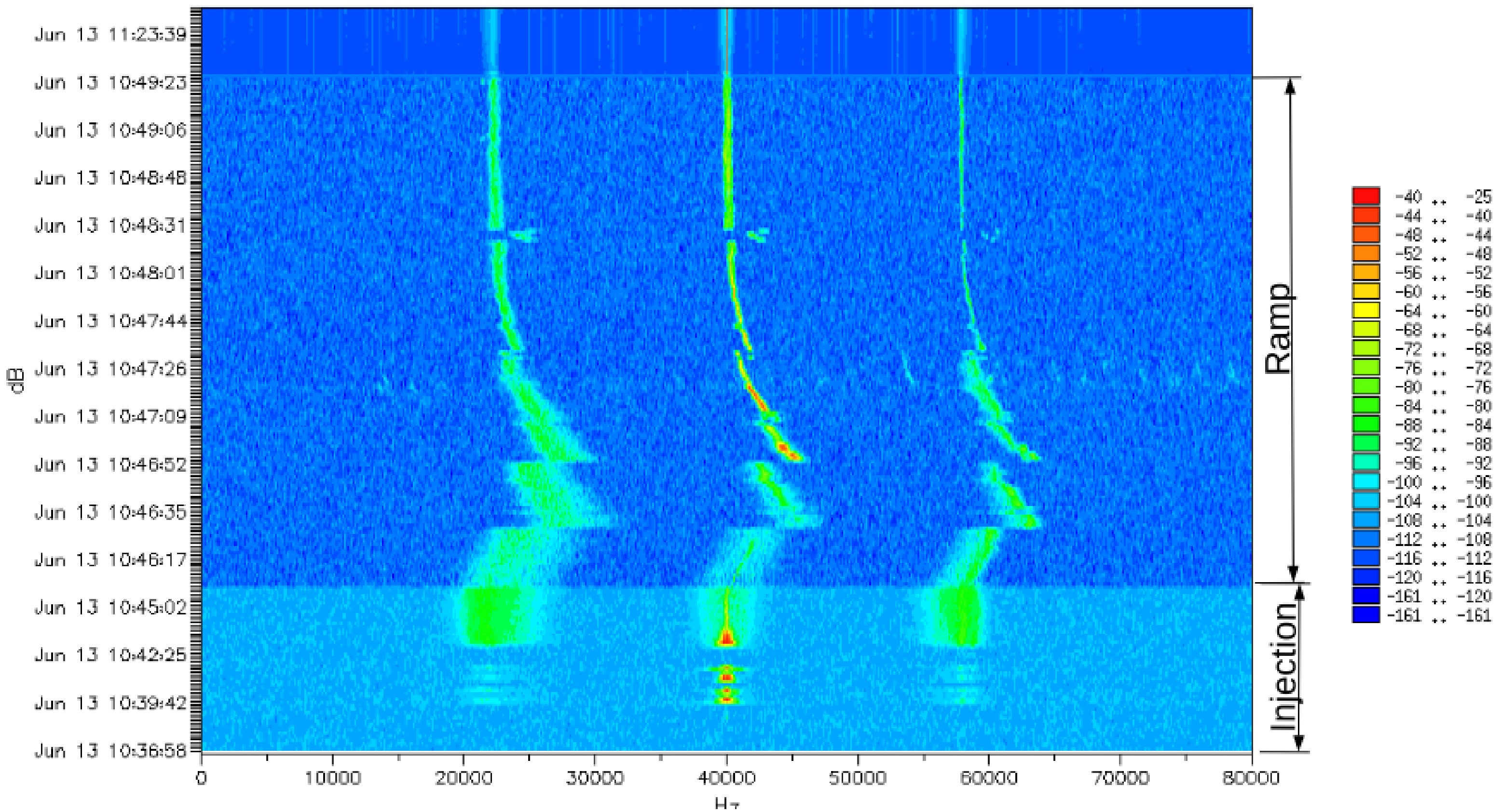
LF Schottky through RHIC Ramp

LF Schottky tracking through RHIC ramp
with 12 bunches.



Note. Discontinuity of the Schottky bands is due to a lagging readout of 28 MHz RF.
The RF traverses 14 revolution harmonics during the ramp.