Beam echoes in the presence of coupling

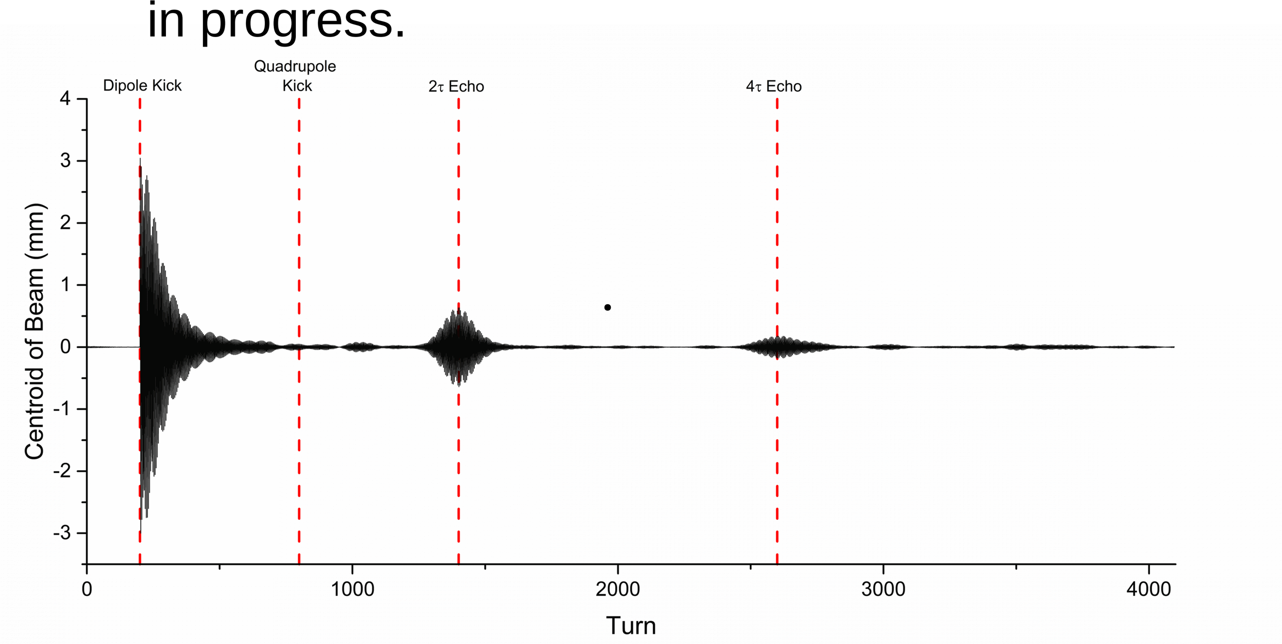
Axel Gross, Case Western Reserve University
Tanaji Sen, Fermilab

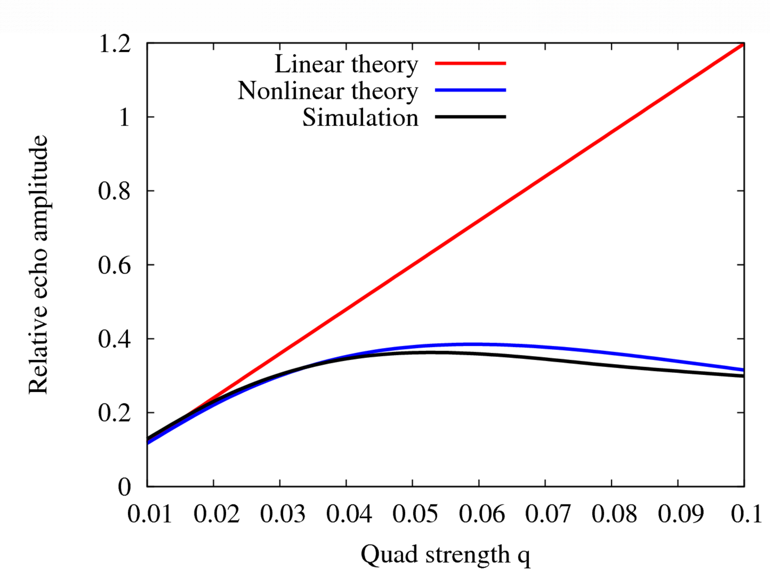
Introduction

- Transverse beam echoes could provide an important new way to measure characteristics of particle beams; however, they are poorly understood.
- The amplitude of transverse echoes are very sensitive to diffusion characteristics and could theoretically provide a method of measurement orders of magnitude faster than current methods (e.g. beam scraping).
- The current theory for transverse beam echoes is first order. In order to understand how many factors influence the echo amplitude, notably the dipole and quadrupole kick strength, a non-linear theory must be developed.
- To facilitate the development of this theory, simulations were developed to:
  - a) Explore the effect of beam echoes in 2 dimensions, especially the consequences of coupling between the dimensions
  - b) Explore the effects of diffusion in multiple dimensions
  - c) Explore the effects of diffusion with coupling
- The eventual goal is to provide recommendations to IOTA (Integrable Optics Test Accelerator) for the planned echo experiment.

Echo Theory

- Transverse echoes are temporary re-coherences of the beam distribution following phase decoherence due to non-linearities in the beam propagation. A typical echo sequence is as follows:
  - a) At t=0; apply a one-turn dipole kick.
  - b) At t=τ; apply a one-turn quadrupole kick.
  - c) An echo signal will appear around t=2τ
  - d) Further echoes will appear at t=4τ, t=6τ, etc, but the maximum echo amplitude decreases with each echo, although neither the linear nor our present version of the non-linear theory predict this. Further development of non-linear theory is in progress.





$$\text{EchoAmpl}_{linear} = \theta\beta Q$$

$$EchoAmpl_{nonlinear} = \frac{\beta\theta Q}{[(1+Q^2-Q_2^2)^2+4Q_2^2]^{\frac{3}{4}}}$$

where:

$Q = q\omega'\epsilon\tau$

$Q_2 = \frac{q^2\omega'\epsilon\tau}{2}$

θ: Dipole kick strength
q: Quadrupole kick strength
ϵ: Initial Emmittance
τ: Time between dipole and quadrupole kick
ω': Slope of the tune with respect to the action
β: Beta function at dipole, quadrupole

Above: Typical echo profile
Lower Left: Comparison between linear and nonlinear predictions of echo amplitude
Lower Right: Analytical echo amplitudes for linear and nonlinear theory

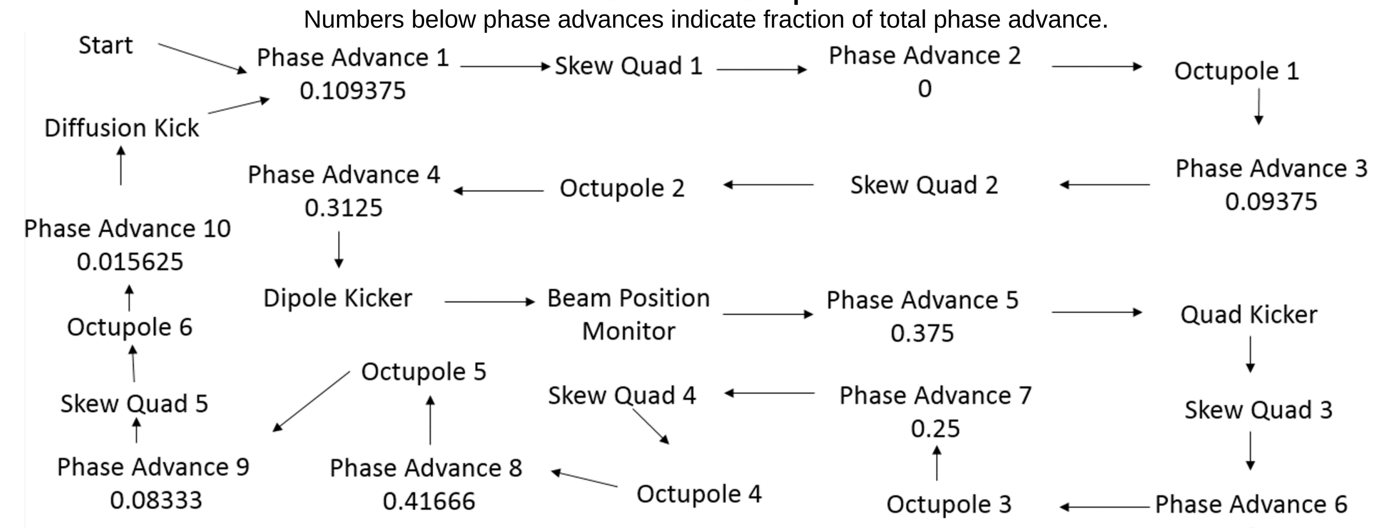
Simulation

- Coded in C, based on previous FORTRAN code
- Parameters are based on 2005 RHIC experiment.

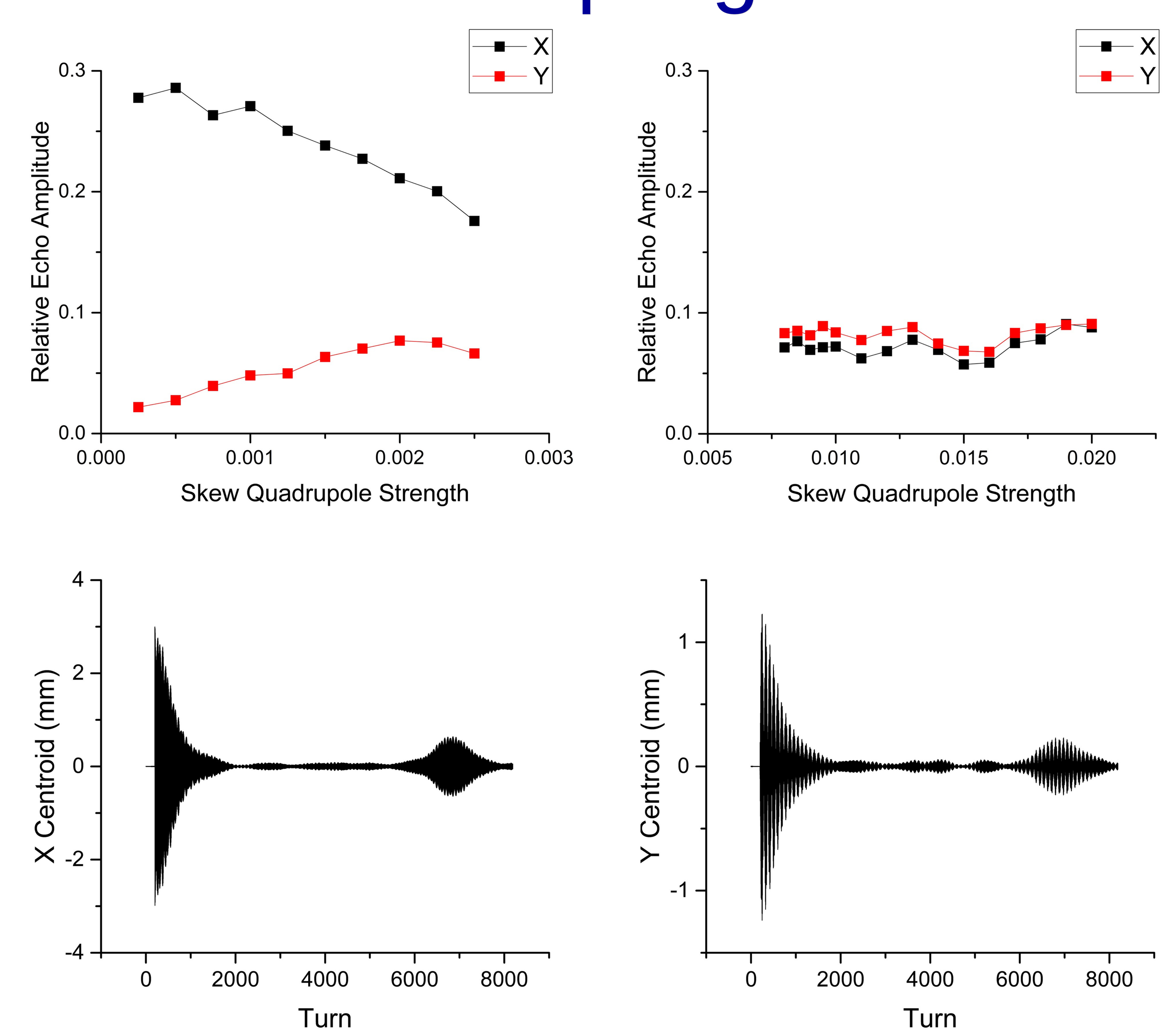
Common Simulation Parameters

Number of Particles	20000
Initial Emittance	1.5E-7
Initial X Tune	0.235
Initial Y Tune	0.215-0.225
Betatron at BPM, Quadrupole, and Dipole (m)	10
Quadrupole Kick Strength (1/m)	0.007
Dipole Kick Strength	3.E-4
Time between Dipole and Quadrupole Kick	600-3000 Turns

Simulation Setup
Numbers below phase advances indicate fraction of total phase advance.

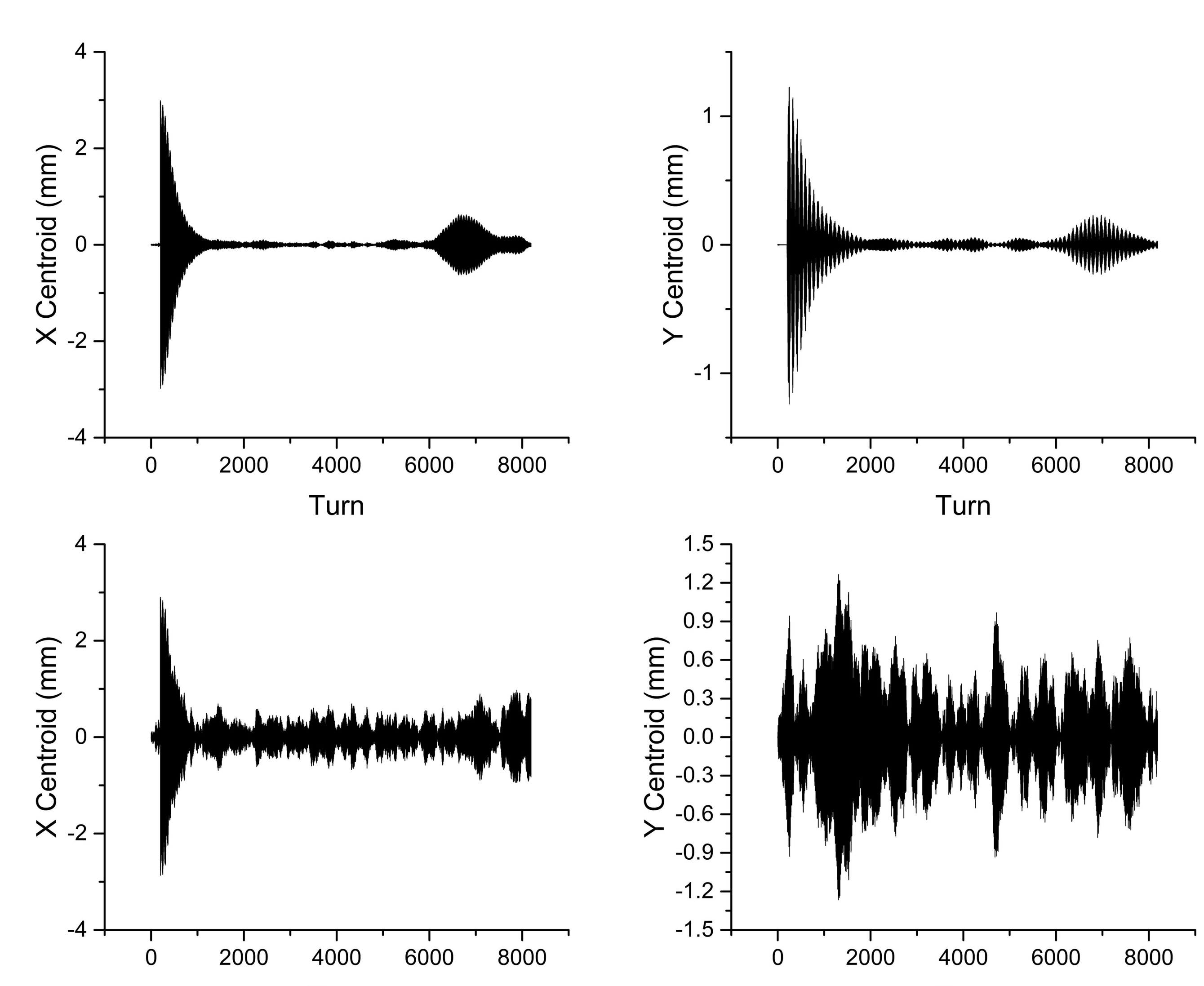


Coupling



Above: Relative Echo Amplitudes above and below decoherence effect at initial tune spread of 0.01
Below: Centroid Profiles at k_skew=0.002, initial tune spread 0.01

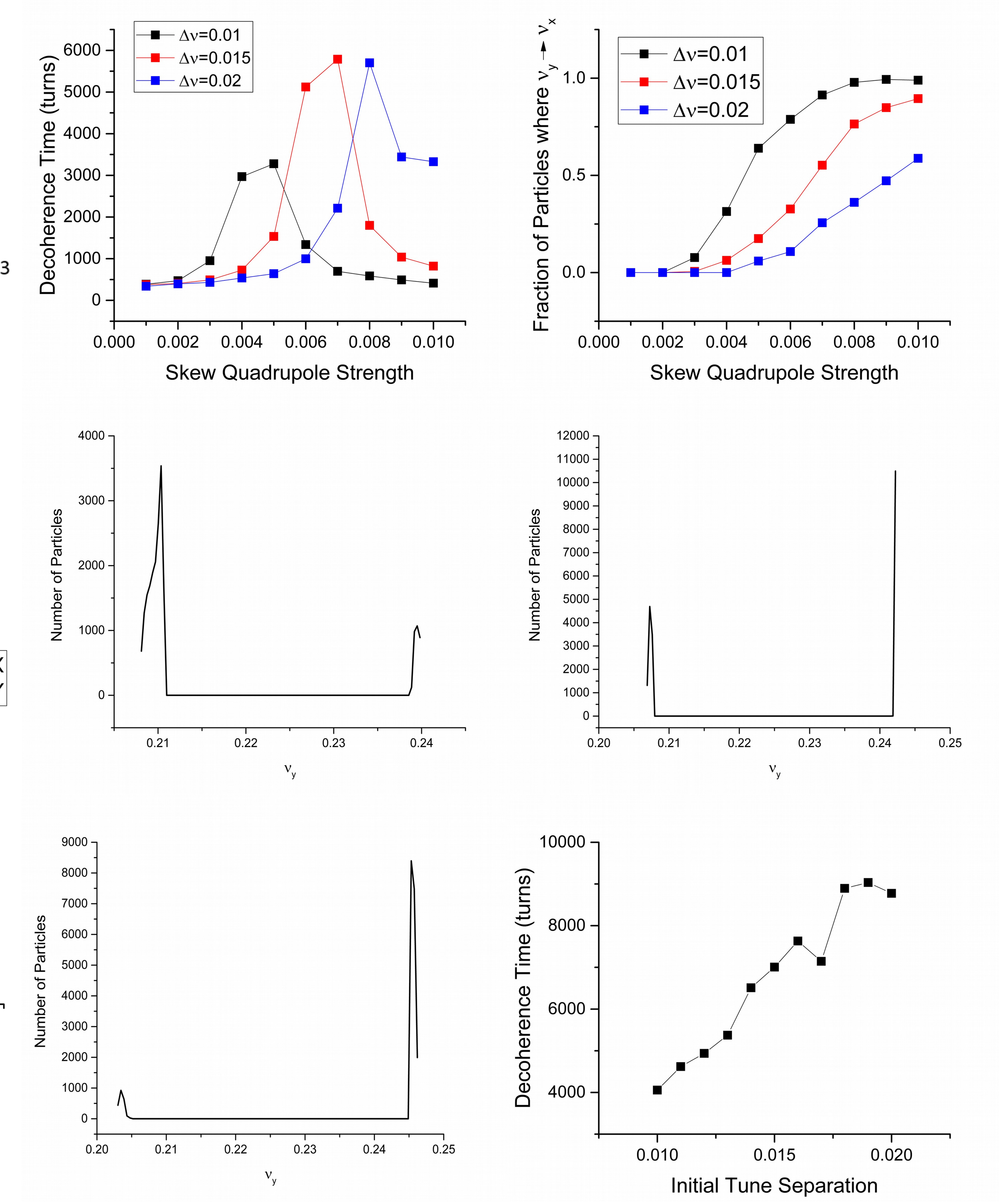
Diffusion



Above: Centroid Echo Profile with k_skew=0, Dipole Diffusion=1.E-6
Below: Centroid Echo Profile with k_skew=0, Dipole Diffusion=1.E-5

Decoherence Effect

- The echo amplitude and pulse width are directly correlated to the decoherence time. How does the decoherence time change with the coupling and initial tune separation?



Top Left: Decoherence time as a function of skew quadrupole strength and initial tune separation
Top Right: Number of particles that shifted y tune to difference resonance from initial tune (20000 particles total)
Y tune histogram below the maximum decoherence **(middle left)**, at the maximum decoherence **(middle right)**, and above the maximum decoherence **(bottom left)**. Initial y tune is 0.215, initial x tune is 0.235.
Bottom Right: Maximum decoherence time as a function of initial tune separation

Conclusions

- Coupling can generate an echo in the y direction off a dipole kick in the x direction, however, at the cost of the echo amplitude in the x direction.
- At certain coupling strengths, the decoherence time is massively increased. We have shown that this is reflected in the narrowing of the tune distribution at these coupling strengths; however, it is unknown what leads to this narrowing and subsequent widening of the tune spread at larger coupling.
- Diffusion in 2 dimensions behaves similarly to in 1 dimension. The coupling in the octupoles is driven at high diffusion strengths, causing an effect similar to a high skew quadrupole strength.
- Things to explore in the future:
  - a) Where do multiple echoes come from?
  - b) What causes the decoherence effect observed at certain skew quadrupole strengths?
  - c) How does diffusion interact with strong coupling?
  - d) Why does the maximum decoherence time increase with increasing initial tune separation?

Acknowledgements

This research was made possible by the Lee Teng Fellowship in Accelerator Science and Engineering hosted by Fermilab. I would like to thank my mentor, Tanaji Sen, program director Eric Prebys, and the teachers of the USPAS for their knowledge and support.

August 10, 2017

Fermilab
U.S. DEPARTMENT OF ENERGY | Office of Science