Study of Beam Echoes in the IOTA Ring

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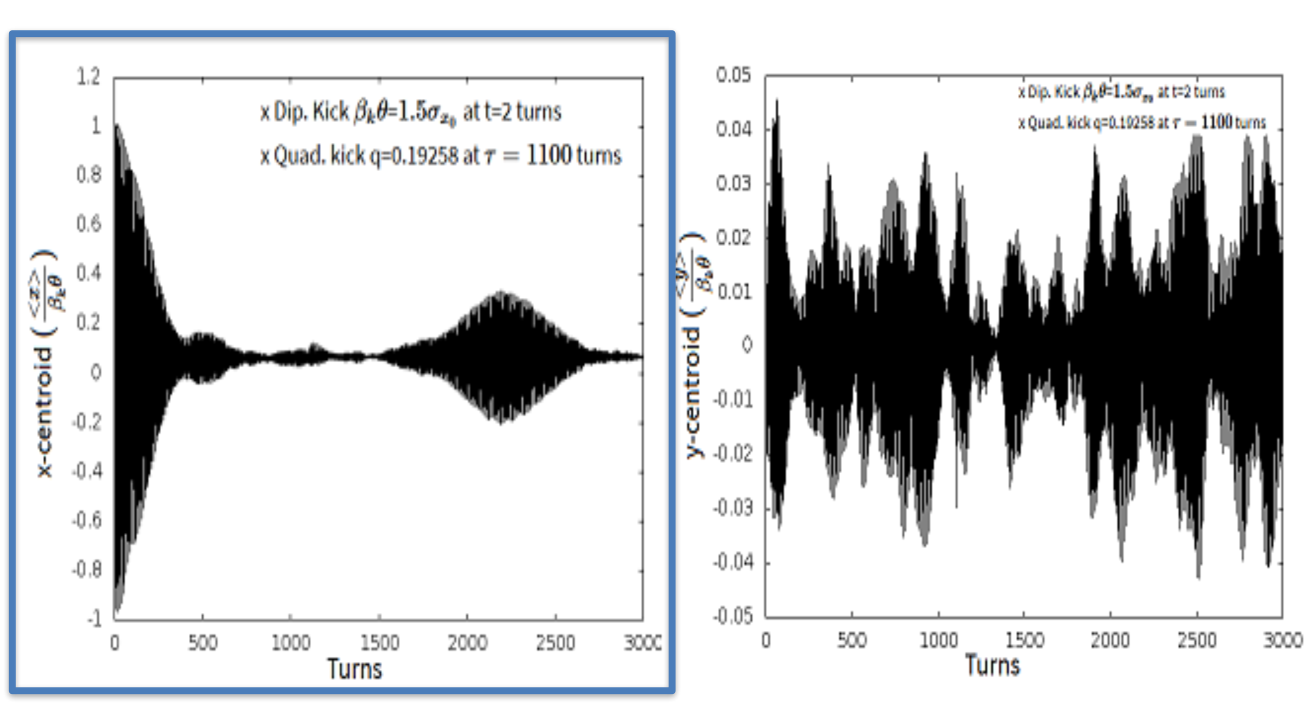
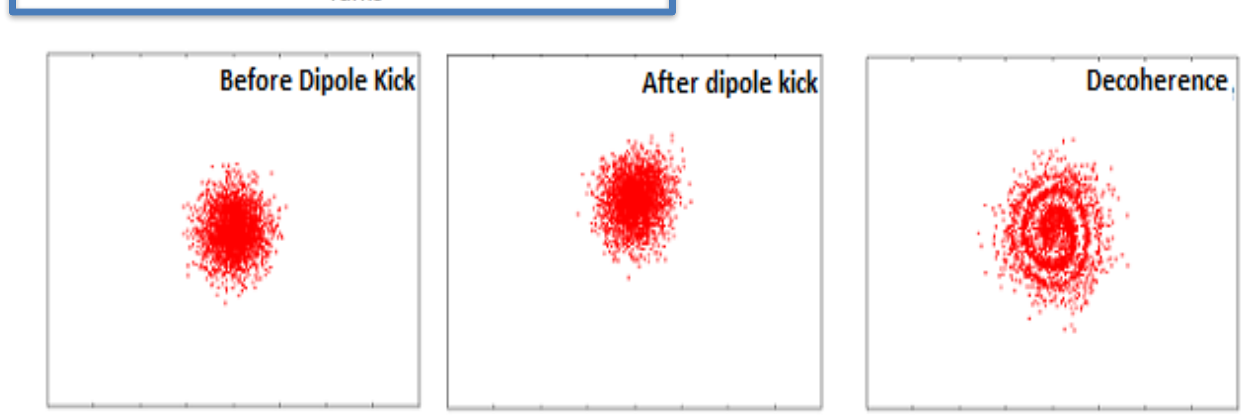
Introduction

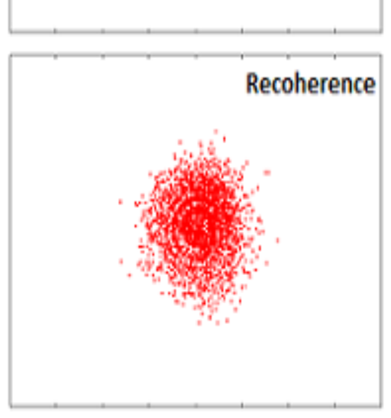
- Diffusion measurements are necessary to keep track of beam evolution in phase space, and thus minimize loss of particles.
- Current methods, like beam scraping, take hours to measure diffusion. Transverse beam echoes achieve this in milliseconds.
- Significance: **testing integrability of IOTA ring via diffusion measurements, and suggest improvements.**
- We perform simulations of the IOTA ring to:
  - Study echo dependence on ring parameters, and test echo theory.
  - Test robustness of dynamic aperture and echoes against coupling and longitudinal momentum spread.
  - Check echo generation in IOTA and practicality for diffusion measurements.

Theory and Simulation

- A beam echo occurs when particles recohere again after decoherence due to nonlinear elements (sextupoles in the IOTA ring).
- To observe echoes, we:
  - Apply a dipole kick at t = 0 turns.
  - Apply a quad kick at t = τ turns.
  - Echo observed at t = 2τ turns.
- Simulations of the IOTA lattice are performed in MADX and C++.
- Dipole kicker strength: 7 mT
  Quad kicker strength at r = 25 mm: 10 mT
- Kicker pulse width less than revolution time (2μs)

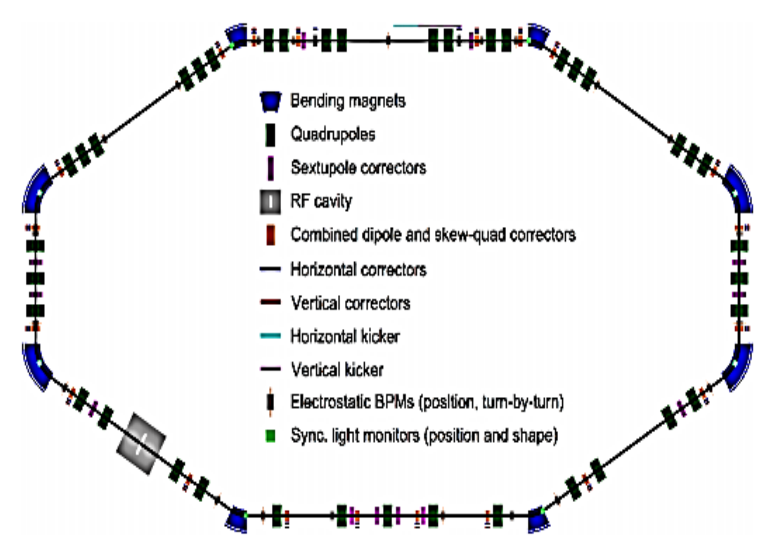






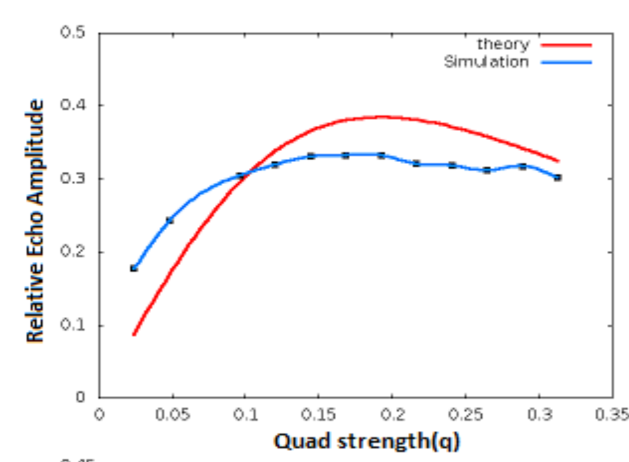
Top: x and y centroid motion in IOTA ring
Middle and Bottom: Beam evolution in phase space in the presence of dipole and quadrupole kicks in IOTA ring

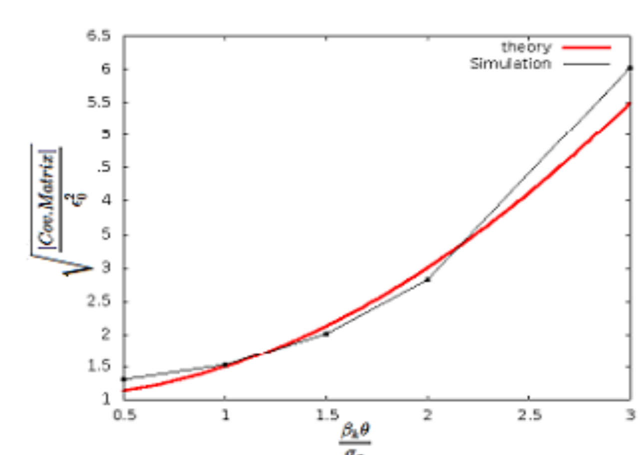
Layout and Parameters of IOTA Lattice

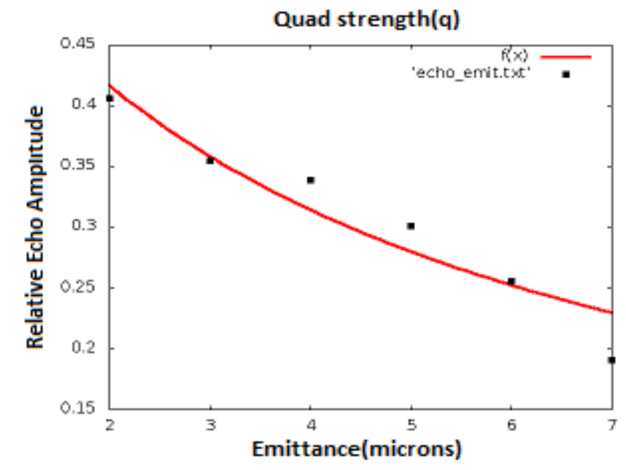


Circumference	40 m
Kinetic Energy	2.5 MeV
Intensity	10^9 protons/bunch
x tune	5.3
y tune	5.3
unnorm. x emittance	4 μm
unnorm. y emittance	4 μm

Verification of 1-D Theory







$$EchoAmplitude_{nonlinear} \approx \frac{Q\beta_k\theta}{(1+Q^2)^{3/2}}$$

where $Q = q\omega'\epsilon_f\tau$,

$q = \frac{\beta_{Quad}}{f}$

$\epsilon_f = \epsilon_0\left(1+\frac{1}{2}\left(\frac{\beta_k\theta}{\sigma_x}\right)^2\right)$

ω' =angular betatron frequency vs. action slope

ϵ_0=initial emittance

σ_x=RMS of initial x distribution

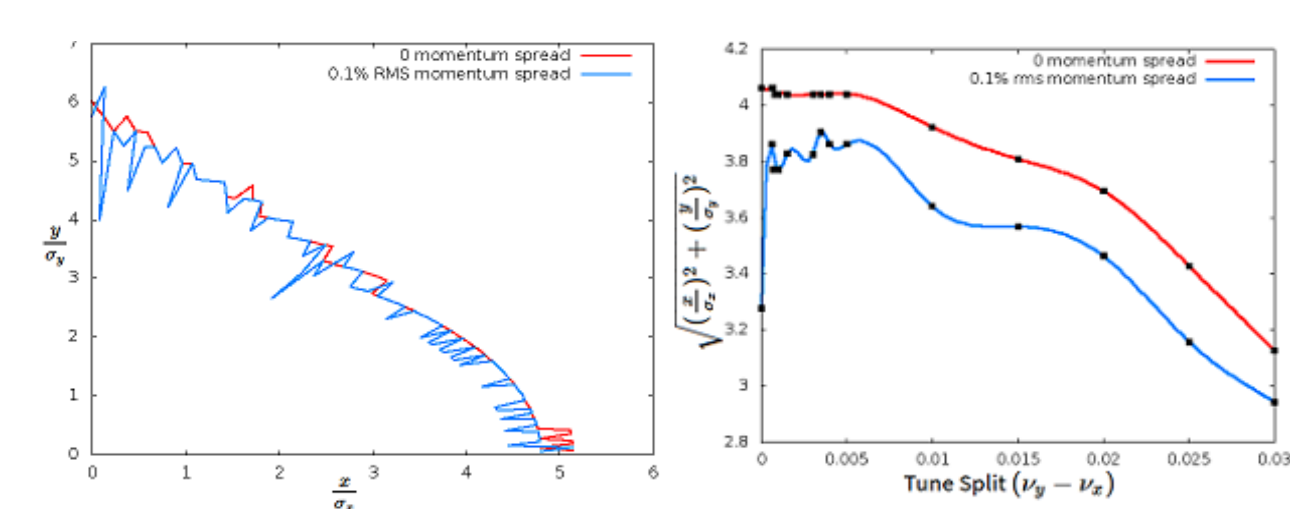
$\beta_k\theta$=dipole kick

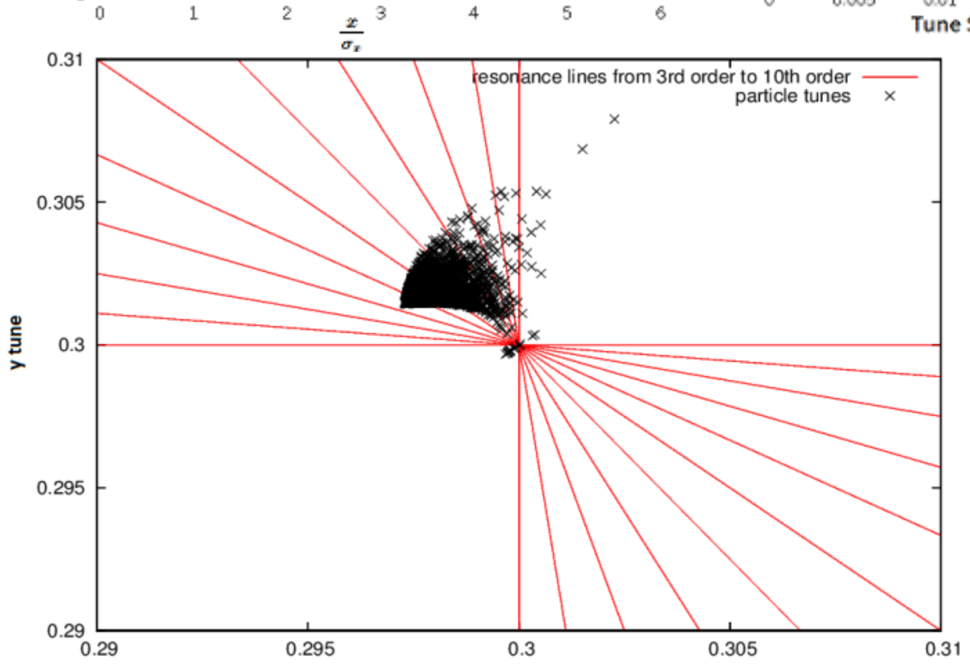
τ=time between two kicks

Top Left: Relative Echo amplitude vs. quad kick strength
Top Right: Final emittance vs. dipole kick strength
Bottom Left: Relative echo amplitude vs. initial emittance
Bottom Right: Theory predictions for echo amplitudes and final emittance

Dynamic Aperture and Resonances

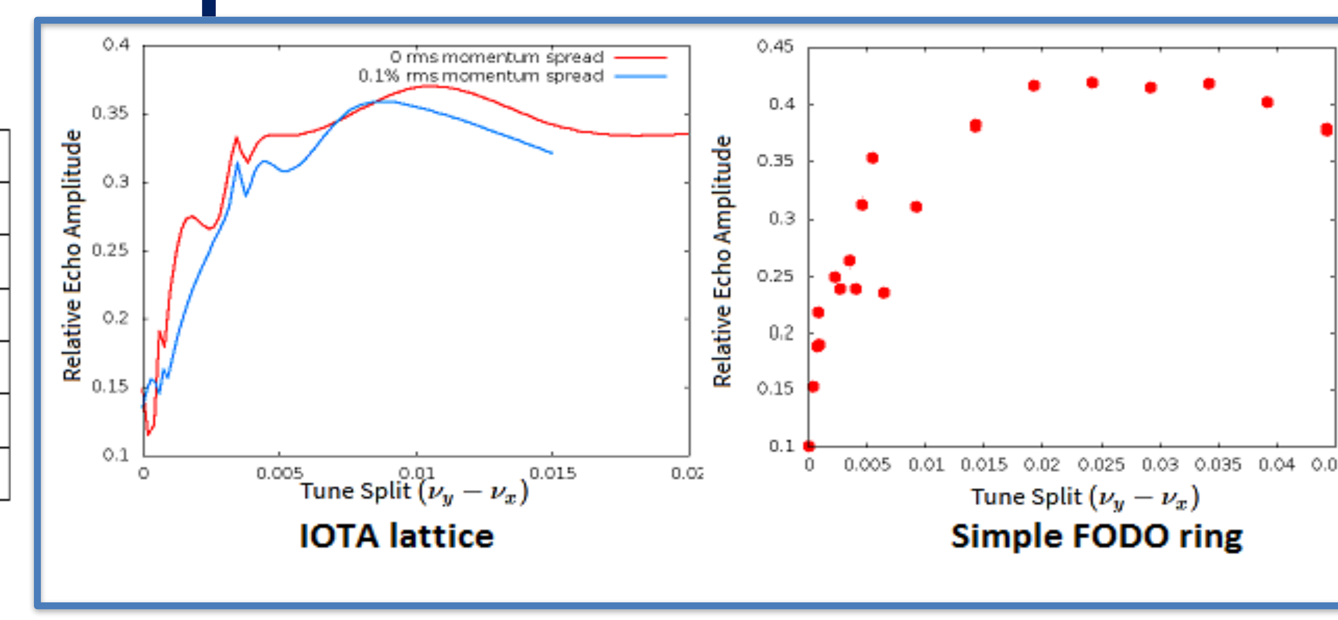
- Ensure higher dynamic aperture to minimize loss of particles, and appropriate tune selection to avoid resonances.



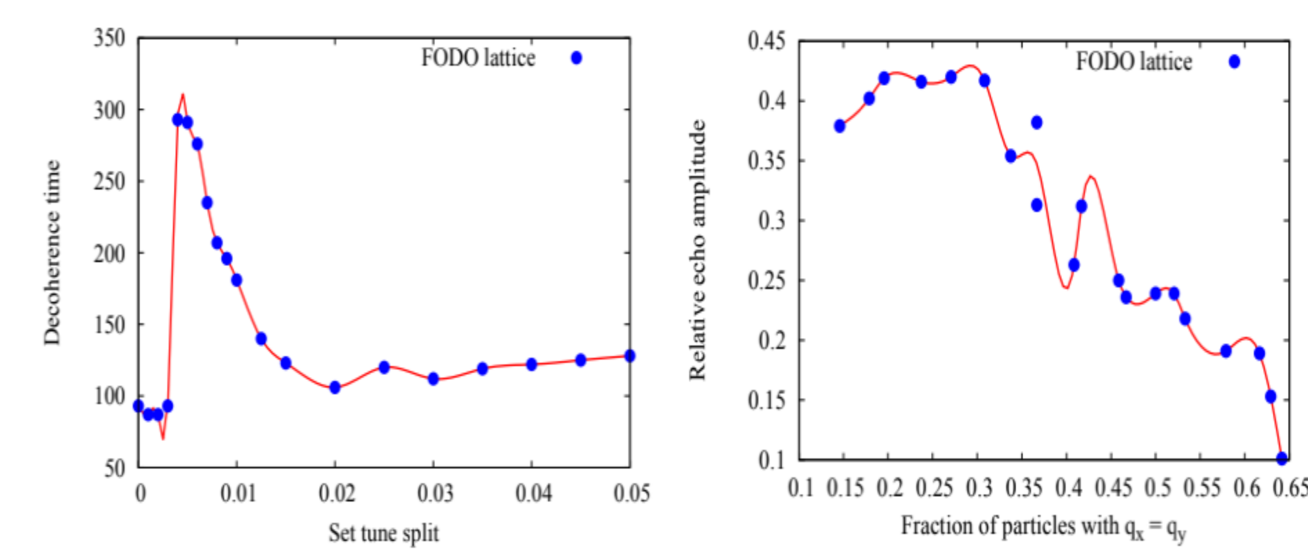


Top Left: Dynamic aperture for 0 tune split
Top Right: Dynamic aperture vs. tune split
Left: x and y tune footprint along with resonance lines for nominal tunes of the IOTA ring.

Echo Amplitude vs. Tune Split



Effects of Coupling



Conclusions

- Echoes generated in IOTA at low intensities (~100 pc) have relative amplitudes reaching 0.38 (saturation) at optimum quad strength. Good enough for measuring diffusion and testing integrability quickly.
- Dipole and quadrupole kicker field strengths are of practical magnitudes.
- Echo amplitudes fairly robust against choice of tunes and longitudinal momentum spread.
- Echo amplitude increases at smaller emittance.
- Strong coupling suppresses echo amplitudes.
- Simulations in agreement with nonlinear theory.

Future Work

- Insert misalignment and gradient errors to test echo sensitivity.
- Addition of nonlinear inserts to the IOTA lattice.
- Use simulations to construct a complete 2-D theory of echoes.
- Increase beam intensity to take space charge effects into account.
- Calculate diffusion coefficients, and check for multiple echoes to get accurate measurements.

Acknowledgments

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