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Electron beam echoes in the IOTA ring

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Introduction

Overview

- We use the Integral Optics Test Accelerator (IOTA) ring to generate electron beam echoes.
- Theoretical models and simulations are used to optimize the echo size with data collection anticipated August 2023.
- If successful, electron beam echoes would be novel.

Why echoes?

- Echoes can be used as a quick diagnostic tool for measuring beam diffusion, an indicator of emittance growth. Specific benefits:
  - test for beam stability in synchrotrons;
  - determine better lattice configurations;
  - measure space charge effects (at high intensities);
  - measure tune shift due to nonlinear forces.

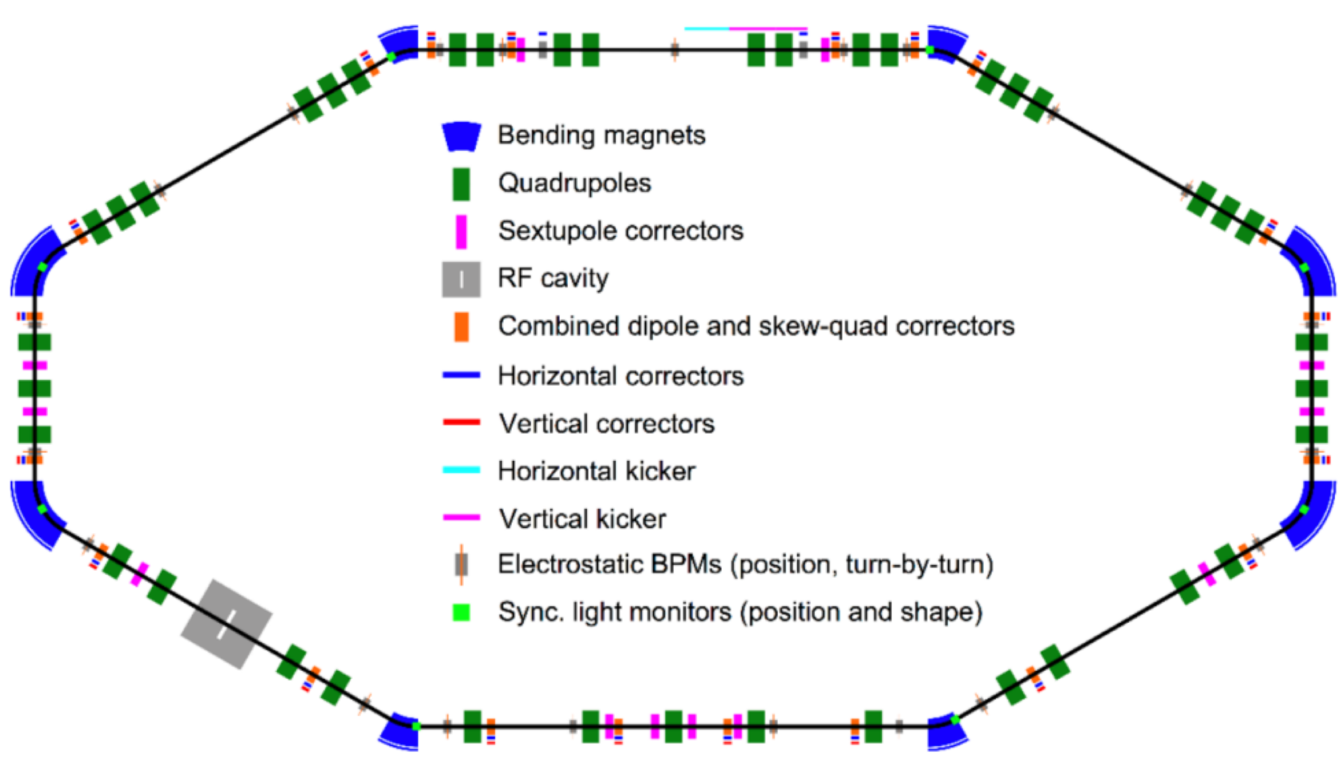


Fig. 1: Schematic of IOTA ring.

Echo Theory and Simulation

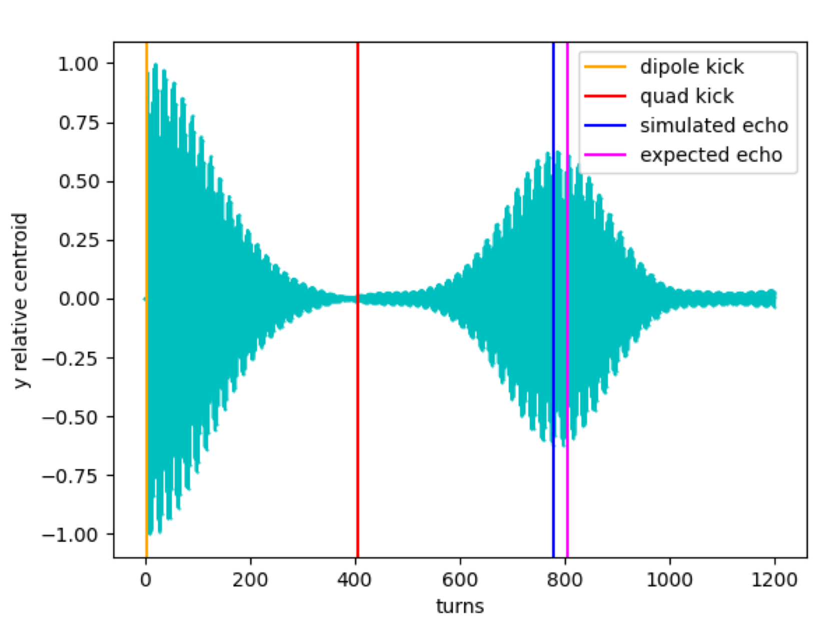


Fig. 2: Example echo simulation. The beam is kicked by the quadrupole magnet at $\tau = 405$ turns and the echo is observed around $2\tau = 805$ turns.

- Transverse beam echoes are generated by two magnetic "kicks."
  - At $t = 0$ the beam is given a dipole kick.
  - At time $t = \tau$ after the beam has decohered, the beam is given a quadrupole kick.
- The expected echo occurs around $t = 2\tau$. Additional, smaller echoes are sometimes seen at $t = 4\tau, 6\tau$.
- Factors such as tune split, kick strength, and delay time affect the amplitude of the kick in experiment.
- We use MADX to simulate echoes in the IOTA ring. Analysis of data was carried out in C++.

Multiple Quadrupole Kicks

- We seek to use multiple quad kicks to generate a larger echo signal.
- An analysis in Mathematica shows that 2 quad kicks is the optimal number of successive-turn kicks to produce the largest echo amplitude. Here we have applied linear beam echo theory.

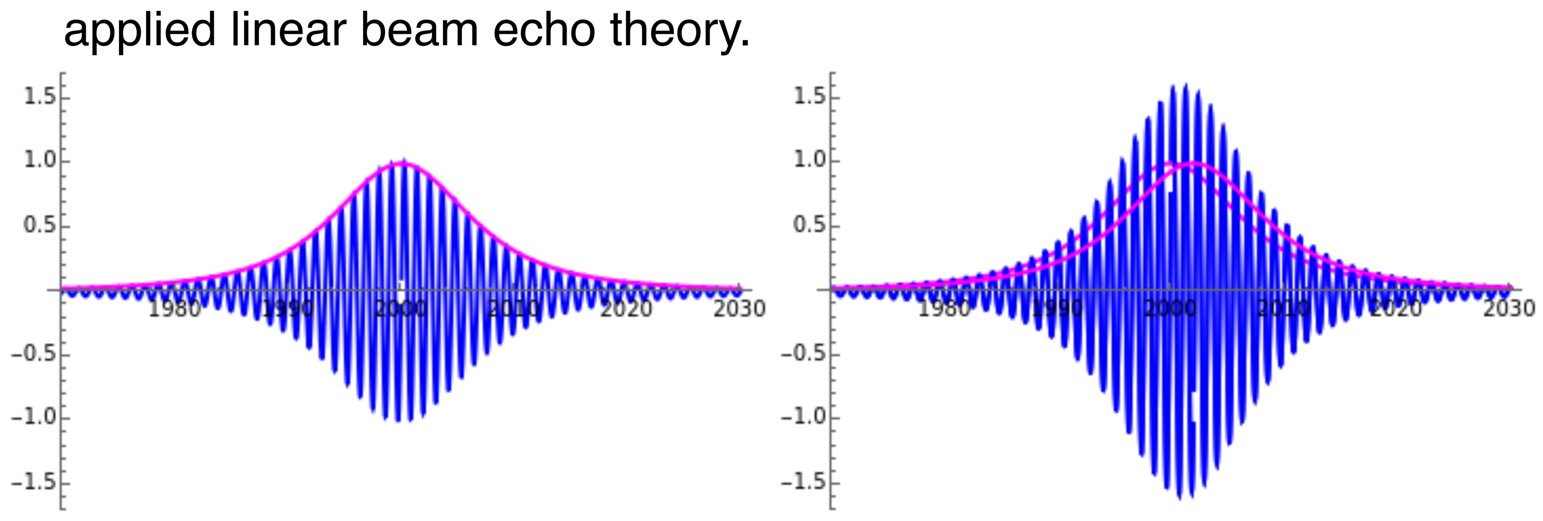


Fig. 3: Expected echoes from one (left) and two (right) successive quad kicks in the linear regime. The orange curve traces the amplitude contribution from individual kicks. The y-axis is the echo amplitude relative to the max one kick amplitude. (Plots generated with Mathematica.)

Optimal Kick Sequence

- Multiple different quad kick sequences were tested to determine the sequence that produces the largest echo amplitude.
- To describe a sequence of kicks, we use a p to indicate a turn with a quad kick of positive polarity and an x to indicate a turn with no quad kick.
- We analyzed various kick sequences:
  - kicks on successive turns $pp\cdots p$;
  - a kick every third turn, n times $(pxx)_n p$;
  - a kick every sixth turn, n times $(pxxxxxp)_n p$;
  - a kick every tenth turn, n times $(px_9)_n p$.
- In general, two kicks, ten turns apart (px_9p) maximizes the echo amplitude.
  - This can be attributed to the fractional tune of IOTA at 0.3.
    - Every ten turns the betatron phase advance is an integer multiple of 2π, and additional kicks are more effective on these turns.

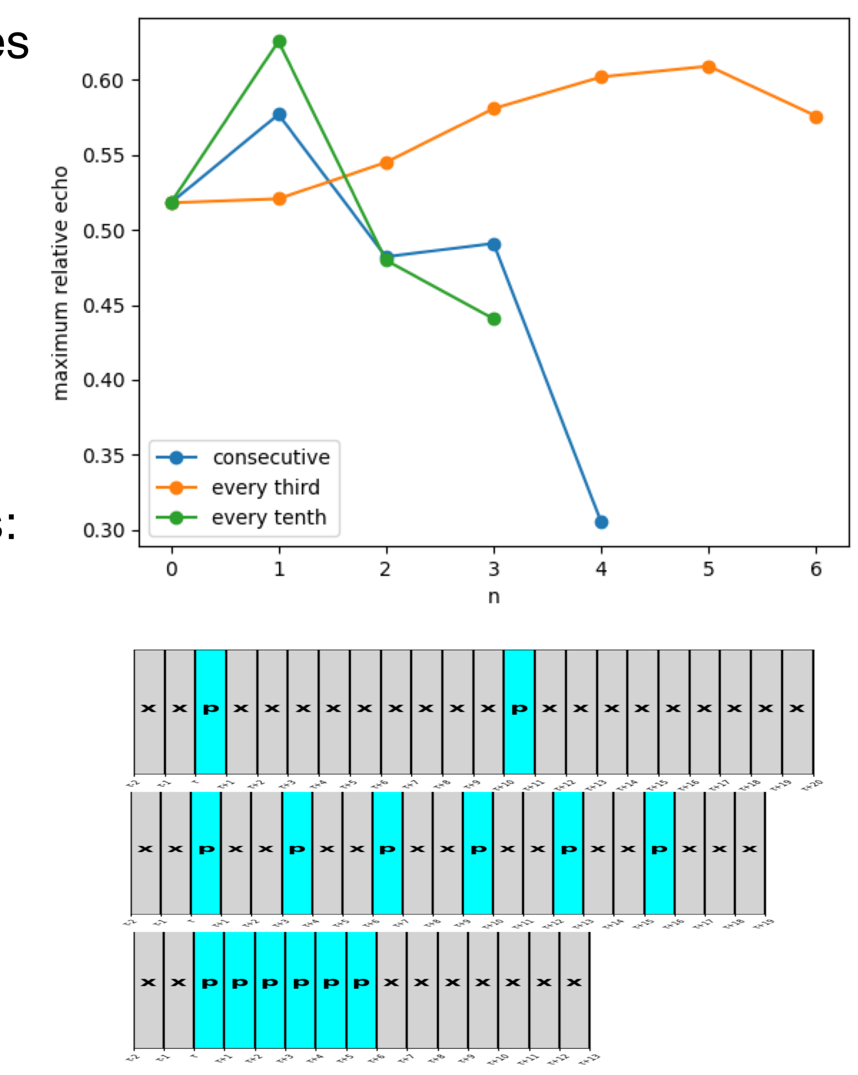
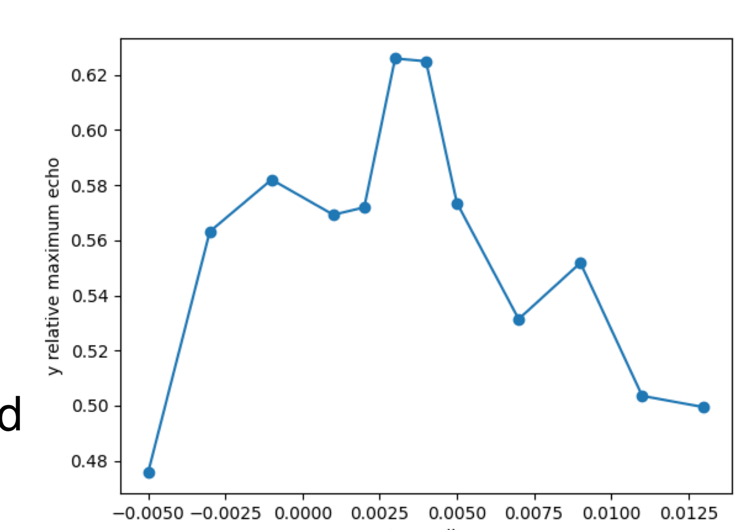
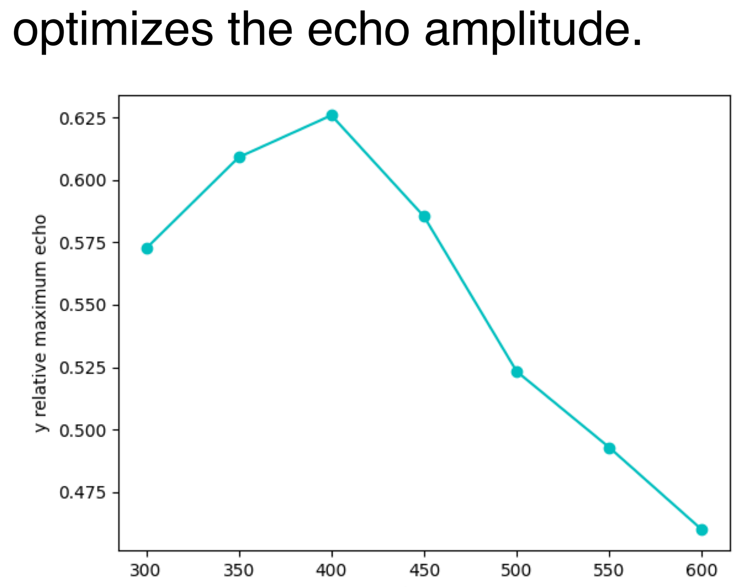


Fig. 4: *Upper*: Plot showing simulated scan of three different series. Represented are n consecutive quad kicks (blue), $pp\cdots p$, kicks every third turn (orange), $(pxx)_n p$, and kicks every tenth turn (green), $(px_9)_n p$. The echo signal is relative to the dipole kick. Note n represents the number of *additional* quad kicks following the initial quad kick. *Lower*: From top to bottom: Pictorial representation of pp, $(pxx)_5 p$, and $px_9\, p$ sequences.

Kick Strength, Tune Split, and Delay Time

- We then ran simulated scans over the quad kicker strength q, tune split $\nu_y - \nu_x$ (indicator of coupling), and delay time to optimize these parameters for maximum echo amplitude.
- We find that a kicker strength of $q = 0.047$, a tune split of $\nu_y - \nu_x = 0.003$, and a delay time around $\tau = 400$ turns optimizes the echo amplitude.





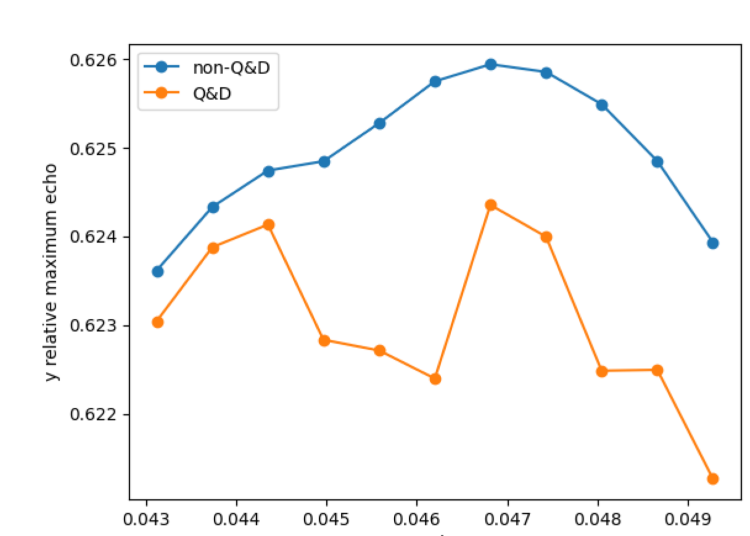


Fig. 6: Scan of delay time τ (left), quad strength q value (bottom right) and tune split (top). The scan over q was done both with and without the consideration of quantum excitation and synchrotron damping effects—the orange and and blue data, respectively. These plots are generated using the "ten sequence" px_9p.

Conclusion

- From this study we used beam echo theory and simulation to optimize the number and pattern of quad kicks, guided by clues from the fractional tune of IOTA. We also scanned lattice parameters (kicker strength, tune split, delay time) to maximize expected echo amplitude in IOTA.
- Some required experimental improvements prior to measurement: a better BPM resolution (5 microns with a stripline BPM vs 150 microns with button BPMs) and higher quad kicker voltage.

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