Quasi-Isochronous Lattices: LADR & OSC Applications

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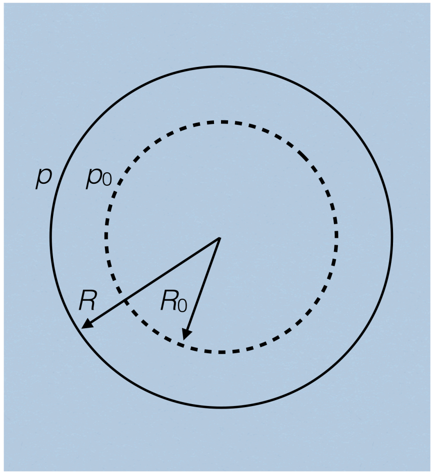
Quasi-Isochronous Lattices



- The momentum compaction factor describes the variation in orbit length wrt the reference for off-momentum particles.
  - Typically considered only as a linear term, but when the linear optics are set to reduce the leading term, higher-order terms will become relevant.

$$\Delta C/C_0 = \alpha_1\delta + \alpha_2\delta^2 + \alpha_3\delta^3 + ...$$

  - (There's also an α_0 term, independent of delta, which depends on betatron motion.)
  - The terms are analogous to the betatron case in the longitudinal plane: quadrupoles control α_1 and lead to a 'natural α_2', which can be corrected using sextupoles; α_3 can be controlled using octupoles, etc.
- Lattices which reduce the momentum compaction of the ring to lower than typical values are referred to as 'quasi-isochronous', or 'low-alpha', lattices.
  - The path length taken by particles as they orbit becomes less dependent on the momentum deviations.
  - Analogously, the slip factor is reduced, so the bunch stays temporally closer to the reference particle.

Low Alpha Motivations

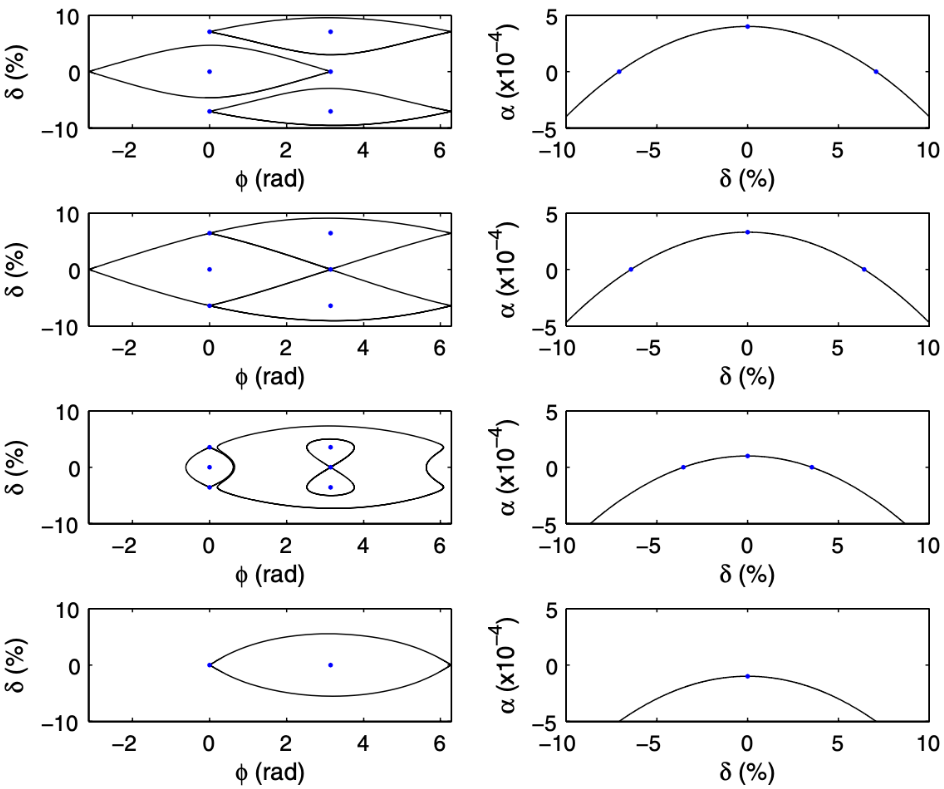
- **New operational modes** enabled by changes to the **longitudinal dynamics at low momentum compaction**.
    - e.g. The formation of alpha buckets results in larger areas of stable phase.
- **Issues injecting into the Passive-OSC lattice** (low emittance) during the previous stage of the program are suspected to be related to uncompensated higher-order terms of momentum compaction.
    - Attaining a firmer understanding of low-alpha operations at IOTA will ensure these problems are not encountered again.
    - Has generally applicability across many lattices used at IOTA.
- Could be a **gateway to new areas of research or scientific programs** at IOTA, if a low-alpha mode became a standard operational configuration.
    - e.g. Steady-state microbunching, discussed later.

Alpha Buckets

Phys. Rev. ST Accel. Beams 14, 040705 (2011)

- Effective control of higher-order compaction terms enables new stables areas of phase space, **alpha buckets**, by changing the shape and zero-crossings of $\alpha(\delta)$.
  - Analogous to regular RF buckets but centered on a non-zero delta and shifted in phase by π.
  - Varying α_2 (typically to ~0) and α_3 allows manipulation of these stable regions of phase space.
- Precise control over these higher-order terms can allow for larger regions of stable phase space for improved injection or storage.

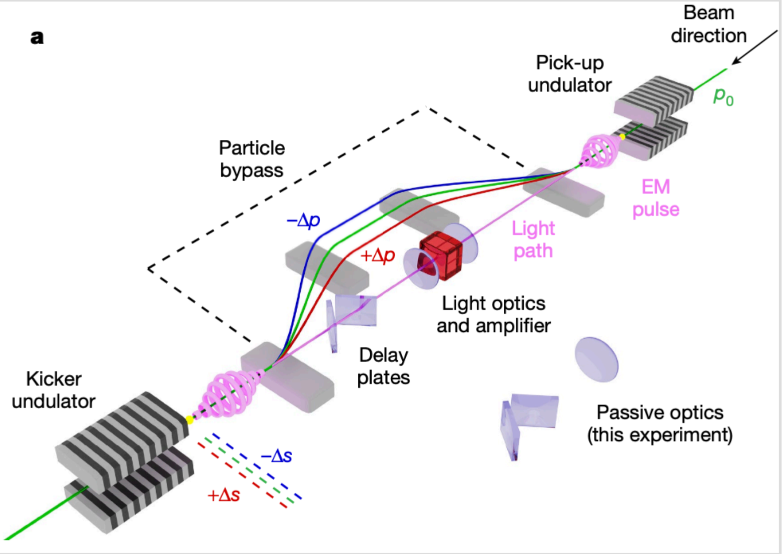
$$\alpha_c(\delta) = \alpha_1 + \alpha_2\delta + \alpha_3\delta_2$$

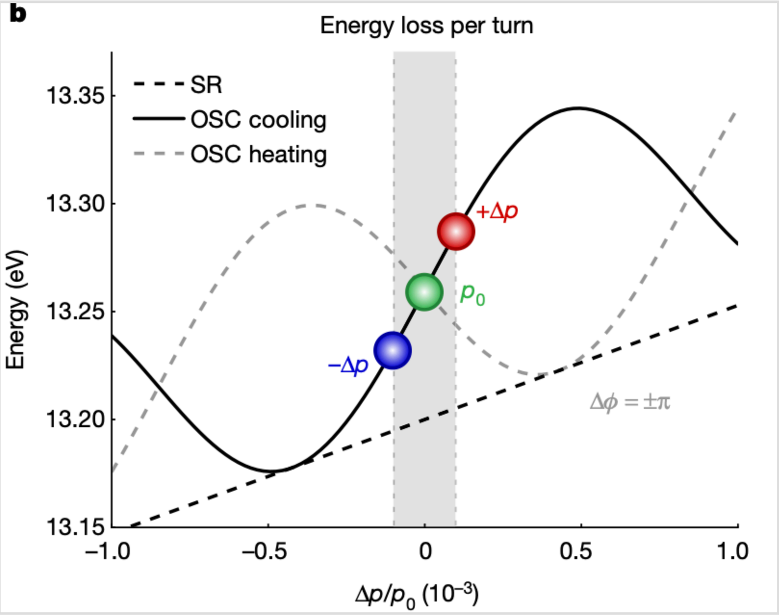


Optical Stochastic Cooling

Nature **608**, 288 (2022)

- **First demonstrated at IOTA in 2021**.
- OSC uses the careful mapping of a particle's radiation on itself following a bypass to apply corrective kicks to its momentum.
  - Each particle will additionally feel 'noise' kicks from each other particle within the bandwidth of the system.
  - Typically hinders cooling and so usually suppressed as much as possible.
- Flexible system enabling cooling, heating and potentially more exotic phase space manipulations in all three dimensions.

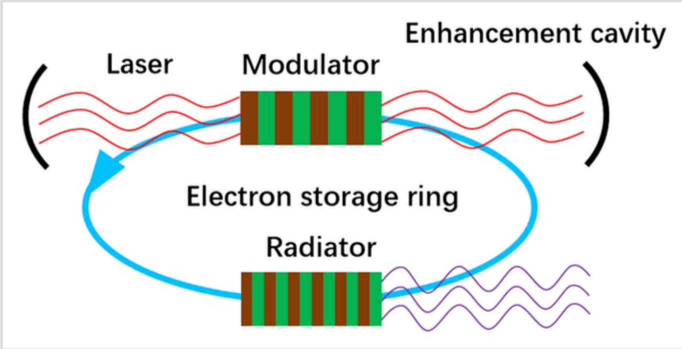


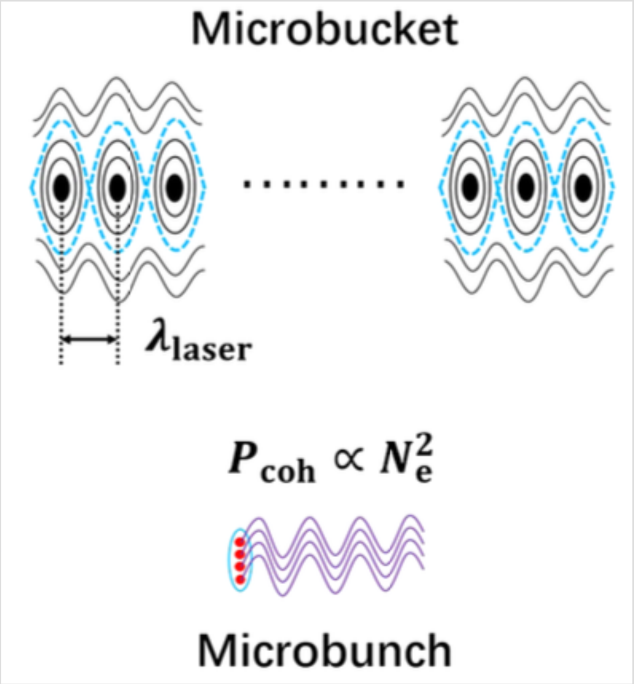


Steady-State Microbunching

PRAB **23**, 044002 (2020)

- The steady-state microbunching (SSMB) concept is a promising application of low-alpha lattices and a highly active area of research.
- **Light source combining high rep rate of storage rings with high brightness of FELs**, with tunable frequencies potentially as high as the x-ray range.
  - Proposed in 2010 (PRL 105, 154801 (2010)) with a one-turn proof of principle demonstration at the Metrology Light Source published in 2021 (Nature 590, 576 (2021)).
- 'Conventional' SSMB utilizes MW stored laser power synchronized to the beam, which modulates bunch particles at the optical wavelength to produce microstructure.





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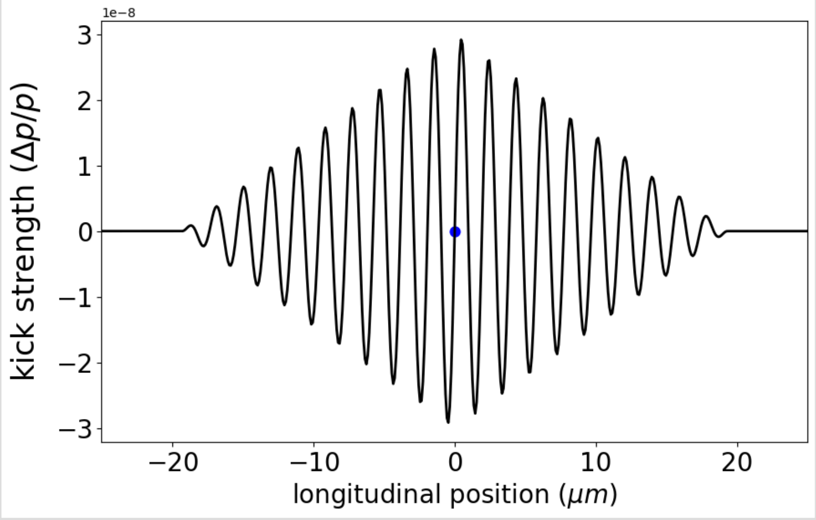
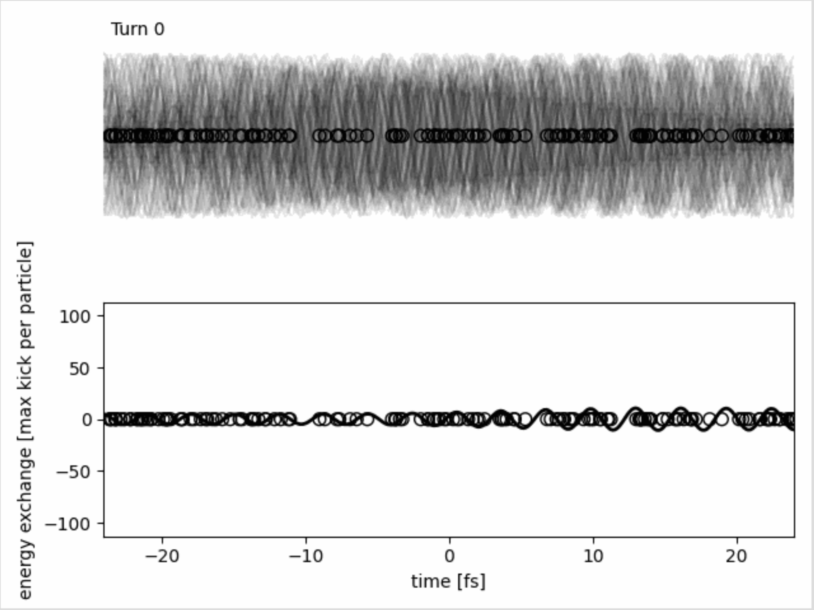
Optical Stochastic Crystallization

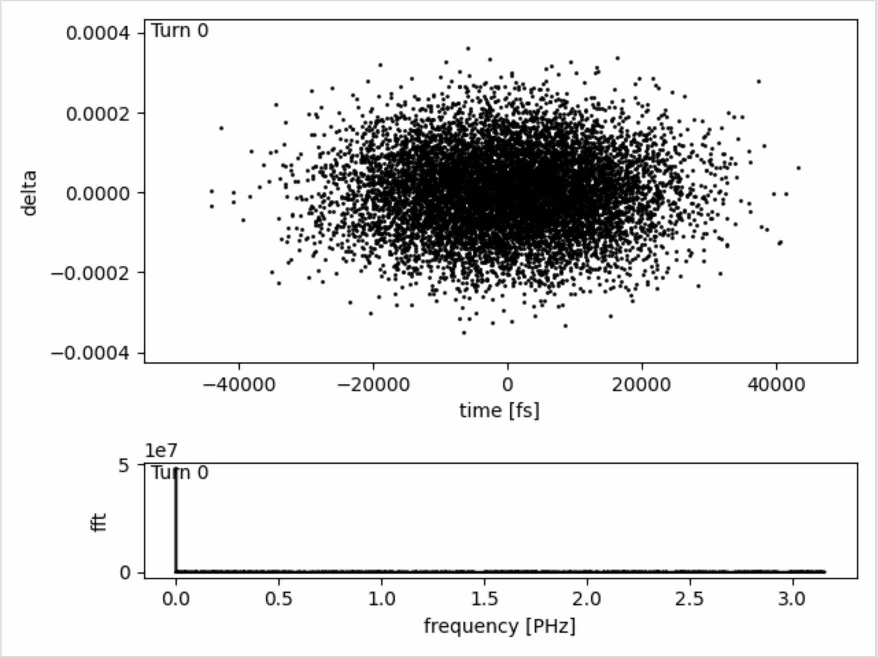
- **We have developed a mechanism which may enable SSMB using only the components of an OSC system**, with careful control of the light and beam optics.
  - We refer to this as **Optical Stochastic Crystallization** (OSX).
  - Effectively comes ‘for free’ with OSC.
- The inter-particle interactions within the optical bandwidth can provide, at sufficient gain, a self-reinforcing mechanism which locks the structure at the optical wavelength.
- An OSX system is ***cool***: combines the beam cooling of OSC with crystallization and advanced beam control.

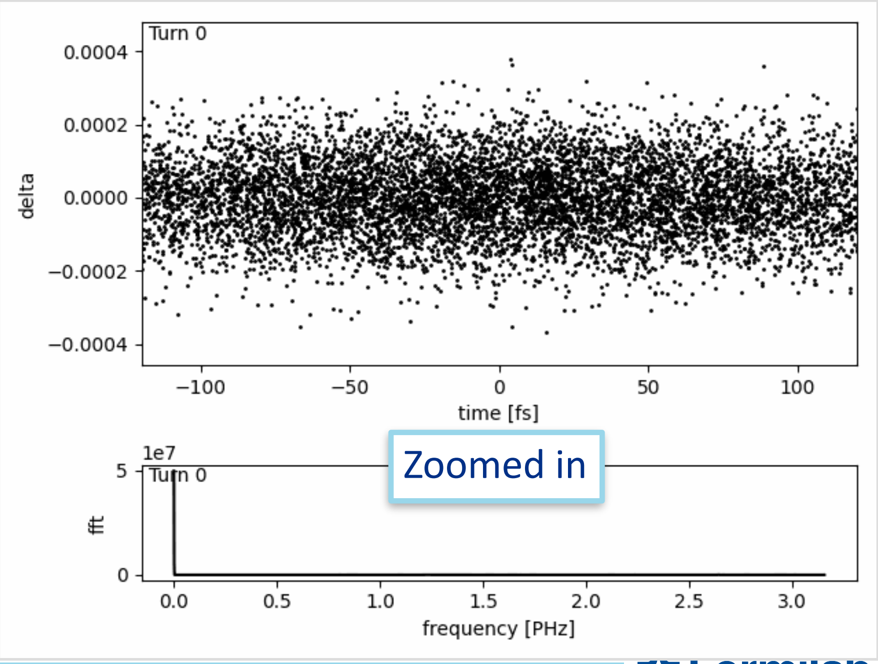




OSX Demonstrations

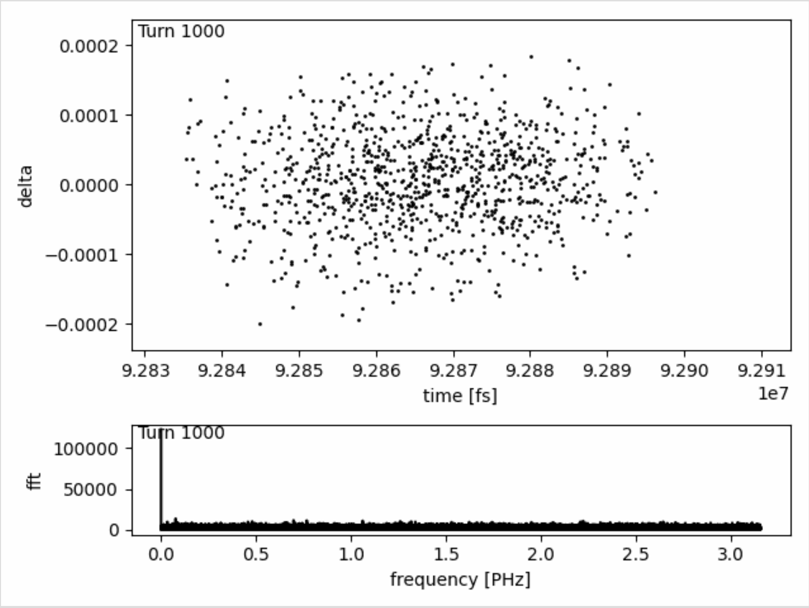
- Currently at the level of **exploring basic feasibility** (similar to the original SSMB proposals).
- A basic 1D toy model of OSC has been used to investigate OSX.
- Requirements:
  - Low compactions (10^{-4} here);
  - Optical OSC amplification (40 dB here);
  - Matched signs of the slip factors between the OSC by-pass and the rest of the storage ring;
  - Low dispersion invariant $\mathcal{H}_x$ at the undulators to reduce bunch lengthening from betatron motion.

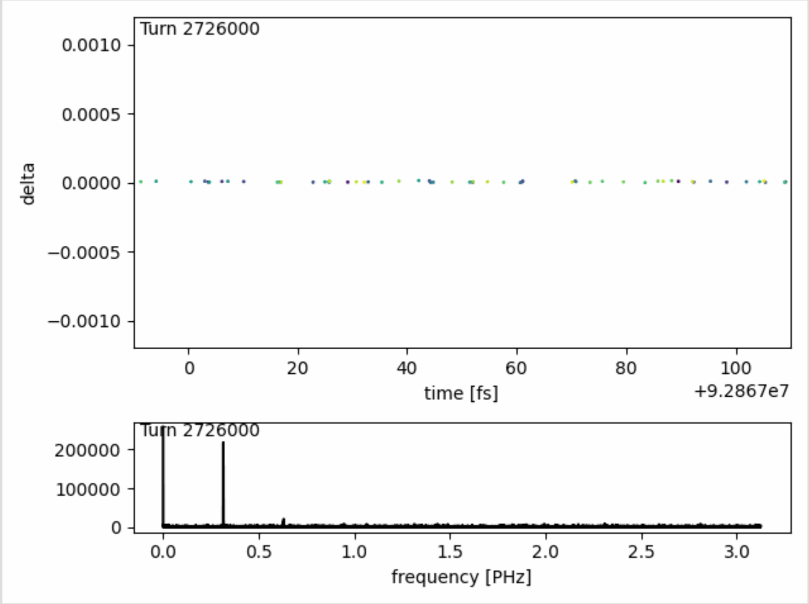




OSX Simulations

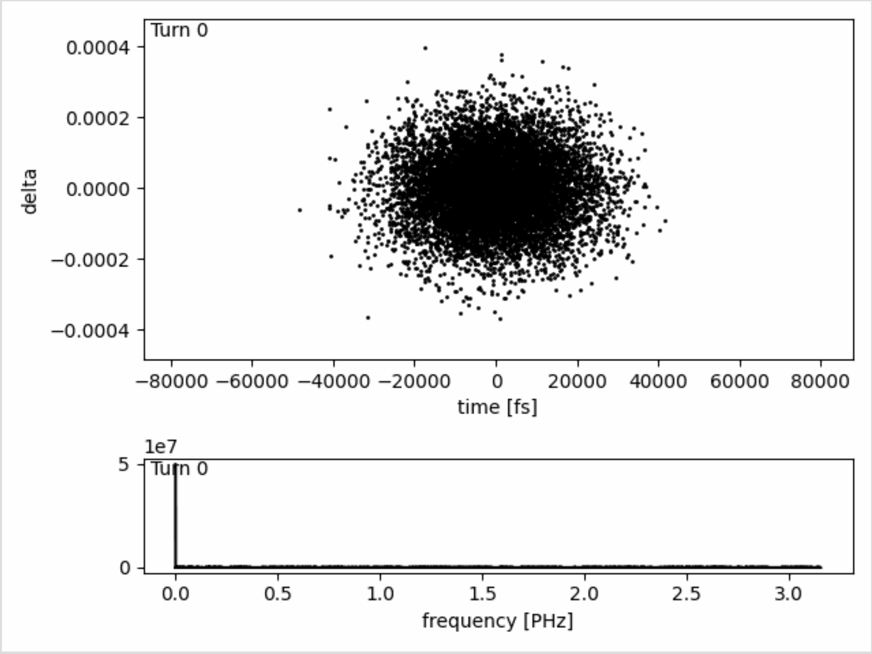
- **Fundamental mechanism has additionally been validated in ELEGANT** using OSC model (PRAB **27**, 012801 (2024)) — this slide.
  - ‘Quick and dirty’ simulation using the Passive-OSC lattice with reduced compaction; same OSC parameters with increased gain.
  - Actively working on a new lattice as part of the amplified OSC program.
- Lots of ongoing work to improve the quality of the simulations.
  - Basic incoherent radiation model with quantum excitation included.
  - Coherent synchrotron radiation and IBS not currently modeled.

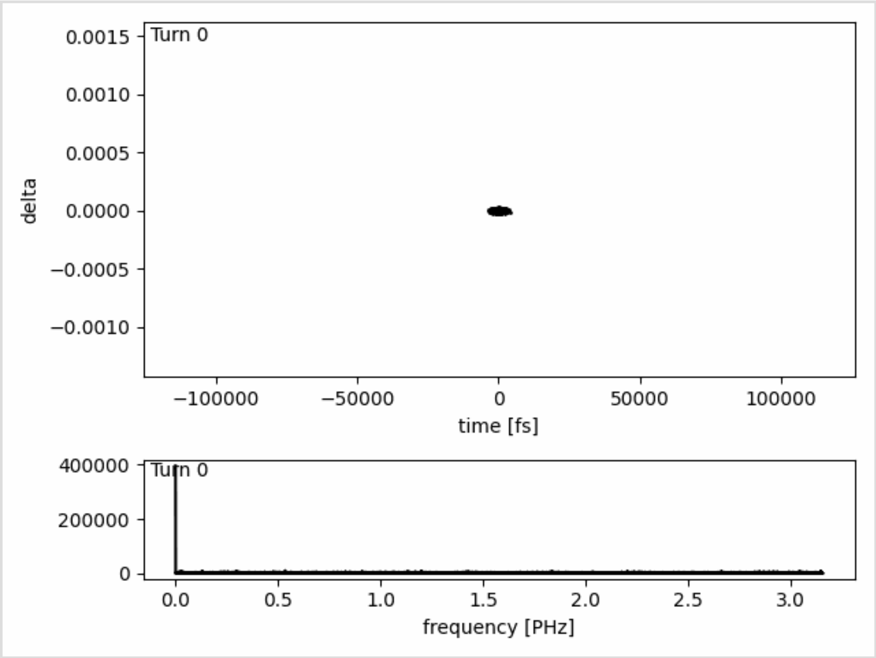




Bunch Manipulations

- Various bunch manipulations have also been demonstrated.
  - Plan to incorporate this simulation into a reinforcement-learning model to produce a 'beam-on-demand' system.
- In the *basic model*, crystallization occurs in almost all cases given sufficient cooling.
  - The models imply the required gain, lattice and bunch densities mean a demonstration *may* be feasible during the next phase of OSC at IOTA.
- More from Jonathan in the OSC talk tomorrow!





Low Alpha Demonstration Research (LADR)

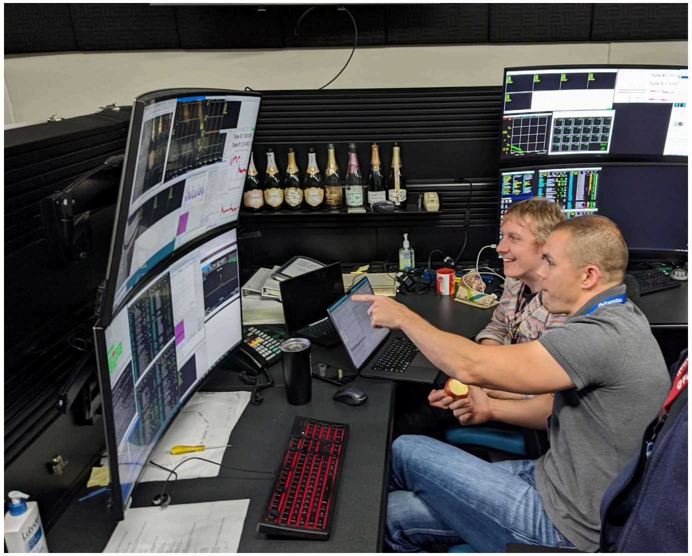
- As a first step towards realizing these potential applications, Jonathan and I proposed the LADR program as a short R&D effort focused on demonstrating the feasibility of low-alpha operations of the IOTA ring.
- Goals (taken from my proposal slides):
  - **Demonstrate the reduction in the leading-order term, α_1, with the linear optics**. Aim to reduce to ~10^{-4} (~50 lower than previously used in IOTA).
    - Use online measurements of synchrotron frequency as a proxy for compaction (with an assumed constant synchrotron energy loss from the model).
  - **Demonstrate correction of the second-order term, α_2, using sextupoles**. Aim to correct this to zero, and demonstrate zero-crossing. Critical for successful low-alpha operation.
  - **Demonstrate control over the third-order term, α_3, using octupoles**. Show the expected effect on lifetime as this is knobbed through zero.
  - **Demonstrate operation of IOTA with alpha buckets**, likely by holding α_3 constant and transitioning particles in a RF bucket as α_1 is knobbed through zero.

$$\Delta C/C_0 = \alpha_1\delta + \alpha_2\delta^2 + \alpha_3\delta^3 + \ldots$$

LADR Operations

Photo credit: Sasha Romanov

- LADR took around 13 shifts in late September/ early October, 2023.
- Around half were used commissioning the lattice; the second half were used to work towards the goals of the program.
- Successfully completed the main objectives: demonstrating control over the leading momentum compaction terms (α_1, α_2, α_3).
    - **Achieved record-low IOTA ring compaction of ~3.4×10^{-4}** (~15x lower than previously operated).
- Unfortunately the run ended before we could reach the target of 1×10^{-4} or attempt to transition to alpha buckets, but nothing was found to suggest this should not be feasible in the future.



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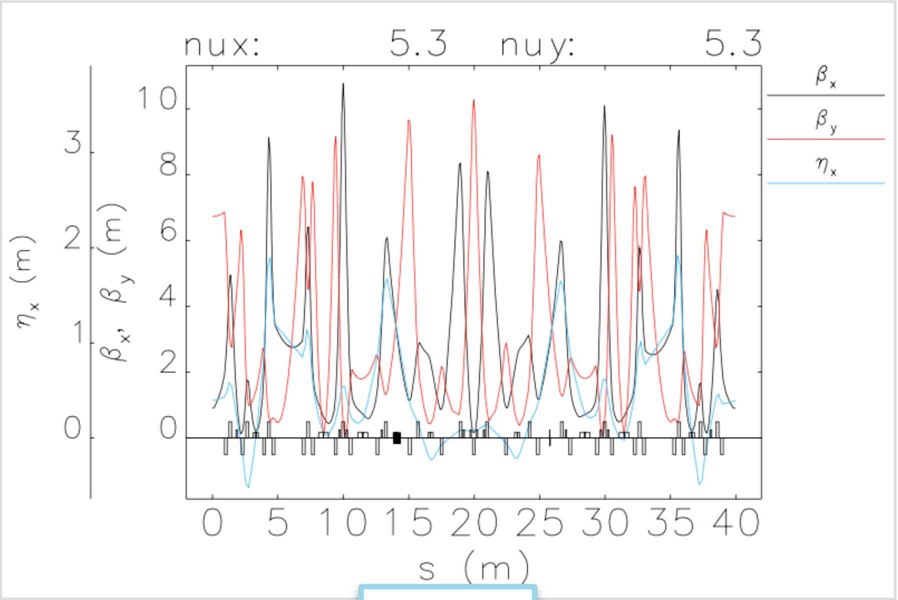
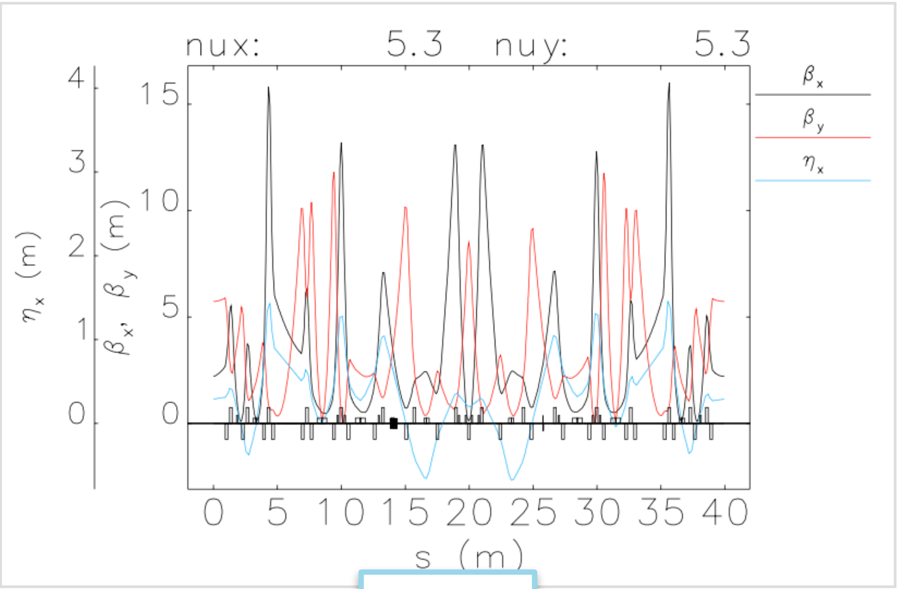
LADR Lattice

- The LADR lattice was modified from the NIO version to ensure minimal disruption to the program.
  - Fully characterized in ELEGANT and MAD-X.
  - Developing knobs for varying the compaction.
- Optimized lattice functions at sextupole and octupole locations for efficient control of higher-order terms.
- Achieving stable injection into the lattice proved challenging.
  - Ultimately had to inject via the NIO lattice and transition with beam.
  - Typically injected >1 mA and worked with 300 μA and below for studies.

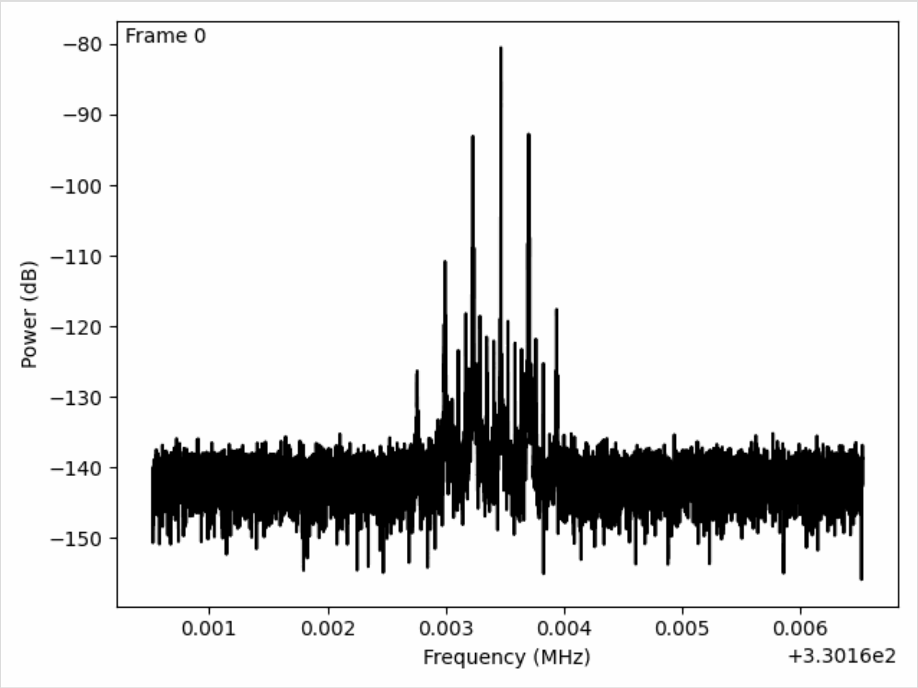


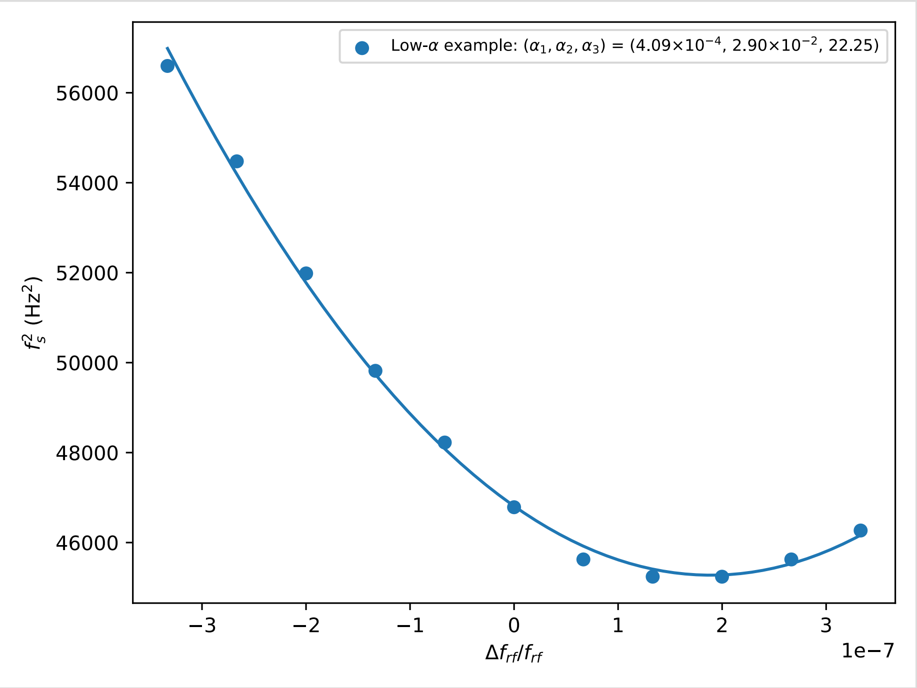
$\alpha_c \sim 10^{-2}$



$\alpha_c \sim 10^{-4}$

Momentum Compaction Measurements





- Used spectrum analyzer attached to wall-current monitor.
- Measure synchrotron frequency from the sidebands over an RF detuning scan; fit for α terms.

$$f_s^2 = \frac{hq_eV_{rf}f_0^2|\eta_1 cos\phi_s|}{2\pi\beta_0^2E_0}\left[1+\frac{s_1}{\eta_1}\left(\frac{\Delta f_{rf}}{f_rf}\right)+\frac{s_2}{\eta_1^2}\left(\frac{\Delta f_{rf}}{f_rf}^2\right)\right]$$

$$s_1 = -\frac{2\eta_2-\eta_1^2}{\eta_1}+\frac{1}{\gamma_0^2}$$

$$s_2 = \frac{3\eta_3\eta_1-2\eta_2^2}{\eta_1^2}-\frac{\eta_2}{\eta_1\gamma_0^2}+\frac{3\gamma_0^2\beta_0^2+2}{2\gamma_0^4},$$

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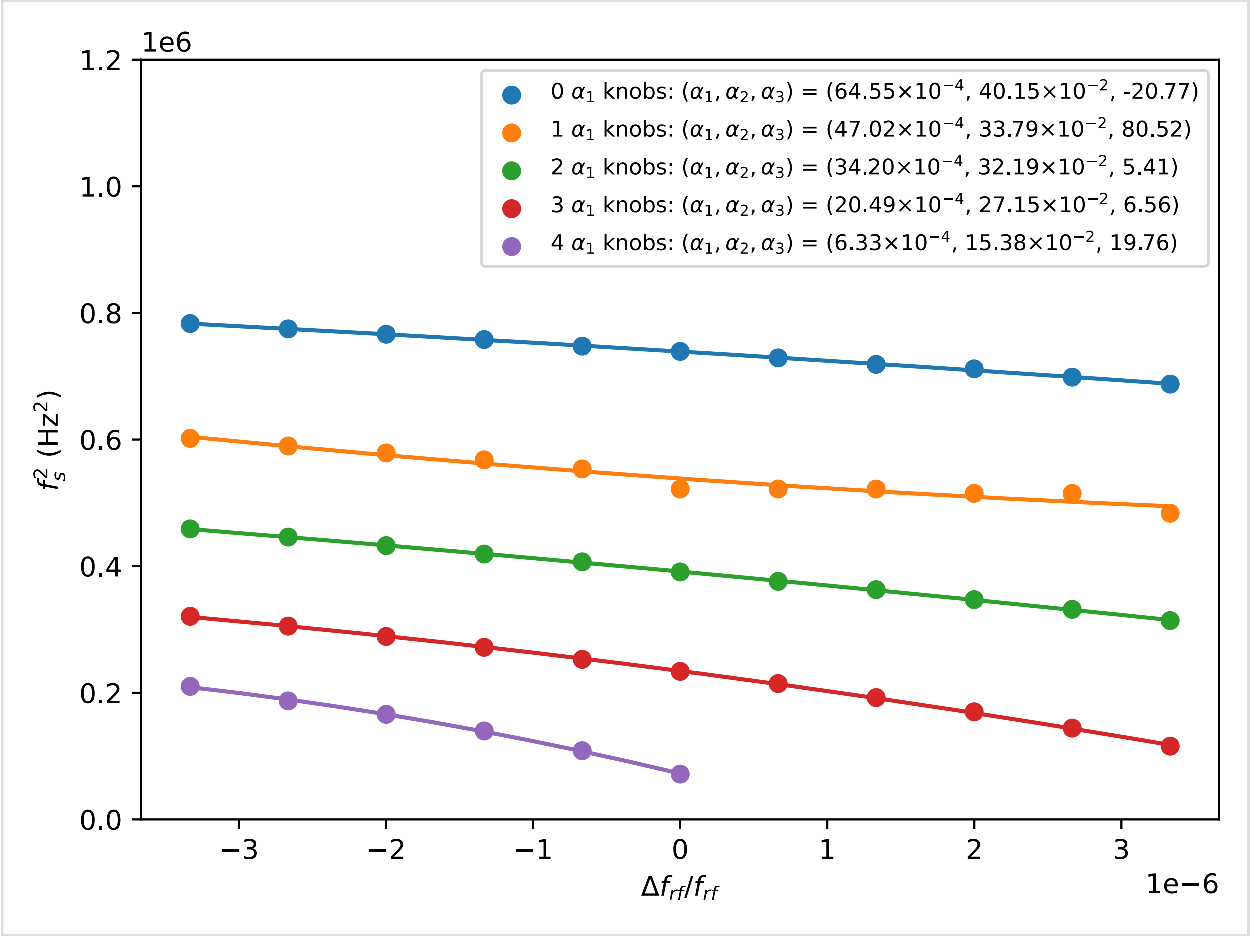
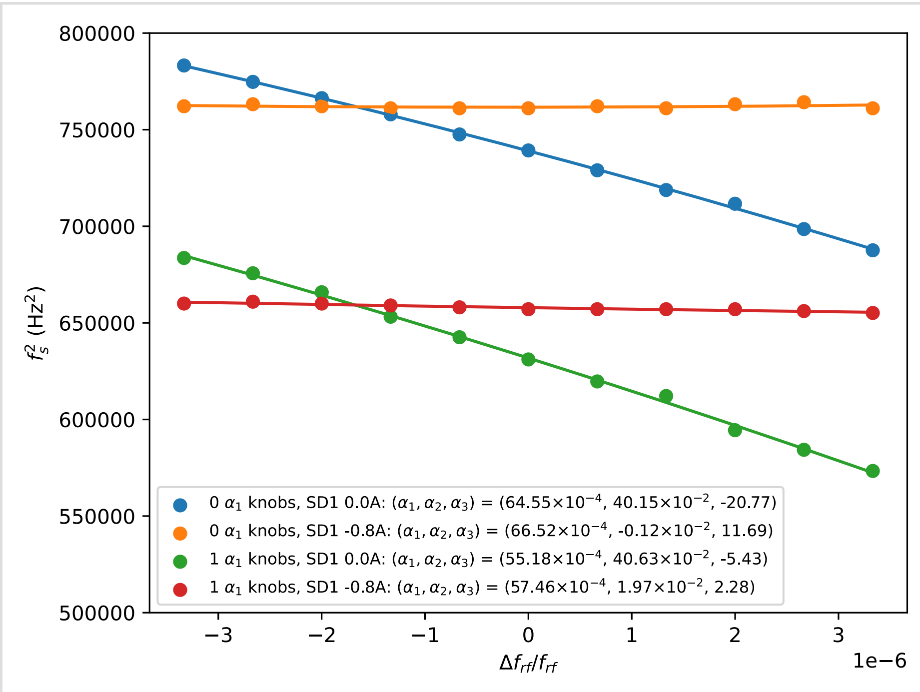
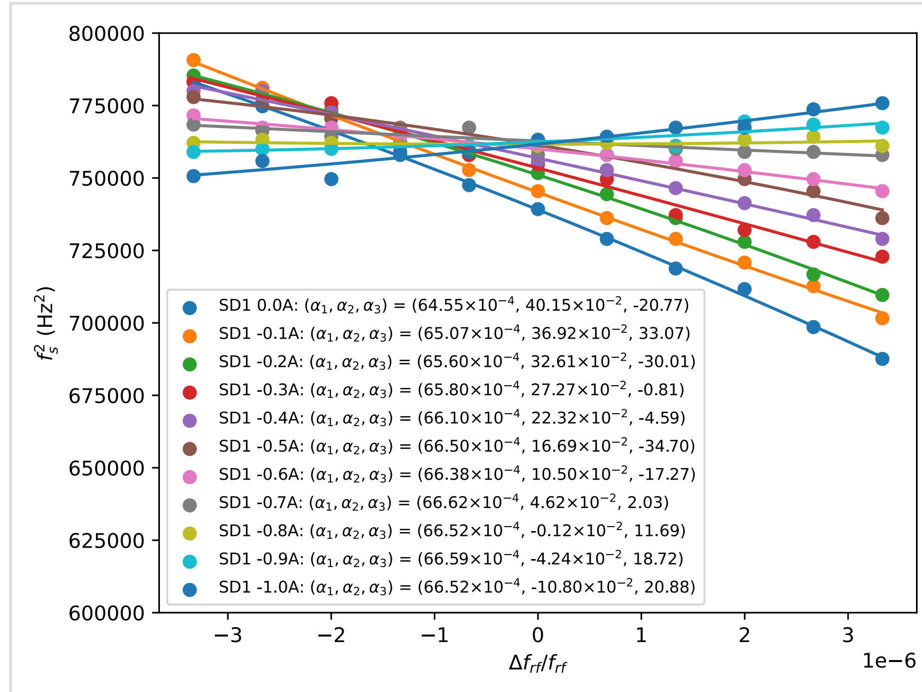
Reducing α_1 using Linear Optics



- Reducing the first-order compaction term using knobs built from the model.

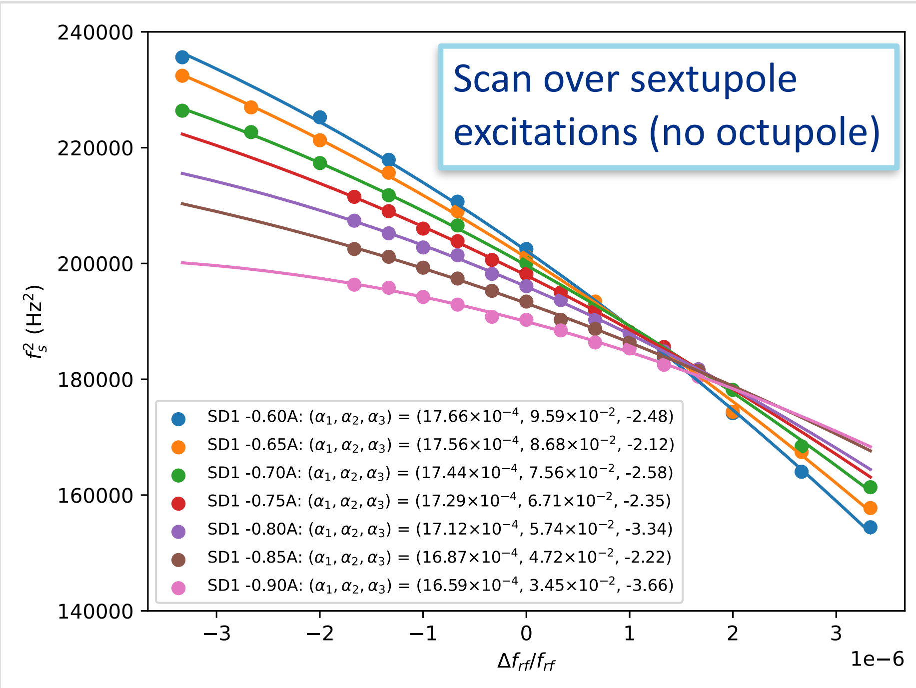
Controlling α_2 using Sextupoles: High Compaction

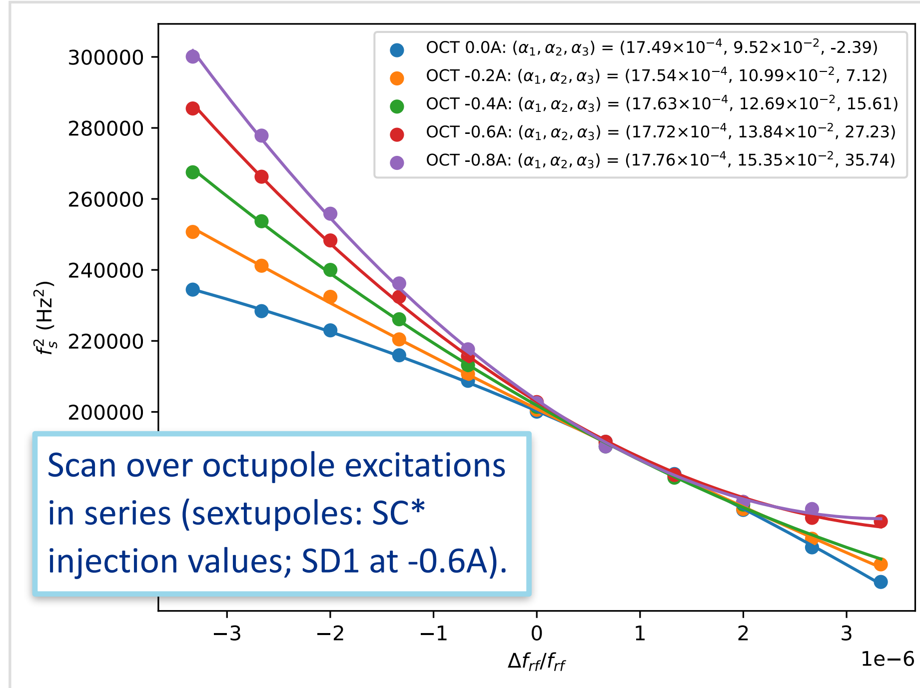




- The SD1 sextupole family were very effective at controlling and correcting α_2 at relatively high momentum compaction.
- Left: before and after correction at two values of α_1; right: sweeping α_2 through zero via a scan over sextupole excitations.

Controlling α_2 and α_3: Lower Compaction

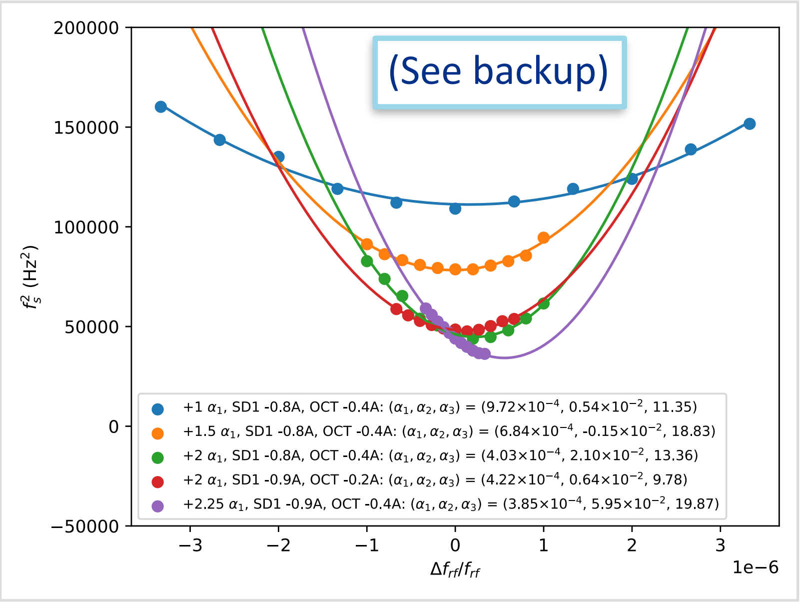


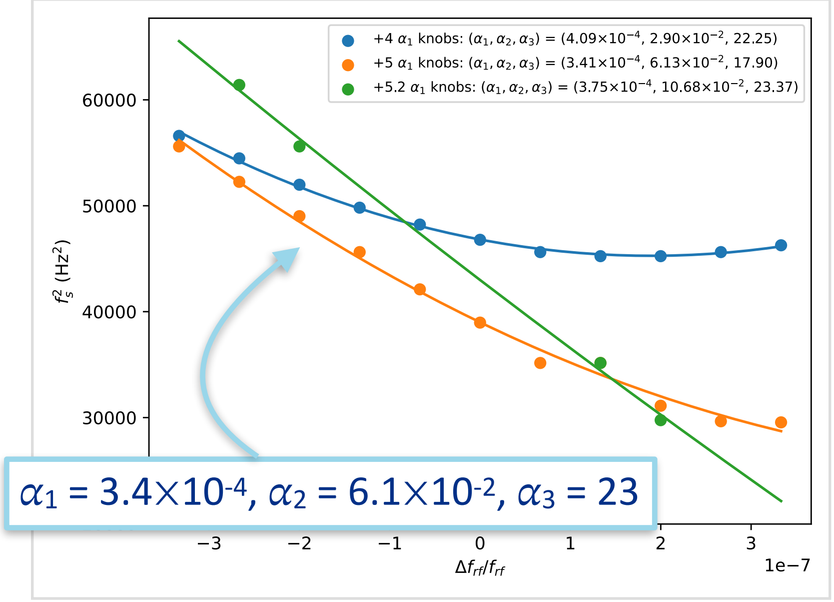


- Following four applications of the α_1 knob to reach ~1.7×10^{-3}.
- It was not possible reduce α_2 as much as before, or to knob through zero.
  - The 'natural' α_3 is negative, which is the opposite to the sign of α_1. It is understood that to improve lifetime and bunch stability, the signs should be the same; octupoles were therefore henceforth used to correct this.

Achieving Low Compactions

- Strategy is to move down slowly, taking sextupole and octupole scans, correcting as much as possible.
  - Should be possible to use a model to assist.
- Record-low measurement (3.4×10^{-4}) shown in the orange (lower plot).
  - As observed, a slight reduction causes immediate beam loss due to further uncompensated higher-order terms.
- The path to zero and beyond was clear, we just didn't quite have enough time.
  - No show-stoppers gives us confidence in achieving quasi-isochronous operations in IOTA!





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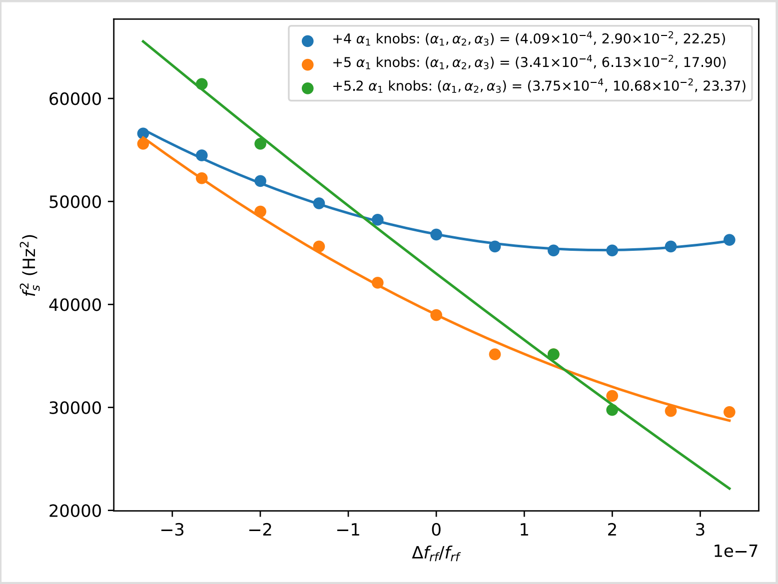
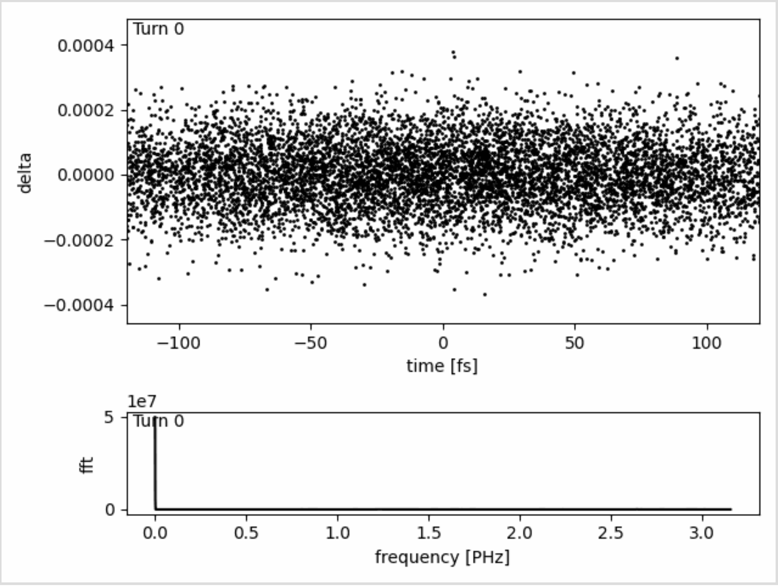
Summary

- Understanding the **beam dynamics in IOTA at lower compactions** is generally important for a lot of use-cases.
  - Specifically will be very relevant for a lower emittance lattice such as OSC.
- Additionally opens the **possibility of new areas of research at IOTA**, such as OSX.
  - Optical Stochastic Crystallization is a potentially very interesting application of OSC, which we are actively working on.
- **LADR successfully demonstrated the basic principles** of controlling momentum compaction terms in low-alpha lattice at IOTA.

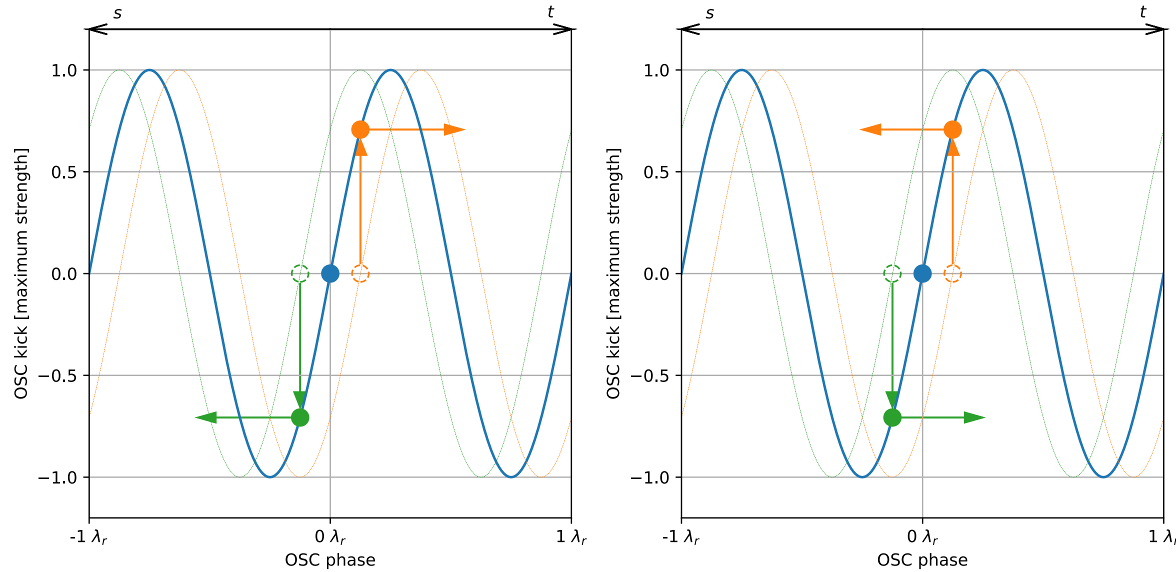


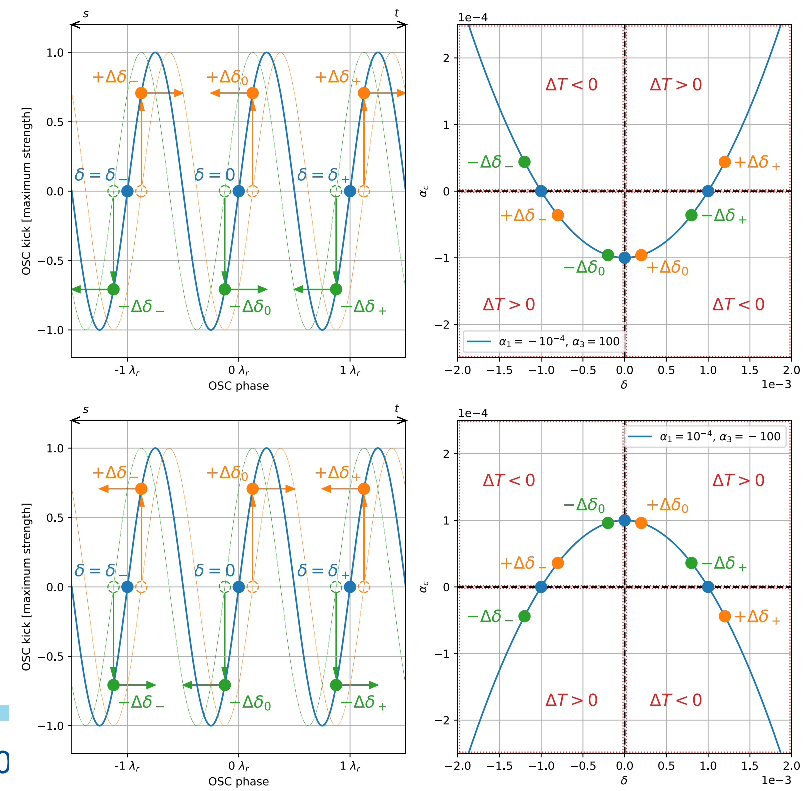


Backups

OSX Slip Factors

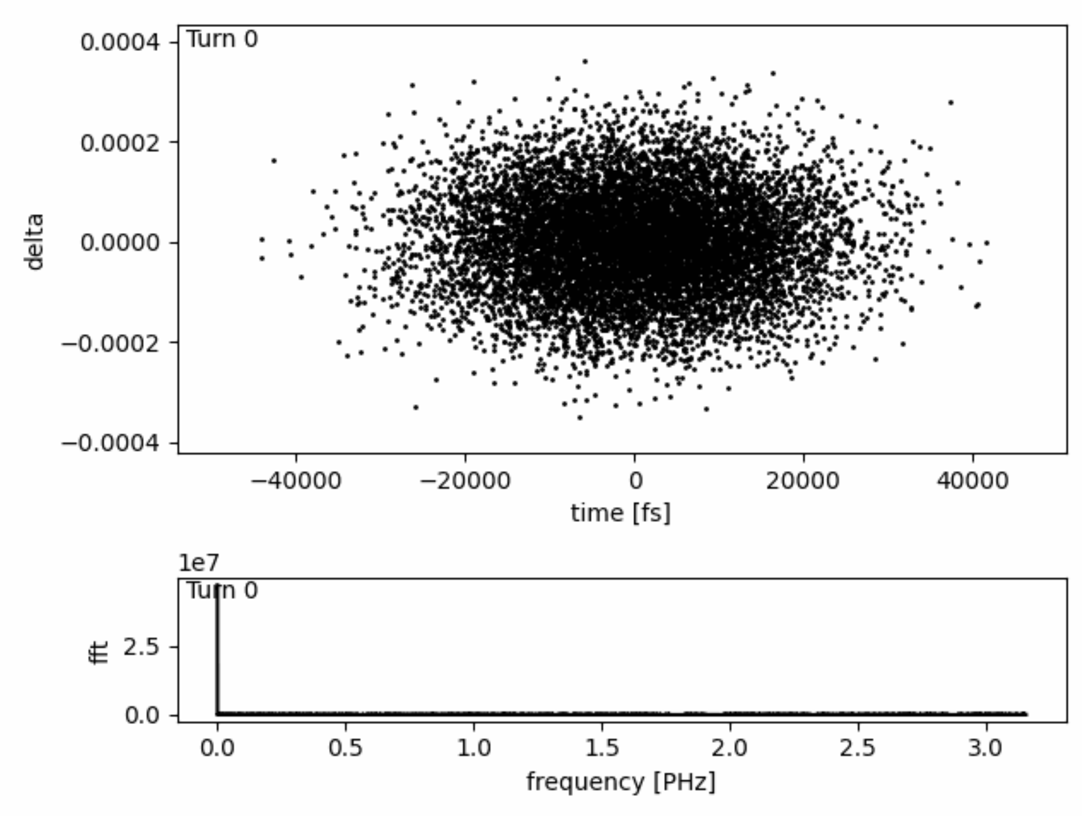
- Demonstration of the required slip factors.
- Top: RF bucket microbunching.
  - Left: $\alpha_1 > 0$;
  - Right: $\alpha_1 < 0$.
- Bottom: alpha bucket microbunching.
  - Left: $\alpha_1 < 0, \alpha_2 = 0, \alpha_3 > 0$.
  - Right: $\alpha_1 > 0, \alpha_2 = 0, \alpha_3 < 0$.





Squish and Bunch Manipulations

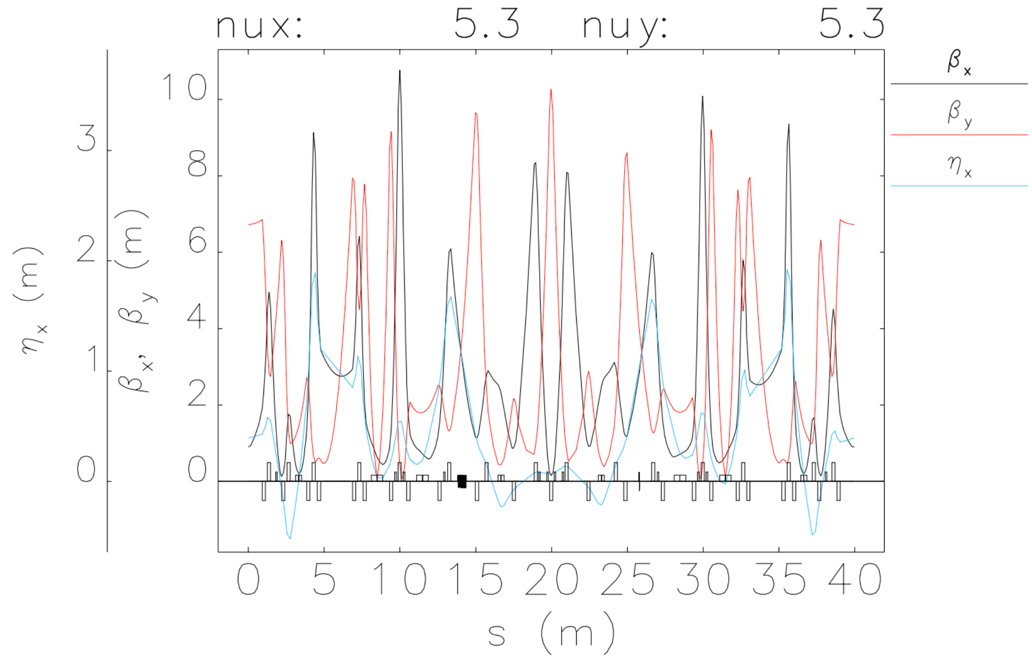
- Turn on OSC with gain to cool, turn off the gain to let the bunch rotate in phase space, turn on again at an opportune time to bunch.



LADR Lattice & Knobs

- The lattice was designed from the NIO lattice, with the compaction reduced.
  - Reducing compaction requires a net reduction in dispersion around the ring.
  - This is achieved either by balancing out positive and negative contributions in different straights or by enforcing zero-crossing in the bend dipoles.
  - The latter is preferred but was found to be unfeasible with the other constraints on LADR. It's possible an improved low-alpha IOTA lattice could be designed without these self-imposed restrictions.

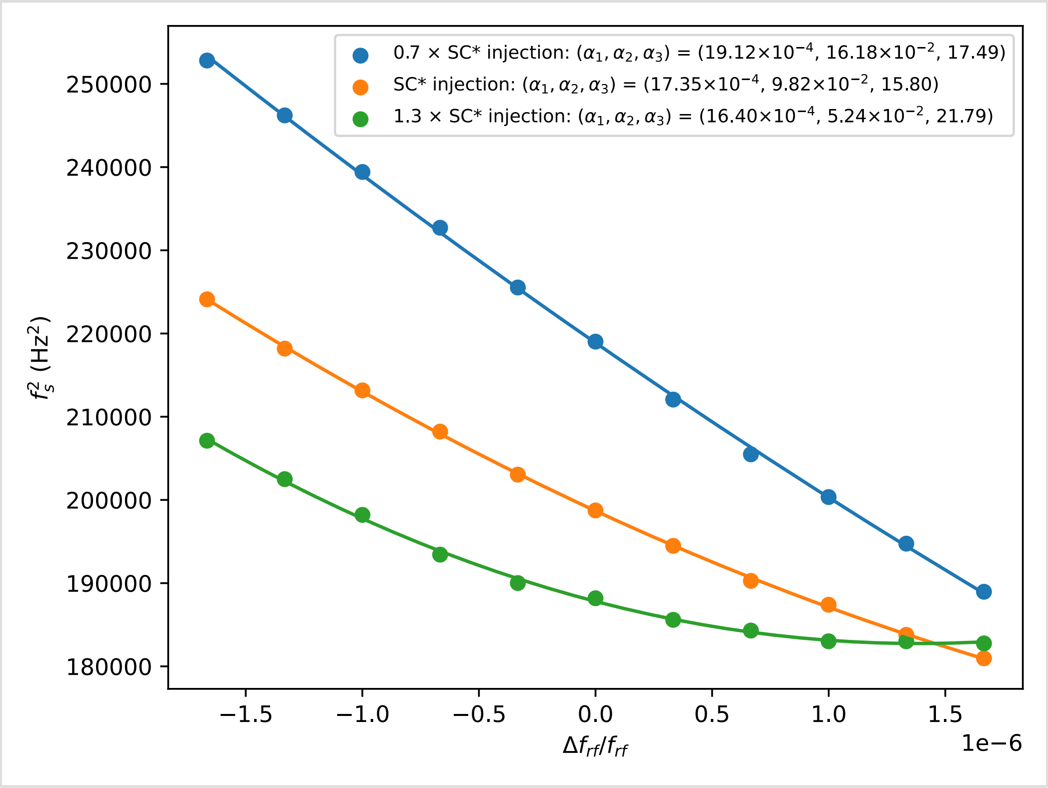
$$I_1 = \oint \frac{\eta}{\rho} ds$$



LADR lattice with ~10^{-2} compaction.

Importance of α_3 at Low Compactions

- Plot shows 'nominal' sextupole excitation and ±30%; octupole currents of −0.4 A to ensure a positive α_3.
- Positive parabolic shape observed when α_2 is reduced sufficiently.
  - An uncompensated α_3 will therefore come to dominate at lower compactions and will inhibit the ability to stably further reduce the compaction.



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Impact of α_2 at Low Compactions

- Blue -> orange: reduce compaction.
- Orange -> green: reduce compaction; second-order term becomes relevant.
- Green -> red: correct second-order term with sextupoles.
- Red -> purple: reduce compaction; second-order term again becomes relevant.