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Low-Alpha Operation of the IOTA Storage Ring

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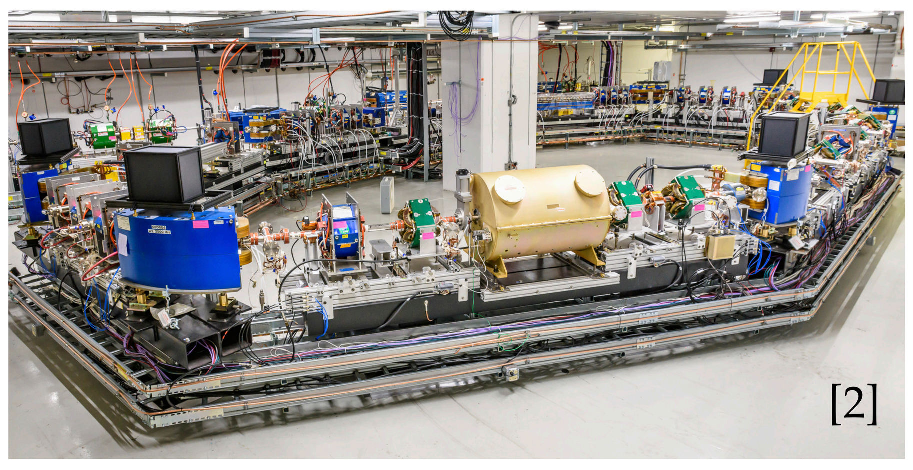
IOTA

- The Integrable Optics Test Accelerator (IOTA) is a 40m storage ring located at the Fermilab Accelerator Science & Technology (FAST) facility [1].
- Injection of electrons from a superconducting linac (50–150 MeV) or protons (2.5 MeV) from a duoplasmatron source (undergoing commissioning).
- Rich science program in non-linear integrable optics, beam cooling, space-charge effects, single-electron, AI/ML controls etc [3].
- First demonstration of Optical Stochastic Cooling (OSC) [4].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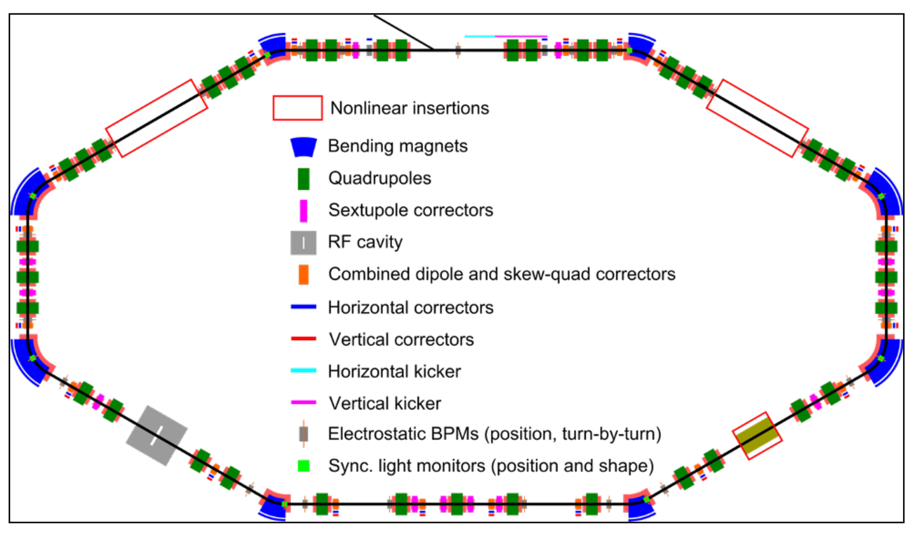
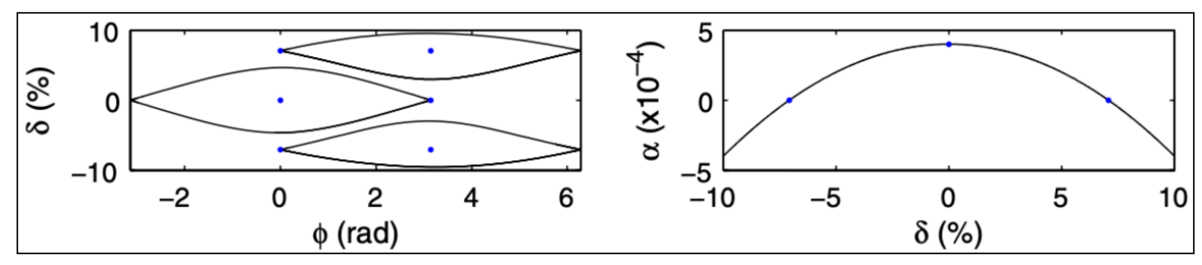
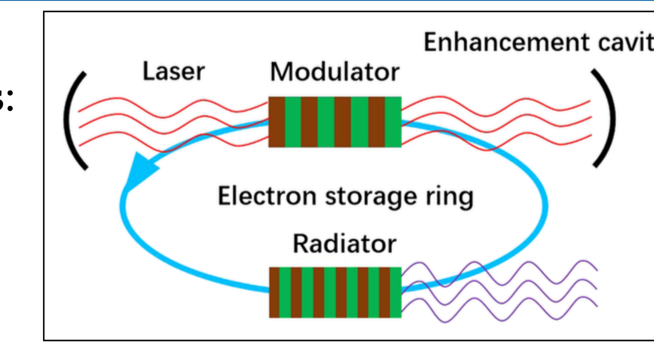


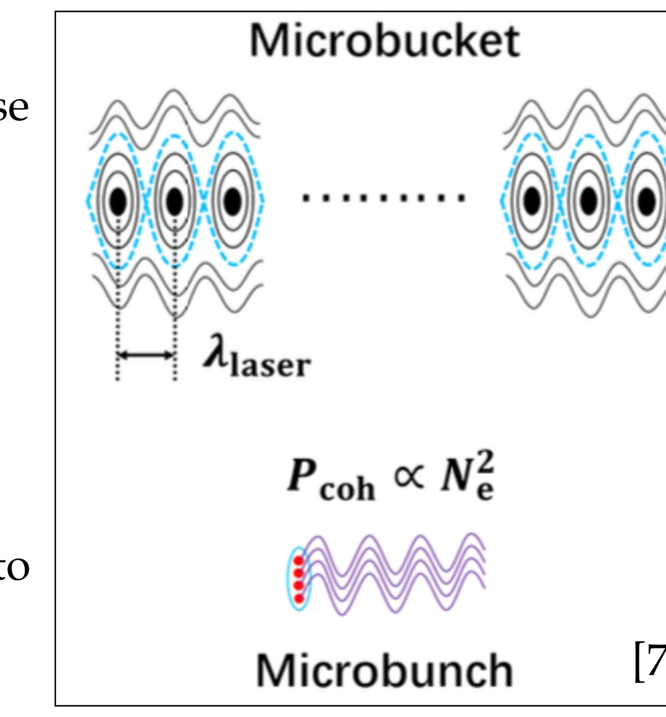
Low-Alpha Storage Ring Motivations

- The momentum compaction describes the variation in orbit length as a function of the momentum deviation δ of the particles:
$$\Delta C/C_0 = \alpha_1\delta + \alpha_2\delta^2 + \alpha_3\delta^3 + \ldots$$
- Reducing the momentum compaction, as in a low-alpha storage ring, results in an overall decrease in the longitudinal spread of particles with respect to the reference over a complete orbit.
- Additionally allows for new areas of stable phase space at a phase of π from RF buckets: alpha buckets [5].



- Steady-State Microbunching (SSMB) is a potential application of low-alpha lattices and a highly active area of research: potential to make a storage-ring based light source with the brightness of an FEL but with a much higher rep rate [6].





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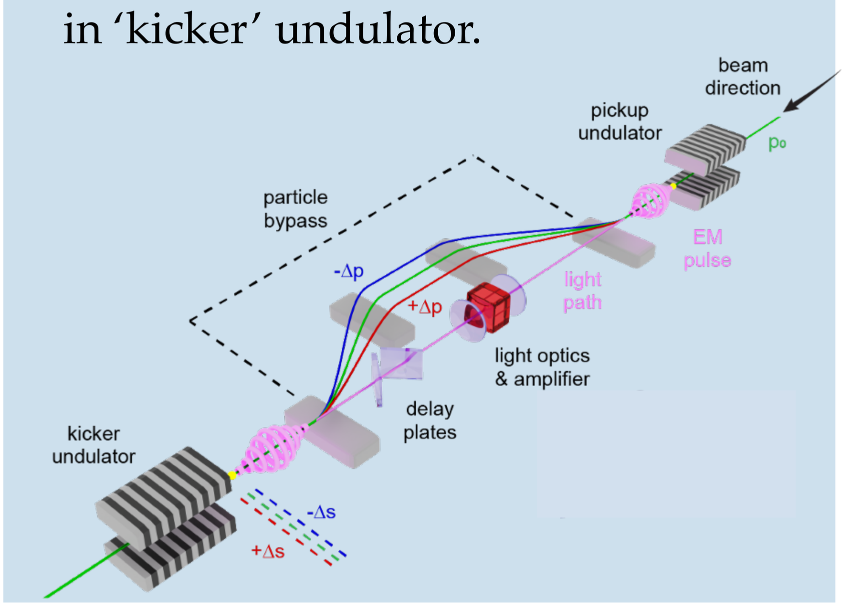
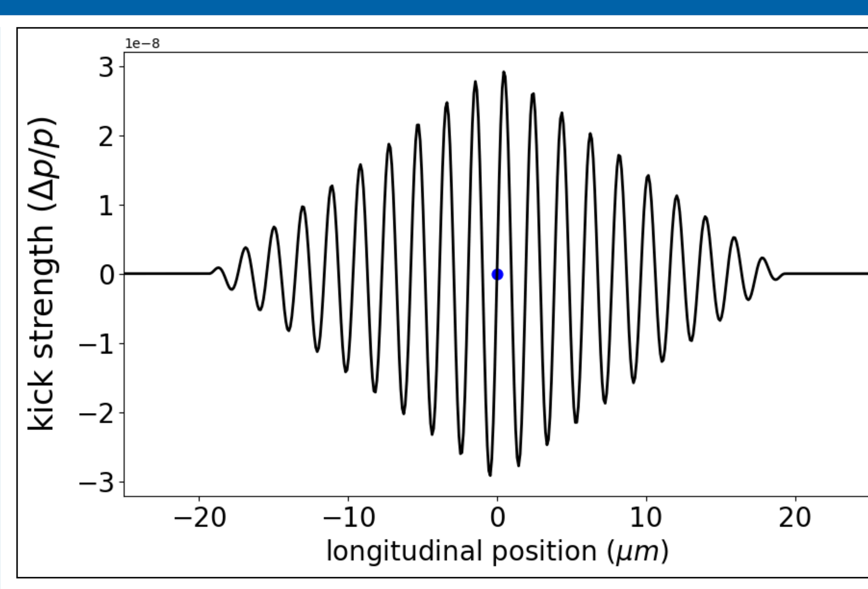
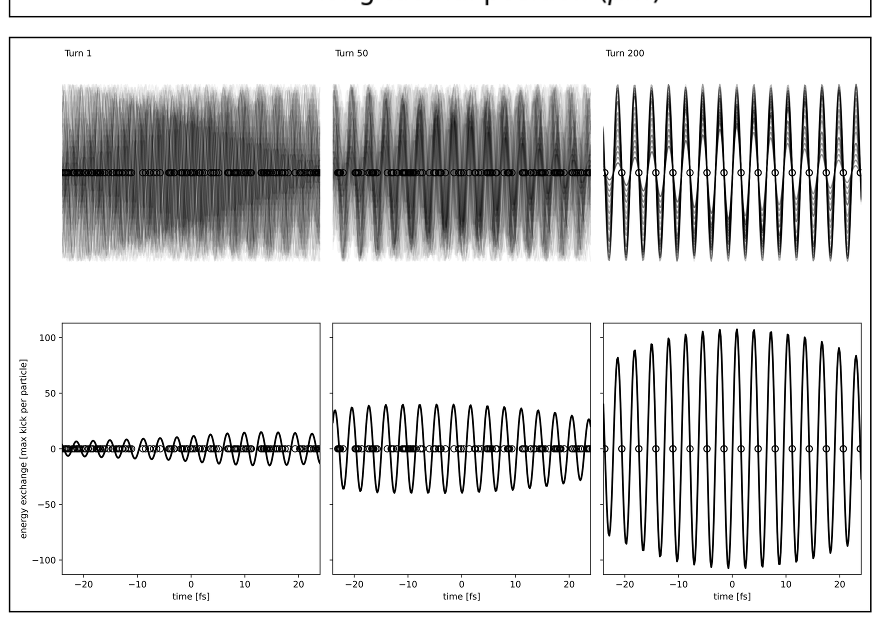
Optical Stochastic Crystallization

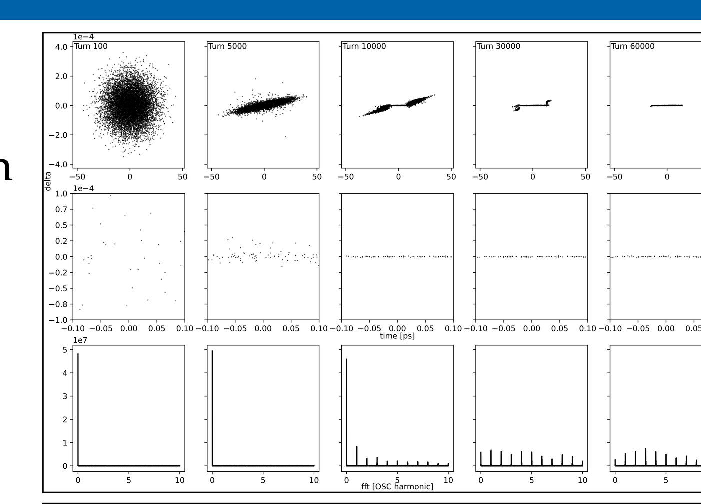
- OSC is an advanced beam cooling technique, with bandwidths ~O(10⁴) greater than stochastic cooling.
- Longitudinal particle positions are encoded in radiation from the 'pickup' undulator; converted to momentum deviation via dispersive bypass.
- Corrective energy exchanges applied in 'kicker' undulator.

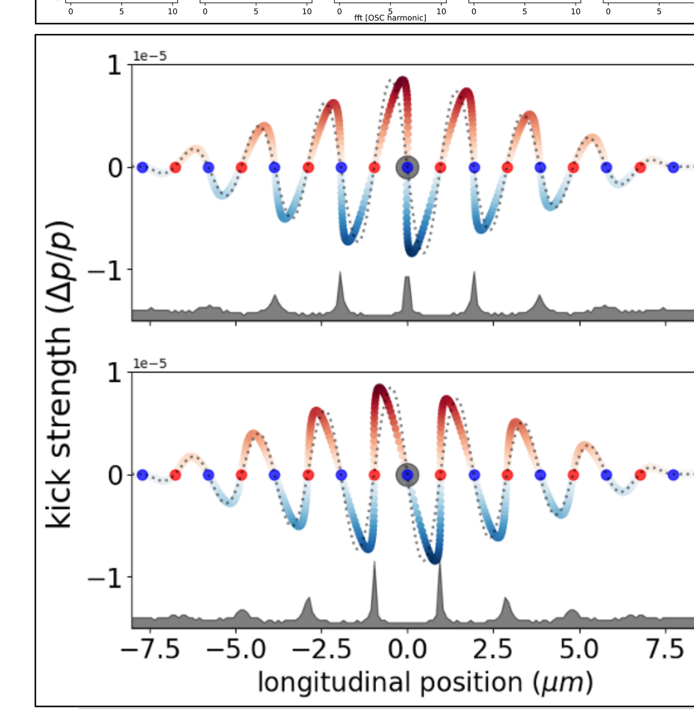






- An OSC system can be operated to produce longitudinal structure at the optical wavelength, which can lead to SSMB with a mutually configured storage ring: Optical Stochastic Crystallization (OSX).
- Ensuring insufficient randomization of particles leads to strong, self-reinforcing collective effects due to each particle feeling the wake of all neighbors within the system bandwidth.
- To promote and sustain SSMB:
  - sufficient gain in the OSC system from optical amplification;
  - sufficiently low momentum compaction with the same sign as the OSC bypass;
  - transverse-longitudinal coupling minimized at the undulators, for example by ensuring the dispersion invariant is sufficiently small.
- First demonstration of OSX planned for the next OSC experiment run.



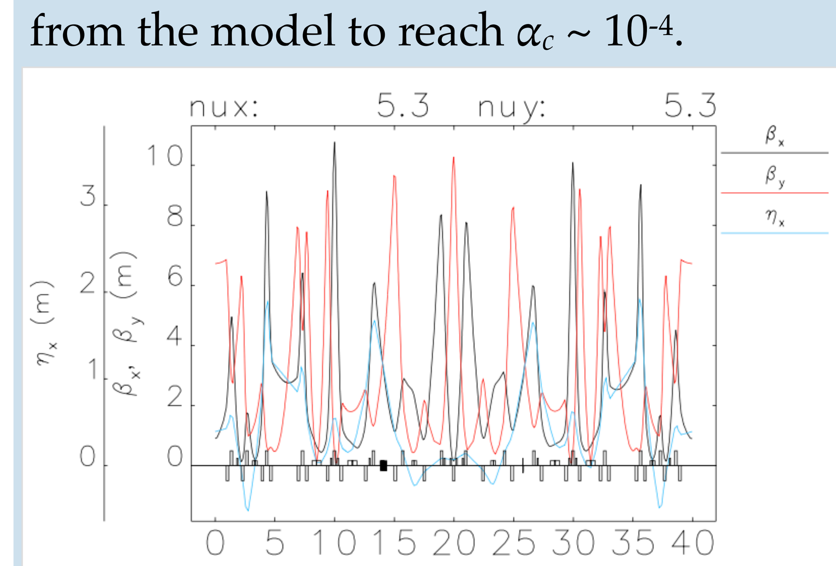


Low Alpha Demonstrations at IOTA

- A short experimental program in Fall 2023 aimed to demonstrate the feasibly of low-alpha operation at IOTA as a first step in realizing these potentials.
- Successfully demonstrated control over the leading three terms α_1, α_2 and α_3 using linear optics, sextupoles and octupoles respectively, including scanning α_2 and α_3 through zero for different values of α_1.
- Developed technique for reaching lower compactions and established low-alpha operations as a potential standard operations mode.
- Achieved lowest compaction of 3.4×10^{-4}, ~15 times lower than previously operated in IOTA.
- Reaching lower compactions and transitioning to alpha buckets was not possible due to the end of the experimental run, though remain feasible.

Lattice

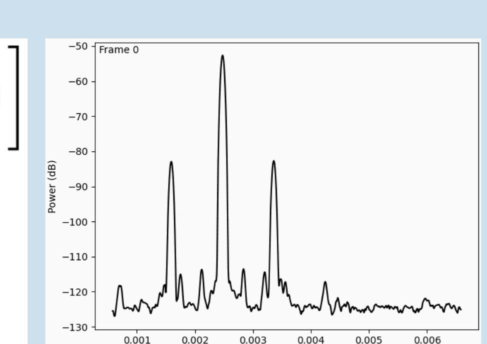
Based on the primary lattice of the IOTA run (non-linear integrable optics), modified to $\alpha_c \sim 10^{-2}$ with knobs built from the model to reach $\alpha_c \sim 10^{-4}$.

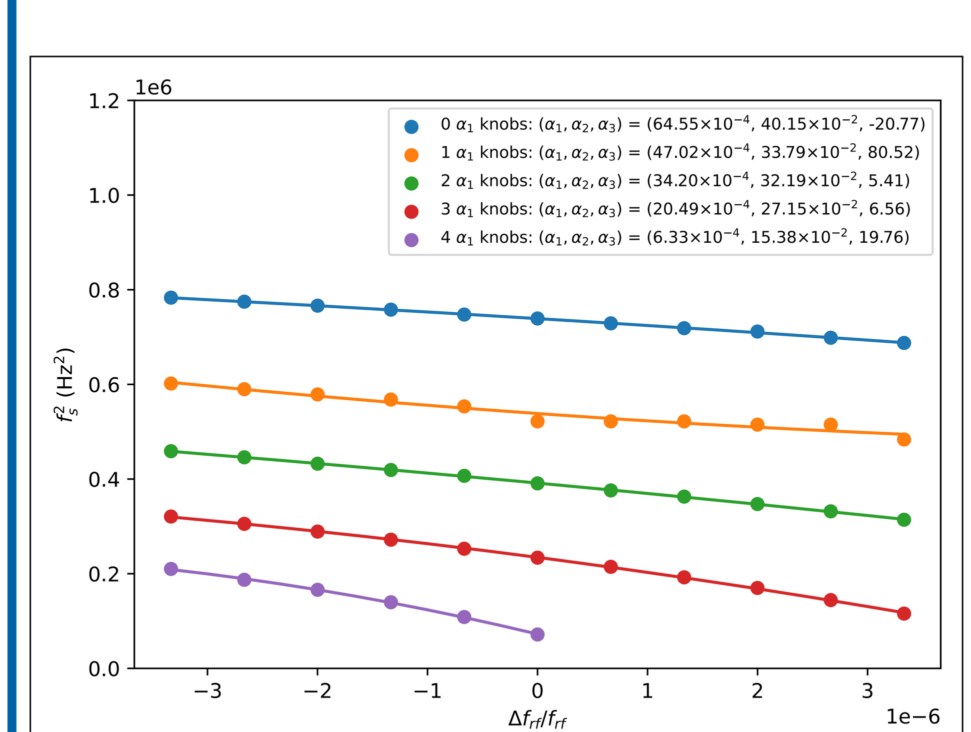


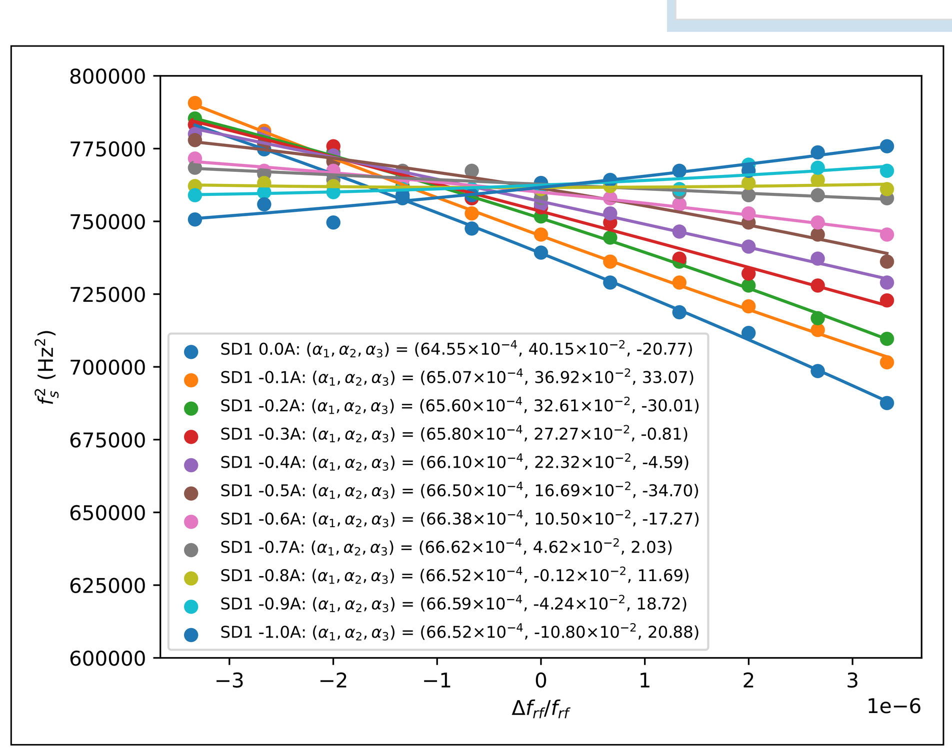
Compaction Measurement

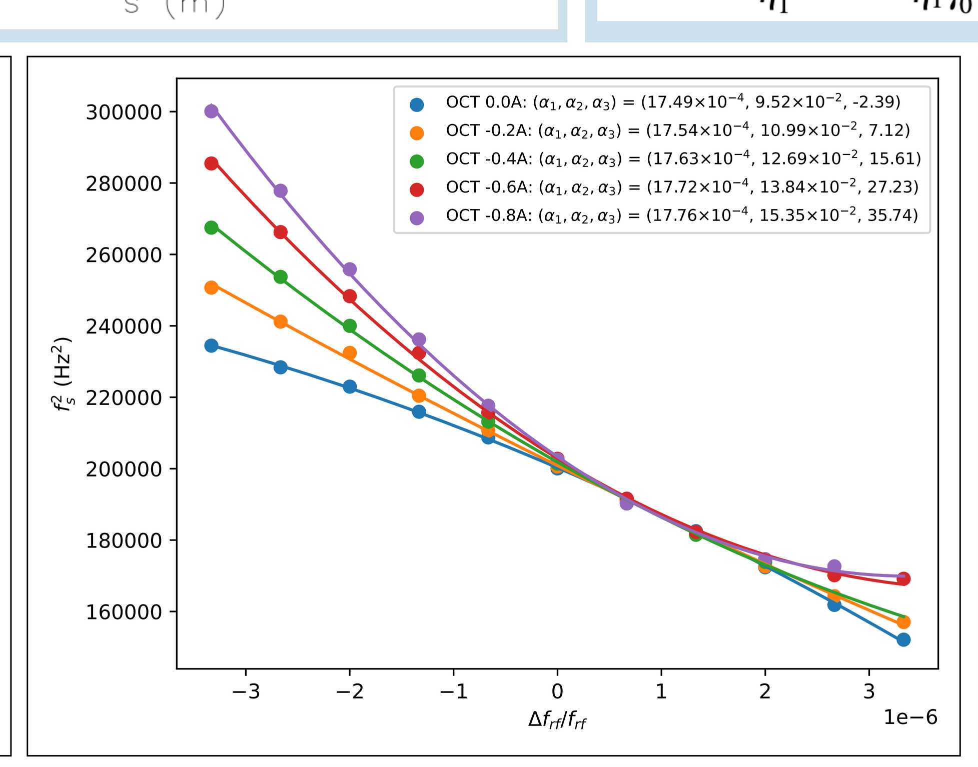
- Compaction estimated from the synchrotron sidebands around a high harmonic of the RF frequency, which were measured using a spectrum analyzer connected to a wall current monitor.
- RF detuning scan enables relationship to be fit to extract measurements of the leading three order terms.
- Average radiation loss is the only assumed input; well understood from models.

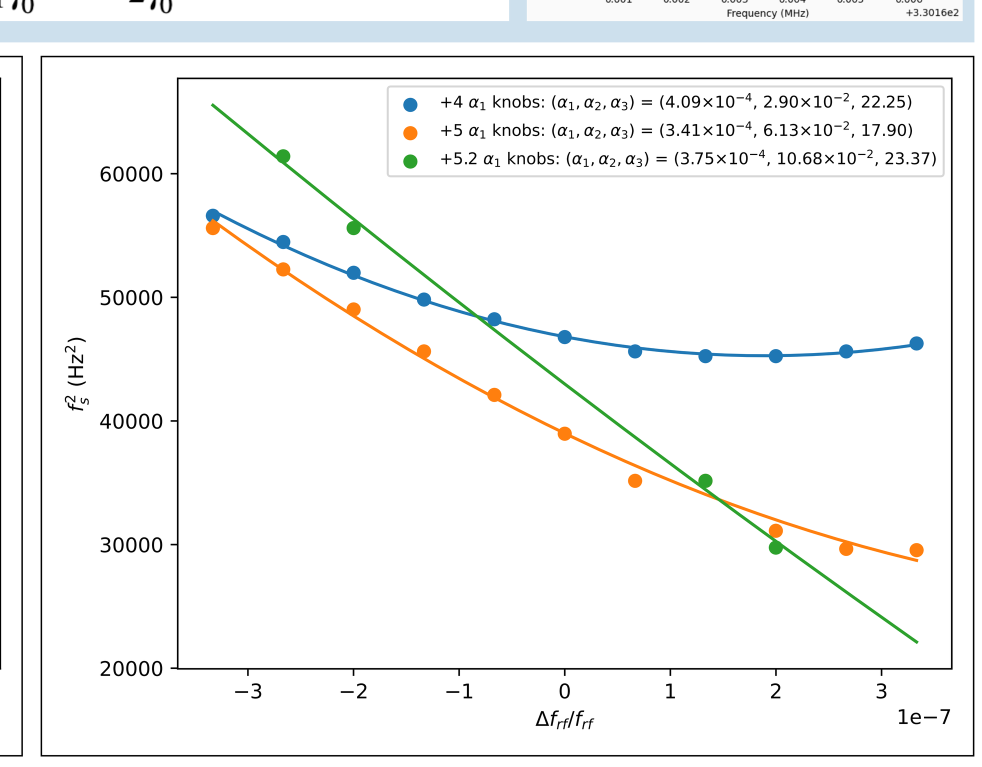
$$f_s^2 = \frac{h q_e V_{rf} f_0^2 |\eta_1 \cos\phi_s|}{2\pi\beta_0^2 E_0}\left[1 + \frac{s_1}{\eta_1}\left(\frac{\Delta f_{rf}}{f_{rf}}\right) + \frac{s_2}{\eta_1^2}\left(\frac{\Delta f_{rf}}{f_{rf}}^2\right)\right]$$
$$s_1 = -\frac{2\eta_2 - \eta_1^2}{\eta_1} + \frac{1}{\gamma_0^2}$$
$$s_2 = \frac{3\eta_3\eta_1 - 2\eta_2^2}{\eta_1^2} - \frac{\eta_2}{\eta_1\gamma_0^2} + \frac{3\gamma_0^2\beta_0^2 + 2}{2\gamma_0^4}$$











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Notes & References

[1] fast.fnal.gov
[2] Photo: Giulio Stancari
[3] JINST **12** T03002 (2017)
[4] Nature **608** 287 (2022)
[5] Phys. Rev. Accel. Beams 14 040705 (2011)
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