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U.S. DEPARTMENT OF ENERGY | Office of Science

Low-Alpha Demonstration Research (LADR) Proposal

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LADR Proposal

- Demonstrate the feasibility of low-alpha (low momentum compaction) operation of the IOTA ring.
  - Support the upcoming Active OSC program to ensure good control over the compaction in the lattice (the initial Passive OSC lattice had initial issues which were resolved by tuning the compaction up from its design value and could have been related to large contributions from higher-order terms).
  - More generally, determine the limits of compaction in the ring for greater understanding of the IOTA optics; expand performance envelope of IOTA to support broader science programs.
  - Could lead to new operational mode (e.g. low-alpha lattices are commonly used in light sources, in steady-state micro-bunching proposals, etc).
- Designed to be as non-intrusive as possible to the ongoing Run4 experimental program, to be enable opportunistic running.
  - Lattice was designed from the NIO optics, maintaining quad polarities etc.
  - The octupoles additionally are of interest to the LADR program.
- Proposal includes 10 (~4 hour) shifts: 4 for commissioning the lattice, 4 for studies, 2 for contingency/investigating unexpected or interesting results.

Low-Alpha Overview

- 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.

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

  - (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 controlled using sextupoles; α_3 can be modified using octupoles, etc.
- Typically low-alpha storage rings use sextupoles to enable fine control over the compaction; the MLS additionally contains four octupoles designed for exactly this purpose.
  - LADR will utilize the octupoles currently in place to demonstrate control over the first three terms.

Effects of Higher-Order Terms

- Effective control of higher-order compaction terms also enables new stables areas of phase space (so-called alpha-buckets), since it changes the shape and zero-crossings of α(delta).
  - Analogous to the 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.

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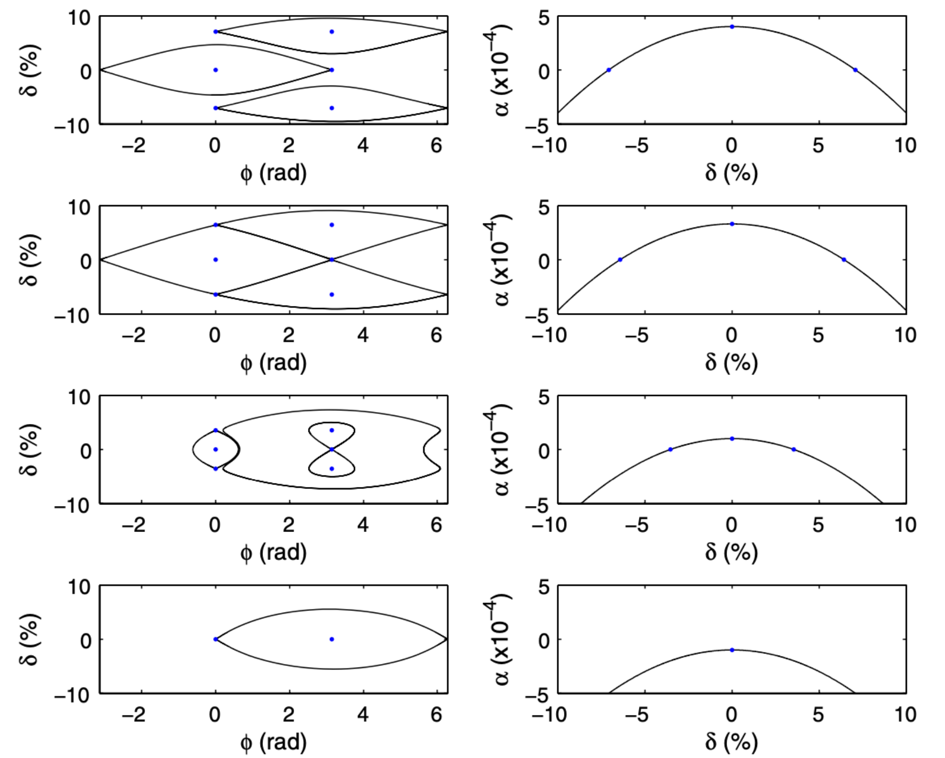


FIG. 1. Figure showing how the separatrices between stable and unstable motion vary as α_1 is reduced from positive to negative values for the case where $\varphi_s = 0$, $\alpha_2 = 0$, and $\alpha_3 < 0$. The right-hand plots show the corresponding values for alpha. The four stages illustrated are rf-bucket regime (top), transition (middle top), alpha-bucket regime (middle bottom), and negative alpha (bottom).

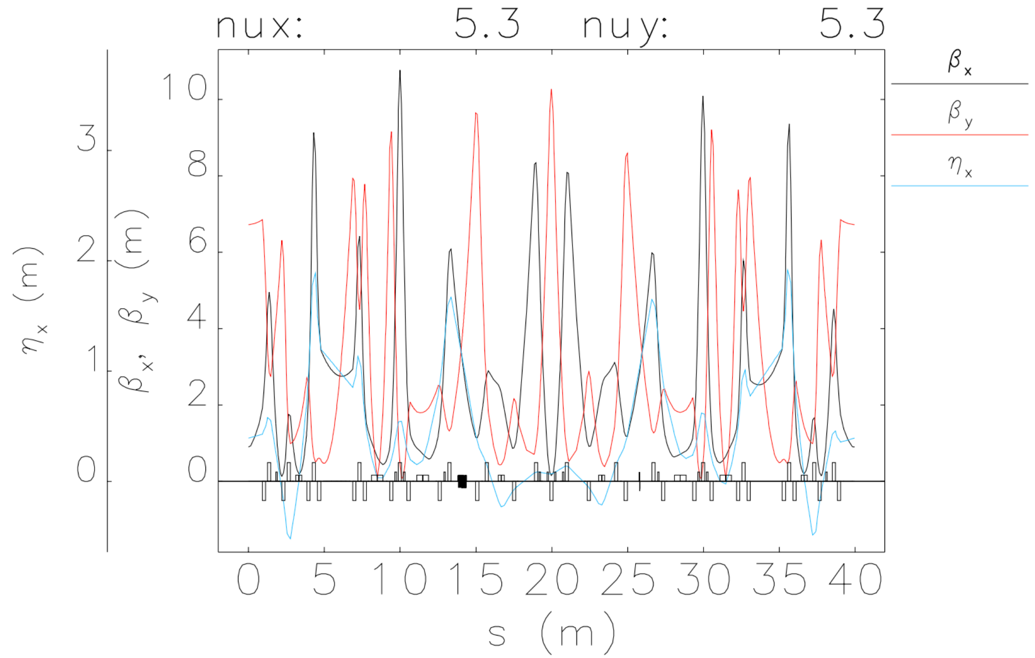
LADR High-Level Aims

- 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.

LADR Lattice & Knobs

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

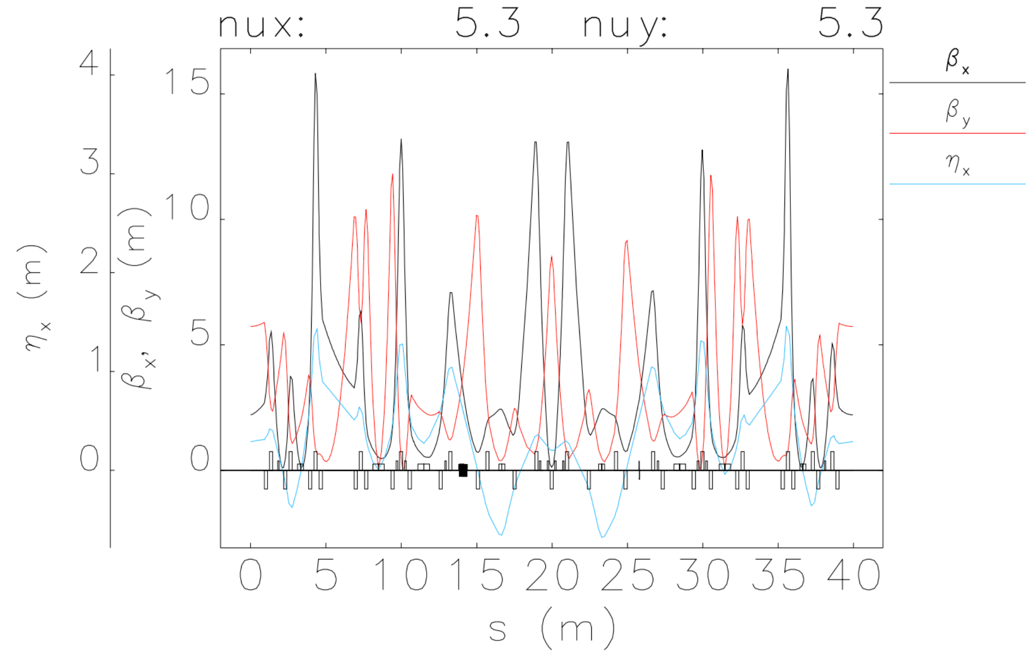
- The lattice was designed from the NIO lattice, with the compaction reduced.
  - Reducing compaction requires a net reduction in dispersion around the ring.
  - This is achieved either by balancing out positive and negative contributions in different straights or by enforcing zero-crossing in the bend 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.



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

LADR Lattice & Knobs

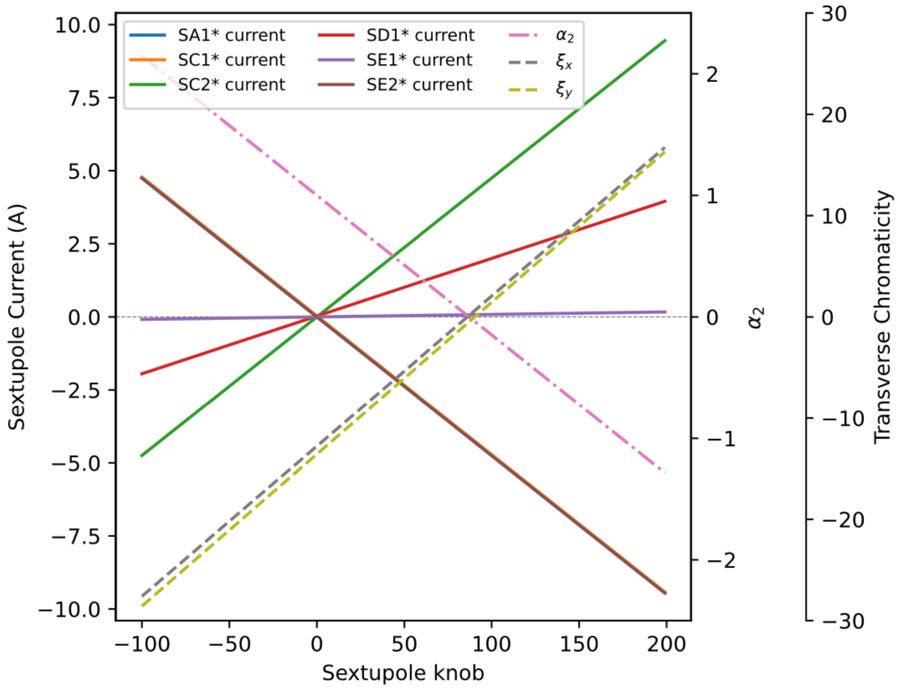
- Knobs developed in ELEGANT can reduce the compaction in the model to 10^{-4}, ~O(1A) quad current changes.
  - Separate knobs using just the BiRa controlled supplies enable fine control near the zero-crossing.
- Additional knobs for the sextupoles and octupoles demonstrate zero-crossings of α_2 and α_3.



LADR lattice with ~10^{-4} compaction.

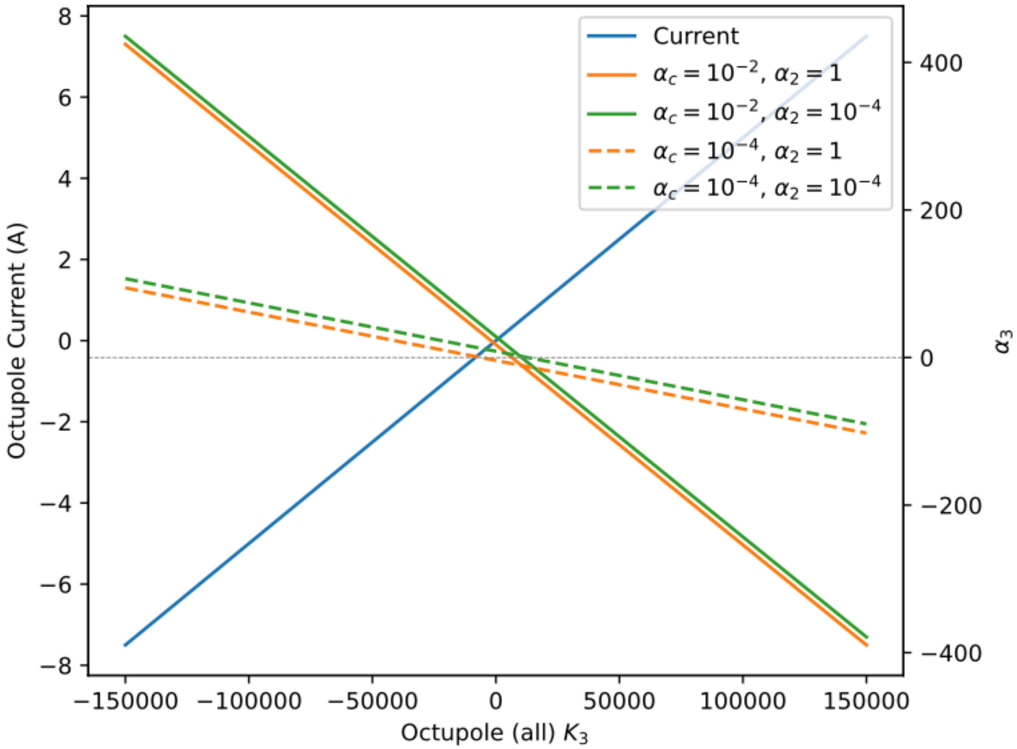
LADR Lattice & Knobs

- Using all six sextupole families enables full control over the second-order optics in all three planes.
  - Simultaneous correction of the transverse chromaticities and α_2.
  - LADR may be possible without any transverse chromaticity correction (it just adds a constant to the orbit length), so we will likely be able to achieve the aims with just one or two families.



LADR Lattice & Knobs

- Similarly, using all 9 octupoles enables excellent control over α_3.
  - Even just one or two can provide a good level of control.



Compaction Measurements

- Compaction will be estimated by de-tuning the RF frequency by Δf_{rf}^2 and measuring the change in synchrotron frequency using a stripline electrode (likely connected to a new CL BPM).
  - Can validate this parasitically during NIO operations.

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

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

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

Required Instrumentation

- Requirements for the synchrotron frequency measurements: strip-line BPM, spectrum analyzer.
- BiRa controls for sextuple and octupole control.
- Single electron diagnostics.

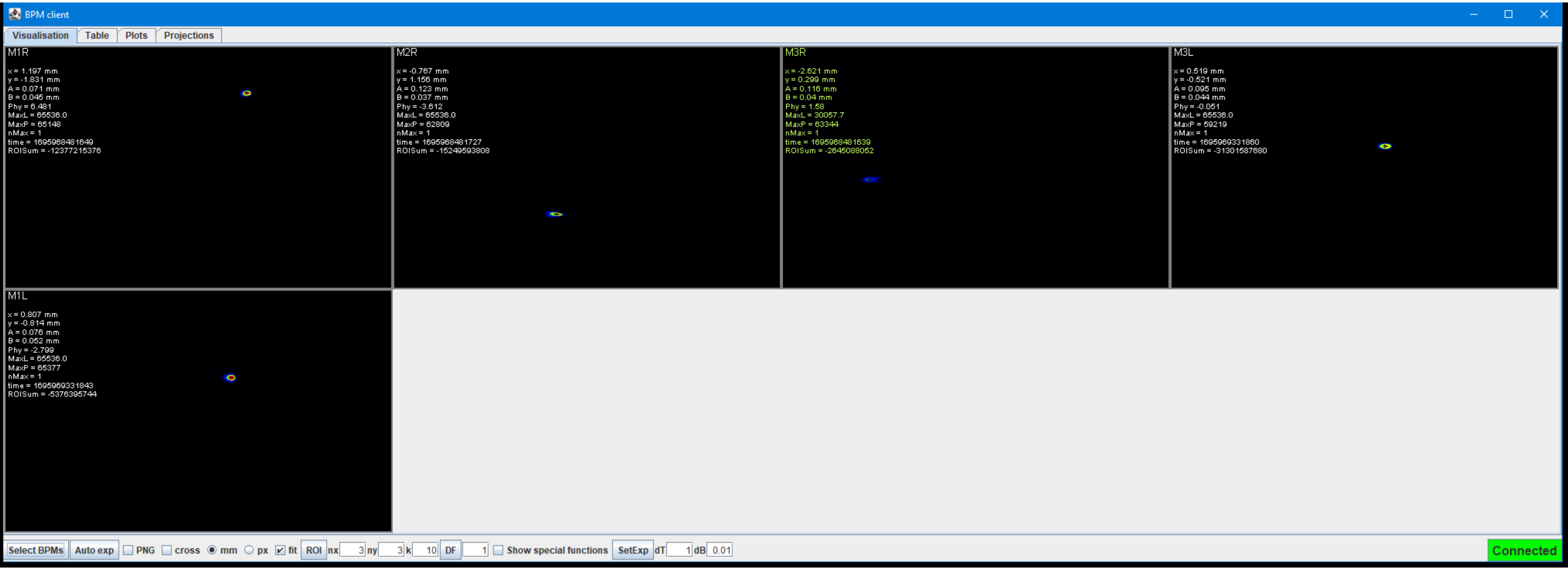
Proposed Shifts

- 4 shifts (4-hour/ea) for commissioning:
  - Shift 1: Initial injection tuning with goal of betatron and synchrotron capture in $\alpha_1 \sim 10^{-2}$ lattice;
  - Shift 2: Injection optimization for intensity and lifetime with goal of sufficient levels for BPMs (>100 μA) and lattice/orbit correction (~10 min);
  - Shift 3: Correction of $\alpha_1 \sim 10^{-2}$ lattice (LOCO and orbit). Validation of all tune, chromaticity and compaction knobs, time permitting;
  - Shift 4: Continue validation of all tune, chromaticity and compaction knobs.
- 4 shifts (4-hour/ea) for studies:
  - Shift 1: Demonstrate correction of α_2 to zero; progressively knob to the $\alpha_1 \sim 10^{-4}$ lattice;
  - Shift 2: Demonstrate expected lifetime dependence on α_3; fully characterize system performance for the $\alpha_1 \sim 10^{-4}$ lattice with $\alpha_3 \gg 0$;
  - Shift 3: Test lower-limits of compaction, ultimately crossing zero and demonstrating transition to alpha buckets, time permitting;
  - Shift 4: Continue demonstration and characterization of performance with ultra-low alpha and alpha buckets.
- 2 shifts (4-hour/ea) for opportunistic studies.

Preliminary Shifts

- Under provision approval status, we have taken two preliminary shifts this week (Wednesday and Thursday night).
  - Initially aiming to get injection into the LADR lattice.
- We worked on injecting directly into the LADR lattice on Wednesday, varying the injection and ring correctors to try to get capture. First turn happened quite quickly, little progress in keeping electrons in for more than one.
- Last night, we were successful in knobbing over from the NIO lattice and using the NIO tune knobs; able to keep 220uA for ~1-2 minutes. Good low current lifetimes (>10 mins) already observed, without significant correction of lattice and orbit.
- Next up is to work on injection configuration: ideally through injection bumps so we can direct directly into the lattice, otherwise by automating the NIO->LADR knobbing process developed last night.

Initial Capture



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Summary & Impacts

- LADR aims to provide a better understanding of the low-alpha capabilities of the IOTA ring and increased confidence in the lattice design for Active OSC, and other future programs.
- Demonstrate feasibility for this new mode of operation, which could impact future science programs and expand the capabilities of the Facility.
  - Initial studies using the model and from basic tracking shows this is possible with the IOTA optics.
- The program could potentially impact regular operations by providing more stable running/injection configurations with improved phase space acceptance.
- Single electron operation in low-alpha mode could merit peer-review publication.