BENCHMARKING THE LINEAR LATTICE OF THE ISIS RCS AS A FOUNDATION FOR FUTURE MODEL-BASED OPTIMISATION

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Abstract

ISIS operates an 800 MeV Rapid Cycling Synchrotron (RCS) delivering protons to neutron and muon targets with a beam power of 0.2 MW. A reliable lattice description is essential for advancing low-loss, high-intensity operation and supports emerging model-driven optimisation enabled by forthcoming Python-accessible controls. A new consolidated low-intensity linear optics model of the ISIS RCS, developed through a continuous programme of systematic measurement-based benchmarking, is presented.

Using enhanced analysis of low-intensity turn-by-turn BPM data, multiple optics measurements have been integrated into a single self-consistent lattice representation. This lattice represents a significant advance over earlier design-only or partially benchmarked descriptions, enabling clearer identification of optics discrepancies and guiding targeted correction measures, including improvements to magnet survey and alignment.

The resulting reference lattice, implemented in MAD-X/cpymad and cross-checked with PTC-PyORBIT, reproduces low-intensity optics with improved predictive performance, particularly for orbit response and optics control. Benchmarks of the consolidated model, resulting improvements, and planned implementation in model-based optimisation of ISIS RCS operation are presented.

MEASUREMENT FRAMEWORK

The ISIS 800 MeV Rapid Cycling Synchrotron (RCS), operational since 1984, has relied on measurement-based validation of its transverse lattice to support high-intensity operation. A defining feature of this programme is the use of low-intensity "chopped" (from 200 µs to 600 ns) diagnostic beams, generated by electrostatic chopping of the $\sim$70 MeV linac beam prior to injection. These short pulses limit space-charge and collective effects, enabling clean observation of coherent transverse motion and providing a reproducible reference state representing the "bare" linear lattice: the machine with AC-powered main magnets and no contribution from programmable dipole and quadrupole correctors.

Early studies used such low-intensity pulses to measure injection oscillations and machine tune without intensity-driven distortions [1, 2]. With the introduction of turn-by-turn BPM diagnostics, lattice parameters could be extracted through tune shifts, relative betatron amplitudes, and $\Delta Q/\Delta I$ measurements [3–5]. More recently, these methods have been extended to orbit response, resonance studies, and alignment modelling [6–8].

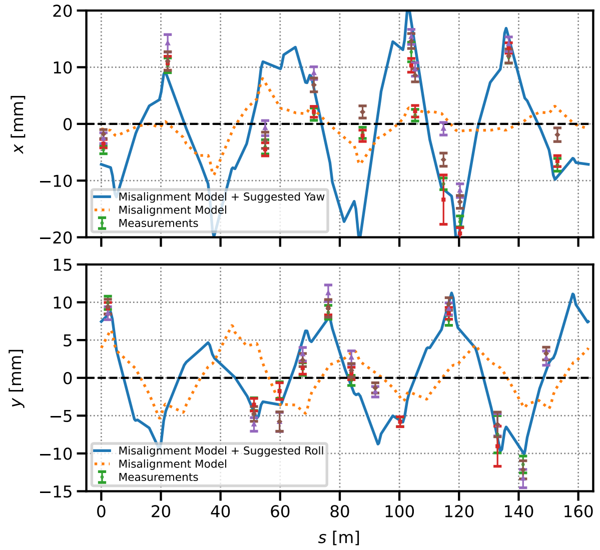

Figure 1: Comparison of measured bare orbit with survey-based misalignment model predictions used to infer main dipole errors.

Turn-by-turn BPM signals are processed to extract coherent oscillation amplitudes, phase, and tune directly from measured data following established methodology [4, 5]. All observables are derived without model preconditioning, ensuring that subsequent comparisons remain measurement-led.

The present work builds on this approach through a set of measurement-driven benchmarking campaigns, culminating in a unified linear lattice model of the ISIS RCS and forming the foundation for model-based operational optimisation.

BENCHMARKING CAMPAIGNS

Orbit Benchmarking and Magnet Alignment

Closed orbit measurements under low-intensity "bare" machine conditions are combined with main magnet survey data to benchmark the lattice at first order. Survey measurements are converted to model-consistent co-ordinates and implemented as misalignments in the lattice [8].

The survey-informed model captures the dominant orbit structure, while residuals provide a model-guided indication

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of likely missing alignment components for follow-up investigation. Based on these residuals, candidate errors in the combined-function main dipoles are investigated, since these are the longest elements and therefore strong candidates for dominant contributions. A minimal set of additional candidate errors is found to improve model–measurement agreement, as shown in Fig. 1: vertical rolls of +1.8 mrad (Dipole 1) and +2.5 mrad (Dipole 2), and horizontal yaws of −1 mrad (Dipole 0) and −3 mrad (Dipole 2). This illustrates how the model is used to both reproduce measurements and suggest plausible missing error components for further investigation beyond directly measurable alignment information.

This methodology guides alignment campaigns, supported by dedicated measurements of main dipole roll angles, with observed operational improvements indicating that key sources of orbit distortion are captured.

Closed-orbit response to controlled corrector excitation during the acceleration cycle is also benchmarked against the model [9]. Individual corrector calibrations are implemented in the lattice, and measured orbit response is compared directly with model prediction.

Tune Control and Bare Tune Benchmarking

Bare tunes measured under low-intensity conditions in the RCS are observed to differ from those expected in the operational tune control application. The operational method of tune control is implemented in the model [9], providing direct reproduction of the operational tune and a more precise representation of envelope behaviour across the accessible parameter space.

This implementation allows more accurate tune determination for detailed studies, including analysis and controlled crossing of resonances. By capturing the measured tune response, the model supports improved interpretation of measured beam behaviour in these regimes [10, 11].

Measurements show a small difference in bare tune between Storage Ring (SRM) and RCS modes of operation. The model framework supports both configurations by scaling main magnet strengths, including both quadrupoles and combined-function dipoles, to match the measured bare tune consistently.

Regular tune measurements are used to benchmark the model tune response, showing consistent behaviour over years and good agreement with the model. The validated model is currently being used to define an improved tune control scheme for future operation. In the context of the ongoing EPICS-based controls upgrade [12], this provides a pathway toward more flexible and accurate envelope control.

Beta Functions and Phase Advance

Beta functions are measured using a combination of $\Delta Q/\Delta I$ measurements at trim quadrupoles [4, 5] and orbit response methods to extract beta functions at BPM and corrector locations. Phase advance is obtained from turn-by-turn BPM analysis, providing a consistent set of optics observables around the ring.

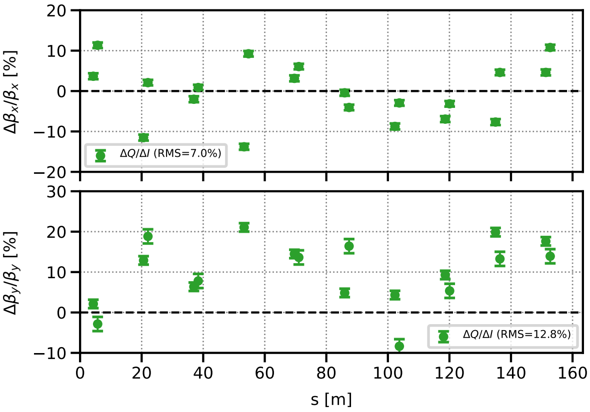

Figure 2: Measured horizontal and vertical beta beating relative to the design lattice.

Measured phase advance and beta functions are compared directly with the lattice model without preconditioning.

These comparisons reveal RMS beta beating of $\frac{\Delta\beta_x}{\beta_x} \approx 7\%$ and $\frac{\Delta\beta_y}{\beta_y} \approx 13\%$ between the measured machine and the design lattice as shown in Fig. 2.

The framework allows direct identification of optics correction schemes within the model. The availability of beta functions at multiple elements enables detailed validation of the optics model across the ring, with consistent comparisons of beta functions, phase advances, and dispersion shown in Fig. 3.

Chromaticity and Dispersion

Chromaticity is measured at injection by varying the main-magnet field and compared with lattice model predictions. Measured and simulated normalised chromaticities, defined here as $\xi = Q'/Q$, are in agreement, with $\xi_x = -1.05 \pm 0.09$ and $\xi_y = -1.23 \pm 0.10$, providing independent validation of the linear optics.

Dispersion is extracted from chromaticity measurements at BPM locations and compared with the model prediction in Fig. 3. The agreement provides an additional cross-check of the momentum-dependent optics.

CONSOLIDATED LATTICE MODEL

The consolidated lattice is implemented in MAD-X format starting from the design optics with improvements from historical studies and updated to be consistent with measured optics. The framework supports both RCS and SRM configurations, with survey-derived misalignments and the conformal rectangular aperture model consistently included.

The lattice integrates the benchmarking observables into a single self-consistent description, incorporating orbit, phase advance, beta functions, chromaticity, dispersion, and the operational tune control system. Observables are compared directly with measurement without preconditioning, so that remaining discrepancies can still be used to guide investigation of missing physical effects or model errors. Methods are

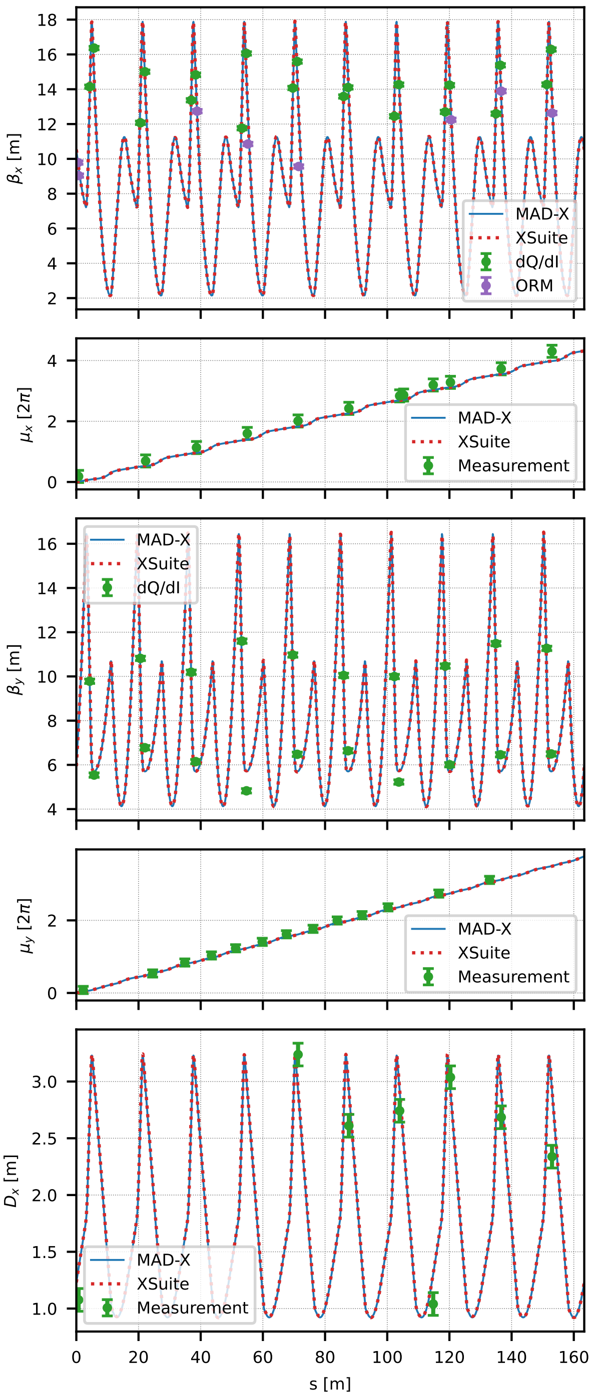

Figure 3: Comparison of measured optics observables with the consolidated bare lattice model.

implemented to adjust the lattice in response to benchmarking measurements, enabling controlled refinement while retaining sensitivity to residual model–measurement differences.

The model is maintained as a canonical reference and deployed across multiple accelerator codes, including MAD-X/cpymad [13, 14], PTC-PyORBIT [15, 16], Elegant [17], Xsuite [18], Simpsons [19], and OPAL [20]. A common definition of magnet length, position, strength, and aperture geometry is used across implementations.

Linear optics and first-order orbit response are consistent across codes, with agreement between matrix-based calculations and tracking. This provides confidence that remaining measurement–model differences reflect physical effects rather than implementation artefacts.

The resulting lattice provides a single reference optics model for the ISIS RCS, supporting both linear optics studies and further resonance and non-linear investigations [10, 11].

MODEL-BASED OPTIMISATION

The validated lattice provides a direct link between measurement and operational capability. Orbit benchmarking, corrector calibration, and optics measurements establish a reliable model of orbit response, optics, and tune behaviour.

These capabilities enable a transition from reactive tuning to predictive, model-based optimisation. The lattice is being integrated with the EPICS-based control system, allowing the measured machine state to be mapped onto the model in near real-time.

A graphical optics interface is under development to combine orbit, optics, tune, and aperture information within a single framework. This will provide virtual diagnostics and enable model-informed optimisation of orbits and beam envelopes. Initially deployed in a read-only configuration, the system will be incrementally extended as further benchmarking results are incorporated, forming the basis of a unified, measurement-driven optimiser for ISIS RCS operation.

CONCLUSION

Regular measurement-based benchmarking campaigns are used to establish and maintain a unified linear lattice model of the ISIS RCS. Tune, phase advance, beta function, dispersion, and orbit observables are consolidated into a single self-consistent description, combining benchmarking activities into a shared modelling framework. The model reproduces low-intensity optics and first-order orbit response and has been cross-validated across multiple accelerator codes, establishing a robust single reference optics definition.

Orbit benchmarking using survey-informed misalignments enables systematic identification of realignment candidates and improved understanding of bare orbits. As the primary constraint of the model, the orbit, combined with measured optics and the implemented aperture, provides a consistent basis for interpreting beam envelope evolution relative to the physical machine and underpins first-order loss prediction. Chromaticity and dispersion measurements support optimisation of off-momentum beam behaviour. The consolidated framework links measurement, modelling, and controls, underpinning real-time virtual diagnostics and future operational optimisation. It forms the basis for progressive, measurement-driven optimisation of ISIS RCS operation.

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