PHASE SPACE MEASUREMENTS ON THE ISIS SYNCHROTRON

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Abstract

The ISIS Neutron and Muon source produces pulsed neutrons and muons for multi-disciplinary scattering and spectrometry experiments. Up to 3×10^{13} protons per pulse are accumulated over a ~200 µs injection period, then accelerated from 70 to 800 MeV in the 50 Hz rapid cycling synchrotron. This beam is then extracted to one of two spallation neutron targets. An electrostatic chopper is installed in the transfer line between the injector linac and the synchrotron, which allows injection of beam pulses between 100 ns – 5 µs, filling a fraction of the machine acceptance of the synchrotron. Beam Position Monitor (BPM) measurements of chopped beams are routinely used to determine synchrotron lattice parameters. As part of ongoing improvements to measurement, modelling and control of ISIS beam dynamics, a new tool has been developed to routinely use these BPM signals to generate phase-space ellipses. Preliminary results from commissioning of this tool are presented, showing good agreement with the linear transverse model of the ISIS RCS.

INTRODUCTION

The ISIS synchrotron accelerates on the rising edge of a 50 Hz sinusoidal field. High intensity proton beams are achieved using charge-exchange injection of H^- ions from the linear accelerator (linac) over 200 µs, corresponding to around 130 beam revolutions. Injection typically begins 0.4 ms before the minimum of the main magnetic field.

To mitigate space-charge effects, transverse phase-space painting is implemented in both planes. In the horizontal plane, the energy mismatch between the fixed linac beam energy and the falling magnetic field of the synchrotron results in a moving dispersive closed orbit. In the vertical plane, a programmable dipole in the injection line is used to vary the injection point vertically throughout the injection period.

The betatron tunes are programmable throughout the acceleration cycle, with the nominal working point set to $(Q_x, Q_y) = (4.31, 3.83)$ [1]. Tune control is achieved using 20 trim quadrupoles, with two installed in each of the ten superperiods. Programmable dipole magnets, seven in each transverse plane, are used to provide orbit correction.

CHOPPED BEAM ELLIPSE RECONSTRUCTION

A diagnostic beam, typically 600 ns, can be produced by the electrostatic chopper located in the transfer line between the linac and the synchrotron. Timing control allows selection throughout the 200 µs injected pulse, enabling the study of time-dependent beam properties. Such beams facilitate detailed measurements of transverse beam dynamics, as the injected beam fills only a limited portion of the machine acceptance.

The synchrotron is equipped with 35 AC-coupled beam position monitors (BPMs), comprising nineteen vertical and sixteen horizontal monitors. For chopped beam measurements, high gain BPM signals are acquired for ~100 µs, allowing turn-by-turn position extraction for 50 turns.

The transverse beam position on the *n*th turn may be described by the following theoretical expression [2]:

$$y_n = A \exp\left(-\frac{(\pi n \delta Q)^2}{2}\right) \cos\left(2\pi n \left[Q_0 + \frac{n\Delta Q}{2}\right] + 2\pi\phi\right) + n\Delta R + R_0. \tag{1}$$

Here,

y_n : beam position on the *n*th turn,
A : initial betatron amplitude,
Q_0 : initial betatron tune,
R_0 : initial closed-orbit offset,
δQ : tune spread,
ϕ : initial betatron phase divided by π,
ΔQ : change in tune per turn,
ΔR : change in closed orbit per turn.

A least-squares fit can be applied to the measured beam positions, allowing the extraction of the lattice parameters as well as the reconstruction of the turn-by-turn beam position at each BPM. Key parameter determination from this expression has been employed operationally for many years. However, it is also possible to use these fitted parameters to generate a visualisation of the transverse phase-space ellipse and to derive the corresponding Twiss parameters.

In practice the spread in betatron frequencies in the beam causes decoherence of the oscillations, seen as damping [3]. In order to omit this effect time dependent parameters are excluded from the fit, simplifying Eq. (1) to:

$$y_n = A \cos\left(2\pi n Q_0 + 2\pi\phi\right). \tag{2}$$

Beam position measurements from two consecutive BPMs can be obtained on a turn-by-turn basis. Given a known monitor separation and phase advance between these monitors, the measurements can be combined geometrically to obtain phase-space coordinates and reconstruct the transverse phase-space ellipse.

Based on this approach, a new control-room software tool has been developed to visualise the transverse phase space using the results of chopped beam measurements. In its simplest implementation, the method is applied to two

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BPMs separated by a drift space. A pair of BPMs separated by a drift (R3VM1 & R3VM2) were selected to validate the tool.

MEASUREMENTS

Comparison to MAD-X Model

To validate the phase-space reconstruction tool against a lattice model, measurements were first performed with a 'bare' machine configuration with a chopped pulse length of 600 ns. This corresponds to operation with only the sinusoidally varying main magnetic field, with no programmable steering dipoles or quadrupole trim elements applied.

Measurements were taken during injection at 0.35 ms before the main dipole field minimum. A comparison between the lattice Twiss parameters, α and β, calculated using MAD-X, and those obtained from the reconstruction tool is shown in Table 1.

Table 1: Comparison of Vertical Twiss Parameters

BPM	**Alpha MAD-X**	**Alpha Measured**	**Beta MAD-X**	**Beta Measured**
R3VM1	−1.36	−1.1 ± 0.2	7.75	7.7± 0.3
R3VM2	−1.90	−1.6 ± 0.1	12.6	11.7± 0.8

Good agreement is observed between the measured Twiss parameters in the vertical plane and those expected from the MAD-X model of the ISIS synchrotron. This provides initial validation of the reconstruction method.

Error calculations on the Twiss parameters are non-trivial. Errors stem from the signal-to-noise ratio of the monitors, initial chopped beam signal fitting and ellipse fitting. Errors quoted here are calculated from deviations of the least-squares ellipse fit to generated phase-space coordinates, and do not fully encompass the whole method. Future development of the application will aim to capture errors from all sources listed above.

Vertical Painting Studies

Vertical phase-space painting during injection is achieved using a programmable dipole magnet in the injection line, commonly referred to as the vertical sweeper. The relationship between the sweeper strength, at flat top of the sweeper field, and the resulting vertical emittance, ε_y, was demonstrated using the phase-space reconstruction tool. Figure 1 shows representative reconstructed vertical phase-space ellipses with increasing sweeper current during injection. The blue points correspond to phase-space coordinates generated from the fitted motion described by Eq. (2), while the red curves are fitted phase-space ellipses from which the Twiss parameters and emittance are derived.

Figure 2 shows the reconstructed vertical emittance as a function of sweeper current for measurements taken at −0.3 ms. As expected, increasing the painting amplitude during injection results in a corresponding increase in emittance, exhibiting an approximately linear dependence with gradient $d\varepsilon_y/dI = (4.33 \pm 0.55)\,\pi\,\mathrm{mm\,mrad\,A^{-1}}$. This is consistent with the expected vertical amplitude range of 90 –180 π mm mrad for a typical operating current range of 30 – 40 A [4].

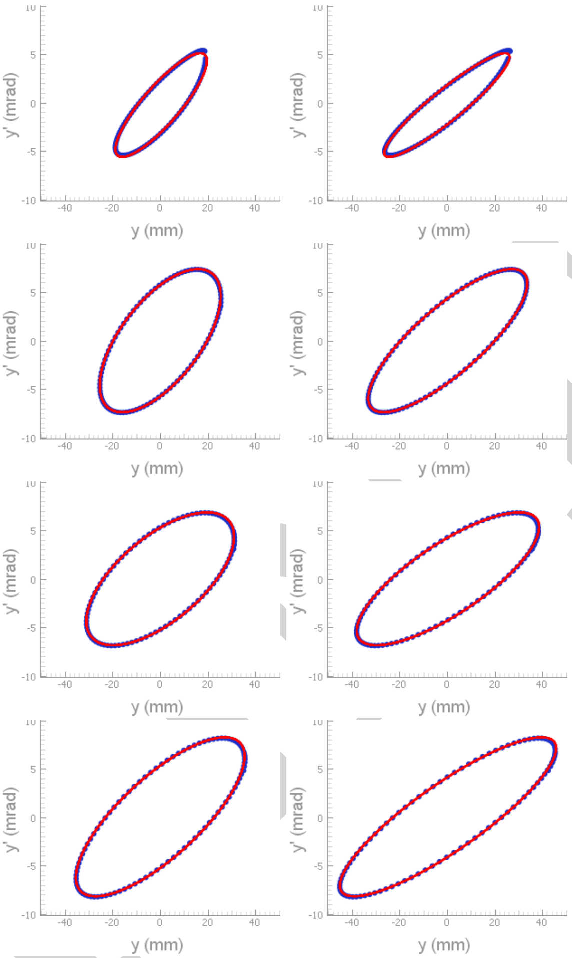

Figure 1: Representative reconstructed vertical phase-space ellipses for BPMs R3VM1 (left) and R3VM2 (right), for vertical sweeper currents of 20, 30, 40, and 50 A (top to bottom).

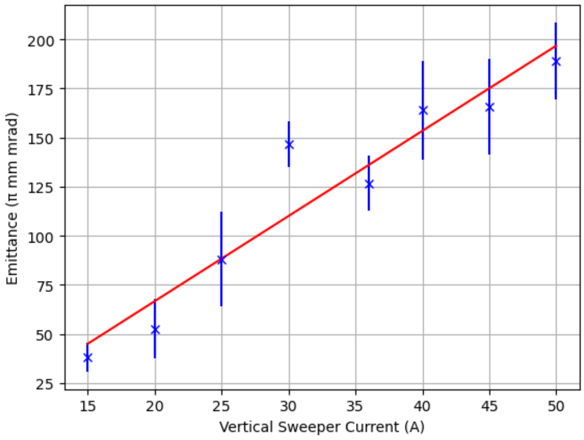

Figure 2: Reconstructed vertical emittance as a function of vertical sweeper current.

Vertical Tune Dependence

The effectiveness of the tool when varying the programmable vertical tune has also been demonstrated. The vertical tune was varied between 3.550 and 3.825, while the horizontal tune was set at a constant value of 4.300. The vertical sweeper current was set at 36 A for all measurements. Outside this tune range, reliable measurements of the chopped diagnostic beam could not be obtained. This is attributed to operation significantly away from the nominal working point, requiring large trim quadrupole currents.

The relationship between β_y and the vertical tune Q_y is shown in Fig. 3. Calculated values from MAD-X are shown in blue, whilst values obtained by the phase-space reconstruction are shown in red. The lattice model predicts an approximately linear dependence. The red lines show a linear regression fit to the measured data. Individual measurements exhibit scatter about the expected linear trend from MAD-X.

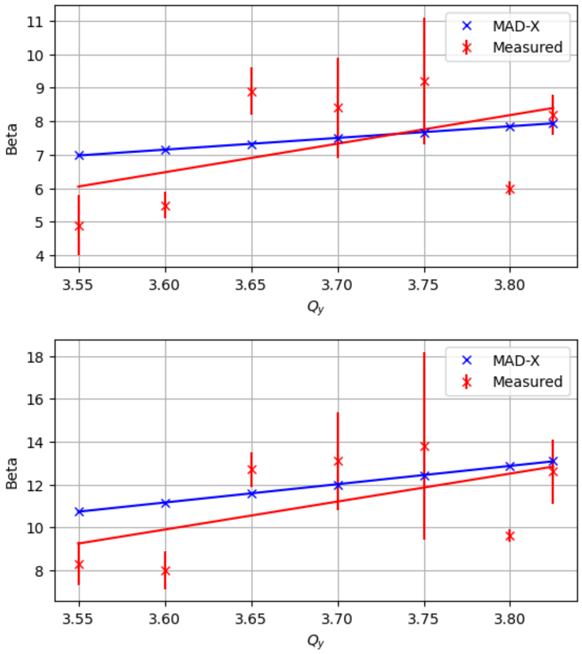

Figure 3: Vertical Twiss parameter β as a function of vertical tune at BPMs R3VM1 (top) and R3VM2 (bottom).

Figure 4 shows the corresponding relationship between the Twiss parameter α and the vertical tune. A similar trend is observed in the results from MAD-X and the ellipse reconstruction, although with a consistent offset of ~0.2 – 0.3.

SUMMARY AND FUTURE WORK

A new tool has been developed to provide rapid reconstruction and visualisation of transverse phase-space ellipses using diagnostic chopped beam measurements. The Twiss parameters obtained show good agreement with predictions in a 'bare' machine configuration and the dependence of the vertical emittance ε_y on painting amplitude has been clearly demonstrated. These results demonstrate a practical tool for beam-based optics validation and machine optimisation, enabling enhanced capability for detailed injection studies and emittance measurements.

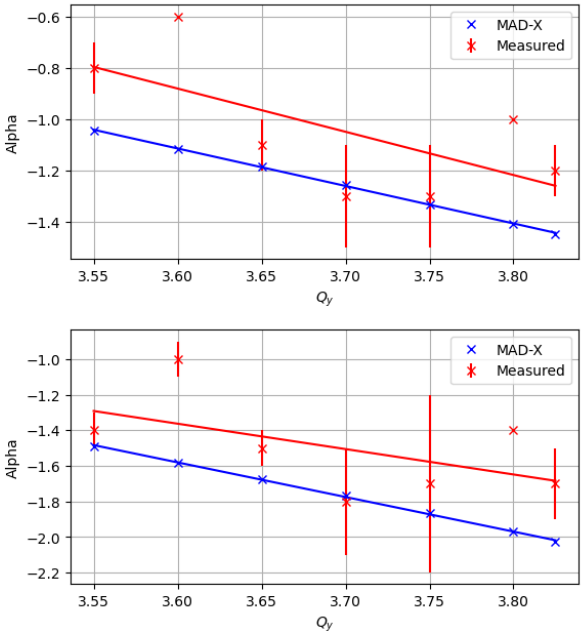

Figure 4: Vertical Twiss parameter α as a function of vertical tune at BPMs R3VM1 (top) and R3VM2 (bottom).

Preliminary studies of tune variation show promising agreement with model expectations, though further work is required to improve measurement reliability across a wider tune range. A key next step is the incorporation of phase advance into the reconstruction tool. The integration of the ISIS lattice model would enable application of the method at any BPM location.

Future work will also investigate the capability of the method to resolve other perturbations to the optics such as those introduced by tune harmonic adjustments or the recently available sextupoles and octopole. These will be validated on both the bare machine and the operating lattice. At the BPM locations studied here, the expected relative change in β is of order 1 % for the maximum change across all programmable harmonics. This level of variation is currently not well resolved by the phase-space reconstruction, and refinements to the process are necessary to reduce errors.

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