PROGRESS ON BEAM MEASUREMENT AND CONTROL SYSTEMS FOR THE ISIS SYNCHROTRON

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Abstract

The ISIS Facility at the Rutherford Appleton Laboratory in the UK produces intense neutron and muon beams for condensed matter research. Its 50 Hz, 800 MeV proton synchrotron delivers a mean beam power of 0.2 MW to two spallation targets.

Recent developments to beam control and measurement systems at ISIS are described. New PXI-based digitising hardware and custom software developed with LabVIEW have increased the capability to study beam behaviour. New, more flexible power supplies for steering and trim quadrupole correction magnets have been commissioned allowing greater control of beam orbits and envelopes. This paper looks at recent linear lattice measurements and attempts to identify the source of lattice errors.

INTRODUCTION

The ISIS synchrotron accelerates up to 3 x 10^{13} protons from 70 to 800 MeV in a 10 ms cycle at 50 Hz. The 163 m circumference ring is filled over 120 turns using charge-exchange injection. Fundamental and second-harmonic RF cavities form and accelerate two bunches with revolution time varying from 1500 – 650 ns. The synchrotron contains 14 horizontal and 16 vertical split-electrode beam position monitors (BPMs) [1].

A new PXI-based data acquisition system has been commissioned for transverse beam dynamics measurements. National Instruments PXI-5124 digitisers can acquire BPM data over the whole 10 ms cycle at up to 300 samples per turn with a digitizing accuracy of ±0.04 mm. Operationally, beam position is repeatable with $\sigma = \pm 0.2$ mm due to signal noise and beam variation. LabVIEW software is used to synchronise and configure the digitisers and acquire, analyse and display the data. In addition to simple analysis to calculate beam positions, software has been developed to analyse the motion of low-intensity diagnostic 'chopped' beams to measure betatron amplitudes and Q values [2].

CLOSED ORBIT CORRECTION

Position Measurement Validation

Historically, the closed orbits of the ISIS synchrotron were routinely corrected to ~1 mm RMS [3] but recently this has proved difficult. Following the replacement of corrector magnet power supplies and the BPM DAQ hardware, a systematic check of the procedure was carried out to find the reason for this change.

The orbit response matrix of the machine was re-measured to confirm the correct polarity and strength/sensitivity of the steering magnets and BPMs. An additional check of horizontal BPM polarity is conveniently made by small variation of the main dipole DC level. The BPM analogue electronics and data acquisition hardware are checked by applying a calibration signal at each monitor before use.

A programme of beam based alignment experiments was introduced to check for physical BPM errors. Here, the beam is stepped across a monitor by varying a steering magnet, at each beam position and the betatron Q scanned by adjustment of the trim quadrupoles. At the point where beam position is invariant with Q it is assumed the beam is transversely centred in the trim quadrupole and therefore the BPM 200 mm downstream.

Results for monitor R4HM2 are shown in Figure 1, each point corresponds to a scan of Q at different transverse positions within the BPM and each line corresponds to the use of a different steering magnet to scan the beam. The y-intercept is where there is no change in beam position as Q is changed. The results indicate an offset for R4HM2 of 2.2 mm with a standard deviation of 0.2 mm.

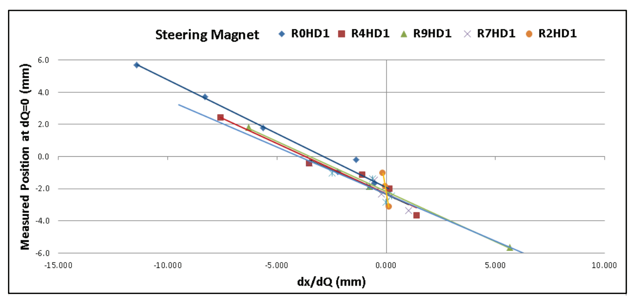

Figure 1: Beam based alignment results for R4HM2. The y-intercept of each data set gives the offset of the monitor.

The measurement was repeated using each steering magnet for most monitors. The experiments revealed monitors with offsets of up to 5 mm, on further investigation this was found to be due to degradation of variable capacitors used to compensate for mechanical manufacturing errors. These had been set correctly prior to installation but the capacitances had changed as the electrolyte degraded over time in the radiation environment of the synchrotron hall. The imbalance of electrode capacitances for R4HM2 revealed an offset equivalent to 1.7 ± 0.1 mm. The capacitances of all monitor electrodes were checked and balanced.

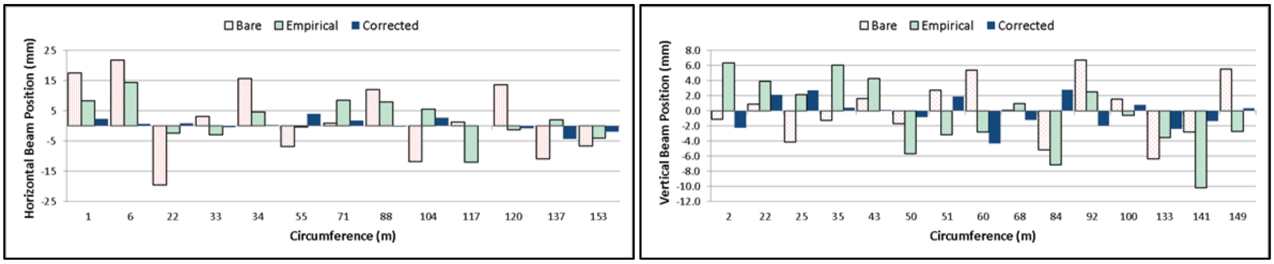

Figure 2: Beam positions measured at 7ms for bare, empirically optimised for beam loss and corrected with MAD-X orbits.

Orbit Correction

The synchrotron closed orbits are measured at 1 ms intervals throughout the acceleration cycle. Ten 50 µs waveforms (30 – 75 turns) are recorded over which turn by turn positions are averaged. The resulting sets of positions are passed to a lattice model constructed using the accelerator design code MAD-X [4]. This calculates a correction function for the six horizontal and seven vertical steering magnets in the ring. Three measurements made at 7 ms for all steering magnets off (bare orbit), following empirical optimisation of beam loss and following correction by MAD-X are shown in Figure 2.

The horizontal bare orbit perturbation of 13 mm RMS was reduced to 7 mm RMS by empirical optimisation of beam losses. Beam positions are reduced to 2 mm RMS in both planes by the MAD-X correction, a further small reduction in beam losses was seen with these settings. A set of steering magnet settings generated by MAD-X can be scaled for beam energy and applied throughout the cycle to produce almost identical beam orbits. This indicates that the lattice imperfections are consistent and scale with beam energy through the cycle.

Bare Orbit Perturbation

The MAD-X lattice model was used to try to find the source of the large horizontal bare orbit perturbation. By adding zero-length kickers to each of the main lattice dipoles and quadrupoles the orbit correction routine could be used to find the *N* most likely sources of the perturbation.

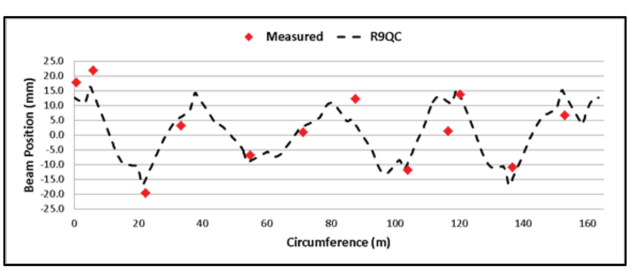

Figure 3: Orbit perturbation due to 14mm horizontal misalignment of R9QC.

Although there are many possible combinations of errors that create a close match to the measured beam positions, the model suggests an error at the defocussing singlet quadrupole in superperiod 9 (R9QC) is the most likely single source of the perturbation, as shown in Figure 3. However, to generate the kick strength calculated by MAD-X, R9QC would have to be misaligned by 14 mm. Transverse alignment tolerance on ISIS is 0.25 mm and such a large error is very unlikely. The error may be due to a shift in the magnetic centre caused by failed windings or the combined effect of errors at a number of lattice positions. Magnetic and electrical measurements will be made on all main lattice magnets during the forthcoming ISIS shutdown (Aug '14 – Feb '15).

BEAM ENVELOPE MEASUREMENTS

The beam envelope on ISIS is controlled via adjustment of 20 trim quadrupole magnets. These magnets are now independently controllable but are normally powered to apply harmonic focussing functions at ~2Q. Measurement of the beam envelope at injection is made by studying chopped beam motion which reveals relative betatron amplitudes at BPM locations. Good agreement is seen between measured and modelled envelope perturbations due to applying a harmonic function of the form $\Delta k \propto \sin(2\pi \times 0.8j)$ where j is the j[th] trim quadrupole, as shown in Figure 4.

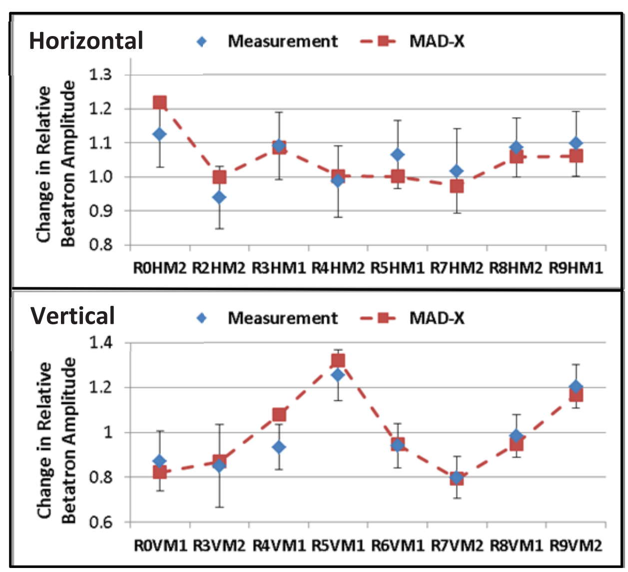

Figure 4: Measured and modelled envelope perturbation due to an applied harmonic focussing function.

Measurement and correction of operational beam envelopes is on-going. Initial results show envelope perturbations of <5% in the horizontal plane but up to 20% in the vertical plane at injection. It is thought this is due to the pulsed injection bump dipoles but further

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experimentation, using a beta kicker to measure betatron amplitudes through the acceleration cycle, is required to confirm this.

TUNE PLANE MEASUREMENT

Measurements have been made to examine the tune plane around the ISIS working point, $(Q_h,Q_v) = (4.31,3.83)$ and identify the main low intensity resonances. These are most likely caused by higher-order field components, field errors or misalignments of the main lattice magnets. It is important to understand the low intensity beam behaviour before studying high intensity effects. Improved knowledge and understanding of the tune plane will benefit, not just operational setup, but also the development of accurate simulations of ISIS which are of vital importance for ongoing studies of intensity upgrades [5].

Method

Experiments were done with a coasting beam at the injection energy of 70 MeV i.e. the main lattice magnets were DC powered and all RF systems were switched off. A 10% pepper-pot beam diluter was used to inject $\sim 1 \times 10^{12}$ particles per pulse. A range of $4.0<Q_h<4.4$ and $3.5<Q_v<3.85$ with a step size of 0.025 was chosen, trim quadrupole functions were set to linearly ramp Q up or down in one plane at a time over 10 ms. Beam intensity recorded during the scan was differentiated to provide a measure of the rate of beam loss with Q and thereby assess the stability of the beam. Chopped beam measurements were used to measure Q at each sample point so that the data recorded as a function of the set Q can be mapped to these values.

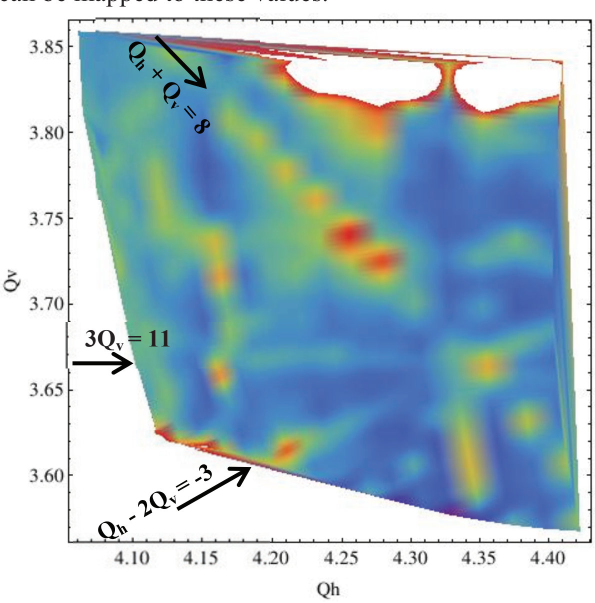

Figure 5: Measured tune diagram with observed resonance lines overlaid.

Results

The resulting tune diagram for the case where Q_h is held constant (at 0.025 intervals) and Q_v linearly increased over 10 ms is shown in Figure 5, there are gaps in the data where beam was completely lost. Three resonances can be identified from this data and are marked on the plot. The raw beam intensity signal and calculated beam loss rate for the scan of $3.5<Qv<3.85$ with $Q_h = 4.25$ is shown in Figure 6.

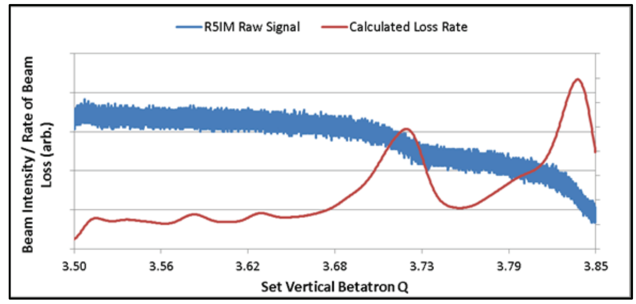

Figure 6: Raw beam intensity and calculated beam loss rate for the scan of $3.5<Qv<3.85$ with $Qh = 4.25$.

The results are an interesting start point for tune plane studies. Measurement will be repeated as any magnet field or alignment errors are found and corrected.

Original designs for the ISIS synchrotron included 12 octupoles and space for sextupoles [6], in fact four octupoles and three sextupoles were installed but had no real impact on beam losses. All but one of each magnet were removed when the second-harmonic RF cavities were installed. Experiments are planned to study the effects of these magnets even though full correction schemes cannot be implemented at this time.

It is expected that higher-order field components are driving some of the measured resonances. Magnetic models of the main lattice elements are being developed and the construction of a magnet measurement facility is planned. These capabilities will assist our understanding of beam behaviour and guide the design of replacement magnets for future ISIS operations and upgrades.

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