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EXPERIMENTAL MEASUREMENTS OF RESONANCES NEAR TO THE ISIS WORKING POINT

P. T. Griffin-Hicks*, B. Jones, B. G. Pine, C. M. Warsop, D. Wright, ISIS, RAL, UK

Abstract

ISIS is the pulsed spallation neutron source located at the Rutherford Appleton Laboratory in the UK. Operation is based on a 50 Hz, 800 MeV proton synchrotron, accelerating up to 3×10^{13} protons per pulse (ppp), which provides beam to two target stations.

ISIS is beam loss limited, so to achieve greater beam intensity and optimal operation, losses must be reduced. Some beam loss may be attributed to resonance lines found in betatron tune space. These could be driven by higher order magnet field components, errors or misalignment. This paper describes work measuring losses against tune space around the ISIS working point.

Experiments have been carried out to measure beam loss against tune in the ISIS synchrotron. The experiments were done at low intensity to minimise space charge and intensity effects. Resonance lines that cause beam loss can be clearly identified and provide new information about the machine. The experimental process has been automated in order to decrease experiment duration and to reduce systematic human error. MAD-X models that compare the beam envelope at different points in tune space to the beam pipe aperture are used to distinguish between losses caused by increased envelope size and losses induced by driven resonances.

INTRODUCTION

Resonance theory predicts the existance of resonance lines in tune space, located where the tune meets the resonance conditions given by Eq. (1) [1],

$$lQ_h + mQ_v = p \tag{1}$$

where Q_h and Q_v are the tunes in the horizontal and vertical directions, respectively; and l, m, and p are integers. The order of a resonance is given by $|l| + |m|$.

When driven, these resonances cause the amplitude of the betatron oscillations to grow rapidly, thus causing loss of particles or even the whole beam [2].

The ISIS synchrotron has a mean radius of 26 m, accumulates 3×10^{13} ppp via charge exchange injection, accelerates from 70 to 800 MeV on the 10 ms rising edge of the sinusoidal main magnet field and supplies two targets via single turn fast extraction. ISIS operates around a nominal tune of $(Q_h, Q_v) = (4.31, 3.83)$. However, the tune of individual particles in the beam will spread out according to the incoherent tune shift, chromaticity, and other effects [3], possibly crossing resonance lines. At peak intensity the ISIS incoherent tune shift is over 0.5 [4]. Therefore it is important to study resonances around the ISIS working point to know

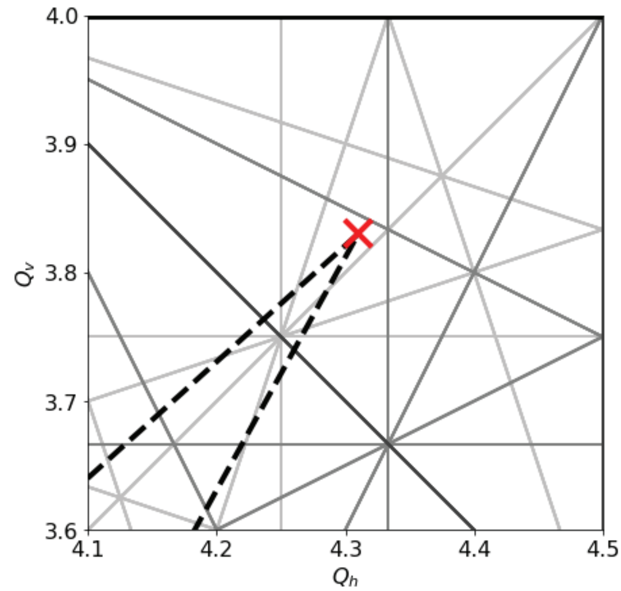

Figure 1: The ISIS working point, red x; the expected range of incoherent tunes at high intensity, as predicted by ORBIT simulations [5], dashed black lines; and resonances up to and including fourth order. Lighter lines are higher order.

whether they are being driven, what effect that may have on the beam, and whether they can be avoided or mitigated. Figure 1 shows the approximate simulated tune spread of the ISIS beam [5] and the resonance lines that are most likely to interact with the beam.

BEAM-BASED EXPERIMENTS

This paper reports on the development of method to measure the effect of resonances on beam loss in the ISIS synchrotron [4]. The synchrotron was put into storage ring mode (SRM) wherein the beam was not accelerated from the injection energy of 70 MeV, the RF systems are switched off so that the beam also remained unbunched, and the main magnet field was constant. The beam was injected in SRM at a stable tune that was then ramped over 2 ms to the starting tunes of a scan. Tunes in each plane were ramped linearly over 8 ms while beam loss and intensity were digitised at a rate of 1 MS/s . In this way, rates of loss could be measured against tune.

The tune is controlled using the 20 trim quadrupoles, two in each superperiod. A linear relationship between the trim quad strength and the tune is used to approximately set the tune. The beam loss and intensity is measured by the sum of the 39 beam loss monitors (BLMs) distributed evenly around the ring and the intensity monitor in superperiod 5 (R5IM). R5IM is a resonant current transformer with a sensitivity of

* peter.hicks@stfc.ac.uk

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$\pm 3 \times 10^{10}$ ppp. The beam loss monitors are argon gas filled coaxial ionisation tubes and have a sensitivity of around 1.2×10^9 lost protons at the injection energy of 70 MeV [6].

The ideal measurement would be made by a beam with a very small tune spread. To reduce space charge tune spread, the intensity was limited to 10 % of operational intensity by reducing the injection pulse length.

Automation

The process of manually adjusting the tune functions and recording data could take many hours, and so the experiment was automated. A LabVIEW [7] program was developed to load the trim quad functions for each scan line and record signals of R5IM and the BLMs from a PXI chassis. Once the synchrotron was set up for SRM this automation allowed for tune scans to be taken in at least 15 minutes, dependent on averaging at each scan line, enabling a series of tune scans to be taken over a single day.

Envelope Analysis

Changing the tune also changes the envelope, and thus may cause non-resonant loss. The envelope of the beam was studied over the tune range of interest to ensure that it did not exceed the design aperture. A MAD-X model of the ISIS superperiod was created and the tune of the model controlled using trim quad strengths.

The rectangular conformal beampipe is matched to the beam envelope at the nominal tune [8]. Assuming an emittance of $300\,\pi$ mm mrad in both planes, the envelope of the beam, $Y(Q_h, Q_v, s)$ where s is distance along the lattice, was compared with the beampipe aperture, $A(s)$. $R(Q_h, Q_v)$, the maximum value of the ratio of envelope to the aperture along the beampipe, is taken to plot against tune, as per Eq. (2).

$$R(Q_h, Q_v) = \max \left[\frac{Y(Q_h, Q_v, s)}{A(s)} \right]_s \tag{2}$$

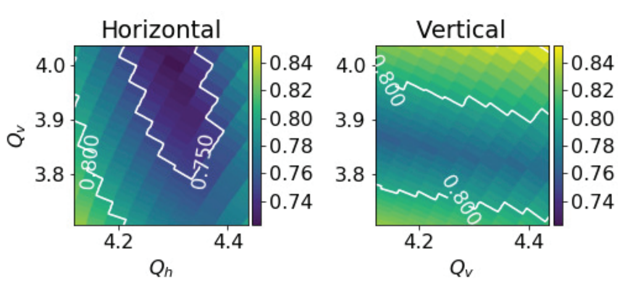

Figure 2: The horizontal and vertical maximum envelope to aperture ratio given by Eq. (2).

Figure 2 shows the values of Eq. (2) corresponding to the horizontal and vertical envelopes, and shows that at no point in the tune range of interest does the envelope exceed the aperture. However, if loss does arise from the envelope size then it is expected that it would gradually increase as the tune is scanned from regions where Eq. (2) is small to regions where it is larger. This would be distinct from the well-defined lines of loss associated with resonances. It is worth noting that regions of increased envelope size may be more sensitive to emittance growth due to driven resonances causing loss than regions of reduced envelope size.

Tune Transformation Map

The ISIS tune controls are based on a linear approximation which is accurate at normal operating intensity for the nominal tune range. However, for tunes far from the working point the actual tune varies significantly from the requested tune. Thus a transformation is required to map the scans to the correct tune. The transformation map used in this paper was obtained by modelling the ISIS lattice with MAD-X and using the trim quad currents output by the tune controls system to give the trim quad strengths for the model. An example transformation map from a regular grid of 31×31 points is shown in Fig. 3. The transformation map used for the results section of this paper has 301×301 points.

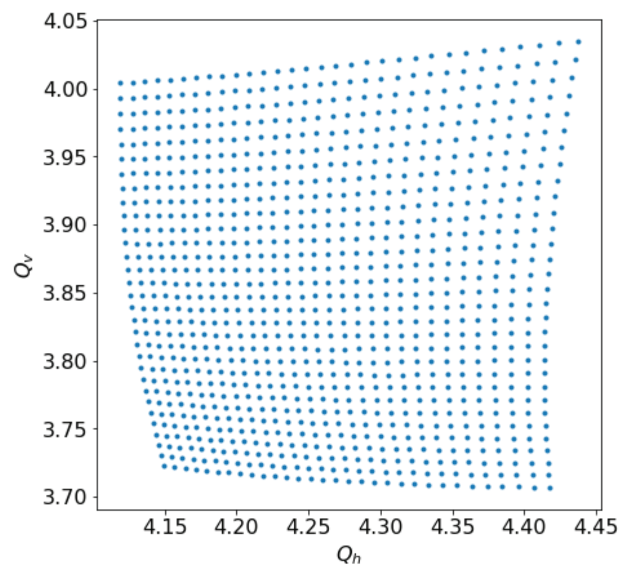

Figure 3: 31×31 point transformation map from a regular grid of points in the set tune range $(Q_h, Q_v) = (4.1 .. 4.5,\ 3.6 .. 4.0)$ to the modelled tune.

RESULTS

Figures 4 and 5 show the measured beam loss from the sum of the BLMs and the time derivative of the intensity. The titles refer to whether the horizontal or vertical tune was scanned in the positive or negative direction while the other tune was held constant. Both the BLM and gradient intensity measurements appear in good agreement, however there is less definition from the gradient intensity measurement.

The varying envelope of the beam may be introducing loss towards the upper right corner, $(Q_h, Q_v) = (4.4, 4.0)$, where the vertical envelopes are large. However, this is also near to the $Q_v = 4$ integer resonance line. Thus it is unclear whether one, the other or both could also be responsible for large losses.

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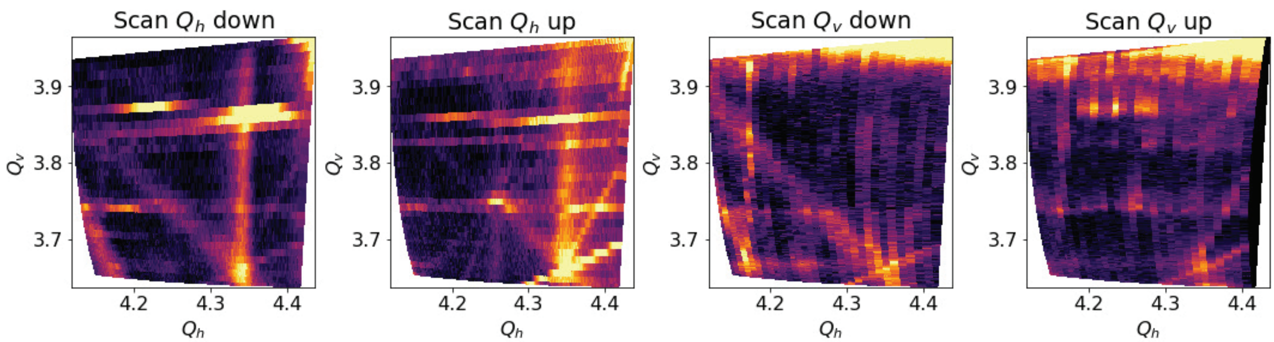

Figure 4: Mapped and offset sum of the measured BLM signals against tune.

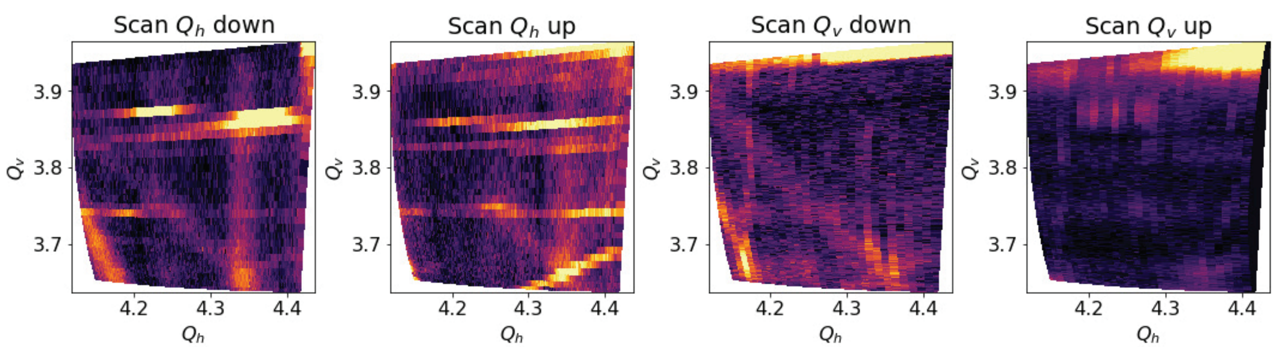

Figure 5: Mapped and offset time derivative of the measured R5IM intensity signal against tune.

The transformation map has successfully removed distortions and reveals the expected linear resonances lines, but there is still a noticable offset. By observing the position of various recognisable lines and nodes, the map can be offset to match the tune plane resonance line diagram in Fig 1. A vertical offset of -0.07 has been applied to Fig. 4 and 5.

It is immediately clear that the directionality of the scan plays an important part in which resonances are driven to produce losses. It is speculated that this may be due to residual space charge effects on the dynamics of the beam and the reduction of intensity of the beam from prior resonance crossings.

The most prominent losses are produced by the third order resonance lines. Resonances up to fourth order are clearly visible, particularly when scanning Q_h up, although even higher order resonances may be visible such as the line present above $Q_v = 3.8$.

SUMMARY

The measurements described in this paper reveal that low intensity resonance lines up to the fourth order, and possibly higher, are present in the ISIS synchrotron. The variation of the beam envelopes with tune may be causing losses close to the $Q_v = 4$ integer resonance line, but the sharp lines of loss measured are believed to be due to driven resonances. The transformation map in Fig. 3 successfully removes distortions arising from the approximation used to set the tune. The automation of the experimental method now allows for the rapid acquisition of data, enabling future experiments to study resonances.

FUTURE WORK

The tune scans developed here are a powerful tool for investigating resonances. Individual lines may be studied to determine their driving terms and whether they may be damped. Studies will involve detailed scans over individual lines and monitoring beam profile behaviour using multi-channel residual gas ionisation profile monitors [9].

So far experiments have been carried out at 10 % of normal operational intensity. Differences between scans at varying intensities could reveal information about resonance lines that are strongly driven by intensity effects.

Resonances may also be driven, for example, by switching on the ISIS sextupole magnets, to determine their effects in comparison to existing driven resonances.

ISIS models will be improved with more information on non-linear driving terms gathered by these experiments, thus allowing for more detailed studies of space charge losses.

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