

COHERENT TRANSVERSE INSTABILITIES ON THE ISIS PROTON SYNCHROTRON AT INJECTION ENERGY

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Abstract

ISIS is the short-pulsed spallation neutron and muon source at the Rutherford Appleton Laboratory in the UK. Its rapid-cycling synchrotron accelerates up to 3×10^{13} protons-per-pulse from 70 to 800 MeV at 50 Hz, delivering them to fixed targets for neutron and muon production. As a beam-loss limited facility, increasing operational intensity necessitates the reduction of beam losses. Although largely mitigated, a coherent vertical instability continues to drive losses at high intensities and remains an active area of research.

Having recently identified a likely source of the instability's driving impedance, we re-examine observations of instabilities on ISIS when operating as a storage ring at its injection energy. We present the updated vertical driving impedance model, compute analytical predictions of instability growth rates excluding space-charge effects with the PyTMCI Vlasov solver, and compare these with experimental observations across a range of vertical tune settings. We also outline future development plans.

INTRODUCTION

ISIS is the world's longest serving, short-pulsed, spallation neutron and muon source. Based in the UK, its rapid cycling synchrotron (RCS) accelerates intense beams of up to 3×10^{13} protons from 70 MeV to 800 MeV, with a 50 Hz repetition rate. Key RCS parameters are listed in Table 1.

Table 1: Key ISIS Synchrotron Parameters

Property	Value
Average Extracted Beam Power	0.2 MW
Number of Bunches (M)	2
Average Radius (R)	26 m
No. of Superperiods	10
Gamma Transition	5.034
Nominal Tunes (Q_x, Q_y)	4.31, 3.83 (variable)
Peak Incoherent Tune Shift	~ -0.5 [1]
Chromaticity (ξ_x, ξ_y)	-1.1, -1.1 [2]

ISIS is a beam-loss limited facility, so minimising beam-loss is a primary objective of R&D efforts. A vertical head-tail instability was first observed during commissioning [3, 4] and remains a major source of beam-loss around 2 ms through its RCS cycle. This is despite mitigation techniques developed to minimise beam-loss. The instability was thought to be driven by resistive wall, but it grew an order of magnitude faster than analytical predictions, and its dipole moment distribution was also not well predicted.

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The dynamics of the 2 ms instability are very complex, making studies challenging with operational beams. Bunched Storage Ring Mode (BSRM) was developed as a way to operate the ISIS synchrotron for instability studies, in a regime more consistent with analytical models [5]. Studies in this mode identified a narrowband vertical impedance centred at ~ 85 kHz. Although its frequency was found to be incompatible with the 2 ms instability seen in RCS mode, its discovery motivated efforts to develop a new low-frequency driving impedance model of the synchrotron from equipment properties [6, 7] and follow-up studies [8, 9]. This paper will present a new analysis of data acquired in earlier studies, briefly introduce the new impedance model, then use it as an input to the PyTMCI Vlasov solver [10]. Its predictions will be compared with experiments and the source of the 85 kHz instability will be identified.

EXPERIMENTAL RESULTS

Experimental Set-up

The injection and accumulation procedures of BSRM are similar to RCS mode, but the injected beams are stored with primary bending and focusing magnets operating with DC. Beams are not extracted, so 100 % beam-loss occurs in the synchrotron hall. To mitigate equipment damage, the repetition rate is reduced from 50 to ~ 1 Hz and beam intensity is reduced by a factor of ~ 10 . This also reduces the ratio of the peak incoherent space-charge (SC) tune-shift to synchrotron tune (the SC parameter) to < 10 , where coherent modes are less affected by direct SC, and theory without SC is more applicable than for an operational beam [5, 11].

For this experiment, the second-harmonic RF system was disabled whilst the total fundamental RF voltage was ramped from ~ 1 kV to 10.8 kV between 0 and 1 ms. Intensity was reduced to 1.68×10^{12} protons-per-bunch with two bunches circulating at a revolution frequency of ~ 675 kHz. Horizontal tune was constant, whilst vertical tune was varied between injected pulses. Measurements were performed with fast acquisition of vertical beam position monitor (BPM) signals.

With certain tune settings the bunches were observed to oscillate coherently, as can be seen in Fig. 1a; a comparison with the orange sum signal shows that only a portion of the bunch was oscillating coherently. Instability growth rates were obtained from the increasing amplitude of BPM difference signals, which were analysed for time windows with low beam-loss to avoid systematic errors. These windows were identified from intensity monitor signals by eye for each tune setting; one example is shown in Fig. 1b with the window indicated by a shaded region.

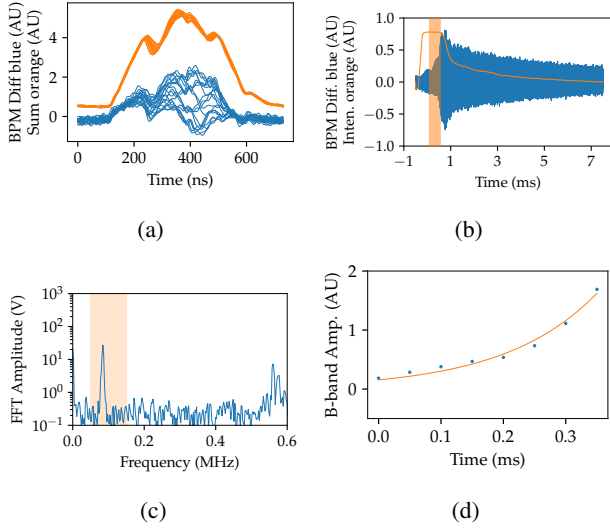


Figure 1: Experimental data from a single dataset of the BSRM experiment (a) sum and difference signals overlaid for several revolutions; (b) BPM difference and intensity monitor signals through the experiment, with the analysis window highlighted; (c) FFT of the difference signal inside the analysis window; (d) amplitudes of the baseband harmonic computed by NAFF with the exponential fit overlaid.

The evolution of the oscillation amplitude was obtained by dividing each window into chunks of $\geq 100 \mu\text{s}$ (~ 67 turns) with a 50% overlap, and finding the baseband oscillation amplitude for each chunk. These amplitudes were obtained with NAFF [12, 13] but to help isolate the baseband frequency, a 5th order Butterworth bandpass filter was first applied to each chunk with offline signal processing tools [14]. The cutoff frequencies for these filters were set by manually inspecting the difference signal FFT, such as the one in Fig. 1c; this figure also indicates the chosen passband for this dataset. Having obtained an amplitude for each chunk of time, such as the example in Fig. 1d, a least-squares fit to $(Ae^{t/\tau})$ was performed and the growth rate, $1/\tau$, was obtained with its uncertainty from the fit parameters; the fitted exponential curve is overlaid in Fig. 1d. This process was repeated for all tune settings.

Growth rate is plotted against baseband frequency for two independent sweeps of vertical tune in Fig. 2. A peak at $\sim 85 \text{ kHz}$ can clearly be seen, as reported previously [1].

IMPEDANCE MODEL

A vertical driving impedance model has been developed for the ISIS synchrotron in the range of the beam's lowest frequency sideband ($\sim 100 \text{ kHz}$) [6, 7]. In this range, the impedance model is dominated by a series of capacitively coupled RF screens [6, 7]. Here, each screen is modelled as a resonator impedance

$$Z_1^\perp(\omega) = \frac{\omega_r}{\omega} \frac{\beta R_\perp}{1 + iQ_r \left(\frac{\omega_r}{\omega} - \frac{\omega}{\omega_r} \right)}, \quad (1)$$

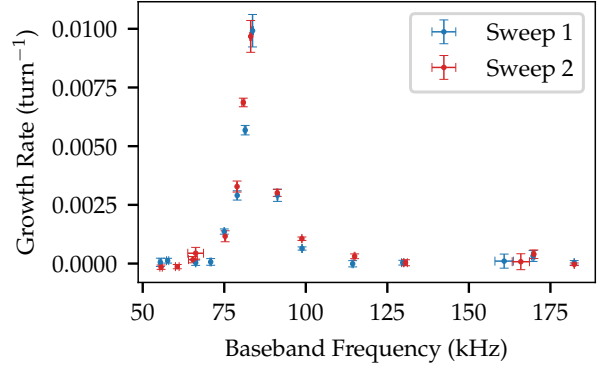


Figure 2: Measured instability growth rate for two repeat experiments versus the baseband betatron sideband frequency.

with the resonator parameters listed in Table 2. An explicit Lorentz- β term has been specified in Eq. (1) and $R_\perp$ is interpreted as the $\beta = 1$ transverse shunt impedance with SI units of $\Omega \text{ m}^{-1}$; ω_r is the resonant angular frequency, and Q_r is the quality factor. For the RF screens, $2\pi/\omega_r$ is on the order of > 3 times the revolution period at injection, so a linear dependence on β is assumed to be a good approximation.

The resonator parameters listed in Table 2 were determined from a combination of CST simulations and bench impedance measurements [6]. Since these resonator impedances will be used in an analytical model which assumes smooth focusing, constant weight coefficients will be applied to account for variations in Twiss- β_y of the real ISIS lattice [15]. The weights are listed in Table 3, and were derived from average values of β_y through each RF screen.

In addition to the RF screen resonators, the impedance model also includes a resistive-wall term, two additional resonators to represent the extraction kickers [6] and an indirect space-charge impedance. The real part of the resulting model is shown for $\beta = 1$ in Fig. 3.

Table 2: Resonator Parameters of the ISIS Impedance Model

Screen	$\frac{\omega_r}{2\pi}$ (kHz)	$R_\perp$ (k $\Omega \text{ m}^{-1}$)	Q_r	Qty
Dipole	(82 ± 5)	(500 ± 170)	(6.1 ± 0.7)	10
Doublet	(94 ± 6)	(255 ± 82)	(6.7 ± 0.2)	10
Singlet	(189 ± 12)	(31.8 ± 0.4)	(4.1 ± 0.1)	10
M. 13	(184 ± 12)	(18 ± 6)	(4.30 ± 0.02)	6
M. 9/10	(162 ± 10)	(14 ± 5)	(4.66 ± 0.02)	6

Table 3: Weights for $Z_1^\perp$ due to Variations in Twiss- β_y

Impedance Source	β_y	Weight
Dipole RF Screen	5.3	0.8
Doublet RF Screen	10.4	1.5
Singlet RF Screen	10.1	1.5
Mod 13 RF Screen	5.8	0.9
Mod 9/10 RF Screen	13.9	2.0

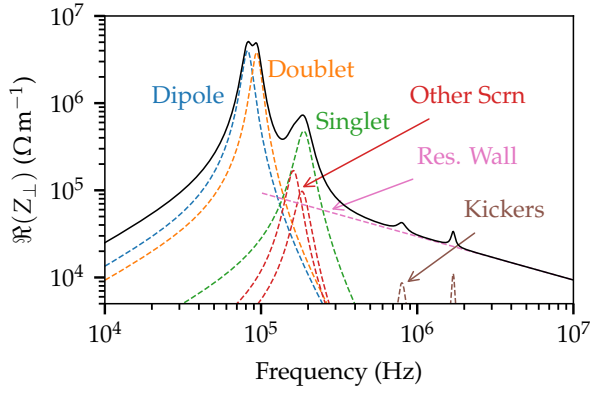


Figure 3: Real part of the ISIS synchrotron vertical driving impedance model with key elements labelled and a sum.

SEMI-ANALYTICAL PREDICTIONS

Semi-analytical predictions of instability growth rates have been made with the Vlasov solver PyTMCI with the new impedance model [10]. PyTMCI is a Python code to find the coherent mode frequencies $\Omega^{l,n}$, for the azimuthal and radial mode numbers l and n . It follows the general approach of finding the eigenvalues of a truncated interaction matrix, derived from the linearised Vlasov equation [16, Ch. 6].

Input Parameters

Calculations were performed for betatron tune values between 3.73 and 3.92, which were chosen from the measured sideband frequencies. Parameters for the ISIS synchrotron were taken from Table 1, but with the intensity reduced to 1.68×10^{12} protons-per-bunch. The synchrotron tune was 0.00454 at the flat-top RF voltage, and a scaled value was used for tune settings where instabilities were analysed during the RF ramp between 0 and 1 ms. The input longitudinal phase-space distribution was derived from a tomographic reconstruction of an averaged and smoothed BPM sum signal, and represented in PyTMCI by a series of 10 generalised Laguerre polynomials. After convergence testing achieved less than a 10 % change in peak growth rate between runs, azimuthal modes up to $l = \pm 20$ and radial modes up to $n = 10$ were considered.

Results and Comparison

To account for uncertainties in the RF screen impedance, 100 calculations were performed for each tune setting, with resonator parameters derived from a random normal distribution with the parameters listed in Table 2. The growth rate of the most unstable mode was found for each calculation, and a mean and standard deviation computed for each tune setting. These PyTMCI results are represented in Fig. 4, with the measured growth rates overlaid from Fig. 2. The peak at ~ 85 kHz agrees well with observations, occurring at the same frequency and predicting the growth rate to within an order-of-magnitude.

Figure 5 shows the measured baseband frequency overlaid with the real part of the impedance model for three

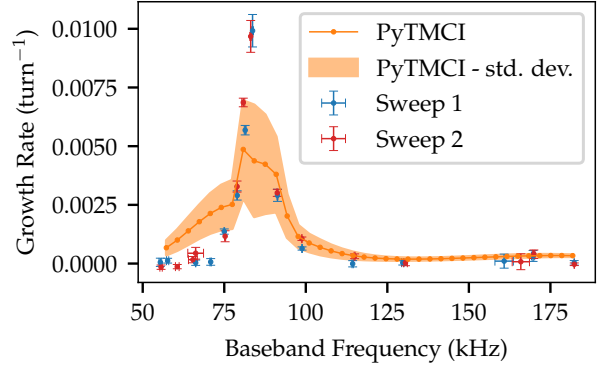


Figure 4: Experimental results from Fig. 2, overlaid with PyTMCI results and a shaded area to represent the standard deviation of the calculations.

different tune settings. The indicated frequencies span the range covered by this experiment and also include the setting with the fastest growth rate. The 85 kHz growth rate peak in Fig. 4 occurs when the baseband frequency overlaps with an impedance peak from the dipole and doublet RF screens. The combination of these devices is therefore identified as the primary driver of the 85 kHz BSRM instability.

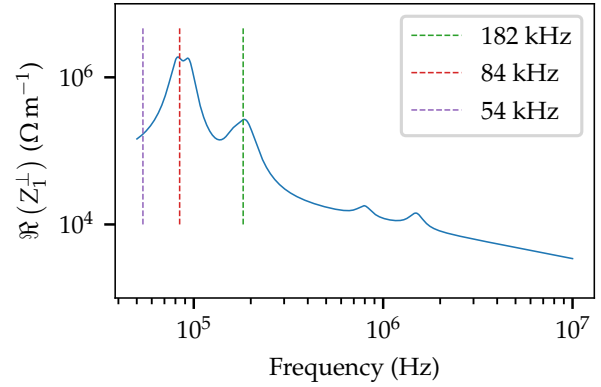


Figure 5: Real part of the ISIS impedance model with the measured baseband sideband frequency for three different tune settings overlaid.

CONCLUSION

Experimental results of coherent vertical instabilities on ISIS in BSRM have been revisited in-light of a new vertical driving impedance model. The experimental results show a peak in growth rate around 85 kHz, which agrees with earlier studies. PyTMCI calculations also predict a peak at this frequency, with growth rates reproduced to within an order of magnitude. Considering the simplified analytical model employed here, this is considered an excellent level of agreement. The drivers of this instability have been identified from Fig. 3, as the dipole and doublet RF screens.

Trials to optimise the RF screen resonator impedances have shown promising early results [7], and efforts to mitigate operational beam-loss are ongoing.

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