MEASUREMENTS AND DAMPING OF THE ISIS HEAD-TAIL INSTABILITY

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Abstract

ISIS is the pulsed spallation neutron and muon source at the Rutherford Appleton Laboratory in the UK. Operation centres on a rapid cycling proton synchrotron (RCS) which accelerates $3{\times}10^{13}$ protons per pulse from 70 MeV to 800 MeV at 50 Hz, delivering a mean beam power of 0.2 MW.

Research and development at ISIS are focused on key aspects of high intensity operation with a view to increasing beam intensity on target, understanding loss mechanisms and identifying viable upgrade routes. At present, the main limitation on beam intensity at ISIS is beam loss associated with the head-tail instability.

This paper presents new measurements of the head-tail instability in both RCS and storage ring modes whilst highlighting the differences between these and theoretical predictions. Macro-particle simulations of the instability are shown in comparison with experimental data. Finally, preliminary tests of an active transverse feedback system to damp the instability are also presented.

INTRODUCTION

The head-tail instability is a primary concern for high intensity operation in many hadron synchrotrons including ISIS and its proposed upgrades [1]. The instability imposes an intensity limit on operations through associated beam loss and consequent undesired machine activation.

The ISIS Synchrotron

ISIS operation centres on a 10 superperiod rapid cycling synchrotron (RCS) with a 163 m circumference. It accelerates $3{\times}10^{13}$ protons per pulse from 70 – 800 MeV on the 10 ms rising edge of a sinusoidal main magnet field (below transition throughout). The repetition rate of 50 Hz results in an average beam power on target of 0.2 MW.

Injection into the synchrotron is via charge exchange of a 70 MeV, 25 mA H^- beam over ~150 turns with painting over both transverse acceptances, collimated at ~300 π mm mrad. The un-chopped, injected beam is non-adiabatically bunched and accelerated by the ring dual harmonic RF system (h = 2, 4) ramping in frequency from 1.3 – 3.1 MHz (h = 2). This results in two long bunches equally spaced around the ring. Nominal betatron tunes are $(Q_x, Q_y) = (4.31, 3.83)$ with peak incoherent tune shifts exceeding ~ -0.5. Beam intensity is currently limited by beam loss and associated activation with the main driving mechanisms being foil losses, longitudinal trapping, transverse space charge and the head-tail instability [2].

Head-Tail Observations at ISIS

Measurements of head-tail on the ISIS synchrotron have consistently shown that the two proton bunches exhibit vertical head-tail motion 1 – 2.5 ms through the 10 ms acceleration cycle [3, 4]. ISIS operates at the natural machine chromaticities ($\xi_x = \xi_y = -1.4$, normalised), without sextupole correction. The instability is currently suppressed by ramping the vertical tune down, away from the integer ($Q_y = 4$), and making the longitudinal charge distribution asymmetric during the time of the instability using the dual harmonic RF system. Both longitudinal and vertical injection painting also have a strong influence on the sensitivity to the instability. However, with increasing beam currents these mitigation strategies become less effective. Lowering the tune further tends to induce beam loss associated with the half integer resonance [5, 6] and injection painting and longitudinal distribution asymmetry have already been optimised fully.

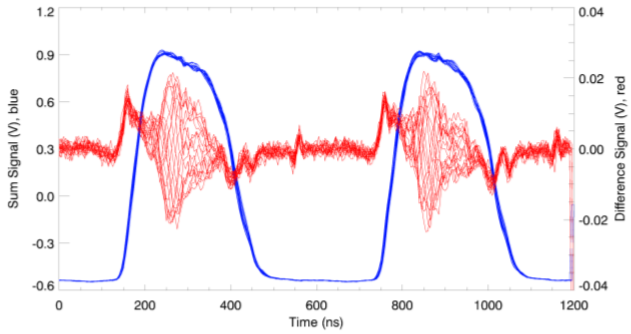

Figure 1: Example sum (blue) and difference (red) vertical position monitor signals over several turns around 2 ms through the acceleration cycle during normal operations.

A typical example of observed head-tail motion during normal, high intensity operations is shown in Fig. 1. The longitudinal bunch asymmetry is clear in the Beam Position Monitor (BPM) sum signal and intra-bunch, head-tail motion is indicated by the difference signal.

In order to remove some of the complexities of high intensity dynamics, further measurements of the instability were made at lower intensity and with single harmonic RF to test against Sacherer theory [7]. These demonstrate a clear m = 1 mode structure (one node along the bunch) as shown in the BPM difference signal in Fig. 2; while theory predicts a higher growth rate for the m = 2 mode (2 nodes along the bunch). Studies are ongoing to determine the cause of this discrepancy.

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SIMULATION MODEL

A stand-alone macro-particle simulations code has been written to study head-tail behaviour on ISIS [4]. The code includes a benchmarked longitudinal dynamics code with smooth focusing transverse dynamics and transverse wakefield kicks to simulate the interaction between the beam and its environment.

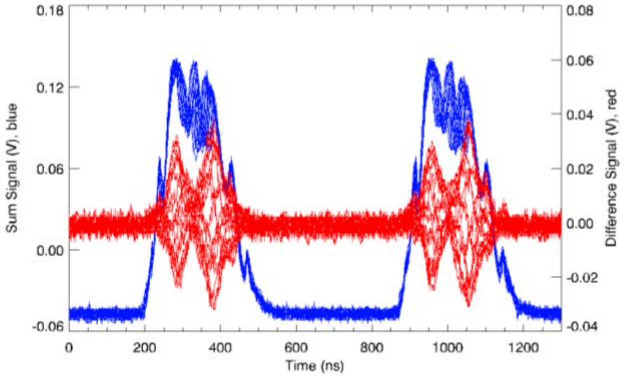

Figure 2: Example sum (blue) and difference (red) vertical position monitor signals over several turns for lower intensity, single harmonic RF operation.

In order to calculate the wake due to a resistive wall or resonator impedance the beam is sliced longitudinally and the wake calculated at each slice due to upstream slices. This may include wakes from previous bunches, preceding turns or from slices within the same bunch.

Benchmark

Following on from previous comparisons with coasting beam theory [4], the code has been evaluated against Sacherer theory for single, low intensity bunched beams in the presence of a narrowband resonator wake. The head-tail instability was characterised by its mode number and its growth rate as a function of beam intensity, tune and chromaticity.

For this benchmark study, one ultra-relativistic bunch was simulated with single harmonic RF, a Hofmann-Pedersen longitudinal distribution [8] of length 100 ns and a matched transverse waterbag distribution of 100% emittance 300 π mm mrad. The narrowband resonator had a resonant frequency of 312 kHz, a transverse shunt impedance of 10 MΩ/m and a quality factor of 15.

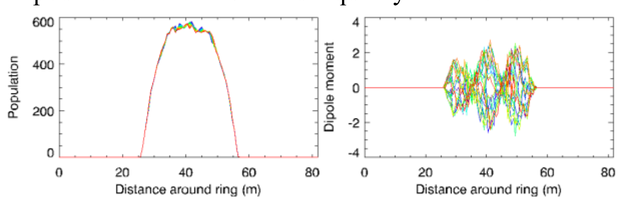

Figure 3: Example simulation output with sum (left) and difference (right) vertical position monitor signals over several turns.

To simulate a BPM the average transverse displacement (Δy_i) and the macro-particle population (I_i) was calculated for each longitudinal slice (i) and each simulated turn of the machine. The BPM difference signal was then computed as the product of these factors ($\Delta y_i I_i$ = the dipole moment of the beam), example shown in Fig. 3. The growth rate was deduced from an exponential fit to the largest betatron sideband as a function of time, calculated from Fourier transforms of the simulated difference signal segmented in time.

Figure 4, left, shows the growth rate as a function of betatron frequency. The dependence of growth rate on chromaticity is shown in Fig. 4, right. All key aspects of physics behaviour are correct with the growth rate peaking at the resonant frequency and decreasing as the chromatic frequency shifts away from the low resonant frequency of the impedance (a chromatic frequency of 312 kHz occurs at a chromaticity of 0.0017). The head-tail mode number also changes with chromaticity as predicted.

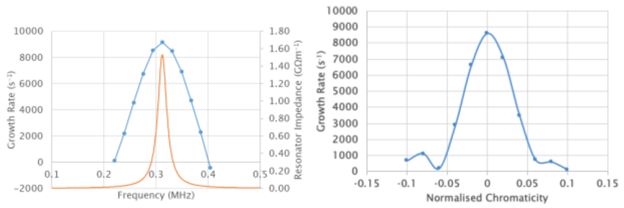

Figure 4: Growth rate (blue) and resonator impedance (red) versus frequency (left) and growth rate versus normalised chromaticity (right).

Comparison with Measurement

Initial comparisons between theory, simulation and observation have been made for lower intensity, single harmonic RF beams at ISIS. Simulations assumed a thick resistive wall impedance with the beam pipe conductivity artificially modified to match the measured impedance at the dominant, lowest betatron sideband. Recent beam-based measurements of the effective impedance at ISIS [4] indicate a low frequency (85 kHz) narrowband type impedance together with resistive wall.

Figure 5 shows the measured (left) and simulated (right) vertical beam position monitor difference signal over several turns. Simulations agree with established theory showing a $m = 2$ mode structure. However, as with previous studies, this does not match experimental observations which exhibit a persistent $m = 1$ mode structure.

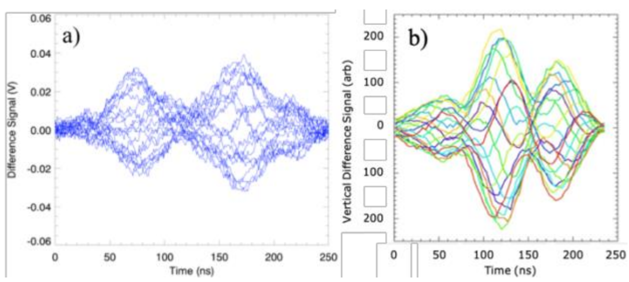

Figure 5: Comparison of BPM difference signals for a) experiment with b) simulation for low intensity, single harmonic RF, RCS beams at approximately 2 ms through acceleration.

THE ISIS DAMPING SYSTEM

Head-tail motion may be counteracted with the use of a transverse feedback system [9]. This method has been implemented at ISIS by using one of the existing BPMs as a pickup and the vertical betatron exciter [10] as a kicker, allowing for a reduced development time for a working prototype. The kicker and BPM are separated by a betatron phase advance of 266° for a vertical tune Q_y = 3.80 [11]. The processing electronics and power amplifiers are located 150 m away in an area free of ionizing radiation.

ISIS BPMs are cylindrical split electrode type with their performance characterised by the ratio of electrode voltage to beam current [12]. The cut-off frequency of the BPM has been lowered to 11 kHz by terminating the capacitive electrodes into 100 kΩ resistors. Finite element simulations of a simplified version of this monitor were performed with both CST Particle and Microwave Studios to verify the expected performance [13].

The ISIS vertical betatron exciter or "Q-Kicker" is a balanced transmission line kicker with window frame ferrites surrounding electrodes above and below the beam. Seven lumped capacitors connect each electrode to the body and a high power resistor terminates each electrode at the upstream aperture. A photograph of the kicker prior to installation is shown in Fig. 6, the ceramic chamber maintains the vacuum whilst the plates and ferrite are in air.

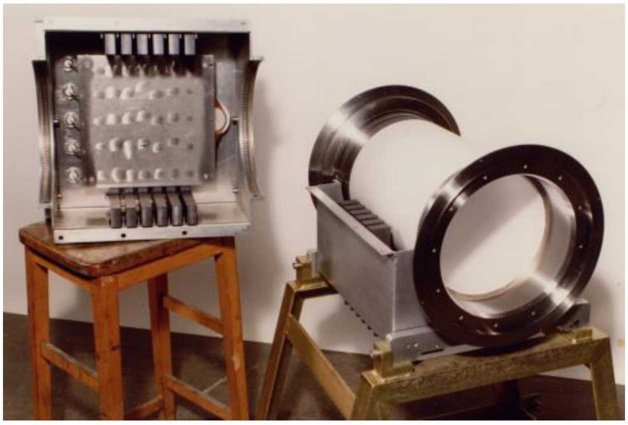

Figure 6: "Q-kicker" with the top half on the left, revealing the ferrites, plates, ceramic vacuum vessel and a terminating resistor.

LLRF and Digital Signal Processing

The feedback system electronics block diagram is shown in Fig. 7. The low-level RF (LLRF) analogue electronics prepare the BPM signals for processing, providing amplification and gating. The Field Programmable Gate Array (FPGA) block consists of a National Instruments NI-5781, 100 MS/s transceiver Flex-Rio front end module [14], backed by a PXIe-7962R Flex-Rio FPGA card.

Each BPM electrode signal is amplified separately at the pick-up, and fed to the LLRF block 150 m away where the differential signal is obtained through a 180° hybrid combiner. This signal is then amplified and fed into the FPGA block which samples the signal, applies the required filtering, delays and software gain, as well as converting the processed signal back to the analogue domain.

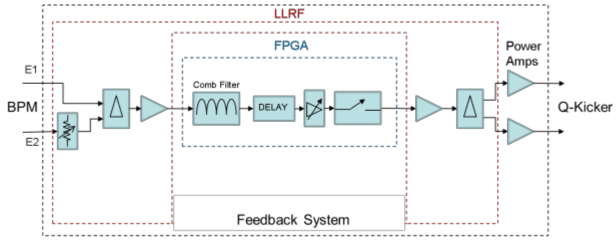

Figure 7: Feedback system electronics block diagram.

The driving clock of the digital processing stage is obtained by multiplying the fundamental RF harmonic by 30. This creates a fixed length filter and digital delays proportional to the ramping revolution frequency. The output gating control and the filter coefficients switching are driven by fixed frequency clocks. A variable digital delay is applied to the processed signal in order to compensate for the fixed delay of the cables and electronics. This delay decreases as the revolution frequency increases, synchronising the correction signal with the beam arrival at the kicker.

Digital filter

A digital Finite Impulse Response (FIR) filter is used for closed orbit offset suppression and betatron phase advance correction. Without proper filtering, constant closed orbit offsets cause DC dipole kicks and can saturate the power amplifiers. The phase advance between the pickup and the kicker, together with a 3 turn signal processing delay, cause a variable betatron phase shift with the changing tune during acceleration (partly to mitigate head-tail). This phase shift is also compensated with the filter.

A 3-tap FIR filter was implemented to cover the range of betatron tunes whilst the head-tail instability is present. The filter calculation is shown in Eq. (1) where the required kick, y, at turn, n, is the weighted sum of the beam slice position measurements x, from three previous turns. The weights (b_0, b_1 and b_2) are the calculated filter coefficients.

$$y[n] = b_0 x[n] + b_1 x[n-1] + b_2 x[n-2]. \qquad (1)$$

To include the full tune range the filter coefficients are matched at several points during the ramp to the set tune and its associated betatron phase, turn delay and phase advance [15-17]. Initial tests of the dynamic filters provided more efficient damping along the instability region. Figure 8 shows the vertical tune variation during the instability and the filter coefficients for the indicated tune values.

Power Amplifiers

As the kicker is a 10 Ω system, each electrode is connected to a custom design Eltac RA994 power amplifier [18] by five URM-67 50 Ω cables terminated in parallel at the kicker end. This amplifier provides five 20 W outputs from a single input.

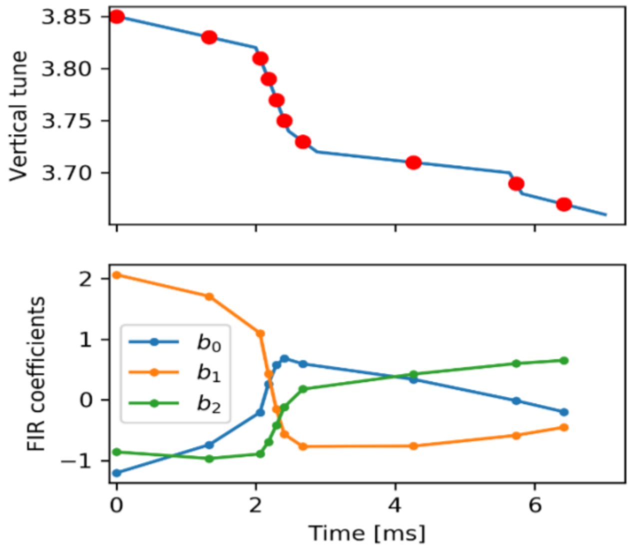

Figure 8: ISIS vertical tune (top) versus time with corresponding optimised 3-tap FIR filter coefficients (bottom).

EXPERIMENTAL RESULTS

The damping system has been successfully tested during normal ISIS, high intensity operation, at the full repetition rate of 50 Hz. Figure 9 illustrates the effect of the damping system on the vertical head-tail motion around 2 ms through acceleration. The purple and red traces show the BPM sum signals with and without damping showing a negligible effect on the longitudinal charge distribution as expected. The BPM difference signals with (green) and without (blue) damping demonstrate the efficacy of the damping system on the vertical head-tail motion.

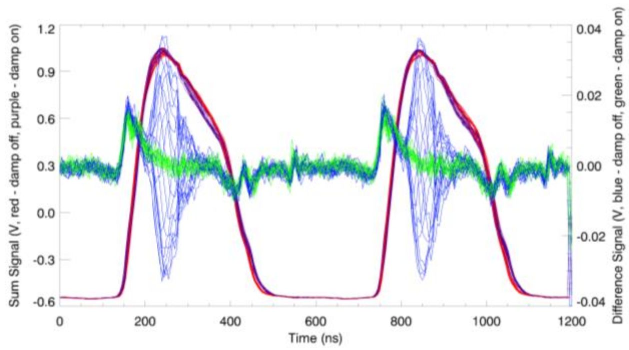

Figure 9: BPM sum and difference signals with (purple, green respectively) and without (red, blue respectively) damping, over 20 turns around 2 ms through acceleration.

The sum of all the beam loss monitors around the ISIS synchrotron is shown in Fig. 10 with and without damping (green and grey respectively). This further validates the usefulness of the ISIS damping system: reducing beam loss and hence machine activation. Figure 10 represents a > 50% reduction in loss above 120 MeV. The residual loss observable at 2 ms is likely due to the rapidly varying tune and RF modifications put in place to mitigate head-tail without the damping system.

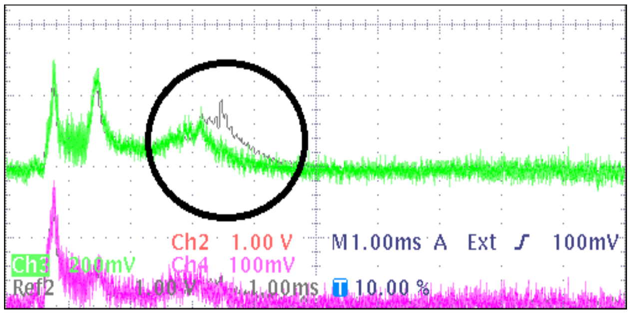

Figure 10: Sum of all beam loss monitors versus time with (green) and without (grey) damping; beam loss outside collimator region (pink).

In order to operate safely without supervision, it is planned to install a system to protect the terminating resistors on the kicker against long term over-voltage conditions. These could occur if the amplifiers or feedback system fail and start oscillating at maximum amplitude. Further commissioning tests are planned with a slower tune variation and without the imposed longitudinal bunch profile asymmetry.

SUMMARY AND FUTURE WORK

Simulation Model

Research and development into the mechanism and mitigation of the head-tail instability at ISIS has been identified as a high priority. Ongoing work to build an instability simulation model verified against theory has been presented. The macro-particle tracking code has been qualitatively benchmarked for a narrowband resonator as a function of beam intensity, tune and chromaticity.

Further work is planned to benchmark the code with resistive wall wakes and compare the results with similar codes such as PyHEADTAIL [19] and TRANFT [20]. Once verified with Sacherer theory, simulations will be compared against a comprehensive set of head-tail measurements made at ISIS as a function of intensity, tune and longitudinal structure. Development of the simulation model will aid in diagnosis of the driving impedance behind head-tail at ISIS, help provide mitigation strategies and support improvements of the damping system.

ISIS Damping System

A damping system has been developed for the vertical plane in the ISIS synchrotron using an existing BPM and a ferrite loaded kicker. The challenges of a fast ramping accelerator with dynamic tune variation have been addressed with a 3-tap FIR filter with updating coefficients through the acceleration cycle. Effective damping of the head-tail motion present during normal ISIS operations has been achieved during tests at the full repetition rate of 50 Hz. This has resulted in a beam loss reduction of > 50% for beam energies above 120 MeV.

The damping system currently uses set tunes, which are input manually, rather than measured values. Calculated values should provide better filter coefficients and as such damp instabilities more efficiently. It is planned to automate the calculation of filter coefficients from measured tunes to improve the system's flexibility during machine setup and operation.

A protection system for the kicker's terminating resistors is proposed to enable more robust, 50 Hz unsupervised operation of the damping system.

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