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OPTIMISATION OF THE ISIS PROTON SYNCHROTRON EXPERIMENTAL DAMPING SYSTEM

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Abstract

The ISIS Neutron and Muon Source, located in the UK, consists of a H^- linear accelerator, a rapid cycling proton synchrotron (RCS) and two extraction lines delivering protons onto two heavy metal targets. One of the limiting factors for achieving higher intensities in the accelerator is the head-tail instability present in the synchrotron around 2 ms after injection. In order to help mitigating this instability, an experimental damping system is being developed. Initial tests using a split electrode beam position monitor (BPM) as a pickup and a ferrite loaded kicker as a damper showed positive results. This paper describes the different developments made to the damping system and planned improvements to optimise its performance for use in user operations.

INTRODUCTION

The ISIS Synchrotron

The ISIS synchrotron accelerates two proton bunches, with a total of 3×10^{13} protons, from 70 MeV to 800 MeV at a repetition rate of 50 Hz, delivering a mean beam power of 0.2 MW to two tungsten targets. Protons are accelerated over 10 ms by first and second harmonic RF cavities, with a fundamental frequency sweep of 1.3 MHz to 3.1 MHz [1].

The Head-Tail Instability at ISIS

The head-tail instability is a primary concern for high intensity operation in many hadron synchrotrons including ISIS and its proposed upgrades [2]. The instability imposes an intensity limit through associated beam loss and the ensuing undesired machine activation.

Measurements on ISIS have consistently shown that the two proton bunches exhibit vertical head-tail motion at $1 - 2.5$ ms through the 10 ms acceleration cycle [3,4]. The instability is suppressed by ramping the vertical tune down away from the integer ($Q_y = 4$) and making the longitudinal distribution asymmetric using the dual harmonic RF during the time of the instability. The longitudinal and vertical injection painting schemes also have a strong influence on the susceptibility to the instability. Lowering the tune further tends to induce beam loss associated with the half integer resonance [5] and other mitigation strategies have little effect on beam loss.

Figure 1 shows a typical vertical BPM sum and difference signal over several turns during the instability, with dual harmonic RF, indicating clear head-tail motion over a portion of the bunch. Measurements of the instability, made with

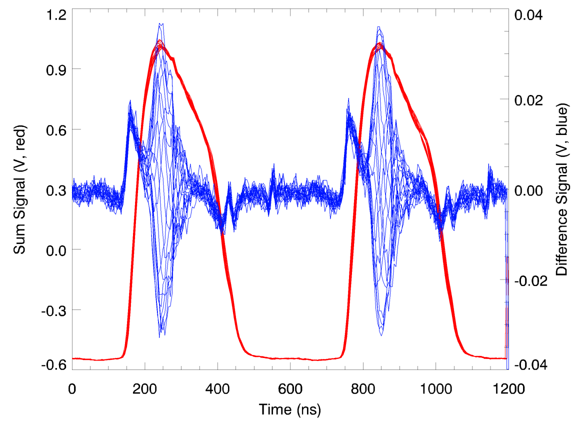

Figure 1: Sum (red) and difference (blue) vertical BPM signals over several turns around 2 ms through the acceleration cycle.

single harmonic RF and at low intensities, give a clear m = 1 mode structure whereas Sacherer theory [6] predicts a higher growth rate for m = 2. Studies are ongoing to determine the cause of the discrepancy.

The major challenge for damping the head-tail motion on the ISIS synchrotron is the fast ramping of both the accelerating frequency and the betatron tune.

THE ISIS DAMPING SYSTEM

Overview

A way of mitigating the head-tail motion is with the use of a transverse feedback system [7]. In ISIS, this has been possible by using one of the existing BPMs [8] as a pickup and the vertical betatron exciter [9] as a kicker, allowing for a reduced development time for a working prototype. The kicker is situated downstream of the selected pickup, providing a betatron phase advance of 266° for a vertical tune $Q_y = 3.80$ [10]. The processing electronics and power amplifiers are located 150 m away in an area free of ionizing radiation.

The ISIS BPMs are cylindrical split electrode type. The performance of such BPMs is characterised by the ratio of electrode voltage to incoming beam current [11]. The lower 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 Studio to verify the expected performance. Low frequency results were obtained by scaling the whole geometry by a factor p and the termination impedance by a factor

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$1/p$, higher frequency simulations were obtained without scaling. The simulated cutoff frequency differed by 1 kHz from the theoretical value, which is attributable to the difference between the measured electrode capacitance and the value produced by the simplified geometry.

The ISIS vertical betatron exciter or "Q-Kicker" is used as a kicker for the feedback system. This is a balanced transmission line kicker with window frame ferrites surrounding plates above and below the beam. Seven lumped capacitors connect each plate to the body and a high power resistor terminates each plate at the upstream aperture. A photograph of the kicker is shown in Fig. 2, the ceramic chamber maintains the vacuum whilst the plates and ferrite are in air.

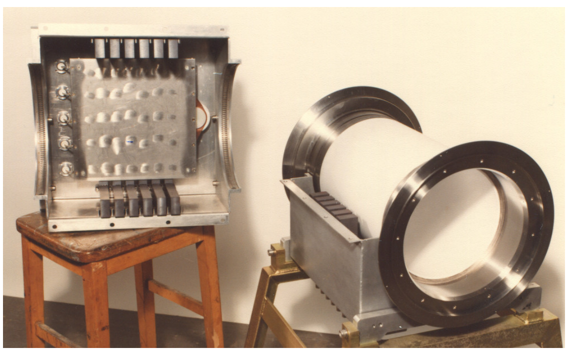

Figure 2: Photograph of the Q-kicker with the top half removed, revealing the ferrites, plates, ceramic vacuum vessel and a terminating resistor.

LLRF and Digital Signal Processing

The feedback system electronics block diagram is shown in Fig. 3. The low level RF (LLRF) analogue electronics condition the BPM signals for processing and provide amplification and gating of the signals for the power amplifiers. The FPGA block consists of a National Instruments NI-5781, 100 MS/s transceiver Flex-Rio front end module [12], backed by a PXIe-7962R Flex-Rio FPGA card.

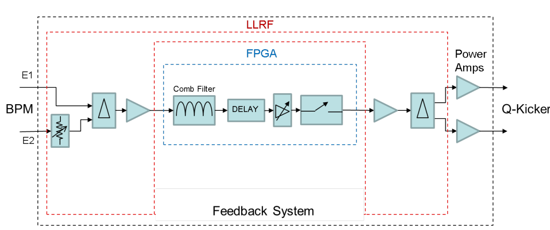

Figure 3: Feedback system LLRF electronics block diagram.

The signals from each BPM electrode are amplified separately, at the pick-up end 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. This block samples the signal, applies the required filtering, delays and software gain, as well as converting the processed signal back to the analogue domain. The driving clock of the digital processing stage is obtained by multiplying the fundamental RF harmonic by 30. This allows a filter of fixed length and digital delays proportional to the ramping revolution frequency. Auxiliary blocks, such as the output gating control and the filter coefficients switching, are driven by fixed frequency clocks. In order to compensate for the fixed delay of the cables and electronics, a variable digital delay is applied to the processed signal. This delay decreases as the revolution frequency increases, synchronising the correction signal with the beam arrival at the kicker. Three filter types have been tested for the feedback system: comb filter, fixed coefficients FIR and variable coefficients FIR; these are discussed in more detail later.

Digital Filter

A digital 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 difference between the pickup and the kicker together with the 3 turn signal processing delay cause a betatron phase shift during the tune ramp, which is also compensated with the filter.

Three different FIR filter approaches were tested. The first and simplest approach was to use a comb filter. The filter removes the DC offset and the revolution frequency components. The correct betatron phase advance for the correction kick is achieved when the filter is combined with 3 additional turns of digital delay. The challenge of this approach was the fixed narrow tune acceptance, which did not cover the entire time length of the head-tail instability due to the relatively large tune ramp.

Better control for the betatron phase shift and tune acceptance was achieved with a 3-tap FIR filter. Its simplified circuit diagram is shown in Fig. 4. The 3-tap FIR filter allows for a correct betatron phase with a chosen tune, turn delay and phase advance [13–15]. Furthermore, the filter covers a larger tune range due to the shorter total group delay in comparison to the comb filter with additional turns of delay. Although this approach gave significantly better tune acceptance than the comb filter, it did not completely cover the instability region.

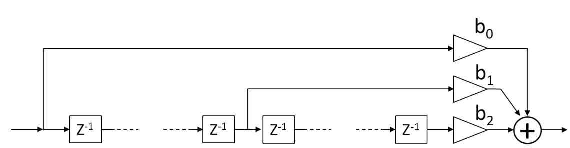

Figure 4: Basic diagram of the FIR filter used in the design. The separation between filter coefficients is a single turn.

The tune acceptance of the feedback system was further expanded to cover the entire instability by dynamically updating the 3-tap filter coefficients along the tune ramp, allowing optimised filter values for each set tune. The first tests for the dynamic filters were performed by giving a list of pre-programmed coefficients to the custom FPGA firmware,

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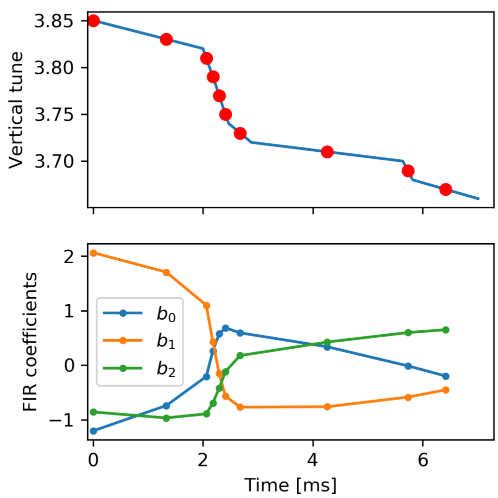

Figure 5: The ISIS vertical tune ramp values (top) and corresponding FIR filter coefficients (bottom) for optimising the tune acceptance along the acceleration ramp.

providing a more efficient damping along the instability region. Figure 5 (top) represents the vertical tune from injection to extraction and the values chosen for filter coefficient calculation, (bottom) the calculated filter coefficients for these tune values.

Power Amplifiers

As the kicker is a 10 Ω system, each plate is connected to a custom design Eltac RA994 power amplifier [16] 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.

EXPERIMENTAL RESULTS

All tests performed have been done at a repetition rate of 1.6 Hz to avoid interfering with the ISIS user operations and prevent any potential damage to the kicker terminating resistors. A system to protect these resistors against long lasting over-voltage conditions will be implemented in the future, to allow for continuous unsupervised operation. Figure 6 shows the BPM differential signal corresponding to the 2 ms instability. The yellow trace represents the beam vertical motion for a single pulse from 2 ms to 4 ms and the blue trace shows the maximum vertical motion envelope recorded over 20 pulses.

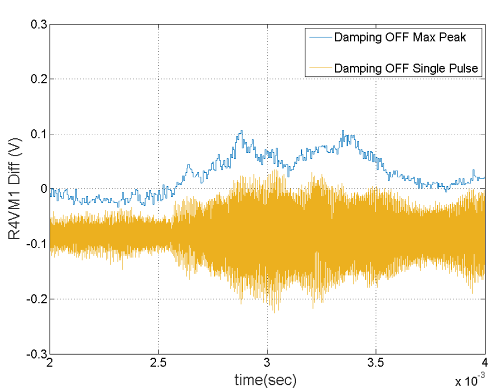

Figure 6: Beam vertical motion with the damping system off.

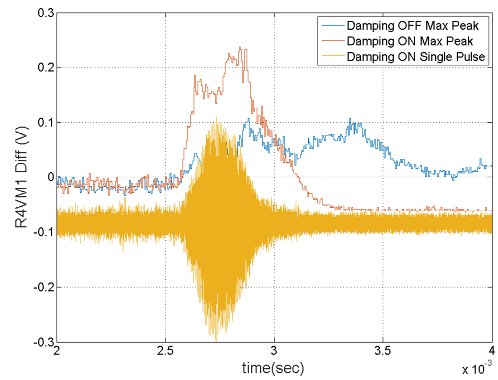

Figure 7: Vertical damping using a comb filter.

Comb Filter Results

Figure 7 compares the beam vertical motion with the damper off and on when using this type of filter. The yellow trace shows the beam vertical motion for a single pulse with the damper on. The blue trace shows the maximum vertical motion envelope over 20 pulses with the damper off and the red trace with the damper on. It can be observed that the system is damping effectively from about 3 ms and onward, but it drives the beam between 2 ms and 3 ms.

The vertical tune varies during the acceleration cycle which changes the phase advance between the pick-up and kicker. This error becomes significant over multiple turns of electrical delay, which are required to achieve the optimised phase advance for damping[1], the error accumulates on every turn causing the system to drive the instability instead of damping it.

Fixed Coefficients FIR Filter Results

By replacing the comb filter with an FIR filter it is possible to reduce the delay from 6 to 3 turns, decreasing the phase advance error and improving the filter acceptance. Figure 8 shows the damping improvement over the 2.5 ms to 3 ms region. Although it performs better than the comb filter setup, it does not completely damp the vertical motion.

Variable Coefficients FIR Filter Results

An FIR filter with variable coefficients has been implemented to improve the filter acceptance for different tune values. The coefficients were calculated from set tunes and changed when this varied by some threshold; these points

[1] The total electronic delay is longer than one revolution period, so extra turns of delay are required to obtain an optimal phase advance for a given tune. The comb filter setup requires 6 turns of delay.

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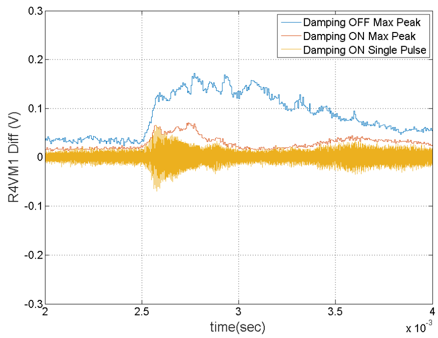

Figure 8: Vertical damping using an FIR filter with fixed coefficients.

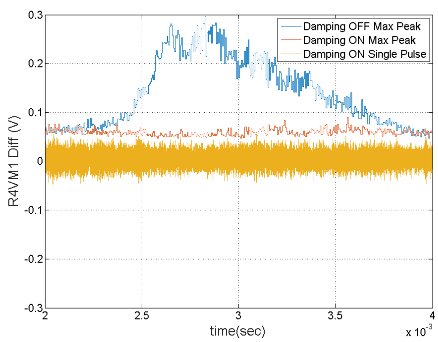

Figure 9: Vertical damping using an FIR filter with variable coefficients.

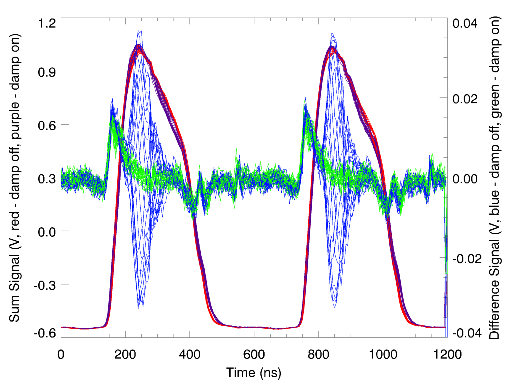

Figure 10: Head-tail vertical motion comparison with the damping on and off. Sum signal (Red and purple), and differential signals with the damping off (blue) and on (green).

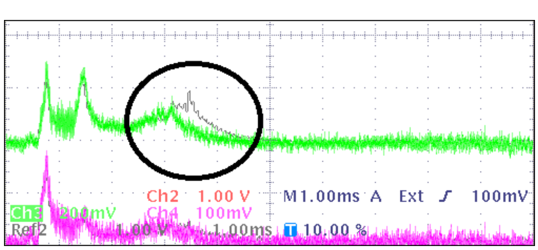

Figure 11: ISIS synchrotron total beam loss reduction around the 2 ms instability.

are indicated by the red points in Fig. 5. It can be observed in Fig. 9 that the vertical motion is effectively damped by using this configuration.

Figure 10 shows the comparison of head-tail vertical motion over several turns with and without the damping system around 2 ms. The red and purple traces correspond to the BPM sum signals, the blue trace to the differential signal with the damping off and the green one the differential signal with the damping on. Figure 11 shows the total beam loss reduction around the instability region. The dark grey reference trace corresponds to the BLM signal with the damper off and the green one with the damper on.

SUMMARY

Achievements

A vertical plane damping system has been developed for the ISIS ring using one of the split-electrode BPMs and an existing ferrite loaded kicker, minimizing the development time for a working system. The fast ramping of the acceleration frequency and the betatron tune have been the key challenge to damp the head-tail motion.

Three filter types have been tested for the digital stage of the damping system: comb filter, fixed coefficients FIR filter and variable coefficients FIR filter. The best results were achieved with the variable coefficients FIR, as it minimises the total required delay and optimises the filter acceptance to accommodate for changes in the vertical tune.

Effective damping of the existing head-tail vertical motion has been achieved for the whole instability region for a repetition rate of 1.6 Hz, resulting in a reduction of beam loss around that area. This will be a major benefit for high intensity operations at ISIS.

Improvements and Future Upgrades

Tests so far have used set tune values however measured tunes would provide more accurate data for filter coefficient calculation.

Because the FIR filter coefficients are obtained off-line, an automated calculation feature from the measured tune values would improve the damping optimisation process.

After demonstrating effective damping at low repetition rates, the system can now be used during ISIS user operations at 50 Hz. An active protection system to avoid damage to the kicker terminating resistors should be implemented for continuous operation without supervision.

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