HIGH-INTENSITY STUDIES ON THE ISIS RCS AND THEIR IMPACT ON THE DESIGN OF ISIS-II

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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) that accelerates 3×10^{13} protons per pulse from 70 MeV to 800 MeV at 50 Hz, delivering a mean beam power of 0.2 MW.

As a high-intensity machine, research at ISIS is predominantly focused on understanding, minimising and controlling beam-loss, which is central to sustainable machine operation. Knowledge of beam-loss mechanisms then informs the design of future high power accelerators such as ISIS-II.

This paper provides an overview of the R&D studies currently underway on the ISIS RCS and how these relate to ongoing work understanding and optimising designs for ISIS-II. In particular, recent extensive investigations into observed head-tail instabilities are summarised.

INTRODUCTION

The ISIS Neutron and Muon Facility has successfully been in operation for almost 40 years, providing neutron and muon beams to the user community for a broad spectrum of materials research [1]. Operation centres on an RCS with a 163 m circumference composed of 10 superperiods. It accelerates up to 3×10^{13} protons per pulse (ppp) from 70 MeV to 800 MeV on the 10 ms rising edge of a 50 Hz sinusoidal main magnet field, resulting in a mean beam power of 0.2 MW. Each beam pulse is extracted to one of two neutron targets (TS1 and TS2) and a small portion of the beam to TS1 interacts with an intermediary, carbon target to produce pions which decay into muons for condensed matter research.

Injection into the RCS is via charge-exchange of a 70 MeV, 25 mA H^- beam over ~130 turns with painting over both transverse acceptances, collimated at around 300 π mm mrad. The injected, essentially coasting, beam is bunched and accelerated by the ring dual harmonic RF system (h = 2, 4). The nominal betatron tunes are (Q_x, Q_y)=(4.31, 3.83) with peak incoherent tune shifts exceeding −0.5. Key ISIS RCS parameters are listed in Table 1. Beam intensity in the ring is loss-limited, with the main beam-losses coming from injection processes, longitudinal trapping, transverse space charge and the head-tail instability.

The main challenge for high-intensity operation of a hadron accelerator is minimising and controlling beam-losses which lead to activation of machine components, restricting hands-on maintenance. This paper presents an overview of R&D studies on the ISIS RCS focusing on the main drivers of beam-loss: building on our existing machine models to better understand the loss mechanisms, looking to methods of reducing beam-loss or increasing beam intensity, and thereby improving machine efficiencies. This paper also presents the impact of current R&D work on the design of a next generation, short-pulse neutron and muon facility, ISIS-II [2, 3].

Table 1: Important ISIS Synchrotron Parameters

Parameter	Value
Energy range	70 – 800 MeV
Beam intensity	3×10^{13} ppp
Gamma transition	5.034
Mean radius	26.0
No. superperiods	10
Dipole field	0.176 – 0.697 T
Nominal tunes (Q_x, Q_y)	4.31, 3.83
Chromaticity (ξ_x, ξ_y)	-1.1, -1.1
No. RF cavities ($h = 2, 4$)	6, 4
Machine accept. (A_x, A_y)	(540, 430) π mm mrad
Injection scheme	H^- charge-exchange
Extraction scheme	Fast, single-turn

Recent studies have been focused on benchmarking models of the ISIS accelerators to experimental data with a view to improving ISIS operations, through beam-loss reduction and control and increased efficiencies, and more reliable loss predictions for new accelerator designs. A detailed comparison of experimental measurements with a linear ORBIT [4] model of the ISIS RCS has been presented by Adams *et al.* [5]. This included dual harmonic RF, 3D injection painting, tune variation, real apertures and collimation, but without detailed magnet errors, and showed reasonable agreement on beam distributions and beam-loss as a function of time. Since then, in order to control and understand the machine better, and to allow more detailed R&D, there is a major effort to improve all aspects of machine modelling, as detailed below.

TRANSVERSE DYNAMICS MODELS

Magnet Models

Given the vintage of the accelerator, only limited data are available on ring lattice magnets: there are detailed measurements and OPERA [6] models of each lattice magnet type [7], but not each magnet. However, good agreement between measurements and models gives confidence in this “generic” data. The OPERA models and measurements are

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providing information for much better models of fringe fields and non-linear terms, Fig. 1. Because individual magnet variations are unknown, this data will have to be combined with beam measurements and modelling, to estimate azimuthal harmonic strengths of driving terms around the ring. Studies are also underway to compare beam trajectories from OPERA field maps with TEAPOT and PTC optics used in PyORBIT [8] simulations, particularly in the complicated combined function dipoles, to ensure accuracy.

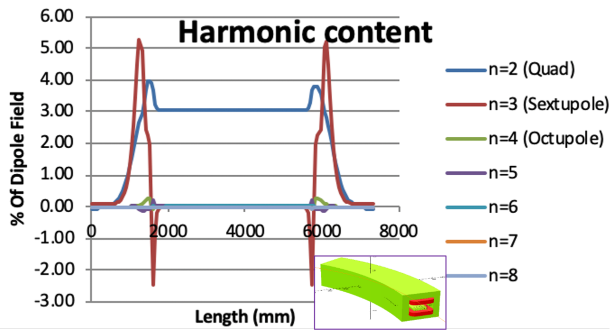

Figure 1: Magnetic field harmonics along the length of an ISIS main dipole from an OPERA model (inset).

Tune Plane Measurements, Lattice Models

Beam-based measurements are also essential to improve models. An important tool developed over recent years is measurement of beam-loss versus betatron tune [9], Fig. 2. These use low-intensity, coasting beams in storage ring mode (SRM) with a DC main magnet field and RF off, to allow important resonant driving terms to be identified.

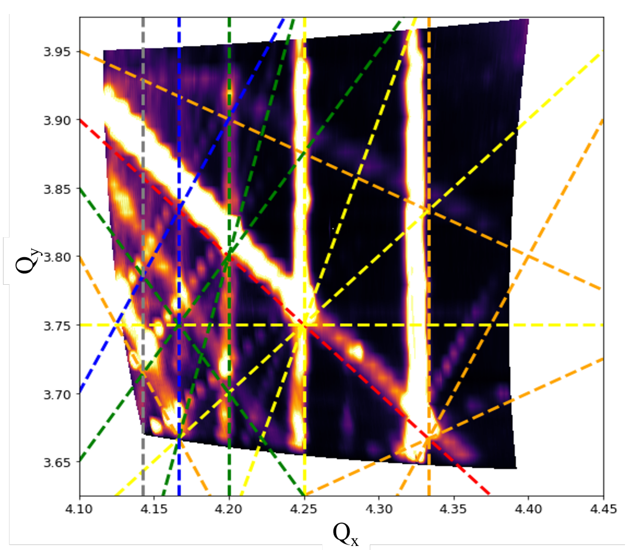

Figure 2: Measured sum beam-loss as a function of Q_x and Q_y for Q_x scanned downwards (right to left).

Interpreting and developing these measurements has also required improvements to lattice models and tune control on the machine [10]. Originally, tune was set by varying the strength of two sets of trim quadrupoles (adjacent to main lattice F and D quadrupoles) via a simple, linear approximation. Better models of tune control have been created, and closely agree with measurements, which also include chromaticity: Figs. 3 and 4. Measurements of tune as a function of current in each trim quadrupole are providing direct measurements of the beta function around the ring for half-integer error correction. New analysis of survey data is being incorporated into lattice models to help detailed studies of dipole errors and orbit correction [10]. Non-linear terms from magnet models will be incorporated into simulations, and optimised to fit measurements.

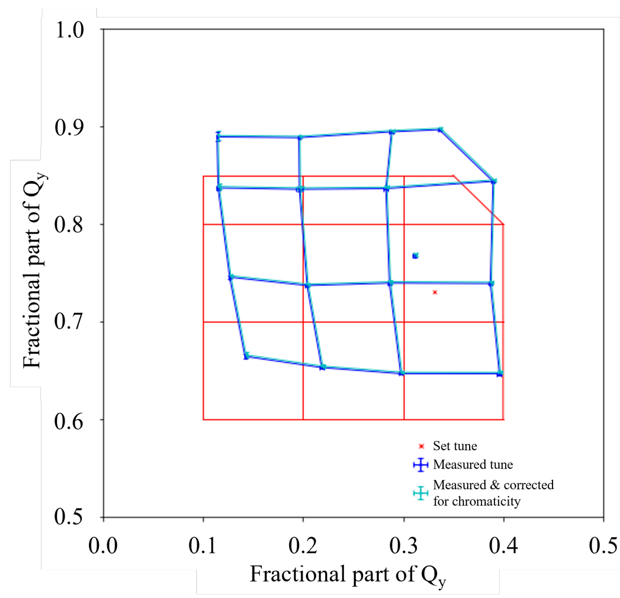

Figure 3: Tune plane showing original linear, "set" tune (red) and measured values (blue).

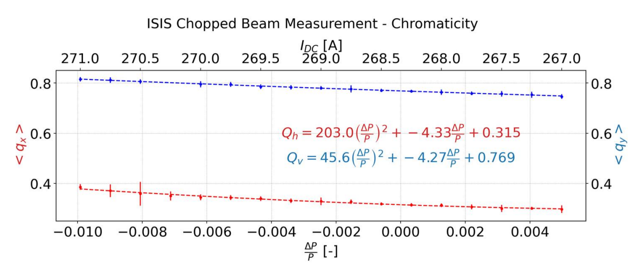

Figure 4: Chromaticity measurement using chopped beams, varying main magnet DC current I_{DC}.

Betatron Resonances and Space Charge

With improved tune control and knowledge of the linear lattice at low intensity, more detailed analysis and research of resonances has become possible, including non-linear terms shown in Fig. 2. Once the low-intensity behaviour is understood, increased intensities may be studied and the effects of space charge explored in detail. Important resonances presently under study are $2Q_y = 7$, $3Q_x = 13$ and $4Q_y = 15$.

The half-integer resonance, expected to be a possible source of beam-loss on ISIS and ISIS-II, has been the subject of much experimental study. Measurements have used coasting beams in SRM, with tune and driving terms being controlled via trim quadrupoles. ORBIT simulations of the complicated process of half-integer crossing during the intensity ramp at injection have compared well with loss and profile measurements, and produced results in line with expectations [11, 12].

However, to understand the process in more detail, measurements are now under-way using adiabatic crossing of the half-integer at low intensity. The adiabatic changes allow predictions of particle trajectories: Fig. 5 (left). This helps understand the observed evolution of beam profiles: Fig. 5 (right). These early measurements are consistent with expectations of two ”lobes” moving outwards, leaving a stable central core. Once these low-intensity measurements are fully understood, the effect of increased intensity, coherent and incoherent effects will be explored.

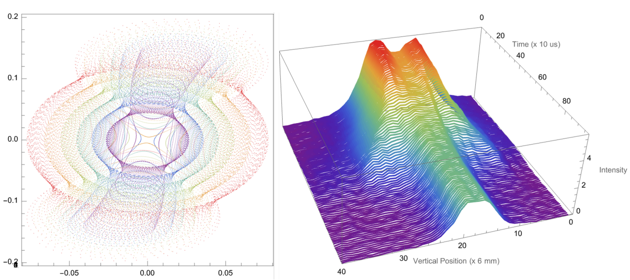

Figure 5: Poincaré map (y, y') during adiabatic crossing of $2Q_y = 7$ from simple simulation (left). Measured vertical profile for the beam adiabatically crossing $2Q_y = 7$ (right).

With the improved lattice model established, detailed studies of 3D painting will be possible, along with the effects of resonances in bunched beams. This will allow further testing of codes and better predictions for ISIS-II designs.

LONGITUDINAL DYNAMICS MODELS

Generally, good agreement has been found between tracking simulations and longitudinal beam profile measurements [5]. However, particularly with recent upgrades to ring RF hardware allowing for better control, benchmarks between model and measurement are being reappraised.

Of particular interest is the analysis of the longitudinal trapping process involving complex, non-adiabatic capture with dual-harmonic RF. With the extra RF control available, further optimisations are possible to injection and trapping efficiency. This ties in with work to build a new MEBT [13] which properly matches the beam between the ISIS RFQ and first DTL tank and includes a fast chopper to allow the injected beam to be chopped into the RF bucket, removing beam-losses associated with trapping (Fig. 6).

Studies are also focused on techniques for bunch compression at extraction from the RCS, as shorter bunches are preferable for muon experiments. A mixture of measurements, tomographic phase space reconstruction and simulations are being explored and compared with the aim of more efficient bunch compression without increased beam-losses from extraction through to the neutron targets [14]. Currently the bunch is adiabatically lengthened by lowering the RF voltage of the $h = 2$ system, and then rapidly increasing it shortly before extraction to rotate the bunch in phase space. An example measurement of bunch compression in normal operation is shown in Fig. 7.

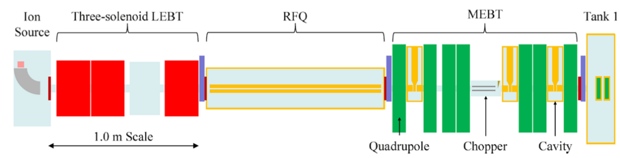

Figure 6: New MEBT to be installed on the ISIS injector.

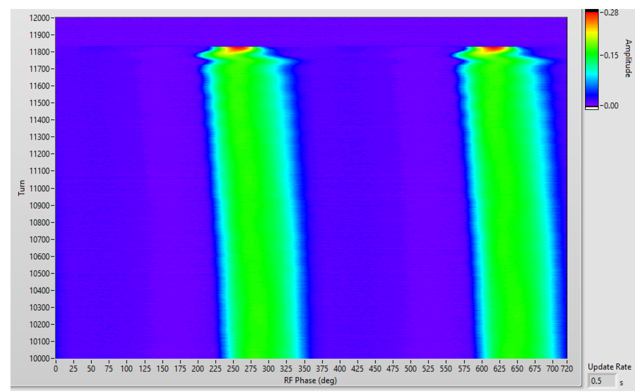

Figure 7: BPM sum signal over the last ~850 turns illustrating bunch compression at extraction from the RCS.

HEAD-TAIL INSTABILITY STUDIES

Background

During ISIS high-intensity operations, the proton beam experiences a coherent vertical instability around 1 – 2.5 ms through the 10 ms acceleration process. Measurements of this instability have been made at a range of beam intensities and with single and dual-harmonic RF acceleration [15–17] with a view to characterise it and develop mitigation strategies.

Figure 8 (left) shows typical beam intensity and sum beam-loss signals in the ISIS RCS for high-intensity operations with the timeframe for beam-loss associated with the instability highlighted. The coherent vertical motion along the bunch over 20 consecutive turns is shown in Fig. 8 (right) indicating a head-tail instability, in this case with intrabunch mode $m = 1$ (one node along the bunch's length).

As beam-losses associated with the instability are over a relatively long time period, and later in the acceleration cycle than other beam-losses, they currently define a key intensity limit on the ISIS RCS. In order to mitigate the instability, ISIS employs a fast vertical tune ramp during the time of the instability (typically from ~3.83 to ~3.74 in 0.5 ms). Fur-

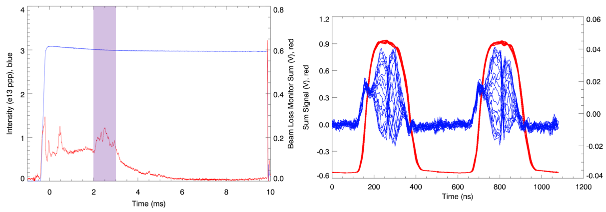

Figure 8: Left: Beam intensity (blue) and sum beam-loss (red) traces as a function of time through the acceleration cycle in RCS operations. The timeframe associated with the beam instability is highlighted. Right: 20-turn extract of the vertical BPM sum (red) and difference (blue) signals during the instability.

ther reduction in beam-losses associated with the instability is achieved with control of the vertical beam distribution through injection painting and use of the dual harmonic RF system to make the longitudinal bunch profile more asymmetric. Unlike many other synchrotrons, ISIS operates without sextupoles to control chromaticity which can suppress head-tail instabilities. A prototype damping system has been tested successfully at 50 Hz [16] and further development is planned to fully commission it for user operations.

Impedance Investigations

Previous experiments have shown that the instability growth rate increases rapidly as the vertical tune is increased toward the integer ($Q_y = 4$), [15]. This led to the resistive wall being cited as the most likely driving impedance. However, beam-based measurements of the effective impedance as a function of frequency indicate a more complex picture, Fig. 9 [16]. The origin of the observed vertical, low-frequency, narrowband impedance is under investigation as a possible driving source for the head-tail instability [18].

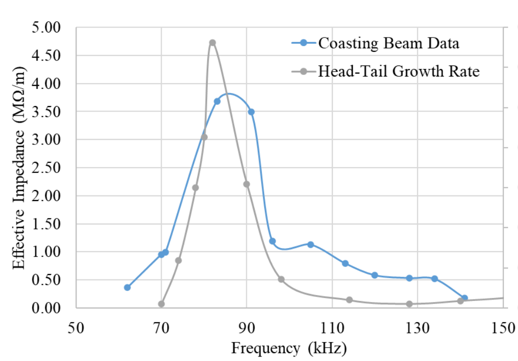

Figure 9: Measured effective transverse impedance as a function of vertical baseband frequency in SRM, overlaid with head-tail growth rate measurements made with a bunched beam stored at injection energy [17].

Extraction kickers are known to produce low-frequency narrowband impedances due to their long cables, and as ISIS extraction is in the vertical plane they were of specific interest. Measurements, however, suggest that the matched terminating resistors effectively damp resonant impedances that would otherwise be caused by the long cables.

Further contributions are expected from the RCS magnets which cover >50% of the ring and include laminated poles, ceramic vacuum vessels and RF shields. Simulations using CST [19] indicate a significant low-frequency impedance from coupling capacitors used in the RF screens, Fig. 10. Bench measurements are underway to ascertain if this is the case and what mitigations may be possible.

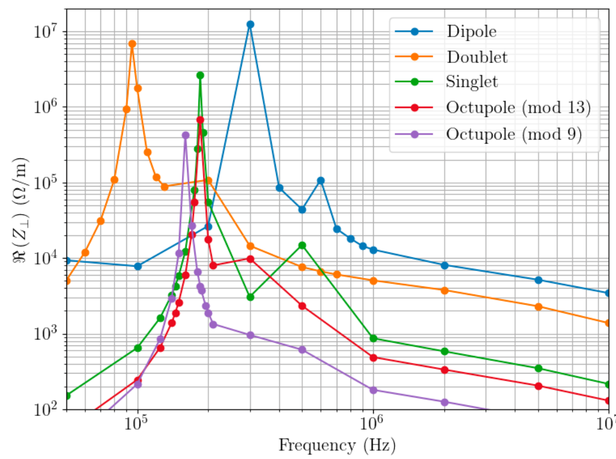

Figure 10: The real part of the transverse impedance for RCS magnet RF screens from CST simulations at low frequency.

Experimental Studies of Head-Tail

In order to understand the dynamics of the instability on ISIS better, a comprehensive set of experiments has been made by bunching beams in storage ring mode (BSRM). This involves putting the machine in SRM (as described above) and powering, typically, a single RF cavity at fixed frequency to bunch, but not accelerate, the beam. This provides a less complicated environment than normal 50 Hz operation, removing the complexities of sweeping RF and betatron frequencies, and enables finer control of beam and lattice parameters. This mode of operation also provides a means to study the impact of space charge on the instability. By reducing the injected intensity to 10% of its nominal value (~3×10^{12} protons per pulse), the instability can still observed whilst maintaining good signal-to-noise ratios on BPM signals.

Measurements were made of the instability in order to characterise the intrabunch mode, the bunch frequency spectra and instability growth rate as a function of the vertical tune and the vertical beam size. An example BPM measurement over 20 turns is shown in Fig. 11, together with the bunch spectra, indicating a mode $m = 2$ with large betatron baseband (lowest frequency sideband). It was also noted that in all measurements the coherent vertical motion occupied as little as half the bunch length.

The data showed a change of intrabunch mode with small changes in vertical tune, although the baseband was consistently amongst the largest in amplitude during the instability.

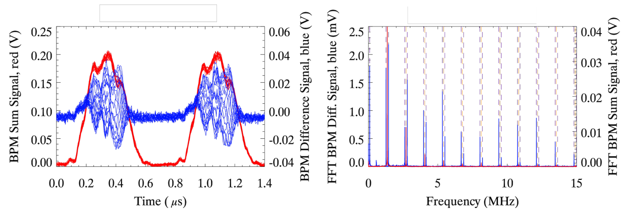

Figure 11: Left: BPM sum (red) and difference (blue) signals over 20 turns in BSRM. Right: FFT of BPM data over 0.5 ms during the instability.

The growth rate as a function of vertical baseband frequency (increasing as the tune is lowered) closely followed the measured effective impedance measured in SRM (Fig. 9) supporting the claim that a narrowband impedance drives the head-tail instability.

Measurements were also made as a function of vertical beam size. Firstly, observations indicated intrabunch mode changes with vertical emittance and corresponding changes in the bunch spectra. Of particular note, however, was the increase in instability growth rate with decreasing emittance (Fig. 12), thought to be due to space charge (see below). This was probed further in PyHEADTAIL (PyHT) simulations [20].

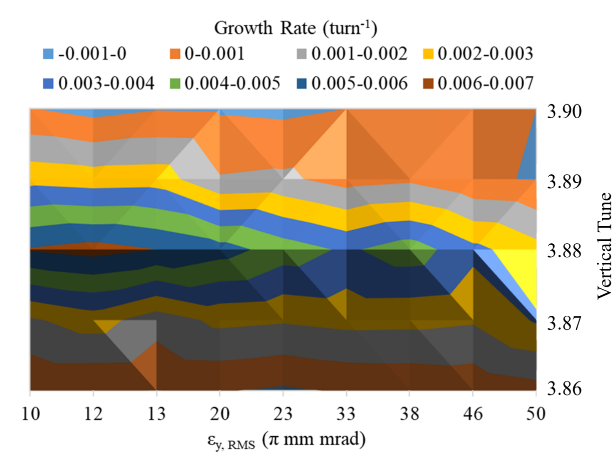

Figure 12: Instability growth rate versus RMS vertical emittance and vertical tune.

Instability Simulations

Instability simulations were set up to replicate, as close as practically possible, the lattice and beam parameters in the BSRM experiments. Simulation specific parameters were chosen to give convergent behaviour whilst allowing for reasonable simulation time.

A smooth-focusing model was utilised in the transverse plane and realistic, non-linear longitudinal motion due to the RF. The impedance was applied as a pure narrowband resonator with characteristics selected to replicate the measured head-tail growth rate as a function of frequency. A transverse, PIC space charge model was included in some simulations to analyse its effect on the instability.

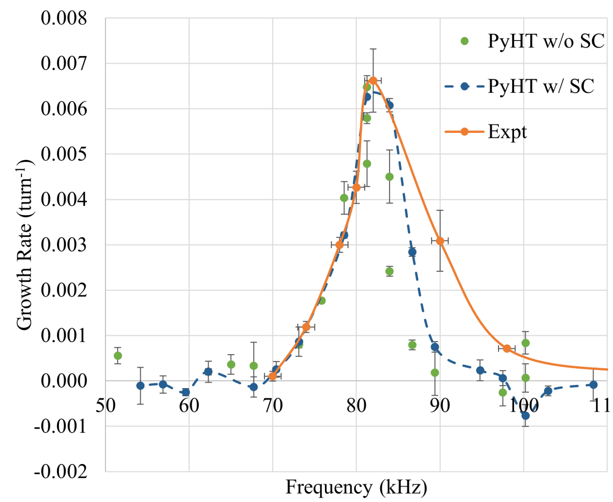

Figure 13: Head-tail instability growth rate versus frequency for experiment (orange) and PyHT simulations with (blue) and without (green) space charge.

In simulations as a function of vertical tune the growth rate as a function of frequency matched the experimental data well (Fig. 13), however the mode structure and associated bunch spectra differed. Simulations also showed the full bunch length oscillating, in disagreement with experiment. When transverse space charge was included a similar dependence of growth rate on vertical tune was reproduced (Fig. 13), however the mode structures differed from both simulations without space charge and experiment.

Effect of Vertical Beam Size

Simulations and measurements of the head-tail instability as a function of vertical beam size were performed to probe the effect of transverse space charge on the instability characteristics. Measurements (e.g. Fig. 12) showed a negative, linear correlation between growth rate and vertical emittance as well as some differences in mode structure. PyHT simulations were used to determine if transverse space charge is the cause for this correlation.

Figure 14 shows the variation of head-tail instability growth rate as a function of RMS vertical emittance at two selected vertical tunes from measurments in BSRM and PyHT simulations with and without transverse space charge. The effect of only adding transverse space charge to the model is clear, going from negligible changes in growth rate without (green and pale blue) to a significant, linear reduction in growth rate with increasing vertical emittance when space charge is included (grey and orange). This appears to confirm that transverse space charge is causing this dependence.

Simulations with transverse space charge also showed different intrabunch mode structures compared to those observed in experiment and to simulations without transverse space charge. Further work is planned, particularly analysing the effect of beam intensity and distribution (both longitudinal and transverse) on the instability's characteristics in measurement and simulation. The progress made on modelling the transverse impedance of components of the ISIS RCS will also be key to benchmarking models and establishing further instability mitigation strategies.

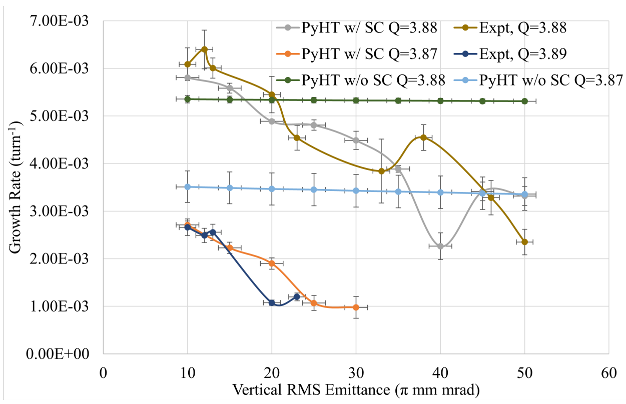

Figure 14: Head-tail instability growth rate versus vertical emittance for experiment at two selected Q_y and PyHT simulations with and without space charge.

ISIS-II DESIGN

Detailed studies are underway to identify the optimal configuration for a next generation, short-pulsed neutron source (ISIS-II) that will define a major ISIS upgrade, with construction expected to begin in ~2031. The working specification for the proposed facility requires 1.3×10^{14} ppp at 1.2 GeV and a repetition rate of 50 Hz. The resultant 1.25 MW beam will supply multiple user targets, producing neutron and muon beams for condensed matter research. Scientific consultation with the user communities as well as neutronics and accelerator experts is ongoing evaluating the scope, cost and sustainability and may change the accelerator technologies and beam parameters.

Figure 15: A possible placement of ISIS-II on the RAL site.

Initial RCS and accumulator ring design options for ISIS-II have been completed [2] building on the experience of existing facilities. These include lattice design; transverse, longitudinal and 3D beam dynamics studies; injection, collimation and extraction designs and assessments of magnetic field and alignment errors together with possible longitudinal and transverse instabilities. A Fixed-Field Accelerator (FFA) option is also being developed (Fig. 15). An FFA is expected to have advantages in regards to sustainability and stable operation together with the possibility of beam stacking. This option requires a high-intensity demonstrator [3].

Impact of ISIS R&D on ISIS-II

Together with operational experience, design studies for ISIS-II have highlighted the need to reliably predict and understand losses at the 0.1 – 0.01% level. As such, accurate simulations of halo evolution become important, and require careful verification.

To help address this issue, as outlined above, a concerted effort is being made to benchmark measurements on the ISIS accelerators to improve models. Plans are underway for benchmarked simulations of the injector, injection painting (longitudinal and transverse), full cycle simulations and predictions of halo with realistic lattice models and modelling of instabilities with calculated impedances including space charge. These enable better predictions of ISIS beam dynamics, leading to more efficient operations, as well as increased confidence in ISIS-II design predictions; specifically forecasts of beam-loss.

These improved models, benchmarked to the ISIS RCS, are also planned to be benchmarked against other high-intensity hadron accelerators and against other simulation codes. These newly developed, advanced models, combined with skilled and experienced researchers, help to push the current state-of-the-art in terms of the high-intensity limit.

CONCLUSIONS

Accelerator R&D is central to improved accelerator performance on the ISIS RCS, enabling more efficient and sustained high-intensity operation. Regular measurements and improved, benchmarked models, together with skilled and experienced researchers, are essential to providing reliable designs for future upgrades to the ISIS RCS as well as next generation machines including ISIS-II.

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