OPERATIONAL EXPERIENCE AND FUTURE PLANS AT ISIS

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Abstract

The ISIS spallation neutron and muon source has been in operation since 1984. The accelerator complex consists of an H^- ion source, 665 keV RFQ, 70 MeV linac, 800 MeV proton synchrotron and associated beam transfer lines. The facility currently delivers ~2.8×10^{13} protons per pulse (ppp) at 50 Hz, which is shared between two target stations. High intensity performance and operation are dominated by the need to minimise and control beam loss, which is key to sustainable machine operation, allowing essential hands-on maintenance. The facility has had several upgrades including an RFQ, Second Harmonic RF system, beam diagnostic DAQ improving beam control and a Second Target station. Future upgrades include a ring damping system and MEBT injection chopper. Operational experience of ISIS and its upgrades are discussed as well as current and future R&D projects.

INTRODUCTION

The ISIS neutron facility has been in operation since 1984 providing neutron and muon beams to the user community for a wide spectrum of materials research [1]. The facility originally consisted of an H^- ion source, 665 kV pre-injector, 70 MeV four tank drift tube linac injecting into a 163 m circumference, proton synchrotron. Un-chopped beam injected into the ring using H^- charge exchange accumulates 2.75×10^{13} protons over 130 turns, non-adiabatically trapped, and fast extracted at 50 Hz delivering a 160 kW beam to a depleted uranium target.

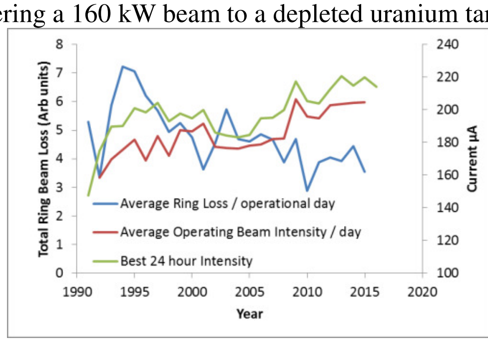

Figure 1: Operating ring beam loss and intensity since 1992.

As with any accelerator facility, post commissioning, there have been many incremental developments to increase operating intensity and improve beam loss control. The main upgrades have been Straight 1 (2002), Pre-Injector (2004), Ring Dual Harmonic RF (DHRF) cavities (2006-2012), Second Target Station (2007), Downstream Extracted Proton Beam line (EPB) refurbishments (2007-2015), with continued machine physics R&D improvements throughout the whole period.

The main challenge for high intensity operation of the facility is minimising and controlling beam losses, especially in the ring, which activate machine components restricting hands on maintenance. Fig. 1 shows yearly average total ring beam loss, operating intensity and best 24 hour operating intensity since 1992. The trend is for decreasing beam loss and increasing operating intensity to the point where we now routinely operate in excess of 220 µA, 176 kW. Whilst upgraded hardware has improved machine reliability this paper concentrates on upgrades and operational experience which have aided beam control.

MAIN ACCELERATOR UPGRADES

Pre-Injector Upgrade

The original pre-injector section of the accelerator consisted of a 665 kV Cockcroft Walton accelerator, Fig. 2 left, followed by a quadrupole and RF buncher matching section delivering a 19 mA, H^- beam to linac tank 1. As part of an intensity upgrade, to meet the demands of increased beams for the second target station, this section was replaced by 3 solenoids and an RFQ in 2004 [2], Fig. 2 right. After 18 months commissioning and soak testing in a dedicated test facility the new components were installed in the accelerator and have been very successful and reliable. The main commissioning issues were surface cleaning inside the RFQ, required to meet high RF field levels.

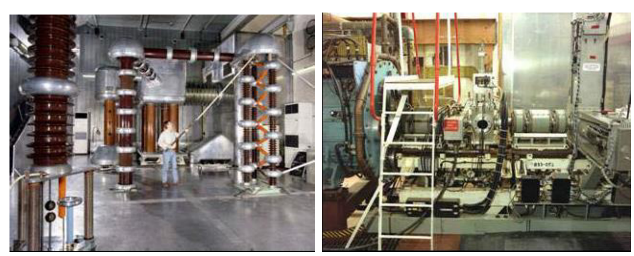

Figure 2: CockCroft Walton set (left) and new RFQ (right).

Typical operation now delivers 35 mA beams to tank 1 with 95 % transmission efficiency. Transverse mis-match into tank 1 reduces the beam current to 26 mA which is then maintained through the remaining linac tanks for injection into the ring [3].

Dual Harmonic RF Upgrade

The ring RF system was originally composed of six, h=2, ferrite loaded cavities delivering up to 160 kV/turn. Ring injection accumulated a DC beam which was then trapped into two bunches non-adiabatically and accelerated up to 800 MeV in 10 ms. Beam losses of 10 % limited operation to ~200 µA. The dual harmonic upgrade [4,5], saw the addition of four, h=4, cavities with 80 kV/turn total peak. Increased bucket acceptance and

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bunching factors reduced trapping and acceleration losses and allowed higher intensity beam of up to 230 μA with equivalent losses. Fig. 3 shows beam loss (left) and intensity (right) during the cycle with and without the additional cavities.

Beam loading on the h=4 RF cavities is the main control issue. Compensation systems, based on existing h=2 hardware, and digital frequency control of both systems are in development [6].

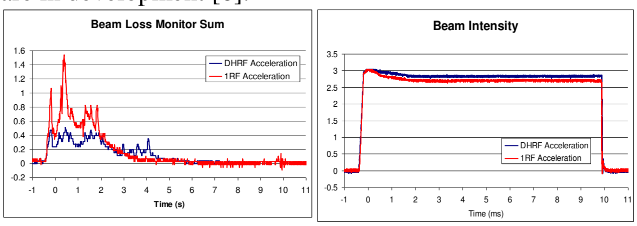

Figure 3: Beam loss (left) and intensity (right) with (blue) and without (red) DHRF cavity operation.

Straight 1 Upgrade

In 2002 the most active straight section in the ring, where collimation and vertical fast extract systems are situated, was redesigned and replaced. The vertical acceptance of the extraction channel was increased, including a new septum magnet, to allow lower beam loss operation. The collimation system was also replaced, including additional, optimised copper and graphite jaws. The increased jaw length was designed to allow for higher energy losses expected with dual harmonic operation. The upgraded system with energy deposition measurements also provides enhanced protection for machine error conditions.

Downstream EPB1 Upgrades

The Muon Facility at ISIS uses a graphite target inserted in an 800 MeV proton beam line ~20 m upstream of Target Station 1. In addition to producing muons this target scatters the incident proton beam causing downstream machine activation. TURTLE simulations suggest for a 10 mm thick target 1.4 % of incident beam is scattered and controlled on downstream collimators but 0.47 % is uncontrolled and deposited on downstream lattice components. A three phase upgrade (2007-2015), across long shutdowns, included: reducing collimator clearance to the primary proton beam from 17 mm to 9 mm, replacing all old quadrupoles with larger aperture versions, adding two extra to improve optic flexibility and adding quadrupole steering elements to allow independent muon and neutron target beam position control. TURTLE studies show proton losses are now localised to the collimators. This has allowed continued operation with tolerable dose levels.

ACCELERATOR PHYSICS AND R&D

High Intensity Limit of the Facility

The main challenge for high intensity operation of the facility is optimising beam loss in the ring. The main loss mechanisms are: injection foil stripping efficiency and scattering, non-adiabatic longitudinal trapping, a vertical head-tail instability driving emittance growth, halo generation associated with high space charge and resonance crossing.

As is the case on many high intensity machines, much operational optimisation is empirical. However, there is an on-going R&D programme to advance measurement, and develop experiments and models that improve understanding of the main loss mechanisms. This is as important for future machines and upgrades as it is for improvement of present performance. Experimental results from machines like ISIS (with particularly high space charge levels) are a valuable benchmark for future designs.

High Intensity Setup

Beam losses in the ring, Fig. 3, can be separated into three main time intervals: injection (-0.4–0.0 ms), trapping (0.0–2.5 ms) and acceleration (2.5–10.0 ms).

Injection loss (1%) is mostly generated by unstripped beam at the foil. Circulating beam losses are derived from emittance growth, mainly through space charge and foil scattering. Painting emittance amplitudes, tune and transverse optics are the effective tuning handles.

Longitudinal trapping loss (3%) results from the non-adiabatic capture process and is strongly affected by the injected beam distributions and the evolution of the RF bucket structure in the ring. The injection energy distribution is managed using linac and debuncher, whilst ring buckets are manipulated using, RF frequency, volts and phase between the h=2 and h=4 systems.

Transverse trapping losses, that are associated with the high incoherent tune depression peaking at >0.5 at 0.4 ms, are managed by ramping tunes, varying injection painting amplitudes and optimising RF parameters. Significant loss due to the head-tail instability is discussed below.

The other critical aspect of tuning is localising beam loss on the collimator systems. This is achieved using closed orbit (13 dipoles) and envelope control (20 trim quadrupoles). Each element is powered independently and controlled in 0.5 ms steps. A typical ring loss distribution is shown in Fig. 4. Peak loss is confined to super period 1 (collimators) with a little out-scatter into super period 2.

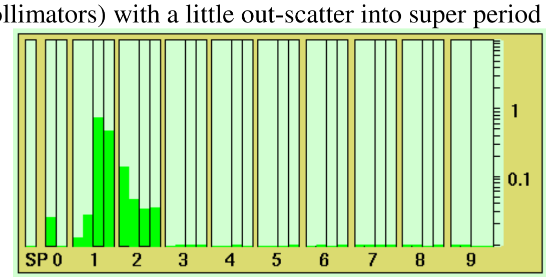

Figure 4: Beam loss around the 10 ring superperiods integrated over the acceleration cycle, 0-10 ms.

High Intensity Capability of the Ring

In its current configuration the ring has accelerated 3.15x10^{13} ppp at low repetition rate, equivalent to a 250 μA beam. Beam losses were at 9 % and well

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controlled, just within the limit of acceptable operation. Increasing intensity further is feasible, but would require use of more machine aperture (via improved alignment) and reduction in head-tail instability losses. Both are actively under study.

Beam Measurements and DAQ Developments

The essential ISIS diagnostics are: intensity toroids, ionisation beam loss monitors (BLMs), position monitors and profile monitors [7]. Intensity monitors and BLMs are used for machine protection, via fast trip systems, as well as determining loss levels and distributions. Diagnostics are used to routinely measure basic parameters such as: transverse position and width and bunch length. In addition they are used, via suitable processing, analysis and modelling, to provide more advanced parameters: injected betatron amplitudes, tunes, closed orbits, beta functions and longitudinal distributions. These measurements are used to correct machine errors, characterise low beam loss operation and are essential for accelerator R&D.

Advances in digitisation speed, acquisition depth and cost have enabled more signals to be acquired at higher resolutions. Increases in computing power allow more detailed analyses and visualisation of acquired data in an operational environment. Two such measurements, longitudinal waterfall and BLM distribution, Fig. 5, are now available, updating at ~2 Hz. Migration to FPGA environments should allow full ring repetition rate, 50 Hz, measurements to be obtained. Such automated fast systems will advance machine operation and tuning from raw signal optimisations to machine parameter tuning.

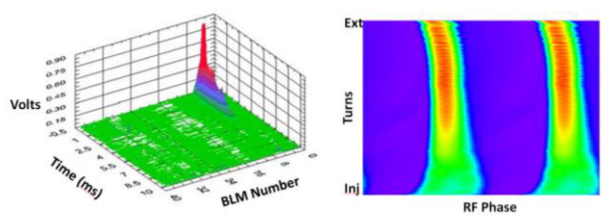

Figure 5: Spatial Beam loss distribution through the cycle (left), longitudinal waterfall plot, (right).

Scintillator Beam Loss Monitors

Beam operational levels were lowered between 2002 and 2006, Fig. 1, to manage a beam loss causing damage to an RF screen inside a main dipole, downstream of the collimator section in straight 1. Investigations concluded that uncontrolled loss escaping the collimators was the cause and conventional BLMs external to the dipole were shielded by the yoke. A non-metallic scintillator based BLM suitable for use in a fast cycling magnet was developed, and placed inside the yoke adjacent to the vacuum vessel.

Fig. 6, shows a scintillator (left) and loss traces (inverted) for the scintillator and BLM at the same lattice location. The scintillators show an equivalent signal thus validating those inside the dipole. These scintillators allowed detailed setup of the collimators and machine optimisations to minimise this loss mechanism [7]. Operational experience shows they do suffer signal degradation in high radiation fields. A study of these effects is in progress. A program to add scintillators to all 10 main ring dipoles will be completed by 2017.

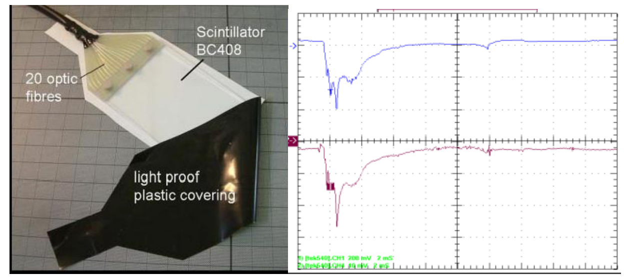

Figure 6: Scintillator (left), scope trace of scintillator and BLM (right) over the operational 10 ms cycle.

Transverse Profile Monitors

Accurate, non-destructive measurement of transverse profiles in the ring is essential for operation, modelling and high intensity R&D. Upgrades to the residual gas ionisation monitors allow beam profile measurements over thousands of turns in each machine pulse using an array of 40 channeltron detectors. Detailed studies of errors caused by ion drift field non-linearities and beam space charge have provided correction schemes and are an important area of development [8]. The detailed evolution of beam distributions these monitors provide are essential for more detailed understanding of beam loss mechanisms.

Head-Tail Instability and Beam Damper

The vertical head-tail instability has been observed in the ring since initial machine operations and typically causes loss at ~2 ms into the acceleration cycle [9]. This instability became more problematic after the DHRF upgrade, probably due to increases in intensity and bunch length: this is now one of the main loss mechanisms limiting operational beam intensity. Losses are minimised by decreasing vertical tune and by setting the bunch line density into an asymmetric shape using the phase difference between the h=2 and h=4 RF cavities.

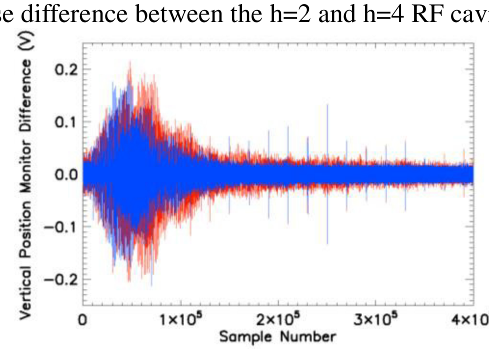

Figure 7: Vertical position monitor difference signal, 2-4 ms. Un-damped (red), damped (blue).

A damper system is now in development to counter this instability. A prototype system, with limited bandwidth

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and power has demonstrated damping operation in recent tests. Preliminary results, Fig. 7, show vertical position with the damper system on (blue) and off (red) from 2-4 ms in the acceleration cycle. A more powerful and wider bandwidth system with stripline pick-up and kicker has been designed and is due for installation in 2017 [10].

Detailed R&D work is also underway to model and understand the complicated head-tail motion, which is significantly modified by space charge. A new simulation code is being developed and detailed investigations of beam impedances have started. Initial measurements using a coasting, 70 MeV, beam show a clear narrowband impedance centred at 85 kHz, Fig. 8 [11].

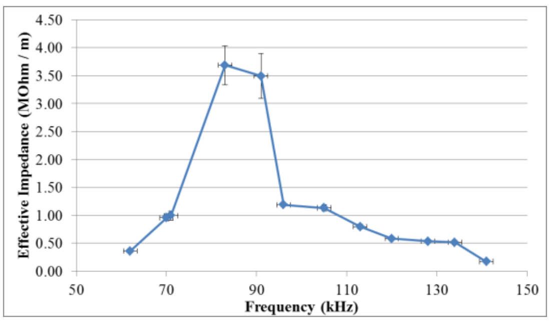

Figure 8: Beam-based measurement of effective impedance versus baseband frequency. Intensity = 1 × 10^{13} ppp.

Development of Ring Models and Simulations

Ring beam dynamics have been simulated in a variety of codes with the ultimate aim to understand and minimise beam loss. These inform tuning strategies during machine operation and contribute to accelerator R&D topics.

2D and 3D beam dynamics simulations with ORBIT [12] have allowed detailed studies of ring beam loss. These used linear lattice models to simulate injection and acceleration with dynamic tune, space charge, apertures and foil scattering. The model predicts 2.7 % loss compared with a measured 7 % loss [13].

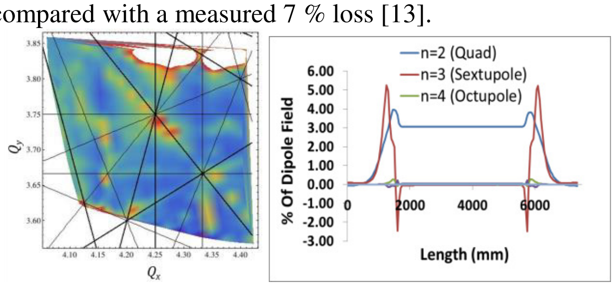

Figure 9: Ring Tune plane scan (left) and Main ring dipole multipole field distributions from OPERA model

New measurements of the tune plane, Fig. 9 left, show many higher order resonance lines not currently in the model. Non-linear magnet strengths, Fig. 9 right, derived from OPERA models and field measurements of magnets are being added to provide a more comprehensive and accurate lattice model for future studies.

Longitudinal dynamics have been simulated in ORBIT and an in-house code [13,14]. These models have been useful in achieving shorter extracted pulse lengths on ISIS for improved muon instrument performance, Fig. 10. Bunch length is compressed by ~50% FWHM with a combination of an adiabatic voltage ramp, switching the bunch length loop off during the final phase rotation and introducing a step function in the RF frequency. In other work, studies of longitudinal stability show the Keil-Schnell-Boussard (KSB) criteria is exceeded under normal ISIS operation. Understanding this effect is important as it is a key parameter for future machine designs.

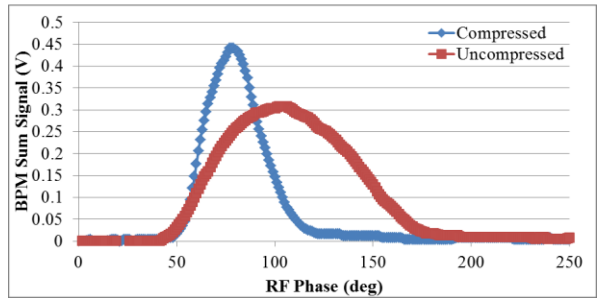

Figure 10: Position monitor line density vs RF phase for compression (blue) and normal operation (red).

FLUKA models are providing essential information on operation of the collimator system, factors determining activation levels, foil losses, operation of beam loss monitors as well as insight into machine damage. In particular, ORBIT beam loss simulation results have been used in FLUKA models of the injection and collimation straights to calculate machine activation, an important metric for current and future machine operations.

Studies of Loss Mechanisms

In addition to the work above, dedicated studies are looking at particular loss mechanisms, specifically half integer and image field losses.

Half integer resonance is often a main loss mechanism in high intensity proton rings, and is believed to contribute to trapping losses on ISIS. Detailed experiments have characterised beam redistributions during resonance crossing at high space charge levels and have been replicated well with comprehensive ORBIT simulations. Present work is concentrating on building simple theoretical models to explain the experimental results [15].

The effects of space charge and image forces in the unusual rectangular, conformal vacuum vessels in the ISIS ring are being studied in detail with the in house code SET3D [16]. Results indicate that closed orbit errors can lead to numerous extra driving terms from image forces, potentially resulting in additional beam loss.

FUTURE PROJECTS

MEBT Upgrade

Transverse beam loss in tank 1 due to optical mismatch from the RFQ can be reduced by installing an upstream MEBT matching section. This consists of quads and

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re-buncher cavities Fig. 11. Simulations predict transmission efficiencies of 96 % through the new section and zero losses in Tank 1 [17] potentially increasing linac beam currents from 26 mA to 35 mA. Beam loading on the linac RF systems may be an issue at the highest currents.

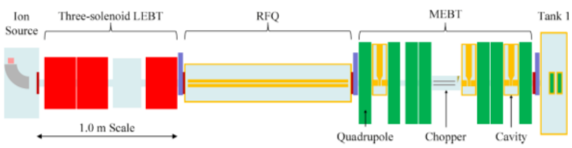

Figure 11: Arrangement of LEBT and MEBT.

The addition of a fast chopper in the MEBT allows direct injection into ring RF buckets. Beam simulations using the ORBIT code, for a 26 mA injection current chopped, with 60 % duty factor, and un-chopped, are shown in Fig. 12. Injection losses increase due to higher space charge levels of the chopped beam and also the increased injection interval, 200 µs to 300 µs, which increases loss due to foil scattering. However losses during acceleration currently associated with trapping at ~0.4 ms are much reduced. Overall beam losses are similar but at lower energy producing lower machine activation. Longitudinal optimisations for a 35 mA injection current case, which should have reduced foil losses is under study. MEBT designs and ancillary installations are in progress with full installation and commissioning due in 2019

Research for ISIS Upgrades

A number of ISIS upgrade options are under study. These range from staged upgrades of the present facility to ‘green field’ designs. A detailed consultation is also underway with expert teams on instruments, neutronics and targets to determine the optimal configuration for the next generation spallation source.

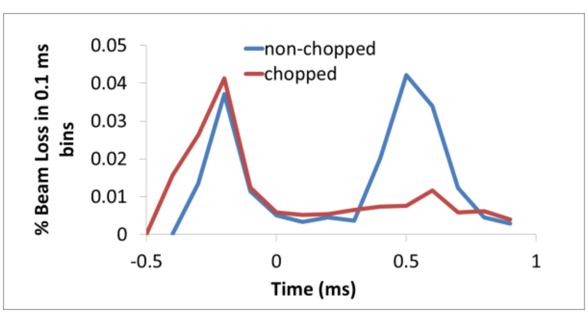

Figure 12: ORBIT simulations of injection and trapping loss, under normal operation and with an injection chopper.

Current ideas include upgrading the injector to 180 MeV, allowing beam powers of 0.5 MW from the existing ring [18], possibly followed by staged upgrades with rings in the existing hall - RCS or FFAG - which could feed multiple targets and be developed well into the multi MW regime. Detailed studies of optimal RCS and FFAG ring designs for these ideas are in progress [19].

The Front End Test Stand (FETS) currently under construction at RAL is a technology demonstrator for use on a high power linac [20]. Designed to deliver 60 mA, H^- beam, at 3 MeV with 10 % duty factor, possible applications include a linac upgrade. First beam through the RFQ is expected by the end of 2016. One exciting possible application for FETS is as an injector for a new "proof of principle" low energy FFAG ring. This would demonstrate the key aspects of performance for a future ISIS upgrade which could exploit all the advantages of a high intensity FFAG ring [19].

CONCLUSIONS

Since first commissioning in 1984, the ISIS facility has undergone a series of upgrades to improve machine performance. Developments to accelerator R&D and diagnostics have aided understanding of how to operate a machine close to the intensity limit in a controlled and sustainable manner. Experience and knowledge gained will be essential to develop ISIS, and design future upgrades.

REFERENCES

[1] D. Findlay,ISIS-Pulsed Neutron And Muon Source,PAC07.
[2] A.Letchford, PAC05, Testing, Installation, Commissioning and first operation of the ISIS RFQ pre-injector upgrade.
[3] C. Plostinar, IPAC12, Modelling the ISIS 70 MeV Linac.
[4] C R Prior, A-11, ICANS-XII, RAL Report 94-025, “Studies of Dual Harmonic Acceleration in ISIS”.
[5] A. Seville, EPAC08, Progress on Dual Harmonic Acceleration on the ISIS Synchrotron.
[6] A. Seville, IPAC13, Progress on the ISIS Synchrotron low power RF system upgrade.
[7] S. Payne, HB2008, Beam Diagnostics at ISIS.
[8] R. Williamson, IPM Simulation and Correction with Strong Space Charge, Proc IPM Simulation Workshop, CERN (2016).
[9] G.H.Rees, Interpretation of the Higher Mode Head-Tail Motion Observed on ISIS, Particle Accelerators, Part Accel V39, 1992.
[10] S. Payne IBIC13, “Stripline monitor design for the ISIS proton synchrotron using the FEA program HFSS”.
[11] R. Williamson, HB2016, Developments of Physics Models of the ISIS Head-Tail Instability.
[12] J.A. Holmes et al., ORBIT User Manual, ORNL Tech. Note SNS/ORNL/AP/011.
[13] D. Adams, PAC12, “Beam loss studies on the ISIS synchrotron using ORBIT”.
[14] R.E. Williamson, HB2012, “High Intensity Longitudinal Dynamics Studies for an ISIS Injection Upgrade”.
[15] C. Warsop, HB2016, “Simple Model for Beam Loss Near the Half Integer Resonance with Space Charge”.
[16] B. Pine, Image Fields in the Rectangular Vacuum Vessels of the ISIS Synchrotron, HB2014.
[17] T Wood, “The ISIS pre-injector reconfiguration”, Review of Scientific Instruments 87, 02B121(2016).
[18] D. Adams, HB2014, “Ring Simulations and Beam dynamics studies for ISIS upgrades 0.5 to 10 MW”.
[19] C Prior, HB2016, “Studies of High Intensity Proton FFAGs at RAL”.
[20] A. Letchford, Linac2014, “Status of the FETS Project”.

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