BEAM LOSS CONTROL IN THE ISIS ACCELERATOR FACILITY

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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 ~2.8x10^{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 dominant beam loss in the facility occurs in the synchrotron due to high intensity effects during the H^- injection and longitudinal trapping processes. Losses are localised in a single region using a collector system. The measurement, simulation and correction systems for these processes are described. Emittance growth during acceleration can also drive extraction and beam transport loss at 800 MeV - measurement and control systems for these are also outlined.

INTRODUCTION

The ISIS accelerator complex has been delivering beams for neutron and muon experiments since 1984. The facility consists of an H^- ion source, 665 keV RFQ, 70 MeV H^- linac, 70 MeV H^- beamline (HEDS), 800 MeV proton synchrotron and two 800 MeV extract proton beam lines, EPB1 and EPB2, delivering beams to Target Stations 1 and 2 respectively. The facility operates at 50 Hz delivering 160-200 kW of beam power shared between two target stations. This equates to synchrotron intensities of 2.5-3.0x10^{13} ppp. A schematic layout of the facility can be found in Fig. 1.

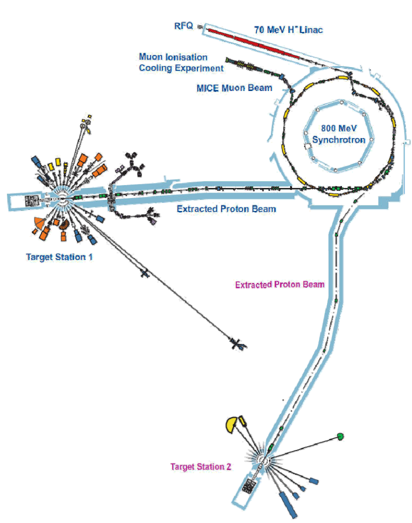

Figure 1: Schematic layout of the ISIS facility.

Operation of the facility depends upon the control of beam losses, particularly in the synchrotron where the high beam intensities have significant effects. This paper describes the beam loss diagnostics on ISIS and how they are presented in a Main Control Room (MCR) environment. Operating levels throughout the facility are presented and methods of optimisation are discussed. Beam loss mechanisms are described and hardware upgrades addressing some of these processes are discussed. Future areas of study are also presented.

ISIS BEAM LOSS DIAGNOSTICS

Beam losses on the accelerators are mainly detected using two diagnostics: resonant current transformers (intensity monitors) and argon gas filled coaxial ionisation tubes (beam loss monitors). Intensity monitors have a sensitivity of ±3 μA in the injector and ±3x10^{10} ppp in the ring and EPBs. Beam losses are calculated based on difference measurements between two points or times in the accelerator. Beam loss monitors (BLMs) are located ~2 m from the beam axis and detect epithermal neutrons produced when a H^- or proton beam hits an accelerator component such as a magnet or vacuum vessel. They are 3 to 4 m long and are distributed to cover almost the whole accelerator to ensure any significant loss is detected. These monitors have a sensitivity of ~1.2x10^9 to 7x10^6 lost protons between 70 and 800 MeV respectively.

Interlock systems compare signals from both diagnostic types to trip levels on a pulse by pulse basis to turn the machine off in the event of a fault. Table 1 shows the distribution of these monitors across the facility.

Table 1: Beam Diagnostic Layout

	Intensity Monitor	**Beam Loss Monitors**
Ion Source	1	0
RFQ	2	0
Linac	4	9
HEDS	4	8
Synchrotron	1	39
EPB1	6	10
EPB2	5	15

Scintillators are also used to detect particle losses in regions where installation of normal beam loss monitors is not practical. At ISIS we use plastic scintillators (BD408) with dimensions 150x100x3 mm. They produce analogue signals in a similar manner to our beam loss

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monitors, allowing temporal analysis. They are currently used inside the challenging environment of a synchrotron fast cycling dipole to detect potentially damaging beam loss out-scattering from the upstream beam collector system. Portable units to monitor radiation hotspots which are shadowed from BLMs are also in development. A full description of all the beam diagnostics on ISIS can be found in [1].

INJECTOR OPERATION

The injector consists of a Penning H^- ion source delivering ~50 mA beam which is transported and matched into a 665 keV RFQ using three solenoids. The H^- beam is then injected into the DTL tank 1 and accelerated to 10 MeV. Diagnostics in this region are limited to intensity monitors alone. Matching and accelerating through this tank is 70-80 % efficient and is tuned using the tank quadrupoles and phase of both the RFQ and tank 1. Studies to improve this efficiency are underway and propose adding quadrupoles and buncher cavities in-between the RFQ and tank 1 [2].

Acceleration through the remaining linac, tanks 2, 3, 4 up to 70 MeV, and transport through the HEDS is mainly lossless and tuned using tank phases and quadrupole settings. Intensity and beam loss monitors are used for fine tuning in this region. Typical intensity driven transmission efficiencies are shown in Fig. 2.

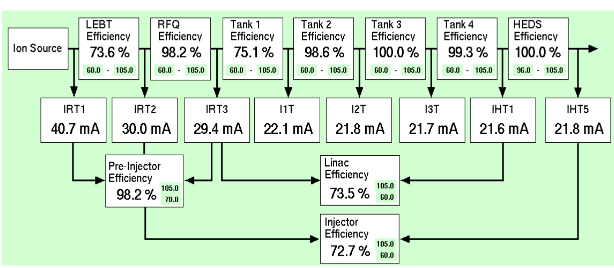

Figure 2: MCR Screen:Injector intensity monitor efficiencies.

Beam loss monitors are used from tank 2 to the end of the HEDS, and are displayed in the MCR as histogram plots where bar height represents the integrated beam loss over the injected pulse in volt seconds (Vs). These monitors have similar sensitivities to ring BLMs hence 0.1 Vs is equivalent to 2.3×10^9 lost H^- particles. A typical plot is shown in Fig. 3.

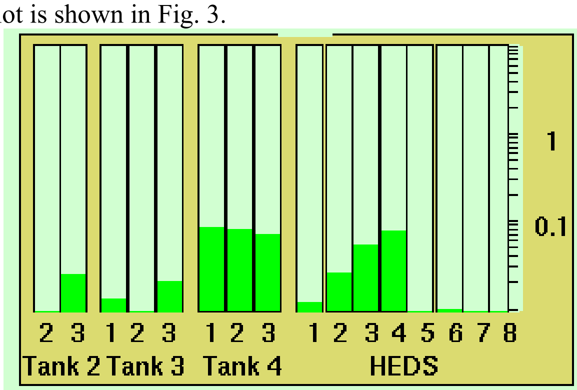

Figure 3: MCR Screen: Injector BLM histogram plot.

SYNCHROTRON OPERATION

Injection

ISIS operates a multi-turn charge-exchange injection scheme. The 70 MeV H^- beam is injected into the synchrotron through a 0.25 μm aluminium oxide foil accumulating ~2.8 $\times 10^{13}$ protons over ~130 turns. The foil is mounted in the middle of four dipole bump magnets which also remove un-stripped beam. The bump is collapsed after injection to limit foil recirculation to ~30 per injected proton. A schematic of the injection elements is shown in Fig. 4.

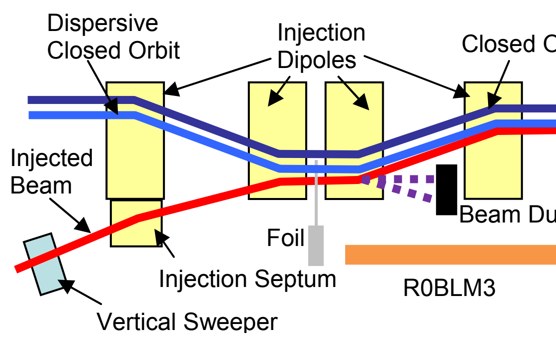

Figure 4: Schematic layout of the injection system.

During injection the beam is painted transversely to reduce space charge forces. Vertical painting is achieved with a programmable dipole upstream of the foil. Horizontal painting makes use of the moving dispersive closed orbit generated by an energy mismatch between the constant injection energy and the changing synchronous energy due to the falling main magnetic field in the ring.

Injection efficiencies are usually >98 % with beam losses predominantly located in the injection straight or on the collector system. Injection straight losses are due to the unstripped beam (~2 %) hitting a beam dump upstream of the last bump dipole. A beam loss monitor in this region (“R0BLM3” see Fig 4) is used to measure this loss and also beam missing the foil. Persistent, untunable increases in the signal provide an early indicator of foil failure. Beam losses on the collectors are from foil scattering emittance growth and closed orbit errors.

Beam losses during injection are optimised by moving the foil and the transverse beam parameters at the injection point in both the ring and the HEDS. The injection design has a fair degree of flexibility to paint over the upper vertical axis or lower vertical axis in both correlated or anticorrelated manners. This has allowed holes in a damaged foil to be avoided to continue user run operations [3].

A fast electrostatic chopper in the injection line allows injected beams of <1 turn into the ring. This allows low intensity lattice parameter measurements as well as injection painting and injected momentum spread measurements [4]. It also allows first turn, low intensity diagnostics measurements which are sometimes required

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to diagnose and overcome major problems (e.g. magnet polarity errors) after upgrade or maintenance periods.

Trapping and Acceleration

After injection the beam is trapped and accelerated from 70–800 MeV in 10 ms. Beam losses during trapping, (0-2.5 ms), are the dominant loss in ISIS and usually limit the running intensity of the facility. Longitudinally the losses are due to the trapping process whereby the accumulated DC beam is trapped into two bunches using the h=2 rf system. This trapping process has been improved with the addition of an h=4 rf system [5] which increases the longitudinal bucket acceptance and the bunching factor. Transversely the losses are due to a combination of high intensity effects driving emittance growth. This is mostly mitigated by ramping the betatron tunes with programmable trim quadrupoles during the acceleration cycle. The operational commissioning of two further h=4 cavities should further improve beam losses allowing higher operating intensities to be achieved whilst maintaining the same total loss levels.

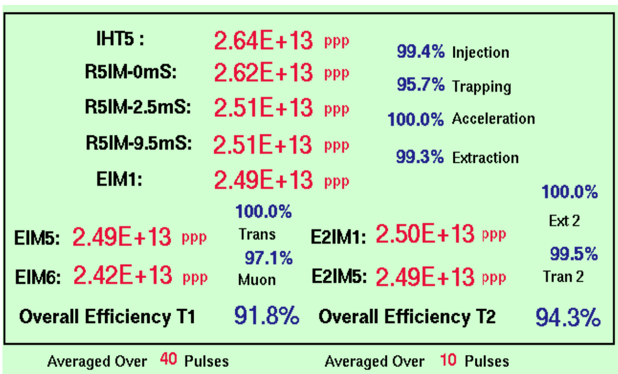

Figure 5: MCR Screen:Typical operating ring and EPB intensity and transmission efficiencies.

Typical operating transmission efficiencies are given in Fig. 5. The ring is generally tuned with reference to three efficiences: injection, trapping and extraction, where injection efficiency is calculated from the beam intensity injected into the ring compared to intensity accumulated at the end of injection (0 ms). Trapping efficiency is calculated from the beam intensity change from 0 ms to 2.5 ms and extraction is calculated from the circulating beam intensity prior to extraction compared to beam intensity at the beginning of EPB1.

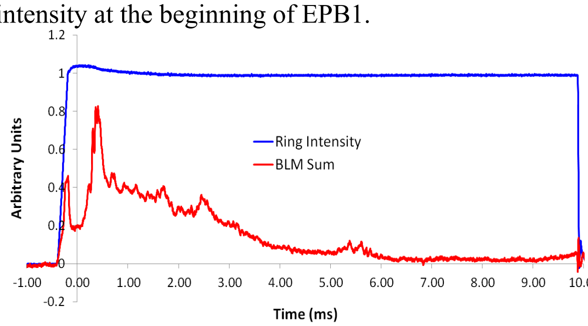

Figure 6: Sum BLM and intensity versus acceleration time.

There are 39 beam loss monitors in the ring which provide both temporal and spatial measurments. The circulating intensity and sum of all 39 BLMs versus time in the acceleration cycle are shown in Fig 6. The integrated beam loss from 0-10 ms for on each BLM is shown in Fig.7.

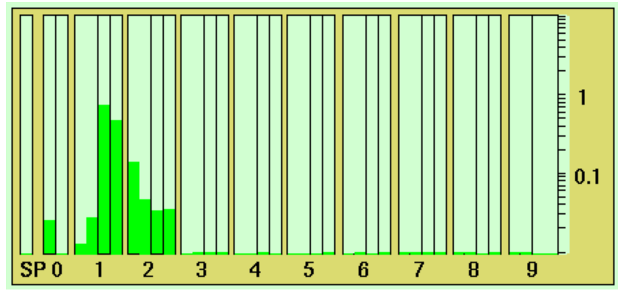

Figure 7: MCR Screen: Integrated ring beam loss (Vs) on each BLM over the acceleration cycle, 0-10 ms.

Extraction

Ring extraction is a two stage process. A vertical closed orbit bump is established over the last 2 ms of acceleration, raising the beam 15 mm underneath the extract septum using four steering magnets. The beam is then extracted on a single turn by exciting 3 fast kicker magnets deflecting the beam ~1 ° into the septum. Beam loss monitor measurements next to the septum register a peak loss of 12 µVs generated by the beam on the extracted turn which corresponds to < 0.1 % intensity loss.

Studies show this loss is a result of vertical aperture constraints of the septum and ring quadrupoles just upstream which limits the transported acceptance to 220±20 π mm mrad. Measurements using orbit bumps and ring BLMs show the beam has a ~100 % emittance of 280±20 π mm mrad. Changing the bump and replacing the septum with a larger aperture unit has increased the acceptance to 280±20 π mm mrad [6] and reduced losses to < 1 µVs. However extraction loss is still susceptible to emittance growth during acceleration. Careful control of betatron tunes and closed orbits maintain these low loss conditions.

Collectors and Loss Control

The beam loss collector system is installed in one of the 10 ring super periods (SP1) near injection and extraction systems, thus localising activation in one region. Two primary jaws, composites of copper and graphite to optimise out-scatter and activation properties, define the machine acceptance in each plane. A set of graphite secondary collimators downstream of the primaries allows for interception of out-scattered protons. All jaws are adjustable (to ~1 mm) and the temperature change of cooling water gives a valuable indication of location and level of loss. Collectors are 310 mm long, allowing for effective interception of beam energies beyond the nominal ~100 MeV trapping loss. More details are in [7]. For present operations primary collectors are positioned at ~75 % of the ring acceptance and intercept ~ 400 W of beam power in each of the horizontal and vertical planes.

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The limited space (betatron phase) available for the collector system has always made the ring dipole immediately downstream susceptible to outscatter and lost beam. Therefore the use of scintillators in this dipole, to ensure effective loss control, has been of particular importance.Figure 8 shows example output from 12 scintillators installed on the inside radius. Output is similar to ring BLMs in the area and shows loss over the whole 10 ms cycle. Each signal (white) shows the usual trapping loss signature (0-2.5 ms) but there are also mid-cycle losses visible which would be tuned out. A reference 'good data' set is shown in red.

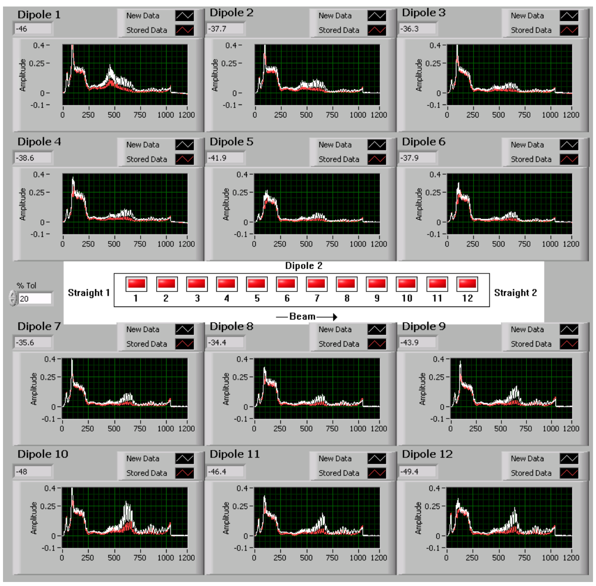

Figure 8: Ring dipole 2 scintillator outputs showing large mid cycle beam loss (white), previous reference (red).

Beam Loss Optimisations

The hardware design philosophy on the synchrotron has been, where possible, to control hardware with programmable function generators, thus providing maximum flexibility. These function generators are custom units allowing temporal control resolution to 5 µs. In practice they are used to tune the ring in 0.5 ms steps (~20 steps in the whole cycle) with linear interpolated values in the intervening times. These units are used on steering magnets, trim quadrupoles, injection vertical sweeper, rf volts, frequency and loop gain. In general two function generators, 'Normal' and 'Experimental', control each piece of hardware. The 'Experimental' function generator can be run at lower frequencies (<1.6 Hz) compared with the 50 Hz 'Normal' function allowing beam loss tuning over a wide parameter space without perturbing user run machine operations.

The most often used and successful tuning elements are trim quadrupoles and steering magnets. The 20 trim quadrupoles are used to vary the operating betatron tunes through the cycle. A system of harmonic (at 2Q) field deviations at various phases can also be applied to manage envelope mismatch. Upgrades currently being commissioned allow individual trim quadrupole control and should allow much more flexibility on envelope manipulation. Steering magnets are used to correct closed orbits or apply local bumps. Again a harmonic system (at Q) allows closed orbit tuning.

Longitudinal losses during injection are minimised by matching the linac injection energy/spread to synchrotron RF buckets by varying linac phases, ring RF volts and frequency. Acceleration losses are optimised by varying the rf volts and phase of the h=2 and h=4 cavities.

The overall strategy on beam loss tuning is to move all beam losses into super period (SP) 1 and 2 and also to minimise the losses there. This is mainly achieved using two signals: BLM sum, the sum of all 39 beam loss monitors in the synchrotron, and the same signal but without monitors in SP1 and 2. Fig. 9 shows these signals for a typical well set up machine. Fig.10 also illustrates more spatially how the ring losses have been confined to a single region of the machine.

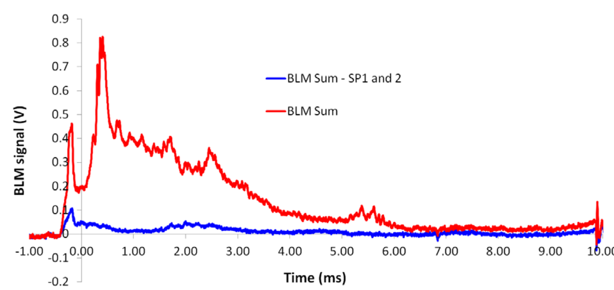

Figure 9: BLM sum and BLM sum without SP1,2.

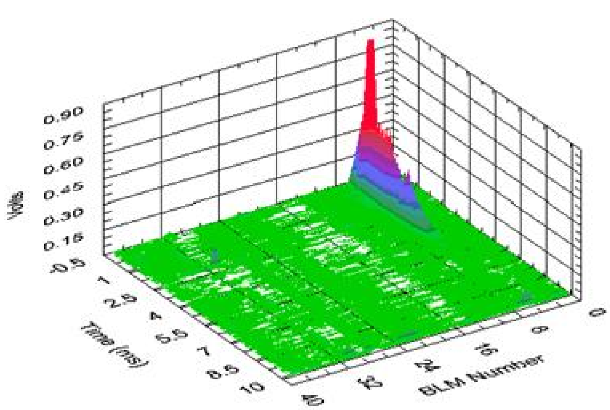

Figure 10: 3D plot of ring BLM number, volts and time.

High Intensity Limitations and Studies

The important high intensity effects on the ISIS ring are associated with the longitudinal trapping process, high transverse space charge and transverse instability. Longitudinal effects are being addressed with the continued study and development of the h=4 rf system. Peak transverse incoherent tune shifts due to space charge are estimated to exceed -0.4, thus running the machine close to the space charge limit. The action of this loss mechanism, and of related image effects, are the subject of current study [8, 9, 10]. The vertical resistive-wall head-tail instability has been observed on the machine,

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but controlled and generally avoided by ramping vertical tunes downwards. However, as intensities have increased with the use of the h=4 rf systems, its effects are increasingly observed with losses at 2 ms into the acceleration cycle. Optimisations of vertical tune and closed orbits are used to minimise the effects. Studies are underway to improve understanding of these effects and designs of damper systems are being developed.

Simulations

The particle tracking code ORBIT [11] has been used to try and understand the high intensity loss mechanisms observed in the ring. The simulation includes injection, foil scattering, acceleration, space charge, apertures, collimators and RF frequency errors. It has been fitted to measured transverse profiles during injection [3] and longitudinal profiles during injection and trapping. Predicted acceleration efficiencies were 97.5% compared to a measured 93 % [12]. Beam losses were deposited on the primary collectors equally between the horizontal and vertical planes as observed on the actual ring. The time structure of the losses is shown in Fig.11 and shows reasonable agreement.

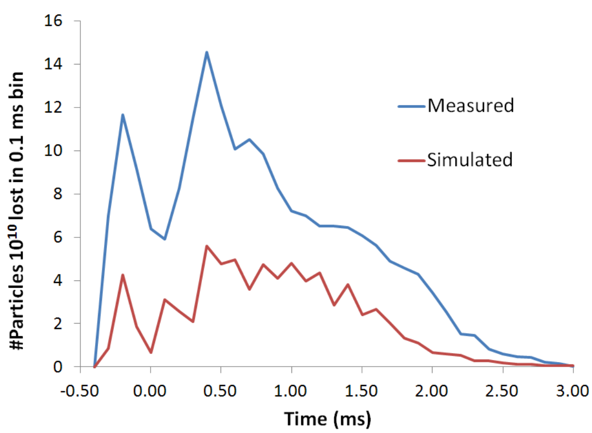

Figure 11: Measured versus predicted beam loss.

The model suggests that half of the loss on ISIS is generated by high intensity effects leading to vertical emittance growth. These mechanisms are the subject of future studies. It is expected that modifications to painted distributions will improve these losses as well as the planned increase in h=4 cavity volts leading to higher bunching factors.

800 MEV TRANSPORT LINES

The 800 MeV proton beam lines, EPB1 and EPB2, transport beams to Target Stations 1 and 2 respectively. Beam intensity and beam loss monitoring show very low loss operation. Figure 12 shows the integrated beam loss for both beam lines.

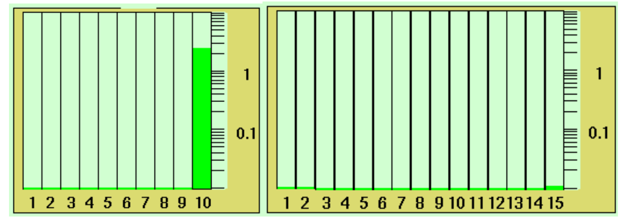

Figure 12: Beam loss readouts, EPB1 (left), EPB2 (right).

Such low loss operation is achieved by setting the aperture to have a minimum clearance of 20 mm outside the measured ~100 % beam emittance of 300 π mm mrad. EPB1 beam loss shows a large (3.5 Vs) signal on BLM number ten, equivalent to 1.2 $\times 10^{12}$ lost protons. This is due to a 10 mm thick carbon target, used for muon production, which is placed on the proton beam axis, scattering the transported proton beam. Downstream collimators intercept most of the scattered beam creating the measured beam losses [13].

CONCLUSIONS

The ISIS beam loss diagnostics and their implementation in the accelerator facility has been presented. Beam loss mechanisms, strategies for optimisations and proposed machine upgrades to mitigate some of the operational issues have been discussed.

The extensive operational experience outlined above, along with detailed simulation and study of high intensity effects at ISIS provides the ideal foundation for proposed ISIS upgrades [14].

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