ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPGW091

BEAM LOSS CONTROL WITH SCINTILLATING MONITORS AT ISIS

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Abstract

The ISIS Facility at the Rutherford Appleton Laboratory produces intense neutron and muon beams for condensed matter research. Since 1984 its 50 Hz, rapid cycling synchrotron has accelerated protons from 70 to 800 MeV and now typically delivers 0.2 MW of beam to two target stations supplying thirty-four instruments.

Control and minimisation of beam loss is vital to the success of high-power proton accelerators. Coverage and sensitivity of beam loss monitoring at ISIS has recently been improved by the installation of scintillating monitors inside the synchrotron's main dipoles. In addition to their primary goal of preventing damage to dipole RF screens, these monitors have also provided a highly sensitive tool for empirical accelerator optimisation.

INTRODUCTION

The ISIS synchrotron accelerates up to 3×10^{13} protons per pulse from 70 to 800 MeV in 10 ms, at 50 Hz. The 163 m circumference ring is filled over 200 µs (130 turns) via H^- charge-exchange injection through a ~1 µm carbon foil. The working point is $(Q_h, Q_v) = (4.31, 3.83)$.

Typically, 1 - 2% of the beam is lost during injection due to foil interactions and stripping inefficiency. The un-chopped injected beam is captured by the dual-harmonic RF system over the first 3 ms of the acceleration cycle. During this time, a further 2-3% of beam is lost.

From 2 to 4 ms during the acceleration cycle, a vertical head-tail instability is observed with resulting losses peaking at 2.5 ms. The vertical betatron tune is rapidly reduced to 3.75 at this time, away from the integer, to reduce the instability growth rate. However, for ≥ 200 µA operation, up to 0.5% of beam is lost in this period. The remainder of the acceleration cycle is virtually lossless until extraction at 9.8 ms. Extraction is vertically upwards via three low impedance, single turn, lumped element ferrite kickers into a DC septum. The process is very efficient with < 0.05% of the beam lost.

BEAM LOSS MONITORING

The beam loss monitoring (BLM) system is vital to the continuing high-power operation of ISIS as it prevents equipment damage and enables essential 'hands on' maintenance procedures by limiting component activation.

Ionisation Chambers

Loss is primarily detected by 3 m long, argon-filled ionisation chambers distributed around the inside radius of the synchrotron at floor level, giving near-total azimuthal coverage for measurement of evaporation neutrons [1]. Signals are processed via wideband (0-20 kHz) amplifiers and digitised by custom FPGA boards. Integrated losses are displayed at 50 Hz in the control room and fed into the interlock chain. The system provides a sensitive, fast but qualitative measurement of loss with a spatial resolution superior to that given by the intensity monitors. Sensitivity of the system increases by a factor of ~100 over the energy range of the synchrotron, with the neutron yield and argon ionisation cross-section. This scaling has proved to correspond well with the activating effect of losses through the cycle [2] and the monitors have allowed safe, high-power operation of ISIS for several decades.

Scintillators

The ionisation monitors are ineffective at measuring losses inside the main dipoles of the synchrotron, which account for 25% of the circumference, as they are shielded by the magnet's thick steel yokes. In the past, RF screens, wire cage structures which provide a low impedance for beam-induced currents, inside dipoles have been damaged by unseen beam loss leading to lengthy periods of downtime for repair [2]. Scintillating BLMs have been installed along the inside radius of each of the ten main dipoles to improve monitoring of these losses [3].

The monitors are 150×100×3.5 mm blocks of the plastic scintillator BC-408. Six monitors, with entirely non-metallic support assemblies to avoid eddy currents, are installed in each dipole, Fig. 1. Optical fibres connect each monitor to a photo-multiplier tube (PMT), these are cabled via custom electronics to a PXI data acquisition system. Data is published at 50 Hz over the site network to allow real-time optimisation of beam parameters. The monitors are sensitive to a wide range of secondary products generated by lost beam striking accelerator components. Prior to installation, each monitor was calibrated with a strontium-90 source and the PMT voltages set accordingly.

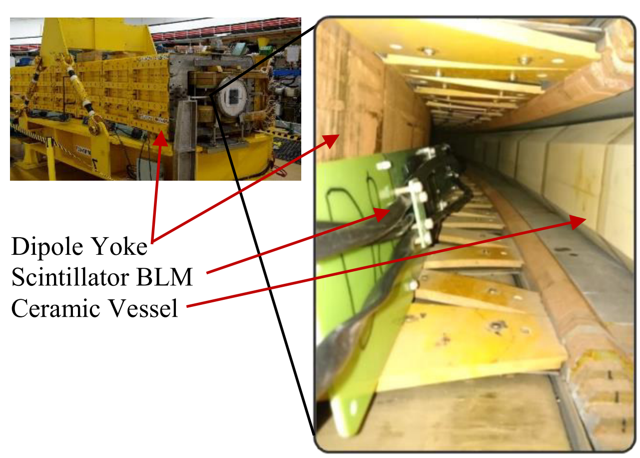

Figure 1: Scintillator BLMs installed inside a synchrotron main dipole between the yoke and ceramic vacuum vessel.

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BEAM OPERATIONS

History (1990s-2000s)

Initial designs for the ISIS ring, then the highest power RCS ever built, sensibly made provision for up to 50 % beam loss (<1% above 100 MeV) in order to achieve the design current of 200 μA [4]. However, after a decade of careful optimisation and development this design current was achieved for user operation in 1995 with only 10 - 12 % beam loss. With continuing improvements to machine components and beam control capabilities, beam loss was gradually decreased to 6 - 7 % by the early-2000s. Beam intensity however, was often restricted to ~170 μA as damage to the RF screens inside dipoles was encountered several times per year [2].

A second neutron-producing target station was added to the facility in 2008 to receive one-fifth of the synchrotron beam power. A program of accelerator upgrades, including complete replacement of the collimation and extraction region and a second-harmonic RF system, were completed to increase operating beam current and thus maintain the output of the original target station instruments. Operating beam current steadily increased over the last decade as these complex upgrades have come to fruition. However, difficulties with the tantalum-tungsten cladding has restricted beam intensity to the new target to 40 μA to improve target lifetime.

The average beam current during user operation is shown in Fig. 2; a fuller account of the operational history of the facility as a whole is given in [5].

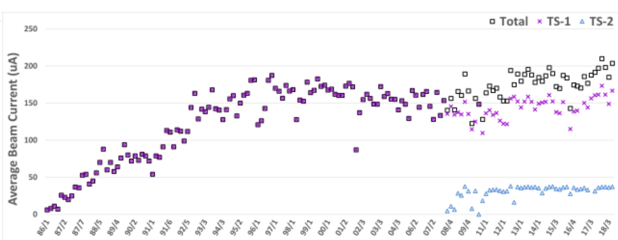

Figure 2: Average beam current per user cycle (excluding downtime) delivered by the ISIS synchrotron.

Recent Experience (2010s)

The first scintillating BLMs on ISIS were installed in Dipole 2, downstream of the collimation region, in 2006 to help combat the recurrent damage to RF screens. The monitors successfully prevented any beam related damage to this dipole while in service. Several *ad-hoc* additional monitors were added in response to radiation hot-spots or suspected aperture restrictions in the following years and these proved useful for machine optimisation. In 2015, it was decided to install monitors in all ten synchrotron dipoles for full coverage.

Installation was performed in sections as the operations schedule allowed. The first dipole set was installed in August 2016, two more in the summer shutdown of 2017, another in January 2018, one in April 2018 and the remaining five in August 2018. Following each phase of installation, machine settings were optimised to reduce the detected losses on the scintillators available, in addition to the standard setup and optimisation procedures using the existing diagnostics. Beam losses and intensity during the period of scintillator BLM installation are shown in Fig. 3. Blue bars indicate the daily average beam loss detected on the synchrotron ionisation loss monitors per beam pulse, the red dots are the daily average beam intensity excluding downtime.

The average loss per pulse, summed over all ionisation BLMs in the synchrotron has been held stable at 1.3 ± 0.3 Vs/pulse from 1991 to 2016 while beam intensity has been varied as synchrotron efficiency permitted. In 2017 the average loss was reduced to 1.1 ± 0.4 Vs/pulse, in 2018 it was 0.8 ± 0.5 Vs/pulse and thus far in 2019, average losses have been reduced to 0.4 ± 0.2 Vs/pulse, a factor of three reduction from the long-term operating level. Simultaneously, average beam intensity during operation has increased by 10% from approximately 200 to 220 μA between 2016 and 2019. This intensity had been reached previously but with higher loss levels and numerous occurrences of beam related damage.

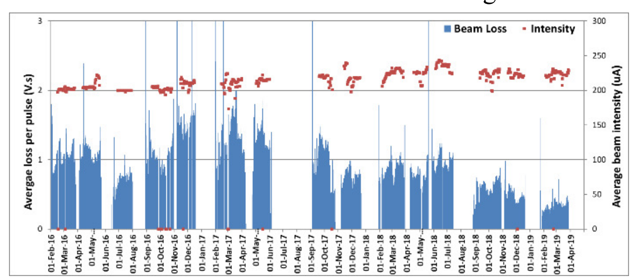

Figure 3: Average daily beam loss and intensity.

New records for highest beam intensity during operation (235 μA) and during machine development time (258 μA equivalent at 1 Hz) and a new record for beam delivery in one day (5.6 mAh) have all been set in FY2018/19. Overall synchrotron efficiency measured by intensity monitors has increased from 94.6 % to 96.1 % over the same period.

SCINTILLATOR BLM PERFORMANCE

Operating Experience

The scintillator BLMs are not themselves responsible for the improved operating efficiency of the synchrotron. All components of the facility undergo continual improvement. Recent key developments include: increases of the ion source output and linac transmission; digital low-level control providing improved stability of the dual-harmonic RF system; addition of low-pass filters to the correction magnet power supplies to remove a resonance causing mid-cycle beam loss. In combination, these developments provide a much more stable base for machine optimisation to build upon. However, the scintillators provide extremely sensitive loss monitoring to enable greater fine-tuning of machine parameters than was previously possible.

In the first user cycle following installation of the full set of scintillator BLMs, measureable loss was found in all dipoles and at all times within the acceleration cycle.

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Standard optimisation procedures for closed orbits and beam envelopes resulted in significant reduction of these losses and improvement to acceleration efficiency. During the machine development time at the end of the cycle, the scintillator BLMs response to collimator position was measured. The collimator aperture had been set to ~77% of the acceptance for more than a decade as losses measured via the ionisation chambers were successfully restricted to the collimation straight and no significant activation or damage was seen elsewhere. The sensitivity and coverage of the new scintillating BLMs has allowed a steady increase of the collimator aperture whilst ensuring loss localisation and protection of the dipole vessels. For the second user cycle, the aperture was increased to 79% and then to 82% for the first cycle of 2019. The effect of these changes are illustrated in Fig. 4**.** Three representative data sets of the sum of all the scintillator BLMs are shown, from September 2018 when the full complement of detectors were first used, November 2018 when losses had been reduced by beam tuning procedures and February 2019 when the collimation system had been re-optimised.

Note that in each of the cases shown in Fig. 4, the intensity monitors showed good efficiency (96 – 97 %) and the ionisation chamber BLM loss levels were similar and perfectly acceptable. The losses were only visible and actionable due to the presence of the scintillator BLMs.

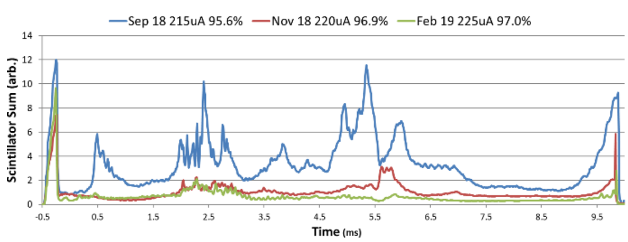

Figure 4: Comparison of losses detected by the scintillator BLMs between September 2018 and February 2019.

Radiation surveys of the synchrotron main dipoles have been made at the end of each user cycle (two hours after beam) since the installation work began, to assess the risk to staff during installation and also to monitor the effect of the reduced beam loss. Comparing July 2018 to April 2019, i.e. the period when all dipoles have been fitted with scintillator BLMs, activation has been reduced by 40% on average as shown in Fig. 5**.** Dipole 2 is immediately downstream of the collimator straight.

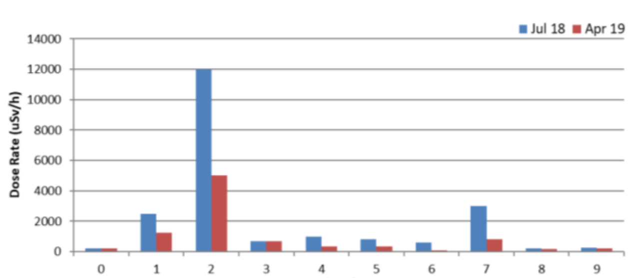

Figure 5: On-contact activation levels of the synchrotron main dipoles before and after scintillator BLM installation.

The reduction in activation approximately corresponds with the proportional reduction in loss. However, the distribution of activation does not match the distribution of losses detected by the scintillators which are generally uniform. This suggests a discrepancy between loss detection by the scintillator BLMs and its activating effect.

Detector Efficiency and Radiation Tolerance

Building upon previous studies of the collimator activation [6], FLUKA models of beam loss inside Dipole 2 indicate that the bulk of the secondary products are 10 - 100 MeV neutrons. The scintillator BLMs are made from BC-408 which was chosen for its high light output for a broad range of radiation. However, it has poor sensitivity to the MeV range neutrons. Tests of alternative materials with higher fast neutron sensitivity such as BC-416 or the boron-doped BC-454 are planned with a view to installing an additional set of monitors in Dipole 2 to monitor collimation efficiency.

The total ionising dose received by the scintillators has been measured using RadFETs [7]. For the worst-case, in Dipole 2, we expect the scintillators to receive 1 – 2 kGy/year. Studies of plastic scintillator degradation following exposure to 6 MeV protons [8] found no significant effect below 1 MGy giving confidence that the ISIS system will provide reliable data for the lifetime of the facility. A prototype set of detectors have been recovered from the synchrotron after exposure to ~20 kGy. It is planned to repeat the pre-installation calibration procedure on these detectors to determine the degradation suffered.

Recalibration of the monitors in service is still a concern as PMT gains may vary and cables will degrade. Regular removal for recalibration is not feasible due to the dose to staff and the risk of damage to the optical fibres. Attempts have been made to calibrate the scintillator BLMs to the main ionisation chamber BLMs by creating small, localised beam losses. However, it has not been possible to produce a significant signal on the ionisation BLMs without saturating the scintillators, the dynamic ranges of the two systems do not overlap sufficiently.

SUMMARY

New scintillator BLMs at ISIS provide full coverage loss monitoring and have proven to be a highly sensitive tool for machine optimisation. They assist with the implementation of continuing accelerator developments which, since 2016, have enabled the facility to increase its science capability (a 10% increase in beam intensity) whilst minimising risks to equipment and staff (a factor of 2 - 3 reduction in beam loss and activation).

ACKNOWLEDGEMENTS

The authors are grateful for the valuable assistance of the ISIS Detectors, Operations and Health Physics groups.

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REFERENCES

[1] M. A. Clarke-Gayther, G. M. Allen, and A. I. Borden, "Global Beam Loss Monitoring using Long Ionisation Chambers at ISIS", in Proc. 4th European Particle Accelerator Conf. (EPAC'94), London, UK, Jun.-Jul. 1994, pp. 1634-1637.

[2] I.S.K Gardner *et al., "*The relevance of ISIS experience to the design of future high intensity synchrotrons", International Conference on High Energy Accelerators, Tsukuba, Japan, 1989.

[3] D. M. Harryman *et al.*, "Beam Loss Monitoring in the ISIS Synchrotron Main Dipole Magnets", presented at the 7th International Beam Instrumentation Conference (IBIC'18), Shanghai, China, Sep. 2018, paper TUPA14.

[4] G.H. Rees, "Features of Beam Dynamics for the SNS Synchrotron", *IEEE Transactions on Nuclear Science,* Vol.NS-28, No.3, June 1981

[5] J.W.G. Thomason, "The ISIS Spallation Neutron and Muon Source - The First Thirty-Three Years", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment.* 917. 10.1016/j.nima.2018.11.129.

[6] H. V. Smith, D. J. Adams, B. Jones, and C. M. Warsop, "Activation Models of the ISIS Collectors", in Proc. 5th Int. Particle Accelerator Conf. (IPAC'14), Dresden, Germany, Jun. 2014, pp. 893-895. doi:10.18429/JACoW-IPAC2014-MOPRI115

[7] D. M. Harryman and A. Pertica, "Online Total Ionisation Dosimeter (TID) Monitoring Using Semiconductor Based Radiation Sensors in the ISIS Proton Synchrotron", in Proc. 5th Int. Beam Instrumentation Conf. (IBIC'16), Barcelona, Spain, Sep. 2016, pp. 379-382. doi:10.18429/JACoW-IBIC2016-TUPG24

[8] H. Jivan *et al.*, "Radiation damage effects on the optical properties of plastic scintillators", *Nuclear Instruments and Methods in Physics Research Section B,* Vol. 409, 2017, Pages 224-228, ISSN 0168-583X, 10.1016/j.nimb.2017.05.061.