

STUDIES OF BEAM LOSS CONTROL ON THE ISIS SYNCHROTRON

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Abstract

The ISIS Facility at the Rutherford Appleton Laboratory in the UK produces intense neutron and muon beams for condensed matter research. The ISIS 800 MeV Proton Synchrotron presently provides up to 2.5×10^{13} protons per pulse at 50 Hz, corresponding to a mean power of 160 kW. A dual harmonic RF system upgrade is expected to increase the power by about 50%. The tighter constraints expected for higher intensity running are motivating a detailed study of beam loss distributions and the main factors affecting their control. Main aims are maximizing the localization of activation in the collector straight, and minimising risk of damage to machine components. The experimental work, developments of the loss measurements systems, and simulation studies are summarised.

INTRODUCTION

The ISIS Synchrotron

The ISIS Synchrotron has a mean radius of 26 m, and presently accumulates 2.8×10^{13} protons per pulse (ppp), over the 130 turn, charge-exchange injection process. The injected beam is painted over both transverse acceptances, and is effectively unbunched. The machine cycles at 50 Hz, accelerating protons from 70 to 800 MeV in 10 ms, using 6 ferrite-tuned RF cavities which provide up to 140 kV per turn. Most loss, totalling ~8% (1.5 kW), occurs below 100 MeV and is the result of the non-adiabatic trapping and high space charge. Single-turn extraction is achieved with a fast kicker system, which deflects 2.5×10^{13} ppp into the target beam line. Presently, a dual harmonic RF (DHRF) upgrade is being installed; the increased trapping efficiency this allows is expected to increase extracted intensities to about 3.7×10^{13} ppp.

Motivation and Aims

The ability to control loss is a major factor determining the highest intensities possible on ISIS, which are set by activation levels and risk of machine damage. Present upgrades are expected to take the mean power in the ring to 240 kW, with future upgrades perhaps going higher. Basic requirements to localise loss efficiently and avoid component damage will require more precise and consistent control of out-scatter from the collimators.

LOSS CONTROL ON ISIS

A key consideration on ISIS is the time or energy of loss; higher energy protons cause more activation and are generally harder to control. The mechanisms that drive loss vary through the cycle, and lead to a complicated time dependent optimisation.

Outline of Collimator Systems

The collimation systems are located in one, well shielded, 5 m drift section covering about 50° in betatron phase. There is a vertical system, and a combined horizontal/momentum system. These each consist of a primary jaw and a number of secondary jaws. The design is based on assumed losses at ≤ 100 MeV, dominated by untrapped particles rapidly spiralling radially inwards, with some provision for transverse emittance growth.

The primary jaws consist of a ~40 mm graphite upstream section, followed by a copper section which sits ~0.4 mm closer to the beam. The principle is that lower activation is achieved with many particles being stopped in the graphite, whilst particles more likely to out-scatter at shallow impact depths receive enhanced scattering from the copper. The horizontal system has a 15 mm long copper section, and is designed to operate in single pass mode. The vertical has a 0.1 mm long copper 'lip', designed for multiple turn deflection. A key part of the present work is to understand the action of these jaws.

Changes for High Energy Loss

Losses at present intensities are mostly below 100 MeV, and it is hoped this will also be the case at higher intensity. However, some loss does occur at higher energy, and simulations suggest that more high energy loss may occur with the DHRF upgrade. With this in mind, long (300 mm) secondary graphite collectors have been introduced, and movable graphite extensions to the primaries have also been added. The secondary jaws are placed at optimal betatron phases with respect to the primaries, and also to protect downstream components. The jaws are adjustable, profiled to the beam envelope, and include measurement of deposited power.

MEASUREMENTS AND EXPERIMENTS

Loss Monitoring Diagnostics

Loss control monitoring, based on beam toroids, and 39 3 m coaxial ionization chambers (Beam Loss Monitors-BLM's) [1] distributed around the inner circumference of the synchrotron, has operated successfully for many years. The BLM's detect evaporation neutrons emitted isotropically from the point where a lost proton hits a machine component, whilst avoiding the forward directed cascade (which would blur spatial information). This gives a set of signals that provide spatial and time information on loss, and are the basis of machine protection. As the proton energy ramps (70-800 MeV), sensitivity (response per proton) increases by $\sim 10^2$. Whilst this energy dependence is beneficial when the signal is used for optimization, giving a greater weighting to higher

energy particles (and higher activation), it means care is required when trying to estimate loss distributions.

Development of Measurements

Recently, a more detailed analysis of the BLM signals $B_i[t]$ has been developed. It is assumed that the instantaneous signal is proportional to the local loss rate:

$$B_i[t] = k[t] \frac{dN_i[t]}{dt} \quad (1)$$

where the parameter $k[t]$ depends on proton energy (i.e. time in the cycle). Presently $k[t]$ is assumed the same for all monitors (see later). To provide a workable number of parameters, whilst allowing for the energy/time dependence, the signals from each of the i BLM's are integrated over j convenient ($\Delta t = 0.5$ ms) intervals, producing a set of L_{ij} that define the loss status:

$$L_{ij} = \int_{t_j}^{t_j + \Delta t} B_i[t] dt \approx k_j \int_{t_j}^{t_j + \Delta t} \frac{dN_i[t]}{dt} dt = k_j \Delta N_{ij} \quad (2)$$

The energy change, and corresponding change in the parameter $k[t]$, is small over these intervals, allowing the 'raw' L_{ij} to be taken as measures of loss distribution at a given time. The integrations (2) are easily performed in software once the $B_i[t]$ are digitised. The values give a precise definition of loss control status, important given the requirement for detailed time dependent loss control.

Experiments

The L_{ij} now give the best estimates of proton loss distributions. A typical operational loss distribution may be found in [2]. Using these ideas, new experiments have been possible estimating the response of the loss distribution R_{ij} to each primary jaw:

$$R_{ij} = \frac{L_{ij}(2) - L_{ij}(1)}{T_j(2) - T_j(1)} \quad (3)$$

where the $L_{ij}(1)$, $L_{ij}(2)$ are the loss values for a particular jaw in positions 1 and 2 respectively, and the $T_j(1)$, $T_j(2)$ are the corresponding total losses during Δt measured from the toroids. The values of the R_{ij} for each jaw give valuable indications of the out-scatter characteristics, e.g. indicating which jaws contribute to loss outside the collector straight. Some caution is required in planning and interpreting measurements, e.g. the effects of secondary collectors and changes in the particle distributions with jaw position. These effects are expected to be small, and work is underway to minimize their influence. First measured values for the horizontal/momentum primary and vertical primary are shown in Figures 1 & 2, for the time interval 0.0-0.5 ms. Note that the vertical system is less efficient than the horizontal, with less loss in the collector straight (monitors 5 & 6) and more downstream (monitors ≥ 7).

These are valuable indications of performance, and allow comparison with simulations.

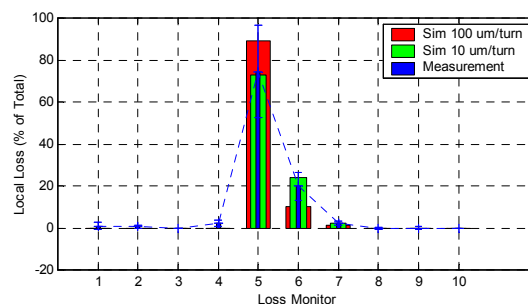


Figure 1: Horizontal Loss Distribution, Measured/Model

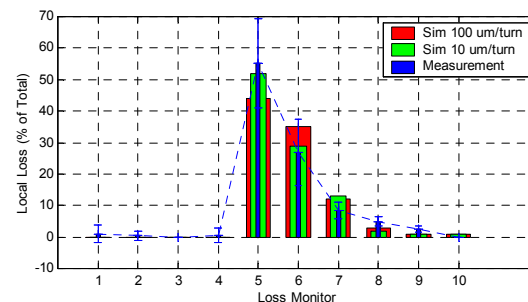


Figure 2: Vertical Loss Distribution, Measured/Model

Predictions for Operations

Using power deposition measurements on the primary jaws, the fraction of beam lost on each can be estimated. With this and the measured R_{ij} of each jaw, the loss distribution due to each jaw for normal operation can be estimated. The results indicate the larger part of loss escaping the collector straight is from the vertical system. This is valuable information for machine optimisation.

Limitations

Only estimates of the k_j are known, and for most purposes the raw values of L_{ij} in volt-seconds are used. Estimates, along with operational experience, have effectively defined a set of L_{ij} that define safe running. Whilst the BLM system was designed as far as possible to make k_j the same for each monitor (keeping the same machine-detector geometries), it was not possible in all locations. Variations of materials and geometry around the machine will lead to variation in the k_j , particularly where monitors are shielded by magnets. Improved calibration, measurement and modelling are under way.

SIMULATIONS: LOSS DISTRIBUTIONS

Simulation Model and Code

A Monte Carlo code, developed for studies on the ESS Rings [3] is being used to model ISIS. This simulates all the important proton interactions, and has been extensively tested against published experimental data. A 3D representation of the collimator jaws and detailed lattice model are included. The intention is to model and understand the proton loss distribution. The high intensity

processes leading to loss are not yet fully known or understood, and so simplified ‘loss modes’ are used. These identify the essential properties of the lost beam (plane, growth rate, energy), and then investigate the effect on performance. The approach is therefore to pick an expected set of loss modes, and produce a corresponding range of predictions. Predicted loss distributions are then binned in regions corresponding to loss monitors for comparison with experiment.

Results: Comparison with Measurement

Predicted loss distributions for momentum loss, and vertical emittance growth with representative growth rates of ~ 10 and $100 \mu\text{m}/\text{turn}$ are shown in Figures 1 & 2, for beam at 100 MeV. It can be seen these reasonably follow the measurements described above. Further confidence is given by similar agreement between measurement and simulation when the copper primary horizontal jaw is replaced with graphite. These are early measurements, with some effects yet to be fully explored, but the fact that out-scatter in downstream components reliably changes with predictions is promising. Simulations with random distributions of misalignments produced results ranging from essentially unchanged, to worst cases with 10% loss shifted after the collimators.

SIMULATIONS: OUT-SCATTER STUDIES

Importance of Out-Scatter

The out-scatter distributions generated by the primary jaws and their interaction with the secondary jaws largely define performance. Using simulations it is possible to study these distributions in detail, track their evolution, and find optimum solutions within the particular constraints of ISIS. Some horizontal results are summarised below.

ISIS Horizontal Collimation

The ‘single pass’ horizontal system relies on interactions with a 15 mm copper section to achieve good efficiencies. Particles not removed by inelastic nuclear interactions emerge with distributions in angle and energy, resulting from scattering and ionisation. Basic aims for a collimation system are to maximise the number of particles stopped on the jaws, whilst minimising the number of particles escaping the system which exceed the machine acceptance.

In Figure 3 the out-scatter distributions in angle and energy, generated by a 100 MeV test beam incident on the primary jaws at a fairly pessimistic impact depth of $10 \mu\text{m}$, are shown. The incident beam has no energy spread. The corresponding distributions after *drifting* through the remaining collector system are in Figure 4.

These show how the primary generates an out-scatter distribution that relies on angular deflection for removal on the secondary jaws: most remaining particles exceed the longitudinal acceptance and are lost elsewhere in the machine. These, and related results, indicate key factors for ISIS are: energy, impact depth, atomic mass of the

primaries, and alignment which strongly determines out-scatter interception and can critically affect operation of combined material primary jaws. The intention is to study different primary jaws, with variations in material and geometry, to identify the optimal configuration.

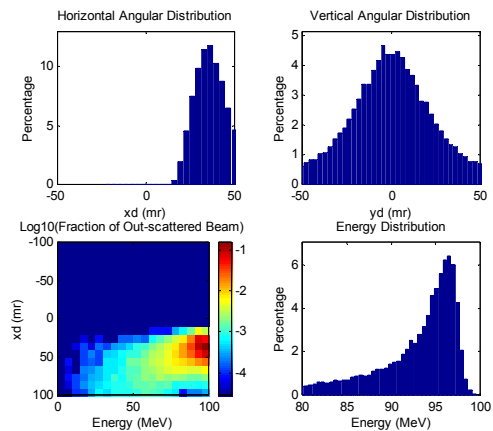


Figure 3: Distributions of 68% Out-Scatter from 100 MeV Pencil Beam on Horizontal Primary, Depth $10 \mu\text{m}$

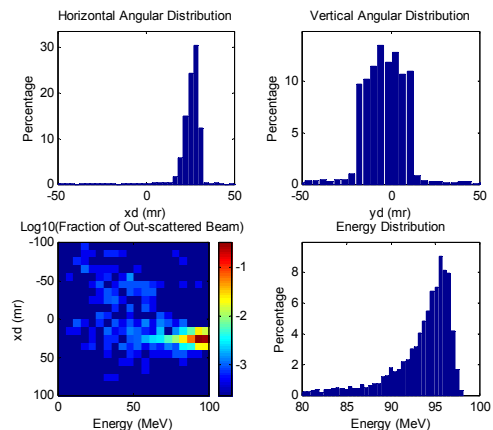


Figure 4: Distributions of 9% Out-Scatter Surviving after Passage through the Remaining Collector System.

SUMMARY

Detailed measurements and simulations of the ISIS ring collimation system seem to agree, and are giving valuable insights. Continuation of this work, and further computer study of out-scatter distributions, should provide the information required to optimize the systems fully.

REFERENCES

- [1] M.A. Clarke-Gayther, “Global Beam Loss Monitoring Using Long Ionisation Chambers at ISIS”, Proc. EPAC’94
- [2] C.M. Warsop, “Beam Loss Control on the ISIS Synchrotron: Simulations, Measurements, Upgrades”, AIP Conf Proc CP693, 2003.
- [3] C.M. Warsop, “Beam Loss Control on the ESS Accumulator Rings”, AIP Conf Proc CP642, 2002.