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PROGRESS WITH CARBON STRIPPING FOILS 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. The facility's 50 Hz rapid cycling synchrotron accelerates protons from 70 to 800 MeV to deliver a mean beam power of 0.2 MW to two target stations. Since 2016, ISIS has routinely used commercially produced carbon based foils for beam stripping during charge-exchange injection.

Recent experience and developments to increase useful foil lifetime are presented including in-house high-temperature annealing of foils prior to use. The installation and performance of a new foil imaging system are described and, finally, the procedure to change the stripping foil is described. Issues with the current arrangements and options for redesign are discussed.

INTRODUCTION

The ISIS synchrotron accelerates 3×10^{13} protons per pulse from 70 to 800 MeV in a 10 ms cycle at 50 Hz. The 163 m circumference ring is filled over 130 turns using charge-exchange injection, a schematic is shown in Fig. 1. Four serially powered injection dipoles produce a 65 mm horizontal orbit bump at the foil. The beam is painted in both transverse planes. Vertical painting is achieved with a programmable dipole in the injection line which sweeps the beam spot down the foil over the injected pulse. Horizontal painting occurs through movement of the dispersive closed orbit in the ring generated by an energy mismatch between the constant injection energy and the sinusoidal main magnetic field. The horizontal injected beam position on the foil is constant over injection. Each proton recirculates through the foil 10 - 20 times. Transverse acceptances of the synchrotron are collimated at ~350 π.mm.mr.

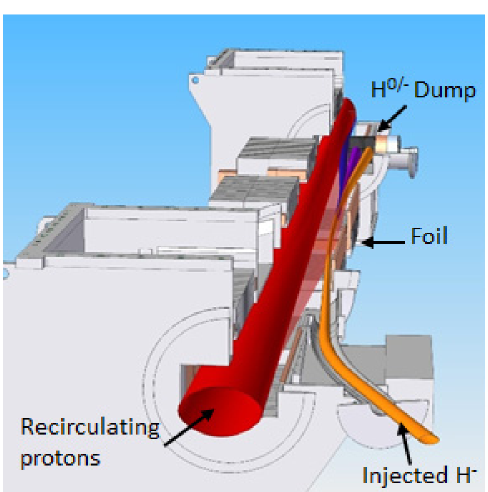

Figure 1: ISIS injection region.

CARBON FOILS

Since 2016, ISIS has operated solely with Diamond-Like Carbon (DLC) 100 μg/cm^2, 50×65 mm foils purchased from Micromatter [1], a spin out company from TRIUMF in Vancouver.

Recent Experience

A method of mounting the foils using four supporting carbon fibres secured to an aluminium frame with an aqueous graphite solution has reliably produced foils that can survive half of a typical ISIS user cycle – a total of 120 – 150 mAh of beam. Following discussion with Micromatter at IPAC 17 it was decided to further anneal foils on-site at ISIS. Foils are now baked at 400 ºC for two hours with additional two-hour temperature ramps from/to ambient. The peak operating foil temperature has been calculated as approximately 250 ºC.

The first annealed foil was tested in May 2017 with 11 hours of 205 μA beam, a total of 2.9 mAh. The foil appeared 'as new' following this test whereas without annealing, foils had shown significant deformation within the first 5 - 10 hours of operation [2]. Images of the foil throughout its lifetime are shown in Fig. 2.

Figure 2: The first annealed DLC foil used – clockwise from top left: before installation, after 2.9 mAh, 17 mAh, and on removal after 136 mAh.

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This foil was used for the pre-cycle commissioning period and again appeared virtually unchanged after another 15 mAh of beam exposure. The foil was replaced at the mid-cycle maintenance day after 136 mAh of beam, it still showed significantly less deformation than un-annealed foils but one or more supporting fibres had snapped allowing the foil to curl.

Since this trial, all foils have been annealed following the same procedure. The second foil survived almost a whole user cycle although operational beam current was reduced to 175 µA due to a fault with the second target station. However, this foil survived a total of 156 mAh, a record for a carbon foil at ISIS. In the latest cycle in early 2018, improvements in RF stability and beam control led to an increase in beam current to 225 µA which resulted in a new record of 5.4 mAh of beam delivered to target in one day. Two annealed foils were used during this cycle seeing 90 and 104 mAh each. However, neither foil reached its full lifetime, both were changed preventatively during downtime for unrelated issues.

IMAGING SYSTEM

A new imaging system for remote inspection of stripping foils in the synchrotron has been installed. The system consists of a 100 mm CF viewing port, an in-vacuum glass mirror and a Mirion R985 radiation tolerant camera [3]. Lighting is provided by a ring of fifty-four SMD-3528 LEDs mounted around the circumference of the viewing port, outside of the vacuum. The camera signal is fed via 75 Ω coaxial cable to a Digital Video Recorder (DVR) which digitises the video signal and streams it to the local area network. An example image acquisition from the system is shown in Fig. 3.

The camera is rated to withstand 1 kGy/h and an accumulated dose of 100 kGy. The dose rate in the use area has been measured using online Total Ionisation Dosimeters (TID) [4] as approximately 0.15 Gy/h during beam operations giving an accumulated dose of ~100 Gy/user cycle. The expected lifetime of the camera is therefore >200 years.

Figure 3: Carbon stripping foil inside the synchrotron via new imaging system.

The system works well and provides the ability to assess foil condition with negligible downtime and zero dose to staff. As all components of the system are fixed in place there can be difficulty in distinguishing foil features from shadows. The image could be improved with a zoom lens and upgraded, flexible lighting and these will be explored.

FOIL CHANGE AREA AND PROCEDURE

When ISIS began operation in the late 1980s foils were mounted on a simple one-piece holder which was manually inserted into the machine and clamped with a vacuum flange. As commissioning progressed and beam powers increased, the aluminium-oxide foils produced in-house began to fail more frequently and the injection region became significantly activated. In 1994, the foil change area was upgraded to allow safe disposal of active foils and to provide a shielded working area in which to prepare a new foil. A model of the mechanism is shown in Fig. 4.

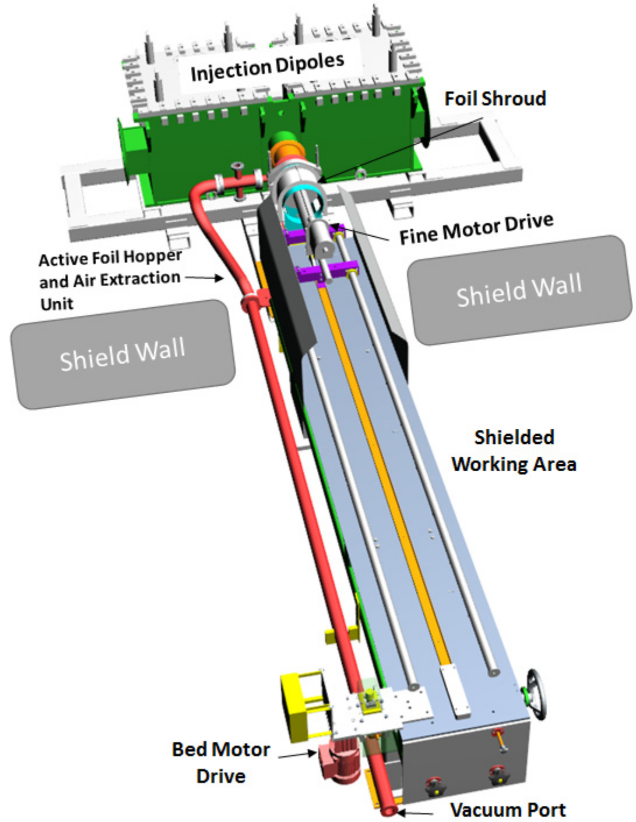

Figure 4: CAD model of the ISIS foil change area with active disposal area close to the machine and shielded working area for installation of new foils.

Foil changes are carried out by two members of the Operations crew on duty at the time of the failure or scheduled change with assistance from Health Physics staff on call. It is a relatively complex process that takes 5 - 6 hours. The active foil is withdrawn from the synchrotron and a vacuum valve seals the ring from the foil chamber.

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The chamber is let up to atmospheric pressure and an air extraction unit is switched on to remove loose foil material. The operator lifts the stainless steel shroud covering the foil and manually removes the foil frame from the holder and drops it into the active foil hopper beneath the chamber. This is manually emptied annually by Health Physics staff; the active foils have an activity density of 5 ± 2 PetaBq/tonne [5] and are therefore classified as Intermediate Level Waste. The cost of disposal of this waste is significant. The operator then wipes the holder until all contamination of active foil fragments have been removed and moves to the shielded working area to install a fresh foil. Once installed, the foil chamber is pumped down to the synchrotron level of 0.5 - 3.0×10^{-7} mbar over 90 minutes. The vacuum valve can then be opened and the foil inserted into the beam path. Fine control of the foil position is available remotely to within ±0.5 mm.

There are several issues with the existing foil area and associated procedures as they presently exist at ISIS, these are described in the following sections.

Operational Impact

Whilst operating with carbon foils, there have been four foil changes during operation, a total of 32 hours of downtime (21.3 h/annum, 8.0 h/change). In the 10 years of operation with aluminium foils up to 2015, there were twelve foil changes due to failure, a total of 87 hours of downtime (9.2 h/annum, 7.3 h/change). Now that a reliable method of foil preparation has been established it is expected that downtime will reduce back to <10 h/annum due to foil damage by mechanical or vacuum issues.

To add context, for typical operation of 200 days in a year with 90% availability, ISIS suffers 480 hours of downtime and therefore foil failures account for 2 - 4 % of all downtime. Taking an average of the ISIS operating budget over the number of days of operation, foil failures cost £100 - 200k per year.

Radiological Safety

The foil change task is currently split into two stages; removal of the used foil and installation of the new foil. The foil removal is carried out in a small section close to the synchrotron to minimise the potential for the spread of contamination of foil fragments. The foil is dropped into a collection hopper and the holder swabbed with an alcohol wipe. The activity of the contamination on the wipe is measured and the process repeated until background levels are reached. The foil holder is then withdrawn into a shielded working area and a new foil installed.

The working area for foil removal and decontamination typically has a dose rate of 1 mSv/h and therefore staff receive a dose of 50 ± 20 µSv during a foil change.

The contamination level was typically several hundred counts-per-second (cps) when using aluminium foils but this has dropped below the hazard control point of 250 cps since using carbon foils.

Upgrade Plan

As the contamination risk is now almost to background level, a new radiological risk assessment has determined that the active working area is no longer necessary and the active foil should be pulled back directly into the shielded area for disposal into a shielded storage flask. This would make the dose for the task As-Low-As-Reasonably-Practicable and <10 µSv.

A redesign of the mounting mechanism to allow installation of multiple foils remotely has been considered but it is thought the cost and operational risk cannot be justified. The port into the synchrotron is only a 16×130 mm slot so a multiple foil system would be mechanically complex. There is also concern over the loss of vacuum in a foil storage chamber containing active foils. However, replacement of the foil chamber vacuum system and valve to the synchrotron to include remote control will reduce the time taken for a change to <3 hours. These two measures offer a significant improvement for future ISIS operations.

NOVEL FOILS

Although an operable carbon foil solution has been found, studies of alternative foil materials and preparation methods are continuing. Silica and carbon aerogels have been sourced and scheduled for off-line testing with a 1.5 keV electron beam as a heat source. These materials have extremely low density and are therefore much thicker, more robust pieces which are considered a promising candidate for stripping ‘foil’ use. However the samples acquired are very brittle and the low thermal conductivity of the materials will lead to higher operating temperatures.

Sample foils have been received from the SNS foil development team to be tested with the ISIS 70 MeV H^- beam. The foils are corrugated around the outer edges of the foil to add strength [6] and have a lifetime of 200 hours in the SNS 1 GeV, 1.4 MW beam. They are thicker than necessary and transversely too small for ISIS operations but beam test results will confirm the viability of collaboration on foil development with SNS.

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