

# INITIAL EXPERIENCE WITH CARBON STRIPPING FOILS AT ISIS

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## Abstract

The ISIS Facility at the Rutherford Appleton Laboratory is a spallation neutron and muon source based upon a 50 Hz rapid cycling synchrotron accelerating  $\sim 3 \times 10^{13}$  protons per pulse from 70 to 800 MeV to deliver a mean beam power of 0.2 MW to two target stations.

Throughout its 30 years of operation ISIS has developed aluminium oxide foils in-house for  $H^-$  charge exchange injection. The manufacturing and installation processes for these foils are time consuming, radiologically dose intensive and require a high degree of skill. Commercially available carbon based foils commonly used at other facilities have the potential to greatly simplify foil preparation and installation in addition to improving beam quality. Similar foils would also be necessary for facility upgrades which increase injection energy to withstand the higher operating temperatures.

This paper describes the initial experience of carbon foils in the ISIS synchrotron including issues relating to handling and mounting foils, their performance under beam operation and plans for further development.

## INTRODUCTION

The ISIS synchrotron accelerates up to  $3 \times 10^{13}$  protons 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 Figure 1. Four serially powered injection dipoles produce a 65 mm horizontal orbit bump at the foil. 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 20-30 times.

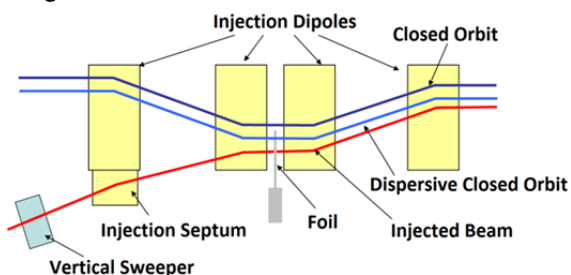


Figure 1: ISIS injection region.

ISIS currently uses 0.5  $\mu\text{m}$  thick, 200  $\mu\text{g}/\text{cm}^2$  aluminium oxide ( $\text{Al}_2\text{O}_3$ ) foils, in theory these foils are 99.8% efficient and operationally injection efficiencies of 98-99% are typical depending on foil condition and

empirical optimisation. The foils are produced in-house through a complex and laborious series of etching, annealing and coating processes, details are given in [1]. They are extremely fragile and the installation and removal processes are technically challenging, time consuming and present radiological risks during disposal. Dose received can vary significantly but 20-100  $\mu\text{Sv}$  per foil change is typical. A foil will almost always last for a whole  $\sim 45$  day user cycle and a new foil is installed for each cycle. Foils are driven into the ring horizontally, only one foil can be installed at a time and replacement or inspection requires access to the synchrotron hall. With the associated power cycling and access control this involves two to three hours downtime.

Following their successful operation at J-Parc [2] and SNS [3] and planned use at CERN PSB [4] and CSNS [5], ISIS has begun trials of carbon stripping foils.

## CARBON FOILS

Several manufacturers offer thin carbon foils suitable for stripping  $H^-$  beams in high power synchrotrons. Micromatter [6], a spin-out company from TRIUMF in Vancouver, was the chosen supplier for ISIS since they had the required size available 'off-the-shelf'.

Diamond-Like Carbon (DLC) 100  $\mu\text{g}/\text{cm}^2$ , 50 $\times$ 65 mm foils were purchased to give the same stripping efficiency as the current  $\text{Al}_2\text{O}_3$  foils. The DLC foils are almost half the size of the current foils but are sufficient to cover the injected beam area, see Figure 2. The current  $\text{Al}_2\text{O}_3$  foils are made larger than necessary so they can be supported on three edges. Reduction of the foil size reduces the number of foil traversals by recirculating protons.

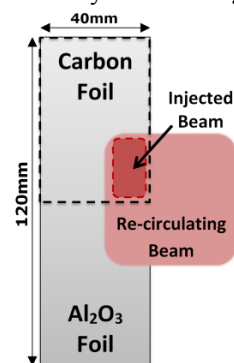


Figure 2: ISIS injection stripping foils schematic.

An aluminium supporting bracket was designed and manufactured in-house to install the carbon foils in the existing mounting mechanism in the synchrotron. An earthed, draught proof mounting jig was also manufactured to aid assembly. An anti-static gun has proved to be a very useful tool to lay the foil flat before clamping in the frame.

The carbon foils are smaller and less dense than the  $\text{Al}_2\text{O}_3$  foils leading to a slight reduction in beam scattering due to foil interaction. For ISIS however, emittance is dominated by space charge effects and therefore no significant change in beam loss level is expected.

The first carbon foil was prepared and installed into the synchrotron in July 2015.

### Initial Results

Initial beam was very poor with just 40% injection efficiency, the position of the injected beam on the foil had to be raised 9 mm to recover >90% efficiency. It appeared that during empirical tuning with the  $\text{Al}_2\text{O}_3$  foil the injection position had been set below the vertical centre of the machine. Following retuning of the synchrotron closed orbit to compensate for this, typical injection efficiency of >97% was recovered.

Operation at 50 Hz with  $\sim 2.5 \times 10^{13}$  ppp was successfully carried out for the four hours allocated to the experiment, a total of 0.7 mAh of beam. Beam was cycled off/on at full power several times to thermally shock the foil, no change in beam loss, vacuum level or injection efficiency was seen during these tests. However, it was necessary to insert the foil a further 4 mm into the synchrotron aperture over the course of the experiment to maintain low loss levels in the injection region.

On inspection the foil was intact but had deformed and curled away from the injected beam necessitating the change in foil position, Figure 3.

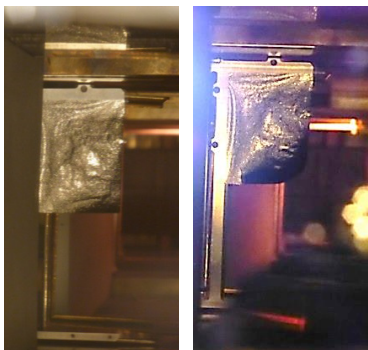


Figure 3: First carbon foil viewed inside the synchrotron before (left) and after (right) 4 hours of operation.

This behaviour was expected following experience with Hybrid Boron-Carbon foils at J-Parc [2]. Although the J-Parc beam conditions are significantly different from ISIS, thermal models [7] of both facilities show similar equilibrium foil temperatures of  $\sim 500$  K. The stabilisation of the foil after  $\sim 7 \times 10^{20}$  injected particles seen at J-Parc corresponds to 72 hours of ISIS operation at 50 Hz.

A second foil was tested in October 2015 with similar results, increased beam loss was observed after 5.5 hours of 50 Hz operation and on inspection the foil had again curled away from the incoming beam.

### Supporting Carbon Fibres

For the third test two carbon fibres were added approximately 5 and 10 mm from the foil edge to prevent the foil curling. The fibres were taken from a reel of

standard lightweight '3K tow'. Each individual strand of the fibre is  $10 \pm 2$   $\mu\text{m}$  diameter, bunches of 10-15 strands were used for each supporting fibre. The fibres were glued to the aluminium frame using undiluted Aquadag [8], a colloidal graphite solution, see Figure 4. An attempt was made to glue the fibres to the foil itself but as it dried the Aquadag shrank into a small ball due to the surface tension and tore the foil.

The addition of the fibres is equivalent to a 5% increase in foil material and was therefore not expected to increase loss levels significantly. No increase in loss beyond normal variation was seen under initial beam, however after six hours of operation loss had increased to unacceptable levels and on inspection it was found that the rear fibre had detached and allowed the foil to curl away from the beam.

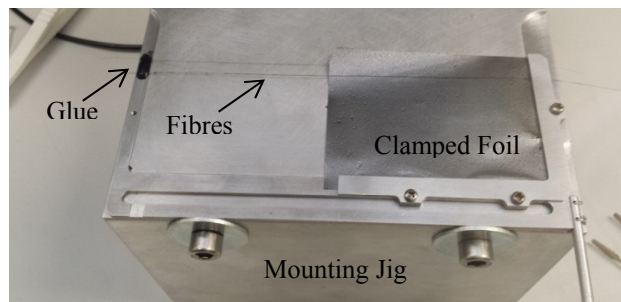


Figure 4: Carbon foil mounted into frame on jig. Supporting fibres are clamped at the top and glued at the bottom.

The foil bracket was redesigned to consist of two C-shaped sections enabling the supporting fibres to be clamped at the top and bottom of the frame. Four fibres of 20-25 strands per fibre were added, two on either side of the foil, see Figure 4.

A fourth test was carried out in December 2015 and a factor of two increase in beam loss at injection was seen and could not be tuned out. It was concluded that this loss was due to the increased number of fibres. The foil survived the 17 hours of 50 Hz beam operation available for the experiment, a total of 3.5 mAh. The foil position was not changed during the test. On inspection the foil was seen to be significantly deformed, Figure 5, more so than the foils operated for  $\sim 6$  hours, but had been held in place well by the fibres. It was not clear if the foil would have continued to deform further.

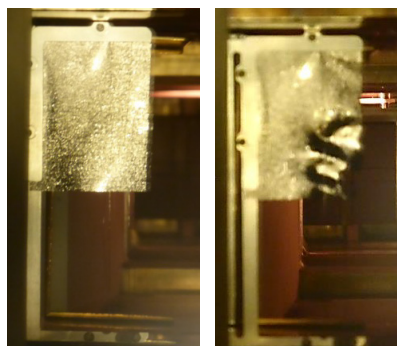


Figure 5: Fourth carbon foil after 0 (left) and 3.5 mAh (right).

In January 2016 another batch of foils was mounted using the same bracket and fibre arrangement but the fibre bunches were reduced back to ~10 strands.

For the fifth test one of these foils was inserted at the beginning of a two-week start-up period and no degradation in performance or movement of the foil was observed during this time in which 29 mAh of beam was injected and it was decided to use the foil during the following 37 day user run. After 10 days of this run a sudden increase in injection loss was seen and retuning of injection was required. Operation was able to continue with increased loss until a scheduled maintenance period on day 15. On inspection the outer rear supporting fibre had snapped and allowed the foil to curl, see Figure 6. Overall the foil survived 88 mAh of beam.



Figure 6: Fifth carbon foil after (left-right) 0, 29 and 88 mAh

In March 2016 a second foil from the batch prepared in January was installed and successfully operated for 117 mAh until the scheduled maintenance day. On inspection the foil was notably deformed but still held by the fibres. Operation continued with this foil until this conference.

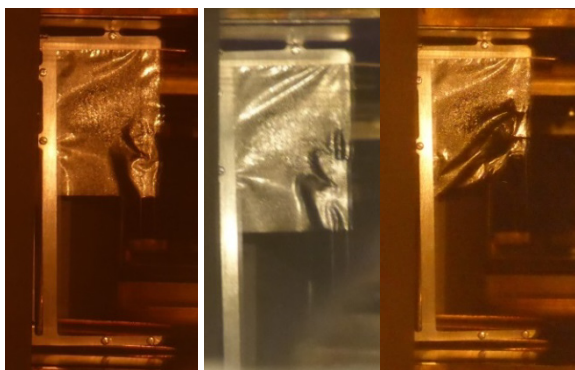


Figure 7: Sixth carbon foil after (left-right) 3, 15 and 117 mAh.

## SUMMARY

Commercially produced carbon foils are now in operational use at the ISIS neutron and muon source. Foils are seen to deform significantly after 5-6 hours of 50 Hz,  $3 \times 10^{13}$  ppp, 70 MeV beam. This deformation appears to continue gradually over several weeks of operation. The addition of carbon fibre strands has been

required to hold the foil in position as it deforms. No measurable additional beam loss is seen using four fibres of 10-15 strands each.

The foils require a factor of twenty less staff time to prepare compared to the in-house produced  $\text{Al}_2\text{O}_3$  foils. The foil change procedure is also significantly simplified with the carbon foils and can now be done in minutes compared to at least an hour with the  $\text{Al}_2\text{O}_3$  foils. This reduces machine downtime and dose received by operations personnel.

## FUTURE WORK

It is planned to continue operation with carbon foils, experimenting with fibre arrangements to establish reliable operation for a least one whole user cycle i.e. up to 50 days or 250 mAh. A redesign of the foil change mechanism is underway and a new camera system will be installed to allow remote foil inspection.

A graphene foil [9] has been purchased from Applied Nanotech in Austin, USA and will be tested later this year. The foil is the same transverse size with a thickness of  $200 \mu\text{g}/\text{cm}^2$ , the minimum available. The high thermal conductivity and tensile strength of these graphene foils make them an excellent candidate for stripping foil application.

An off-line test stand consisting of a vacuum chamber with electron and ion guns is being developed for the testing of various beam diagnostic systems and components. The chamber will be used to monitor foils under heating. An electron gun will be used to provide 0.3 mA, 1.5 keV DC beam with 15 mm diameter to produce a comparable heat load to typical ISIS operation.

## ACKNOWLEDGEMENTS

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