AN OVERVIEW OF THE PREPARATION AND CHARACTERISTICS OF THE ISIS STRIPPING FOIL

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Abstract

The ISIS facility at the Rutherford Appleton Laboratory is a pulsed neutron and muon source, for materials and life science research. H^- ions are injected into an 800 MeV, 50 Hz rapid cycling synchrotron from a 70 MeV linear accelerator, over ~130 turns by charge exchange injection. Up to 3×10^{13} protons per pulse can be accelerated, with the beam current of 240 µA split between the two spallation neutron targets.

The 40×120 mm aluminium oxide stripping foils used for injection are manufactured on-site. This paper gives an overview of the preparation and characteristics of the ISIS foils, including measurements of foil thickness and elemental composition. Consideration is also given to the beam footprint on the foil and how this could be optimised.

THE ISIS INJECTION SYSTEM

Injection into the synchrotron occurs via 70 MeV H^- charge exchange injection over 200 µs (~130 turns) beginning 400 µs before field minimum of the 50 Hz sinusoidal main dipole field. The foil is mounted in the middle of four dipole magnets which create a 65 mm symmetrical horizontal orbit bump and remove any un-stripped beam, Fig. 1. The bump collapses immediately after injection, in 100 µs, limiting re-circulations to ~30.
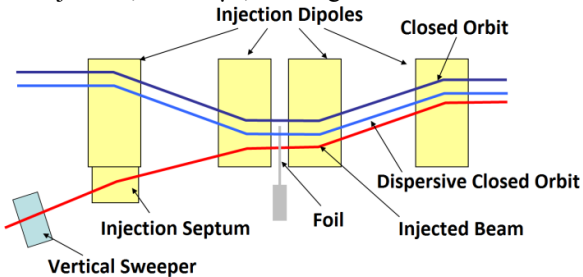

Figure 1: Schematic of the bump and injection magnets overlaid with the trajectories of the incoming H^- beam, and circulating protons.

Throughout the injection process the beam is painted transversely to reduce the effect of space charge forces, Fig. 2. The injected beam spot is fixed horizontally but painting is realised in this plane by the 20 mm movement of the dispersive closed orbit generated by the energy mismatch between the constant injection energy and changing synchronous energy of the ring. Vertical painting is achieved with a programmable dipole located upstream of the foil. The dipole current is swept such that the beam is moved 12 mm on the foil. The flexible positioning and painting system allows beam to be injected even when some areas of the foil are damaged, this can extend the useful foil life and avoid a foil change.

Operational experience shows that foil lifetimes are often in excess of 200,000 µA hrs, with an average of ~80,000 µA hrs, limited primarily by mechanical factors. A new foil is posted in preparation for each ISIS user cycle in order to avoid a foil change during the cycle which would require access to the synchrotron hall and result in ~4 hrs without beam.
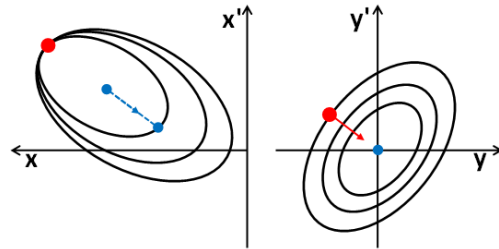

Figure 2: Phase space painting (schematic) on the foil in the horizontal and vertical planes. The injection spot is marked in red, with the closed orbit marked in blue.

MOTIVATIONS

It is important to understand the properties of the stripping foil to optimise machine operations and design future upgrades.

Previous papers and reports [1, 2] give conflicting statements about the thickness and composition of the stripping foil. Most state that the foil is aluminium oxide (alumina) and that the thickness is 0.25 µm or 50 µg cm^{-2}. Using the accepted density of aluminium oxide, 3.95 g cm^{-3}, the quoted areal density and thickness of the foil are inconsistent. These discrepancies prompted a fresh study of the foil production mechanism and measurements of the resulting foil properties.

FOIL PREPARATION

The stripping foils used in ISIS operations are manufactured on site. Production requires numerous complex, non-automated stages and the skill, experience and judgement of staff is heavily relied upon to create usable foils. In total it takes around 20 hours to produce a single foil via the following eight stages, Fig. 3:

1. A 0.15 mm thick sheet of 99% pure aluminium is cut to 70×130 mm, two mounting holes are punched through and two wedges clipped out of the edges of the sheet in preparation for final installation.
2. One long edge of the aluminium sheet is then bent in a custom jig to strengthen it. The top short edge of the sheet is slid into a slot in a pre-prepared custom made mounting pin that is used to hold the foil in the mounting mechanism in the synchrotron.

3. At this stage the aluminium sheet is annealed in a vacuum furnace at a temperature of 360 °C for eight hours. The sheet is then anodised at 180 V, for 10-15 minutes, creating an alumina coating. The anodising solution is made from a mixture of 10 ml of analytical water and 6 g of ammonium hydrogen tetrahydrate. The annealing process is then completed by heating the sheet to 280 °C for another eight hours.

4. The edges of one side are masked in a custom jig and the alumina layer inside the masked region is removed by hand with wire wool.

5. The sheet is then suspended in a solution of methanol (1000 ml) and (30 ml) bromine to etch away the exposed aluminium, leaving just a thin transparent film surrounded by a frame. Once a visual inspection confirms that all of the required aluminium has been removed the thin foil is washed in an acetone bath.

6. The delicate foil is then placed in a vacuum chamber (10^{-7} Torr) and a 0.18 μm layer of aluminium is electrostatically evaporated onto both sides of the foil. The deposited thickness is monitored by a quartz crystal.

7. The non-mounting edge of the frame is removed using a scalpel to expose the foil edge and then the foil is stored for up to six months over silica beads in (non-vacuum) containers. The silica beads act as a desiccant to prevent the foils from deteriorating due to hydration in air. After six months any unused foils are disposed of.

8. Immediately prior to installation in the synchrotron a scalpel is used to detach other parts of the foil from the frame. The extra cuts leave only the top edge, very bottom corner and top half of the secured edge supported, Fig. 4. These cuts reduce any residual mechanical stress, increasing the foil lifetime.
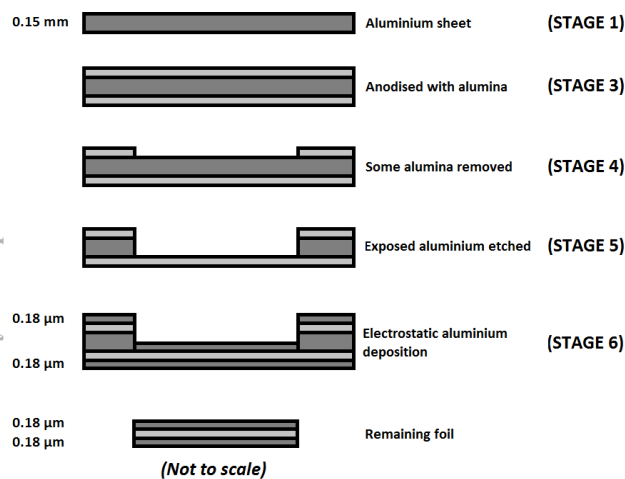

Figure 3: 'Cut-through' schematic of the production of the ISIS stripping foil. The stages identified correspond to those outlined in the foil preparation section.
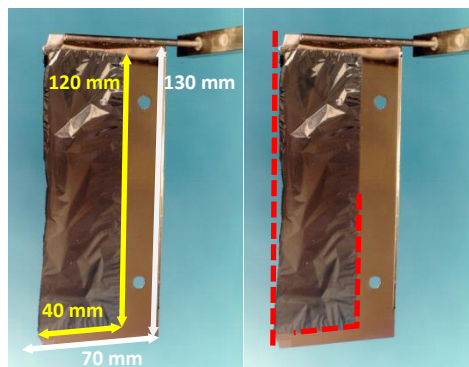

Figure 4: Two completed stripping foils. Left shows the dimensions of the final foil area compared to the original aluminium sheet. Right shows the cuts made to the foil.

FOIL MEASUREMENTS

A series of studies were undertaken to measure and understand the thickness and composition of the ISIS stripping foil.

Thickness

From the foil preparation stages, Fig. 3, it can be seen that the thickness due to electrostatically deposited aluminium is expected to be 0.36 μm. The amount of the alumina onto which the aluminium is deposited is controlled by the anodising conditions. Because the anodising is conducted at a constant voltage, rather than constant current, it is not possible to calculate the expected thickness of the anodised layer. However, early foil development documents [3] refer to the anodic layer being built up at a rate of 13 Å V^{-1} when using 190 V and an assumed current density of <2 mA cm^{-2}. This would give an expected thickness of alumina of 0.247 μm.

Thickness measurements on foil samples were made using a surface profiler [4]. In this technique a probe was used to measure the step-height at the foil edge, Fig. 5. Measurements were made for cases where the probe moved onto the foil from the substrate and conversely from the foil onto the substrate. For the four samples the average thickness was measured as 0.5450 ±0.0005 μm with a standard deviation of 0.02 μm.
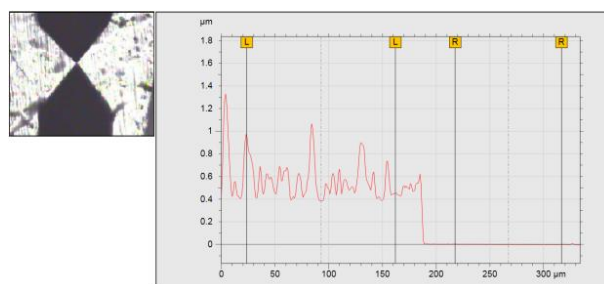

Figure 5: Top left shows the probe (and probe shadow) moving along the sample foil surface. Right shows the probe position which is used to obtain the step-height of the foil.

Accelerator System Design, RF, Injection and Extract

Some significant (~0.5-1 μm) changes in foil thickness were observed over ~10 μm probe movements. An Atomic Force Microscope (AFM) [5] was used to assess the surface roughness and measured it to be ~200 nm, Fig. 6. The changes in the profiler probe height could be attributed to the probe dragging and piling up foil material as it moves.
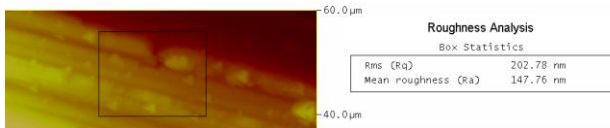

Figure 6: AFM image of surface roughness.

A total measured thickness of 0.545 μm and a known thickness of deposited aluminium of 0.36 μm indicates that the thickness of the remaining alumina in the foil samples is 0.185 μm, which is thinner than the 0.247 μm expected. The constant voltage anodising method results in many uncertainties in the thickness control of the anodic layer for each foil and the components and concentration of anodising solution may have changed since the initial development [3].

Mass

Using the accepted density of aluminium (2.7 g cm^{-3}) and aluminium oxide (3.95 g cm^{-3}), along with the measured thickness, the expected mass of a foil sample with dimensions $40 \pm 5 \times 120 \pm 5$ mm is 8.2 ± 1.4 mg. Samples of ISIS foils, removed from their frames, were weighed by carefully sandwiching a foil between sheets of weighing paper (of measured mass) [6]. The resulting average mass was 11.530 ± 0.005 mg with a standard deviation of 0.070 mg between three samples. This discrepancy suggests that there may be other impurities present in the foil.

Composition

The foil composition was analysed using energy dispersive x-ray spectroscopy (20 keV) [7, 8]. Twelve separate points on a small foil sample were analysed with the resulting spectra showing the proportion of each material detected. As expected, the main foil constituents were oxygen (60.45%) and aluminium (37.11%), with traces of other elements present, Table 1. The spectroscopy composition results match well to the expected distribution in aluminium oxide, Al_2O_3.

Table 1: Elemental Composition (%) of the Foil Sample

Element	Composition (%)
Oxygen (O)	60.45
Aluminium (Al)	37.11
Sulphur (S)	1.33
Copper (Cu)	0.48
Silicon (Si)	0.32
Titanium (Ti)	0.10
Iron (Fe)	0.08
Potassium (K)	0.08
Magnesium (Mg)	0.05

It is possible that small amounts of impurities could have been introduced during the foil manufacture, or may have arisen from the substrate adhesive used in the spectroscopy measurement. Assuming all of the aluminium detected is associated with the aluminium oxide compound then there is 4.79% more oxygen present than anticipated. This is likely to be due to the oxidation of the impurities. Similar to the AFM result an image from the Scanning Electron Microscope (SEM) used in the spectroscopy showed some non-uniformity in the foil structure.

A neutron diffraction pattern was also obtained from the foil samples using the medium resolution powder diffraction instrument at ISIS, Polaris [9]. This instrument specialises in the rapid characterisation of crystal structures in small samples. It was hoped that this technique would show the sample crystal structure, including any trace impurities. Three entire foils were required in order to see any crystalline diffraction above the noise, Fig. 7. The foils were compressed into a thin walled glass capillary tube for the measurement.
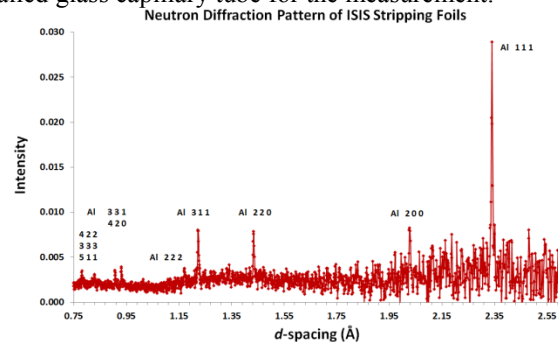

Figure 7: Neutron diffraction pattern observed from an experiment on Polaris showing the miller indices of the planes present in crystalline aluminium.

Simulated diffraction patterns for crystalline aluminium and alumina were compared to the obtained diffraction pattern, Fig. 7. This analysis showed that all the peaks present were associated with pure aluminium. There were no strong peaks present at d-spacings of 1.4, 1.6 or 2.1 Å which would be expected for crystalline alumina. This was anticipated because the anodising technique produces amorphous alumina. Because of the small sample size there is a high noise level in the data, if there were any crystalline alumina it would be <10% of the total content. The low intensity of crystalline aluminium detected is assumed to be the remnants of any un-etched aluminium sheet, or non-oxidised deposited aluminium.

Results Summary

Results from the composition analysis suggest that oxidation of the final layers of electrostatically deposited aluminium had occurred. An oxide layer naturally forms on an exposed aluminium surface and this is expected on the foil samples as they are not stored under vacuum conditions after preparation. If it is assumed that the entire foil material is aluminium oxide the expected mass would be 10.3 ± 1.8 mg, which is consistent with the

measured mass of 11.53 mg. As observed through the AFM and SEM measurements there is an inherent surface roughness and any non-uniformity in the anodising, etching or deposition processes could result in variation in foil mass.

The consistent results obtained in this series of measurements suggest that the ISIS stripping foil is best described as a 0.55 μm, 215 μg cm^{-2}, aluminium oxide foil. Previously quoted thicknesses of 0.25 μm or 50 μg cm^{-2} may correspond to the expected thickness of the anodised alumina layer or the thickness of electrostatically deposited aluminium on a single side, respectively. It is also possible that the foil production method has drifted over time towards the production of thicker foils than originally specified to achieve the increased foil lifetimes. The effect of thicker foils on accelerator operations is discussed in a later section of this paper.

BEAM MEASUREMENTS

Beam Size

Injection efficiency may be improved by decreasing the transverse foil size. A smaller foil means less re-circulating beam hits the foil so the effects of beam scattering, energy straggling and heat stress on the foil are reduced. Measurements have been undertaken to understand the minimum foil size that could be acceptable for use in ISIS operations. Using a beam diluted to 10% with a pepper-pot absorber, to limit component activation, the circulating beam intensity was measured as a function of horizontal foil position, Fig. 8.
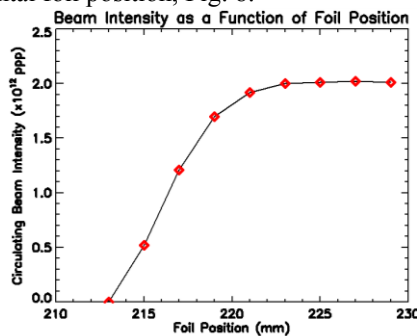

Figure 8: Graph of horizontal foil position against measured circulating beam intensity showing that the injected beam has a diameter of ~10 mm.

Results show that under typical operating conditions the beam has a horizontal diameter of 10 ±2 mm. Errors in the measurement arise from pulse-to-pulse variations in injection position and intensity as well as fluctuations in circulating beam current. The foil position is routinely set at ~230 mm to accommodate the unstable injection spot and any potential halo on in the injected beam.

There is no capability for moving the foil in the vertical plane, but the painting amplitude of the vertical beam is 12 mm. At the end of injection the beam footprint on the foil is ~10 × 50 mm [10], Fig. 9. Although the foil takes up the full vertical aperture only the top half is used for

stripping. Removing the bottom half of the foil would significantly reduce the number of foil re-circulations but may affect the structural integrity of the foil.

The Chinese Spallation Neutron Source (CSNS) plans to run with a smaller, 21 × 60 mm, 100 μg cm^{-2} boron-doped carbon stripping foil [11]. Mounting and supporting a smaller foil poses extra challenges, with many solutions involving the use of thin silicon carbide support wires [12]. Aiding the research of both organisations, plans are being made to test CSNS foils on ISIS during dedicated machine study time.
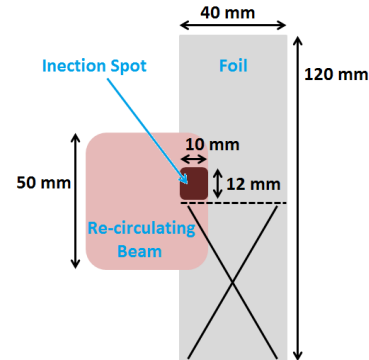

Figure 9: Schematic of the beam footprint on the foil at the end of injection. The dark red spot is the painted space and the light red area is accumulated beam.

Energy Loss

Predictions of expected energy loss per traversal for alumina foils of 50-215 μg cm^{-2} are 0.4 and 1.6 keV respectively.

One technique identified for measuring this energy loss on ISIS involves producing ~100 extra foil traversals by moving the start time of the injection bump. The additional energy losses would correspond to changes in beam revolution frequency of 0.35-1.5 ns. This measurement is very challenging at currently available data acquisition rates. Studies to further increase the number of foil traversals by moving the horizontal closed orbit onto the foil are planned in the future.

EFFECT OF FOIL MATERIAL AND THICKNESS

With improved knowledge of the foil characteristics, simulations of the ISIS stripping foil were reviewed using an in-house single pass code [13]. Assessments were made of the stripping efficiency and scattering that would be expected from both the previously assumed 50 μg cm^{-2} and newly measured 215 μg cm^{-2} aluminium oxide foil. The code includes the effects of inelastic nuclear interactions, single large-angle Coulomb scattering and multiple small-angle Coulomb scattering.

Results show that the increase in thickness yields an increase in stripping efficiency from 97.2% to 99.9%. However, it also leads to increases in scattering which could result in loss. Further detailed simulations should be completed to understand the current extent of foil scattering at ISIS.

Operationally the ISIS injection efficiency, calculated from toroid current monitors, is ~97-99%. A high stripping efficiency is consistent with experience as this measure of injection efficiency includes contributions from all injection loss mechanisms.

CONCLUSIONS AND FURTHER WORK

Measurements of the properties of the ISIS stripping foil have been made, resulting in a more consistent understanding of the foil preparation techniques, material composition and thickness. Combining all of the measurement results together the foil used for ISIS operations is best described as 0.55 μm, 215 μg cm^{-2}, aluminium oxide.

Details of the foil production mechanism have been provided. The foil manufacture is a complex multi-stage process that relies on individual skill. It is thought that certain stages of the foil production (masking, anodising, electrostatic deposition) may have drifted from the initial method over time as operations at increasing beam intensities and the ability to store foils without degradation necessitated longer-lasting foils. A new foil is posted, as a conservative approach, for each ISIS user cycle even though the lifetimes can be far in excess of this.

At 40×120 mm the ISIS foil occupies a large proportion of the machine aperture. For future upgrades to ISIS it is anticipated that a smaller foil could be used to reduce the number of re-circulating particles interacting with the foil, thereby reducing unwanted scattering and heating effects. As part of this study the minimum horizontal foil size currently required on ISIS was measured. Mounting a smaller foil could be a challenge; it is hoped that experience of operating with smaller foils will be gained by testing CSNS foils on ISIS.

ACKNOWLEDGEMENTS

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