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Operation with Carbon Stripping Foils at ISIS

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Introduction

ISIS is a pulsed neutron and muon source for physical and life science research. The 50 Hz proton RCS delivers 220 μA, at 800 MeV, to two spallation neutron targets.

For over 30 years ISIS has used 40×120 mm aluminium oxide stripping foils for charge exchange injection. **This poster gives an overview of operation with commercially available 40×60 mm diamond-like-carbon (DLC) and graphene stripping foils.**

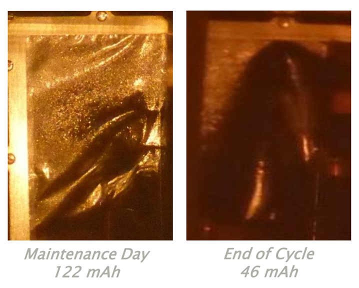
2016-17 Operation

Financial year 2016/17 was the first to use only carbon-based stripping foils on ISIS. In total 9 foils were used to inject 758 mAh of H^- beam over 191 user days, which were split into 5 cycles. Each cycle begins with 1-2 weeks of accelerator start-up and ends with 3 accelerator development days. 1-2 maintenance days are scheduled per cycle.

Cycle 2016/01

1st ISIS cycle to use only DLC foils

- 100 μg/cm², 40x60 mm, DLC with fibres installed for start-up
- Inspected on maintenance day (122 mAh) and left in, but rising injection losses necessitated a change 4 days later (140 mAh)
- Replacement foil deformed quickly over last 10 cycle days (46 mAh)


Maintenance Day 122 mAh — End of Cycle 46 mAh

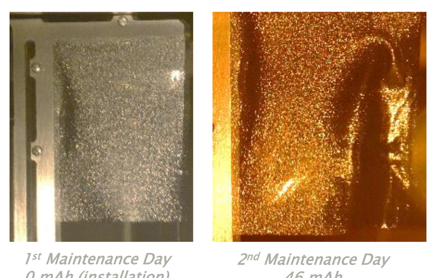
Cycle 2016/02

- Scheduled to run only to ISIS second target station (40 μA, 10 Hz)
- 100 μg/cm², 40x60 mm, DLC with fibres survived entire cycle with less deformation, as expected
- ANSYS calculations of peak temperature: 383 K (10 Hz), 492 K (50 Hz)


End of start-up 1 mAh — Maintenance Day 18 mAh — End of Cycle 32 mAh

Cycle 2016/03

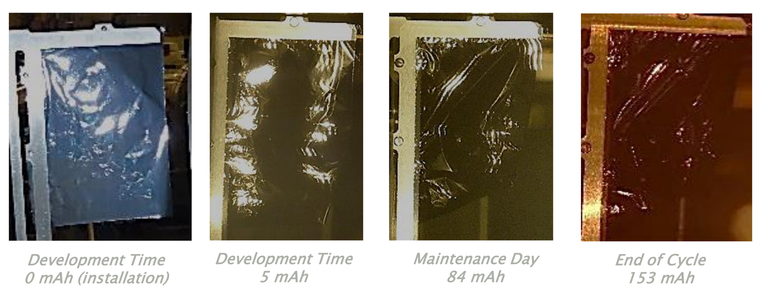
- 100 μg/cm², 40x60 mm, DLC with fibres installed for start-up
- Removed on 1st maintenance day after 61 mAh, for radiological analysis
- Replacement inspected on 2nd maintenance day (46 mAh), looked good so left in
- Replaced at end of cycle (92 mAh) for 200 μg/cm², 40x60 mm, graphene foil tests


1st Maintenance Day 0 mAh (installation) — 2nd Maintenance Day 46 mAh

Graphene was chosen for its high thermal conductivity and tensile strength, aiming to avoid deformation seen with DLC foils. A 200 μg/cm² graphene foil (minimum available thickness) was purchased from Applied Nanotech and mounted without supporting fibres.

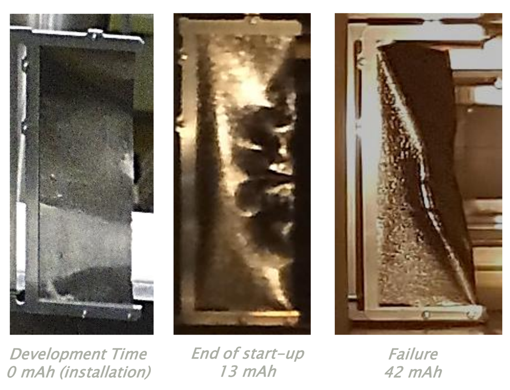
Cycle 2016/04

- Graphene foil survived 5 mAh during development time and was left in for cycle start-up
- Inspected on mid-cycle maintenance day (84 mAh)
- Deformed more slowly than DLC and appeared to stabilise
- Replaced at end of cycle (153 mAh) for test of 100 μg/cm², 40x120 mm ('full height'), DLC with no fibres


Development Time 0 mAh (installation) — Development Time 5 mAh — Maintenance Day 84 mAh — End of Cycle 153 mAh

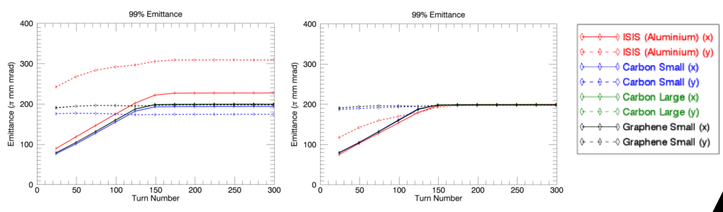
Cycle 2016/05

- 'Full Height' DLC left in for start-up, failed 5 days into cycle (42 mAh)
- Replaced with 100 μg/cm², 40x60 mm, DLC with fibres
- Inspected on 1st maintenance day (27 mAh)
- Replaced on 2nd maintenance day (93 mAh)
- Removed at end of cycle (83 mAh)


Development Time 0 mAh (installation) — End of start-up 13 mAh — Failure 42 mAh

Operations Summary

DLC and graphene perform well under beam, with no detectable additional losses, 97-98% injection efficiencies.


99% emittance with no space charge or apertures for the ISIS painting scheme (left) and small painting adjustments to achieve the same final emittance (right)

ORBIT models show emittance blow-up with foil size and thickness, but the scattering can be compensated with small changes in painting, agreeing with operational experience.

The manual foil change procedure is quicker and simpler with carbon-based foils. After a typical 1 hr cool-down the working area dose rates are 250-1000 μSv/hr with a typical staff dose 30-40 μSv.

Mounted foils are stored in boxes with silica beads to control humidity. However, when prepared months in advance of cycles the unconstrained graphene foils have been observed to curl.


Graphene foils curled in storage

Summary

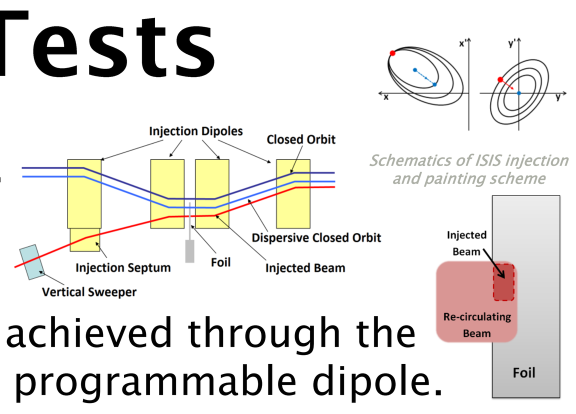
Commercially available carbon-based foils are easier to handle and install than the fragile aluminium oxide foils. Under beam they perform well with no measureable additional losses. However, the foils degrade over time, reducing the available lifetime.

The only carbon-based foil to withstand an entire cycle was the graphene foil in cycle 2016/04, seeing 153 mAh. To maximise availability and minimise staff dose the foil should survive a full user cycle: 45 days, 90% availability, 220 μA, a total of *214 mAh*

Further 200 μg/cm² graphene foil operational tests are planned, along with comparisons of 100 μg/cm² hybrid-boron-carbon (HBC) and 200 μg/cm² DLC foils.

Initial results from high temperature annealing tests are promising, and along with developing strategies for improving handling and storage, and further optimisation of foil size and thickness, may offer increases in foil lifetimes.

ISIS Injection & Previous Tests



Schematics of ISIS injection and painting scheme

70 MeV H^- ions are injected into the RCS over 200 μs (130 turns). A 65 mm symmetric horizontal bump is provided by four dipole magnets and collapses in 100 μs after the end of injection.

Injection begins 400 μs before field minimum, horizontal painting is achieved through the dispersive closed orbit. Vertical painting is provided by an upstream programmable dipole. The measured injection spot size is 12-15 mm in diameter.

First tests of DLC foils on ISIS were made in 2015, a 100 μg/cm², 50x65 mm foil, purchased from Micromatter, was clamped in an aluminium frame, leaving 40x60 mm available for beam.

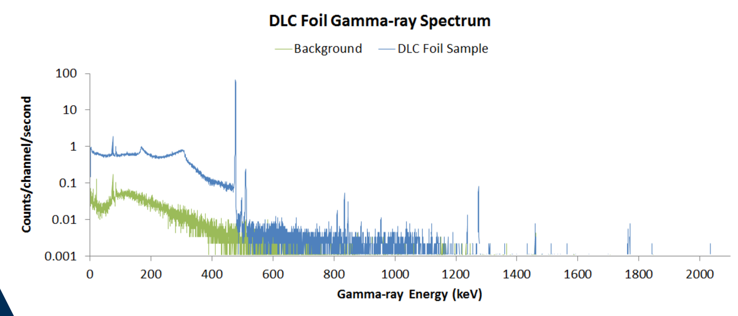
Initially the foils survived 1 mAh, but this was extended to ~100 mAh operation with the use of four strands of supporting carbon fibre.

This setup: 40x60mm, 100 μg/cm², four fibre strands, is used in current operations.


Preparing DLC foils with fibres — DLC no fibres 1 mAh (top), DLC with fibres 15 mAh (bottom)

Radiological Analysis

Gamma-ray spectroscopy was used to obtain the residual nuclei inventory of the foil retrieved from cycle 2016/03.



A Canberra BE3825 detector was used, 65 cm from foil, for 15 minutes.

The strongest peak, 477 keV, corresponds to Be-7, as expected.

A FLUKA model of the DLC foil, aluminium frame and carbon fibres agrees with measurements, foil traversals being the largest uncertainty.

The C-12 to Be-7 cross-section was calculated as 10±2 mb.

Published values (22-50 mb) also suggest that the number of foil traversals was overestimated.

	Measurement	FLUKA
Be-7 Components	96.3% peak area	>99% of residuals
Be-7 Activity (Bq)	2.14×10^7	7.94×10^7
Dose Rate (μSv/hr)	250	310

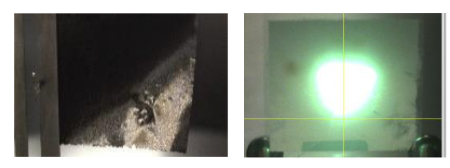
Electron Beam Tests


DLC foil in electron gun test vessel

A 1.5 keV electron gun was used to irradiate a DLC foil.

With the maximum 100 μA output, a 3.6 mm beam spot was used to best replicate the power density of a 15 mm ISIS injection spot. ANSYS simulations predicted a 200°C peak temperature.

The foil deformed within 0.1 s, but there were no further changes after 17 hours. With the gun pulsed at 50 Hz the foil was observed to flutter.


Deformation of DLC foil — Electron beam spot focussed on phosphor screen

A second DLC foil was annealed at 400°C for 2 hours and appeared smoother and tension changed. After 11 hours of irradiation no deformation was seen.

During production the Micromatter DLC foils are annealed at 160-240°C for 2 hours. Initial results from higher annealing temperature have shown improved foil response to beam.


DLC foil after high temperature annealing — Annealed DLC foil after 11 hours DC irradiation

Thickness Measurements

Visually the graphene foils appear smooth, whereas the DLC structure is rough and can include large grains. Measurements of DLC and graphene thickness and roughness were made using a touch probe, surface profiler and atomic force microscope (AFM).

An areal density, for the graphene foil, of 240±36 μg/cm² was calculated using the average measured thickness and bulk density, quoted as 1.8±0.2 g/cm³.

A 14368±48 mm² sample of DLC foil weighed 1.880±0.005 mg, giving an areal density of 129±5 μg/cm², compared to 115±10 μg/cm² calculated using the average measured thickness and accepted DLC density (2 g/cm³). The quoted tolerance of DLC foil thickness was ~10%.

A 100 μm² area from each foil was imaged with the AFM and the RMS roughness for DLC was measured to be double that of graphene.

	Thickness (μm)		Roughness (nm)
	Touch Probe (±0.05 μm)	Profiler (±0.0005 μm)	AFM (±0.15 nm)
DLC	0.60	0.5470	29.50
Graphene	1.30	1.3740	16.20

References and Acknowledgements

DLC Foils: Micromatter Technologies Inc. http://www.micromatter.com/
Graphene Foils: Applied Nanotech, Inc. http://www.appliednanotech.net/

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