STRIPPING FOIL SIMULATIONS FOR ISIS INJECTION UPGRADES

H.V. Smith, D.J. Adams, B. Jones, C.M. Warsop
ISIS, STFC, Rutherford Appleton Laboratory, UK

Abstract

ISIS, the pulsed neutron and muon spallation source located at the Rutherford Appleton Laboratory (UK), currently delivers a mean beam power of 0.2 MW to target. A 70 MeV H^- linear accelerator feeds into a 50 Hz, 800 MeV proton synchrotron (through a 0.3 μm aluminium oxide stripping foil), accelerating up to 3×10^{13} protons per pulse.

Potential injection scheme upgrades, aiming to raise average beam power towards 0.5 MW with a new 180 MeV linear accelerator, are being studied. Detailed consideration of the injection stripping foil forms a key element of this study: scattering, stripping efficiency and foil lifetime are significant factors in determining loss levels, which consequently limit operational intensity.

This paper describes the identification of a suitable stripping foil specification for successful 180 MeV H^- charge exchange injection into the ISIS synchrotron. A simulation code was developed to investigate electron stripping, scattering events and temperature rises, in order to witness their subsequent effect on foil lifetime. ANSYS models were also used to investigate the heat transfer and temperature distribution within thin foils.

INTRODUCTION

Injection into the ISIS synchrotron with energies higher than 70 MeV has the potential to increase beam intensity, aiming to deliver up to 0.5 MW beam power, with an optimised injection scheme and reduced space charge. Throughout the course of the injection upgrade study, an injection energy of 180 MeV has been assumed, along with parameters from a linac design [1].

The current ISIS injection scheme comprises a 0.3 μm aluminium oxide stripping foil located at the centre of a four dipole injection chicane [2].

A main figure of merit in describing stripping foils is the stripping efficiency. This is dependent upon electron-loss cross sections which are related to the foil material, foil thickness and incident particle energy. Increasing the beam energy and intensity would make the present aluminium oxide foil unsuitable. Thicknesses required for stripping would cause the expected temperatures to exceed the foil's melting point. Other suitable foil material candidates have been investigated.

ISIS operation shows that on average, foil lifetimes are in excess of 80,000 μAh and are limited largely by mechanical factors. Foil changes are carried out manually by ISIS personnel. It is important to consider the effect of increased temperatures on the foil lifetime for potential upgrades.

FOIL INTERACTION SIMULATIONS

An in-house simulation code has been developed, using C++, to model foil-beam interactions. Included in the model are effects from both multiple coulomb scattering and nuclear inelastic collisions. Stripping efficiency and the lifetime of partially stripped H^0 in Stark states have also been considered. Aluminium oxide foils (as presently used) and carbon foils were modelled; although recent developments in the production and lifetime testing of Hybrid Boron doped Carbon (HBC) foils, and their successful operation at KEK/J-PARC, may prove them to be suitable for upgraded injection into ISIS.

At 70 MeV, ISIS currently operates with a stripping efficiency of 97-98%. Simulations suggest the efficiency is 97.2%, giving good confidence in the model.

Activation due to beam loss is envisaged to be five times higher when injecting at 180 MeV, so the loss levels need to be equally reduced, to ~0.5%. Figure 1 shows the stripping efficiency of carbon at varying thicknesses for 180 MeV incident energy. The minimum thickness necessary to create the required reduction in controlled loss is 160 μg/cm^2. However, a thickness of 200 μg/cm^2 has been assumed in simulations, to allow for variation in manufacturing and some foil degradation during operation.

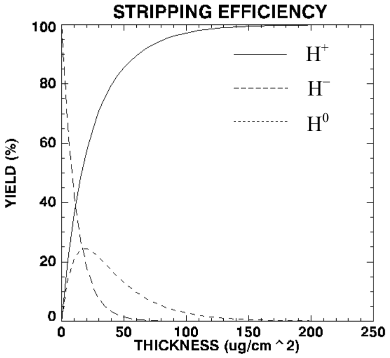


Figure 1: Stripping efficiency of carbon at 180 MeV. Percentage yields of H^+, H^- and H^0 are shown.

Beam loss at the foil is also dependent on the number of foil hits by circulating beam. Optimisation is ongoing, but the current estimate for the expected number of foil traversals per proton is ~5 [3].

Assuming a 200 μg/cm^2 carbon foil, the proportion of beam calculated to undergo a nuclear inelastic scatter is 2.4×10^{-6} and the estimated emittance growth of the injected beam due to multiple coulomb scattering is 2.25×10^{-3} π mm mrad [2]. This small emittance growth does not affect the transverse painting [3] and the rarity of inelastic scatters leads to acceptable loss levels of 0.27 W along the ~5 m injection straight.

Injection at 180 MeV will require injection dipole fields of up to 0.18 T, compared to 0.11 T for 70 MeV. This increases the proportion of partially stripped H^0 atoms in Stark states that are stripped inside the third injection dipole from 3.1% to 29.2%. Considering the differences in stripping efficiency between the 70 MeV and 180 MeV injection scenarios this corresponds to an extra 4 W of beam that will be lost in the injection straight. Detailed designs of the new straight will attempt to accommodate this loss.

FOIL TEMPERATURE STUDIES

Besides mechanical failures and vacuum rises, foil lifetimes are heavily affected by temperature. Heating due to prolonged exposure to high intensity beams can cause evaporation of the foil surface. Such a reduction in thickness lowers the stripping efficiency, ultimately limiting foil lifetime and potentially exceeding allowed heat loads on the beam dump. Excessive temperatures over a localised region of foil can also create small holes, thus rendering the foil unusable.

At lower temperatures, where evaporation and thinning are not problems, foil lifetimes are limited by radiation and mechanical damage. Such effects have not been considered or modelled in the following analysis.

Numerical Solution

A temperature solver was created to investigate the temperature rises of the beam spot only. This analysis employed a combination of Euler and midpoint numerical methods to solve the heat equation (Eq. 1), where both the foil temperature and thickness are coupled and dependent on time. (*u* is temperature, and α the thermal diffusivity).

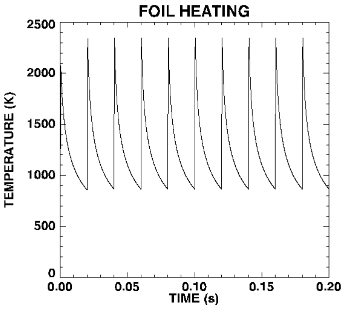
$$\frac{\partial u}{\partial t} = \alpha \nabla^2 u + Q \qquad (1)$$

This treatment is similar to that discussed elsewhere [4, 5]. Conduction effects in the foil are neglected. Q is the heat density transfer per unit volume and is therefore dominated by radiation effects. Heat distribution over the central beam spot is assumed to be uniform.

Simulations of 30 days of continuous ISIS operation at 180 MeV showed that the carbon foil thickness would reduce from 200 $\mu g/cm^2$ to 199.990 $\mu g/cm^2$ in this time frame, which is acceptable: operational experience at J-PARC has not shown any significant thinning of their foils, consistent with this result [6].

Peak temperatures obtained in this study were 2358 K with a temperature of 866 K reached after radiative cooling between pulses. Figure 2 shows the temperature profile and parameters used [1].

A separate code was written, which assumed foil thickness does not vary with time, allowing an analytic solution. Results from this code verified the previous result, providing confidence in both models. Results were also benchmarked against J-PARC foil temperature estimates and KEK measurements [7].



Injection Spot Size	1 mm × 2.2 mm
Peak Current	25.6 mA
Pulse Length	500 μs
Repetition Rate	50 Hz

Figure 2: Temporal temperature variation, from the numerical solver with associated parameters [1].

In all numerical (and following ANSYS) simulations an emissivity of 0.8 was assumed for a carbon foil. This value is typical of various forms of carbon and graphite, with emissivities spanning 0.65 – 0.95 over the range 300 – 3000 K [8].

ANSYS Simulation

The numerical solutions of beam-spot temperatures are useful, but it is more realistic to include the effect of heat dissipation across the foil. For this purpose ANSYS [9, 10] simulations were created.

3D foil models were created in ANSYS using the same parameters as the numerical method (Fig. 2). A uniform heat distribution over the elliptical beam spot, and radiation to ambient temperature, gave peak temperatures of 2304 K which are comparable to the numerical solution. Convective properties were not considered, to represent the vacuous conditions.

More realistic simulations, assuming a Gaussian beam distribution, with the same parameters (Fig. 2), were performed. Results obtained are displayed in Figure 3.

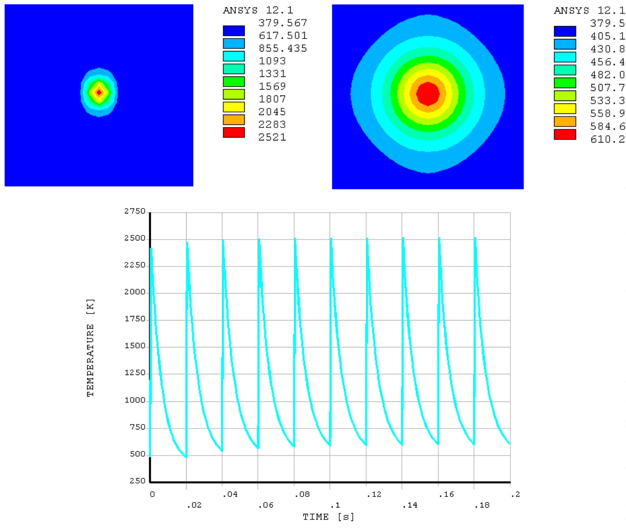


Figure 3: Temperature dissipation directly after an injection pulse and after cooling between pulses can be seen in the top left and right plots respectively. (Note that the contour scales are different in both plots to show clear gradients). The temporal temperature profile is displayed, bottom centre, and can be compared to Figure 2.

As expected, the peak temperatures reached in the ANSYS simulations with Gaussian beam, 2521 K, are higher than those with a uniform distribution and temperatures reached after radiative cooling, 610 K, are lower than with the numerical solver. This is because the Gaussian beam profile assumed in the ANSYS model implies that the temperature at the centre of the beam spot will be higher than where a uniform heat deposition was supposed. Thermal conduction was included in the ANSYS model and as such the combination of conduction and radiation effects leads to a lower cooled temperature than in the numerical model where conduction effects were neglected.

Developments were made to the ANSYS model: conduction effects were varied between the foil plane and thickness directions, and supports and a surrounding beam pipe were added. None of these adaptations had appreciable effects nor significantly altered the foil temperatures.

Foil thickness was kept constant in this simple ANSYS model. For computational reasons only a 10 mm × 10 mm square foil was considered.

Realistic Beam Distributions

Data from 3D parallel ORBIT [11] simulations of ISIS 180 MeV injection [3] has been used in ANSYS, to observe foil temperature evolution for a more realistic beam distribution. Foil hits, over a grid equal to the ANSYS mesh size, were counted every turn in the ORBIT simulation and used to generate a realistic foil heat load in ANSYS. Looking at injected beam only, the peak temperature obtained was 826 K (Fig. 4). An adaptation of the numerical solver was also used and compared well, giving a peak of 828 K. In both cases, the foil size was scaled to encompass 10σ of the beam.

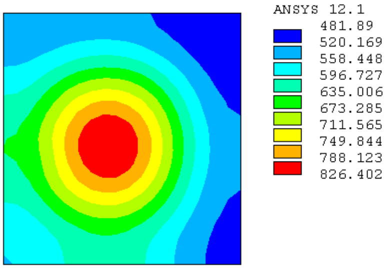


Figure 4: ANSYS temperature contour plot for ORBIT injected beam only.

As well as focusing on the injection spot it is also important to consider the heating effect from re-circulated protons, especially if the number of foil traversals per proton is high. ORBIT simulation data, including re-circulated beam, was analysed and the effect of the extra traversals can clearly be seen with the peak temperature increasing to 1657 K in Figure 5. Contours in Figure 5 show the central injection spot and how the temperature is, in this case, dominated by foil re-circulations in the bottom left corner. Such analysis will help in further optimisation of the injection scheme.

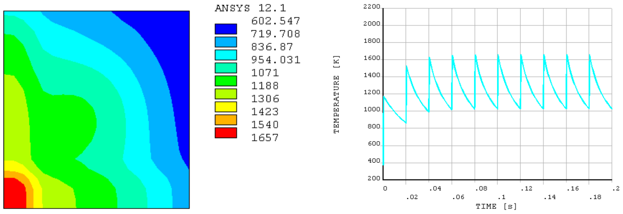


Figure 5: Injection spot and proton re-circulation hits on a representative pulse are shown in the left plot and the temperature profile for the hottest area in the right plot.

CONCLUSIONS AND FUTURE WORK

Simulation results from the foil interaction code and foil temperature models have been combined to suggest that a carbon foil of > 160 μg/cm^2 would be suitable for H$^-$ charge exchange injection into ISIS at 180 MeV. Although maximum temperatures, including re-circulation effects, are expected to be ~1650 K they should not cause any significant problems. Similar carbon foils, of ~200 μg/cm^2 thickness, are already in use at J-PARC for beam powers up to 300 kW.

Simulation capability will be enhanced by incorporating the foil interaction code and temperature calculations into the SET [12] tracking code which is currently being developed at ISIS. Further foil studies and injection scheme optimisation are planned.

Work is ongoing with ANSYS simulations with the aim of witnessing structural effects on the foil and studying heating effects of double layered HBC foils under investigation at KEK.

REFERENCES

[1] G. H. Rees, “Linac, Beam Line and Ring Studies for ISIS Upgrades”, ASTeC internal report, GHR1, 2009.

[2] B. Jones, “Injection Upgrade on the ISIS Synchrotron”, IPAC ’10, p. 639.

[3] C. M. Warsop et al. , “Status of Injection Upgrade Studies for the ISIS Synchrotron”, IPAC’11, WEPS106.

[4] S. G. Lebedev, A. S. Lebedev, Phys. Rev. STAB 11, 020401-1 – 020401-7 (2008).

[5] C. J. Liaw et al., “Calculation of the Maximum Temperature on the Carbon Stripping Foil of the Spallation Neutron Source”, PAC ’99, p. 3300.

[6] I. Sugai et al., “Development of thick hybrid-type carbon stripper foils with high durability at 1800 K for RCS of J-PARC”, NIM A: Vol 561 (2006) 16-23.

[7] Y. Takeda, KEK, Private communications.

[8] Y. S. Touloukian, D. P. DeWitt, “Thermophysical Properties of Matter”, Plenum, Vol 8 (1972), p. 7, 35.

[9] ANSYS® [Mechanical APDL], 12.1, ANSYS, Inc.

[10] P. Loveridge, RAL, STFC, Private Communications.

[11] J. Galambos, “ORBIT - A Ring Injection Code with Space Charge”, PAC ’99, p. 3143.

[12] B. G. Pine, C. M. Warsop, “Ring Transverse Beam Dynamics for the ISIS Injection Upgrade”, IPAC ’11, WEPS104.