SIMULATION OF DOUBLE LAYER CARBON STRIPPING FOILS FOR ISIS INJECTION UPGRADES

H.V. Smith, D.J. Adams B. Jones, C.M. Warsop, ISIS, STFC, Rutherford Appleton Laboratory, UK
Y. Irie, Y. Takeda, KEK, Ibaraki, Japan

Abstract

ISIS, the pulsed neutron 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, 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 presently being studied [1]. This paper highlights recent results from temperature studies of double layer carbon foils, suitable for injection at 180 MeV into ISIS, using ANSYS. Experimental results from KEK were used to benchmark models and the variation of temperature as a function of foil separation was investigated.

INTRODUCTION

At present a single 0.3 µm aluminium oxide stripping foil is used to remove electrons from incoming 70 MeV H^- ions. Upgrading the ISIS injection energy to 180 MeV would render such a foil unusable [2]. Previous studies [2] have indicated that a single 200 µg cm^{-2} carbon foil would be suitable for use in an upgraded ISIS injection scheme. Hybrid Boron-doped Carbon (HBC) foils, produced at KEK, of a similar thickness are currently used for 180 MeV injection at J-PARC [3].

Recent experimentation with double HBC foils systems at KEK [4, 5] prompted this study.

DOUBLE FOIL SYSTEMS

The main advantage of using a double foil system is the significant reduction in foil operating temperatures, compared to a single thicker foil, through an increase in available area for radiative cooling and decreased foil thicknesses. Reducing the foil operating temperature could lead to an increase in foil lifetime.

The stripping efficiency for a system of two thinner foils, of equal thickness, can be shown to be equal to that of a single foil of double thickness.

An existing in-house foil interaction code has been used to determine the average number of collisions each particle undergoes whilst traversing foils. The number of multiple coulomb scattering collisions was found to be equal in the single and double foil systems. The frequency of inelastic scattering events was also unchanged, as expected.

However, operational difficulties may arise through the use of double foil systems since thinner foils would be more fragile than a single thick foil, creating possible problems during storage, mounting and insertion.

KEK Experiments

Experimentation with small, ~10 mm radius, double layer stripping foils has been conducted by the foil target group at KEK [4]. HBC foils were bombarded with approximately 80 µA of H^- DC beam from the 650 keV Cockroft Walton accelerator and measurements of peak temperature were taken using digital optical pyrometers. No measurement of foil separation was possible due to the mounting procedures used. Qualitatively, it was estimated that foil separation was, on average, of the order of 1 mm. However, up to 5 mm foil separation was observed around the beam spot after prolonged irradiation.

RESULTS

Temperature distribution models for single foils were created using ANSYS [2]. The model has been extended to simulate expected temperatures in double foil systems. Heat transfer was considered in terms of radiation from each foil to ambient temperature and radiation between the inward facing surfaces of both foils. Conduction was included, but convection neglected.

Benchmarking ANSYS Modelling

Results from the ANSYS simulations have been compared to data from experiments at KEK. A uniformly distributed beam over a 5 mm beam spot was assumed and an emissivity of 0.34 was used, which was equal to the measured emissivity value for HBC foils from the same experimental period at KEK [4].

Simulated temperatures compare well with KEK experimental results, Table 1. Measurement errors may have arisen from the calibration of the optical pyrometer. All material properties (excluding emissivity) were defined for carbon, rather than HBC, in the simulations, which may also be a source of errors.

Table 1: Temperature measurements of the upstream foil compared to simulated temperatures of both upstream and downstream foils for four different double foil systems. The foil separation was assumed to be 1 mm.

Sample	Measured (K)	Simulated (K)
(202+202) µg cm^{-2}, 73.4 µA	1673	1676, 1676
(320+103) µg cm^{-2}, 72.8 µA	1837	1810, 1526
(226+223) µg cm^{-2}, 84.4 µA	1769	1781, 1780
(188+185) µg cm^{-2}, 84.8 µA	1694	1707, 1703

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Foil Separation Analysis

An important part of the study was to investigate the variation of temperature with foil separation, Fig. 1. KEK DC beam conditions were modelled, in a general case, by assuming an 80 μA beam. Separations were varied, in order of magnitude step sizes, between 1 μm and 0.1 m. A reduced step size was used over the 0.1 - 10 mm range. Mesh density and convergence testing was conducted at each separation to ensure aspect ratios between finite elements were consistent and sufficient.

It was found that significant reductions in foil operating temperature could be achieved by using a double foil system with a separation of 0.1 - 1 mm, whilst maintaining practicality.

Modelling two 100 μg cm^{-2} carbon foils showed that for small separations the peak temperature of the double foil system approaches the peak temperature for a single 200 μg cm^{-2} foil, 1586 K. For large separations the peak temperature approaches the peak temperature expected for a single 100 μg cm^{-2} foil, 1335 K, Fig. 1. This behaviour was repeatable for all foil thicknesses modelled (50, 100, 200 and 300 μg cm^{-2}) in double foil systems.

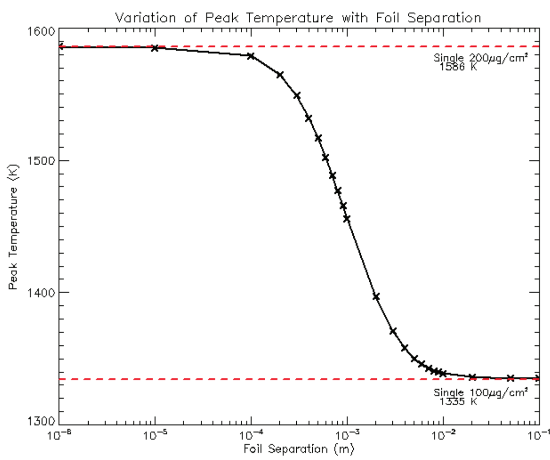

Figure 1: Simulated results of peak temperature with foil separation for two 100 μg cm^{-2} foils. Temperatures for single layer 200 μg cm^{-2} and 100 μg cm^{-2} foils are shown.

Consideration of Solid Angle Subtended

The variation of solid angle subtended by each foil, with foil separation and geometry, is an important consideration as this will directly impact the amount of possible heat transferred by radiation between two foils.

A theoretical approach was taken to calculate the average solid angle subtended, by evaluating and integrating over all points on the foil area, Fig. 2. The resulting relationship for the average solid angle subtended, α (sr), was obtained in terms of foil dimensions w, h and foil separation d, Eq. 1. As expected the average solid angle subtended for large foils does not reduce to zero over the same separation range as small foils, Fig. 3. It is expected that α correlates closely with the system's ability to radiate energy away from the foils and thus reduce peak temperatures.

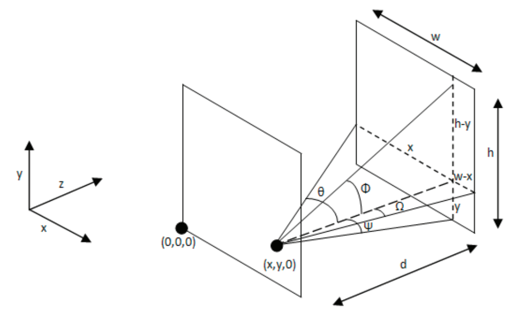

Figure 2: Schematic of a double foil system with solid angle seen from a point. Foils have geometric dimensions *w* and *h*, with separation *d*.

$$\alpha = \left(2\operatorname{atan}\left(\frac{w}{d}\right) + \frac{d}{w}\ln\left|\frac{1}{\left(\frac{w}{d}\right)^2+1}\right|\right) * \left(\frac{2d}{h}\left(\sec\left(\operatorname{atan}\left(\frac{h}{d}\right)-1\right)\right)\right) \quad (1)$$

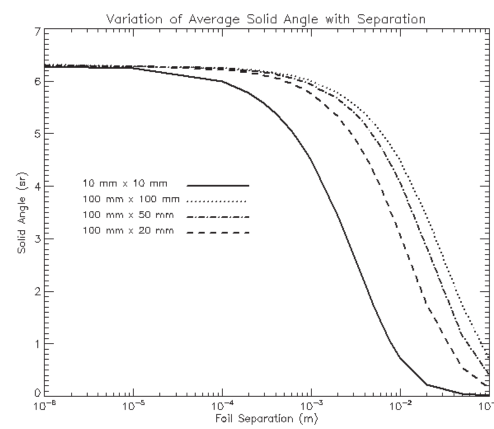

Figure 3: Variation of average solid angle subtended, 0 - 2π sr, with foil separation. The separation required to reduce the solid angle varies with foil dimensions.

Empirical Predictions

Variations of temperature and average solid angle with separation have a similar form, Fig. 4. An empirical formula, linking the peak temperature and average solid angle as functions of separation was deduced and tested against simulated results, Eq. 2, Table 2.

$$T(d) = T_{Single}\left(1 + 0.188\frac{\alpha(d)}{2\pi}\right) \quad (2)$$

Table 2: Comparison of simulated temperatures with those obtained through the empirical formula (Eq. 2) where $w = h = 1\times10^{-2}$ m and each foil is 100 μg cm^{-2}

Gap (m)	Simulated (K)	Calculated (K)
1×10^{-6}	1586	1585
1×10^{-5}	1585	1583
1×10^{-4}	1579	1573
1×10^{-3}	1456	1513
1×10^{-2}	1339	1363
1×10^{-1}	1335	1334

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Over the range 1×10^{-4} - 1×10^{-2} m the average discrepancy between empirical calculation and simulation results is 38 K (~2.6%), Table 2. The approximation is most consistent with results for large and small separations, where the two functions are most similar. The empirical constant, 0.188, was obtained by taking the ratio of the temperature range to the single foil temperature.

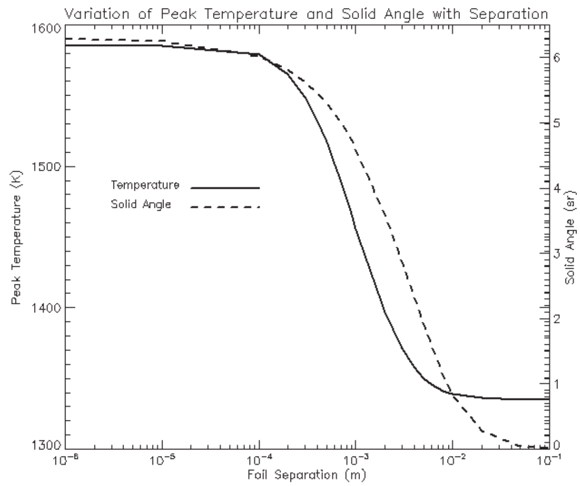

Figure 4: Variation of peak expected temperature (from simulation) and average solid angle (Eq. 1), with foil separation distance.

ANSYS Model Limitations

Surface-to-surface radiation modelling demands that a small finite element mesh be created, to enable a high resolution calculation of the radiative view-factor between the foils. Successful modelling of large foil sizes, 110 × 40 mm, as used on ISIS, requires mesh densities of over 200 × 200 for 1 mm separation and over 200,000 × 200,000 for 1 µm separation. For computational reasons the analysis of such cases was not possible.

However, modelling of large single layer foils is achievable since no consideration of surface-to-surface radiation is required. This allows peak temperatures of double foil systems for large foils to be estimated, Eq. 2.

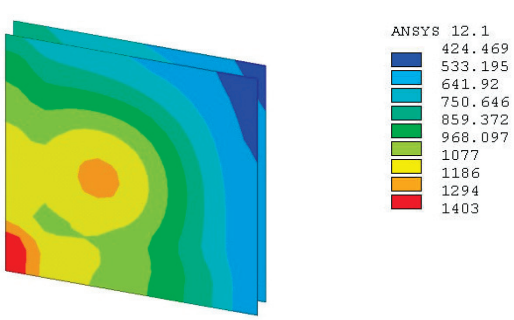

Figure 5: Isometric view of two 100 µg cm^{-2} foils with 1 mm separation for 180 MeV ISIS injection using ORBIT data. Temperature contours are displayed in K.

ISIS INJECTION UPGRADES

Reductions in foil temperature achievable using a double foil system were explored for ISIS injection upgrades, Fig. 5. Data from ORBIT [6] simulations, with realistic injected beam distributions, was used. This allowed heating effects from both injected and re-circulating beam to be modelled. A separation of 1 mm gave a peak temperature, dominated by proton re-circulations, of 1403 K. This is a significant reduction from 1657 K, the temperature for a single 200 µg cm^{-2} foil under the same bombardment [2].

CONCLUSIONS

Using a double foil system can lower the peak operational temperatures of electron stripping foils, potentially increasing foil lifetime and improving structural stability, whilst maintaining overall stripping efficiency. Emittance growth from multiple coulomb scattering, and inelastic scattering rates, remain equal to those of a single thicker foil.

There is a strong relationship between foil temperature and foil separation. This is consistent with the variation with distance of the solid angle subtended. Separations of 1×10^{-4} - 1×10^{-3} m produce significant temperature reductions whilst maintaining operational practicality. An empirical relation has been derived, allowing approximate peak temperatures to be calculated for double foil systems of any geometric dimensions, given single foil data.

Peak foil temperatures for the proposed ISIS injection energy upgrade to 180 MeV have been modelled using double foil systems. Distributions including injected and re-circulated beam from ORBIT simulations have been used. The peak temperature expected is 1403 K. This is 254 K lower than in the equivalent single foil scenario. Such a reduction in temperature would be beneficial to the lifetime and structural integrity of the foil.

ACKNOWLEDGMENT

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