A CARBON FOIL STRIPPER FOR FRIB *

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Abstract

The US Department of Energy Facility for Rare Isotope Beams (FRIB) at Michigan State University includes a heavy ion superconducting linac capable of accelerating all ions up to uranium with energies higher than 200 MeV/u and beam power up to 400 kW. At an energy of approximately 16.5 MeV/u we plan to strip the beam to reduce the voltage needed in the rest of the linac to achieve the final energy. The design of the stripper is a challenging problem due to the high power deposited (approximately 0.7 kW) in the stripper media by the beam in the small beam spot. One of the options being considered is a carbon foil stripper. We have developed a test chamber to study the thermal-mechanical properties of different stripping media candidates (amorphous carbon, graphene, diamond). This chamber utilizes an electron beam to deposit powers similar to what the FRIB stripper will see in operation. The thermo-mechanical studies are a necessary condition but not sufficient. The effect of radiation damage must also be studied. We have utilized heavy ions (Pb) from the K500 cyclotron to study this issue. We present in this paper a summary of the requirements and the status of the studies.

INTRODUCTION

An overview of the FRIB accelerator can be found in [1] in this conference. The challenge of the FRIB stripper is due to the high energy loss of the very heavy ions that FRIB will accelerate. At the stripping energy of approximately 16.5 MeV/u, the beam power will be close to 40 kW. Taking the example of a solid carbon stripper, the power deposited on the stripper is of the order of 700 W. To reduce the emittance growth at the stripper due to the angular scattering, it is necessary to operate with a small spot size at the stripper (the scattering from the foil and the beam divergence add in quadrature). The solid stripper is just one of the alternative solutions to the stripper being studied. A liquid lithium stripper, a gas stripper and a plasma stripper are also being considered [2]. This paper describes the R&D on the solid stripper exclusively.

The major concerns in these conditions are the thermal stresses and radiation damage. The linear energy transfer to the carbon is shown in Figure 1 where only the electronic loss is calculated, being the dominant term at these energies. The two curves correspond to the energy at which the experiment described later was performed (8.1 MeV/u) and the energy at the FRIB stripper (16.5 MeV/u). It can be seen that there is a very large variation with atomic number, with values reaching 25 keV/nm for uranium.

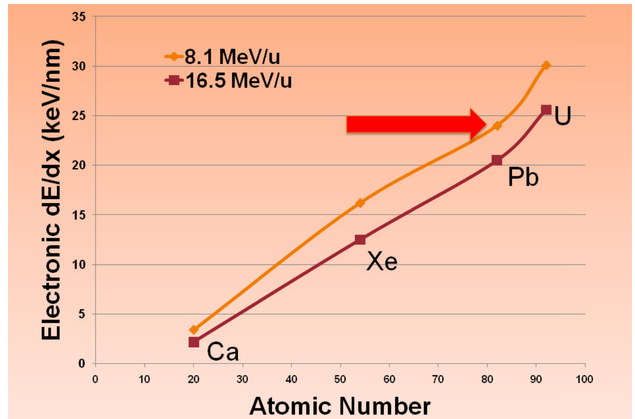

Figure 1: Electronic energy loss as a function of the atomic number in carbon. The data has been calculated for two different energies. 8.1 MeV/u is the energy used for the experiment at the K500, and 16.5 MeV/u is the FRIB energy at the stripper. The arrow indicates the ion used in the experiment.

STRIPPER FOIL TEST CHAMBER

With the purpose of studying the thermal and mechanical issues we built a test chamber that allows heating the stripper foils with an electron beam produced by an electron gun borrowed from GSI.

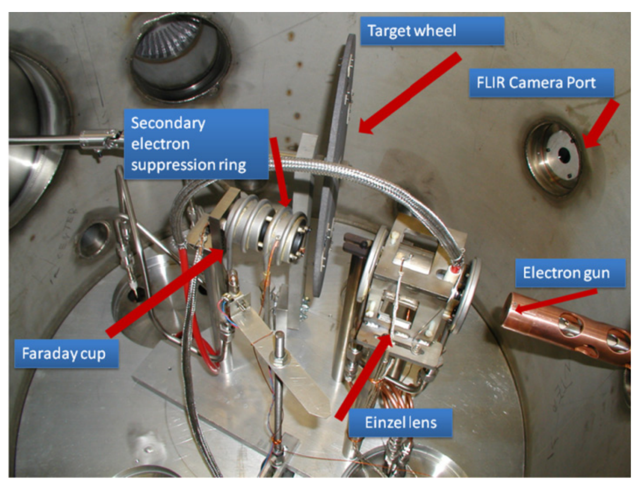

Figure 2: Inside of the foil test chamber.

The main objective of the experiment in the chamber was to obtain confidence that the estimates of the temperature distribution in the foil were correctly calculated and we could then predict the sublimation rate for the carbon foils.

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The electron beam is focused by an einzel lens and is then intercepted by the foils to be tested. A Faraday cup is located behind the target wheel where the foils are mounted. A rotating vacuum feed-trough rotates the wheel between the different test foils. Two ports allow the utilization of several diagnostic instruments. A low temperature infra-red (IR) camera (FLIR E45, maximum temperature is 900 C) is located in one of the ports with a ZnSe viewport. The other larger port is used with a MIKRON M9200 IR camera that operates between 900 and 3000 C in four different overlapping ranges. This camera operates in the shorter wavelength area of the spectrum. The size of this viewport allows sharing it with a Fibre Optic Spectrometer (FOS) from StellarNet and a B&W TV camera.

The FOS was calibrated with a calibration lamp of known temperature. This procedure corrects for the viewport and fibre transmission as well as the detector sensitivity. The temperature determinations with the FOS were performed by fitting a black body curve to the spectrum between 400 and 800 nm (this assumes an emissivity that is independent of the wavelength).

Stationary Beam Test

Using a non-rotating beam we studied the temperature distribution in transverse space and the time evolution of the transient heating process.

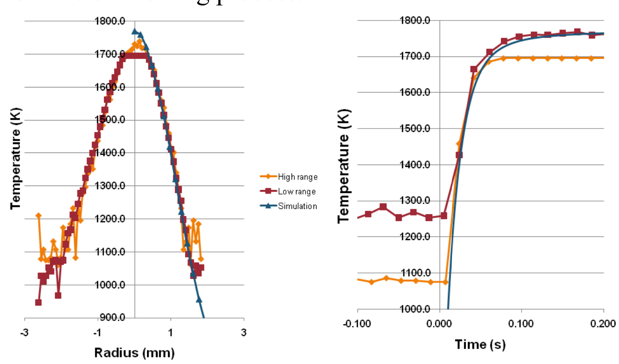

Figure 3: Non-rotating beam test, showing good agreement between the calculation and the measurements of the temperatures in the transverse space and the time dependence during the heating of the foil.

Figure 3 shows good agreement between the simulation of the temperature distribution as a function of radius and with the measurement as a function of time during the heating. There are two curves in the graphs labelled *high* and *low* range because the MIKRON camera cannot span the whole range of interest in a single measurement. The calculations and the measurements agree but the foil emissivity was set at 0.32 for the calculations and in the camera. This value of the emissivity is also needed to match the camera measurements with the FOS measurement.

Rotating Beam Test

The einzel lens third electrode has been split in four independent electrodes. This configuration allows biasing the electrodes to steer the beam and produce a rotary motion of the beam, to simulate a rotating disk in front of a stationary beam by applying two sinusoidal waves in quadrature. Figure 4 shows the electrode configuration of the exit "ground" electrode.

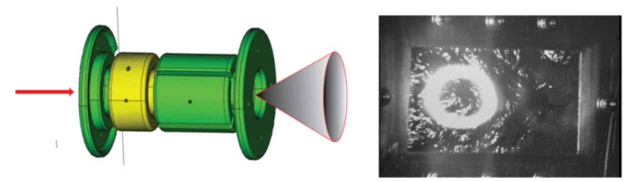

Figure 4: Electrode configuration of the einzel lens showing the deflecting electrodes (left). On the right we show the beam path on the foil when two sinusoidal waves in quadrature are applied.

This configuration is important because the initial FRIB plan was to build a rotating disk instead of a stationary foil to better distribute the heat and damage of the stripper. Also RIKEN is using a rotating disk as their stripper in some tests [3].

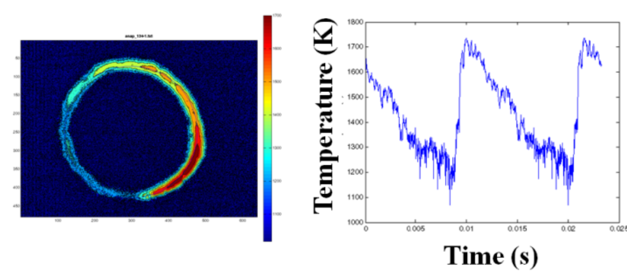

Figure 5: The picture on the right shows the output of the MIKRON IR camera for a beam rotating at 86 Hz, while the right graph shows the time dependence of the temperature showing the heating and cooling for a point on the heated circle.

The temperature measurements confirmed that we can calculate the thermal behaviour of the foils and predict the sublimation effects in FRIB.

RADIATION DAMAGE

The radiation damage effects were studied in the K500-K1200 Coupled Cyclotron Facility (CCF) at NSCL/MSU. The beam from the K500 is injected radially into the K1200 and stripped at a radius of approximately 0.33 m. Several foils from different origin were mounted on the stripper carrousel and tested with an 8.1 MeV/u beam.

After tuning the beam at low intensity the foils were moved to the stripping location and the beam was stripped at intensities of 20, 50 and 100% of the maximum intensity available. The average intensity was controlled with a chopper operating at 2 kHz. The calculated temperature of the foils is shown in Figure 6. Notice that the difficult environment where the stripper is located (in vacuum, in a 5 T magnetic field and inside the high voltage accelerating RF electrode) prevents us from installing any diagnostics to monitor the foil, so we must rely on the calculated temperatures.

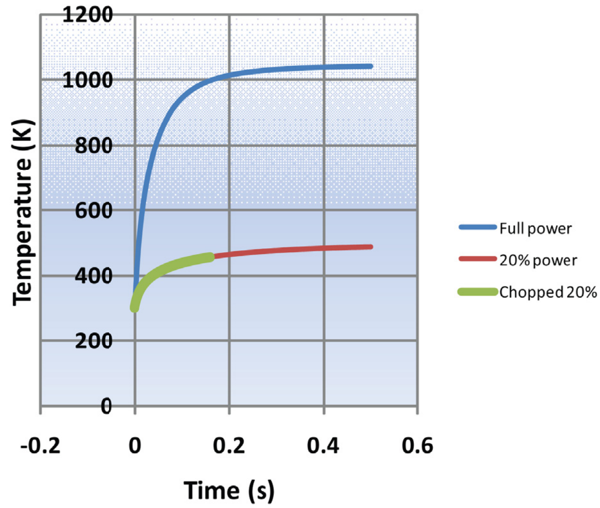

Figure 6: Calculated temperature of the stripper foils during the Pb experiment in the K1200. Even at full power the temperature is below 1100 K, so sublimation should not be an issue. The effect of chopping at 2 kHz is similar to decreasing the current to 20% because of the long time to achieve equilibrium.

As shown in the figure the temperature is low enough to remove the possibility of damage by sublimation.

The figure of merit we considered was the number of ions extracted from the cyclotron divided by the number of ions injected and hitting the foil. The results for the different foils are shown in Figure 7.

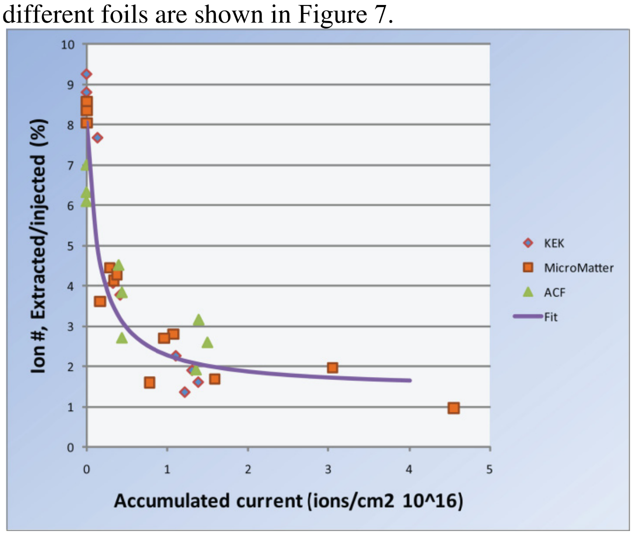

Figure 7: Percent of ions extracted from the K1200 as a function of the dose of Pb ions hitting the stripper foil for foils of different origin.

The graph shows no significant difference between the foils from different origins. The very fast decrease makes the acceleration of intense very heavy ions not practical in the cyclotron.

Most of the foil had grown in the transverse direction and measurements with an alpha source confirmed that they become thinner in the region hit by the beam. This effect seems consistent with the "ion hammering" phenomenon described by Klaumunzer and collaborators [4].

The foils were inspected with an Scanning Electron Microscope (SEM) at the Advance Microscopy Centre at MSU.

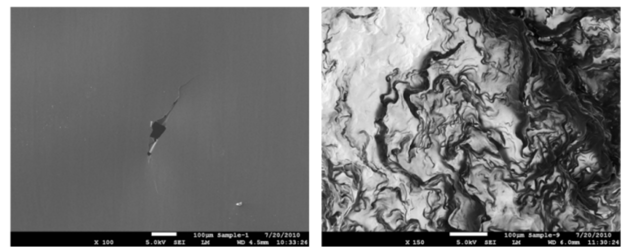

Figure 8: SEM photographs of the unused carbon foil (left) showing a small pinhole for illustration and a foil exposed to the Pb beam on the right.

The "ion hammering" effect seems to appear above a certain value of the electronic dE/dx that depends on the target material and above a certain fluence. The horizontal arrow in Figure 1 indicates where the experiment was operating. We did not find any reference to this threshold value for carbon.

CONCLUSION

The radiation damage observed in the foils exposed to a Pb beam in the K1200 cyclotron showed effects similar to what has been described as "ion hammering". The very fast decay of the foil performance makes this type of stripper very unlikely to satisfy the FRIB requirements. We are consequently looking at other options for FRIB [2].

REFERENCES

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