UPGRADE OF THE FRIB PROTOTYPE INJECTOR FOR LIQUID LITHIUM FILM TESTING*

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Abstract

The development of a uniform and stable high velocity, thin liquid lithium film stripper is essential for the future Facility for Rare-Isotope Beams (FRIB). The formation of such a film has been demonstrated recently at ANL. The next step is to be able to measure the film thickness and verify its temporal and spatial stability under high power density ion beam irradiation. Intense beams of light ions generated by the FRIB prototype injector can be used to accomplish this task. The injector consists of an ECR ion source followed by a LEBT. Previously, a DC 3.3 mA/75 kV proton beam was delivered downstream of the first bending magnet. The proton beam power will be brought to the required level by adding a second accelerating tube. A low energy electron beam (LEEB) technique, based on the thickness-dependent scattering of electrons by the film, was proposed as a fast-response on-line film thickness diagnostic. A LEEB test bench has been designed and built to verify this technique off-line. The transmission of electrons through carbon foils of different thicknesses was measured and compared with the results of CASINO simulations. Comparing the experimental and numerical results we should be able to have a quantitative measurement of the film thickness.

INTRODUCTION

Charge strippers can play an essential role in heavy ion accelerators because they increase the acceleration efficiency by increasing the charge-to-mass ratio of the beam and therefore decrease construction costs. Conventional stripping foils are typically made from different solid materials. However, even rotating solid thin films [1] will not be able to withstand the power density deposited by ion beams from next generation radioactive ion beam facilities, such as FRIB and the RIKEN RIBF. Some liquid metals have low vapor pressure and good thermal properties, allowing such a stripper to withstand extreme heat load from ion beam deposition. A windowless, liquid lithium stripper/target concept has been proposed at ANL a few years ago [2]. The formation of a liquid lithium film with estimated thickness of about 10-15 μm was succesfully demonstrated in a proof of principle experiment [3]. A photograph of the liquid lithium film is presented in Fig. 1. The demonstrated thickness fits well into the range of 6 – 20 μm (0.3 – 1 mg/cm^2) required for the strippers of next generation radioactive ion beam facilities. The adjustment of the film thickness to the desired value can be accomplished by varing the liquid lithium drive pressure, nozzle opening size, and jet deflection geometry. A direct and accurate fast-reponse measurement of the film thickness is required. The temporal and spatial stability of the liquid lithium film under about 130 W/mm^2 (400 W power over spot with diameter of about 2 mm) power density deposited into the film by an ion beam should be demonstrated as well.

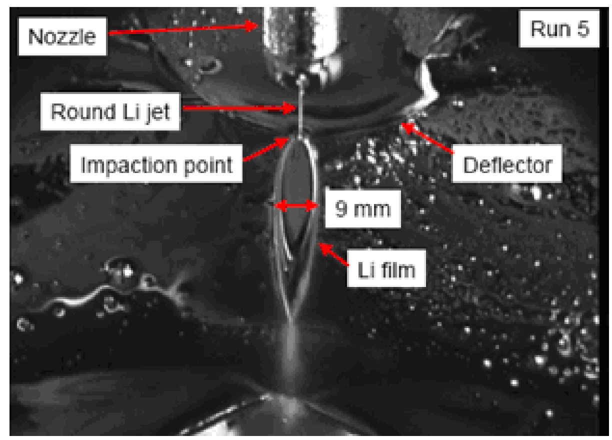

Figure 1: 9 mm wide liquid Li film flowing at about 58 m/s with thickness of about 10 μm.

FILM THICKNESS MEASUREMENTS

For film thickness measurements, we have proposed [4], designed and built a low energy electron beam (LEEB) monitor, which is based on the thickness-dependent scattering and absorption of electrons by the film. A similar approach is used at GSI for on-line target monitoring [5]. Fig. 2 shows the LEEB monitor test setup, which includes a 30-kV commercial electron gun (E-gun) [6] (EMG-4212/EGPS-4212 electron gun and power system, Kimball Physics, Inc), a 90° double-focusing bending magnet specifically designed for the LEEB monitor, an electrostatic gridded lens, a movable holder with carbon foils of different thickness, a P47 scintillator, and a Faraday cup (FC). Commercially available carbon foils from ACF-Metals [7] with density 1.83 g/cm^3 and thicknesses in the range of 3.22 – 12.3 μm were used for the LEEB monitor calibration. Taking into account that liquid lithium density is equal to 0.511 g/cm^3, the corresponding liquid lithium film thicknesses will be in the range of 11.5 – 44.1 μm. A Faraday cup (FC) with an input aperture diameter of 48 mm has an outer grounded shield for secondary particles and is equiped with a biased suppression ring. The FC-foil distance can be varied from 150 up to 285 mm. The bending magnet is used to protect the E-gun from the lithium environment which is required

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for future measurements of liquid lithium film thickness. It should prevent lithium vapor, mist, and splash from reaching the E-gun thermocathode, which may cause fast degradation of the E-gun performance. The incident angle of the electron beam on the foils and the P47 scintillator is 45º.

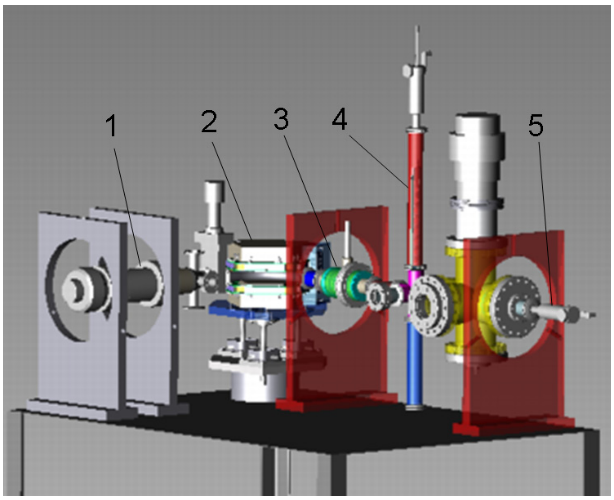

Figure 2: Low energy electron beam monitor: 1 – e-gun, 2 – bending magnet, 3 – electrostatic gridded lens, 4 – movable carbon foils and scintillator holder, 5 – movable Faraday cup.

Such a geometry is required for future temporal and spatial liquid lithium film stability tests under high power density ion beam irradiation. The ion beam will be focussed normally to the film surface. Varying the E-gun extraction grid, and focussing potentials together with the gridded electrostatic lens potential, we obtained an electron beam spot about 2 mm in diameter at the location of the foils as shown in Fig. 3.

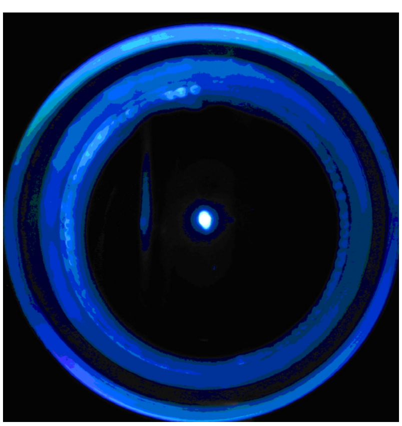
Figure 3: Image of focused electron beam on the P47 scintillator.

The transmission of electrons to the FC is defined as the ratio of FC currents measured with and without the film intercepting the beam. The measured and simulated (by CASINO [8]) dependence of the 30 kV electron beam transmission to the FC on the carbon foil thickness is presented in Fig. 4 for a 150 mm FC-foil distance. For these simulations CASINO was especially modified by Dr. Drouin to output detailed particle coordinates after the target foil which allowed us to transport them to the FC and obtain a simulated transmission equivalent to the measured one. One can see that the simulated transmission is close to the measured one, but it is systematically lower. The most probable reason for this is the reflection of electrons, scattered by the foil into a wide solid angle, on the vacuum pipe wall. A fraction of these electrons can reach the FC input aperture and contribute to the FC current. This effect is not included in the CASINO simulations. The diameter and length of the vacuum pipe between the foil chamber and the FC chamber are 36 mm and 120 mm, respectively. Future liquid lithium film thickness measurements will be free of this effect, because the film and FC will be placed both inside a vacuum chamber with a large diameter. These data indicate that a sensitivity in film thickness variation of about 1% is achievable.

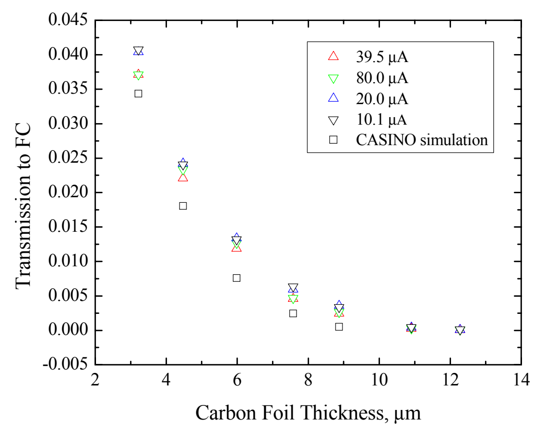

Figure 4: Measured (for different E-gun currents) and simulated by CASINO dependence of electron beam transmission to FC on carbon foil thickness.

According to CASINO simulations, there is some dependence of the transmission on the foil material for the same equivalent foil thickness. Because of that, the procedure for correct and accurate liquid lithium film thickness measurements should include the following steps:

- measurements of transmission dependence on carbon foil thickness for known foil thicknesses
- reconstruction of this dependence using CASINO code simulations
- simulations of transmission dependence on liquid lithium film thickness by CASINO code
- correction for the Z-dependence based on these simulations.

The temporal stability of a liquid lithium film under high power ion beam irradiation can be monitored using the LEEB monitor as well. A time resolution of about 1 µs is measurable. In the near future the LEEB monitor will be coupled to the liquid lithium thin film apparatus for thickness measurements.

UPGRADE OF THE FRIB PROTOTYPE INJECTOR FOR LIQUID LITHIUM FILM TESTING

Over the last few years, an FRIB prototype multiple charge state injector system was designed and built to demonstrate the possibility of extracting, analyzing and combining several charge states of a heavy-ion beam from the ion source to the point of injection into an RF accelerator. The injector consists of an ECRIS placed on a high-voltage platform and an achromatic LEBT (Fig. 5). The possibility of doubling the intensity of heavy ion beams in high-intensity linacs for future radioactive beam facilities has been recently demonstrated [9].

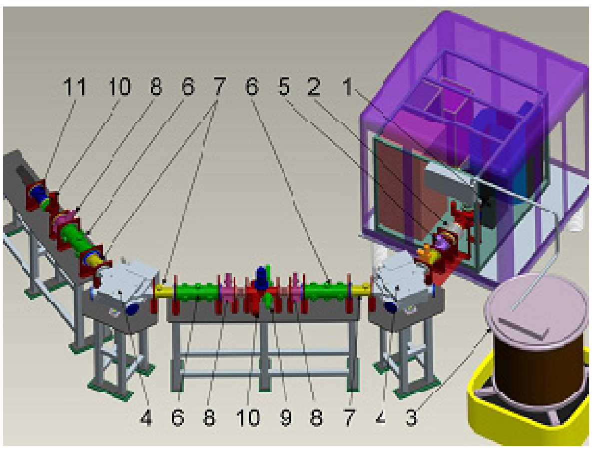

Figure 5: General view of the injector: 1- all permanent magnet ECRIS installed on HV platform, 2- 75-kV accelerating tube, 3- isolation transformer, 4- 60° bending magnet, 5- Einzel lens, 6- electrostatic triplet, 7- electrostatic steering plates, 8- rotating wire scanner, 9- horizontal slits, 10- Faraday cups, 11- emittance probe.

Previously, we have studied the production of high intensity light ion beams from the ECR ion source with the aim of using such beams for liquid lithium film spatial and temporal stability testing. A DC 3.3 mA proton beam has been demonstrated downstream of the first bending magnet [10]. Simulations using the TRACK code showed that a 3.3 mA proton beam can be transported to the liquid lithium film without losses then focused onto a spot with an RMS diameter of about 2 mm, containing about 70% of the beam. Thus, the power density of the proton beam deposited into the liquid lithium film will be about 120 W/mm^2, which is close to practically interesting value for testing. The range of a 165 keV proton in liquid lithium is about 3 μm, so the beam power will be fully deposited in the film.

The upgrade of the FRIB prototype injector for liquid lithium high power testing will include:

- Adding a second accelerating tube to increase the proton beam energy up to 165 keV
- Adding a gridded electrostatic lens (GEL) or solenoid downstream of the last electrostatic triplet for beam focusing on to the film.

It is not clear before testing whether a GEL grid will withstand such an intense DC proton beam irradiation. The GEL will be replaced by solenoid, if it turns out that the grid life-time is not long enough.

The new vacuum chamber which will accommodate the hardware for liquid lithium film formation and the LEEB monitor was designed. It allows irradiation of the film by a high power density proton beam and simultaneous on-line film thickness monitoring using the LEEB. The liquid lithium film spatial and temporal stability testing under high power density proton beam irradiation is planned for the near future.

CONCLUSION

A low energy electron beam (LEEB) monitor was designed and built for accurate measurement of liquid lithium film thickness. The dependence of transmission on carbon foil thickness was measured and compared with results of CASINO simulations. Some discrepancy between the measurements and simulations can be explained by reflections of electrons scattered by foils from the vacuum pipe walls into the FC aperture. This effect is avoided in the design of the new vacuum chamber for liquid lithium film thickness measurements and stability testing. The LEEB apparatus will be used for on-line monitoring of liquid lithium film temporal stability under ion beam irradiation with high power density. A time resolution of about 1 μs is achievable.

The FRIB prototype injector will be upgraded to provide a proton beam power density in the liquid lithium film of about 120 W/mm^2 for spatial and temporal stability testing. It will be the first time that the liquid lithium stripper will be tested under high power density ion beam irradiation.

ACKNOWELEDGEMENT

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