ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUBB1

CHARGE STRIPPER DEVELOPMENT FOR FRIB*

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Abstract

The Facility for Rare Isotope Beams (FRIB) at Michigan State University is building a heavy ion linac to produce rare isotopes by the fragmentation method. The linac will accelerate ions up to U to energies above 200 MeV/u with beam powers up to 400 kW. At energies between 16 and 20 MeV/u the ions will be stripped to higher charge states to increase the energy gain downstream in the linac. The main challenges in the stripper design are due to the high power deposited by the ions in the stripping media (~ 30 MW/cm^3) and radiation damage if solids are used. For that reason self-recovering stripper media must be used. The baseline stripper choice is a high-velocity, thin film of liquid lithium with an alternative option of a helium gas stripper. We present in this paper the status of the R&D and construction of the final stripper. Extensive experimental work has been performed on both options.

INTRODUCTION

Michigan State University was charged by the Office of Science of the Department of Energy of the US to design and build the Facility for Rare Isotope Beams (FRIB) at the end of 2008. The facility is funded by the Office of Nuclear Physics with contributions and cost share from Michigan State University. The goal of the facility is the production of rare isotopes produced by the in-flight separation method. This method provides fast development time for any isotope and allows short lived isotopes to be available. The facility will provide fast, stopped and reaccelerated beams of secondary ions.

One of the main components of the facility is a driver linac capable of producing beams of ions from the low mass region up to U at energies above 200 MeV/u and with a total beam power on target of 400 kW [1]. The linac is folded in three segments running parallel to each other with two 180 degree bends in between. After the first segment linac and before the first bend a charge stripper is located to increase the Q/A of heavy ions by more than a factor two.

This paper describes the options considered for the charge stripper and the status of their design and construction.

CHARGE STRIPPER CHALLENGES

Traditional charge strippers in accelerators are designed utilizing thin films of solid materials, in many cases carbon [2]. The main difference between FRIB and accelerators that strip intense H^- beams is that even though the currents are lower in FRIB, the energy loss per ion per unit length is much higher for heavy ions than for protons (see Figure 1).

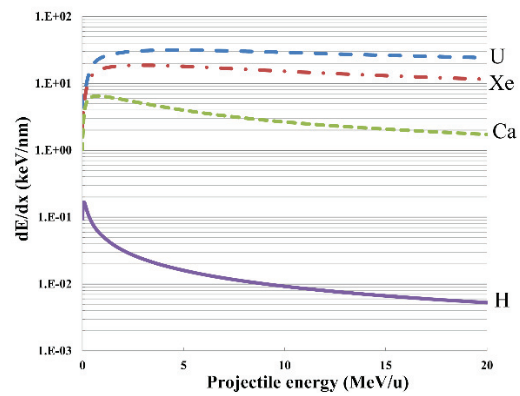

Figure 1: Comparison of the energy loss per unit length in carbon foils for some heavy ions and protons. A single U ion deposits three orders of magnitude higher power than a proton of the same velocity. Stripping energies at FRIB are between 16 and 20 MeV/u.

There appears to be a critical threshold in the linear energy deposition for the formation of tracks in graphite of the order of 7 keV/nm, with a track produced for every ion with energy above 18 keV/nm [3]. Heavy ions like Xe and U have a dE/dx higher than this threshold, while protons are much lower.

Besides the radiation damage, the thermal effects are also important. At the energies of the FRIB stripper the U beam would deposit about 30 MW/ cm^3 power densities in the carbon foil.

Given the above considerations we have looked at two options for the charge stripper, liquids and gases. Both can be made to survive the high power deposition and no lattice damage occurs.

OPTIONS

Liquid Lithium Stripper

A liquid lithium charge stripper was first proposed by J. A. Nolen [4] from Argonne National Laboratory (ANL). A fast moving film (~ 50 m/s) would be able to carry away the thermal energy deposited by the beam before reaching high temperatures (below boiling). Lithium has some very attractive properties when used as stripping media, it has a very low vapor pressure at the melting temperature (181 C and 1.5 10^{-9} Torr) compared with other potential liquids like mercury (2 mTorr at room temperature). It has a high boiling point (1342 C) and it

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has a large heat capacity (4169 J/(kg C) at the melting point)

But unfortunately, on the negative side, it is pyrophoric and reacts strongly with water. This creates a hazard when significant amounts of lithium are needed in the system. In the FRIB design we have minimized the volume of lithium in the charge stripper module, keeping the volume around 5 liters within an Ar container.

The proposed mechanism for the thin film formation consisted on a high velocity round jet of lithium hitting a flat, highly polished, deflector where the film is then formed, "reflecting" from the deflector. Several types of jet instabilities had been studied during the years involving (non-metallic) liquids injected in a gaseous environment. Since jet instability phenomena in vacuum involve only the surface tension, viscous force, and inertial force, they are expected to be a function of these three parameters and characteristics of the applied disturbances [5-6]. Combinations of two dimensionless parameters, the Reynolds number, Re (= inertial force/viscous force) and the Weber number, We (= inertial force/surface tension force), could be used to represent effects of these three parameters. The initial work of the ANL group started with the mapping of the regions of flow instabilities in the We and Re numbers plane.

Tests were carried out using water as a simulant for the lithium to avoid the overhead of working with the hazardous lithium. Using Re-We scaling, a Li film at 10 µm thick, 473 K, and 50 m/s, for example, is equivalent to a water film at 58 µm thick, 303 K, and 6.4 m/s.

A liquid lithium test chamber was setup and used to verify the formation of the film at a velocity of approximately 58 m/s, 9 mm width and with a thickness of about 13 µm (see Figure 2).

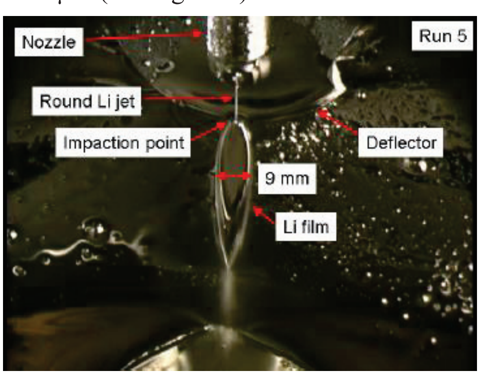

Figure 2: Liquid lithium film formed by impact of a high velocity jet on a deflector at the ANL lithium test stand [6].

In 2009 a collaboration was established between MSU and ANL to continue the studies of the lithium film formation at ANL. The goal was to measure in detail the thickness of the film, its stability and the effect of beam power deposition on the film. A low energy electron beam monitor was built to measure the thickness of the lithium film in real time. It is based on the thickness dependent scattering and absorption of electrons by the film [7]. It is based on a similar instrument developed at GSI [8]. The monitor was calibrated utilizing carbon foils of known thickness. The stability measurements in the new chamber were successful and confidence in the proposed solution grew, allowing FRIB to adopt the liquid lithium charge stripper as the baseline design. The remaining test was to prove that the power deposited by the beam did not disrupt the film.

With that purpose the Low Energy Demonstration Accelerator (LEDA) proton source from Los Alamos National Laboratory (LANL) was borrowed and moved to MSU where it was reconditioned after ten years in storage. A new transport line was designed and tested. This new transport line was matched to produce a focused beam at the correct position with a diameter of 3 mm on the lithium film in the vacuum chamber in the test stand at ANL. Once the transport line was commissioned it was transported to ANL and matched to the lithium loop test stand. This beam line had to be built in such a way that no water was used in the last section that would reside inside the containment room of the lithium chamber. This forced us to use electrostatic focusing in the last section. A photo of the beam impinging on the lithium film is shown in Figure 3.

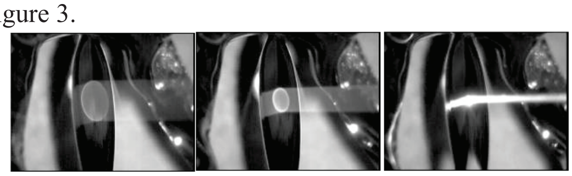

Figure 3: Proton beam from the LEDA source impinging on the liquid lithium film at the ANL test stand. The beam comes from the right. The beam stops in the film. The focusing increases from the left photo to the right photo.

The 65 kV proton beam from LEDA stopped and deposited on the lithium film power densities comparable to the expected power deposition of the U beam in FRIB [9]. Only at the maximum focusing of the proton beam we could notice the film being perturbed, splitting, but away from the impact point. It would not affect the stripper performance. This behavior was not observed in a later experiment in similar conditions [9].

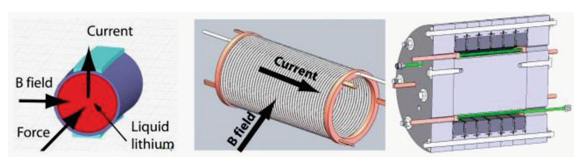

Figure 4: Electromagnetic pump developed for liquid lithium. The current (~ 2000 A) is axial in the helical coil while the magnetic field (~ 6 kG, generated by permanent magnets) is radial. The force on the lithium is in the azimuthal direction. The gray squares in the cross section show the permanent magnets.

The ANL system was "once-through", i.e. the lithium was pushed through the nozzle by a high pressure Ar and then pushed back to its original tank by a low pressure Ar after each run. For FRIB we need a continuous pumping scheme. We have designed an electromagnetic pump based on an In/Ga pump designed and tested by R. Smither at ANL in 1995 [10]. The pump principle is

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explained in Figure 4. We have selected SmCo permanent magnets due to their higher resistance to radiation effects than NdFeB magnets.

Helium Gas Stripper

H. Okuno of RIKEN, Japan, proposed the use of helium gas as a stripper for heavy ions for their RIBF facility. The average charge state generated by the stripping with the heavy gases (N_2 and Ar) was lower than what was required by the booster cyclotron [11-12-13]. The main drawback of using helium is the cost. A large amount of gas has to be pumped very fast to decrease the density variation originated by the thermal energy deposited by the beam. Helium is difficult to pump and a large system of pumps is used in RIKEN to recirculate the gas.

P. Thieberger suggested the use of plasma windows to decrease the conductance from the high pressure gas cell to the rest of the beam line [14]. The plasma window concept was developed by A. Hershcovitch [15]. It basically consists of a wall stabilized arc that is established at each end of the high pressure stripper cell and heats up the helium gas that escapes through the hole for the beam. The gas expands, increases the velocity in the channel and a choked flow condition is established. The higher gas viscosity contributes to the decrease in conductance.

A series of experiments were performed at Brookhaven National Laboratory (BNL) to demonstrate the feasibility of operating a plasma window with apertures of 6 mm diameter. Previous experiments had all been done with smaller (3 mm) apertures. With electron currents of approximately 90 A a reduction factor of 8 was achieved in the gas flow escaping the gas cell. A new setup at MSU (see Figure 5) is being commissioned with the goal of increasing the current in the plasma and improving the conductance reduction, as well as determining the long term performance of the setup over two weeks, expected duration of an experiment at FRIB.

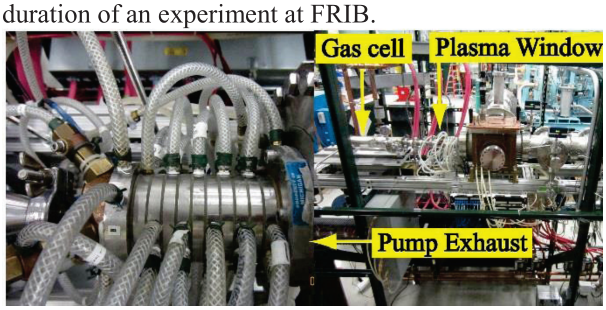

Figure 5: Left photo: close-up of the plasma window, cathodes on the left. Right Photo: Helium gas cell test stand at MSU.

CURRENT STATUS OF THE LIQUID LITHIUM CHARGE STRIPPER

We have completed the design of the charge stripper module for FRIB and are in the process of manufacturing the different components (see Figure 6). The magnet for the liquid lithium pump has been completed, waiting for the brazing of the helical coiled tube where the lithium flows. The thick steel secondary containment vessel is under construction and the internal components of the vessel are at different stages in the procurement chain. We expect to have the module built by the end of 2015 in a temporary location above ground in the FRIB building.

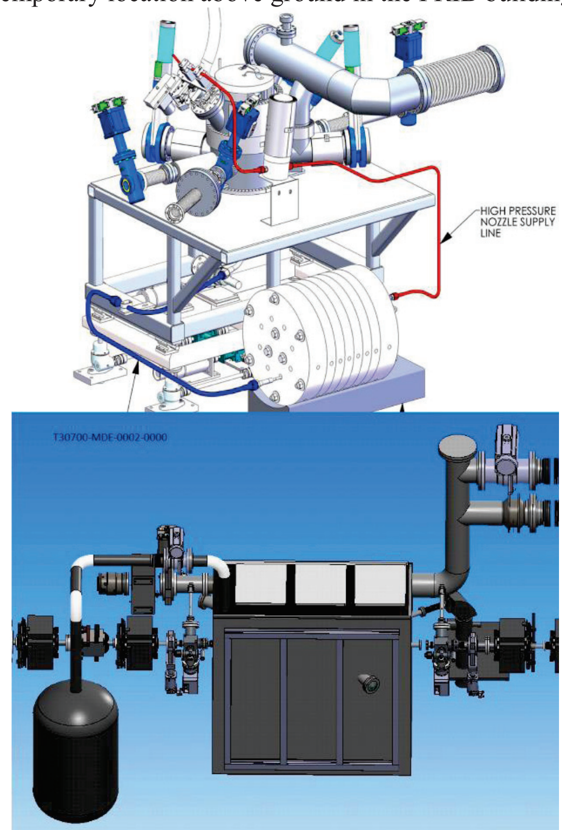

Figure 6: Top: The components of the liquid lithium stripper are shown. The pump is in the forefront. Bottom: we show the steel secondary containment vessel (2 m long) that will remain full of Ar. A vent to a scrubber is shown on the upper right and the Ar supply tank on the lower left.

CONCLUSION

The liquid lithium option was selected as the baseline design for the charge stripper for FRIB. The R&D showed the feasibility of achieving the correct film thickness and that the film survives power deposition by protons comparable to the power deposition of the heavy ions at peak beam power at FRIB. A working module is expected to be finished by the end of 2015. This work is a collaboration between ANL and FRIB.

As an alternative option the helium gas stripper contained by plasma windows is being pursued in collaboration with BNL.

ACKNOWLEDGEMENT

We would like to acknowledge the help provided by D. B. Chojnowski and J. R. Specht from ANL, C. Carlson and L. Cannizzo from BNL.

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