DEVELOPMENT OF A LIQUID LITHIUM CHARGE STRIPPER FOR FRIB*

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Abstract

The Facility for Rare Isotope Beams (FRIB) being built at Michigan State University for the US Department of Energy (DOE) will deliver heavy ion beams with beam power of 400 kW. SRF cavities accelerate the ions to energies above 200 MeV/u. At energies of 16-20 MeV/u a charge stripper increases the charge state just before the first bend in the linac (a second bend is located downstream). Due to the high power deposition on the stripping media and radiation damage solid strippers are not practical. The baseline design selected a liquid lithium film stripper. This stripper has been developed in collaboration with Argonne National Laboratory (ANL). A stripper module is being built at MSU with an estimated completion date of December 2015. We plan to operate the stripper outside the FRIB tunnel for 18 months to learn the reliability and stability issues before final installation in the accelerator.

INTRODUCTION

Michigan State University was charged by the Office of Science of the DOE 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 of any element to be available.

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, 2]. The linac is folded in three segments running parallel to each other with two 180 degree bends in between. After the first linac segment 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 design and construction of the liquid lithium charge stripper and the extensive experimental work done up to now.

WHY LITHIUM?

As described previously [3], liquid lithium was selected as the baseline design for the FRIB charge stripper because traditional solid carbon strippers have very limited lifetime under heavy ion bombardment [4]. There is no solid lattice that can be damaged by the high energy deposition and the flowing liquid takes away the heat deposited by the beam on the stripping media. The use of lithium was initially proposed by the ANL group at the time of the Rare Isotope Accelerator (RIA) R&D [5]. Lithium has several properties that make it the preferred liquid metal for this application.

The vapour pressure of lithium at its melting temperature (186 C) is quite low (~ 10^{-7} Pa). If we compare with Hg for example, mercury has a vapour pressure of ~ 10^{-1} Pa at room temperature and when heated by the beam it will be even higher.

The heat capacity of lithium is quite high (~ 4.2 J/g/C at 200 C) meaning that it will have a limited temperature increase when exposed to the beam, and its boiling point (1336 C at 1 bar) is much higher than the melting point.

The major drawback of lithium is its pyrophoricity. [6] It will burn in oxygen and nitrogen producing caustic fumes (oxide and nitride). Contact of molten alkali metal with concrete will cause spalling of the concrete and spattering of the metal. Special precautions must be taken to avoid any contact of the lithium with water or humid air.

EXPERIMENTAL WORK

Production of the Lithium Film

The film thickness required to achieve near equilibrium charge state is of the order of 10 µm. We need the film to move fast through the beam to take the heat away. Speeds of close to 50 m/s are necessary. The initial ANL experiments [7] created a high velocity jet of liquid lithium by pressurizing a tank with argon gas that contained the liquid and pushing the lithium through a small diameter nozzle. This high velocity jet impinged on a flat plate that created the thin film, about 9 mm wide as illustrated in Fig. 1.

The original experiments proved the feasibility of creating the lithium film using pressurized liquid at temperatures around 200 C.

Stability and Thickness Measurements

In 2009 a collaboration was established between FRIB and ANL to continue the experimental work at ANL with the objective of measuring the thickness and stability of the lithium film.

A limitation on these experiments was that the flow of lithium could be maintained for less than 30 minutes because the liquid would flow from the supply tank to the

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receiving tank and the flow had then to be reverted and start over.

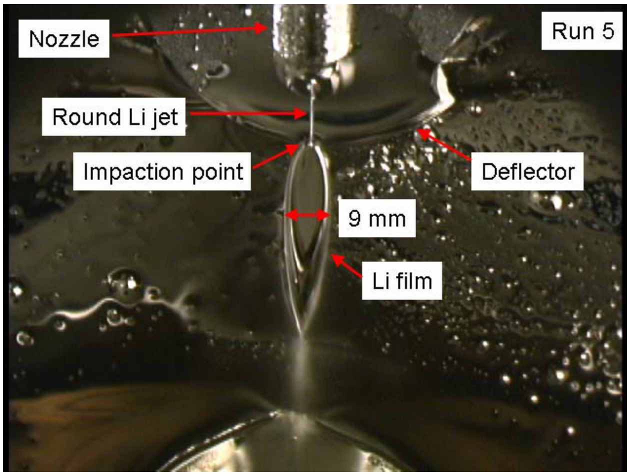

Figure 1: Formation of the liquid lithium film in the ANL test stand. The high speed jet from the nozzle hits the deflector plate forming the thin film.

The stability of the film is a major concern because variations in its thickness would create variations in the energy loss of the beam and consequently probable losses downstream from the charge stripper. The linac lattice has been designed accepting a stripper thickness variation of +/- 20%.

With the goal of measuring the film thickness the ANL group used an electron gun beam following a technique developed at GSI [8]. It utilizes an electron beam (~ 20 keV) to traverse the film under study. The electrons are scattered by the film and the fraction intercepted by a Faraday cup downstream depends on the film thickness. The process is calibrated with standard carbon foils, allowing a real time measurement of the lithium film thickness, see Fig. 2. [9]

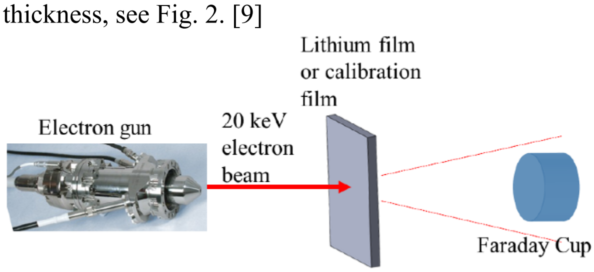

Figure 2: Monitoring the liquid film thickness in real time is possible by measuring the scattering of an electron beam, see text for details.

The experiments showed that a stable film with the correct thickness (~ 10 μm) could be established. [10]

Proton Beam on Film Experiment

A proton beam of 65 keV was used to demonstrate that the lithium film could survive the power deposited by the FRIB beam. The Low Energy Demonstration Accelerator (LEDA) ion source from the Los Alamos National Laboratory (LANL) [11] was utilized in the experiment. The source was modified with a new beamline at FRIB with the goal of later matching it to the lithium loop at ANL. The new beamline produced a 3 mm diameter beam at the location where the lithium film would later be located at ANL. The restriction of not having water cooled elements near the lithium loop was satisfied by utilizing an electrostatic einzel lens with a positive voltage of ~ 30 kV. An additional safety measure was to focus the beam through a 4 mm diameter aperture at an intermediate image.

The modified source and beamline were installed at ANL and connected to the lithium vacuum chamber used in the previous experiments. An isolated beam dump located downstream of the lithium film recorded the proton current that traversed the film. More details of the experiment can be found in [12]. It is important to note that to avoid any water in the area of the lithium loop the beam dump was air cooled, limiting the time the beam could be on the dump.

The einzel lens was used to focus the proton beam on the film until a small spot was achieved, see Fig. 3. The concern was that increasing the power density could induce the formation of bubbles in the film or disrupt it. In that case we would detect current on the Faraday cup behind the film.

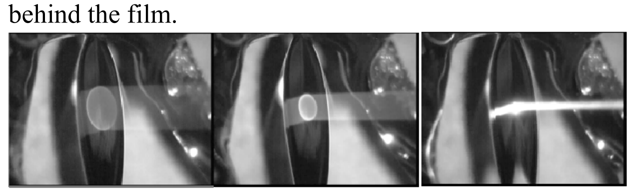

Figure 3: Photos of the proton beam (coming from the right) on the liquid lithium film. The einzel lens voltage increases from the left photo to the right photo. The film is seen to break up at the maximum power but below the interaction point with the beam.

Table 1 shows the estimated beam parameters in the experiment compared to the FRIB conditions. Due to the much shallower penetration of the low energy (65 keV) protons, the whole energy is deposited in the first 1.5 μm, giving a higher power density in the experiment than in the FRIB condition.

Figure 3 shows three photos of the lithium film with different focusing of the proton beam. The photo on the right shows the highest power density and the splitting of the film below the impact point. Even when this splitting was occurring no proton current was detected on the beam dump, indicating that the film was intact at the impact point.

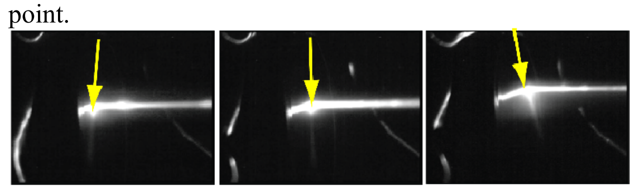

Figure 4: The beam spot is displaced from the left to the right of the lithium film showing the heat trails, visualizing the flow lines of the heated liquid.

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The photos of Fig. 4 visualize the flow lines of the heated lithium. The proton beam impact point was moved in the direction transverse to the liquid flow. The flow lines seem to converge to the impact point of the lithium jet on the deflector plate, see Fig. 1.

Table 1: Comparison of the beam parameters in the FRIB case and in the proton beam experiment.

	FRIB	Exp.	Ratio
Beam power (W)	700	299	0.43
Beam size σ (mm)	0.62	0.7	1.17
Beam penetration (μm)	10	1.5	0.15
Power density (kW/mm^3)	58	129	2.2

CHARGE STRIPPER MODULE DESCRIPTION

The charge stripper consists basically of a main vacuum chamber where the lithium film is formed, an electromagnetic pump that produces the pressure to form the liquid jet, the auxiliary equipment in the lithium loop and a secondary containment steel vessel that encloses them.

Main Vacuum Chamber

The vacuum chamber that contains the nozzle and deflector is shown in Figures 5 and 6. The position of the flange where the deflector plate is mounted determines the location of the chamber in the beamline. The nozzle has to be accurately positioned with respect to the deflector and an adjustable mount is being constructed that will allow precise positioning of the impact point of the lithium jet. Two ports in the chamber connect the stripper to the beam line upstream and downstream. One other port is used for the electron beam dump (Faraday cup). Other ports in the chamber are used for observation, illumination and vacuum pumping.

The chamber is mounted on a table that can be moved in the plane transverse to the beam path. The objective is to tune the beam along the axis of the beam line and then adjust the position of the vacuum chamber to place the center of the lithium film on the beam path.

Several heater cartridges are wrapped around the chamber to maintain it at temperatures above the melting point of lithium and avoid condensation on the chamber walls.

The ports connected to the chamber as well as the tubing connecting the different components are wrapped with heating tape to be able to systematically heat and cool down the system in an ordered fashion. The goal is to start the heating from the open surfaces of the solid lithium and progress toward the center of the loop (the E&M pump). The cooling order is the opposite.

A large vacuum manifold connects the chamber to a couple of cryo-pumps that are located outside the secondary steel vessel. The pump compressors will be located outside the tunnel in the final configuration. Special care has been taken to eliminate all copper gaskets from the system because the extreme damage that lithium produces on copper products. No aluminum is present in the system either.

The viewer ports are covered with shutters unless they are in use to minimize the possible coating of them with lithium.

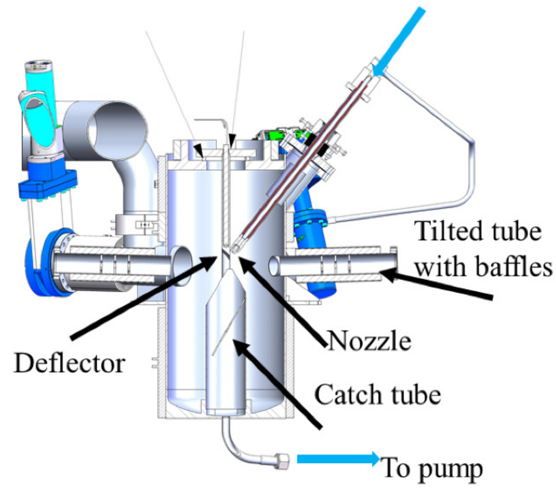

Figure 5: Main vacuum chamber showing the incoming lithium on the upper right and the exit to the pump in the lower right.

The catch tube shown in Fig. 5 has been included to minimize the splashing of the lithium on the chamber walls. The liquid film enters the tube through a narrow slit and is captured inside.

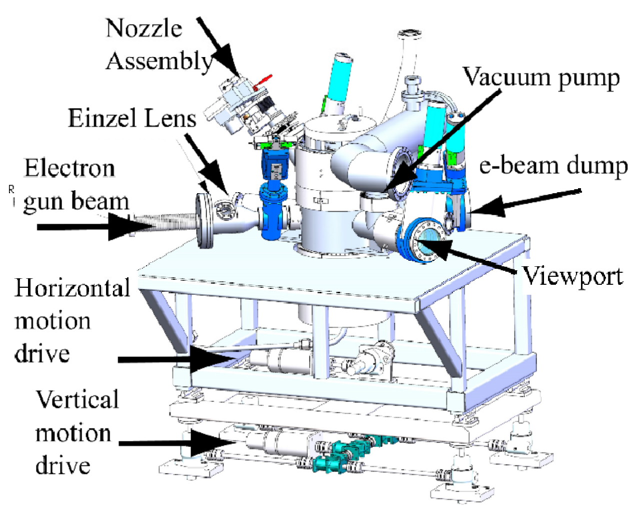

Figure 6: Description of some of the ports on the main vacuum chamber shown in the previous figure.

Secondary Containment Vessel

The secondary containment vessel has multiple purposes. It acts as a radiation shield to limit the exposure from the activated components in the main vacuum chamber. It also serves as a containment for the argon gas used to blanket a possible lithium leak from the air components (oxygen, nitrogen and water vapour).

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The vessel is shown in Fig. 7 located in the test area of FRIB where it will be commissioned until installed in the FRIB tunnel in about 18 months. It is built from 25 mm thick steel plate.

Figure 7: Photo of the secondary containment vessel installed in the test area of FRIB. The vessel is 2 m long.

The panels visible in the photo will be used to mount the multiple feedthroughs. More than 100 thermal sensors will be used to monitor with redundancy the temperatures of the various zones in the internal lithium loop. About 27 heaters will be used to maintain the temperatures in the different areas. Other panels will be used to bring the power to the electromagnetic pump described below. Two large removable doors allow the insertion of the components. For normal operation the panels on top of the vessel will be removed.

Electromagnetic Pump

The helium flow is established by a permanent magnet DC electromagnetic pump. The most common liquid metal pumps utilize an AC supply but the requirement of a very constant pressure to maintain the film thickness constant rules out such pumps. We have built a high temperature version of a DC pump developed by R. Smithers [13].

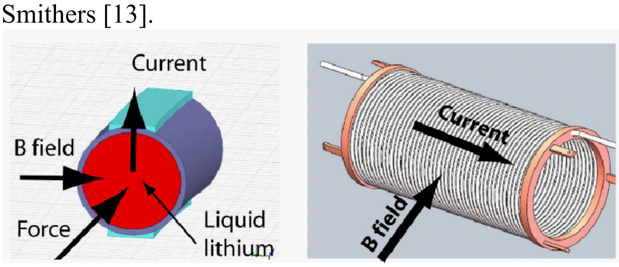

Figure 8: Principle of operation of the lithium electromagnetic pump. The DC current flows on the helical tube from turn to turn, parallel to the helix axis. The magnetic field produce by permanent magnets is radially oriented.

The lithium flows in a helical stainless steel tube subjected to a radial magnetic field generated by rings of SmCo permanent magnets and a DC current that moves from turn to turn in a direction parallel to the axis of the helical tube (see Fig. 8). The force in the lithium is then in the azimuthal direction propelling it along the helix. The permanent magnets produce a radial field of approximately 0.7 T. We estimate that the current required to achieve a pressure of 15 bars is below 2000 A. If the tests show that a lower pressure is achieved due to friction, turbulence or other effects, more rings with permanent magnets (see Fig. 9) can be added to the pump and a longer helical tube used.

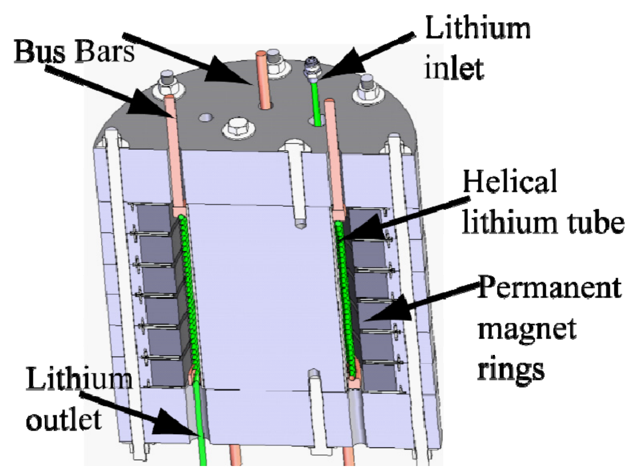

Figure 9: Basic elements of the DC electromagnetic pump. Four bus bars introduce the current into the helical tube. Six rings of permanent magnets produce the radial magnetic field. The magnet is completed by an inner core, two end caps and a return yoke.

The radial magnetic field has been measured and agrees quite well with the simulations, see Fig. 10.

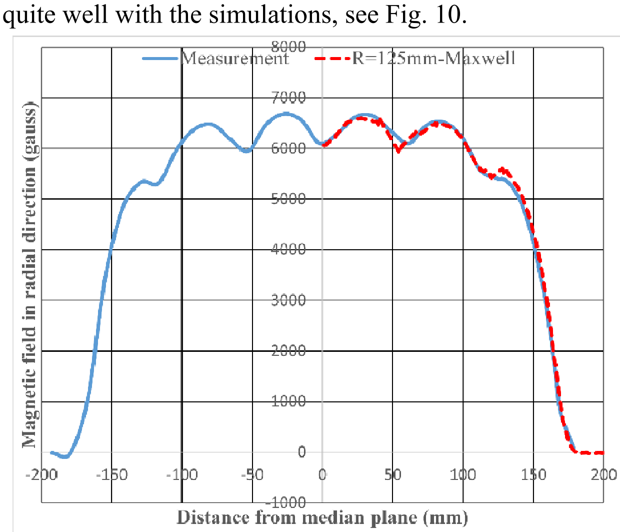

Figure 10: Measured (blue) and calculated (red) radial magnetic field in gauss vs. mm.

We are in the process of manufacturing the helical tube and we will next test the pump by itself to measure the pressure. The pump magnet during assembly is shown in Fig. 11. Five of the six permanent magnet rings are

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visible as well as two of the four hydraulic cylinders used to control the motion of the components during assembly.

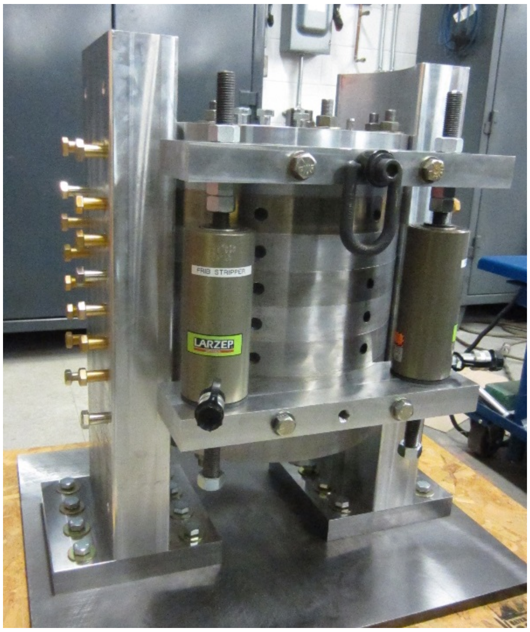

Figure 11: Liquid lithium pump during assembly. The hydraulic cylinders (only two are shown) are removed after final assembly.

HAZARD MITIGATION

Multiple precautions have been taken to minimize the possibility of a fire of the lithium in the stripper module. We have minimized the amount of liquid in the system and expect to load it with approximately five liters of liquid. We mitigate the danger in case of a leak from the lithium loop into the secondary containment vessel by maintaining it filled with argon (slightly above atmosphere) during operation. When doing maintenance through the panels on top of the containment vessel the lithium will be solid at room temperature and we will keep the argon in the vessel.

If a loss of vacuum is detected in the main chamber, we will isolate the gate valves that connect the stripper to the rest of the accelerator, turn off the electromagnetic pump and introduce argon into the stripper chamber. At the same time we will start the cool down of the system.

The multiple heaters will be controlled by a PLC that will open and close the relays feeding the AC to the heaters. Each circuit has two relays in series, with one of them permanently closed and the other relay cycling. In case that we detect that a relay stayed closed after receiving the order to open, the redundant relay will be ordered to open and interrupt the current.

CONCLUSION

The design and construction of the liquid lithium charge stripper is proceeding on schedule at FRIB. It follows a series of experimental developments and tests in a collaboration between FRIB and ANL. No show-stoppers have been found but extensive tests are planned before the stripper module is installed in the FRIB tunnel in mid-2017. During the testing period we will monitor the reliability and stability of the lithium film over long periods (~ two weeks) matching the expected duration of a FRIB experiment.

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