Thick and Thin Liquid Lithium Targets

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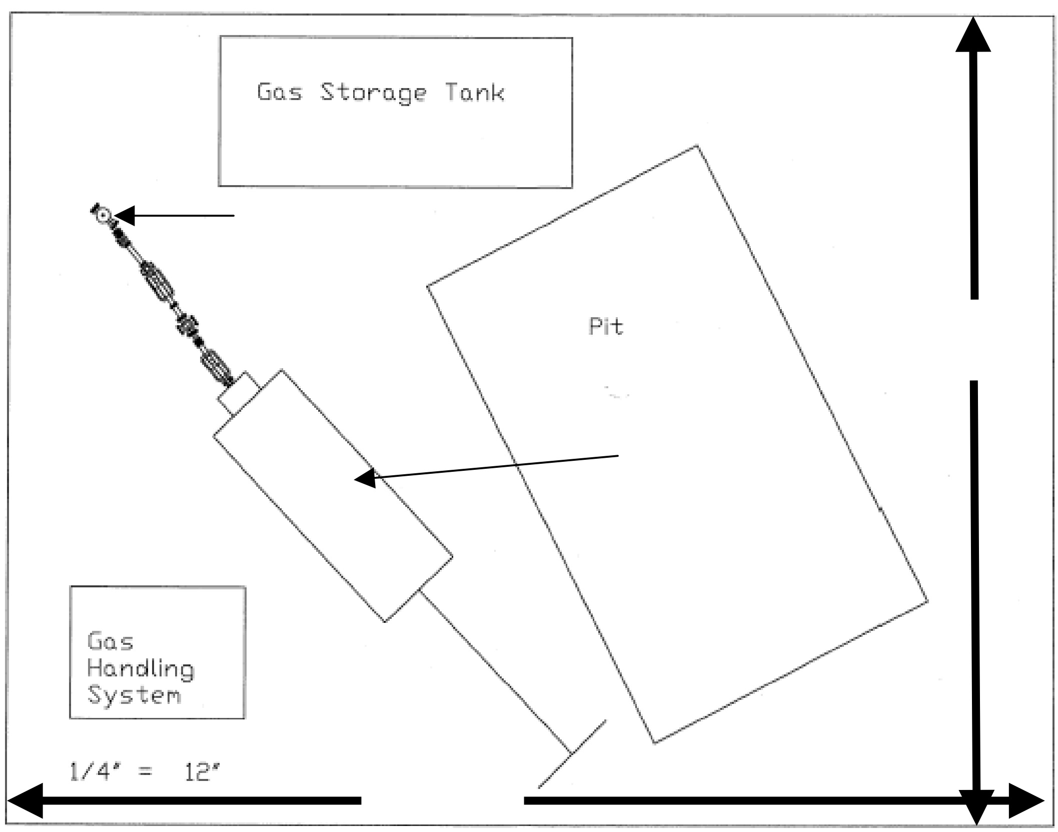
Liquid lithium target technology exists at Argonne and will play an important role in the Rare Isotope Accelerator (RIA) facility [1,2]. The high-power heavy-ion beams produced by the driver linac have large energy deposition density in solids and in many cases no solid materials would survive the full beam power. One particular application of liquid lithium technology in RIA is a windowless target for the production of radioactive ions via fragmentation, consisting of a jet of about 3 cm thickness of flowing liquid lithium, exposed to the beamline vacuum [1,2]. To demonstrate that power densities equivalent to a 300-kW RIA uranium beam, deposited in the first 4 mm of a flowing lithium jet, can be handled by the windowless target design, a high power 1 Mev Dynamitron was leased and a test stand prepared to demonstrate the target's capability of absorbing and carrying away a 40kW heat load without disrupting either the 5 mm x 10 mm flowing lithium jet target or the beam line vacuum. The vault floor plan layout for the 40 kW test is shown in Fig. 1. It was also necessary to modify the existing windowless lithium target system [1] to increase the lithium inventory so high power tests could be run in a heat-sink mode. The 40kW heat load is deposited by a 1 mm dia. 40 mA beam of 1 Mev electrons from the Dynamitron.



To date the target system has been modified to hold an increased lithium inventory of 6 liters. Instrumentation has been added to more accurately measure the lithium flow rate, including an EM flow meter and a pressure transducer to measure the pump discharge pressure. A stand-alone secondary containment and dry scrubber system have been integrated into the system, to permit testing in a nuclear physics laboratory setting. The modified target system and all supporting subsystems, such as vacuum, heating, instrumentation, and data acquisition were first tested as a unit and then moved to a high-bay vault with 7-ft. thick concrete walls, which obviate the need for additional radiation protection, as personnel will be excluded from the vault during accelerator operations. The Dymanitron has been leased, and is currently being shipped to ANL; arrival is scheduled for the first week of September. Instrumentation for both visual and IR imaging of the beam-target interaction are under development. Multi-pixel per mm resolution of the visual image of the 1 mm dia, beam spot has been achieved, see Fig. 2. This will enable the observation of any surface waves, disruptions, perturbations, etc. of the beam-jet interaction.

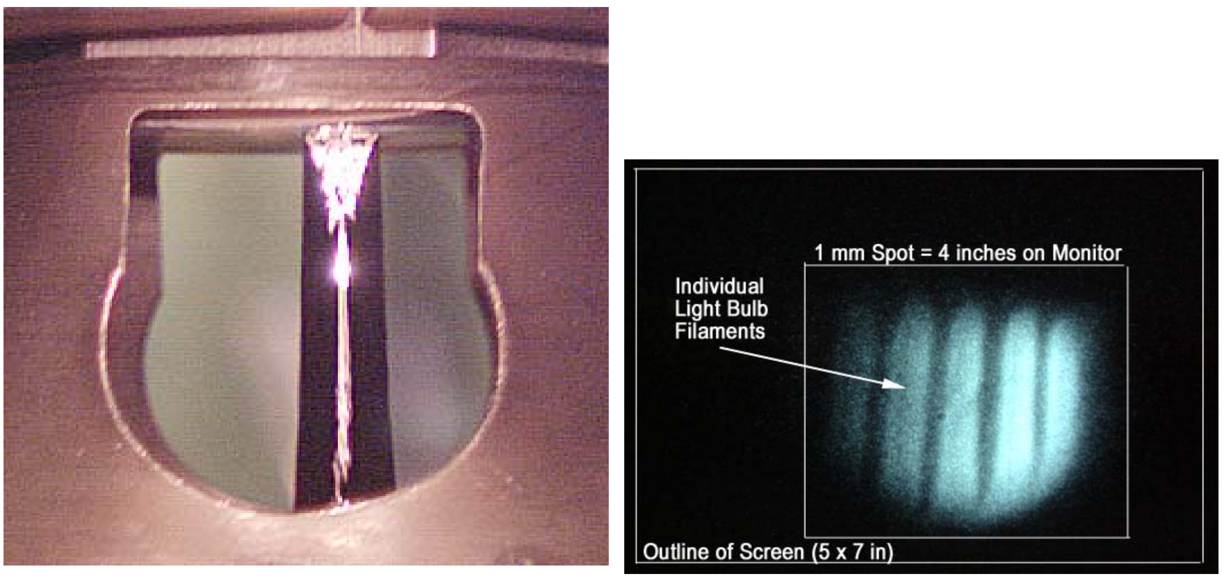


Fig. 2 Liquid Lithium Jet and Simulated Jet-Beam Spot Image

Once the windowless target-beam interaction has been demonstrated to be stable and well behaved, additional data will be collected to establish the safe operating envelope to be used as the supporting basis for future safety analysis documentation.

A second application of liquid lithium technology to RIA is in thin-film strippers (also windowless) needed within the driver linac to increase the charge state for more efficient acceleration. First designs have been developed for a high pressure, high velocity jet for the stripper. Preliminary experiments with water jets were carried out last year, see Fig. 3. In FY2003, we also conducted a series of measurements, in collaboration with the group at Texas A&M University (TAMU), aimed at a test of the lower energy stripping predictions. Using 10.5-MeV/amu 238 U 38+ ions from the TAMU cyclotron, we measured charge state distributions in a variety of thin carbon and beryllium stripper foils using a magnetic spectrograph. The results were extremely encouraging in terms of mean charge states and efficiencies, though somewhat different from the computer simulations. Analysis of the data is continuing and there is some hope of extracting angular information from the data as well.

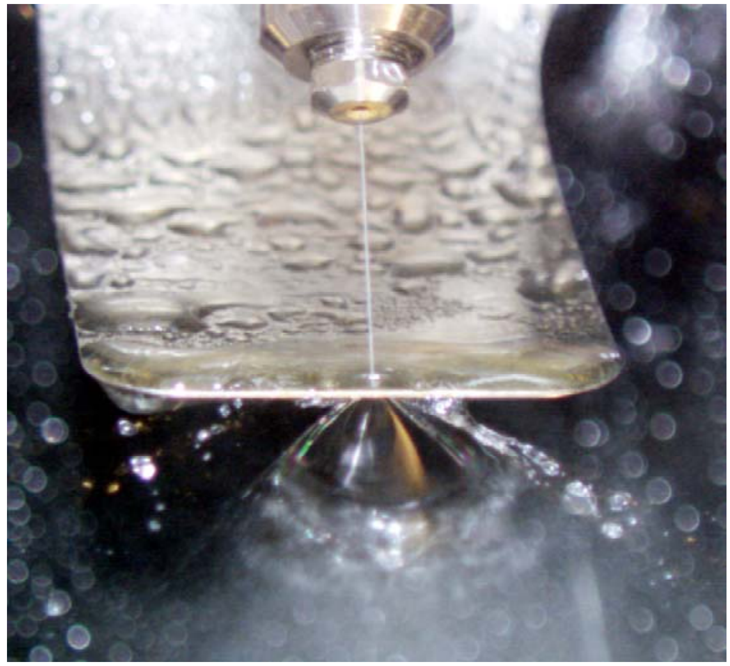


Fig. 3. Water film, 0.25 mm diameter orifice, 33 m/s jet velocity, 15 atmospheres driving pressure, >2 micron film thickness, under partial vacuum, Film area ~ 1 cm diameter

In addition, new sophisticated codes are now available to calculate how the charge state distribution evolves for a fast beam going through materials. However, these codes have not been validated in the ion energy range of interest for the RIA stripper films. It is important to determine the validity of the predictions of these codes and we will test the charge distribution of uranium beams through a lithium sample at energies corresponding to the first (9.3 MeV/u) and second (85 MeV/u) stripping points. The lower energy test will be performed at the ATLAS facility while the higher energy measurement should be possible at the upgraded coupled cyclotron facility at MSU once the machine reaches its design goals. These studies must be done over about several orders of magnitude of dynamic range since in the driver linac a charge state carrying even below 1% of the total beam power can still correspond to close to a kilowatt of beam power. Furthermore, energy and angular straggling effects must be known to a high level of accuracy to quantitatively predict beam losses down stream in the driver linac. These tasks will be carried out during FY2004.

A demonstration of the thin lithium stripper film concept is now necessary. This will be done using the liquid-lithium test facility at ANL. New requirements include the development of a high pressure liquid lithium pump and diagnostic methods for evaluating the stability and thickness of the films. Since neither the required film thickness nor the required film speed are known with great confidence at this time, one objective of the work is to establish the film thickness vs. velocity operating window which can be reliably attained in the presence of a hard vacuum at roughly 230°C. Some nozzle testing in water has already begun, taking advantage of the rough equivalence in kinematic viscosity between lithium and water ($\nu \sim 9x107\ m^2/s$), thus the same Reynolds numbers can be achieved for equal film thickness and velocity. Water is a good working fluid for nozzle testing, but its applicability to film flow in this case is limited. Based on previous analysis, the required thickness for very heavy ions approaches the limit where the surface tension will break the continuous flow and the continuous liquid surface turns into droplets. From the hydrodynamic point of view, the two most important modes of film instability are caused by surface tension, which is the dominant effect in this problem, if we disregard the interaction with the beam. These instability modes are varicose, or squeezing mode, and asymmetric, or bending mode. Of these two, the bending mode is most unstable. The film will be stable in bending if the Weber number, $We=2\sigma/(\rho u^2 h)$ is less than unity, where σ is the surface tension, ρ is the fluid density, u is the fluid velocity, and h is the film thickness. Since the surface tension of lithium is roughly 5 times higher than water, and water testing is not possible in a hard vacuum, it is necessary to carry out the remainder of the work with lithium in vacuo. Therefore, a lithium film vacuum test apparatus will be constructed in which a number of thin film generation methods will be explored and characterized. Several liquid lithium-in-vacuum technology issues will be resolved in the lithium film vacuum test apparatus. They include [approximate milestones are indicated]:

High temperature, high pressure pump development [first half of FY2004]: Due to the large nozzle pressure drop, an unusual lithium pump, having low flow rate but high discharge pressure, is required to produce the high velocity thin stripper film. We propose to develop a higher pressure (~400 psi) version of the permanent-magnet-based liquid gallium pump (~200 psi) developed by R. Smither at the APS. The Smither design will have to be modified to use SmCo magnets rather than NdFeB due to the higher operating temperature required for lithium vs. gallium.

Film production and stability [second half of FY 2004]: Liquid lithium sheets in this thickness range have not been produced in any environment, gaseous or vacuum. The thin film may issue directly from a slit-shaped nozzle, or first from a small-diameter, round nozzle (~0.25 mm diameter) then onto a flat surface from which the desired thickness and velocity are established. The first approaches used for the lithium films will be based on tests being carried out this year with water. The approach will also be guided by hydrodynamic simulations. Instability modes discussed above will be investigated.

Nozzle design and erosion resistance [second half of FY2004]: The surface finish of the nozzle is critical due to the fact that the scale of the surface imperfections in the nozzle must be much smaller than the desired film thickness (a few microns). Additionally, erosion of an initially acceptably smooth nozzle surface may produce destabilization and also long-term thickness variation. These two considerations will be investigated, and can be pursued initally with water testing using velocity and film thickness diagnostics described below. Initally a stainless steel nozzle will be evaluated since its erosion rates with lithium look promising even though no data exist at the relatively low temperatures to be used here. More exotic alloys will be evaluated only if necessary.

Lithium purification and chemistry control[FY2004]: The large surface area of lithium inherent in the thin film, combined with its extremely high chemical reactivity, may lead to contamination issues which may require mitigating features in the system design. Flowing lithium jets have been successfully produced under vacuum conditions with no remarkable lithium contamination issues observed. However, in this thin film stripper system, the surface area to volume ratio will be roughly 1000 times greater than previously attained, potentially leading to a proportional increase in the contamination of the lithium. If necessary, trapping methods that have been applied on a larger scale for IFMIF can be adapted to this application.

Lithium velocity distributions [FY2005]: Some means of measuring the lithium velocity distribution in the vicinity where the beam strikes the film is needed to compare with model predictions. One approach is PIV, Particle Image Velocimetry. For fluid mechanics applications, this method can resolve small flow structures, and their flow properties. Using a high spatial resolution CCD camera and synchronized laser pulses, PIV image capture and analysis techniques can measure velocities of surface features ranging from mm/sec to supersonic speeds.

Average film thickness [second half of FY2005]: Methods such as X-ray energy dependent attenuation or electron beam energy loss/scattering will be developed for use in the high temperature, hard vacuum environment. X-rays with energies in the 5 keV range for water and 1 keV range for lithium can be used to measure the time averaged film thickness, for films in the 10 micron range, as appropriate for the first stripper. Higher energy X-rays can be used for the thicker films required for the second stripper. A focussed electron beam in the 20 keV energy range may also be used to measure average, and possibly time fluctuating thicknesses.

Film thickness variations [FY2005]: Differential interferometry on front and back of the film may have to be developed for this purpose if the electron-beam scattering method suggested above does not prove to be viable.

Film stability at high power density [FY2005]: Once a viable long-term solution to the creation of the high-velocity thin lithium films is developed, it will be necessary to test the film stability at power densities equivalent to the future RIA uranium beams. The energy loss of a 100-kW uranium beam in the first stripper is 100 W, in a film thickness of 10 microns. There is currently no high energy uranium beam in the world even approaching this proposed beam power for RIA. However, this situation can be simulated realistically by stopping a focussed 10 keV, 10 mA electron beam in such a film.

If conventional hydrodynamic methods of generating and stabilizing the film prove difficult, MHD methods may offer the control features needed to produce and maintain the stripper film. ANL has a long history of experimental and modeling experience in liquid metal MHD for magnetic fusion applications, including most recently, work on liquid metal MHD jets within the plasma chamber. Initial examination of the thin film-MHD problem indicates that an applied magnetic field may indeed stabilize the film.

The specialized equipment required for this work is a fast CCD imaging system for velocity distribution measurements during the second year, and a high-power low energy electron gun for uranium beam power simulations during the second year

References

[1] J. A. Nolen, C. B.Reed, A. Hassanein, V. J. Novick, P. Plotkin, J. R. Specht, (EMIS-14) 14th International Conference on Electromagnetic Isotope Separators and Techniques Related to their Applications, May 6-10, 2002, Victoria, B.C. Canada.

[2] J. A. Nolen, C. B.Reed, A. Hassanein and I.C. Gomes, Nuclear Physics **A701**, (April 22, 2002) pp. 312c-322c.