A LIQUID LITHIUM HIGH POWER THIN FILM STRIPPER FOR RIA

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Introduction. The Rare Isotope Accelerator (RIA) facility is the highest priority for new construction in nuclear physics in the US and a major strategic initiative for Argonne National Laboratory. The main components of RIA are a high-power multi-beam superconducting heavy-ion accelerator, a production complex where isotopes are created via ISOL techniques, fragmentation techniques, or new approaches combining advantages of both techniques, and finally a high-efficiency post-accelerator based on the Argonne Tandem Linear Accelerator (ATLAS) linac. The RIA driver linac requires two strippers to increase the charge states of the heavy ion beams. The development of a uniform and stable high velocity thin liquid lithium film stripper would increase the reliability and beam quality of the RIA driver. The alternative, a rotating wheel of carbon foils, is a much less desirable solution. Results from measurements performed to determine the best materials and optimum thicknesses for stripper films at the two energies required for the RIA driver linac indicate that lithium is an excellent choice for the lower energy (first) stripper and that the optimum thickness is about 6 microns Ref. [1]. Higher energy tests, for the second stripper, showed that lithium is not optimum for that case.

To provide consistent stripping characteristics, the thickness of the film must remain constant. In addition, to avoid excessive vaporization of the liquid, the mass flow rate of the jet must be high enough ($>\sim 50$ m/s) to remove the thermal energy deposited in the film from the beam without a significant temperature rise. Therefore, producing a very thin, stable, film jet with a high flow rate in a vacuum environment is a key element in the development of a liquid stripper. Our primary objective is to demonstrate that the required parameters can be achieved in lithium, however, since neither the required film thickness nor the required film speed are known with great confidence at this time, a secondary objective is to establish the film thickness vs. velocity operating window, in the neighborhood of these nominal values, which can be reliably attained in the presence of a hard vacuum at roughly 230°C.

1. Jet stability. Ref. [2] showed that a liquid jet is inherently unstable, meaning that a slight disturbance in the jet is spontaneously amplified and the jet eventually breaks up into small droplets by capillary pinching. Two different modes of instability are possible: (a) absolute instability, and (b) convective instability. In general, as the jet velocity increases, the instability mode shifts from absolute to convective, Ref. [3].

Absolute instability occurs when the surface tension of the fluid is dominant over the inertial forces in the fluid. This is the case when the fluid velocity is small, thus the liquid does not form a stable jet, but forms droplets as soon as it exits from the nozzle. Obviously, it is not possible to operate the liquid stripper in this regime. As the jet velocity increases, the inertia becomes dominant and the instability shifts to the convective mode, in which a disturbance propagates and grows only in the downstream direction. Because the disturbance does not grow in time, as the liquid exits from the nozzle, a continuous jet is formed that extends to a point at which the spatially growing disturbance in the jet eventually breaks up the jet. When the amplitude of the disturbance imposed on the jet grows large enough, capillary pinching due to the surface tension of the fluid causes the breakup of the jet.

In higher jet velocity ranges, no experimental measurements in vacuum have been reported, and thus, the intact length of the jet is not known. However, experiments in air show that the intact length of a circular jet decreases as the liquid in the jet becomes turbulent, Ref. [4]. Therefore, in a vacuum environment, it is reasonable to assume that as the velocity of the jet increases further, turbulence in the jet will prevent the intact length from extending indefinitely. Since jet instability phenomena in a vacuum involve only the surface tension, viscous force, and inertial force, the intact length is expected to be a function of these three parameters and characteristics of the applied disturbances. For this same reason, it is possible to draw a stability diagram in 2-D space that consists of the Weber number, We, and the Reynolds number, Rn, as parameters, defined in the usual way, Ref. [5], as ratios of the inertia force to the surface tension force and of the inertia force to the viscous force, respectively. This fact suggests that any liquid jets in vacuum would behave similarly and the diagram should be universal and applicable to any liquids as long as both We and Re are matched. This fact allows the use of Li simulants for the experiment instead of using liquid Li as a working fluid, significantly reducing complexity, difficulty, and cost of performing experiments.

The intact length of the jet strongly depends on the amplitude of the initial disturbance and the size of the liquid jet, in other words, it depends on the physical dimensions of the nozzle, the surface finish of the nozzle interior, externally induced pressure fluctuations in the fluid, mechanical vibrations, etc. Quantities such as surface finish, pressure fluctuation, and vibration in a real system are extremely hard to determine. Therefore, it is not reasonable to attempt to theoretically estimate the maximum intact length with a high degree of accuracy. Instead, an experimental measurement is absolutely necessary.

2. Approach. Because of the extreme technical difficulty in working with liquid lithium, the approach was divided into three primarily experimental steps: (1) develop a liquid thin film formation scheme, (2) develop a film stability diagram for the film production scheme using Li simulants (water and FC-3283), and (3) demonstrate the thin film liquid lithium jet, confirming that the intact length of the film is sufficient to be used as a stripper.

2.1. Development of a liquid thin film formation scheme. The most straightforward method to produce a liquid film would be a direct method, using a slit nozzle whose dimensions match the required film dimensions. For the 1st stripper, however, since the film thickness required from nuclear physics considerations is of the order of a few micrometers and the width of the film must be of the order of a centimeter, it was considered extremely difficult to fabricate and manage such a high aspect-ratio nozzle with a very narrow opening.

Another method is to produce a film indirectly. In this method, liquid issues from a round nozzle, forming a round jet, which subsequently impacts on a deflector on which the round jet transforms into a thin film. Preliminary experiments showed that a thin water jet can be produced using a round nozzle and a metal deflector. In this method, it is expected that the velocity of the thin film would be similar to, but slightly less than, that of the round jet, requiring relatively large drive pressure.

To reduce the drive pressure required in the indirect method, two variations were considered, (1) use of a rotating deflector, and (2) use of a notched deflector. In the rotating deflector design, the deflector is a rotating round disk. The flow direction of the round jet is parallel to the circumferential direction of the rotating disk. As the jet impacts on the disk, the rotation of the disk is expected to accelerate the jet. As a result, the film velocity is expected to be higher than that of the initial jet velocity before impact. In the notched deflector design, the deflector has two cuts on it and the cuts form a notch. The round jet hits at the base of the notch and the film is formed within the notch. As the film is formed, both sides of the film are expected to attach to the deflector, enhancing the stability of the film at low jet velocity. The simple indirect method, using a stationary deflector was selected as the prime candidate film forming scheme.

2.2. Experimental development of a film stability diagram using Li simulants. To significantly reduce complexity, difficulty, and cost of performing experiments with Li, several series of hydrodynamic stability experiments were performed using Li simulants to determine the range of stable jet formation, and to investigate film behavior. Specific objectives of the experiments included investigating the effects on film formation and breakup of: surrounding air pressure, drive pressure (thus jet velocity), nozzle diameter, angle of jet impingement relative to the deflector plate, distance between the nozzle exit and the deflector, jet-to-deflector edge distance, and orifice material of construction.

It was considered necessary to use at least two different simulant fluids to test whether the stability diagram represented by Re and We numbers is universal for other working fluids with different physical properties, as linear stability theory suggests. If so, then this diagram would provide a range of design parameters such as nozzle diameter and film velocity, that are potentially capable of producing a stable, smooth liquid lithium film.

After analyzing several potential Li simulants, water and 3M's FC-3283 were selected not only because of their inert and non-hazardous characteristics (which significantly reduce complexity, difficulty, and cost of performing experiments), but also because the difference between the physical properties of FC-3283 and those of water, for the same combination of Re and We, is similar to that between water and lithium. Therefore, results obtained for FC-3283 and water are expected to extrapolate to lithium.

Fig. 1 shows that threshold data (the velocity below which no film formation was observed) for both water and FC-3283, form a single, relatively narrow, band in Re–We space, indicating the stability boundary above which film formation is expected (shaded region in Fig. 1). The fact that the same boundary is exhibited by the two different fluids suggests that this stability boundary is universal. At jet velocities corresponding to a 10 μm thick, 50 m/s Li film (6.4 m/s for water and 0.83 m/s for FC-3283) no films were formed due to absolute instability, suggesting that the minimum film velocity will not be set by thermal requirements, but by hydrodynamic requirements. Values for velocity and thickness in Fig. 1 are for Li. This figure suggests that a Li film ~ 4 μm thick at $>\sim 100 - 150$ m/s would be stable.

2.3. Experimental demonstration of thin Li film formation. To experimentally demonstrate the formation of a thin Li jet that has the correct physical dimensions to be used as a first stripper for RIA, a Li stripper film loop was designed and built based on the results discussed above. The loop is a once-through type and Li is driven by compressed Ar gas. The maximum design drive pressure is 13.8 MPa (2000 psig). Experiment run time is longer than several minutes with a Li inventory of ~ 20 liters. The nozzle orifice is changeable. The Li jet issues into

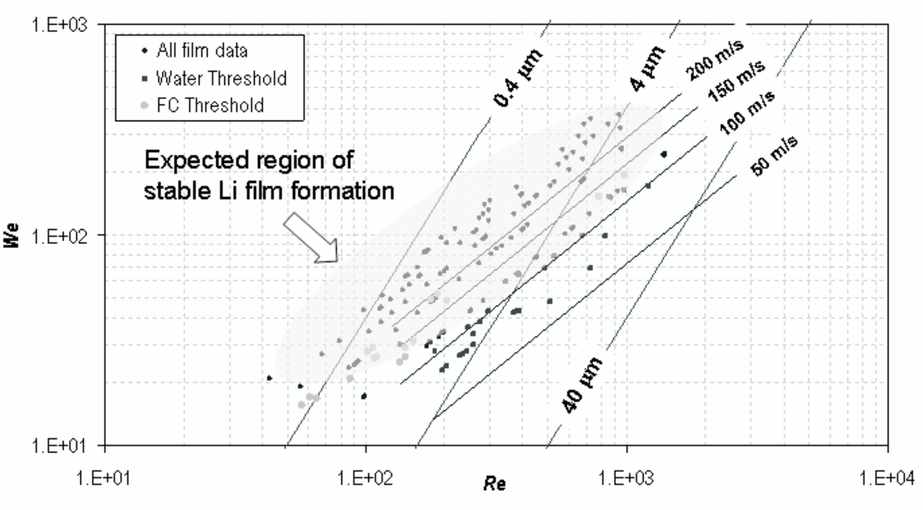

Fig. 1. Film stability diagram using FC-3283 and water.

the vacuum chamber in which the pressure is maintained at $<\sim 10^{-4}$ Pa ($\sim 10^{-6}$ Torr). The nozzle assembly is movable such that fine adjustment can be made.

3. Summary and conclusions. A series of experiments for development of the 1st stripper using liquid lithium for RIA was conducted. For film production, the indirect method using a stationary deflector appears to be the best scheme, in which a round jet from a round nozzle impacts on a deflector on which the round jet transforms into a thin film. It was experimentally shown that films of different fluids appear to behave in a similar manner when their Re and We are kept the same. This fact suggests that results obtained using Li simulants are directly applicable to estimate the behavior of a Li film. After conducting various preliminary experiments using water and FC-3283, several critical design parameters needed to successfully form a good quality Li film were determined. Although a larger nozzle size is better to avoid potential plugging, it was found that a nozzle diameter of ~ 0.5 mm may be the largest size possible that forms an acceptable film. Also, to form a stable Li thin film, it is estimated that a Li jet must be issued at $>\sim$ 100– 150 m/s (corresponding drive pressure of 3–6 MPa). The angle of incidence should be between 30–45 degrees and the relative position of the nozzle to the deflector must be adjustable with a resolution of ~ 0.1 mm.

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