

Research Proposal for Development of an Electron Stripper Using a Thin Liquid Lithium Film for Rare Isotope Accelerator

prepared by
Nuclear Engineering Division
Argonne National Laboratory

About Argonne National Laboratory

Argonne is managed by The University of Chicago for the U.S. Department of Energy under contract W-31-109-Eng-38. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov.

Availability of This Report

This report is available, at no cost, at <http://www.osti.gov/bridge>. It is also available on paper to the U.S. Department of Energy and its contractors, for a processing fee, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone (865) 576-8401
fax (865) 576-5728
reports@adonis.osti.gov

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor The University of Chicago, nor any of their employees or officers, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or The University of Chicago.

Research Proposal for Development of an Electron Stripper Using a Thin Liquid Lithium Film for Rare Isotope Accelerator

by
Y. Momozaki
Nuclear Engineering Division, Argonne National Laboratory

February 13, 2006



Argonne National Laboratory is managed by
The University of Chicago for the U. S. Department of Energy

Table of Content

Table of Content	iii
Abstract.....	1
Background.....	2
Detailed Technical Issues and Tasks	5
Proposed Research Methods and Plans	9
Theoretical Part of Research.....	10
Experimental Part of Research.....	12
Acknowledgment	15
References.....	15

Abstract

Hydrodynamic instability phenomena in a thin liquid lithium film, which has been proposed for the first stripper in the driver linac of Rare Isotope Accelerator (RIA), were discussed. Since it was considered that film instability could significantly impair the feasibility of the liquid lithium film stripper concept, potential issues and research tasks in the RIA project due to these instability phenomena were raised. In order to investigate these instability phenomena, a research proposal plan was developed. In the theoretical part of this research proposal, a use of the linear stability theory was suggested. In the experimental part, it was pointed out that the concept of Reynolds number and Weber number scaling may allow conducting a preliminary experiment using inert simulants, hence reducing technical difficulty, complexity, and cost of the experiments. After confirming the thin film formation in the preliminary experiment using simulants, demonstration experiments using liquid lithium were proposed.

Background

Progress in nuclear physics using various accelerators has greatly expanded our knowledge on matters. However, since only stable nuclear species can be accelerated by these conventional accelerators and also used as a target material, almost all our information in nuclear physics are limited to those of relatively stable nuclei. Lack of information on unstable nuclei has prevented us from understanding fundamental nuclear physics. For example, even the origin of heavy elements is not well understood, since they are thought to be created through the cascade of nuclear reactions involving unstable nuclei. To extend our knowledge on the unstable nuclei, several new accelerator projects to produce unstable isotope beams are planned worldwide [1,2]. One of these is the Rare Isotope Accelerator (RIA) project in the US [3,4]. The RIA would open a wide window of research in physics, including study on the nature of the nucleus and the origin of heavy elements as well as experimental examinations of the theoretical models on the creation of these elements in events such as supernova explosions. In addition to these immediate contributions to physics, applications of the isotope beam could be found in many other areas such as in material science or in nuclear medicine [5,6].

The basic and main elements of the RIA facility include a driver linear accelerator (linac), target, fragments separator, and post accelerator, as shown in Figure 1 [3,4]. Independent efforts to develop these components are currently being carried out at several locations in the US. However, existing facilities and technologies at ANL could allow The Laboratory to be in the leading position for development and construction of these critical components.

One of the challenges in the RIA project is developing a high power driver linac, which is capable of accelerating the variety of heavy ions to high energy. For an ion accelerator in general, heavy neutral atoms are initially ionized to a certain charge state in a driver ion source, such as an Electron-Cyclotron-Resonance (ECR) ion source in which ionization takes place by collisions with high-energy electrons. The ions are then injected into the accelerator section and accelerated in an electromagnetic wave. To accelerate the charged ions more efficiently over a given length and field strength, increasing the charge state, thus, increasing the charge-to-mass ratio is important [7]. The electron stripper is used for this purpose. As the ion beam passes through the stripper material, the electrons are stripped off from the ions by means of charge exchange, producing ions at different charge states. Multiple charge state operation of the linac using superconducting accelerators enables the system to accept several different charge states, enhancing the beam output power by more than a factor of 10 for Uranium ions. More than one stripper could be employed to achieve even higher charge states for efficient acceleration for heavy ions at different energies [8].

Simplified Schematic Layout of the Rare Isotope Accelerator (RIA) Facility

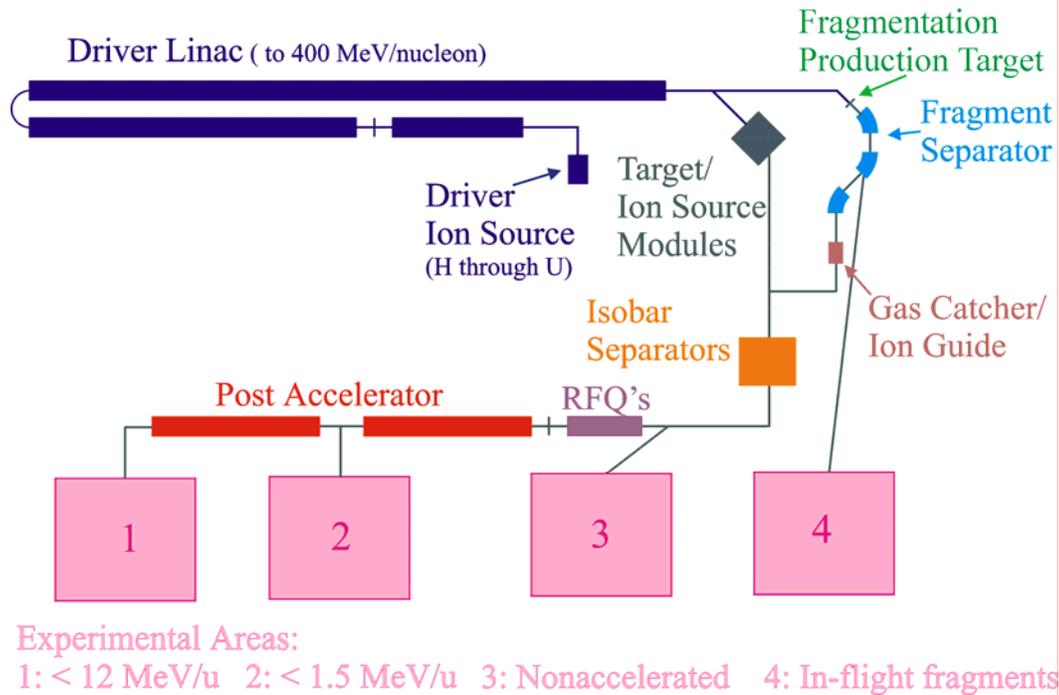


Figure 1. Schematic Layout of RIA Facility.

A stripper material could be solid, liquid, or gaseous, as long as it strips electrons from ions and can handle a large energy input from exposure to the beam. A gas stripper, which typically consists of a differentially pumped chamber filled with a gas, could be a good choice for certain situations, since the gas would not be damaged by heating from the beam. At high beam energy, however, the obtainable charge state could become significantly lower than when a solid or a liquid stripper is used [9]. In addition, when the gas is heated up after exposure to the beam, the gas density will change, although the stripper itself is physically intact. As a result, the stripping characteristics may deviate from nominal values, perturbing the beam quality [10]. To avoid heating problems, it is necessary to circulate a large amount of gas or to increase the gas pressure, which would lead to difficulty in confining the gas in the high vacuum accelerator environment.

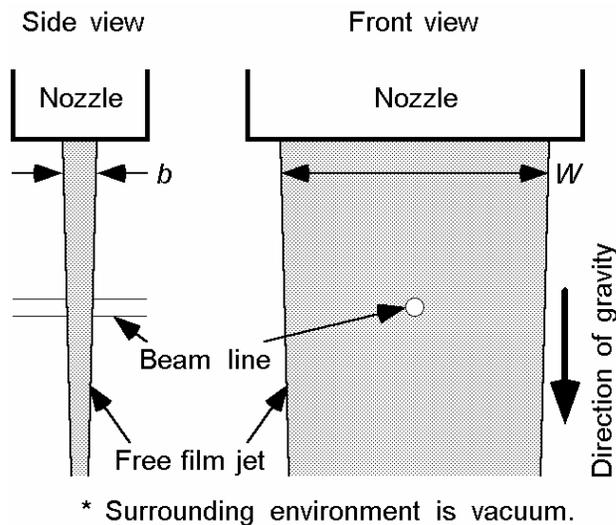


Figure 2. Schematic of Liquid Stripper.

A solid material with low vapor pressure would not contaminate the high vacuum environment; instead, thermal management and the radiation damage of the stripper become the main technical issues. One type of solid stripper is a thin film mounted on a rotating wheel [11]. As the wheel rotates, the energy input to the film is spread and the portion of the film previously exposed to the beam is cooled while that heated section is away from the beam line. There are disadvantages of this method, however. Any slight variation in the thickness of the film along the circumference of the wheel would cause a change in the stripping characteristics, which would disturb the beam quality. To effectively accelerate such a disturbed beam, a complex dynamic tuning of the accelerating field and phase would be required in the down stream [9]. Furthermore, when beam power is increased, the lifetime of the stripper is shortened by the intensive radiation damage and heating. Eventually, the instantaneous power deposit will reach such a level that any solid material would immediately melt or vaporize [9]. Therefore, for the stripper employed in a high-power ion beam system such as RIA, the use of a liquid stripper seems more attractive than a gaseous or solid stripper. Since the working liquid must have good thermal properties in order to remove very high heat input and preferably low vapor pressure, the use of liquid metals appears most promising [9]. A liquid film stripper proposed for use in RIA is schematically pictured in Figure 2.

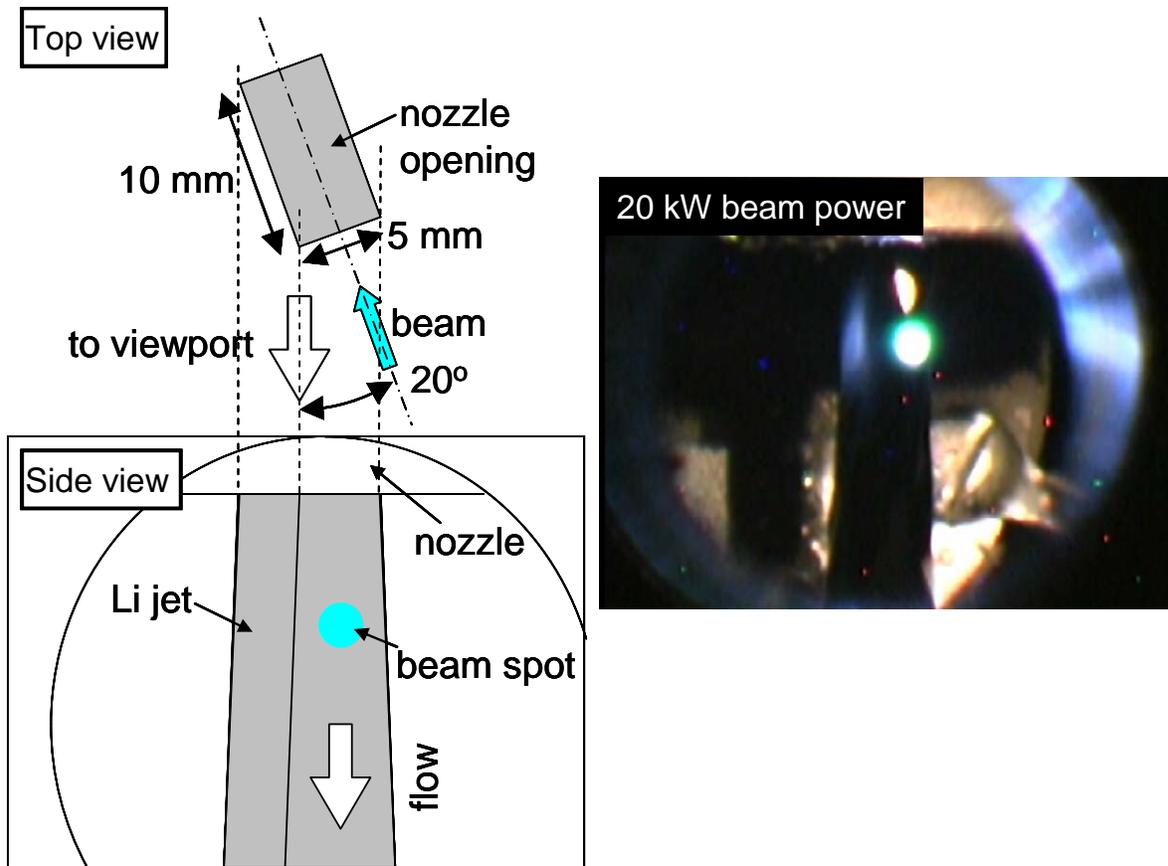


Figure 3. High Power Electron Beam Irradiation on Liquid Lithium Jet at ANL.

Recently, feasibility of using liquid lithium (Li) as a target for RIA was investigated at ANL. Experiments were conducted to verify the capability of the liquid Li jet to carry large amount of heat deposit in a high vacuum environment in an accelerator. The experimental setup consisted of the Dynamitron electron beam accelerator, the beam line, and the Li loop. Because of high radiation level during the experiments, the setup had to be operated remotely. The Dynamitron is capable to generate up to 20 mA electron beam at 1 MeV (= up to 20 kW). This high power electron beam was steered, focused in the beam line and delivered to the Li jet issued from the rectangular nozzle (5 mm × 10 mm cross section, see Figure 3) in the Li loop. Preliminary analysis showed that 80% of the beam power was deposited in the Li jet and the rest was emitted as X-ray to surrounding structures. Two viewports were mounted to the Li loop near the nozzle for illumination and observation purposes. In the loop, lithium was maintained in a liquid form under vacuum and circulated by the DC electromagnetic pump during experiments. Bulk Li temperature was typically maintained at 200 – 220 °C, however, it could increase to ~280 °C when the high energy beam was applied for long period of time (more than several minutes). The Li jet velocity could reach at as high as 7 m/s. During experiments, the digital video camera recorded the liquid Li jet through the viewport as shown in Figure 3 and temperatures at various different locations on the Li loop and the pressure in the Li loop were monitored.

It was experimentally shown that the irradiation of the high power electron beam on the liquid Li jet did not disturb the Li jet at all (Figure 3). Despite the large heat input to the very small area (spot of approximately 1mm in diameter) on the jet, no visible indication of severe local vaporization of Li nor significant increase in the background pressure of the Li loop were observed. In contrast, when a 1 kW electron beam was applied to the solid Li, the beam immediately melted and subsequently boiled Li. These observations manifested the superiority of the liquid target concept over the solid target concept in high power accelerator applications. Details of the experiment can be found elsewhere [12,13]. Due to similarity in existing technical issues in the liquid target and stripper concepts, this justification is also valid for the stripper applications. These experimental results obtained at ANL are very promising and support the development of the liquid Li stripper for the RIA. Specific issues and tasks associated with the development of such a liquid stripper are discussed in the next section.

Detailed Technical Issues and Tasks

Although the use of a liquid metal as an electron stripper has potential advantages over gaseous or solid materials, there are technical issues that need to be considered. If Li is used as a working fluid, a preliminary investigation, from the viewpoint of nuclear physics, indicates that the optimum thickness of such a liquid stripper could be as little as ~10 μm, depending on the beam energy [9]. To provide consistent stripping characteristics, the shape, especially, the thickness of the film must be kept constant and stable. In addition, to avoid excessive vaporization of the liquid, the mass flow rate of the jet must be high enough 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 [3,9].

A jet issuing from a nozzle has been investigated for more than a century. It has been shown that a liquid jet emanating from a nozzle is inherently unstable, although the viscosity of the liquid tends to stabilize the jet. This means that a slight disturbance in the jet is spontaneously amplified and the jet eventually breaks up into small droplets, which is caused by capillary pinching [14]. Jets with higher viscosity remain intact longer than jets with lower viscosity. Figure 4 shows two different modes of instabilities for the circular jet: (a) absolute instability, and (b) convective instability depending on their characteristics. In general, as the jet velocity, U , increases, the instability mode shifts from absolute to convective. In addition to these instabilities, if the liquid jet is issuing into a non-vacuum environment (for example, air), as the jet velocity further increases, the inertia force of the surroundings relative to the surface tension force of the liquid becomes significant and the breakup of the liquid jet due to “atomization” starts dominating that due to capillary pinching [14]. Since the proposed liquid stripper will be constructed in vacuum, this will not be an issue. Thus, the following discussions are only for the case in which the inertia force of the surroundings relative to the surface tension force of the liquid is negligible.

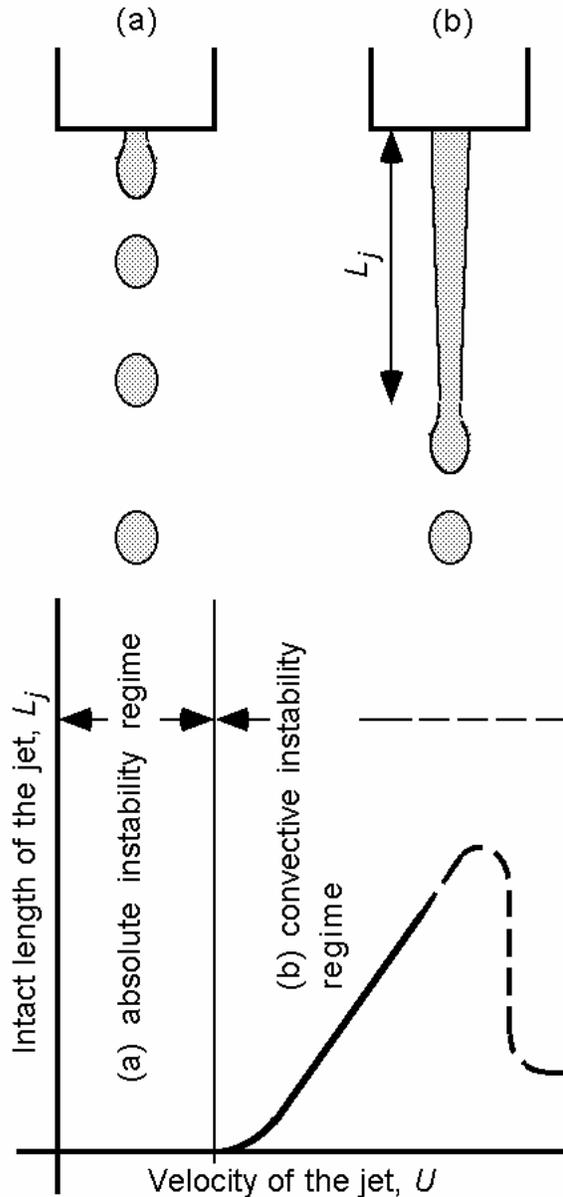


Figure 4. Evolution of Circular Jet in Vacuum.

Figure 4 shows two different modes of instabilities for the circular jet: (a) absolute instability, and (b) convective instability depending on their characteristics. In general, as the jet velocity, U , increases, the instability mode shifts from absolute to convective. In addition to these instabilities, if the liquid jet is issuing into a non-vacuum environment (for example, air), as the jet velocity further increases, the inertia force of the surroundings relative to the surface tension force of the liquid becomes significant and the breakup of the liquid jet due to “atomization” starts dominating that due to capillary pinching [14]. Since the proposed liquid stripper will be constructed in vacuum, this will not be an issue. Thus, the following discussions are only for the case in which the inertia force of the surroundings relative to the surface tension force of the liquid is negligible.

Absolute instability occurs when the surface tension of the fluid is dominating over the inertial force of the jet. This is the case that the fluid velocity is small. A disturbance propagates both in space as well as in time. Thus, the liquid does not form a stable jet, but forms droplets as soon as it exits from the nozzle as shown in Figure 4a. 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

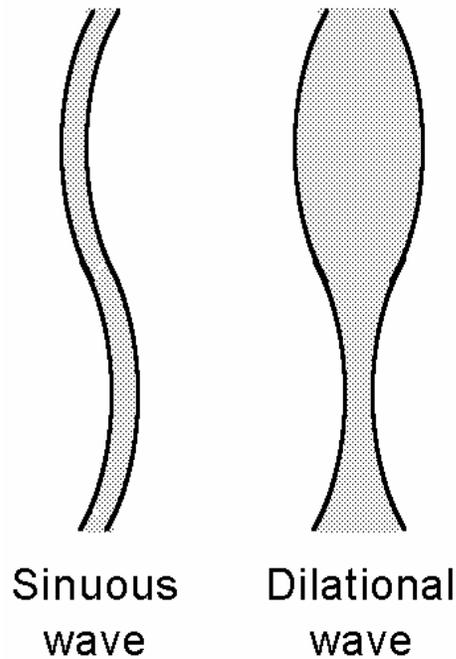


Figure 5. Side views of Sinuous and Dilational Disturbances in Film Jet.

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 the point at which the spatially growing disturbance in the jet eventually breaks up the jet as shown in Figure 4b. It is theoretically shown that only specific disturbances can actually appear on the surface of the jet. For example, for a circular jet, only axisymmetric disturbances along the flow direction appear, because non-axisymmetric disturbances are attenuated [15]. For a film jet (two-dimensional rectangular jet, as shown in Figure 5), only sinuous (or bending) and dilational (or varicose) disturbances can exist. The sinuous mode grows faster than the dilational mode [16]. Therefore, the sinuous mode is assumed to be responsible for the breakup of the film jet [17]. When the amplitude of the disturbance imposed on the jet grows large enough, finally capillary pinching due to the surface tension of the fluid causes the breakup of the jet. In Figure 4b, L_j represents the length of the continuous portion of the jet, which is called *intact length* [14].

The intact length, L_j for a circular jet is schematically presented as a function of the jet velocity, U in the bottom of Figure 4. In higher jet velocity ranges (dashed line in the bottom of Figure 4), no experimental measurements in vacuum have been reported, and thus, the intact length of the jet is not known. However, when atomization is negligible, experiments in air show that the intact length of the circular jet decreases as the liquid in the jet becomes turbulent [18]. Therefore, it is reasonable to assume that as the velocity of the jet further increases in a vacuum environment, turbulence in the jet prevents 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. 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, and other mechanical vibrations, etc. Especially, the quantities such as surface finish, pressure fluctuation, and vibration in the real system are extremely hard to determine. Therefore, it is not reasonable to theoretically estimate the maximum intact length with a high degree of accuracy, unless disturbances with known characteristics that dominate all other disturbances with

unknown characteristics are imposed on the jet. Thus, to determine the intact length of the jet for the present purpose, an experimental measurement is necessary.

Although theoretical estimates of the intact length of the jet are not practical in reality, theoretical studies on the instability using linear stability theory have been quite successful in providing qualitative descriptions of the breakup and predicting the existence of instabilities. This information would greatly narrow the range of conditions needing to be experimentally explored. In the analysis using linear stability theory, the disturbance is expanded in Fourier Series and each term is represented by a complex sinusoidal wave function, Ψ , expressed as [15,16,17,19],

$$\Psi = \phi \exp i(kx - \omega t), \quad (1)$$

where ϕ is the amplitude of the initial disturbance, k is the wave number, x is the distance taken along the stream direction, ω is the frequency, and t is time. A small disturbance is imposed on the jet, which satisfies the set of transport equations including the mass conservation equation and the Navier-Stokes (momentum) equation, forming a set of non-linear differential equations. Linearizing these differential equations yields the eigenvalue problem for the wave number, k , and the frequency, ω . If any complex eigenvalues for the frequency, ω , are found and $\text{Re}(-i\omega) > 0$, the exponent in eq. (1) increases with time and the disturbance will grow in time, corresponding to the case of absolute instability. On the other hand, if all eigenvalues for the frequency, ω , are found to be real or $\text{Re}(-i\omega) < 0$, the exponent in eq. (1) does not increase with time and the disturbance in the jet will not grow in time. This case corresponds to convective instability. Although this approach can identify the mode of instabilities, the linearized differential equations are not adequate to describe the spatial behavior of the jet. To theoretically calculate the intact length, the original non-linear differential equations must be solved with a precisely known initial disturbance, which is not available. Thus, the spatial behavior of the jet cannot be theoretically obtained.

An example of a typical stability diagram is presented in Figure 6. This figure conceptually maps the regions of instability using the Weber number, We , and the Reynolds number, Re , which are the ratios of the inertia force to the surface tension force and of the inertia force to the viscous force, respectively. The Weber number and the Reynolds number are expressed as [20],

$$We = \frac{\rho U^2 R_h}{\sigma}, \text{ and } Re = \frac{\rho U R_h}{\mu}, \quad (2)$$

where ρ is the liquid density, U is the average jet velocity, R_h is the hydraulic radius of the nozzle, σ is the surface tension of the liquid, and μ is the liquid dynamic viscosity. Figure 6 shows that in the region where $We > We_{CR}$, one has a convective instability and where $We < We_{CR}$, one has an absolute instability. We_{CR} is the critical Weber number and is expressed as a function of Reynolds number [19,20]. Also in this figure, the

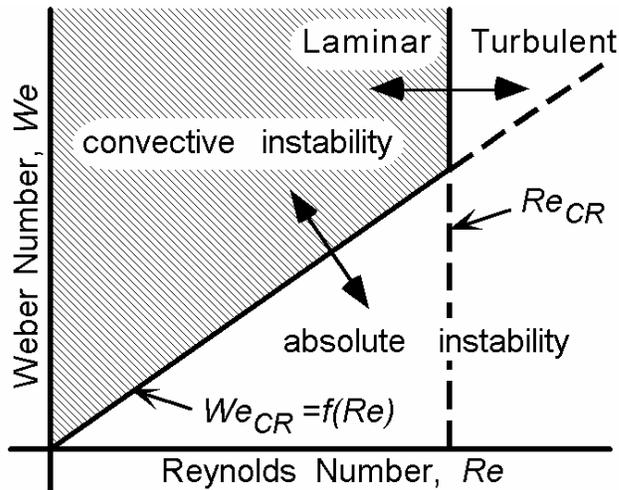


Figure 6. Schematic Representation of Stability Diagram for the Jet in Vacuum.

region where $Re < Re_{CR}$ indicates that the liquid flow in the nozzle remains laminar at the exit of the nozzle, spouting out smoothly without any internal disturbances forming the jet with constant shape, whereas the region of $Re > Re_{CR}$ is where the liquid in the nozzle reaches turbulent and the liquid jet at the exit of the nozzle is expected to be wavy, shortening the intact length, which is not suitable for stripper operation. The smooth jet formation with a finite length is expected only in the shaded area in Figure 6. Conducting experiments to measure the intact length to assess the feasibility of the liquid stripper is necessary only in this shaded area.

Based on the above discussions, tasks for developing a thin film liquid stripper are twofold:

- (1) theoretical analysis of the film instability using linear stability theory to obtain a stability diagram. This diagram will provide the range of design parameters, such as nozzle width and the film velocity, that are potentially capable of producing a stable, smooth film, and
- (2) experimentally test the nozzle fabricated within the design range to measure the actual intact length of the film jet and to confirm that the intact length of the film is sufficient to be used as a stripper.

Proposed Research Methods and Plans

The ion beam primarily considered to be stripped in RIA is a Uranium (U) beam. Since it has the heaviest mass among all other stable ions, stripping a U beam to increase the charge-to-mass ratio would be expected to result in the most effective improvement in acceleration. The driver linac for RIA is designed to produce 2.5×10^{13} U ions per second at 400 kW. Two strippers are planned to be installed at two different locations in the beam line at which the beam energy is ~ 10 MeV/u and ~ 85 MeV/u, respectively. The primary candidate for the working fluid is liquid Li. Numerical calculations show that Li ($Z = 3$) yields higher charge states at energy at ~ 10 MeV/u than other materials with higher atomic number [21,22]. Lithium has a relatively low melting point, low vapor pressure, low density, and good heat capacity [23]. These characteristics greatly reduce the complexity of designing a liquid stripper. Preliminary study has shown that the

optimum thickness of the Li film at the lower energy is $\sim 10 \mu\text{m}$ and that at the higher energy is $\sim 400 \mu\text{m}$. The required film velocity to avoid excess vaporization of Li is $\sim 50 \text{ m/s}$ with a beam diameter of 2 mm . The corresponding energy depositions are estimated to be $\sim 380 \text{ W}$ and $\sim 5 \text{ kW}$ in the strippers at the lower energy and at the higher energy, respectively [3,9]. These requirements from the viewpoints of nuclear and thermal properties will be confirmed and refined as necessary. To maintain low vapor pressure, the operating temperature of Li is set at slightly above its melting point ($\sim 473 \text{ K}$). Physical properties (density, ρ , surface tension, σ , and dynamic viscosity, μ) of Li needed to calculate We and Re and vapor pressure, p , can be expressed as functions of temperature as [24],

$$\rho(\text{Kg/m}^3) = 278.5 - 0.04657T + 274.6 \times \left(1 - \frac{T}{3500}\right)^{0.467}, \quad (3)$$

$$\sigma(\text{N/m}) = 0.398 - 0.147 \times 10^{-3} T, \quad (4)$$

$$\mu(\text{Pa} \cdot \text{s}) = \exp\left(-4.164 - 0.6374 \times \ln T + \frac{292.1}{T}\right), \text{ and} \quad (5)$$

$$p(\text{Pa}) = \exp\left(26.89 - 0.4942 \times \ln T - \frac{18880}{T}\right), \quad (6)$$

where the liquid temperature, T , is in Kelvin.

Theoretical Part of Research

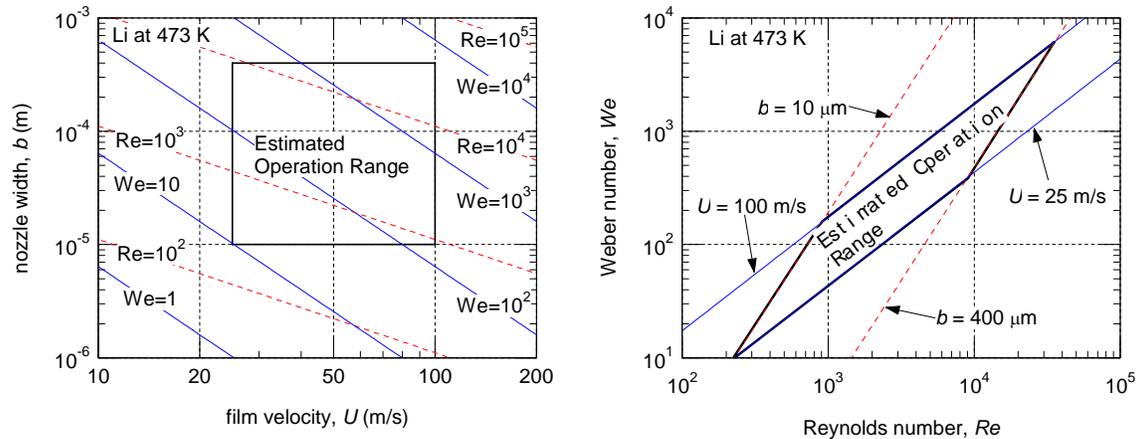


Figure 7. Estimated Range of Operation for Li.

Using nuclear and thermal properties of the working fluid (Li), the reasonable range of the film dimension and the flow rate are finalized and the corresponding range

of We and Re are obtained. The hydraulic radius, R_h to calculate We and Re for a two dimensional rectangular nozzle is given as,

$$R_h = b, \quad (7)$$

where b is the thickness of the film or the width of the nozzle (Figure 1). This range of We and Re gives the requirements for realizing a stable film jet to be operated as the liquid stripper. Figure 7 shows an example sketch of the operating range of a liquid Li film at 473 K based on preliminary results, in which the film thickness and the film velocity are assumed to vary from 10 μm to 400 μm and from 25 m/s to 100 m/s, respectively.

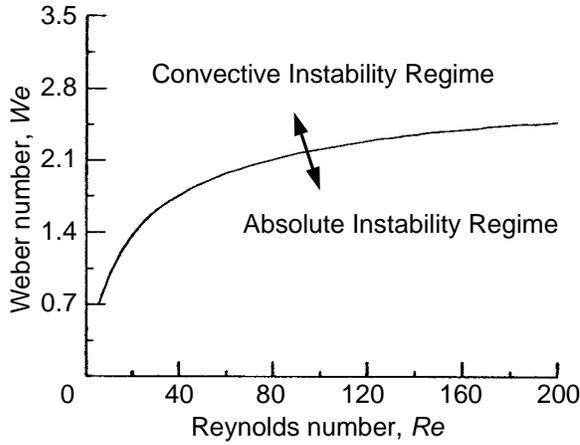


Figure 8. Instability Diagram for Circular Jet.

There are many theoretical investigations on the jet stability analysis using linear stability theory, mostly for circular jets, providing satisfactory results on mapping the instability diagram [14,19]. The same approach will be employed for a thin, two-dimensional film jet. A set of differential equations, including the mass conservation and the Navier-Stokes equations, is appropriately expanded in Cartesian coordinates and the eigenvalue problem is formulated accordingly, with boundary conditions for the thin film configuration. This eigenvalue problem can be numerically solved with available numerical packages, for example the FORTRAN IMSL package. Eigenvalues obtained thus give an instability diagram as a function of the dimensionless parameters, We and Re , which is similar to Figure 6. Figure 8 is an example of an instability diagram for a circular jet in vacuum, obtained numerically by Leib and Goldstein [19]. This range of We and Re shown in Figure 8, gives the requirement for a circular jet in vacuum to stably exist.

The combination of these ranges is used to pinpoint the realistic and reasonable conditions that need to be investigated experimentally to measure the intact length of the jet. Based on the results obtained in the theoretical instability study, specific design parameters to construct the experimental setup will be determined. The details of the experimental part of the investigations are described next.

Experimental Part of Research

Since the intact length in vacuum with a minimal disturbance is expected to be a function of three parameters (surface tension, viscous force, and inertial force), it can be expressed as a function of only two dimensionless parameters, We and Re . Therefore, to estimate the intact length of the specific system and working fluid, we may use a different working fluid to simplify the experiment without losing the applicability of the results, as long as We and Re are kept in the same range. Handling liquid lithium is extremely difficult and dangerous because it is highly reactive in air and requires a heated loop ($> \sim 450$ K) to maintain it in liquid phase. For this reason, we will seek the possibility of using other working fluids, such as gallium (Ga) or mercury (Hg), which have lower melting point and preferable chemical characteristics, eliminating the need of heated and isolated systems. Density, surface tension, dynamic viscosity, and vapor pressure for Li, Ga, and Hg are compared Table 1 [25,26,27].

Table 1. Physical properties for Li, Ga, and Hg.

	Density ρ (Kg/m ³)	Surface Tension σ (N/m)	Dynamic Viscosity μ (Pa-s)	Vapor Pressure p (Pa)
Li at 473 K	513	0.328	5.69×10^{-4}	1.26×10^{-7}
Ga at 303 K	6110	0.709	2.13×10^{-3}	very low ($< 10^{-7}$)
Hg at 303 K	13521	0.485 (at 298 K)	1.53×10^{-3} (at 298 K)	3.08×10^{-1}

Based on these physical properties, equivalent operating ranges for Ga and Hg are found as shown in Figure 9. Both working fluids require lower jet velocity than that for Li, which may be considered as a technical advantage, however, the equivalent nozzle width for both working fluids are smaller than that for Li, which adds more technical difficulty. Especially for Hg as shown in Figure 9b, the required nozzle width is 1.86 μm , which may be too small to manufacture. This information also provides the required pressure to drive the film to flow from the nozzle for each working fluid. The fluid flow in the nozzle must be kept laminar to produce a stable film. Thus, the required pressure for each liquid can be calculated assuming the flow is in laminar regime as [28],

$$\Delta p = \frac{1}{2} \rho U^2 \times 4f \times \frac{L_n}{D_h}, \quad (8)$$

where f is the Fanning friction factor, L_n is the nozzle length, and D_h is the hydraulic diameter ($= 2R_h$) and f is given as [28],

$$f = \frac{24}{Re_h}, \text{ and } Re_h = \frac{\rho U D_h}{\mu}. \quad (9)$$

Calculated values for the required pressure for various liquids are listed in Table 2. Note that these values are calculated based on several assumptions:

- (1) the flow is laminar in the nozzle,

- (2) the length of the nozzle is 1 mm, and
- (3) the maximum pressure requirement occurs at the largest film velocity and the narrowest nozzle width.

Except for liquid Li, the required pressure to drive the film specified in the design diagram may be too high. Available pumping systems may impose another design limitation. These technical issues will be further considered in determining the possibility of using a low temperature liquid metal to substitute for liquid Li.

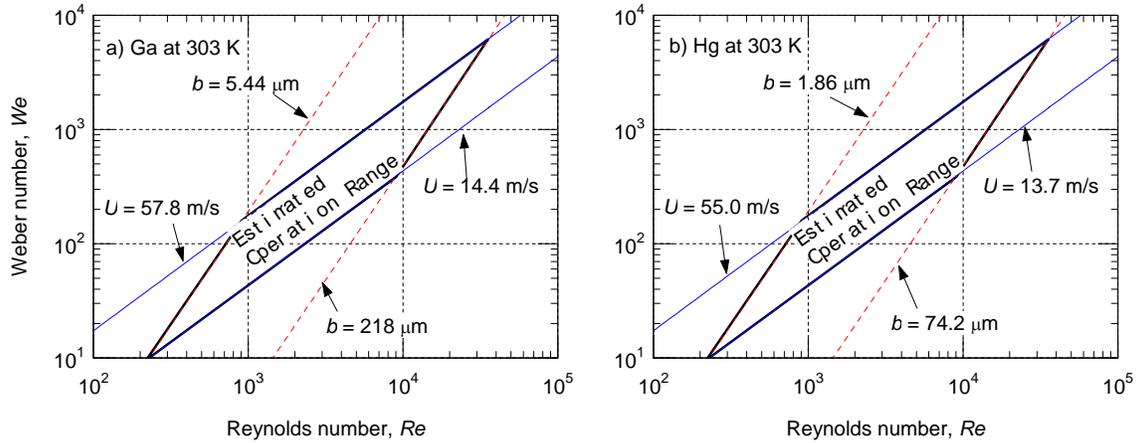


Figure 9. Equivalent Operating Conditions for Ga and Hg.

Table 2. Maximum Pressure Requirement for Li, Ga, and Hg.

	Maximum Required Pressure (Pa)
Li at 473 K	6.83×10^6 (990 psi)
Ga at 303 K	49.9×10^6 (7240 psi)
Hg at 303 K	291×10^6 (42200 psi)

Upon the completion of the theoretical part of the research and based on the appropriate parameter space given in terms of We and Re , the nozzle dimensions and the test fluid will be determined. Reducing the initial disturbance in the liquid at the nozzle is expected to increase the intact length of the film jet, therefore, not only the nozzle dimensions and the type of the test fluid, but also the surface finish of the nozzle interior and the wettability of the nozzle material with the test fluid require special attention. Since the required volumetric flow rate is small, the experiments to measure the intact length of the film jet with various nozzles could be conducted using either a closed loop system or a once-through system (Figure 10). For example, assuming the width of the film, W (in Figure 1), is 1 cm, a conservative estimate gives the volumetric flow rate of 0.4 liter/sec at the maximum nozzle width (400 μm) and film velocity (100 m/s). To sustain this condition for 100 sec, only 40 liter of the liquid is required. In any case, the film jet should be injected into a vacuum to eliminate the effects of interfacial shear between the film and the surrounding atmosphere for accurate measurements. Interfacial

shear tends to enhance the instability of the fluid, shortening the intact length of the film. Therefore, if conducted in non-vacuum environments, measured values for the intact length would give the conservative estimates. Using the once-through configuration reduces the number of components required to perform the experiments. Most significantly, the once-through configuration does not require a high pressure pump. Therefore, for this configuration, lesser budgets and time than for the closed loop system will be needed. Each configuration will be further investigated and the most suitable configuration will be determined.

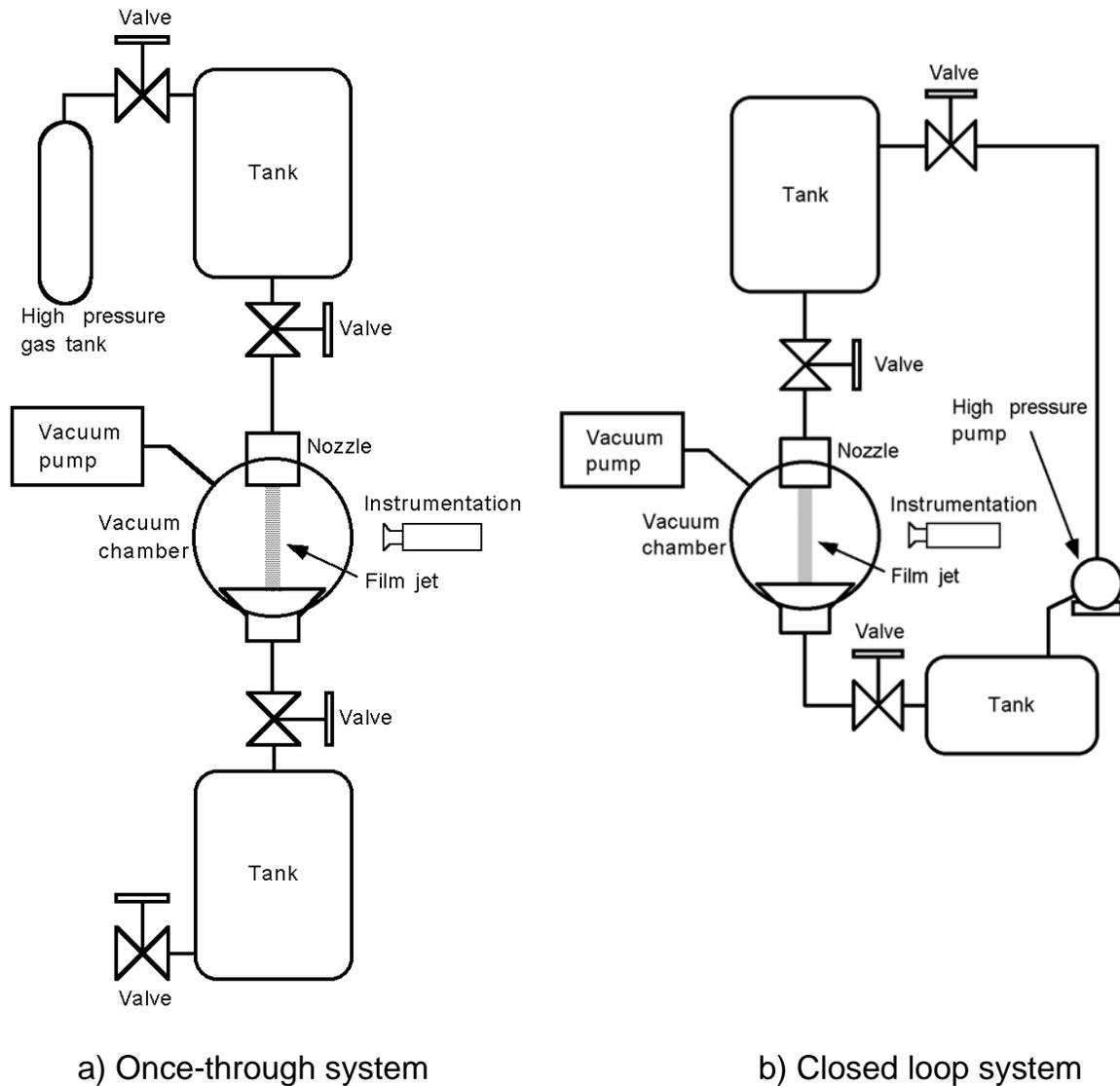


Figure 10. Example of Experimental System Configurations.

To determine the intact length, the thickness, and the uniformity of the film jet, reliable diagnostic methods must be developed. Measuring optical reflection from the surface of the film could be used to determine the surface conditions of the film. Also, measuring the transmission and reflection characteristics of the film jet using β or γ ray

may allow one to estimate the thickness as well as the surface profile of the film. These measurement techniques could be separately verified using the low temperature, non-vacuum experimental setup.

The experimental setup will be constructed after all design parameters are determined. If the use of another low temperature liquid metal is justified, a thin film demonstration setup will be constructed and the data for the intact length will be collected. Using the data obtained for the film dimensions, a separate numerical analysis could be conducted to investigate the electromagnetic interaction between the film and the ion beam. If the intact length of the film is found not satisfactory, using guide wires or applying a magnetic field for magneto-hydrodynamic (MHD) stabilization of the film could be considered. Since an electrically conductive media, such as liquid metal, tends to flow along the magnetic field lines, applying a magnetic field parallel to the flow may improve the stability of the jet. However, this additional stabilization increases the complexity of the system and should be avoided, unless it is justified that such stabilization is absolutely necessary.

After demonstrating that the nozzle produces a stable thin film, a thin film stripper nozzle for liquid Li is planned to be fabricated. At first, the Li film stripper will be tested without beam heating to confirm that liquid Li at the designed operating conditions forms a thin film jet. Finally, the demonstration of the stripper with beam heating will be conducted, which completes the development of the thin liquid Li stripper.

Acknowledgment

The author is greatly thankful for Drs. Claude B. Reed and Jerry A. Nolen in providing this opportunity and helping to write this proposal.

References

- [1] Ozawa, A., (2001) "Recent Radioactive Ion Beam Program at RIKEN and Related Topics," *PRAMANA-J. Phys.*, vol. **57** (2-3), pp. 525-533.
- [2] Munzenberg, G., (2001) "Nuclear Structure Physics at GSI: Results and Perspectives," *Nucl. Phys. A*, vol. **682**, pp. 88c-97c.
- [3] Nolen, J. A., (2002) "The U.S. Rare Isotope Accelerator Project," Invited paper at the *XXI International LINAC Conference*, Gyeongju, Korea, August 19-23.
- [4] Savard, G., (2001) "The U.S. Rare Isotope Accelerator Project," proceedings of *2001 Particle Accelerator Conference*, June 18-22, Chicago, IL, pp. 561-565.

- [5] Eickhoff, H., Haberer, T., Kraft, G., Krause, U., Richter, M., Steiner, R., and Debus, J., (1999) "The GSI Cancer Therapy Project," *Strahlentherapie und Onkologie*, vol. **175** (s2), pp. 21-24.
- [6] Hellemans, A., (1999) "Bringing Supernovae Down to Earth," *Nature*, vol. **409**, pp. 448-450.
- [7] Ostroumov, P. N., Pardo, R. C., Zinkann, G. P., Shepard, K. W., and Nolen, J. A., (2001) "Simultaneous Acceleration of Multiply Charged Ions through a Superconducting Linac," *Phys. Rev. Lett.*, vol. **86** (13), pp. 2798-2801.
- [8] Shepard, K. W., (2002) "The RIA Driver Linac," proceedings of *XXI International LINAC Conference*, Gyeongju, Korea, August 19-23.
- [9] Reed, C. B., (2002) *private communication*.
- [10] Bieniosek, F. M., Anderson, K., Pasquinelli, R. J., Popovic, M., Schmidt, C. W., Webber, R., Larson, D. J., and Young, P., (1997) "Charge Stripper and MEFT for the ³He RFQ Accelerator," proceedings of *1997 Particle Accelerator Conference*, May 12-16, Vancouver, BC, pp. 3837-3839.
- [11] Ostroumov, P. N., (2002) "Heavy-Ion Linac Development for the U.S. RIA Project," proceedings of *International Conference on Heavy Ion Accelerator Technology*, January 14-18, New Delhi.
- [12] Nolen, J. A., Reed, C. B., Novick, V. J., Specht, J. R., Bogaty, J. M., Plotkin, P., and Momozaki, Y., (2005) "Behavior of Liquid Lithium Jet Irradiated by 1 MeV Electron Beams up to 20 kW," *Review of Scientific Instruments*, vol. **76**, 073501.
- [13] Nolen, J. A., Reed, C. B., Novick, V. J., Specht, J. R., Plotkin, P., Momozaki, Y., and Gomes, I. C., (2005) "A High Power Beam-on-target Test of Liquid Lithium Target for RIA," ANL-05/22.
- [14] Lin, S. P., and Reitz, R. D., (1998) "Drop and Spray Formation from a Liquid Jet," *Annual Review of Fluid Mechanics*, vol. **30**, pp. 85-105.
- [15] Chandreskhar, S., (1961) *Hydrodynamic and Hydromagnetic Stability*, Oxford University Press.
- [16] Hagerty, W. W., and Shea, J. F., (1955) "A Study of the Stability of Plane Fluid Sheets," *Journal of Applied Mechanics*, pp. 509-514.
- [17] Chigier, N., and Dumouchel, C., (1995) "Atomization of Liquid Sheets," *Recent Advances in Spray Combustion: Spray Atomization and Drop Burning Phenomena*, Edited by Kuo, K. K., Reston, VA, American Institute of Aeronautics and Astronautics, Chapter 10, pp241-259.

- [18] Debler, W., and Yu, D., (1988) "The Break-up of Laminar Liquid Jets," *Proc. R. Soc. London, Ser. A*, vol. **415**, pp. 107-119.
- [19] Leib, S. J., and Goldstein, M. E., (1986) "Convective and Absolute Instability of a Viscous Liquid Jet," *Phys. Fluids*, vol. **29** (4), pp. 952-954.
- [20] Lin, S. P., Hudman, M., and Chen, J. N., (1996) "Absolute and Convective Instability of a Liquid Jet," proceedings of *Fourth Microgravity Fluid Physics & Transport Phenomena Conference*, August 12-14, Cleveland, Ohio, pp. 534-538.
- [21] Portillo, M., (2002) "Beam Physics Developments for a Rare Isotope Accelerator," *Ph.D. Dissertation*, Michigan State University.
- [22] Nolen, J. A., (2002), *private communication*.
- [23] Nolen, J. A., Reed, C. B., Hassanein, A., and Gomes, I. C., (2002) "Liquid-Lithium Cooling for 100-kW ISOL and Fragmentation Targets," *Nucl. Phys. A*, vol. **701**, pp. 312c-322c.
- [24] Ohse, R. W., (1985) *Handbook of Thermodynamic and Transport Properties of Alkali Metals*, Blackwell Scientific, Oxford.
- [25] Priede, J., Cramer, A., Bojarevics, A., Gelfgat, A. Yu., Bar-Yoseph, P. Z., Yarin, A. L., and Gerbeth, G., (1999) "Experimental and Numerical Study of Anomalous Thermocapillary Convection in Liquid Gallium," *Phys. Fluid*, vol. **11** (11), pp. 3331-3339.
- [26] Hardy, S. C., (1985) "The Surface-Tension of Liquid Gallium," *J. Cryst. Growth*, vol. **71** (3), pp. 602-606.
- [27] *CRC handbook of chemistry and physics 82nd edition*, Editor Lide, D. R., 2001, Boca Raton, FL
- [28] Sadik, K., Shah, R. K., and Aung, W., (1987) *Handbook of Single-Phase Convective Heat Transfer*, John Wiley & Sons.