Development of a Liquid Lithium Charge Stripper for FRIB

F. Marti[a], P. Guetschow[a],

Y. Momozaki[b], J. A. Nolen[a,b], C. B. Reed[b]

[a] MSU, [b] ANL

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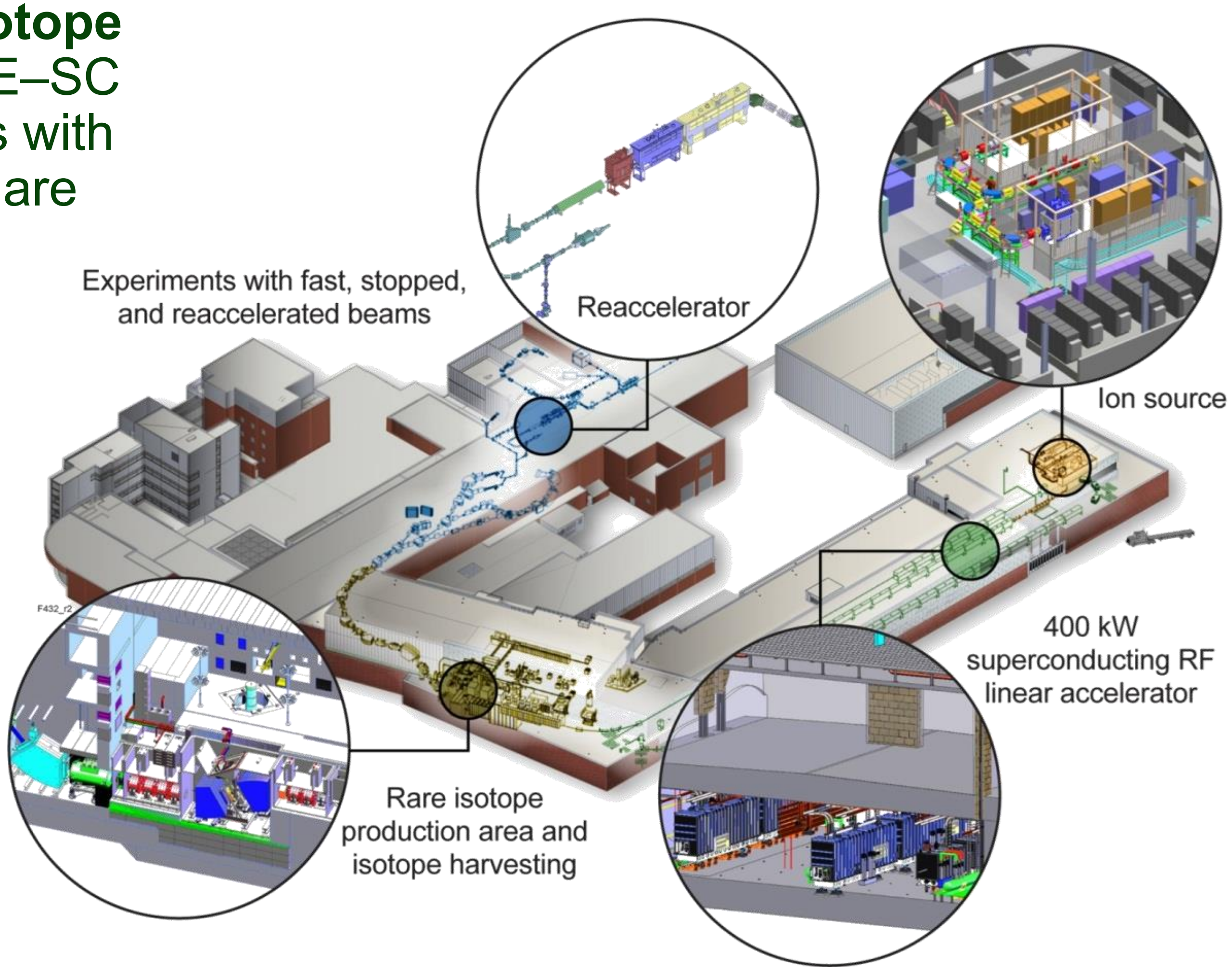
Outline

- What is FRIB?
- Charge stripper options
- Baseline Choice
- Experimental work performed
- Status of the design and fabrication
- Future work

What is FRIB?

- The **Facility for Rare Isotope Beams** is funded by DOE–SC Office of Nuclear Physics with contributions and cost share from Michigan State University
- Key features are 400 kW beam power for all ions and E/A> 200 MeV/u
- Separation of isotopes in-flight provides
  - Fast development time for any isotope
  - All elements and short half-lives
  - Fast, stopped, and reaccelerated beams

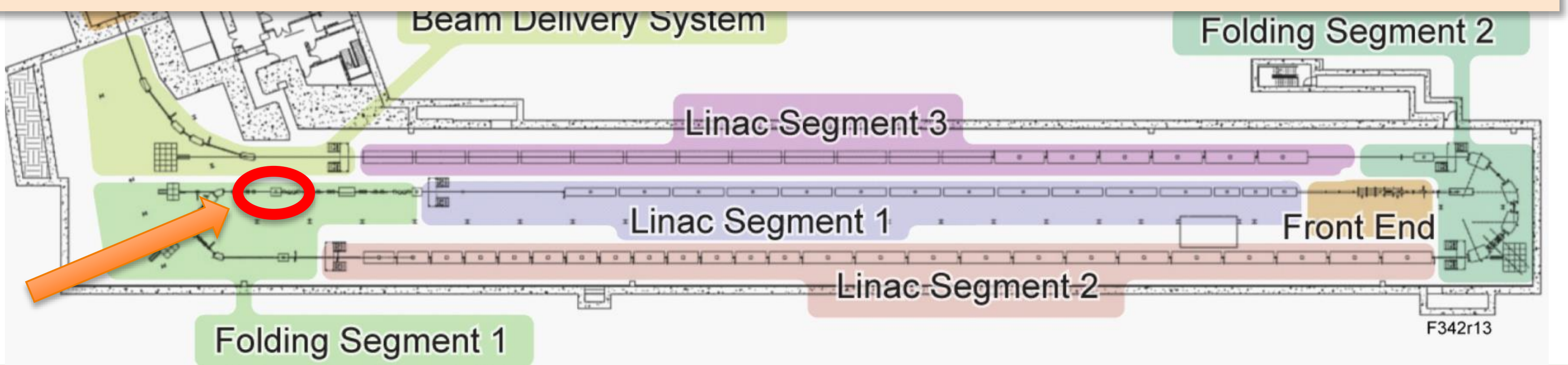


FRIB Driver Linac Layout

A Superconducting Radio Frequency folded linac layout was chosen with two ECR ion sources located above the linac tunnel. A four vane RFQ will accelerate the ions to 0.5 MeV/u.

The stripper is located at the end of Linac Segment 1 (β = 0.041 and 0.085 cavities). where ions have energies between 16 and 20 MeV/u. The bend will select multiple charge states of the stripped beam (up to five charge states for uranium ions) for simultaneous acceleration in the rest of the linac.

After acceleration in Linac Segment 2 (β = 0.29 and 0.53) to energies of ~ 150 MeV/u the beam turns a 180 degree bend and into Linac Segment 3 (β = 0.53).

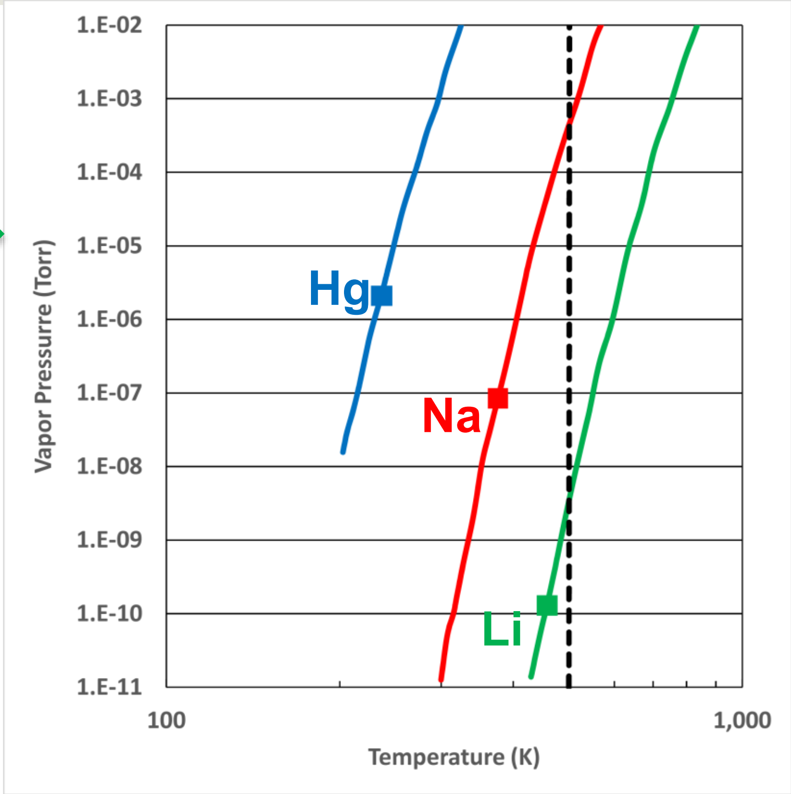


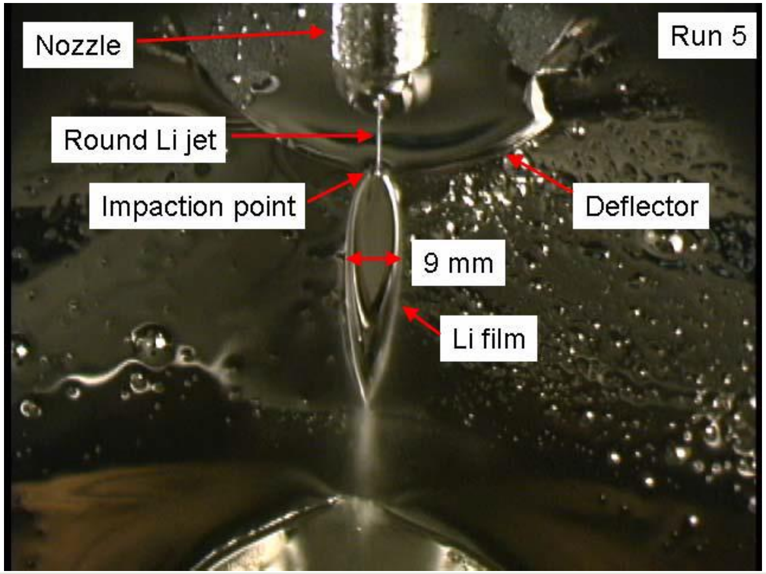
Options Considered

- Solid carbon foils can be used only with low Z ions at low intensities
- We need to utilize a stripping media that doesn't suffer radiation damage to the material lattice and can remove the heat quickly
- Two options are available, liquids and gases
- For liquids, lithium is the best option.
  - It has a relatively low melting point (181 C), low vapor pressure at that temperature (10^{-7} Pa), high boiling point (1342 C), high heat capacity and low viscosity.
  - The negative aspect is that it is pyrophoric, safety concerns
- For gases, helium is the best candidate.
  - The average charge state after stripping is higher than for heavier mass gases (like N_2 or Ar)
  - It is difficult to pump and expensive to replenish, we need to recover and recirculate. Developed at RIKEN (H. Okuno, H. Imao and colleagues)
  - MSU and BNL developed a plasma window based system

Liquid Option: Lithium

- Originally proposed in 2003 by J. Nolen[a] (ANL) for the RIA driver linac
- Compared with other liquid metals it has a very low vapor pressure at the melting point
- A series of experiments were performed at ANL under the DOE RIA R&D program [b].
  - Verified feasibility of the production of a thin lithium film

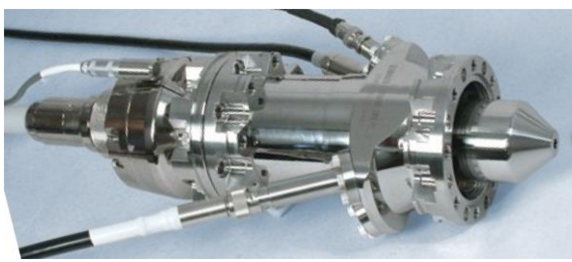


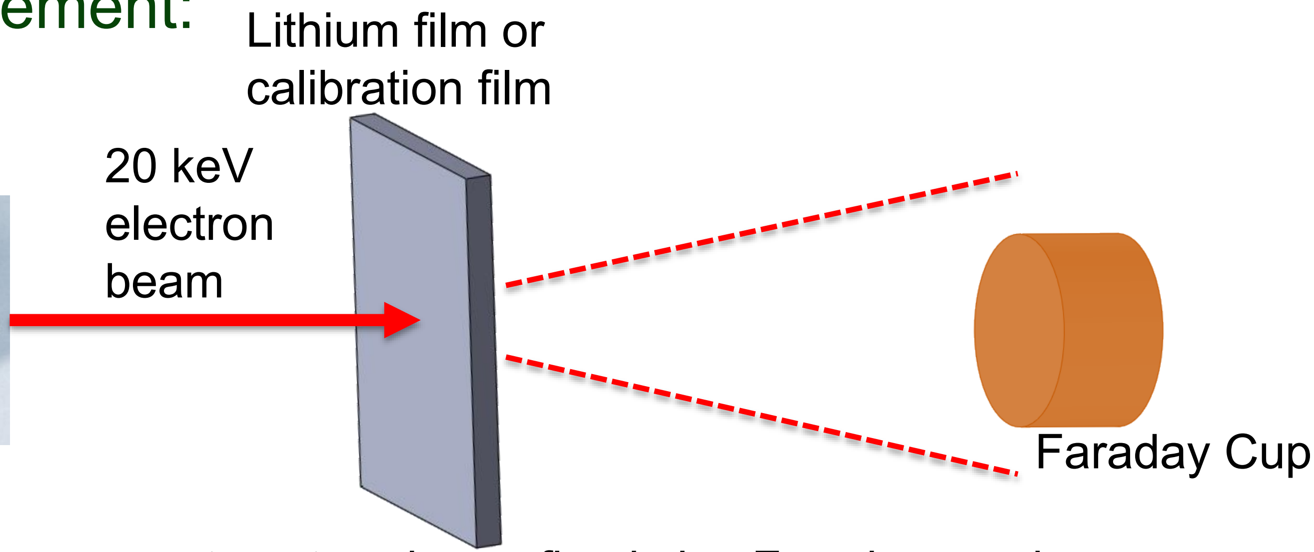


a) 2003 Thin-film liquid-lithium stripper for the RIA driver linac. DOE RIA R&D proposal.
b) Y. Momozaki et al., JINST 4 (2009) P04005

Liquid Lithium Selected as Baseline for FRIB

- A collaboration with ANL was established after MSU was selected to design and build FRIB and more R&D was performed to verify the stability and thickness (~12 μm, +/- 5% for 1 mm diameter spot) of the lithium film [(a)].
- Thickness measurement:



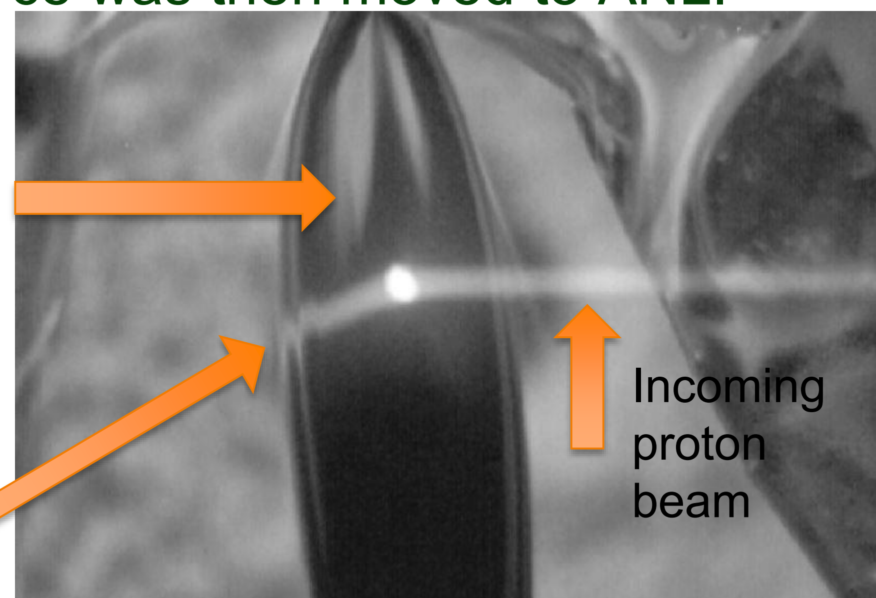


The fraction of the electron current captured on a fixed size Faraday cup is determined by the scattering, function of the film thickness

a) C. B. Reed at al., FRIB Lithium Stripper Thickness and Stability Measurements, ANL/NE-11/01

Can the Thin Film Survive the Power Deposition? YES

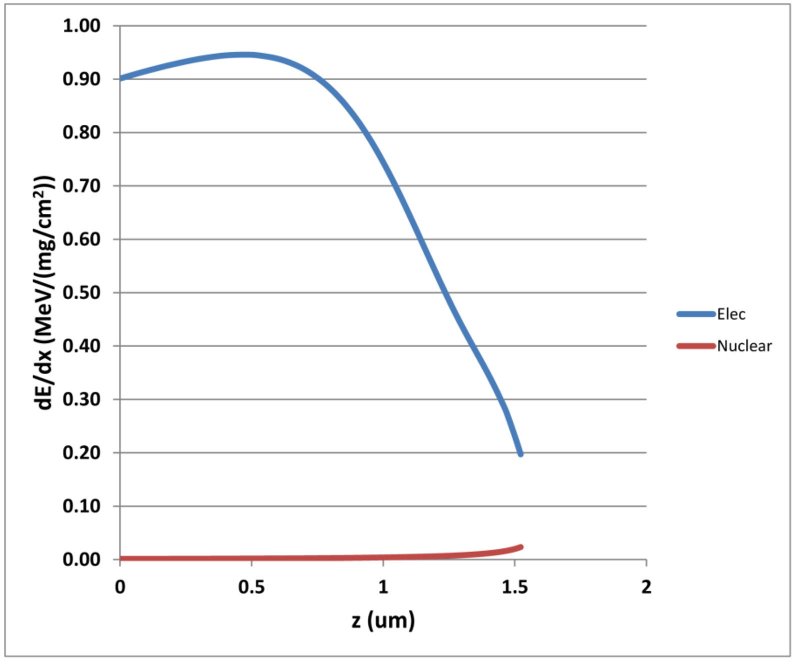
- The major question we needed to answer was related to the possibility that the power deposited on the film by the beam would produce bubbles and destroy the film in the process
- We borrowed the LEDA (LANL) proton source and adapted it at MSU with a new beam line to produce a proton beam of 3 mm diameter and power density comparable to the power deposited by the uranium beam at the FRIB stripper. The source was then moved to ANL.



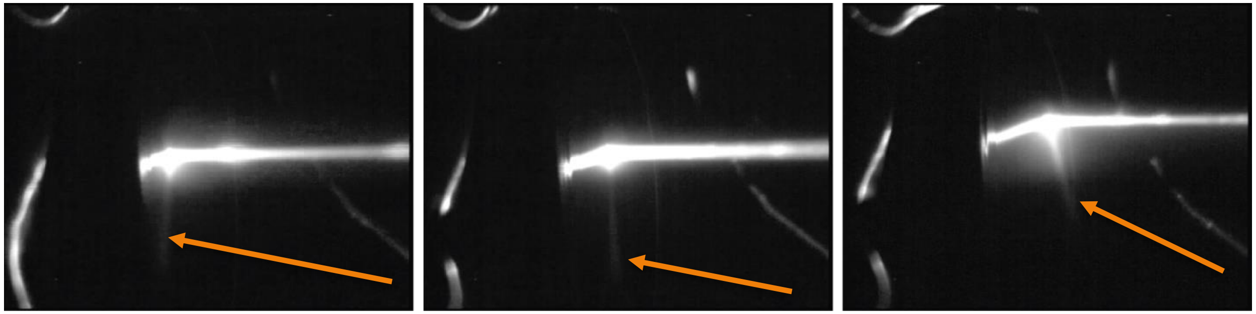
Visualizing the Flow of Heated Lithium

- The proton beam (65 kV, 300 W) stopped completely in the lithium film.

Energy loss of a 65 kV proton beam on lithium calculated with SRIM. The power is deposited on the first 1.5 um.



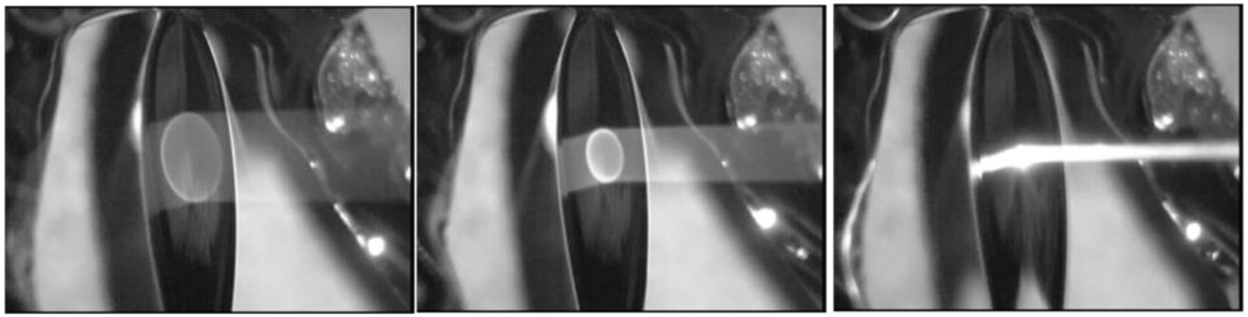
Still frames showing the trail of heated flow lines. By moving the impact point from left to right the flow lines can be visualized.



Achieved Power Densities Comparable to FRIB

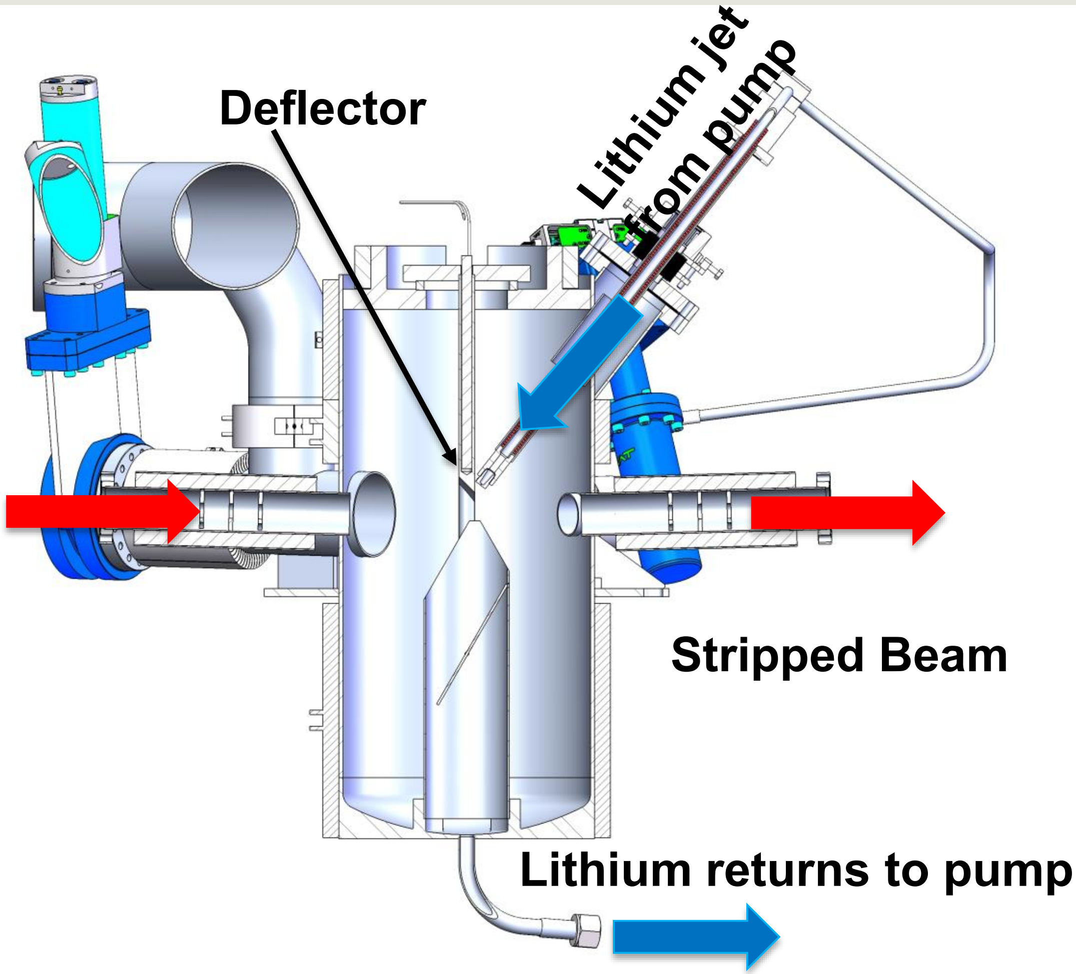
- The highest power density split the film below the impact point, without disturbing the interaction volume.
- 30% of the maximum power deposition expected at FRIB (or 200% of power density if deposition depth is included)

The LEDA proton beam coming from the right stops in the lithium film. Three different focusing settings are shown. The rightmost image shows film splitting

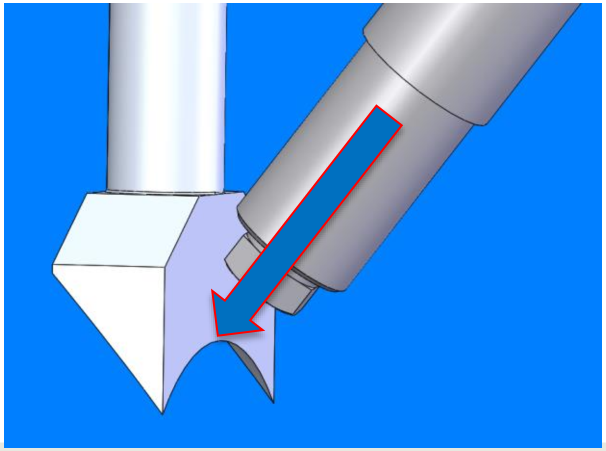


Y. Momozaki et al., J. Radioanal. Nucl. Chem. DOI 10.1007/s10967-015-4074-9

Stripper Film Produced by High Velocity Jet

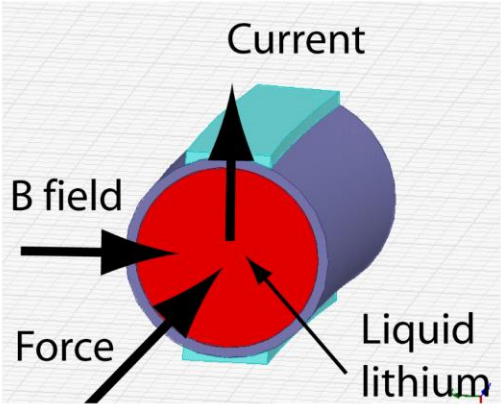


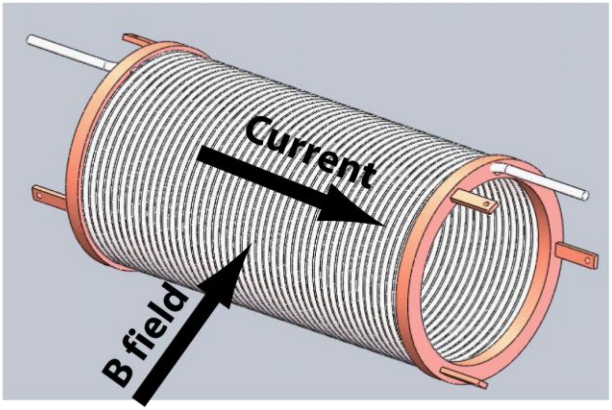
The thin lithium film needs to move very fast (~ 50 m/s) to remove the heat away from the impact point.
This is achieved by producing a high pressure (~15 bars) lithium jet in a 0.5 mm diameter nozzle.
The jet impinges on a flat deflector and produces the thin film.



How do we Pump the Lithium at the Required Pressure?

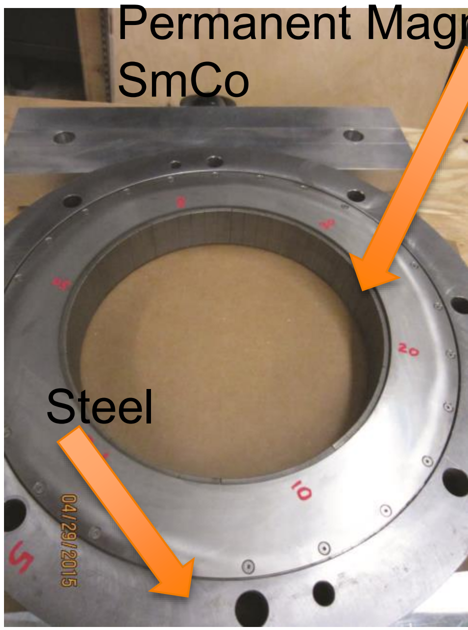
- The experiments performed at ANL used a single pass lithium system, allowing runs of ~20 minutes before recycling
- In other applications the liquid metals are moved by rotary electromagnetic pumps. These pumps do not provide the pressure stability needed by our stripper, the pressure determines the film thickness
- We have developed a DC permanent magnet pump where the lithium circulates in a helical tube with current moving parallel to the coil axis and a magnetic field perpendicular to the axis (pressure required ~ 15 bars). This is a high temperature version of a pump developed for Ga/In by R. Smither at ANL.

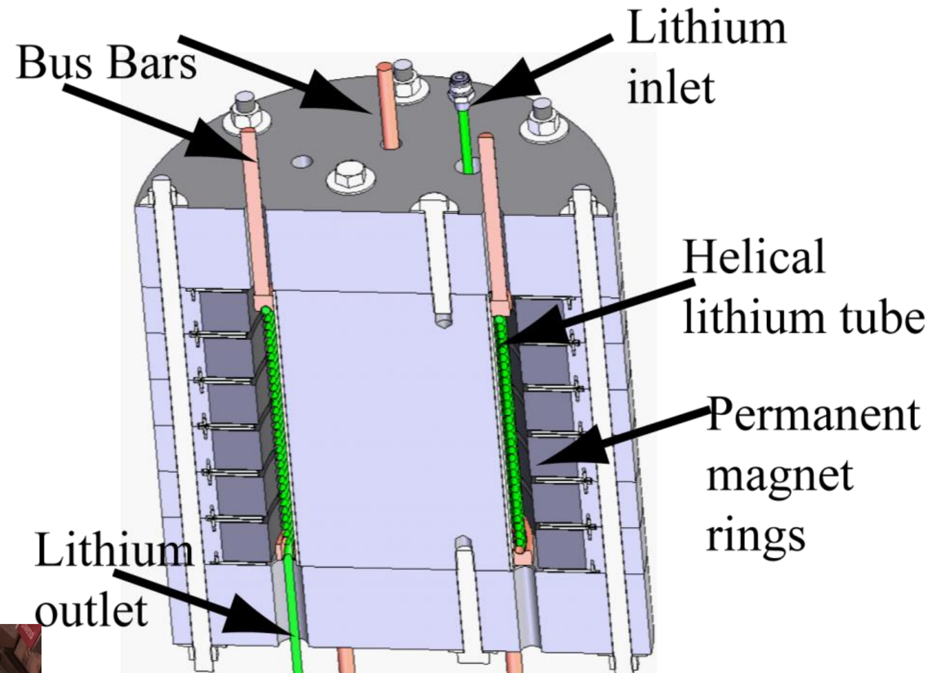




DC Electromagnetic Pump Design

- Four bus bars connect the power supply to a ring brazed to the helical stainless steel tubing
- The pump design is modular, if more pressure is needed, more permanent magnet rings can be added



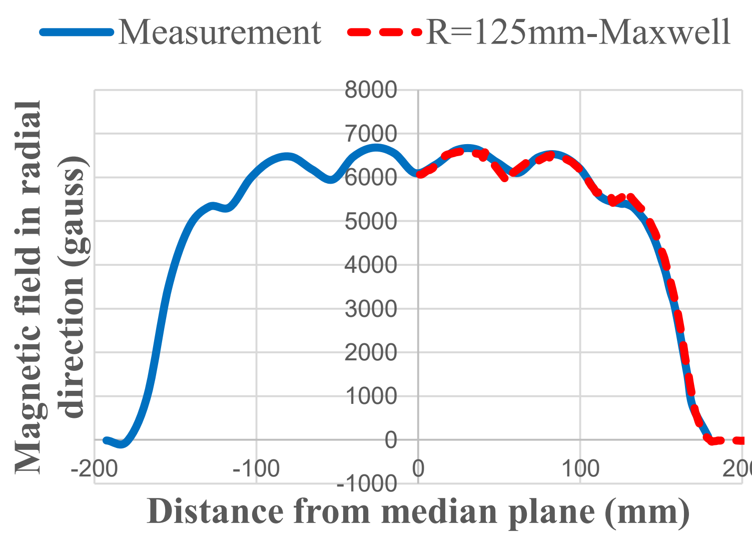


- SmCo was selected because it is resistant to radiation and can operate at high temperature (~ 200 C).

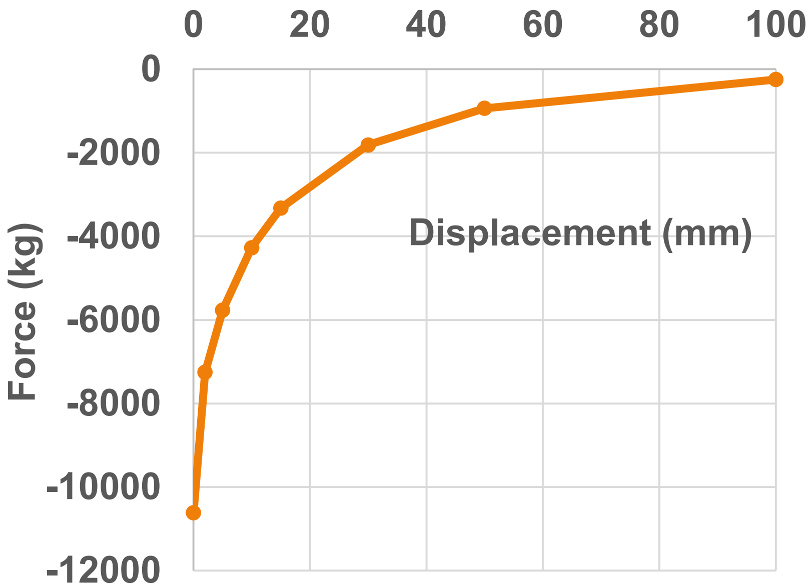
Assembly of the Lithium Pump

- Six rings of permanent magnets are assembled between two steel end caps
- A central steel core completes the magnetic circuit

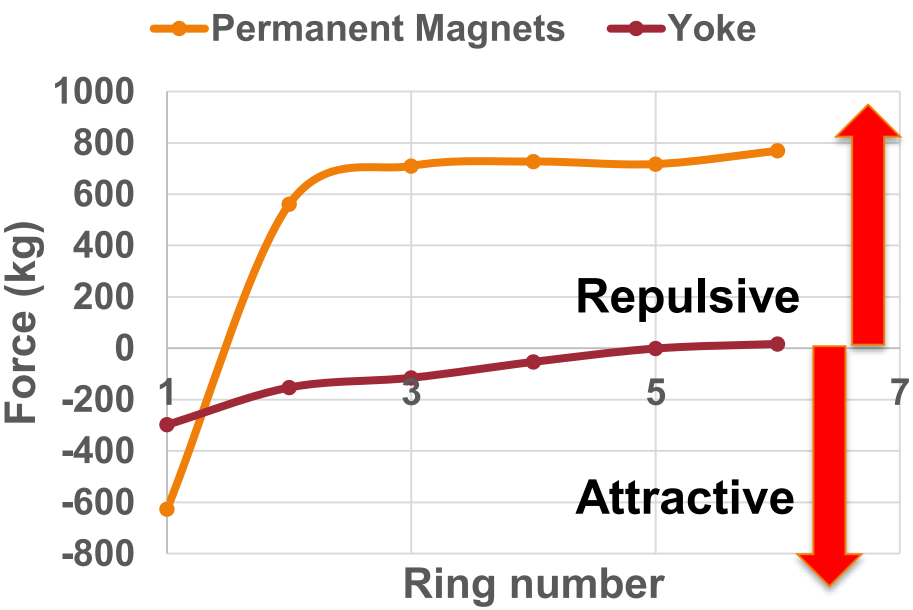
Four hydraulic jacks (two visible in the photo) removed after assembly is completed



Large Forces Present During Pump Assembly

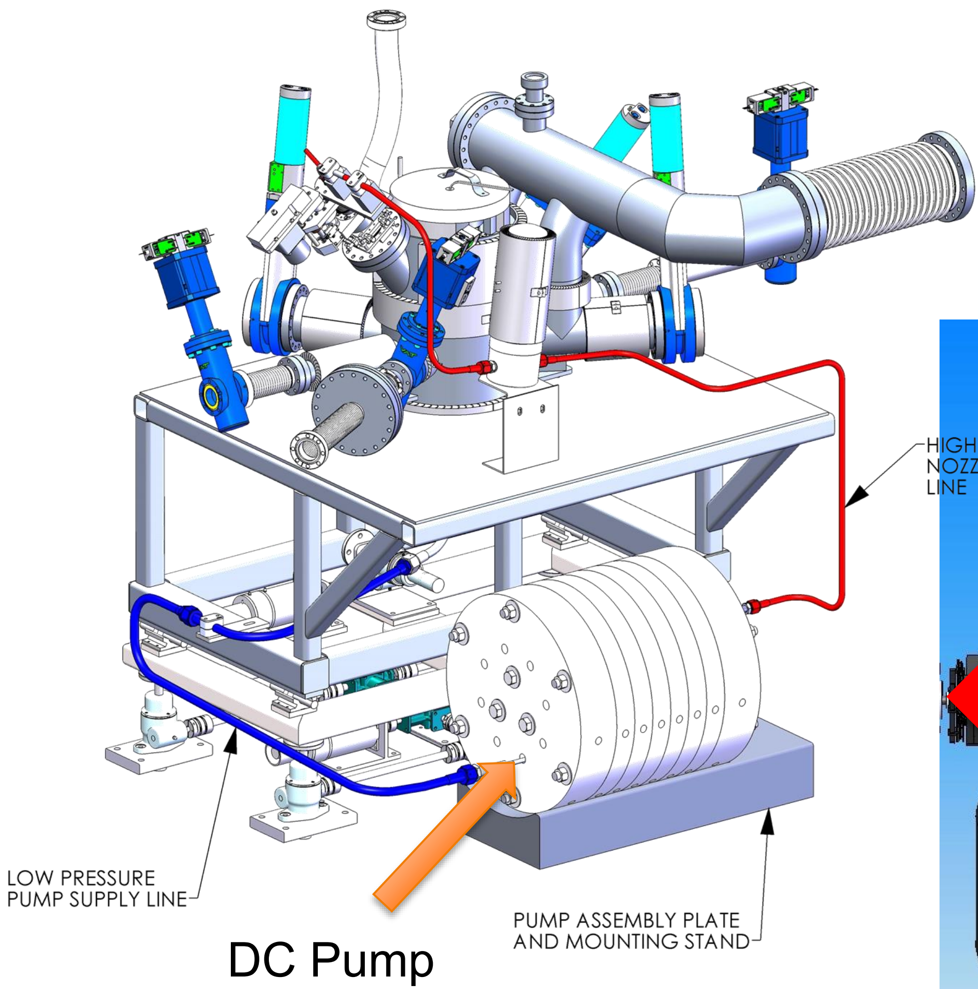


Attractive force on the top cap when approaching the final position as a function of distance

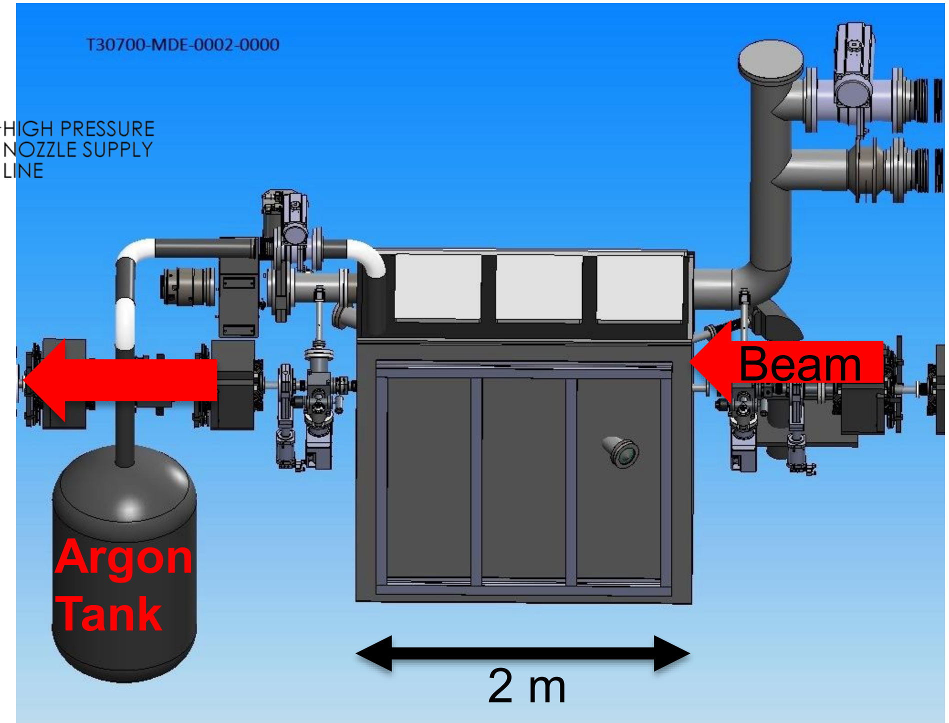


Forces on the rings during assembly when located 2 mm away from final position

Charge Stripper Module Design



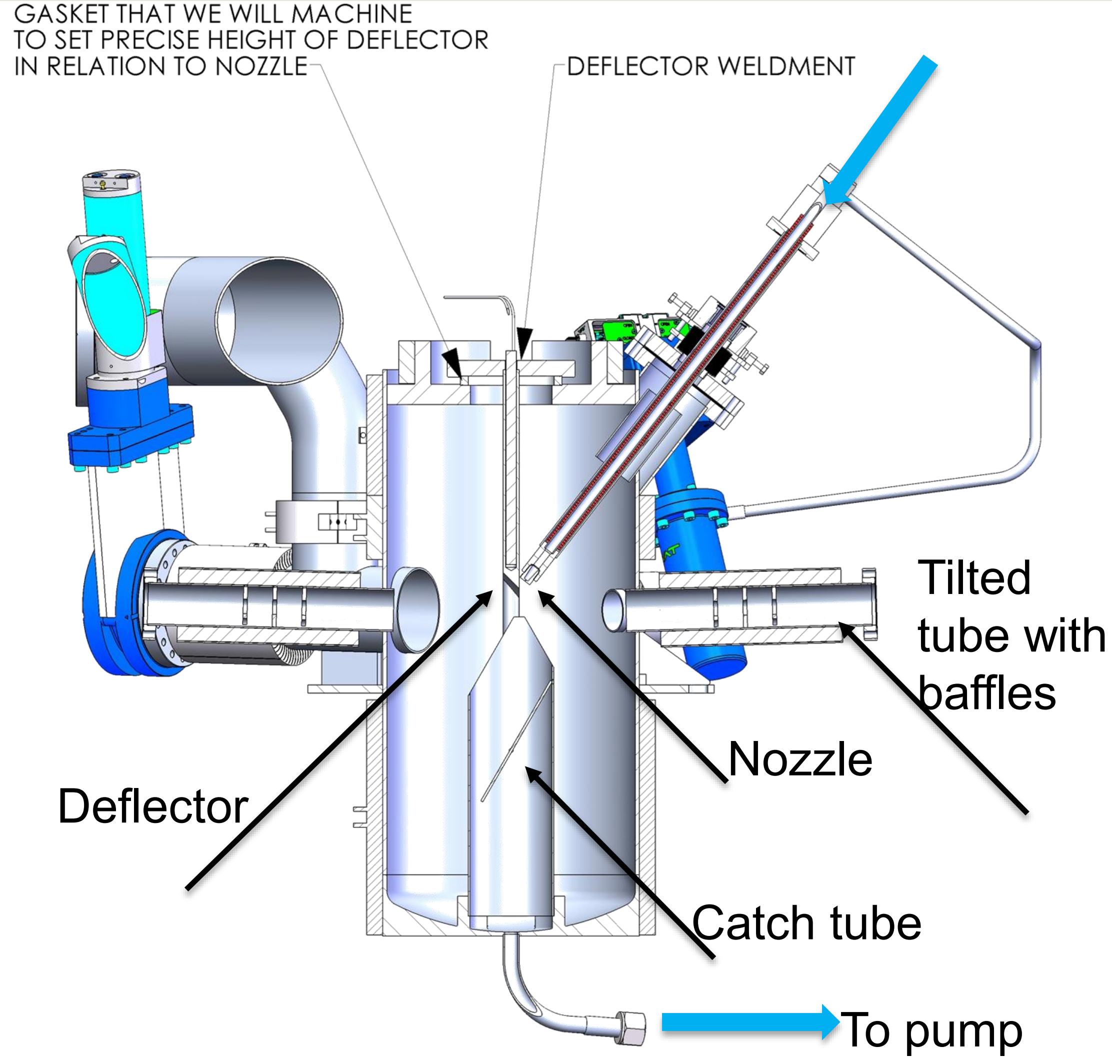
- Safety is a main concern. Primary chamber is contained in a secondary vessel continuously filled with inert argon gas.



Main Vacuum Chamber

Lessons learned from the ANL experiments:

- We have included heaters in both the deflector and nozzle assemblies. The lack of heaters delayed the start of lithium flow in the system
- We have inserted a "catch tube" to capture the liquid lithium and decreased the amount of lithium deposited on the walls of the chamber
- Increased the number of heating zones to better control the wall temperature



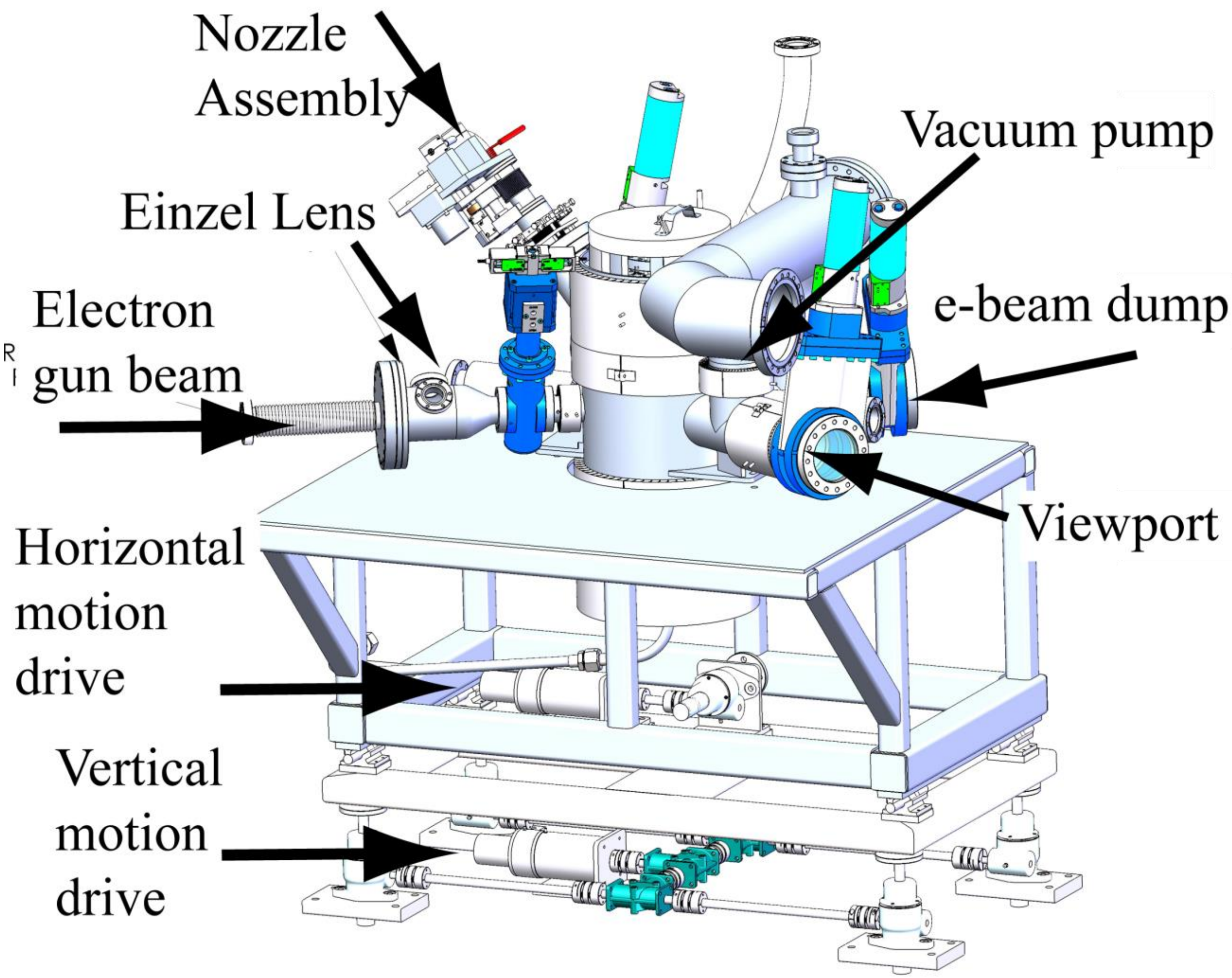
The Film is Positioned with Respect to the Beam

A set of motors move the table with the lithium vacuum chamber up and down, left and right with respect to the beam.

The film is moved with respect to the beam.

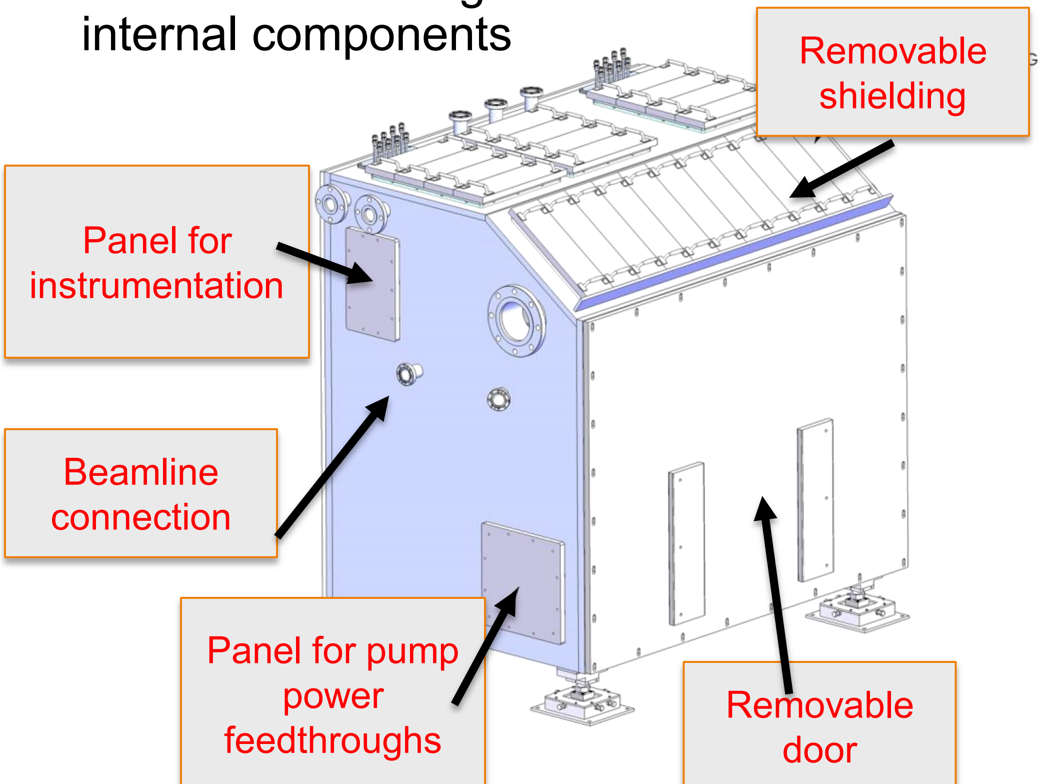
The beam remains on the beamline center while we move the lithium film

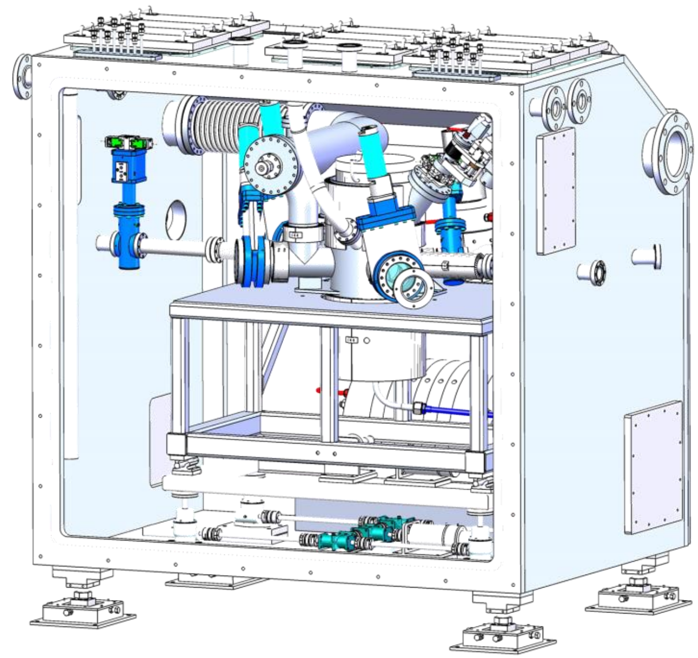
A concern is that wear of the nozzle may change the film formation in a time shorter than the maintenance period and the motion of the table allows for some compensation

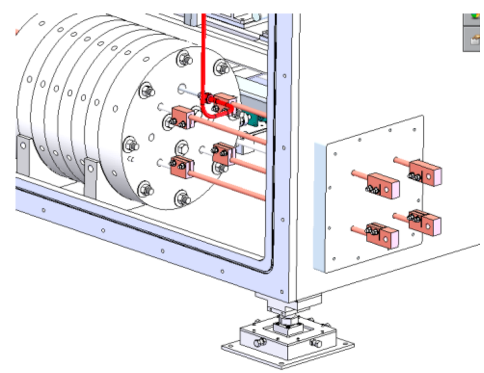


Secondary Containment Vessel

- This vessel provides:
  - An inert atmosphere surrounding the main vacuum chamber, in case of a liquid lithium leak
  - Radiation shielding from the activated internal components







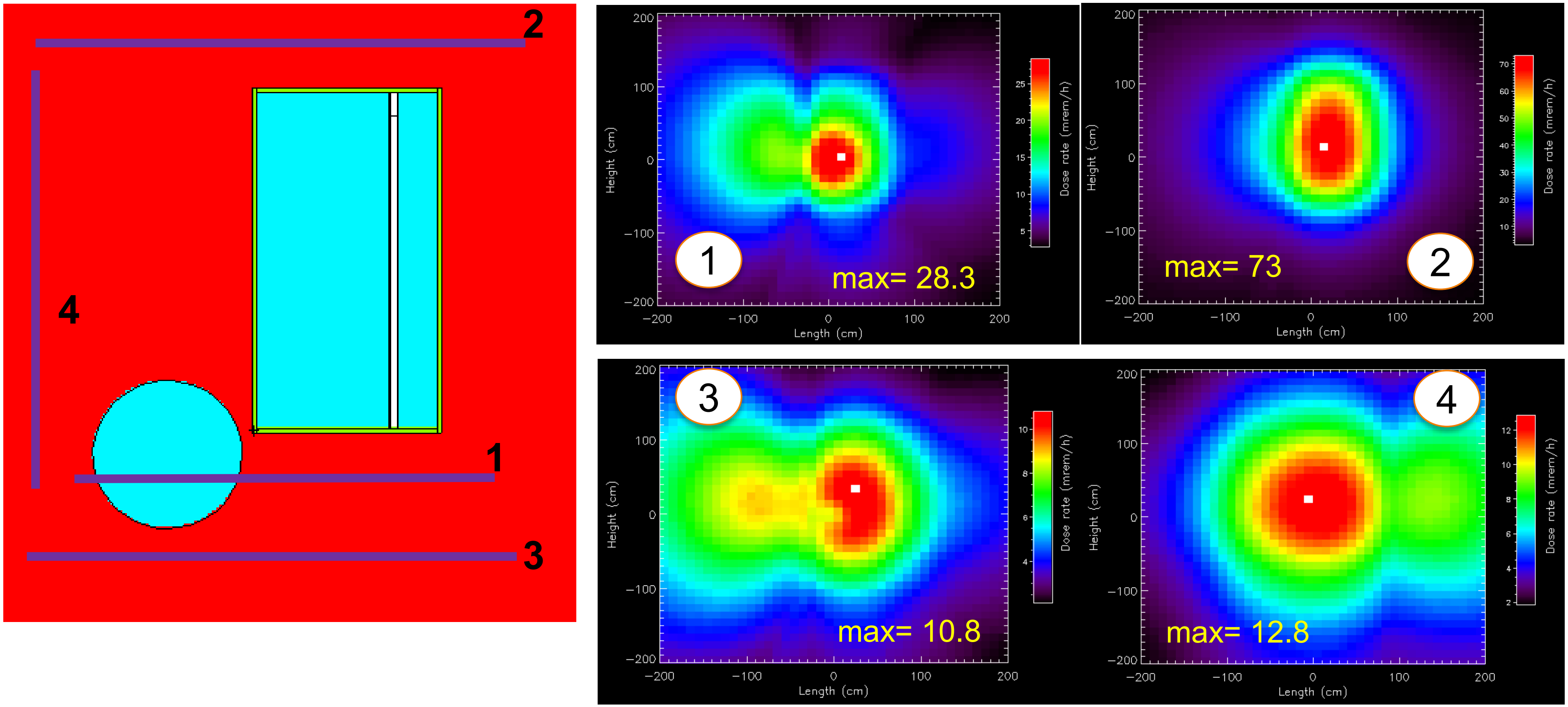
Secondary Containment Vessel at MSU

The secondary containment vessel will be filled with argon as a safety measure against a possible leak from the lithium loop. The removable panels will contain the feedthroughs for the heaters, temperature sensors and power.

Hazards Associated with the Lithium Stripper

- Activation of the lithium, and the argon gas in the secondary containment vessel as well as in the argon storage tank
- Compatibility of lithium with standard materials is a serious concern. For example no aluminum can be used, nor copper vacuum gaskets
- Liquid lithium catches fire when in contact with water, oxygen or nitrogen
- If a loss of vacuum is detected on the main lithium chamber:
  - We shut off the valves that connect the stripper to the rest of the beamline
  - The lithium pump is turned off
  - We initiate a sequenced controlled cooling of the system
- The main chamber is enclosed in the secondary containment vessel that is continuously filled with argon just above atmosphere and in case of a fire it is exhausted through a scrubber

Dose Rate Maps in mrem/hour Near Stripper



Worst case scenario: ^{18}O beam 637 MeV/u, 10 year irradiation (not in baseline)
These simulations were done with 19 mm thick wall, later increased to 25 mm in actual construction. Calculations performed by D. Georgobiani, M. Kostin and R. Ronningen

Stripper Controls are Being Installed

Over 27 different zones are defined and individually heated. Each heater is controlled by two relays in series for safety. If the main operating relay fails closed the backup relay (in series and always closed) opens up.

The PLCs automatically control the heating and cooling process. The heating starts in the zones with open surfaces and continues to the innermost volume. The cooling is done in reverse.

Future Work

- The stripper module is being fabricated and we expect to have most of it ready for commissioning by the end of 2015
- We plan to install it in the tunnel in late 2017
- In the testing period we plan to:
  - Optimize the nozzle design to obtain a “flatter” stripper film
    - » The beamline can accept a +/- 20 % variation of stripper thickness (energy spread)
    - » The measurements at ANL showed that this was achieved
  - Determine long term (days instead of hours) stability of the film
  - Study wear rates of nozzle, deflector, etc.
  - Determine maintenance required to minimize unexpected breakdowns

At Least They are not Shooting at Us!

NRL/MR/6180--94-7490

DTIC ELECTE AUG 1 1 1994 S B D

Use of Copper Powder Extinguishers on Lithium Fires

JOSEPH T. LEONARD

Navy Technology Center for Safety and Survivability
Chemistry Division

R. BURNS
J. BEITEL
R. OUELETTE

Hughes Associates, Inc.
Columbia, MD

R. DARWIN

Naval Sea Systems Command
Washington, DC

July 8, 1994

USE OF COPPER POWDER EXTINGUISHERS ON LITHIUM FIRES

BACKGROUND

The MK 50 Torpedo is a lightweight antisubmarine warfare (ASW) weapon that can be operationally delivered from fixed-wing aircraft, ASW helicopters, and surface combatants. The torpedo is propelled by a Stored Chemical Energy Propulsion System (SCEPS) which utilizes 7.25 kg (16 lb) of lithium metal fuel housed in a stainless steel boiler assembly. Prior to torpedo launch, the lithium metal is in a solid state. However, hazard assessment tests conducted on the MK 50 Torpedo have indicated that direct mechanical damage to the boiler assembly (such as that caused by a bullet or fragment) can possibly breach the structure and cause molten lithium to leak [1]. This situation would occur only if the boiler assembly is penetrated and the boiler start charge is activated, causing the lithium metal to become molten. When lithium is in its molten state, it will react with both the oxygen and nitrogen in the air causing a fire on the exposed surface of the lithium mass.

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- I. Silverman (Soreq, Israel).