



# FRIB

## Heavy Ion Charge Stripping at FRIB

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# Outline

- What is FRIB?
- Charge stripper options
  - Comparison
- Baseline Choice: Liquid lithium
  - Experimental work performed
  - Status of the design and fabrication
- Alternate charge stripper: Helium gas
  - Experimental work performed
- Future work



# What is FRIB?

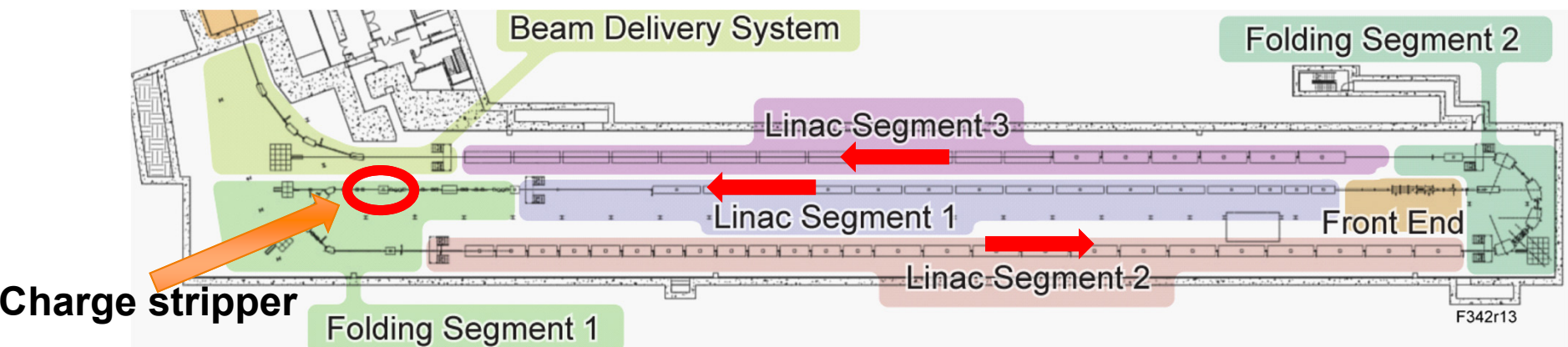
## US-DOE SC and Michigan State University

The **Facility for Rare Isotope Beams** will produce secondary beams by the projectile fragmentation method at the production target. The fragments will be separated in flight providing fast development for all ions. The facility will provide fast (at the energy emerging from the target), stopped and reaccelerated beams.

Key features of the driver linac are **400 kW beam power** for all ions and  **$E/A > 200$  MeV/u**

A Superconducting Radio Frequency folded linac layout was chosen with two ECR ion sources located above the linac tunnel.

The stripper is located at the end of Linac Segment 1 (after the  $\beta = 0.041$  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.

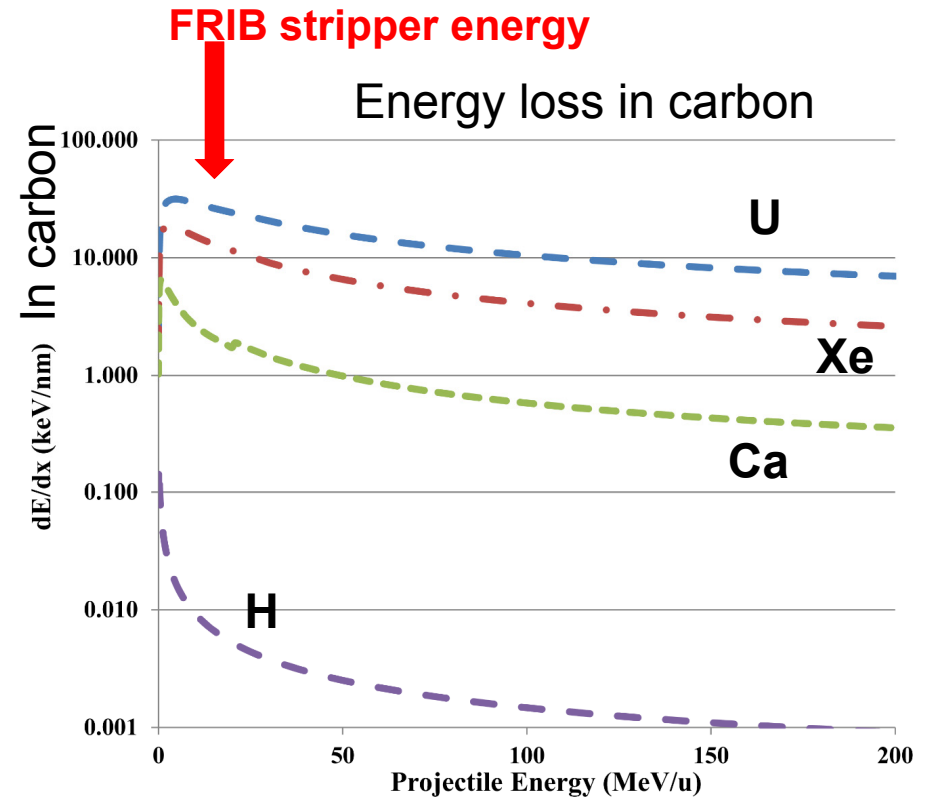


# Why not a carbon foil stripper?

▪ The energy loss of the heavy ions in material is much higher than for protons. It is a challenge to dissipate the power.

- The expected energy deposition in the carbon foil stripper is of the order of  $30 \text{ MW/cm}^3$
- The radiation damage at the FRIB fluence is very high

One of the main differences between heavy ion and proton accelerators is the much higher (~ four orders of magnitude) energy deposition per unit length of the heavy ions compared with the protons

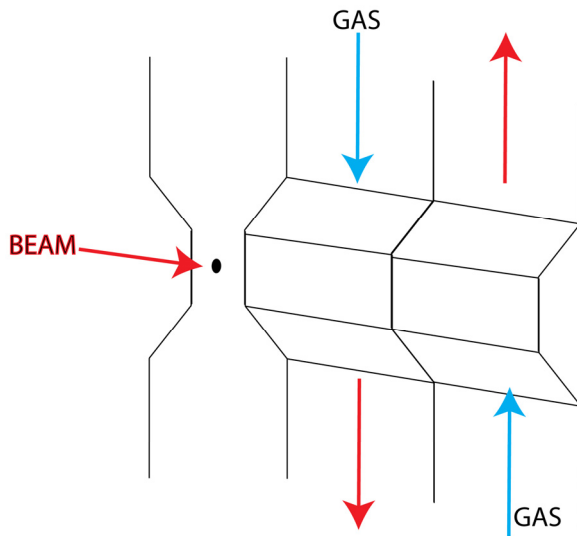


# Options considered

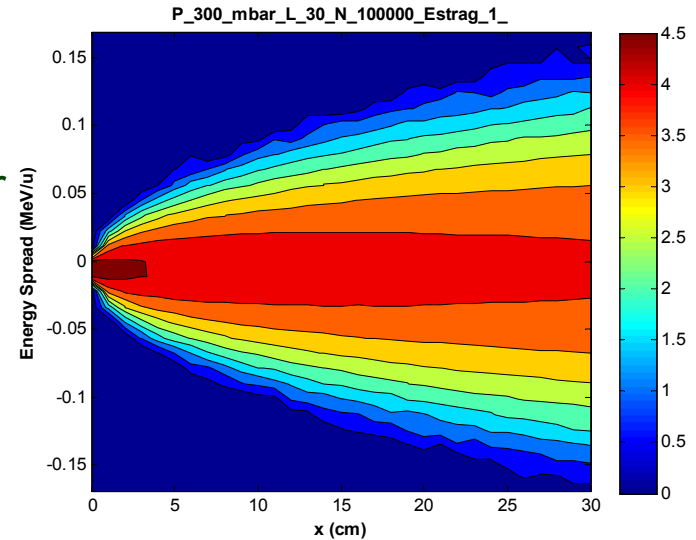
- Solid carbon foils can be used only with low mass ions at low intensities
  - We need to utilize a stripping media that doesn't suffer radiation damage to the material lattice and can remove the heat quickly
- Two options are available, flowing liquids and gases
- For liquids, lithium is the best option.
  - 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 are important
- 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

# Energy spread in helium gas

- A larger energy spread is expected from the helium gas than from the liquid lithium film stripper



- Energy spread increase along a 30 cm gas cell at a pressure of 300 mbar neglecting density variation due to heating
- $10^5$  ions starting at  $^{238}\text{U}^{34+}$  (16.5 MeV/u)
- Color bar shows the logarithm of the density




- The heating of the helium gas will change its density, varying the energy loss and increasing the emerging energy spread
  - To minimize the effect we plan on counter flow sections of the stripper at high transverse velocity.

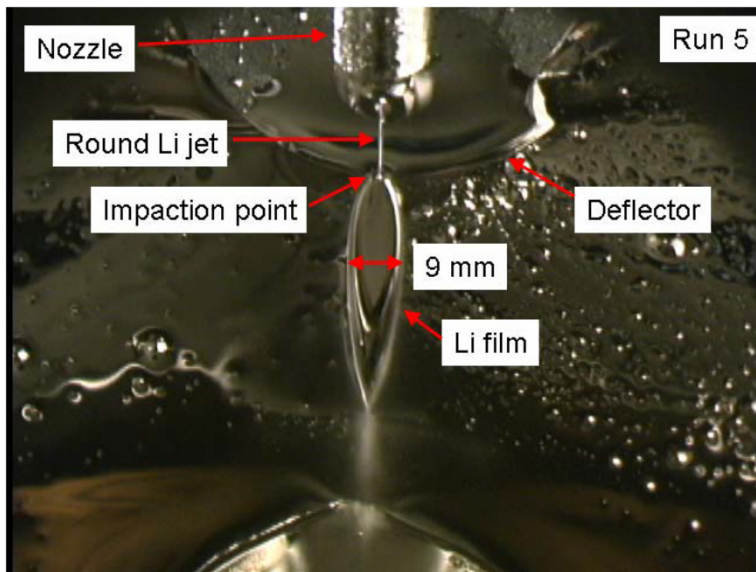
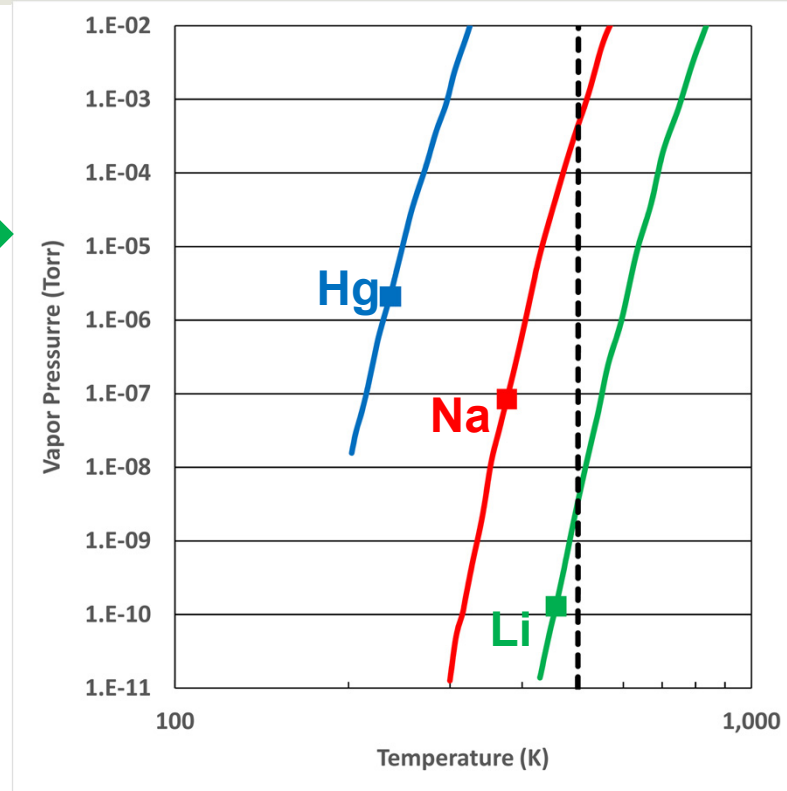
# Comparison of the two options

	Advantages	Disadvantages
Liquid lithium	<ul style="list-style-type: none"><li>• Expected to provide higher charge state</li><li>• Has been tested with high power beam deposition (stopping protons)</li><li>• Smaller energy spread than gas stripper</li></ul>	<ul style="list-style-type: none"><li>• Requires electromagnetic pump that needs to be tested</li><li>• High safety concern because of the fire hazard</li><li>• Requires mitigation of possible contamination of superconducting cavities</li></ul>
Helium gas	<ul style="list-style-type: none"><li>• Less safety concerns than liquid lithium</li><li>• No contamination to superconducting cavities</li></ul>	<ul style="list-style-type: none"><li>• Expected lower charge state than liquid lithium</li><li>• Difficulty in containing helium, needs replenishing</li><li>• Higher energy spread than the lithium charge stripper</li><li>• No beam tests yet, need to develop counterflow</li></ul>



# Liquid option: Lithium

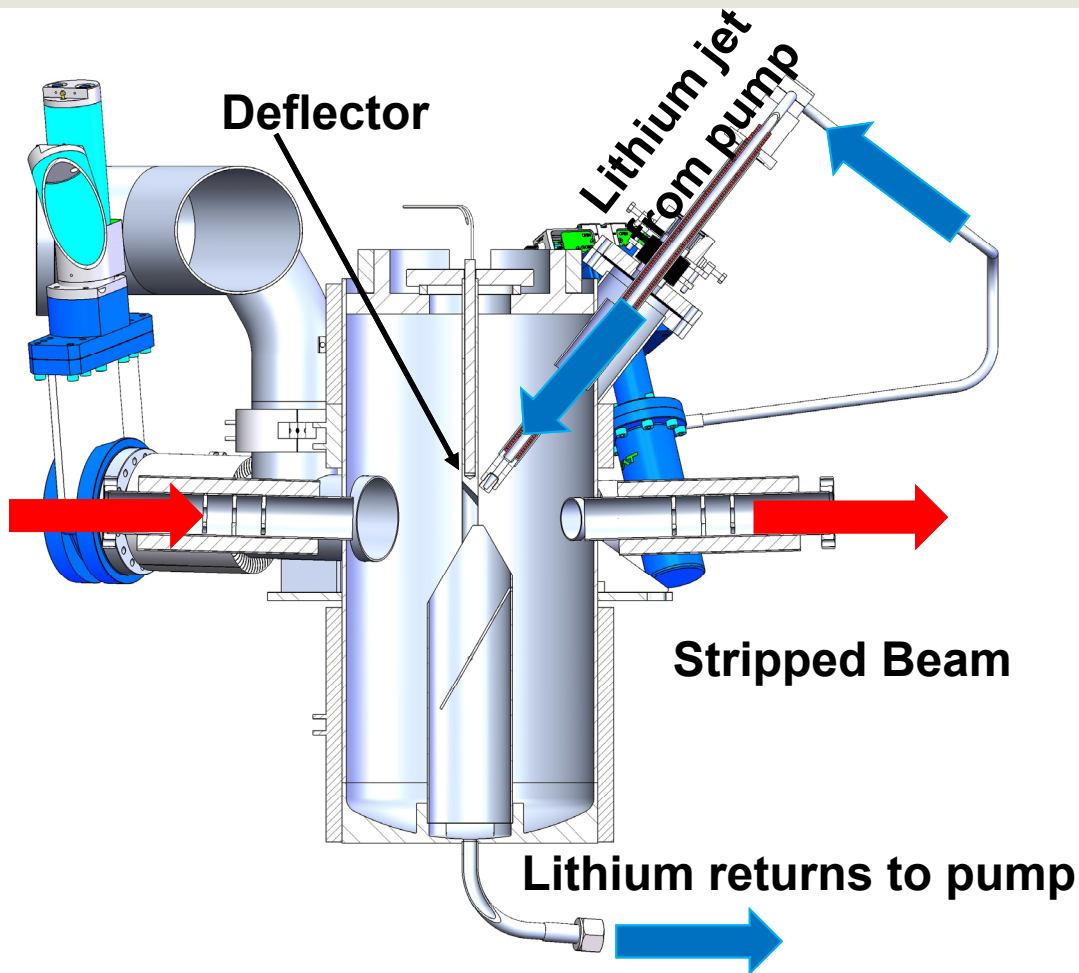
- Originally proposed in 2003 by J. Nolen et al<sup>(a)</sup> (ANL) for the RIA driver linac
- Compared with other liquid metals it has a very low vapor pressure at the melting point 
- A series of experiments were performed at ANL under the DOE RIA R&D program <sup>(b)</sup>.
  - Verified feasibility 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

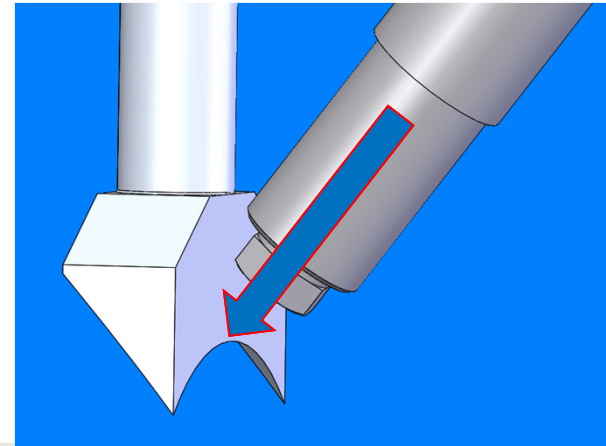


# Stripper film produced by high velocity jet



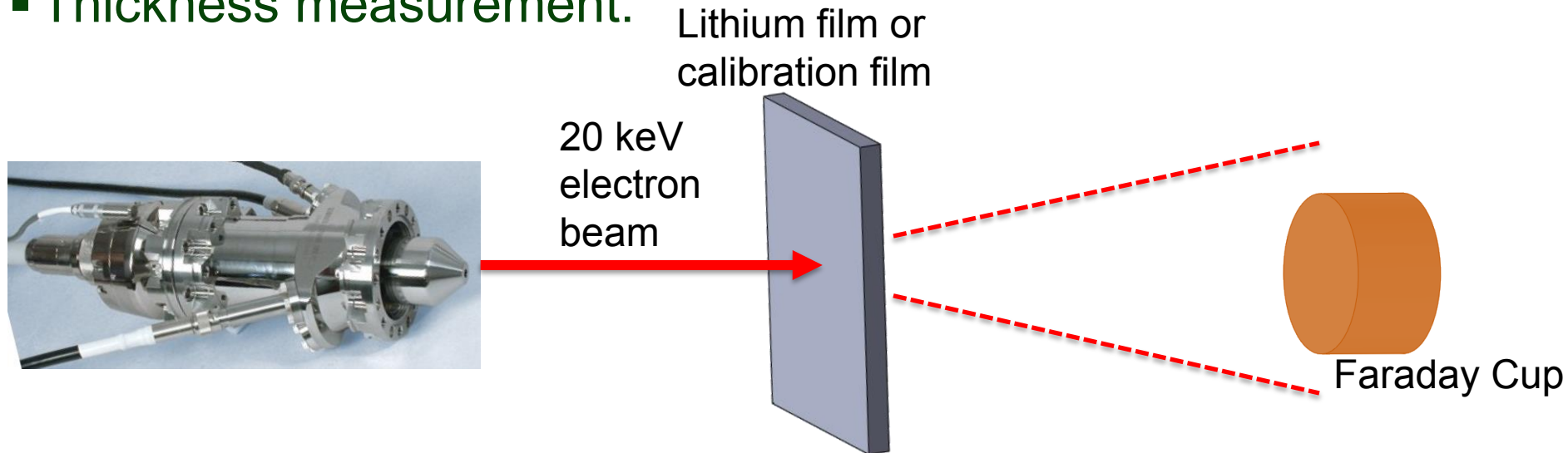
The thin lithium film needs to move very fast ( $\sim 50$  m/s) to move the heat away from the impact point.

This is achieved by producing a high pressure ( $\sim 15$  bars) lithium jet in a 0.5 mm diameter nozzle. The jet impinges on a flat deflector and produces the thin film.



# 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 ( $\sim 12 \mu\text{m}$ ,  $\pm 5\%$  for 1 mm diameter spot) of the lithium film <sup>(a)</sup>.
- 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

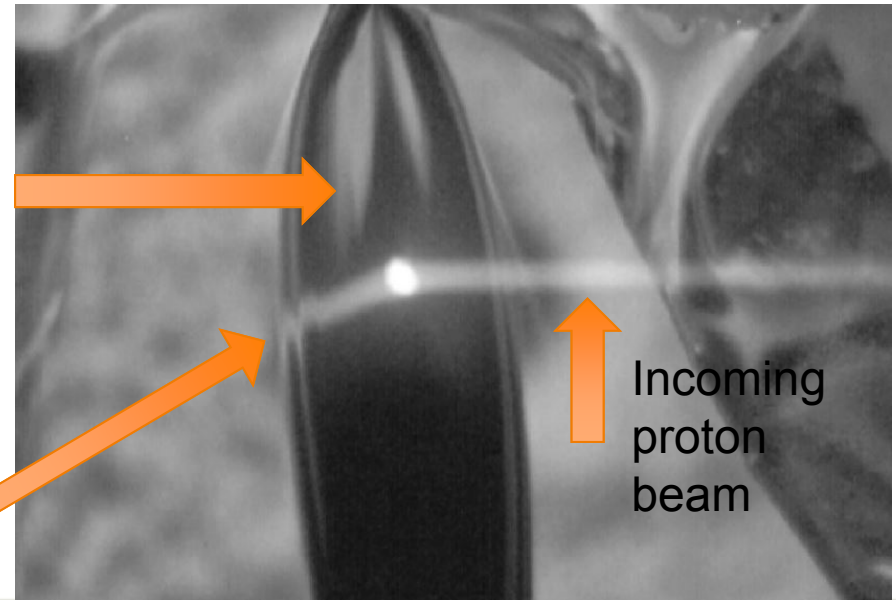
a) C. B. Reed et al., FRIB Lithium Stripper Thickness and Stability Measurements, ANL/NE-11/01

# 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 evaporation and/or boiling 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.

Lithium film,  
metallic reflection  
surface

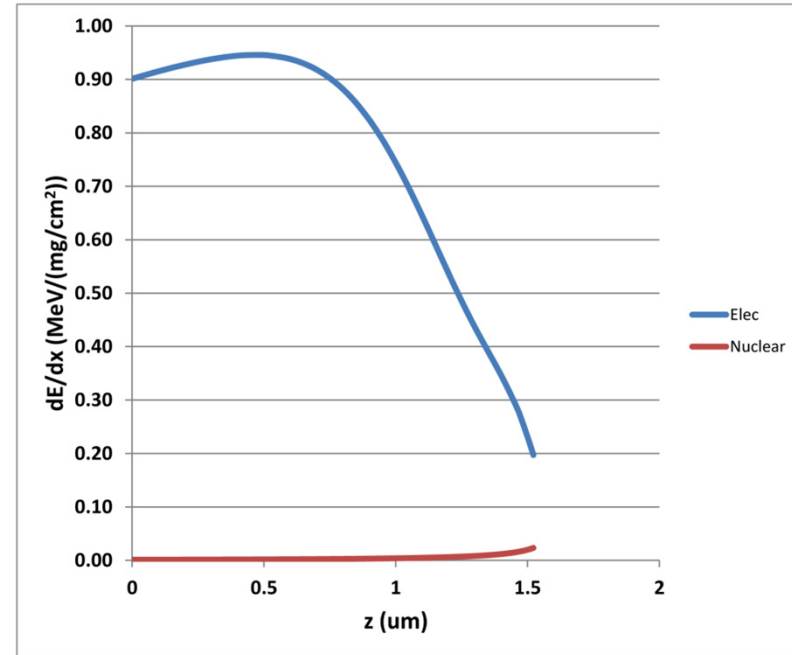
Reflection of the  
incoming beam on  
the lithium surface



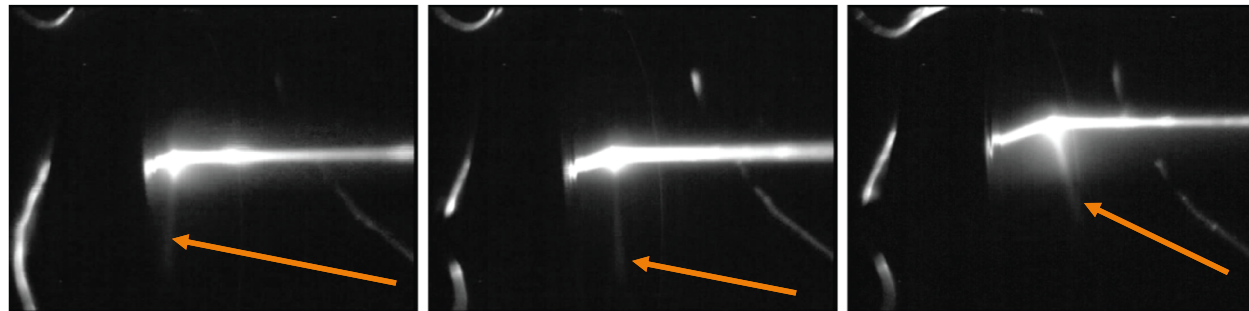
# Visualizing the flow of heated lithium

- 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  $\mu\text{m}$ .



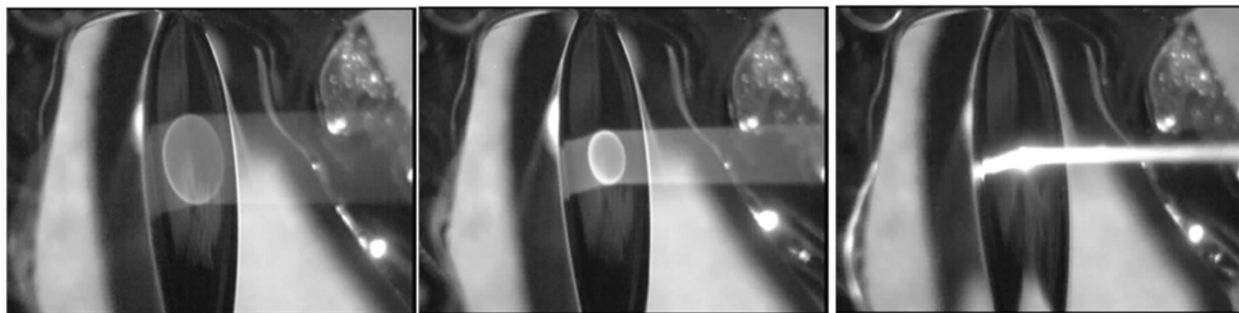
Still frames showing the trail of heated flow lines. By moving the impact point from left to right the flow lines can be visualized.



# 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 but only appeared in some instances

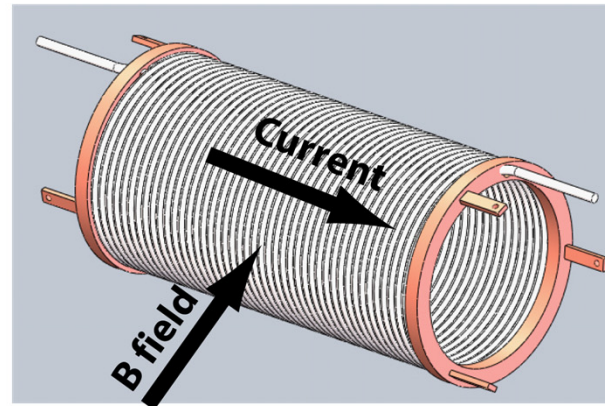
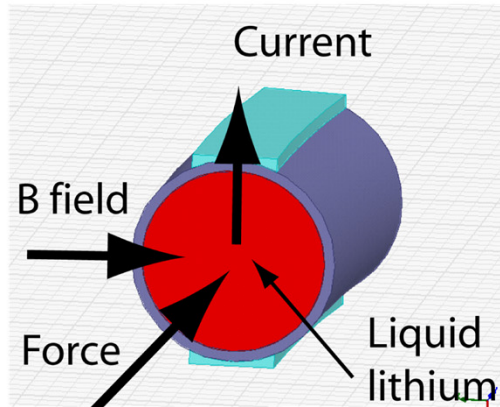


Y. Momozaki et al., J. Radioanal. Nucl. Chem. DOI 10.1007/s10967-015-4074-9



# How do we pump the lithium to the required pressure?

- The experiments performed at ANL used a single pass lithium system, allowing runs of ~20 minutes before recycling. Pressure determines the film thickness and velocity.
- In other applications the liquid metals are moved by rotary electromagnetic pumps. These pumps are mostly used in high volume low pressure applications and 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.

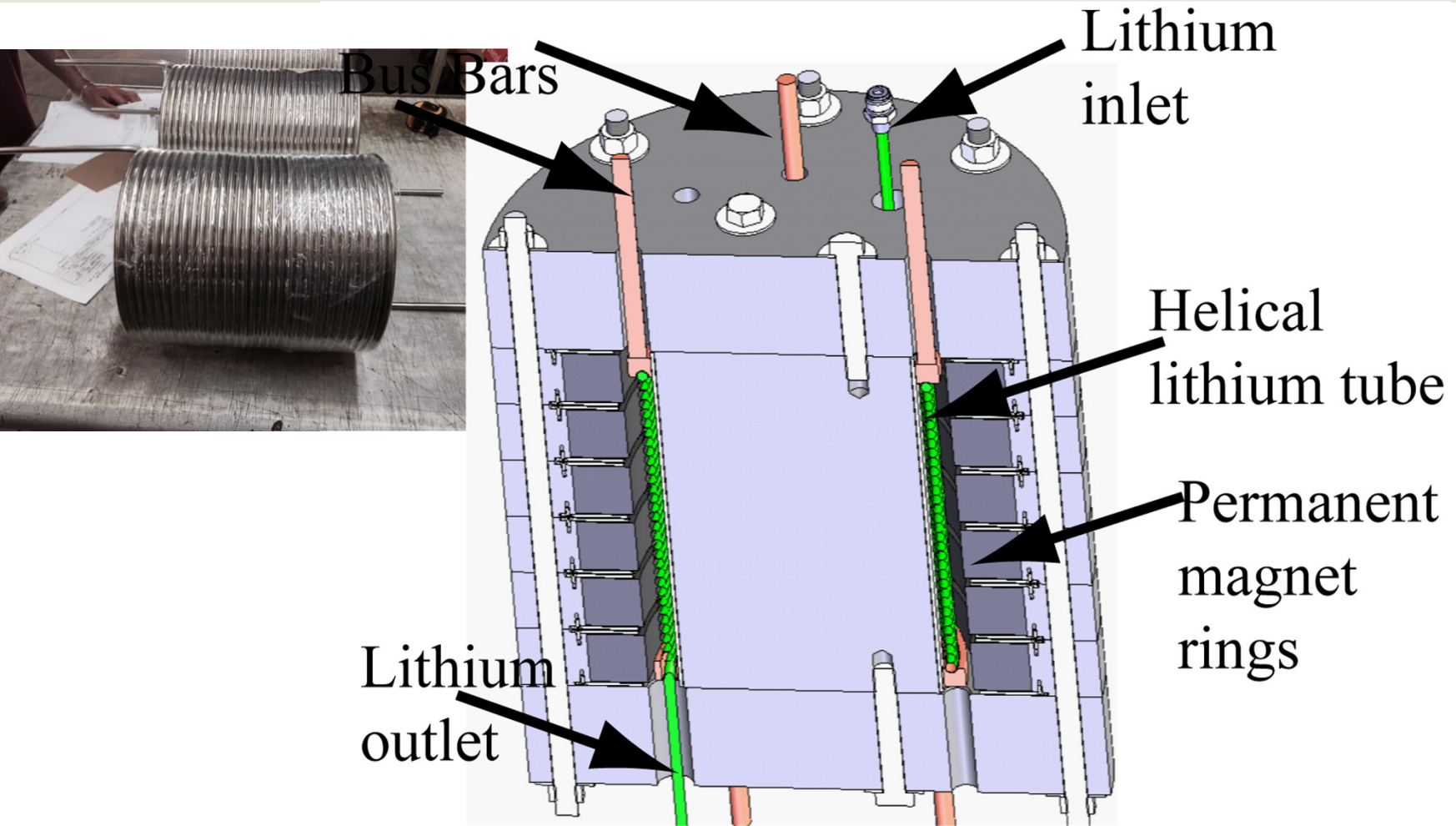


# DC electromagnetic pump design

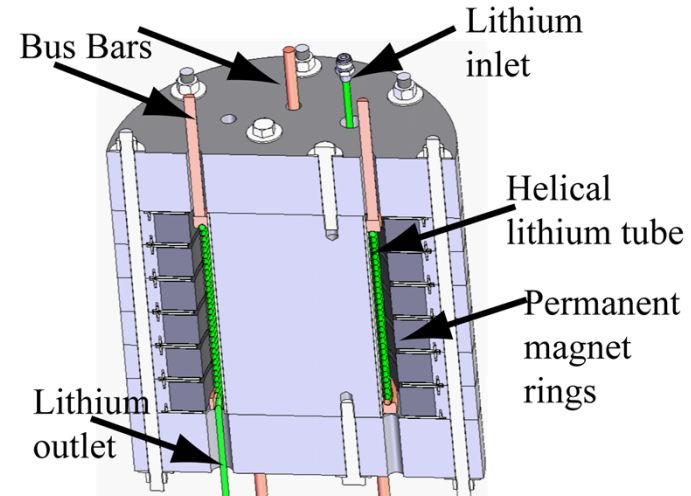




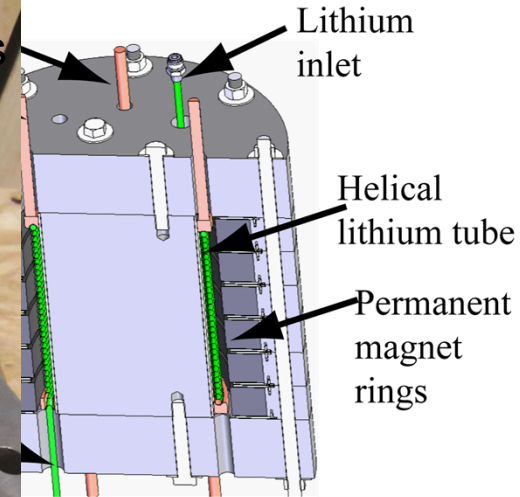
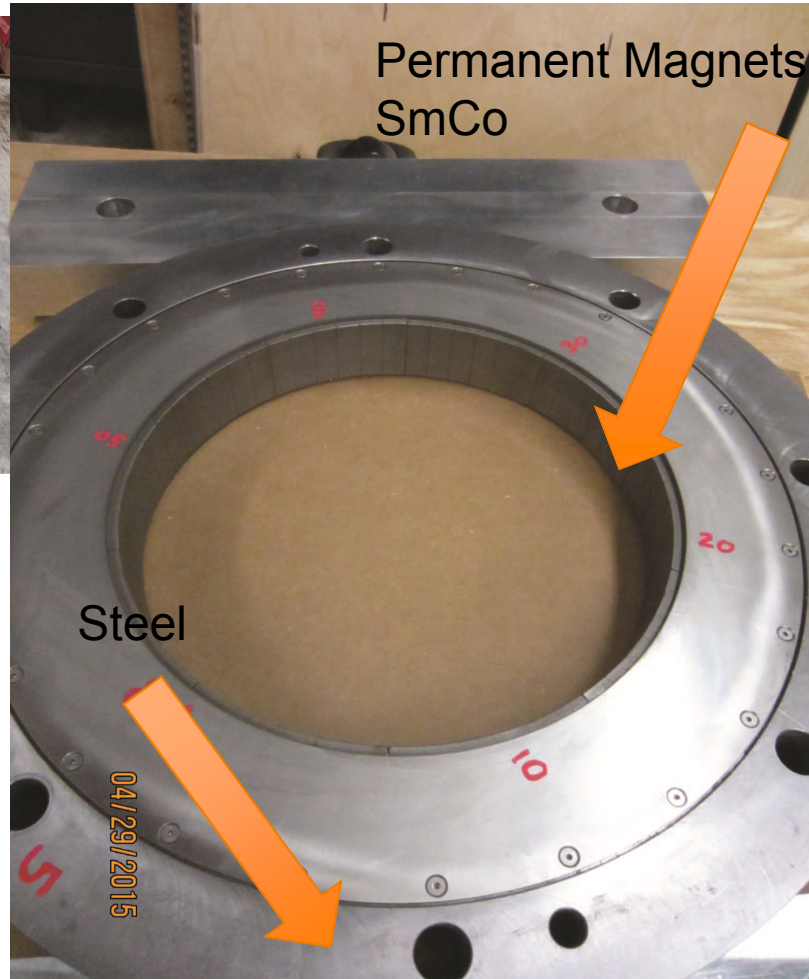
# DC electromagnetic pump design



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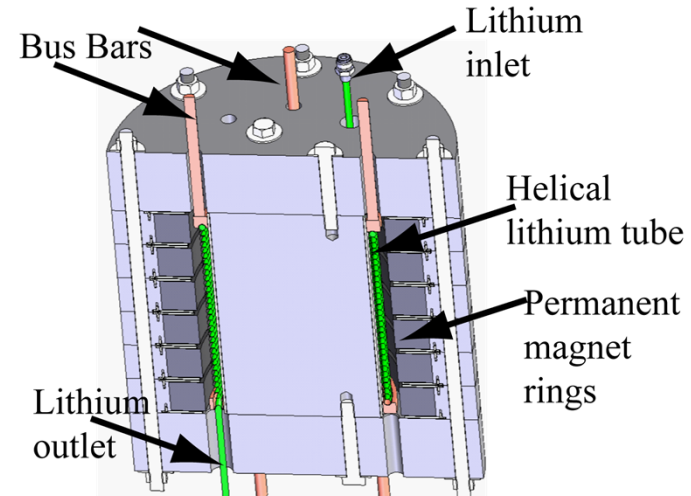
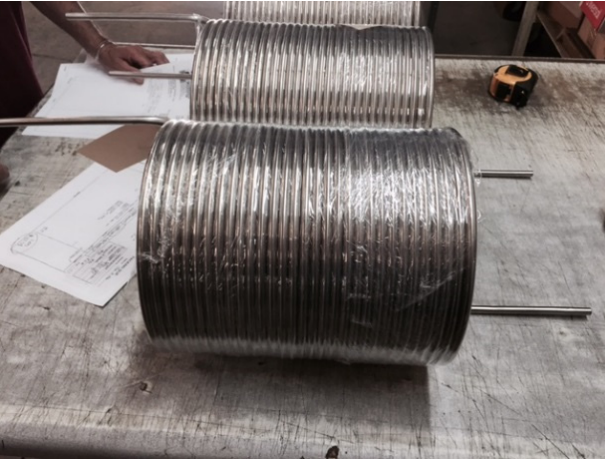


# DC electromagnetic pump design

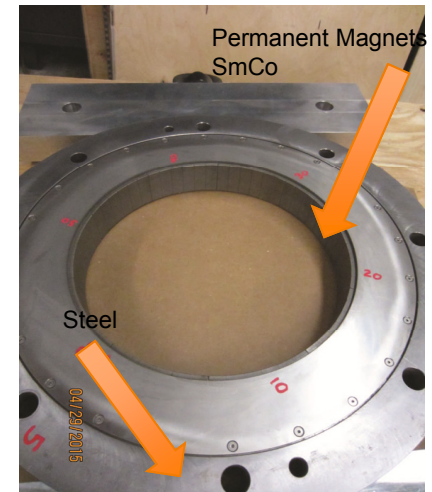




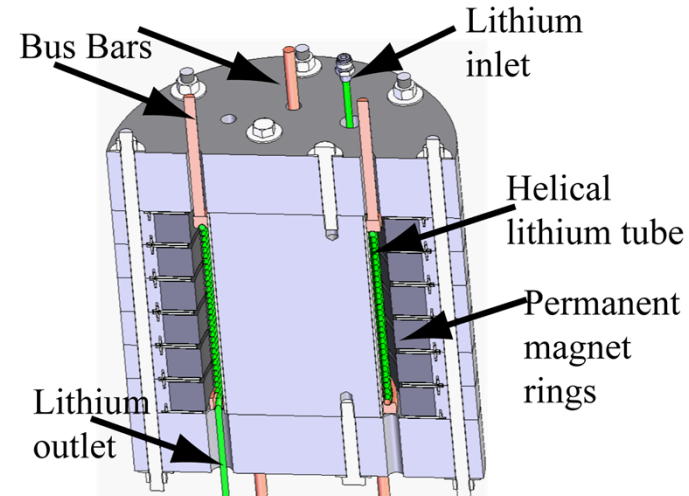
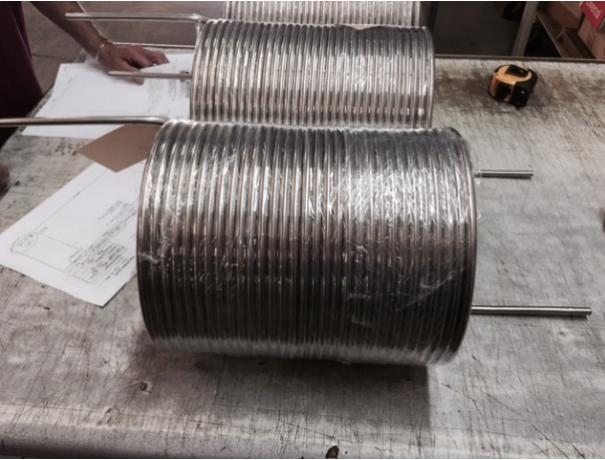
# DC electromagnetic pump design



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

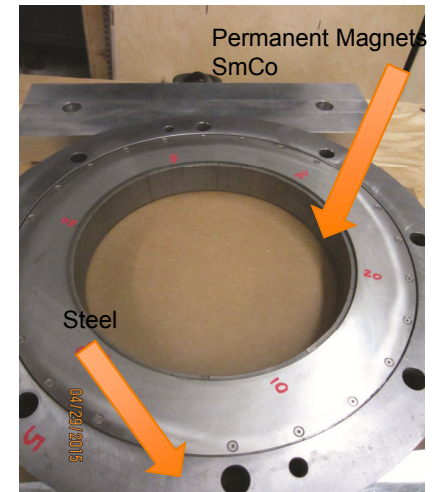


# DC electromagnetic pump design



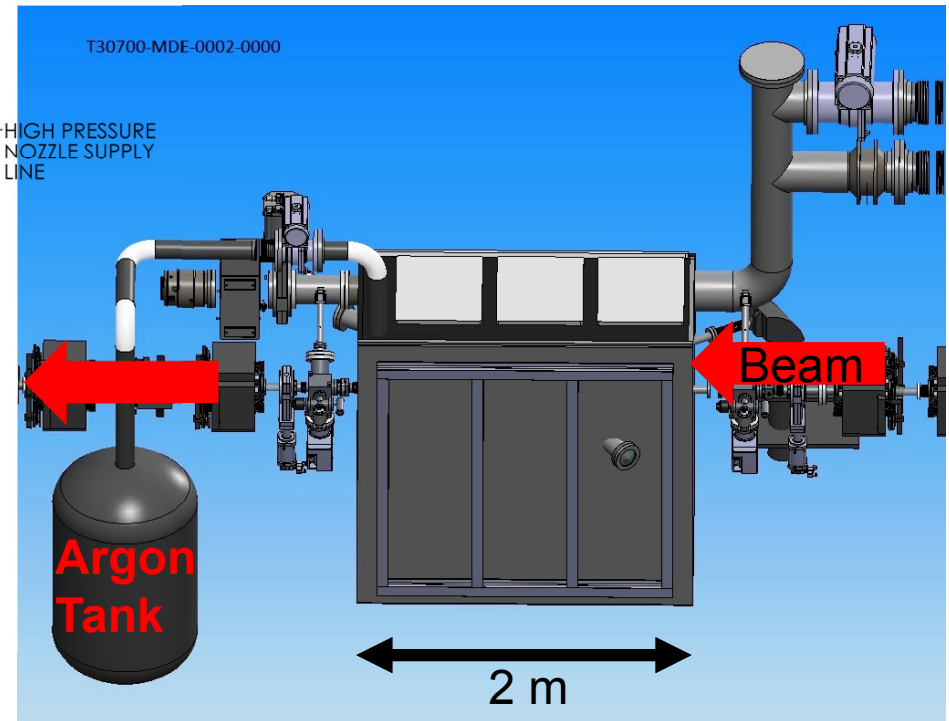
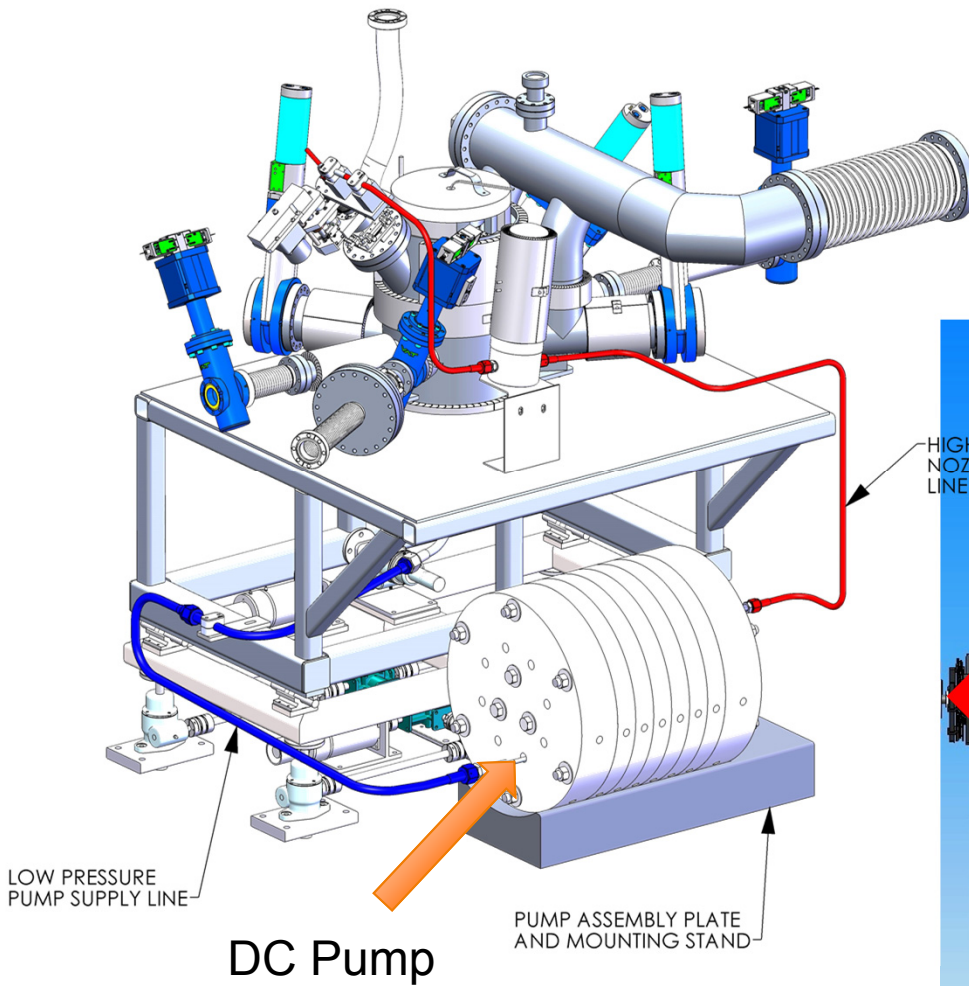
Pump design is modular and if more pressure is desired more rings can be added and the helical coil replaced  
The pump has been built and is being tested at a private company

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



# Charge stripper module design

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





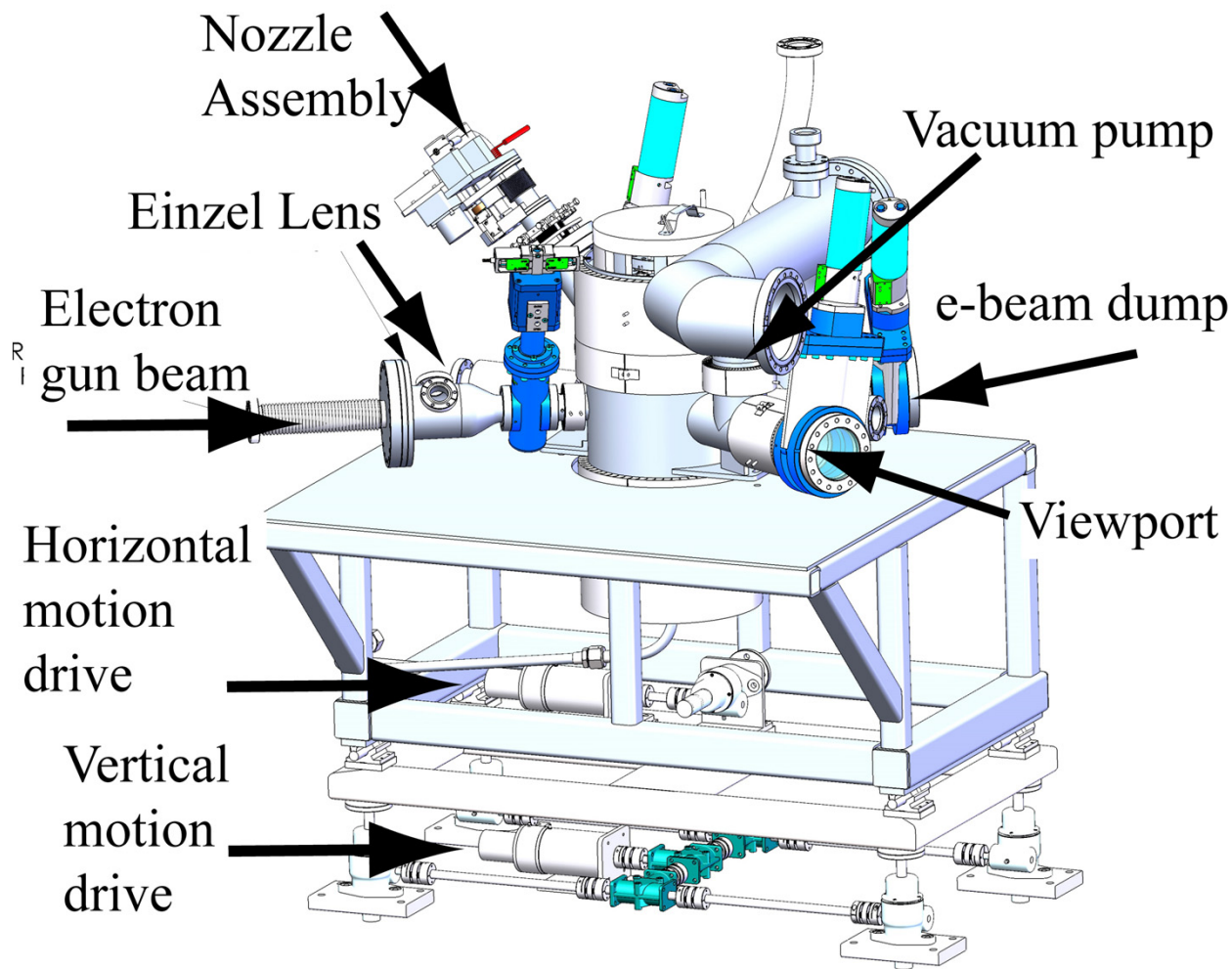
# The film is positioned with respect to the beam

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





# Hazards associated with the lithium stripper

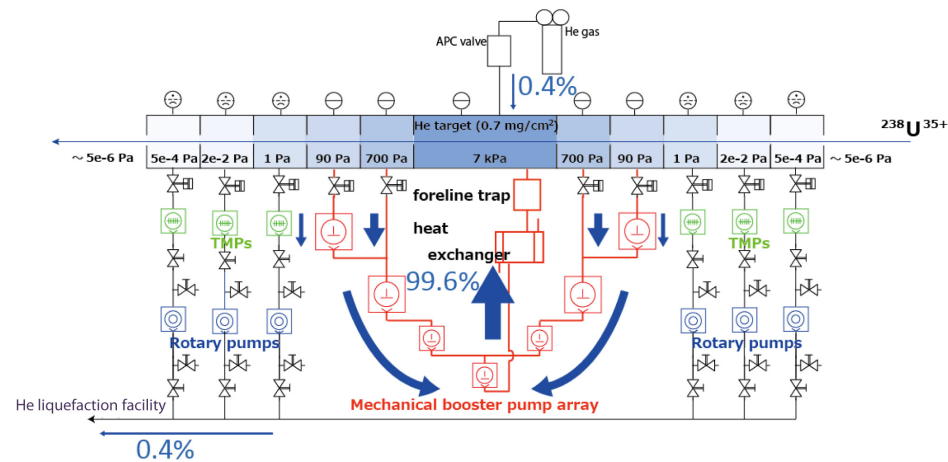
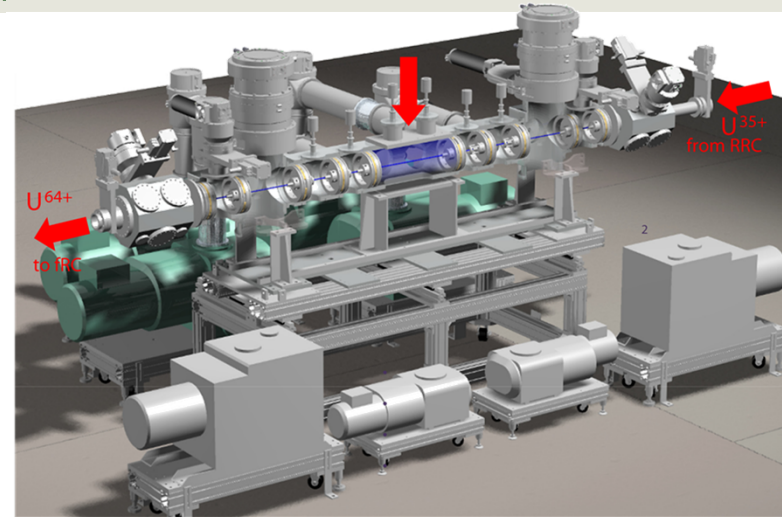
- Activation of the lithium (mostly  $^7\text{Li}$ ), and the argon gas in the secondary containment vessel as well as in the argon storage tank
- Compatibility of lithium with standard materials is a serious concern. For example no aluminum can be used, nor copper vacuum gaskets
- Liquid lithium catches fire when in contact with water or oxygen and reacts with 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

# Future work

- The liquid lithium stripper module is being assembled and we expect to have most of it ready for commissioning by the end of 2016.
- We plan to install it in the tunnel after the initial commissioning period
  - To simplify commissioning a carbon foil will be used. Only low intensity and low and medium mass ions will be used in commissioning.
- 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

# Helium gas charge stripper RIKEN development

- The development of a helium gas stripper for high intensity heavy ions was started by H. Okuno<sup>(a)</sup> at RIKEN, Japan
- It was experimentally verified that the average charge state emerging from a helium stripper was significantly higher than that from an argon or nitrogen gas cell<sup>(b)</sup> at the RIKEN and FRIB energies
- The integrated gas thickness needed to reach equilibrium at RIKEN's energies is lower than for FRIB beams. Even at their lower pressures a complex pumping system is needed to capture most of the gas that escapes from the stripper cell.

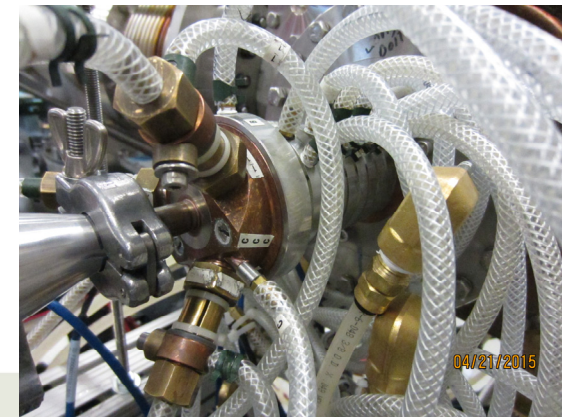
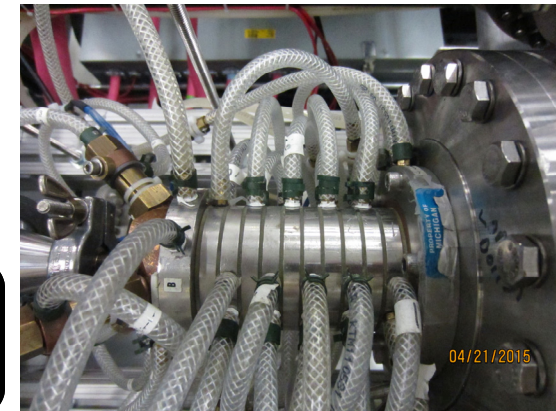
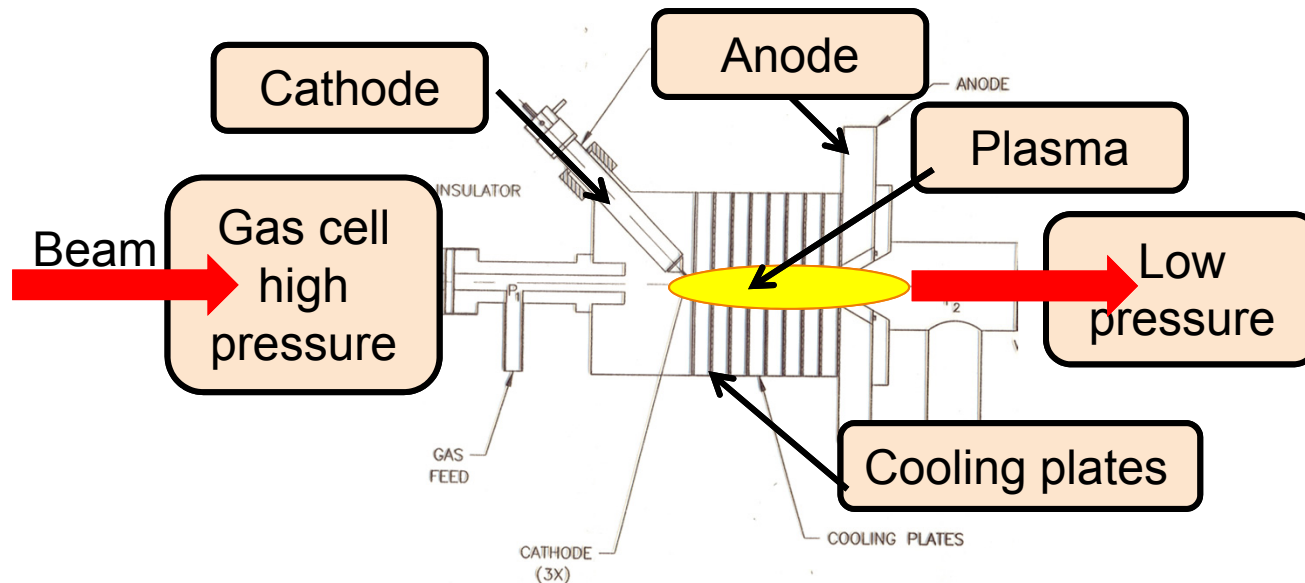


(a) H. Okuno et al., PRSTAB **14** (2011) 033503

(b) H. Imao et al., PRSTAB **15** (2012) 123501

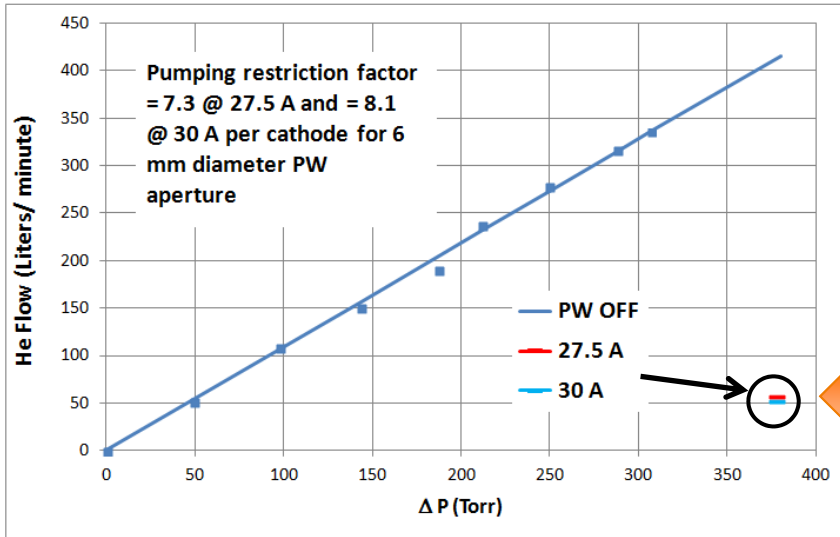
# How to reduce the helium loss?

- P. Thieberger<sup>(a)</sup> (BNL) proposed the use of plasma windows to reduce the conductance from the gas cell to the rest of the beamline in the FRIB stripper.
- A. Hershcovitch (BNL) developed the original concept of the plasma window<sup>(b)</sup>. It consist of a wall stabilized plasma that heats the gas trying to escape from the high pressure cell. The increased velocity of the gas achieves a choked flow condition and higher viscosity, limiting the mass flow.



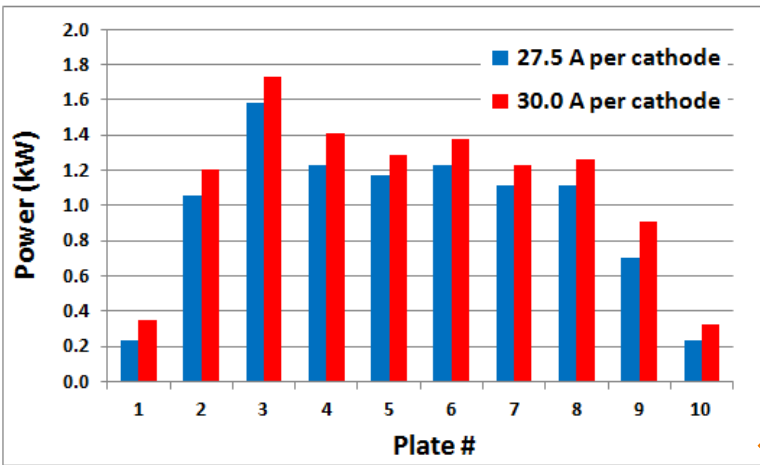
- (a) P. Thieberger, Stripper and Target Technology for High Power Heavy Ion Beams Workshop, East Lansing (2009)
- (b) A. Hershcovitch, J. Appl. Phys. 79, 5283 (1995).

# Results from R&D at BNL for a 6 mm aperture

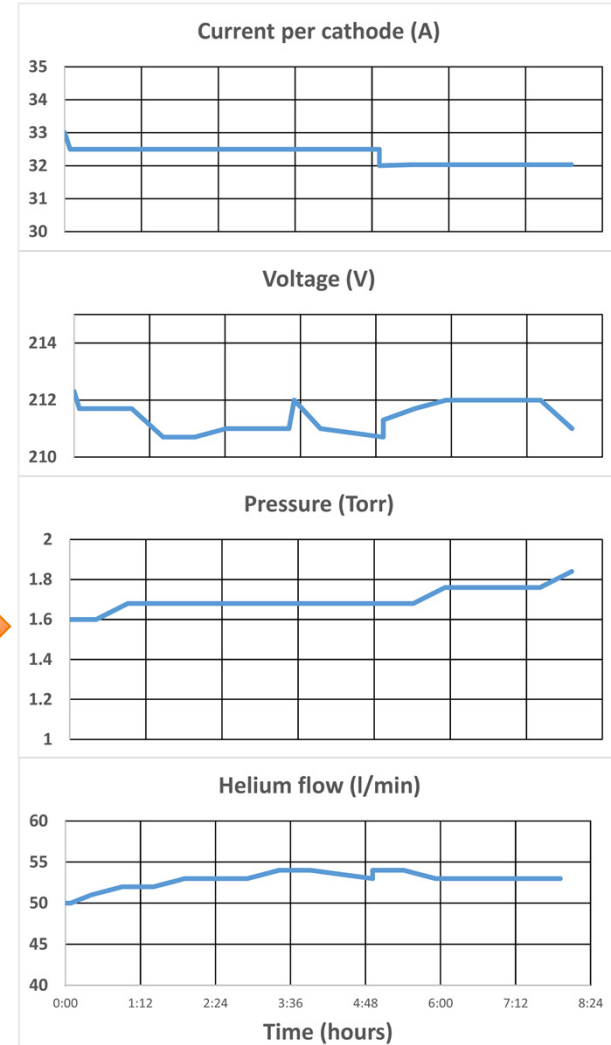


A conductance reduction factor of 8 was achieved at 30 A

Results from an 8 hour test

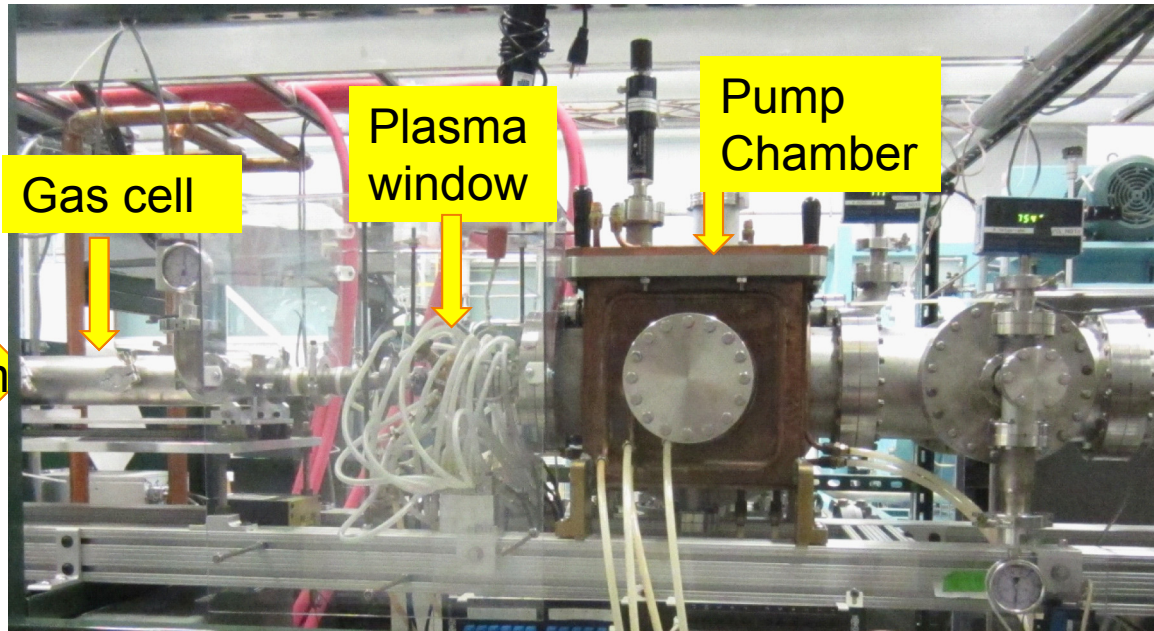


Discharge power dissipated in each plate of the 6 mm aperture plasma window as measured by the cooling water temperature increase.





# Test stand with plasma windows at MSU



The goal is to improve the helium containment and improve the lifetime of the components.

Cathode lifetime is an issue due to erosion of the W electrodes.

The plasma has damaged some of the window plates, we need to improve the cooling.

A large pump (not shown) is recycling the gas toward a buffer tank and back into the gas cell

A heat exchanger will remove the heat deposited by the beam in the gas

# Acknowledgements

- We would like to acknowledge the following collaborators that contributed to the work presented here:
- J. Specht (ANL),
- J. Sherman (retired LANL),
- I. Silverman (Soreq, Israel).
- H. Okuno and the RIKEN team
- FRIB team

