



# Charge Stripper Developments for FRIB

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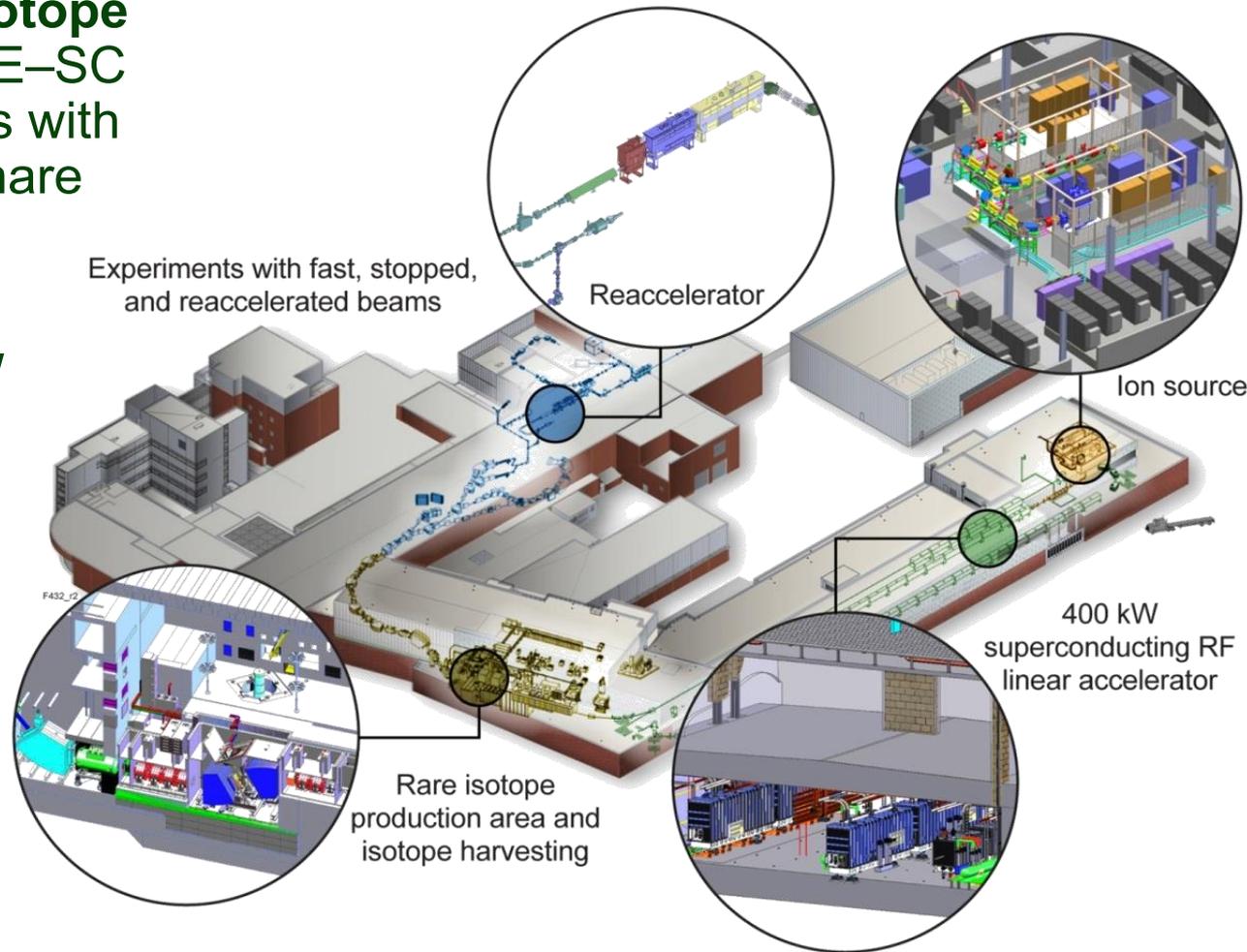
# Outline

- Brief description of FRIB
- Challenges of the FRIB charge stripper
- Options considered
- Development and current status of the liquid lithium charge stripper
  - Film formation (at ANL)
  - Beam on film tests (at ANL and MSU)
  - Electromagnetic pump
  - Status of the construction
- Development and current status of the helium gas charge stripper
  - Feasibility and initial measurements (at BNL)
  - Development and endurance tests (at MSU)
- Summary



# 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

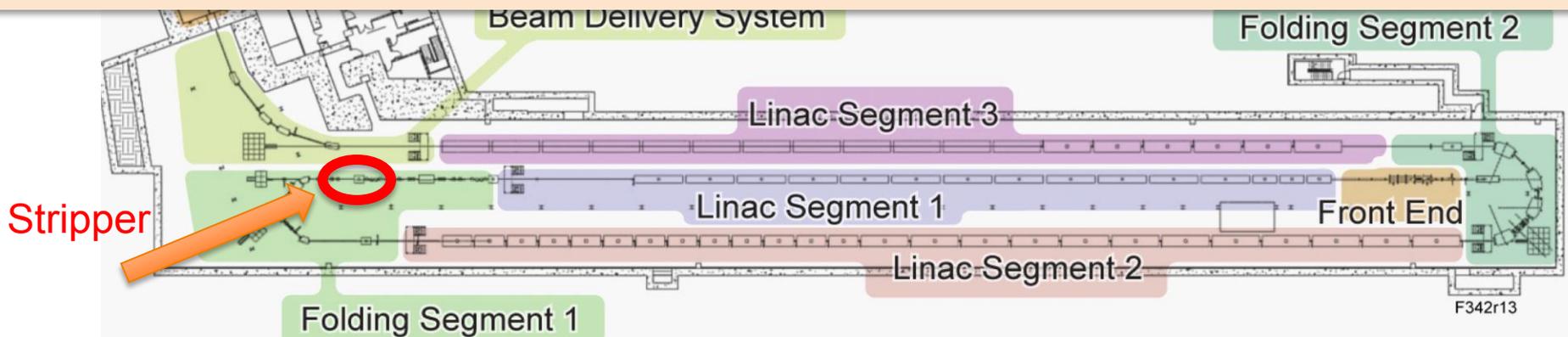


# FRIB Driver Linac Layout

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.

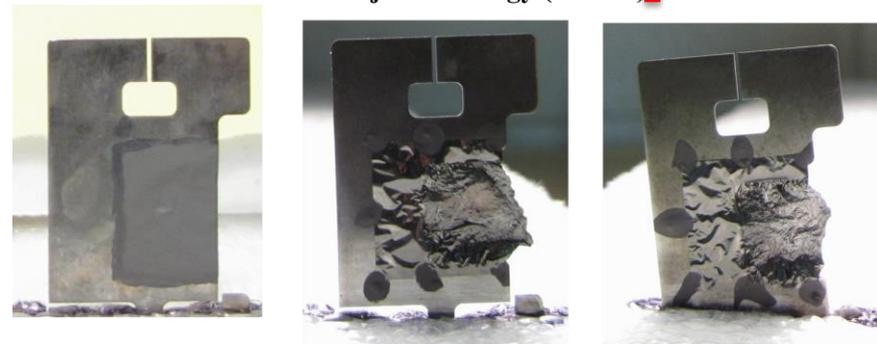
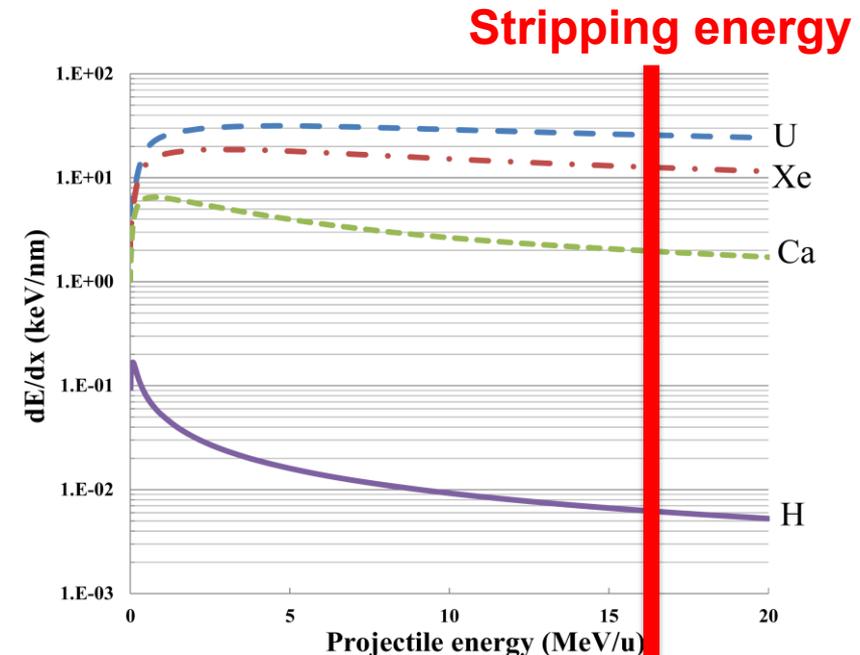
The stripper is located at the end of Linac Segment 1 ( $\beta = 0.041$  and 0.085 cavities), where ions have energies between 16 and 20 MeV/u. The bend will select multiple charge states of the stripped beam (up to five charge states for uranium ions) for simultaneous acceleration in the rest of the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

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



# Challenges of the FRIB Charge Stripper

- Full beam diameter at the stripper  $\sim 3$  mm.
- Estimated stripper thickness for carbon film  $\sim 3 \mu\text{m}$ .
- Power deposition density on the stripper for uranium beam (400 kW final power) in carbon film is approximately  $30 \text{ MW}/\text{cm}^3$ .
- Heavy radiation damage to solids in this energy range ( $\sim 16 \text{ MeV}/u$ )
- $dE/dx$  orders of magnitude larger than for protons



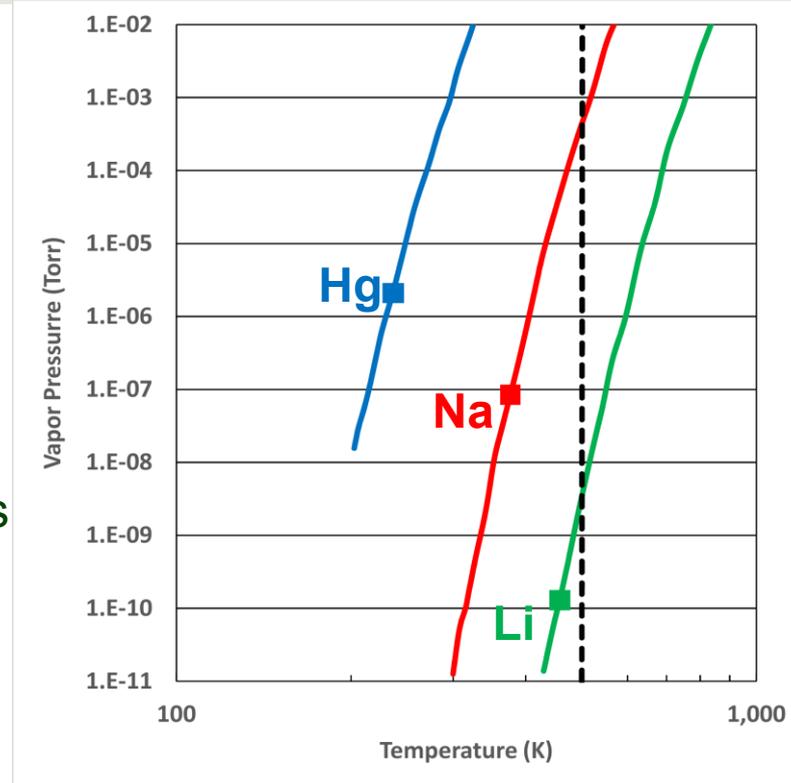
Carbon foils after irradiation by Pb beam ( $\sim 8 \text{ MeV}/u$ )

# 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<sub>2</sub> or Ar)
  - It is difficult to pump and expensive to replenish, we need to recover and recirculate

# Liquid lithium charge stripper development

- Originally proposed in 2003 by J. Nolen<sup>(a)</sup> (ANL) for the RIA driver linac
- 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 collaboration 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>(c)</sup>.
- A later set of experiments demonstrated that the power deposition of a high power beam (protons) would not destroy the thin film <sup>(d)</sup>.

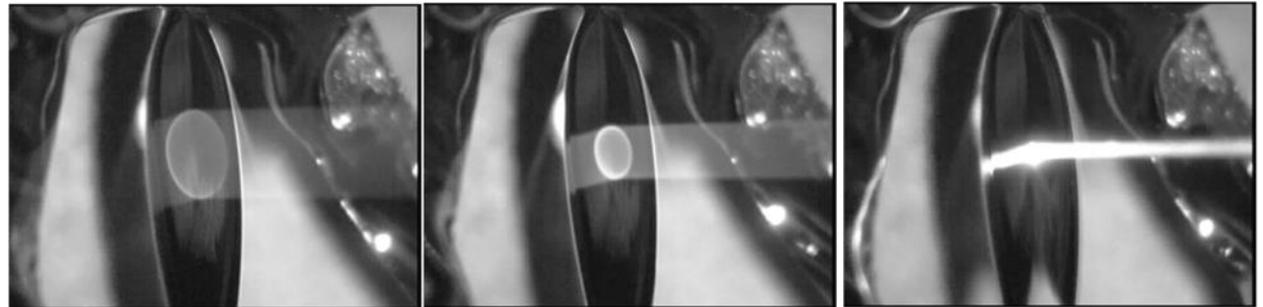


- 2003 Thin-film liquid-lithium stripper for the RIA driver linac. DOE RIA R&D proposal.
- Y. Momozaki et al., JINST 4 (2009) P04005
- C. B. Reed et al., FRIB Lithium Stripper Thickness and Stability Measurements, ANL/NE-11/01
- Y. Momozaki et al., J. Radioanal. Nucl. Chem. DOI 10.1007/s10967-015-4074-9

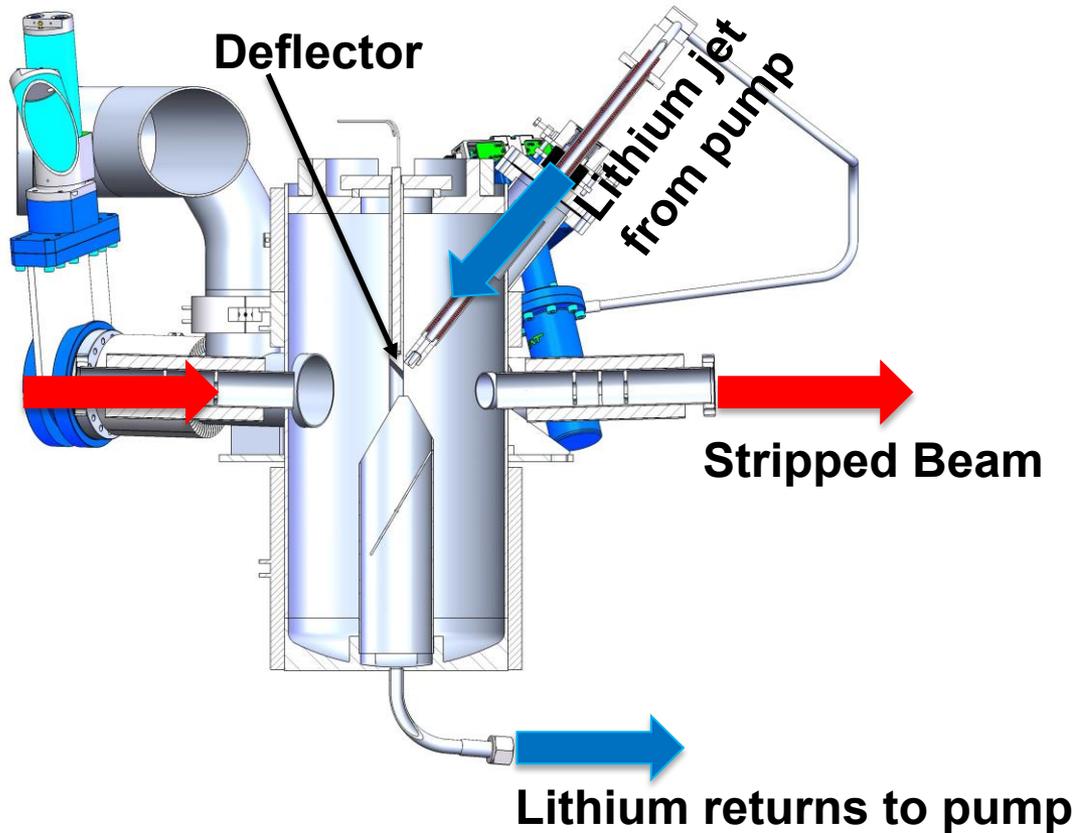
# Can the thin film survive the power deposition? YES

- 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 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.
- The proton beam (65 kV, 300 W) stopped completely in the lithium film. The highest power density split the film below the impact point, without disturbing the interaction volume.

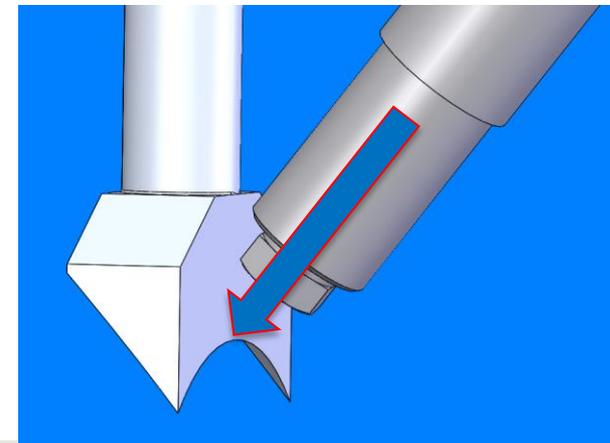
The LEDA proton beam coming from the right stops in the lithium film. Three different focusing settings are shown. The rightmost image shows film splitting



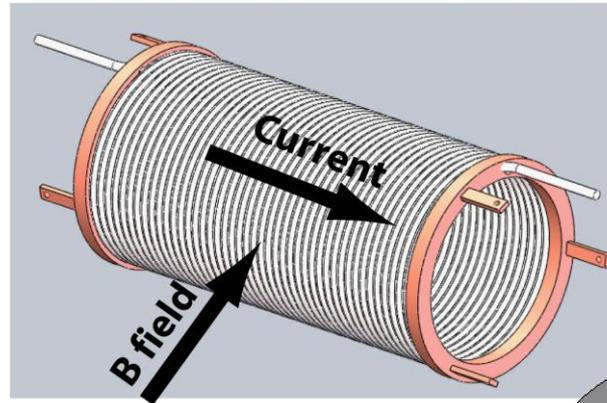
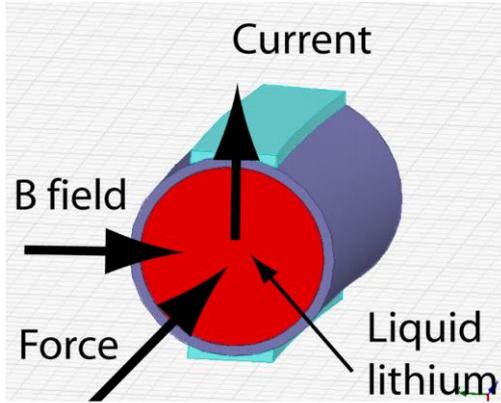
# Stripper Film Produced by High Velocity Jet



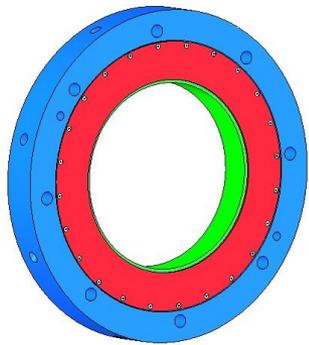
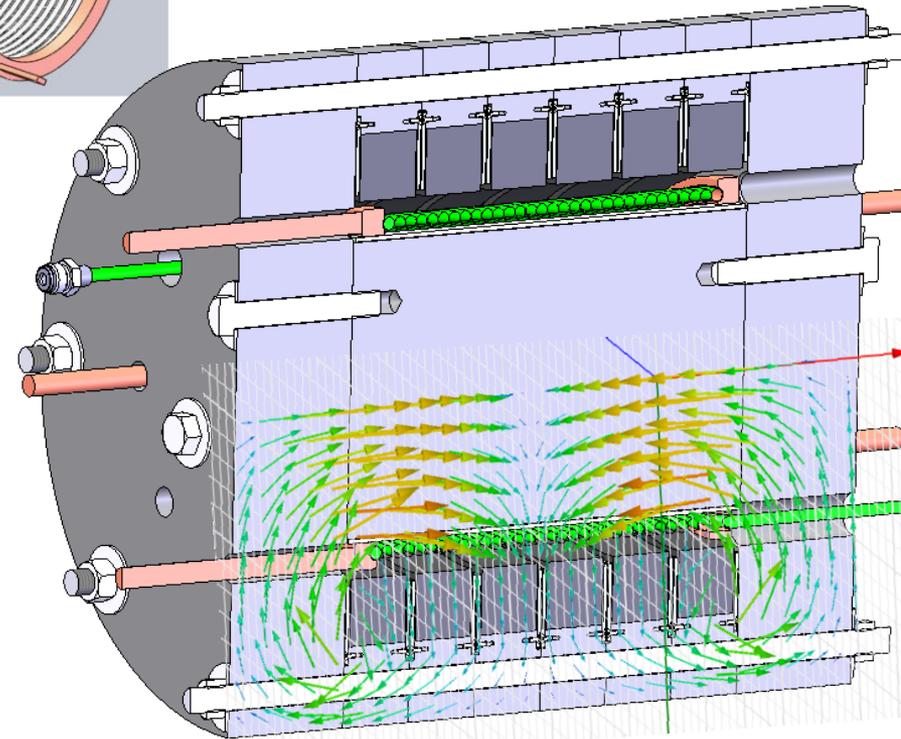
The thin lithium film needs to move very fast ( $\sim 50$  m/s) to remove the heat away from the impact point. This is achieved by producing a high pressure ( $\sim 200$  psi) lithium jet in a 0.5 mm diameter nozzle. The jet impinges on a flat deflector and produces the thin film.



# Electromagnetic Pump Design



Based on a indium/gallium pump designed and tested by R. Smither (ANL, 1995)



Sm Co  
Permanent  
magnets

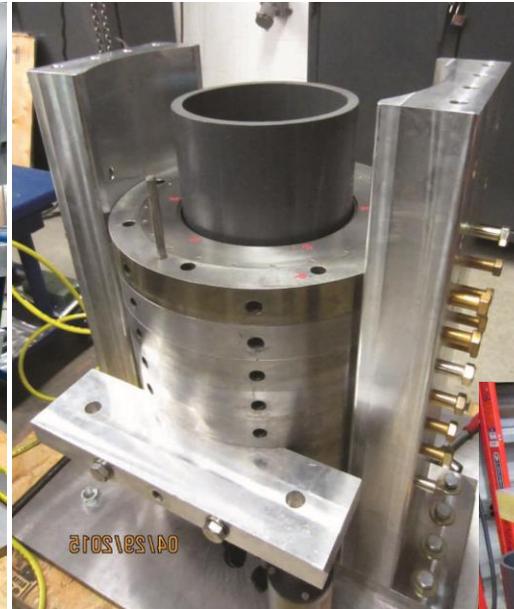
Steel

# Assembly of Pump Magnet



Steel

Permanent Magnets  
SmCo



Large forces (~12,000 kg) have to be controlled during the assembly process.

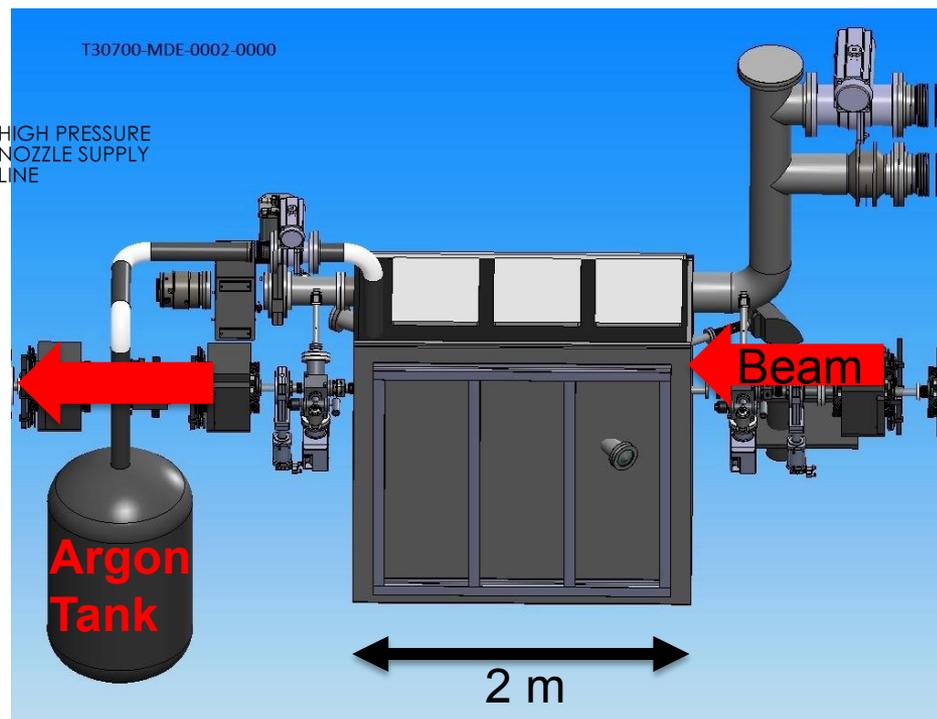
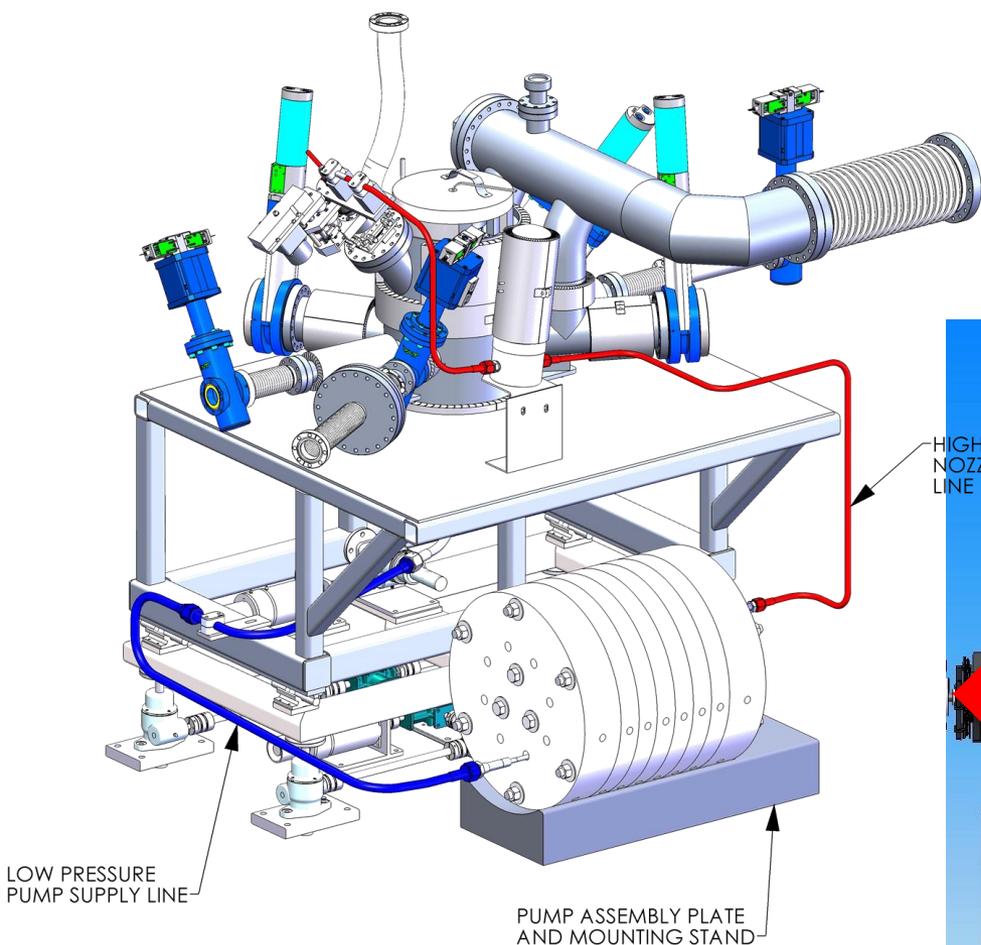
The first ring is attracted to the lower cap. The following rings are repelled. The top cap is attracted with ~ 12,000 kg force.



We have performed the assembly of the pump before the helical coiled tube was available. Four hydraulic cylinders control the ring motion.

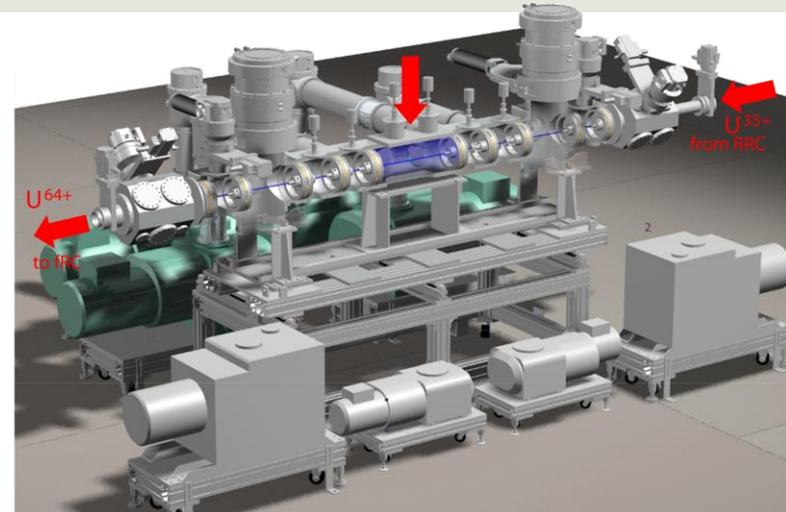
# Charge Stripper Design Has Been Finalized

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

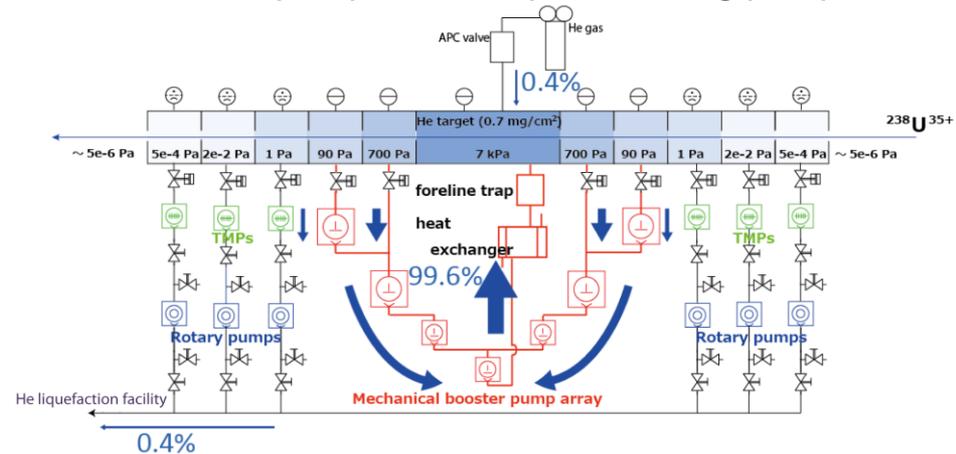


# Helium Gas Charge Stripper

- The development of a helium gas stripper for high intensity heavy ions 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>.
- 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.



7 booster pumps, 6 TMP plus backing pumps

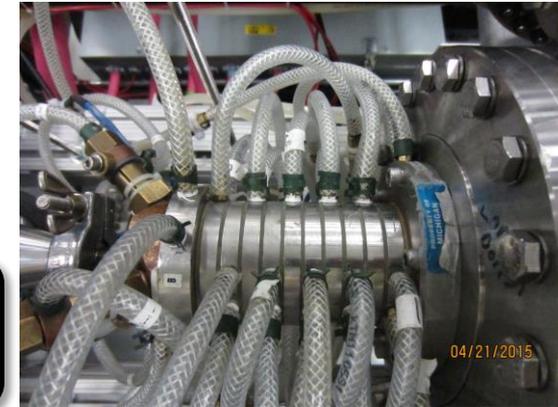
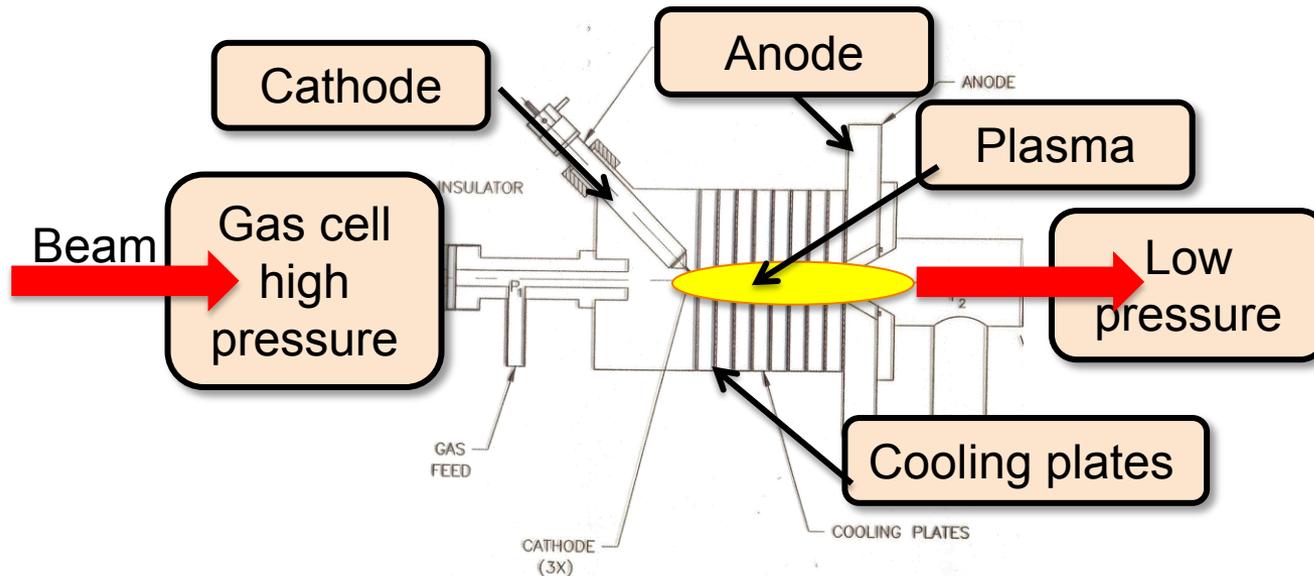


(a) H. Okuno et al., PRSTAB **14** (2011) 033503

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

# How to Reduce the Helium Loss?

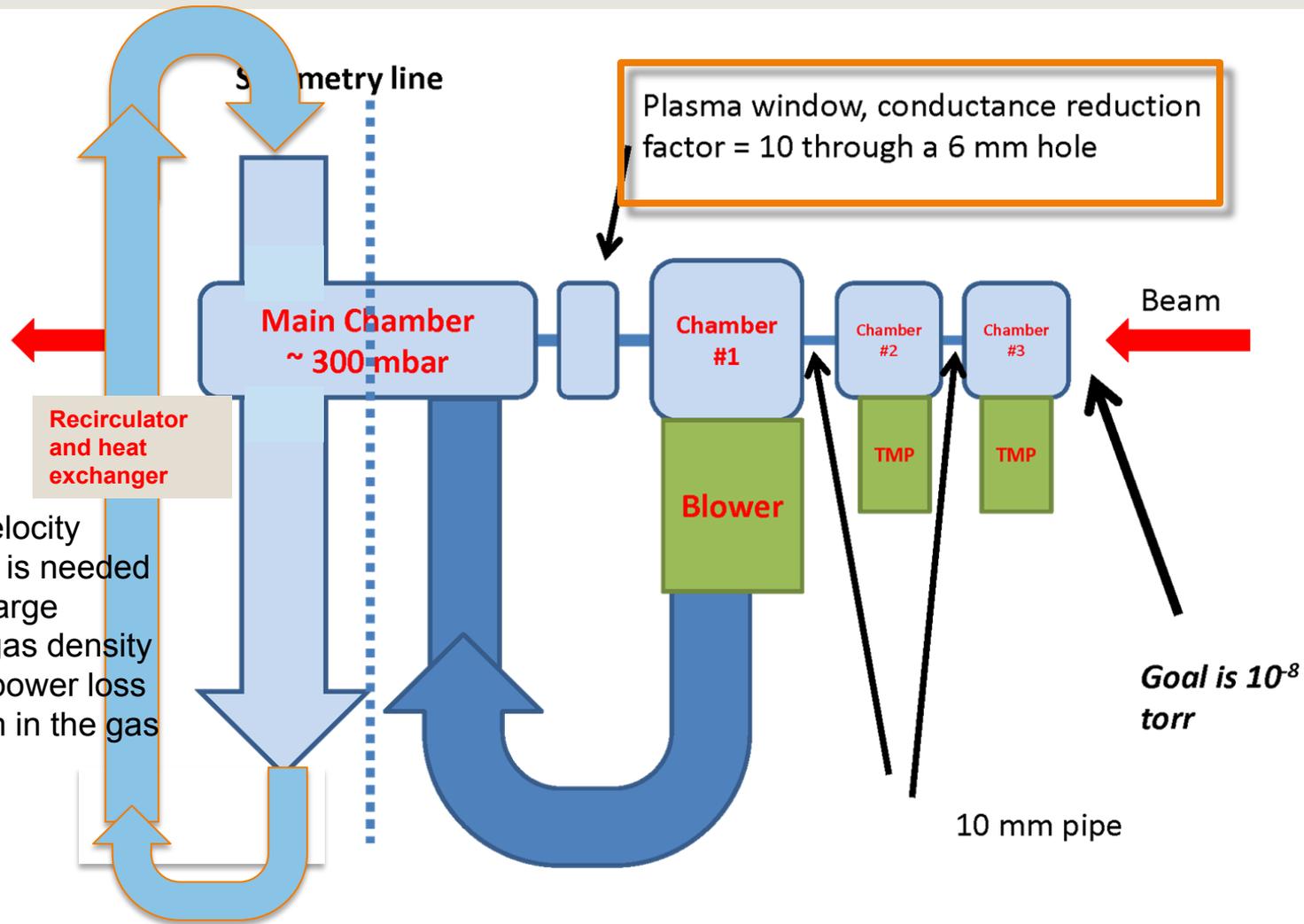
- P. Thieberger<sup>(a)</sup> (BNL) proposed the use of plasma windows to reduce the conductance from the gas cell to the rest of the beamline in the FRIB stripper.
- A. Hershcovitch (BNL) developed the original concept of the plasma window<sup>(b)</sup>. It consist of a wall stabilized plasma that heats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



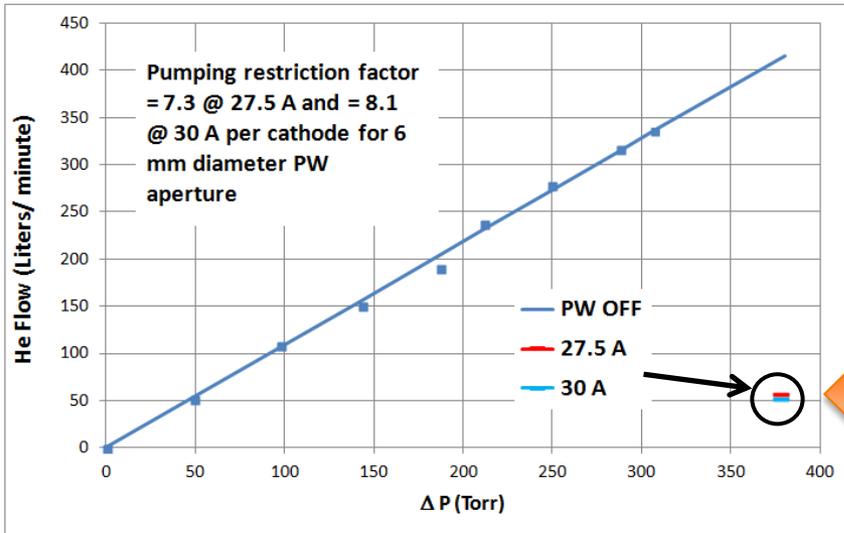
(a) P. Thieberger, Stripper and Target Technology for High Power Heavy Ion Beams Workshop, East Lansing (2009)

(b) A. Hershcovitch, J. Appl. Phys. 79, 5283 (1995).

# Possible configuration for FRIB

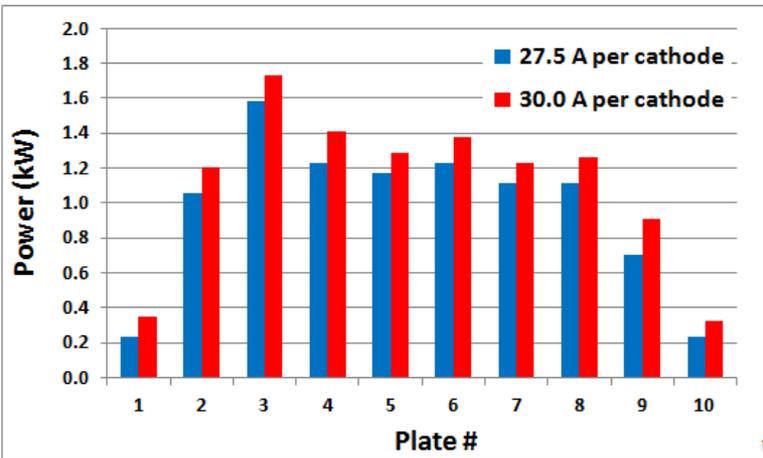


# Results from R&D at BNL for a 6 mm Aperture

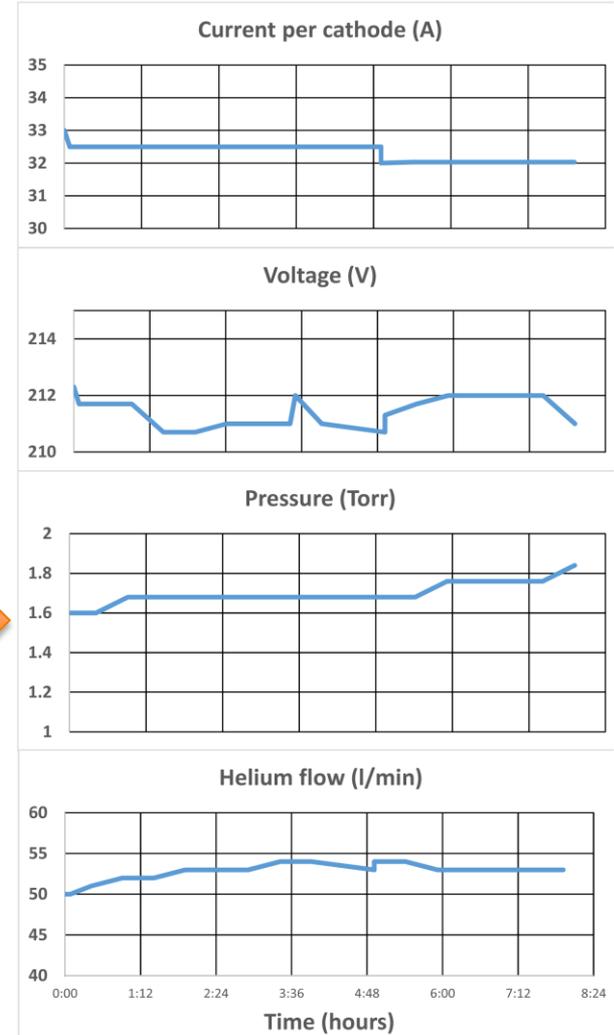


A conductance reduction factor of 8 was achieved at 30 A

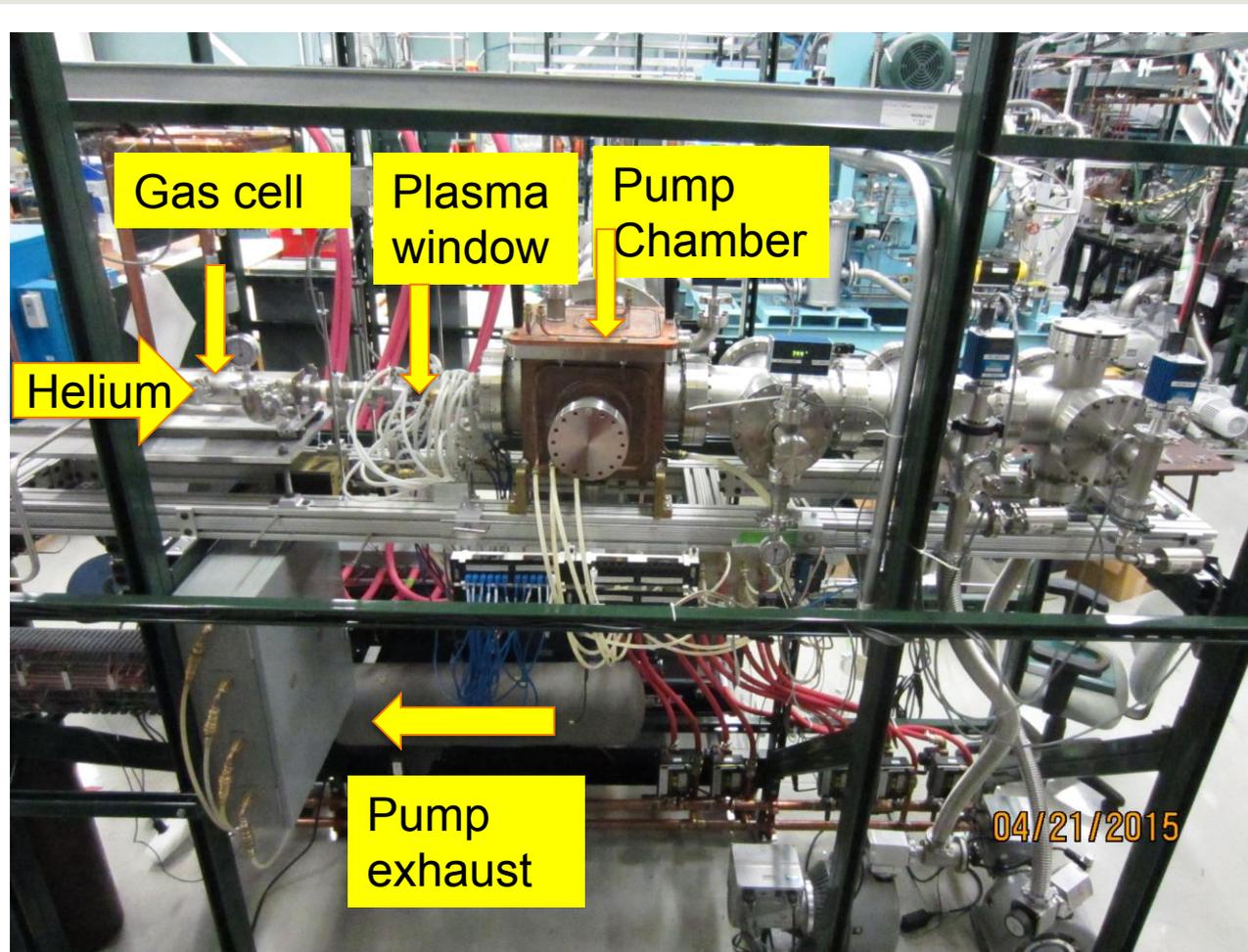
Results from an 8 hour test



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.

# Summary

- The baseline design of the charge stripper for FRIB is based on a liquid lithium film
  - Development has been performed in collaboration with ANL
  - A charge stripper module is under construction and we expect to start commissioning by the end of the 2015
  - The goal is to determine a maintenance plan and reliability issues
  - The liquid lithium charge stripper will be ready for installation in the tunnel in mid 2017
- An alternative helium gas stripper with plasma windows is being researched
  - A research program in collaboration with BNL confirmed its feasibility
  - We continue its development at MSU

