Heavy Ion Strippers

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Facility for Rare Isotope Beams

Michigan State University

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Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Outline

- Challenges for the stripper
- Major efforts at the present time
  - Gas strippers
  - Solid strippers
  - Liquid strippers
  - Plasma strippers
- Examples from major facilities
- Path forward

Challenges for the stripper

- Example: U on carbon foil for FRIB
  - Beam energy = 16.5 MeV/u, power deposited on foil~ 700 W
  - Beam spot diameter = 3 mm, foil thickness~ 3 μm
  - average power density ~ **33 kW/mm³**
- Thermal issues
  - Sublimation of carbon foils
  - Differential expansion from support materials
  - Formation of low density volumes in gases
- Mechanical stresses
  - Fatigue in solids
- Radiation damage
  - Phase changes with different properties (amorphous→graphite)
  - Large effect for the heaviest ions (Uranium)

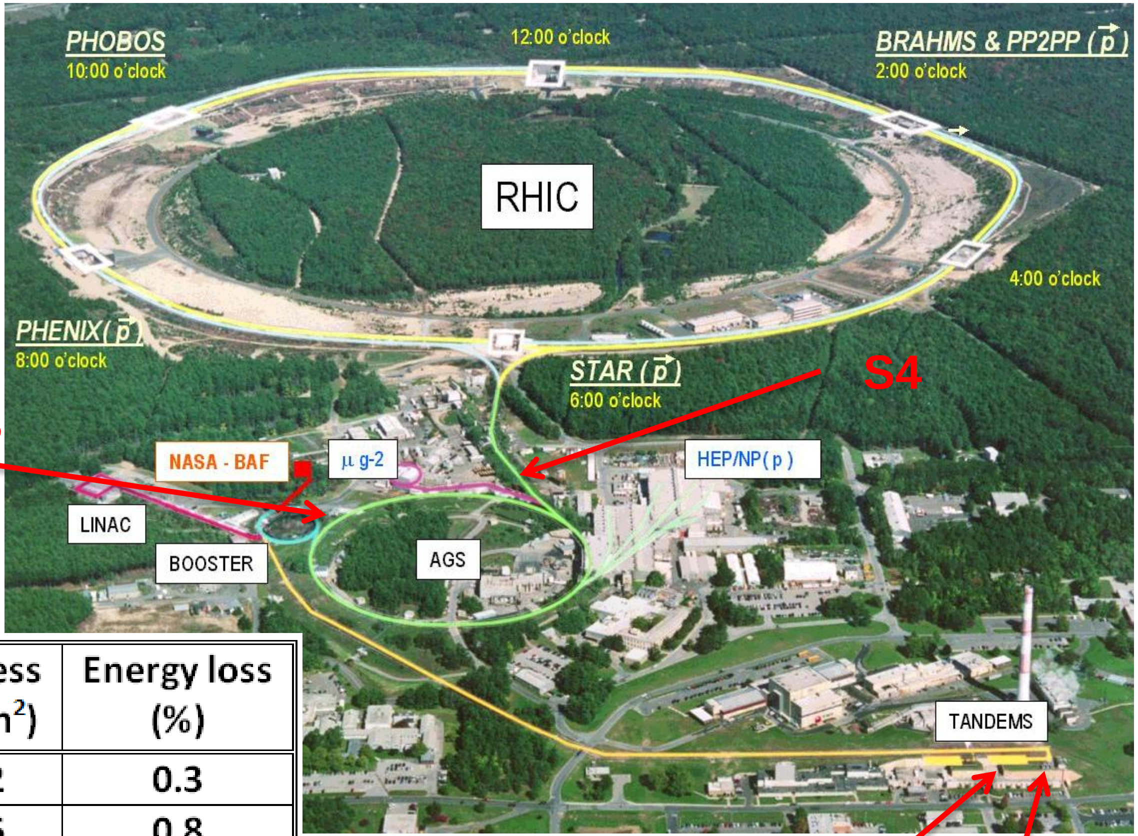
Gases vs. solids

- In1954 it was known that solids were better strippers, Bohr and Lindhard predicted that the higher stopping power of solids than gases was due to the higher charge of the ions moving inside the solid
- The idea was that the time between collisions in a solid was shorter than the time for relaxation of an excited atomic level, preventing the decay to the ground state that occurred in the gases
- Geissel et al. in 1981 found the difference in stopping powers but not enough to justify the large difference in charge states
- Betz and Grodzins introduced an enhanced Auger electron emission effect from ions leaving the solid target
- Later experiments* (1989) confirmed the density effect and verified that it disappears for energies where the ions are fully stripped

*R. Bimbot et al., NIM B44 (1989) 1 and 19; J, Herault et al., NIM B61 (1991) 156

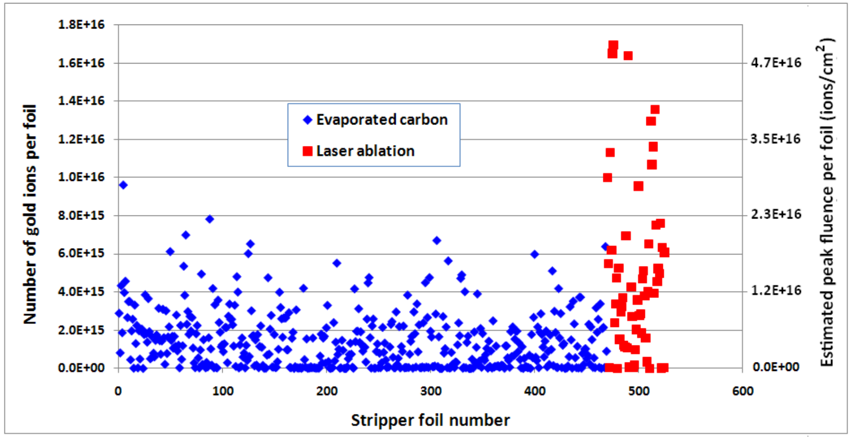
Brookhaven (USA)

The Tandems have now been replaced by a high charge-state Electron Beam Ion Source (EBIS). Strippers S3 and S4 remain unchanged.



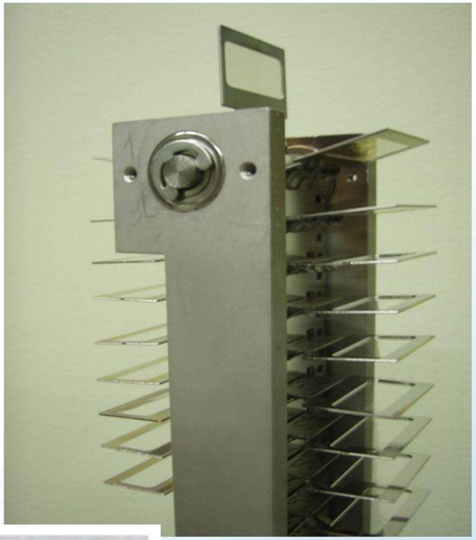
	Gold energy (MeV/u)	Material	Thickness (mg/cm^2)	Energy loss (%)
S1	0.08	Graphite	0.002	0.3
S2	1.0	Graphite	0.016	0.8
S3	100	Aluminum Vitreous C	6.4 9.2	2.7
S4	10000	Tungsten	48.9	0.02

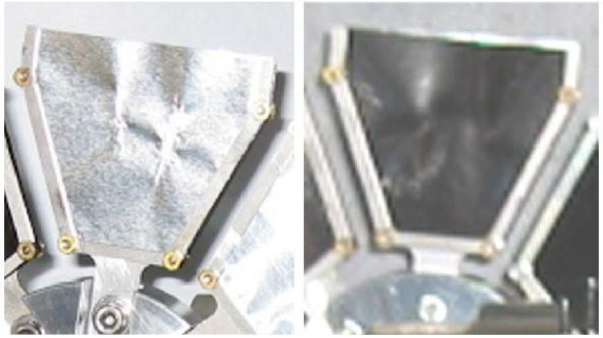
BNL challenges



(S1) Terminal Foils

- Inside pressure vessel
- Terminal Voltage (14MV)
- Au^{-1} to Au^{+12} (20% efficient)
- 2μg/cm² (collodion coated)
- 22mm x 9.4mm
- Two ladders per tandem
- MP7 ~ 600 foils
- MP6 ~500 foils
- Oscillate foils increases lifetime x3
- Oscillation period 1 minute
- Arc 10-12 foils/day
- LPA 3-4 foils/day



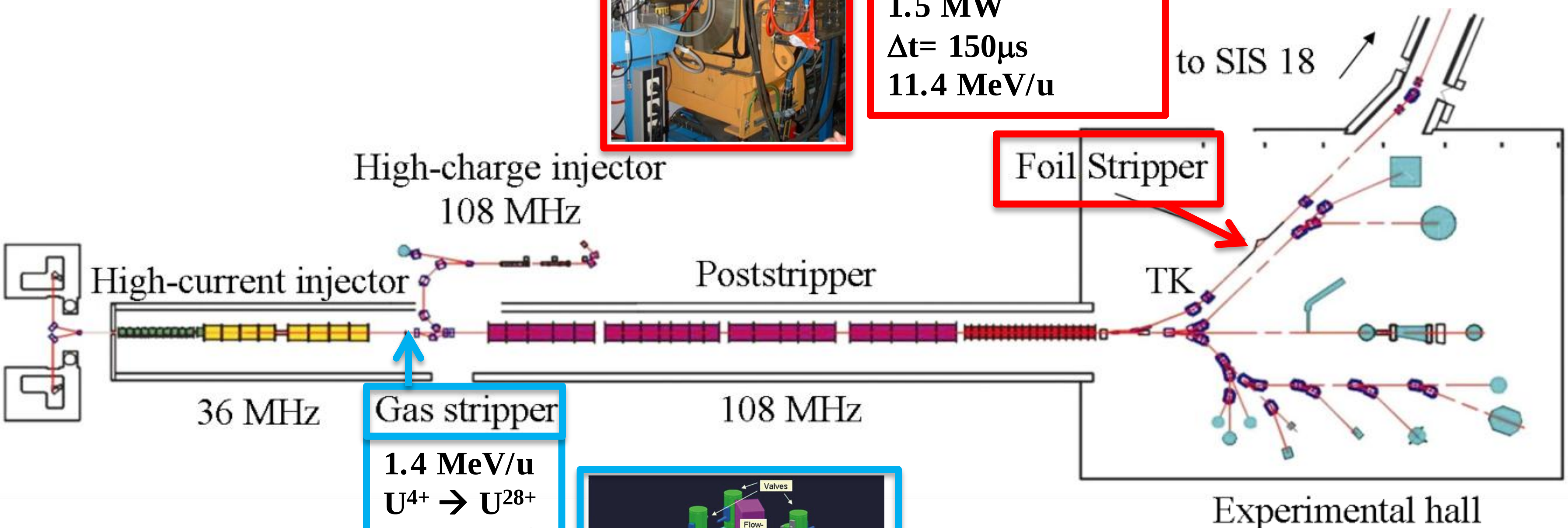


(S3) Aluminum + Glassy carbon stripper after 2007 RHIC gold run. Some radiation damage is observed. This stripper located between the AGS Booster and the AGS is by far the most challenging one since 2.7% of the total energy is lost leading to synchronization problems and strict uniformity requirements. **The thickness is minimized by an initial rapid stripping in Al and the larger equilibrium charge state reached in carbon.**

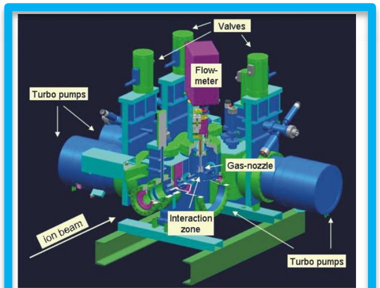
P.Thieberger et al., PRST-AB 11 (2008) 011001

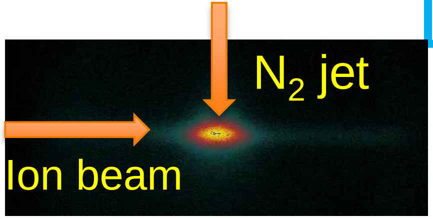
GSI (Germany)

$U^{28+} \rightarrow U^{73+}$
(13%) 15 → 5 emA
1.5 MW
Δt= 150μs
11.4 MeV/u



1.4 MeV/u
$U^{4+} \rightarrow U^{28+}$
10 μg/cm²



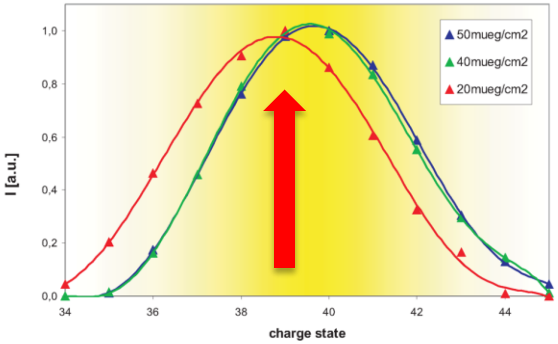


Courtesy W. Barth- GSI 2012

GSI single foil stripper

- An option to overcome the space charge limit in the SIS is to replace the gas stripper at 1.4 MeV/u **and** the foil stripper at 11.4 MeV/u with a single thin foil (20 µg/cm^2) at 1.4 MeV/u for high current operation
- Experiments have shown that $\mathbf{^{238}U^{39+}}$ can be delivered to the SIS18
- 1 Hz pulses of a 100 µs length and 5 emA were tested with the foils lasting approximately 11 hours and accumulated doses of $3*10^{16}$ ions. With a beam spot of 22 mm diameter the doses corresponds to **$0.8*10^{16}$** ions/cm^2

Post-irradiation tests indicate "**Beam-induced graphitization of the amorphous stripper foil leads to in-plane tensile stresses due to the higher density of the crystalline phase**"

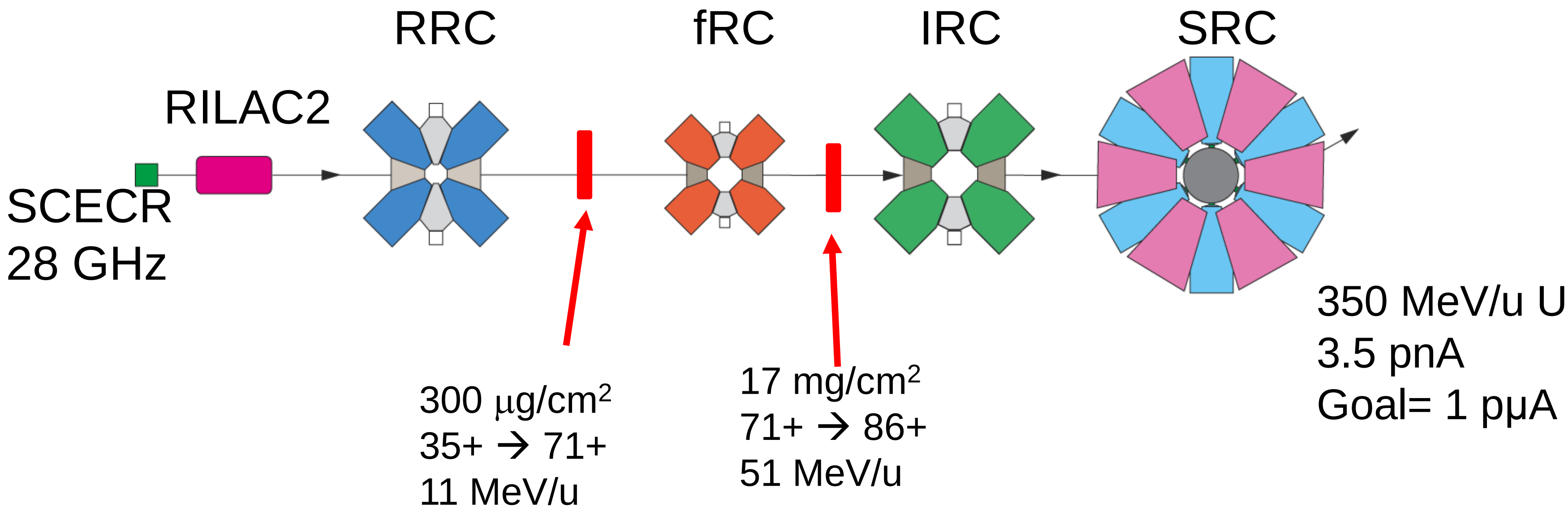


20% of U in 39+

W. Barth et al., INTDS 2012 and M. Tomut INTDS 2012

Courtesy W. Barth- GSI 2012

RIKEN (Japan)



At present 1st stripper < 200 W, expect 100 X more

R&D programs for the first stripper (2008-)

1: Large carbon foils on a rotating cylinder

2: N_2 gas stripper

3: low-Z gas stripper

Selected as solution for the first stripper

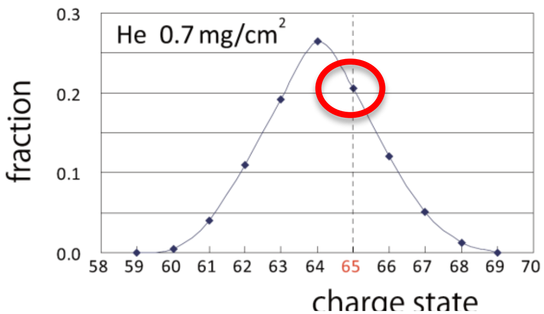
H. Okuno

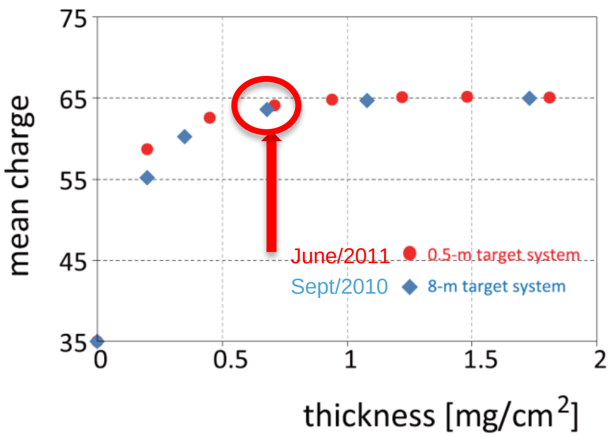
RIKEN NISHINA CENTER

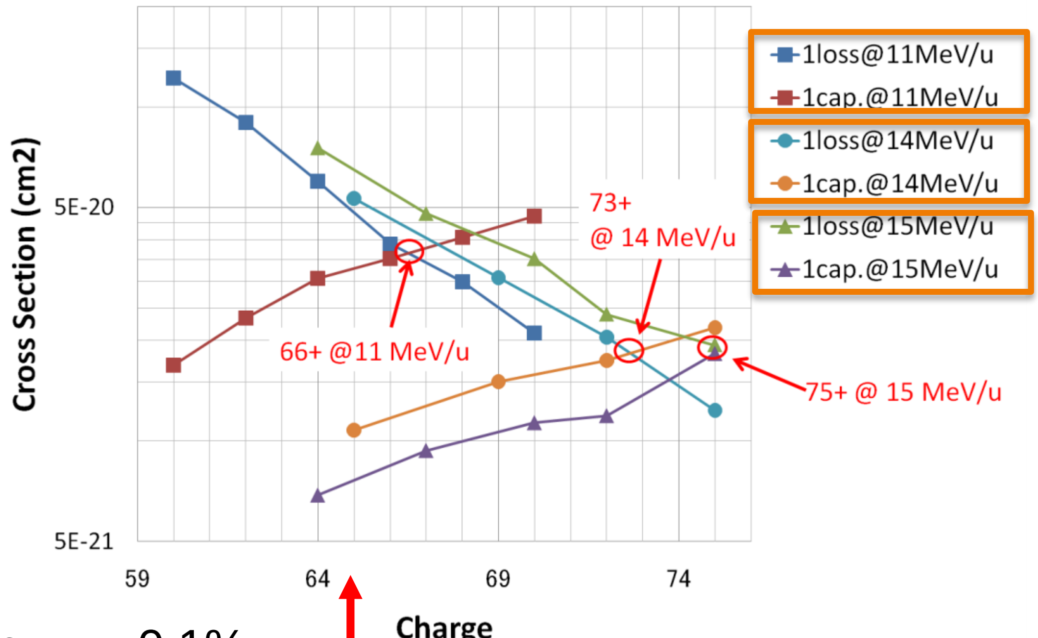
Equilibrium charge from measured σ_{loss} and $\sigma_{capture}$ in He gas at RIKEN

H. Okuno, et al., PRST-AB 14 (2011) 033503
H. Imao, et al., IPAC11, TUPS088. H. Imao, et al., IPAC12, THPPP084

RIKEN NiSHiNA CENTER







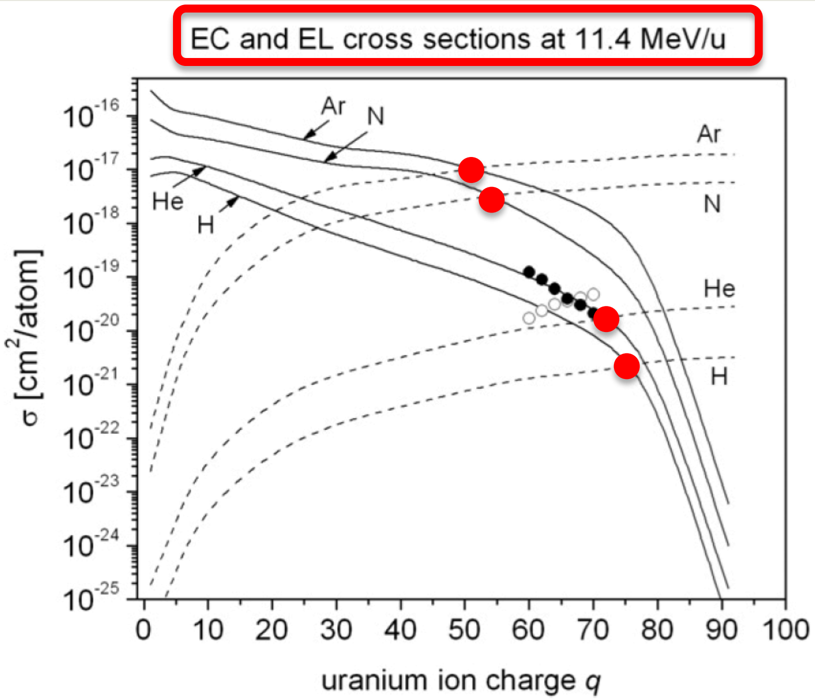
Gas $\sigma_{\Delta E/E}$ =0.1%

Foil $\sigma_{\Delta E/E}$ =0.17%

Acceptable with fRC: 69+

Acceptable with modified fRC: 65+

Equilibrium charge state for different gases



V. P. Shevelko et al., NIM B 278 (2012) 63

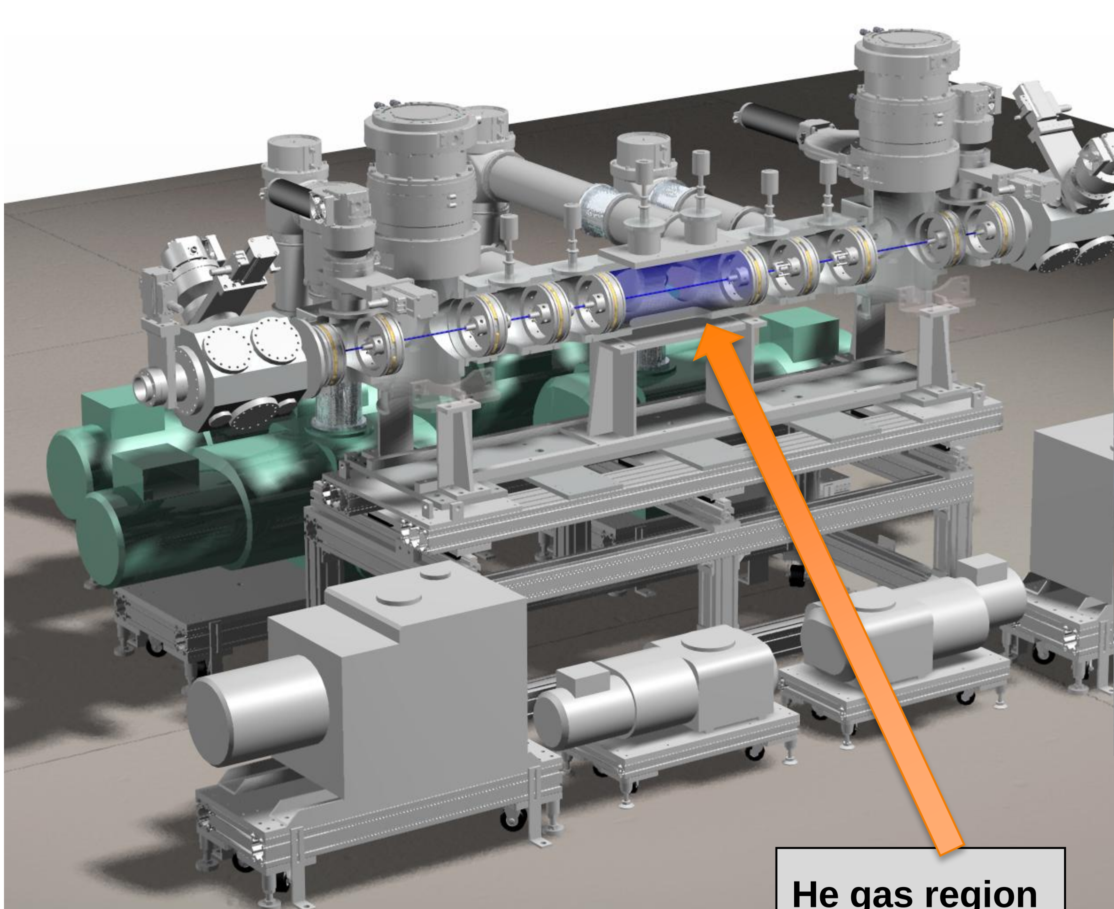
- Calculated cross sections
  - Electron loss = solid curves
  - Electron capture = dashed
- Open and solid circles are RIKEN's measurements

Reaction	Energy (MeV/nucleon)	V_p/V_{1s}
Ar + H_2	1.25	7.1
U + He	22	14.9
U + N_2	56	6.8
U + He	11	10.5
U + He	14	11.9
U + He	15	12.3
U + N_2	11	3.0
U + N_2	14	3.4
U + N_2	15	3.5

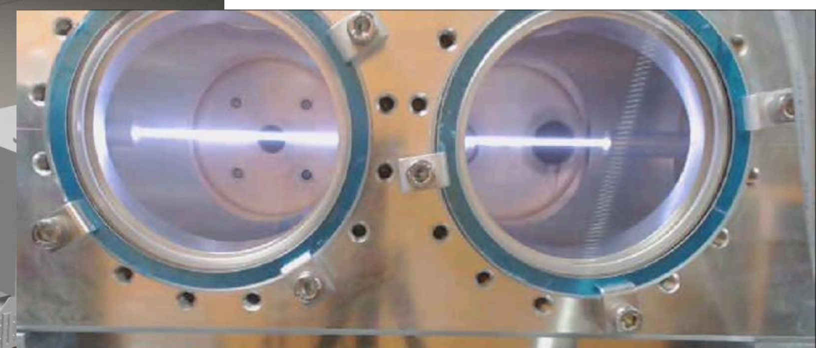
H. Okuno et al., PRSTAB 14 (2011) 033503

- Electron capture is suppressed when the projectile velocity significantly exceeds the velocity of the 1s electrons (fastest electrons) in the target

The new He gas stripper at RIKEN



He circulating vol.: 300m^3/day
(unique recycling system)
5 stage diff. pumping: 21 pumps
Large beam aperture: >Φ10 mm
8 order pres. Reduction: 7 kPa⇒10^{-5} Pa



2012 Jan. Installation **OK!**
Mar. Offline test **OK!**
Apr.- Test w/ U beams **in progress!**

Future work:

Study impurities: oil, water, N_2, or O_2 (Increase capture cross section)

High power beam easily makes a “hole” in gas due to heat generation?

He gas recycling system

He gas region
- 7 kPa
- 50 cm
- 0.7 mg/cm^2

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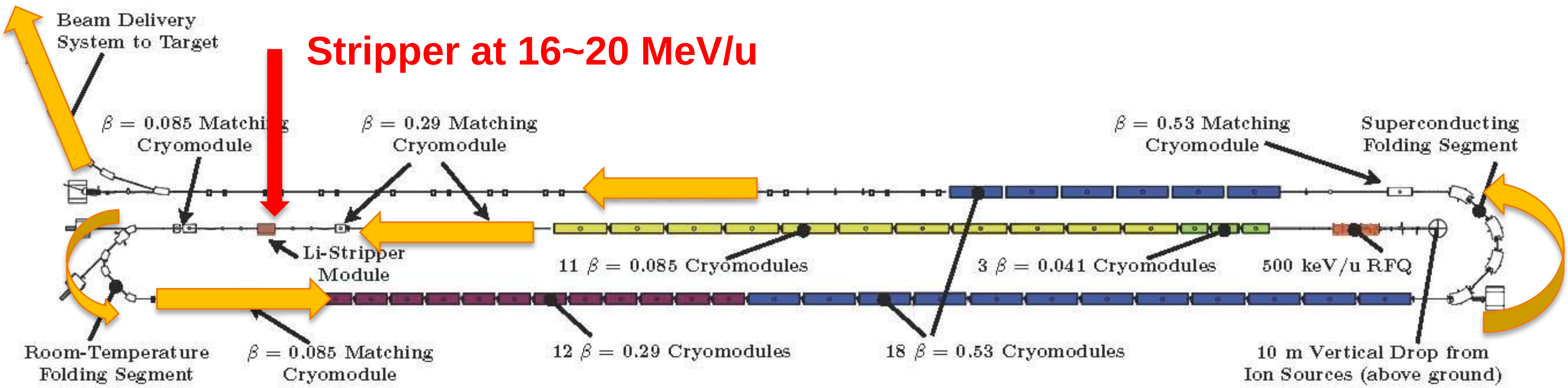
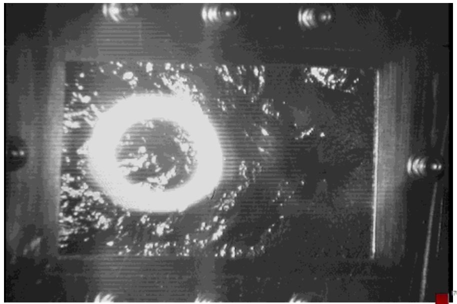
H. Imao and
H. Okuno

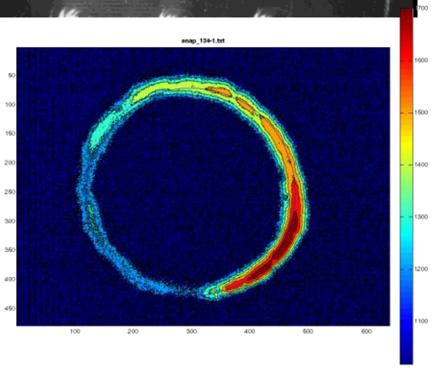
FRIB (USA): a folded linac

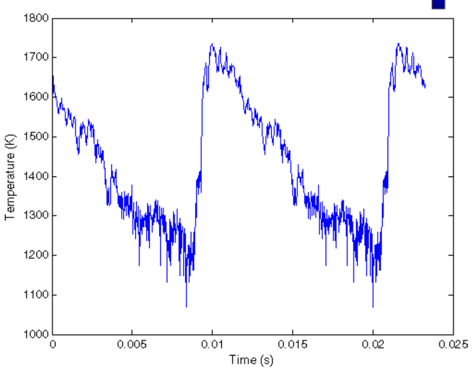


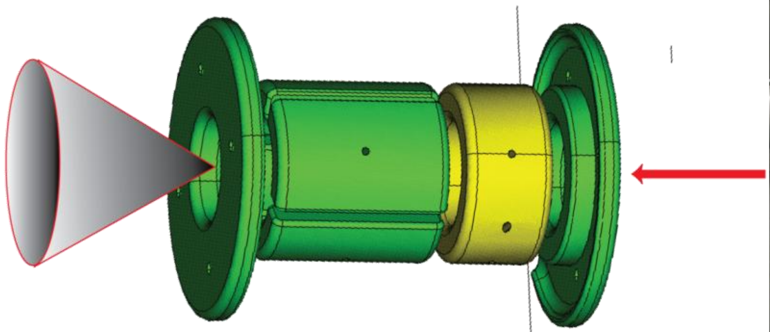
- Linac E/A ≥ 200 MeV/u, up to Uranium, 400 kW on target
- One stripper at an energy of approximately 20 MeV/u
- Beam power at the stripper ~ 40 kW
- Beam spot size at stripper ~ 3 mm diameter, ΔE/E acceptance = ±20% in Li thickness
- Options considered:
  - Solid carbon foils, liquid lithium film, He gas

Solid strippers tested at MSU: we understand the thermal behavior

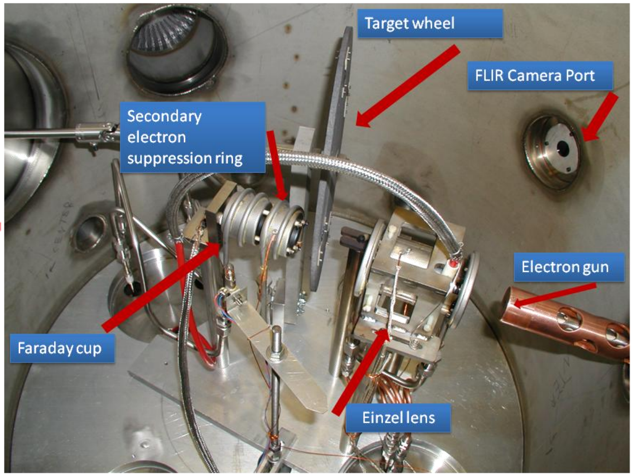


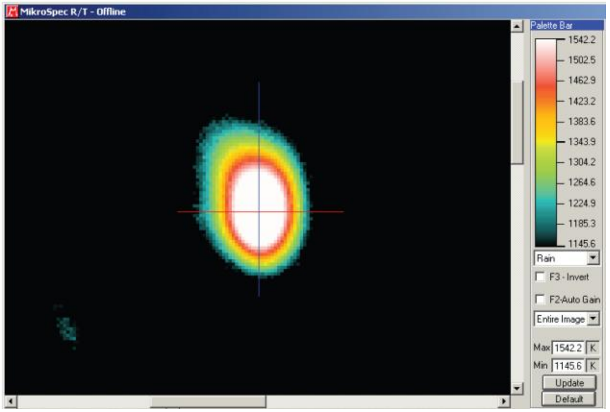


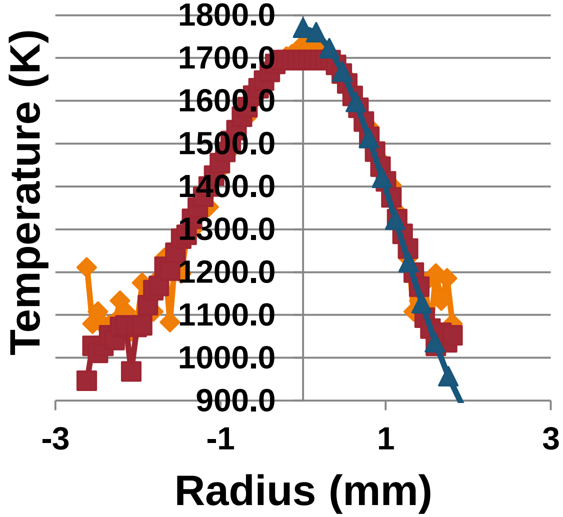




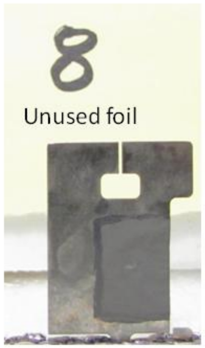
Electron gun beam on a foil from MicroMatter (500 µg/cm^2 foil, 86 Hz, 33 W)

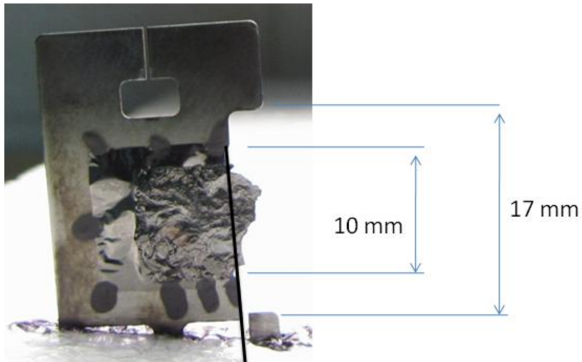


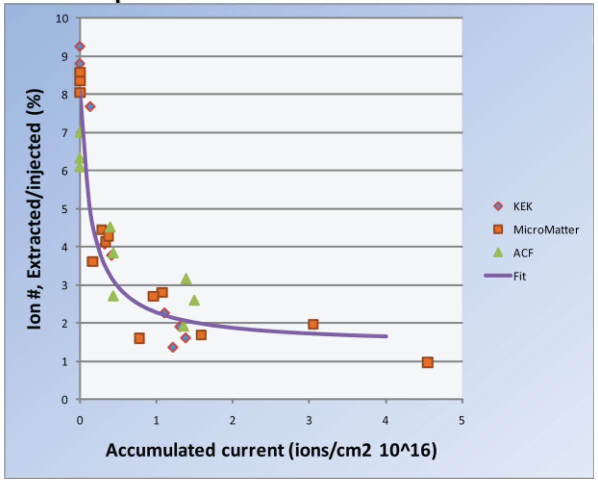




Radiation tests at MSU cyclotrons: 8.1 MeV/u Pb beam, short lifetime







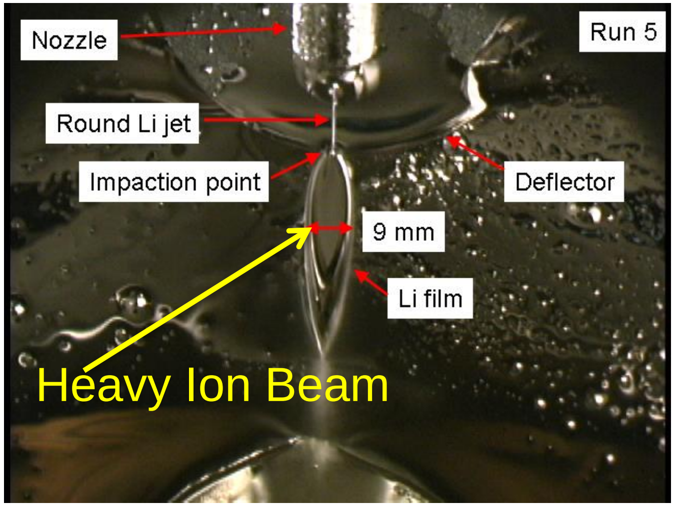
- Experiment performed in the K1200 cyclotron (27+→63+)
- Significant decay observed at 10^{14} ions in 4 mm^2 in the cyclotron test = 2.5 10^{15} ions/cm^2
- We need to study temperature dependence. Is there annealing?

Foil thinning (ion hammering?) displaces the peak of the stripped beam charge distribution toward lower charge states. Foil thickness measured with α source.
Also observed at RIKEN but not at GSI ?

A. Benyagoub and S. Klaumunzer, Radiation Effects and Defects in Solids, 1993, vol. 126, pp. 105-110

Liquid lithium stripper

- Original proposal by J. Nolen (ANL)
- Preliminary R&D done under DOE RIA program and continued under FRIB support
- Why liquid metals?
  - A liquid metal flowing in front of the beam can take the heat away efficiently
  - Not susceptible to radiation damage
- Why Lithium?
  - High heat capacity
  - Low melting point (180 C)
  - Low vapor pressure
- Demonstrated
  - Achieved film of correct thickness (~ 10 μm)
  - Stability of the film under no beam conditions
- To do:
  - Demonstrate stability under beam power deposition and end

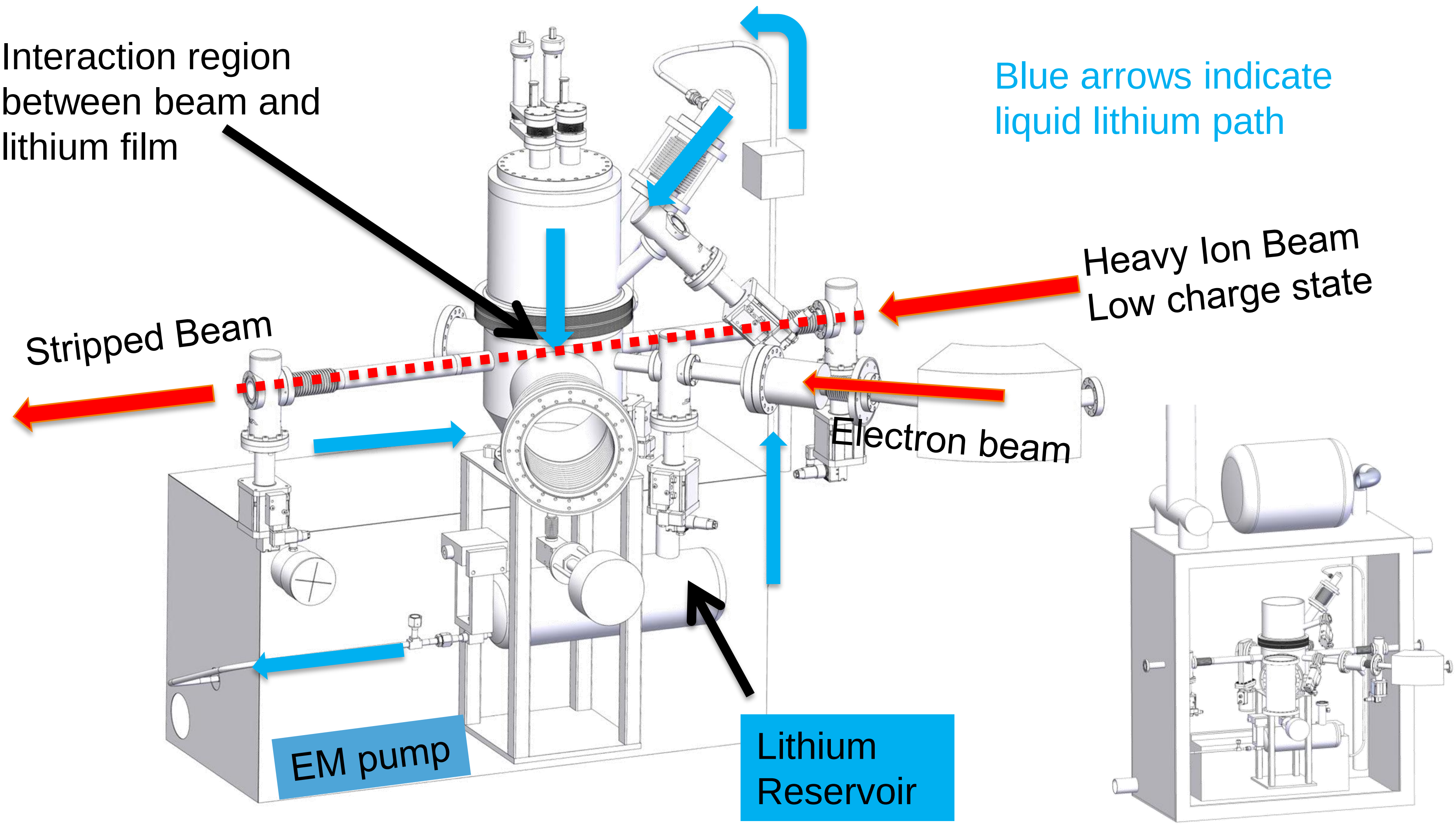


Y. Momozaki et al., JINST 4 (2009) 04005

Next steps in liquid lithium stripper development for FRIB

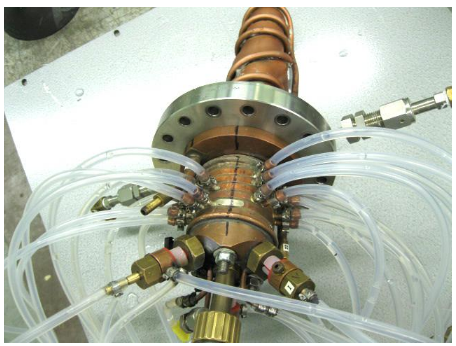
- Verify stability of liquid film when high power deposition from the beam is present (~700 W on a 3 mm diameter spot)
- We are re-commissioning the LANL LEDA ion source and LEBT to obtain the correct power deposition on lithium but with protons
  - 10 mA at 70 kV
- The source will then be moved to ANL to match with the lithium loop and test with beam
- H. Okuno (RIKEN) suggested that the lower density of Lithium could shift the average charge state of U to lower values than with the solid targets.
  - We performed a preliminary test at MSU with in situ evaporation but target inhomogeneity prevented a clean measurement
  - Will perform a second test at ATLAS (ANL) with different evaporation method

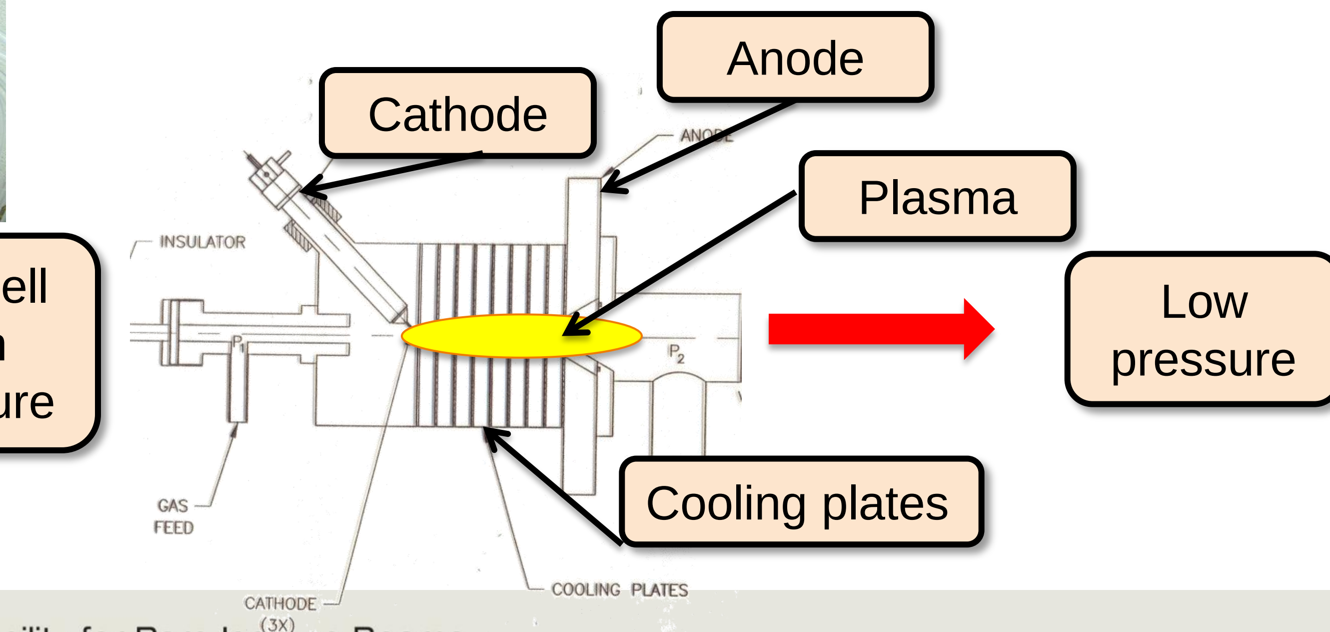
Liquid lithium prototype concept for FRIB



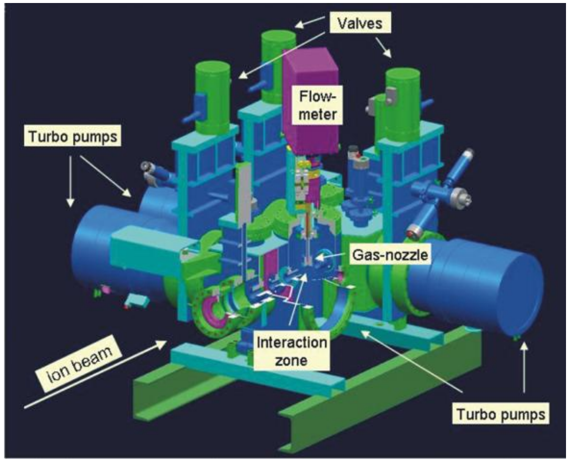
He gas stripper: Plasma windows to improve gas containment

- Developed by A. Hershcovitch (BNL) -Phys. of Plasmas, **5** (1998) 2130
- How does it work?
  - High temperature plasma compensates higher density on gas side **P=k(nT)**
  - Higher viscosity in the plasma due to high temperature





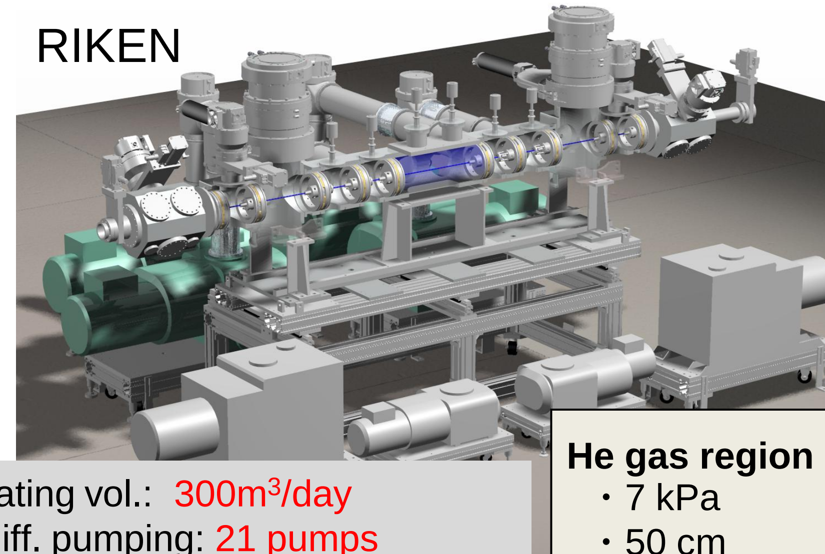
Why bother with plasma windows?



GSI

10 µg/cm^2

RIKEN



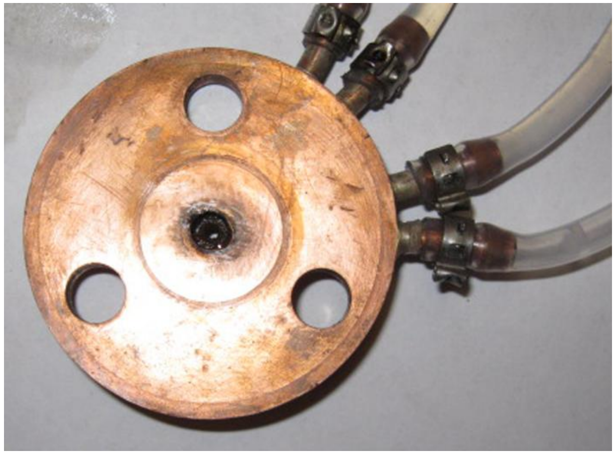
He circulating vol.: 300m^3/day
5 stage diff. pumping: 21 pumps
8 order pres. Reduction: 7 kPa⇒10^{-5} Pa

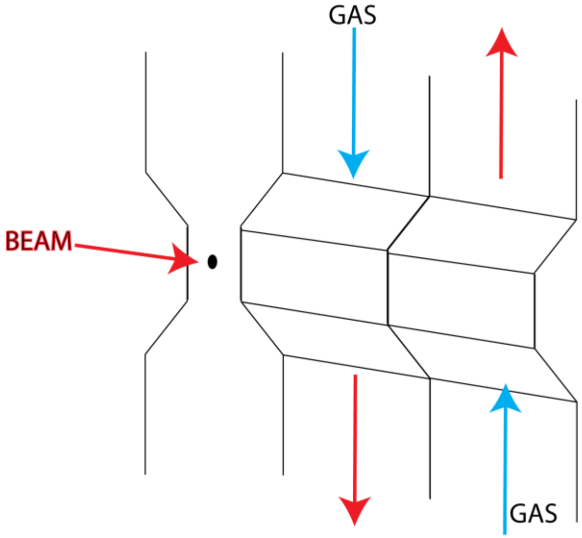
He gas region
- 7 kPa
- 50 cm
- 0.7 mg/cm^2

- FRIB alternative stripper expects to use a He gas target L= 30 cm at P > 1/3 atmosphere~ **35 kPa**, about **5 times higher pressure than RIKEN** and we must go down to **10^{-6} Pa** before reaching nearby SRF cavities. RIKEN is also experimenting with plasma windows
- Plasma windows provide the opportunity of decreasing significantly the conductance between the gas cell and the rest of the system

Experimental work at BNL for FRIB

- A. Hershcovith, P. Thieberger, L. Snydstrup, L. Cannizzo
- Experiments have been done so far with "old" plasma window plate design
- Conductance reduction = (pressure with plasma off)/(pressure with plasma on) on the low pressure side for 1/3 to ½ atmosphere in cell
- Achieved a factor **20** of conductance reduction in endurance tests (~20 hours)
- Achieved a factor **100** of conductance reduction in short (1 hour) tests
- Designing a new plasma window with larger aperture (6 mm instead of 3 mm) and higher cooling capacity plates
- Heating of the gas will produce low density "hole", compensate with counter flow and high velocity flow



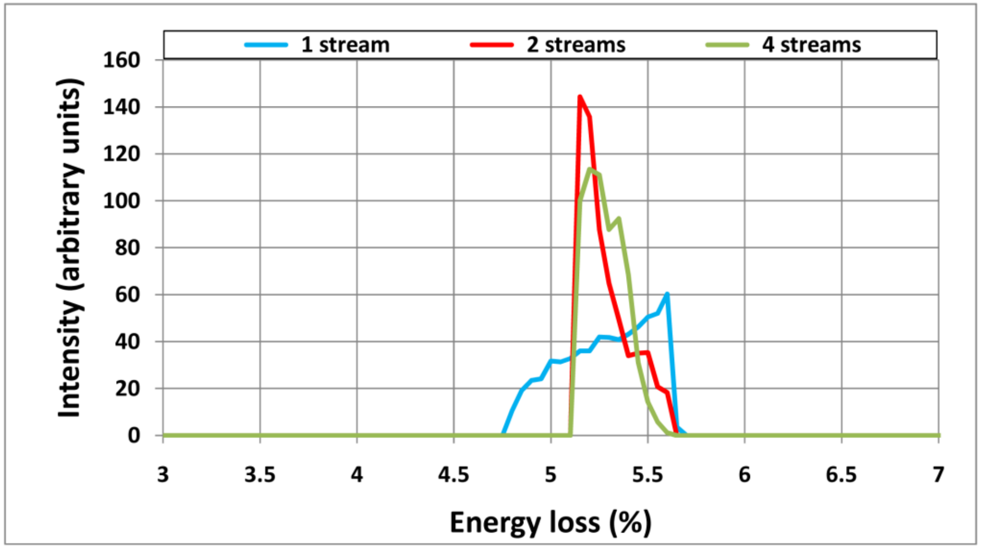


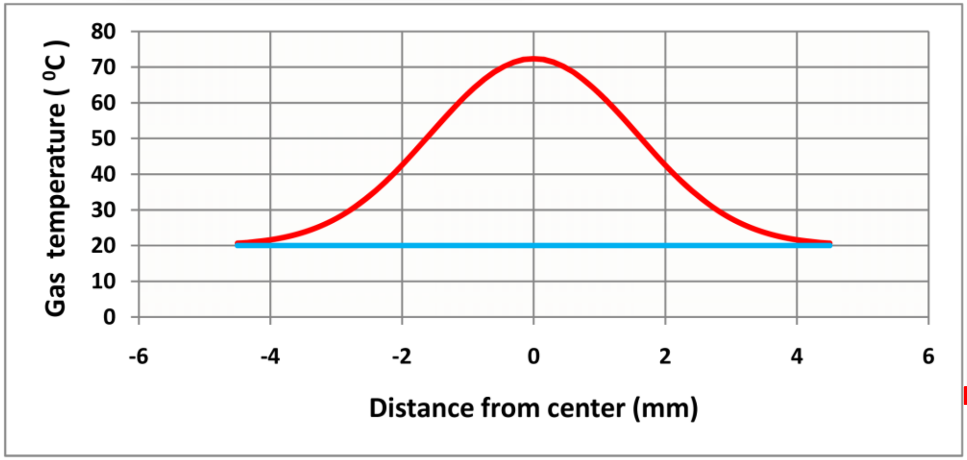
Power deposited in gas will change density
P. Thieberger (BNL)

Input

Stripper thickness (mg/cm^2)	1.7
Total stripper length (cm)	30
He gas velocity (m/s)	120
Input gas temperature (^{0}C)	20
Effective throat width (mm)	24
Beam intensity (particle μA)	10.3
Beam rms width (mm)	1.5

16.5 MeV/u U beam stripping in transverse He streams.





Calculated

Beam power	40.4	kW	
Power loss in He	2.14	kW	
He gas pressure	0.35	atm	
He mass flow rate	49.0	g/s	0.108lb/s
He flow rate at STP	298.3	l/s	10.53cft/s
Flow rate at input T and P	864.0	l/s	30.51cft/s

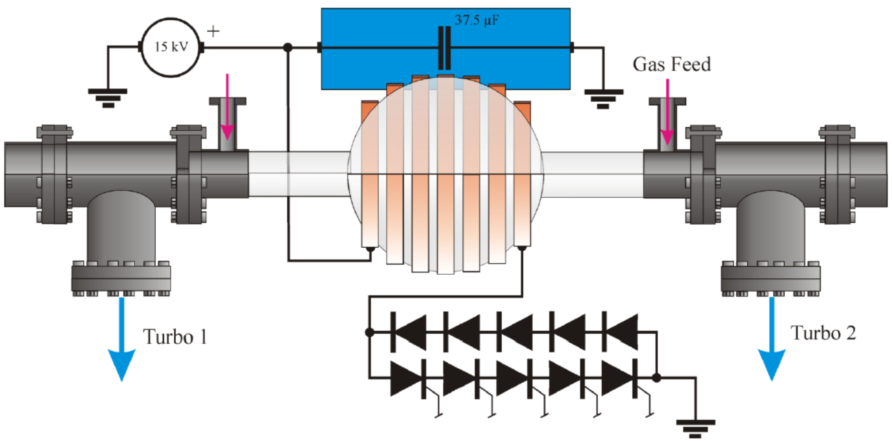
Why plasma strippers?

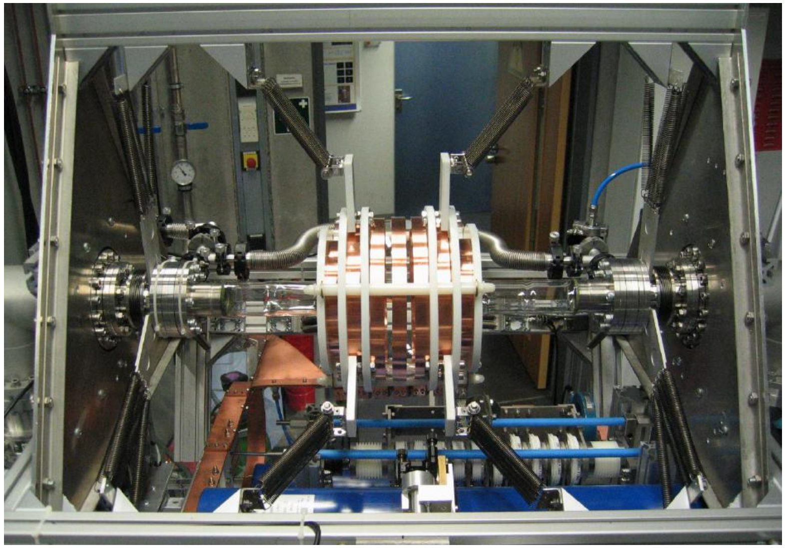
- The ion charge state is determined by the equilibrium between ionization and recombination during the traversal
- The direct capture of a free electron by a moving ion violates the simultaneous conservation of energy and momentum. The excess binding energy must be taken away by radiative recombination, 3-body recombination or dielectronic recombination, all low probability processes
- This restriction lowers the electron capture cross section compared to the bound electron case increasing the charge of the ion compared with a cold target. This effect is more important at low energies. At higher energies the high relative velocity also depresses the capture process.

E. Nardi and Z. Zinamon, Phys. Rev. Lett., 49 (1982) 1251.

J. Jacoby et al., Phys. Rev. Lett. 74 (1995) 1550.

Scheduled plasma stripper experiment at GSI- 4 MeV/u U





- Charge state and energy loss of heavy ions after interaction with a θ-pinch discharge
  - Christian Teske, Ge Xu, Joachim Jacoby, Tim Rienecker – Frankfurt
- Objectives:
  - Plasma stripper device for high intensity ion beams
  - Achievable charge states of ions traversing through a q-pinch plasma

Path forward

- Several facilities in operation (RIKEN) or under construction (FAIR, FRIB) need strippers that will handle high power heavy ions
- Non-traditional strippers (high pressure thicker gas targets, liquid lithium films and plasma strippers) are being developed
- The main issue remaining to be answered is their stability under high power deposition
  - Will the gas target develop a hole?
  - Will the liquid film break up under the beam effect?
- We expect to get answers to some of this questions in the next couple of years. We should know more before LINAC 2014!

Acknowledgements

- Argonne National Lab. (USA)
  - J. Nolen, D. Chojnowski, Y. Momozaki, C. B. Reed, J. Specht
- BNL (USA)
  - A. Hershcovitch, L. Snydstroup, P. Thieberger
- Frankfurt
  - J. Jacoby
- GSI (Germany)
  - W. Barth, O. Kester, M. Tomut
- LANL (USA)
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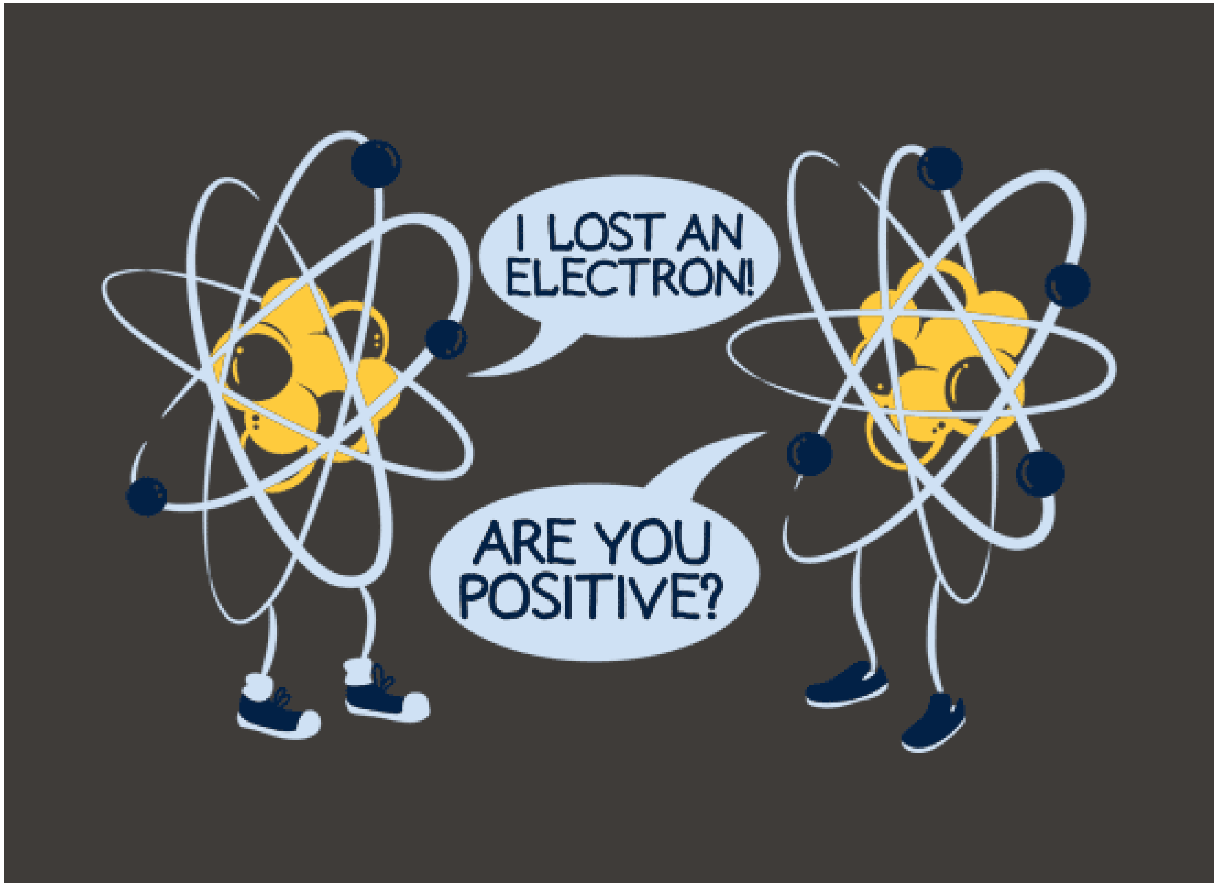
- RIKEN (Japan)
  - H. Okuno, H. Kuboki, H. Imao, H. Kasebe
- MSU
  - P. Guetschow, W. Mittig and T. Xu
- And others I am missing…

- Thank you for your attention



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