Cyclotron Gas Stopper and Advanced Low-energy Ion Transport Techniques

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Outline

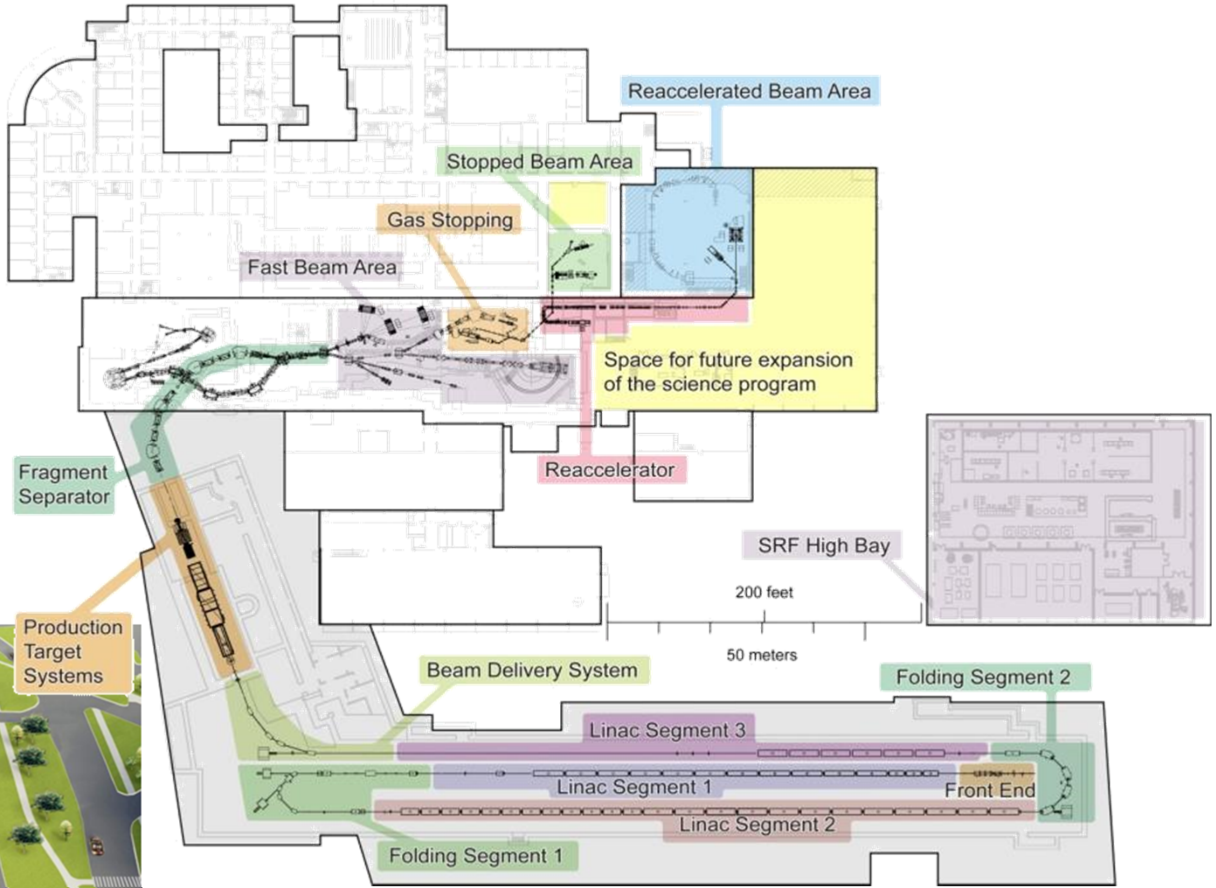
- **Stopped beams from projectile fragmentation at NSCL**
- **Cyclotron gas stopper development**
  - **Simulations in support of final design**
- **Advanced low-energy ion transport techniques**
  - **Ion surfing**
  - **Ion conveyor**

Keywords: rare isotopes, gas stopping, thermalization, ion surfing, ion conveyor

Thanks to
G. Bollen, M. Brodeur, D.J. Morrissey, R. Ringle, S. Schwarz

FRIB - Facility for Rare Isotope Beams at MSU
World-leading next-generation rare isotope beam facility

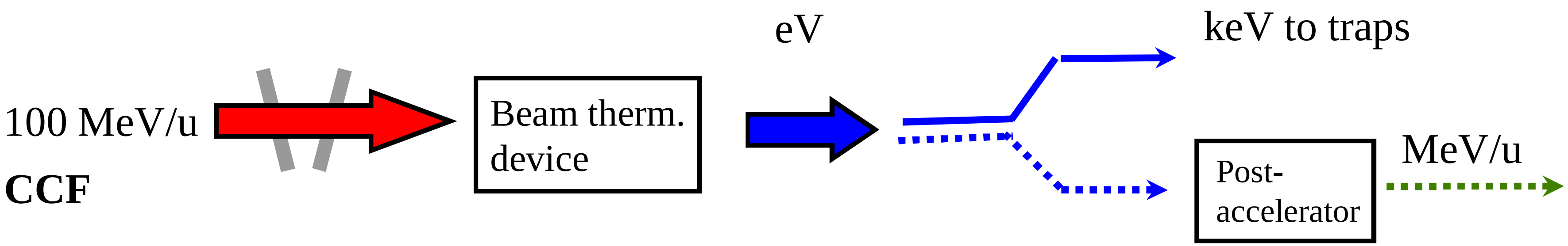
- Rare isotope production via in-flight technique with primary beams up to 400 kW, 200 MeV/u ^{238}U
- Fast, stopped and reaccelerated beam capability



Stopping and Manipulation of Ions (SMI) needed for science at NSCL and FRIB

The role of beam thermalization devices

Beam thermalization devices converts RIB produced by projectile fragmentation into low-energy high-quality beams.

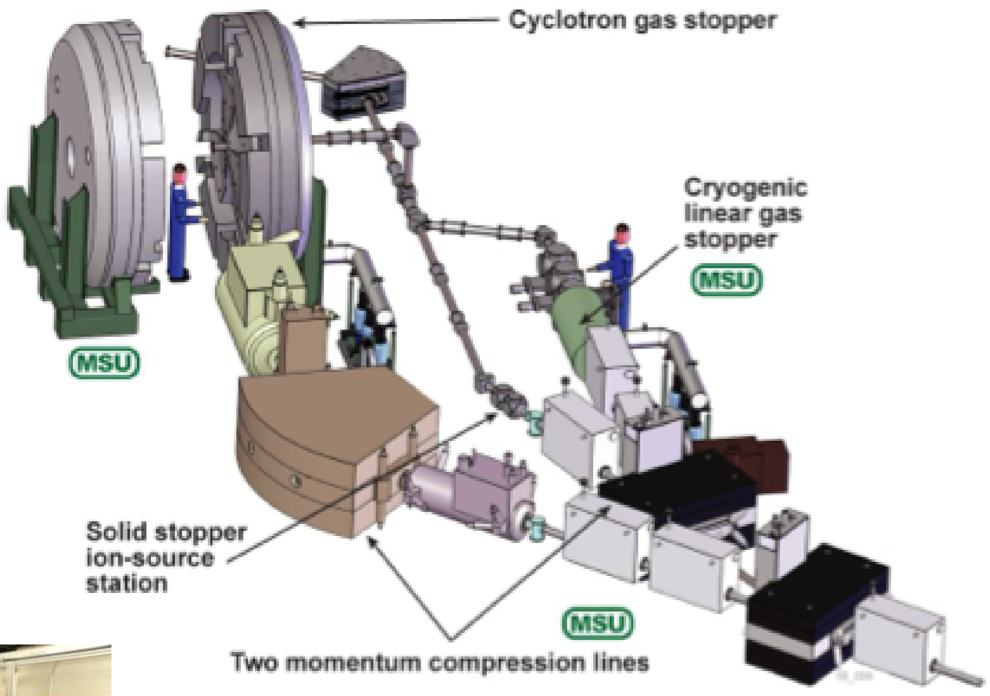


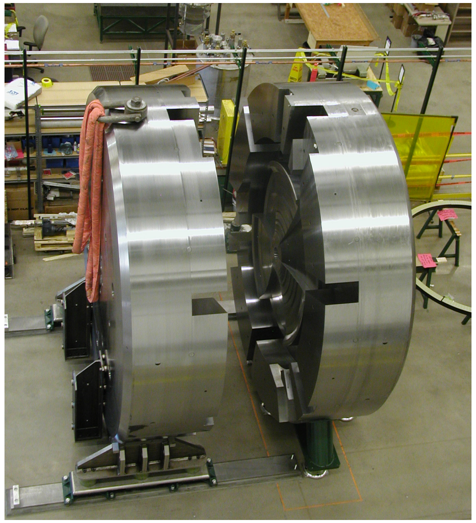
These high-quality beams will either be sent to:
- Traps (the LEBIT mass measurement Penning trap)
- Laser spectroscopy (BECOLA)
- Re-accelerated beam experiments

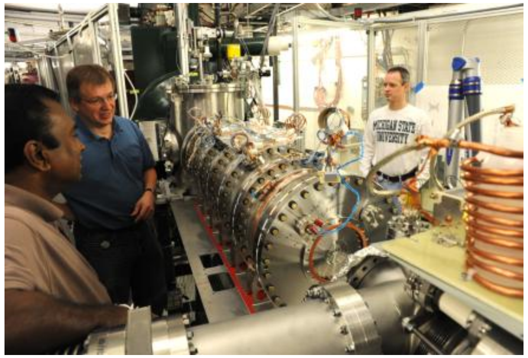
Therefore, beam thermalization devices will be a key step for the delivery of RIB to nuclear science experiments.

Beam Stopping

- Multi-facetted beam stopping approach
  - Cyclotron gas stopper
    - Lighter ions, 10^8/s
  - Relatively low gas pressure
  - Solid Stopper

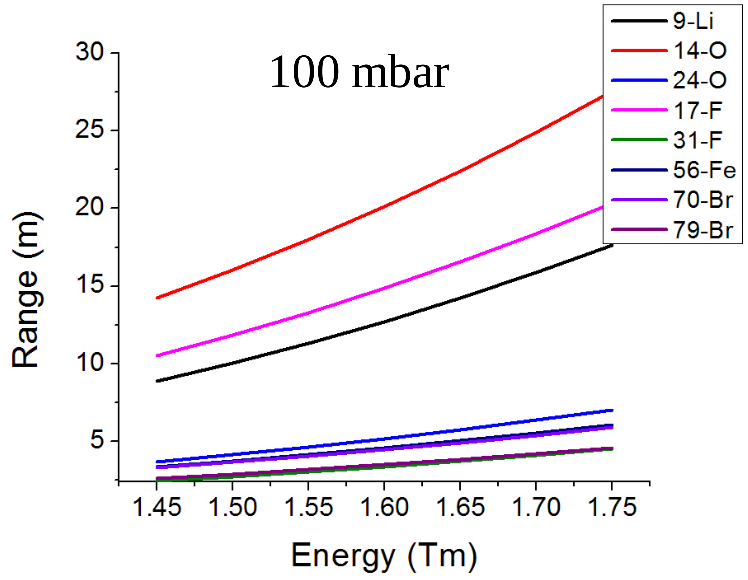






Gas stopper / catcher
- low angular straggling
- Traditional → Linear Gas cell with RF fields

Cyclotron Stopper



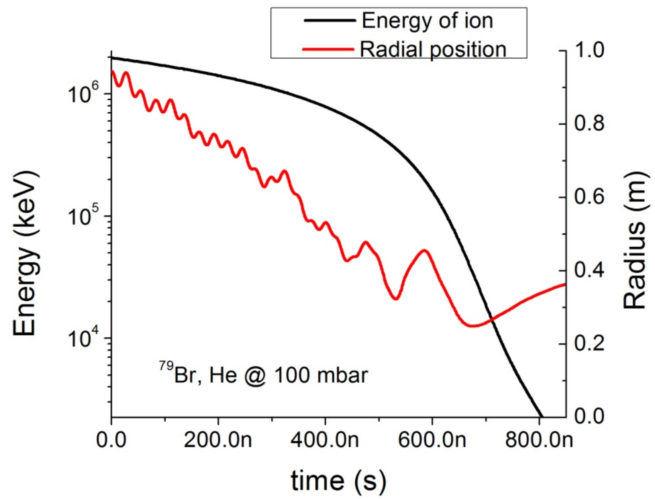
$$\rho = \frac{p}{Bq} = \frac{\sqrt{2mE}}{Bq}$$

How it works

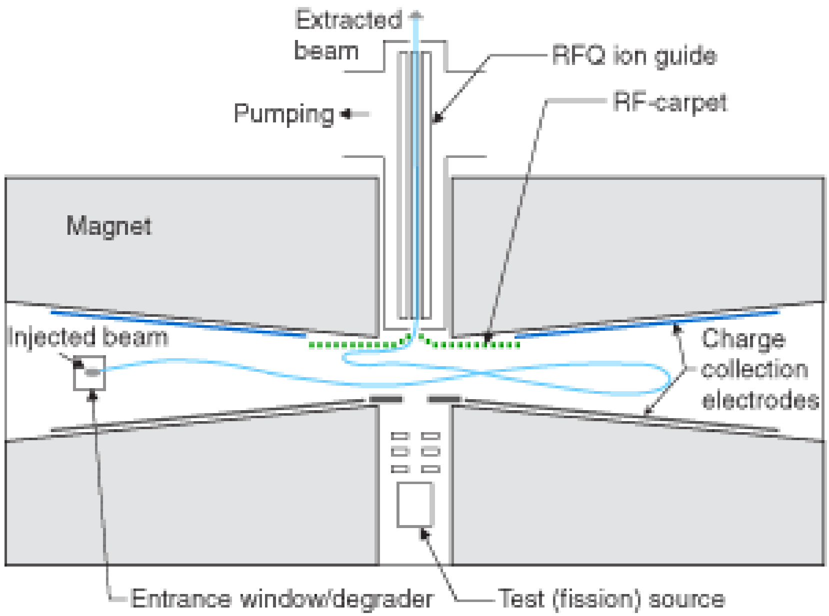
- Energetic ions injected on large radius
- Energy lost due to interaction with gas
- Inward spiral motion of ions
- Carpet-based transport to center
- Axial extraction of ions

Advantages:

- Low space charge due to bigger cell volume
- Stopping region and ionization region are separable → better extraction



Cyclotron Stopper
From Concept to Final Design



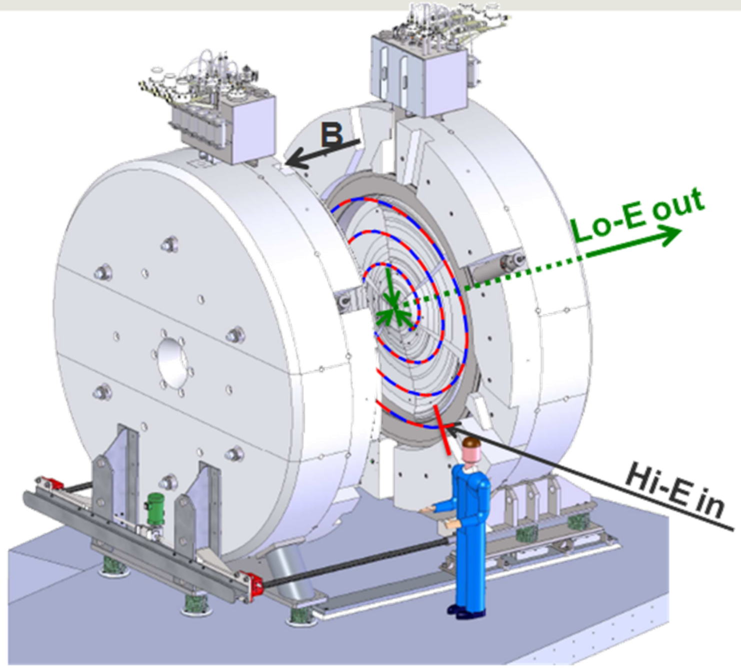
Focusing cyclotron magnet – gas-filled chamber
Stopping not range limited

G. Bollen, D.J. Morrissey, S. Schwarz, NIM A550 (2005) 27

G. Bollen et al., NIM B266 (2008) 4442

M. Sternberg. G. Savard, NIM A 596 (2008) 257

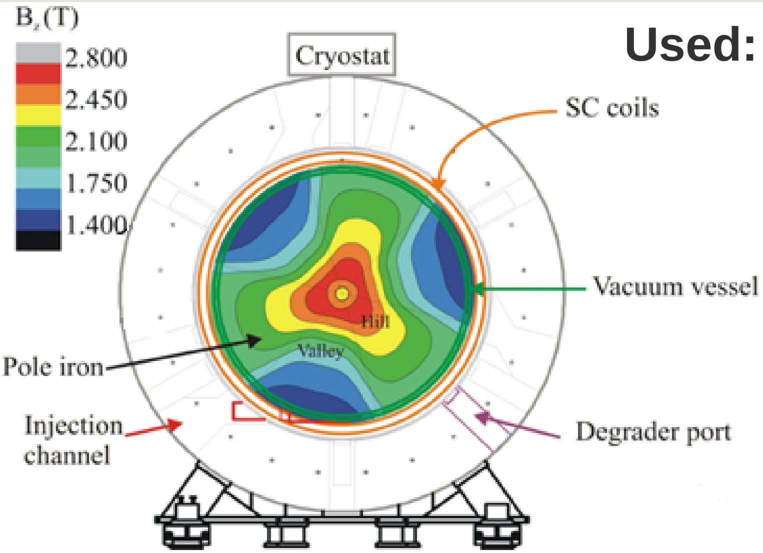
Related work:
- Decelerate antiprotons: J. Eades and L. M. Simons, NIM A 278 (1989) 368
- Proposal to stop lighter ions: I. Katayama et al., HI 115 (1998) 165



Warm iron superconducting cyclotron dipole
2 superconducting coils, iron dominated

Magnetic field (max)	2.7 T
Six sectors, 3hills / 3valleys, k = -0.28	
Diameter	3.8 m
Injection radius	0.95 m
Axial gap	180 mm
Beam rigidity	2.6 Tm → 1.6 Tm

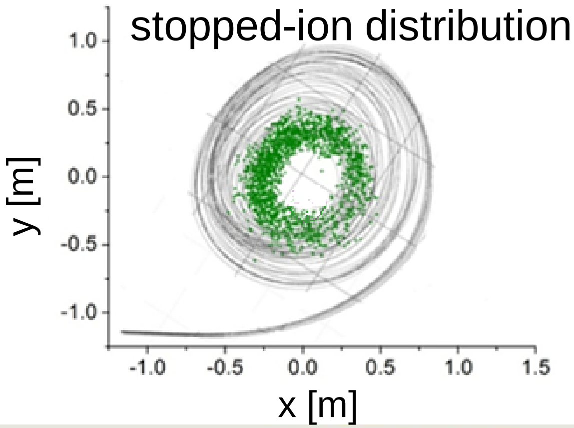
Cyclotron Gas Stopper
Detailed Stopping Calculations



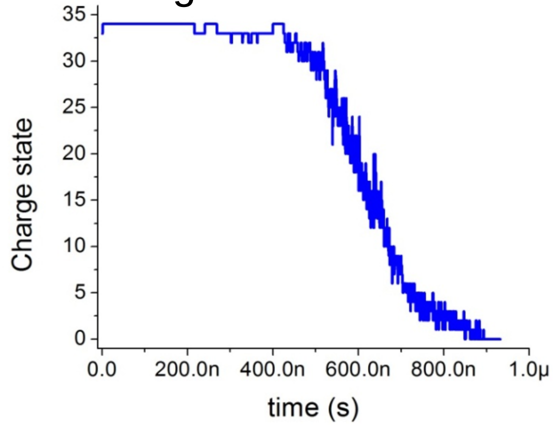
Used:
- + Magnetic field (TOSCA 3d)
- + Relativistic ion motion
- + Energy loss by collisions with buffer gas:
  SRIM, stopping and range tables
- + Improved charge exchange:
  hi-energy: ETACHA,
  lo-energy: combination of formula
  interpolate between extremes
- + Small-angle-scattering (Amsel's framework)
- + Energy loss at degrader: ATIMA

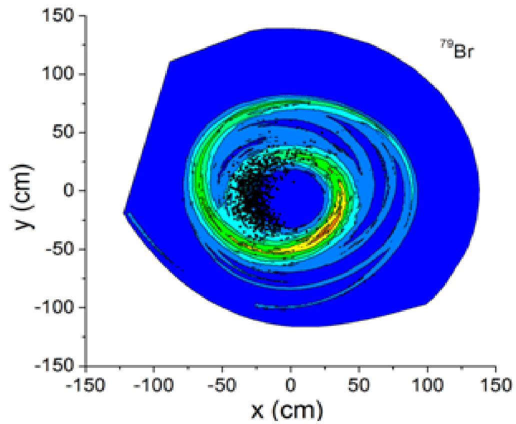
Cases: ^{9}Li, $^{14,24}O$, $^{17,31}F$, $^{24,40}Si$, $^{56,70}Fe$, $^{70,79}Br$, ^{127}I

^{79}Br trajectory and stopped-ion distribution

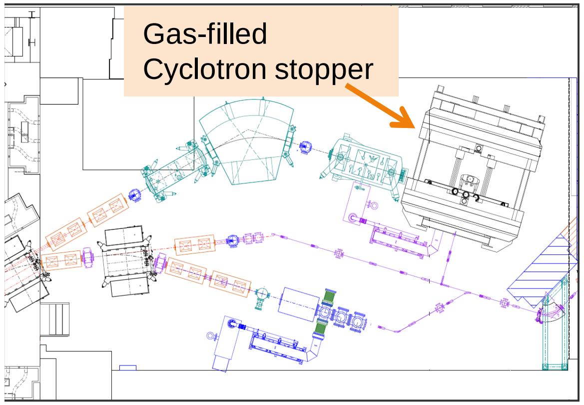


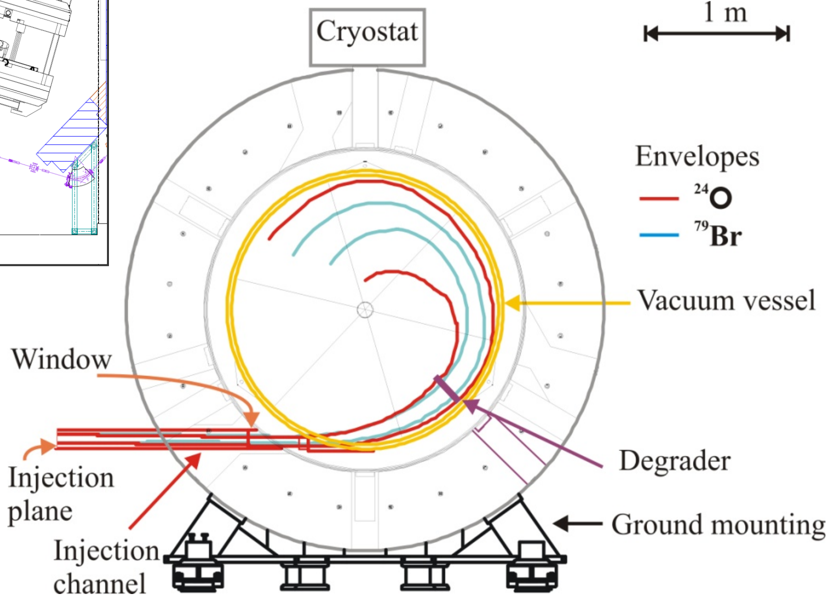
Charge-state evolution

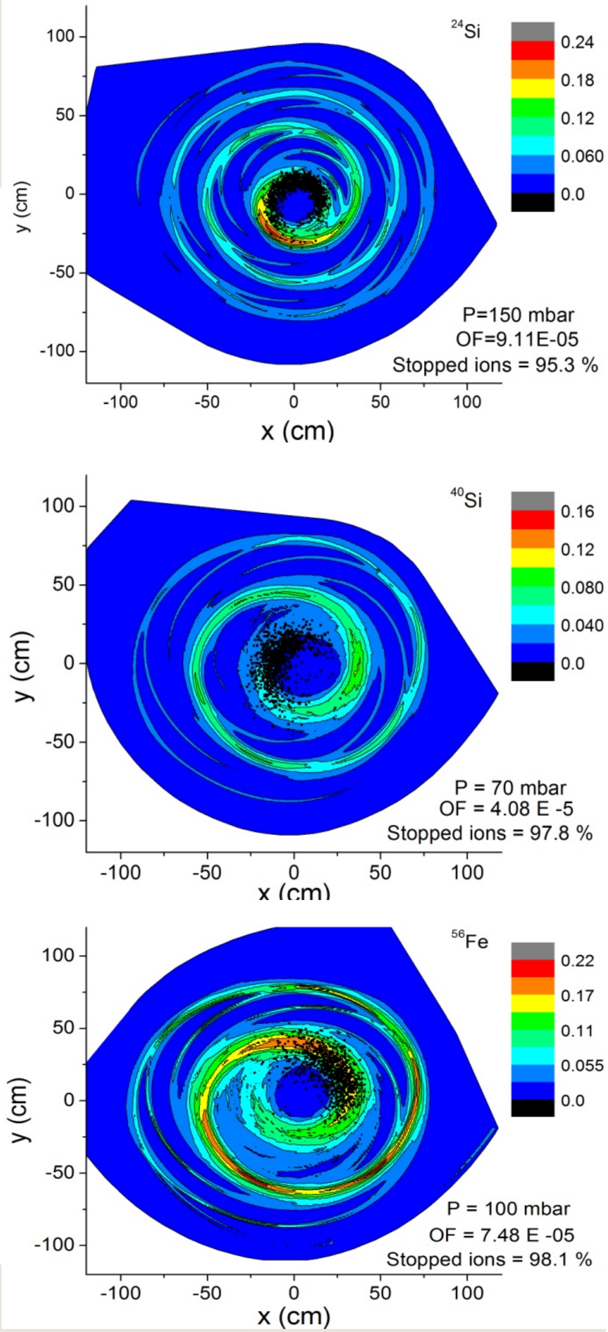




Cyclotron Gas Stopper
Stopping Calculations





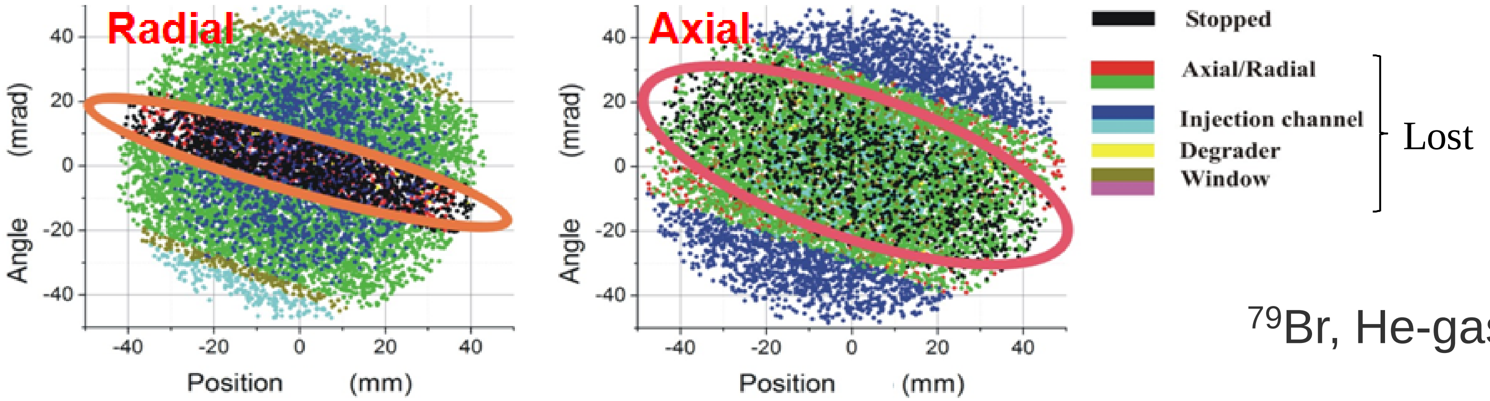


- Taken into account in detail
  - Beam properties after momentum compression
  - Optics of injection channel
  - Vacuum chamber boundaries

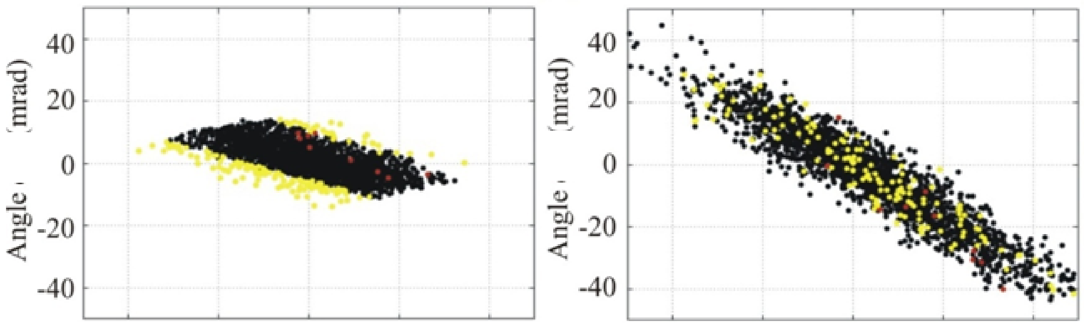
NSCL FRIB

Cyclotron Gas Stopper
Acceptance and Stopping Efficiency

Ninad Joshi,
Stefan Schwarz



^{79}Br, He-gas @ 100mbar



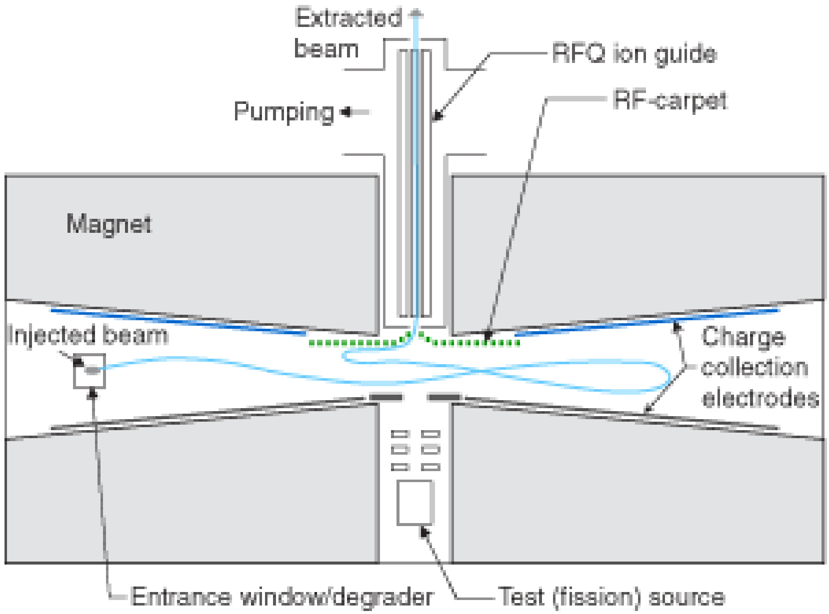
← LISE++ output phase spaces, transport matched to stopped-ion distributions above TRANSPORT code

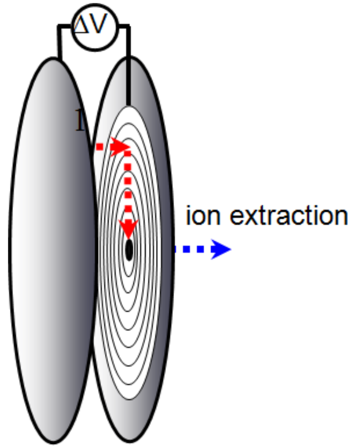
Ion	Radial ***Acceptance*** **CycStop**	Radial ***Emittance*** **LISE++**	Axial ***Acceptance*** **CycStop**	Axial ***Emittance*** **LISE++**	Efficiency
79Br	897	227	1190	424	98.1%
56Fe	740	153	1165	419	96.9%
40Si	853	336	1187	1098	86.5%
24O	707	1550	1179	1038	64.9%

→ High acceptance (~**700-1000 π mm rad**)
→ High stopping efficiency
→ Stopping area r<0.5m

NSCL FRIB

Cyclotron Gas Stopper
Ion Extraction

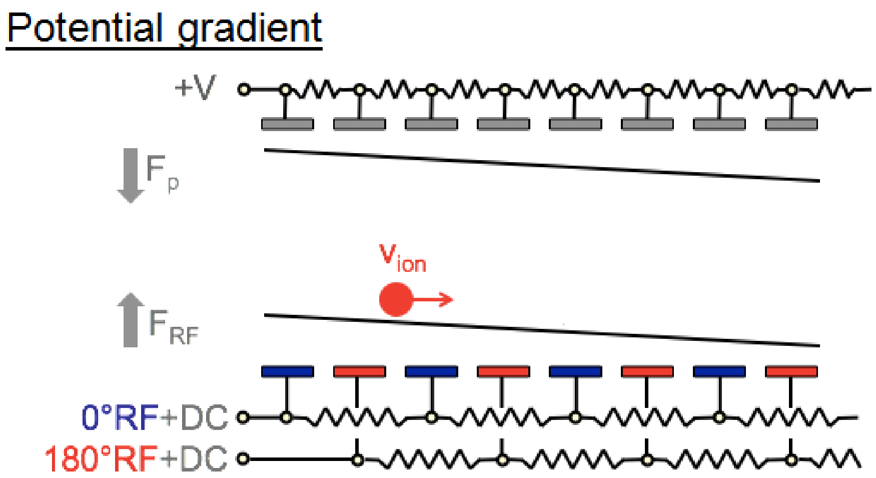




Requirements:
Fast and efficient transport over distance of 50 cm

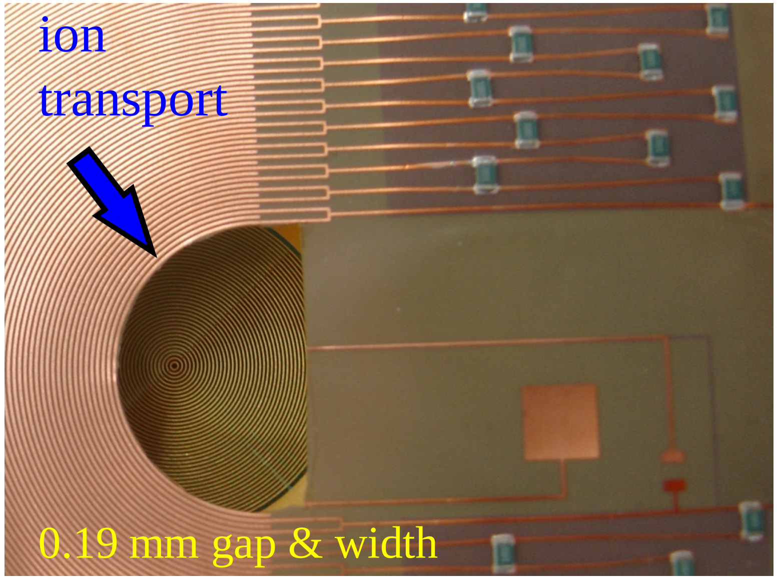
- Classical approaches, considered and partially tested
  - RF carpets with DC potential gradient
  - RF multipoles
- Challenges:
  - Maximum RF and DC voltages limited by discharges
  - Ion transport in strong magnetic field

Classical Ion Transport
RF Carpet with Potential Gradient

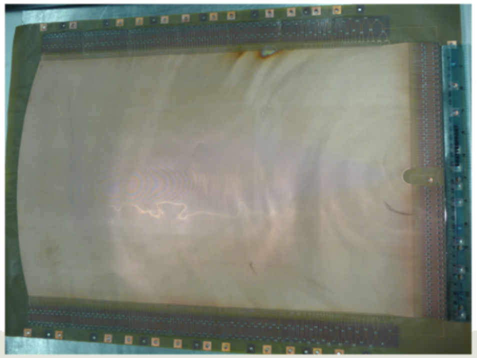


- Transport using potential gradient
- Complicated circuitry
- Drag field discharge-limited
  → limit on $T_{1/2}$ that can be extracted

*M. Wada et al., NIM A **204**, 570 (2003).*
*G. Savard et al., NIM B **204**, 583 (2003).*
*S. Eliseev et al., NIM B **266**, 4475 (2008).*
*M. Ranjan et al., EPL **96**, 52001 (2011).*



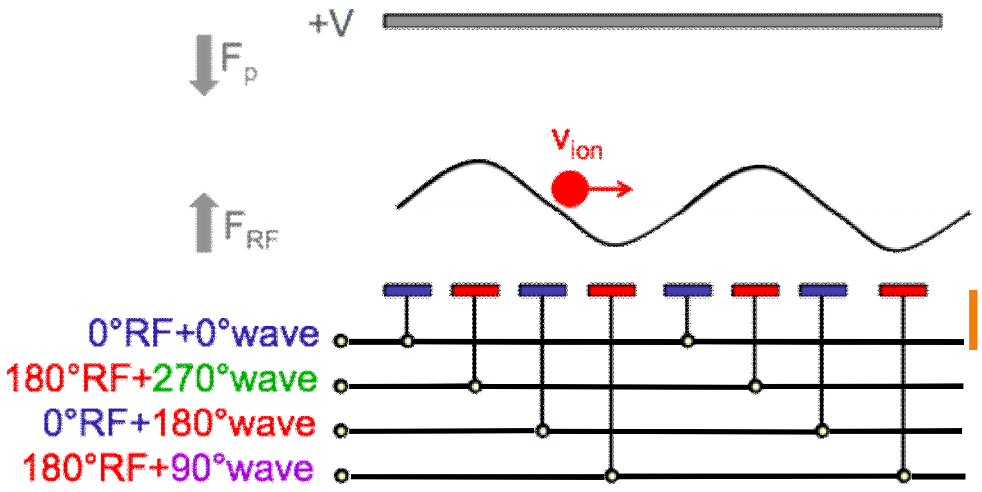
RF carpet with potential gradient for Cyclotron Gas Stopper fabricated, transport studied and demonstrated



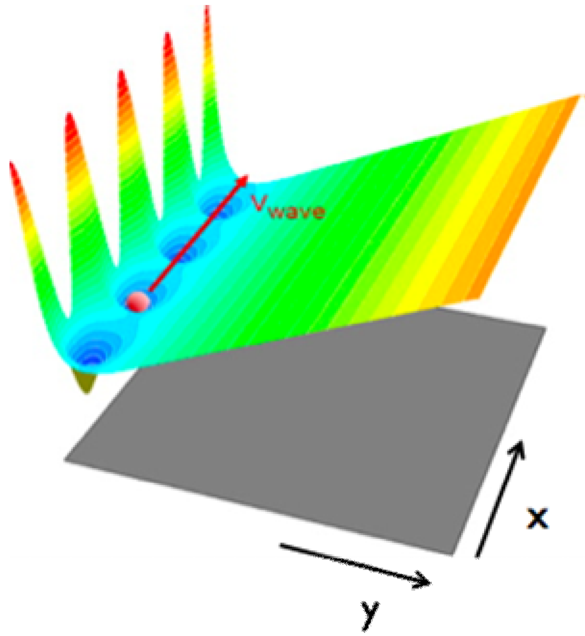
Advanced Ion Transport
Ion Surfing

Potential gradient replaced by a travelling wave

M. Brodeur



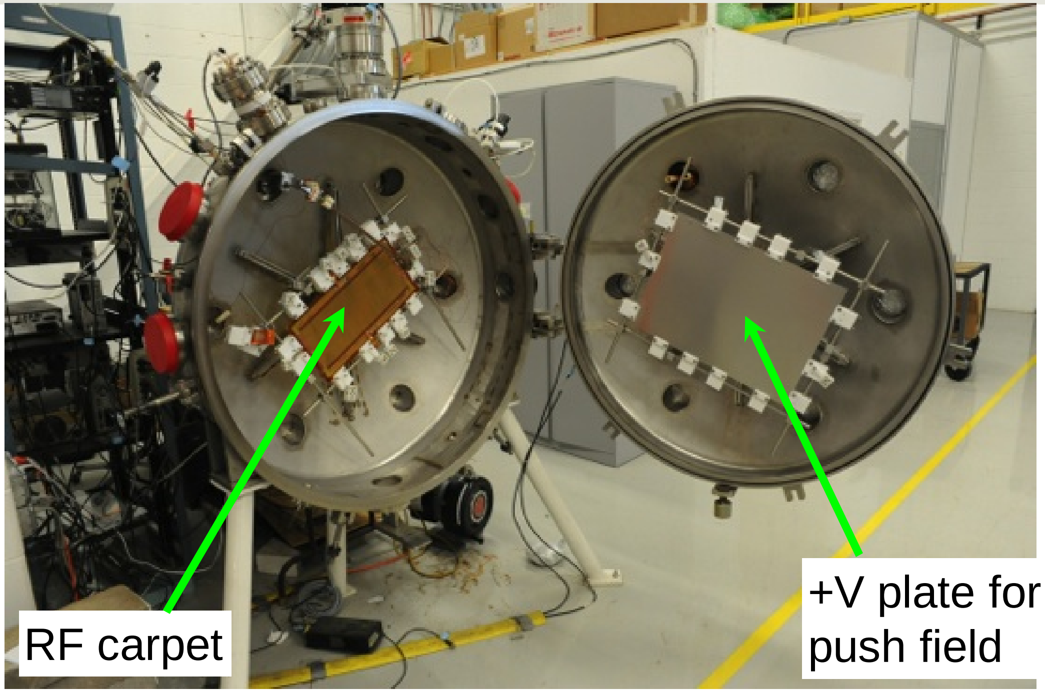
Snapshot of the pseudo-potential with traveling wave

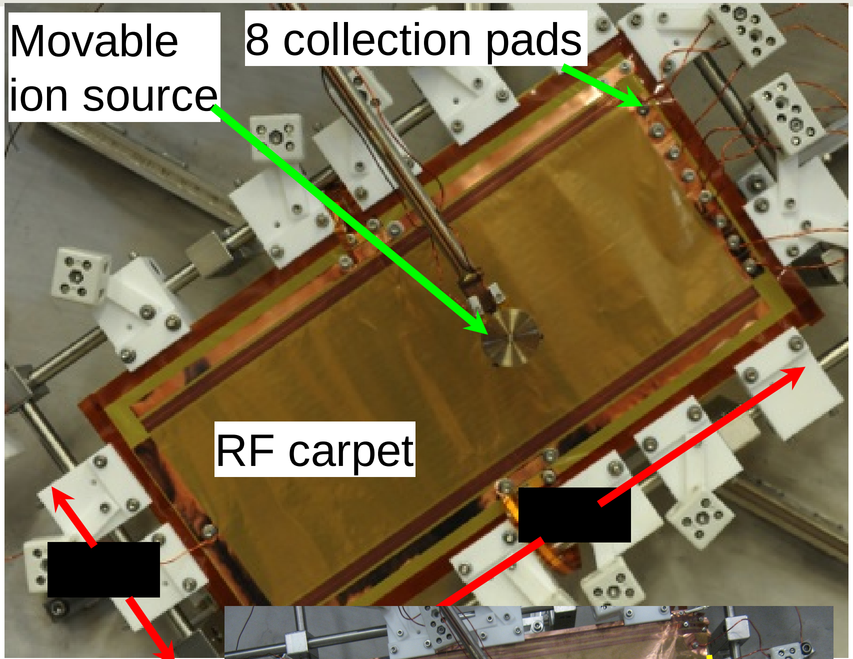


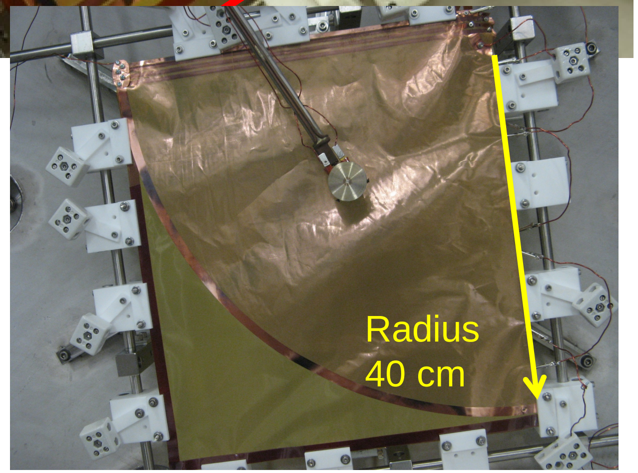
- Transport using travelling wave
- Simpler circuitry
- No high-voltage involved, ion speed not discharge-limited
  → can extract shorter-lived isotopes

G. Bollen, IJMS 299, 131 (2011)

Ion Surfing Demonstration
Test setup for RF carpet R&D

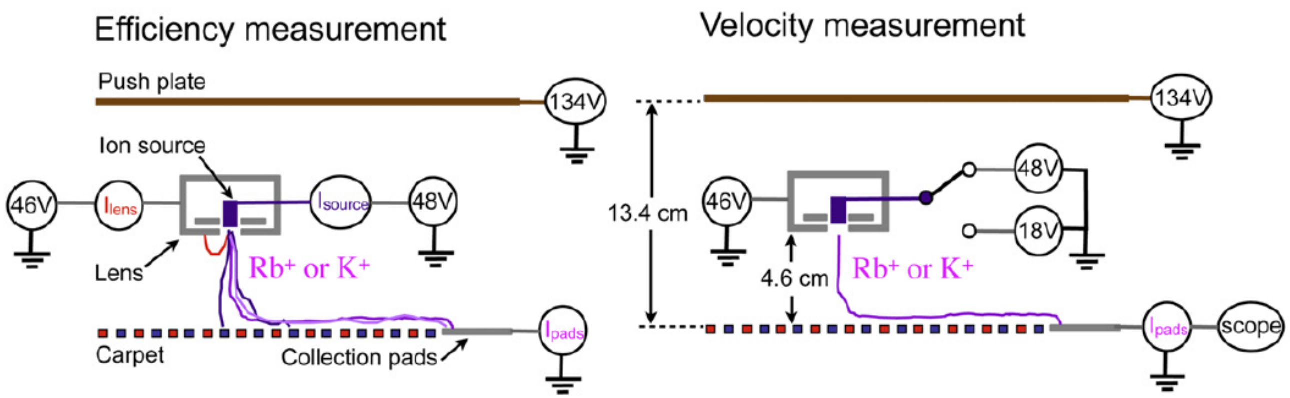






- Movable surface ion source
- Push field plate & RF carpet
- RF & traveling wave circuitry
- pA-meters to read transported ion current

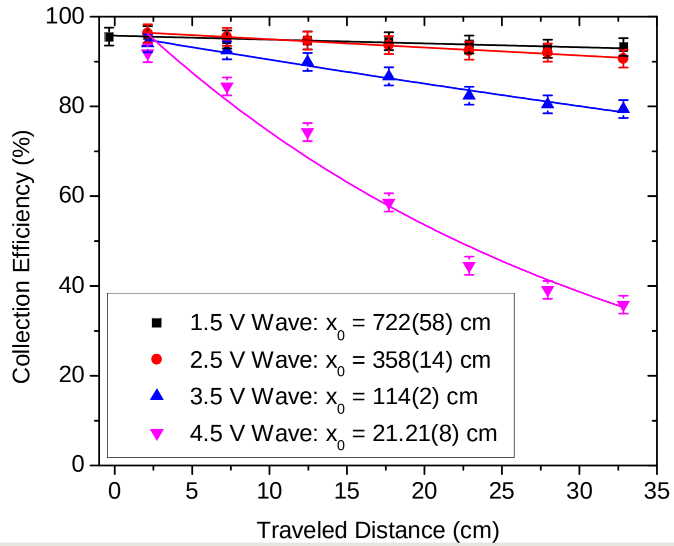
Ion Surfing Demonstration
Efficiency with Distance and Wave Amplitude



K^+, 80 mbar, 20 V/cm Push, 6.8 MHz RF, 75 Vrf, 60 m/s Wave

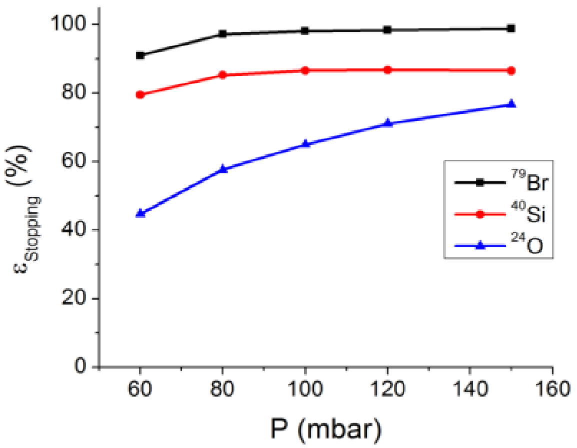
$$\eta_{coll}(x) = 2^{-x/x_0}$$

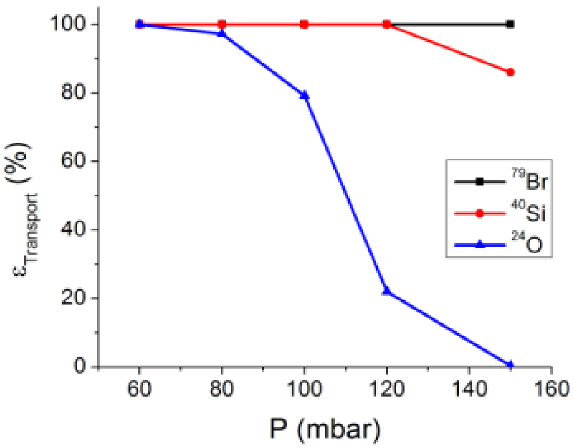
η= Collection efficiency
x = distance traveled
x_0 = “half distance”

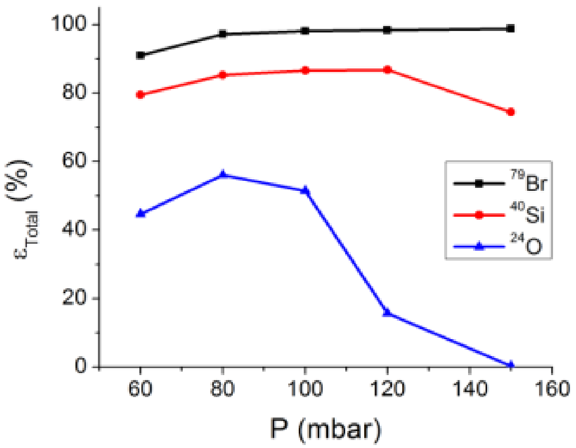


Cyclotron Gas Stopper
Expected Overall Efficiency

Efficiency predicted by simulations







Stopping * **Carpet transport** = **Total extraction**

Ion Transport after Extraction from Cyclotron Gas Stopper

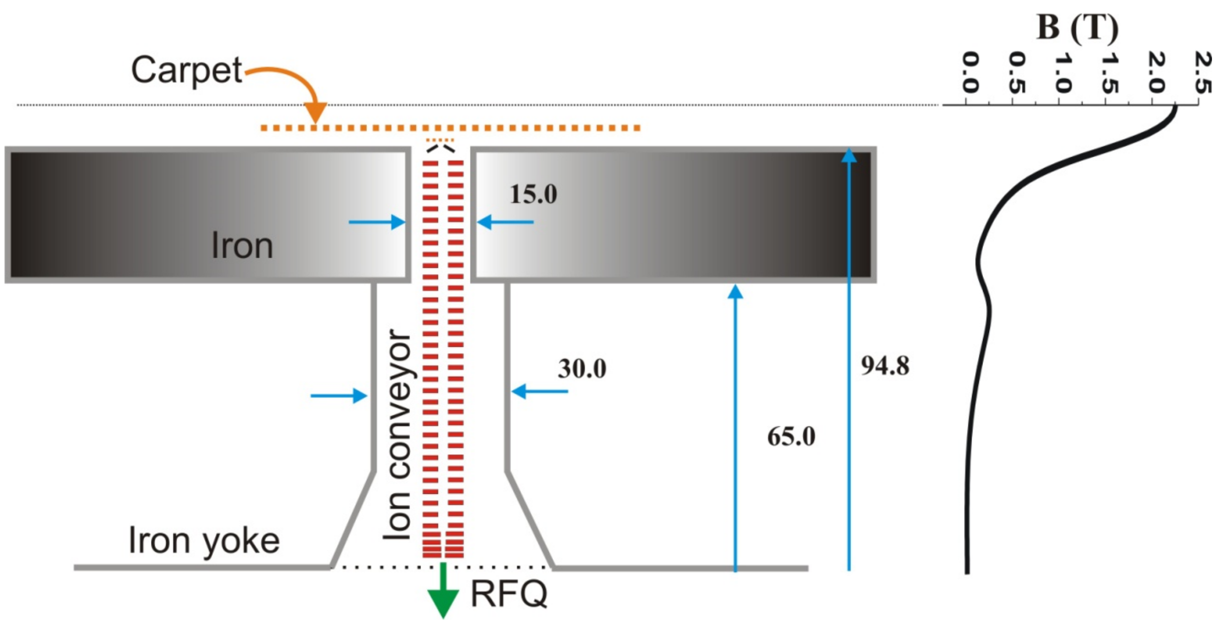
After leaving stopping region, need quick & efficient transport through magnet yoke.

<u>"Traditional" approach</u>:

- RFQ ion guide →
- RF funnel →

<u>Issues for the Cyclotron Gas Stopper</u>:

- Don't work well if magnetic field is along axis
- Pressure in region: 2 to 30 mbar limits voltages that can be applied for DC gradient, → slow extraction.



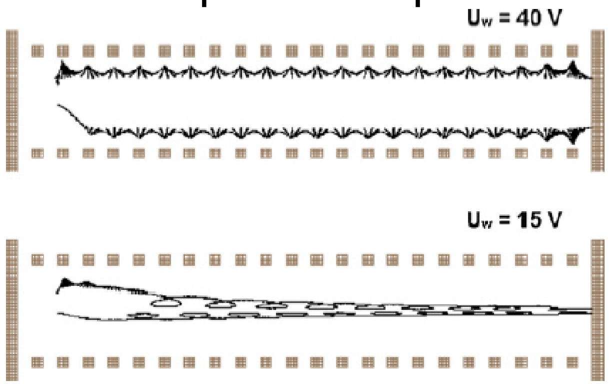
<u>Different approach needed</u>

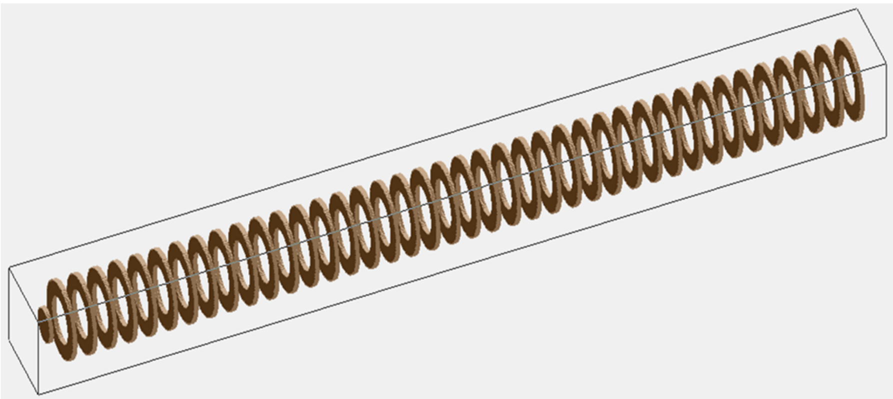
Ion Conveyor*

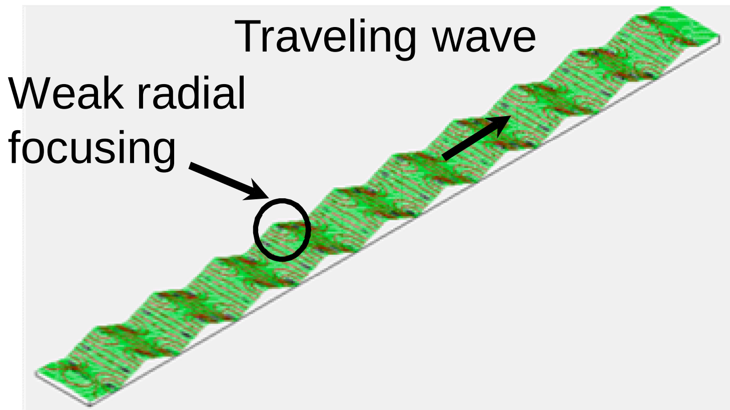
**) A.W. Colburn, EJMS 10, 149 (2004)*

- Use traveling wave in stacked cylindrical electrode system
  - Slipping mode to keep ions away from electrodes
  - No additional RF needed
- Longitudinal transport and transverse focusing
  - Longitudinal “transport” field that is visible in center
  - Sufficient transverse field strength to achieve focusing
  - Wave length comparable to diameter

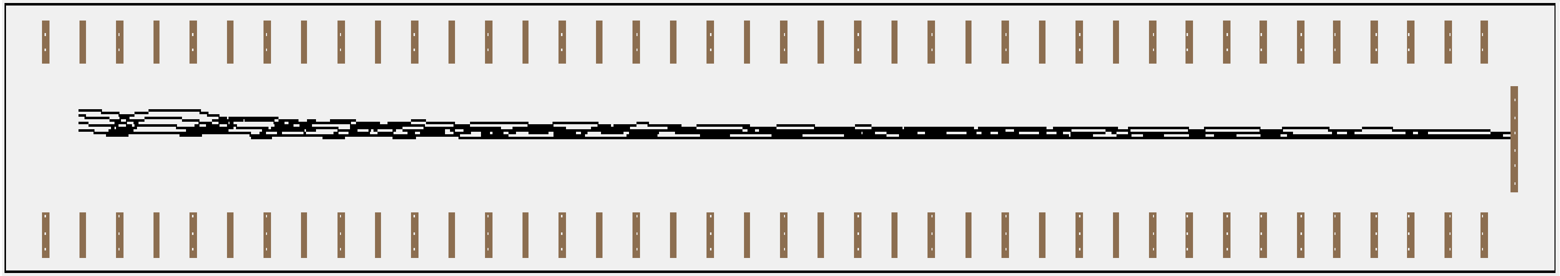
Motivated by ion surfing between planar carpets







Ion Squeezing
First Attempts

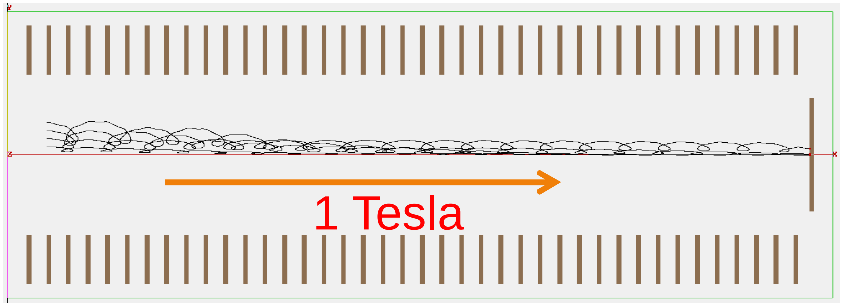


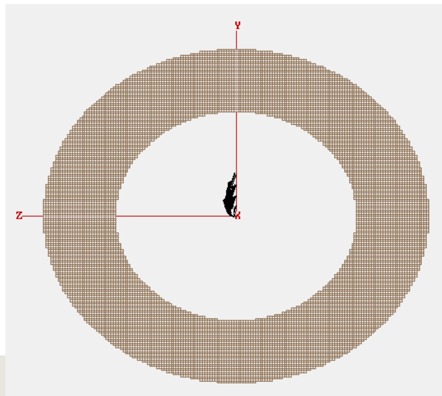
v_{avg} = 600 m/s

V_{wave} = 25 V

- Electrode structure:
  Inner radius 5 mm, pitch 5mm,
  period of 4 electrodes,
  length 180 mm
- Wave:
  Amplitude 25 V
  Frequency 100 kHz
  λ = 4*5mm
  → wave velocity = 2000 m/s
- Pressure: 5 mbar
- Ion: $^{39}K^{+}$

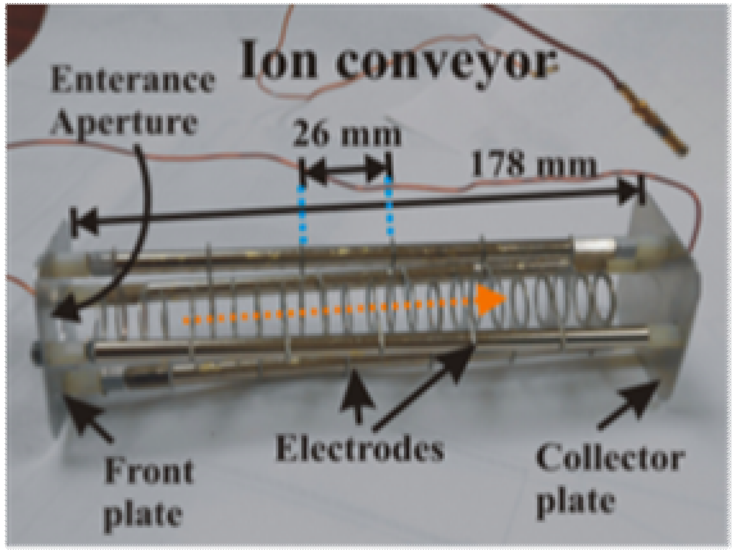
Effect of Magnetic Field is small

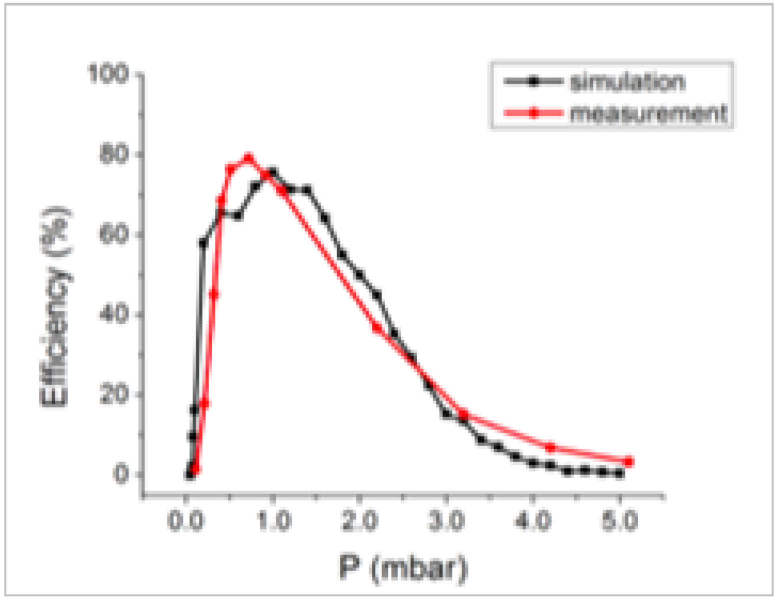




Ion Squeezing
First Prototype of Ion Conveyor

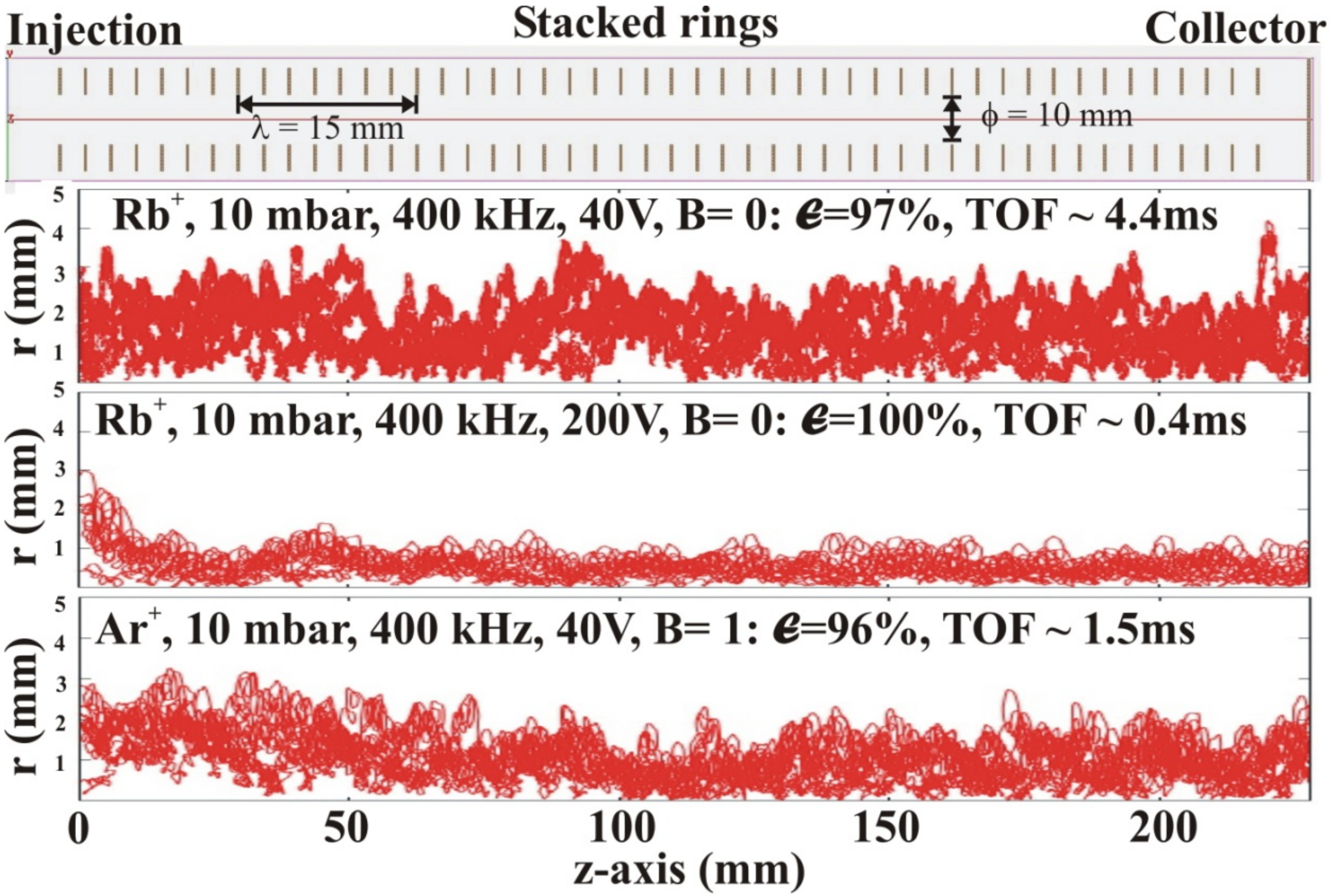
- 4 phases traveling wave, 19V max, up to 500 kHz
- Ring structure made on the fly from stockroom material
- Rb^+ ions from surface source





Good agreement between measured efficiencies and simulations including hard sphere collisions (IonCool code)

Ion Conveyor Detailed Simulations



v_{avg}=50 m/s

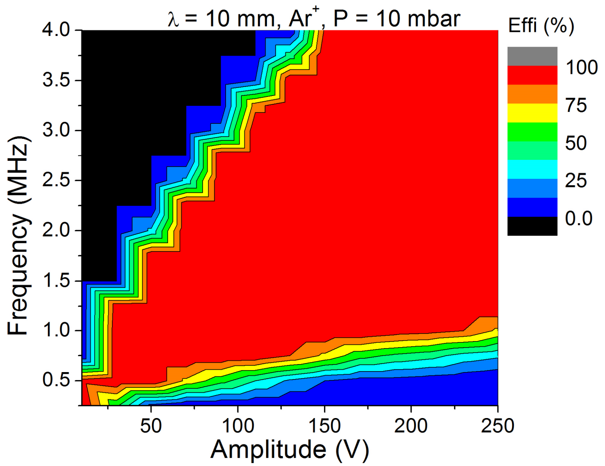
v_{avg}=500 m/s

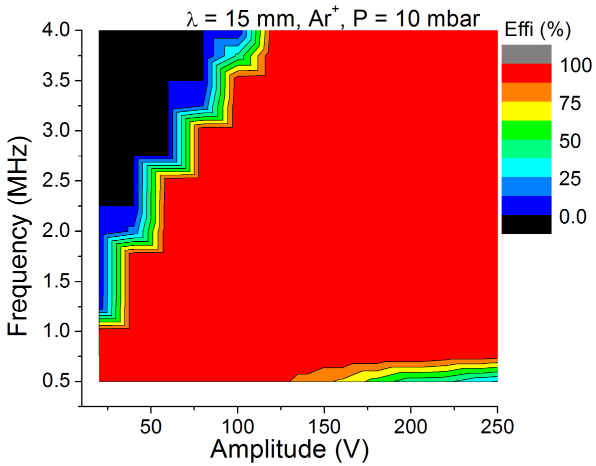
v_{avg}=150 m/s

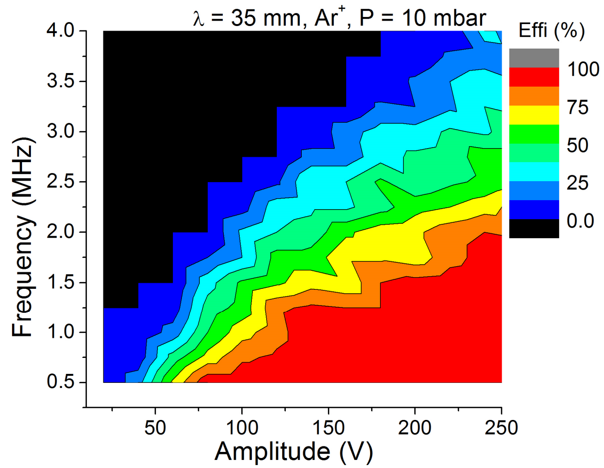
Ion Squeezing works well in mbar pressure range - fast and simple

Ion Conveyor Optimization

- Different structures
  - Radius
  - Wavelength
  - Electrodes per wavelength (= number of RF signals needed)
- Pressure range 2-20 mbar (10 mbar nominal operating pressure assumed)



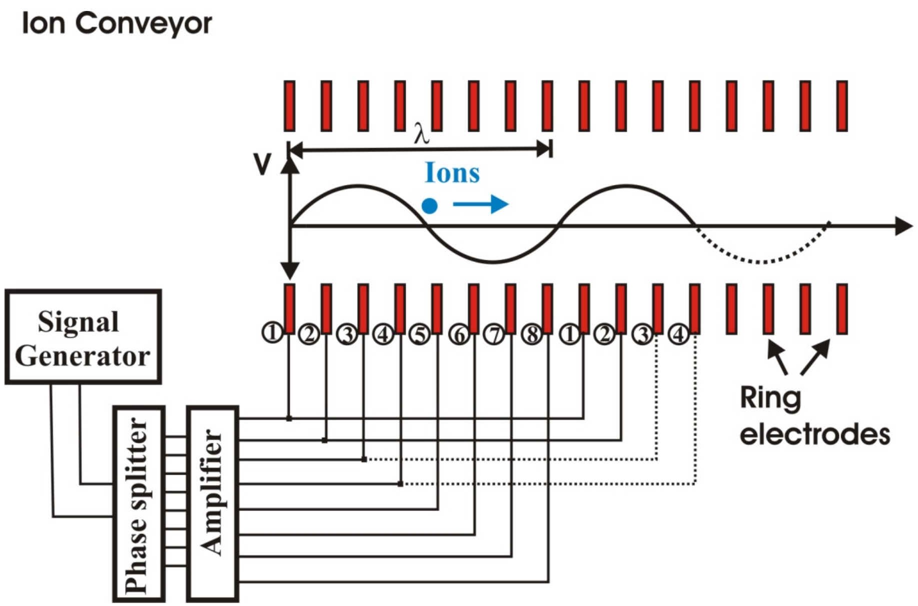


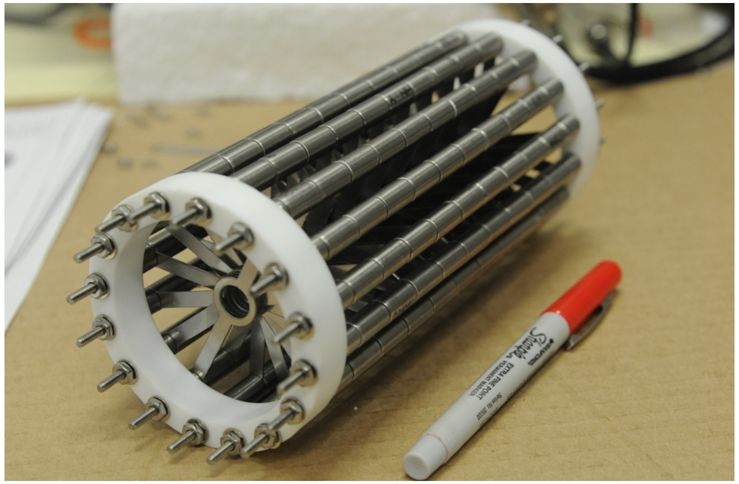


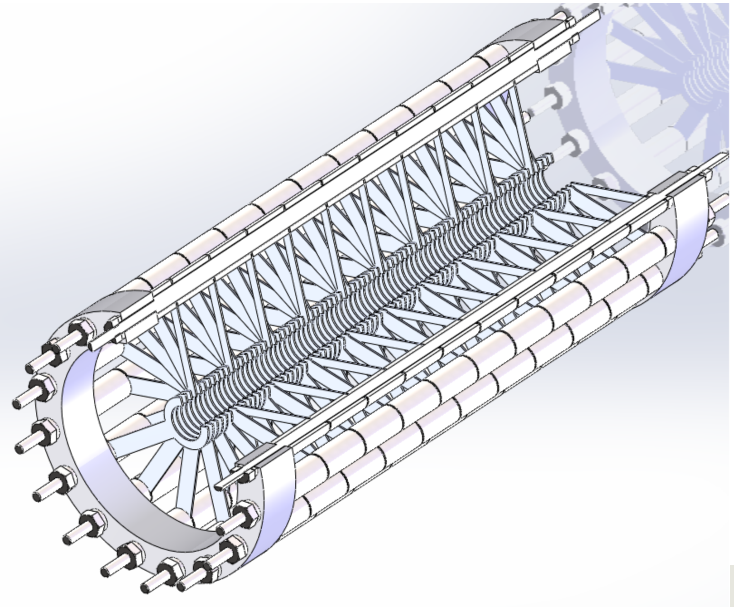
→ Ring diameter of 10 mm, wavelength 15 mm with 8 electrodes/period

Testing of Ion Squeezing
Final Prototype of Ion Conveyor

- Designed ion conveyer
  - 10 mm diameter
  - λ= 15mm
  - 8 phase traveling wave
- Prototype assembled and under test



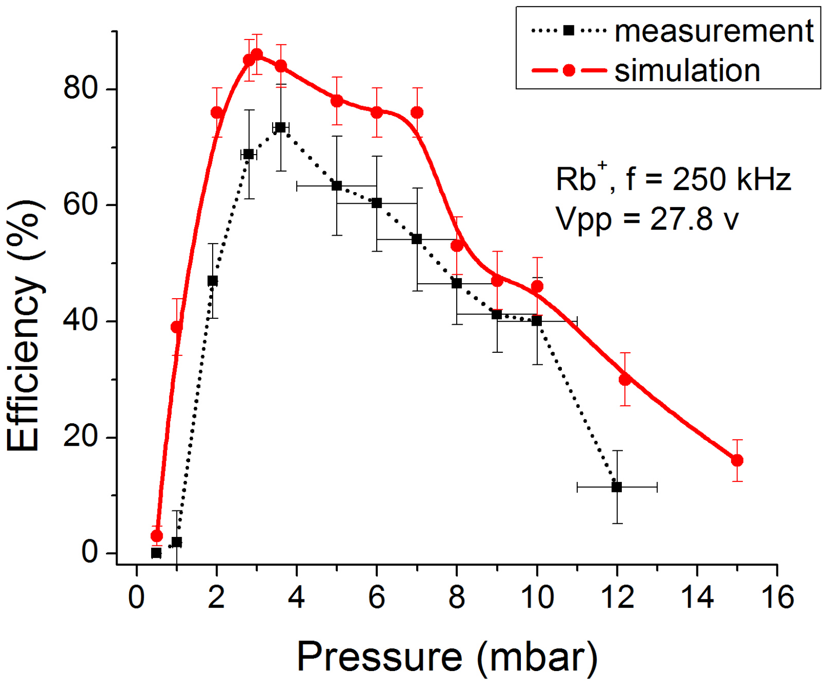


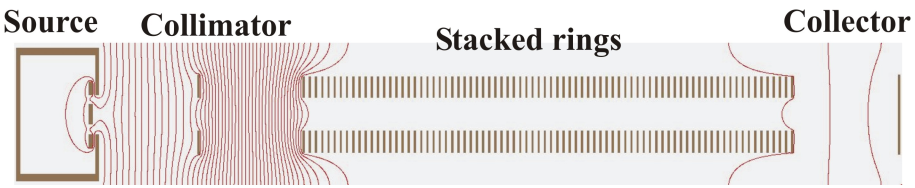


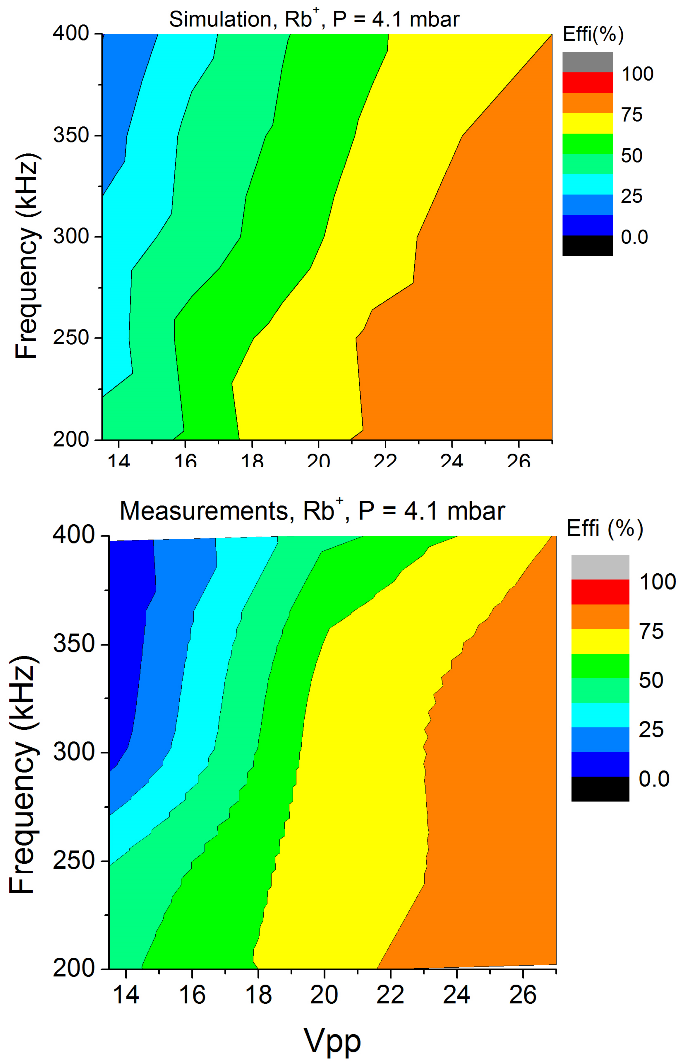
Ion Conveyor experiments

Good a agreement between experiment and simulations

Efficiency includes losses at injection

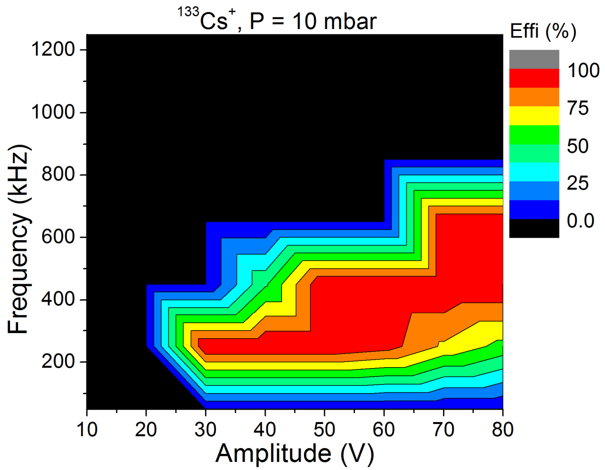


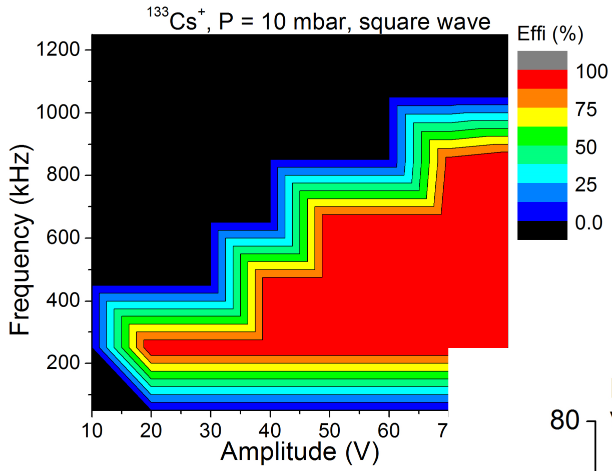




Square Wave

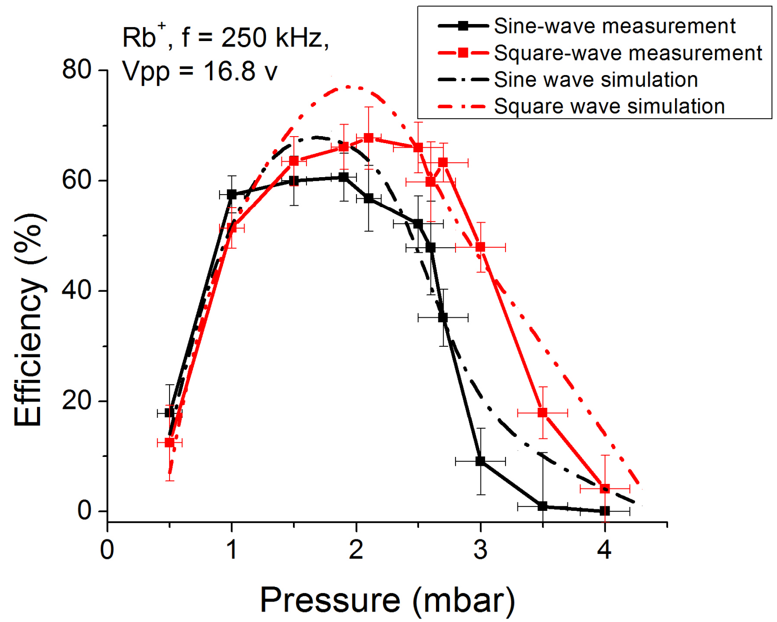
Can we use Square wave instead sine wave ?



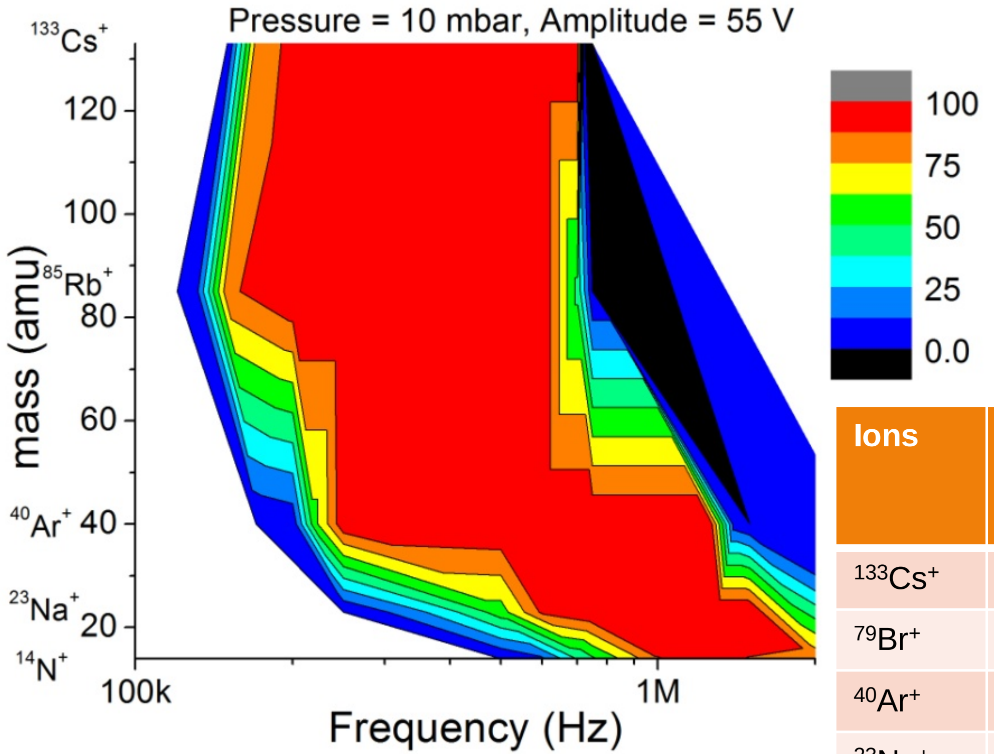


Yes we can !!

- Square wave generation is cheaper but noisy
- It supports tranport over wider pressure range
- But Peak-Peak voltage between two consecutive phase is larger for a short time



Ion Conveyor Optimization



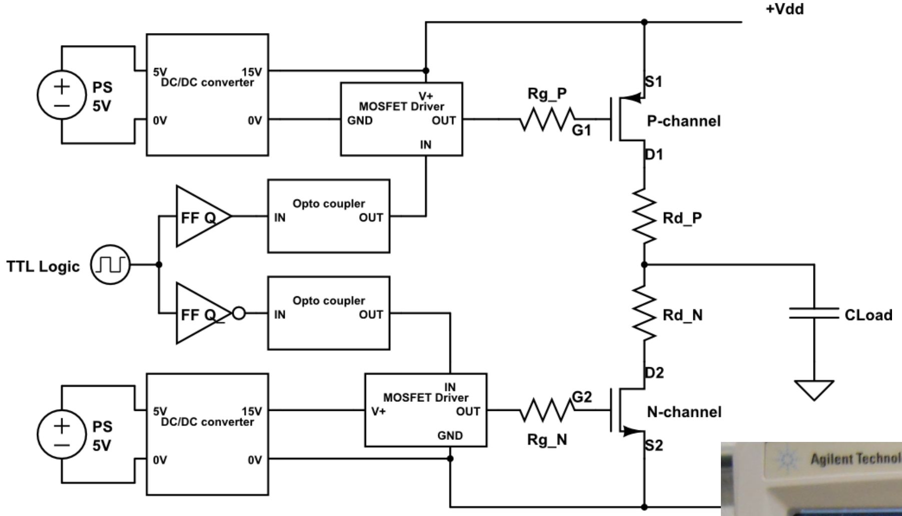
Suitable for wide range of masses

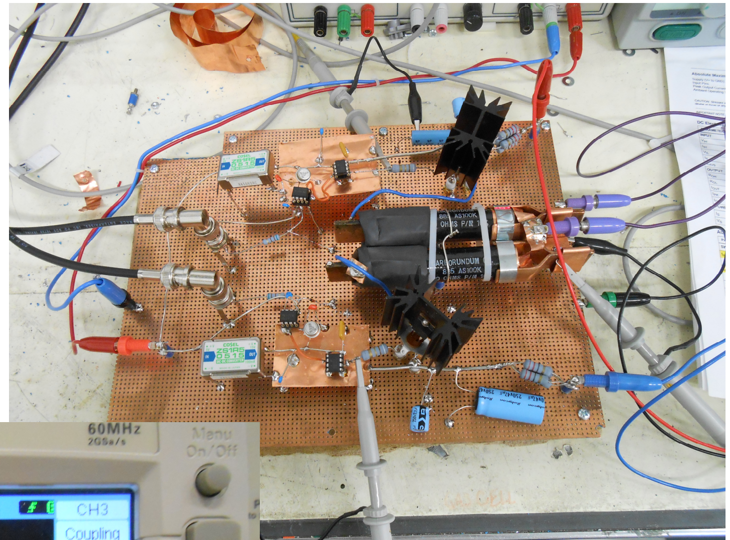
Ions	Minimum Required *	Typical Freq Range	Typical Amplitude range	Typical pressure range
$^{133}Cs^+$	35V @ 250 kHz	200-400 kHz	50 – 70 V	5-20 mbar
$^{79}Br^+$	35V @ 250 kHz	200-400 kHz	50 – 70 V	7-20 mbar
$^{40}Ar^+$	35V @ 400 kHz	400-700 kHz	50 – 60 V	7-20 mbar
$^{23}Na^+$	35V @ 600 kHz	600-1000 kHz	50 – 70 V	7-20 mbar
$^{14}N^+$	50V @ 1.5 MHz	2- 3.5 MHz	55 – 70 V	6-12 mbar

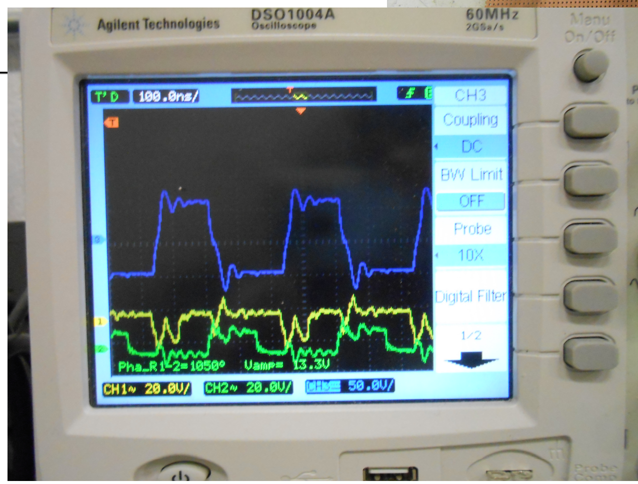
Ion squeezing well suited for efficient and fast ion transport at mbar gas pressures and strong magnetic fields

Driver Circuit

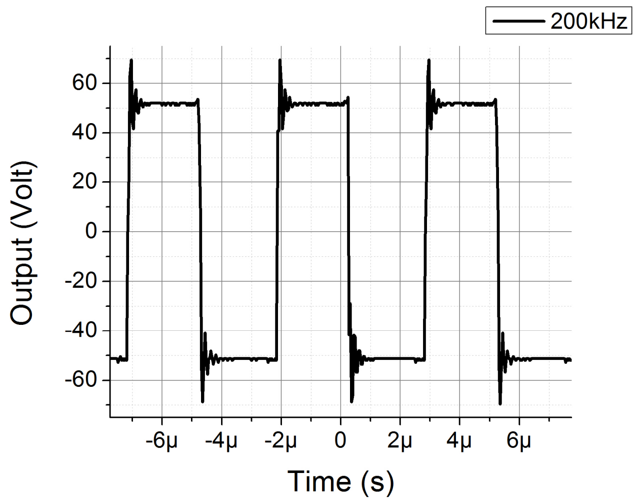
- MOSFETs in push-pull configuration
- Solid ground plating required to reduce SNR and ringing effects



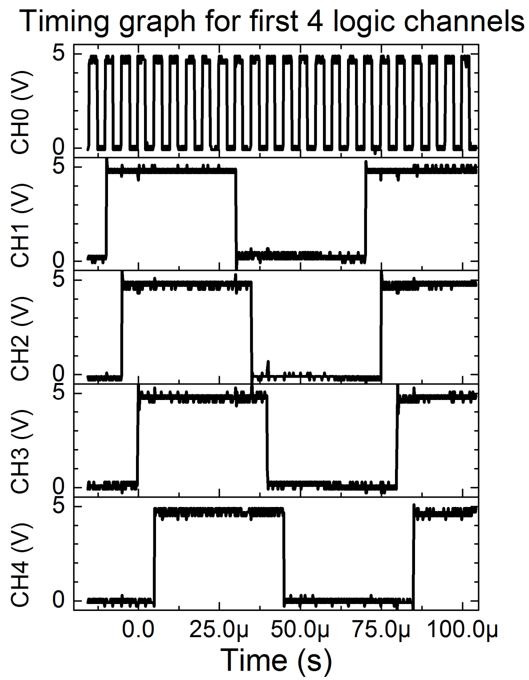


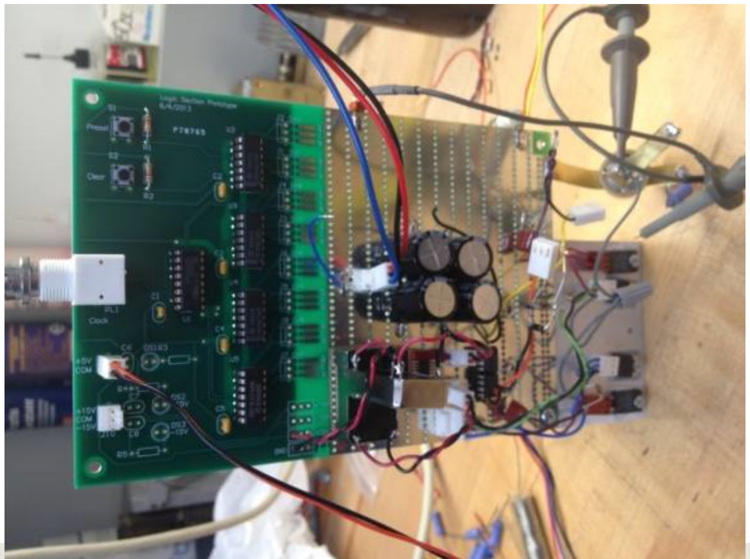


Driver Circuit …. Continue …

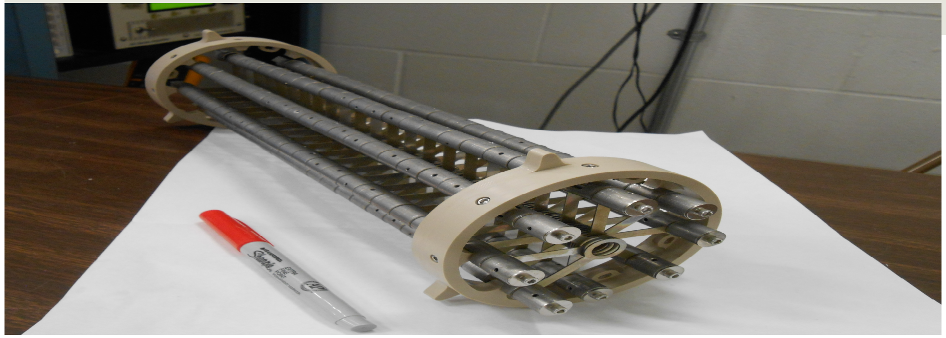


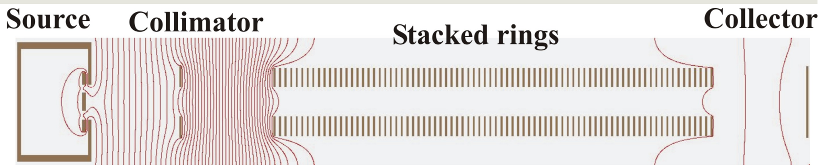
- Eight channels
- Tested upto 3 MHz with load of 1nf

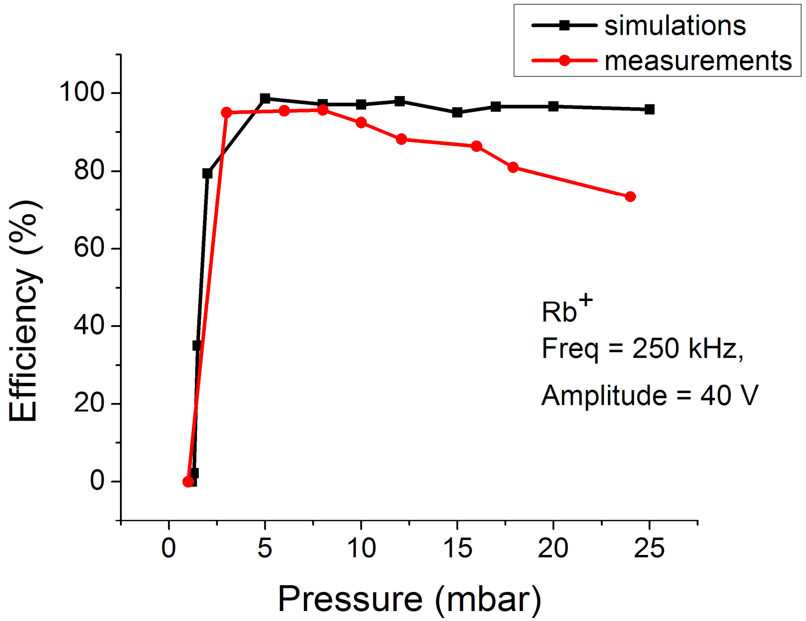


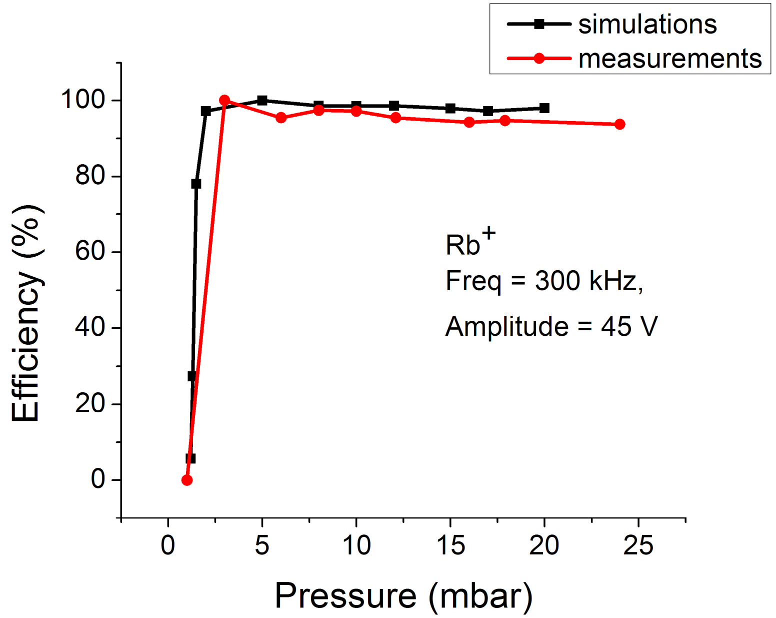


Experimental confirmation



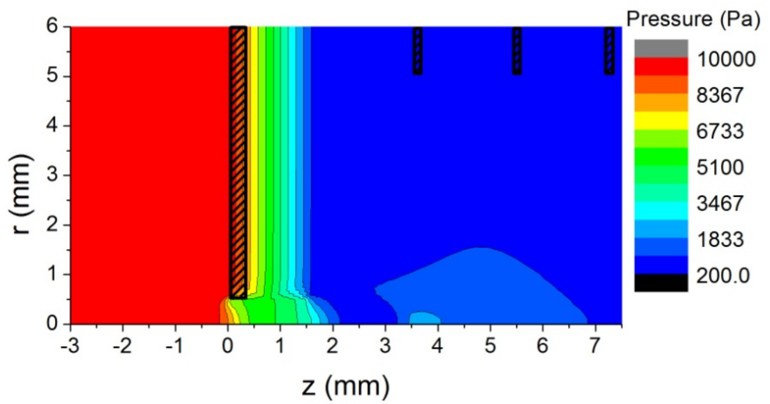


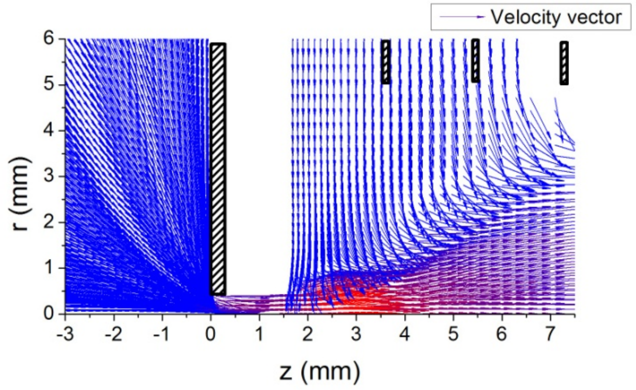


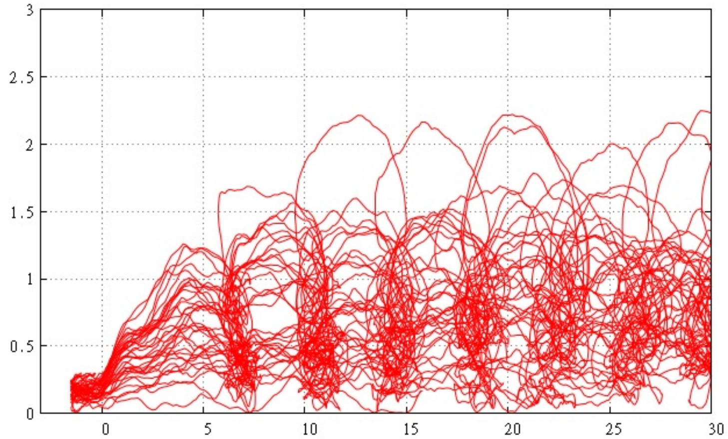


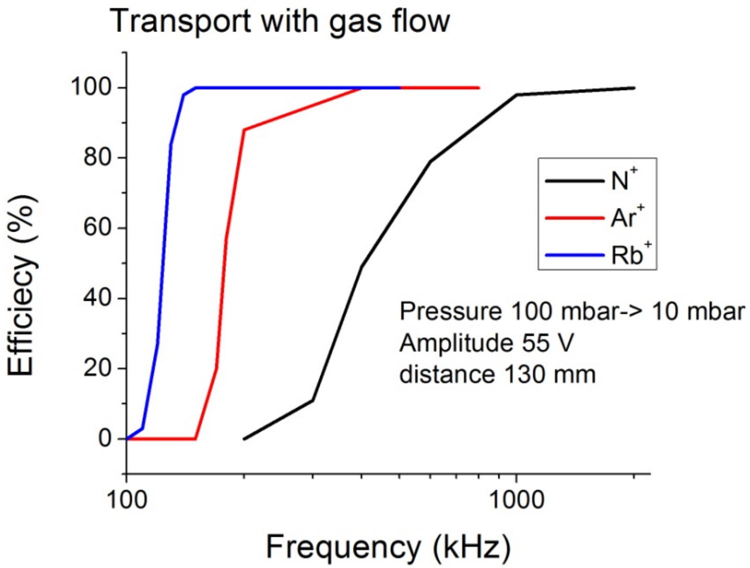
- Rb+ ions have been tested and 100% efficiency achieved
- Na+ ions also tested and about 80% efficiency achieved

Gas Flow Calculation



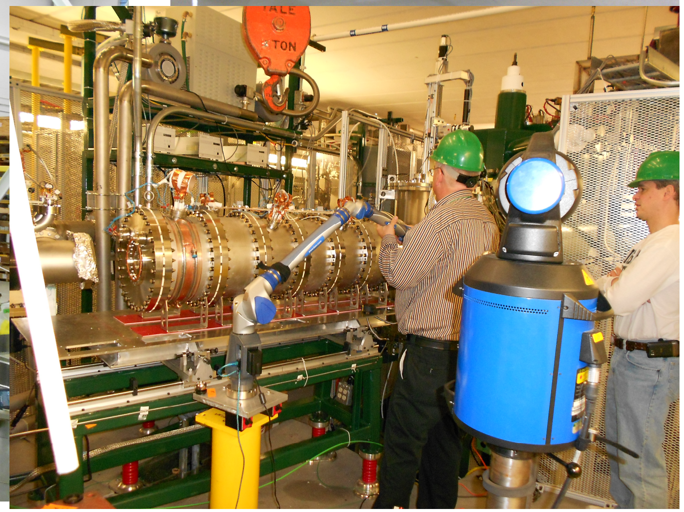






FRIB NSCL

CYC-STOP
MAGNET
YOKE STEEL

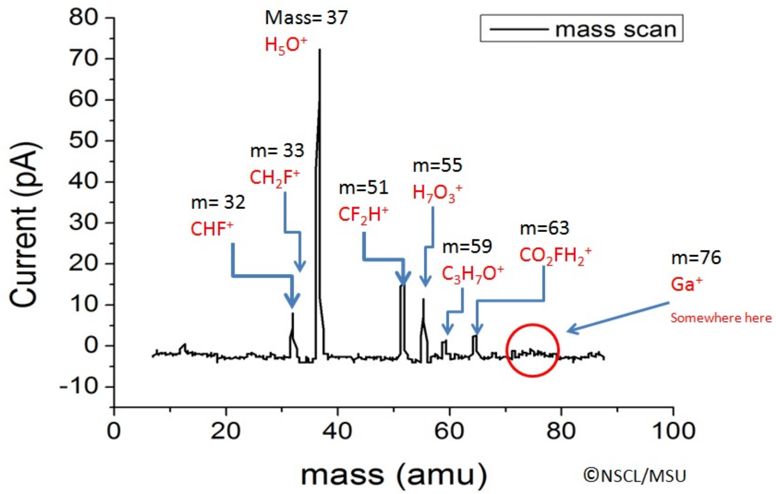


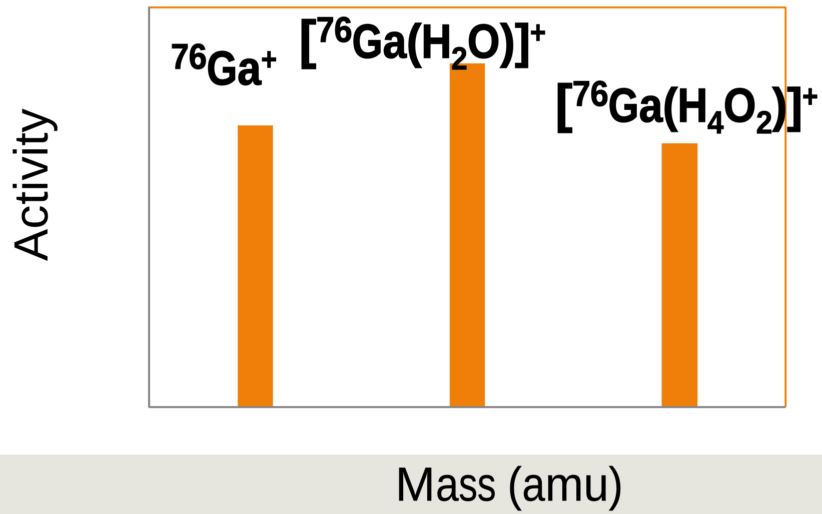
Potential Challenges

He-gas Gas catcher

- **Stopping efficiency**
  - ➢ **Dependence on pressure and isotope mass**
  - ➢ **lighter ion have larger stopping range**
- **Extraction**
  - ➢ **Faster extraction required for short lived nuclei**
  - ➢ **Space charge issue needs to investigated**
- **Contamination issues**
  - ➢ **He-gas purity highly desired**
  - ➢ **Contaminants forms molecular ions**

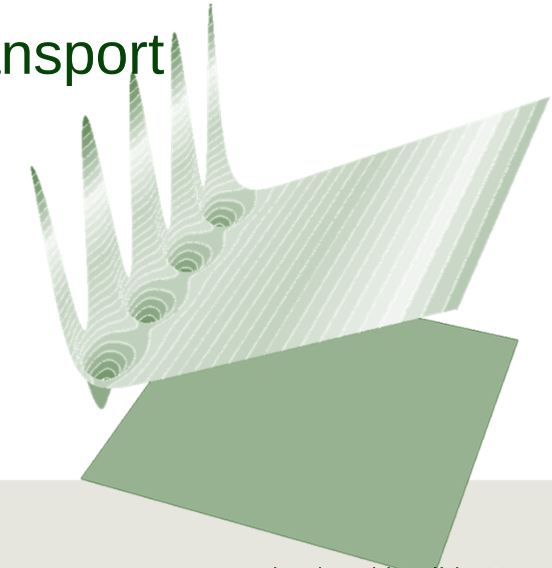
Results from initial run of $^{76}Ga^+$





Summary

- Stopping and Manipulation of Ions (SMI) critical for “stopped” and reaccelerated beams at NSCL now and FRIB in the future
- Cyclotron gas stopper simulations supported final design
  - Cyclotron gas stopper: Magnets being tested
- Ion surfing demonstrated as a powerful new transport techniques for ions in gases
- Ion Conveyor (ion squeezing) well suited for ion transport at mbar pressures and in strong magnetic fields



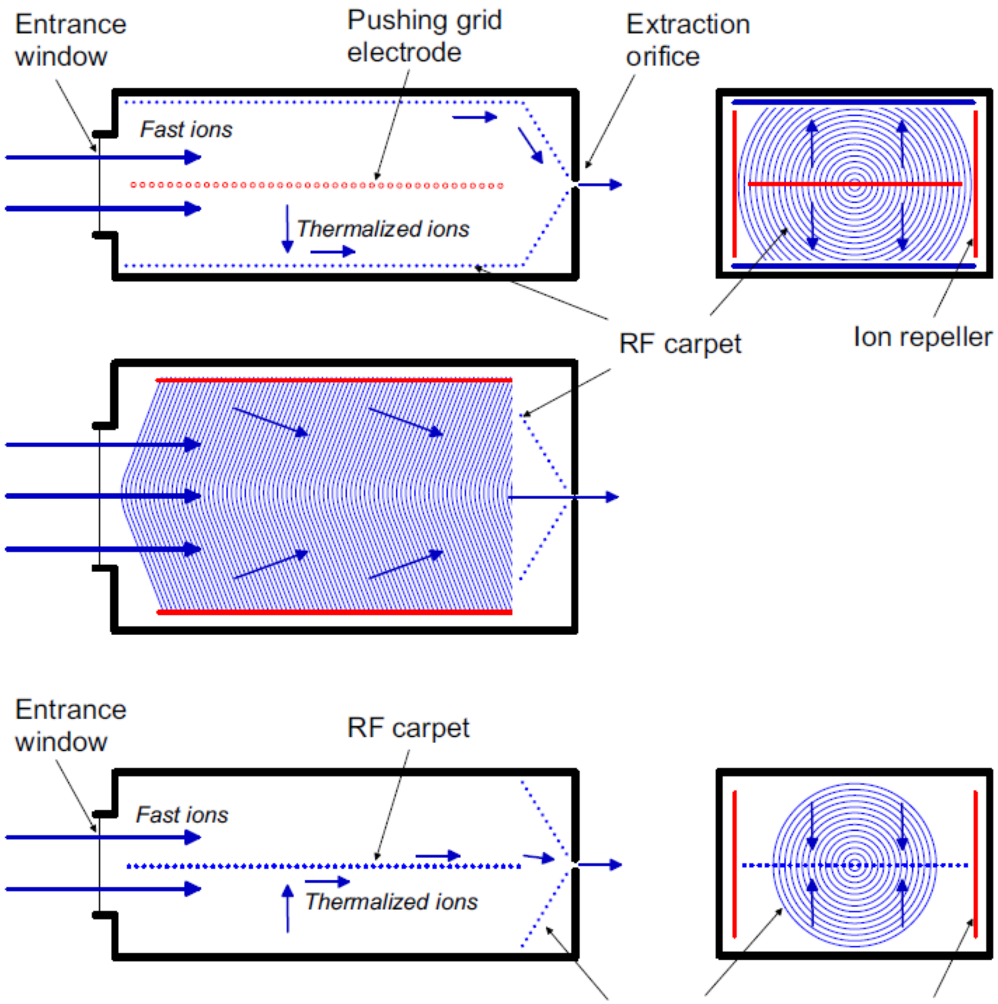
Thank you for your attention !!

Linear Gas Stopper with Ion Surfing Concept

- **Simple and fast**
- Already adopted for SLOWRI

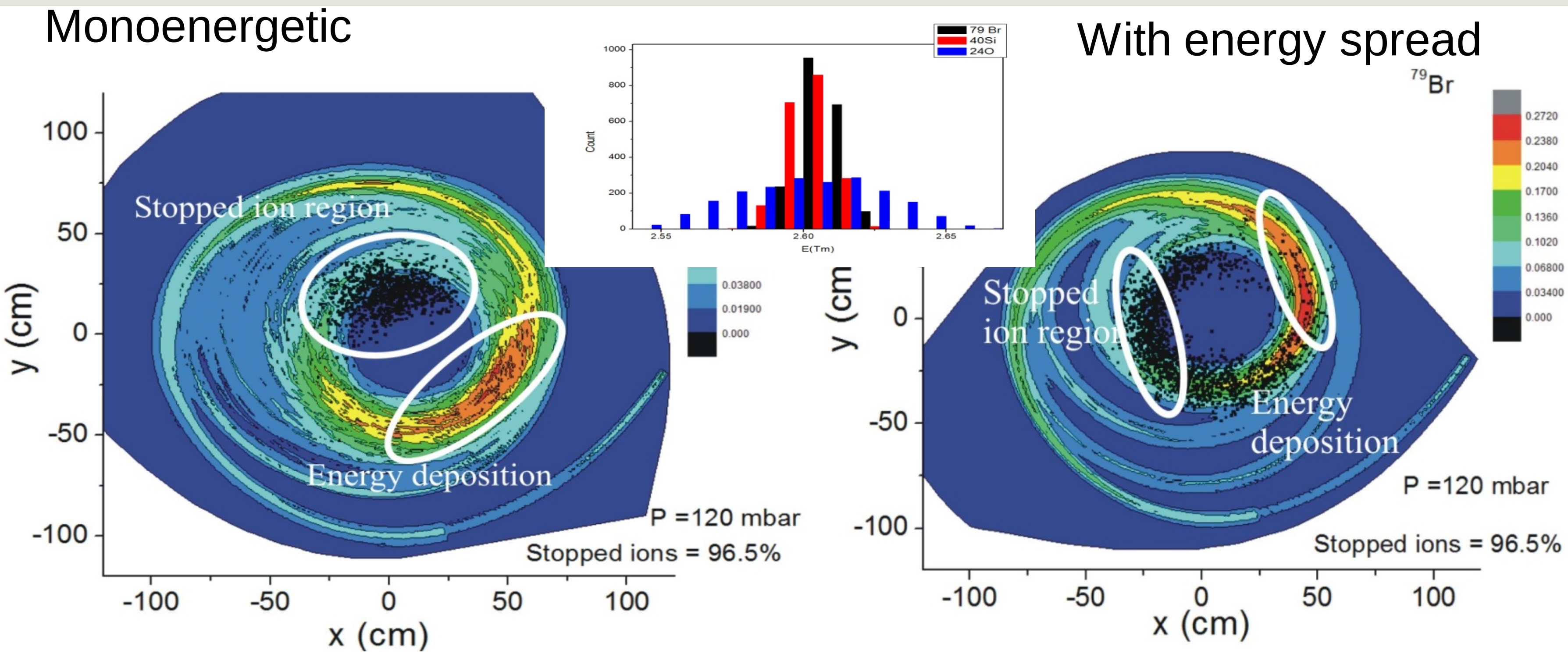
  M Wada

- Central electrode can mitigate plasma effect issues
  → higher beam rates



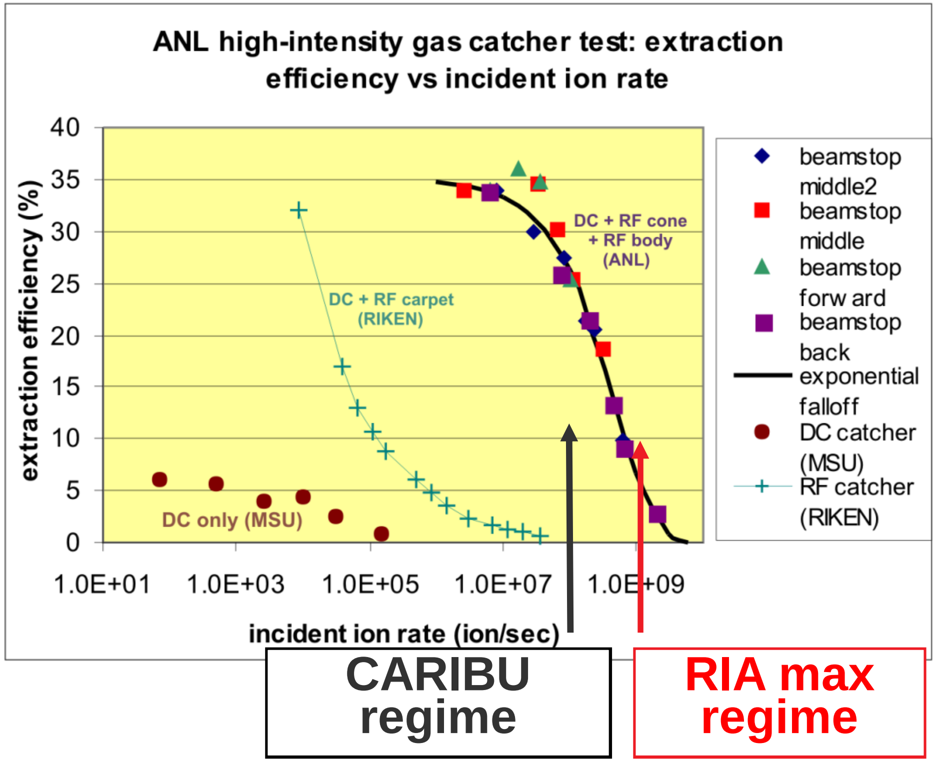
G. Bollen, IJMS 299, 131 (2011)

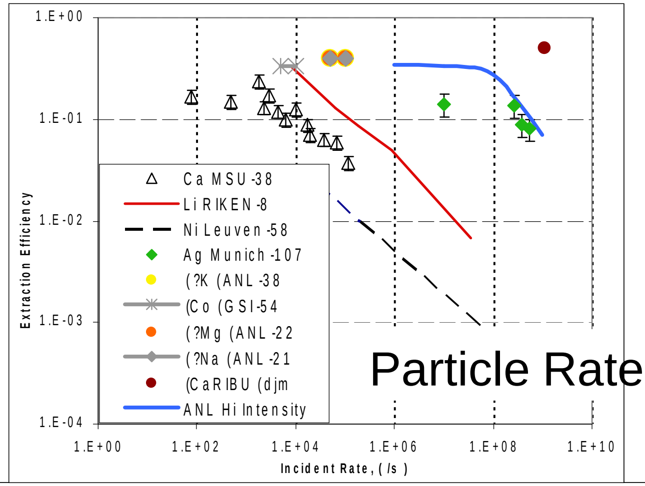
Energy Spread

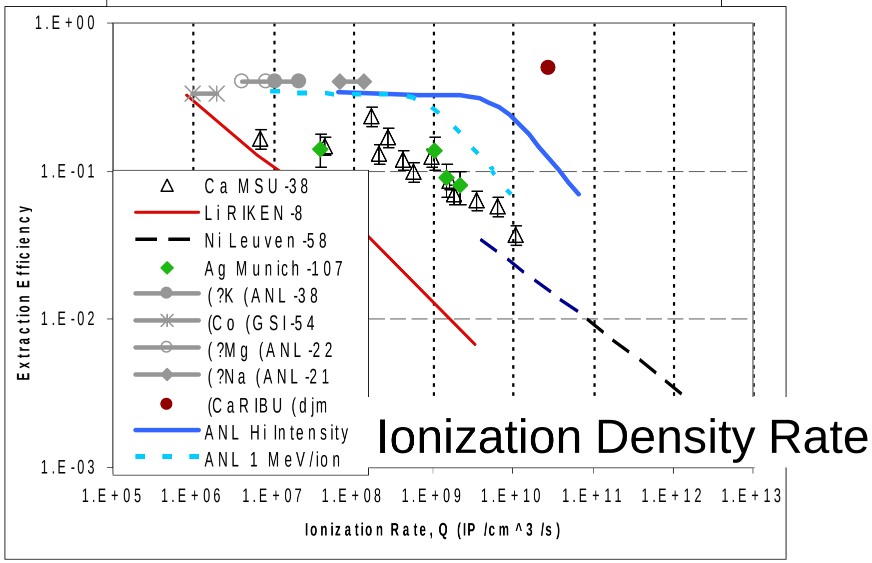


• Space-charge effects to be investigated ...

Incident rate







NSCL FRIB