Gas Stopper Developments for Improved Purity and Intensity of Low-Energy, Rare Isotope Beams

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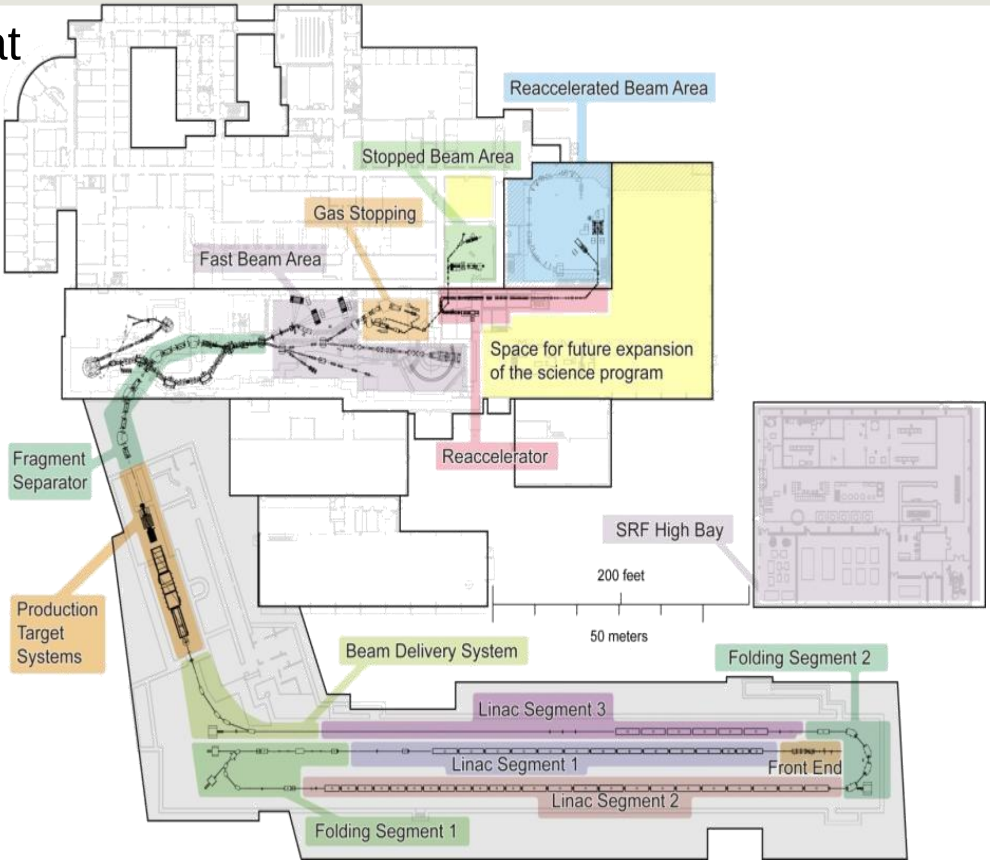
Outline

- Facility for Rare Isotope Beams (FRIB)
  - Gas stopping concepts for production of low-energy, rare-isotope beams
  - Current (and pending) gas stoppers at FRIB
  - User needs and challenges
- Developments Enabled by This Project
  - Development of simulation tools to optimize ion transport in the presence of space charge
  - Development of a demonstrator collision-induced-dissociation (CID) gas cell for improving beam purity
- Status Updates
  - Concentrate on CID gas cell
- Project Management Updates
- Summary and Outlook

FRIB – Facility for Rare Isotope Beams
World-Leading Next-Generation Rare Isotope Beam Facility

- FRIB will produce ~1000 NEW isotopes at useful rates (4500 available for study)
  - Higher-energy primary beams (200 MeV/ u for uranium)
  - Highest intensity rare isotope beams available anywhere
- Fast (~ 200 MeV/u), stopped (~ 30 keV), and re-accelerated (~ 6 MeV/u) beams available.

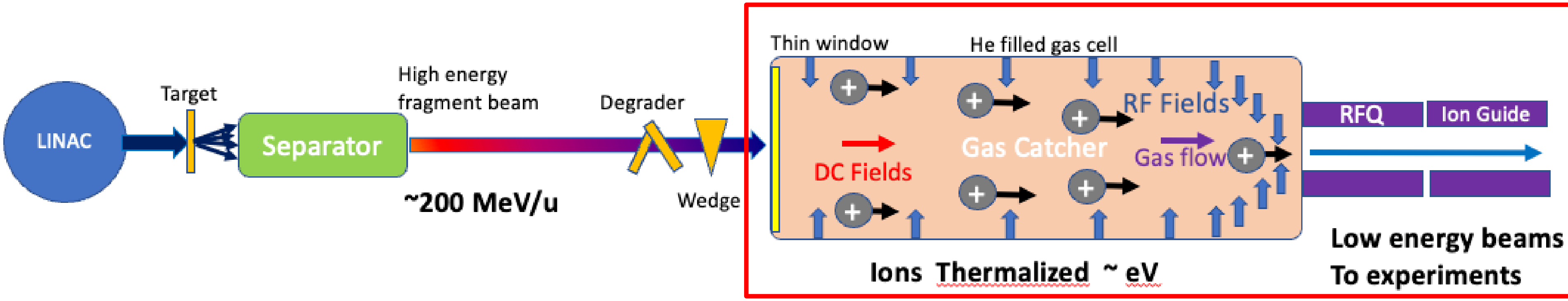
(requires gas stopping)



Now open for business!

~40% of approved experiments use beams requiring gas stopping.

Beam Stopping of Fast Projectile Fragments

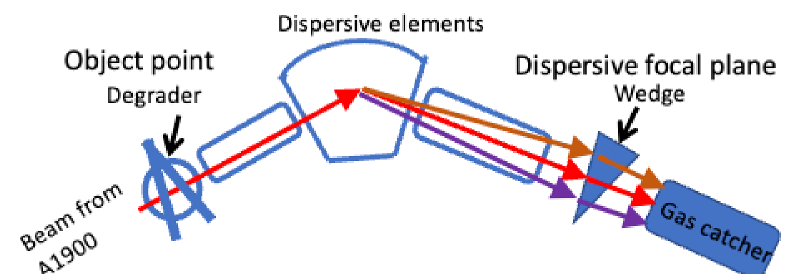


30-60 kV platform

- ❖ Production of fragments from high-energy beam
  - Large momentum spread due to reaction mechanism and production target.
- ❖ Bρ and ΔE separation
  - A1900/ARIS separator (High acceptance: 5% Δp/p), achromatic wedge
- ❖ Momentum compression and thermalization
  - Narrow momentum spread beams lead to high stopping efficiency[1]
- ❖ Gaseous ions collection
- ❖ Low energy beam transport

Method for producing an ideal incident beam:

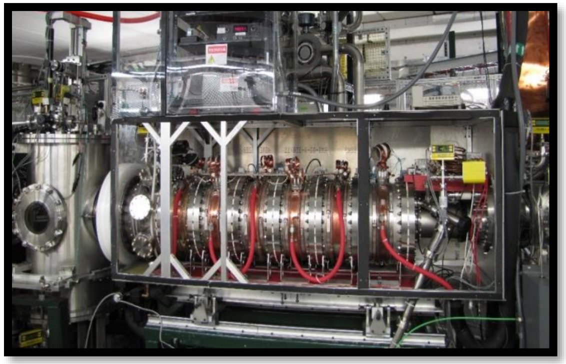
- Degrade beam at the object point
- Bunch momentum spread with wedge at the dispersive focal plane[2,3]



[1]L. Weissman et al. NIM A **522** (2004) 212
[2]H. Weick et al., NIM B **164-5** (2000) 168
[3]H. Geissel et al., NIM A **282** (1989) 247

Beam Stopping at FRIB
ISOL-Like Beam Properties at a Fragmentation Facility

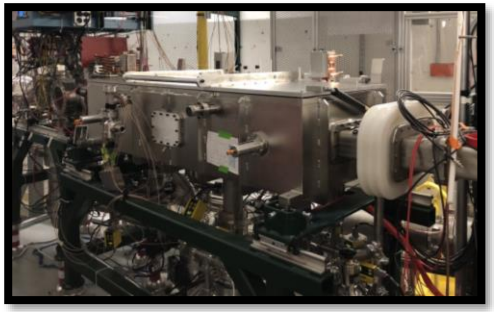
Original system: ANL Linear Gas Stopper[1]



- Filled with ~100 mbar He
- Ions lose energy in collisions with He atoms
- DC + RF electric fields and gas flow used to transport ions through

[1]C.S. Sumithrarachchi, *et al.* NIM B **463**, 305–309 (2019)

State of the Art: Advanced Cryogenic Gas Stopper[2]



- Cryogenic (40 K) for higher beam purity
- Optimized for good efficiency with high beam rates
- Currently in operation

[2]K. R. Lund *et al*. NIM B **463**, 378–381 (2019)

In progress: Cyclotron Gas Stopper[3]

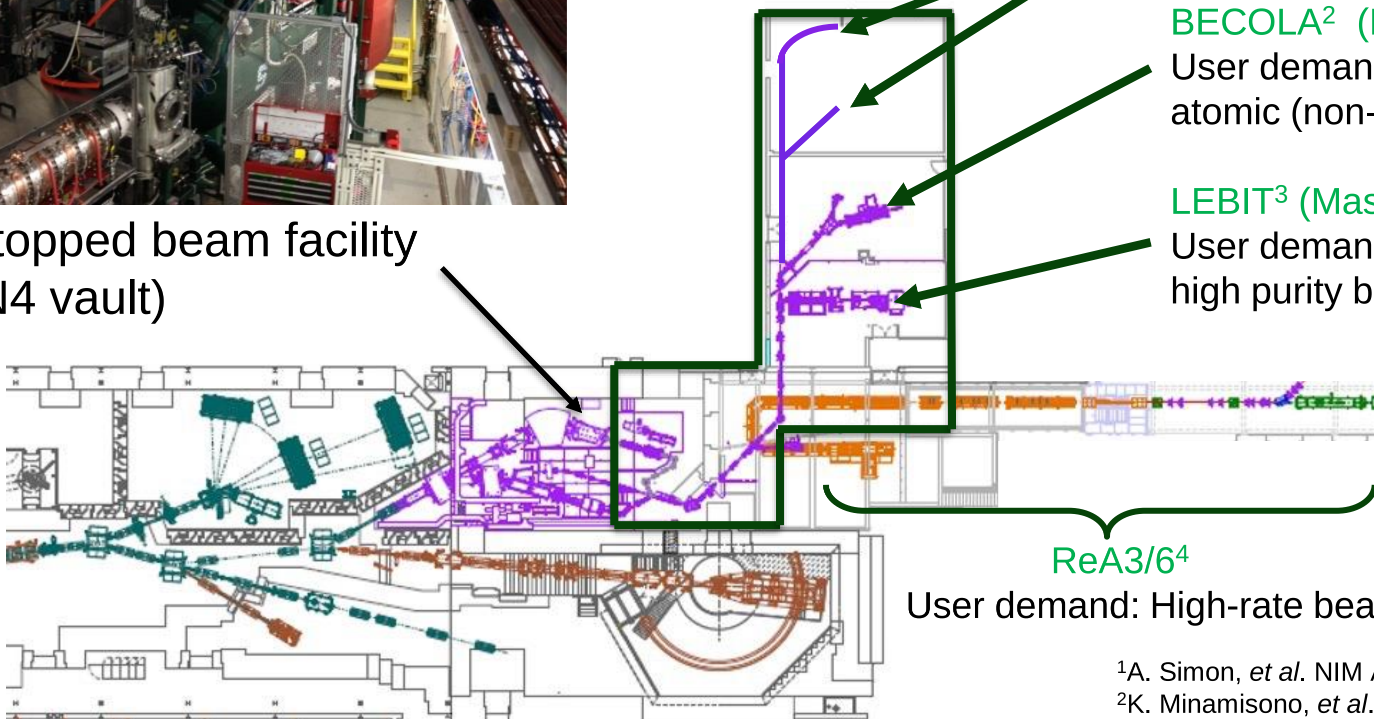
- Ions lose energy, spiral towards center
- Spiral path provides long stopping distance
- Good for light ions
- First beam extracted

[3]S. Schwarz *et al.* NIM B **463**, 293–296 (2020)

Experiments Using Stopped and Re-Accelerated Beams Have Different Requirements

Stopped beam facility (N4 vault)

Low-energy beam area



Decay experimental stations[1]
User demand: High purity beams

BECOLA[2] (Laser Spectroscopy)
User demand: High rates with atomic (non-molecular) ion beams

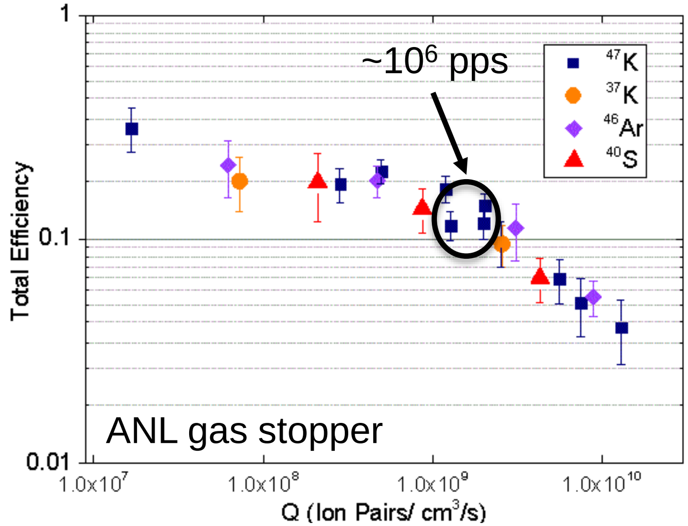
LEBIT[3] (Mass measurements)
User demand: Very low rates with high purity beams

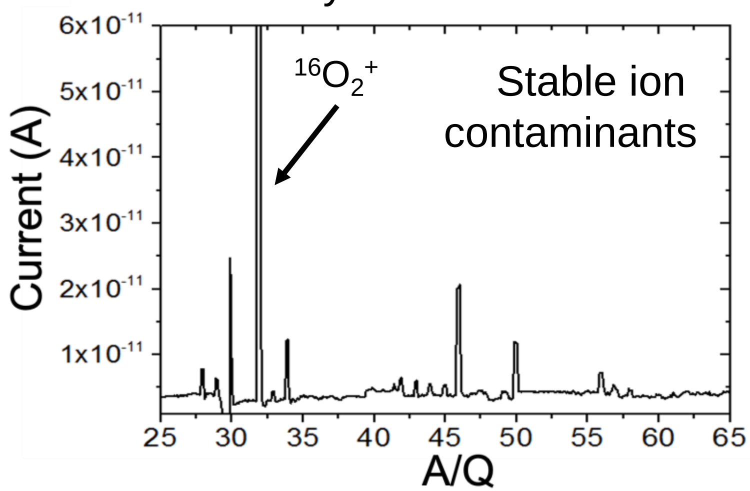
ReA3/6[4]
User demand: High-rate beams

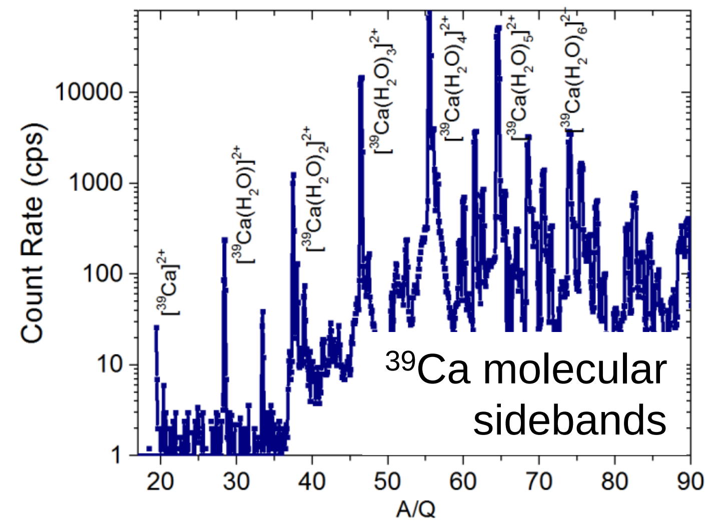
[1]A. Simon, *et al*. NIM A **703**, 16–21 (2013)
[2]K. Minamisono, *et al*. NIM A **709**, 85–94 (2013)
[3]R. Ringle, *et al*. Int J Mass Spectrom **349**, 87–93 (2013)
[4]A. C. C. Villari, *et al*. Proceedings of LINAC2016 **390** (2018)

Challenges to Beam Purity, Rate, and Molecular Formation

- Generation of large space-charge fields
  - He^+/e^- created during stopping process
  - Can hinder transport efficiency
- Molecular ion formation with stopped rare isotopes
  - Spreads rare isotope across several mass peaks
  - Reduces efficiency through mass separator
- Large stable molecular ion beams
  - Trace contaminants in buffer gas or on surfaces are ionized during stopping process
  - Can cause efficiency losses in extraction

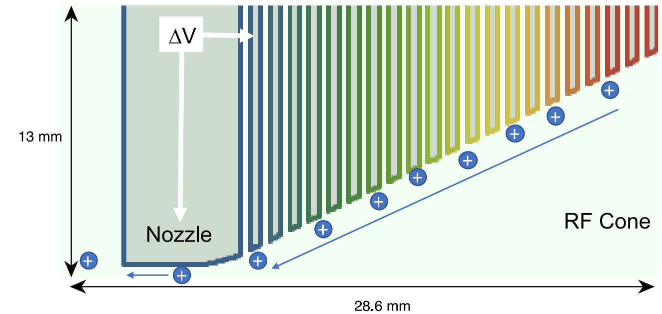


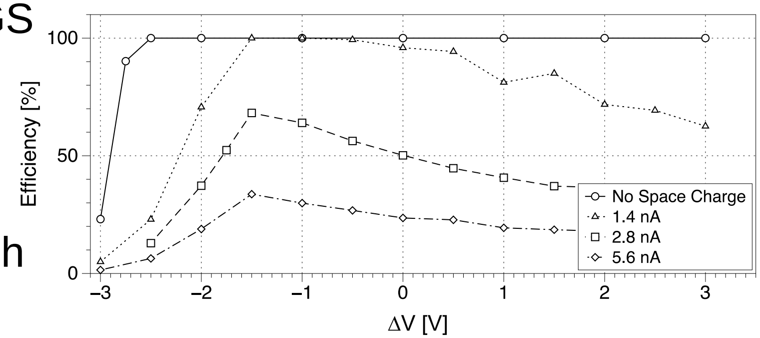




Next Generation Gas Stopper Developments Enabled by This Project

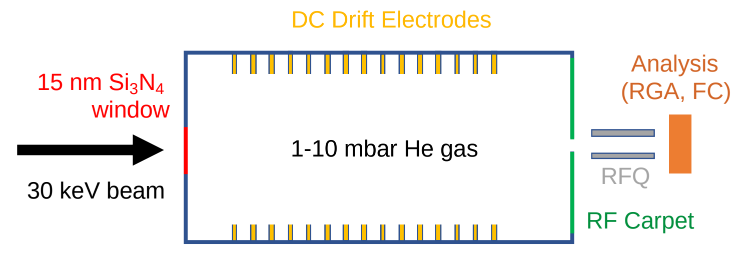
- Development of simulation tools to optimize ion transport efficiency through the stopping volume in presence of space charge
  - Use IonCool[1] and adapt particle-in-cell[2] (PIC) code to simulate transport efficiency in realistic space-charge fields
  - Validate using ion transport measurements across ACGS RF carpet





- Development of simulation tools to optimize extraction efficiency
  - Adapt PIC code to study ion extraction efficiency through orifice in presence of large stable molecular beams.
  - Validate using measurements performed with ANL and ACGS

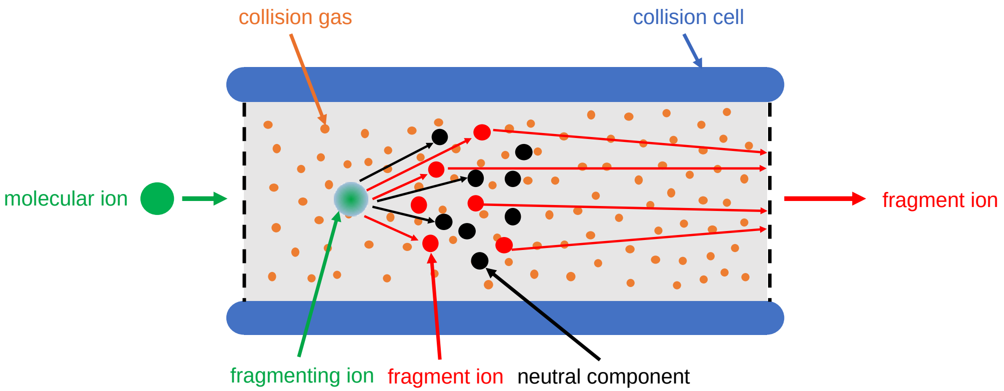
- Build and test a low-pressure collision-induced-dissociation (CID) gas cell to purify beams
  - Study transmission efficiency through 20 nm thick $Si3N_4$ entrance windows
  - Study CID process in molecular beams generated offline using existing ions sources



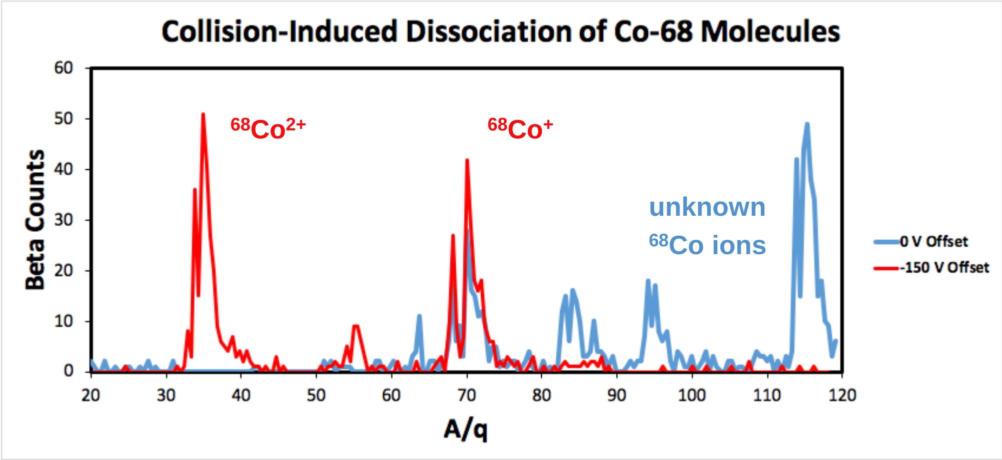
[1]S. Schwarz, NIM A **566**, 233–243 (2006)
[2]R. Ringle, Int J Mass Spectrom **303**, 42–50 (2011)

Collision-Induced Dissociation (CID) can Purify Rare Isotope Beams

- CID is a mass spectrometry technique widely used in analytical chemistry[1,2]
- Molecules are accelerated into a buffer gas
- Inelastic collisions transfer some energy into the internal modes, breaking bonds

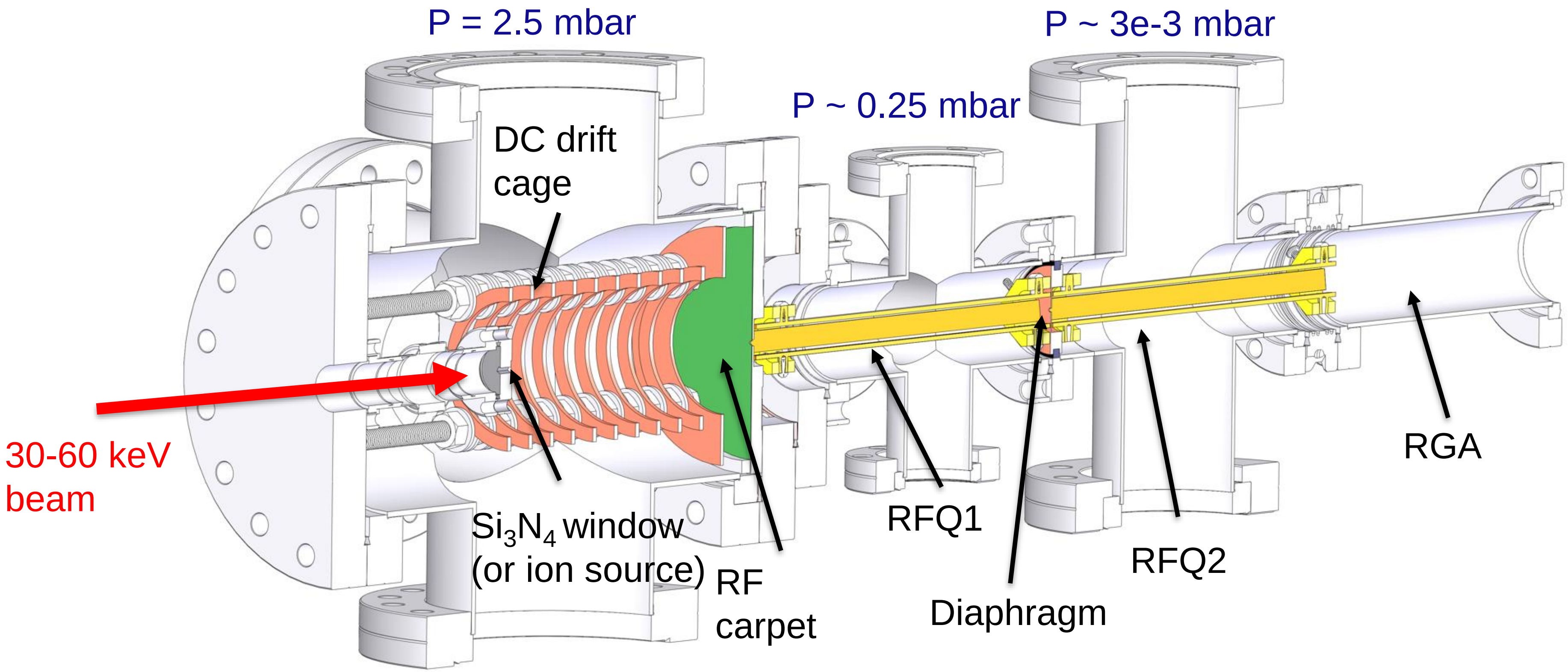


- CID is currently used at FRIB by applying a potential offset between the gas stopper and RFQ.
- Demonstrated in multiple experiments
- Not violent enough to break the strongest molecular bonds
- **A dedicated device needs to be developed to break the strongest molecular bonds**



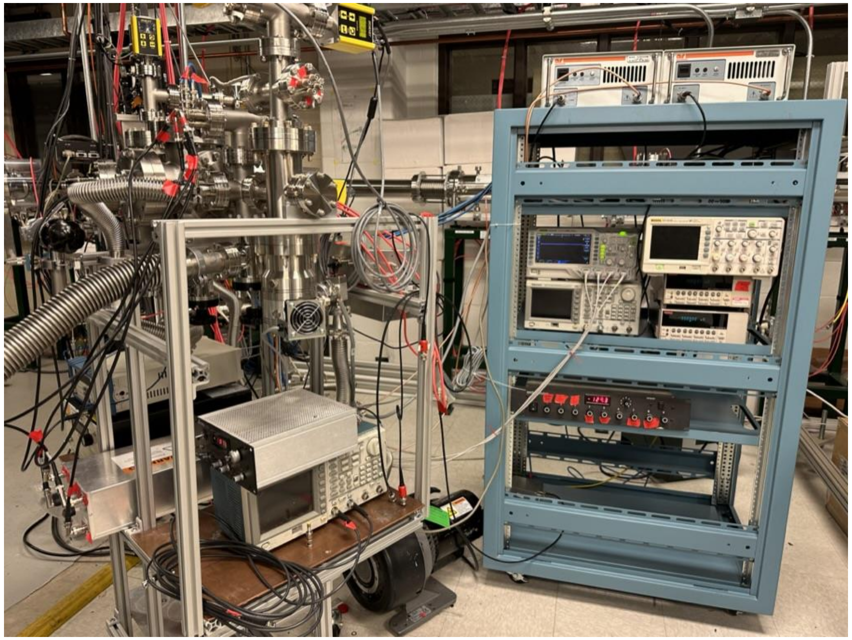
[1]J.M. Wells, S.A. McLuckey, Meth. Enzymol. **402** (2005) 148–85
[2]L. Sleno, D.A. Volmer, J. Mass Spectrom. 39 (2004) 1091–112

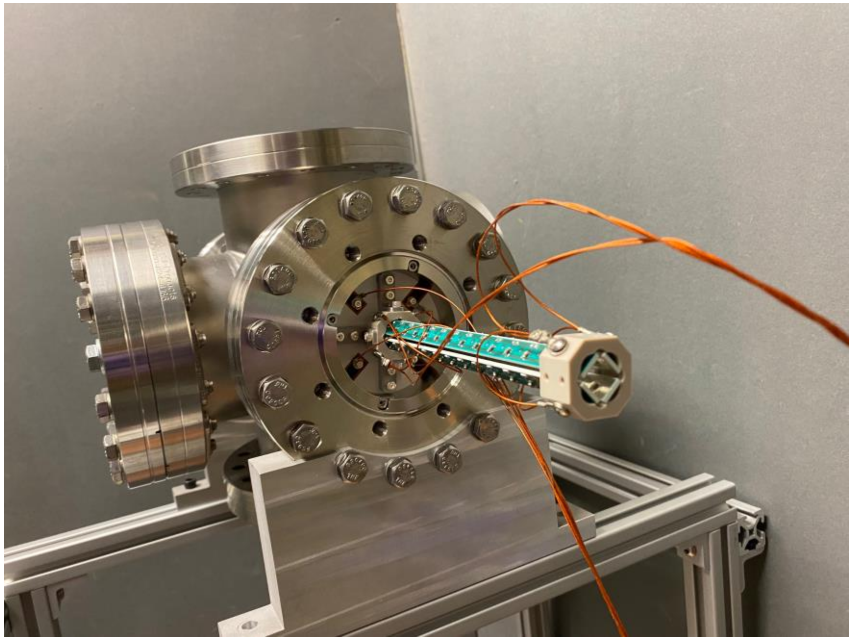
Demonstrator CID Gas Cell Will Enable Feasibility Studies

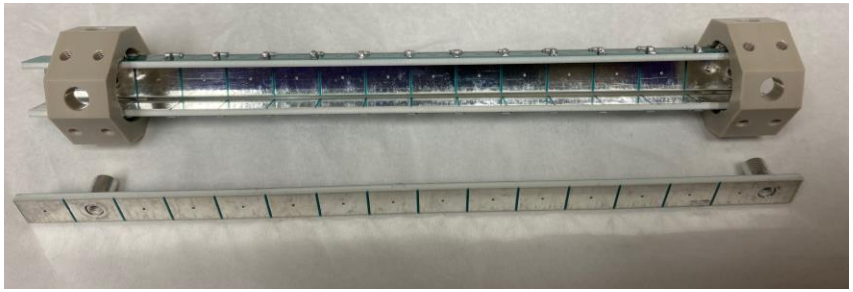


- 30-60 keV molecular or atomic ion beams provided by existing gas cells
- Ions are transported by DC drift cage to RF carpet
- Ions are extracted through small orifices into RFQ1&2 for transport and differential pumping
- Ion species identified by RGA with ionizer disabled
- **System is complete and functional. Offline commissioning using K ion source.**

Completed CID Gas Cell Demonstrator

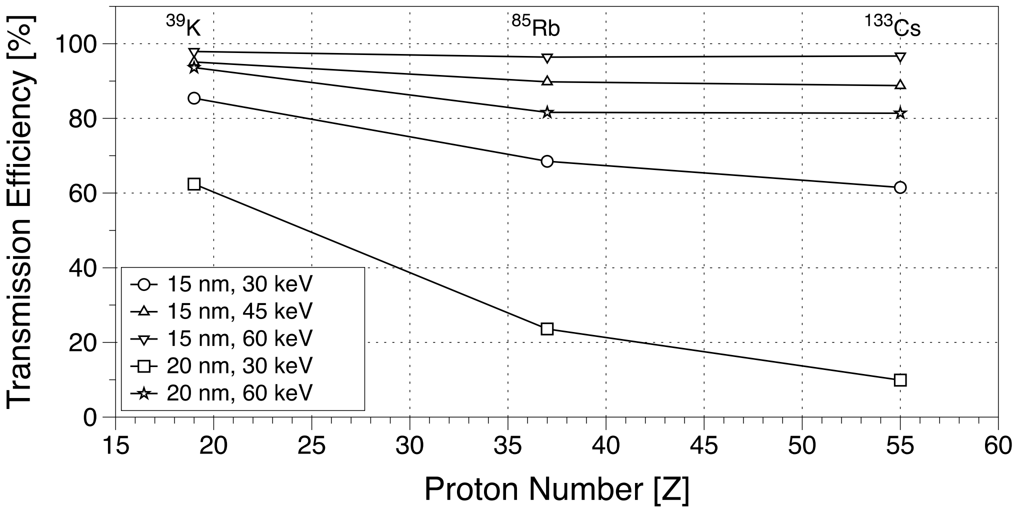


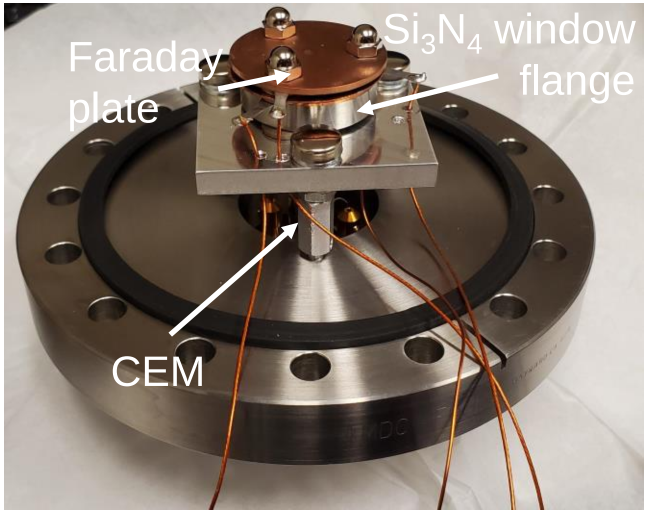




Ion Transmission Efficiency Studies through Si_3N_4 Windows

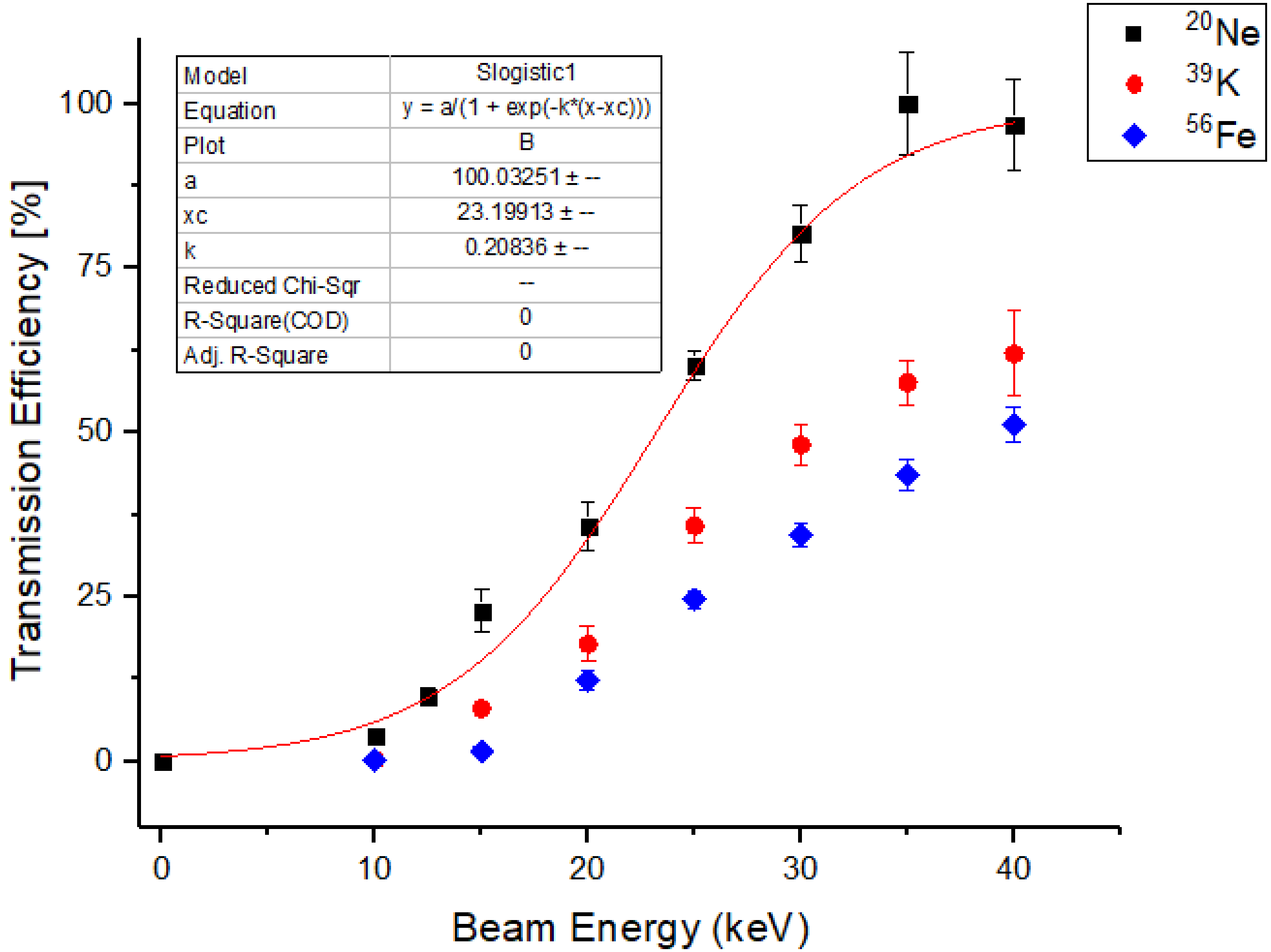
- Need to quantify ion transmission efficiency through thin Si_3N_4 windows
- SRIM can provide an estimate, but may not be accurate at this thickness
- Built a detector to measure ion transmission efficiency
  - Channeltron (CEM) for single-particle counting
  - Faraday plate with hole to measure incident current on Si_3N_4 window
  - **Installed and measurements have been performed.**



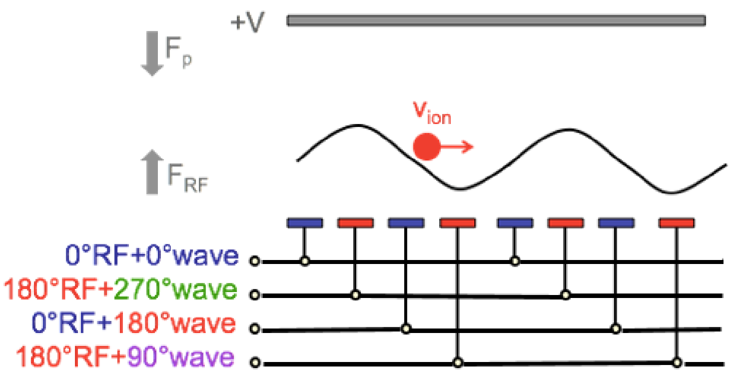


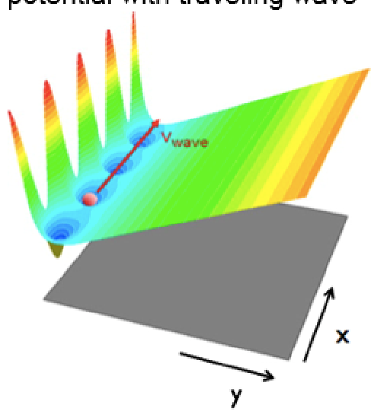
Initial Transmission Studies Show Promising Results

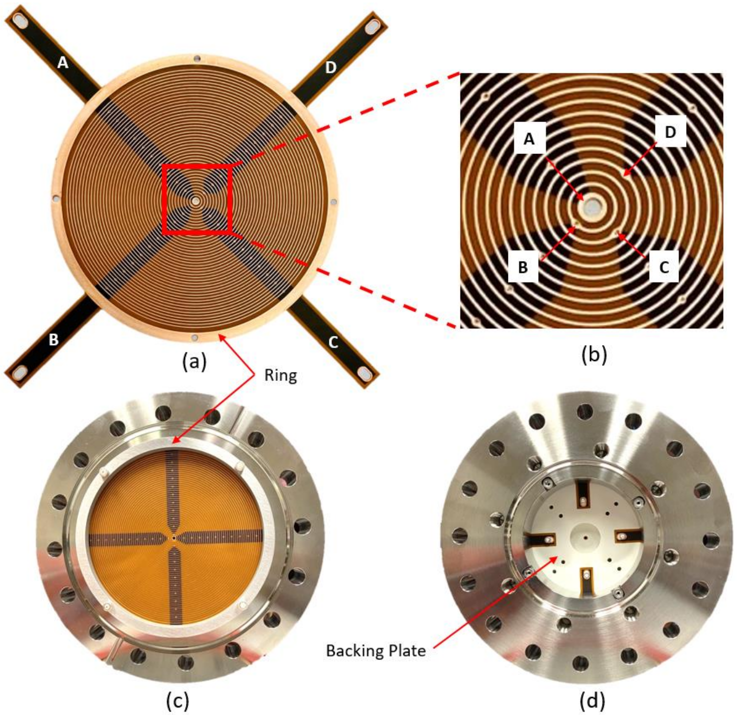
- Only statistical errors considered
- Limited to 40 kV maximum beam energy
- Trend for different masses show expected trend
- Some inconsistencies developed over time.
- Longer term testing and more data would be helpful



Ion Transport Across the RF Carpet







Traditional ion surfing method[1]

- High-frequency (MHz) RF
- Low-frequency (kHz) travelling wave
- High transport speeds and efficiencies demonstrated[2,3]

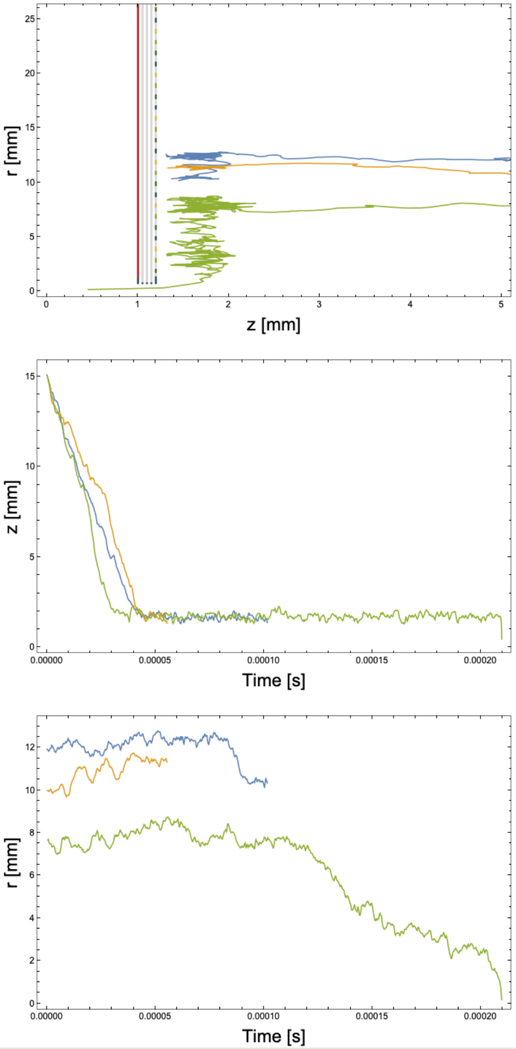
Pure-surf RF carpet

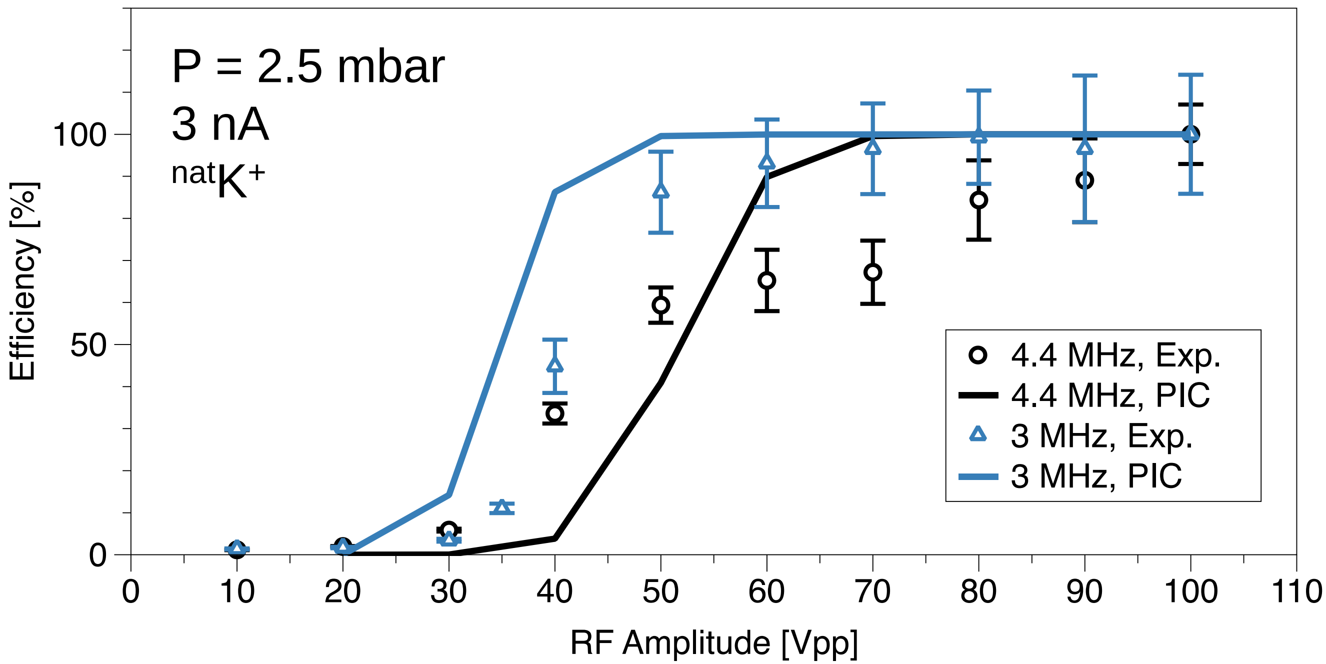
- Simplifies RF circuit
- Higher push-field tolerance

- CID RF carpet can be run in traditional or pure-surfing modes
- **Incident ion current will impact transport efficiency!**

[1]G. Bollen, Int. J. Mass Spectrom. **299**, 131 (2011).
[2]M. Brodeur, *et. al.*, Int. J. Mass Spectrom. **336**, 53 (2013).
[3]A. E. Gehring, *et. al.*, Nucl. Instrum. Meth. B **376**, 221 (2016).

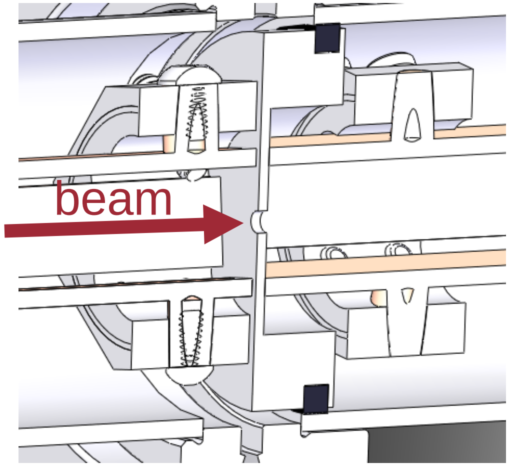
Particle-in-Cell Simulations Reproduce Ion Transport Across RF Carpet

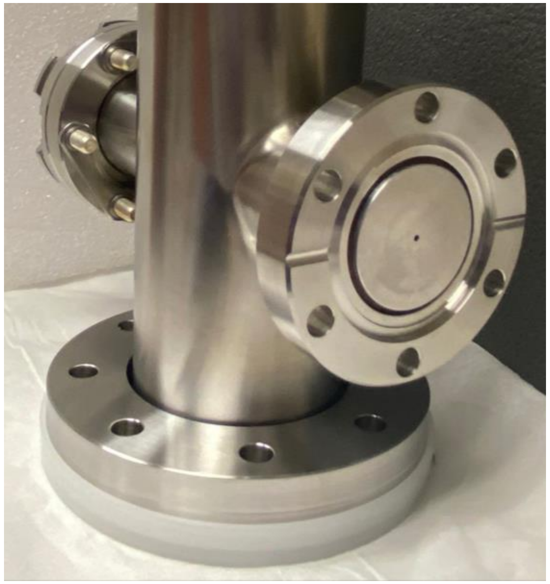


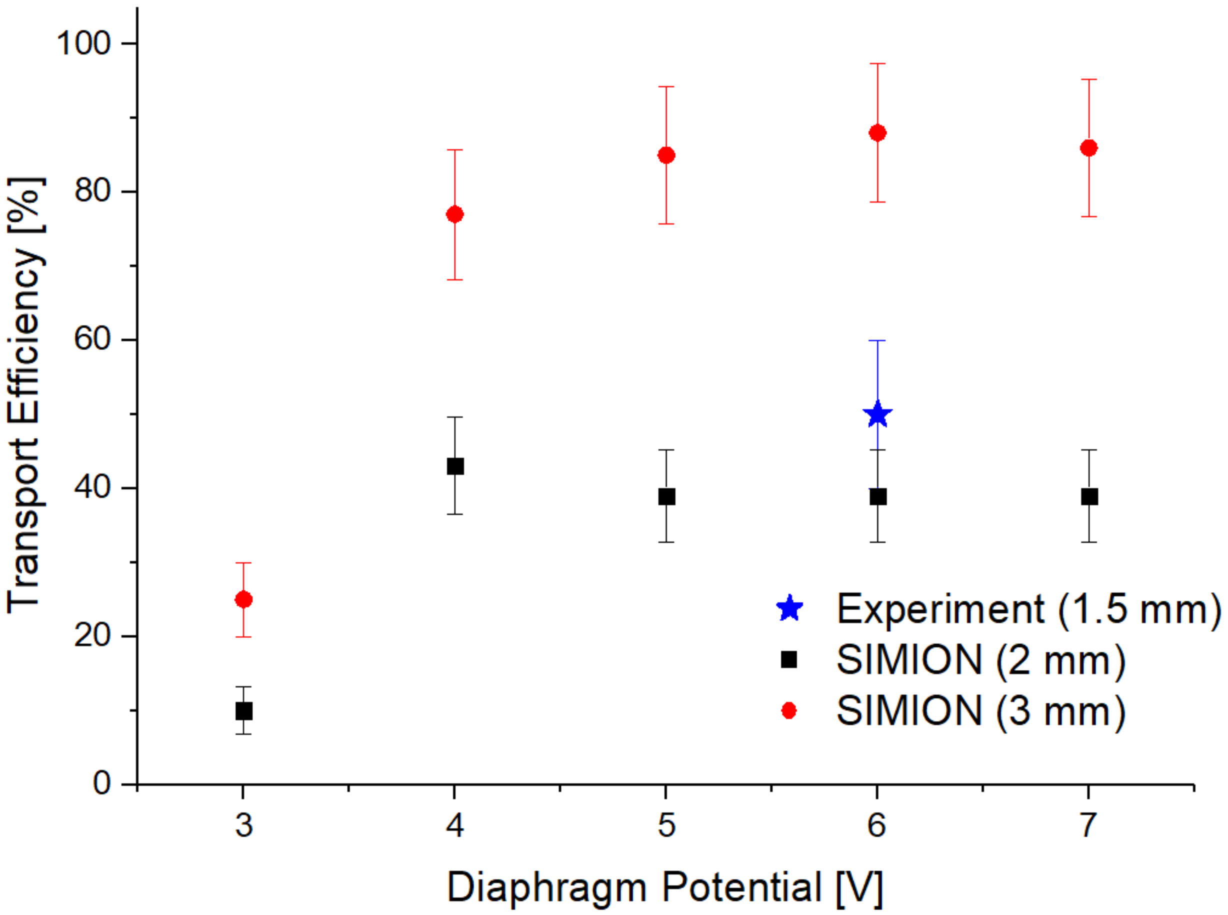


- PIC simulations reasonably reproduce experimental trends
- Increased ion current makes transport more difficult
- Can be used in the future to optimize RF carpet geometry for high-current transport

Ion Transport Through Diaphragm Shows Good Agreement with Simulation

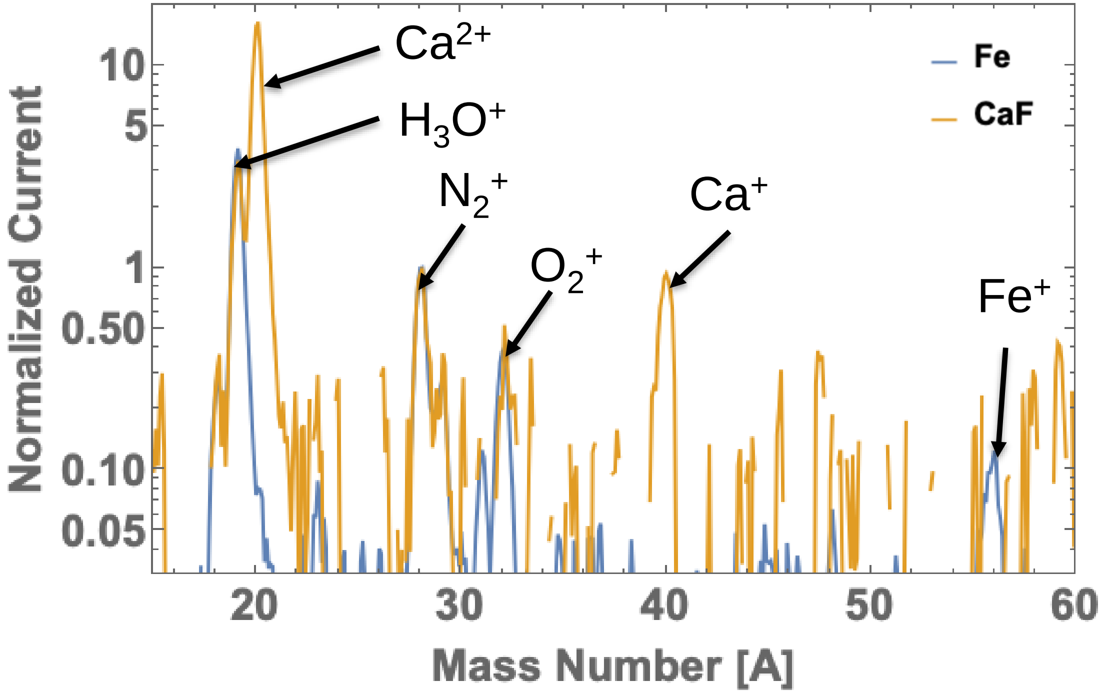






CaF^+ Molecule Successfully Broken

- CaF^+ delivered from BMIS ion source
- Pressure:
  - 1-2x10^{-3} mbar
- Incoming current
  - ~1 nA (~ 10% efficiency)
- Reasonable resolution for single mass identification
- Currents normalized to N_2 peaks
- **Clear evidence of molecules being broken!**



Project Management (Financials)

Final financial breakdown

	FY21	FY22	FY23	Totals
a) Funds allocated	$122k	$234k	--	$356k
b) Actual costs to date	$106k	$191k	$59k	$356k
c) Budget request	$122k	$234k	--	$356k

Item/Task	FY21	FY22	FY23
	($)	($)	($)
Simulation/CID effort	84,219	145,887	59,162
CID hardware	5,667	9,857	0
Materials & supplies	13,738	10,174	0
Fabrication costs	2,516	10,928	0
Travel	0	13,852	0
Publication costs	0	0	0
Total	106,140	190,698	59,162

Project Management (Schedule)

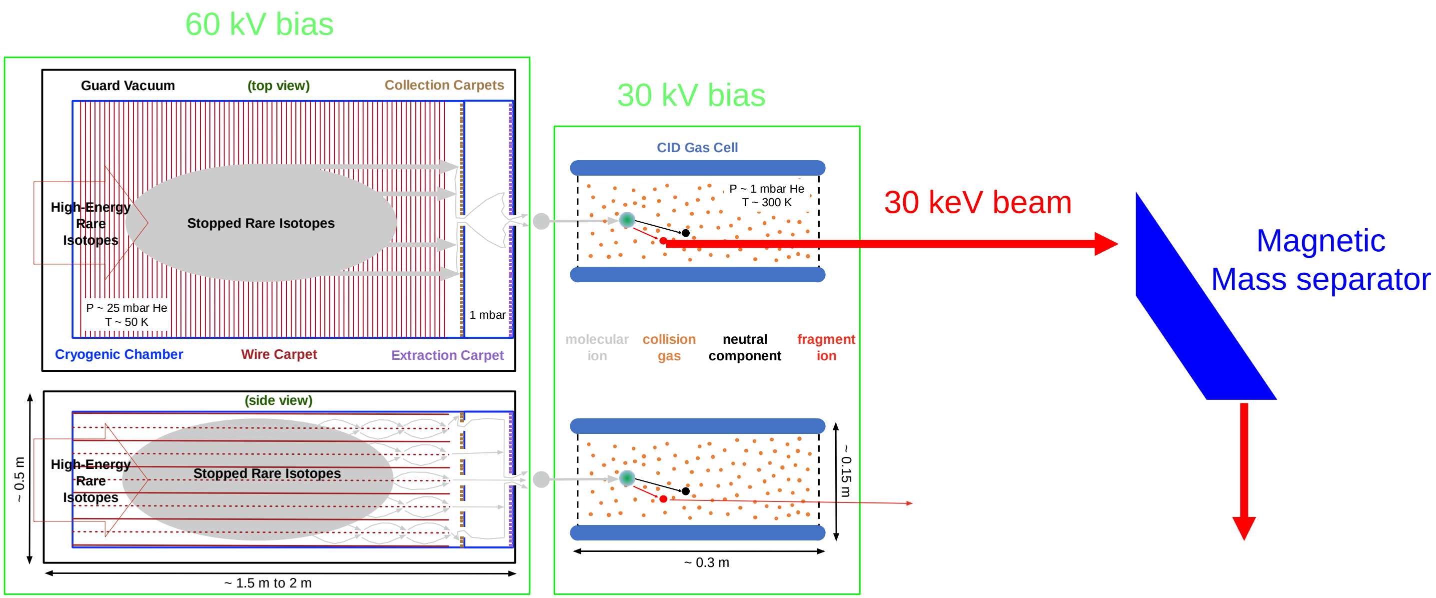
Task (RF carpet ion transport simulations)	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Collect results from previous 4-phase simulations	100%											
Complete missing 4-phase simulations		100%										
Develop 8-phase simulation				100%								
Execute 8-phase simulations								100%				
Analyze results										100		

Task (CID gas cell demonstrator)	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q 10	Q 11	Q 12
Procure Si_3N_4 windows and mounts	100%											
Assemble Faraday cup for transmission measurements	100%											
Measure transmission of windows						100%						
Design prototype CID gas stopper				100%								
Procure prototype CID gas stopper hardware							100%					
Fabricate prototype CID gas stopper						100%						
Install prototype CID gas stopper on d-line extension							100%					
Test prototype CID gas stopper with stable beam											100%	
Analyze results												100

Task (Particle-in-cell simulations)	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Development of single-layer RF carpet simulations	100%											
Execution of single-layer RF carpet simulations		100%										
Development of extraction simulations		100%										
Execution of extraction simulations		100%										
Development of multi-layer RF carpet simulations			100%									
Execution of multi-layer RF carpet simulations										100		
Analyze results, execute follow up simulations (if needed)											100	
Develop conceptual design based on all objectives												100

Summary and Outlook

- For the first time we have a complete simulation pipeline for transport and extraction of rare isotopes from linear gas stoppers
  - Agrees well with current experimental results
  - Has already yielded dividends with improvements to ACGS
  - Well positioned to deliver developments that will increase the rate capability of future linear gas stoppers
- A demonstrator CID gas cell with thin Si_3N_4 window has been developed to evaluate its feasibility in removing stable beam contaminants
  - Device is operational
  - Optimization is happening offline with dedicated ion source
  - **Multiple molecular beams demonstrated to be broken.**



Acknowledgements

NP-DOE DE-SC0021423

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- **Postdoc : Nadeesha Gamage**
- **Student : Daniel Puentes**

- **Beam delivery : Chandana Sumithrarachchi and Stefan Schwarz**

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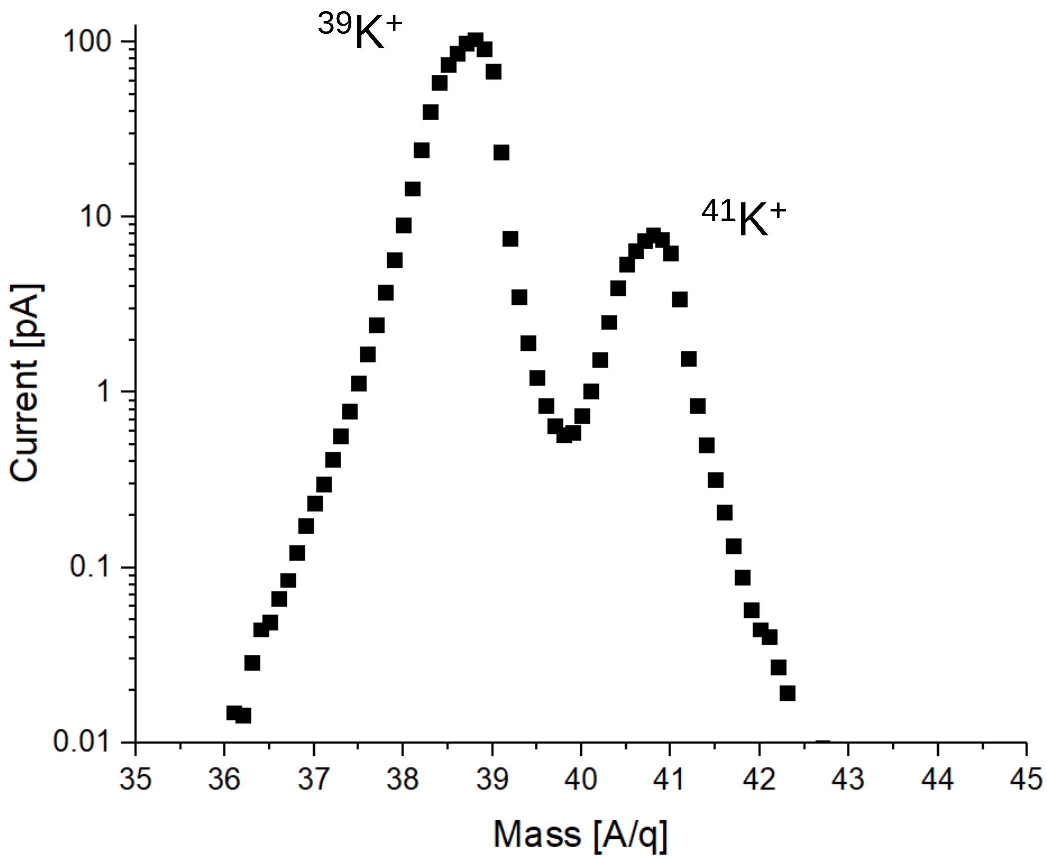
Backup Slides

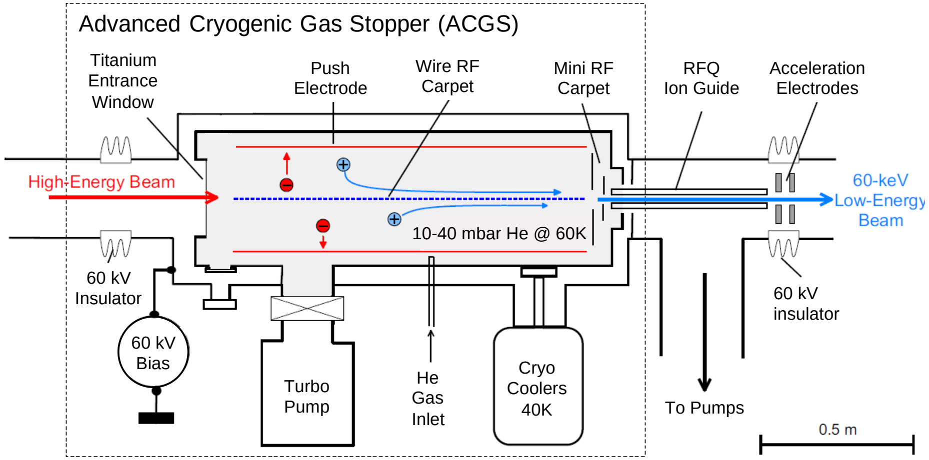
$^{39,41}K^{+}$ Successfully Transported and Detected at RGA

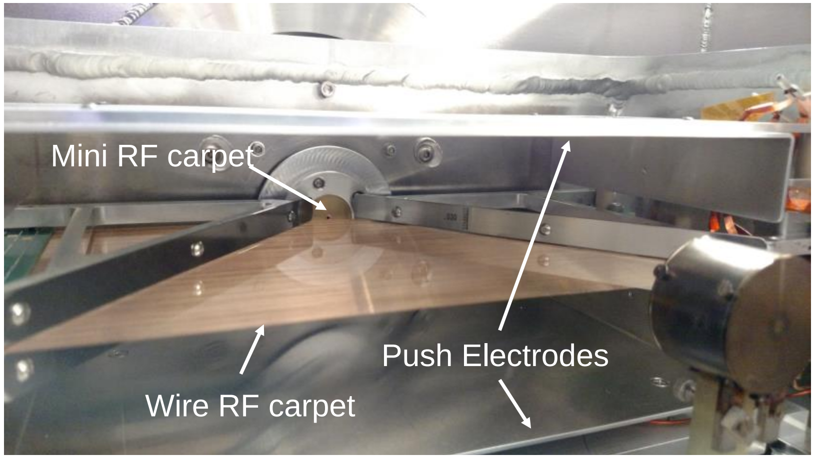
- Both $^{39}K^{+}$ and $^{41}K^{+}$ observable with current settings
- Pressure:
  - 1-2x10^{-3} mbar
- Incoming current
  - ~1 nA (~ 10% efficiency)
- Reasonable resolution for single mass identification
- Next steps:
  - Improve injection into RGA to improve efficiency
  - **External molecular beams starting this week!**

RGA mass spectrum



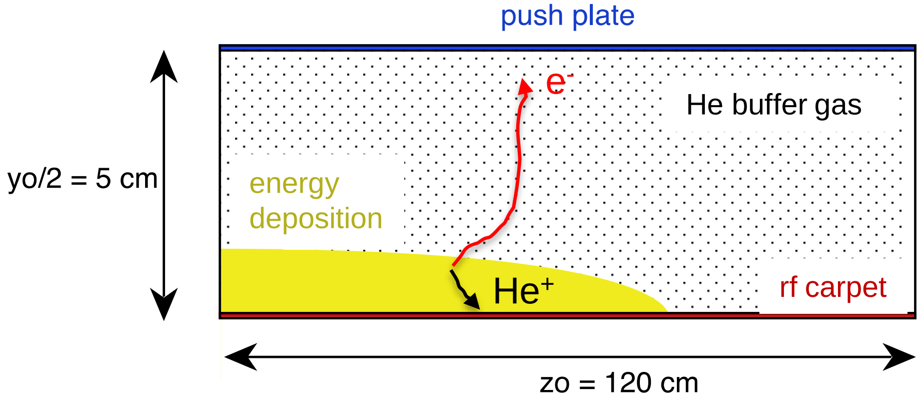
PIC Simulations Have Been Developed to Study Ion Transport and Extraction Efficiencies



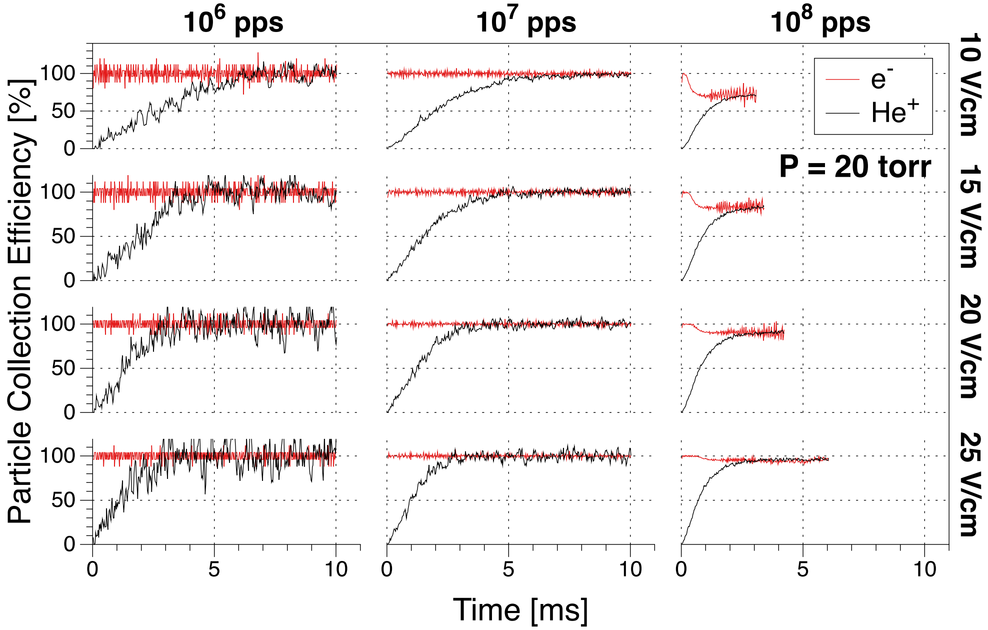


- Total electric field at the surface of the wire RF carpet
  - Each stopped rare isotope generates ~ 10^6 He^+/e^- pairs
  - Slow He^+ ion removal increases space charge in ACGS body, reducing transport efficiency
  - **Increase He^+/e^- collection speed**
- Charge capacity of extraction carpet and orifice
  - Charge exchange and/or direct ionization of impurities in He buffer gas generates beams of stable molecules
  - Extraction efficiency can be compromised by large stable beam currents
  - **Increase charge throughput**

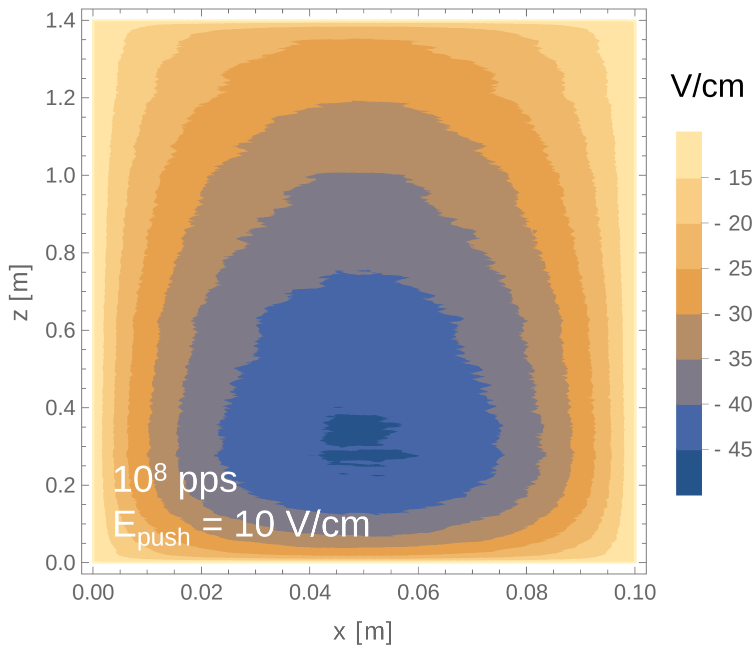
Calculating the Total Electric Field at the Surface of the RF Carpet



- PIC 3D Cartesian geometry
- Energy deposition from LISE++
- He^+ and e^- included
- SDS gas collision model[1]
- P = 20 Torr @ 50 K

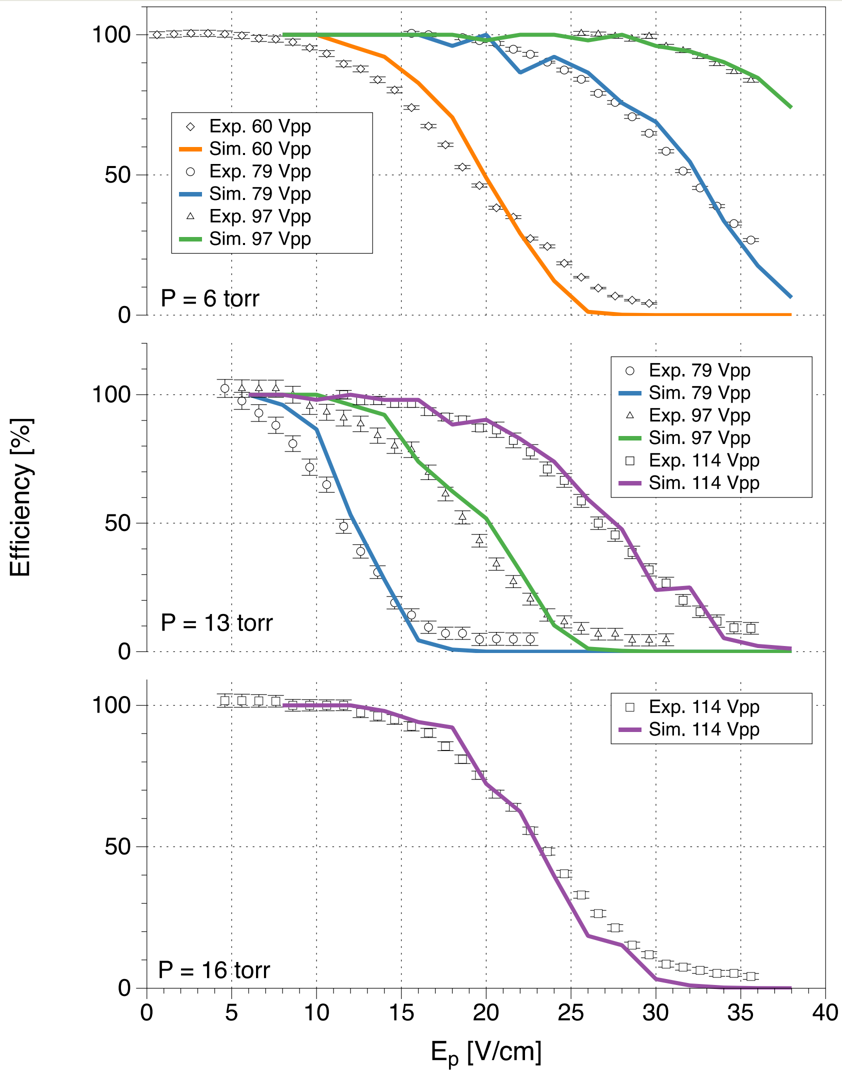


total electric field strength at RF carpet surface

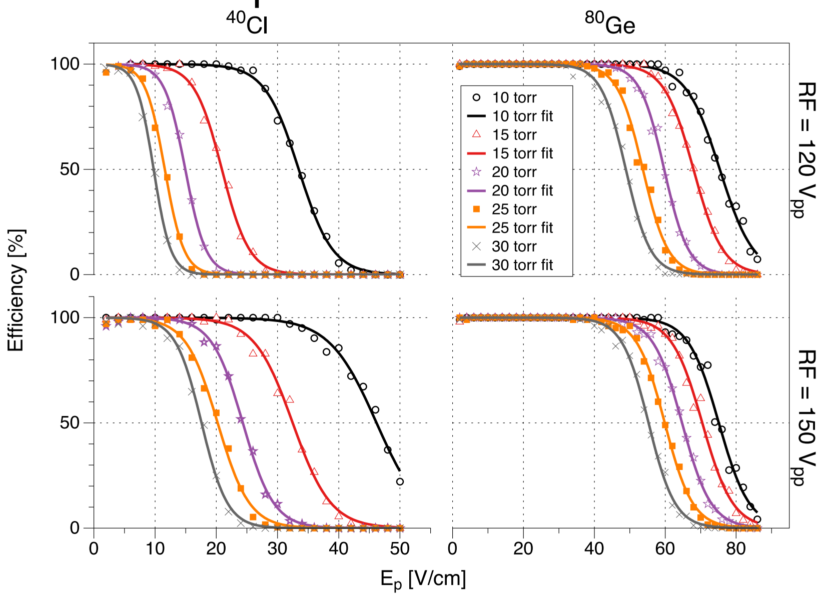


[1]A.D. Appelhans & D. A. Dahl, Int J Mass Spectrom **244**, 1–14 (2005)

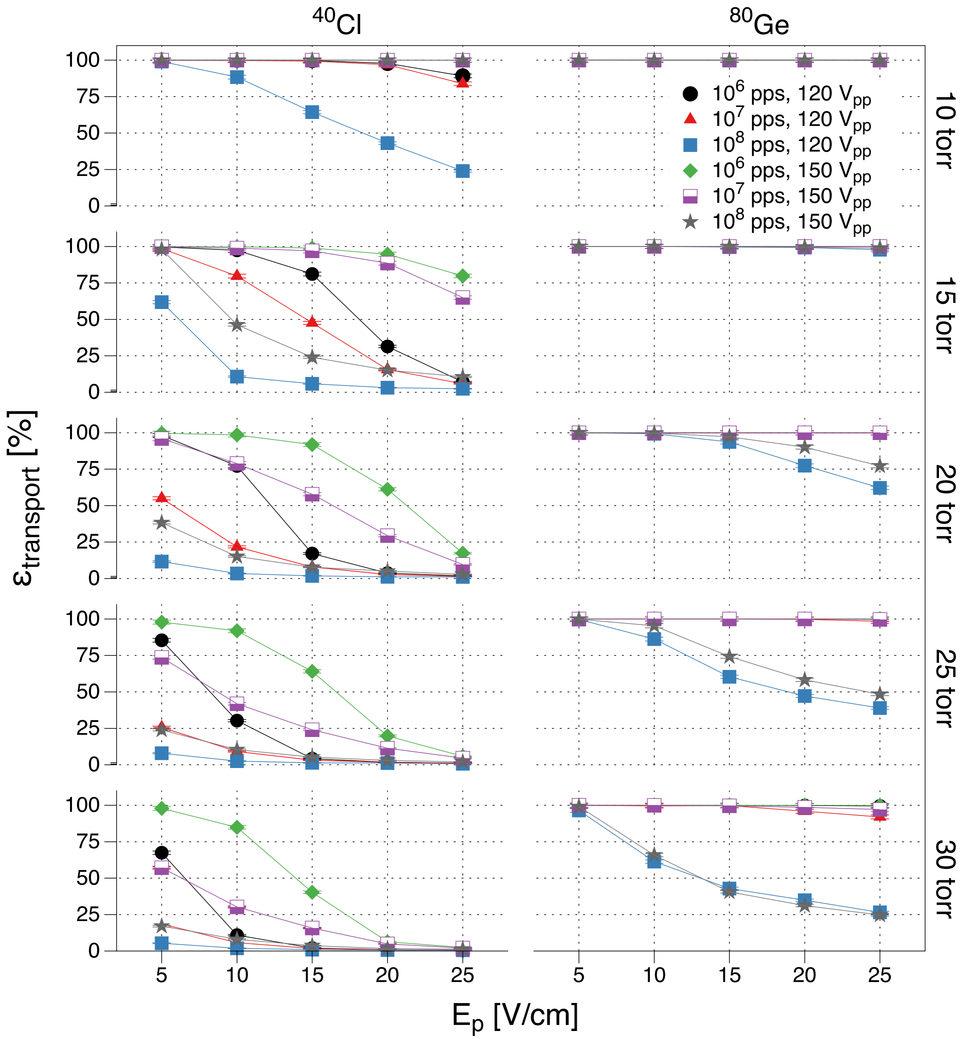
IonCool Accurately Calculates Ion Transport Efficiency Across ACGS RF Carpet



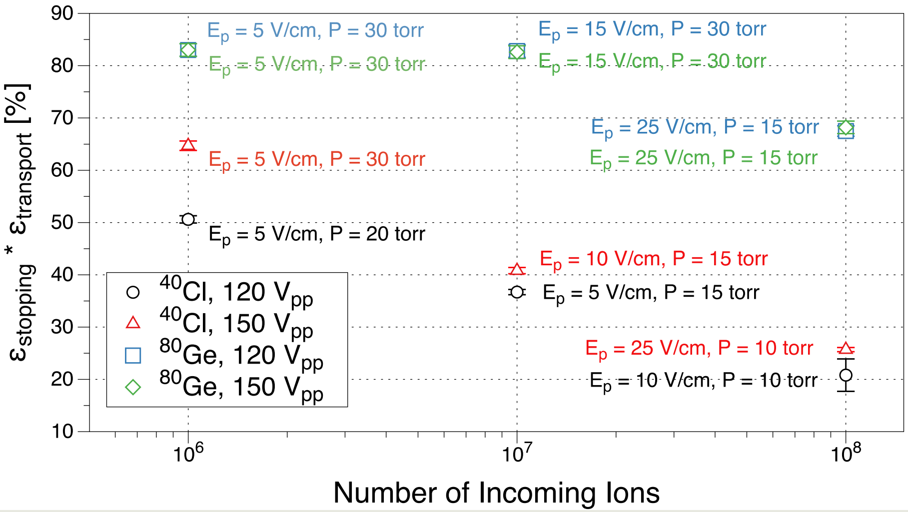
- Need to determine ion transport efficiency as a function of E_{push}
  - Using ACGS, ion transport efficiency of $^{39}K^+$ was measured
  - Multiple pressures at T=50K.
  - **IonCool simulation results show good agreement with experiment**
  - Confident in IonCool results to make broader predictions



Total RF Carpet Transport Efficiency from PIC and IonCool

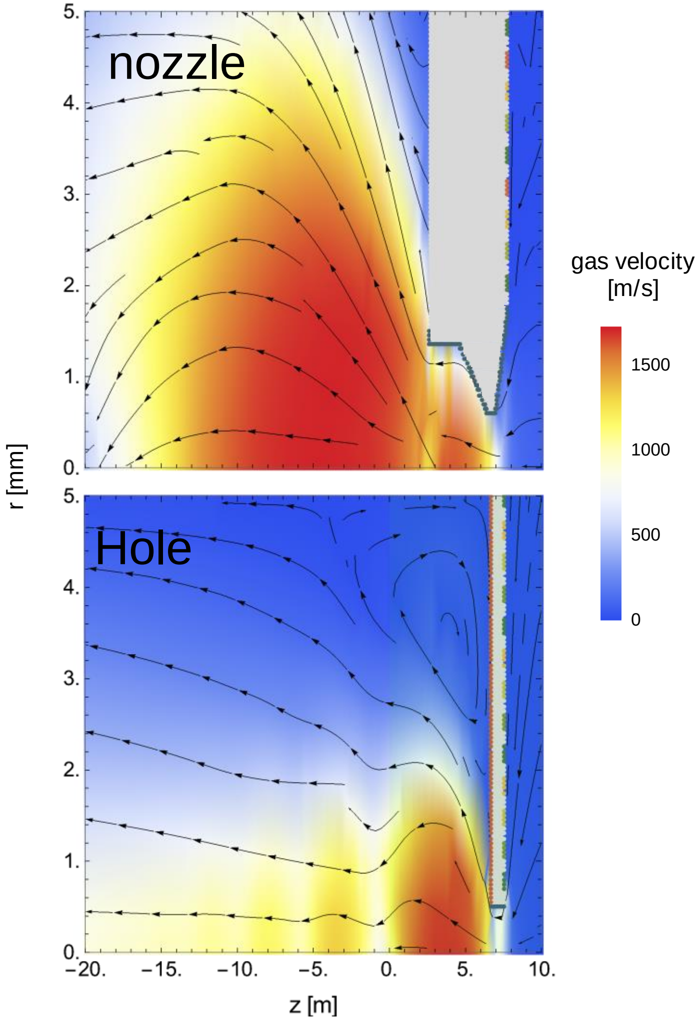


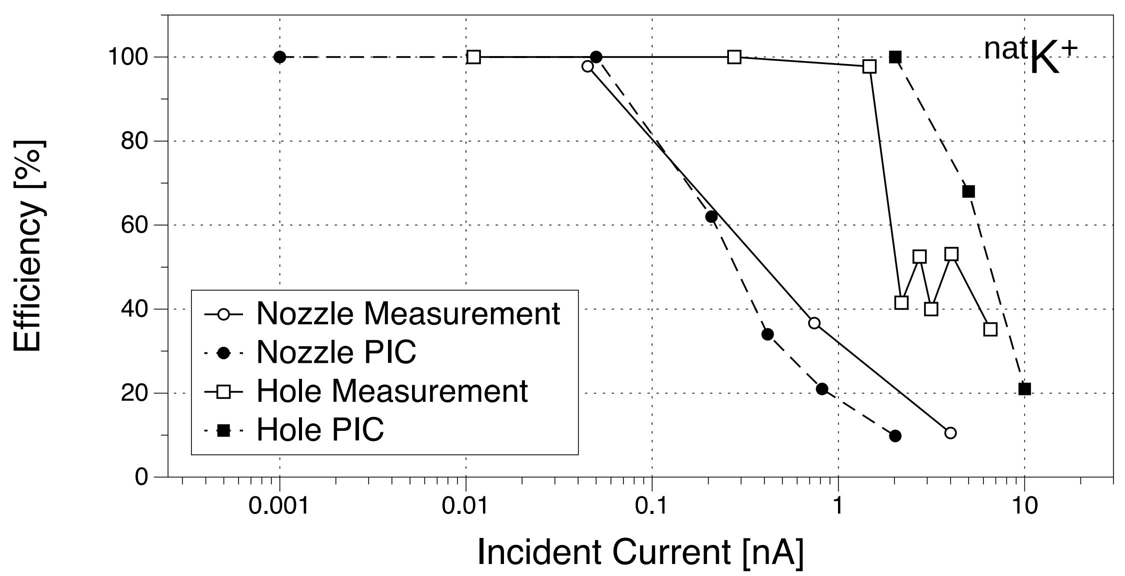
- Combine IonCool and PIC results to calculate total transport efficiency
  - Stopped rare isotope distribution obtained from LISE++
  - Monte-Carlo approach used to calculate transport efficiency
  - **Folding in stopping efficiency determines optimum total efficiency that is rate dependent[1]**



[1]R. Ringle, R. *et al*. NIM B **496**, 61–70 (2021).

PIC Simulations of ACGS Extraction System Yield Efficiency Improvements

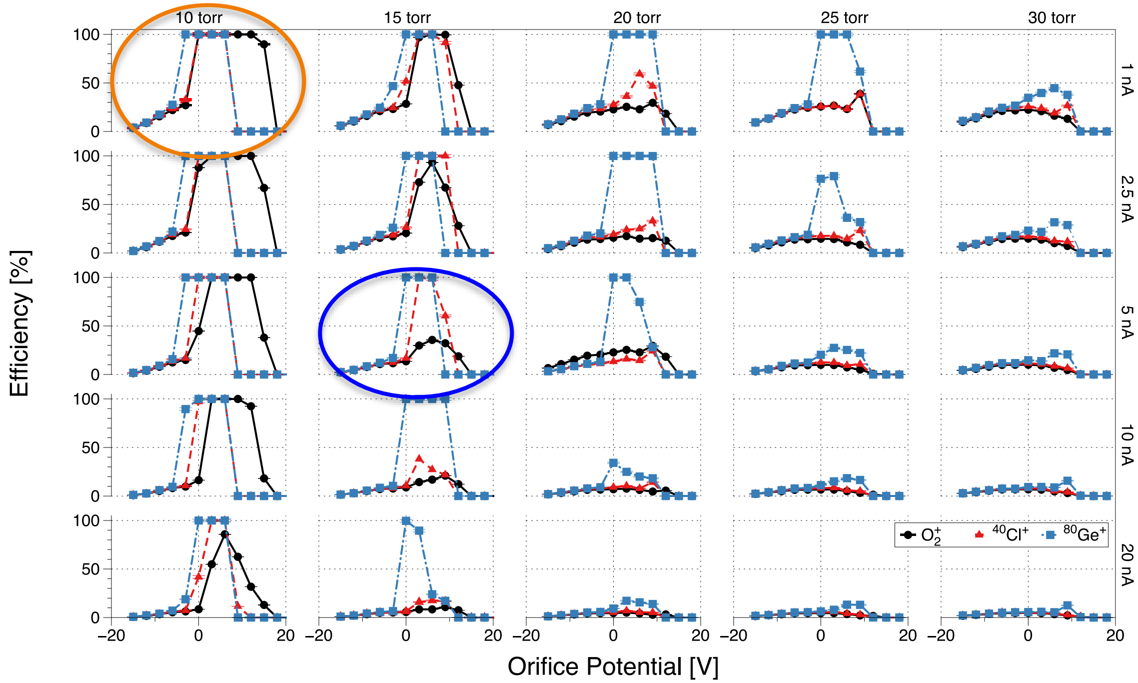




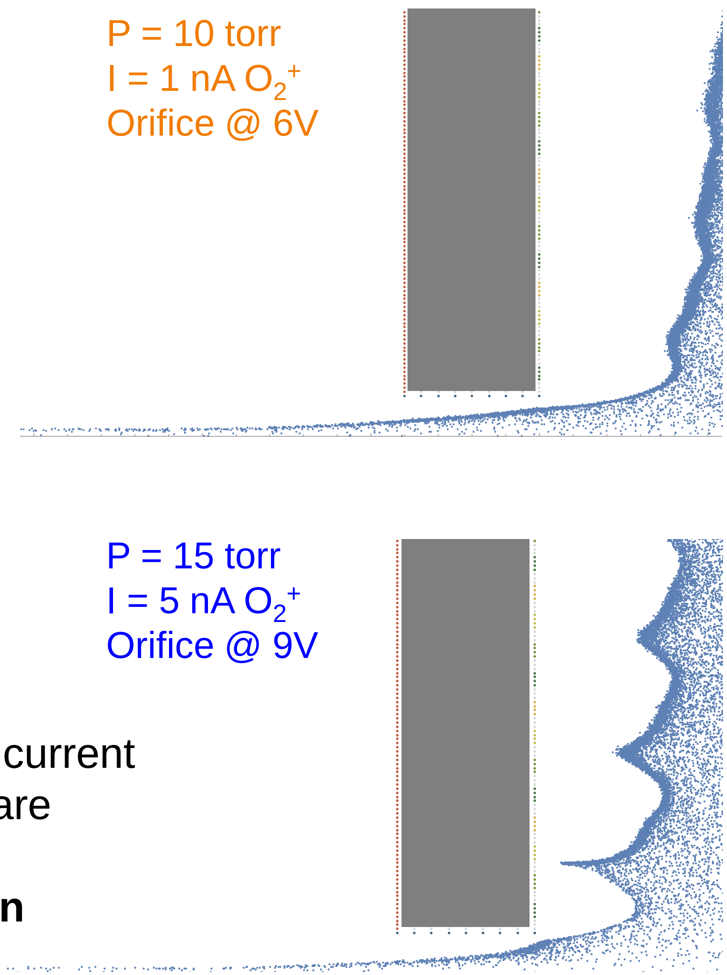
- 2D cylindrical RZ geometry
- Gas flow calculated with COMSOL
- Traveling wave transport across RF carpet[1,2]
- Compared original ACGS “nozzle” extraction to a simple hole
- **Simulations accurately predicted significant gain in throughput for the hole vs. nozzle**

[1]G. Bollen, Int J Mass Spectrom **299**, 131–138 (2011)
[2]M. Brodeur *et al.*, Int J Mass Spectrom **336**, 53–60 (2013)

Contaminant Ions Can Have a Significant Impact on Extraction of Rare Isotope Beams



P = 10 torr
I = 1 nA O_2^+
Orifice @ 6V



P = 15 torr
I = 5 nA O_2^+
Orifice @ 9V

- Scan potential applied to orifice and vary the incident O_2^+ current
- Once steady state is reached, create tracer particles for rare isotopes ($^{40}Cl^+$ and $^{80}Ge^+$)
- **O_2^+ current can have a significant impact on extraction efficiency of rare isotopes**
- **Many studies complete and underway to optimize performance**