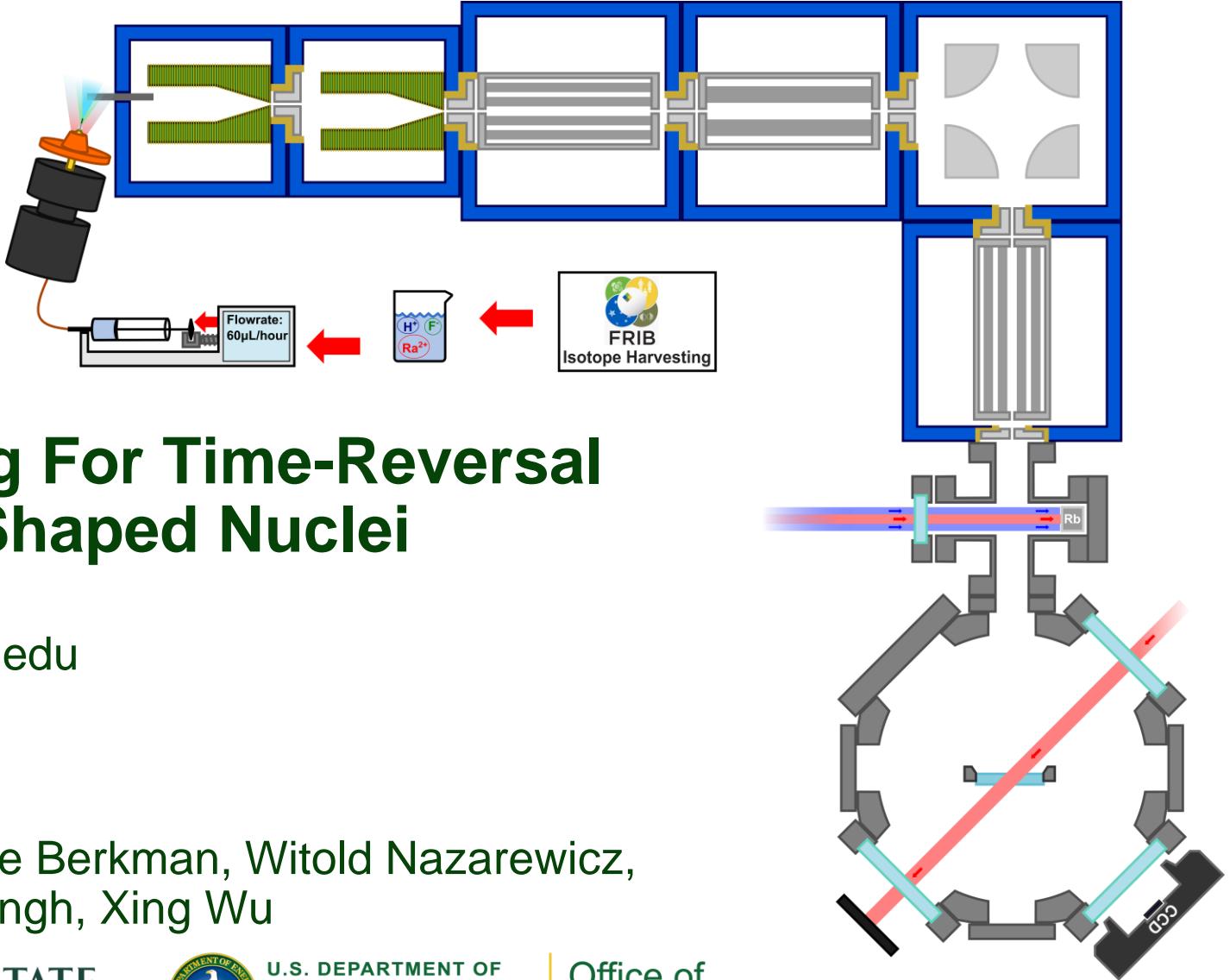


May 06th, 2024, 1:30 PM FRIB Room 1200 First Committee Meeting



Progress Towards Searching For Time-Reversal Violation Using Pear Shaped Nuclei

Aiden Boyer
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2024-05-06

Special thanks to guidance committee: Sophie Berkman, Witold Nazarewicz, Stuart Tessmer, Jaideep Singh, Xing Wu



**MICHIGAN STATE
UNIVERSITY**



U.S. DEPARTMENT OF **ENERGY**

Office of Science

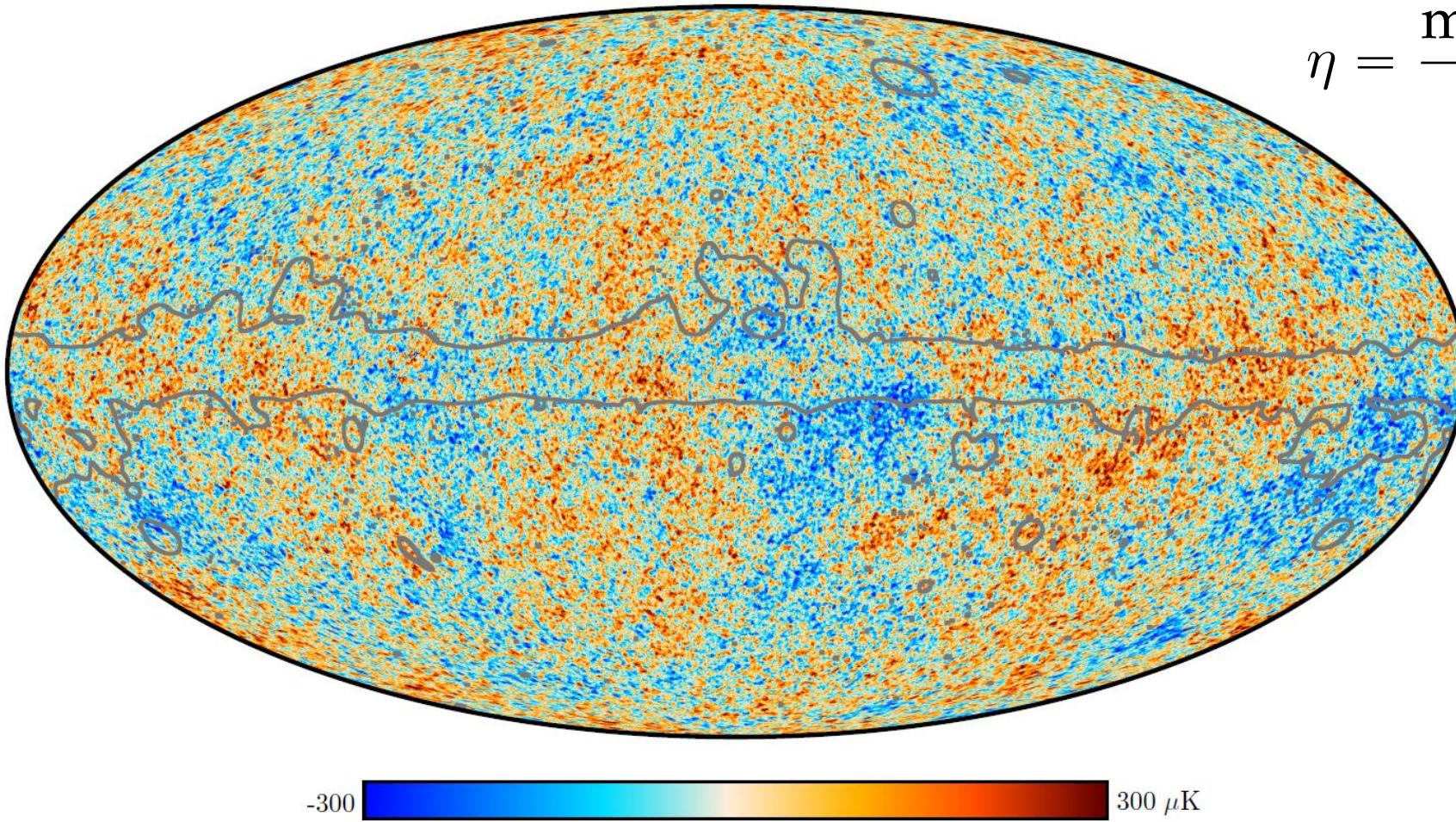
This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633.

This work is supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics under Award Number DE-SC0022299.

This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Award Numbers DE-SC0019015 and DE-SC0019455.

Cosmic Microwave Background Anisotropy

Why More Matter Than Anti-matter?



Planck (2018) <https://www.cosmos.esa.int/web/planck/picture-gallery>

$$\eta = \frac{\text{matter} - \text{antimatter}}{\text{relic photons}} \propto \sin(\delta)$$

$$\eta_{\text{exp}} \approx 10^{-9}$$

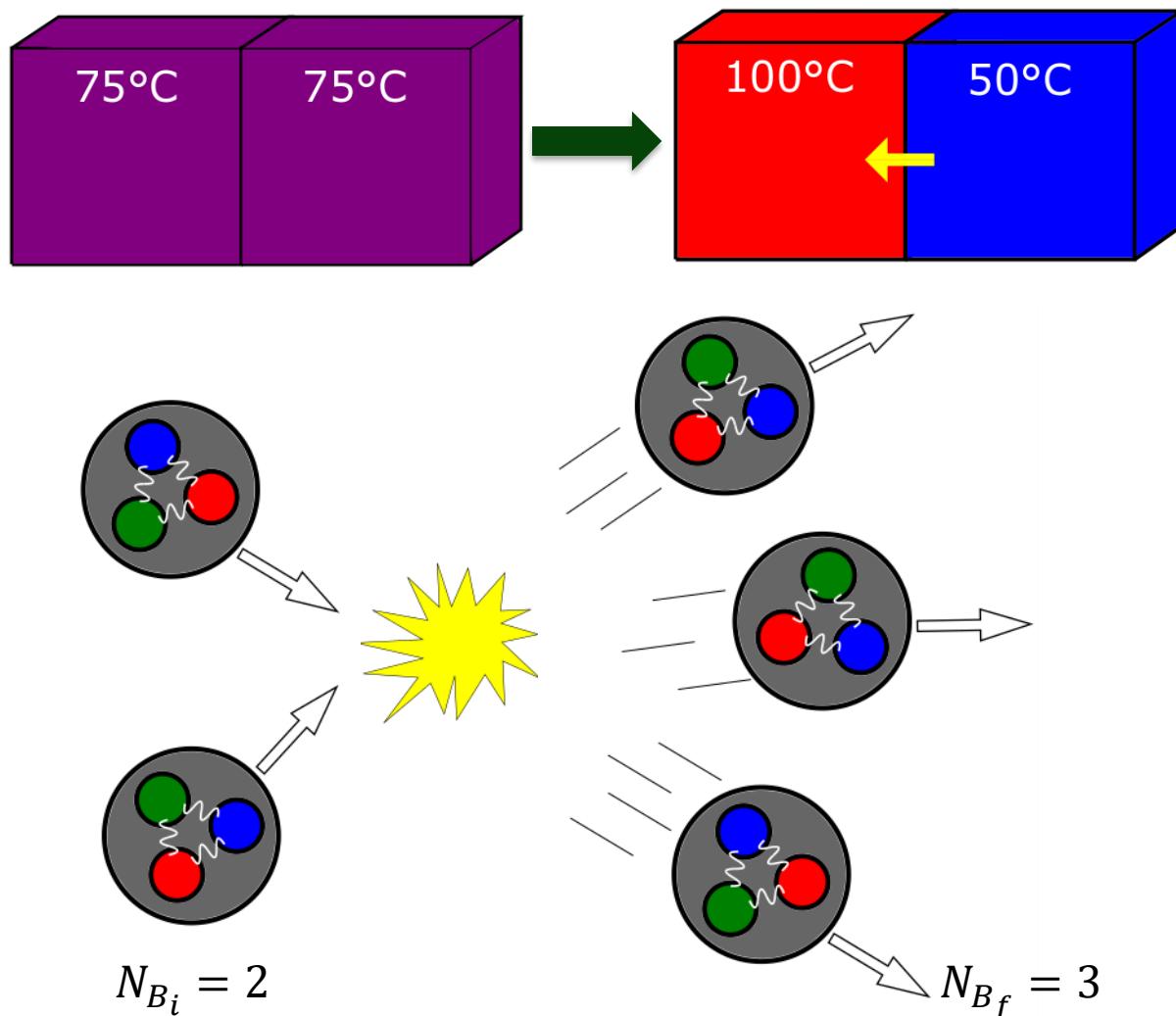
PDG2023



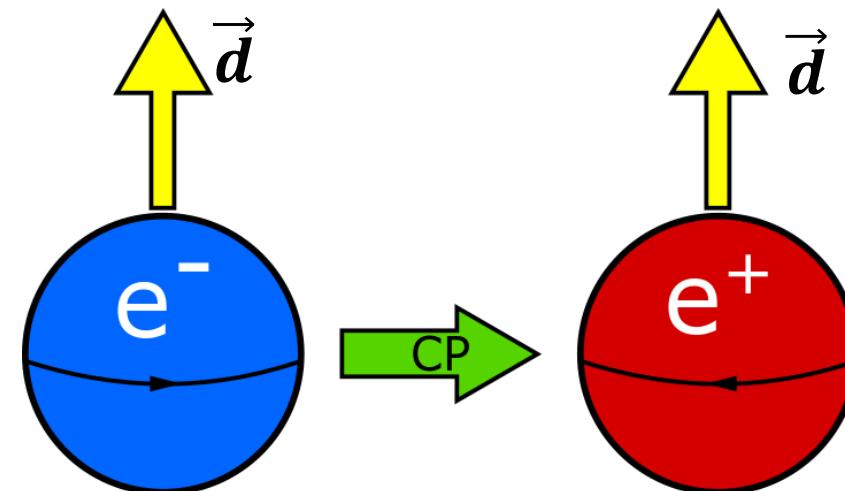
$$\eta_{\text{CKM}} \approx 10^{-26}$$

Huet & Sather PRD 51:379 (1995)

Sakharov Conditions: Baryon Asymmetry Possible If...



1. Departure from thermal equilibrium
2. Baryon number violation $N_{B_i} \neq N_{B_f}$
3. C, CP Violation



A. D. Sakharov *JETP Letters*, 5:1 (1967)

Different Avenues To Search For CP Violation

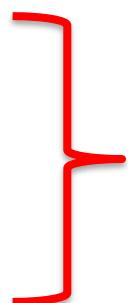
- High Energy Searches

- Neutrino oscillations
- Kaon decays
- B meson decays



- Low Energy Searches

- Ortho-positronium
- Permanent electric dipole moments



Permanent Electric Dipole Moments (EDMs)

A Signature Of CP Violation

- An EDM is a measurement of separation of charge

$$\vec{d} = \int \vec{r} \rho_Q d^3r = d \frac{\langle \vec{J} \rangle}{J}$$

$$\mathcal{H} = -(\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}) = -\frac{(\mu \vec{J} \cdot \vec{B} + d \vec{J} \cdot \vec{E})}{J}$$

Quantity	P (Parity)	T (Time-reversal)
\vec{J}	Even (+)	Odd (-)
\vec{B}	Even (+)	Odd (-)
\vec{E}	Odd (-)	Even (+)
$\vec{J} \cdot \vec{B}$	Even (+)	Even (+)
$\vec{J} \cdot \vec{E}$	Odd (-)	Odd (-)

CPT Theorem: T-Violation = CP-Violation

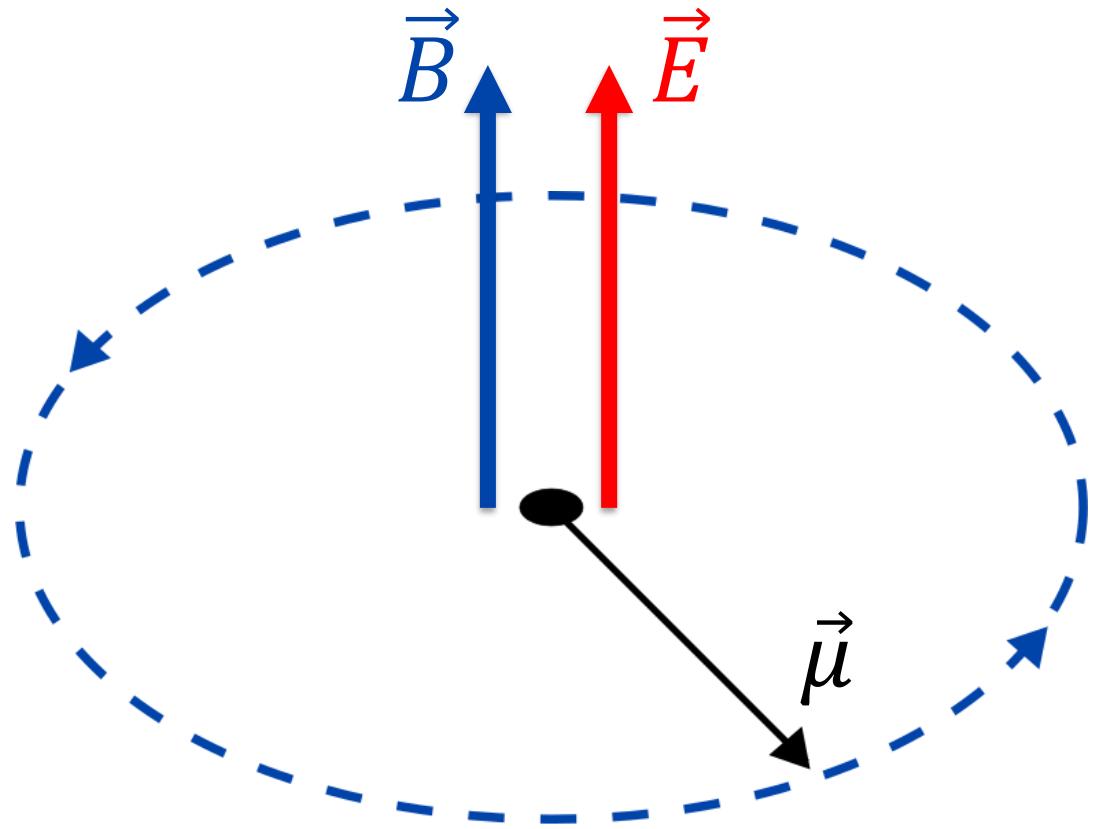
Multiple Experiments With Different Test Particles Different Sensitivities To CP Violation

System	Best Limit (95%) 1E-28 e cm	SM estimate 1E-28 e cm Chupp et al. <i>RMP</i> 91:1 (2019)	Method (Location)
Neutron	220	$\sim 10^{-4}$	ultracold neutrons in a bottle (PSI) Abel et al. <i>PRL</i> 124:8 (2020)
“Electron”	0.11	$\sim 10^{-7}$ Ema et. al. <i>PRL</i> 23:231801 (2022)	cold ThO beam (Chicago/Harvard/Northwestern) Andreev et al. <i>Nature</i> 562:7727 (2018)
Hg-199	0.05		trapped HfF ⁺ (JILA/Boulder) Roussy et. al. <i>Science</i> 381:6653 (2023)
	0.074	$\sim 10^{-6}$	atoms in vapor cell (UW-Seattle) Graner, et al. <i>PRL</i> 116:16 (2016)

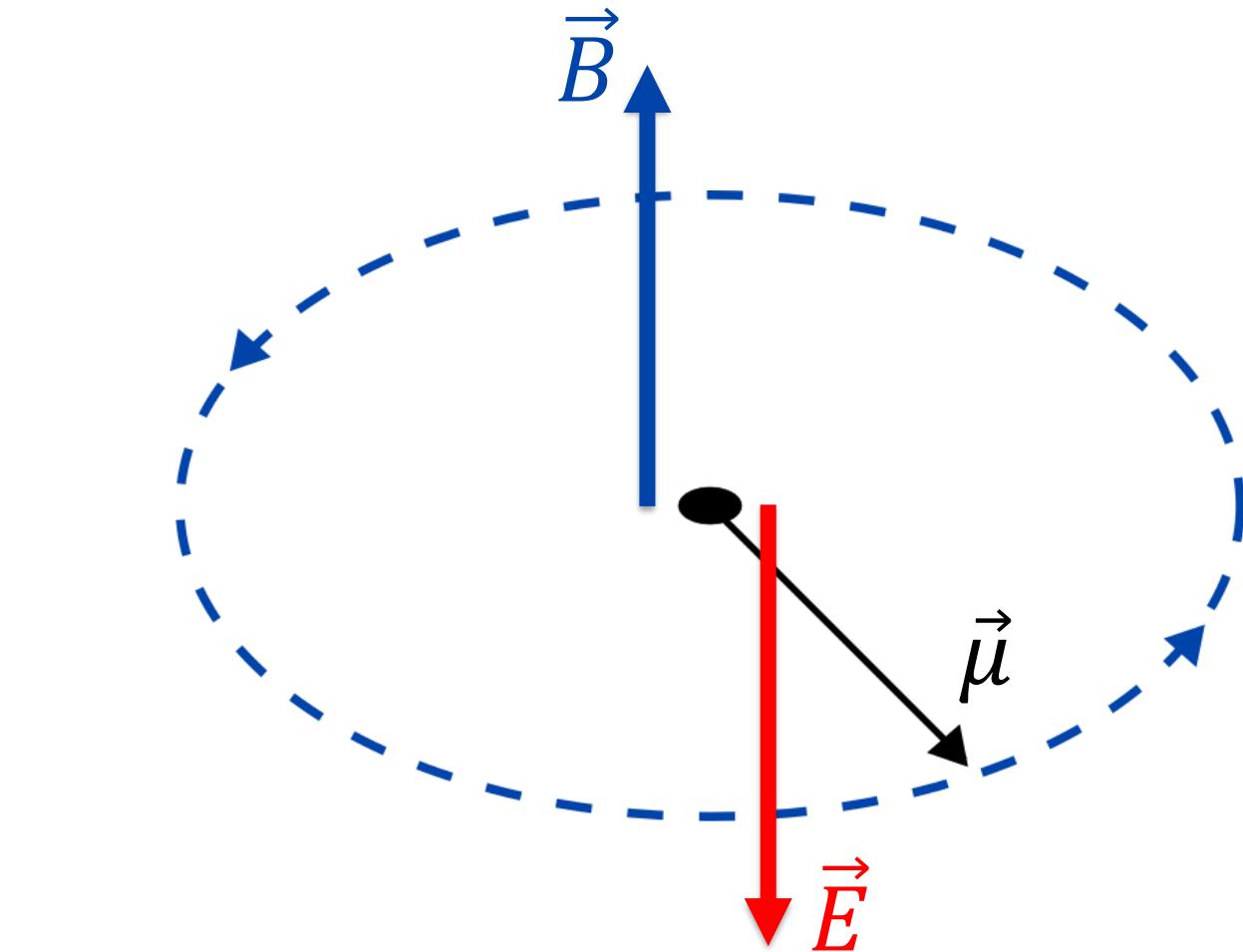
ALL CONSISTENT WITH ZERO

EDM Measurements Always Measure Frequency

Ex: Spin Precession Of A Spin-1/2 Particle



$$h\nu_{\text{up}} = 2(\mu B_{\text{up}} + dE_{\text{up}})$$



$$h\nu_{\text{down}} = 2(\mu B_{\text{down}} - dE_{\text{down}})$$

EDM Measurements Always Measure Frequency

Ex: Spin Precession Of A Spin-1/2 Particle

- Ideal: $B_{\text{up}} = B_{\text{down}} = B$ and $E_{\text{up}} = E_{\text{down}} = E$

$$\Delta\nu = \nu_{\text{up}} - \nu_{\text{down}} = \frac{2(\mu B + dE) - 2(\mu B - dE)}{h} = \frac{4dE}{h}$$

- Reality: $B_{\text{up}} \neq B_{\text{down}}$ and $E_{\text{up}} \neq E_{\text{down}}$

$$\Delta\nu = \nu_{\text{up}} - \nu_{\text{down}} = \frac{2\mu\Delta B + 2d(E_{\text{up}} + E_{\text{down}}) + \frac{1}{2}\alpha(E_{\text{up}}^2 - E_{\text{down}}^2) + \text{Others}}{h}$$

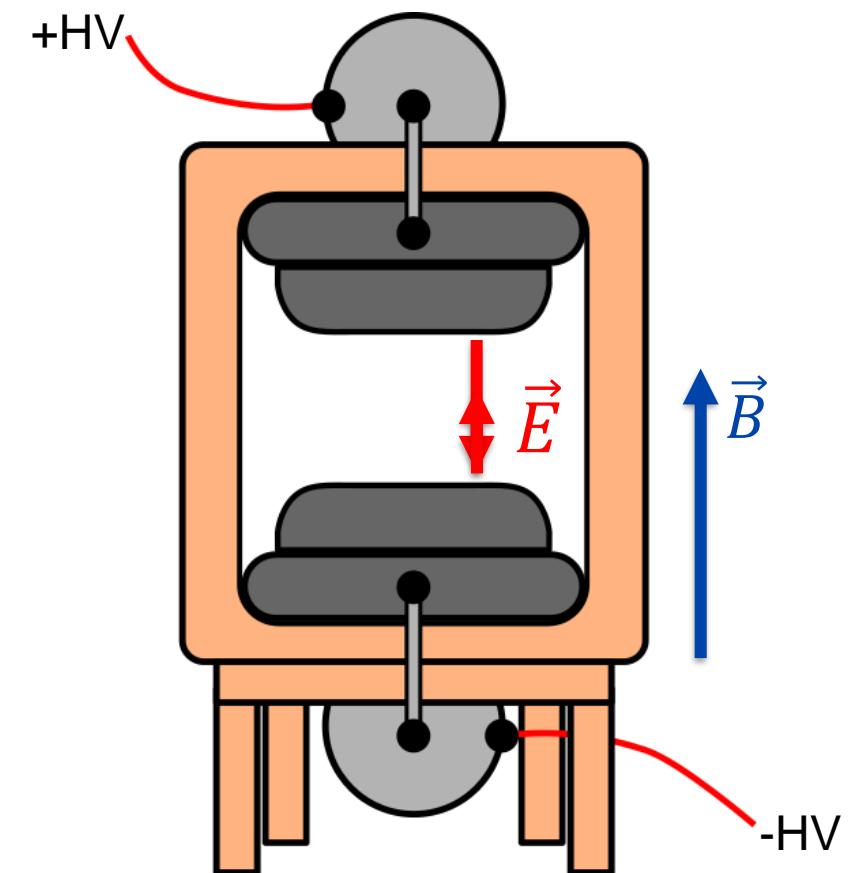
False EDM Signal

Systematic Effects In An EDM Measurement

$$\Delta\nu = \nu_{\text{up}} - \nu_{\text{down}} = \frac{2\mu\Delta B + 2d(E_{\text{up}} + E_{\text{down}}) + \frac{1}{2}\alpha(E_{\text{up}}^2 - E_{\text{down}}^2) + \text{Others}}{h}$$

- Nonzero ΔB , or transient fields
 - Characterize B fields
 - Minimize external fields
 - Limits statistical precision

- Imperfect field reversal
 - Poignant if magnitude of E field is not the same



Statistical Sensitivity Of An EDM Measurement

$$\sigma_v = \frac{1}{2\pi\tau} \rightarrow \frac{\sigma_d}{\sqrt{N_m}} = \frac{\hbar}{2\bar{E}\sqrt{\varepsilon N_a T\tau}}$$

Spin precession observation time (Interrogation Time)

Number of Δv measurements

Average E field magnitude

Total number of probed particles

Experimental efficiency

Total integration time

Spin precession observation time (Interrogation Time)

Number of Δv measurements

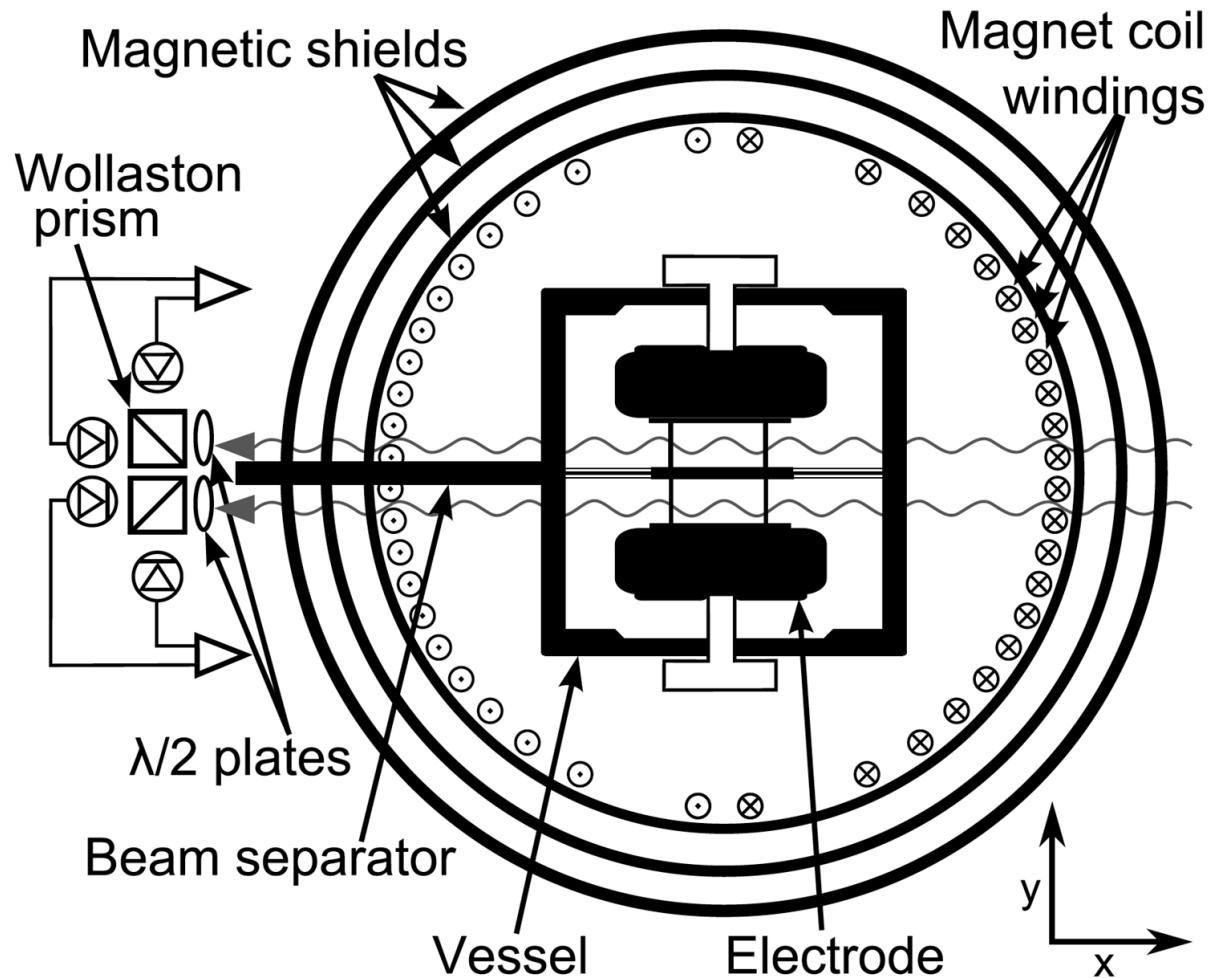
Average E field magnitude

Total number of probed particles

Experimental efficiency

Total integration time

Gold Standard: Hg-199 EDM Search



- Highest precision atomic EDM
 - Mercury vapor cell
 - Frequency resolution \sim nHz
 - Systematically limited by 10nm scale motion of vapor cell
 - Further improvements nontrivial
- To achieve a better limit, need entirely new techniques

The best limit on atomic EDM:

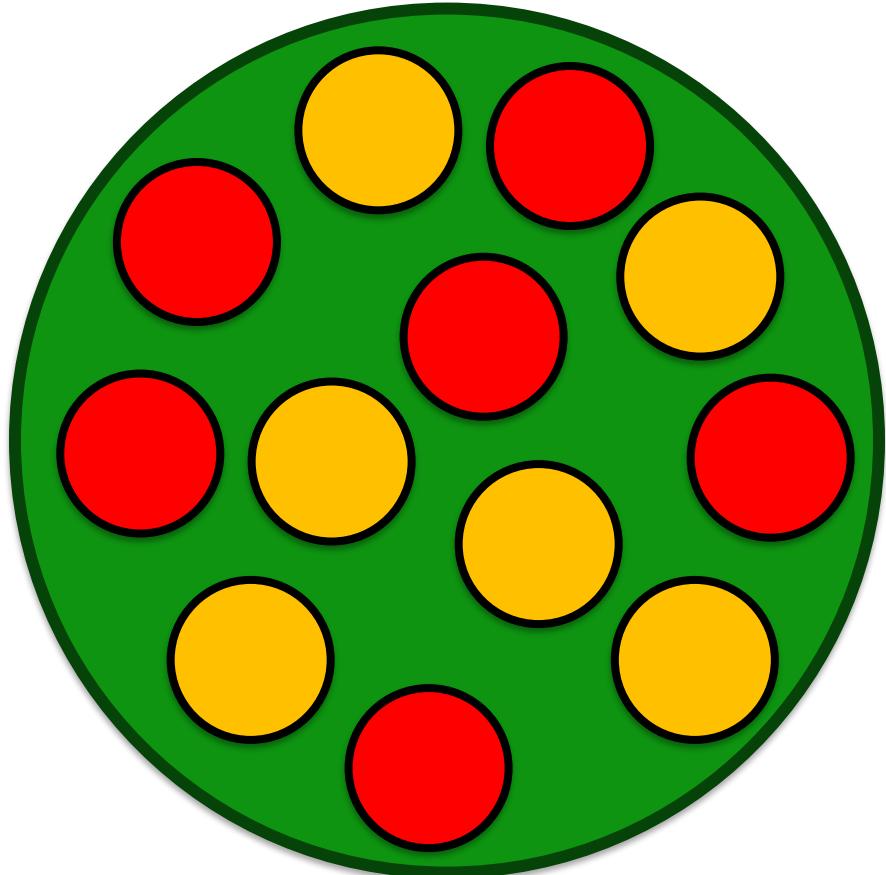
$$\text{EDM}({}^{199}\text{Hg}) < 0.074 \times 10^{-28} \text{ e-cm (95% C.L.)}$$

SM estimate: $\sim 10^{-34}$ e-cm

Graner et al. *PRL* 116:161601 (2016), Chupp et al. *RMP* 91:1 (2019)

Octupole Deformed Nuclei

Typical perception of nuclei

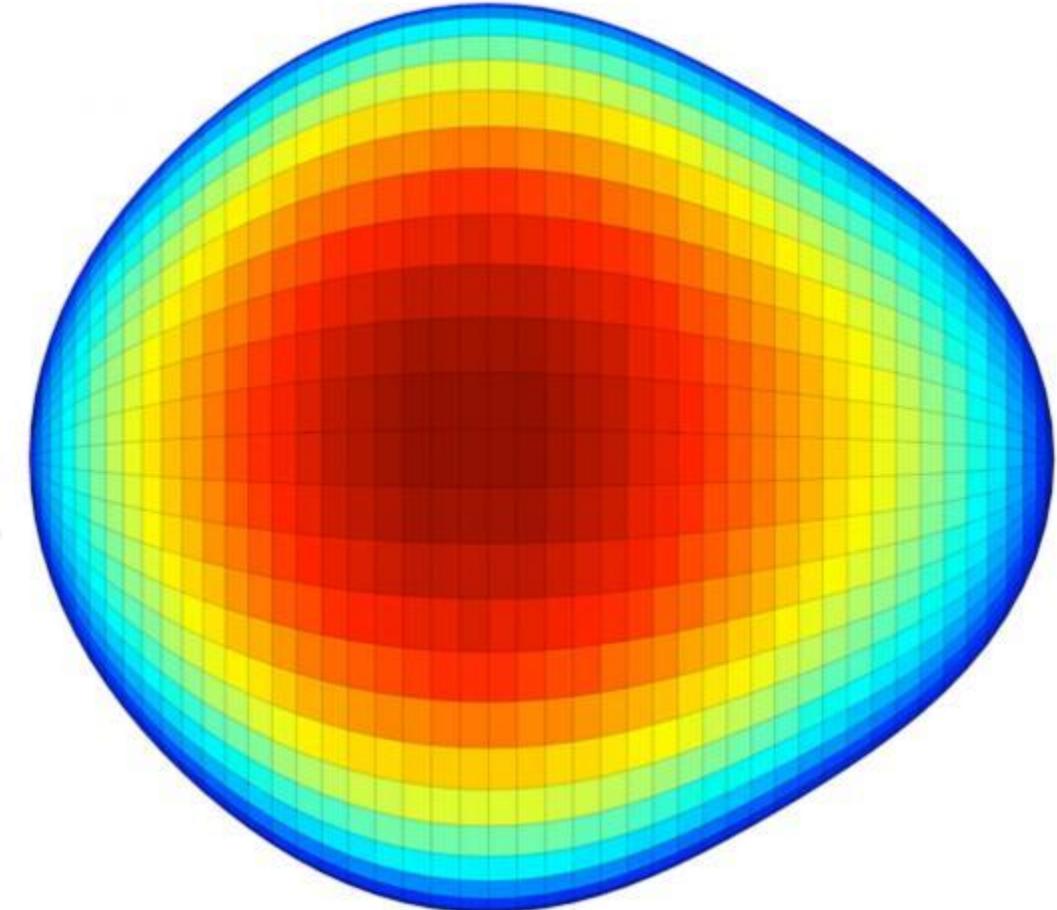


Jahn Teller
effects



Microscopic
shell effects

One realistic representation



Cern (2020)

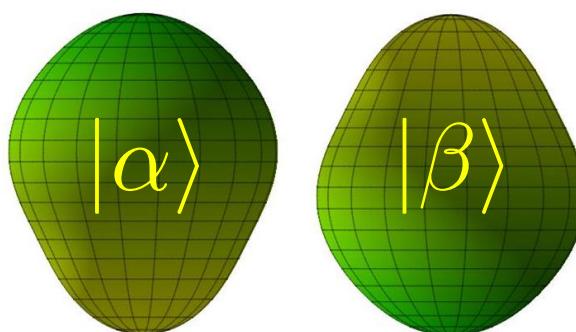
<https://cds.cern.ch/images/CERN-HOMEWEB-PHO-2020-012-1>

^{225}Ra : enhanced sensitivity to T-violation due to pear-shaped nucleus

$$S_z = \frac{\langle er^2z \rangle}{10} - \frac{\langle r^2 \rangle \langle ez \rangle}{6}$$

$$S \equiv \langle \Psi_0 | S_z | \Psi_0 \rangle = \sum_{k \neq 0} \frac{\langle \Psi_0 | S_z | \Psi_k \rangle \langle \Psi_k | V_{PT} | \Psi_0 \rangle}{E_0 - E_k} + \text{c.c.}$$

Parity Doublet



$$|\Psi_1\rangle = \frac{|\alpha\rangle - |\beta\rangle}{\sqrt{2}}$$

$$|\Psi_0\rangle = \frac{|\alpha\rangle + |\beta\rangle}{\sqrt{2}}$$

55 keV

Total Enhancement Factor:
EDM (^{225}Ra) / EDM (^{199}Hg)

Skyrme Model	Isoscalar	Isovector
SIII	300	4000
SkM*	300	2000
SLy4	700	9000

^{225}Ra : Dobaczewski & Engel *PRL* 94:232502 (2005)

^{199}Hg : Ban et al. *PRC* 82:015501 (2010)

- Atomic EDMs induced by Nuclear Schiff Moments (NSM)
 - Schiff *PR* 132:1937 (1963)

- Nearly degenerate parity doublets
 - Haxton & Henley *PRL* 51:1937 (1983)

- Large intrinsic Schiff Moment due to octupole deformation
 - Auerbach, Flambaum, & Spevak *PRL* 76:4316 (1996)

Unknown P- & T-
Violating physics!

The Laser Trap Ra EDM Experiment (Argonne/MSU)

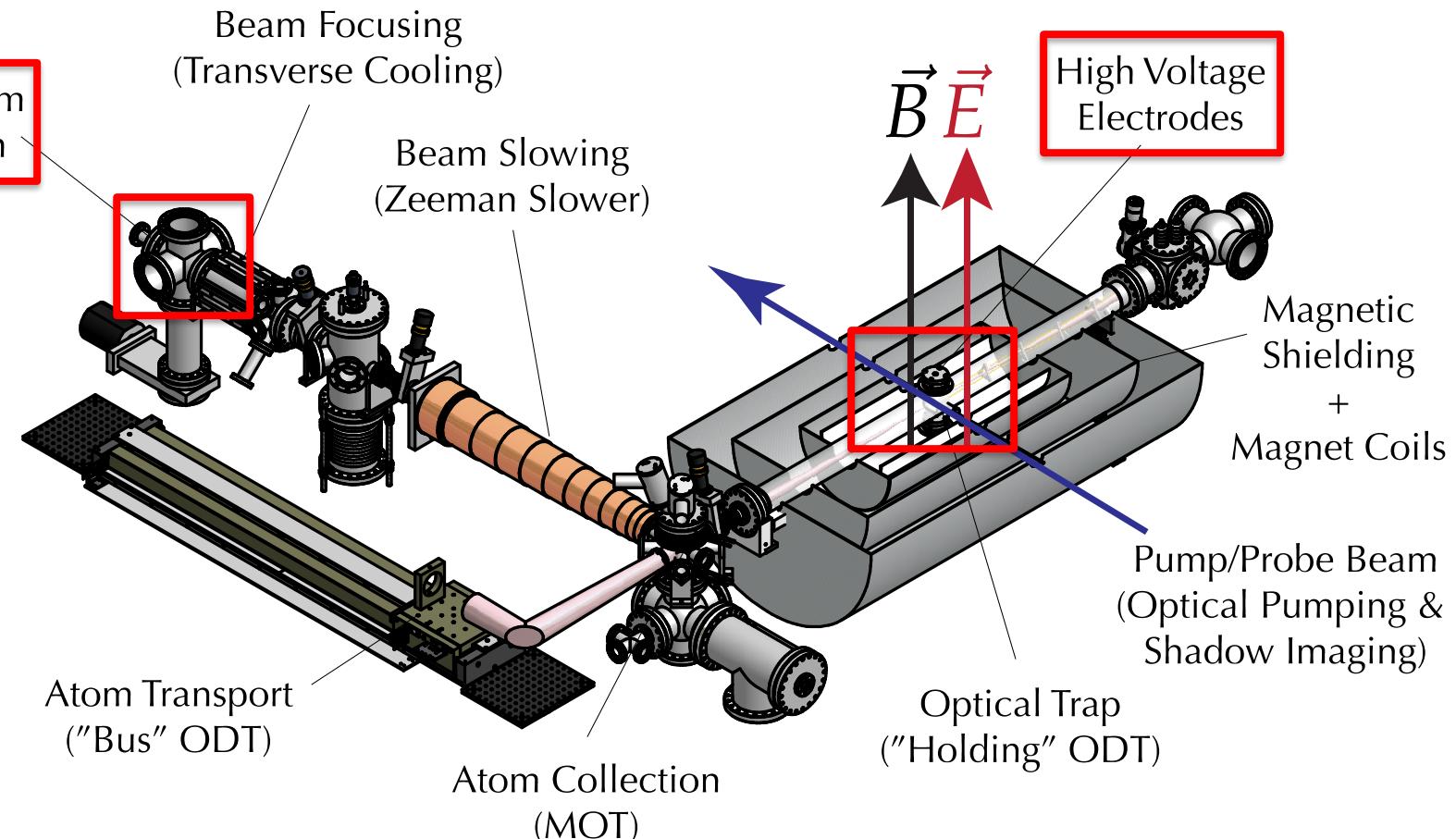
^{225}Ra atomic EDM measured less than $1.4 \times 10^{-23} \text{ e cm}$ (95% confidence upper limit)

Bishof et. al. PRC 94:025501 (2016)

▪ Argonne/MSU Collaboration

- Gordon Arrowsmith-Kron, Himanshi, Aiden Boyer, Jaideep Singh

1. Load oven with radium
2. Heat oven to ~500 Celsius
3. Focus atomic Ra beam
4. Slow Ra atomic beam
5. Trap atoms in 3D MOT
6. Overlap with laser for ODT
7. Translate ODT focus to measurement region



Completely statistics limited

Several upgrades underway

Planned Upgrades To The Laser Trap Ra EDM Experiment

System	Current Limit (e*cm)	Goal Sensitivity (e*cm)	Reference
Ra-225	1.4E-23	1E-28	PRC, 94, 025501 (2016)

$$\frac{\sigma_d}{\sqrt{N_m}} = \frac{\hbar}{2\bar{E}\sqrt{\varepsilon N_a T \tau}}$$

N_a : Number of atoms measured
 \bar{E} : Average Electric field strength
 τ : Spin precession time

T : Total time of experiment
 σ_d : EDM statistical uncertainty
 ε : Efficiency of experiment

Upgrade	Variable	Factor of Improvement	Effect on Sensitivity
High Voltage	\bar{E}	~ Factor of 10 larger E, better systematics	~ 10
Blue Slower	N_a	~ Factor of 60 larger N	~ 10
QND	ε	~ Factor of 1000 more photons scattered	~ 100
Spin Precession	τ	~factor of 5 higher spin precession time	~3*
Isotope Harvesting	T	New source of Ra-225 gives more total measurement time	~3**

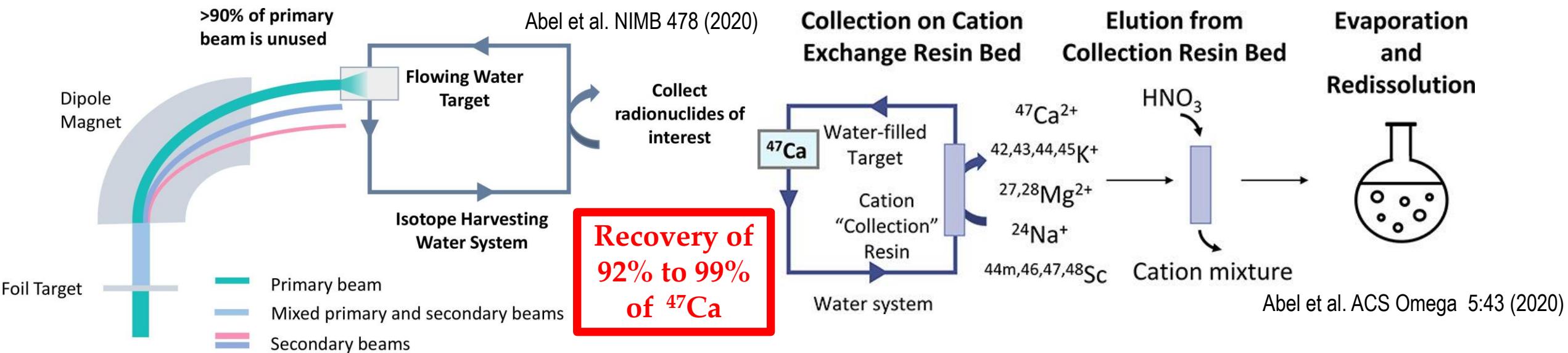
*Our colleagues at USTC have demonstrated higher precession time

**Will have a steady supply of Radium for experiment

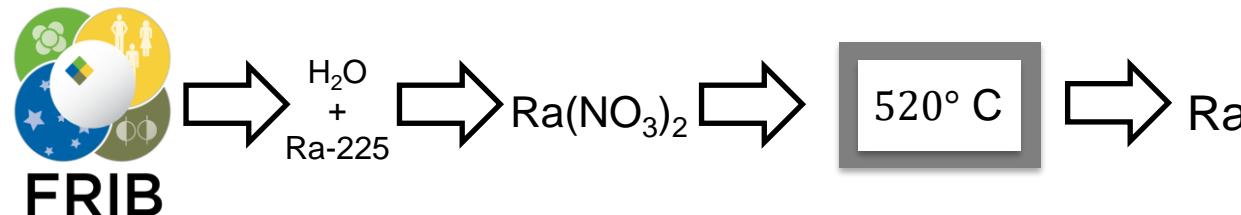
MSU

Argonne

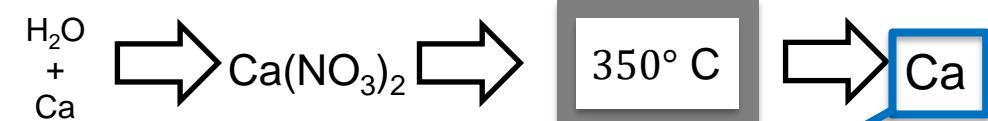
Sourcing ^{225}Ra From FRIB's Isotope Harvesting Program



Eventual Goal:



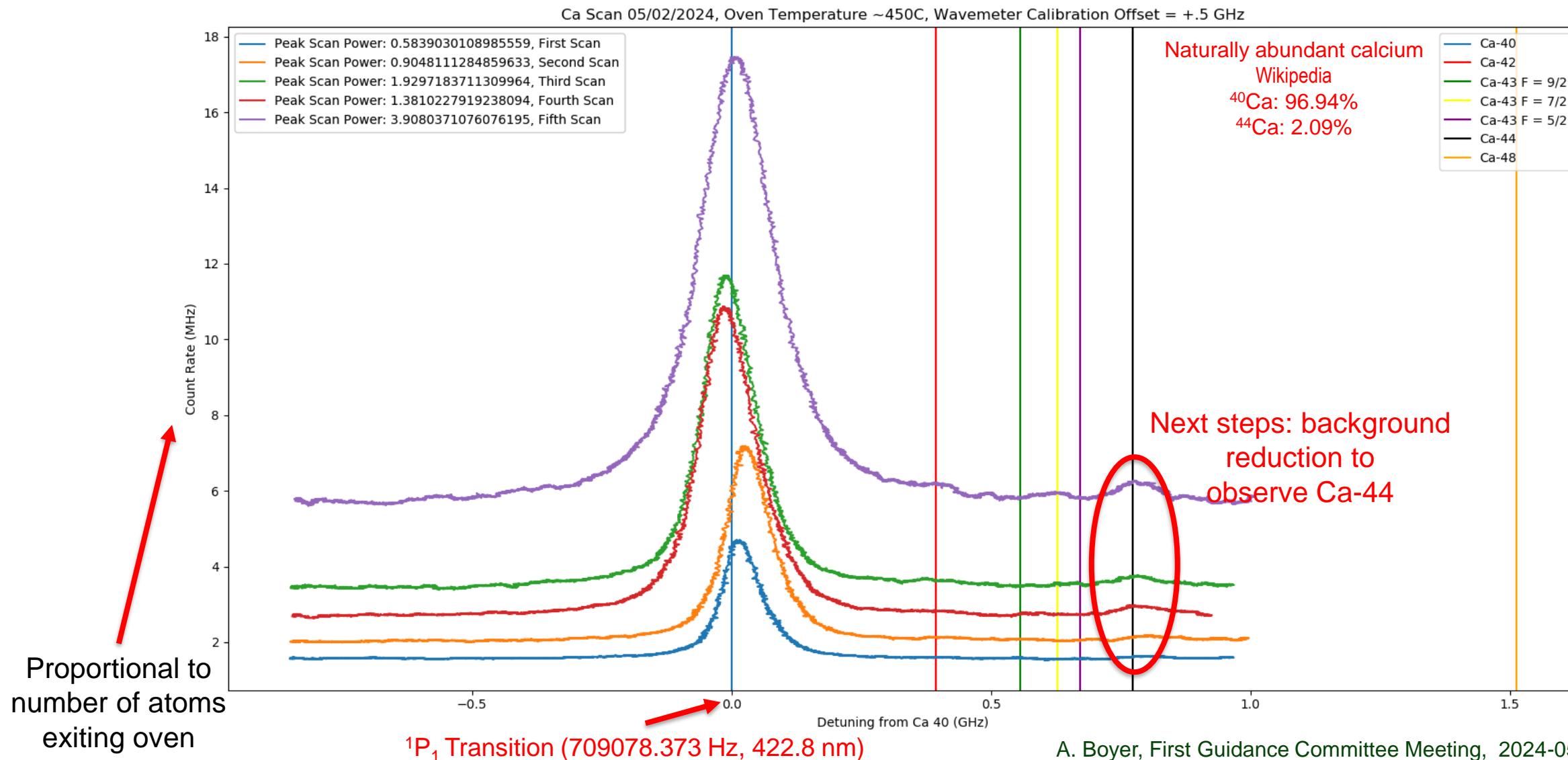
Current Goal:



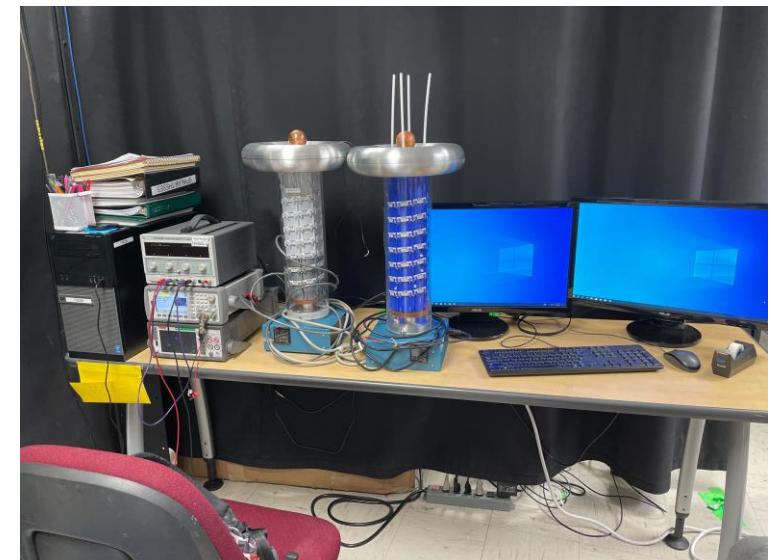
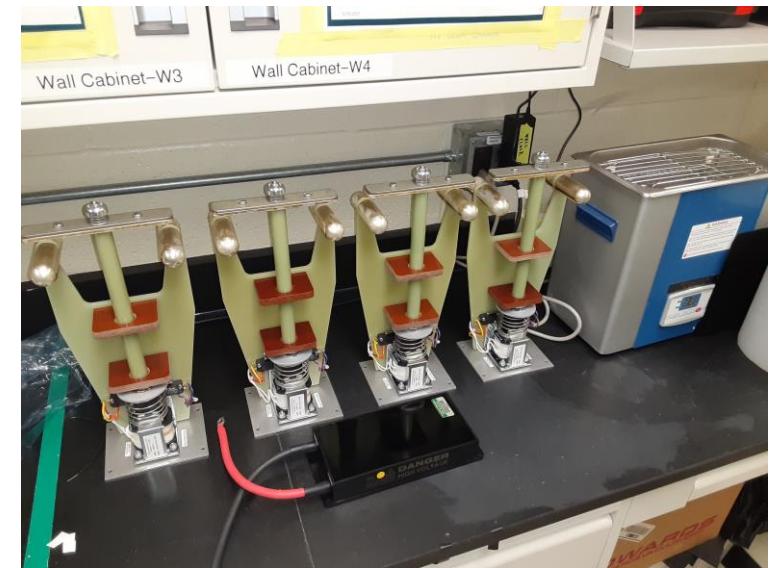
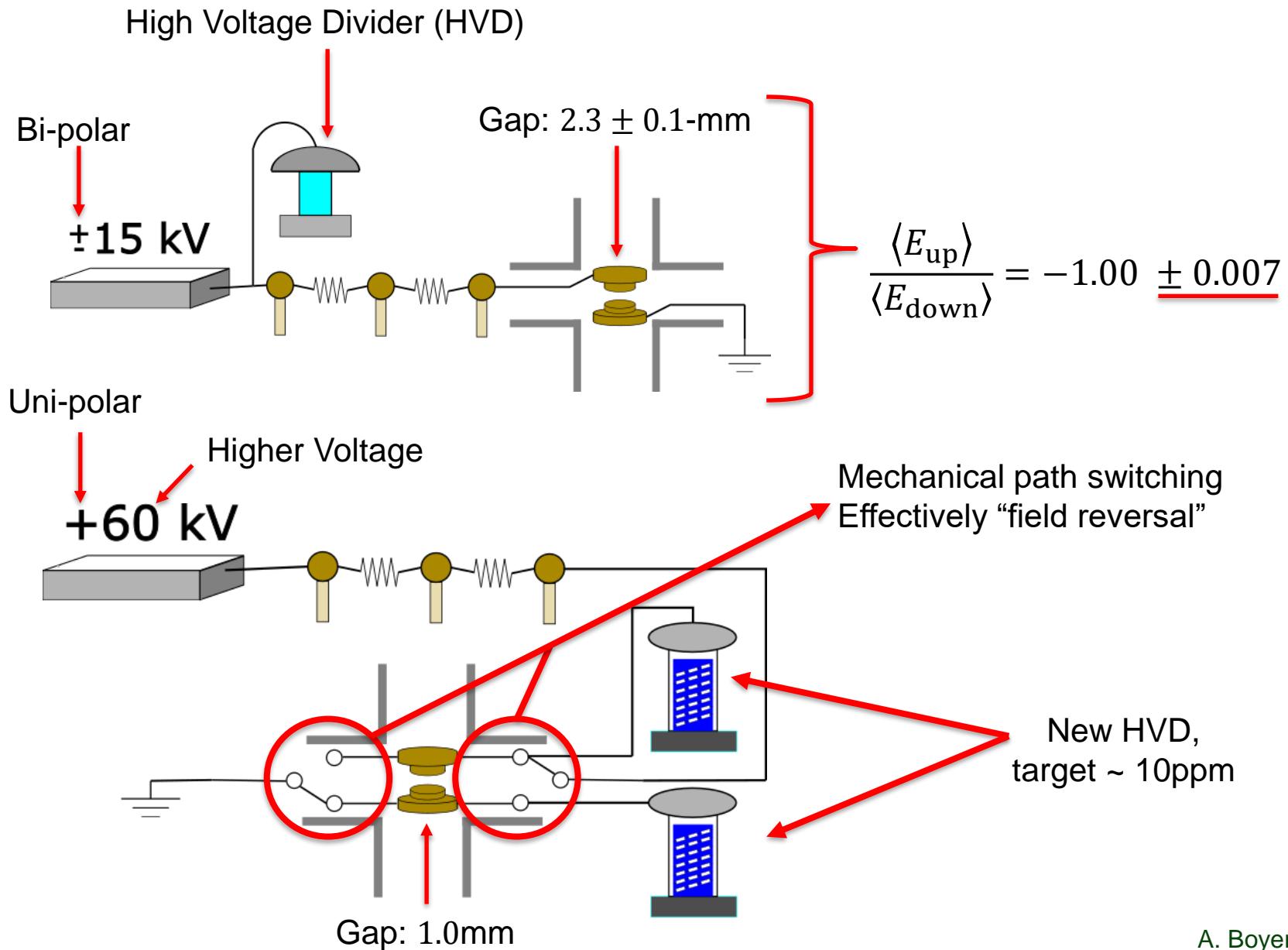
Similar electronic structure to ^{225}Ra + not radioactive = good stable surrogate

Isotope Harvesting Efficiency Studies With Atomic Beam Fluorescence

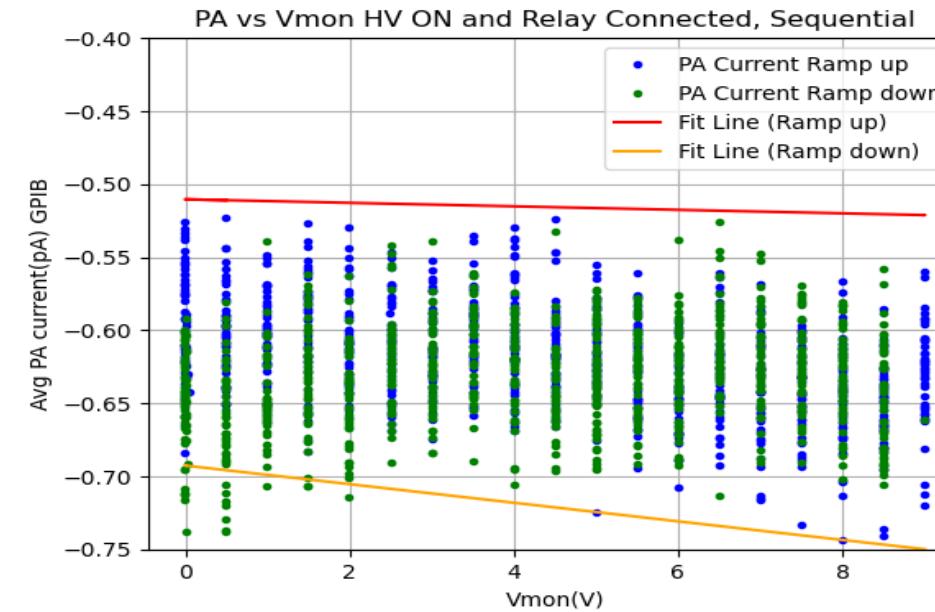
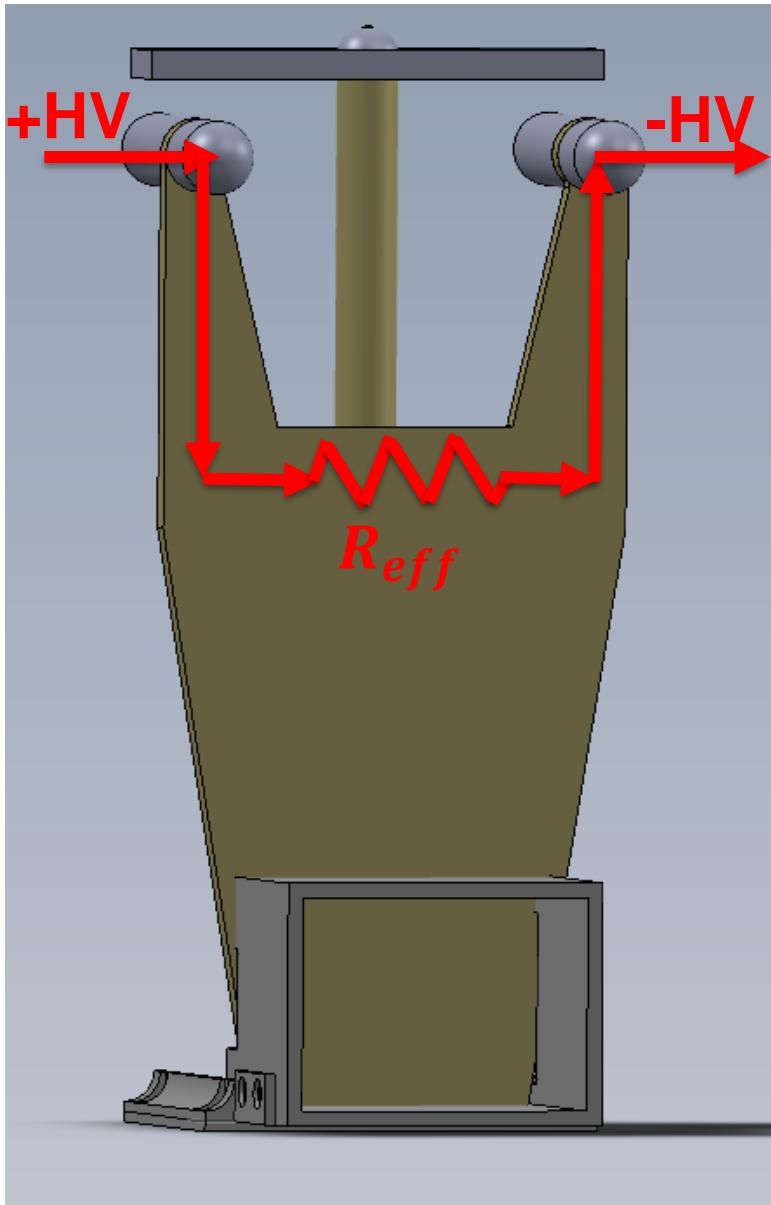
ABF: Load an oven with sample \Rightarrow Bake sample into atomic beam \Rightarrow Talk to atomic beam with lasers



High Voltage Development



Currently: Investigating Leakage Currents In Relays

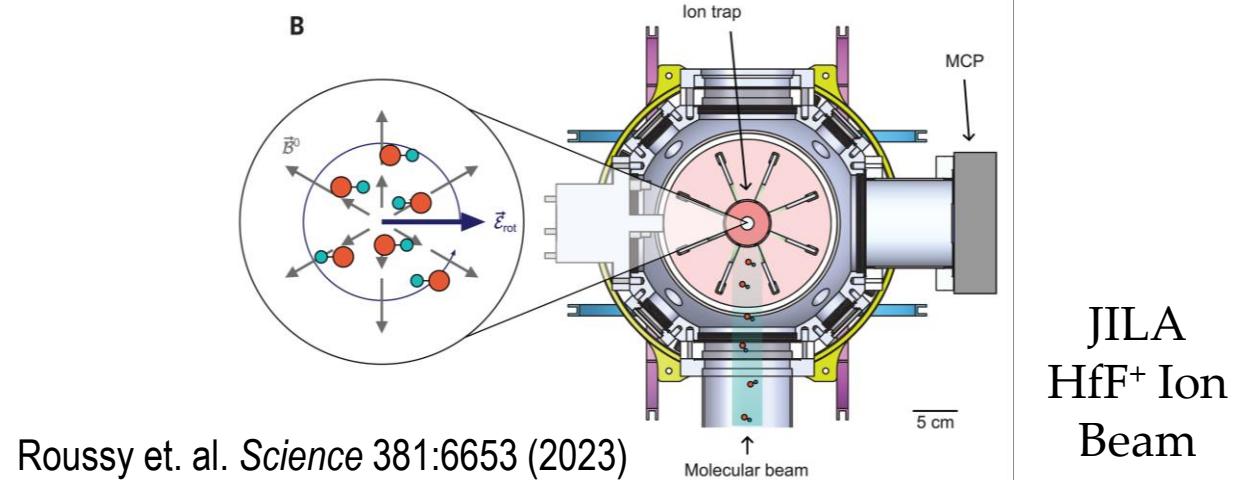
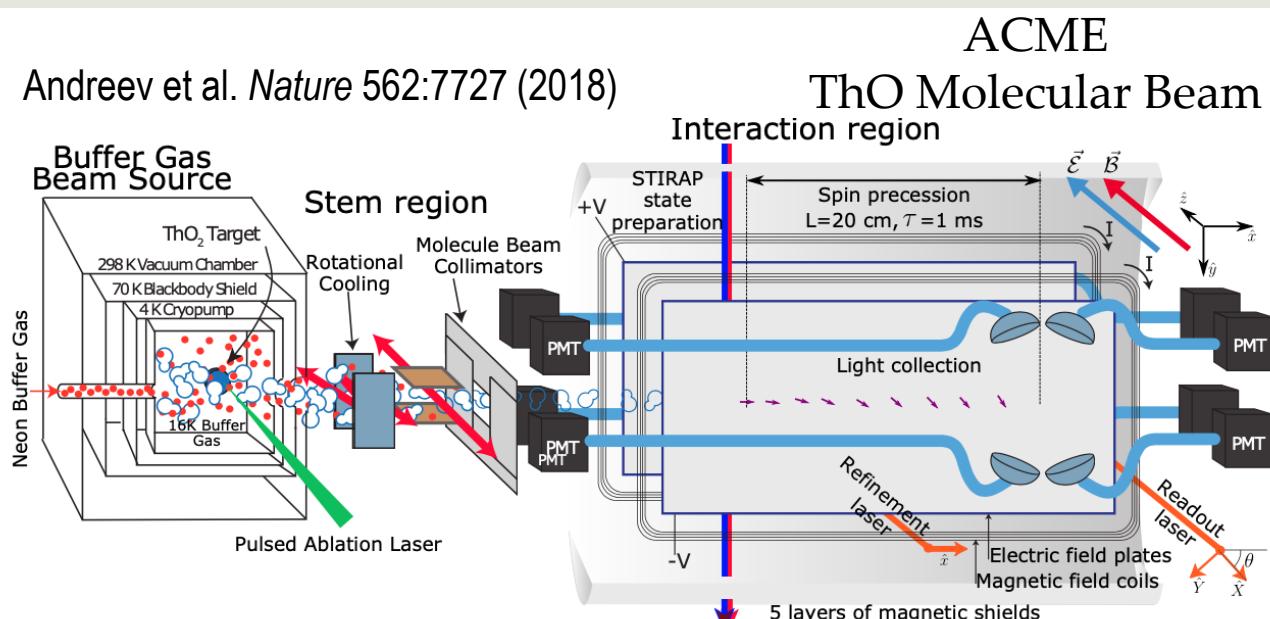


- Quantify resistance through relays to determine if they limit experimental sensitivity
 - Commercial supplier gave estimate
 - Our own estimate: $R \sim 10^{12} \Omega$
- Slope proportional to relay resistance
 - Slope (ramp up): $-6.583 \times 10^{-16} \text{ A/V} \pm 2.614 \times 10^{-15} \text{ A/V}$
 - Slope (ramp down): $-2.12 \times 10^{-15} \frac{\text{A}}{\text{V}} \pm 2.614 \times 10^{-15} \text{ A/V}$
 - $R \sim 10^{14} \Omega$

Polar Molecules As An Ultrasensitive Tool For electron EDM Searches

- Internal molecular electric dipole moment alignment
- Control systematics
 - Molecule dependent internal co-magnetometry
- Diatomic polar molecules have large internal electric fields (~100 MV/cm for nuclei)
 - Kudashov et al. *PRA* 87:020102 (2013)
 - Kudashov et al. *PRA* 90:052513 (2014)
- Typical lab fields (~0.3 MV/cm)
 - R. Ready et al, *NIMA* 165738 (2021)

Andreev et al. *Nature* 562:7727 (2018)



JILA
HfF⁺ Ion
Beam

Implanting Molecules With Pear-shaped Nuclei In Cryogenic Solids

- Improved statistics

- Efficient trapping of many different species (N_a)
- High number densities (N_a)
- Stable, chemically inert confinement (T)

- Control of Systematics

- Orientation locking of polar molecules along crystal axes believed to be possible Vutha et al., *PRA* 98:032513 (2018)
- Laser accessible J.T. Singh *Hyp. Int.* 240:29 (2019)

- Challenges:

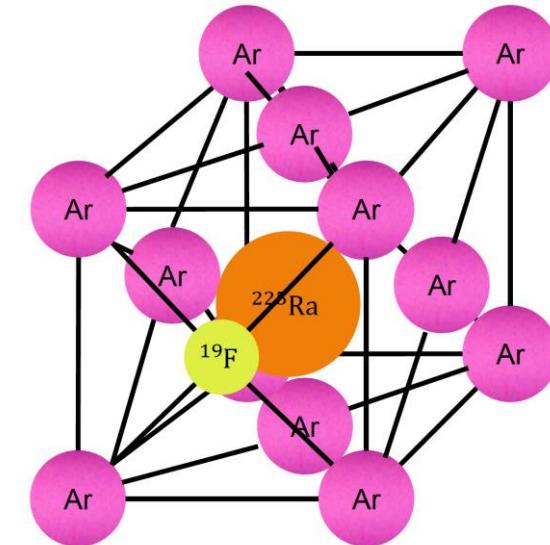
- Quantum control in rare gas solids

- **How do we form these molecules?**

J.T. Singh DOE ECA 2018

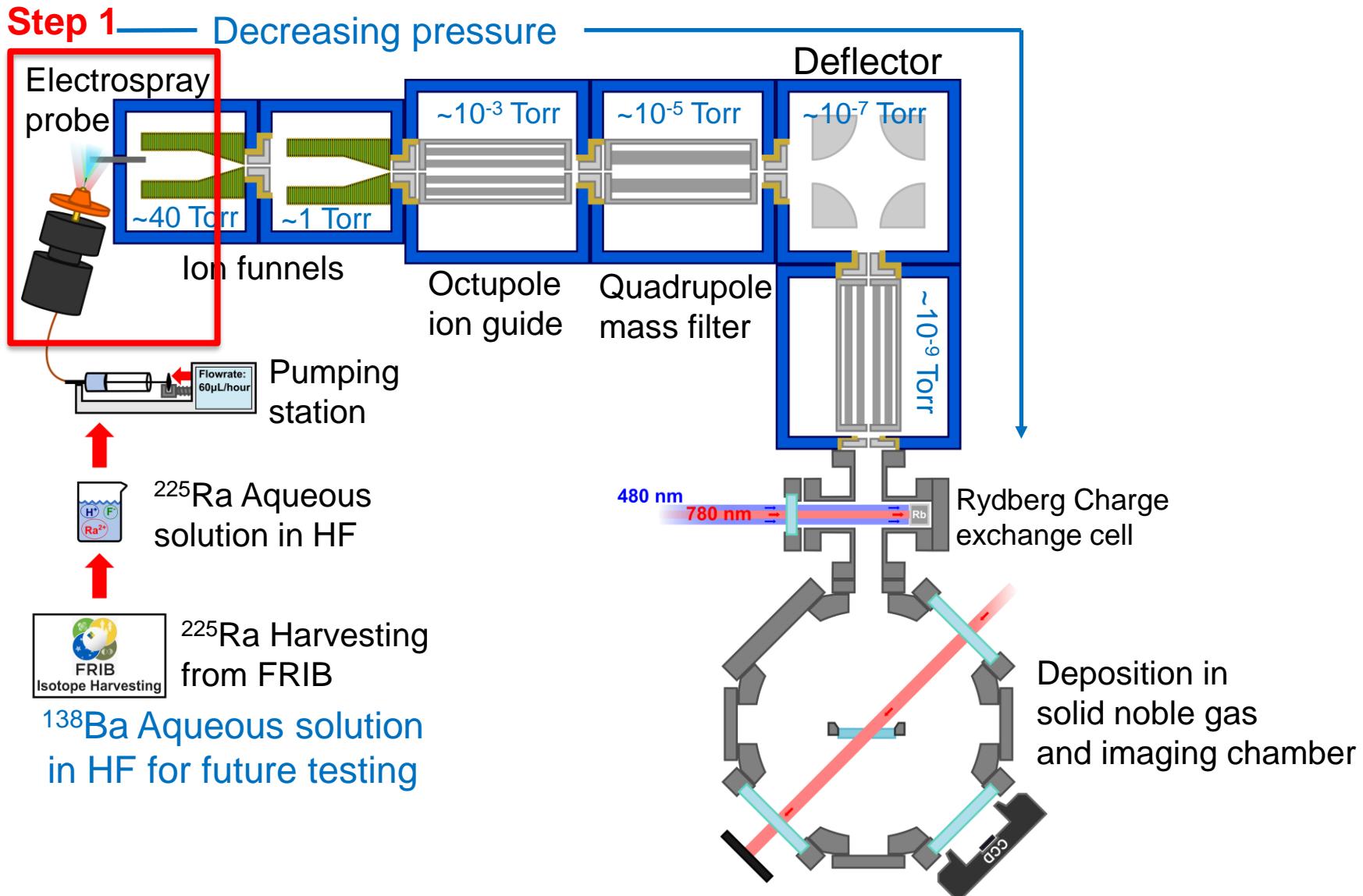
- **How do we implant them into solids?**

Ballof et al. *NIMB* 541 (2023)

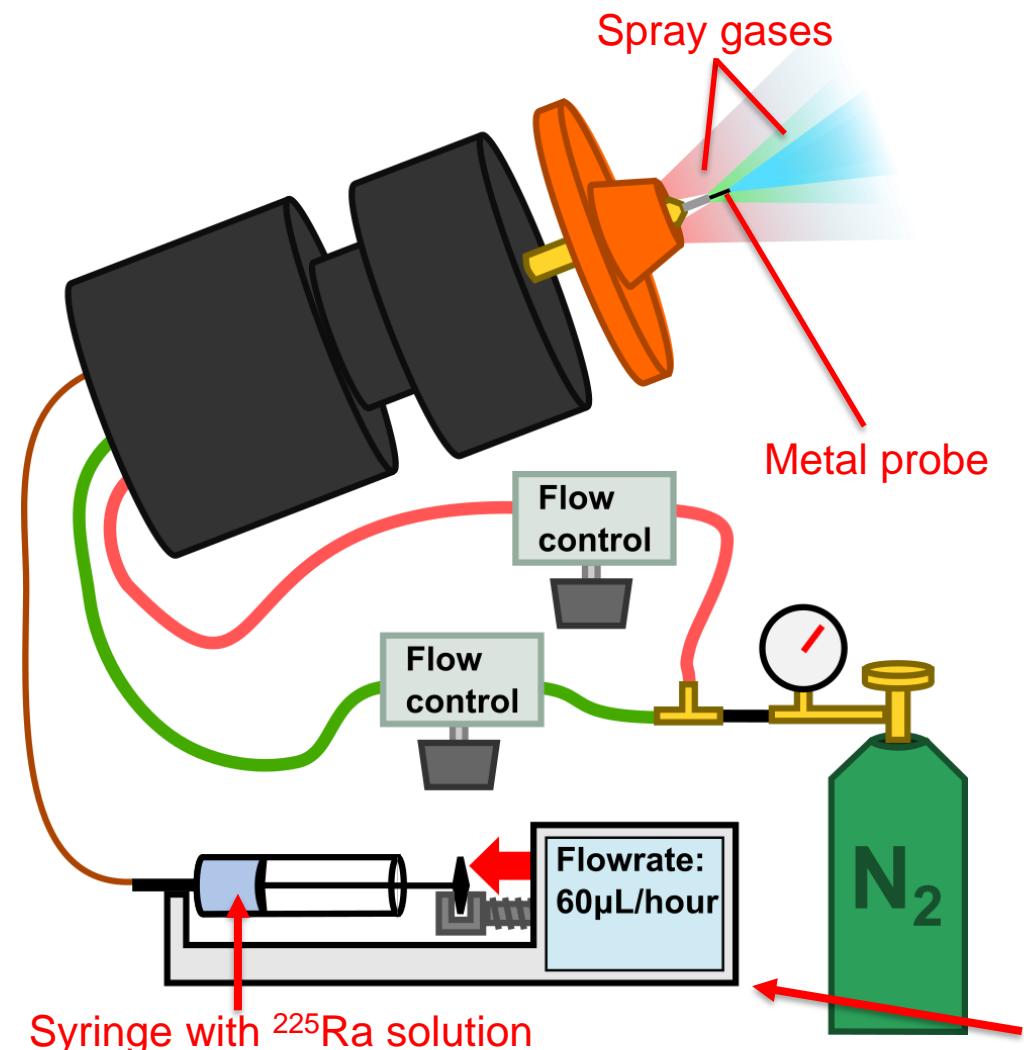


$$\frac{\sigma_d}{\sqrt{N_m}} = \frac{\hbar}{2\bar{E}\sqrt{\varepsilon N_a T \tau}}$$

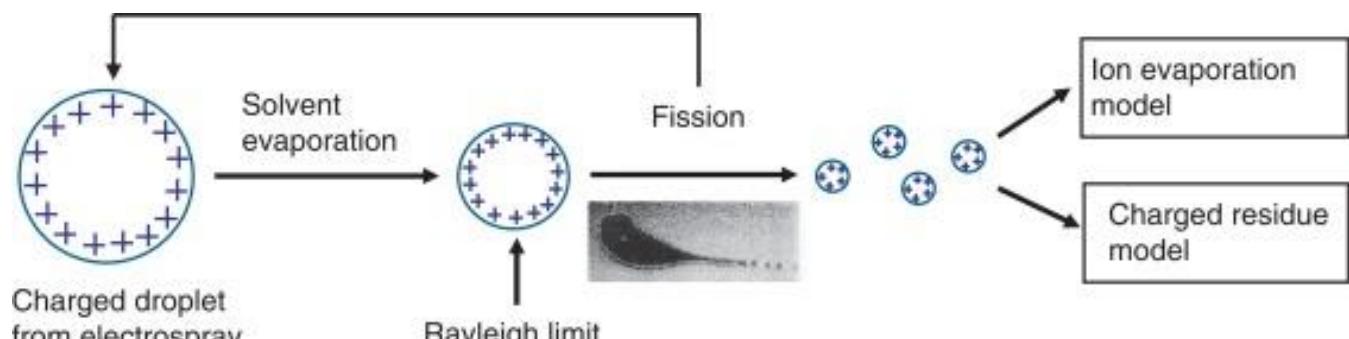
The FRIB-EDM³ approach:



Step 1: Producing Molecular Ions With Electrospray Ionization

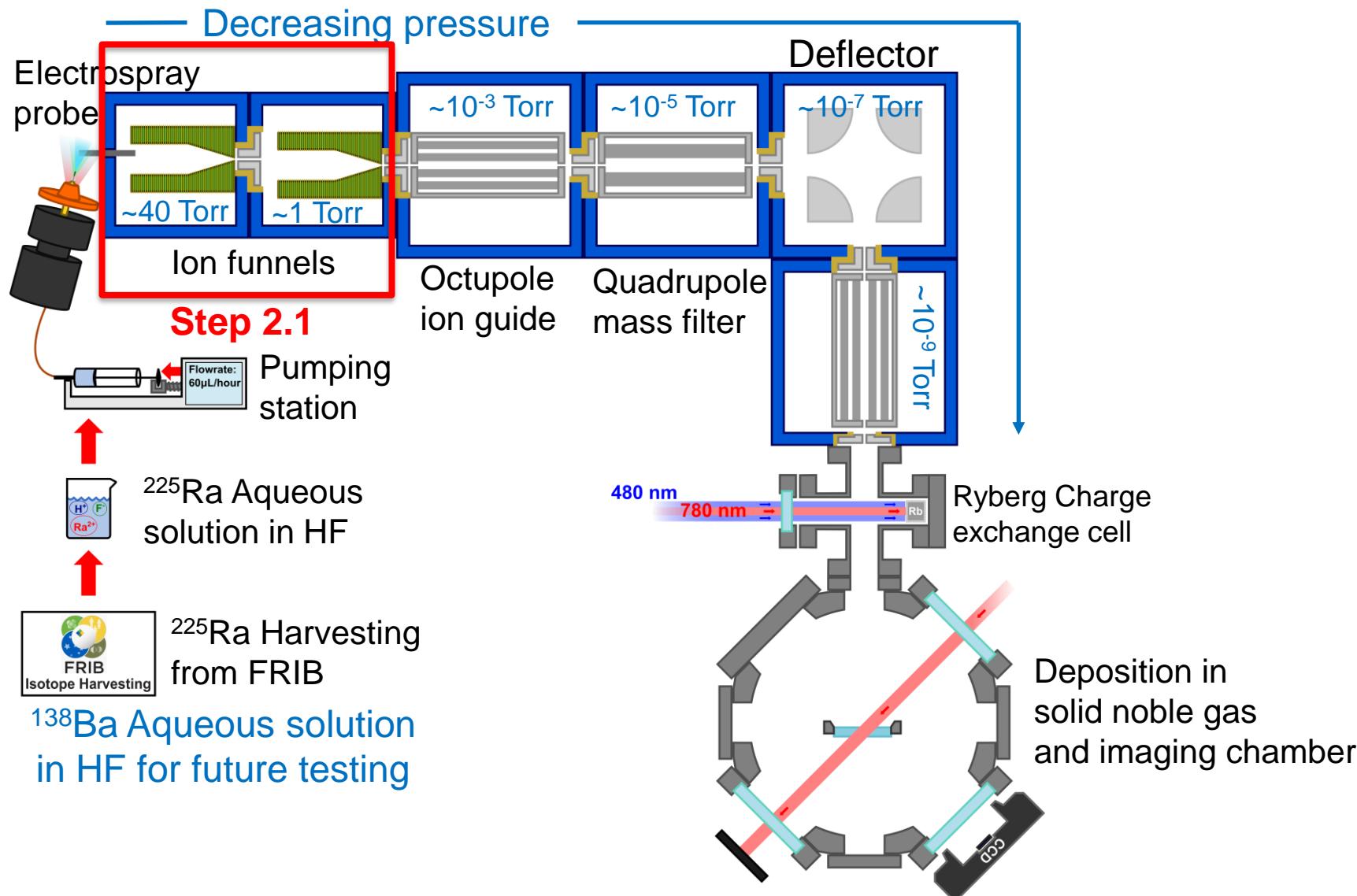


- High DC bias (1-3 kV) to produce plume of charged droplets
- Desolvation by spray gases, electrostatic repulsion
- Gas-phase ions drawn to heated entrance capillary by DC gradient

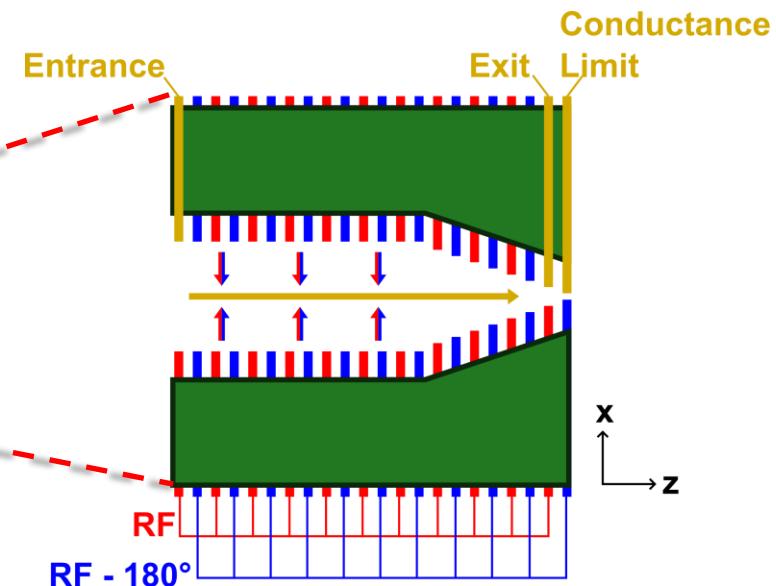
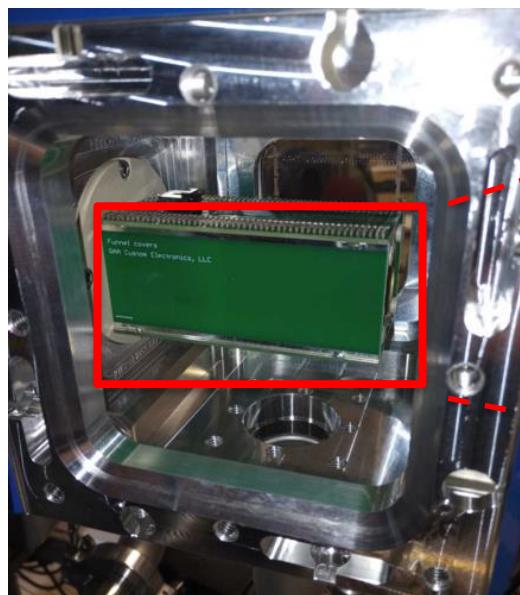
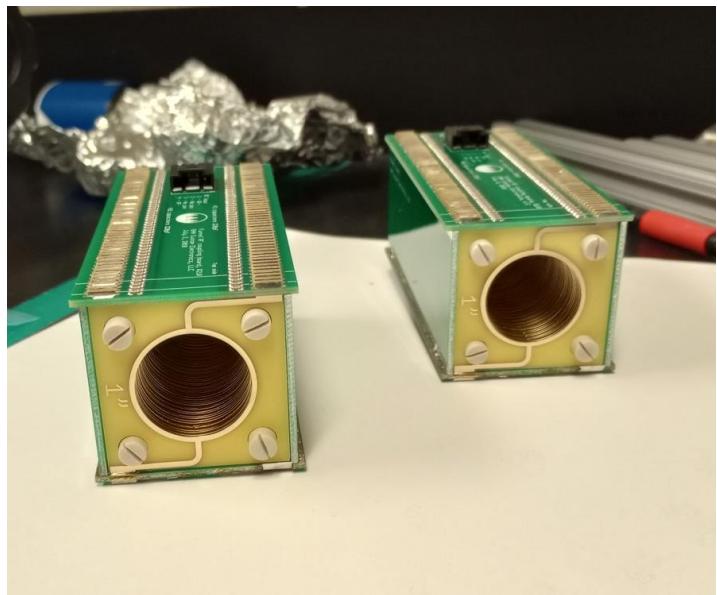


Tang et al Encyclopedia of Spectroscopy and Spectrometry 476 (2017)

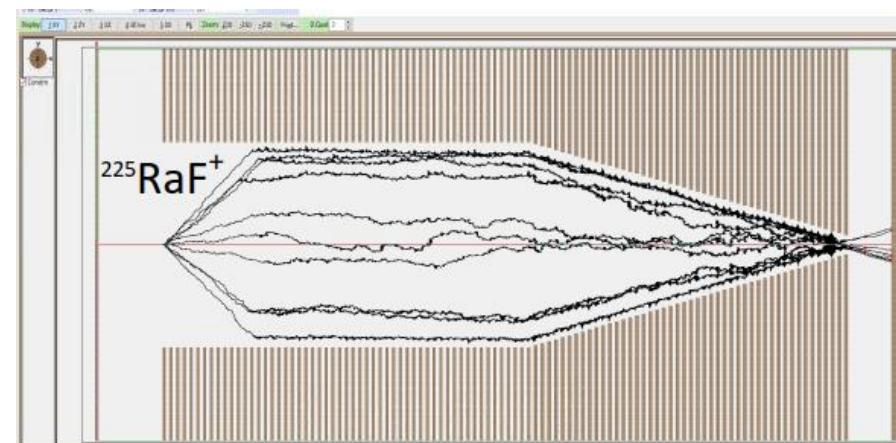
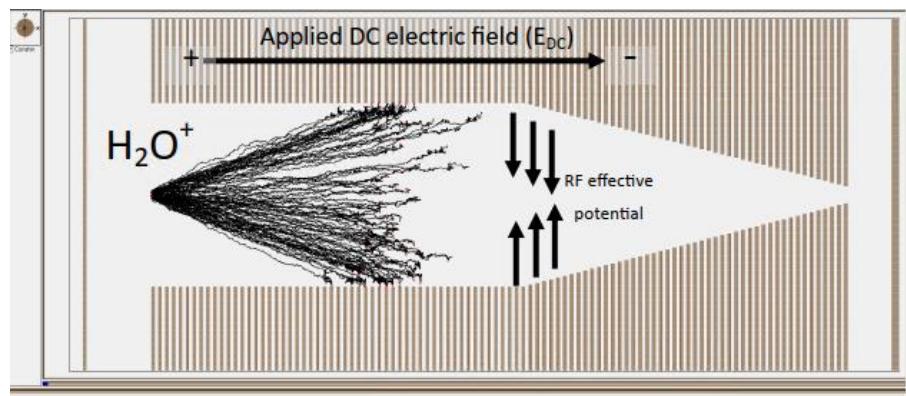
The FRIB-EDM³ approach:



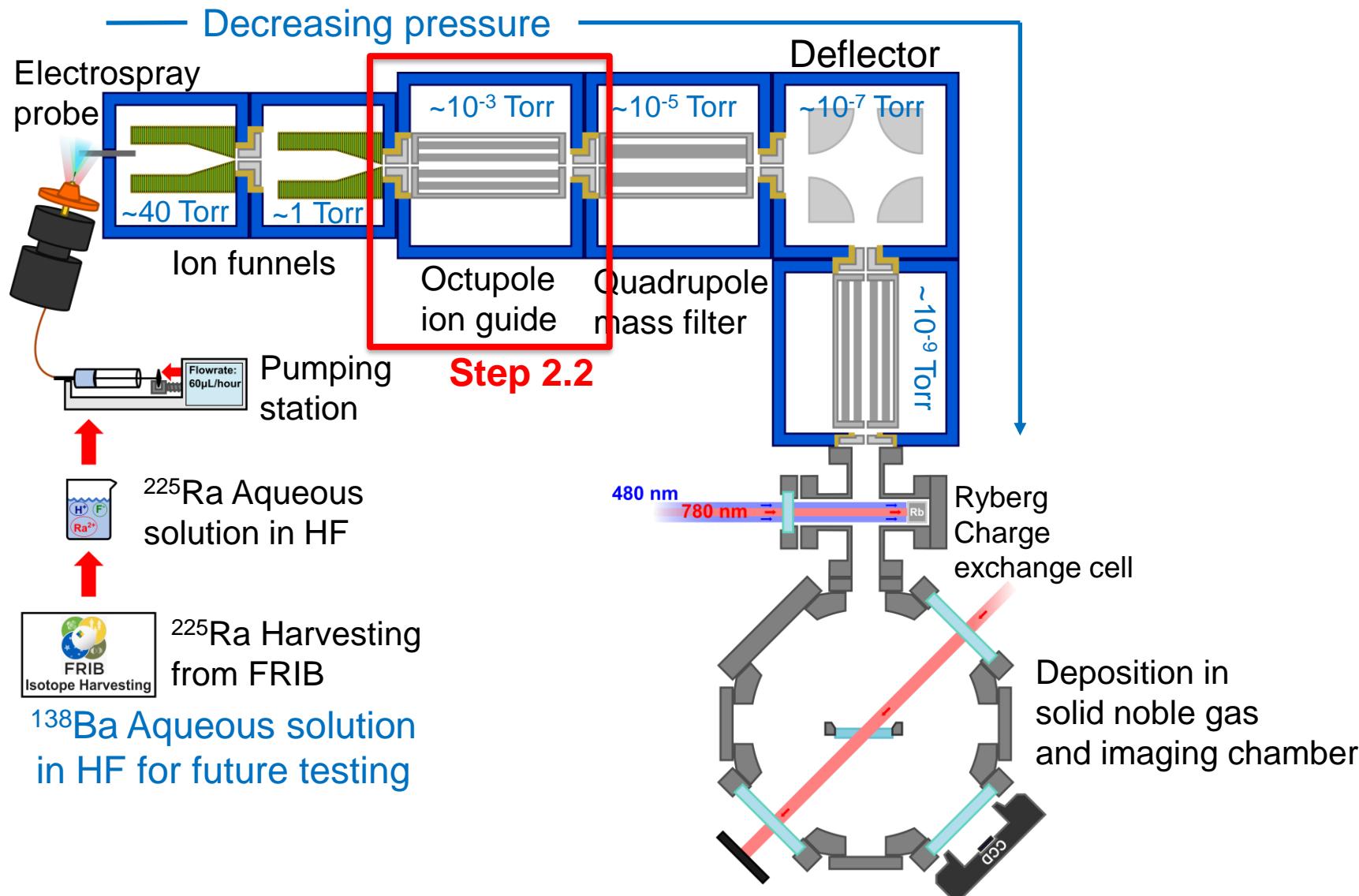
Step 2.1: Filtering By Mass-To-Charge Ratio (Ion Funnels)



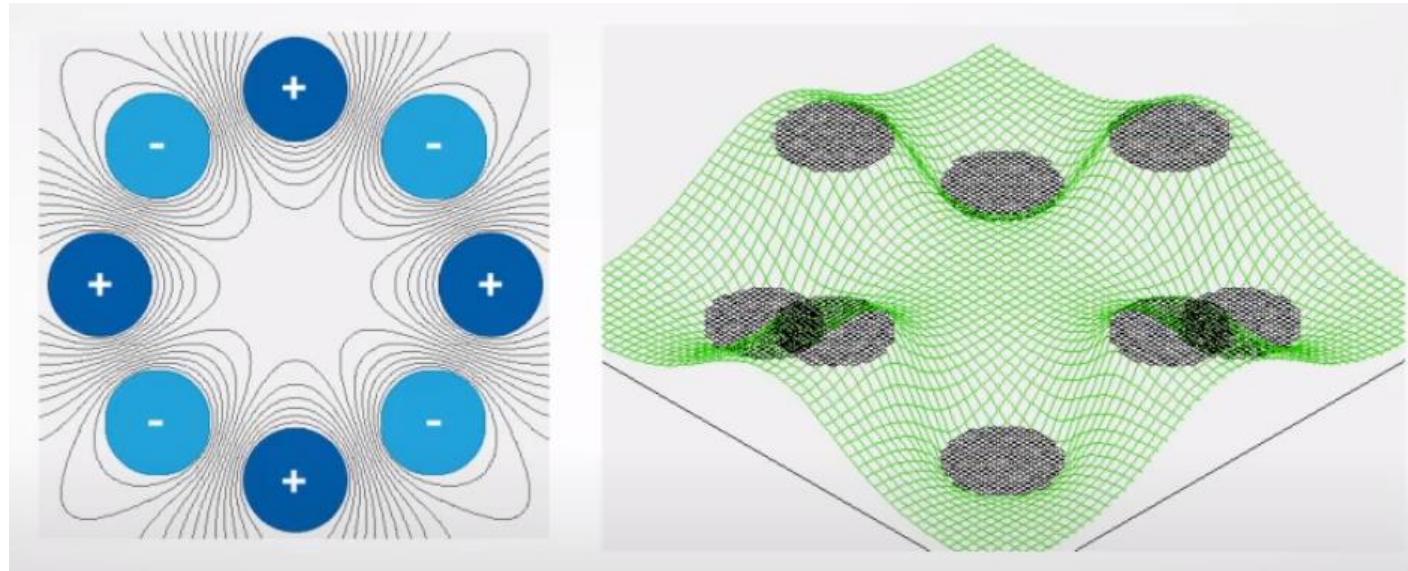
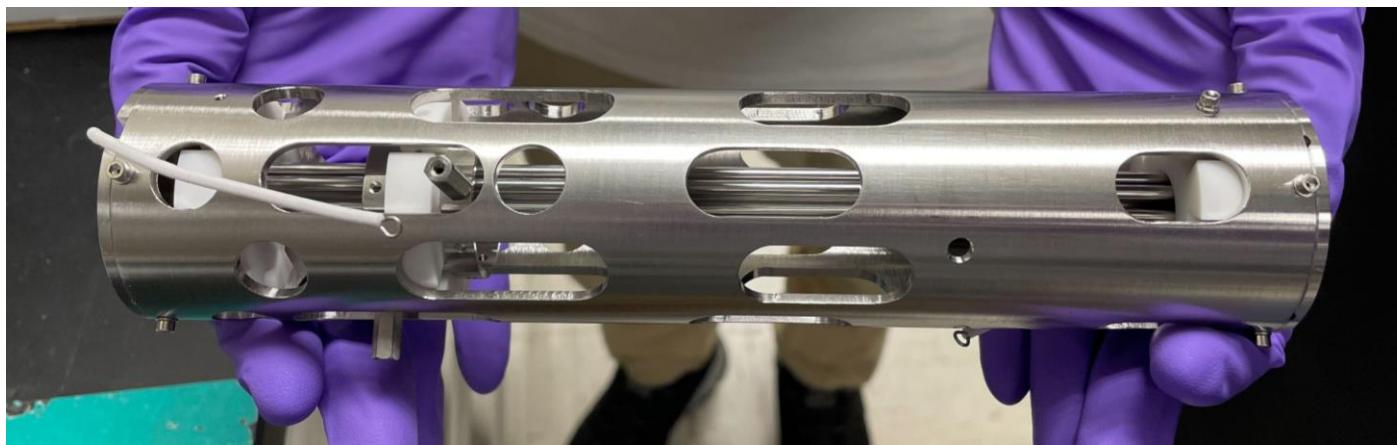
GAA Custom Electronics (Gordon Anderson)



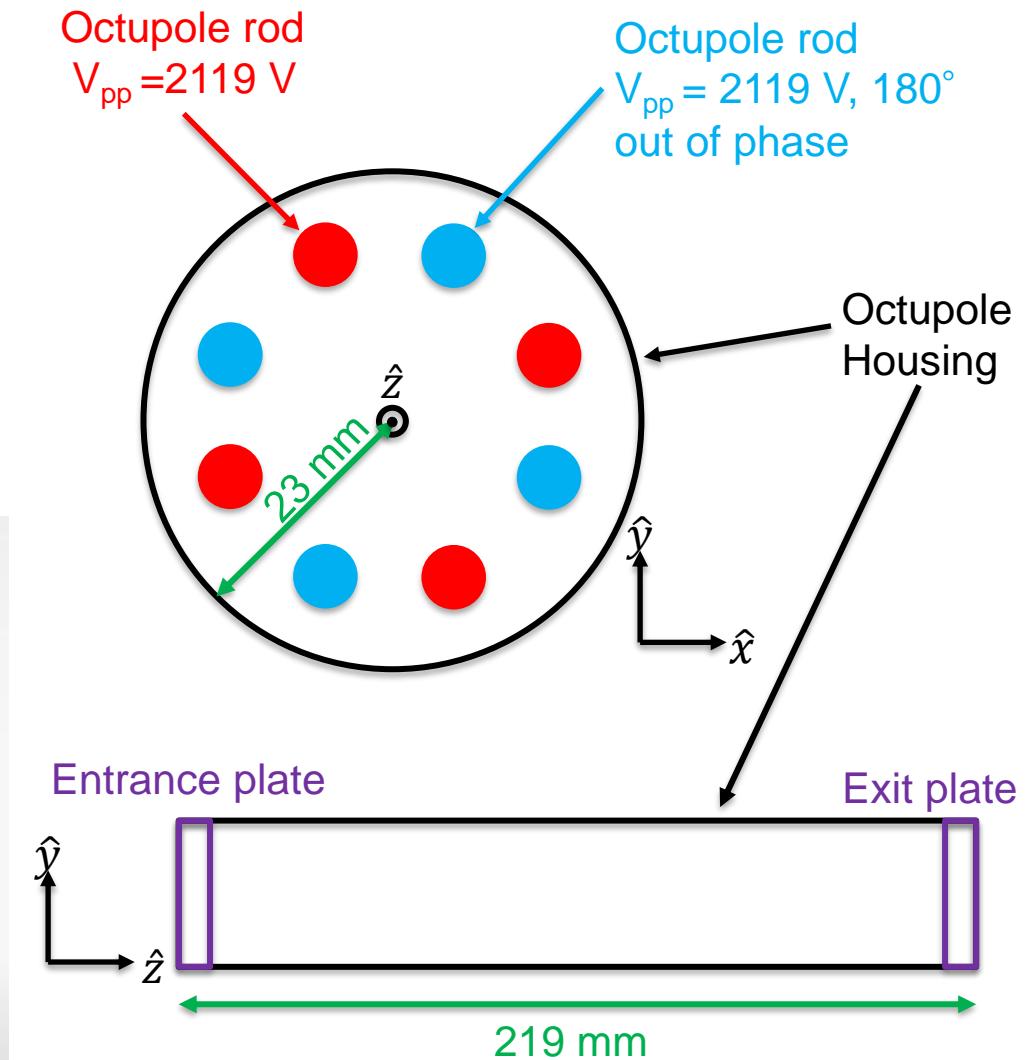
The FRIB-EDM³ approach:



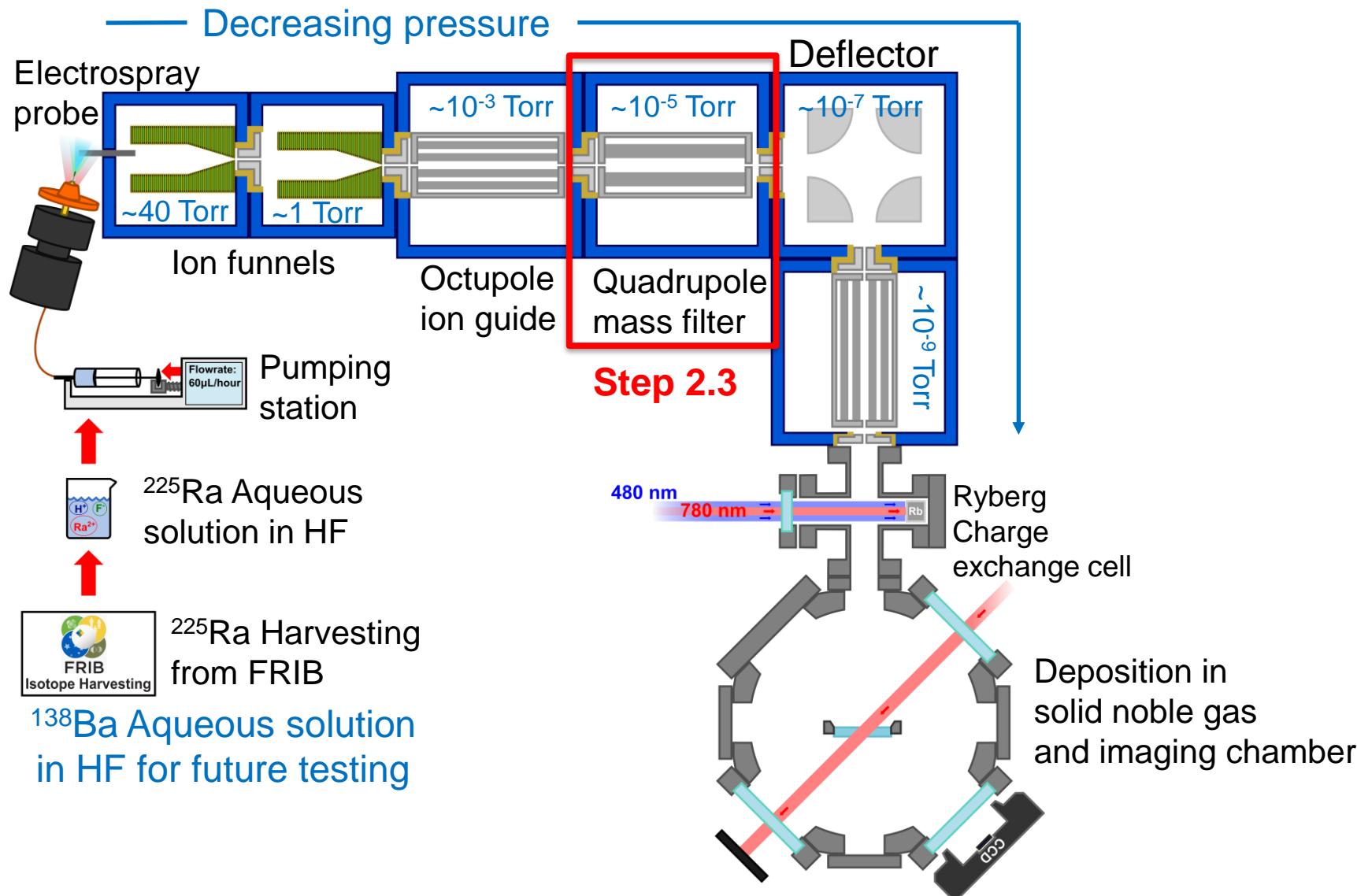
Step 2.2: Differential Pumping With Octupole Ion Guides



Mass Spec Pro
(<http://www.massspecpro.com/technology/ion-optics/multipole-ion-guide>)



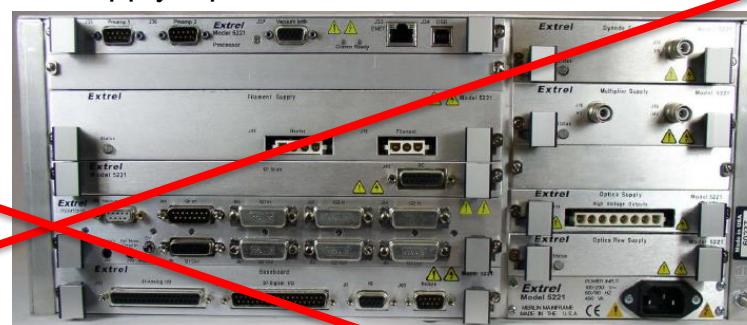
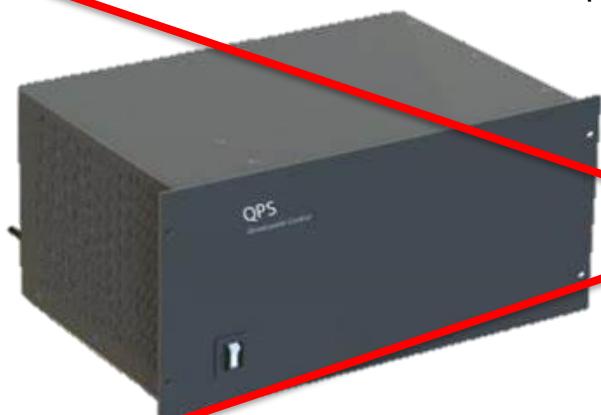
The FRIB-EDM³ approach:



Step 2.3: Isotopic & Molecular Selection with A Quadrupole Mass Filter

- Quadrupole and Octupole operated similarly

Extrel QPS Quadrupole Power Supply Operators Manual

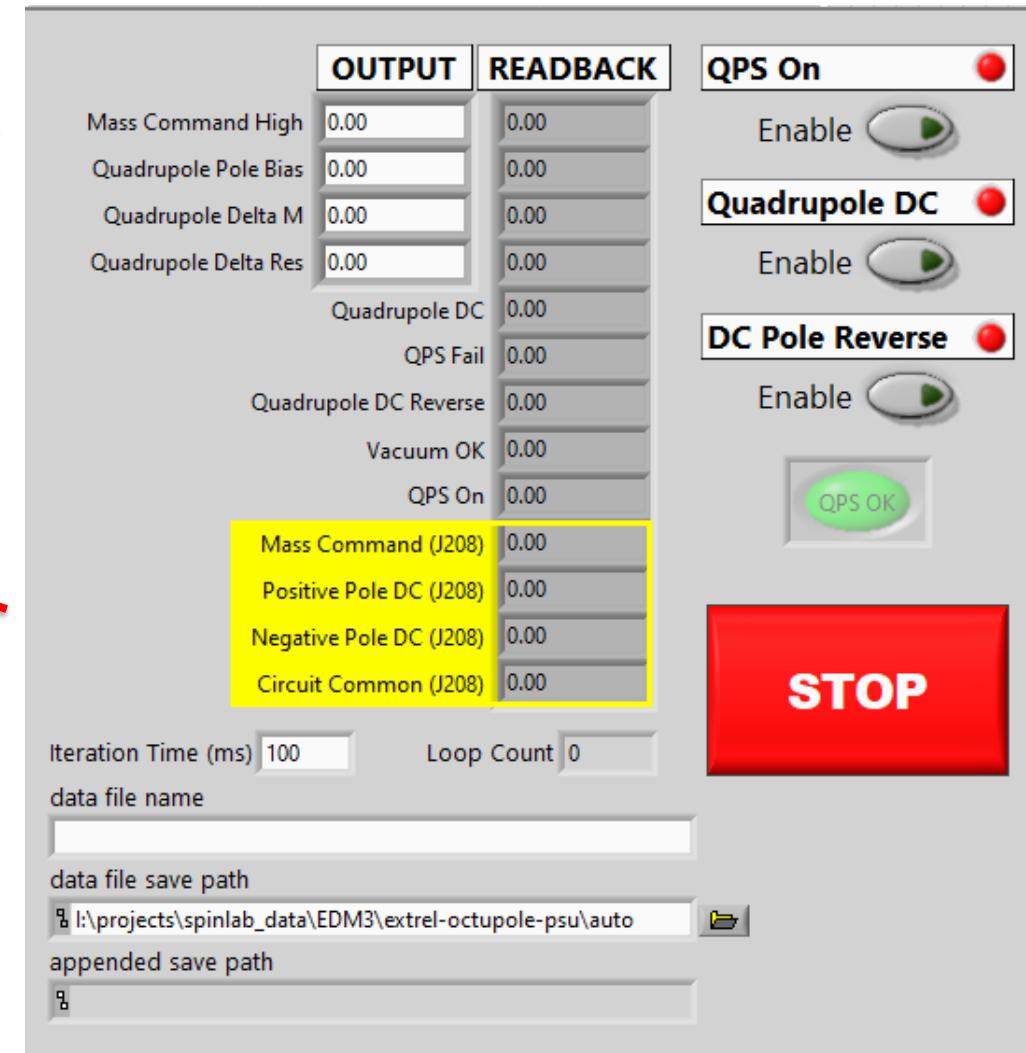


- Goal: More compatible controls

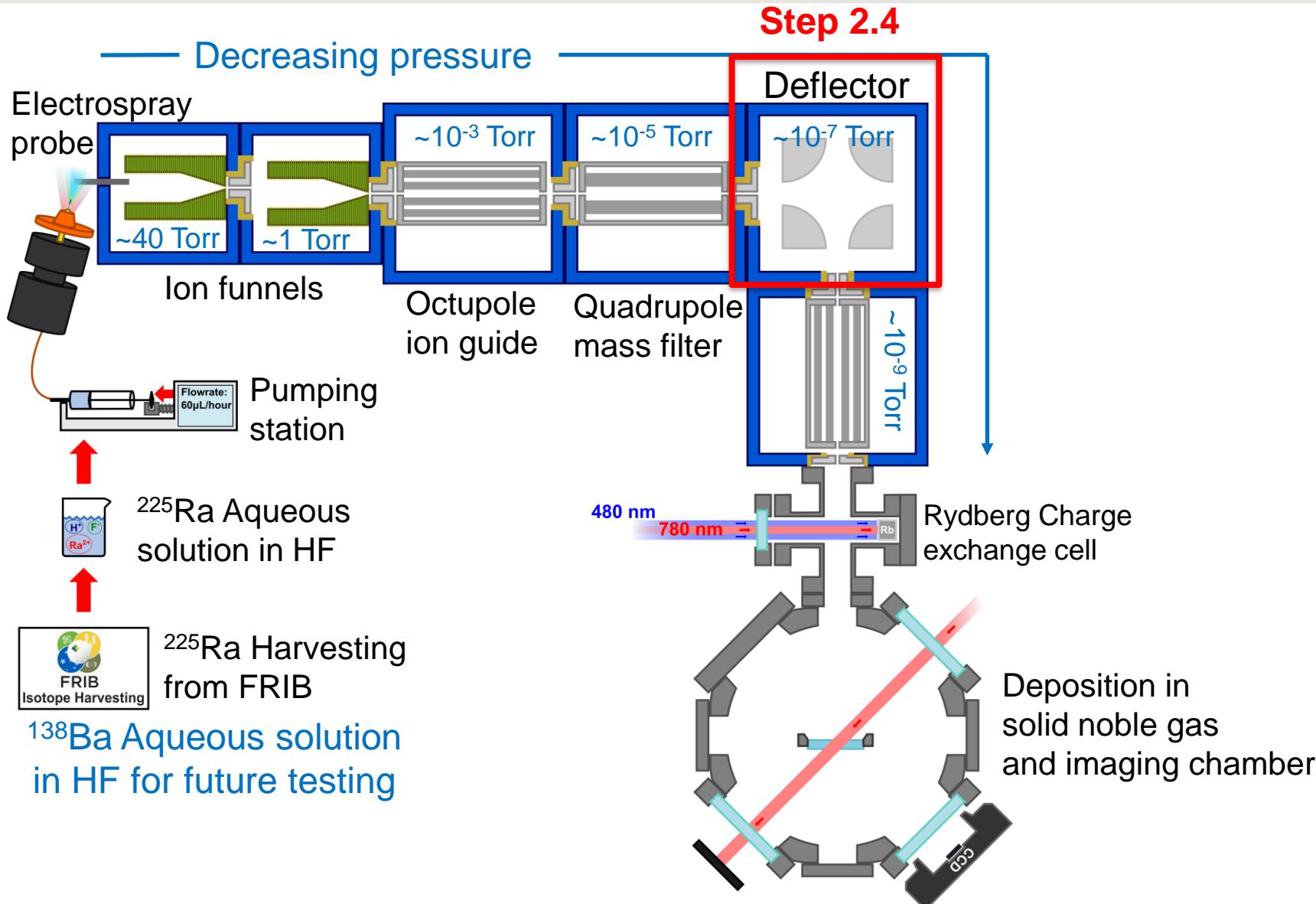
- No computer control with commercial option

- Control with LabVIEW software and National Instruments DAQ

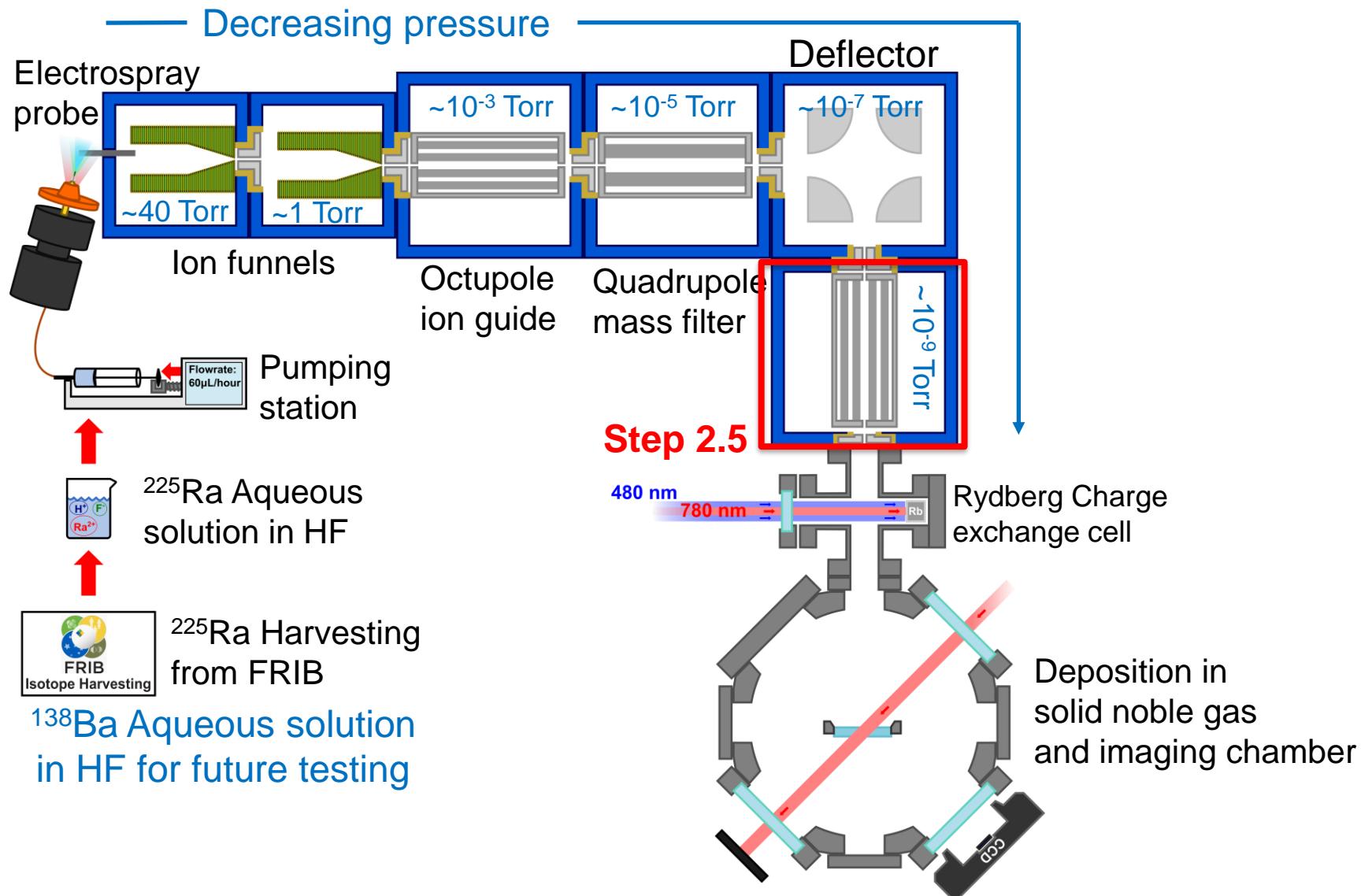
- Better data visualization
- Control voltages similar, but not the same
 - » Not all commands for quadrupole used for octupole



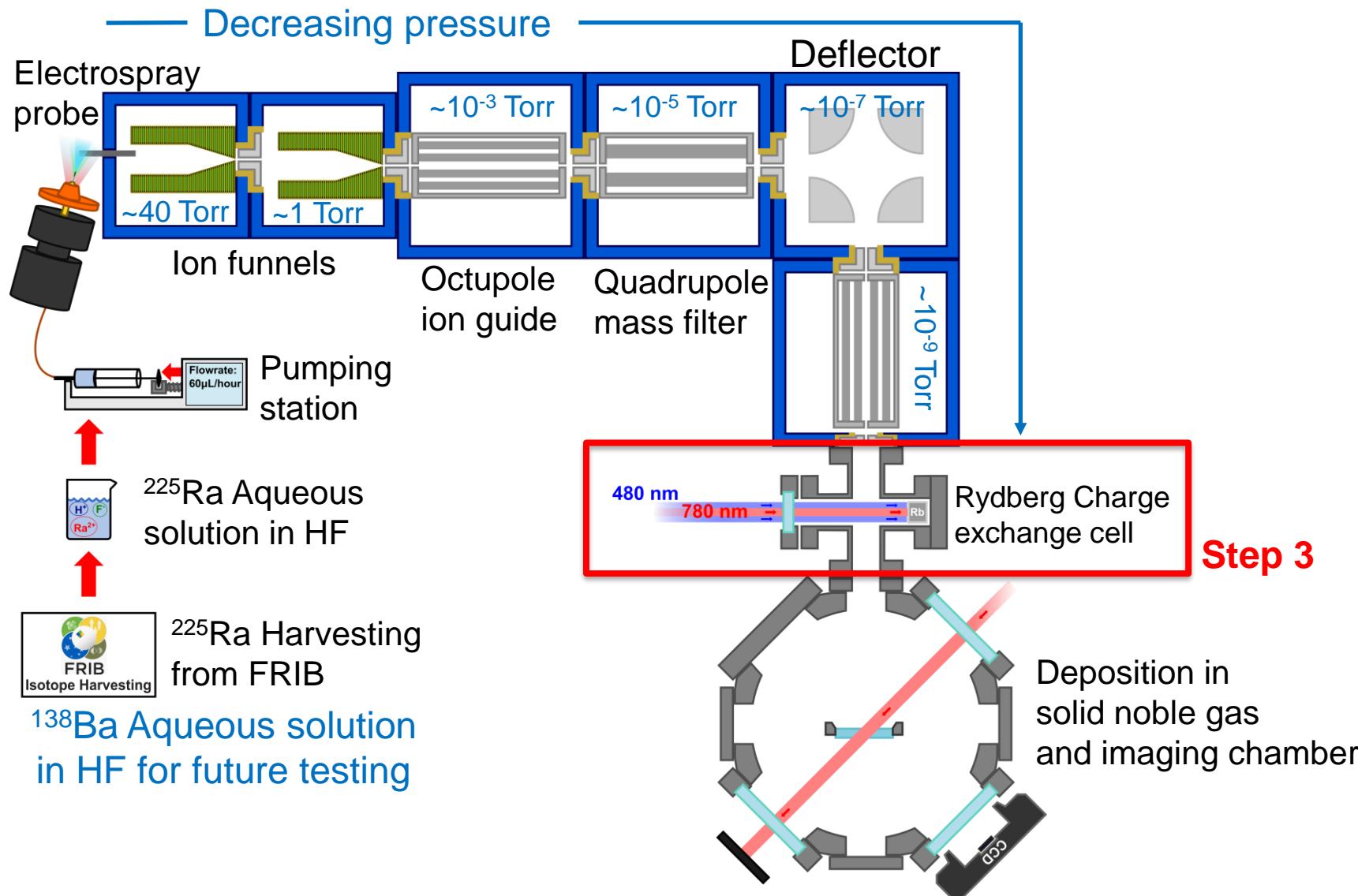
The FRIB-EDM³ approach:



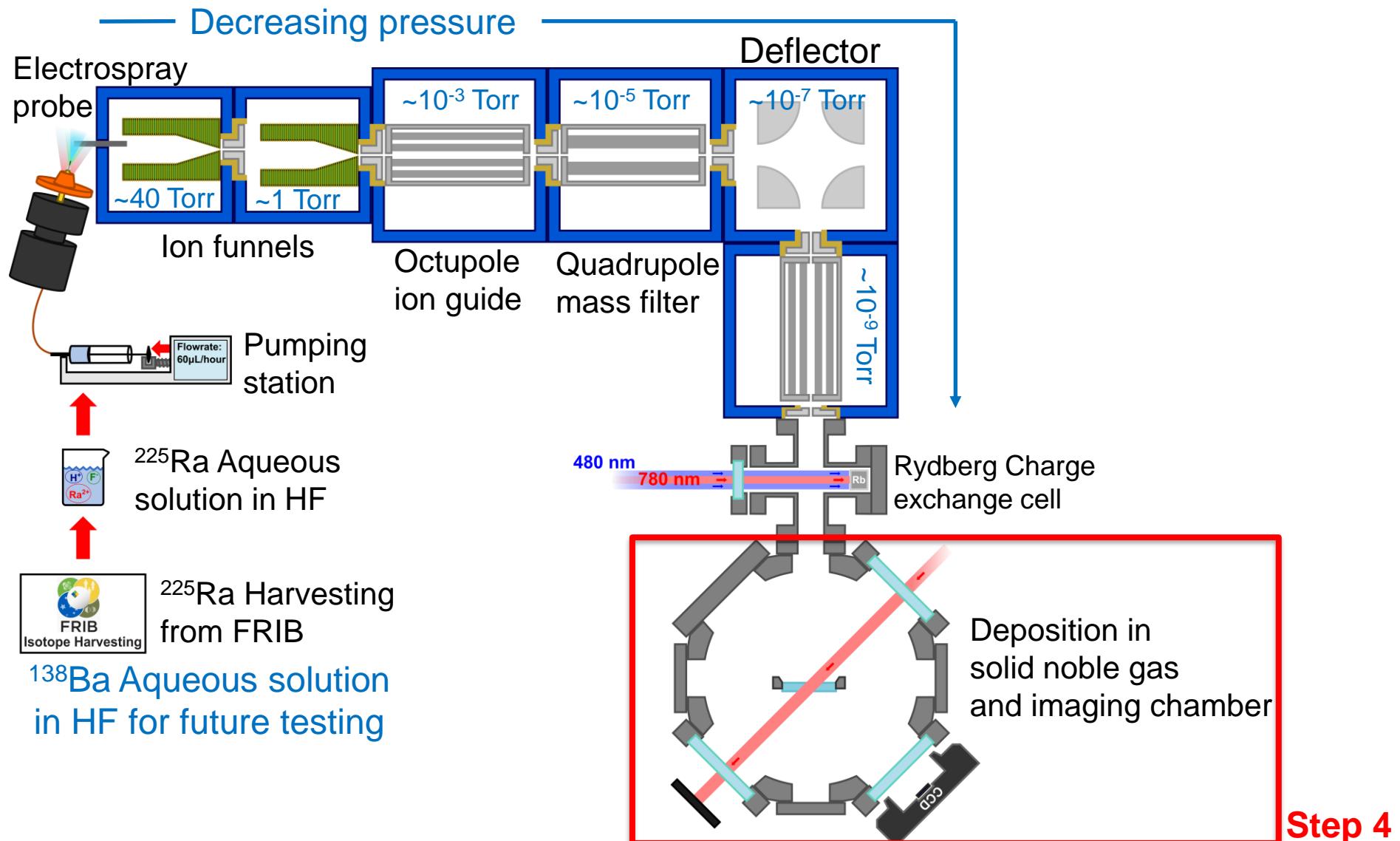
The FRIB-EDM³ approach:



The FRIB-EDM³ approach:



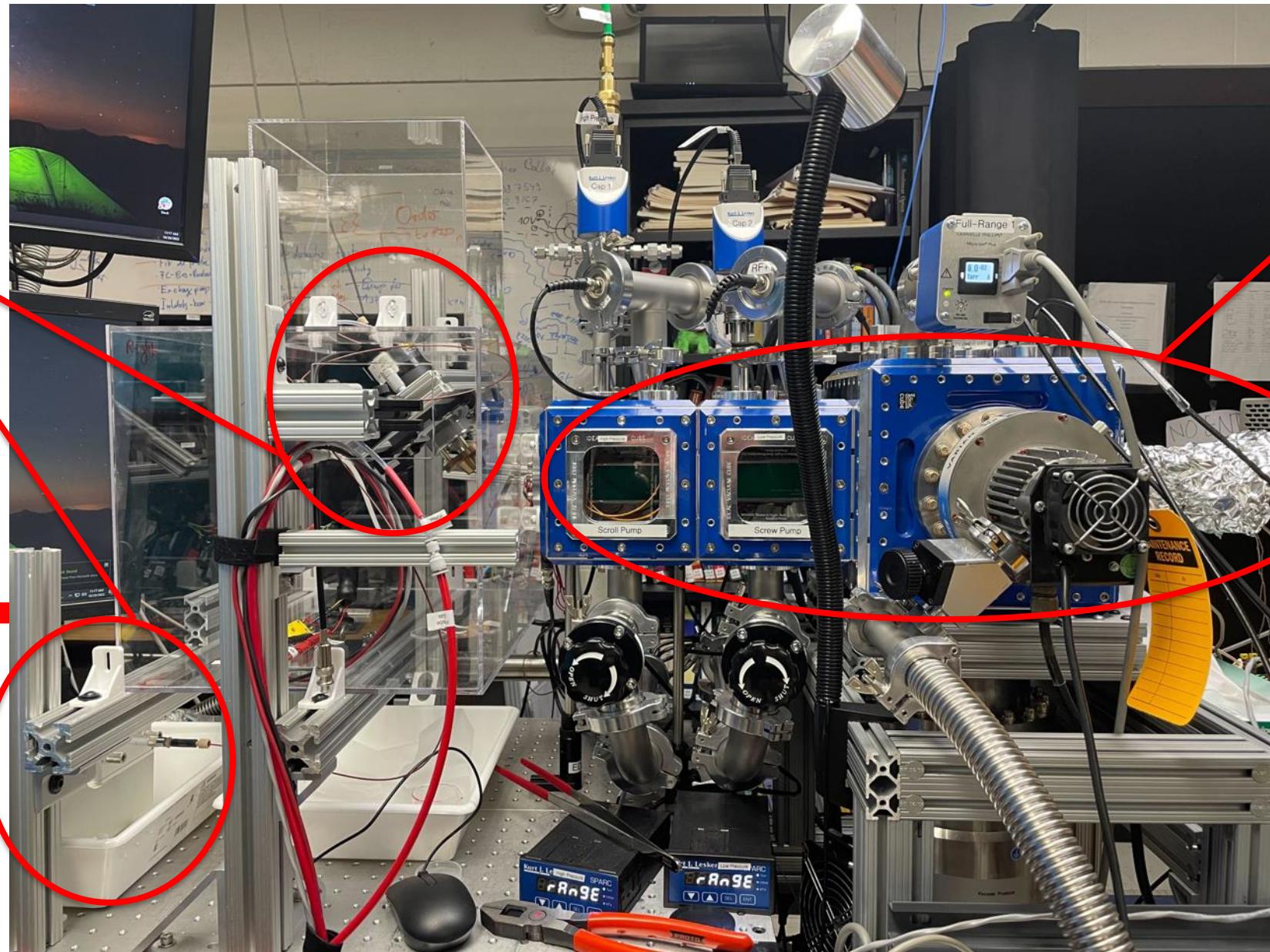
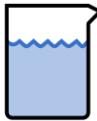
The FRIB-EDM³ approach:



Current Funnel Test Stand

Syringe Pump
Electrospray probe

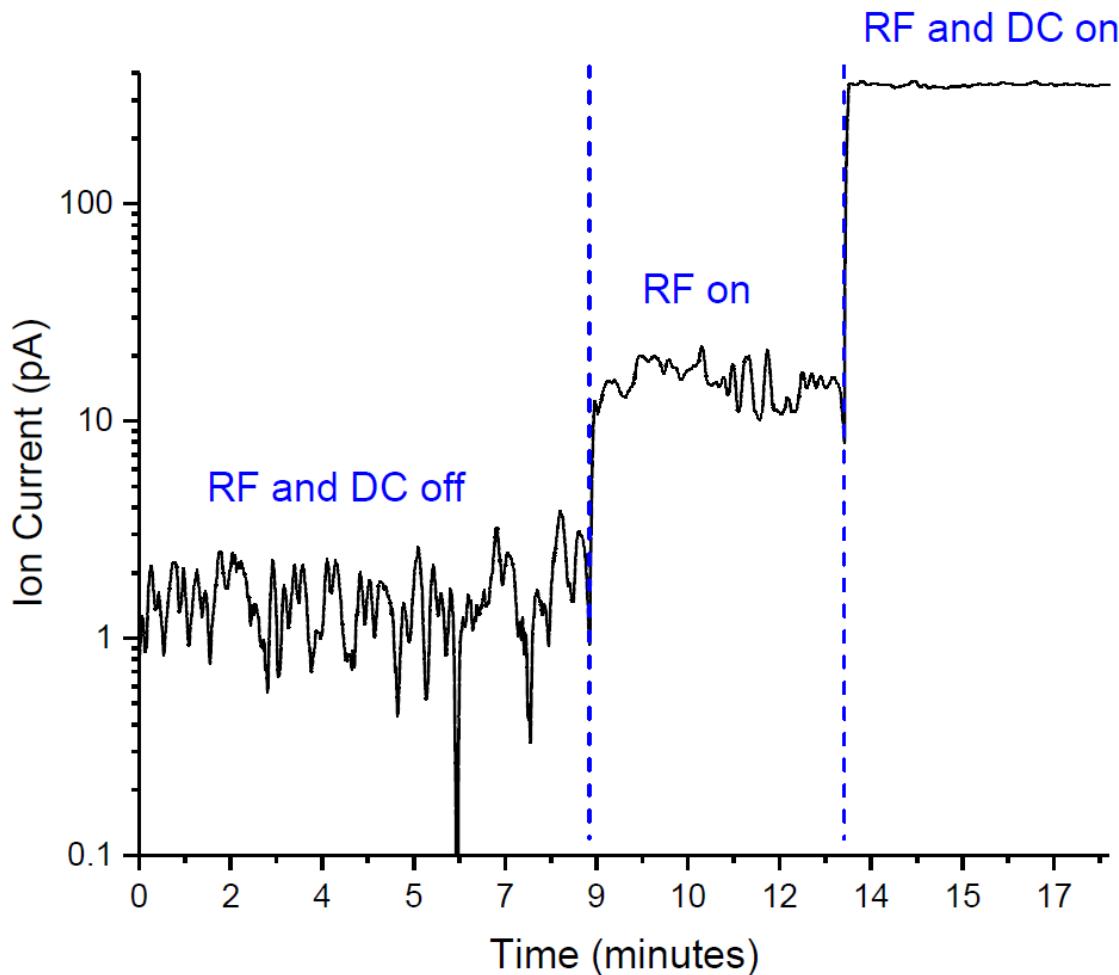
Isopropanol + water



Ion filtering
(Funnels,
Octupole, RGA)

RGA
300

Ion Funnels Work Well!



- **Stable ion beams are possible**
 - Can be used during installation to test ion optics
 - Optimizing applied bias
- **Challenges:**
 - Low reproducibility
 - Lack of control over positioning and probe alignment
- **Moving forward:**
 - Re-design electrospray
 - Acquire parts to finish assembly
 - Development measurement scheme for NSM
 - » Need to understand RaF/BaF spectroscopy to identify science state

Thank You For Your Attention!

- Matter-antimatter asymmetry cannot be explained with currently observed CP violation
- EDMs are a powerful tool for probing additional CP violation sources for BSM theories at a table-top scale
- Octupole deformed nuclei offer enhancements up to 10^3 when compared to ^{199}Hg
- ANL/MSU RaEDM Laser Trap statistically limited, but believed to be capable of 10^{-28}e-cm sensitivity; MSU working on High Voltage and Isotope Harvesting upgrades
- Forming polar molecules with octupole deformed nuclei could provide statistical enhancement and improved systematic control
- FRIB-EDM³ aims to embed these molecules into noble gas crystals for a high precision EDM/NSM measurement

Special thanks to:

Gordon Arrowsmith-Kron, Meyhar Dudeja, Yoann Gueye, Himanshi, Karina Martirosova, Ange Ntivuguruzwa, Nicholas Nusgart, Erin White, Adrian Yearby, Sebastian Miki-Silva ...
and to our collaborators at CERN, York University, University of Toronto (EDM³)
and Argonne National Lab (RaEDM)

Backup



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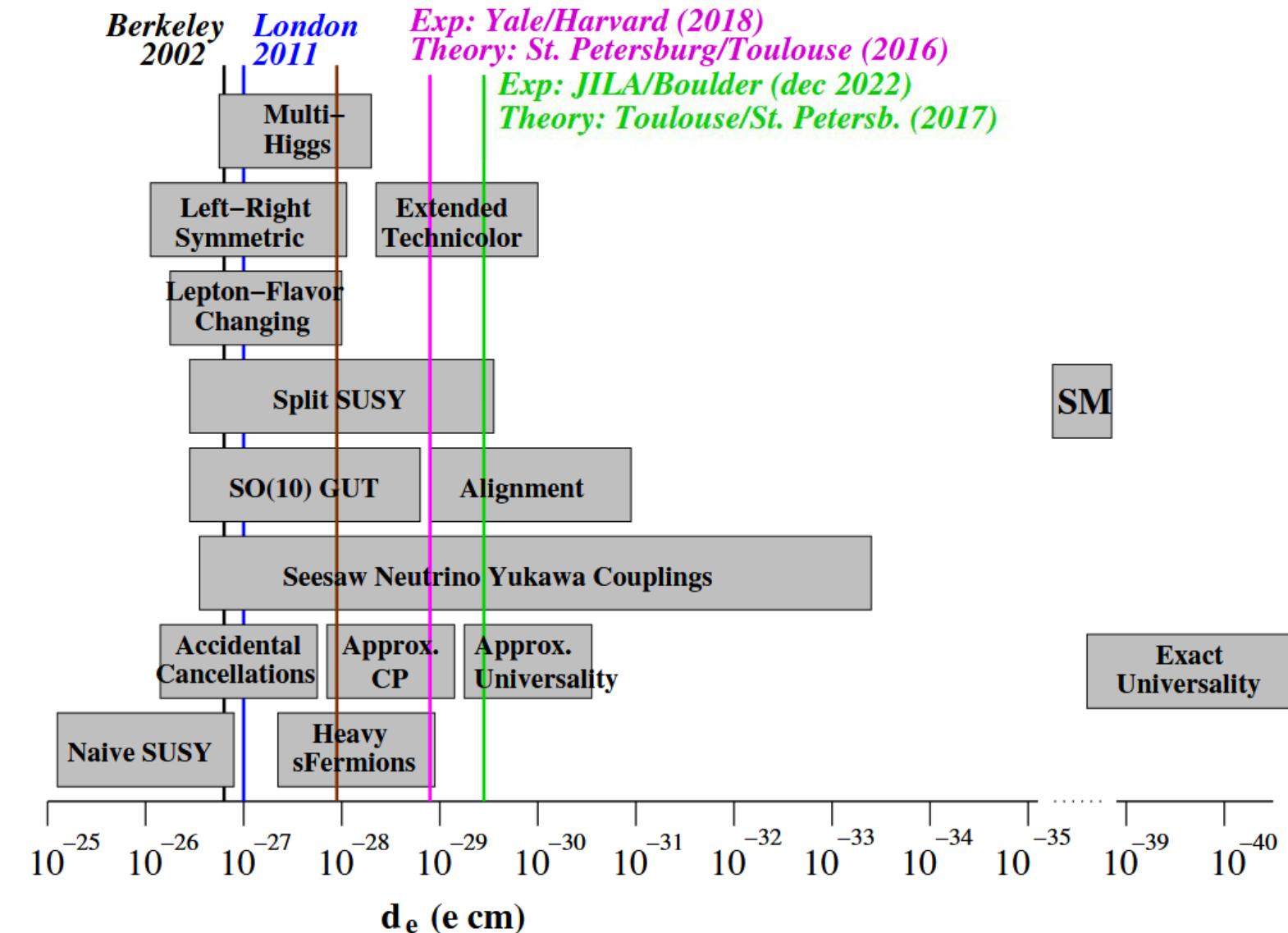
Office of
Science

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633.

This work is supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics under Award Number DE-SC0022299

This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Award Numbers DE-SC0019015 and DE-SC0019455

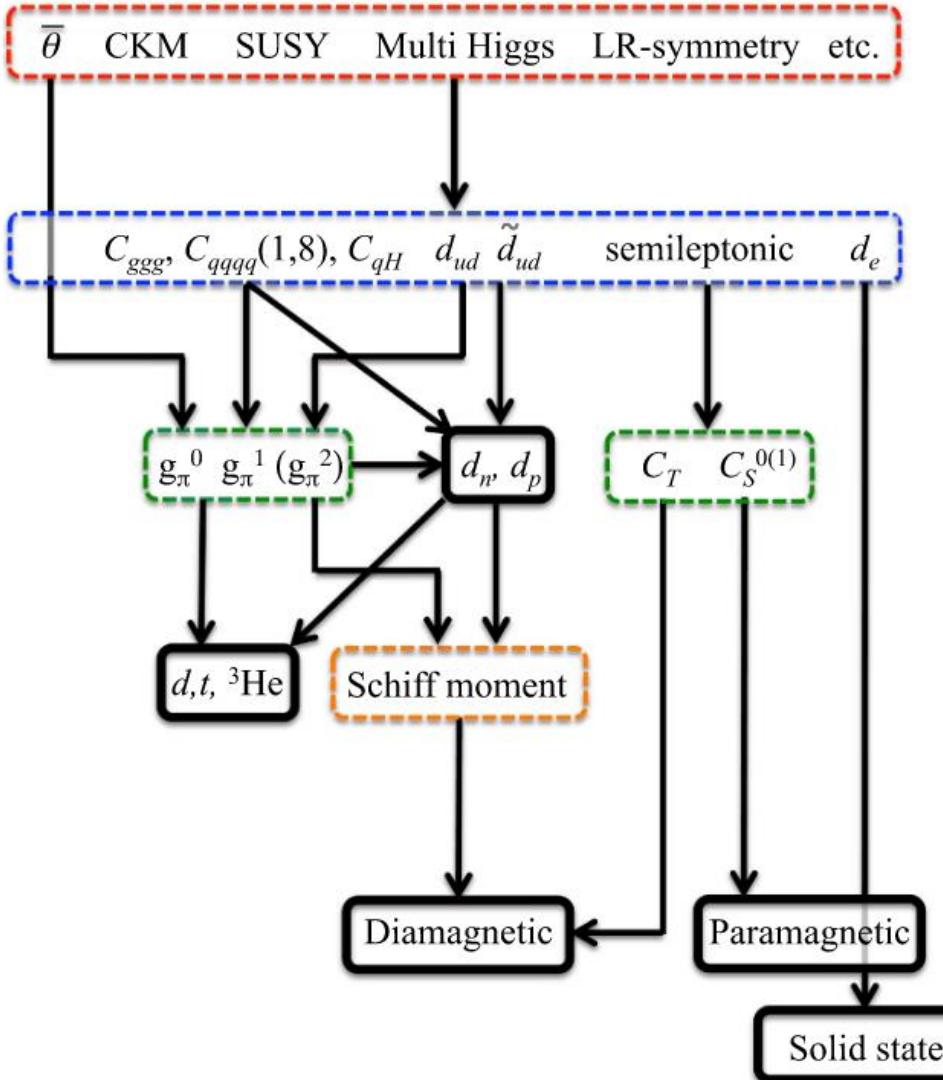
EDMs help constrain Beyond Standard Model (BSM) Theories



Multiple CP Violating Sources Contribute To EDMs In Different Ways

Chupp et al., 2019

Fundamental theory



Sources of CP-violation

Particle Physics Theory

Effective Field Theory

Lattice QCD Theory

Nuclear Theory

+

Nuclear Experiment

Atomic Theory

+

Atomic Experiment

Molecular Theory

Molecular Experiment
Radiochemistry

...EDMs

$$d_i = \sum_j \alpha_{ij} C_j$$

For system i , contribution j

Permanent Electric Dipole Moments (EDMs)

Explicitly Time-Reversing The Hamiltonian

- An EDM is a measurement of separation of charge

$$\vec{d} = \int \vec{r} \rho_Q d^3r = d \frac{\langle \vec{J} \rangle}{J}$$

$$\mathcal{H} = -(\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}) = -\frac{(\mu \vec{J} \cdot \vec{B} + d \vec{J} \cdot \vec{E})}{J}$$

$$T(\mathcal{H}) = -\frac{(\mu[T(\vec{J} \cdot \vec{B})] + d[T(\vec{J} \cdot \vec{E})])}{J} = -\frac{(\mu(+1)(\vec{J} \cdot \vec{B}) + d(-1)(\vec{J} \cdot \vec{E}))}{J}$$

$$T(\mathcal{H}) = -\frac{(\mu(\vec{J} \cdot \vec{B}) - d(\vec{J} \cdot \vec{E}))}{J}$$


EDMs violate T symmetry

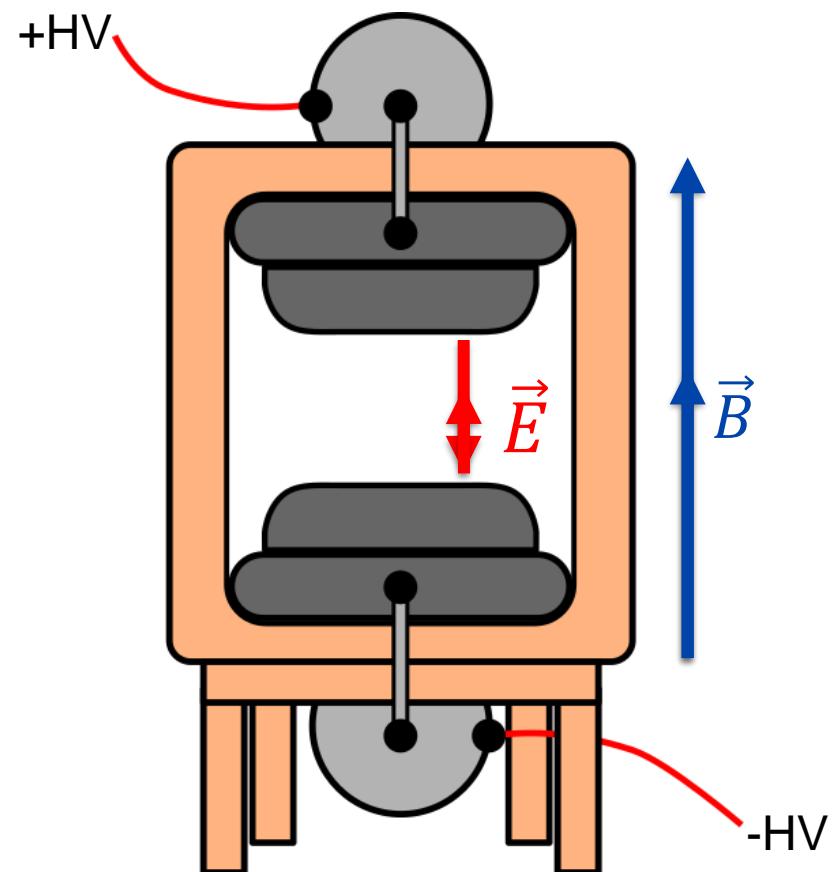
CPT Theorem: T-Violation = CP-Violation

Quantity	P (Parity)	T (Time-reversal)
\vec{J}	Even (+)	Odd (-)
\vec{B}	Even (+)	Odd (-)
\vec{E}	Odd (-)	Even (+)
$\vec{J} \cdot \vec{B}$	Even (+)	Even (+)
$\vec{J} \cdot \vec{E}$	Odd (-)	Odd (-)

Systematic Effects From Magnetic Fields

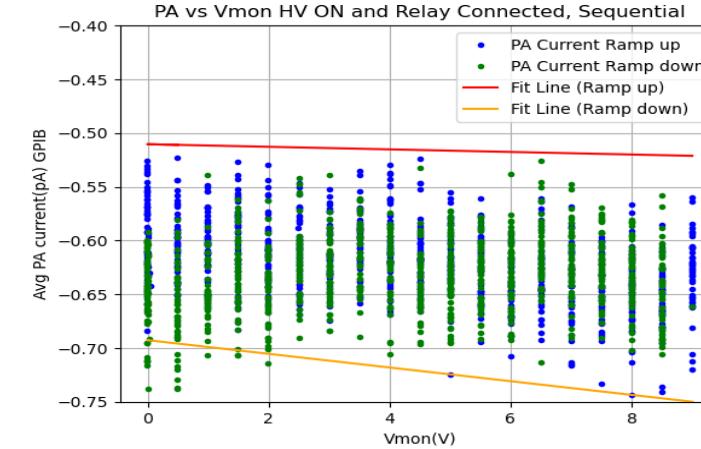
$$\Delta\nu = \nu_{\text{up}} - \nu_{\text{down}} = \frac{2\mu\Delta B + 2d(E_{\text{up}} + E_{\text{down}}) + \frac{1}{2}\alpha(E_{\text{up}}^2 - E_{\text{down}}^2) + \text{Others}}{h}$$

- Time-dependent B
 - Unstable, Non-zero ΔB
 - Motional B-fields contribute to this
- Leakage currents
 - False EDM signal via B field from electron motion
 - Path dependent
 - Changes sign with applied E field
- Imperfect field reversal
 - Poignant if magnitude of E field is not the same

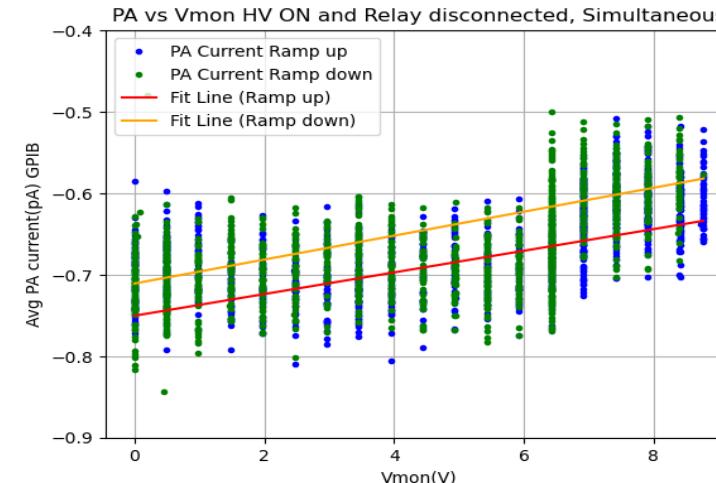


Investigating Leakage Currents In Relays

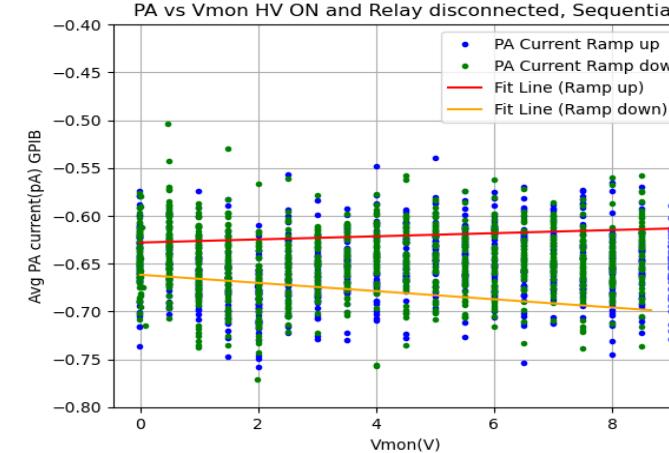
Slope (Ramp up): -0.00119748142156826
 Offset (Ramp up): -0.5104525276821329
 Uncertainty in Slope (Ramp up): 0.007842396493092929
 Uncertainty in Offset (Ramp up): 0.04078486073400088
 Slope (Ramp down): -0.006361197981024371
 Offset (Ramp down): -0.6926985073189889
 Uncertainty in Slope (Ramp down): 0.007842396493092929
 Uncertainty in Offset (Ramp down): 0.03947362279435042



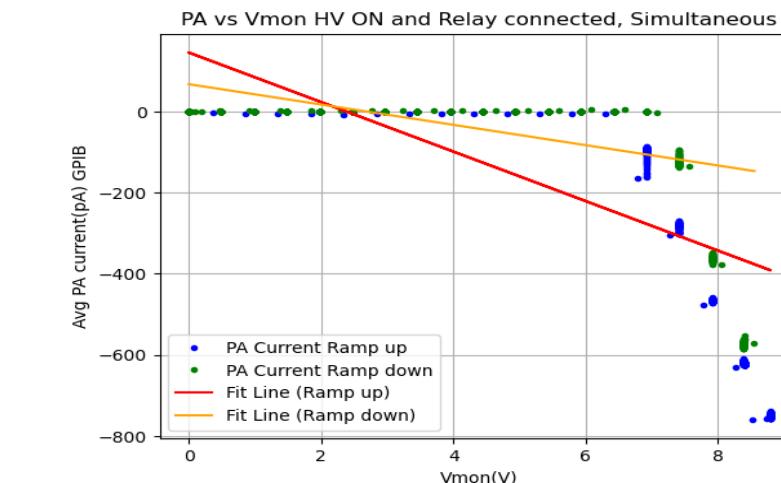
Slope (Ramp up): 0.013291636228117477
 Offset (Ramp up): -0.7583726252398086
 Uncertainty in Slope (Ramp up): 0.002200606194644498
 Uncertainty in Offset (Ramp up): 0.012301588163834209
 Slope (Ramp down): 0.014695888743254528
 Offset (Ramp down): -0.7108381534780931
 Uncertainty in Slope (Ramp down): 0.002200606194644498
 Uncertainty in Offset (Ramp down): 0.011069554878273699



Slope (Ramp up): 0.001631115157426319
 Offset (Ramp up): -0.6279872051550691
 Uncertainty in Slope (Ramp up): 0.0027363274576107997
 Uncertainty in Offset (Ramp up): 0.014212043557506753
 Slope (Ramp down): -0.004280687709964285
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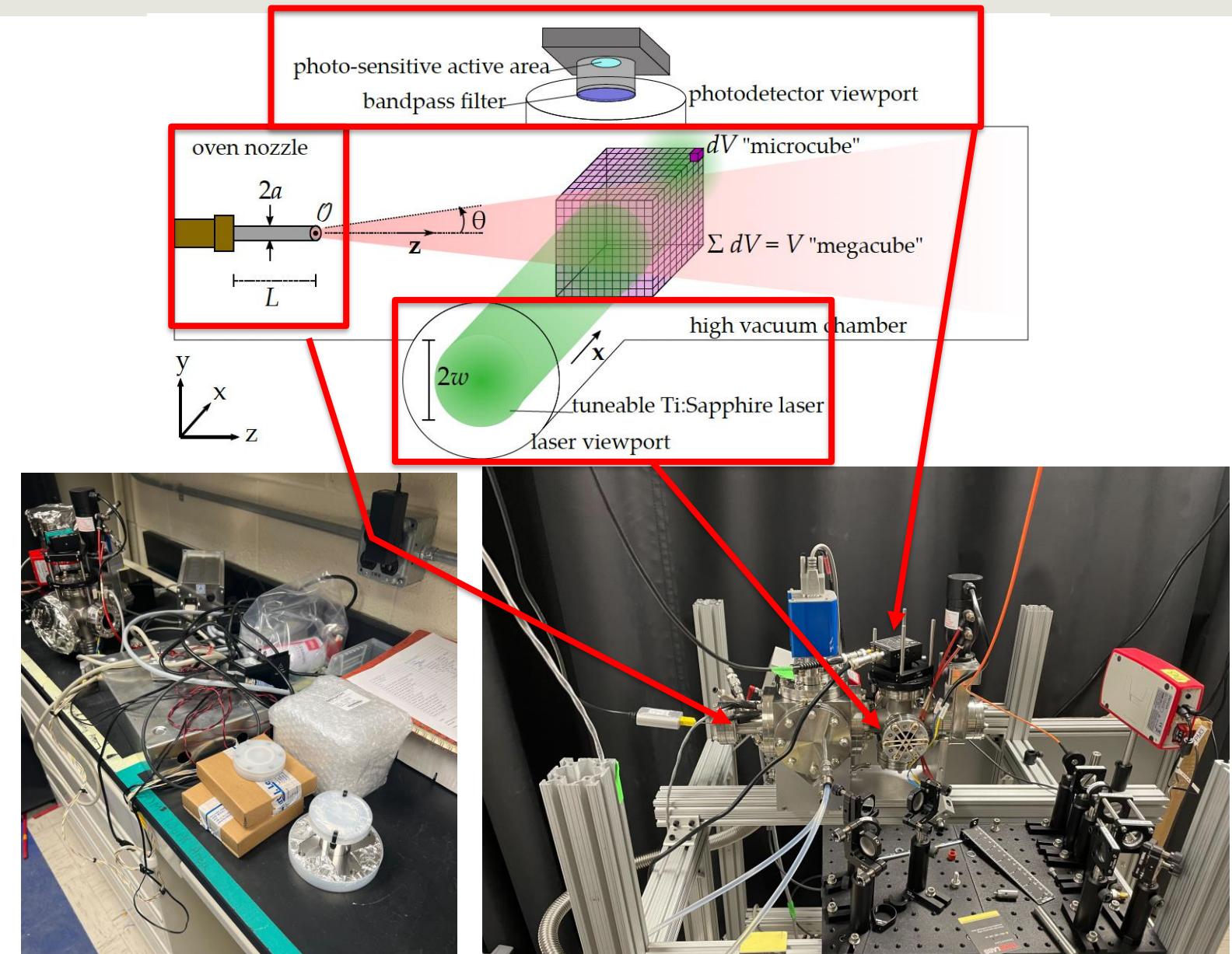
Slope (Ramp up): -60.97627444670523
 Offset (Ramp up): 144.72016844769715
 Uncertainty in Slope (Ramp up): 1.186621521943295
 Uncertainty in Offset (Ramp up): 6.7448028683670875
 Slope (Ramp down): -0.02802824999774
 Offset (Ramp down): 66.8966408190035
 Uncertainty in Slope (Ramp down): 1.186621521943295
 Uncertainty in Offset (Ramp down): 6.417749113049019



- Quantify resistance through relays to determine if they limit experimental sensitivity
 - Commercial supplier gave estimate
 - Our own estimate: $R = 3.3 \times 10^{12} \Omega$
- Slope proportional to relay resistance
 - Data (1 Relay) suggests $R \sim 10^{15} \Omega$

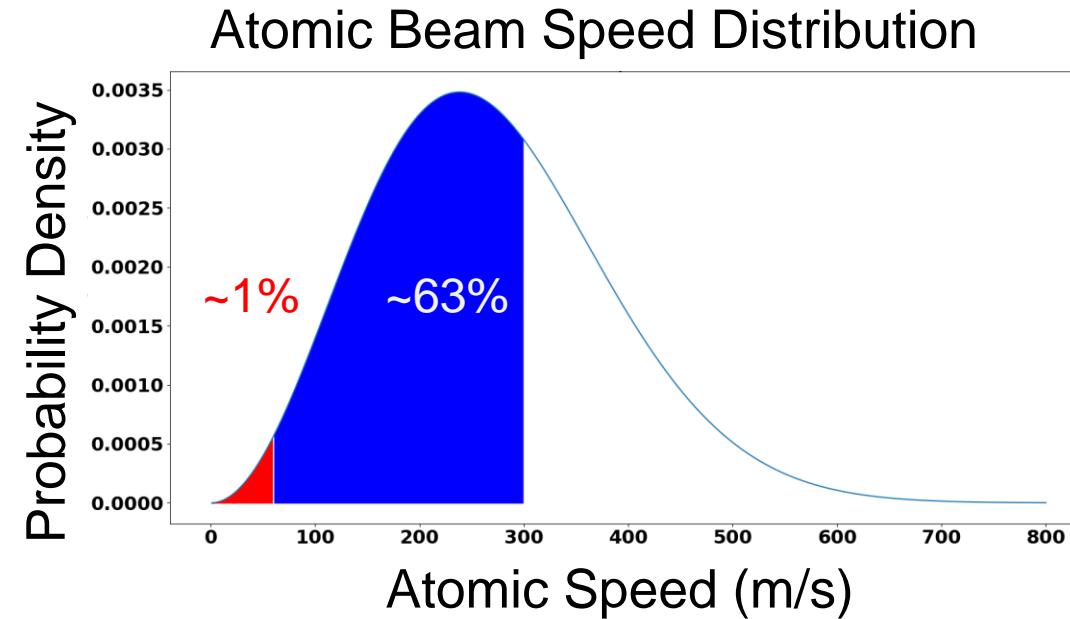
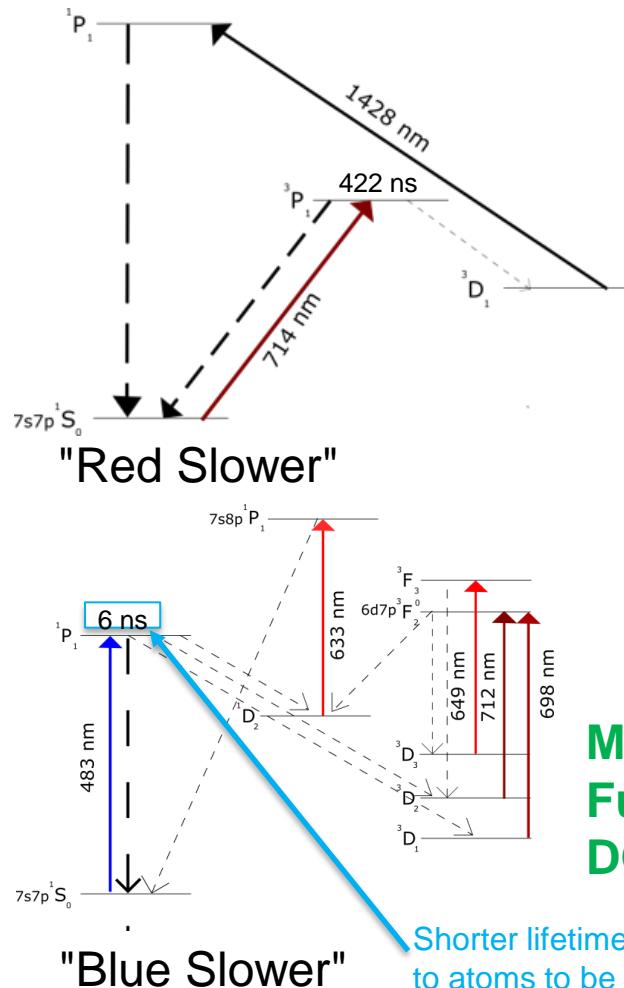
Isotope Harvesting Efficiency Studies With Atomic Beam Fluorescence

- How can we characterize what we'd get from Isotope Harvesting?
 - Load sample
 - Produce atomic beam
 - Fluoresce atomic beam
 - Compare to a simulation
 - Characterize angular distribution, atomic flux



- So far:
 - Assembled oven
 - Acquired metallic calcium
 - Restored laser functionality
 - Successfully Fluoresced atomic Calcium

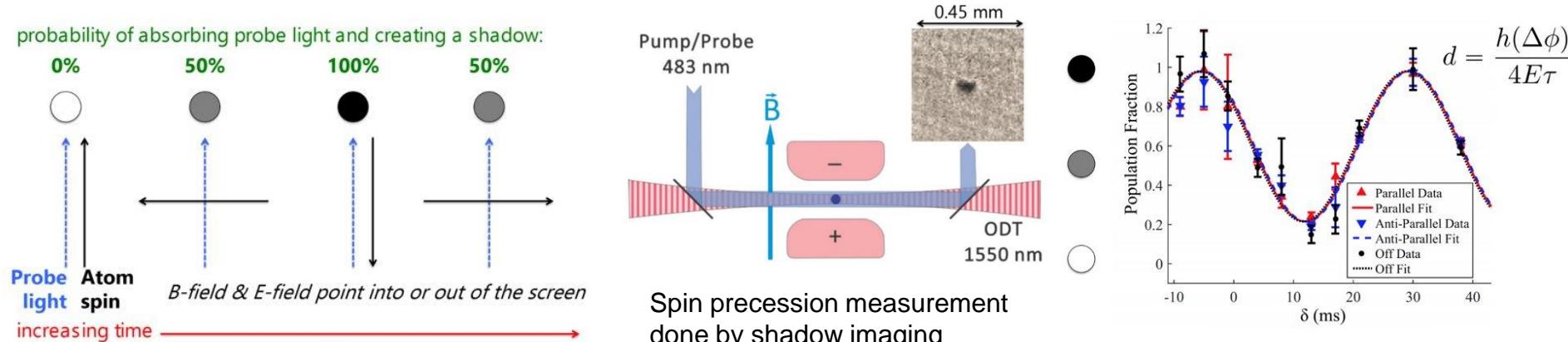
Blue Slower Scheme: More Atoms Trapped In 3DMOT



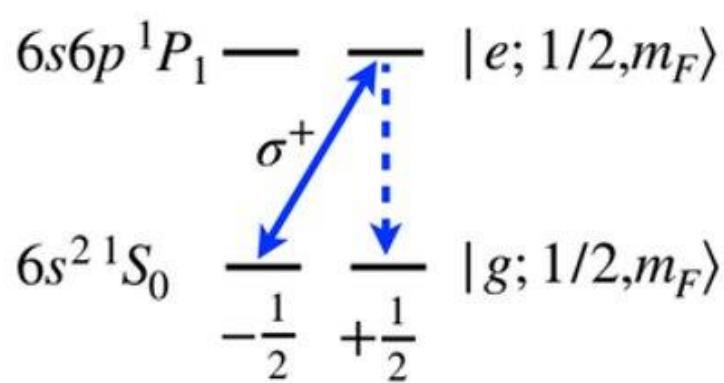
More lasers = more \$\$\$
Funded generously by
DOE office of physics

New maximum capture
speed: 300 m/s

Improved Spin Detection Efficiency: Quantum Non-Demolition (QND)

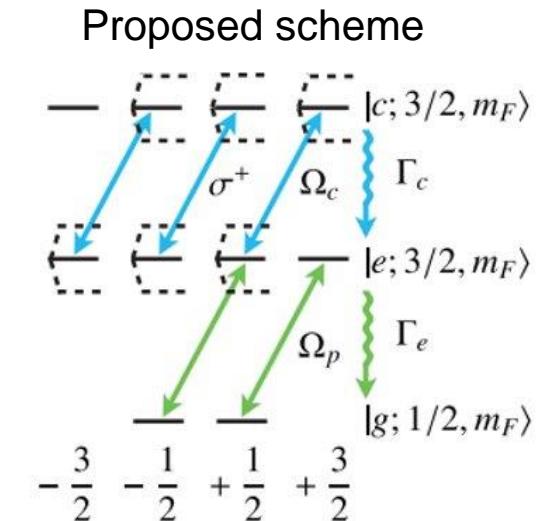


T.A. Zheng et. al,
Phys. Rev. Lett. **129**, 083001



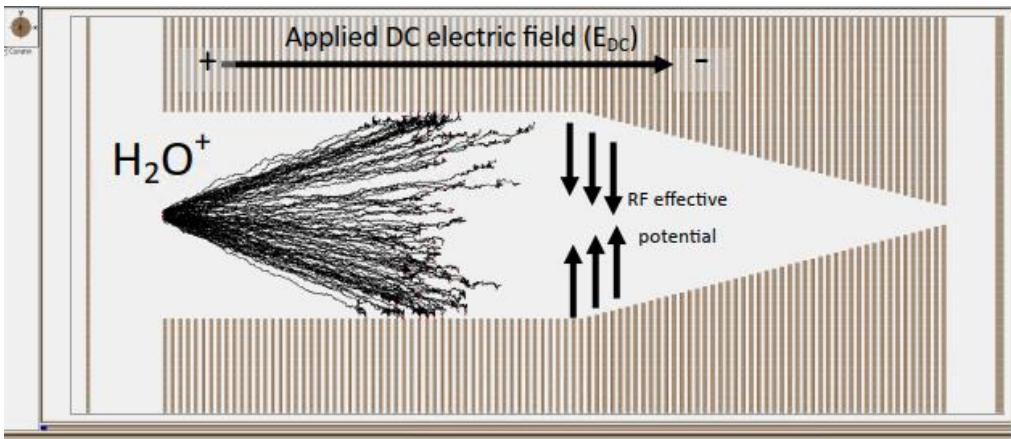
Only ~ 3 photons scattered per atom

Y.A. Yang et. al,
Phys. Rev. A. 19, 054015

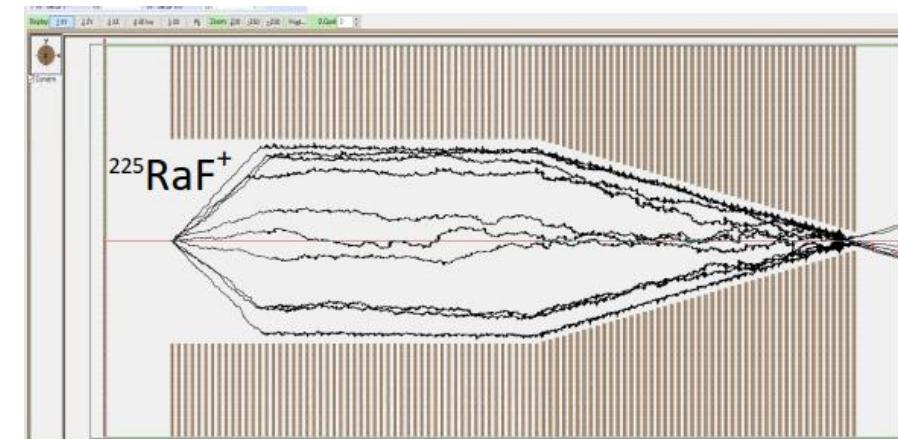


~1000 photons scattered per atom

Ion Funnel Simulation Parameters

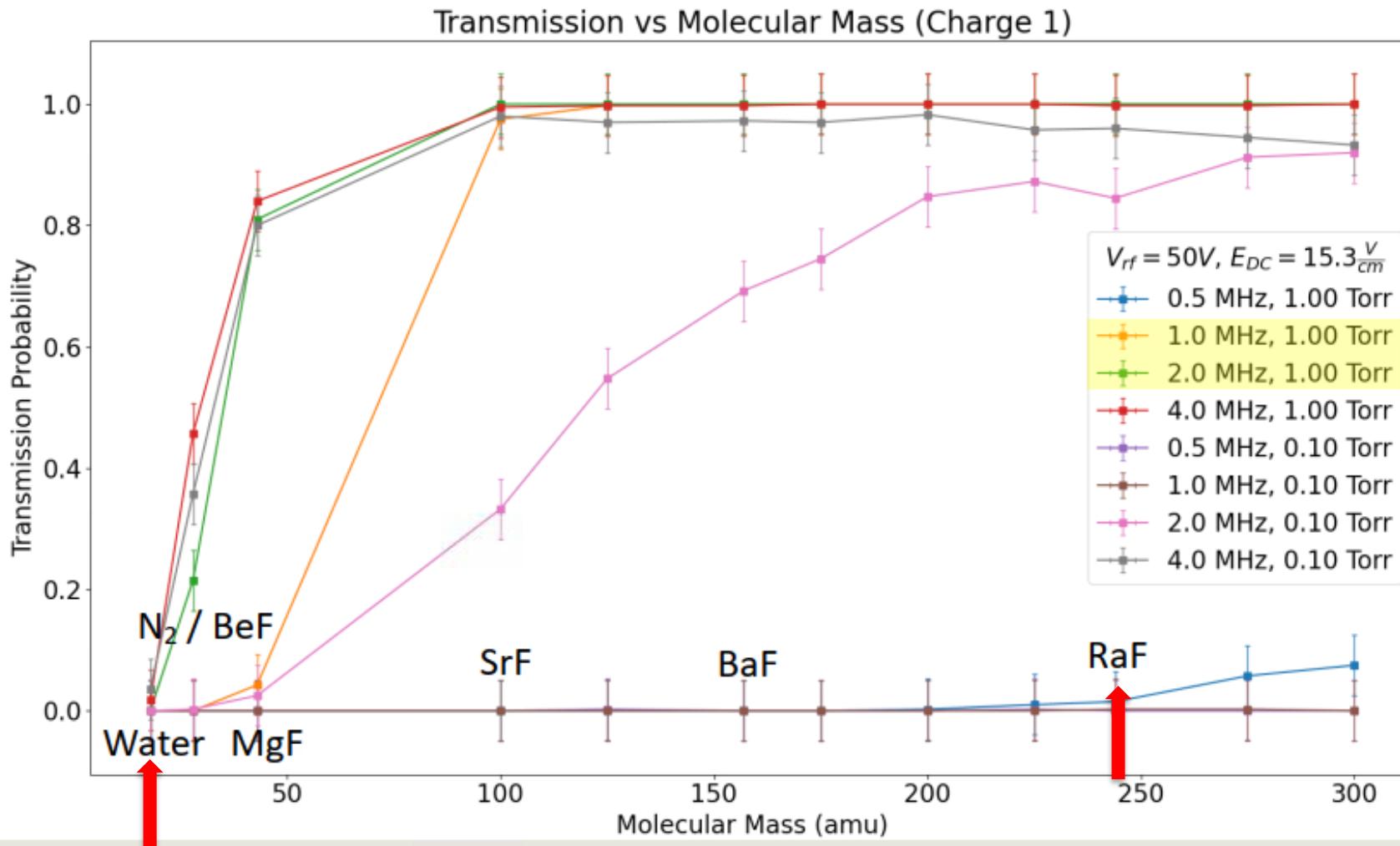


Temperature: 273 K
RF Frequency: MHz
RF Amplitude: 120 V
DC Field: 15.3 V/cm
Ambient Pressure: 0.5 Torr
 m/z : 18



Temperature: 273 K
RF Frequency: MHz
RF Amplitude: 120 V
DC Field: 15.3 V/cm
Ambient Pressure: 0.5 Torr
 m/z : 244

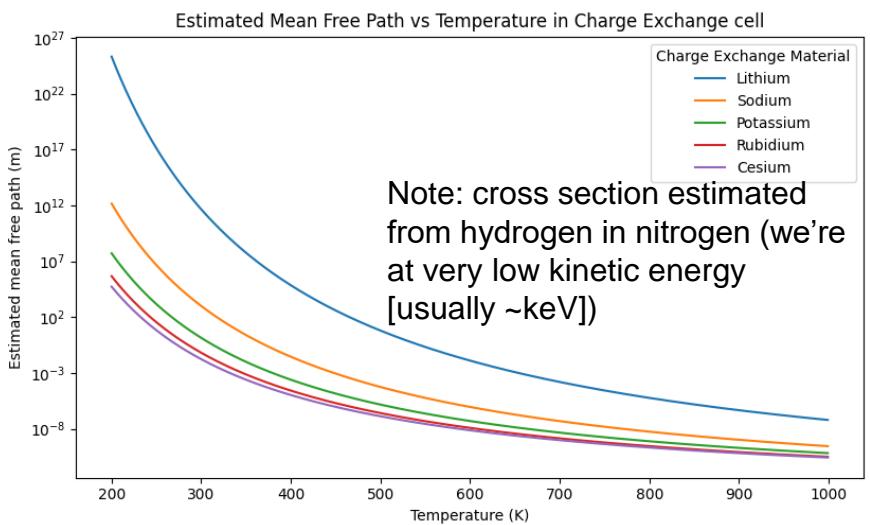
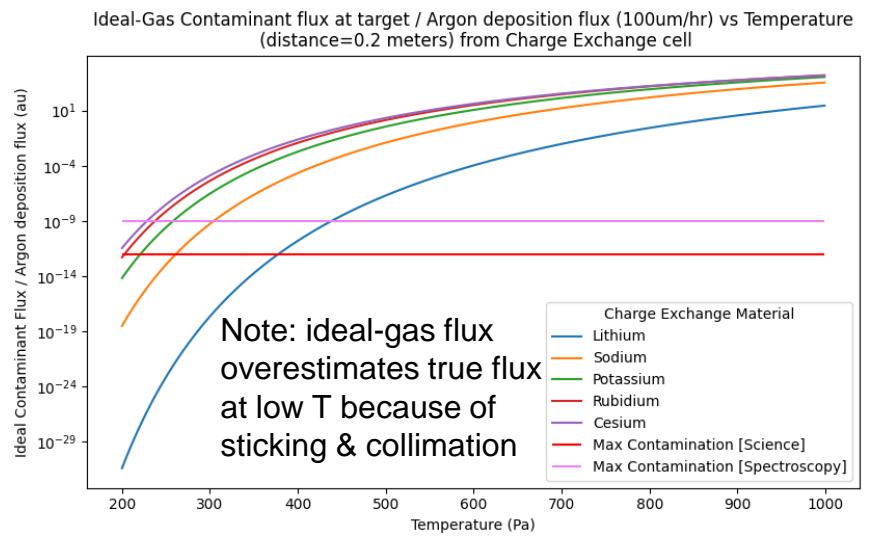
Ion Funnel Simulation For Varying Mass-To-Charge



Choice of RF and ambient pressure suppress water completely!

Neutralizing Molecular Ions With A Charge Exchange Cell

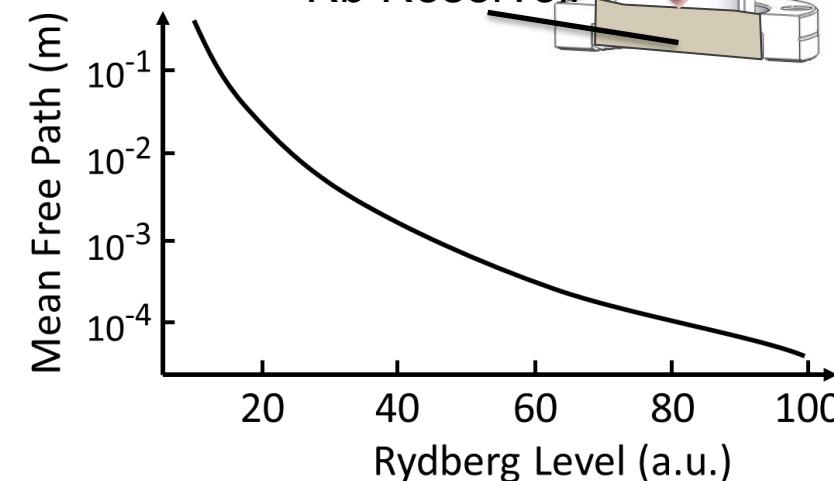
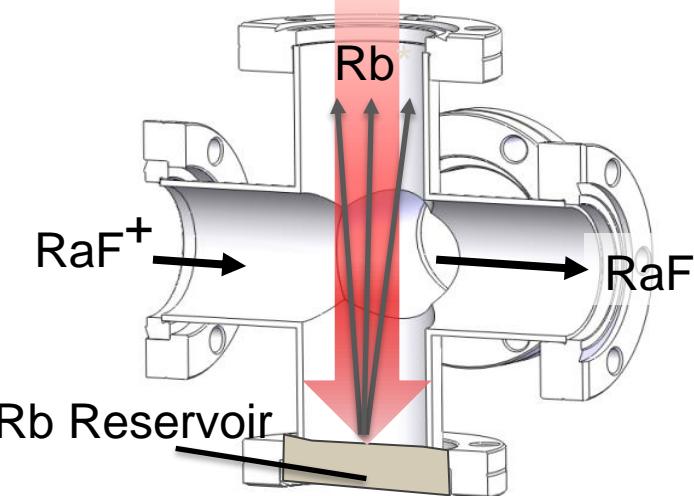
- (Alkali) Charge exchange cells are a conventional method of neutralization
 - Typically use alkali atoms
 - $A + B^+ \rightarrow A^+ + B$
- Problem: need both
 - High efficiency (don't have much ^{225}Ra)
 - Low contamination ($\sim 1 \text{ ppb} - 1 \text{ ppt}$)
- Very difficult to satisfy both at same time
- Solution: make the alkali atoms bigger
 - Rydberg atoms: have 1 atom in high n



Neutralizing Molecular Ions With A Charge Exchange Cell (Pt. 2)

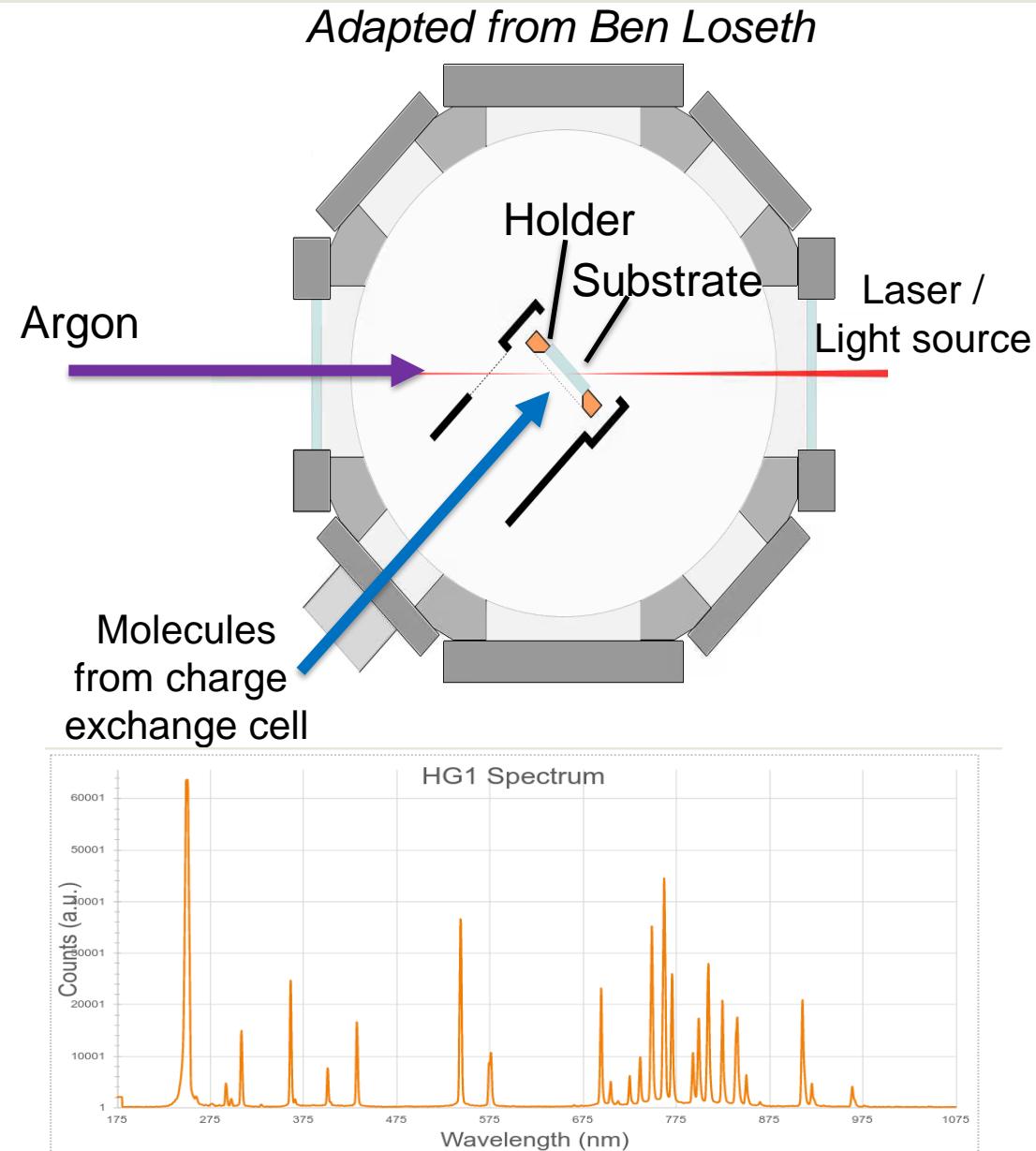
- Rydberg atoms: atoms with 1 or more electrons in high n orbital
 - Physically large ($r \propto a_0 n^2$)
 - Low binding energies
 - Have enormous charge exchange cross sections $\sigma \propto n^4 a$ → can easily be 10000x ground state σ)
- Use visible / IR lasers to excite, don't need high power (only ~10 mW each with 2 lasers) [cite arc]
 - Can use even less power with more lasers
- Enables high efficiency with low number density (low temperature)
 - Results in much less contamination
 - At low temperature, atoms tend to stick to walls instead of bouncing → further reduces contamination

Rydberg charge exchange cell rough layout (adapted from J. Ballof 2022)
Laser: 780 nm, 477 nm



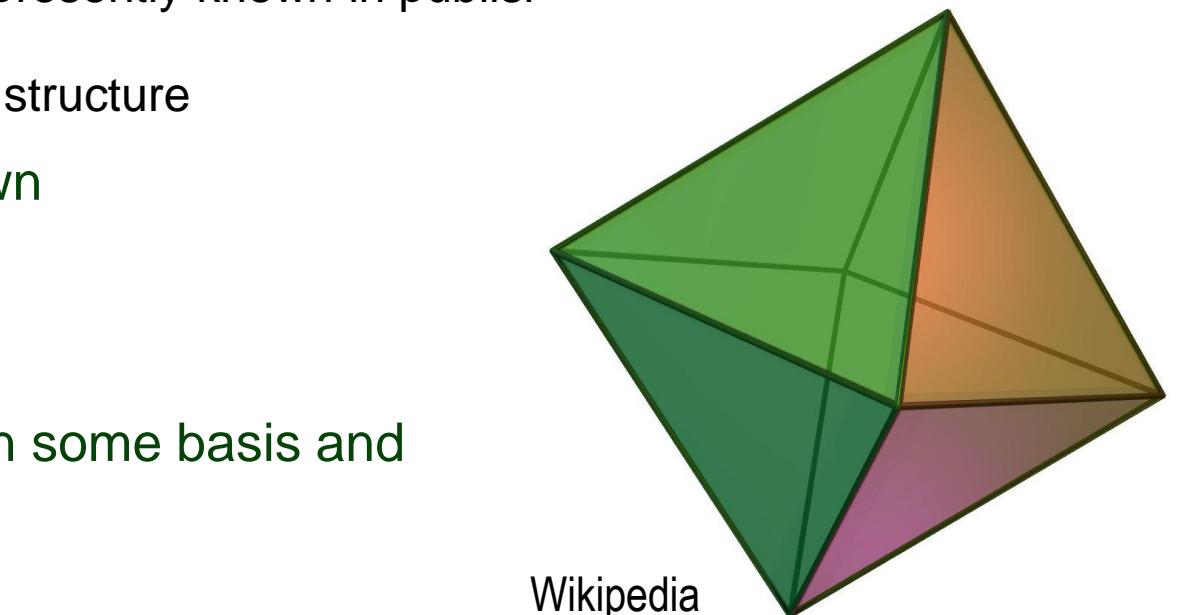
Co-deposition using the pSAM technique

- Plan to co-deposit the polar molecules as the argon film is grown
- Growth rate $\lesssim 100$ um/hr
 - Limited by source throughput
- Target/cryostat chamber design will be based on existing setup
 - Modifications needed
- Temperature ~ 4 K
- Substrate is 1" diameter sapphire
- Will use a combination of white light sources and lasers to perform spectroscopy
- Will do both
 - Fluorescence measurements
 - » ex: find out molecular energy levels/(hyper)fine structure
 - Absorption measurements:
 - » ex: characterize argon films



A Nuclear Schiff Moment Measurement Scheme For RaF/BaF

- Need a measurement scheme to actually perform the experiment
 - Which states to transition to and from
 - Need to know the rotational-hyperfine spectrum for this
- No NSM measurement scheme for ^{225}RaF exists
 - Furthermore, precise hyperfine structure of ^{225}RaF is not presently known in published literature
 - MIT group is leading the effort to determine the hyperfine structure
- However, structure of similar molecule ^{138}BaF is known
 - Measurements well known Chem Phys 71 389 (1982)
 - ^{138}BaF is simpler: only has one nonzero nuclear spin
- Approach: calculate matrix elements of Hamiltonian in some basis and numerically diagonalize
 - Hamiltonian has two parts “intrinsic” to the molecule
 - » Rotational, Hyperfine
- The noble-gas matrix
 - Exact potential not known
 - Use the well-known “Devonshire potential” as a model

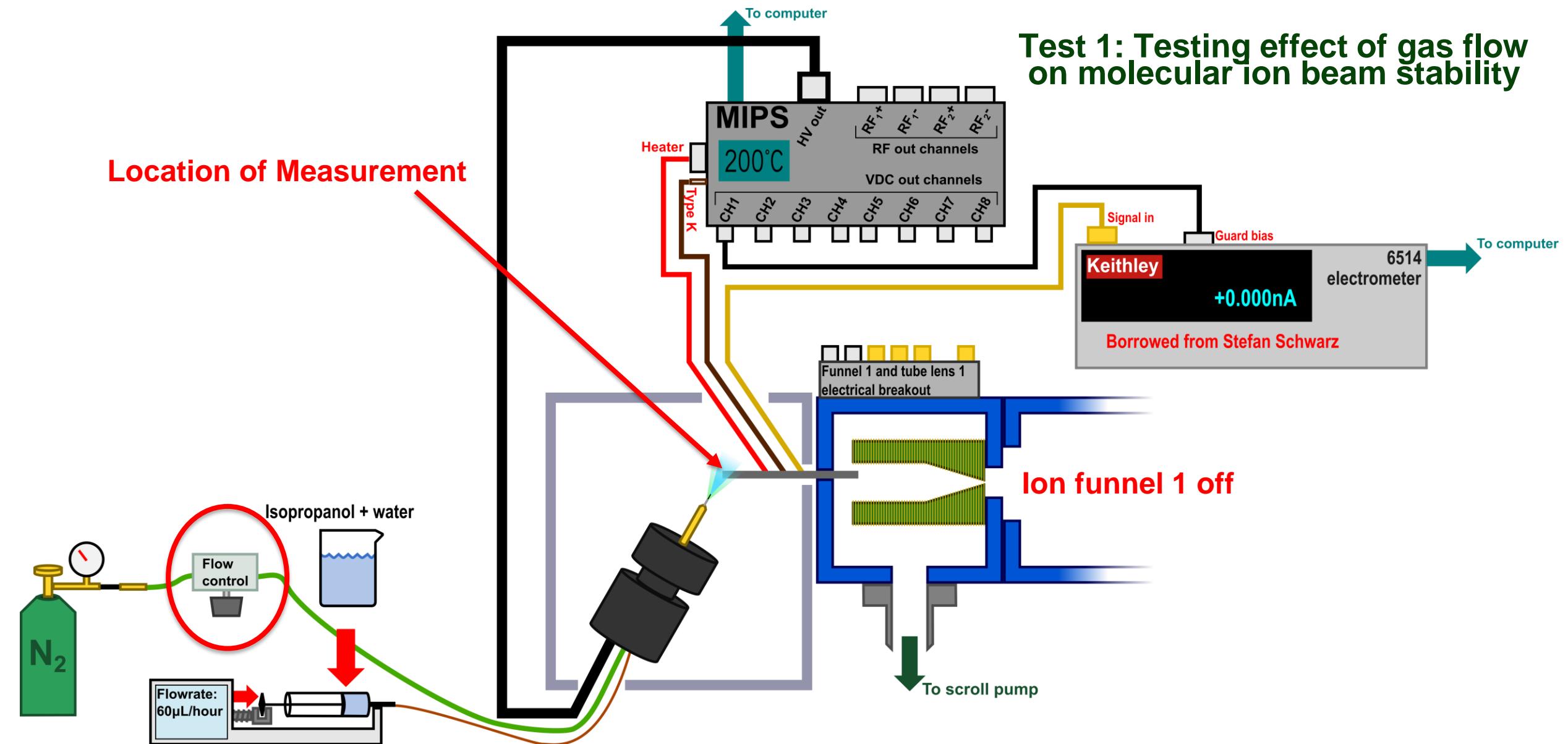


<https://en.wikipedia.org/wiki/Octahedron#/media/File:Octahedron.jpg>

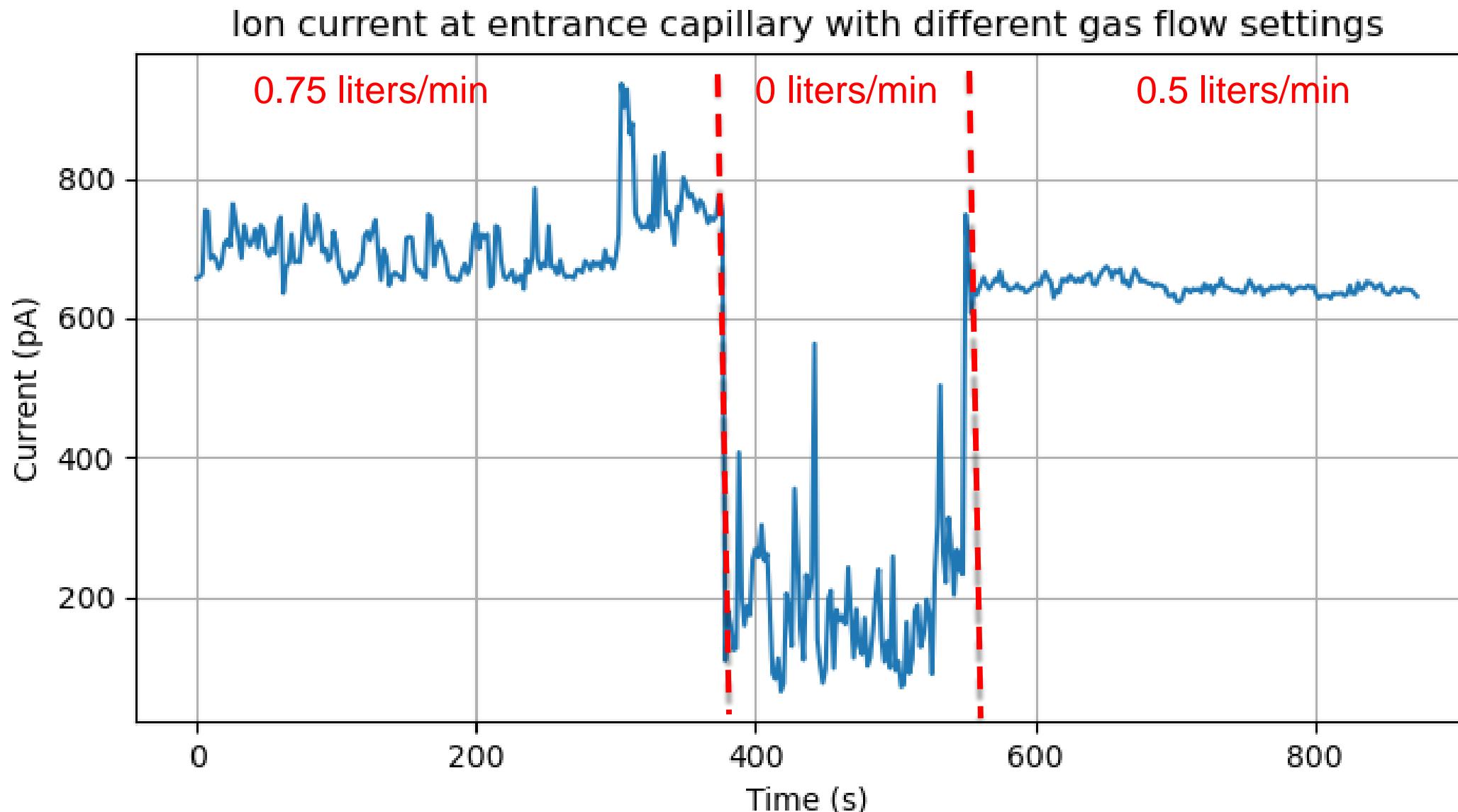
PRA 98, 032513 (2018)

FRIB-EDM³ Testing: How Do Desolvation Gases Affect Molecular Ion Beam Stability

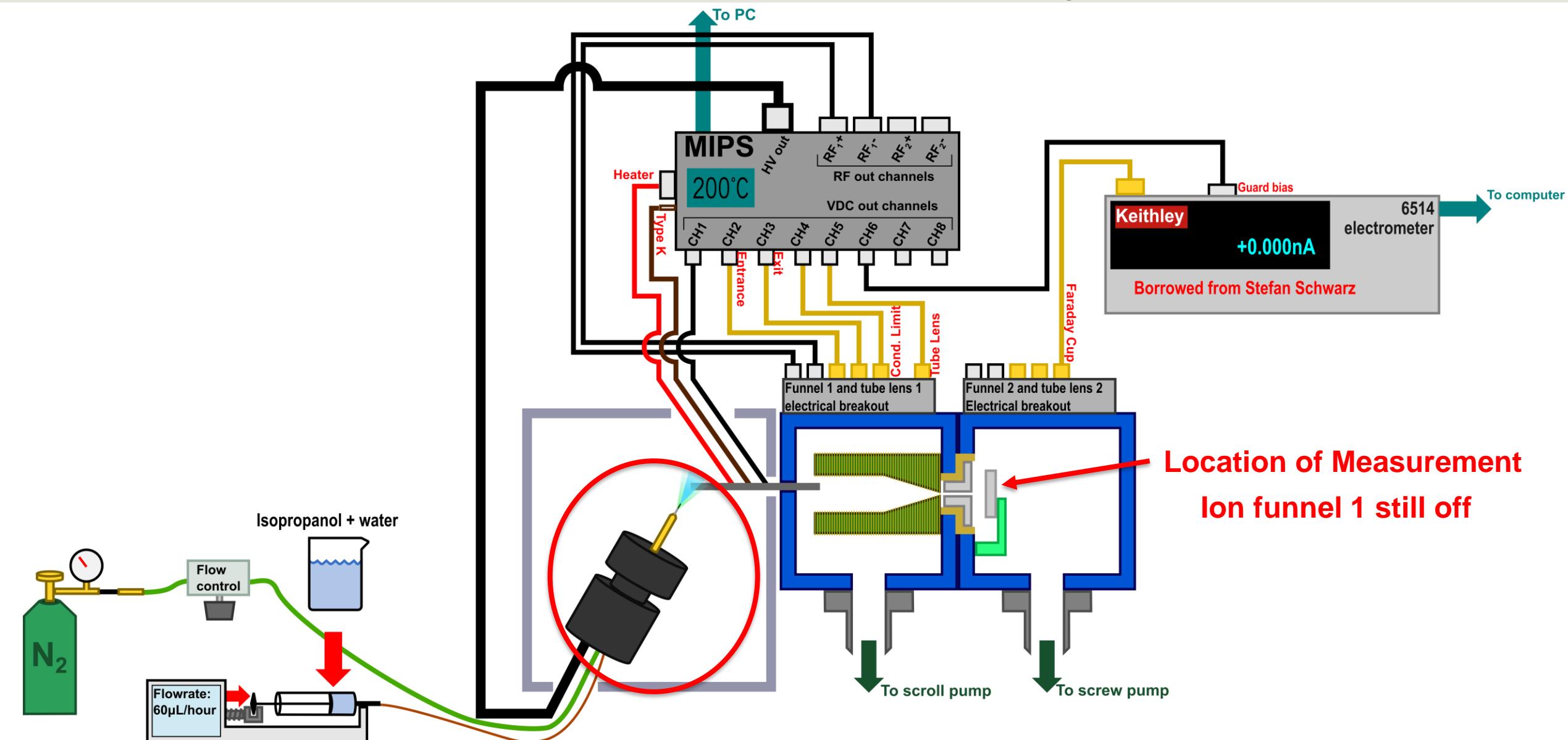
Location of Measurement



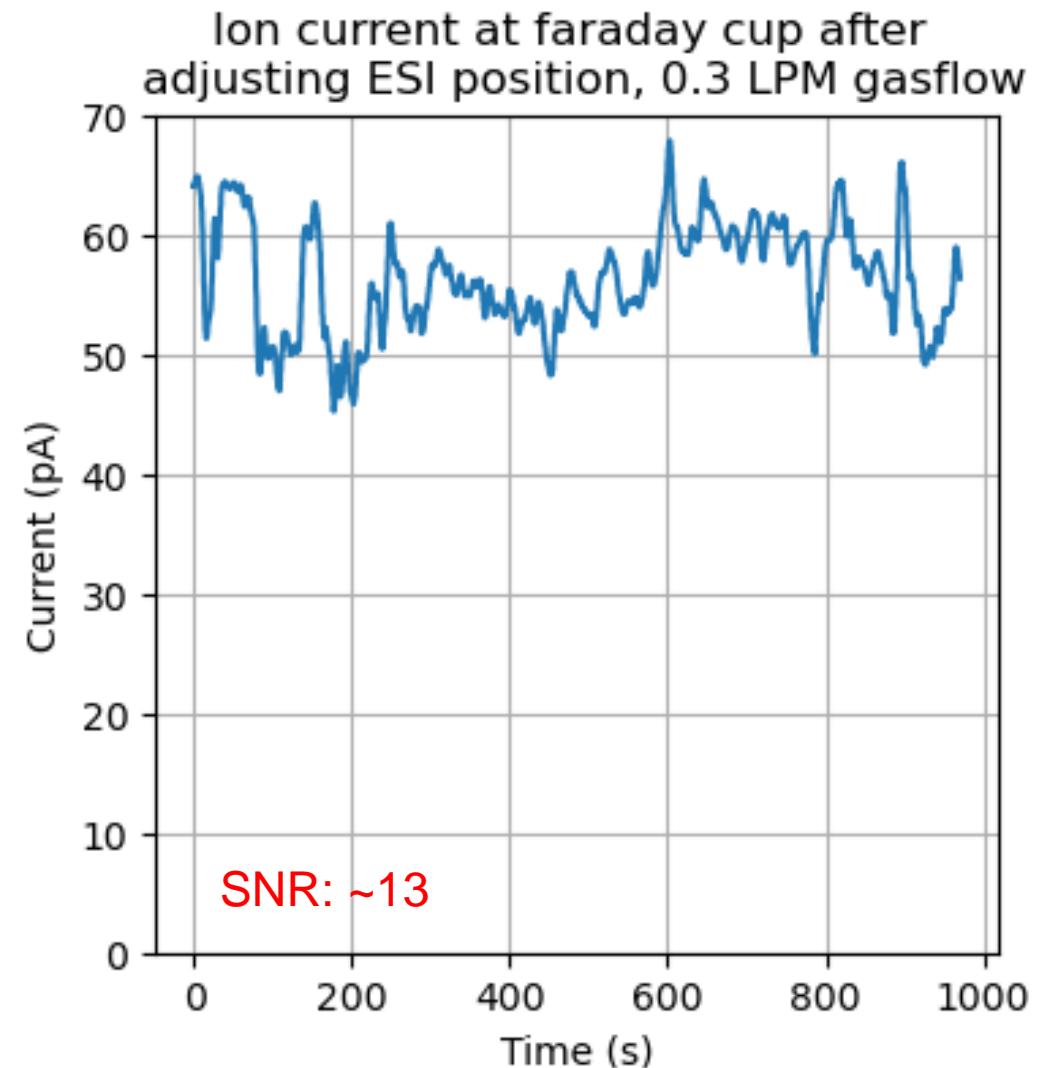
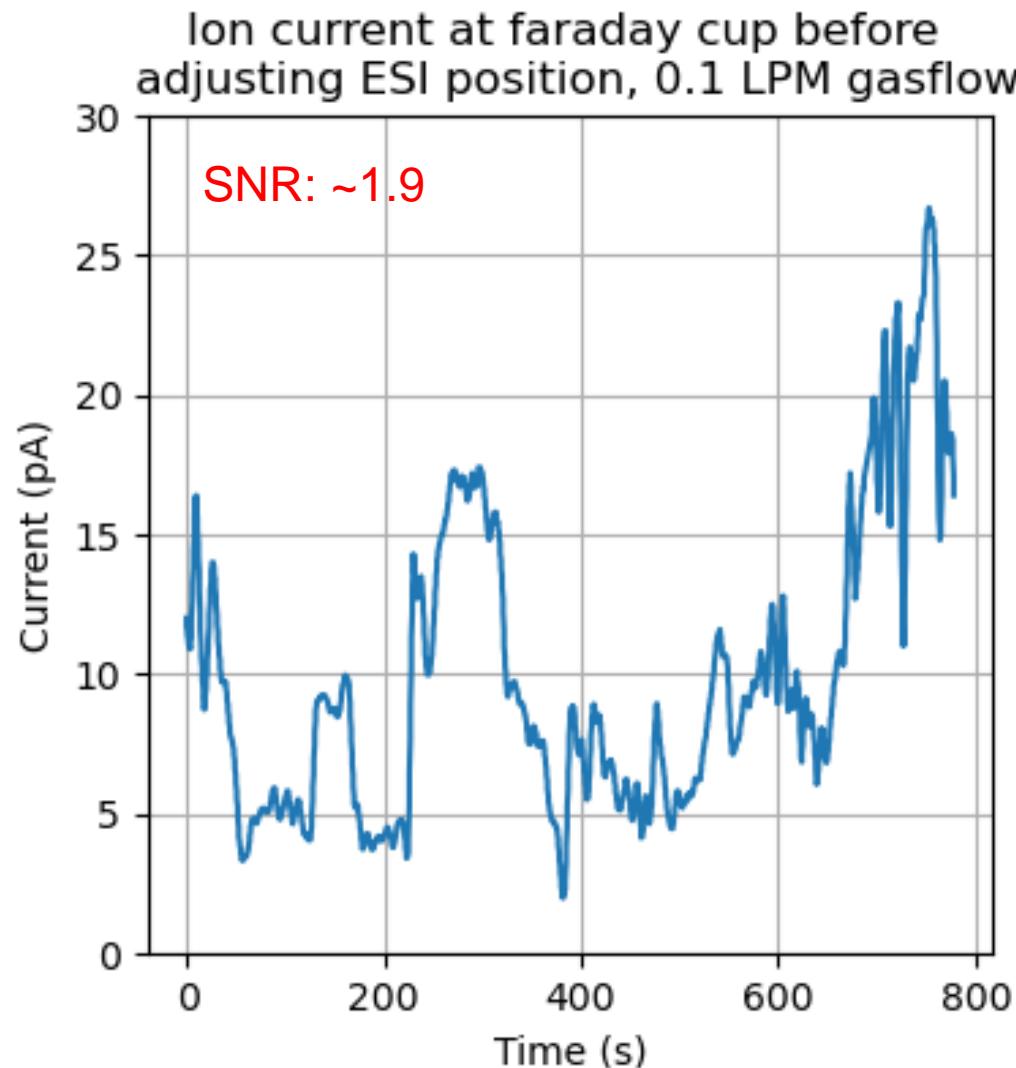
FRIB-EDM³ Testing: Gas Flow Improves Ion Formation



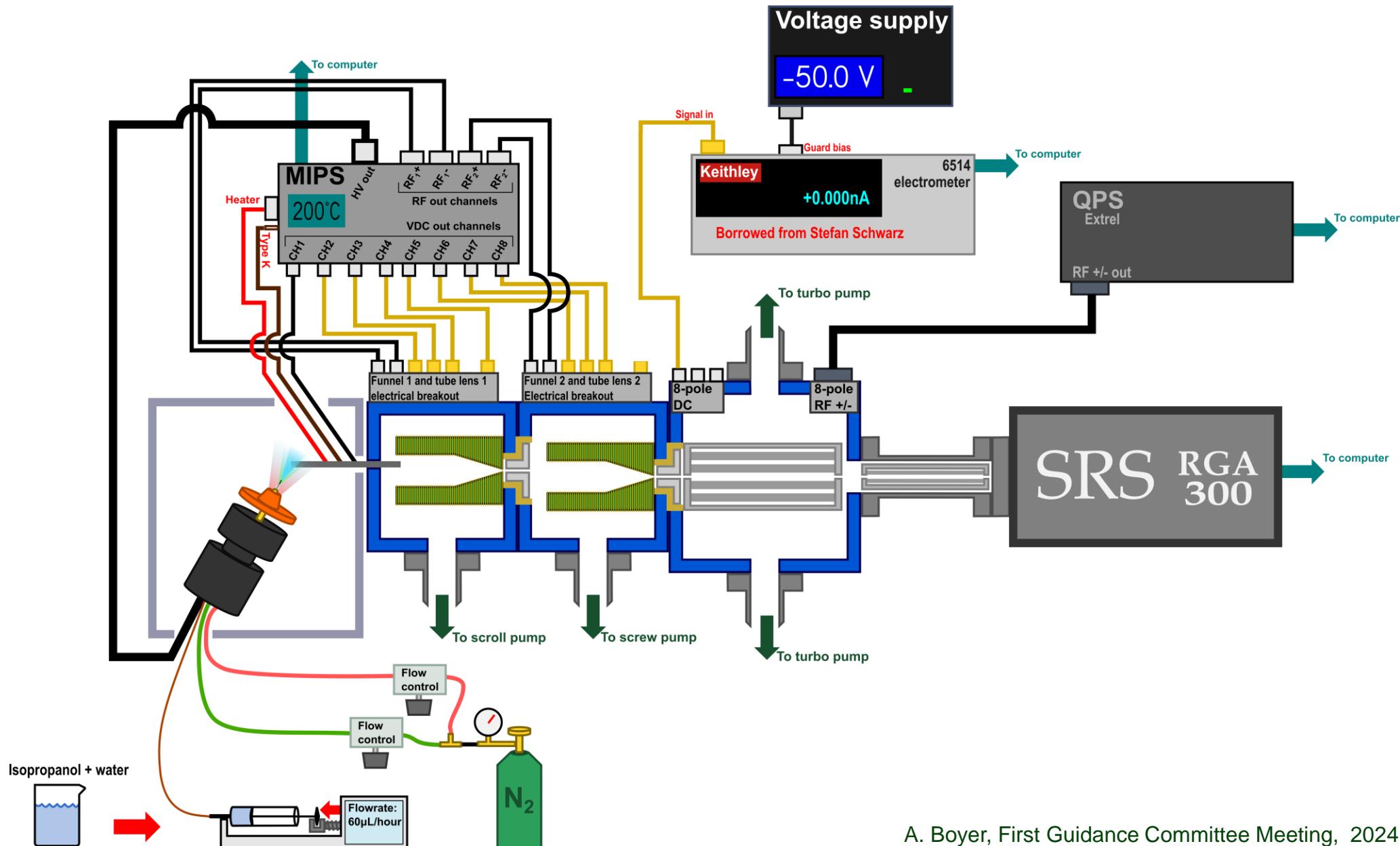
FRIB-EDM³ Testing: How Does Electrospray Probe Position Affect Molecular Ion Beam Stability?



FRIB-EDM³ Testing: Electrospray Probe Position Really Matters

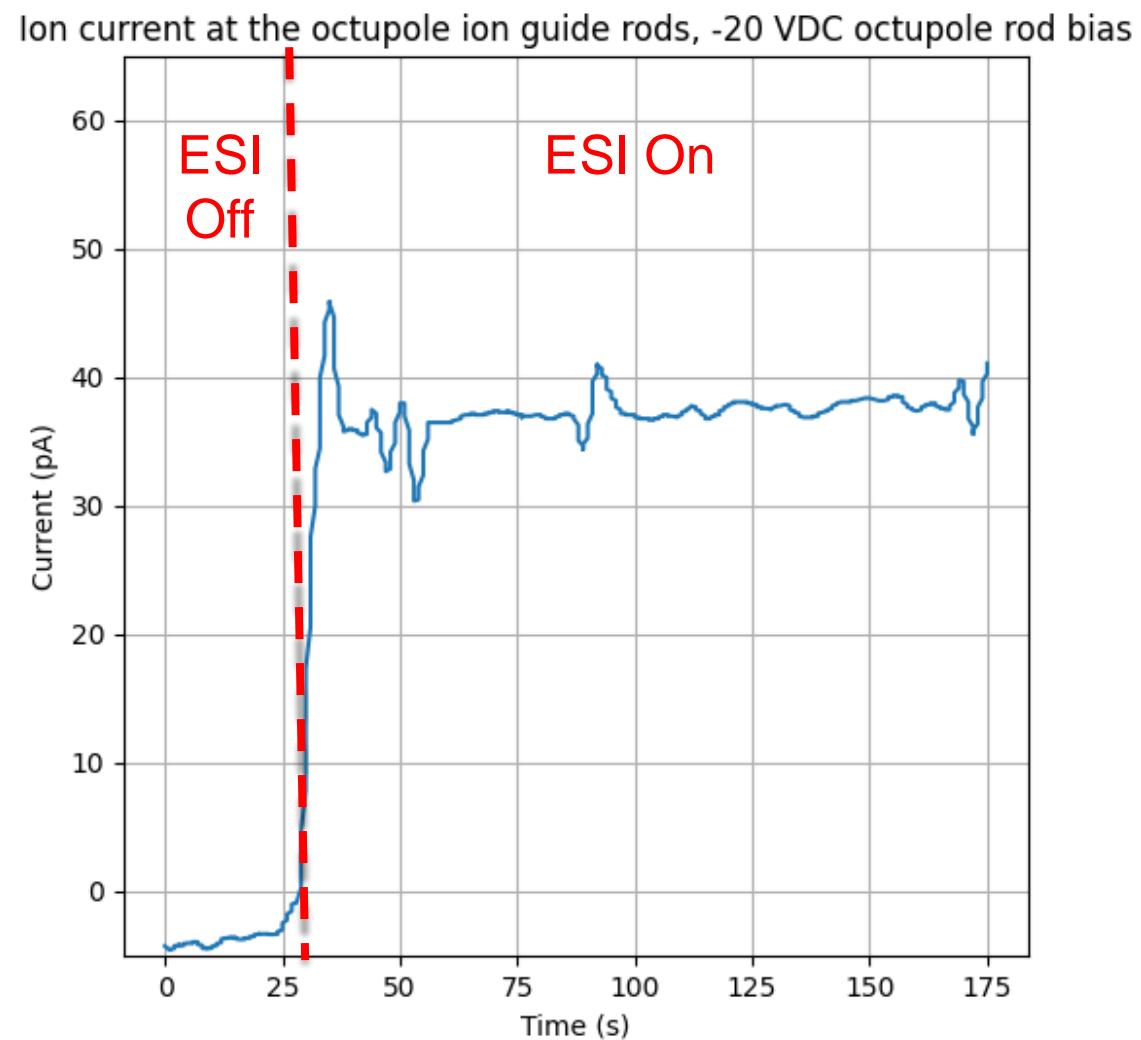


FRIB-EDM³ Testing: Can We Transmit Ions Through The Octupole Ion Guide?



FRIB-EDM³ Testing: Modifications Were Needed To Get Ion Currents Through The Octupole

- Funnels 1 and 2 installed and working
 - Ion currents through these funnels possible
- Initially, no ion transmission through octupole ion guide
 - Ion beam divergence before octupole
 - Optimal RF unknown
- Connected octupole rods to DC bias
 - No focusing effect
 - Next: Apply RF and characterize transmission



Private Portion Of Meeting



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This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Award Numbers DE-SC0019015 and DE-SC0019455

Quarterly Goals, Present – May 2025

- 2024 Q2 (Now – June):
 - Literature review of sub-ambient pressure nanoelectrospray
- 2024 Q3 (July – September):
 - Preliminary design of new electrospray source based on review
- 2024 Q4 (October – December):
 - Modifications to design, acquisition of parts, assemble nanoelectrospray source
- 2025 Q1 (Jan-March):
 - Commission new nanoelectrospray source
- 2025 Q2 (April – May)
 - Optimize new nanoelectrospray source
 - Compare performance to initial source

PhD Timeline

- 2024-2025
 - Design & fabricate nanoelectrospray ionization source (improve reproducibility of ion beams)
- 2025-2026
 - Commission & optimize nanoelectrospray ionization source
 - Design molecular spectroscopy cryostat
- 2026-2027
 - Fabricate molecular spectroscopy cryostat
 - Perform laser-induced fluorescence measurements of molecules in solids
- 2027-2028
 - Write dissertation