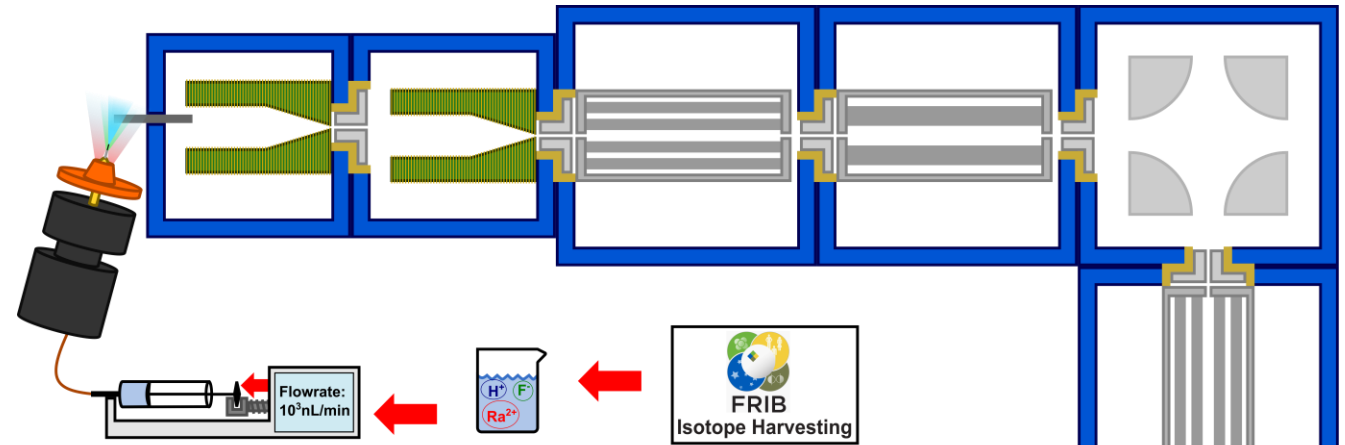


October 09, 2024, 11:18 – 11:30 AM
 Fall Meeting of the APS Division Of Nuclear Physics
 Boston, Massachusetts
 Mini-Symposium: Next-generation Techniques for
 Fundamental Symmetries and Neutrinos II
 Hilton Boston Park Plaza, Studio 1, Lobby Level
 Talk K13.00005



The FRIB-EDM³ Instrument: A Tool For Creating And Spectroscopically Studying Radioactive Molecules For Tests Of Fundamental Symmetries

[APS DNP 2024, Abstract K13.00005](#)

Aiden Boyer*, Nicholas Nusgart, Meyhar Dudeja, Jaideep Singh
 *boyera@frib.msu.edu

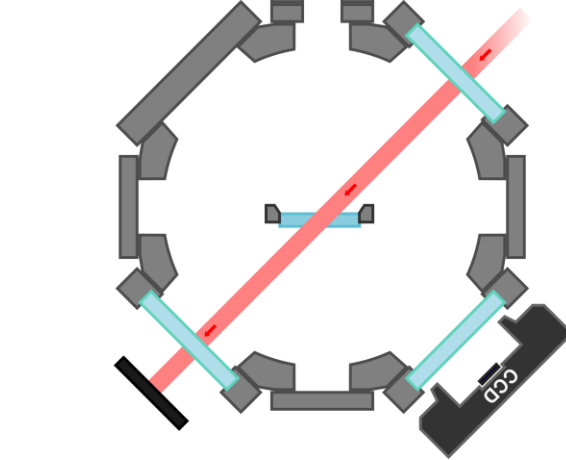


MICHIGAN STATE
 UNIVERSITY



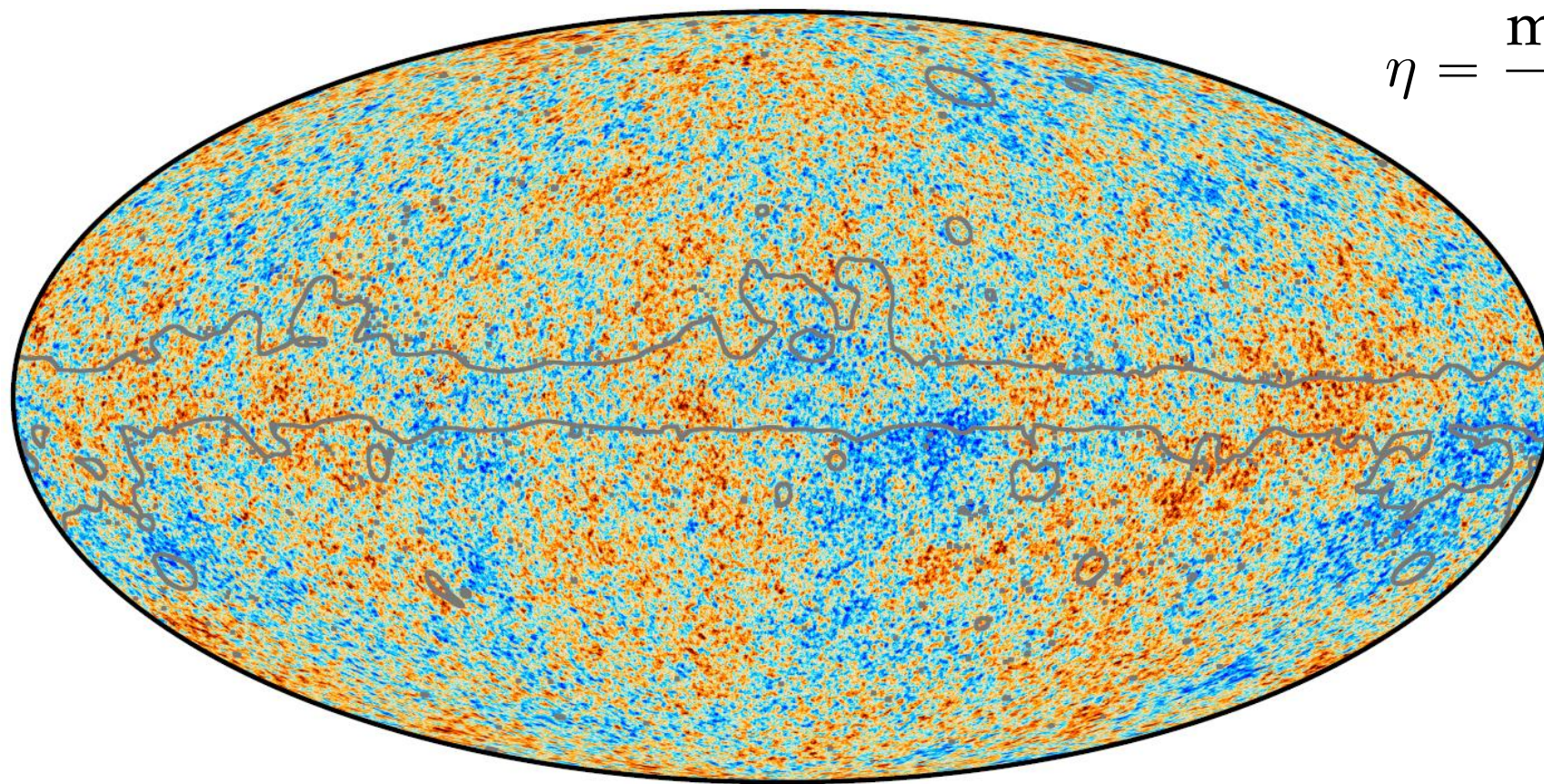
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 Science



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 Number DE-SC0019015.

More Sources of CP Violation Needed To Explain Abundance Of Matter Over Antimatter In The Visible Universe



-300  300 μK

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

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

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

PDG2024



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

Huet & Sather PRD 51:379 (1995)

Permanent Electric Dipole Moments Are A Signature Of T Violation

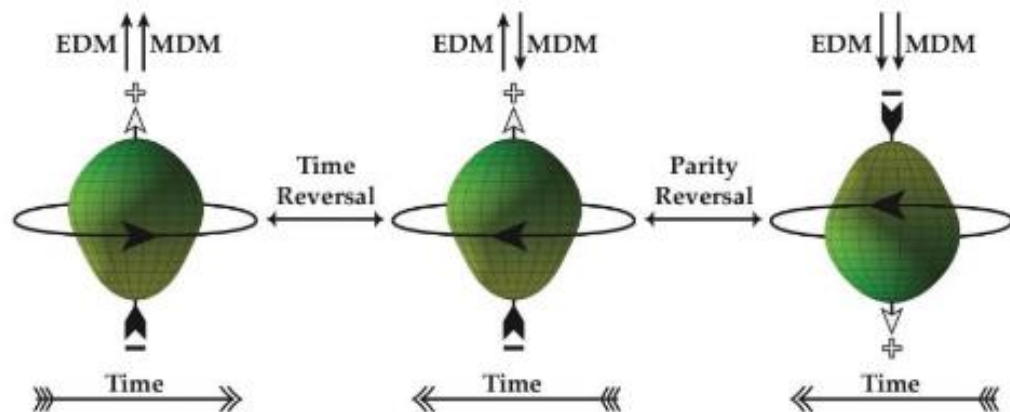
Quantity	P (Parity)	T (Time-reversal)
\vec{J}	Even (+)	Odd (-)
\vec{B}	Even (+)	Odd (-)
\vec{E}	Odd (-)	Even (+)
$\vec{J} \cdot \vec{B}$	Even (+)	Even (+)
$\vec{J} \cdot \vec{E}$	Odd (-)	Odd (-)

- EDMs measure a separation of charge

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

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

J	Total angular momentum
B	Magnetic field
E	Electric field
d	Electric dipole moment
μ	Magnetic dipole moment
ρ_Q	Charge Distribution



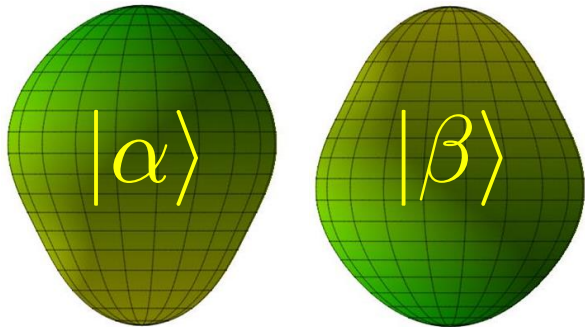
CPT Theorem: T-Violation = CP-Violation

Pear-shaped Nuclei Have Large Sensitivity To Symmetry Violations

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

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

²²⁵Ra Parity Doublet



55 keV

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

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

- **Nearly degenerate parity doublet**

Haxton & Henley PRL 51:1937 (1983)

- **Large intrinsic Schiff moment due to octupole deformation**

Auerbach, Flambaum, & Spevak PRL 76:4316 (1996)

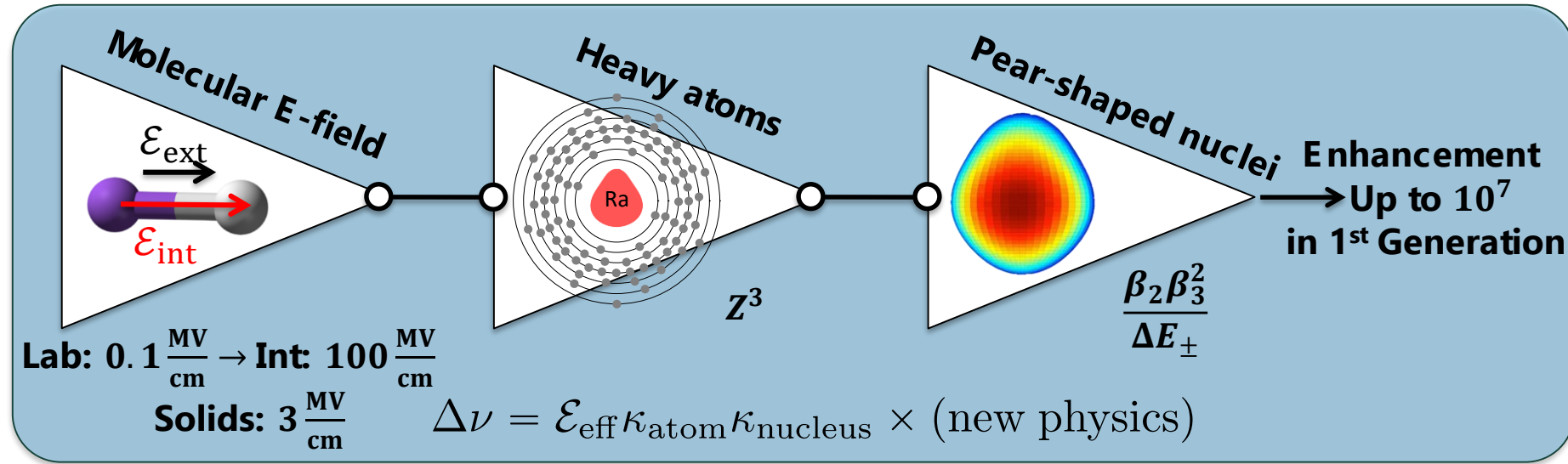
Total Enhancement Factor: EDM (²²⁵Ra) / EDM (¹⁹⁹Hg)

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

²²⁵Ra: Dobaczewski & Engel PRL 94:232502 (2005)

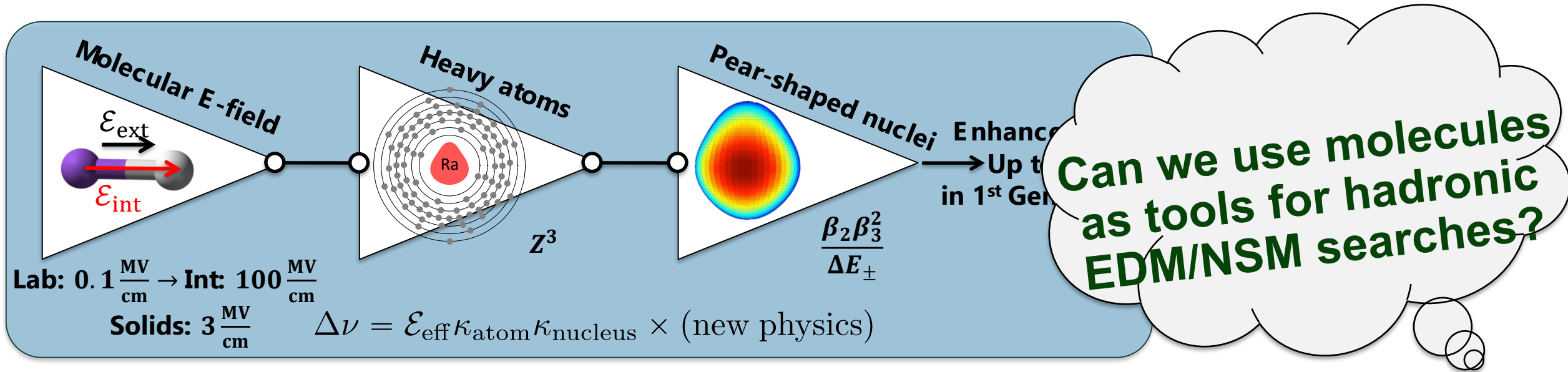
¹⁹⁹Hg: Ban et al. PRC 82:015501 (2010)

Radioactive Polar Molecules With Pear Shaped Nuclei Have Enhanced Sensitivity To T Violations And Systematic Control



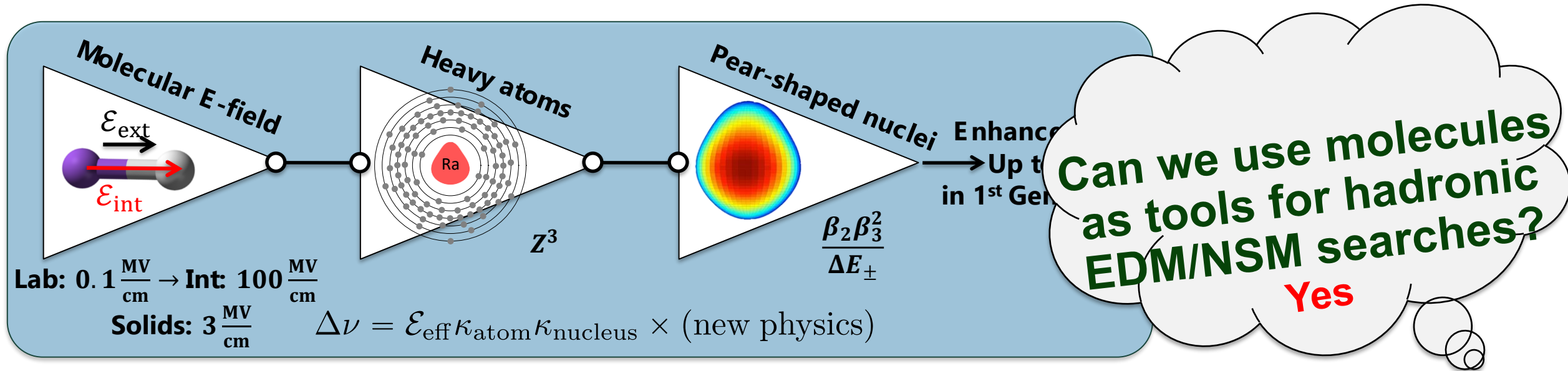
- Polar molecules have been demonstrated as an ultrasensitive tool for electron EDM searches
 - Easy to align molecule dipole moment with applied field
 - Molecule dependent co-magnetometry via energy splittings
 - Large internal fields produce larger splittings

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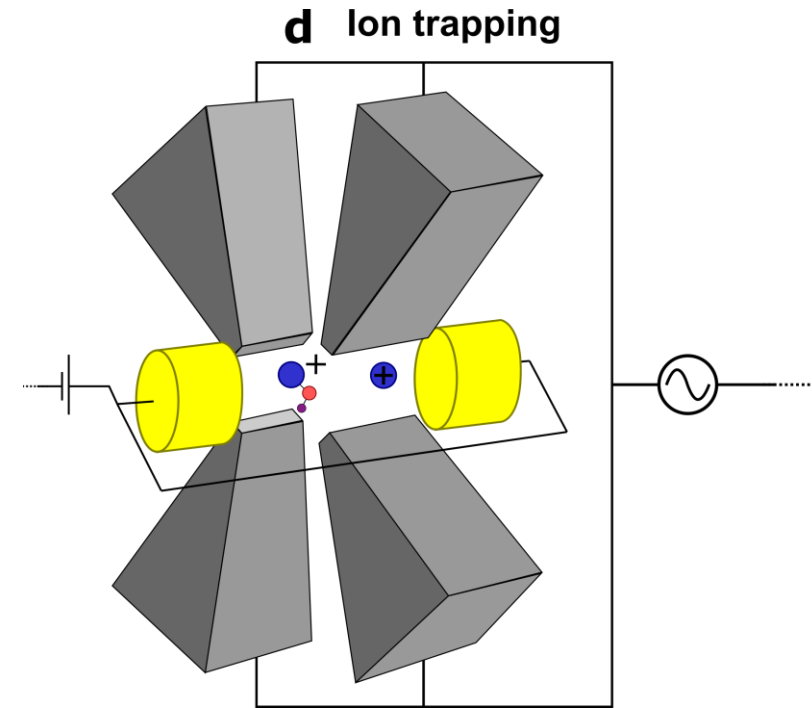
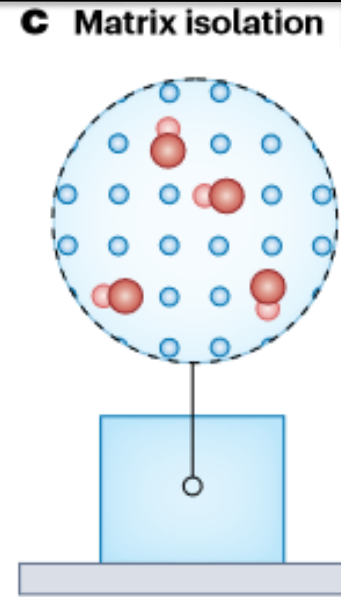
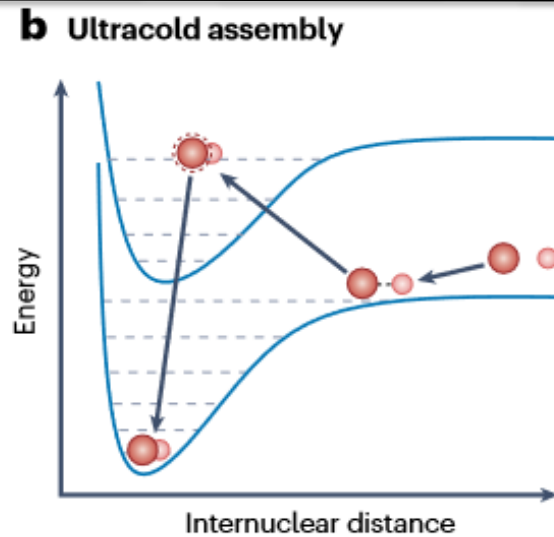
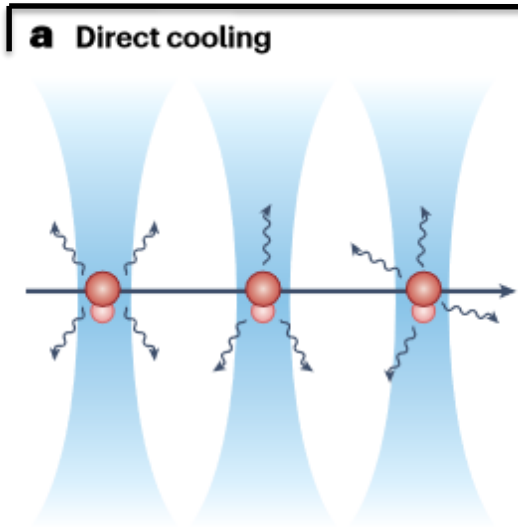


- Polar molecules have been demonstrated as an ultrasensitive tool for electron EDM searches
 - Easy to align molecule dipole moment with applied field
 - Molecule dependent co-magnetometry via energy splittings
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- Polar molecules to be implemented in upcoming hadronic searches
 - CeNTREX: ^{205}TlF (Stable, Olivier O Grasdijk (E10.00004))
 - RaX: ^{225}RaF and $^{225}\text{RaOH}$ (Pear-shaped, not stable)
 - FrAg: $^{223}\text{FrAg}$ (Pear shaped, not stable)
- Radioactive polar molecules challenging to use
 - Creation and handling of short-lived isotopes
 - How do we efficiently form molecules with these isotopes?

Contemporary Techniques For EDM Searches Using Molecules

DeMille et al. Nature Physics 20:741 (2024)



- Nicholas Hutzler (2WB.00003): RaOH and RaOD
- Sepehr Ebadi (E10.00002): RaF and RaOH
- Silviu-Marian M Udrescu (E10.00008): RaF
- Facility for Rare Isotope Beams:
 - Xing Wu (K13.00007), Sebastian Miki-Silva (K13.00008)

- David DeMille (D01.00001)

- Eric Hessels & Amar Vutha Vutha et al. Phys. Rev. A 98:032513 (2018)

Facility for Rare Isotope Beams:

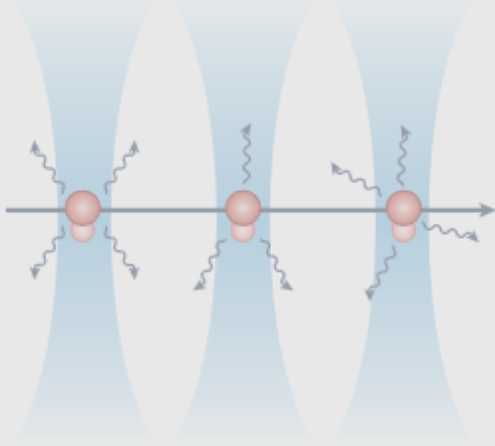
- Jaideep Singh J. T. Singh Hyp. Int. 240:29 (2019)
- Aiden Boyer (K13.00005)
- Nicholas Nusgart (K13.00006) Ballof et al. NIMB 541:224 (2023)

- JILA Collaboration Roussy et al. Science 381:46 (2023) Cairncross et al. PRL 119:153001 (2017)

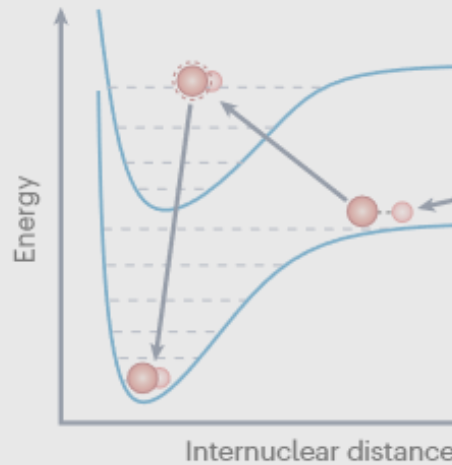
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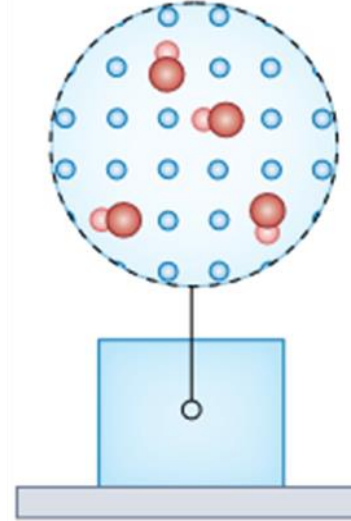
a Direct cooling



b Ultracold assembly



c Matrix isolation



Advantages

- Capable of trapping a wide variety of species
- Large number of molecules (10^{13}) can be trapped in a small volume (1mm^3)
- Stable, chemically inert confinement
- Optically transparent, growth techniques well established
 - Karina Martirosova (D06.00006)

Concerns

- High molecular production efficiency desired
 - Cryogenic buffer gas beam: $\sim 1\%$
- Pure molecular beam needed to ensure purity in medium

- Nicholas Hutzler (2WB.00003): RaOH and RaOD
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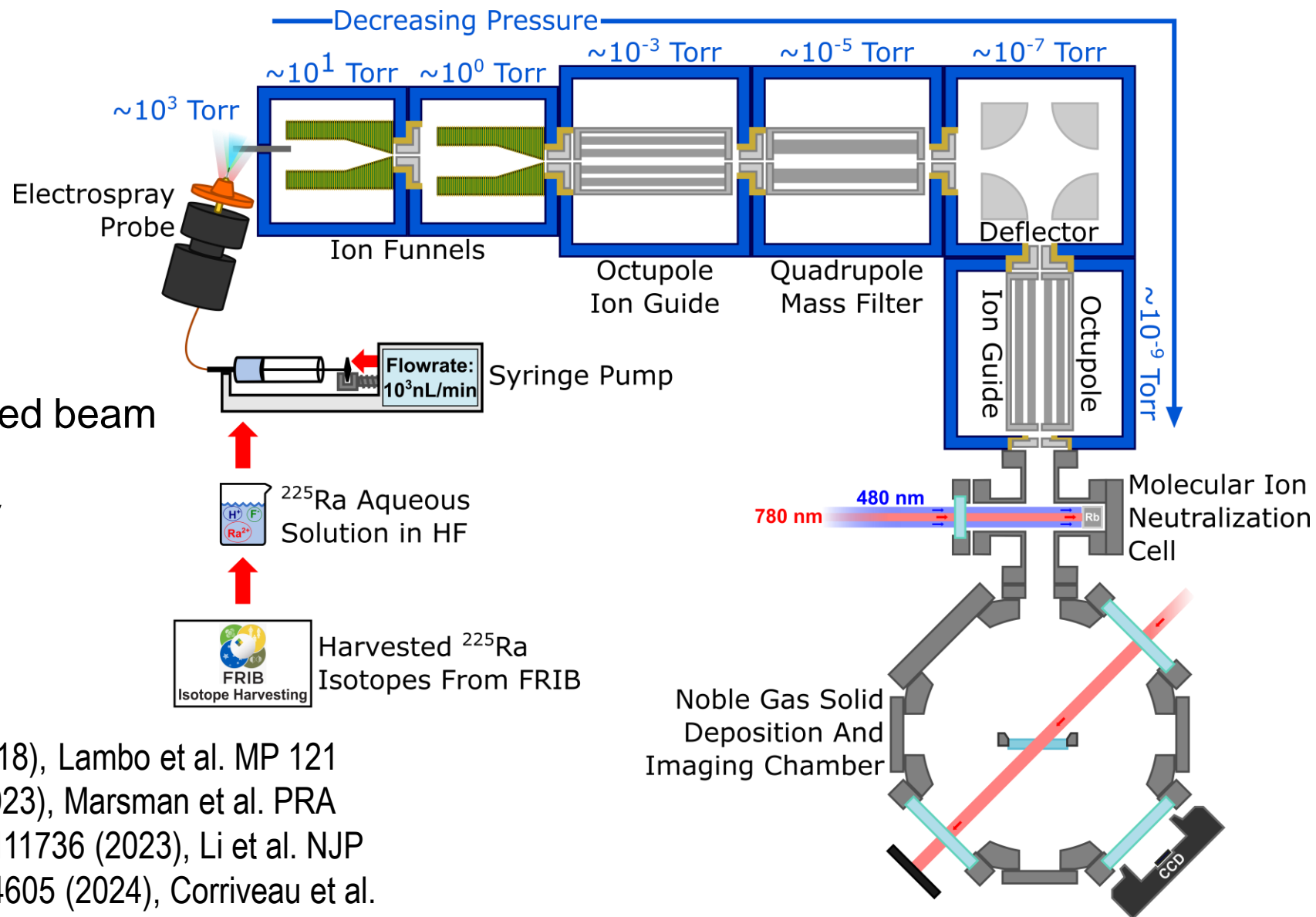
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FRIB-EDM³: Radioactive Molecules In Noble Gas Solids

We are adapting a technique intended for an electron EDM measurement used by our collaborators at York University and the University of Toronto towards measuring NSMs

Our Goals Are:

- Form a pure, isotopically selected beam of molecules
- Ultra-high vacuum compatibility
- Ultra-high molecular formation efficiency



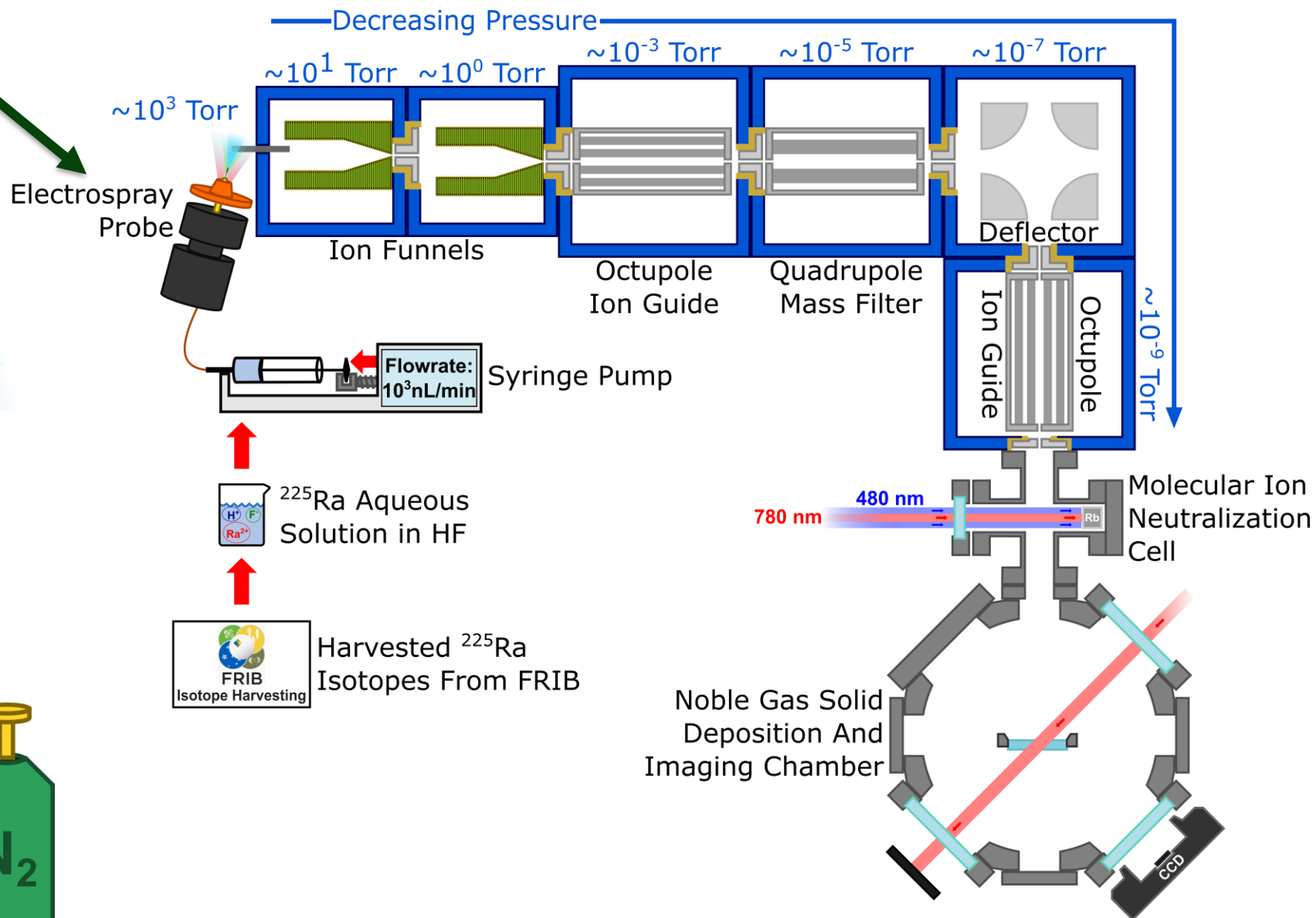
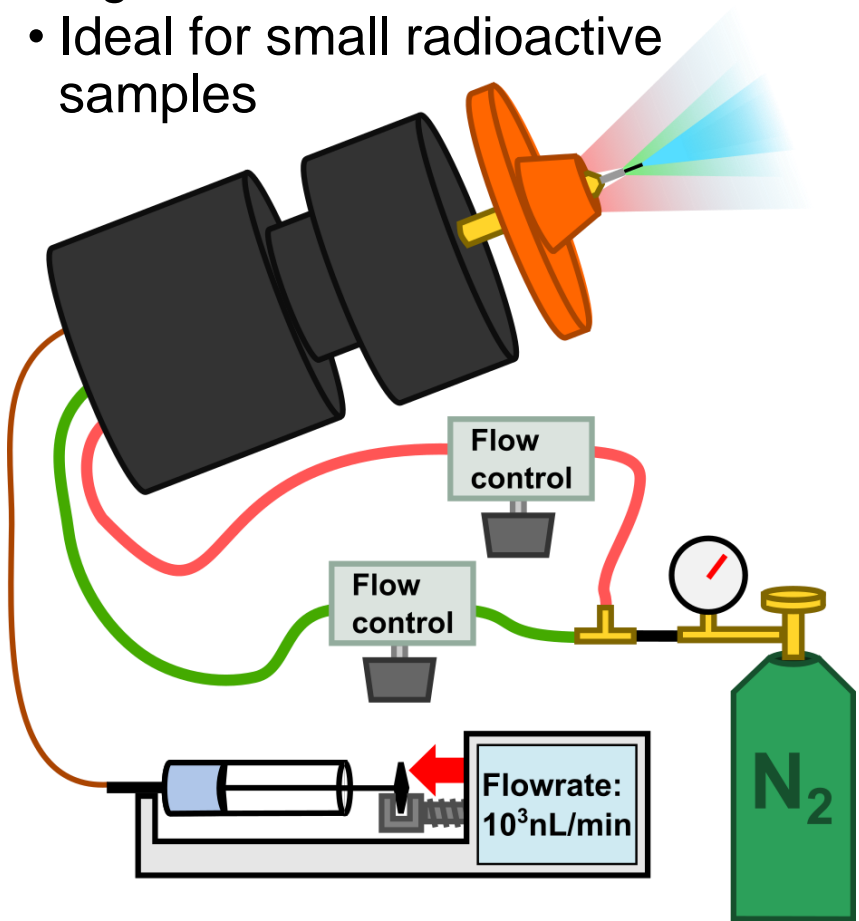
See also: Vutha et al. PRA 98:032513 (2018), Lambo et al. MP 121 (2023), Marsman et al. PRA 108:012811 (2023), Marsman et al. PRA 107:032811 (2023), Koyanagi et al. JMS 391:111736 (2023), Li et al. NJP 25:082001 (2023), Heinrich et al. arXiv 2410.04605 (2024), Corriveau et al. arXiv 2410.04591 (2024), and Yau et al. arXiv 2410.04598 (2024)

FRIB-EDM³ Frontend Forms and Collects Molecular Ions

Marginean et al. Anal. Chem. 82 (2010)

Electrospray Ionization

- Creates molecular ions from aqueous precursor
- Ion utilization efficiencies as high as 50%
- Ideal for small radioactive samples



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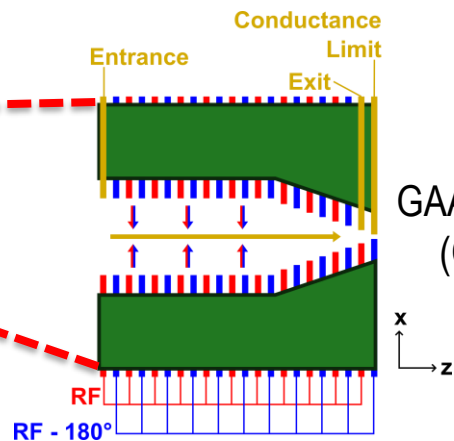
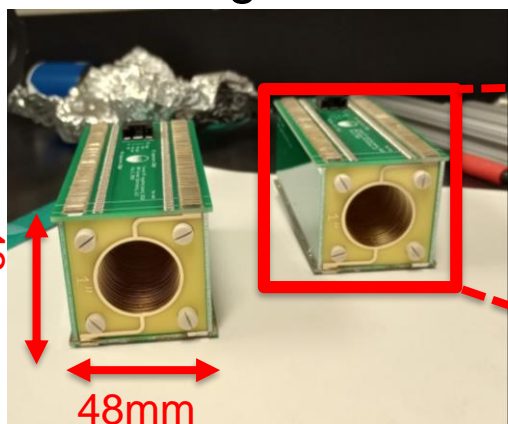
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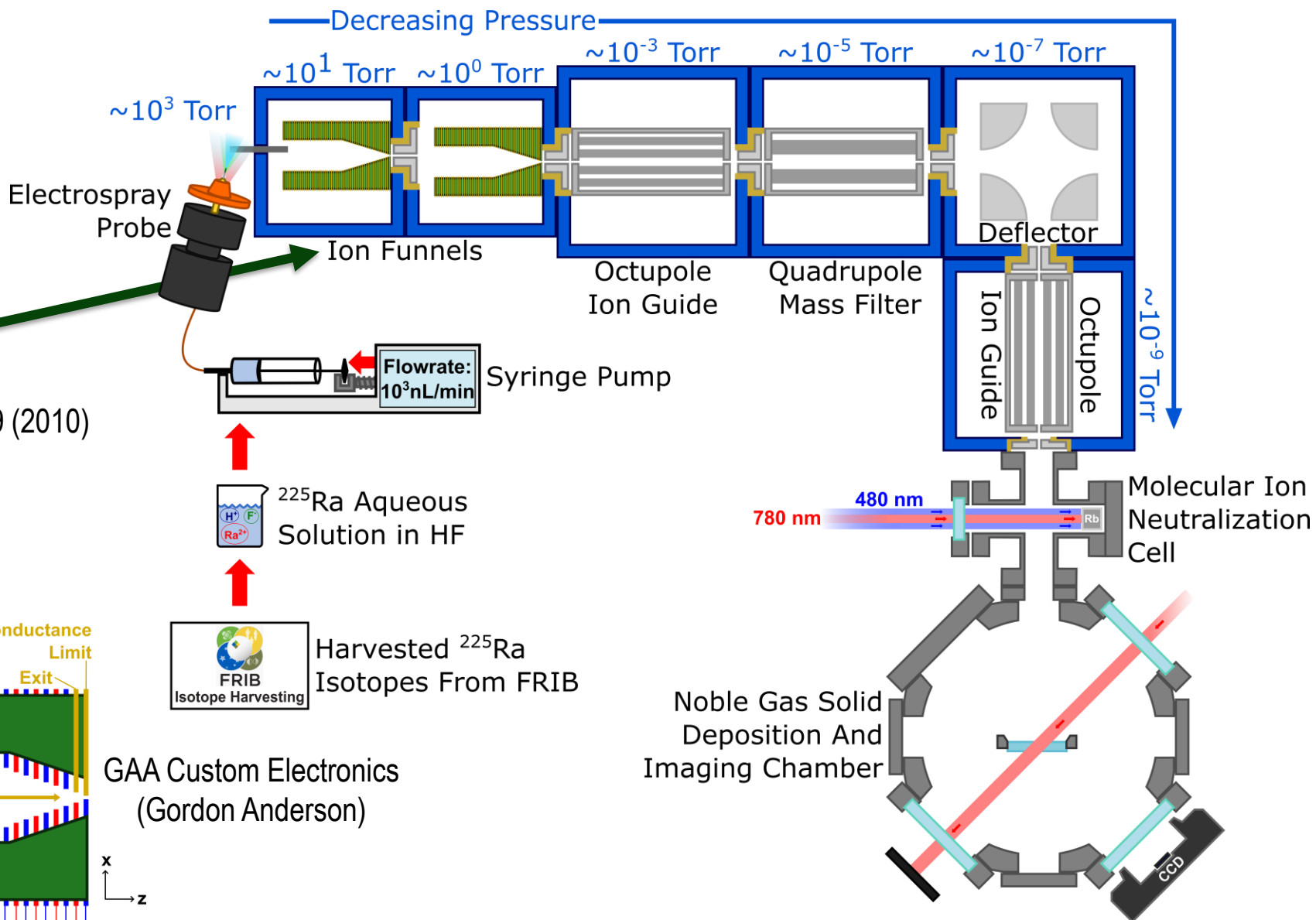
Ion Funnel

Kelly et al. Mass Spec. Rev. 29 (2010)

- Collimates ion spray into beam
- Separates ion beam from inlet gas load



GAA Custom Electronics
(Gordon Anderson)



Harvested ²²⁵Ra Isotopes From FRIB
FRIB Isotope Harvesting

²²⁵Ra Aqueous Solution in HF

Noble Gas Solid Deposition And Imaging Chamber

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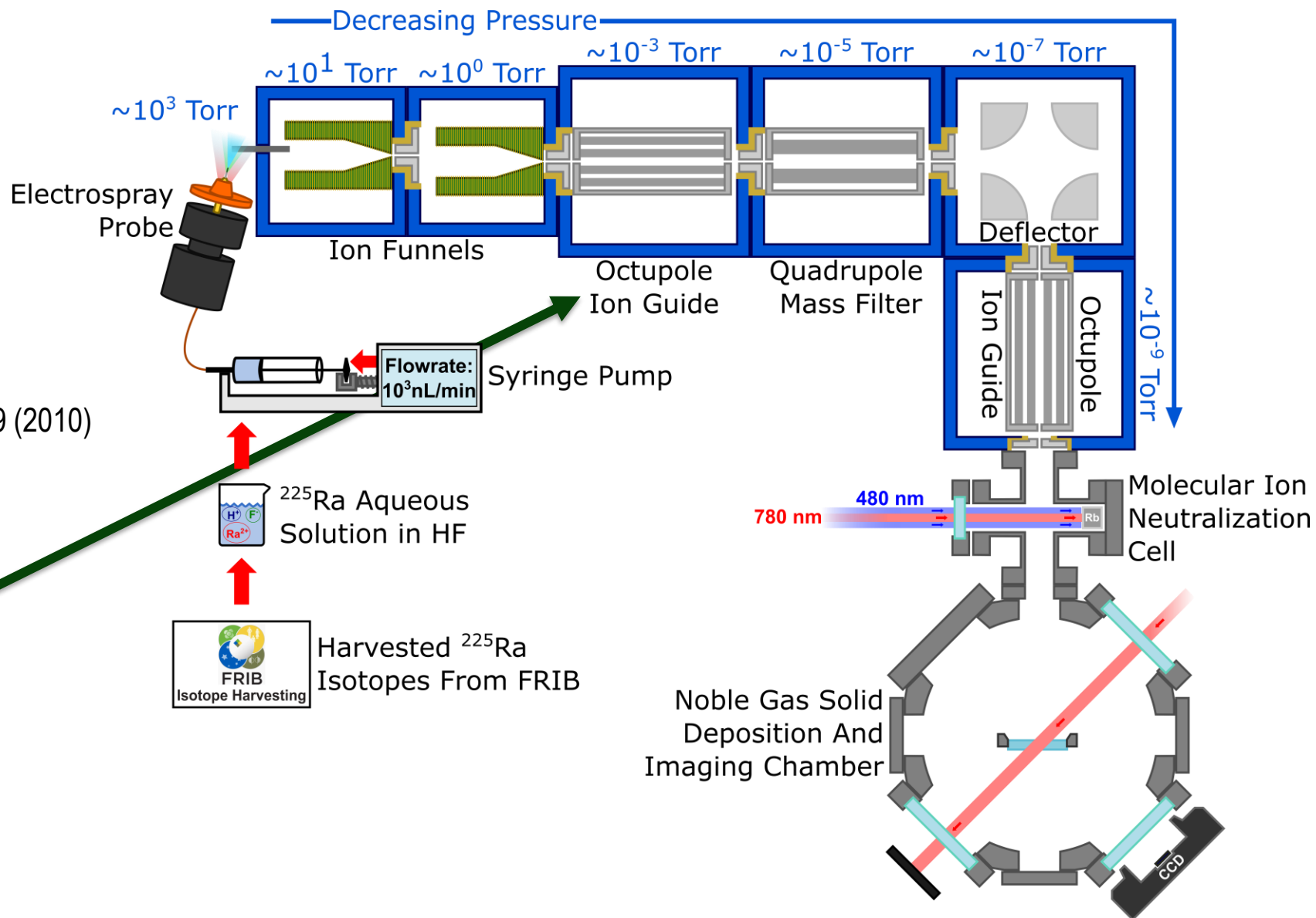
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Octupole Ion Guide

- Differential pumping
- Transport ion beam from funnels to mass filter



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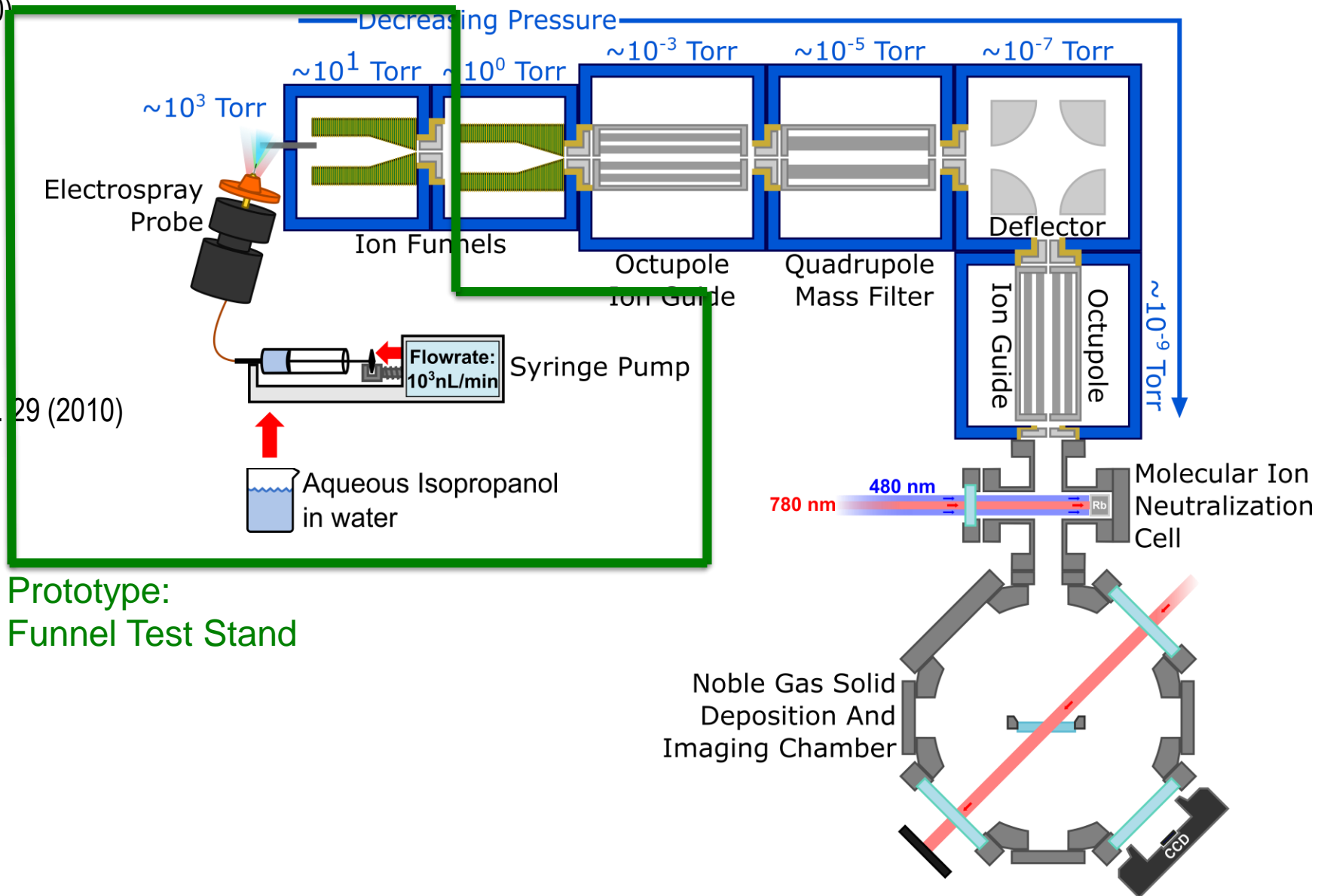
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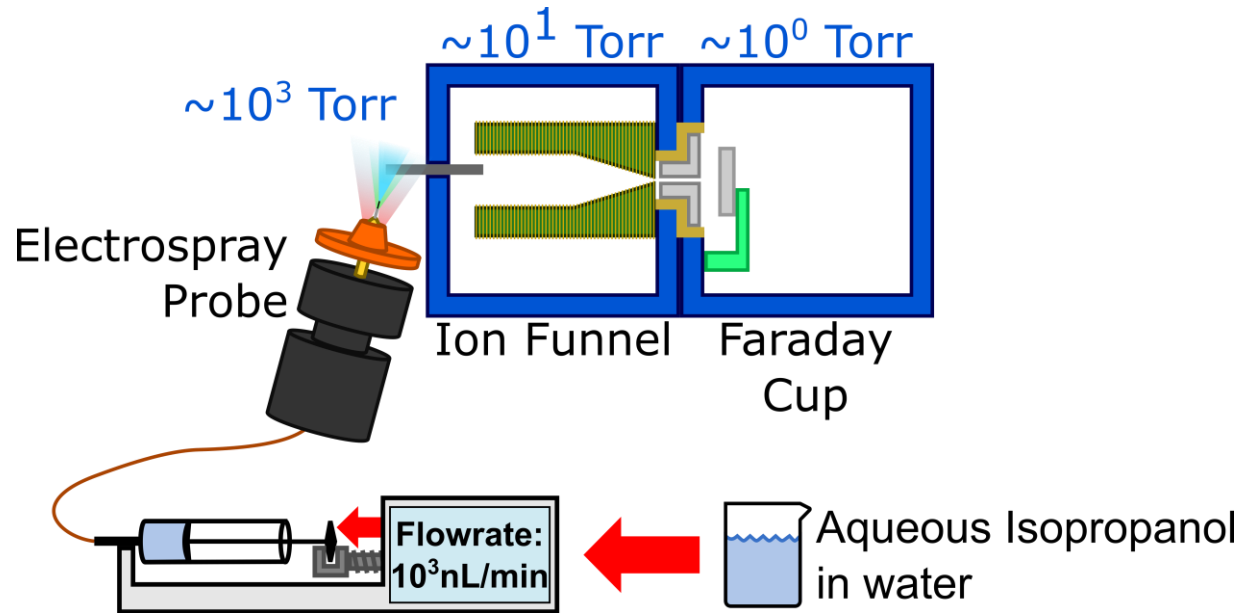
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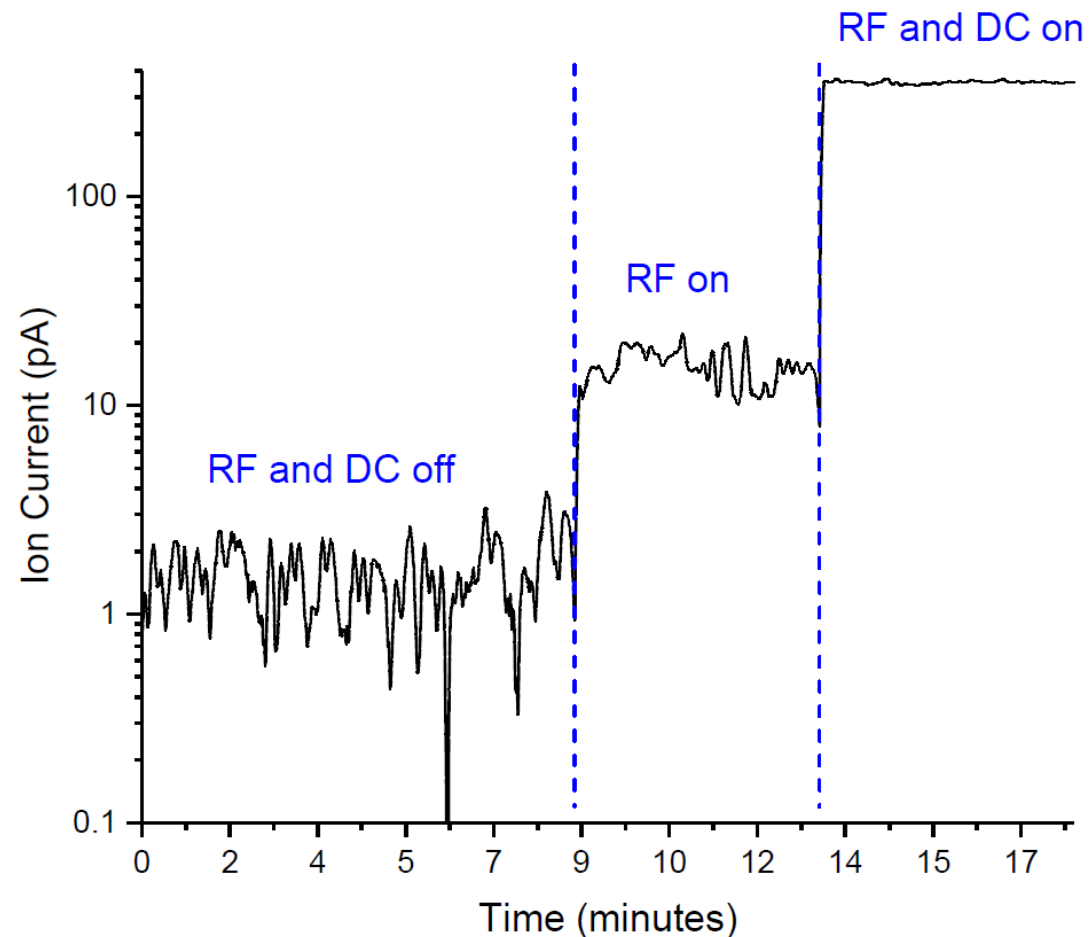


Prototype:
Funnel Test Stand

Prototype Funnel Test Stand Indicates This Technique Can Work

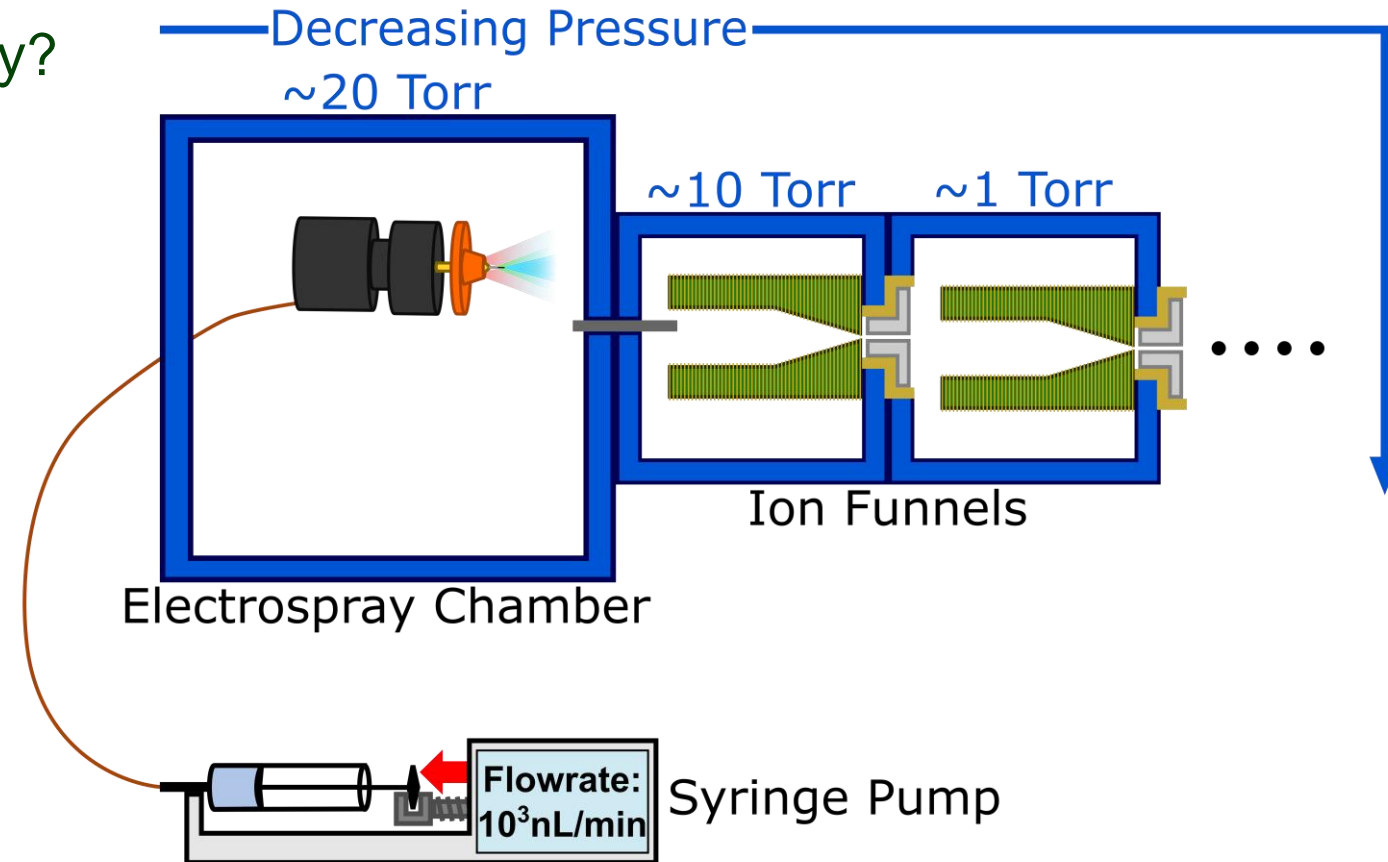


- **Stable ion beams possible**
 - Can be used to test ion optics by optimizing applied biases
- **Low reproducibility**
 - Dependence on ambient temperature and humidity
 - Losses at high pressure interface
 - Losses due to high flow rate
- **Lack of control over positioning and probe alignment**



Sub-ambient Pressure Nanoelectrospray Ionization (SPIN) Could Allow For High Formation Efficiencies (~50%)

- How can we correct the low reproducibility?
 - Losses occur at the high pressure interface
 - » Reduce the pressure differential

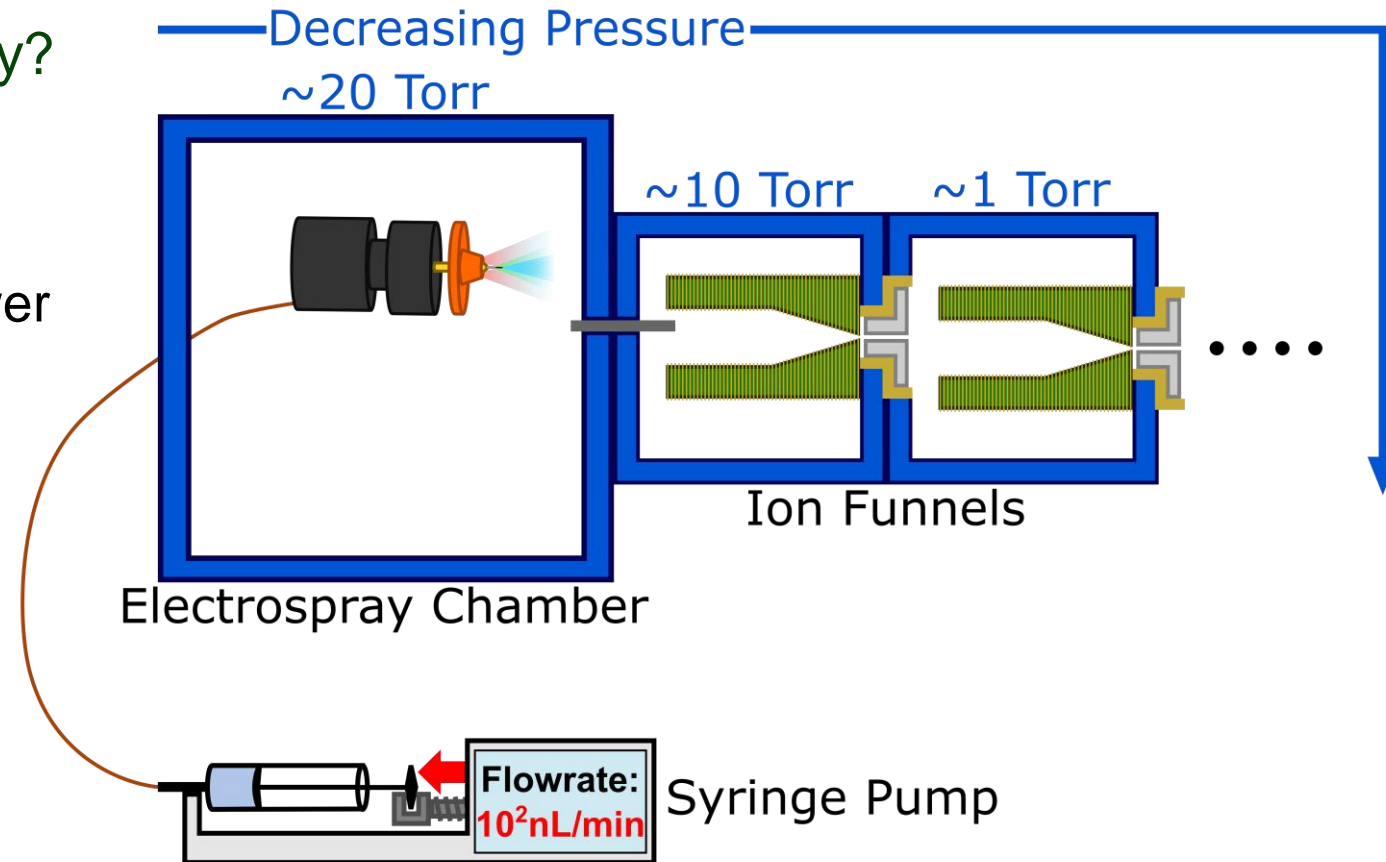


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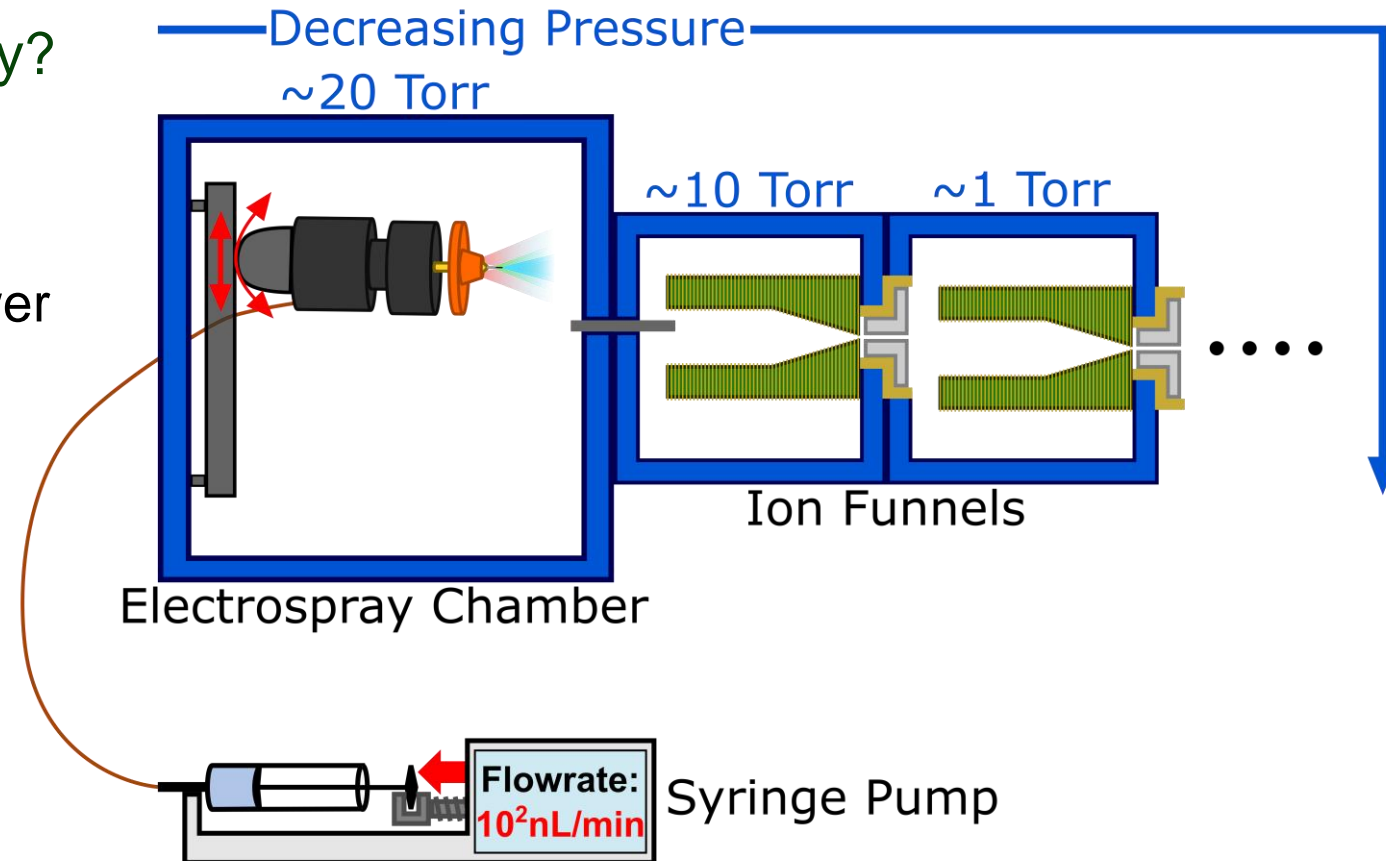
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Marginean et al. Anal. Chem. 82 (2010)
 - Ion transmission depends on probe tip positioning and alignment
 - » Mount on six-axis translation stage



Current Activities For FRIB-EDM3

- Design new electrospray ion source
 - Precise position and probe alignment
 - Temperature and humidity controls
 - Ambient pressure control
 - Lower flow rates
- Understand the hyperfine, Zeeman, and Stark structure of molecules embedded in noble gas solids
 - Nicholas Nusgart (K13.00006)
- Design RF quadrupole mass filter assembly
 - Dependent on ion beam characteristics

Thank You For Your Attention!

- Permanent electric dipole moments (EDMs) of fundamental particles could provide information about new physics symmetry violations in the standard model
- Use of molecules with pear shaped nuclei in an EDM measurement can offer sensitivity enhancements $\sim 10^7$ when compared to current state of the art
 - Several new approaches which aim to improve the sensitivity of molecular-based EDM searches
- We are developing a technique to efficiently form molecules and implant them in a noble gas matrix
 - Applicable to many short-lived isotopes
 - Initial prototype built and commissioned
 - Designing improvements to electrospray to improve ion production and utilization

Special thanks to:

Jochen Ballof, Sebastian Miki-Silva, Mia Au, Peyton Lalain, Sebastian Rothe, Ben Arend, Brandon Ewert, Patrick Glennon, Eric Hessels, Greg Koyanagi, David Leimbach, Ryan Ringle, Stefan Schwarz, Amar Vutha

Spinlab @ MSU: Yousuf Alishan, Gordon Arrowsmith-Kron, Aiden Boyer, Meyhar Dudeja, Yoann Gueye, Himanshi, Lindsey Hickman, Nicholas Koester, Karina Martirosova, Skylar Milne, Marie-Ange Ntivuguruzwa, Nicholas Nusgart, Jaideep Singh, Erin White, Adrian Yearby



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DE-SC0022299



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