Bridging the gap between hot, radioactive ion beams, and cold, precise ion trap measurements

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Massachusetts Institute of Technology

Why trap radioactive atoms

$$\delta\nu_i^{A,A'} = M_i \frac{A' - A}{A'A} + F_i \lambda^{A,A'}$$

$$\lambda^{A,A'} = \delta\left\langle r^2 \right\rangle + \frac{C_2}{C_1}\delta\left\langle r^4 \right\rangle + \frac{C_3}{C_1}\delta\left\langle r^6 \right\rangle$$

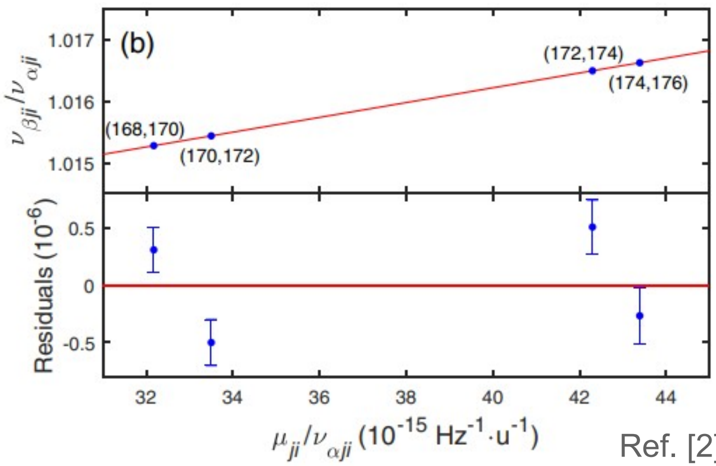
- Precision isotope shift $\delta\nu_i^{A,A'}$ measurements:
  - In-flight radioactive techniques limited to MHz → $\langle r^2 \rangle$
  - Down to mHz precision possible with trapped ions [1]
  - $\langle r^4 \rangle$ accessible at kHz level, gives access to surface thickness σ [2]

[1] T. Manovitz, PRL 2019, doi: 10.1103/PhysRevLett.123.203001.
[2] P.-G. Reinhard, PRC 2020, doi: 10.1103/PhysRevC.101.021301

Why trap radioactive atoms

- Non-linear King plots for searches of new bosons [1] or higher-order nuclear effects e.g. Yb^+ [2]

  5 stable spin 0 Yb isotopes, many more unstable at radioactive ion beam facilities



Ref. [2]

$$\delta\nu_i^{A,A'} = M_i \frac{A'-A}{A'A} + F_i \lambda^{A,A'}$$

$$+ \alpha_{NP} X_i \gamma_a$$

See ref. [1]

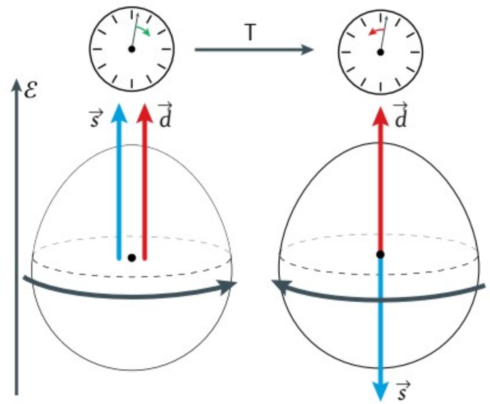
[1] J. C. Berengut PRR 2020, doi: 10.1103/PhysRevResearch.2.04344
[2] I. Counts et al. PRL 2020, doi: 10.1103/PhysRevLett.125.123002.

Why trap radioactive molecules

Sensitivity for BSM effects can be greatly enhanced by both radioactive species and polyatomic molecules for:

Searches for time-reversal/CP symmetry violation:

- Electron electric dipole moments with e.g. $Ra^{225}OCH_3^+$ [1]
- Nuclear electric dipole moments and magnetic quadrupole moments with e.g. $RaOH^+$ [2, 3]



[1] P. Yu and N. R. Hutzler, PRL 2021, doi: 10.1103/PhysRevLett.126.023003
[2] V. Flambaum, PRC 2019, doi: 10.1103/PhysRevC.99.035501
[3] D. E. Maison J. Chem. Phys. 2020, doi: 10.1063/5.0028983

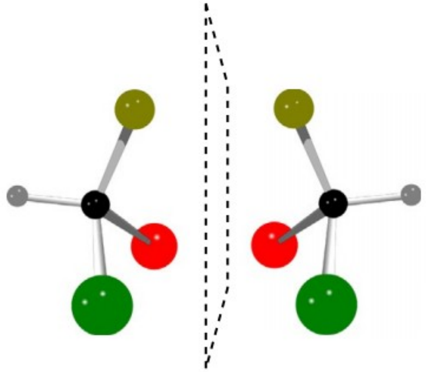
Why trap radioactive molecules

Sensitivity for BSM effects can be greatly enhanced by both radioactive species and polyatomic molecules for:

Searches for dark matter candidates [4]

Searches for parity violation:

- Heavy isotopes in chiral molecules – nuclear spin-independent PV [5]
- And nuclear spin-dependent effects PV [6]



[4] V. Flambaum PRD 2020 doi: 10.1103/PhysRevD.101.073004
[5] M. Quack "Fundamental and approximate symmetries, parity violation and tunneling in chiral and achiral molecules", Elsevier Inc., 2020 [6] Hao PRA 2020 10.1103/PhysRevA.102.052828

Challenges to trapping radioactive atoms and molecules

Radioactive ion beams	Ion trap spectroscopy

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Hot environments (300-3000 K)	Doppler and collision limited, often cryogenic (~4 K) !

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$$\sigma_d \propto \frac{1}{t\sqrt{N}}$$

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Ion trap spectroscopy

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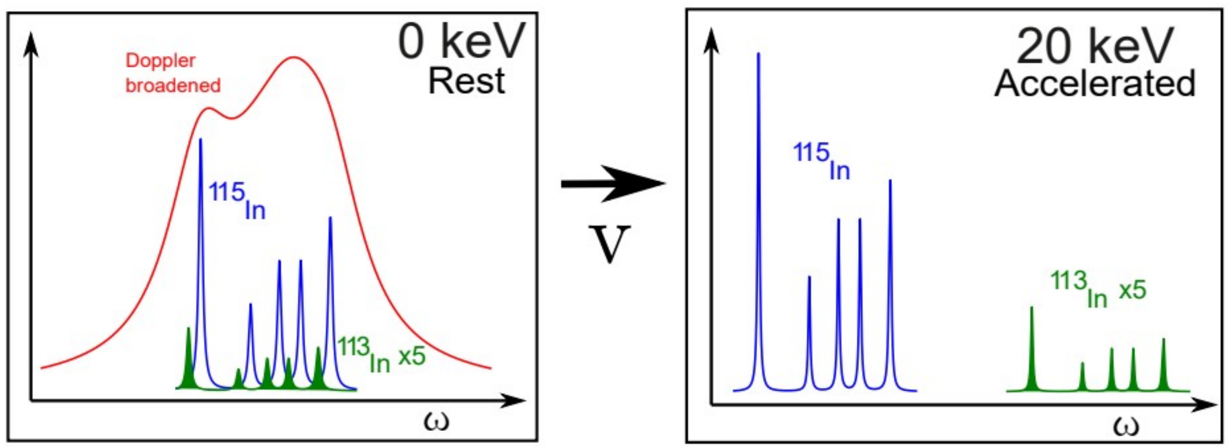
Collinear Resonance Ionization spectroscopy allows highly efficient ionisation and purification on keV beams

Principle of Collinear Laser Spectroscopy



Acceleration to keV beam energies with velocity ν reduces the velocity spread $\delta\nu$ as the energy spread ΔE is conserved [1, 2]:

$$\Delta E = m\nu\delta\nu$$

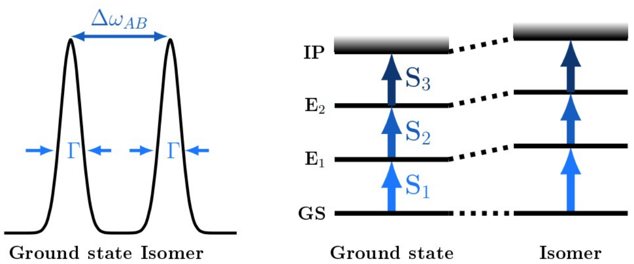
Allowing narrow linewidth laser spectroscopy without cooling

[1] S. L. Kaufman doi: 10.1016/0030-4018(76)90267-4.
[2] W. H. Wing, doi: 10.1103/PhysRevLett.36.1488.

Collinear Resonance Ionization Spectroscopy

- Selectivity enhanced by linewidth and number of resonant steps to reach IP (~10^7 per step):

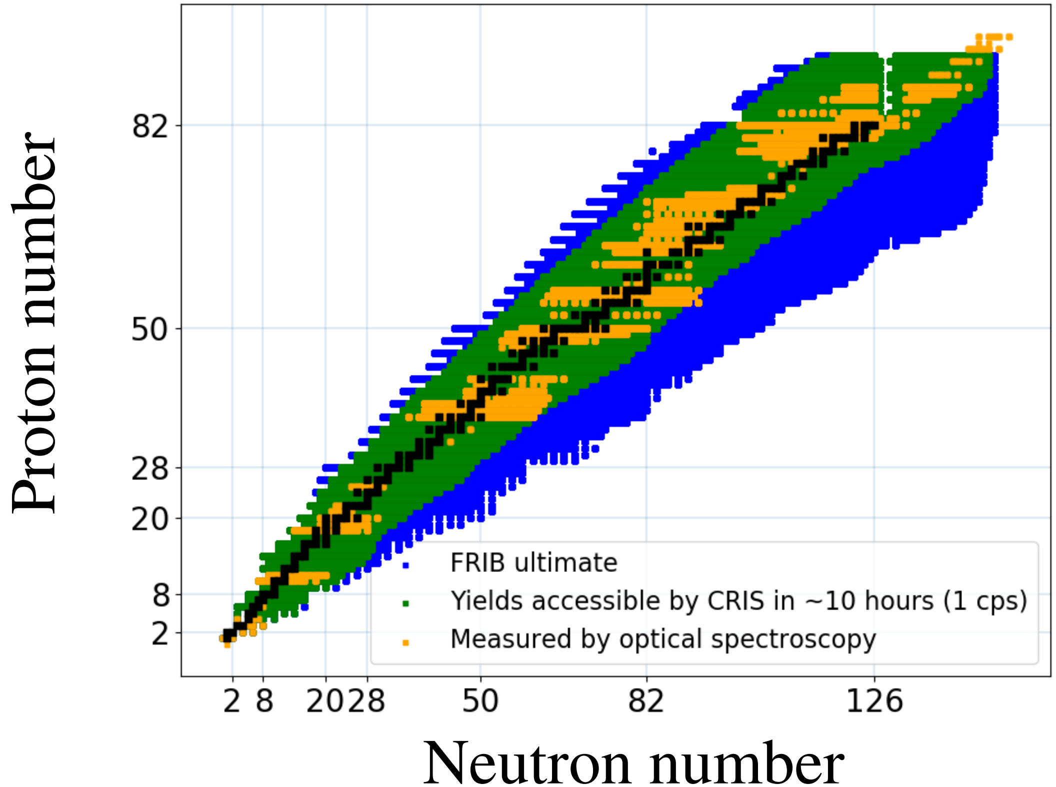
$$S = \prod_{n=1}^{N} \left(\frac{\Delta\omega_{AB,n}}{\Gamma_n} \right)^2$$



- Implemented at ISOLDE, CERN using bunched ions and pulsed lasers [1] and soon to be used at FRIB, USA
- Allowed hyperfine structure measurements (~20 MHz linewidth) in atomic systems some of the lowest production rate isotopes to date (<20 ions/s) [2]

[1] A. R. Vernon et al., Sci. Rep., doi: 10.1038/s41598-020-68218-5
[2] R. P. de Groote et al., Nature Phys 2020, doi: 10.1038/s41567-020-0868-y

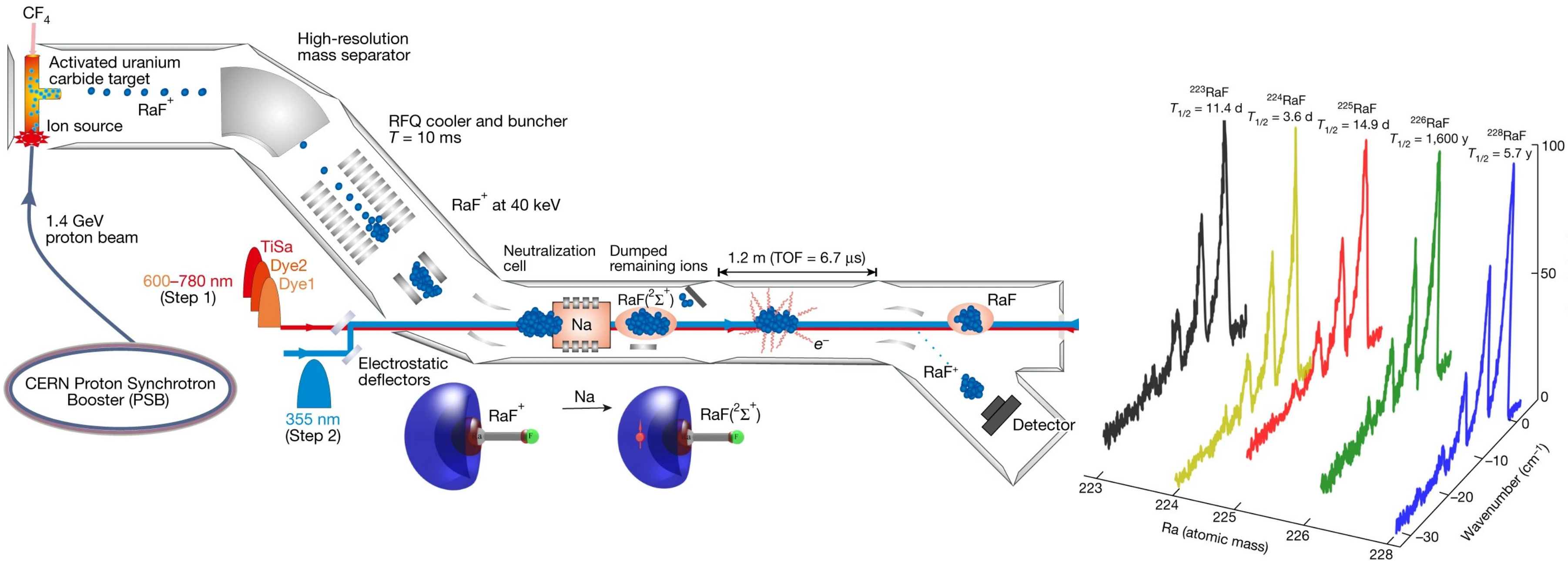
Laser spectroscopy prospects at FRIB



[Thanks to Oleg Tarasov for the FRIB yield data]

Collinear Resonance Ionization Spectroscopy

- Equally well allows vibrational, rotational and hyperfine structure to be resolved in radioactive molecules without cooling e.g. RaF [1, 2]:



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[1] R F Garcia Ruiz et al, Nature, 2020, doi: 10.1038/s41586-020-2299-4
[2] S. M. Udrescu et al., PRL 2021, doi: 10.1103/PhysRevLett.127.033001

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Ion sources start with large sample sizes ?

→ Efficient ion catcher and ion guide with differential pumping

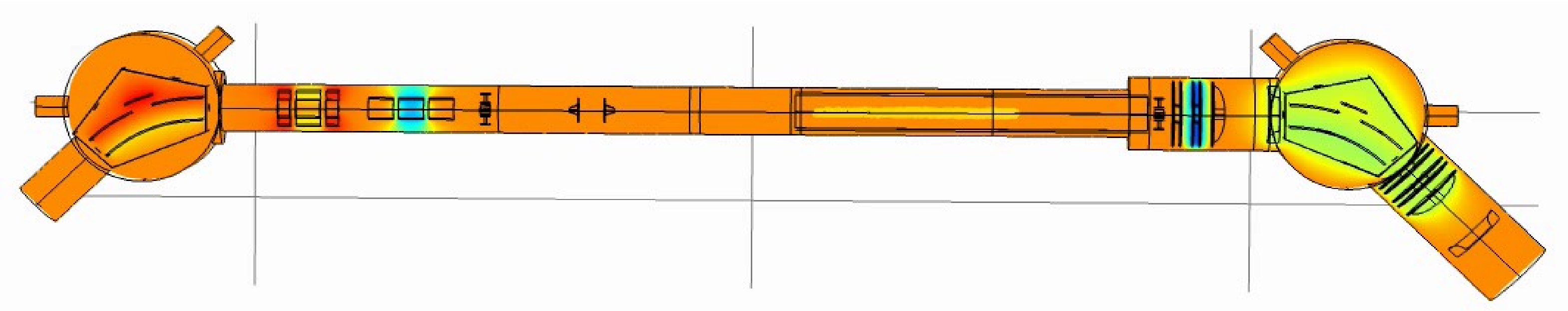
eV required for injection and traps ideally at ground potential ?

→ In-flight potential switch and deceleration

In-flight potential switch and deceleration

Radioactive ions already bunched into ~2 us for background suppression and efficient overlap with pulsed lasers

2 us at 30 keV becomes ~1 m long for a 20 amu beam



Potential switch provided by resonant ionisation from neutral to ion (or alternatively by a HV switch)

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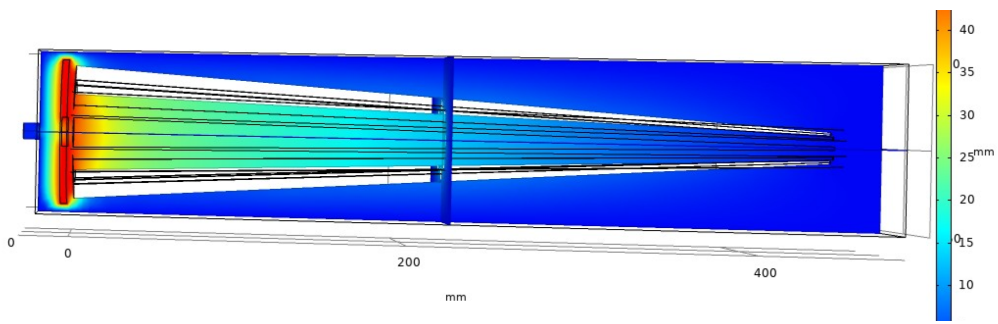
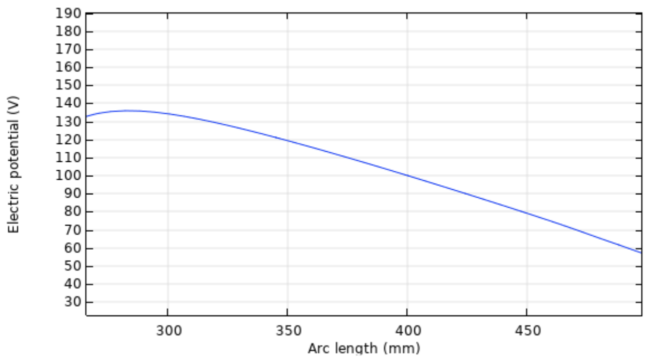
eV required for injection and traps ideally at ground potential ✓	}	In-flight potential switch and deceleration

Ion catcher and guide

- Need a collisional cell for efficient deceleration and to make injection independent of keV beam energy.
- Conical octupole guides allow for guiding to a small aperture for differential pumping. Often used in mass spec community [1] but rely on gas flow.
- High resistance wires can be used to provide an axial guiding field [2]:





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[1] D. Gerlich, The production and study of ultra-cold molecular ions. in: Low temperatures and cold molecules. ISBN-13 978-1-84816-209-9
[2] Wilcox, B. E. (2002) https://doi.org/10.1016/S1044-0305(02)00622-0

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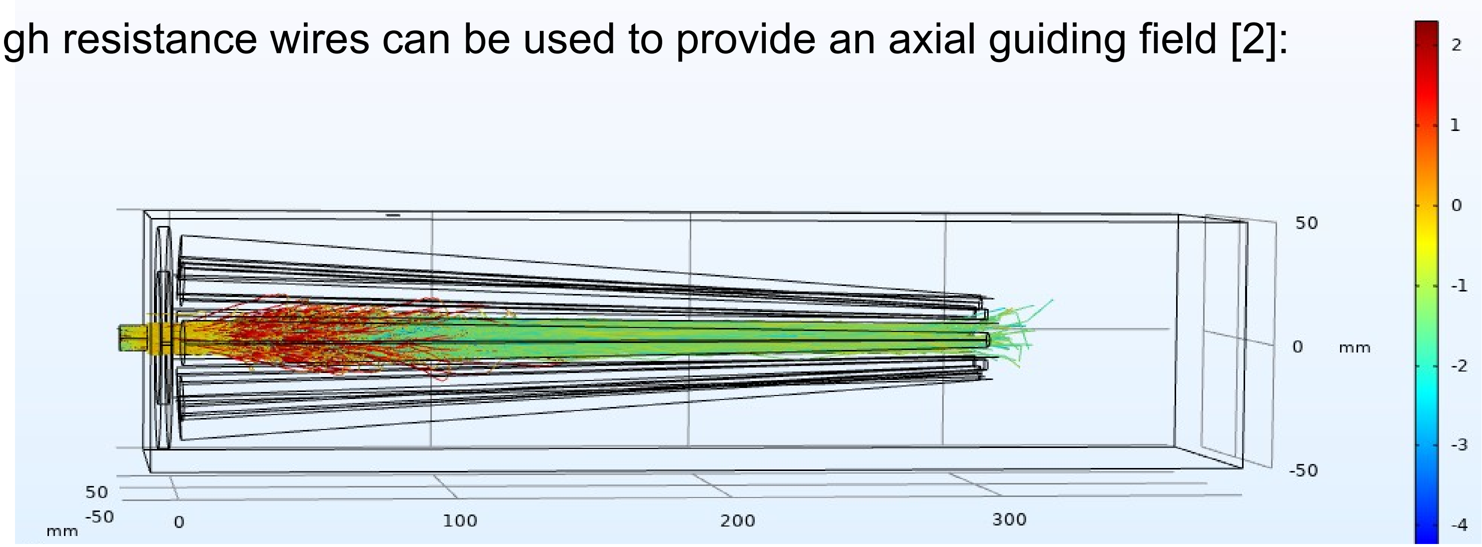

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Challenges to trapping radioactive atoms and molecules

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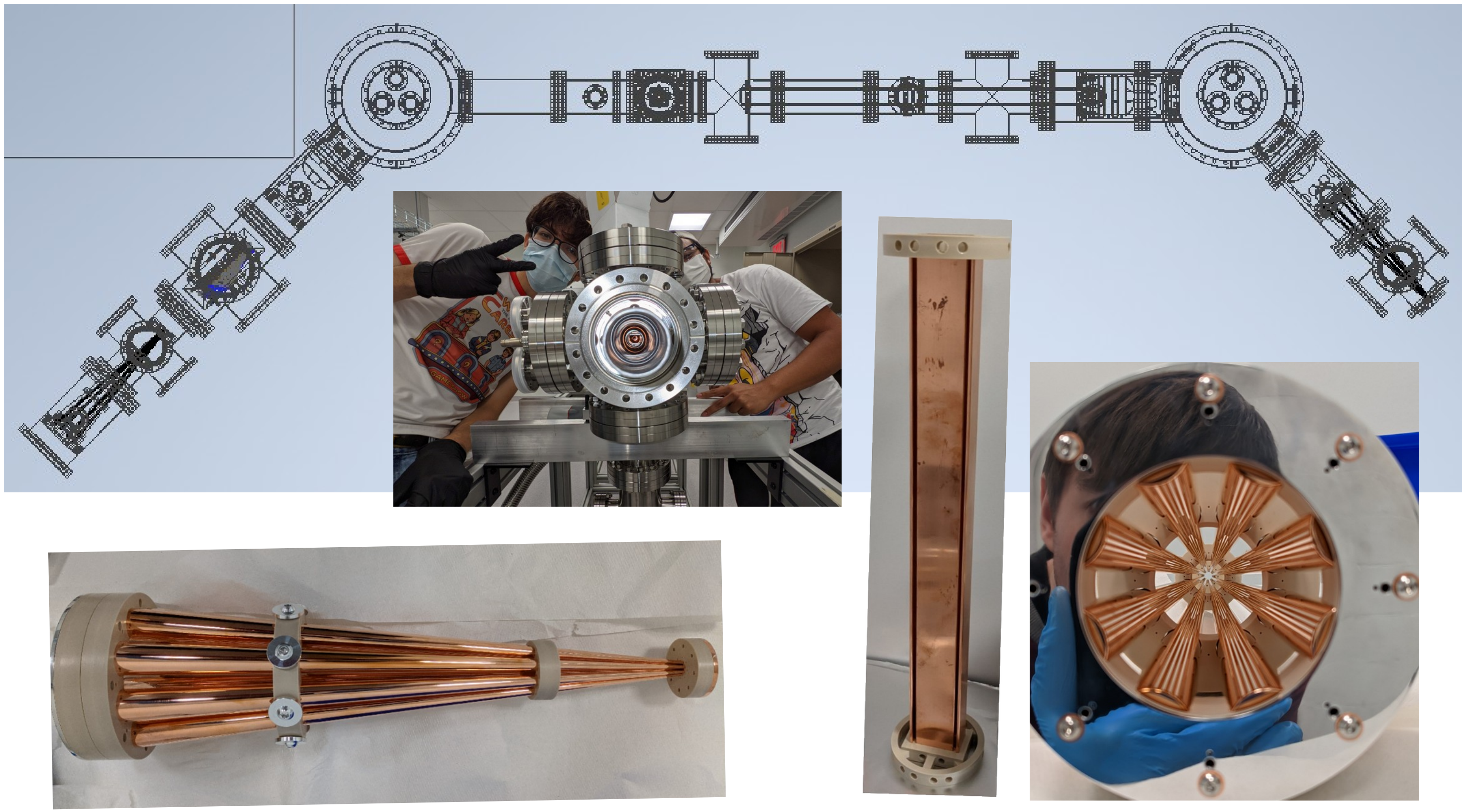
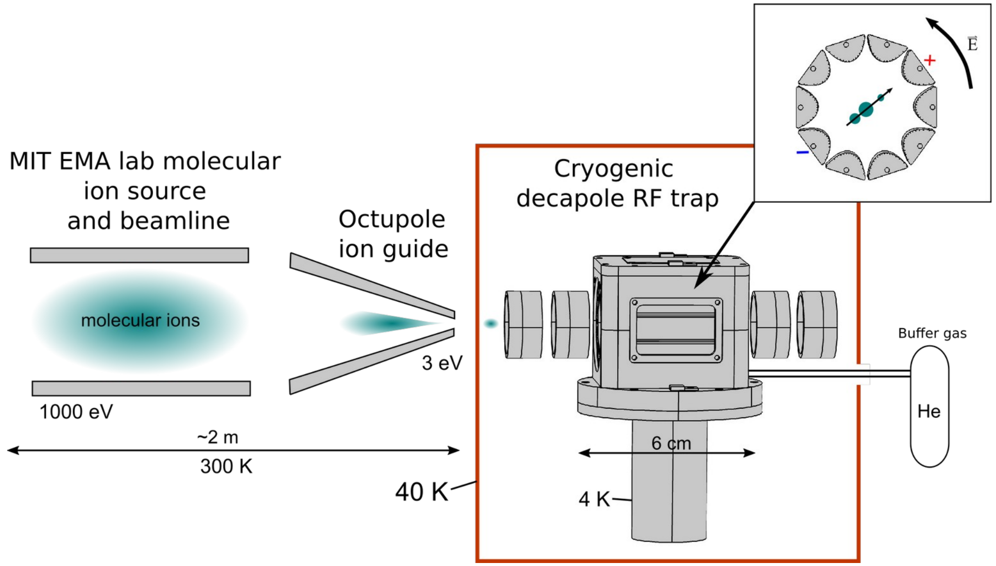
eV required for injection and traps ideally at ground potential ✓	In-flight potential switch and deceleration

Trapping radioactive atoms and molecules... WIP



Next steps

- Demonstrate efficient deceleration and trapping with Yb^+
- Trapping with $BaOH^+$, Stark spectroscopy, Ramsey spectroscopy
- Upgrading to cryogenics
- Testing at radioactive ion beam facilities (FRIB, ISOLDE, TRIUMF) for e.g. $RaOH^+$



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Thanks for listening!

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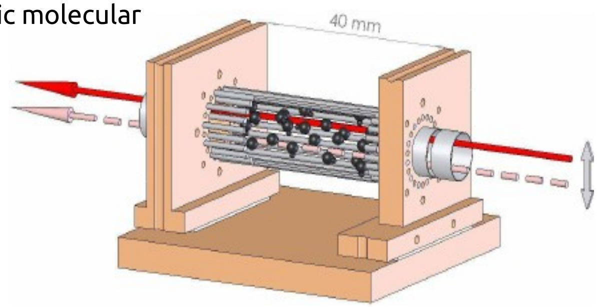
A cryogenic trap for radioactive atoms and molecules

Requirements:

1. Compatible with cryogenic cooling to ~4 K to for spectroscopy of atoms and molecules (low RF heating)
2. Allow rotating electric field
3. Laser access from multiple directions
4. Efficient injection and long storage time for use with radioactive samples

Cryogenic molecular [1,2]



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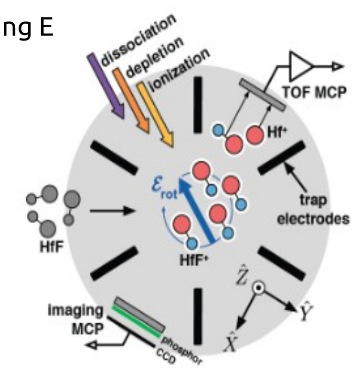
Rotating E [3]



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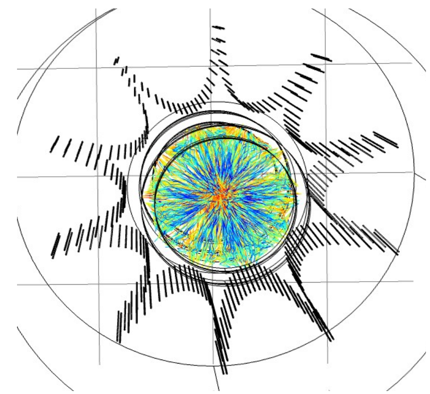

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[1] Asvany (2014). COLTRAP: A 22-pole ion trapping machine for spectroscopy at 4 K. https://doi.org/10.1007/s00340-013-5684-y
[2] Trippel (2006). Photodetachment of cold OH- in a multipole ion trap https://doi.org/10.1103/PhysRevLett.97.193003
[3] Cairncross (2017). Precision Measurement of the Electron's Electric Dipole Moment Using Trapped Molecular Ions. https://doi.org/10.1103/PhysRevLett.119.153001

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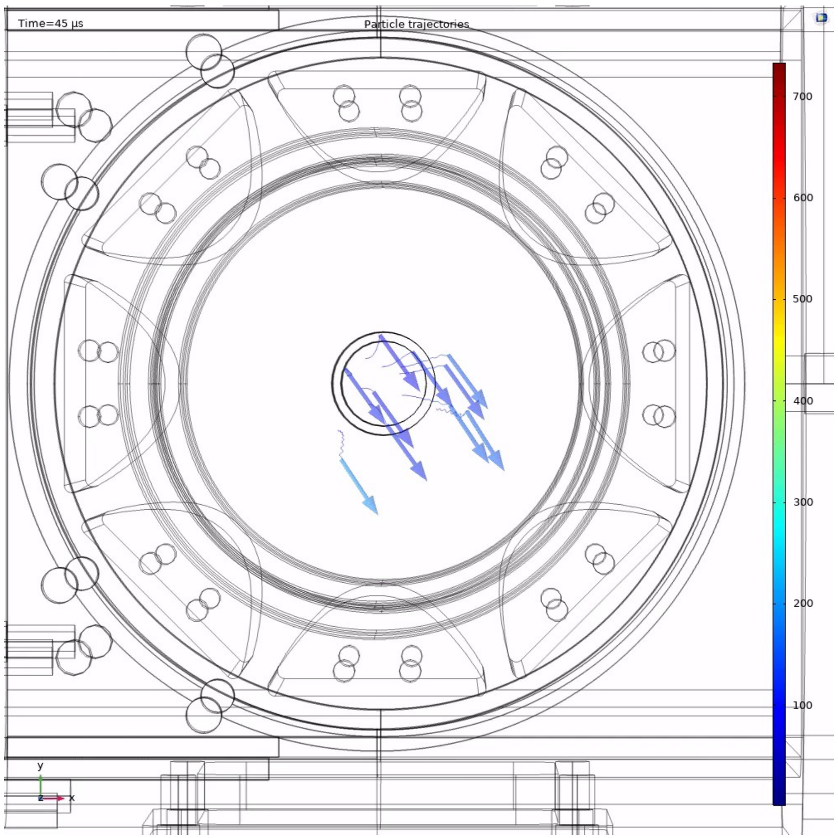

Rotating E field with trapping simulation

MIT PhD student Alex Brison