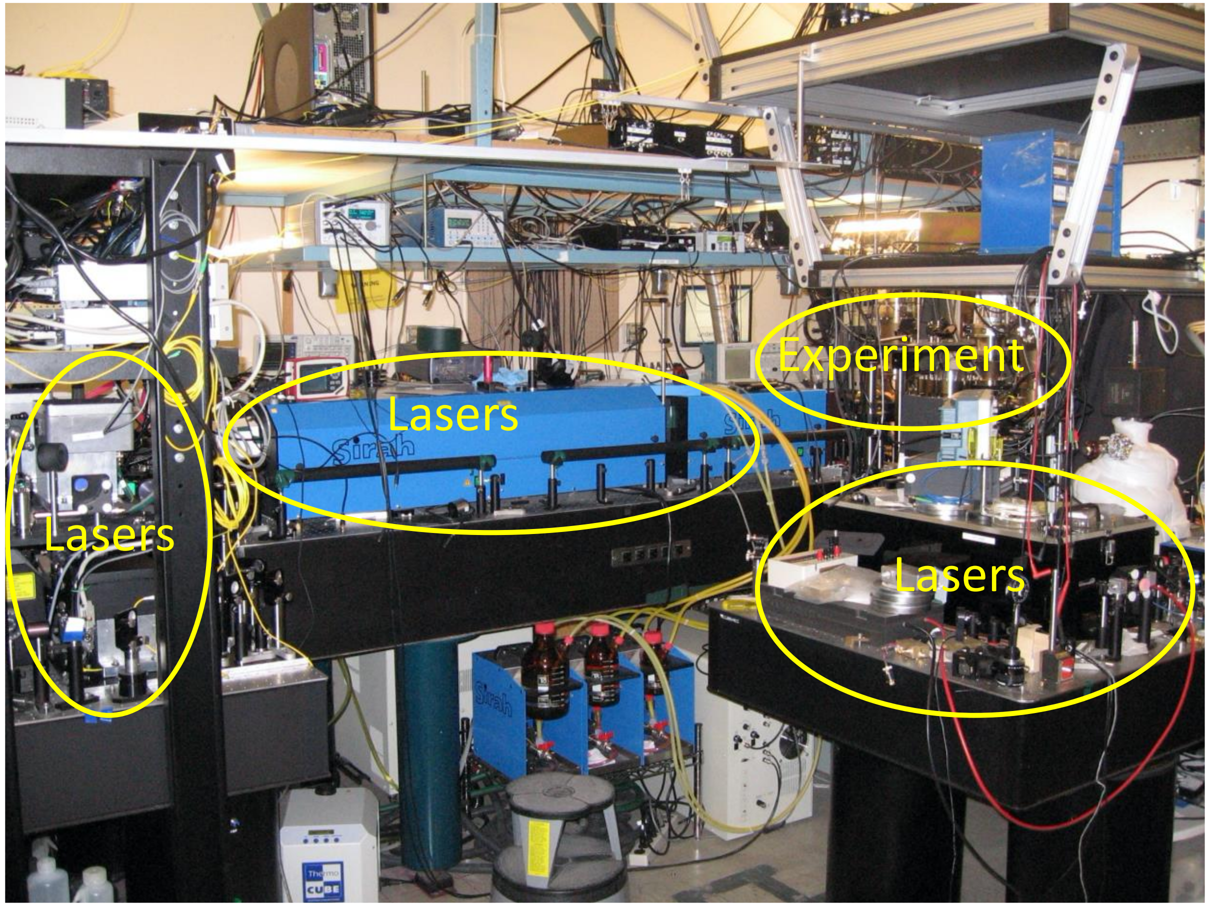
JILA electron's electric dipole moment experiment with ThF^+

Sun Yool Park

March 2, 2026

EDMs2026 : WE-Heraeus Workshop

Tabletop precision measurement:
Looking for more CP symmetry violation…



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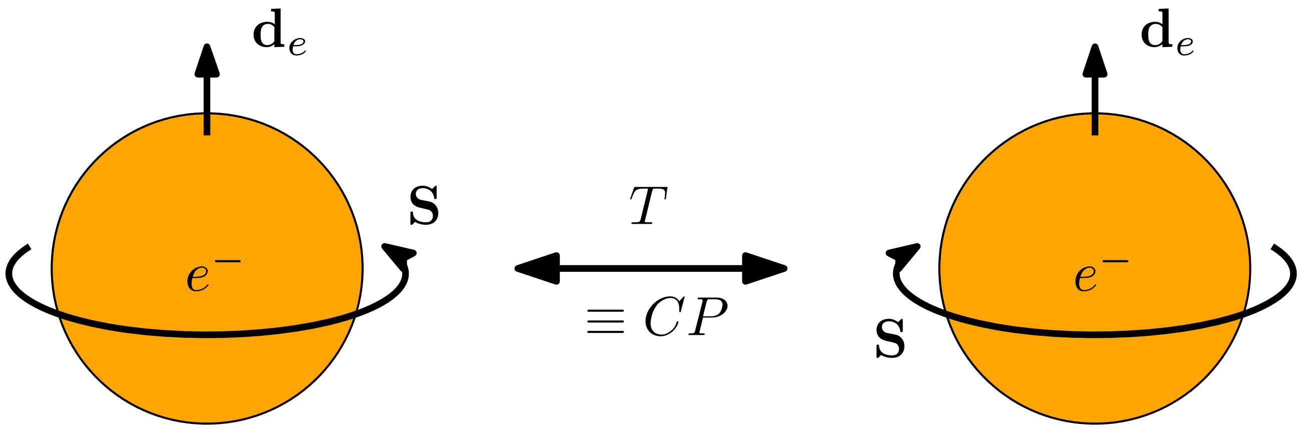
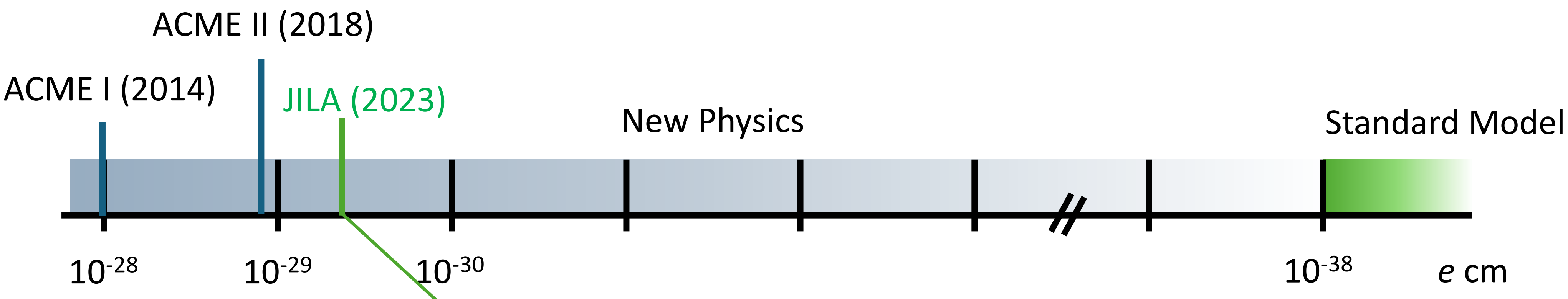
What is an *eEDM*?

- A nonzero eEDM would violate T-symmetry (or CP-symmetry)
- Most BSM t … :DM
  - Often at c …
  - (Null-) me … heories
- "Backgroun … :ment can be attributed t …



  - The Standard Model only predicts a finite value of the eEDM at the four-loop level (~ 10^{-38} e cm)

Experimental upper bound on eEDM



4.1×10^{-30} e cm

Cairncross, et al. *Physical Review Letters* 119.15 (2017): 153001.
Baron, et al., *Science* 343.6168 (2014): 269-272.
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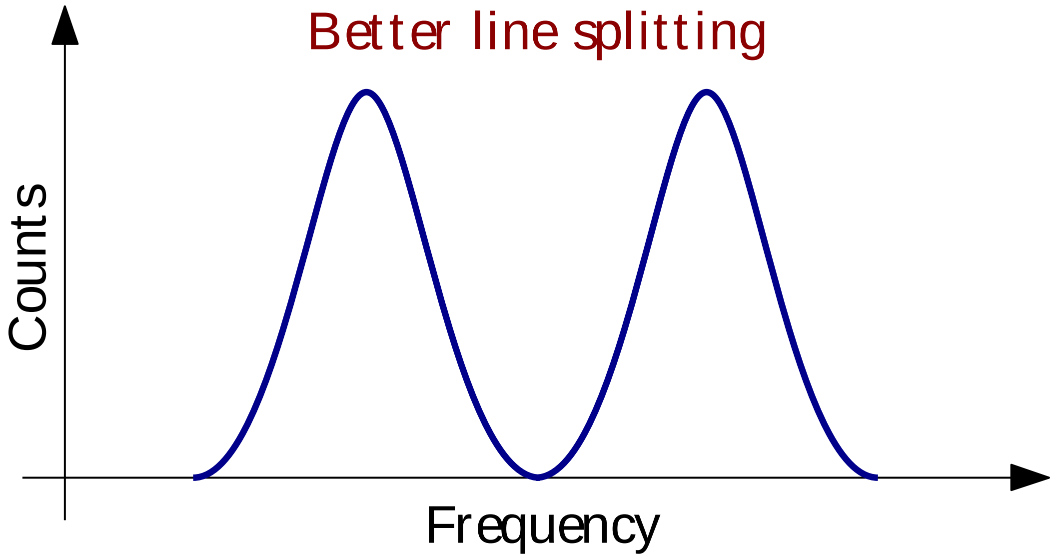
eEDM sensitivity: figure of merit

$$\delta d_e \sim \frac{1}{\mathcal{E}_{\text{eff}}\,\tau\,\sqrt{N}}$$



How do we enhance edm signal at JILA?

1. Using carefully chosen quantum states within a carefully chosen molecule (molecular ion)
2. Performing differential and normalized measurement whenever possible
3. Designing experiments where we can increase sensitivity
   - Having long coherence time (~ x10)
   - Improving count rate by parallelizing multiple experiments

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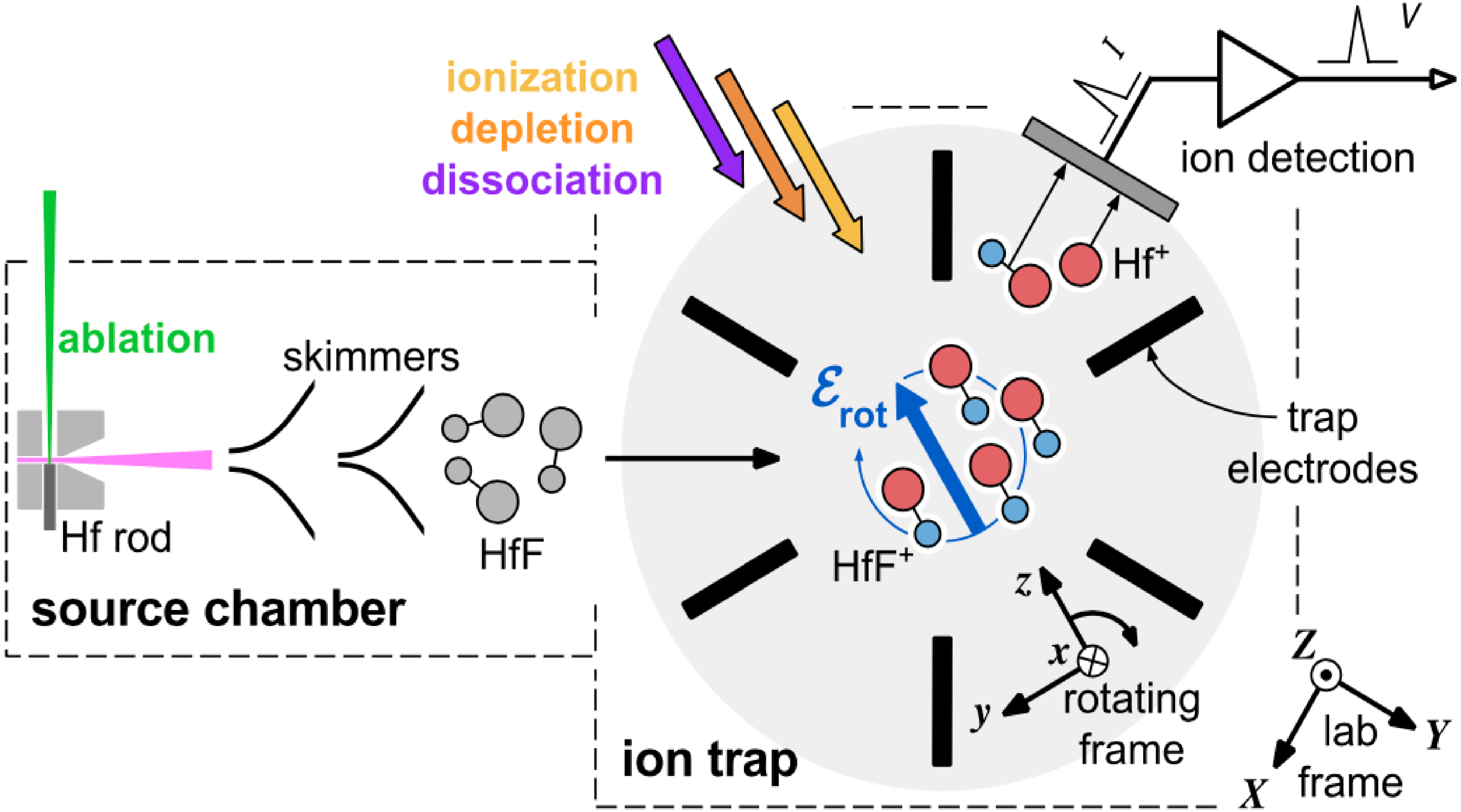
Previous generations

$$\mathcal{E}_{\text{eff}} \approx 23\,\text{GV}\,\text{cm}^{-1}$$

$$2d_e\mathcal{E}_{\text{eff}} = -14.6 \pm 22.8_{\text{stat}} \pm 6.9_{\text{syst}}\ \mu\text{Hz}.$$



New generation molecule: ThF^+

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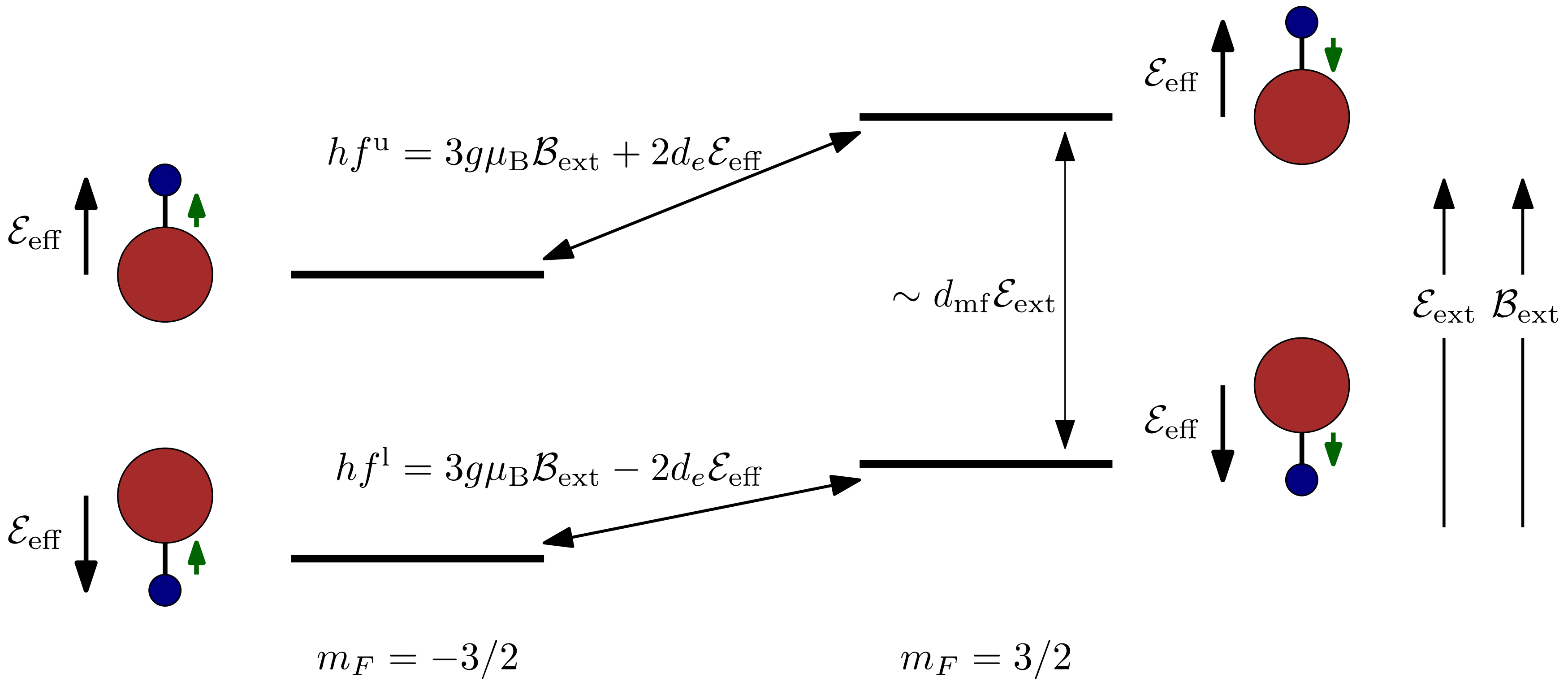
Parity doublets & co-magnetometry

- $^3\Delta_1$ state offers two pairs of eEDM sensitive states
- Simultaneous interrogation enables intrinsic co-magnetometry



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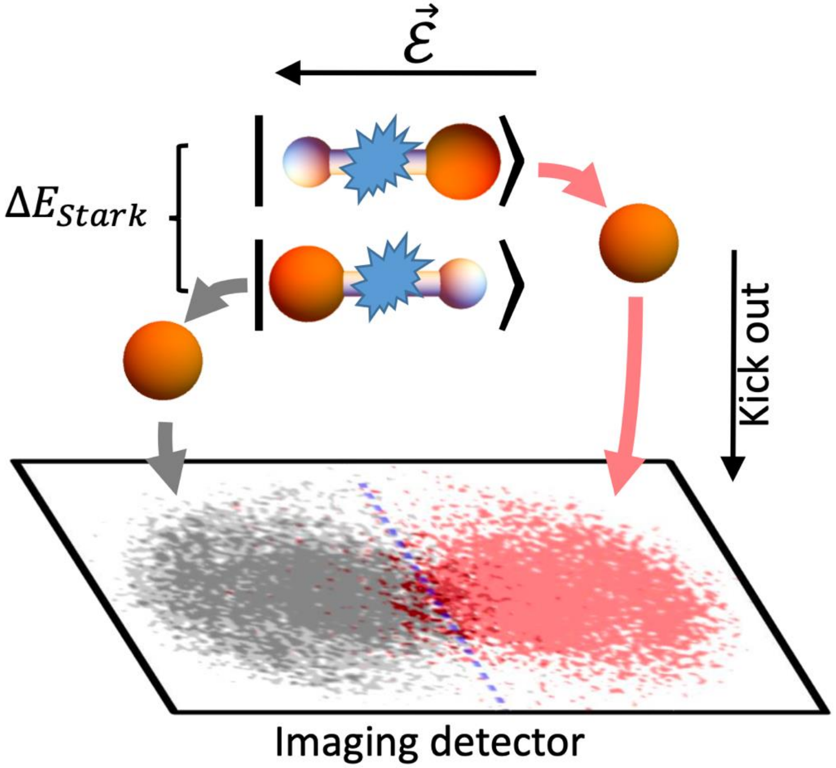
Developed with Tanya Zelevinsky

REMPAD: Two-state detection

Resonantly **E**nhanced **M**ulti**P**hoton **A**symmetric **D**issociation

1. Hf^+ is ejected with energy from dissociation.
2. Ejection direction depends on quantum state before dissociation.
3. Ions on the left (right) correspond to one (another) quantum state.



Zhou *et al.*, Phys. Rev. Lett. **124**, 053201 (2020)

Zhou et al. Phys. Rev. Lett. **124**, 053201 (2020)
Beswick et al. J. Chem. Phys. **129**, 164315 (2008)
McDonald et al. Nature **535**, 122 (2016)
Majewska et al. Phys. Rev. A **98**, 043404(2018)

New generation improvements

- Use ThF^+ instead of HfF^+

	ThF^+	HfF^+
Effective *E*-field	35.2 GV/cm	23.4 GV/cm
Science state	ground	meta stable
Expected Coherence	~20 s	2 s

Denis, et al. *New Journal of Physics* 17 (2015): 043005
Skripnikov, et al. *Physical Review A* 91 (2015): 042504
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- Use ThF^+ instead of HfF^+
- Putting ThF^+ in previous apparatus

$$\delta d_e \sim \frac{1}{\mathcal{E}_{\text{eff}}\,\tau\sqrt{N}}$$

(x 1.5) (x 3) = x 4.5 improvement

(x 1.5) (x 10) = x 15 improvement

→ upper limit ~ 3 x 10^{-30} e cm ?

→ upper limit ~ 1 x 10^{-31} e cm ?

$$f_{\text{rep}} \approx 1/\tau$$

$$\delta d_e \sim \frac{1}{\mathcal{E}_{\text{eff}}\sqrt{\tau}\sqrt{N_{\text{single}} \cdot T_{\text{int}}}}$$

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- Use ThF^+ instead of HfF^+
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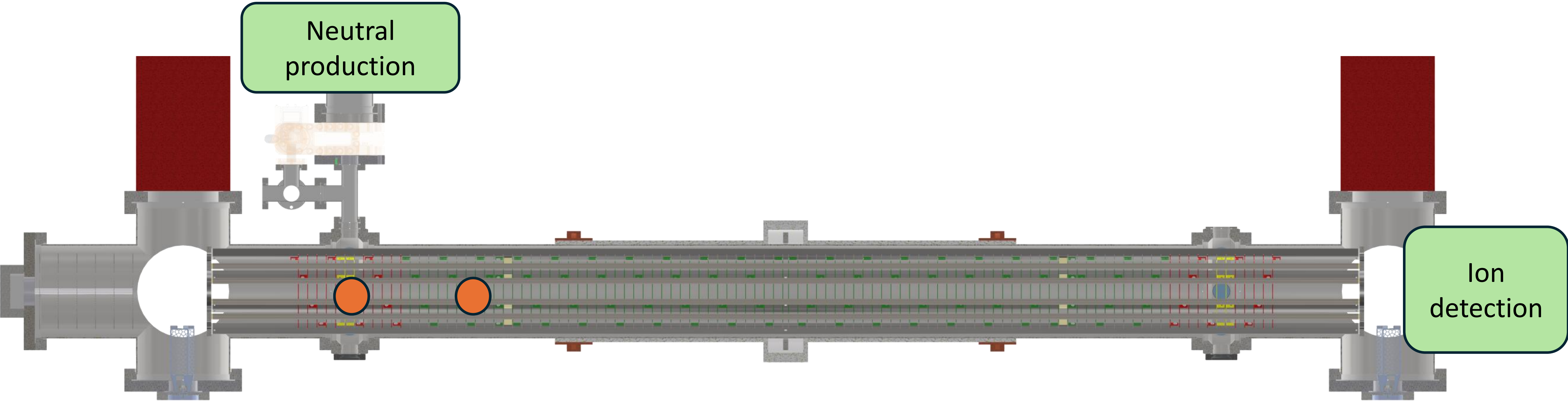
$$\delta d_e \sim \frac{1}{\mathcal{E}_{\text{eff}} \tau \sqrt{N}}$$

$$f_{\text{rep}} \not\approx 1/\tau$$

Multiplexing is necessary to take full advantage of long coherence time

New generation: Bucket Brigade



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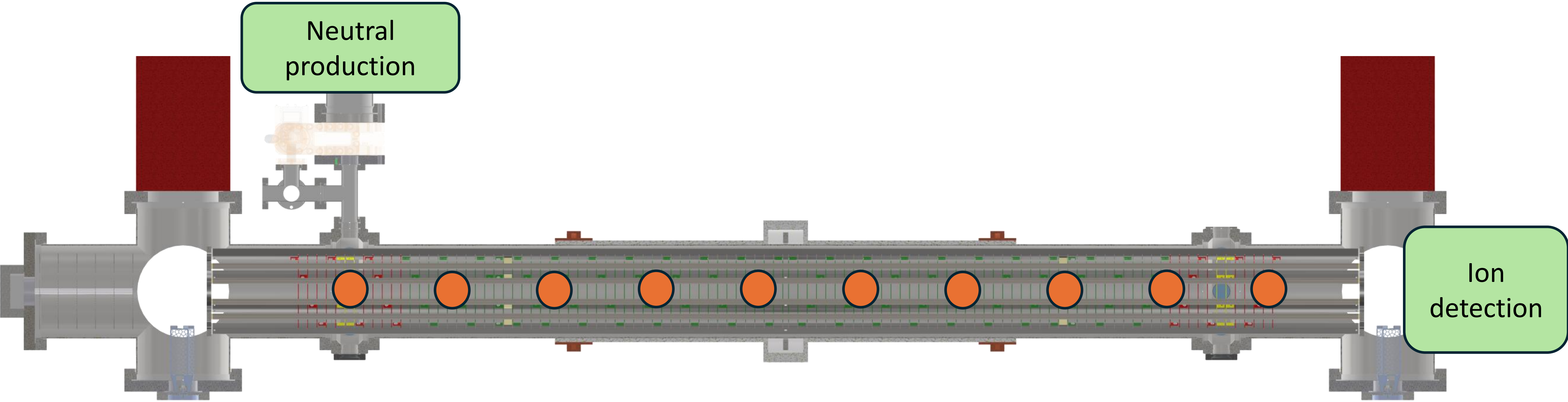
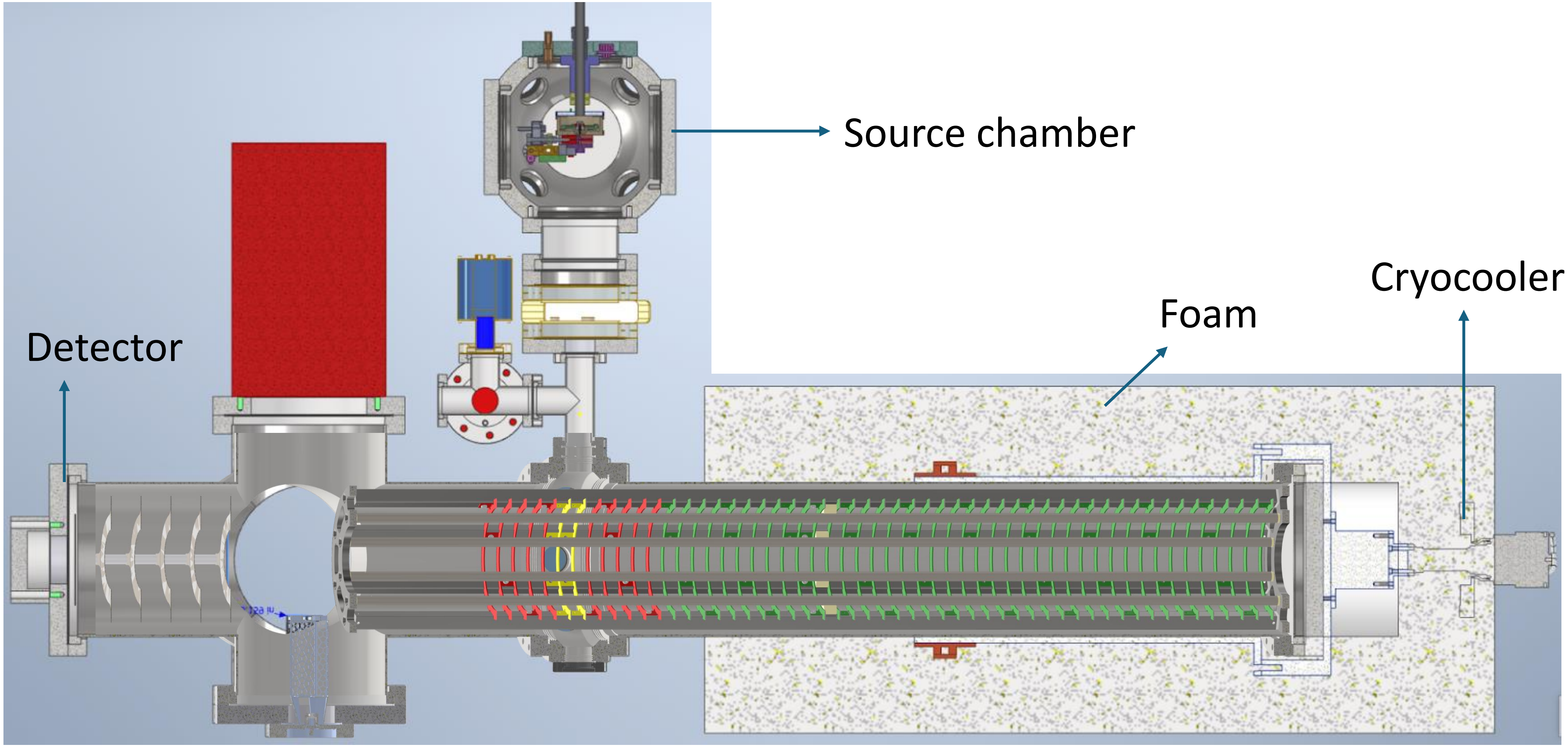
New generation: Bucket Brigade



Prototype experiment



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Prototype experiment

$$\delta d_e \sim \frac{1}{\mathcal{E}_{\text{eff}} \tau \sqrt{N}}$$

- Requirements for continuous-mode operations
  - Electrode design
  - Maintaining Ramsey fringes during translation
  - Localized pi/2 pulse
- Requirements to do precision measurement
  - Achieving long coherence
    - Ion loss
    - Investigate decoherence/dephasing effects

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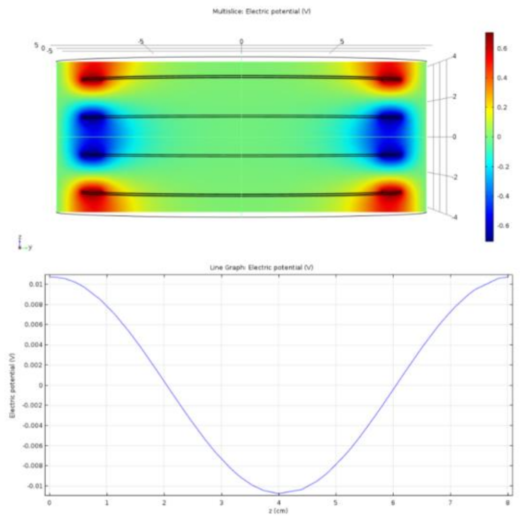
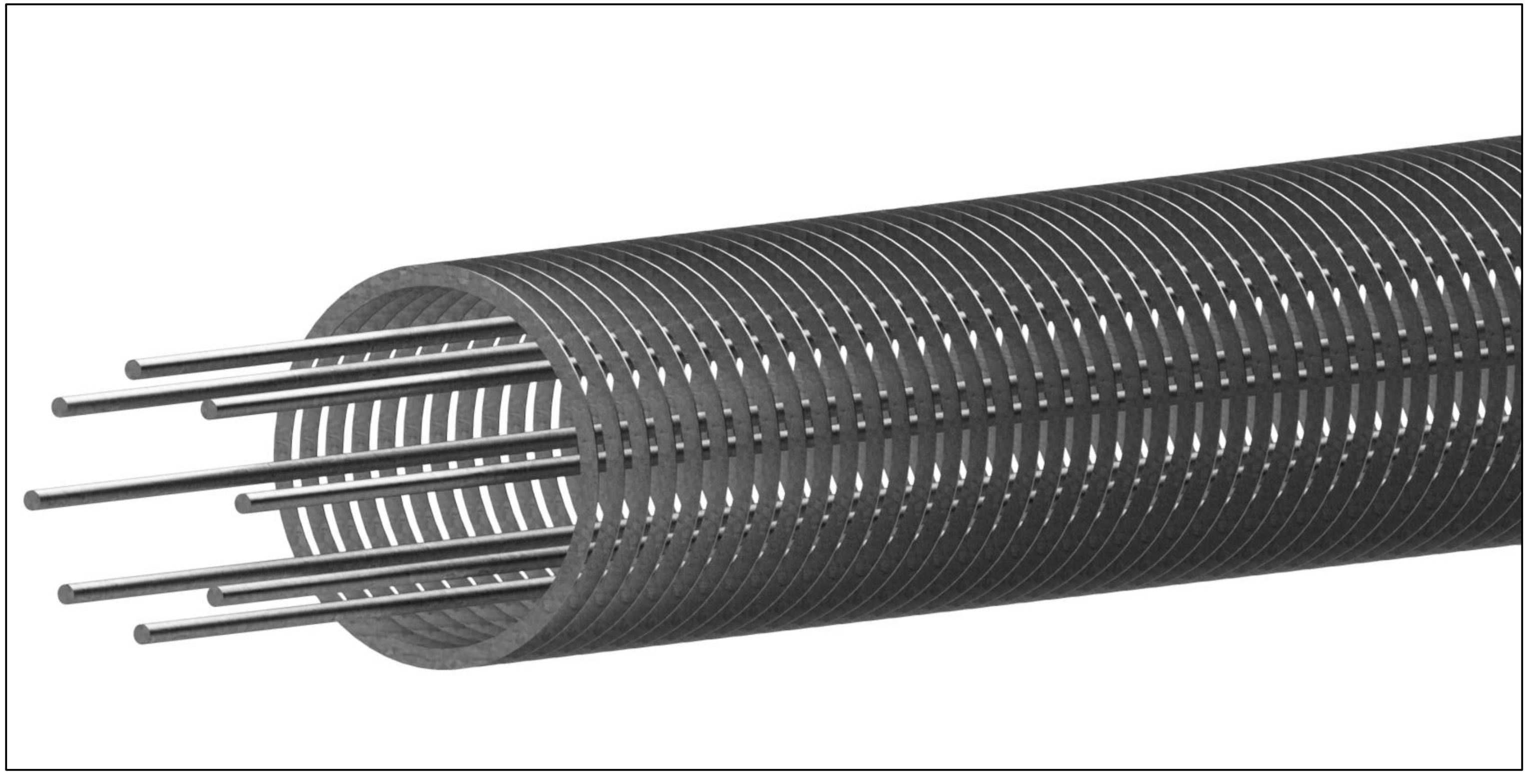
Prototype electrodes

Rings

(Side view)





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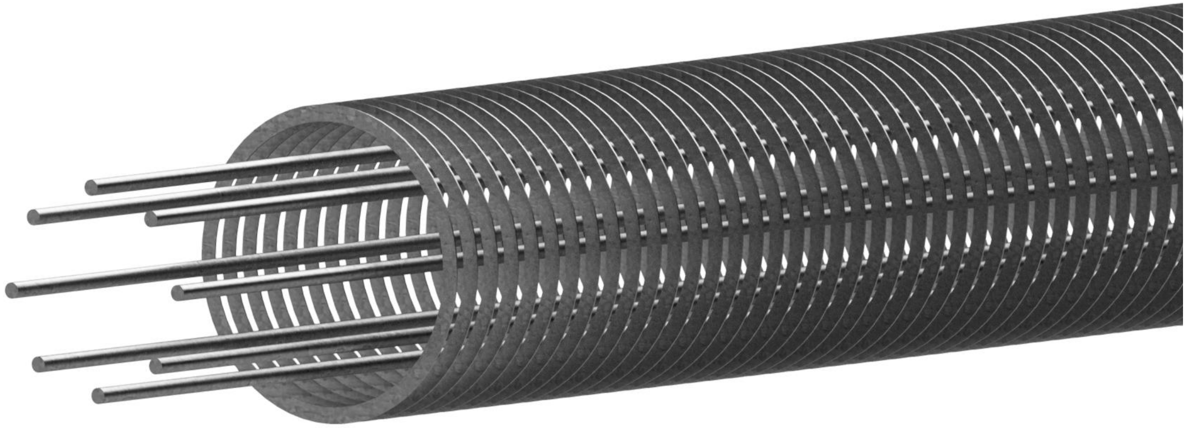
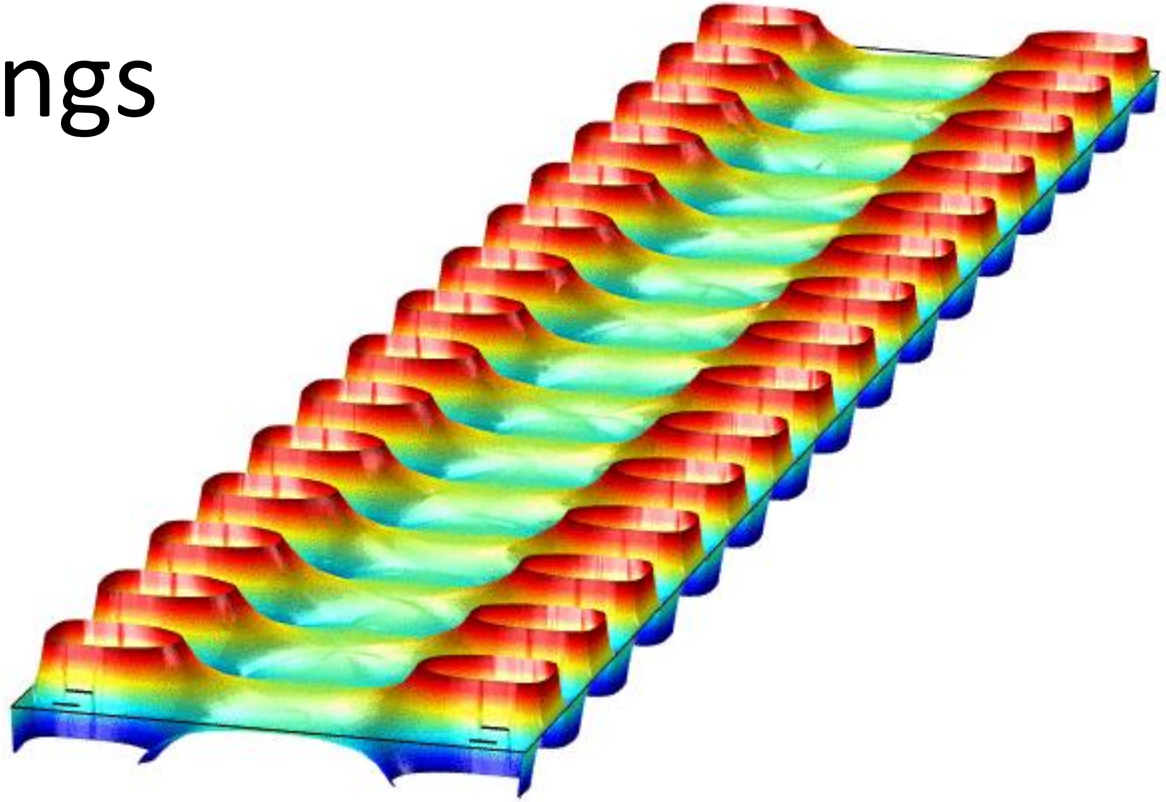
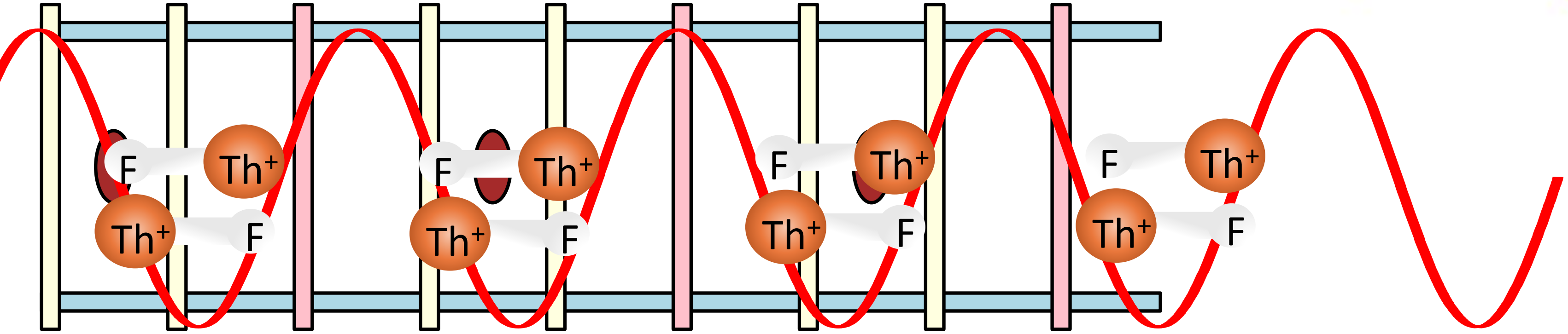
Prototype electrodes: rings







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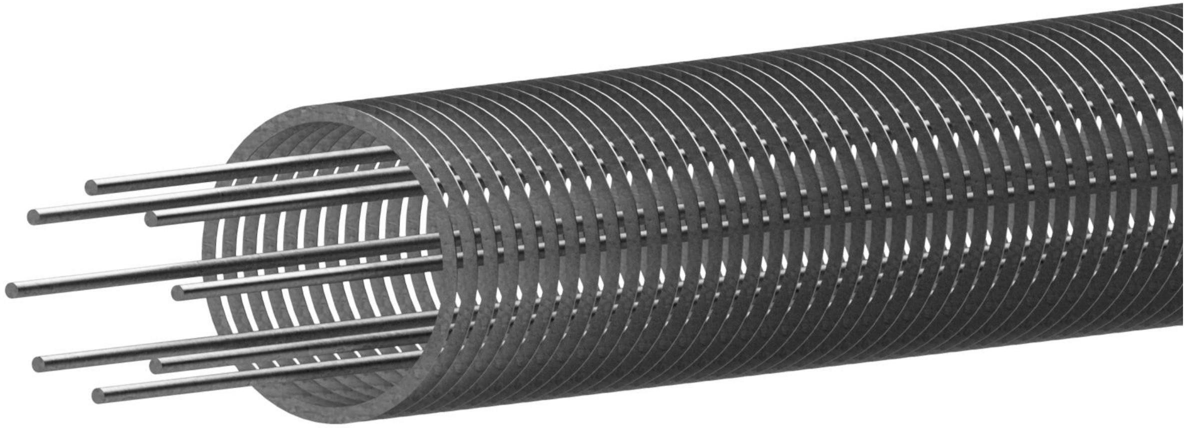
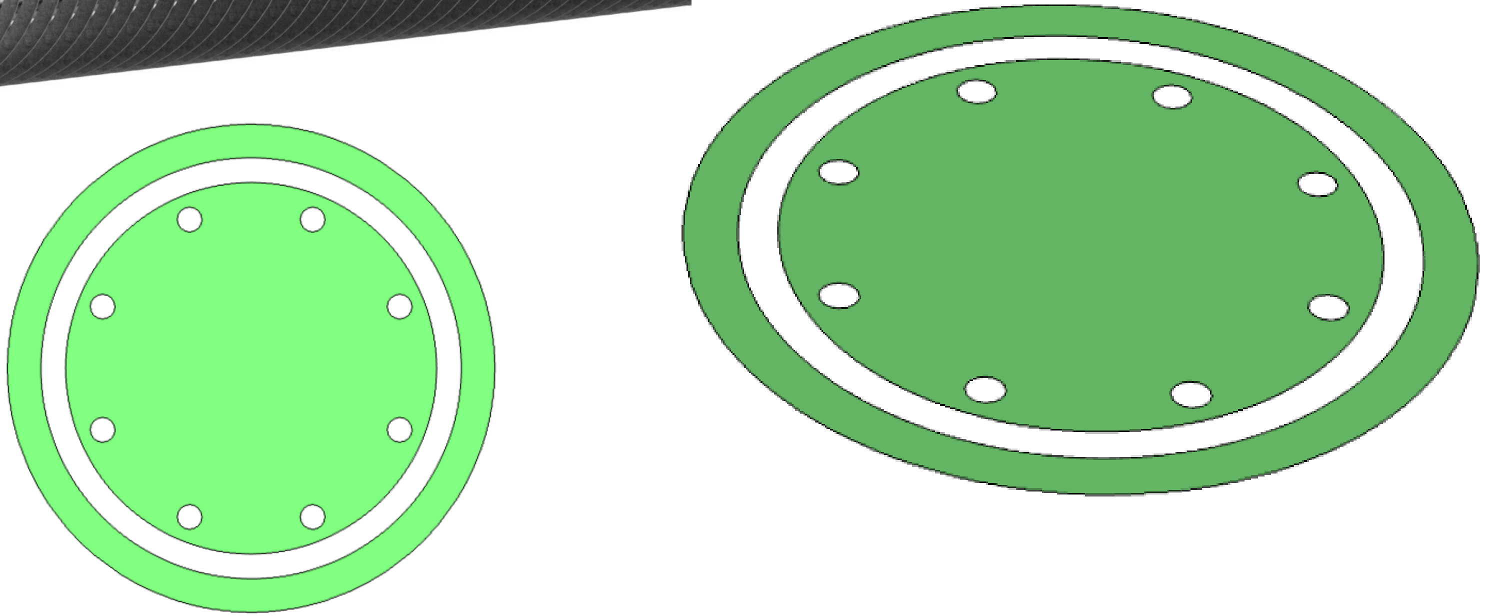
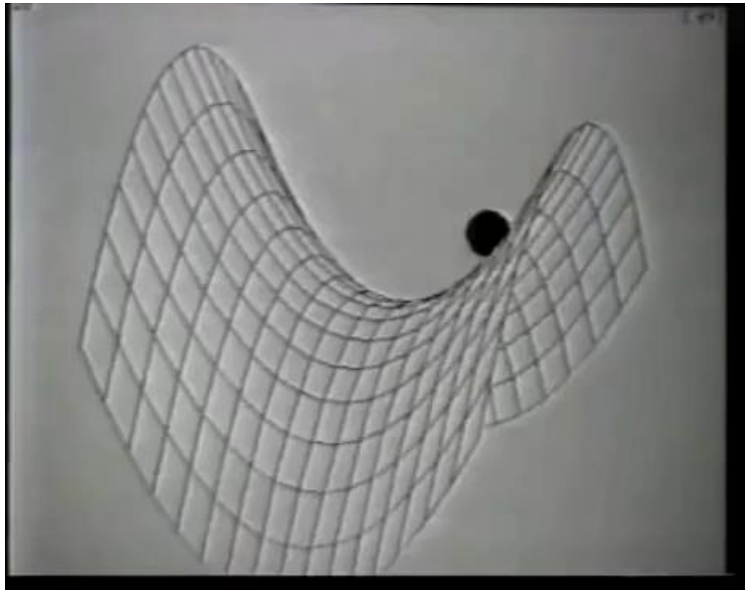
Prototype electrodes: rods

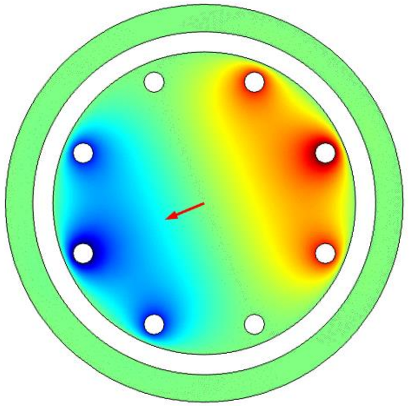




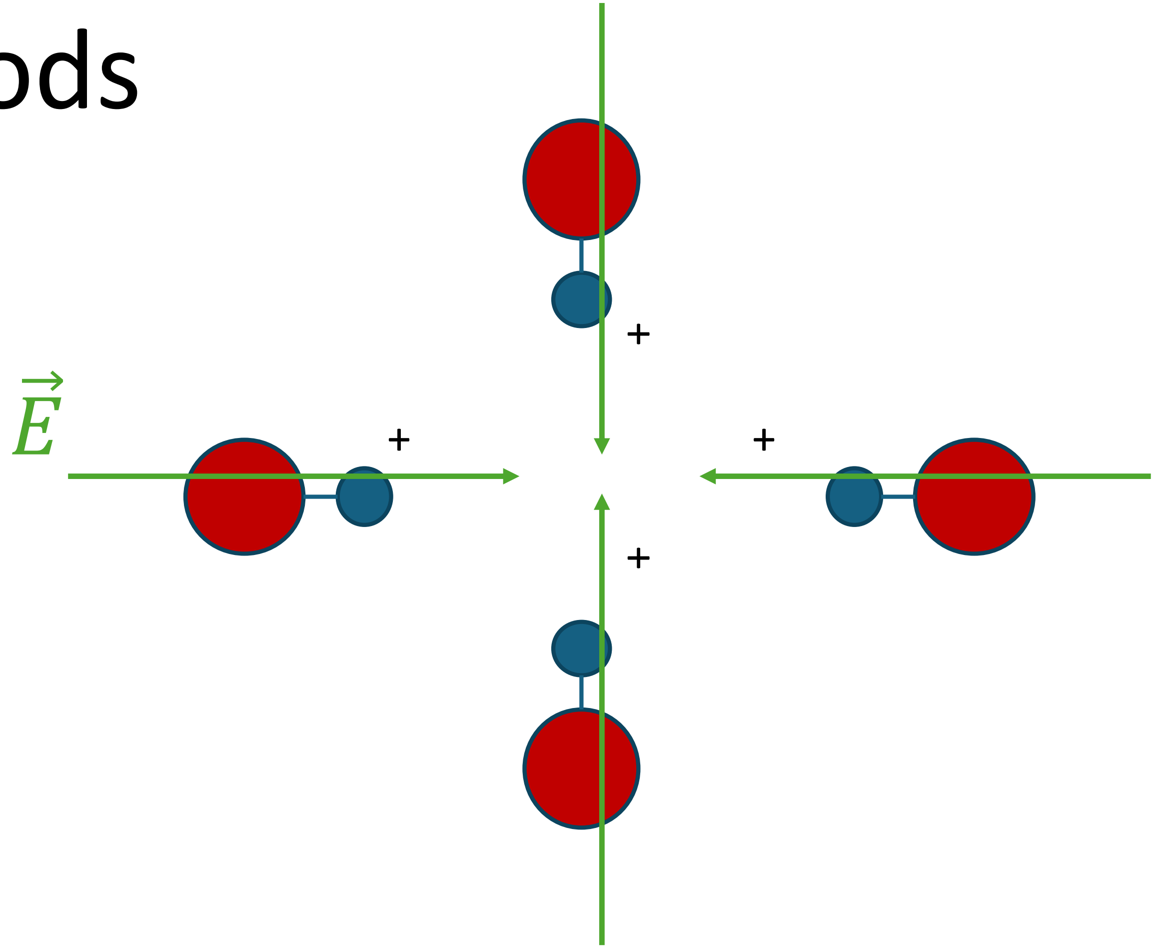


Prototype electrodes: rods

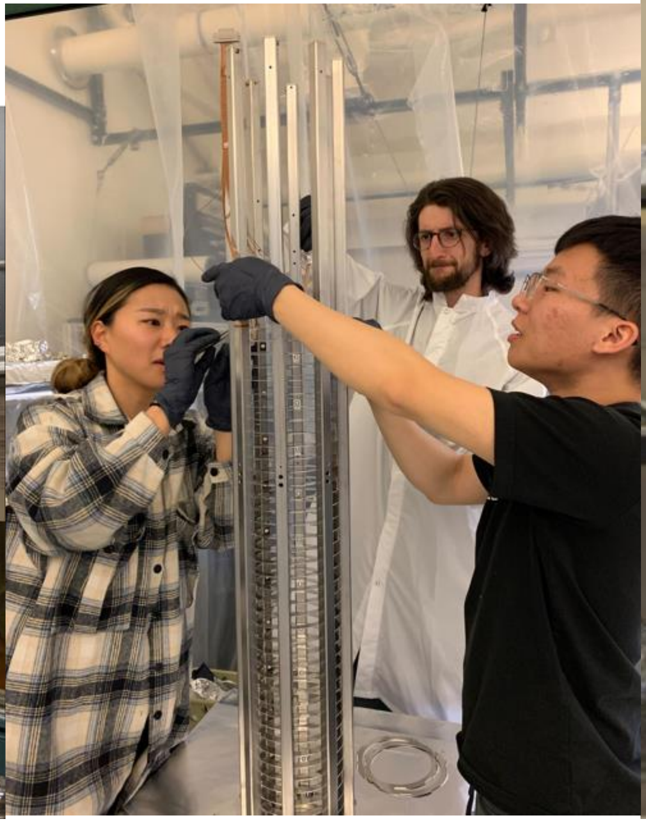
Rods

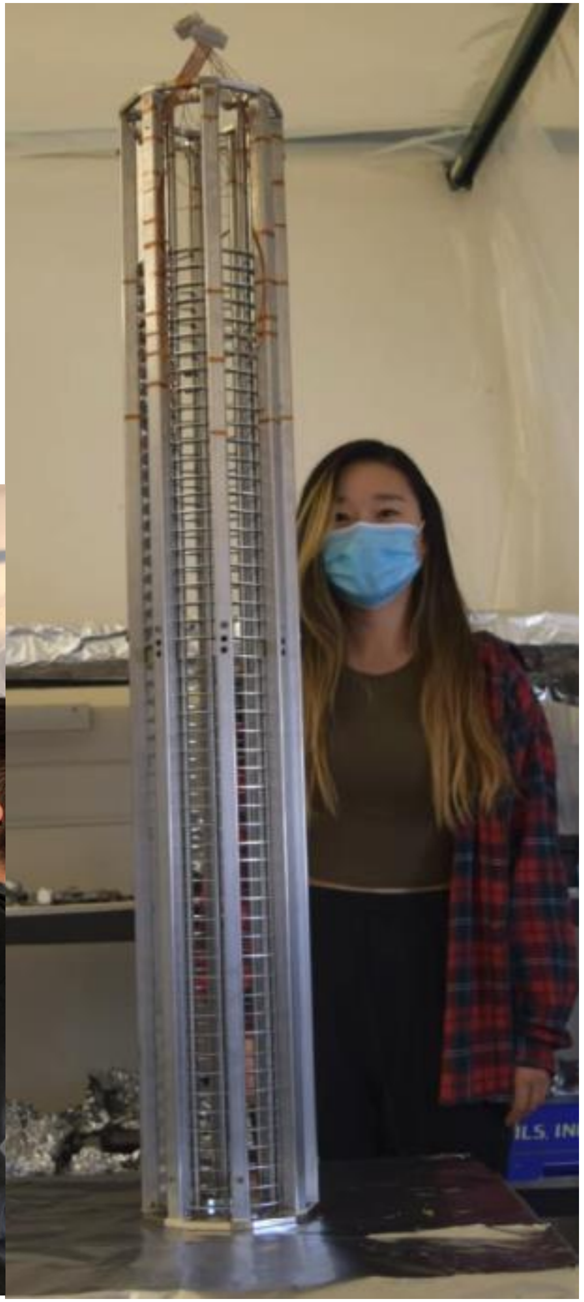


Polarize molecules
150 kHz



Apply ***rotating*** electric field to polarize molecules





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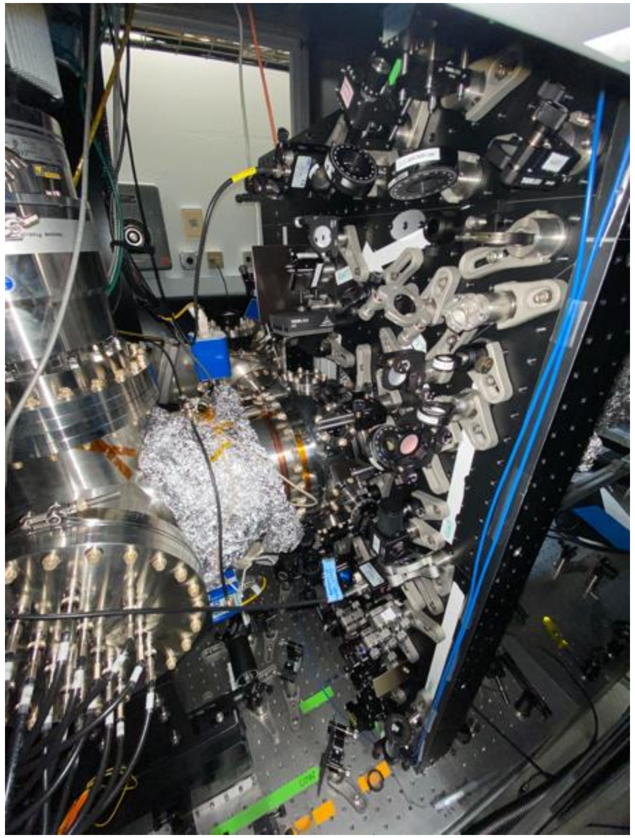

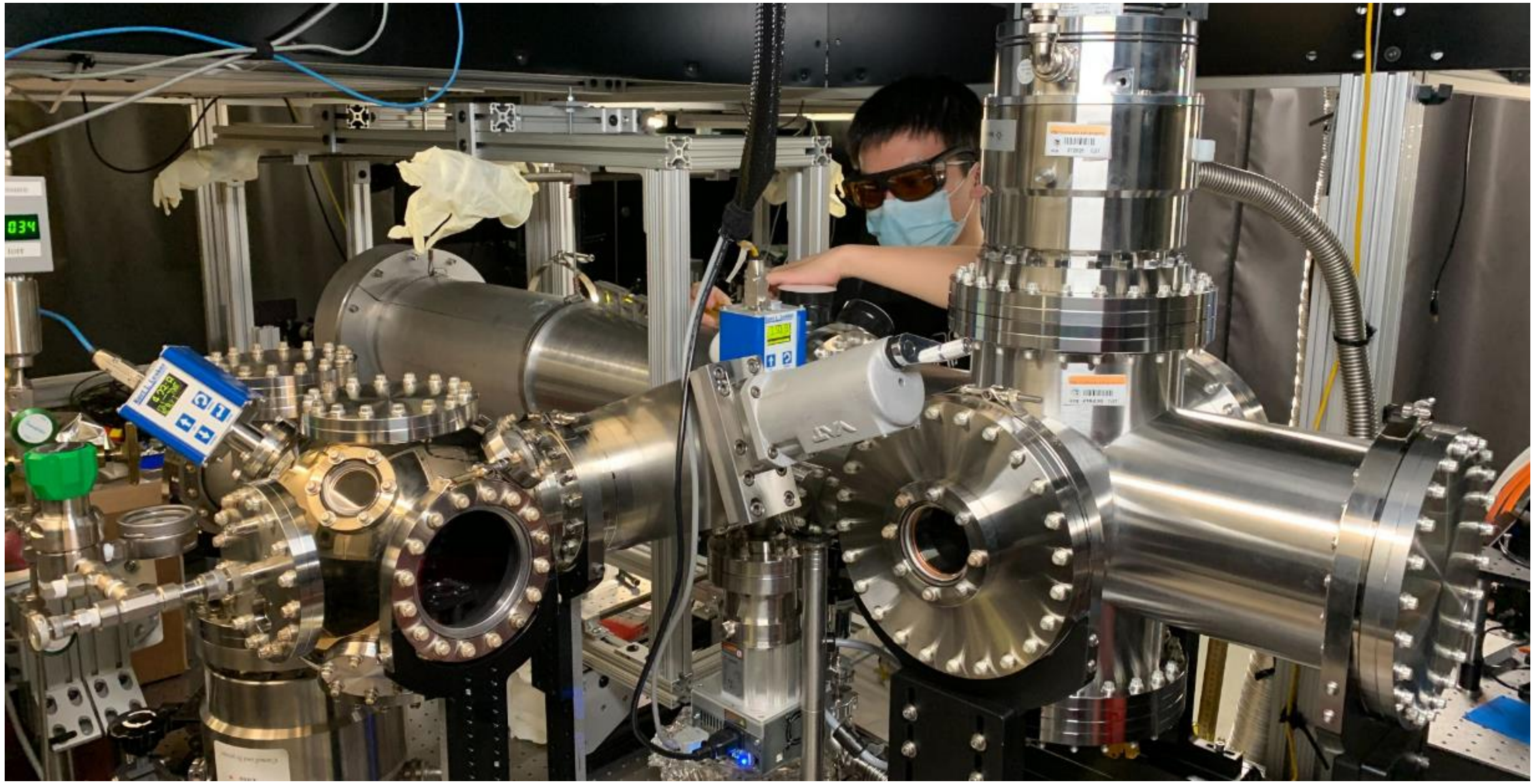

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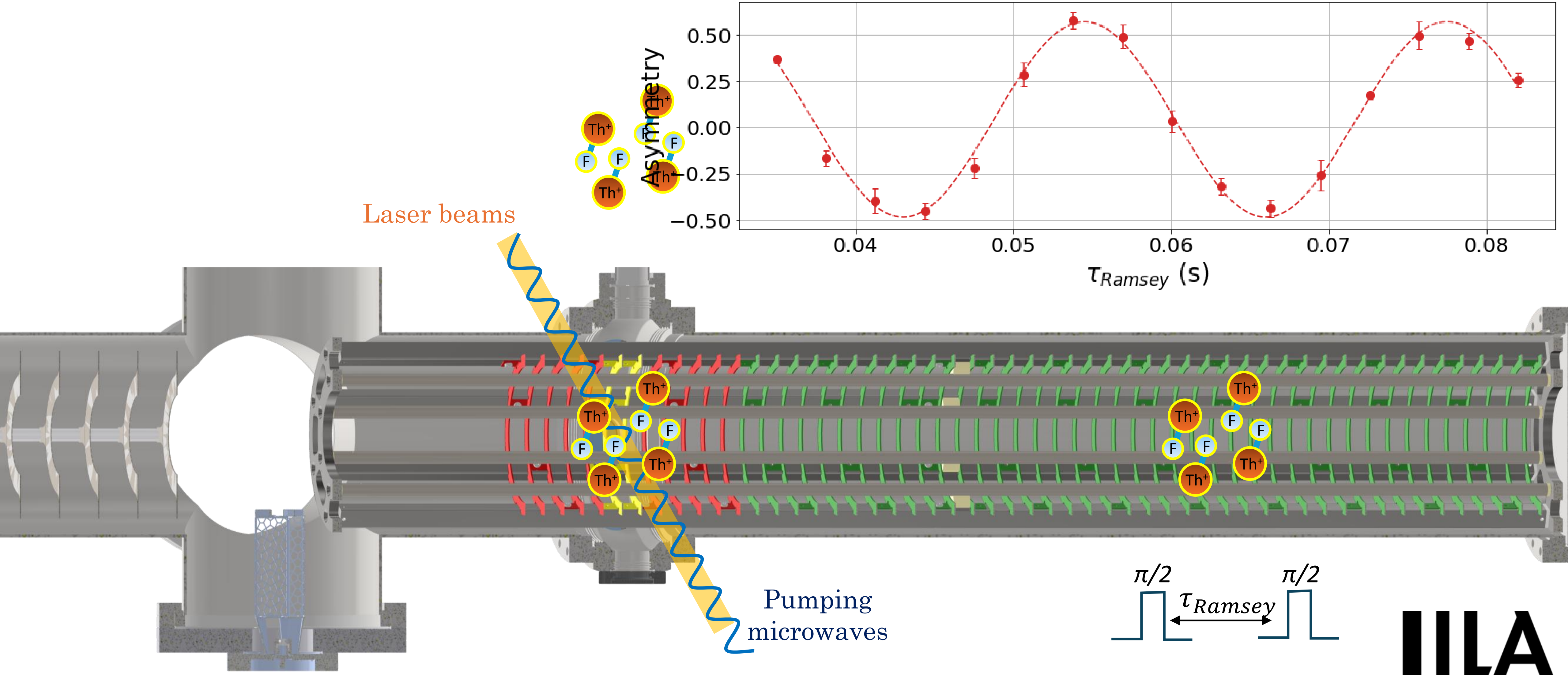

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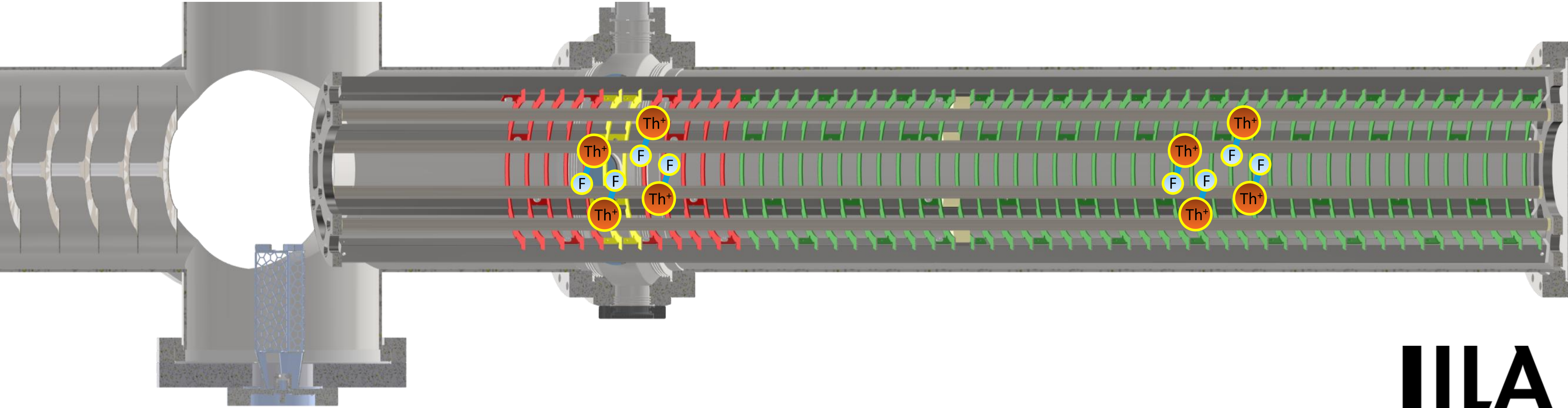
Towards continuous-mode quantum measurement



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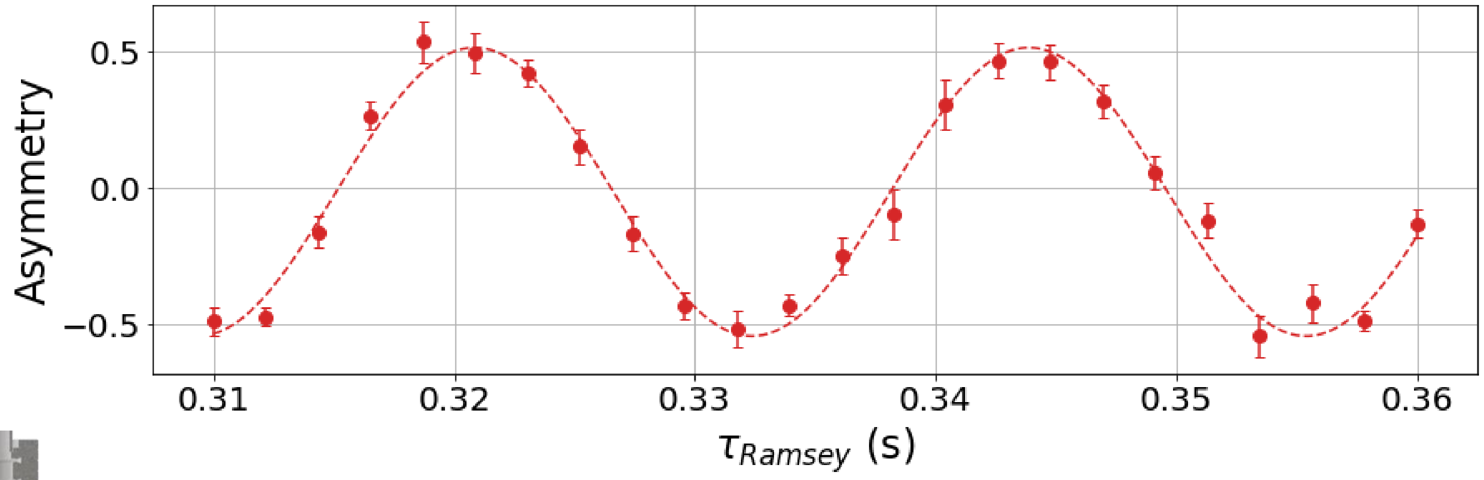
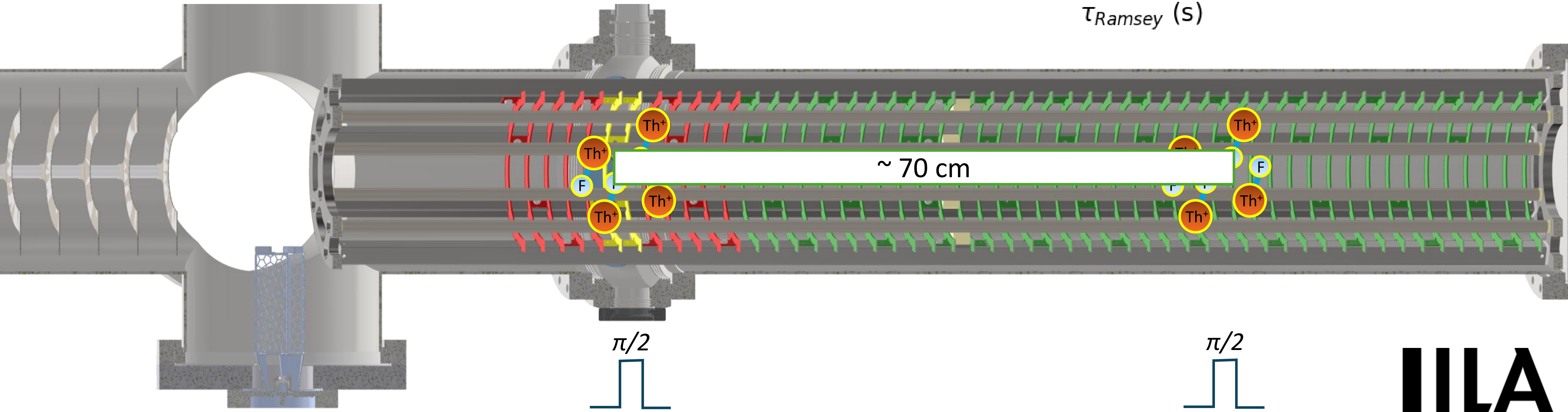
Towards continuous-mode quantum measurement

Quantum evolution stays coherent during translation





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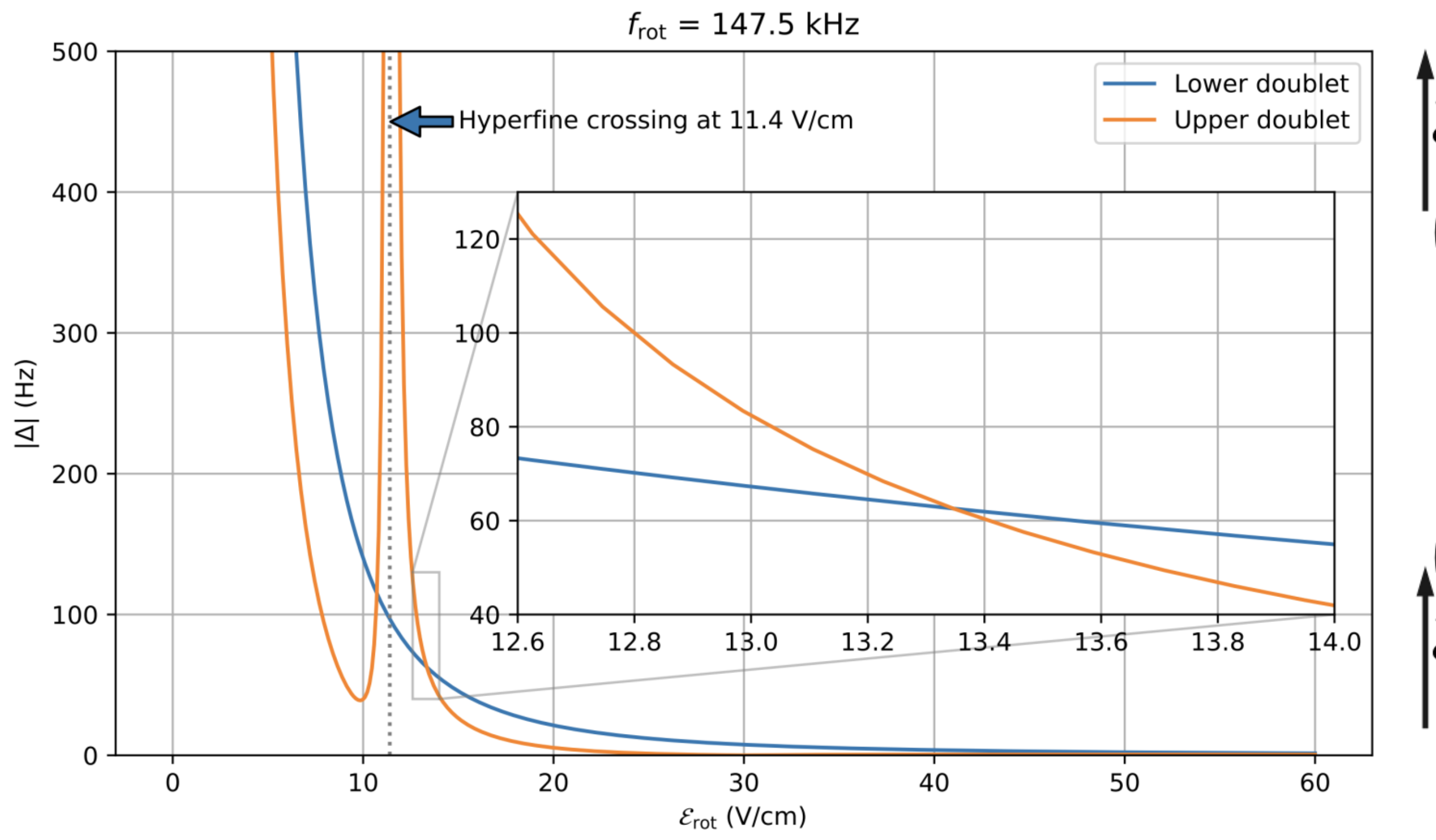
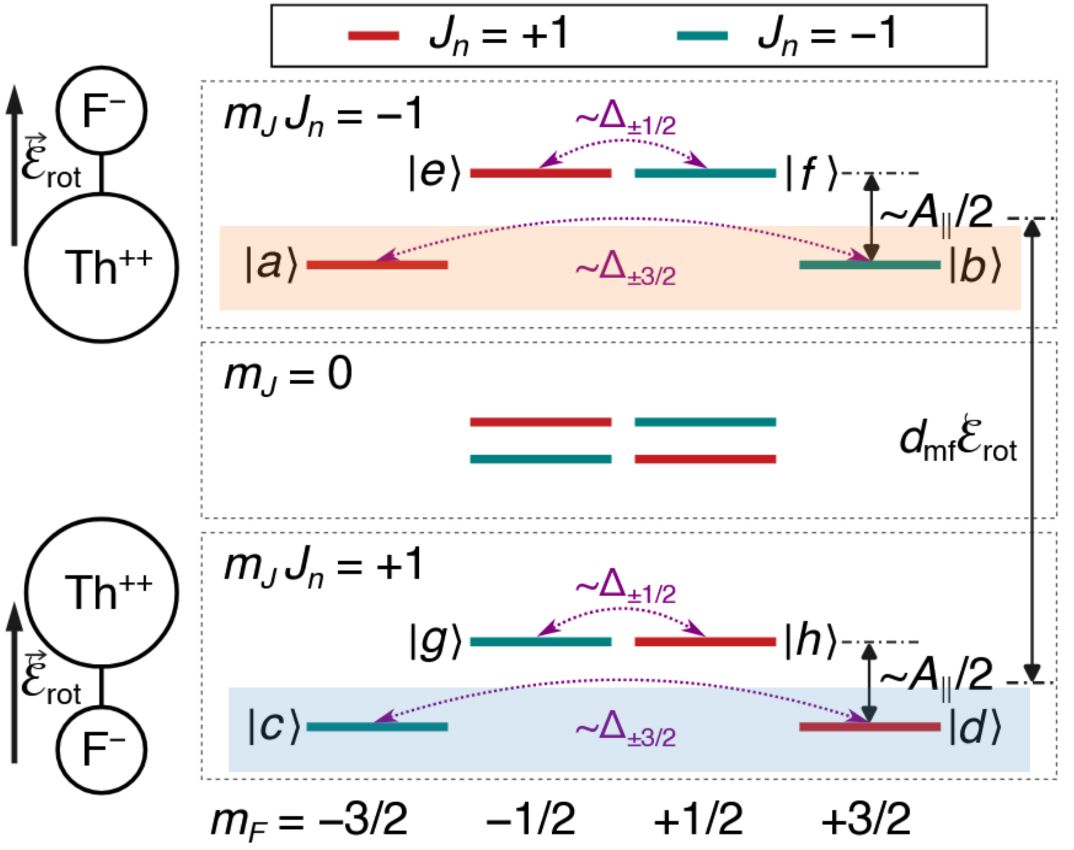
Continuous-mode challenges: current scheme for pi/2 pulse





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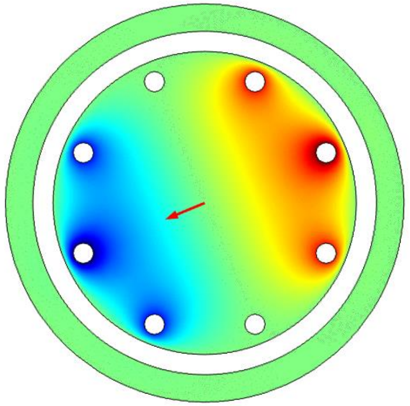

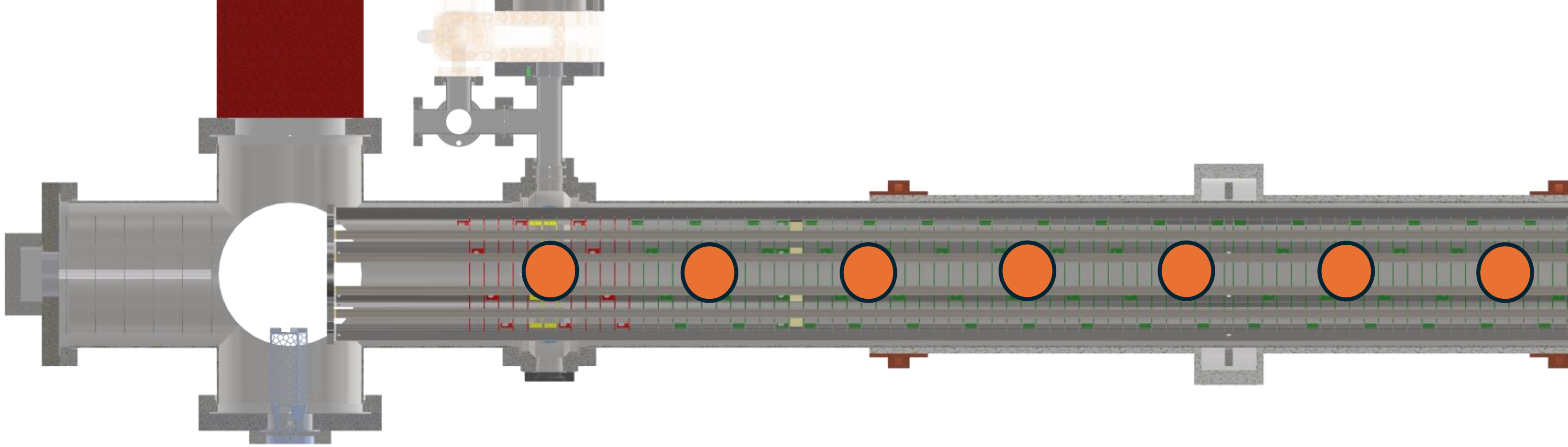

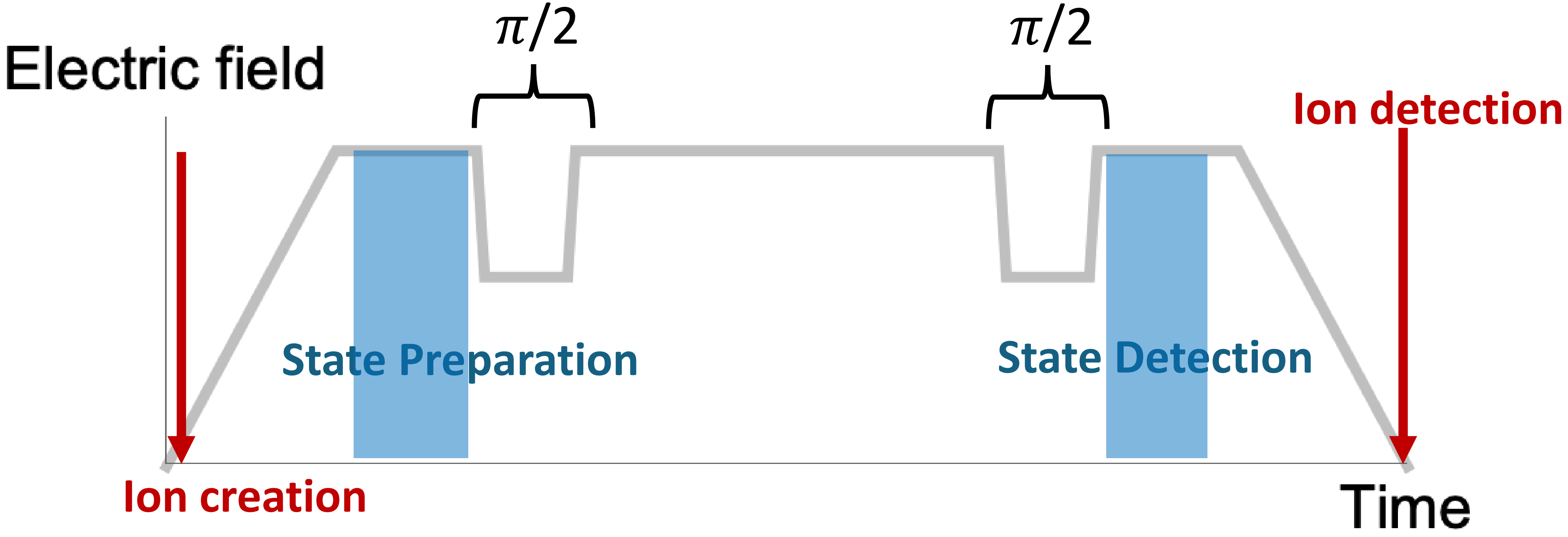

$\pi/2$
$\pi/2$
Electric field
Ion detection
State Preparation
State Detection
Ion creation
Time

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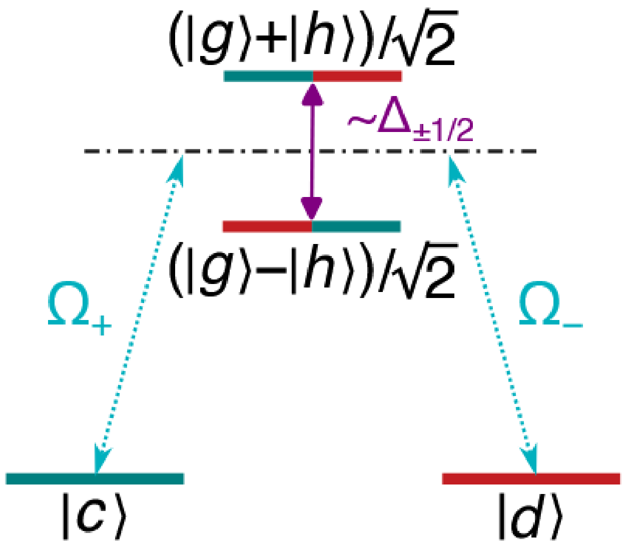
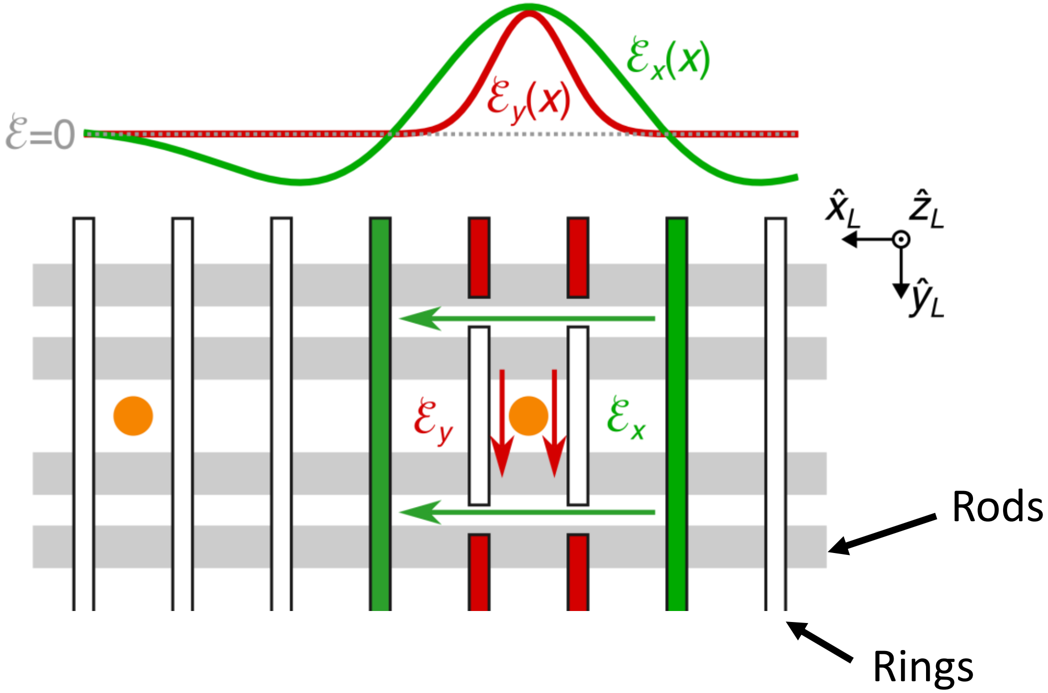
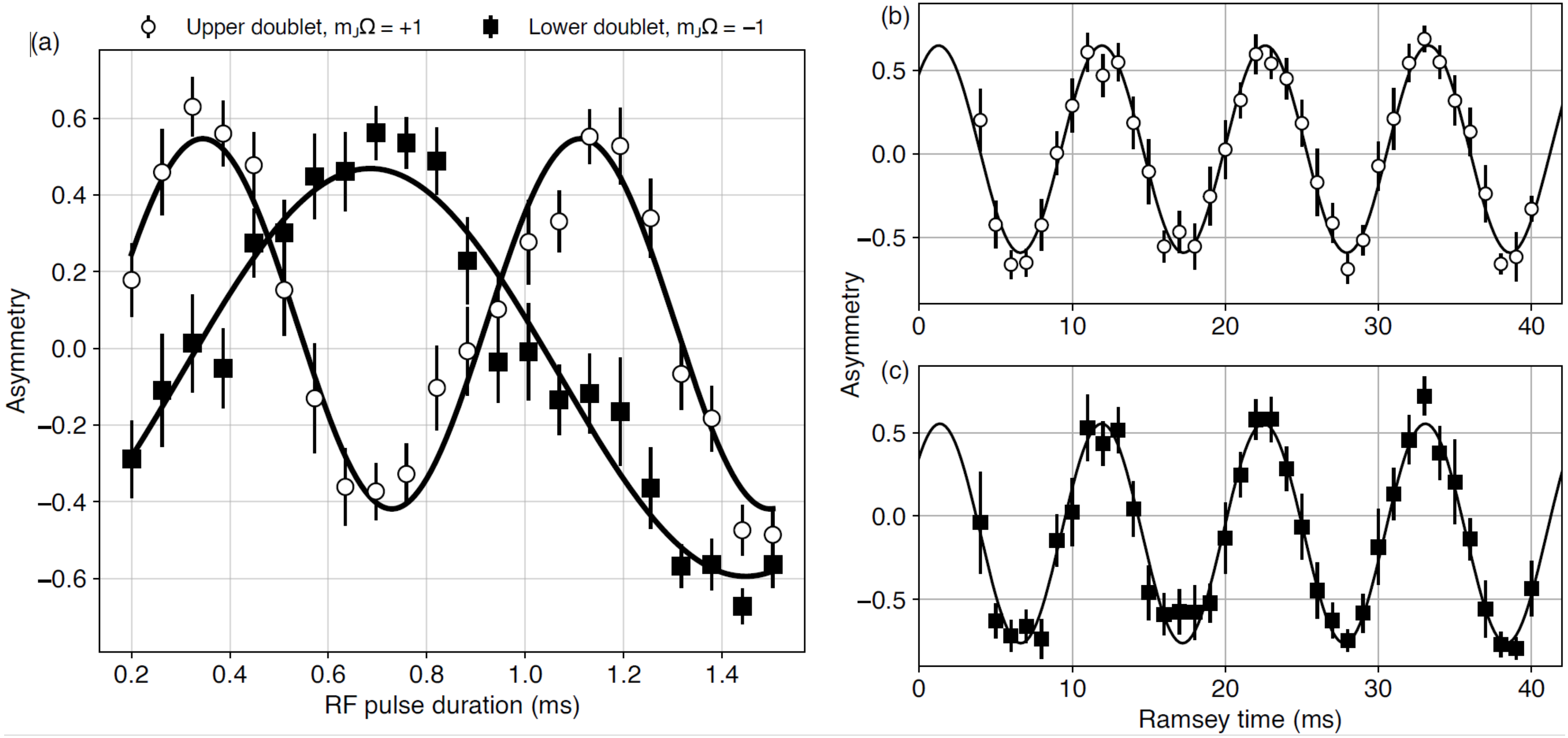
New *localized* pi/2 pulse scheme





- We use E field generated from *rings* to drive hyperfine splitting
- This gives us localized π/2 pulse

Localized π/2 pulse



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Prototype experiment

$$\delta d_e \sim \frac{1}{\mathcal{E}_{\text{eff}} \tau \sqrt{N}}$$

- Requirements for continuous-mode operations
  - Electrode design
  - Maintaining Ramsey fringes during translation
  - Localized pi/2 pulse
- Requirements to do precision measurement
  - Achieving long coherence
    - Ion loss
    - Investigate decoherence/dephasing effects

In theory, ThF+ has infinite coherence time.

In practice, it can be limited by technical and environmental mechanisms

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Loss rates in our experiments

Ramsey contrast

$$\Gamma_{\text{Ramsey}} = \Gamma_{\text{Berry}} + \Gamma_{\text{dephasing}} + \cdots$$

- Γ_{Berry}: Ion-ion collisions induced Berry's phase
- $\Gamma_{\text{dephasing}}$: Field inhomogeneity and temporal fluctuation (shot to shot f_{Ramsey} difference)

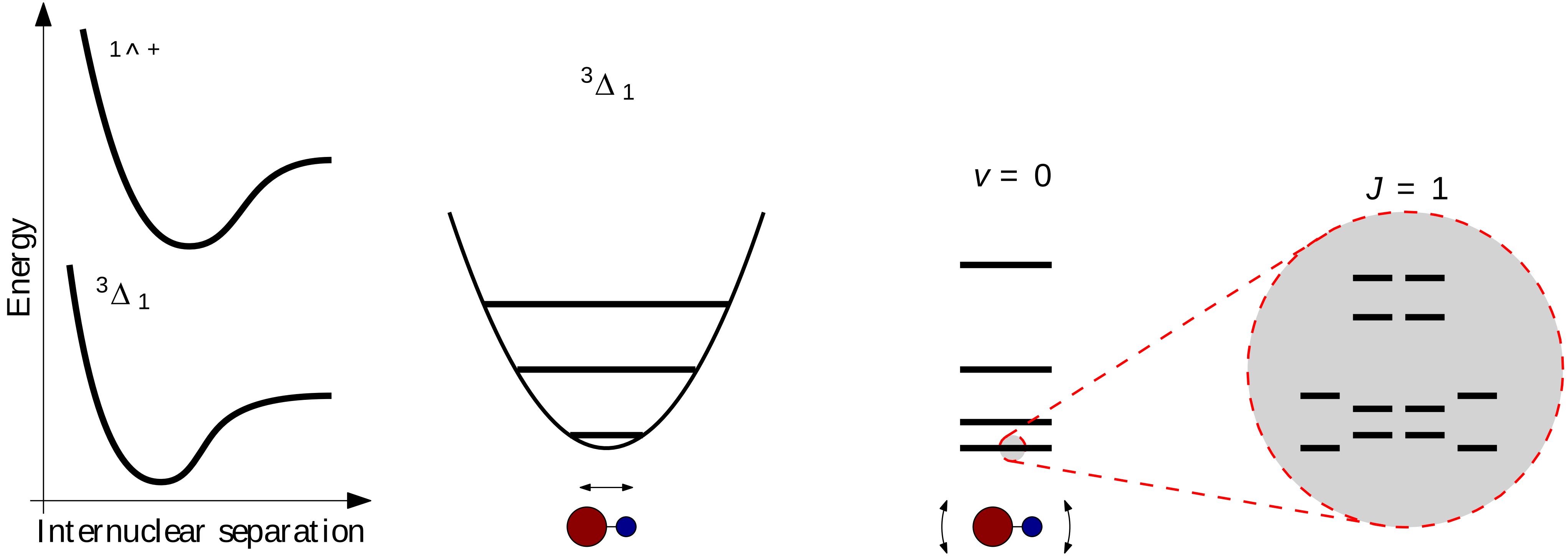
Count

$$\Gamma_{\text{mF}=3/2} = \Gamma_{\text{ion}-\text{ion}} + \Gamma_{\text{J}=1} + \Gamma_{\text{ThF}^{+}} + \ldots$$

$$\Gamma_{\text{J}=1} = \Gamma_{\text{Ion}-\text{neutral}} + \Gamma_{\text{BBR}}$$

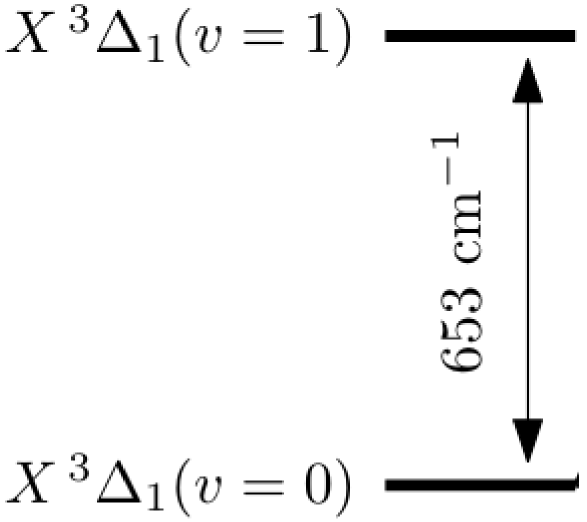
- $\Gamma_{\text{ion}-\text{ion}}$: Ion-ion collisions that changes mF levels
- $\Gamma_{\text{ThF+}}$: ThF+ ions loss. Currently limited by heating and Erot ponderomotive force
- $\Gamma_{\text{ion}-\text{neutral}}$: Ion-neutral collision induced rotational level change
- Γ_{BBR}: Black-body radiation pushes ions out of the science states

Quantum manifold (J=1) lifetime



Electronic	Vibrational	Rotational	Hyperfine, parity, and m_F
& 1000 cm^{-1}	⇠ 600 cm^{-1}	& 1 cm^{-1} ⇠ 30 GHz	⇠ MHz

Blackbody Radiation Excitation limits coherence time at room temperature

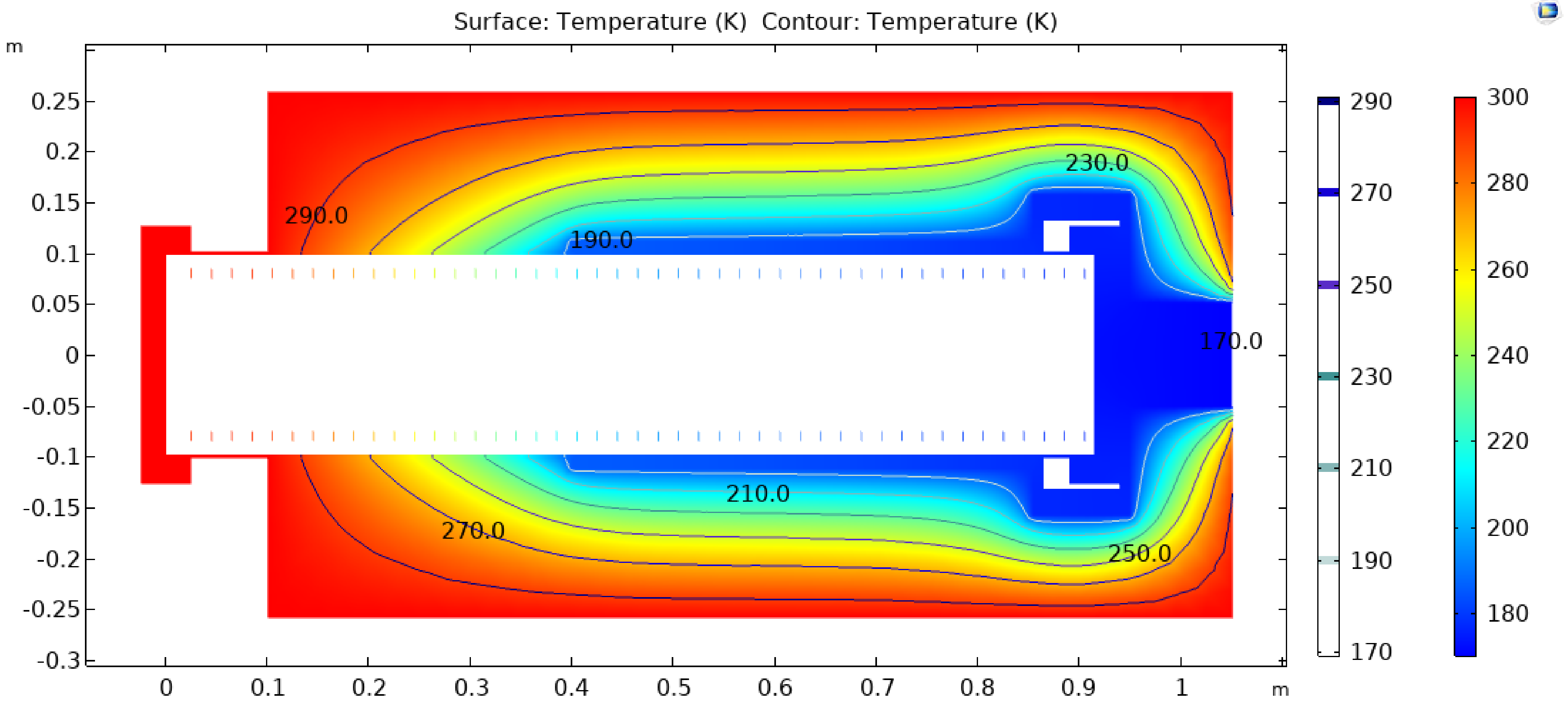


Science state

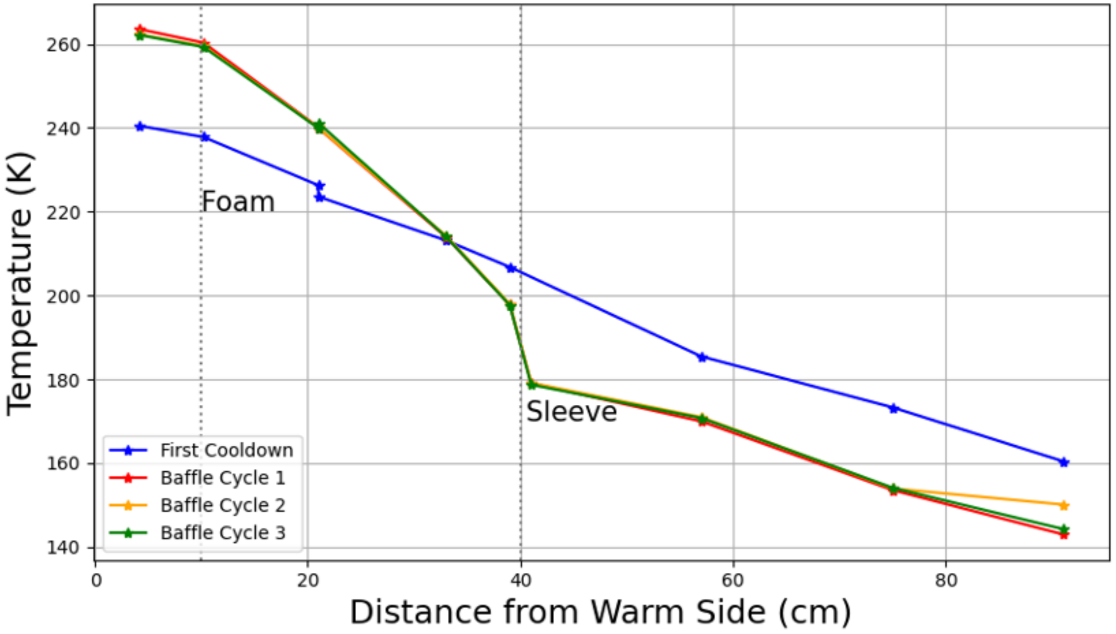
BBR excitation time in seconds

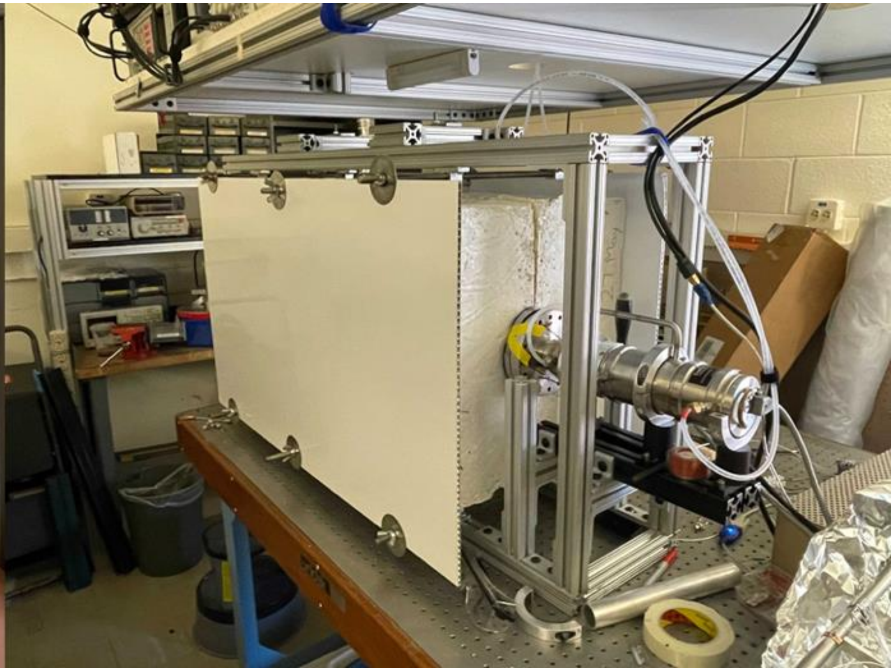
$v' \leftarrow v''$	77 K	120 K	150 K	180 K	200 K	300 K
$1 \leftarrow 0$	35800	449	93.5	32.8	19.3	3.89

Cold region



Surface: Temperature (K) Contour: Temperature (K)
m
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
m
290.0
190.0
230.0
170.0
210.0
270.0
250.0
290
270
250
230
210
190
170
300
280
260
240
220
200
180


Temperature (K)
Distance from Warm Side (cm)
260
240
220
200
180
160
140
0
20
40
60
80
Foam
Sleeve
First Cooldown
Baffle Cycle 1
Baffle Cycle 2
Baffle Cycle 3



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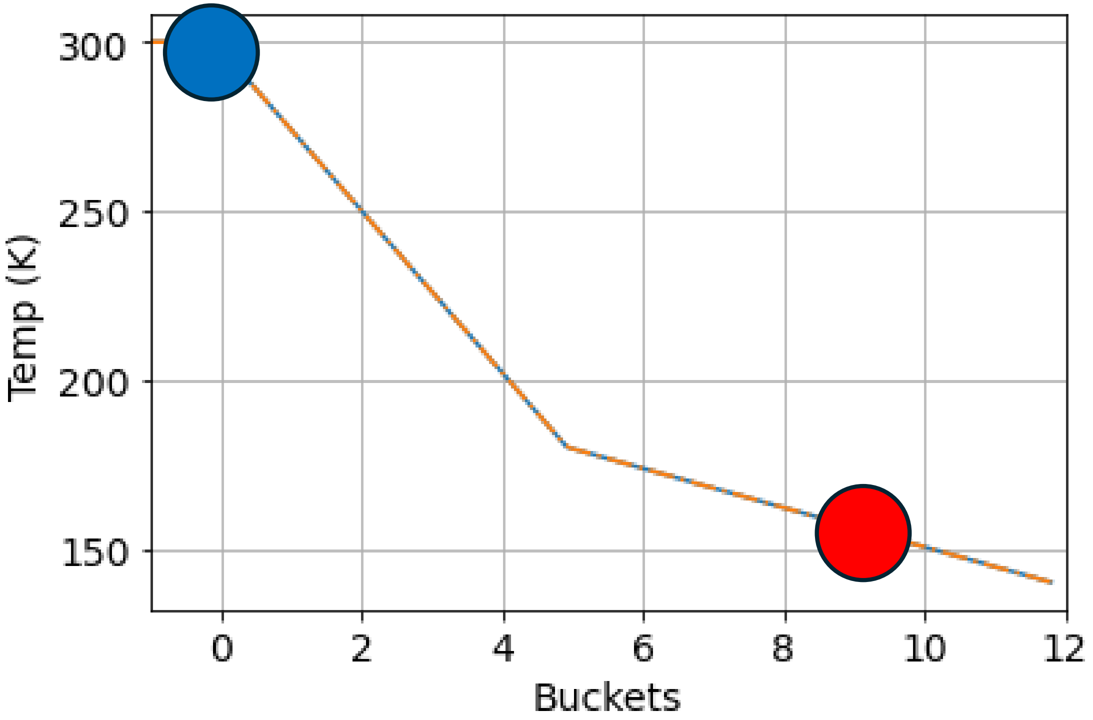
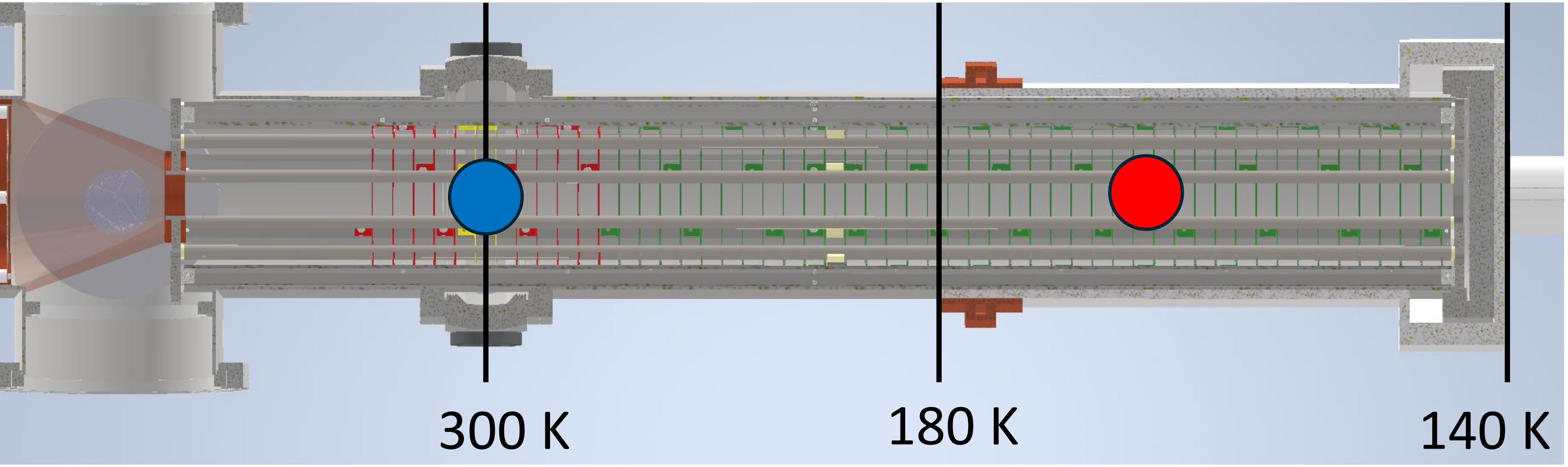
Quantum manifold lifetime: Γ_{BBR}



1 bucket = 8 cm



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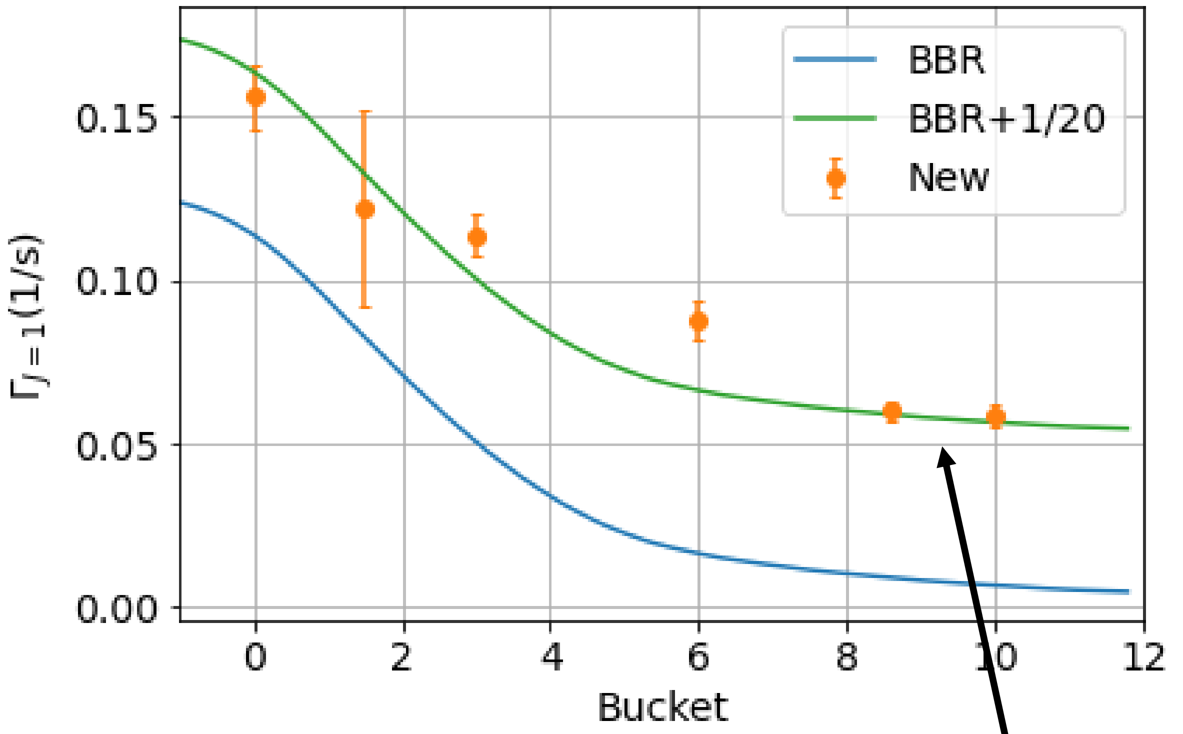
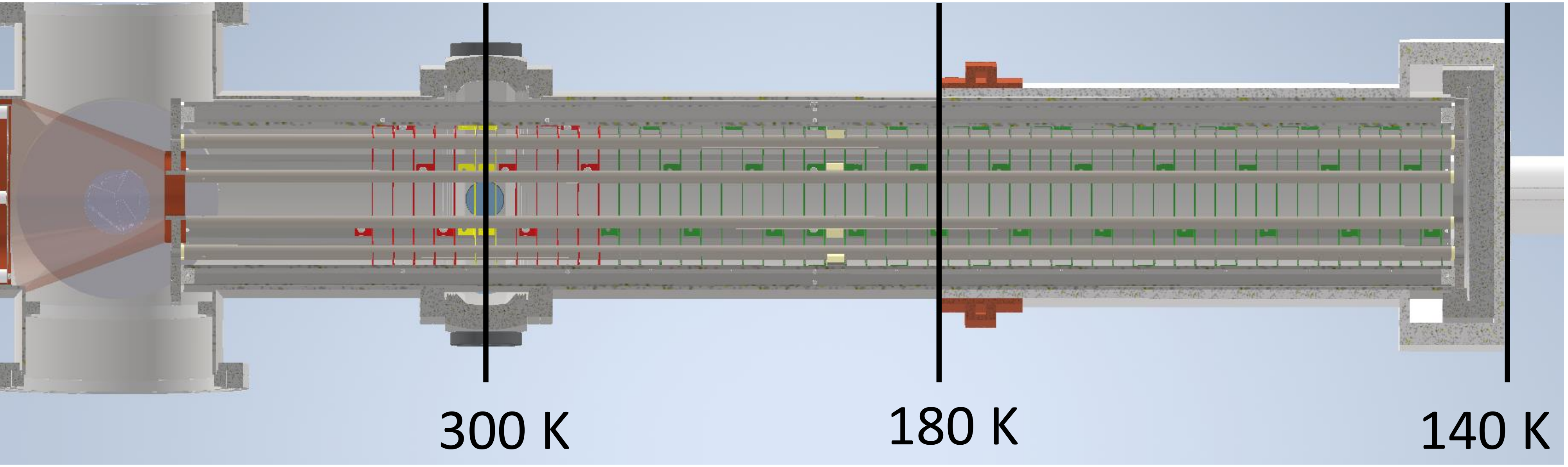


Decay from H_2

1 bucket = 8 cm



Achieving long coherence: investigating decoherence/dephasing effects

- Spatial and temporal field homogeneity
  - Rotating electric field
  - Background magnetic field gradient

Achieved!

Field requirement:

→ fractional field homogeneity requirement <0.01 %

→ absolute magnetic field gradient stable to 0.3μG/cm

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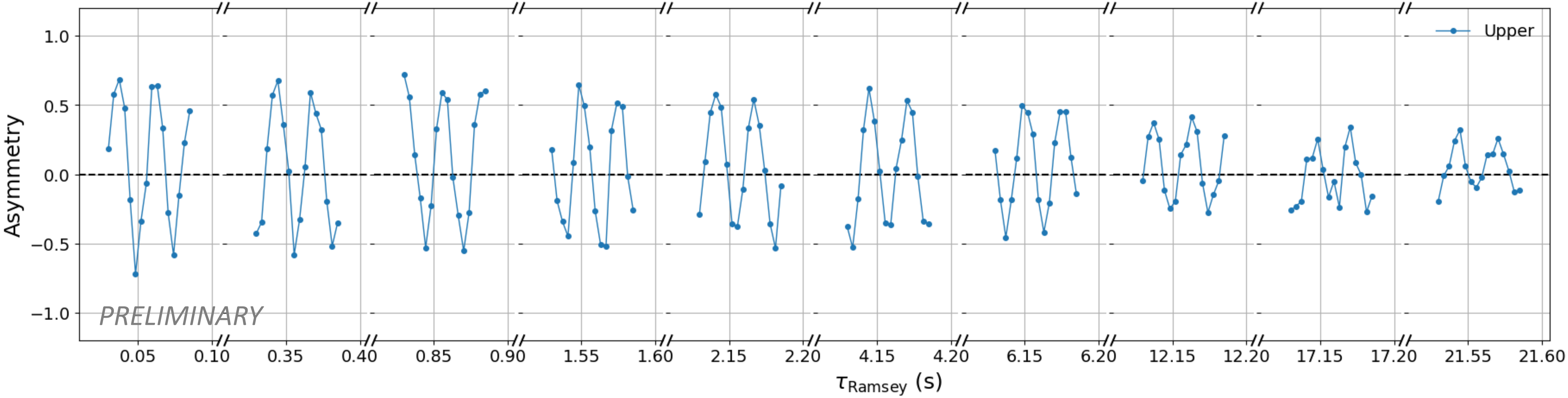
Long coherence time

Goal: improved measurement of the eEDM in the next 2 years



Current status: Ramsey fringes with >21 s of spin coherence with ThF^+

Park, et al., In preparation

Summary

- ~20 second coherence time, longest experimentally observed in literature in molecules
- Tested electrode geometry
  - Demonstrated coherence during translation
  - Demonstrated localized pi/2 pulse scheme
- Implementing upgrades in the prototype
  - New electronics to generate rotating electric field at higher frequency
  - Better understanding of our trap, can use new trap configurations
  - Improved ion detection scheme
- Actively designing the next-generation apparatus and software architecture
- Mock measurement in the prototype
  - Will not be record measurement but a new measurement using ThF^+
  - First proof of principle experiment for “batch-mode” mode for precision measurement

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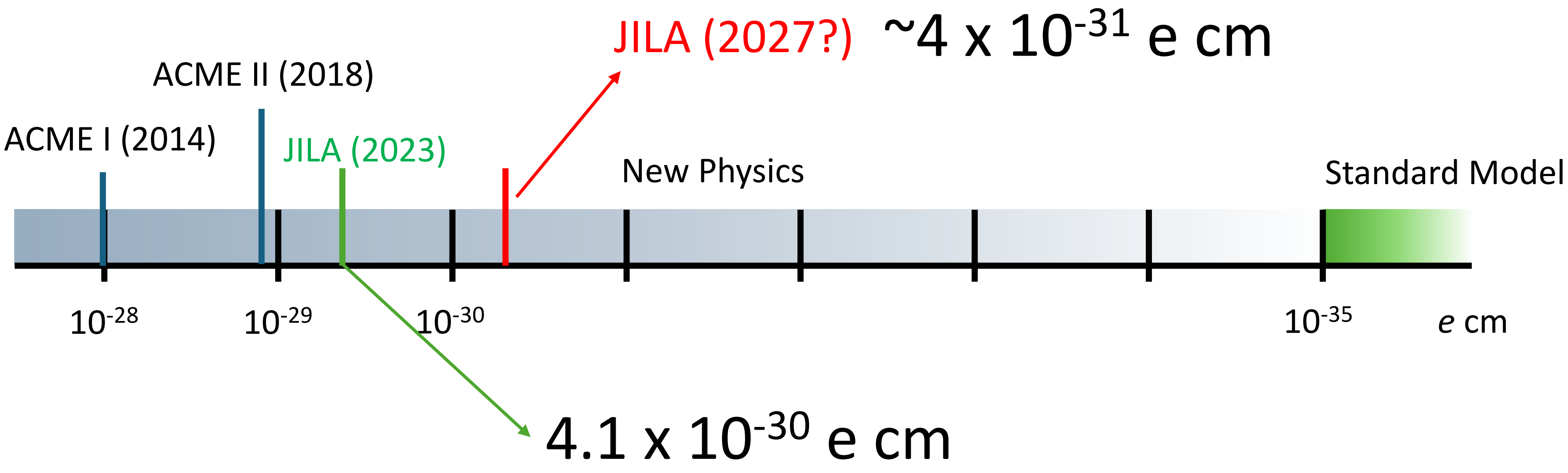
Experimental upper bound on eEDM



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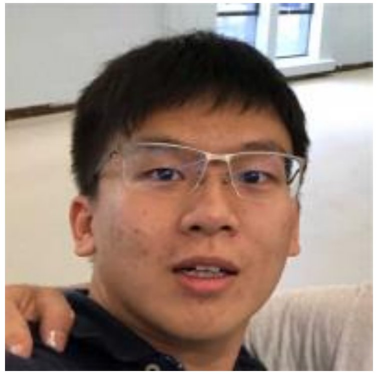
Roussy, et al. *Science 381.6653* (2023): 46-50

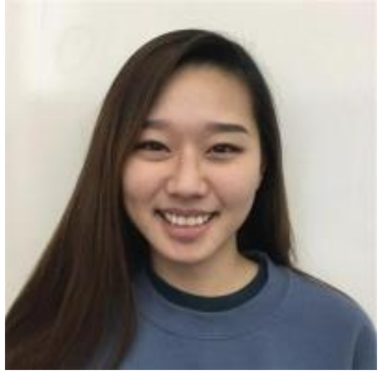
eEDM Members

Past member/current collaborator: Kia Boon Ng

Undergraduate: Rohan Kompella

PIs: Eric Cornell, Jun Ye





Postdoc: Michail Athanasakis-Kaklamanakis
Graduate students: Patricia Hector-Hernandez, Tuan Nguyen, Anzhou Wang, Sun Yool Park

JILA

Acknowledgement

• Marsico Research Chair

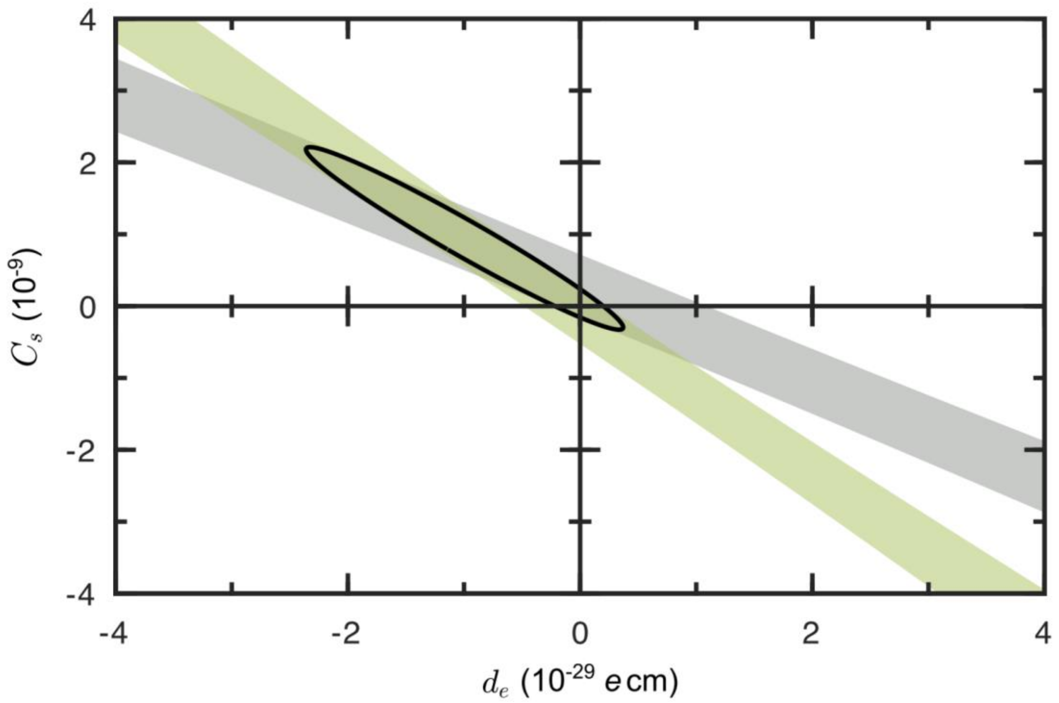
Thank you for your attention!

Global analysis

Nuclear interactions with the electron can also give rise to eEDM

$$E^{CP} = 2d_e\mathcal{E}_{\text{eff}} + 2C_sW_s$$

C_s: a pseudoscalar-scalar electron-nucleon coupling
W_s: molecule-specific constant



Green: 90% confidence level from JILA using HfF+
Grey: 90% confidence level from ACME using ThO

T. Chupp, et al., Rev. Mod. Phys. **91**, 015001 (2018)
T. Fleig, M. Jung, J. High Energy Phys. 2018, 12 (2018).
Roussy, et al. *Science 381.6653* (2023): 46-50)
ACME Collaboration, Nature 562, 355–360 (2018)

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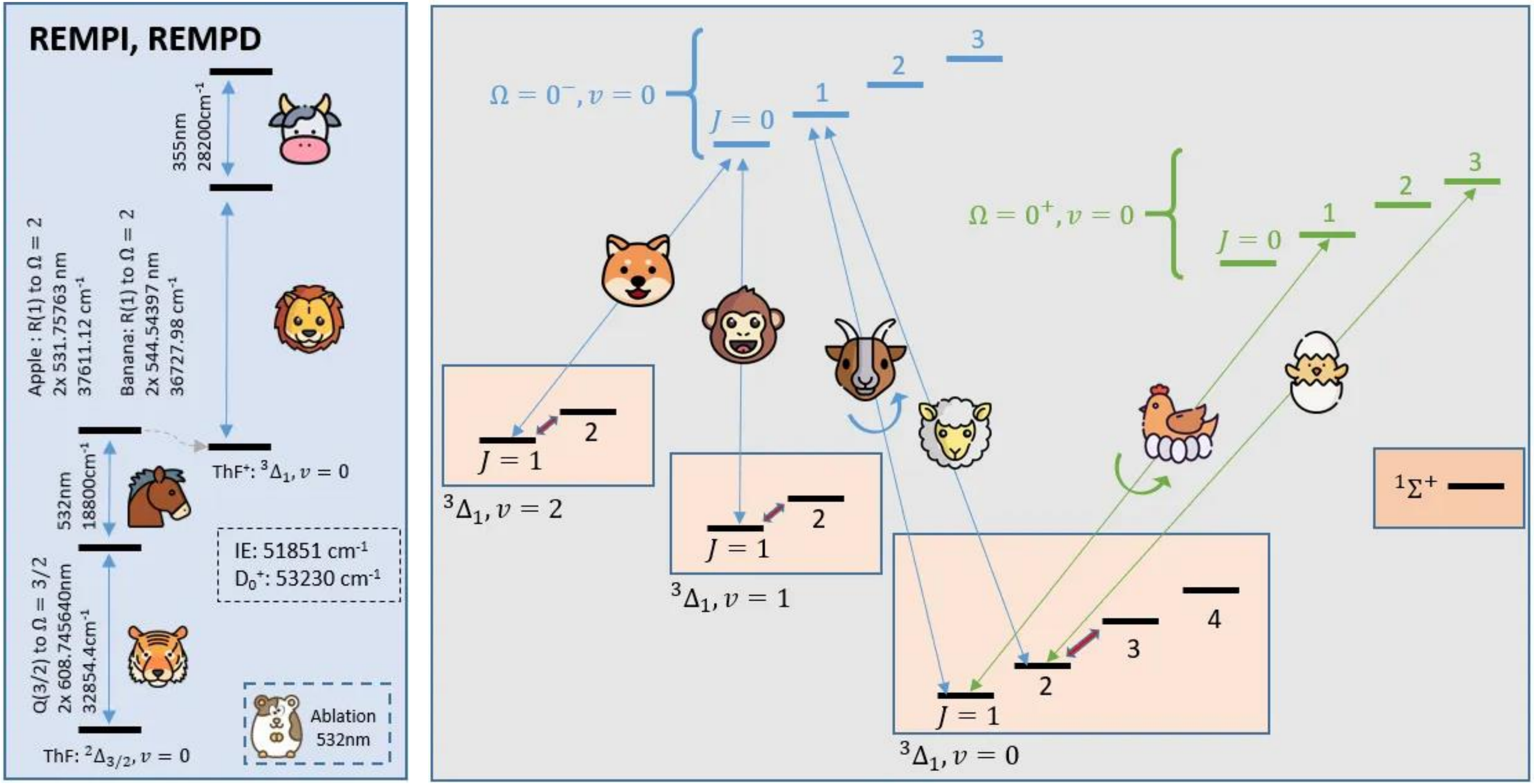
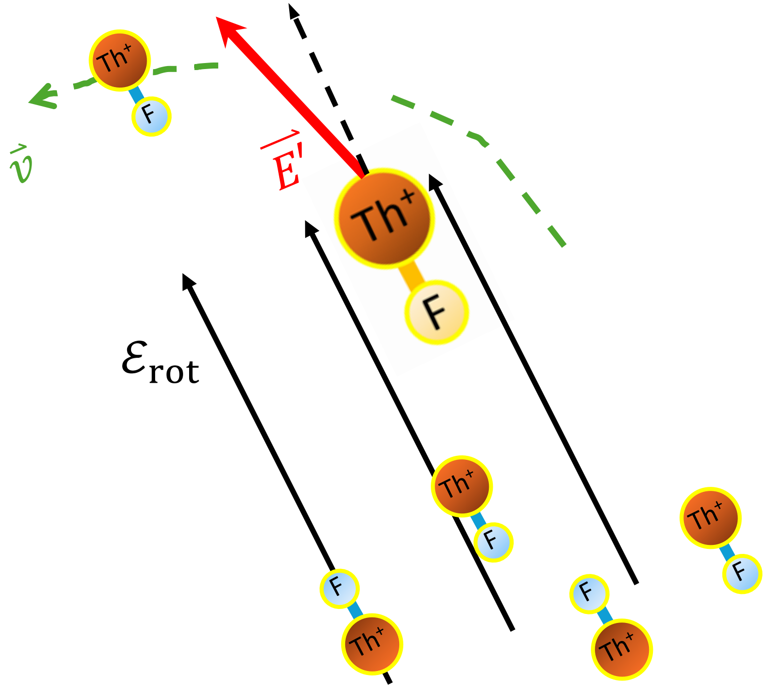


REMPI, REMPD
355nm
28200cm-1
Apple : R(1) to Ω = 2
2x 531.75763 nm
37611.12 cm-1
Banana: R(1) to Ω = 2
2x 544.54397 nm
36727.98 cm-1
ThF+: 3Δ1, v = 0
532nm
18800cm-1
Q(3/2) to Ω = 3/2
2x 608.745640nm
32854.4cm-1
IE: 51851 cm-1
D0+: 53230 cm-1
Ablation
532nm
ThF: 2Δ3/2, v = 0
Ω = 0−, v = 0
J = 0
1
2
3
Ω = 0+, v = 0
J = 0
1
2
3
J = 1
2
3Δ1, v = 2
J = 1
2
3Δ1, v = 1
J = 1
2
3
4
3Δ1, v = 0
1Σ+

Ramsey coherence time: $\Gamma_{\text{ion-ion}}$

In the high collision energy limit (each collision results in decoherence),



$$\mathcal{E}_{\text{Ion-ion}} \sim \mathcal{E}_{\text{rot}}$$

$$\Gamma = n\,\sigma\,v \sim \frac{n\sqrt{T}}{\mathcal{E}_{\text{rot}}} \sim \frac{\omega^2}{\mathcal{E}_{\text{rot}}}$$

With adiabatic cooling/heating

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Improved state detection

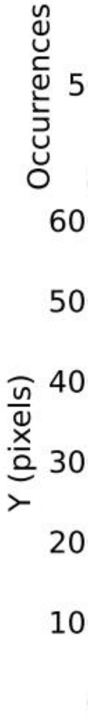
REMPAD protocol

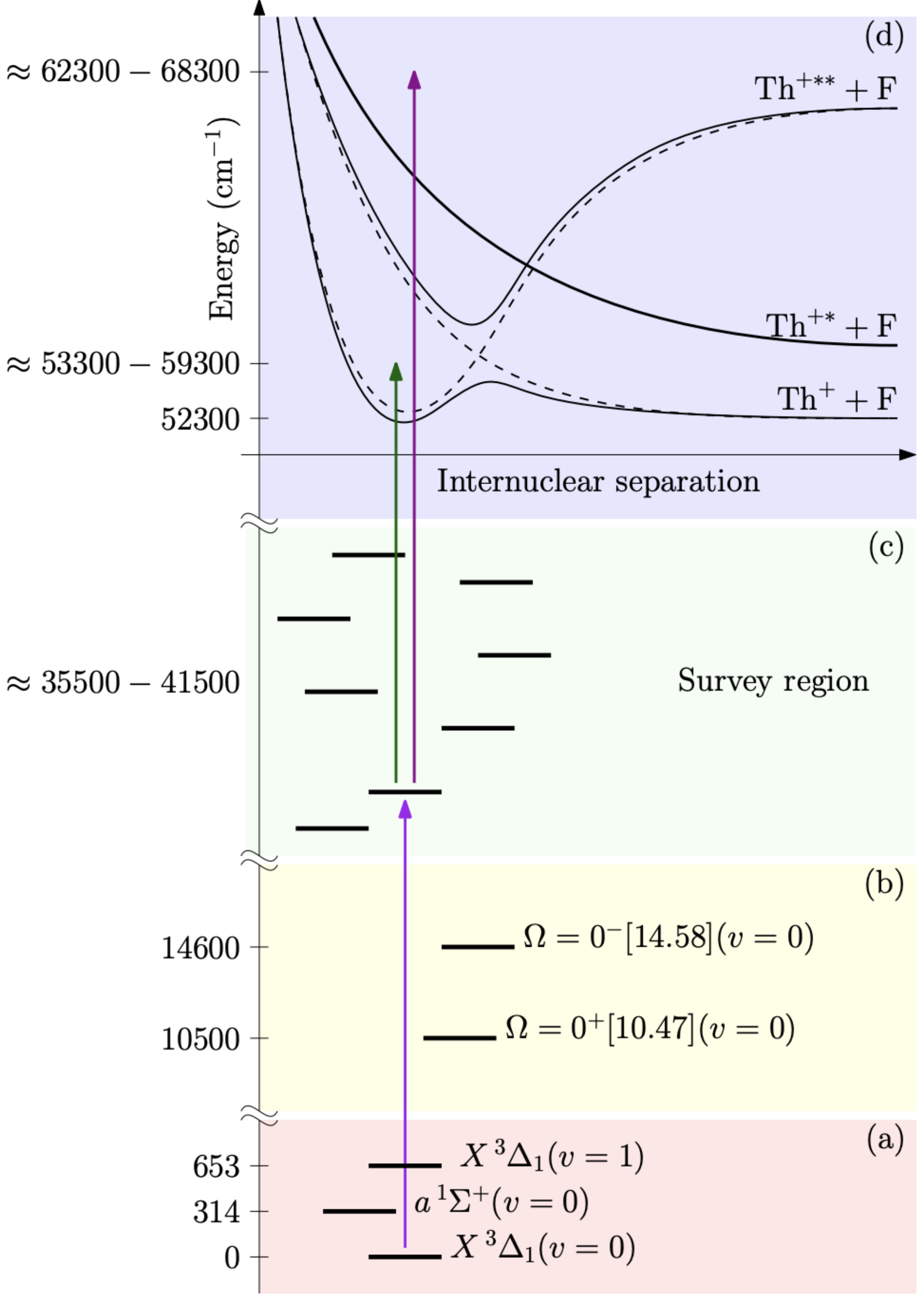
Resonantly **E**nhanced **M**ulti**P**hoton **A**symmetric **D**

Previously, dissociation efficiency ~ 4%

Survey spectroscopy over 6000 cm^{-1} to look for a “better” dissociation transition

New transitions with dissociation efficiency as high as 57(15)% with good dissociation anisotropy



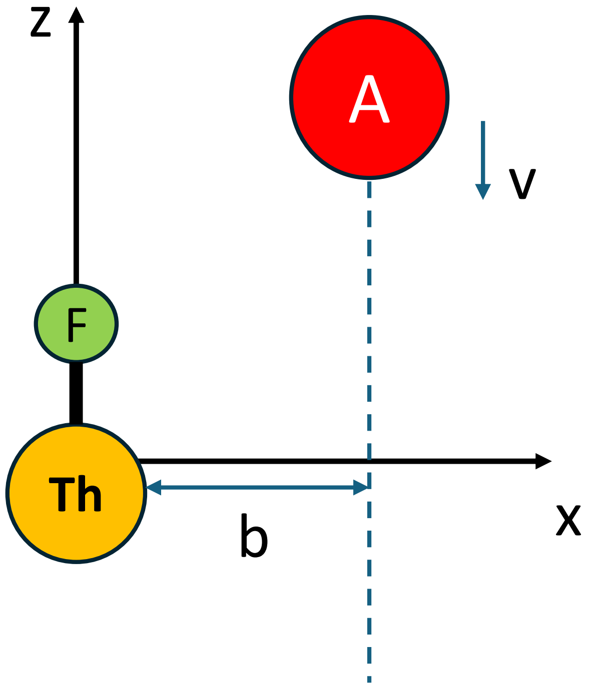


J=1 lifetime: $\Gamma_{\mathrm{ion-neutral}}$

- Langevin-like collisions between ions and neutral gas
- Can induce rotational level changes

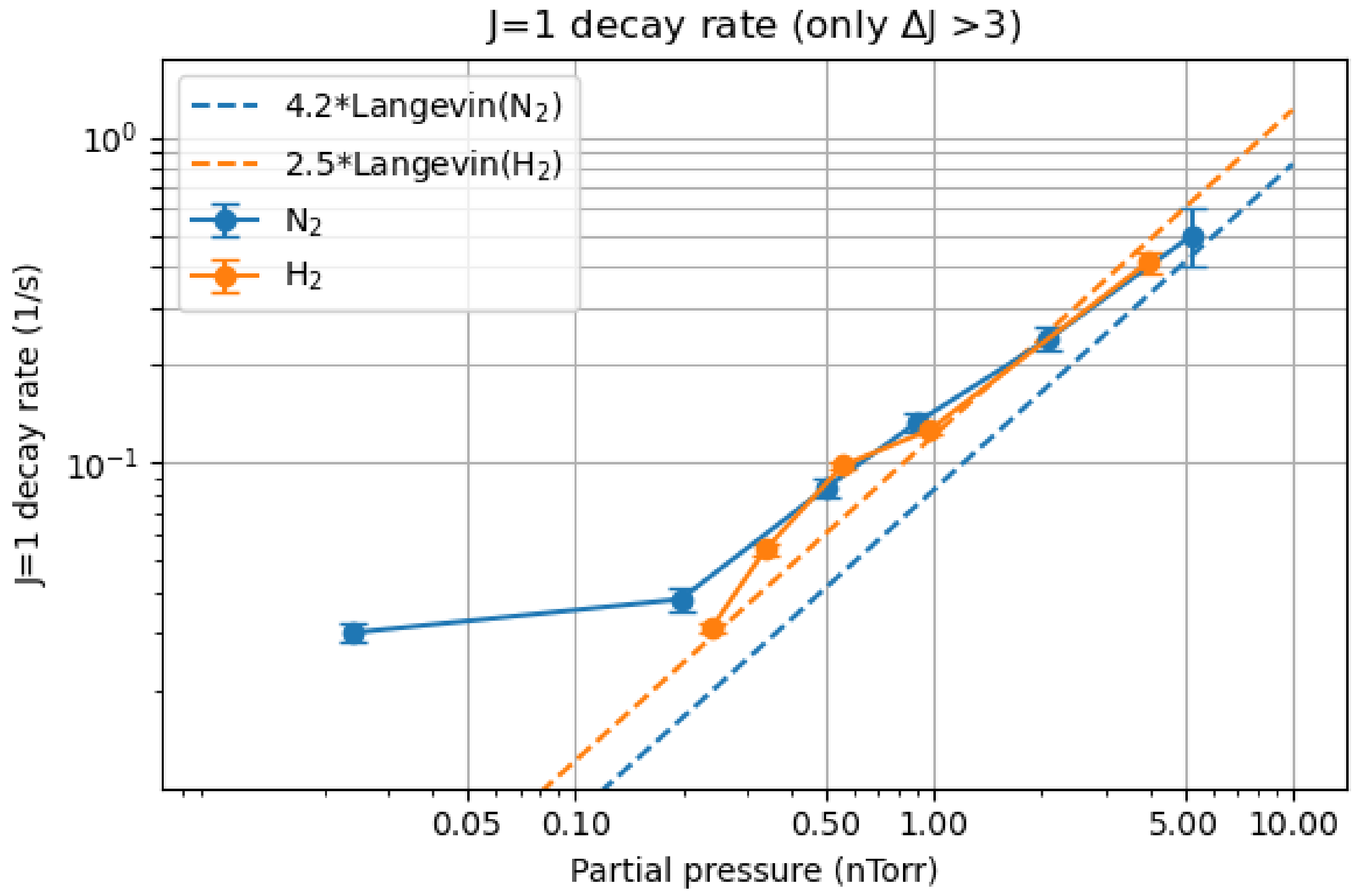
$$d_{mf} * \ \mathcal{E}_{coll} * T_{pass} \sim \hbar\, \omega_J$$

A = Neutral background gas (Ne, N_2, H_2, …)



J=1 lifetime: $\Gamma_{\text{ion}-\text{neutral}}$

- $\Gamma_{J-\text{level changing}} \gg \Gamma_{\text{Langevin}}$
- Add N_2 and H_2 to the system and observed their effect on J=1 decay rate.
- Quantitatively agree with numerical simulation within a factor of 2~3.



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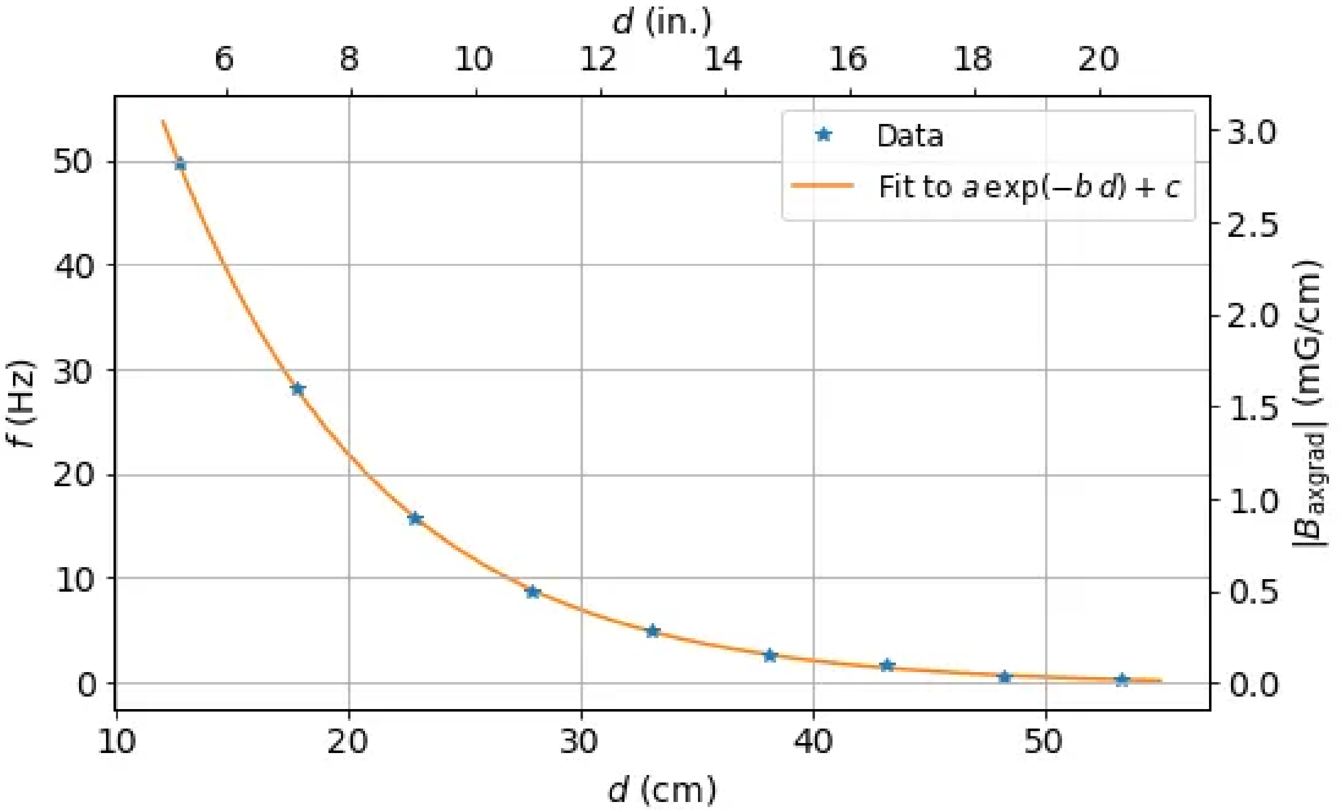
At 10^{-4} level, (almost) all effects matter



Magnetic field from cryocooler

Sad and frustrated grad student

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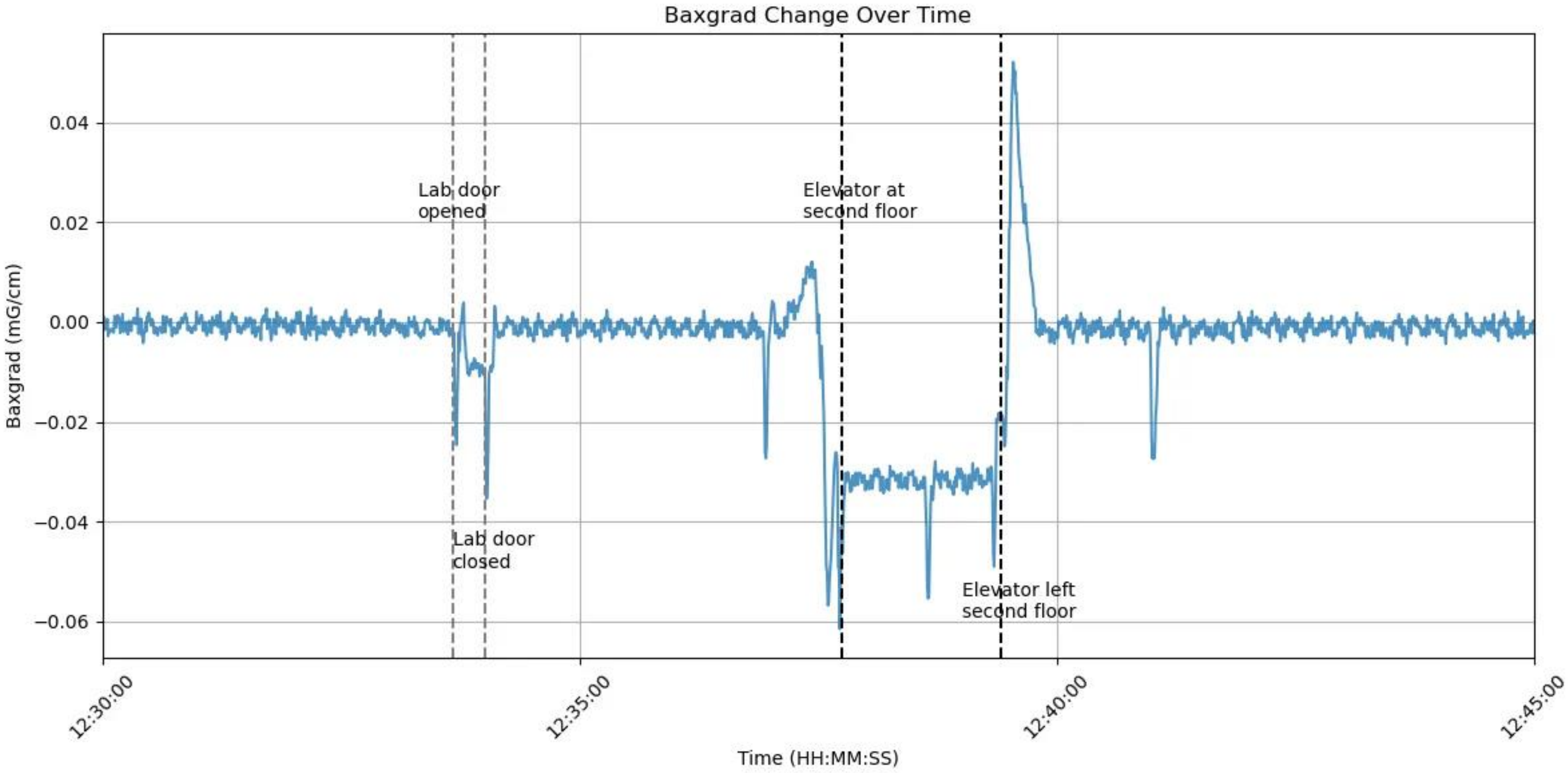
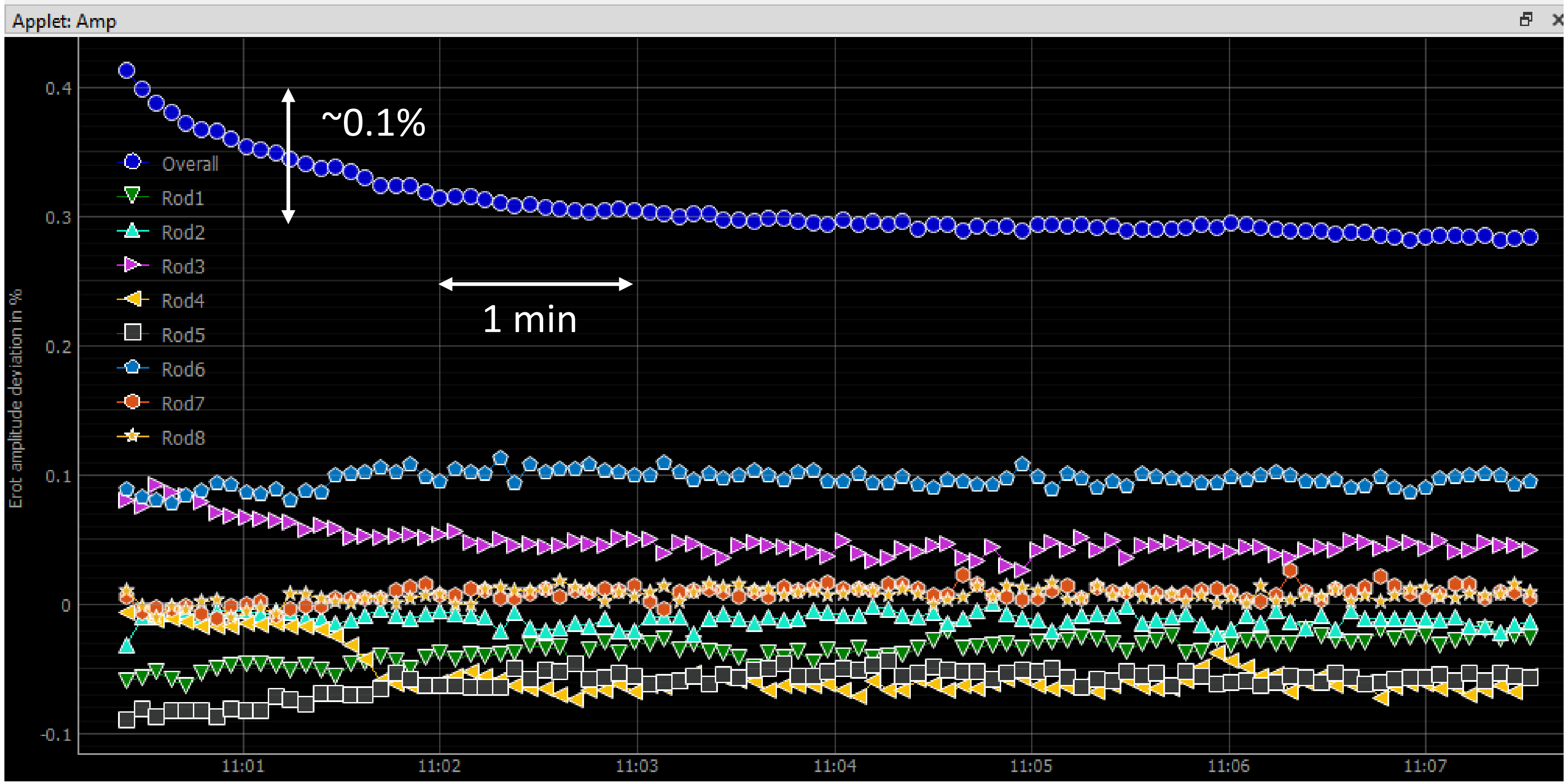
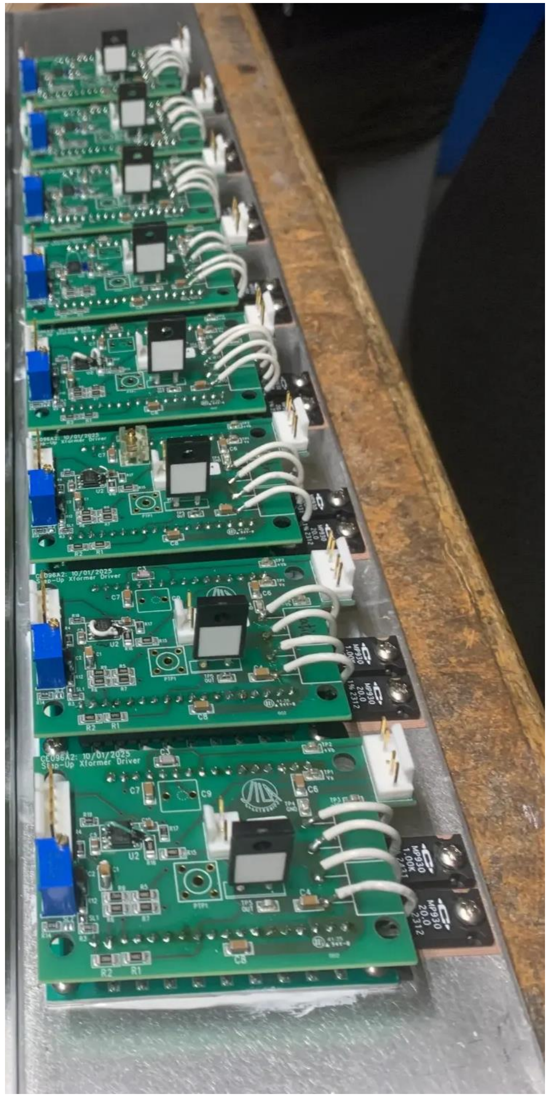
Magnetic field from elevator/door





Power op-amps warming up



Switches

- Repeat experiment slightly differently
- Take sum-/difference- combination

Channel	Leading term	Interpretation
f^0	$3\|g_F\|\mu_B \mathcal{B}_{\rm rot}/h$	Avg. precession frequency
f^B	$3\|g_F\|\mu_B \mathcal{B}_{\rm rot}^{\rm nr}/h$	Non-reversing $\mathcal{B}_{\rm rot}$
f^D	$3\delta g_{\rm eff}\mu_B \mathcal{B}_{\rm rot}{\rm sgn}(g_F)/h$	Level-dependent g-factor
f^{BR}	$-3\langle\alpha\rangle f_{\rm rot}{\rm sgn}(g_F)$	Geometric phase
f^{BD}	$-2d_e\|\mathcal{E}_{\rm eff}\|\,{\rm sgn}(g_F)/h$	eEDM shift

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