

Measuring the electron EDM using ultracold YbF molecules

Elise Wursten

EDMs2026: WE-Heraeus Workshop

1-6 March 2026

IMPERIAL

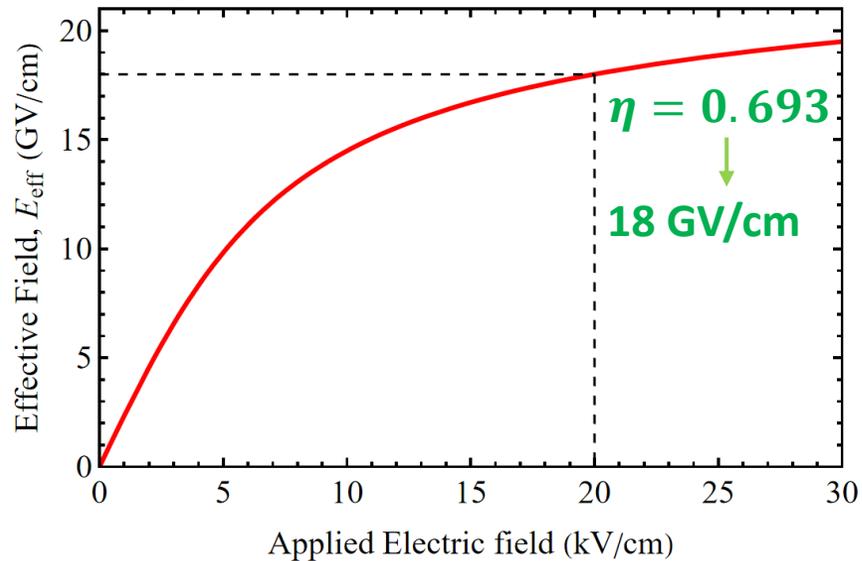
YbF is the best molecule ever

$$\sigma_{de} = \frac{\hbar}{2 |E_{\text{eff}}| \tau C \sqrt{N}}$$

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Large Effective Field (max 26 GV/cm)



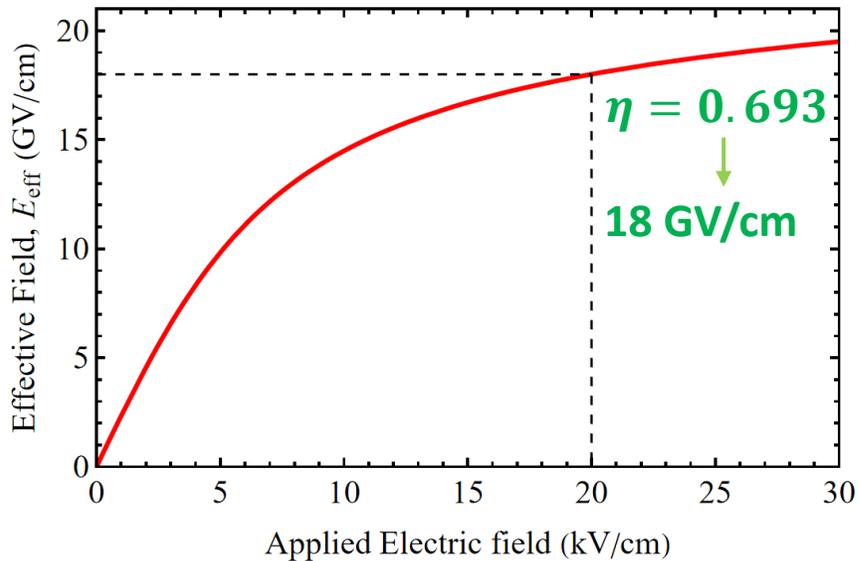
$\eta = 0.693$

18 GV/cm

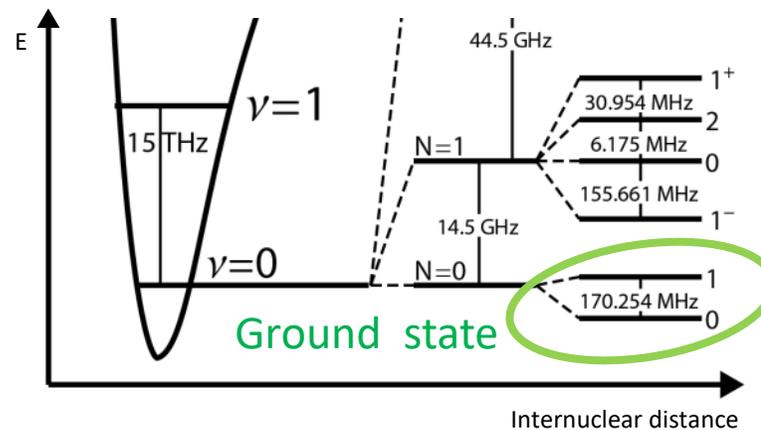
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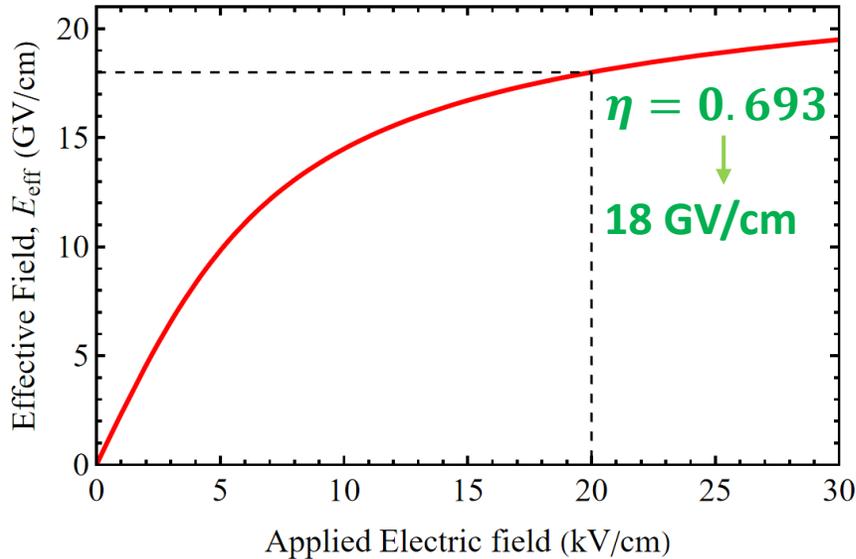


Long coherence times



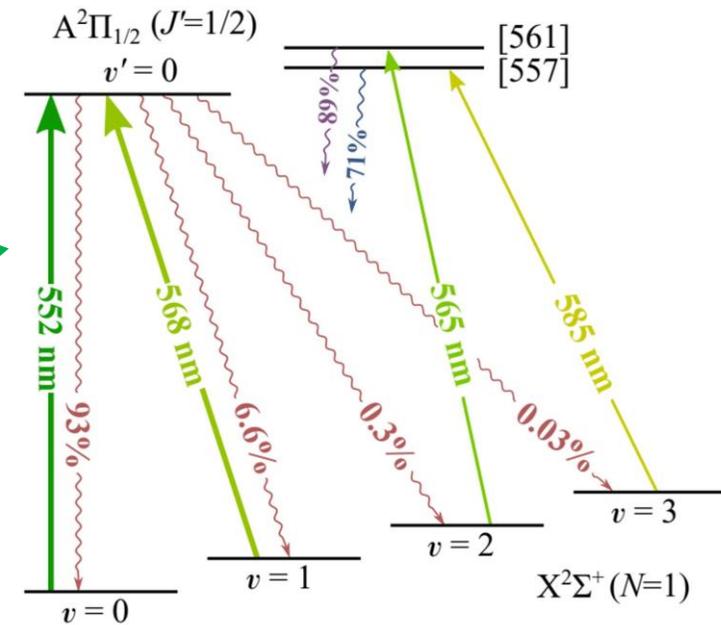
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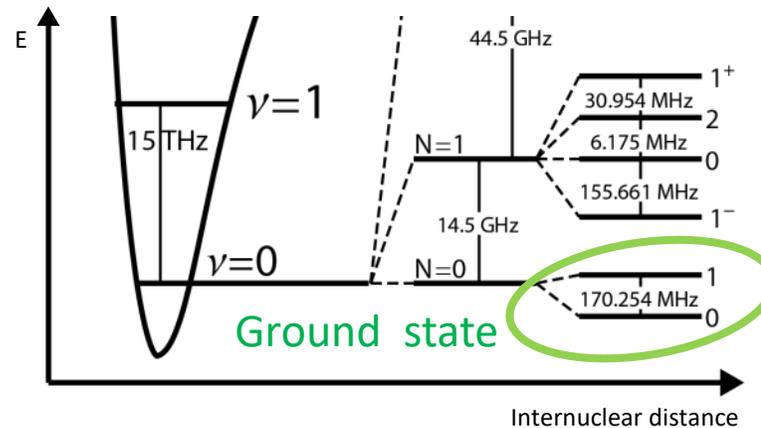


$$\sigma_{de} = \frac{\hbar}{2 |E_{\text{eff}}| \tau C \sqrt{N}}$$

Suitable for Laser Cooling

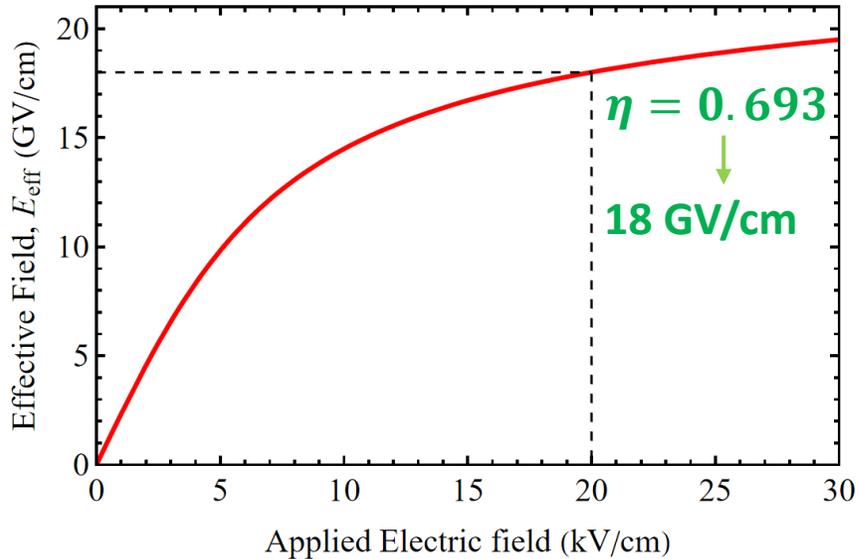


Long coherence times

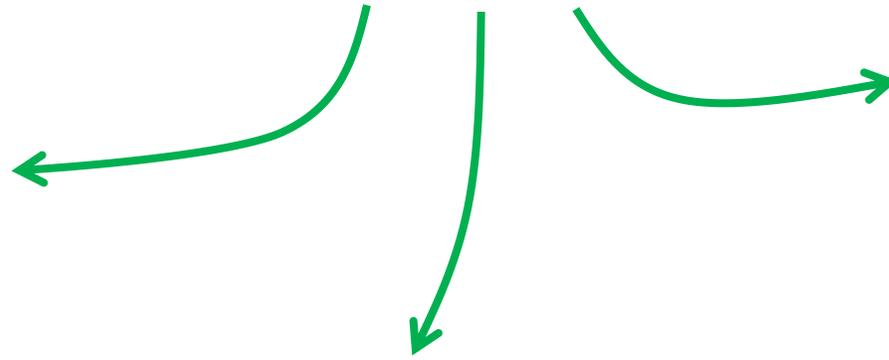


YbF is the ~~best~~ ^{worst} molecule ever

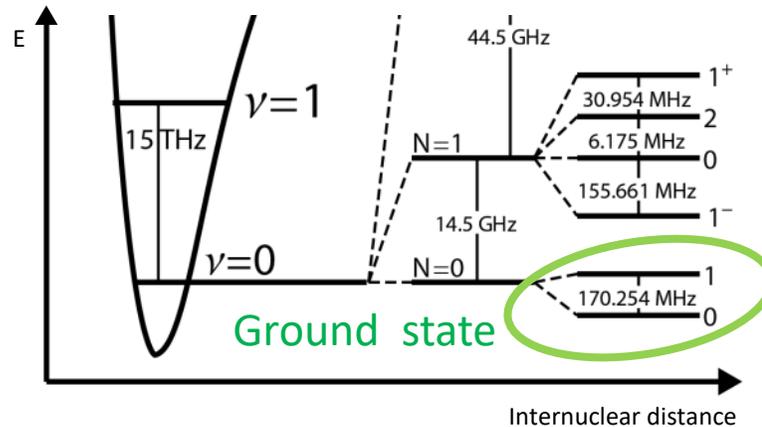
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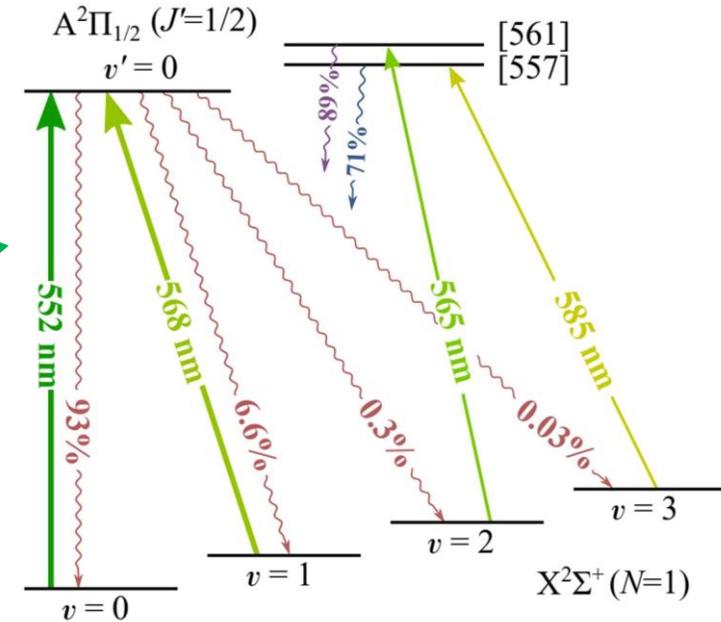
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Long coherence times



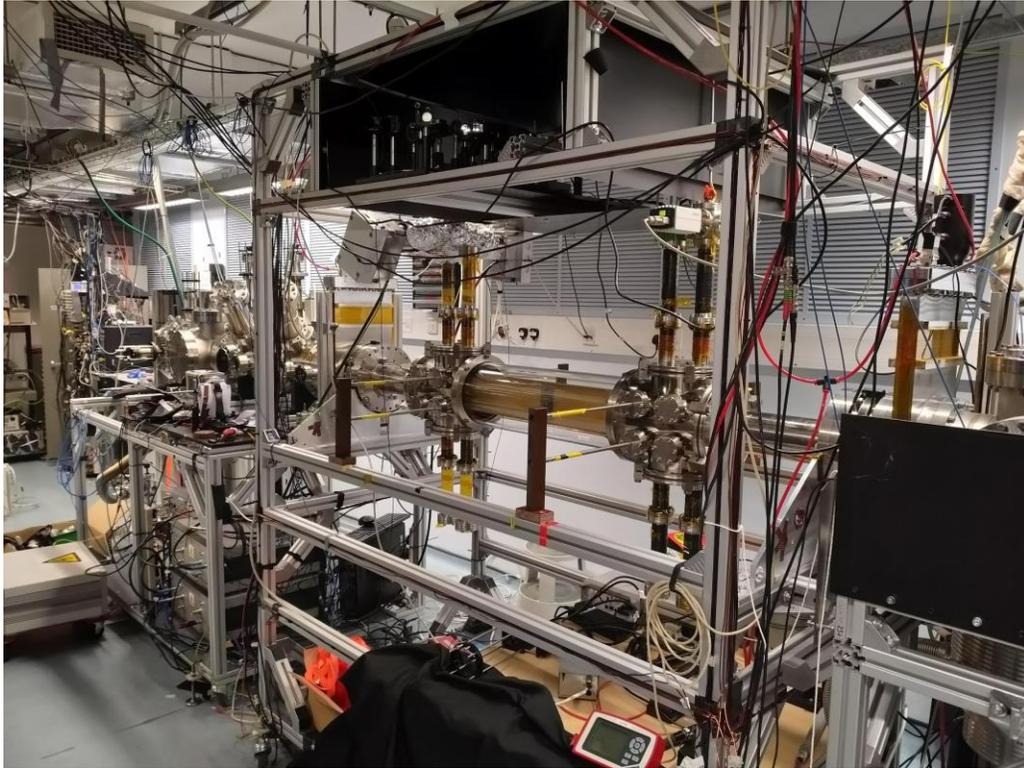
Suitable for Laser Cooling



$H = -\mu \cdot B - d_e \cdot E_{\text{eff}}$
 YbF is magnetic nightmare:
 $\mu = \mu_B$
 $d_e = 10^{-30} e \text{ cm}$ in $E=18 \text{ GV/cm}$
 is equivalent to $B = 0.3 \text{ fT}$

eEDM experiments with YbF at Imperial

Beamline experiment



Mike Tarbutt



Ben Sauer



Jongseok Lim



Shirley Zheng



Ferruccio Castellini



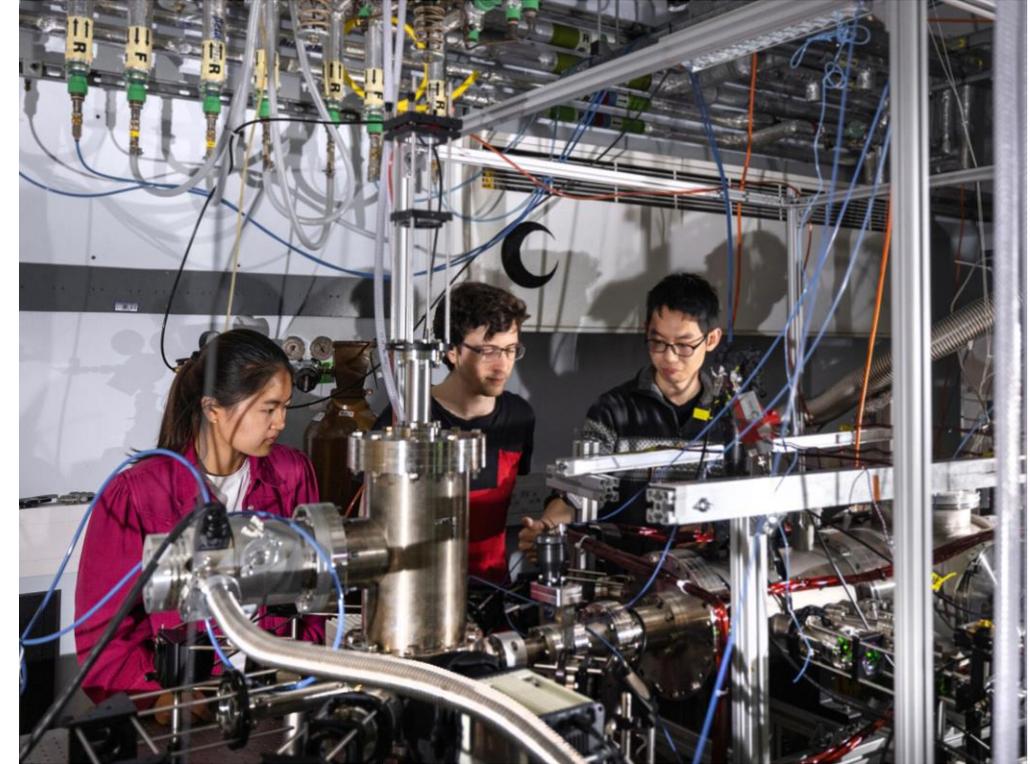
Michael Ziemba



Elise Wursten



Rhys Jenkins



Optical lattice experiment



Guanchen Peng



Clément Debavelaere

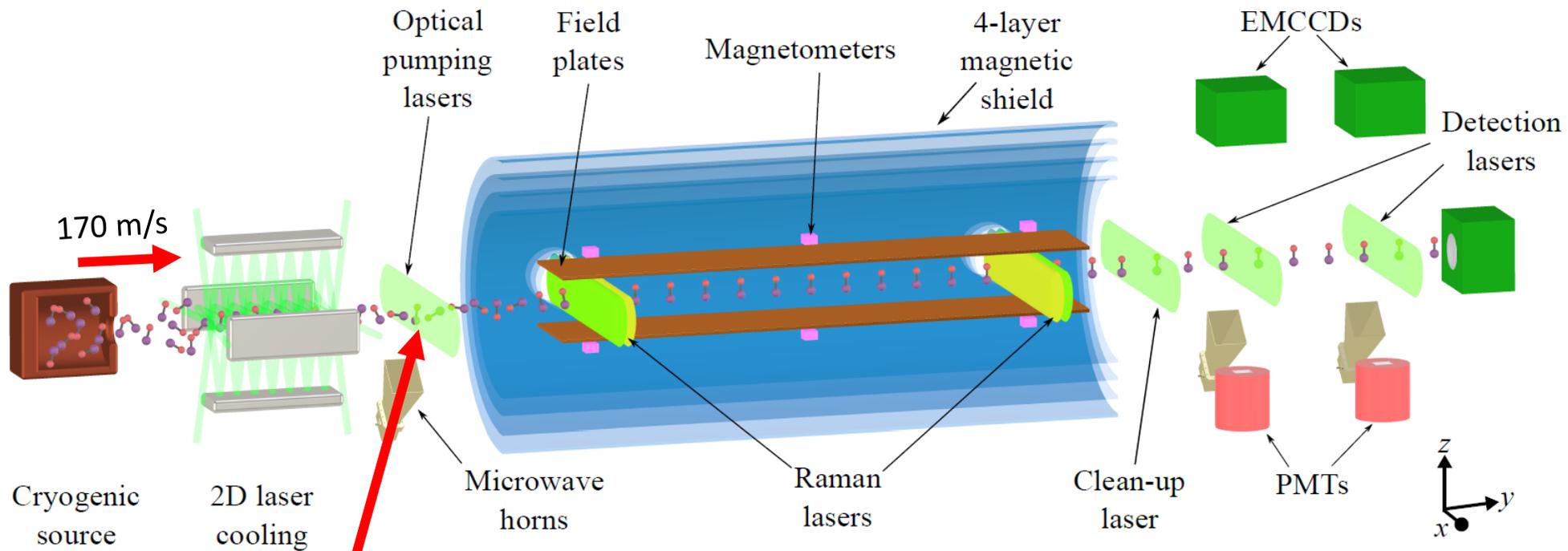


Simeng Li



Horacio Septien-Gonzalez

eEDM measurement

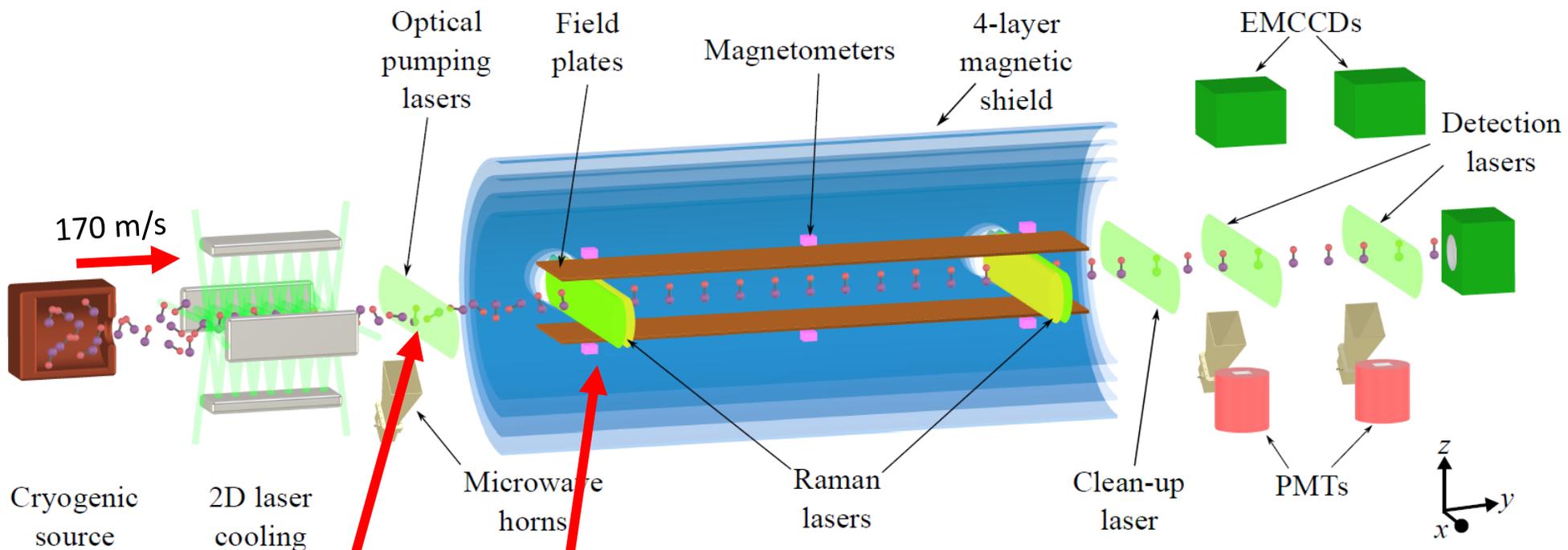


Initialise

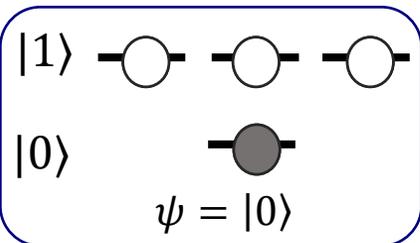
$|1\rangle$ ○ — ○ — ○ →

$|0\rangle$ ●
 $\psi = |0\rangle$

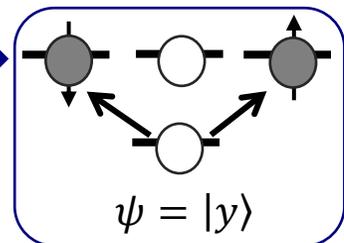
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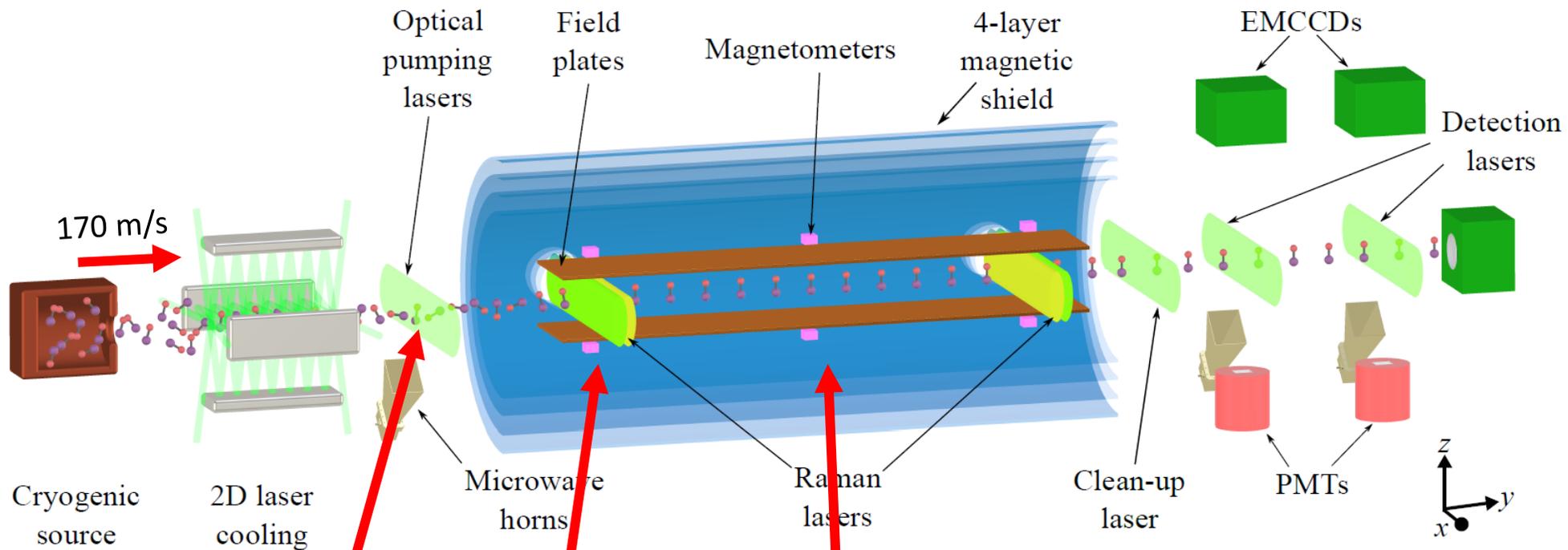
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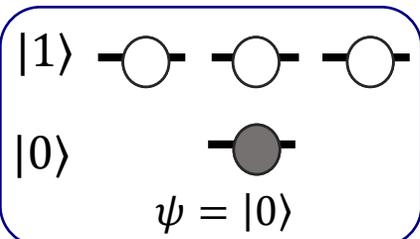
Polarise



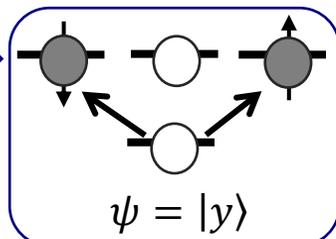
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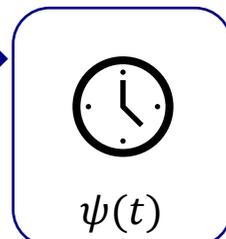
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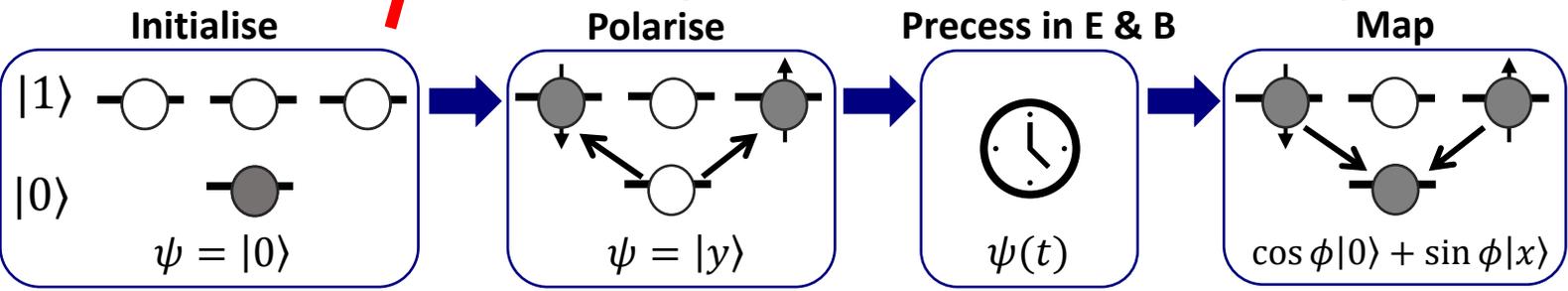
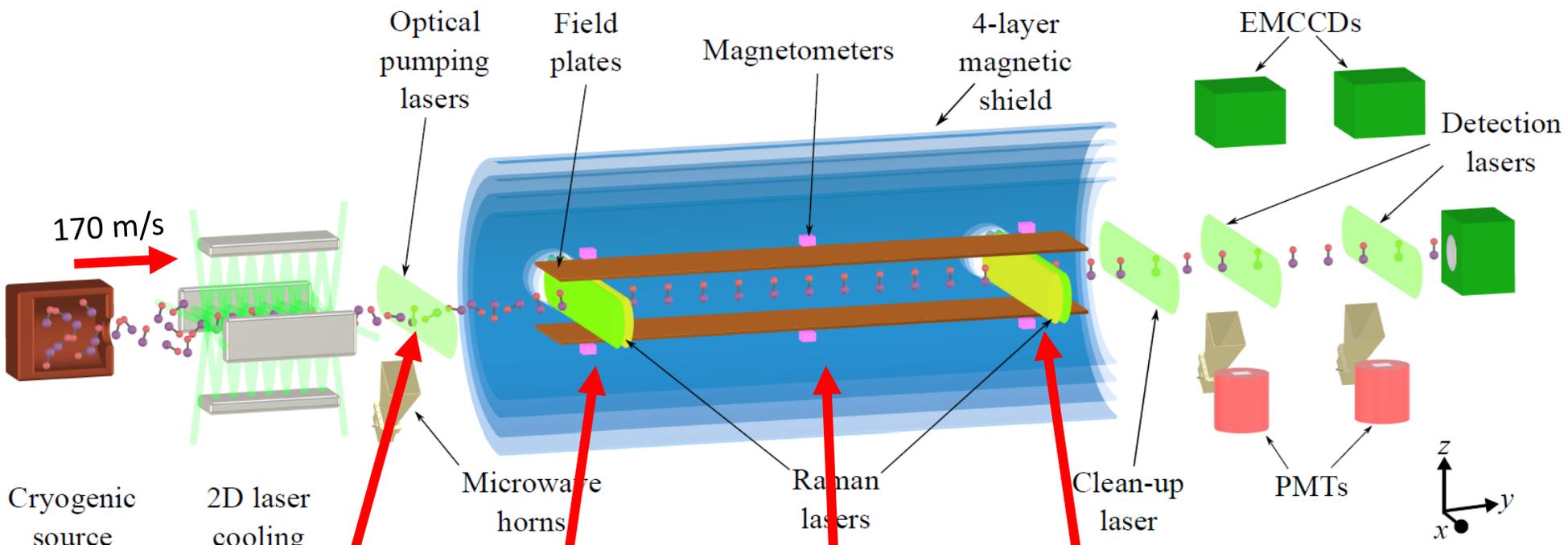
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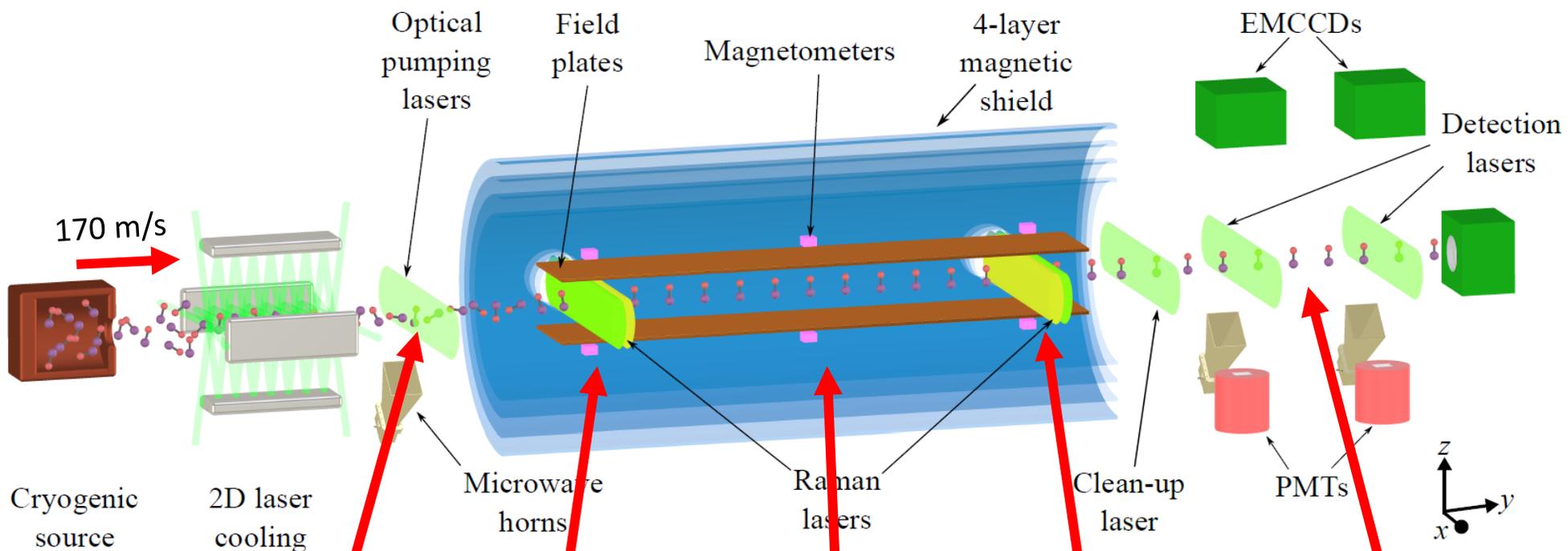
Precess in E & B



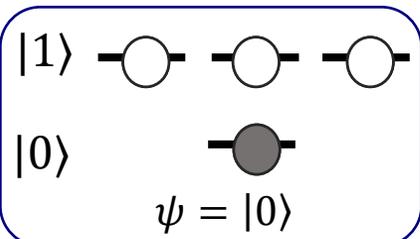
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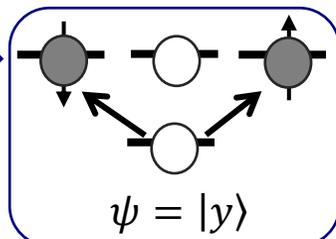
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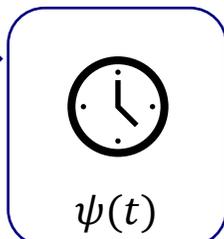
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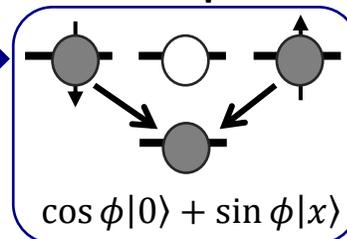
Polarise



Precess in E & B



Map

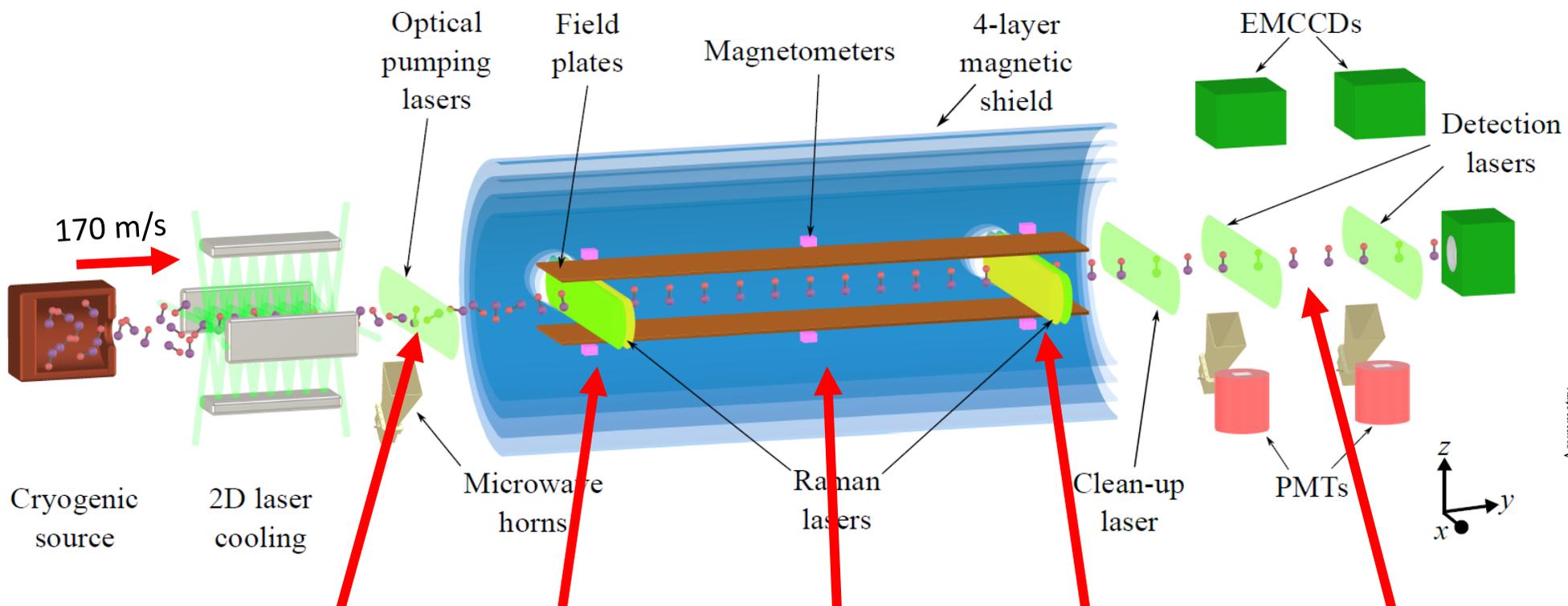


Measure

$$N_1 = \sin^2 \phi$$

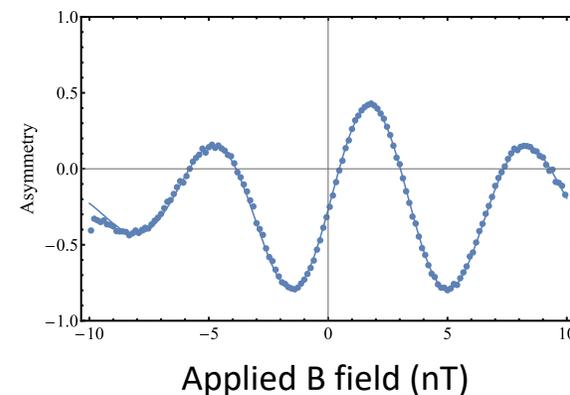
$$N_0 = \cos^2 \phi$$

eEDM measurement

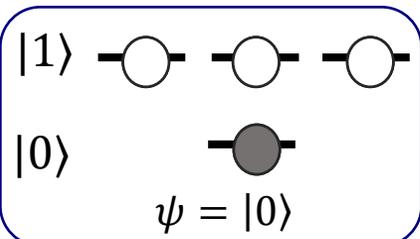


Accumulated phase

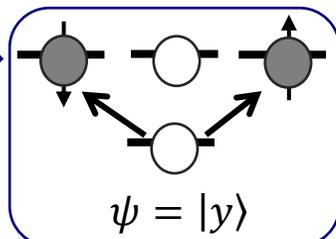
$$\phi = (\mu_B B - d_e E_{\text{eff}}) \frac{\tau}{\hbar}$$



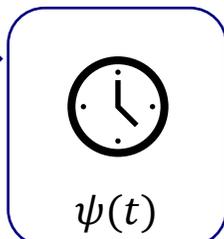
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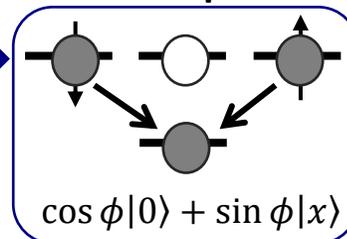
Polarise



Precess in E & B



Map

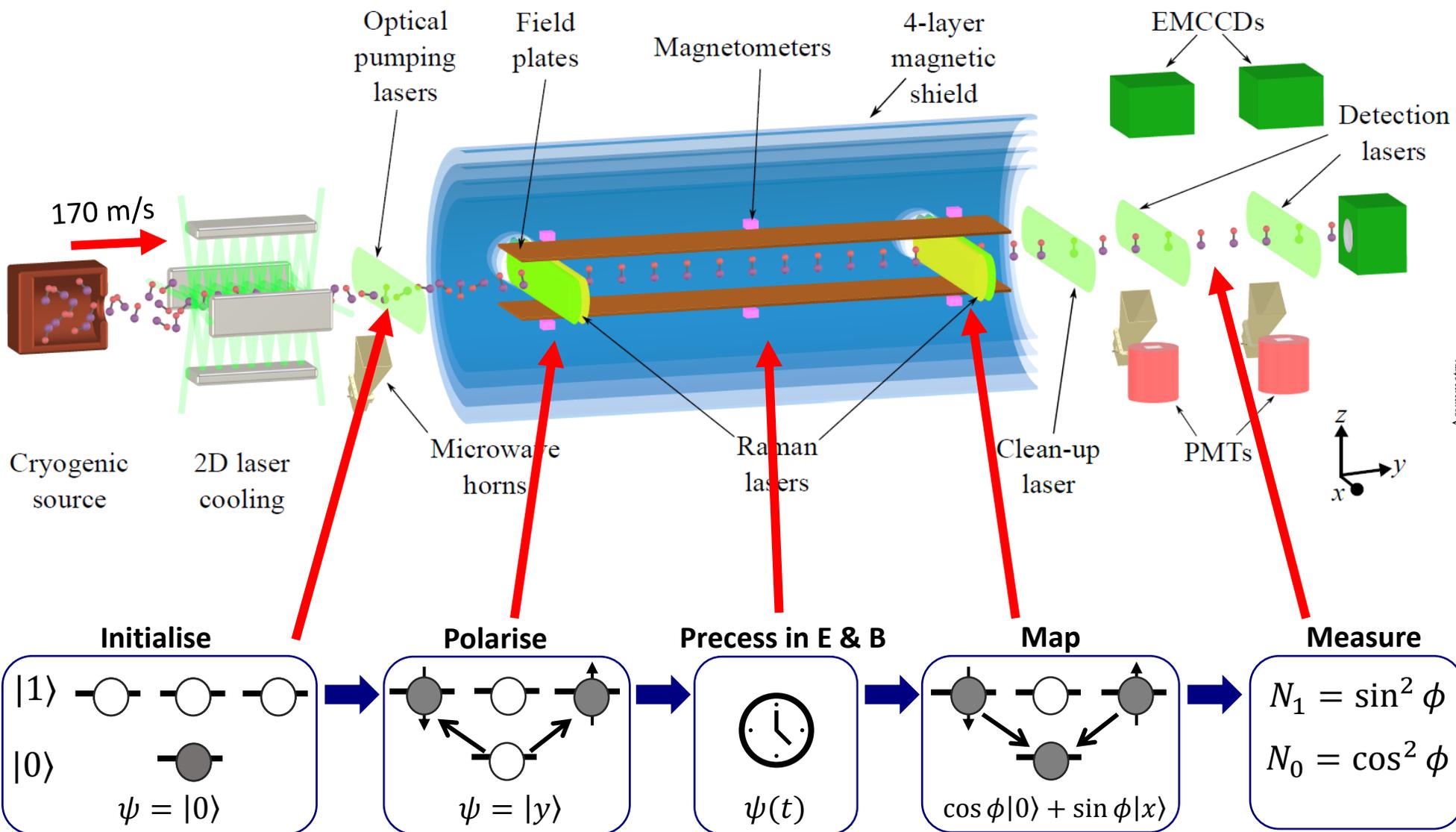


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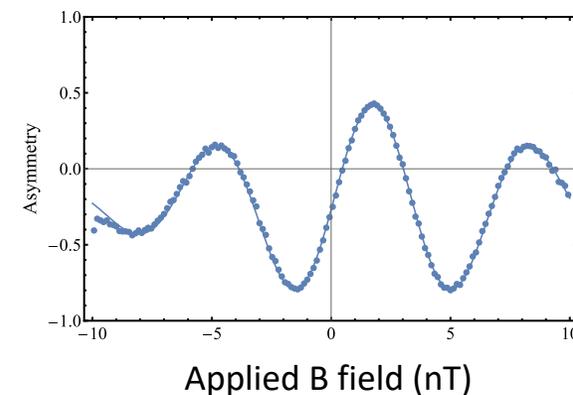
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eEDM measurement

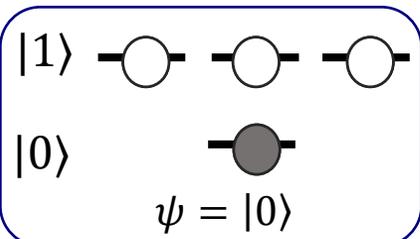


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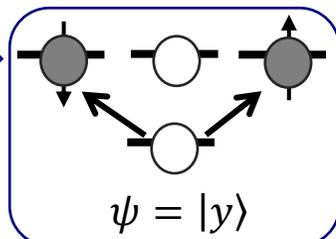
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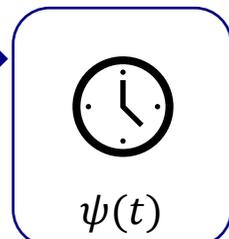
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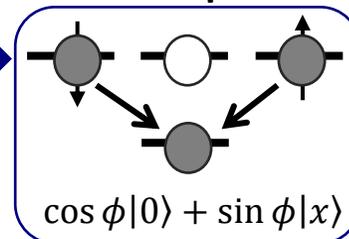
Polarise



Precess in E & B



Map



Measure

$$N_1 = \sin^2 \phi$$

$$N_0 = \cos^2 \phi$$

Statistical sensitivity

$$\sigma_{d_e} = \frac{\hbar}{2 |E_{\text{eff}}| \tau C \sqrt{N}}$$

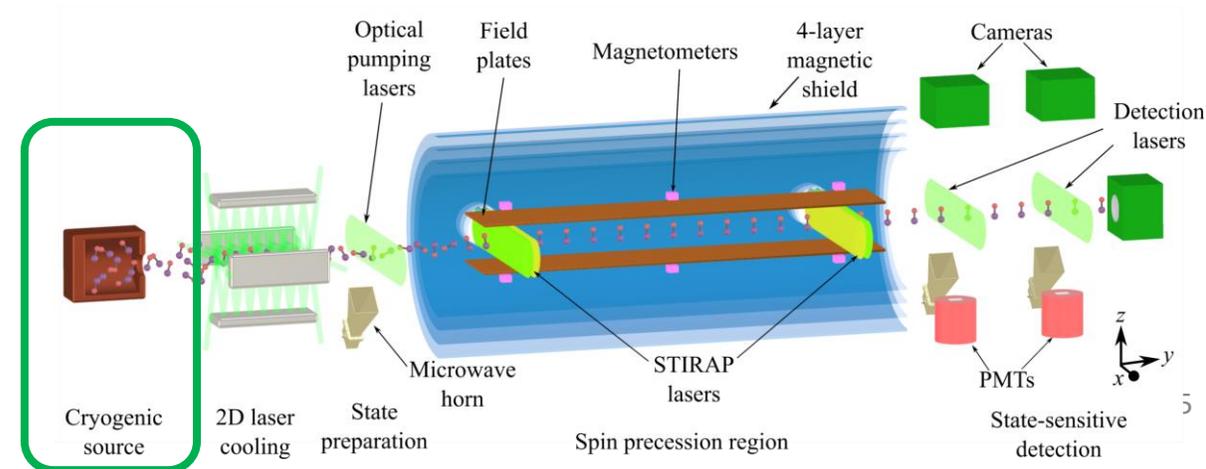
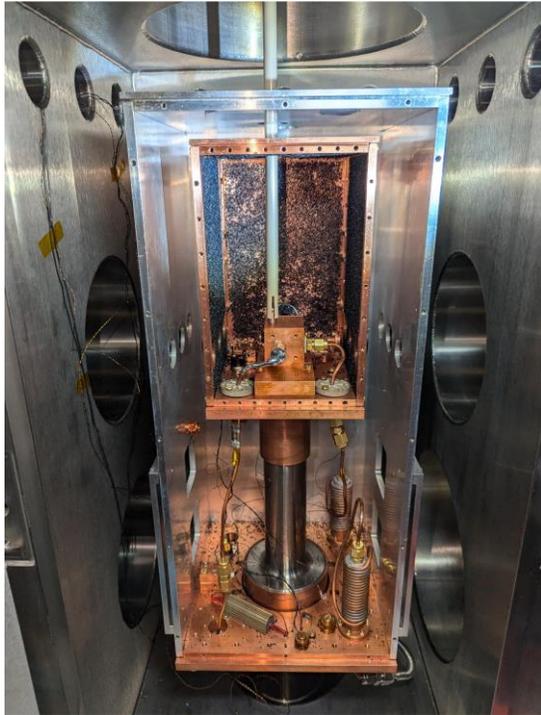
eEDM beamline setup

Cryogenic buffergas source

- Ablate Yb with a YAG laser
- mix with SF6 gas
- He as buffergas at 4K

Produces about 10^{10} molecules per steradian per pulse (every 200ms)

Creates a **diffuse** YbF beam with a mean forward velocity of about **170m/s**, most molecules are in the N=1 rotational state



eEDM beamline setup

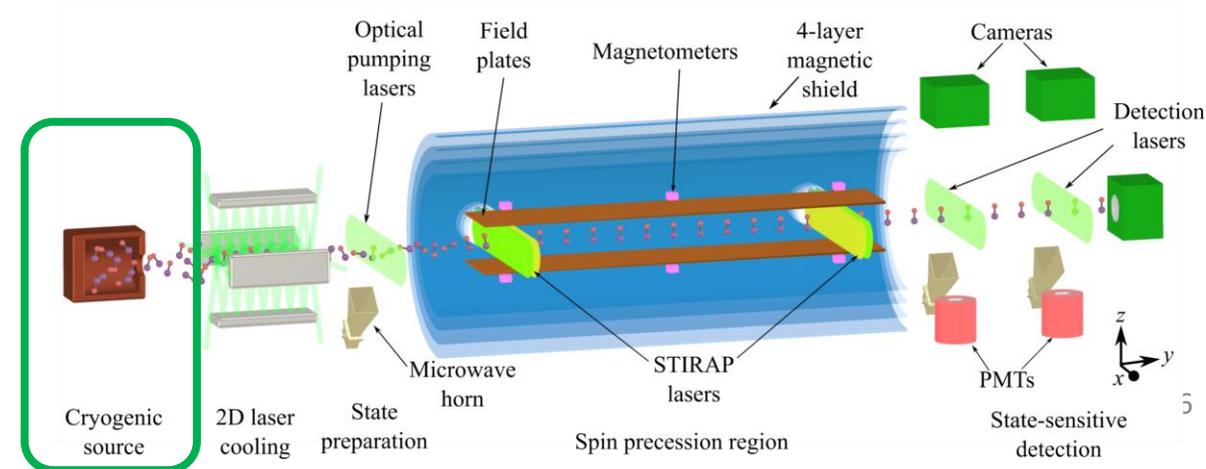
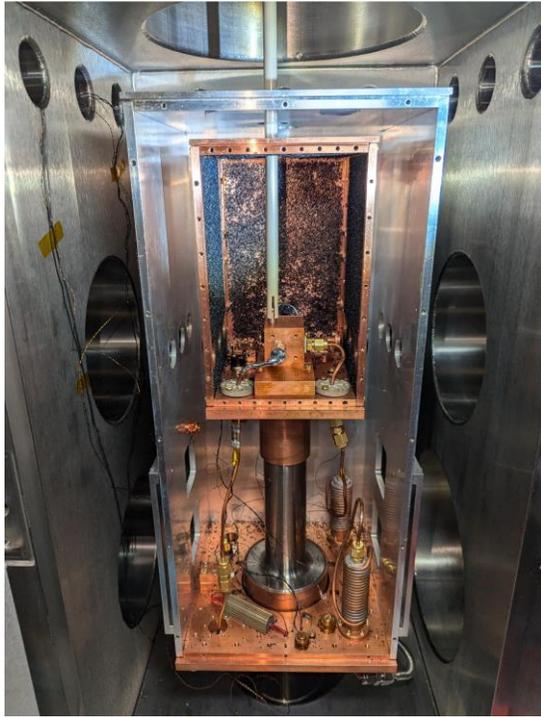
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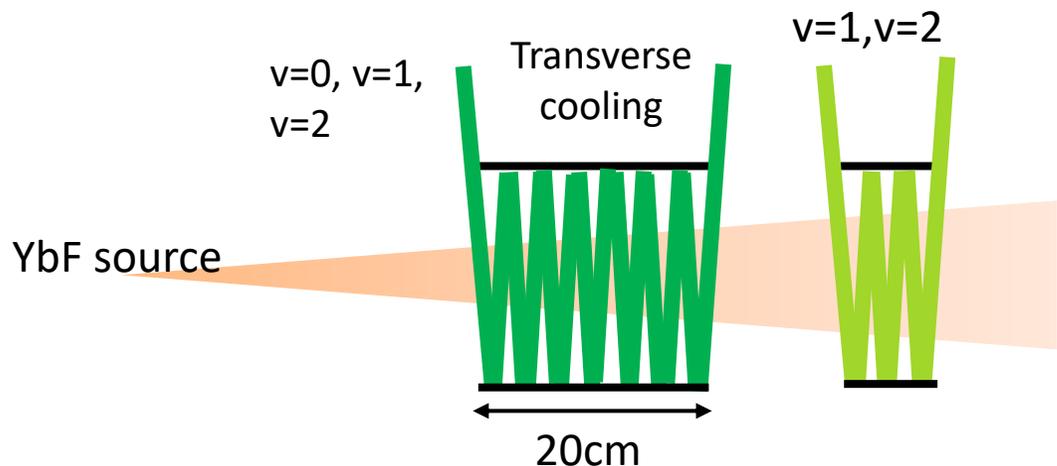
Creates a **diffuse** YbF beam with a mean forward velocity of about **170m/s**, most molecules are in the N=1 rotational state

Beamline is almost 5m long, so we need transverse cooling to increase the number of molecules reaching the detector!

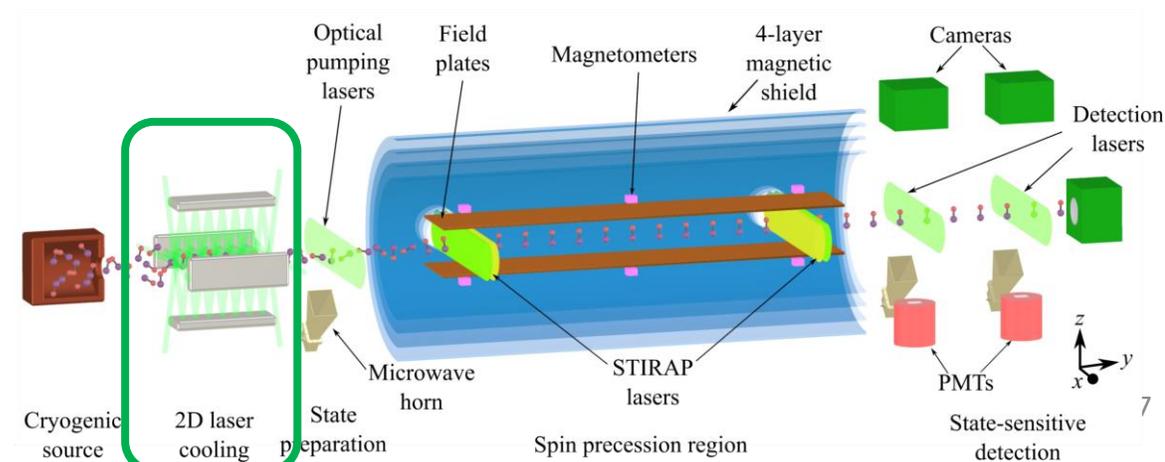
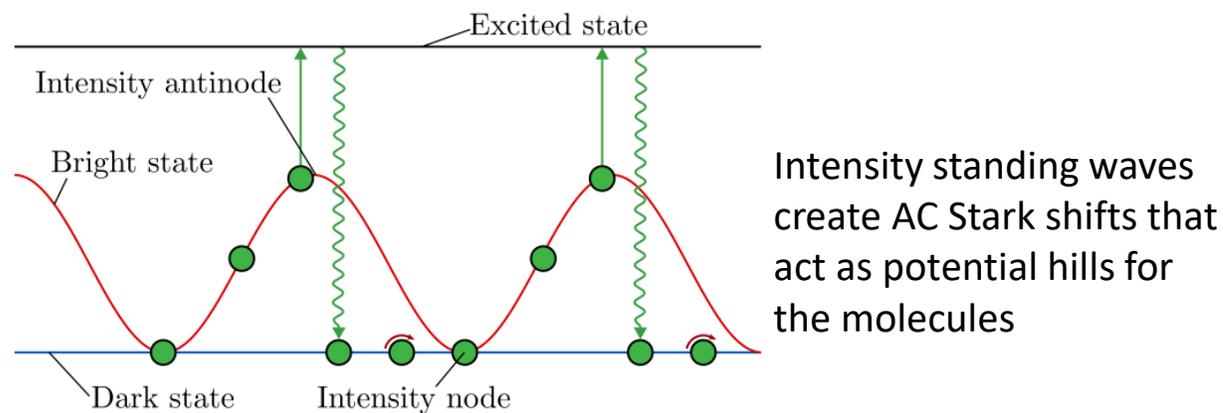


eEDM beamline setup

Transverse laser cooling

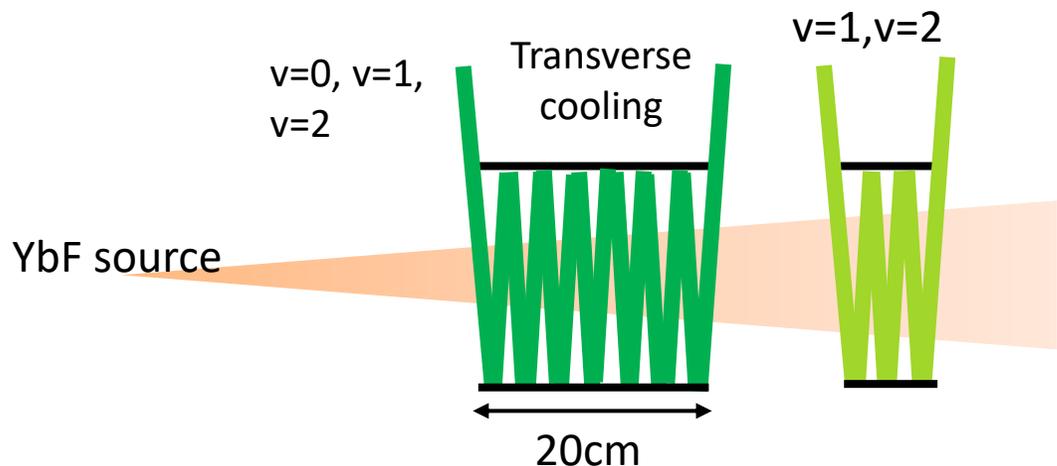


Based on magnetically assisted Sisyphus effect (MASE)

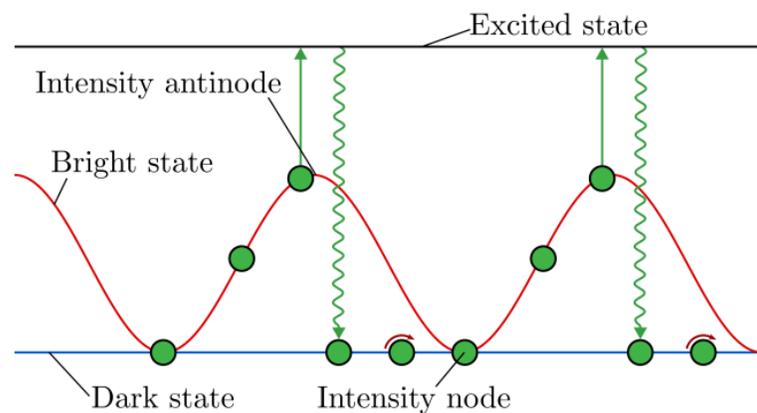


eEDM beamline setup

Transverse laser cooling

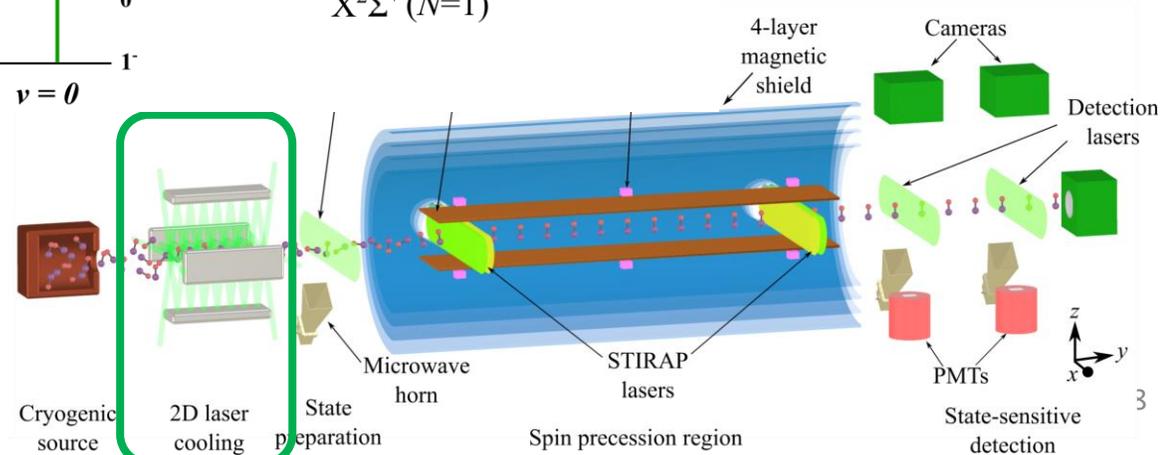
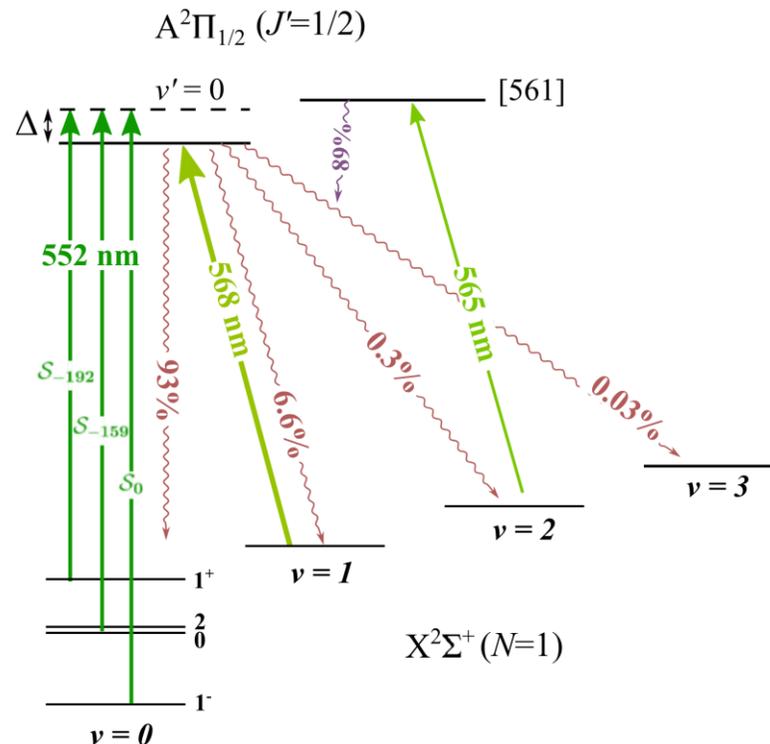


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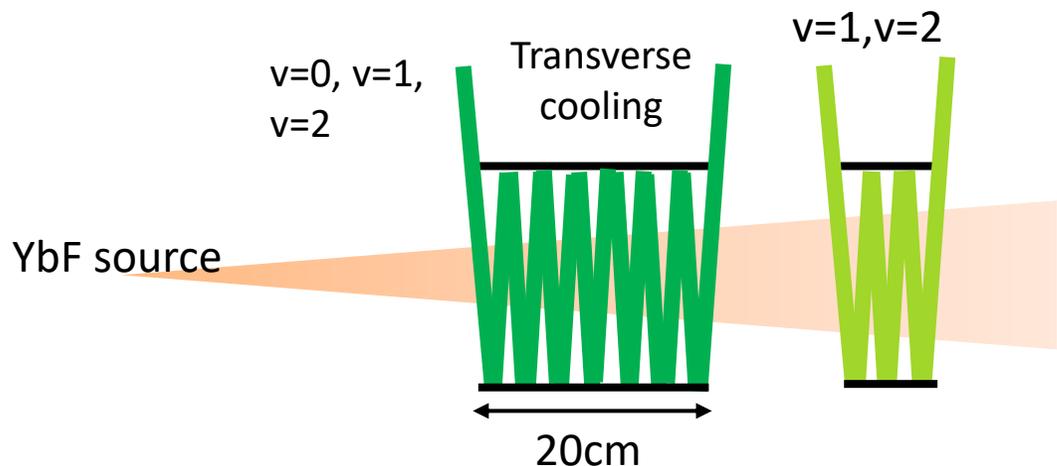
Intensity standing waves create AC Stark shifts that act as potential hills for the molecules

Cycle is not completely closed, need 2 vibrational repumps

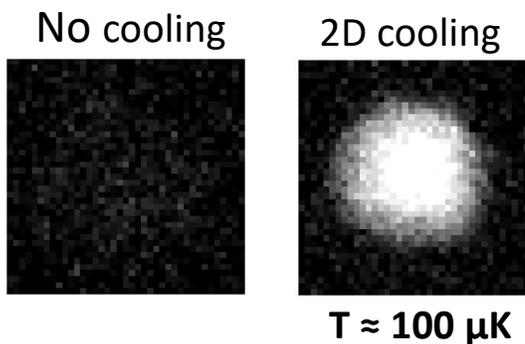


eEDM beamline setup

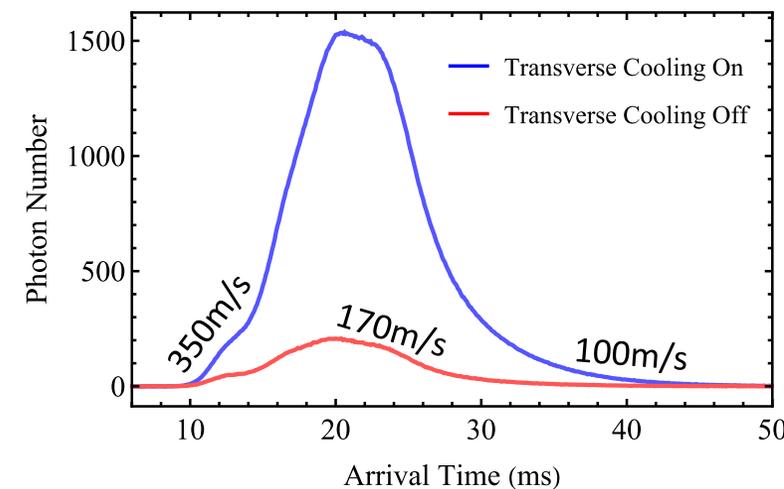
Transverse laser cooling



Camera at 5m distance

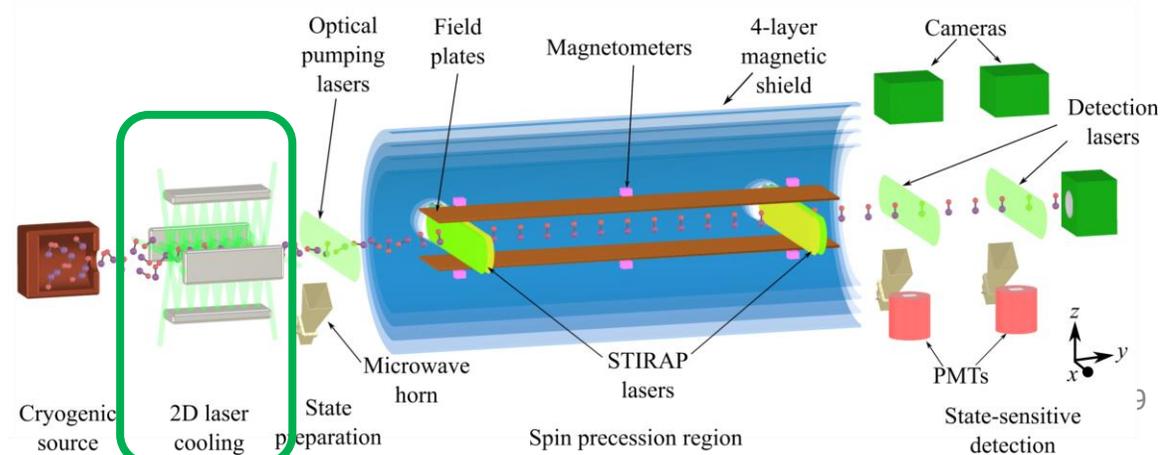


Time-of-Flight measured at the end of the beamline



Performance:

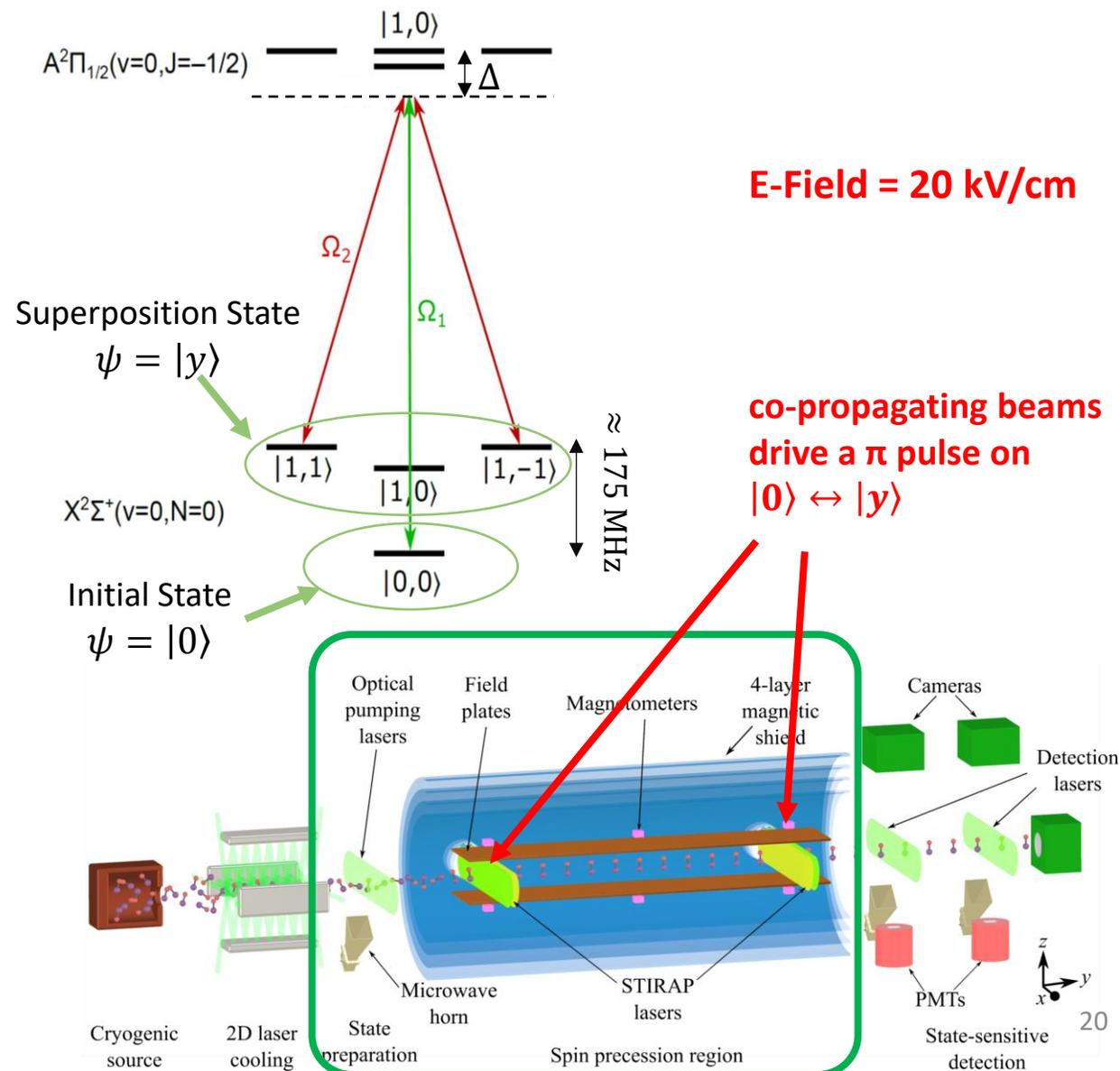
- Well over 10^6 molecules per shot
- 7-fold increase of molecule number by cooling
- Peak enhancement of 10 for slowest molecules



eEDM beamline setup

State preparation & state mapping

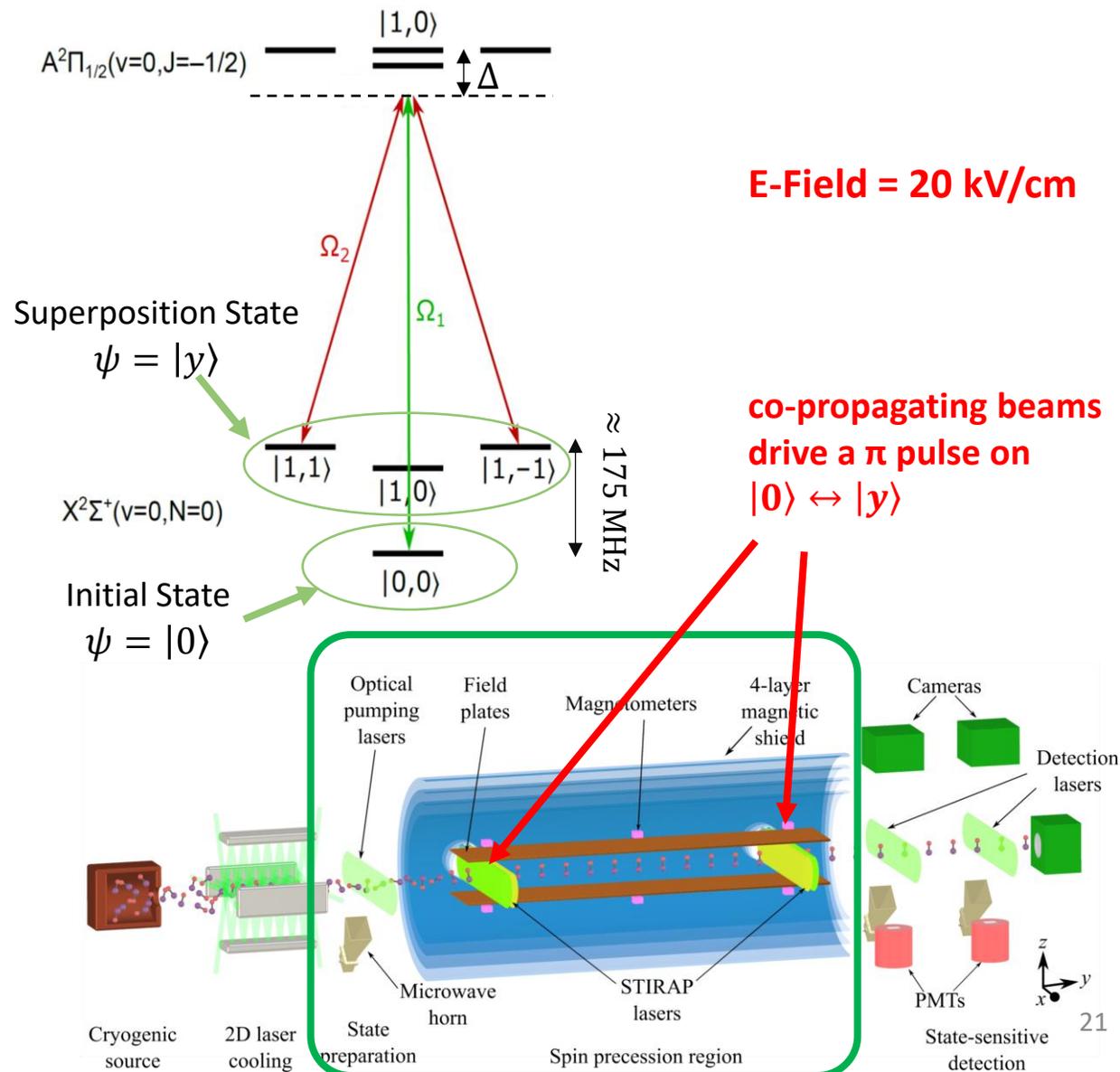
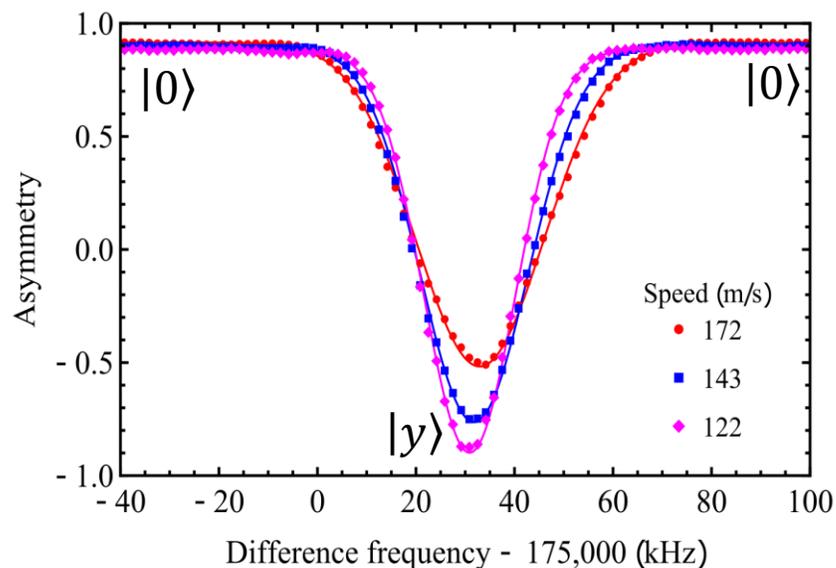
- Optically pump molecules to rotational ground state
- Raman transition to prepare the eEDM sensitive state



eEDM beamline setup

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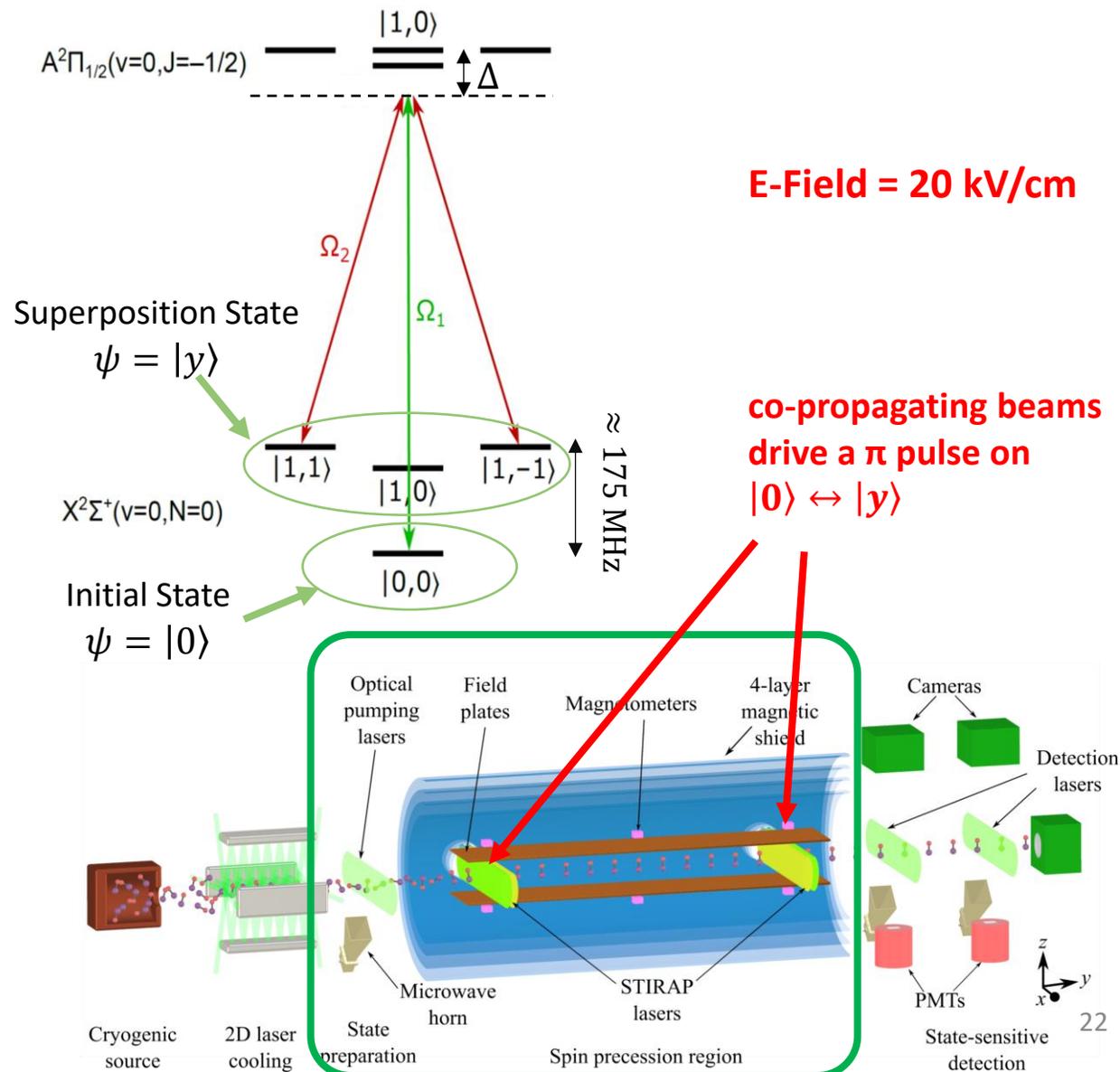
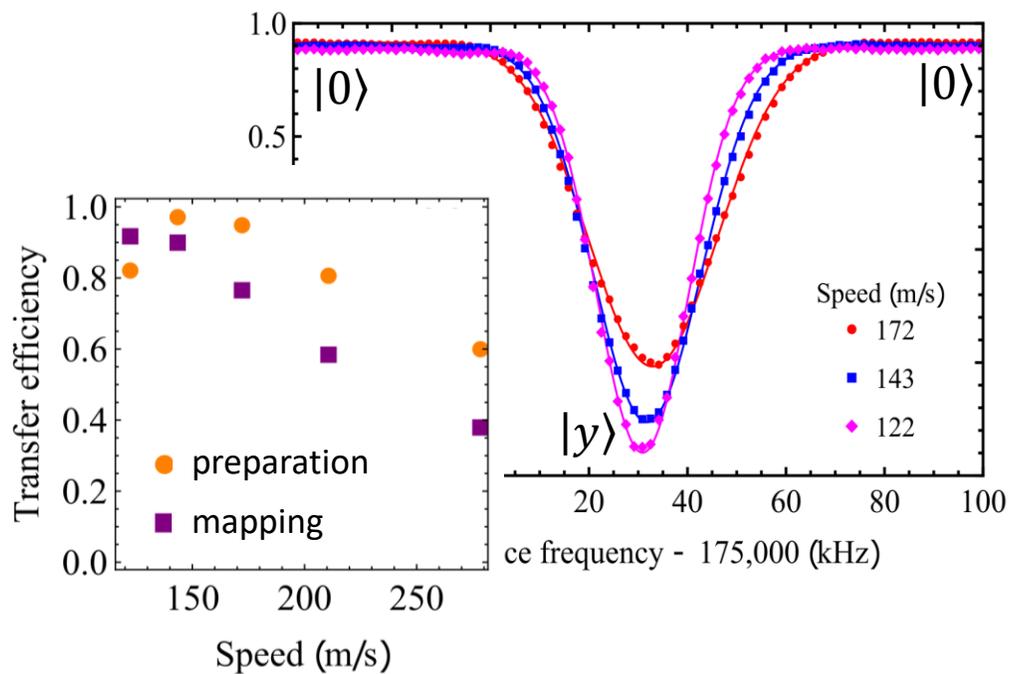
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- Transfer efficiency has a velocity dependence



eEDM beamline setup

State preparation & state mapping

- Optically pump molecules to rotational ground state
- Raman transition to prepare the eEDM sensitive state
- Transfer efficiency has a velocity dependence
- **Defines the contrast $C=0.65$**



eEDM beamline setup

Detectors

- State selective detection scheme
- MWs connect $|0\rangle$ and $|1\rangle$ to $N=1$ in separate detection sites
- Once in $N=1$, we have a cycling transition and detect the fluorescence, about 14 photons are scattered per molecule

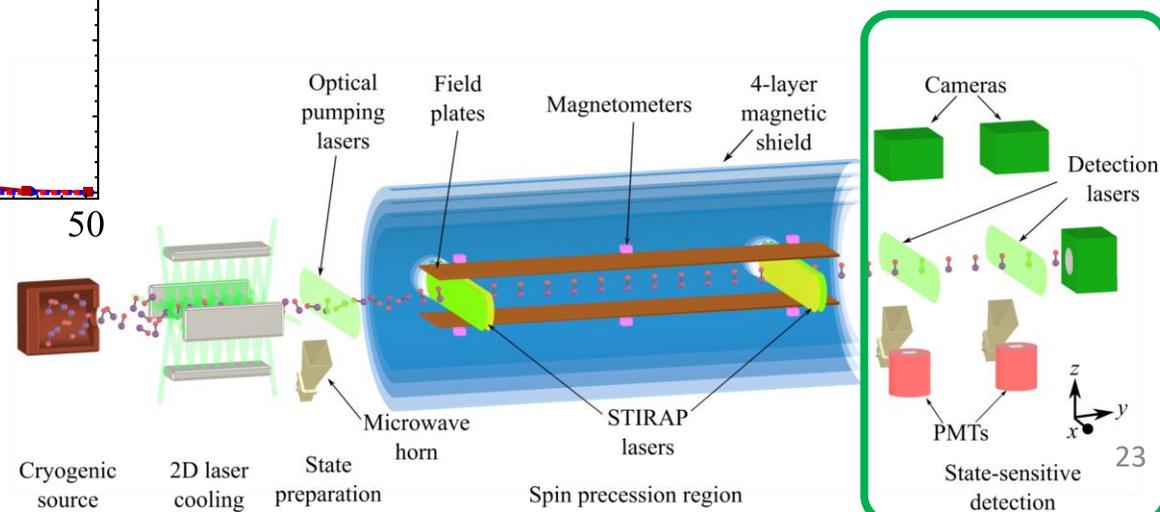
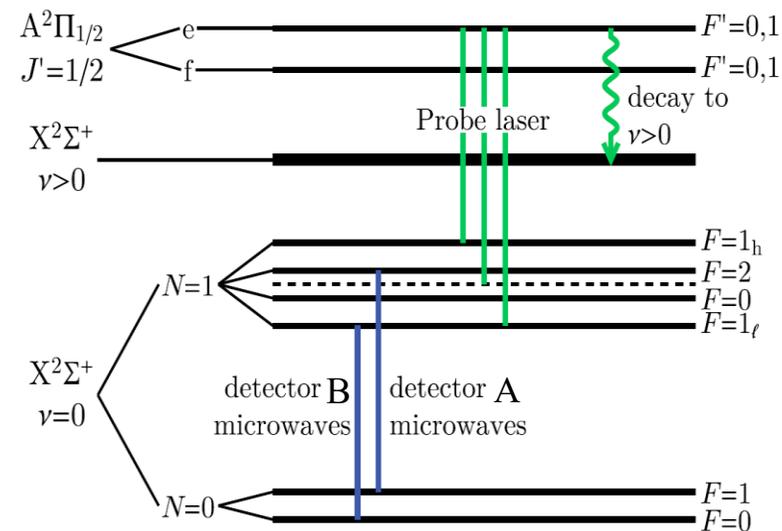
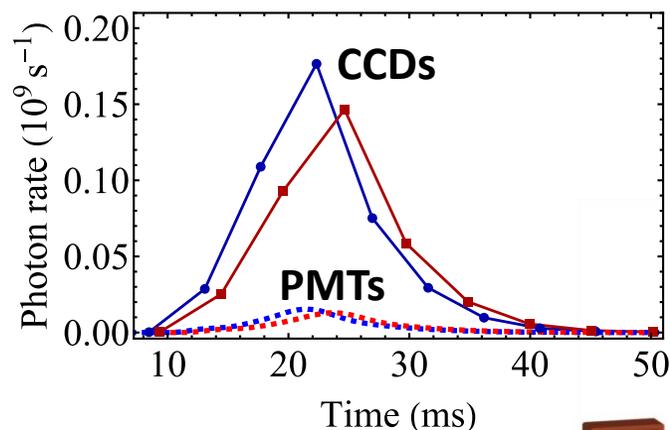
Two types of fluorescence detectors:

- **EM CCDs:**

- QE=91.8%,
- Detection efficiency 54%
- Time resolution of 4.6ms

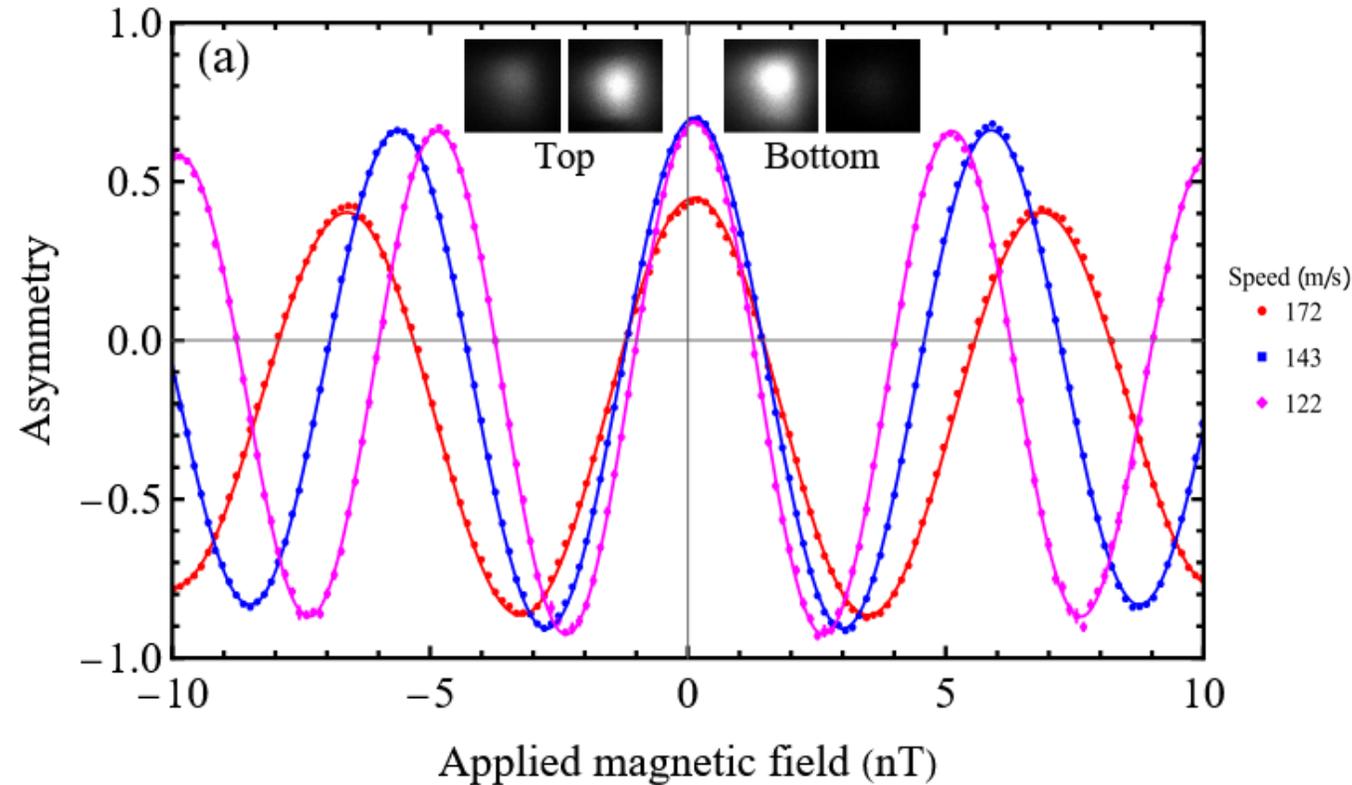
- **PMTs**

- QE=7%
- Detection efficiency 4.5%
- Time resolution of 100 μ s



eEDM sensitivity

Measured Asymmetry = $\frac{|0\rangle - |1\rangle}{|0\rangle + |1\rangle}$
as a function of applied magnetic field



Accumulated phase

$$\phi = (\mu_B B - d_e E_{\text{eff}}) \frac{\tau}{\hbar}$$

Statistical sensitivity:

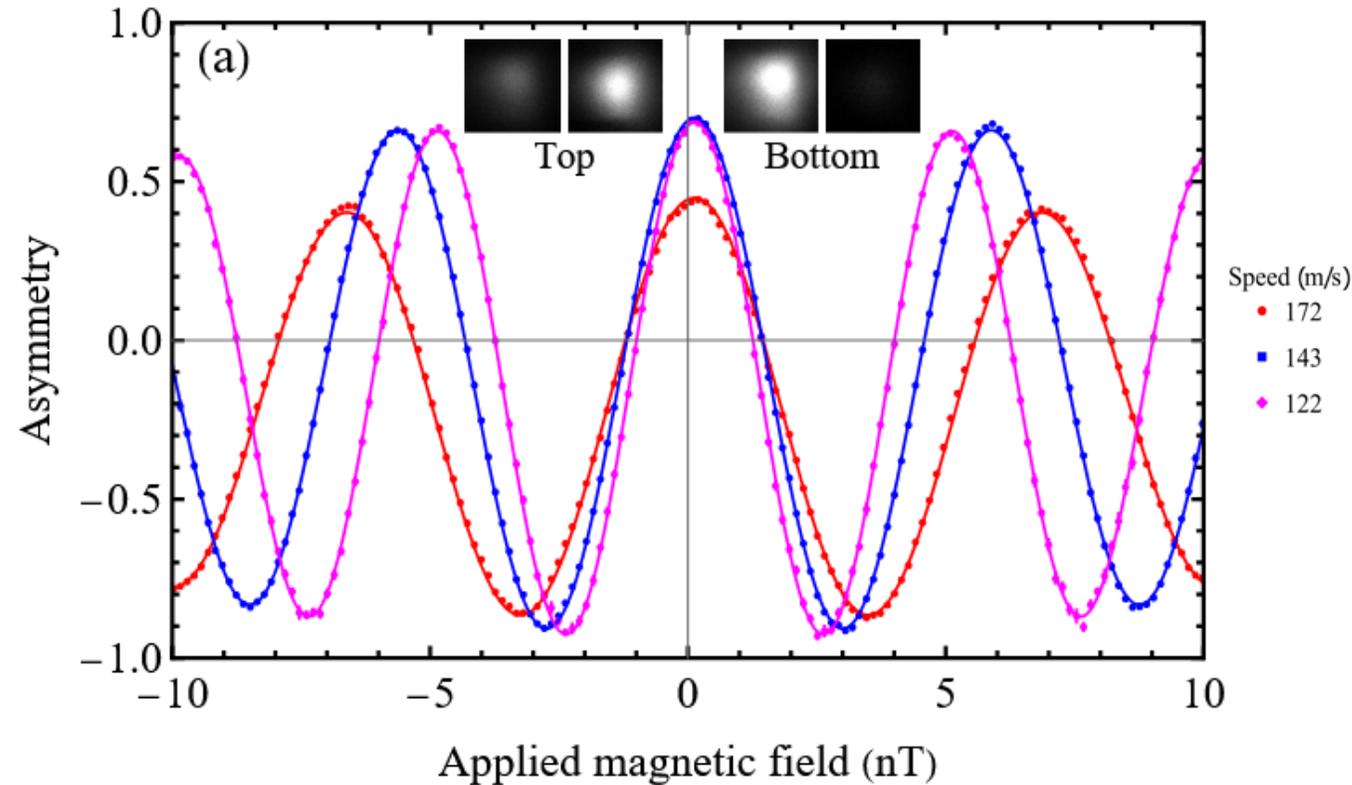
$$\sigma_{d_e} = \frac{\hbar}{2 |E_{\text{eff}}| \tau C \sqrt{N}}$$

- N: 2×10^6 molecules per shot
- E_{eff} : 18GV/cm
- τ : 170 m/s beam at 0.77m interaction region length \rightarrow 5ms precession time
- C: Contrast of 0.65
- Acquisition rate of 5Hz, duty cycle of 50%

Gives 8.6×10^{-30} e cm per day

eEDM sensitivity

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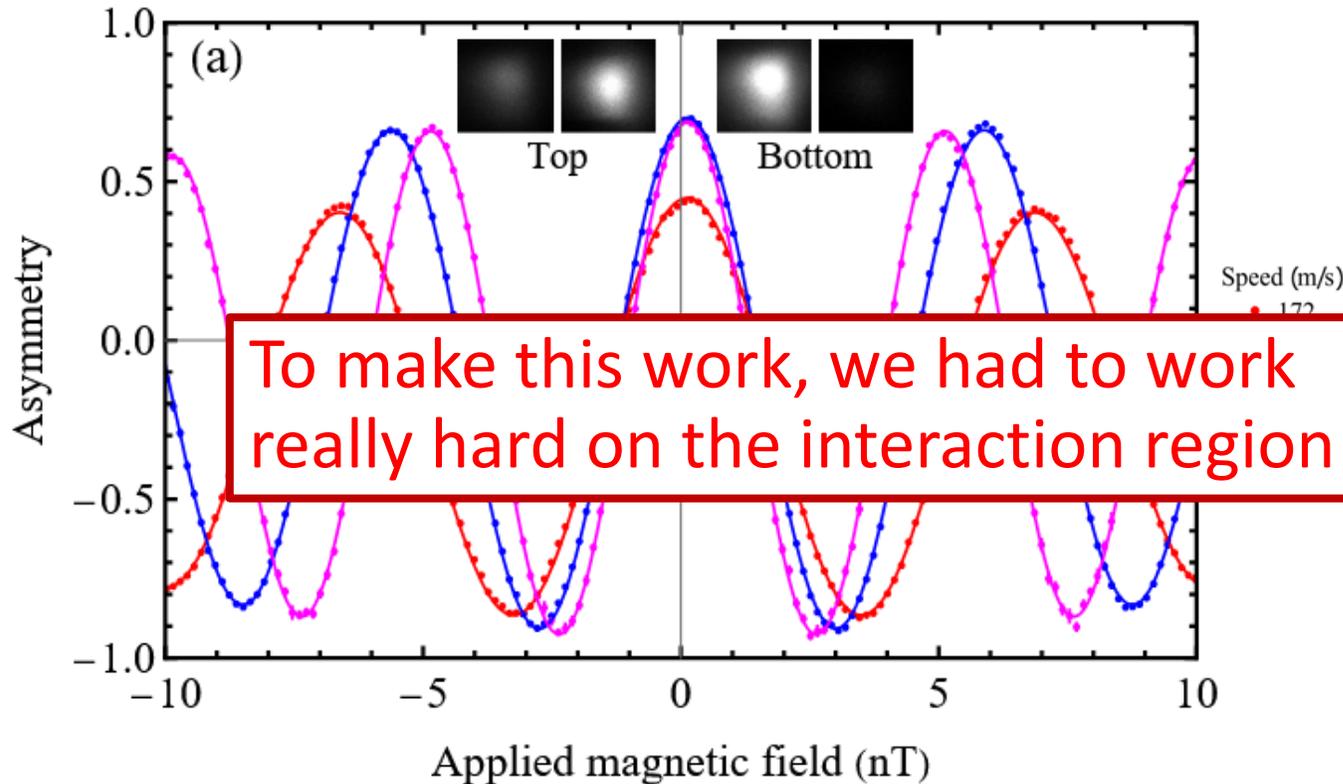
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Could get 2.4×10^{-30} e cm per day with 1K source and rapid adiabatic passage

Interaction region

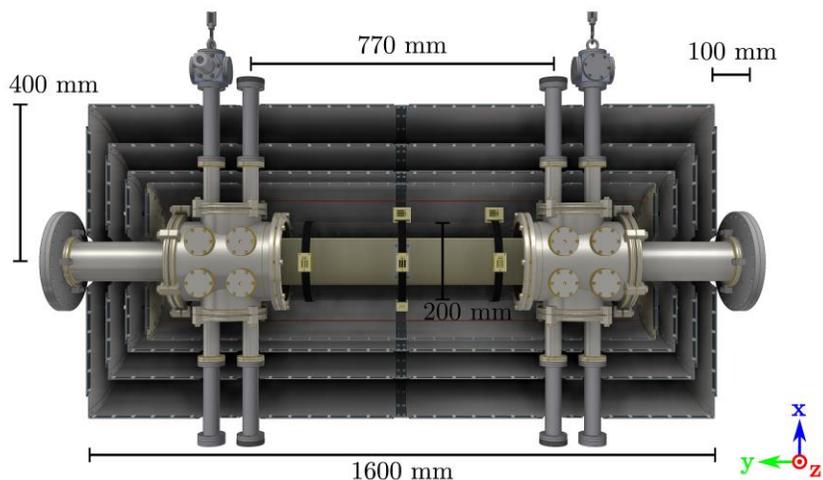
Spin precession region

YbF eEDM state is magnetically sensitive ($g = 1$):

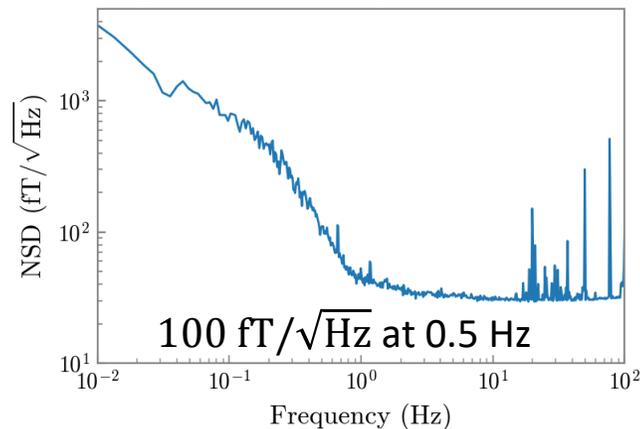
- 4-layer mu-metal shield with 10^5 - 10^6 shielding factor
- Array of magnetometers to monitor the field & gradients
- Magnetic-field noise at E-switch frequency of $100 \frac{\text{fT}}{\sqrt{\text{Hz}}}$
- Sensitivity to E-correlated B Fields $< 0.1 \text{ fT}$ in a week

E-Fields: 20 kV/cm

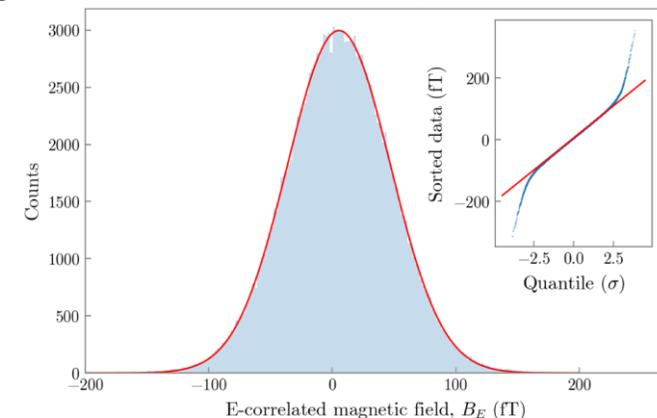
- Leakage currents below nA
- Glass vacuum chamber, titanium connections
- Alumina-plates with TiN coating ($1\mu\text{m}$)
- Johnson-noise $< 1 \times 10^{-31} \text{ e.cm/day}$



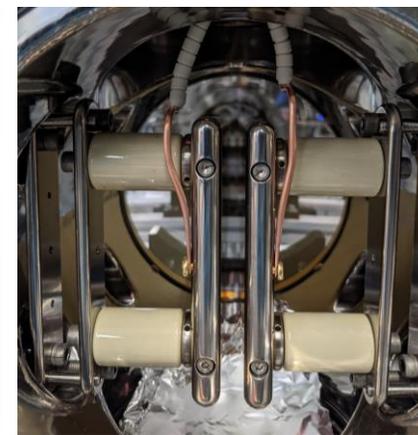
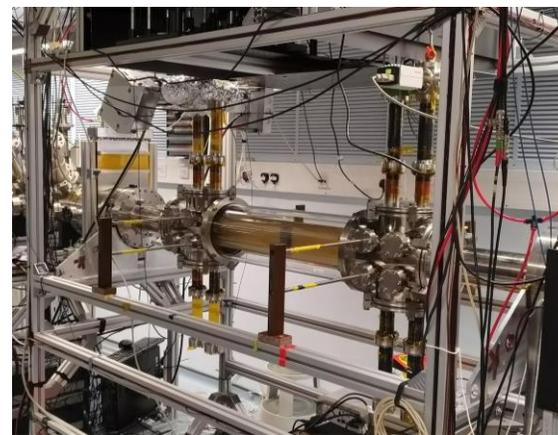
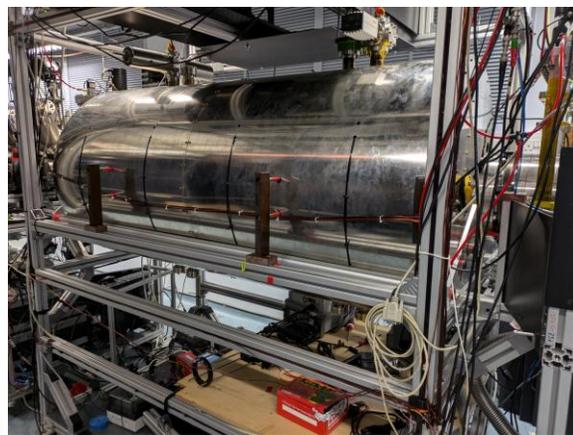
Noise spectral density in E-field direction



E-correlated magnetic field

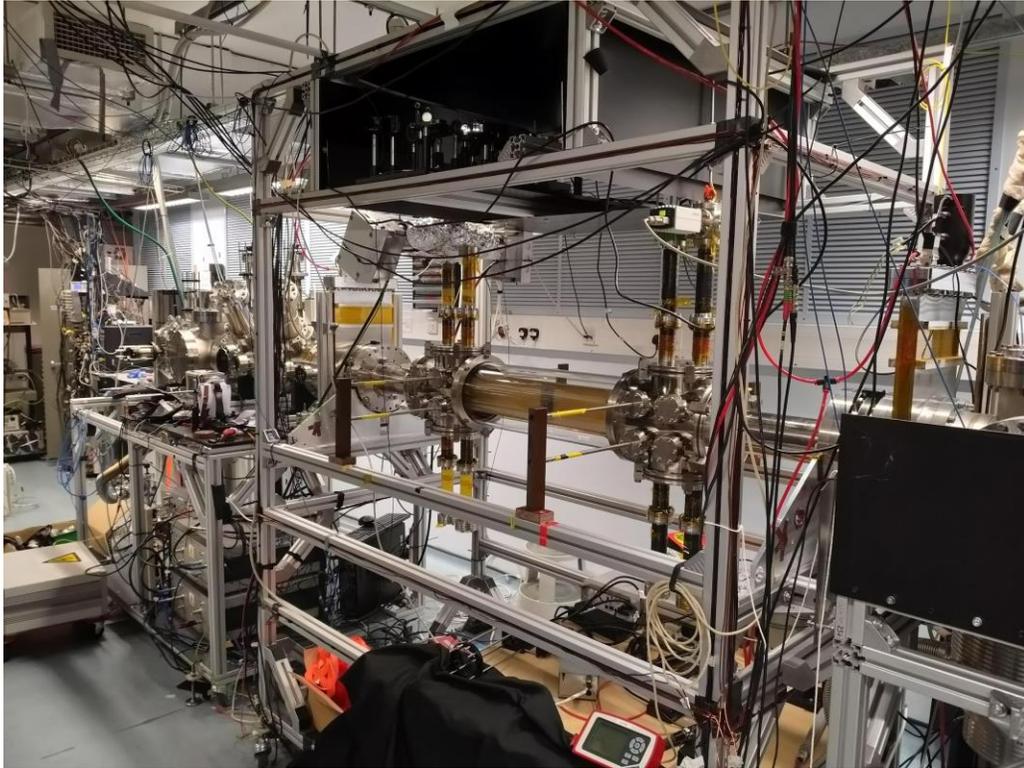


0.11 fT precision reached in 104 h

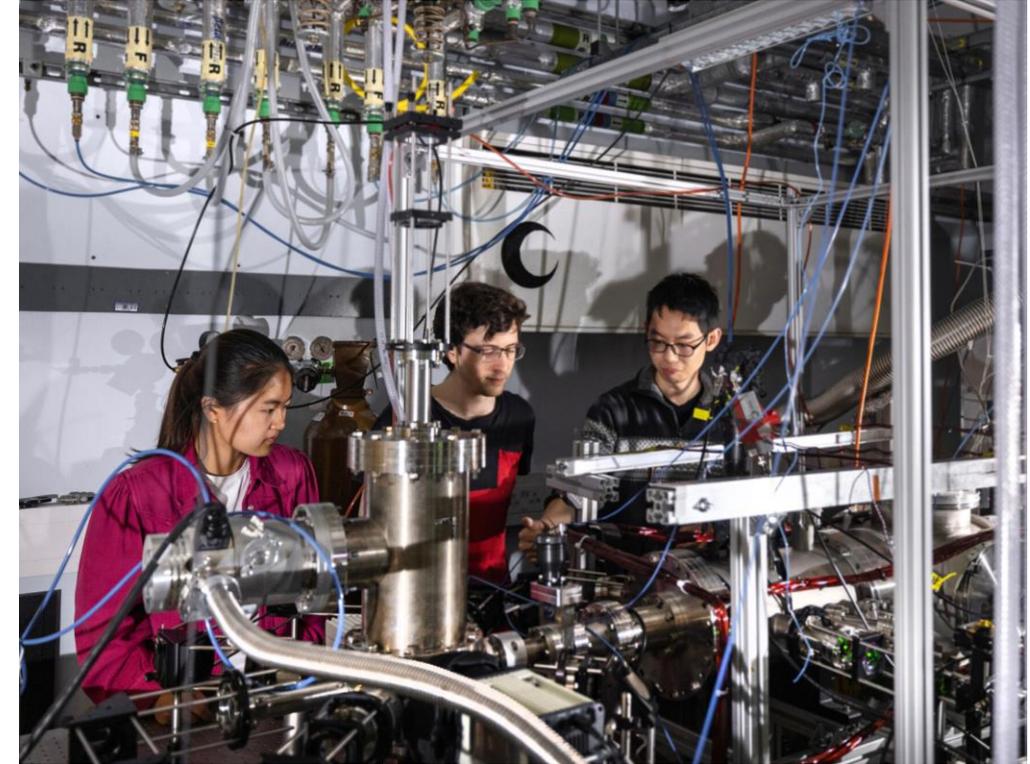


eEDM experiments with YbF at Imperial

Beamline experiment

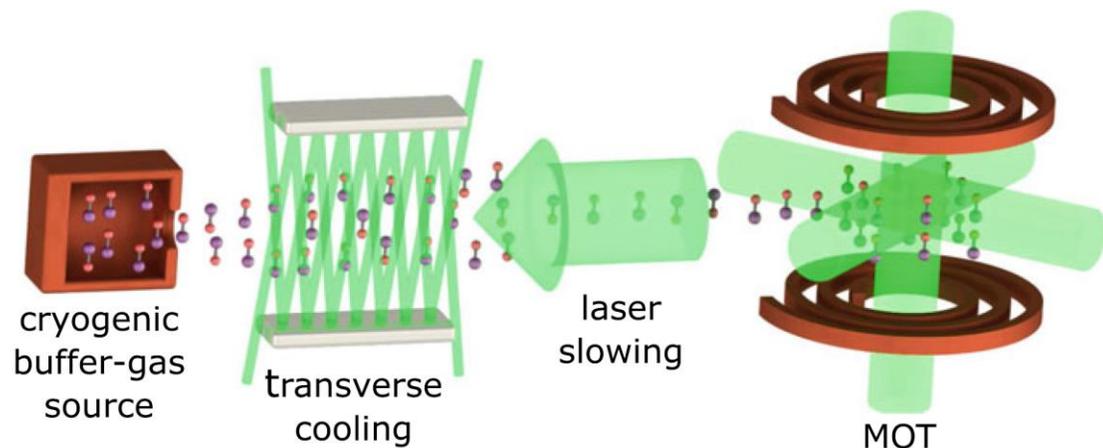


Optical lattice experiment

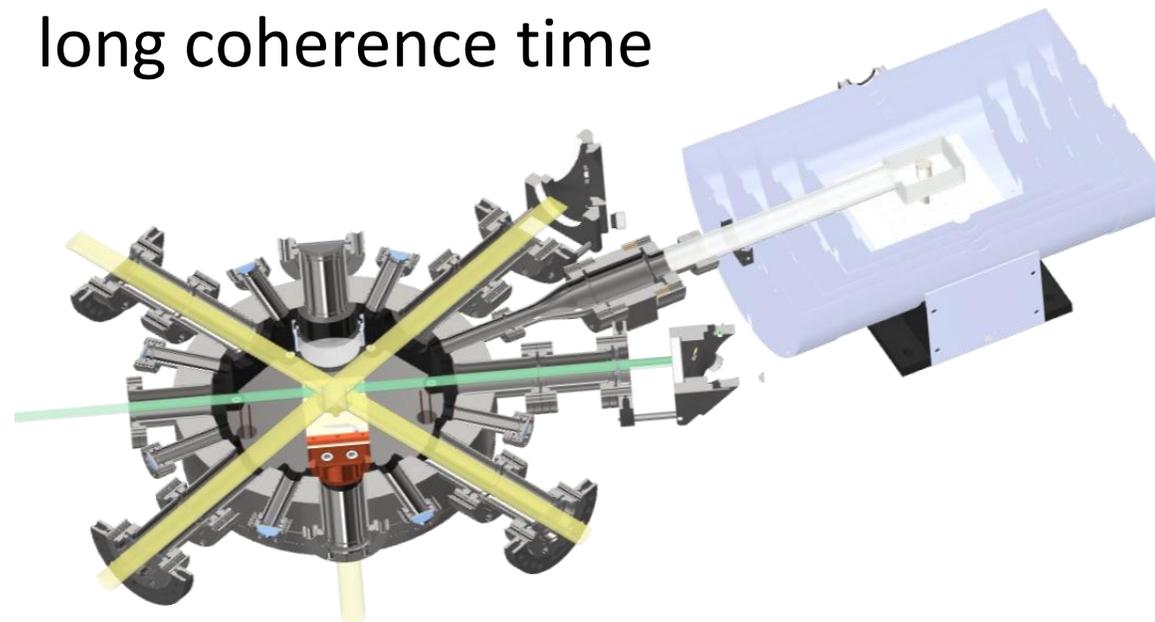


Lattice eEDM

Phase 1:
Trap YbF molecules in a Magneto-Optical Trap (MOT)



Phase 2:
Transfer molecules to an optical lattice in a dedicated science chamber and measure eEDM with long coherence time

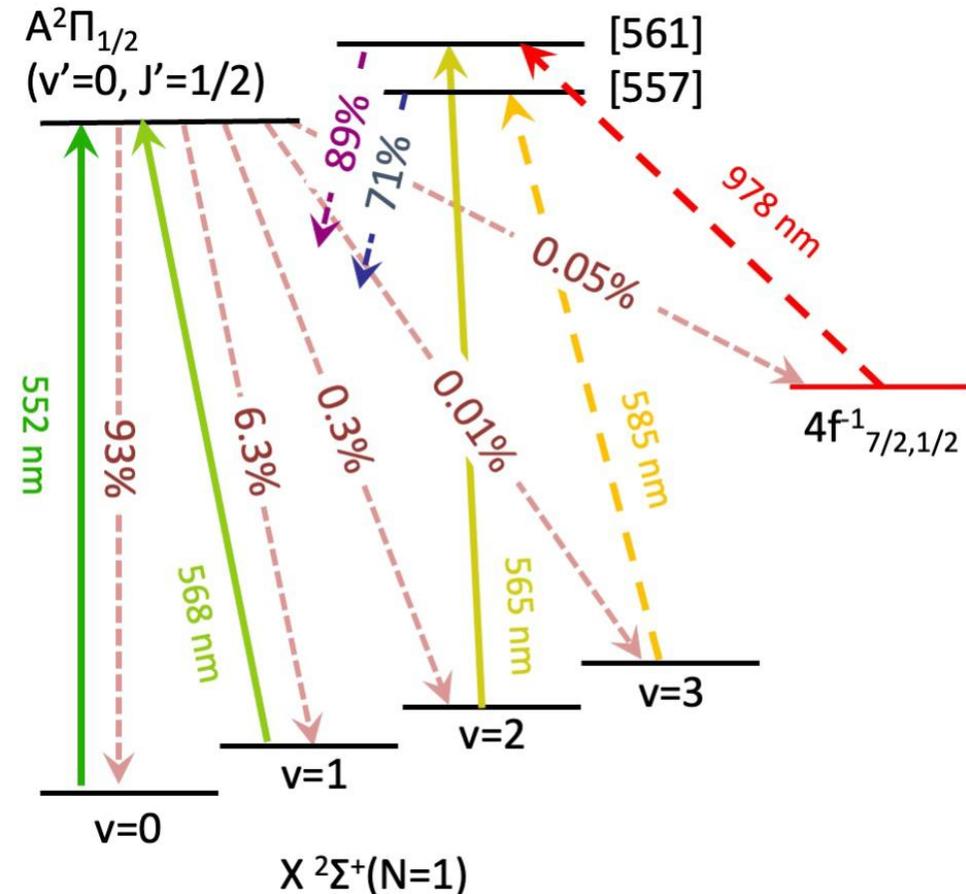


Lattice eEDM – Phase 1

Requirements on slowing:

- 1K source with 2-chamber cell has mean velocity of 80m/s
- One photon scattering changes the velocity by 3.7mm/s
- So you'd need 4×10^4 scattering events, meaning leaks in the cycle are a much larger problem than at the beamline experiment
- Capture velocity of the MOT is 10m/s

Identified a leak to the 4f hole state:

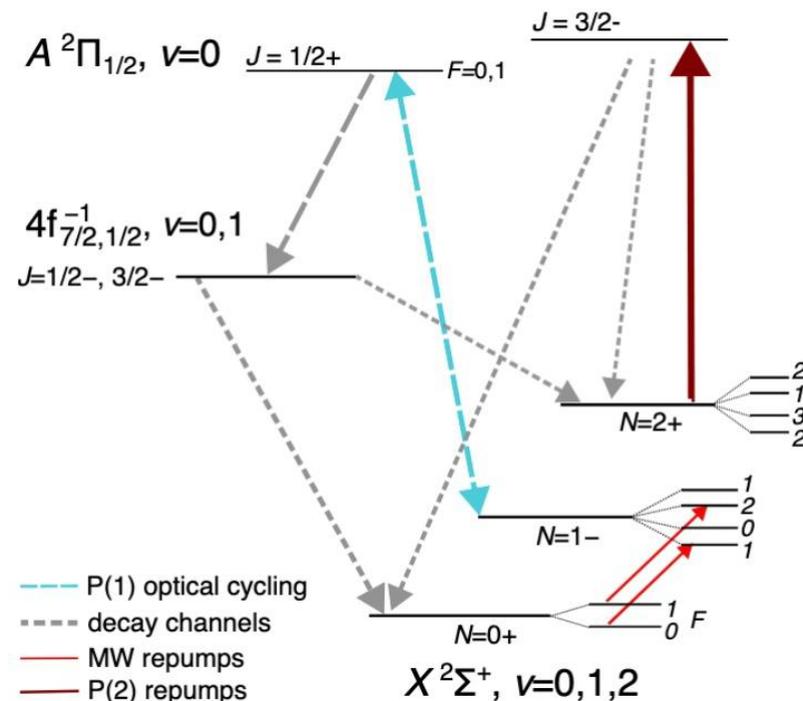


Lattice eEDM – Phase 1

Requirements on slowing:

- 1K source with 2-chamber cell has mean velocity of 80m/s
- One photon scattering changes the velocity by 3.7mm/s
- So you'd need 4×10^4 scattering events, meaning leaks in the cycle are a much larger problem than at the beamline experiment
- Capture velocity of the MOT is 11m/s

Plugged leak to the 4f hole state with MW and a repump

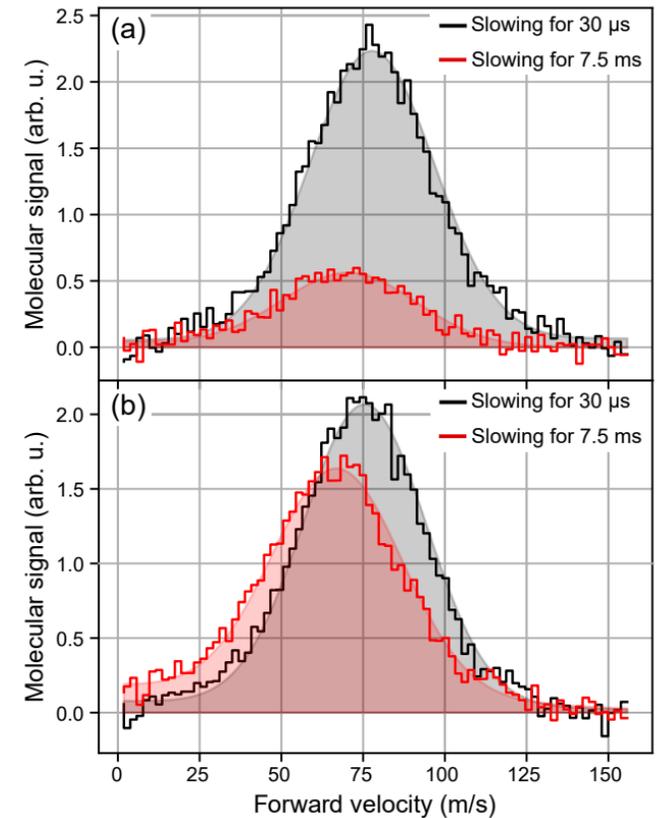


Lattice eEDM – Phase 1

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- Capture velocity of the MOT is 11m/s

Demonstrated Radiation Pressure Slowing:



Expect first YbF capture any day now!

Summary

Lattice EDM sensitivity

$$\sigma_{de} = \frac{\hbar}{2 |E_{\text{eff}}| \tau C \sqrt{N}}$$

- N: 10000 molecules per shot
- E_{eff} : 18GV/cm
- τ : 1s precession time
- C: Contrast of 0.9
- Acquisition rate of 14 shots per minute

estimated 1.4×10^{-30} e cm per day

Beamline sensitivity:

- N: 2×10^6 molecules per shot
- E_{eff} : 18GV/cm
- τ : 5ms precession time
- C: Contrast of 0.65
- Acquisition rate of 5Hz, duty cycle of 50%

Gives 8.6×10^{-30} e cm per day

Could get 2.4×10^{-30} e cm per day with 1K source and rapid adiabatic passage

Thanks



GORDON AND BETTY
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ALFRED P. SLOAN
FOUNDATION



Funded by
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**Science and
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Facilities Council**

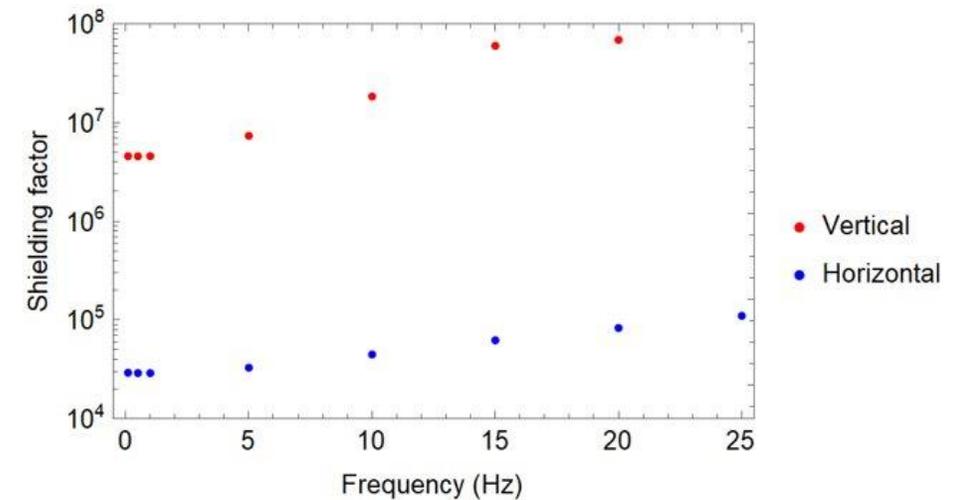
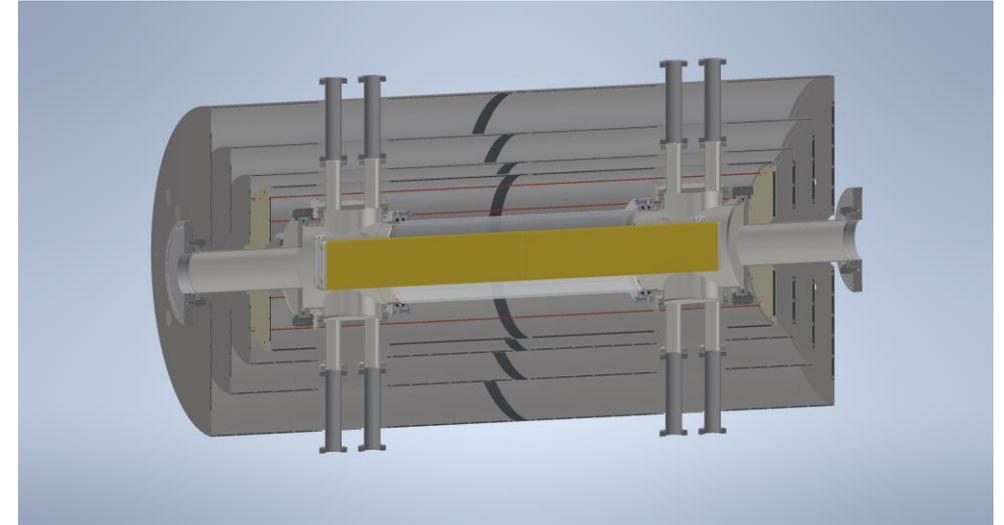
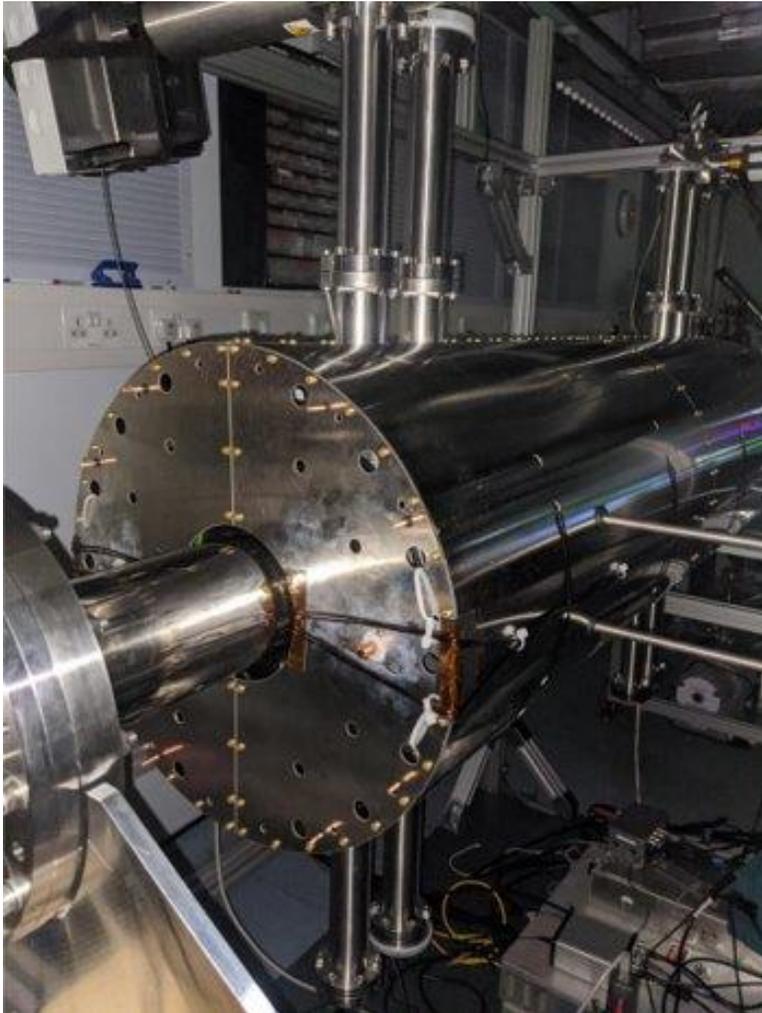


**Engineering and
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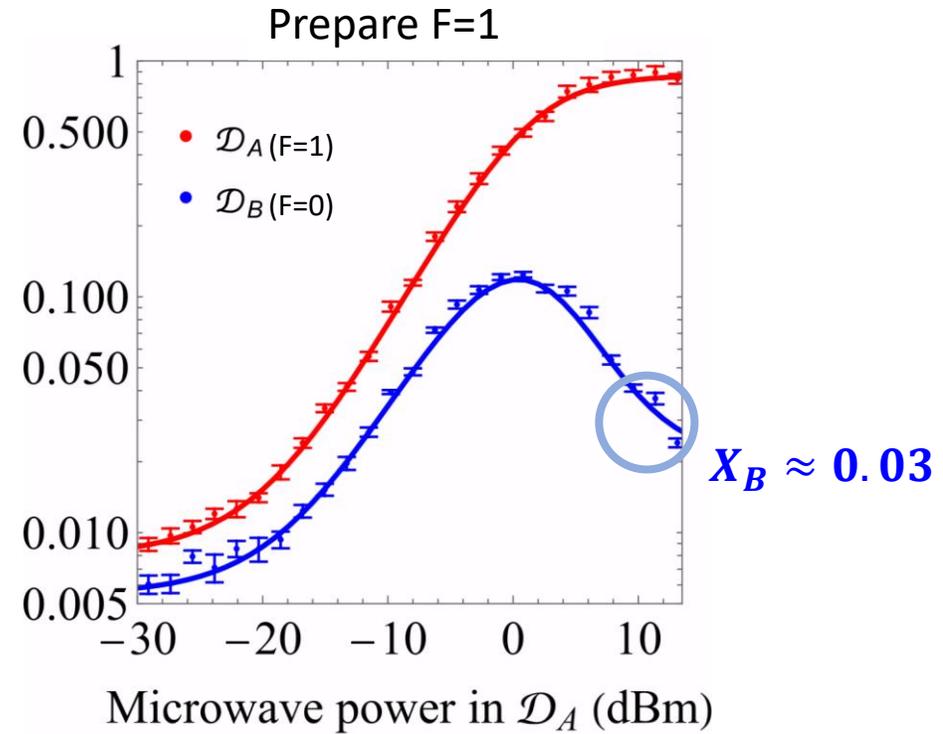
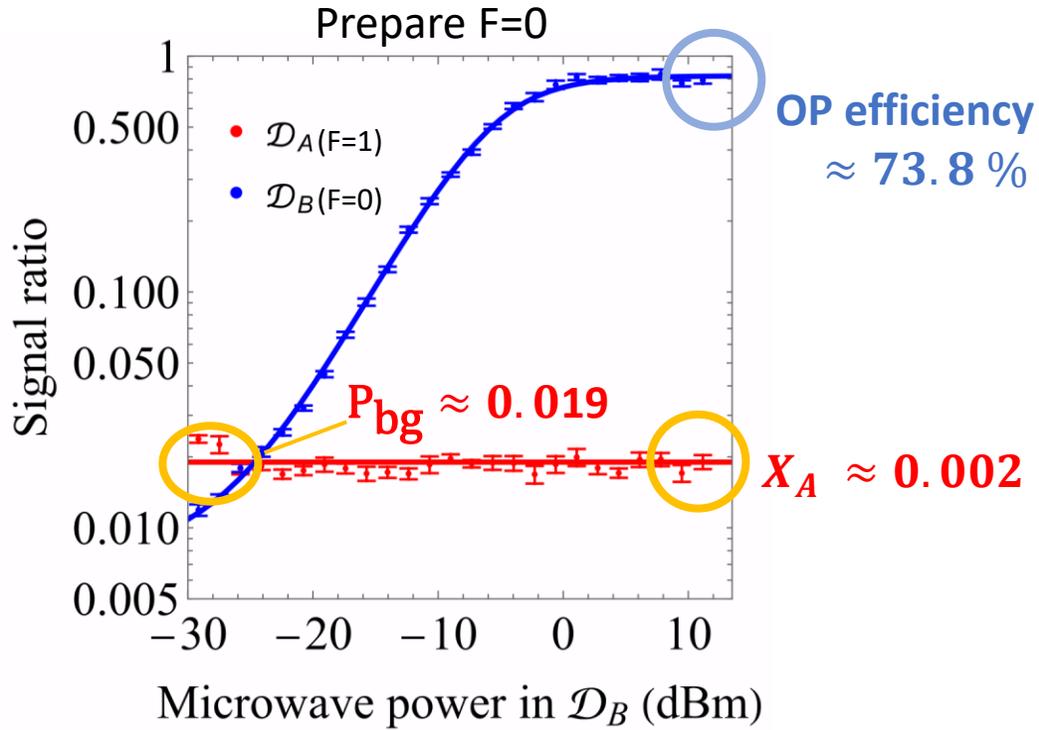
Appendix: Magnetic noise and related systematics

- $1 \text{ fT} = 4 \times 10^{-30} \text{ e.cm}$
 - Background magnetic field below 1 pT
 - Gradients below 10 pT / cm
 - Magnetic noise below 20 fT/VHz at the E-switch frequency (equivalent to $2 \times 10^{-31} \text{ e.cm}$ in one day)
 - Eliminate all ferromagnetic material
 - Eliminate metals from spin-precession region to reduce Johnson noise
 - Magnetic shield with shielding factor $>10^6$ (in direction of E-field)
- Natural enemy of eEDM: magnetic field correlated with electric field reversal
 - Measure E-correlated fields with noise floor below 20 fT/VHz
 - Reduce E-correlated leakage currents below 10 pA (at 20 kV/cm)

Appendix: Magnetic noise – The shields



Detection MW



MW absorbing foam everywhere to avoid MW leakage

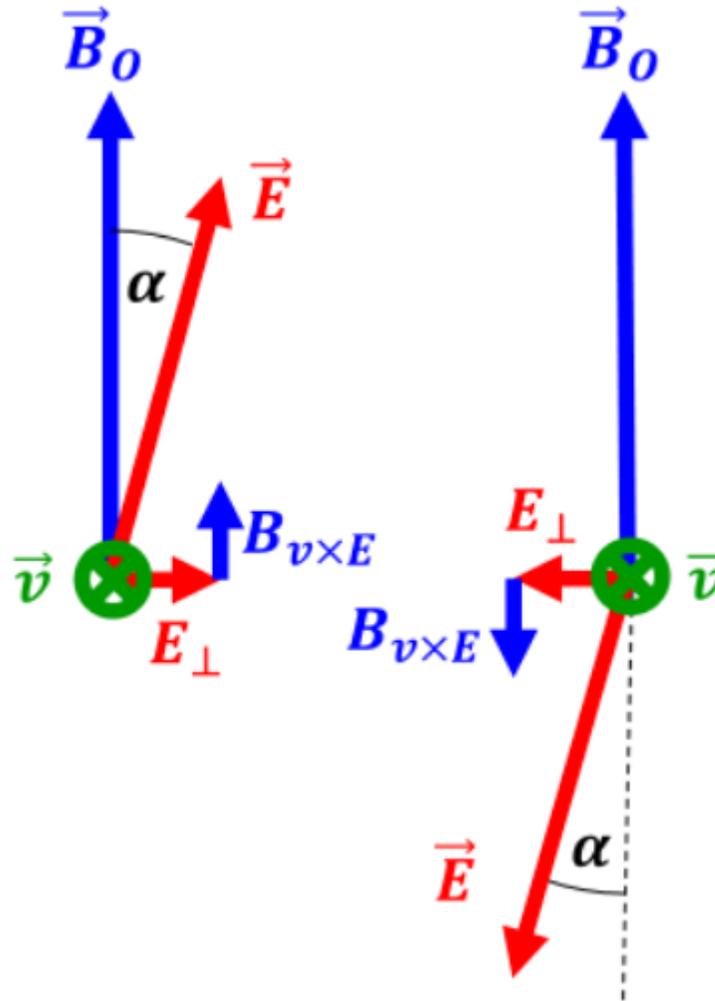
Systematics

Procedure is to find all knobs to turn and make them worse

- E-correlated magnetic field change
- Efield magnitude changes depending on polarity (Stark shift changes)
- Motional magnetic field ($v \times E$)
- E-correlated changes in Raman pulses
- Geometric phase

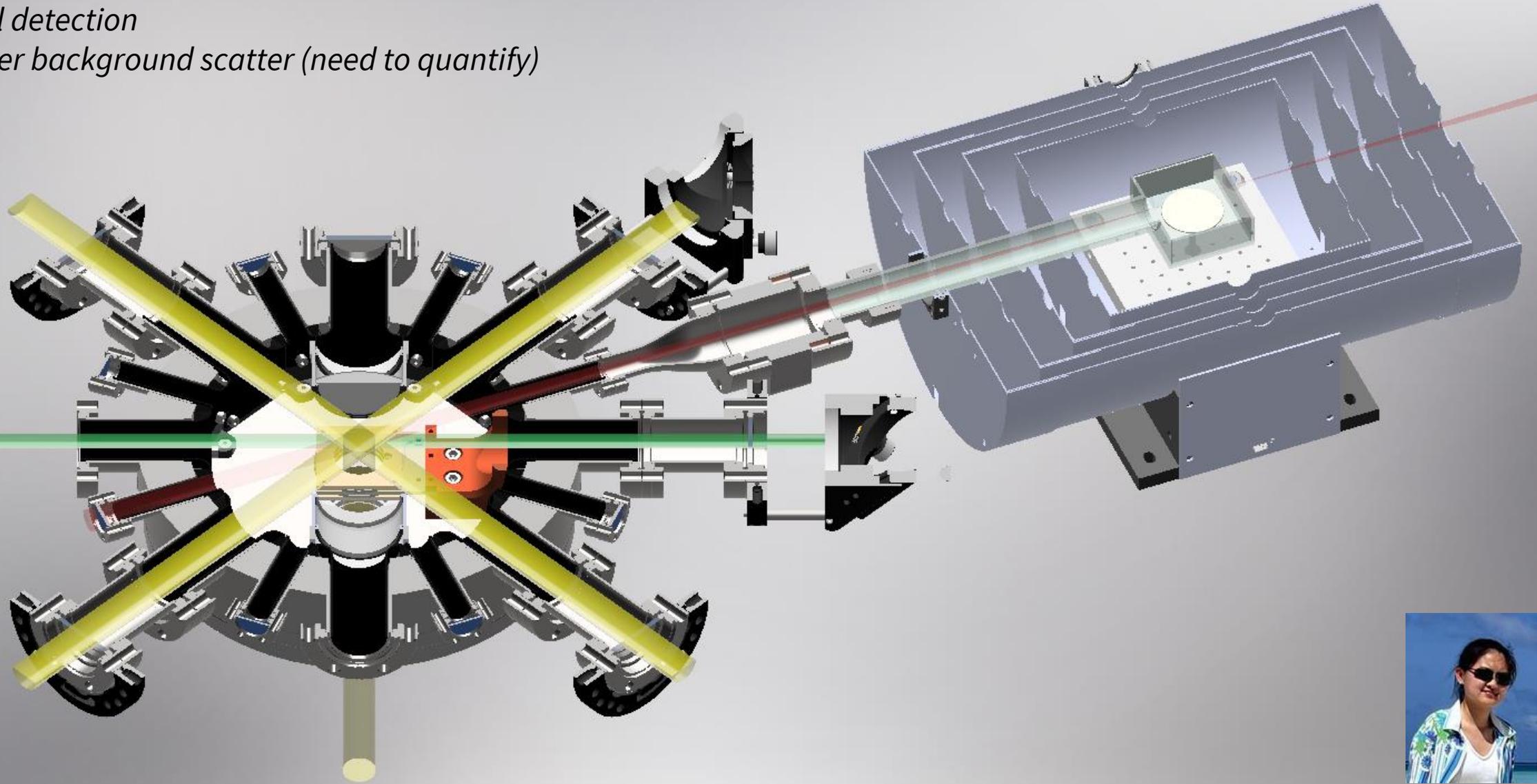
Systematics: $\vec{v} \times \vec{E}$

$$\vec{B}_{v \times E} = -\frac{\vec{v} \times \vec{E}}{c^2}$$

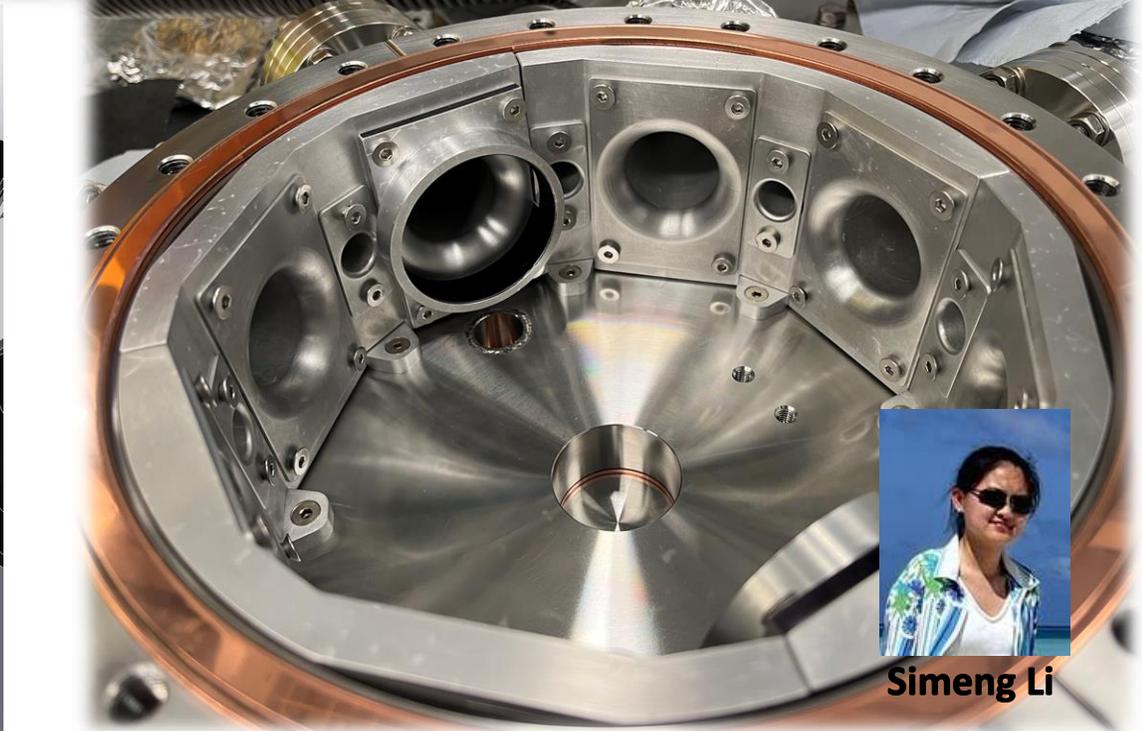
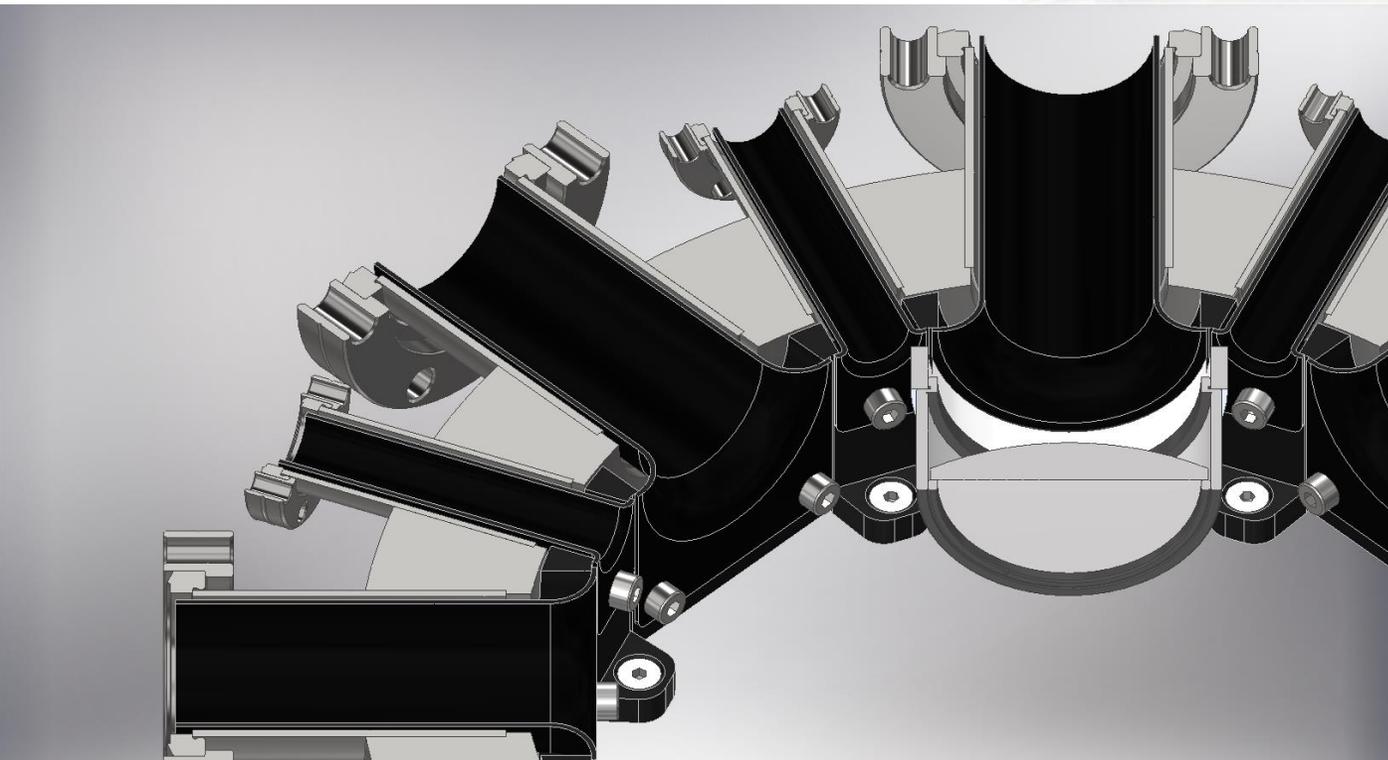
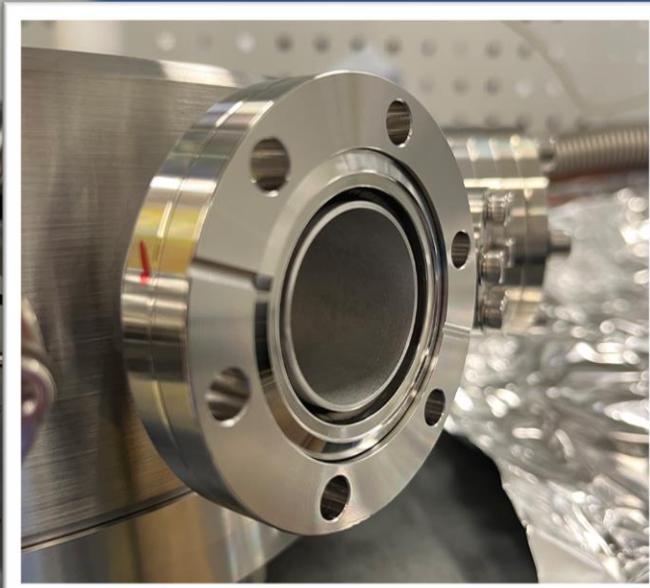


Future Arrangement – Stage 2 MOT & EDM Chamber

- *More access ports – required for the lattice*
- *Dual detection*
- *Lower background scatter (need to quantify)*



Simeng Li



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Lattice

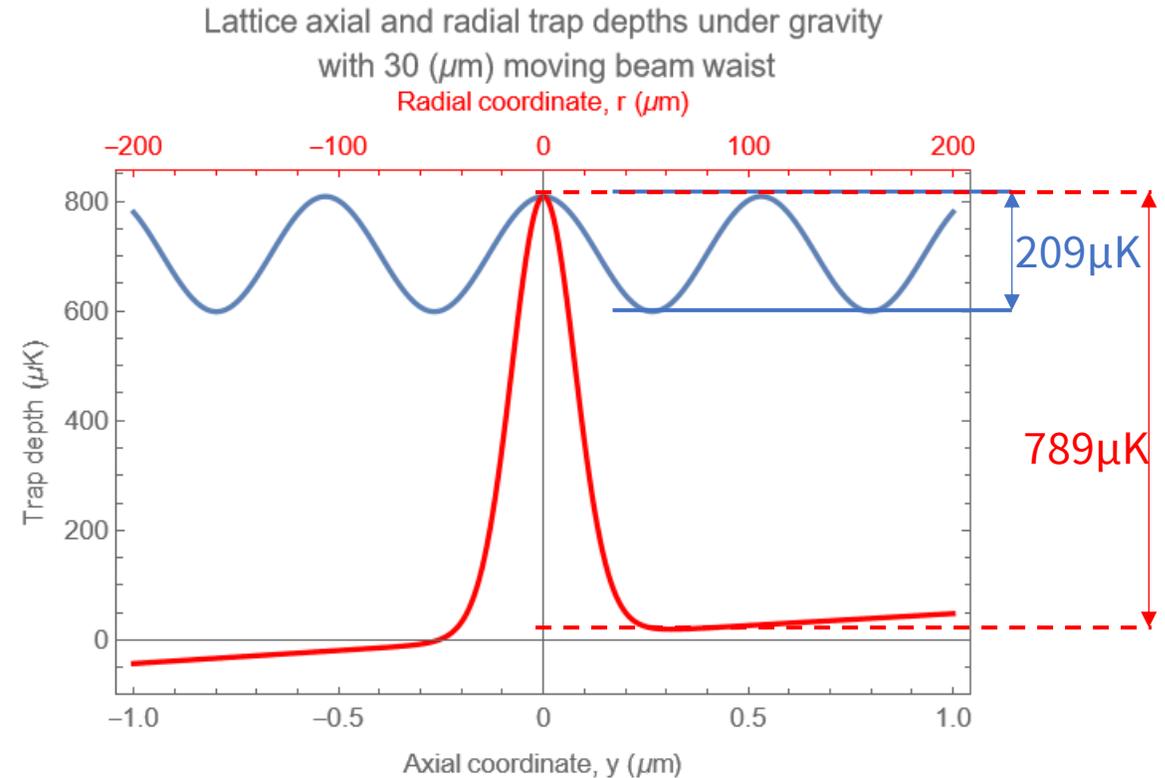


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Transport scheme – Harvard

- Moving lattice (frequency shift)
- Moving focus (of one)

	Harvard	Our target
Distance	0.46m	~0.5m
Round trip time	50ms	~50ms



*50W in each beam

EDM Chamber



Simeng Li

EDM chamber design

4-layer mu-metal magnetic shield

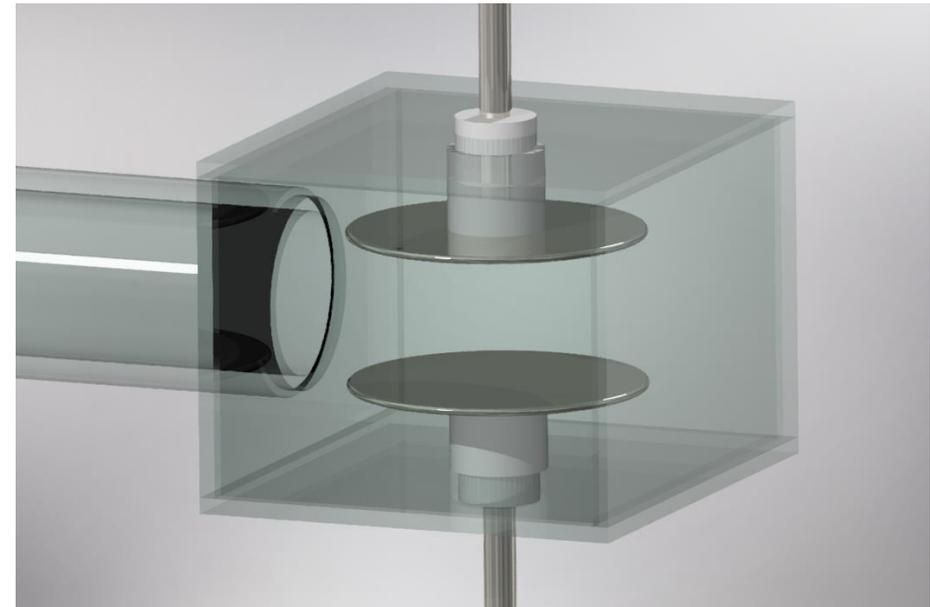
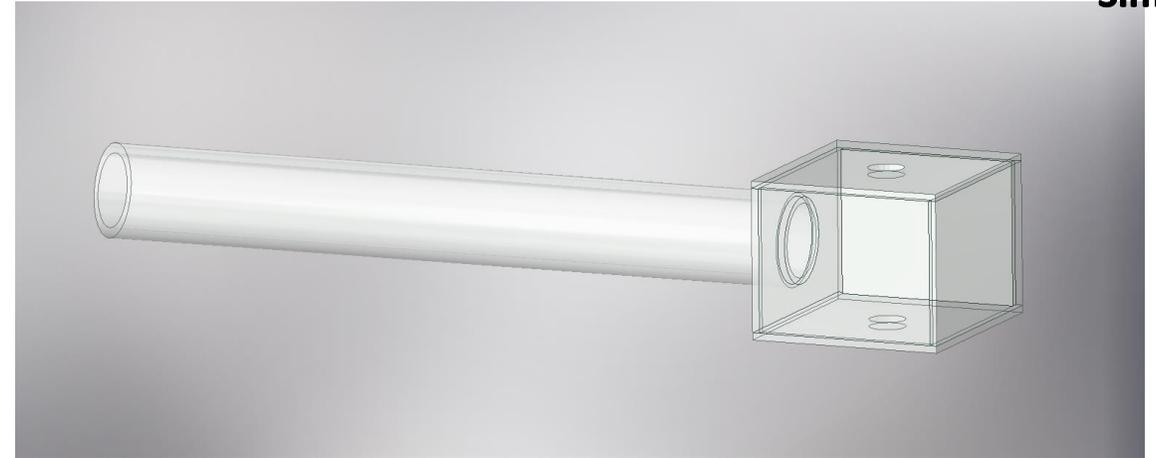
- Shielding factor > 1 million

Custom made glass cell

- Plan: make & assemble in house

Electrodes

- Ceramic + titanium coating



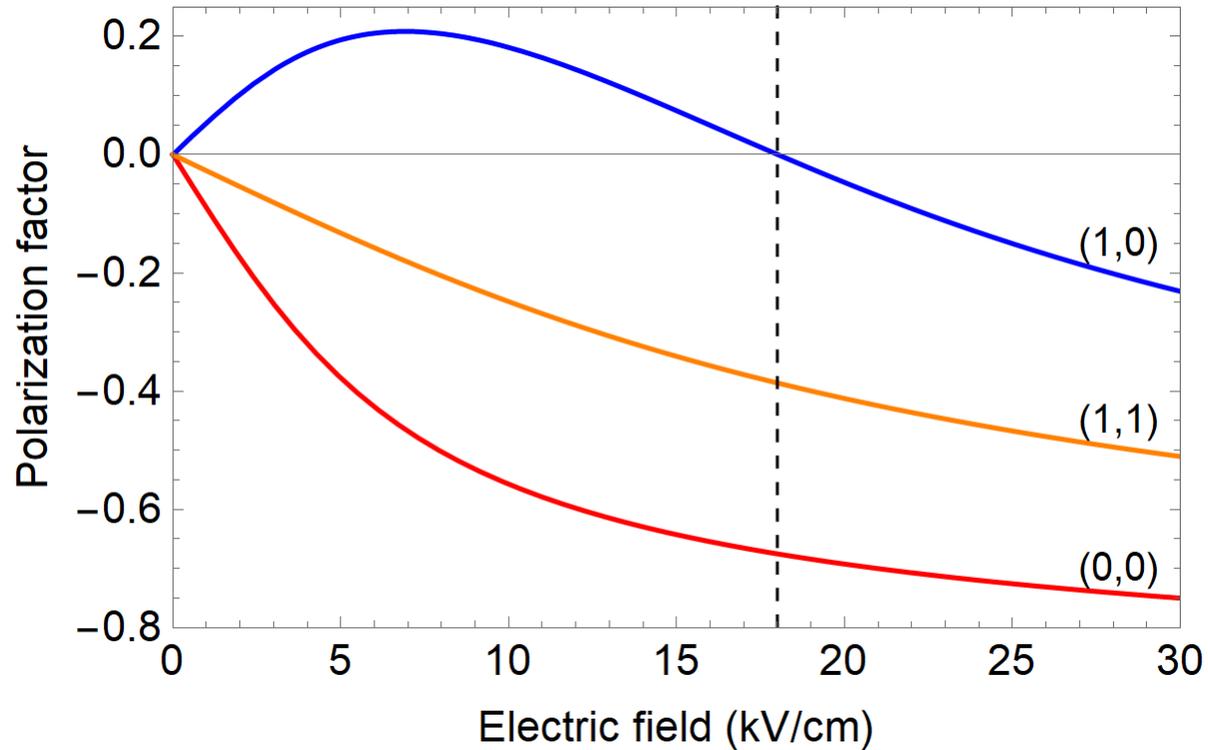


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EDM Chamber Concept Test

Co-magnetometry



In insensitive to d_e , sensitive to μ

In insensitive to d_e and μ

Sensitive to d_e and μ