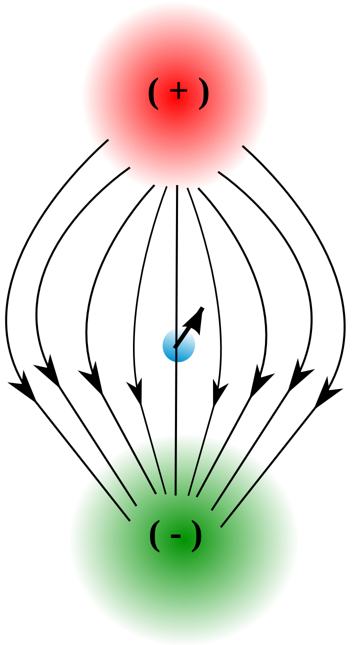
A search for the electric dipole moment of the electron using thorium monoxide

Amar Vutha
York University



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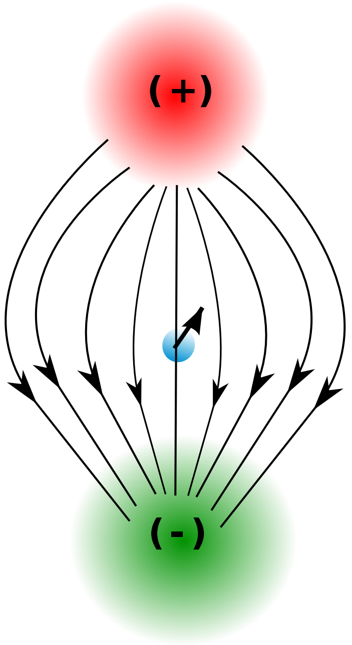


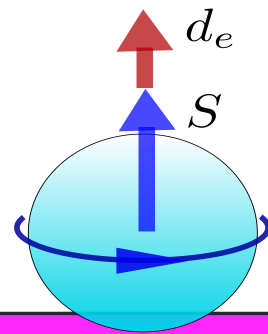
ACME Collaboration

Funding: National Science Foundation

ACME Collaboration

+ Wes Campbell (UCLA)

The eEDM layer cake



$$d_e \longleftarrow \text{CP-violation}$$

QFT

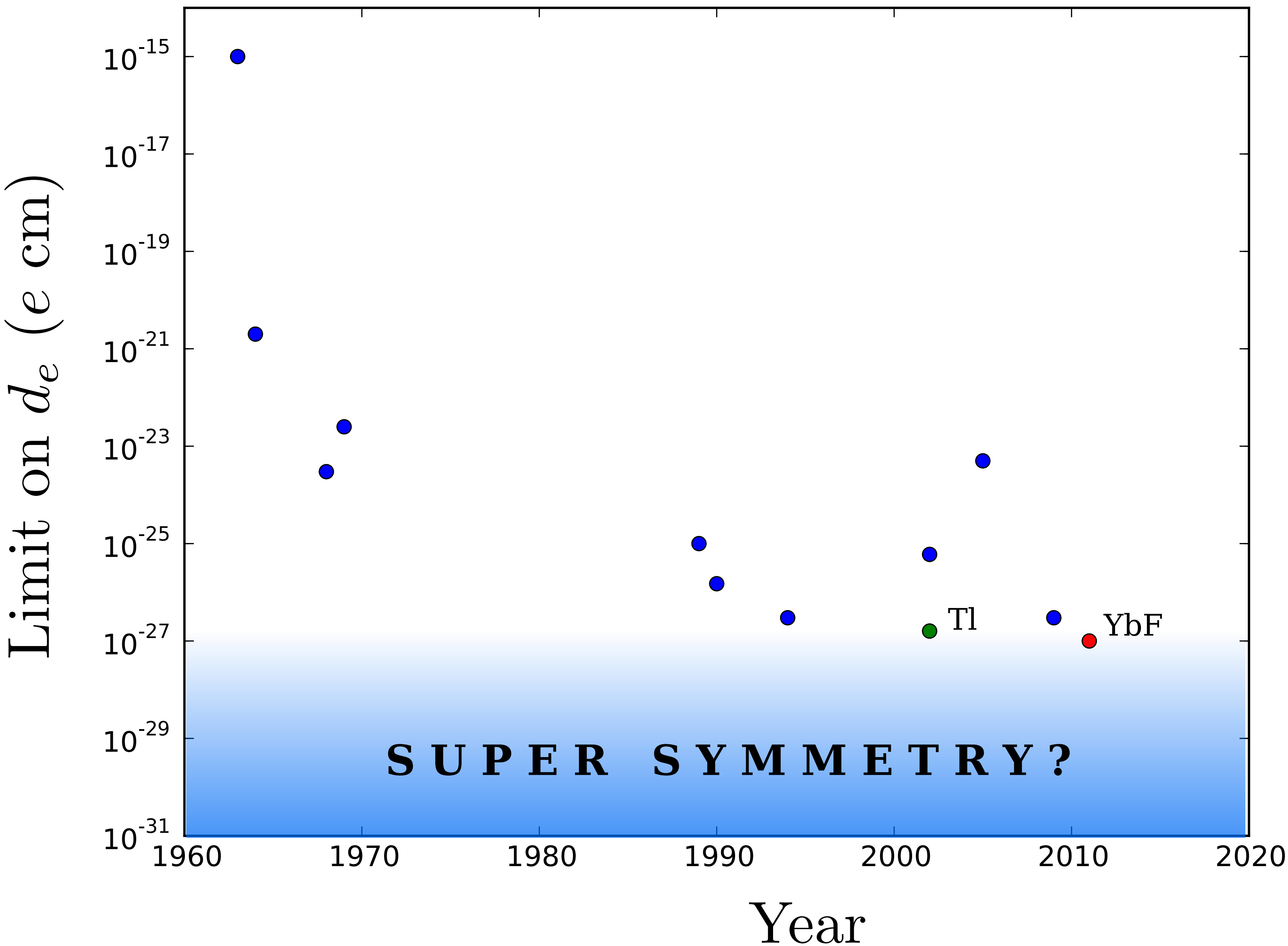
$$W_{EDM} \longleftarrow d_e \mathcal{E}_{eff}$$

Atomic theory

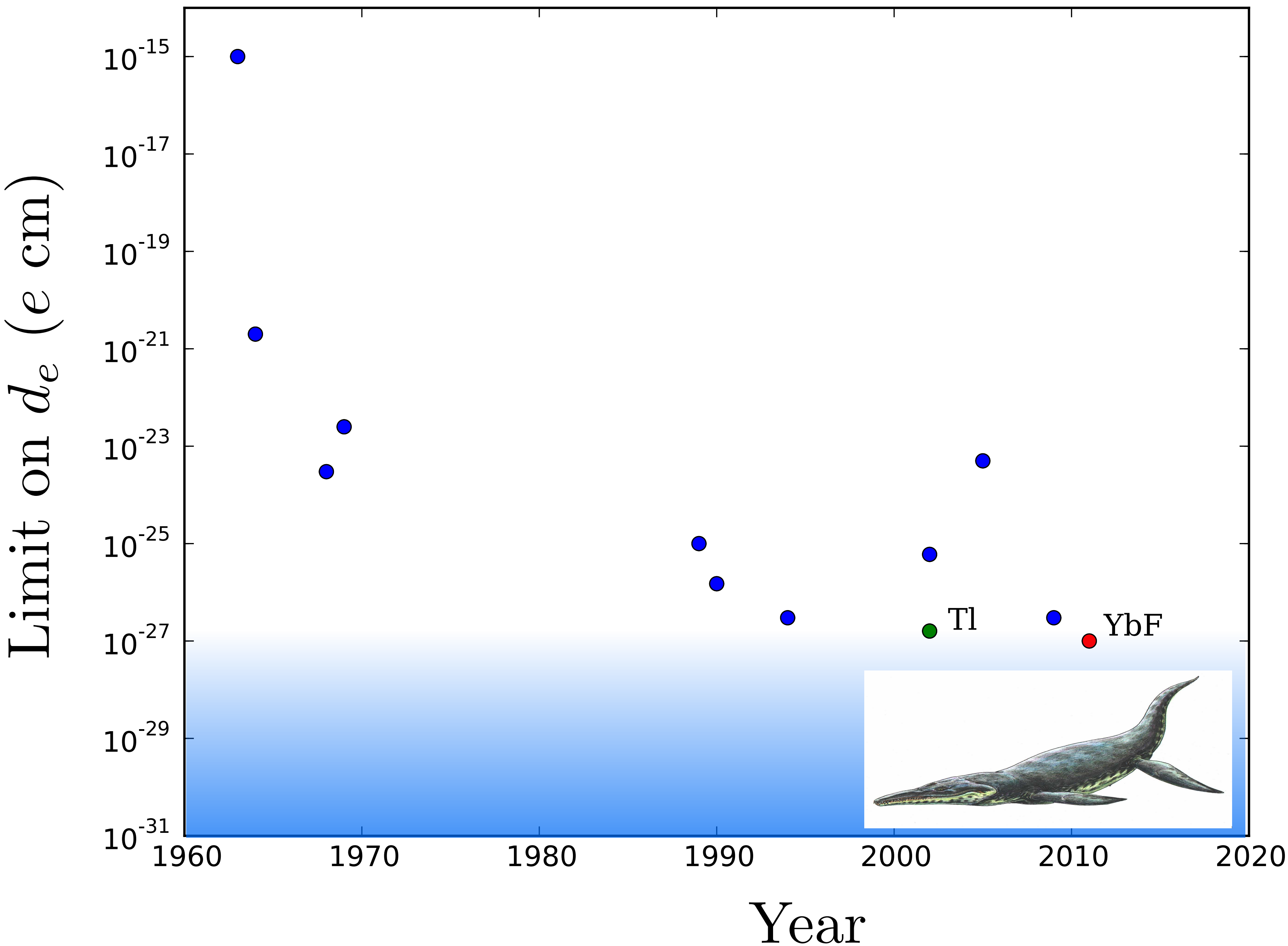
$$\langle H_{EDM} \rangle = -\vec{J} \cdot \hat{\mathcal{E}}_{lab} \times W_{EDM}(\mathcal{E}_{lab})$$

Expt.

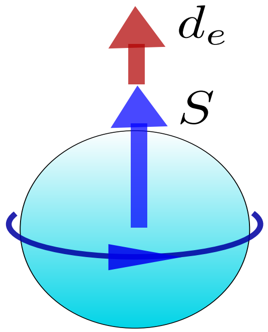
Electron EDM experiments



Electron EDM experiments



How do we measure W_{EDM} ?



$$\langle H_{EDM} \rangle = -\vec{J} \cdot \hat{\mathcal{E}}_{lab} \times W_{EDM}(\mathcal{E}_{lab})$$

$$\langle H_{Zeeman} \rangle = -\vec{J} \cdot \hat{\mathcal{B}}_{lab} \times \nu_{Larmor}$$

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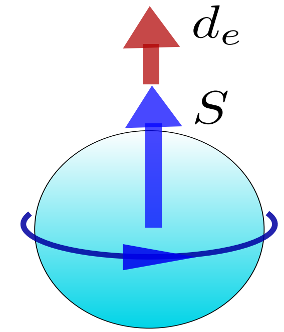

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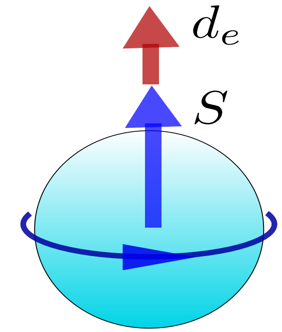
$$\langle H_{Zeeman} \rangle = -\vec{J} \cdot \hat{\mathcal{B}}_{lab} \times \nu_{Larmor}$$

$$\delta W \approx 200\ \mu\text{Hz} \Rightarrow \delta d_e \approx 10^{-29}\ e\ \text{cm}$$

Meyer & Bohn, *Phys. Rev. A* 78, 010502 (2008)

How do we measure W_{EDM} ?



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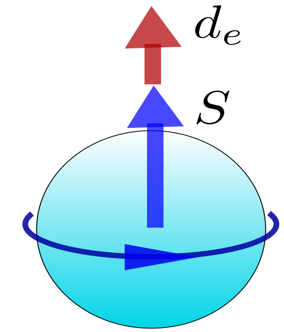
$$\langle H_{Zeeman} \rangle = -\vec{J} \cdot \hat{\mathcal{B}}_{lab} \times \nu_{Larmor}$$

$$\delta W = \frac{1/\tau}{\sqrt{\dot{N} T}}$$

How do we measure W_{EDM} ?



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$$\delta W = \frac{1/\tau}{\sqrt{\dot{N}T}}$$

coherence time

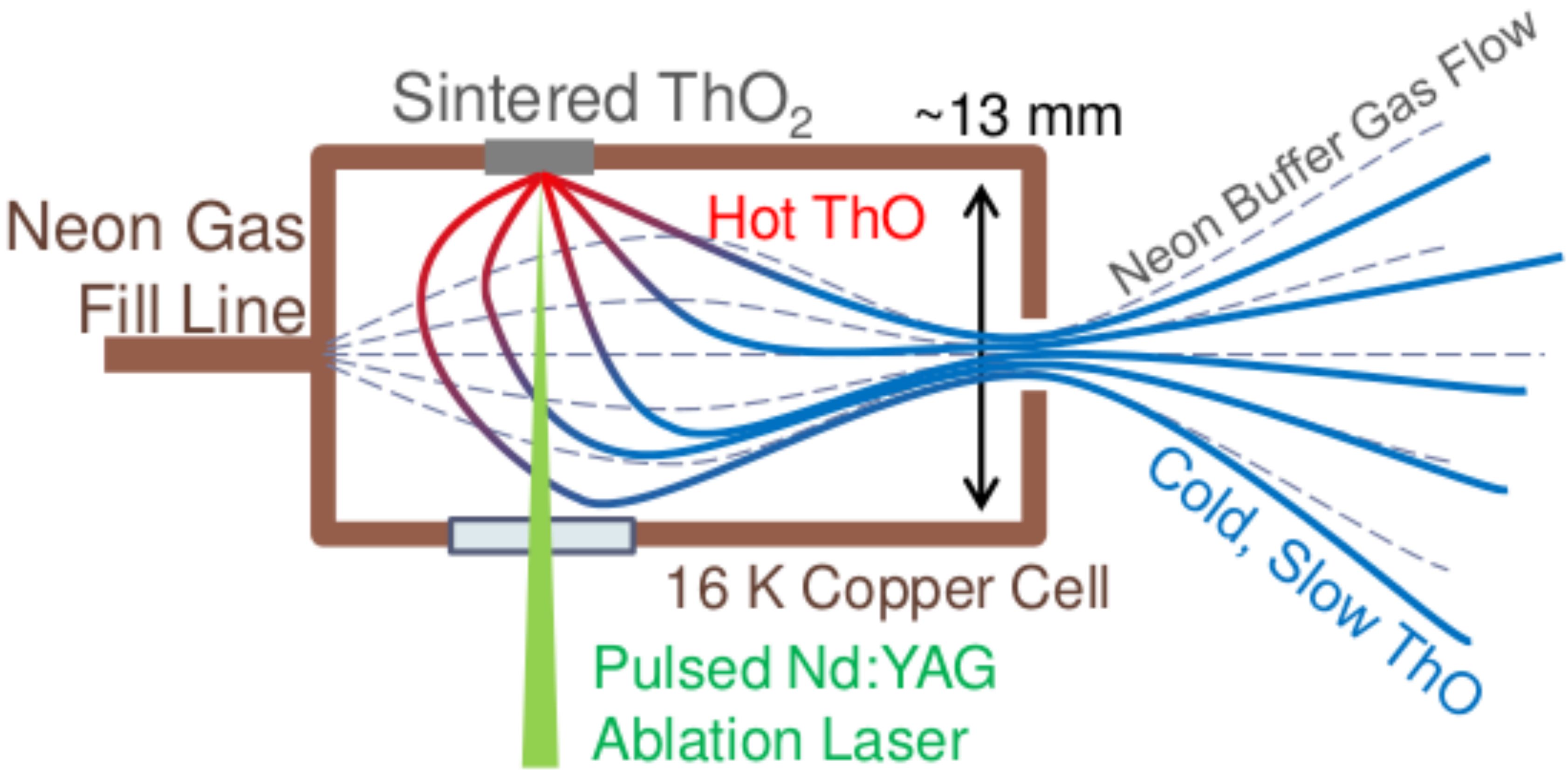
integration time

detection rate

Step 1: Produce a molecular beam

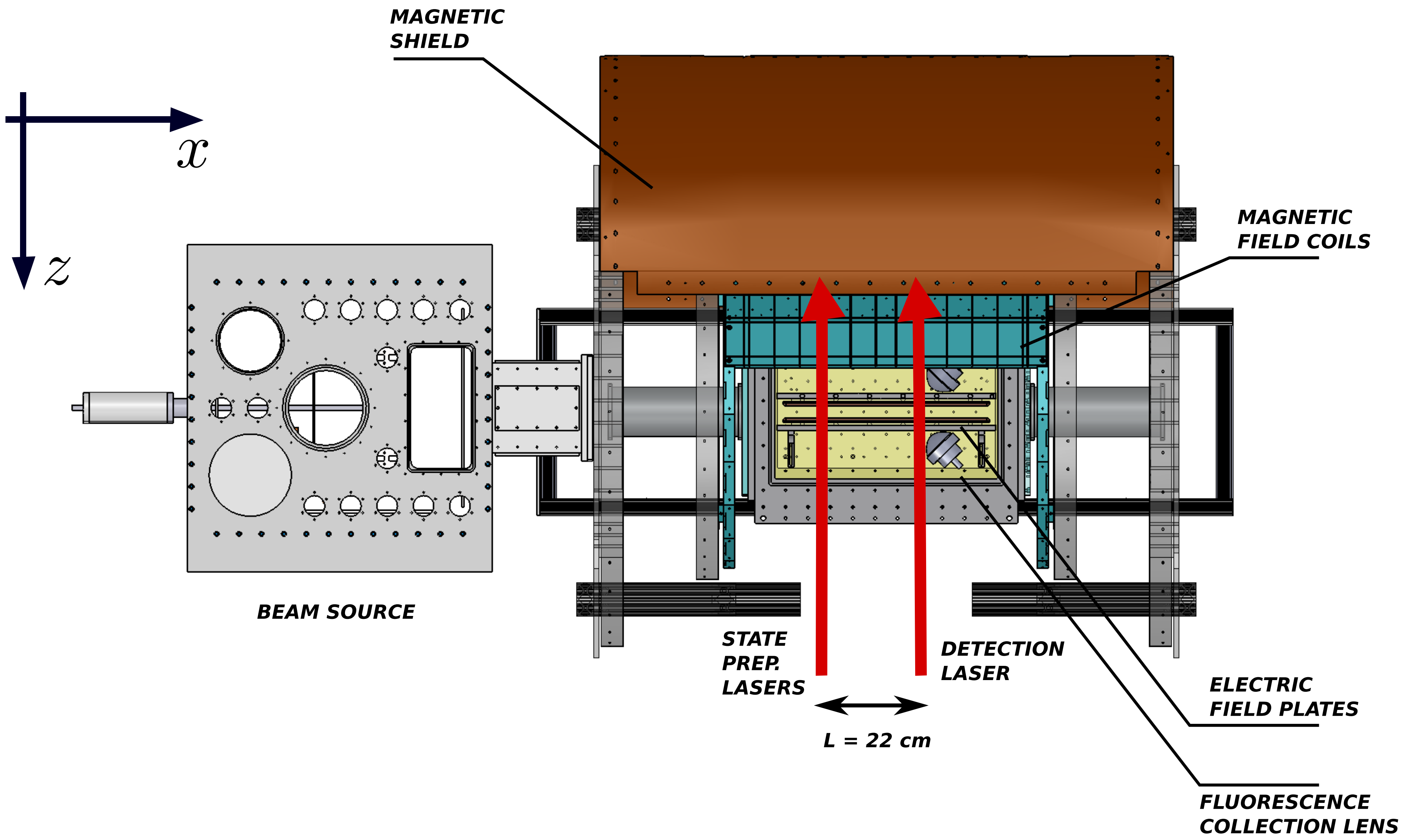
Neon-cooled ThO beam

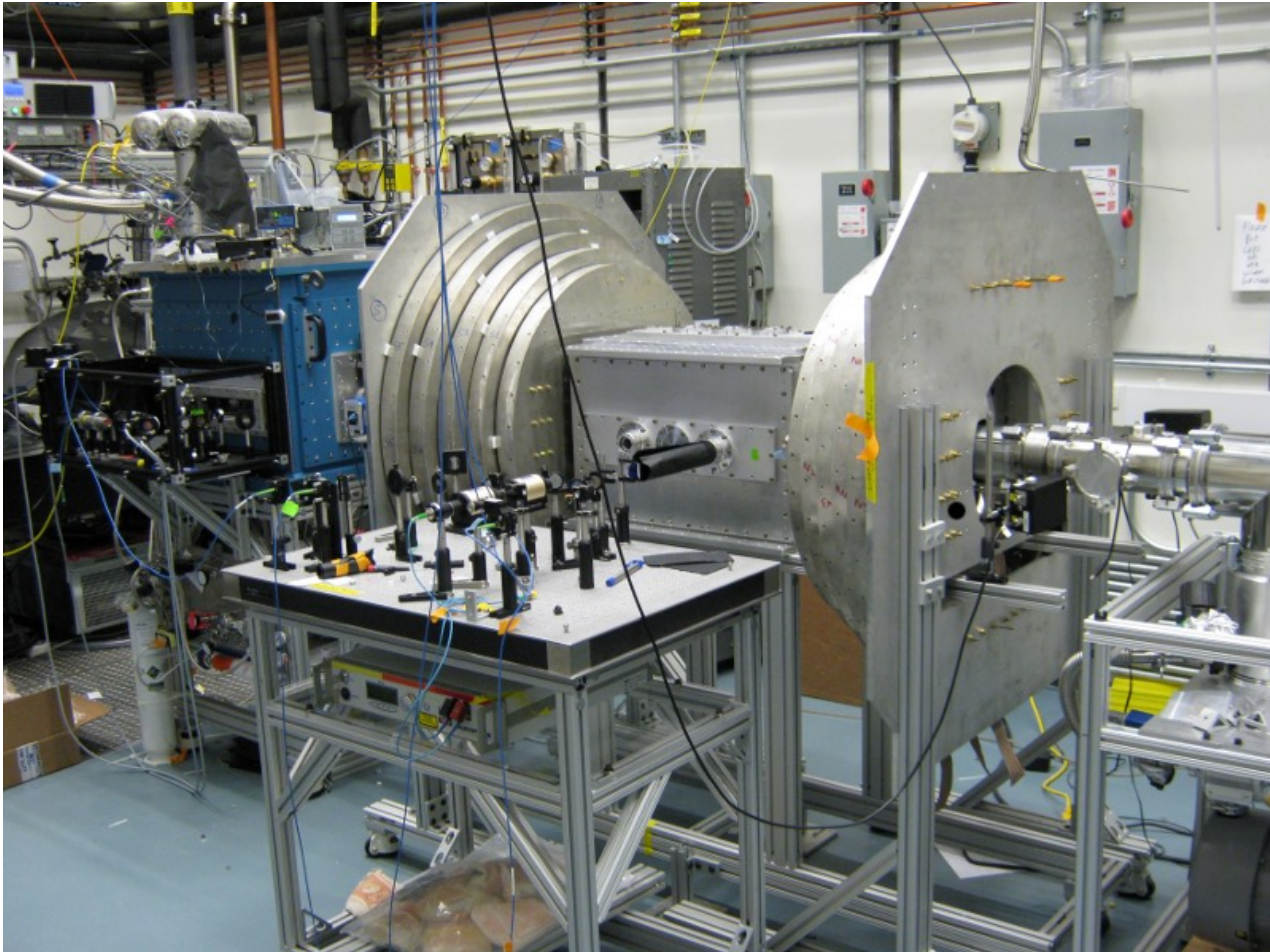
$$\dot{N}_0 \simeq 10^{13}/\mathrm{s}/\mathrm{sr}$$



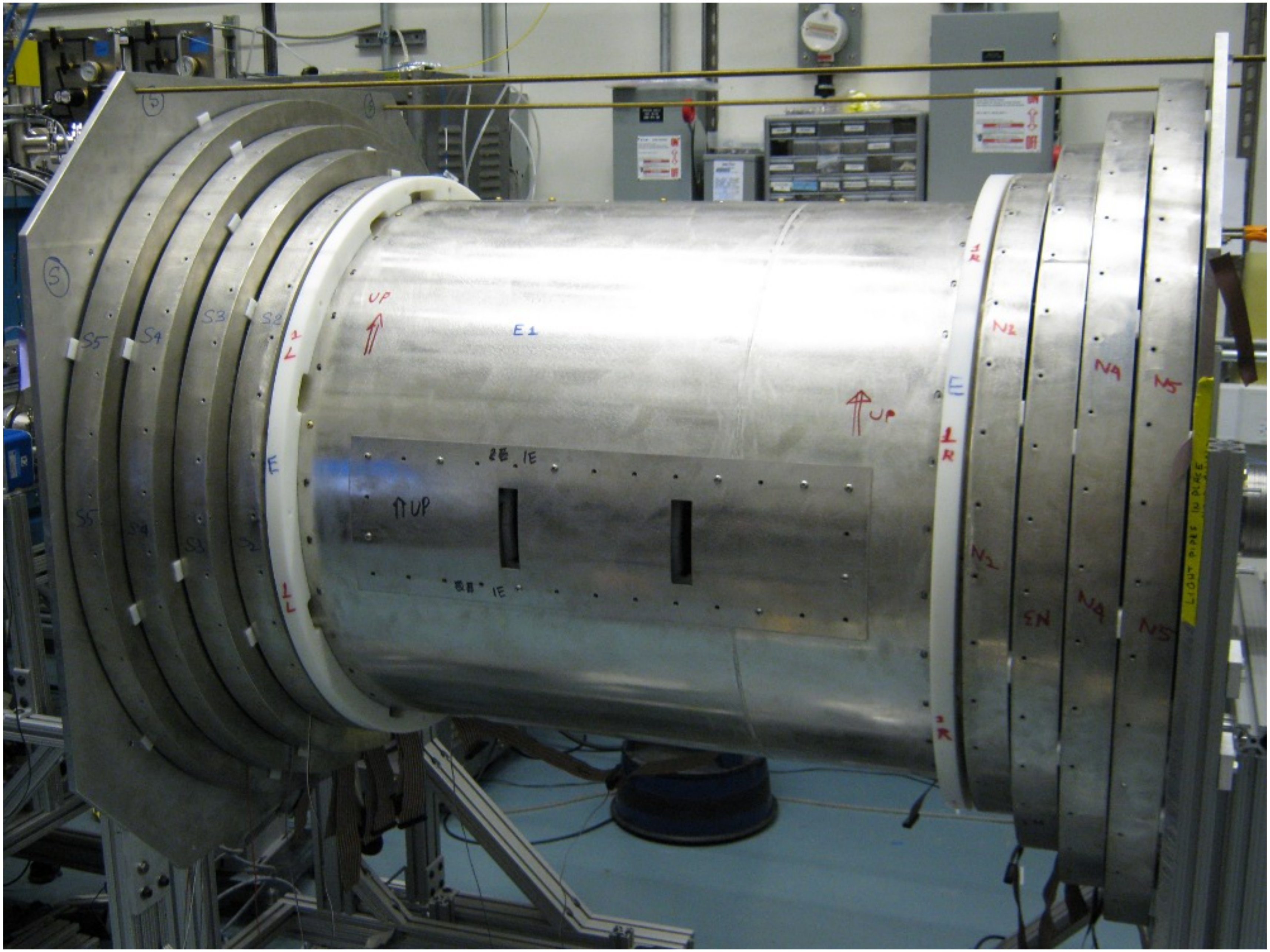
Step 2: Polarize your molecule

eEDM apparatus: Overview

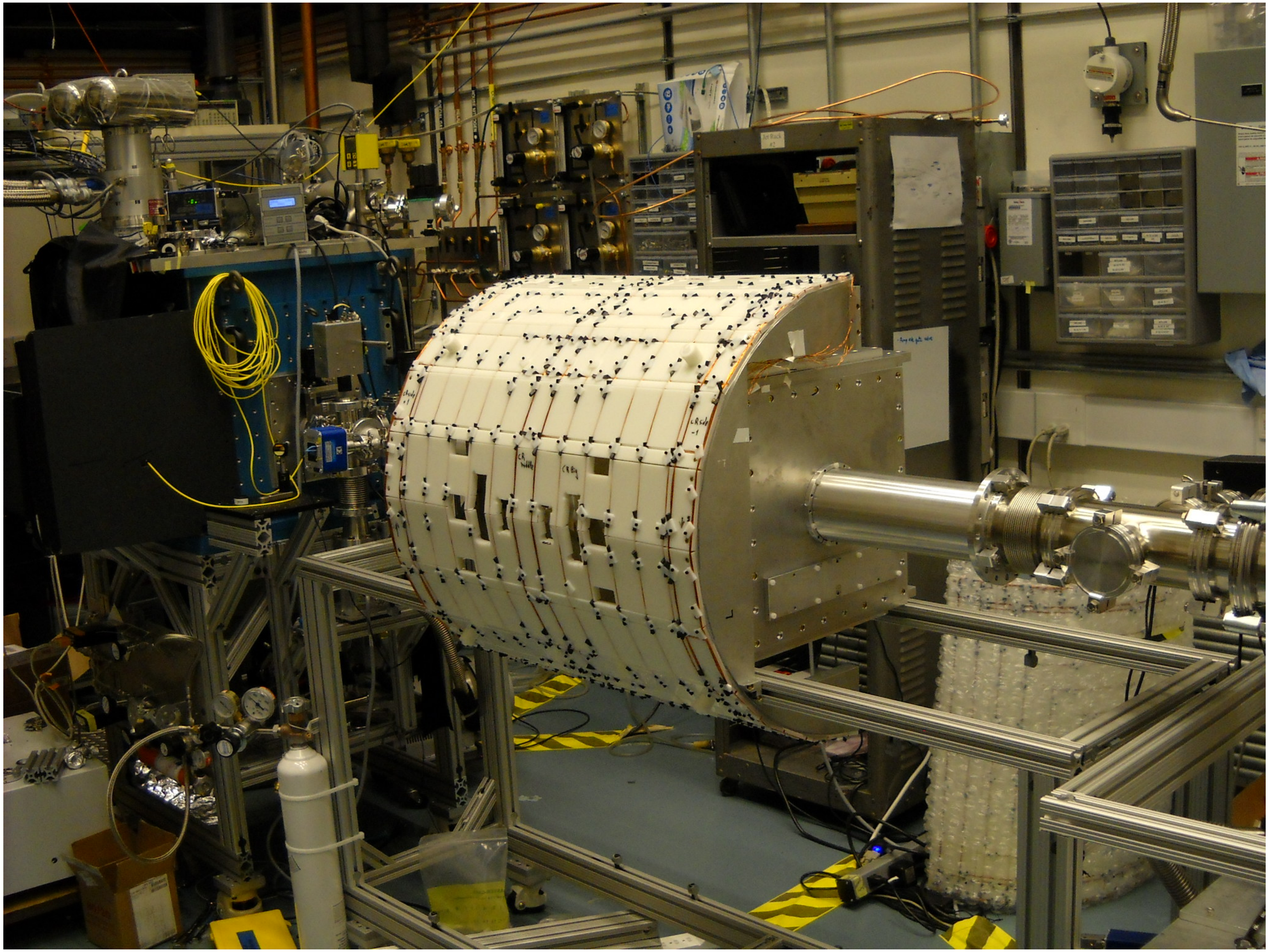




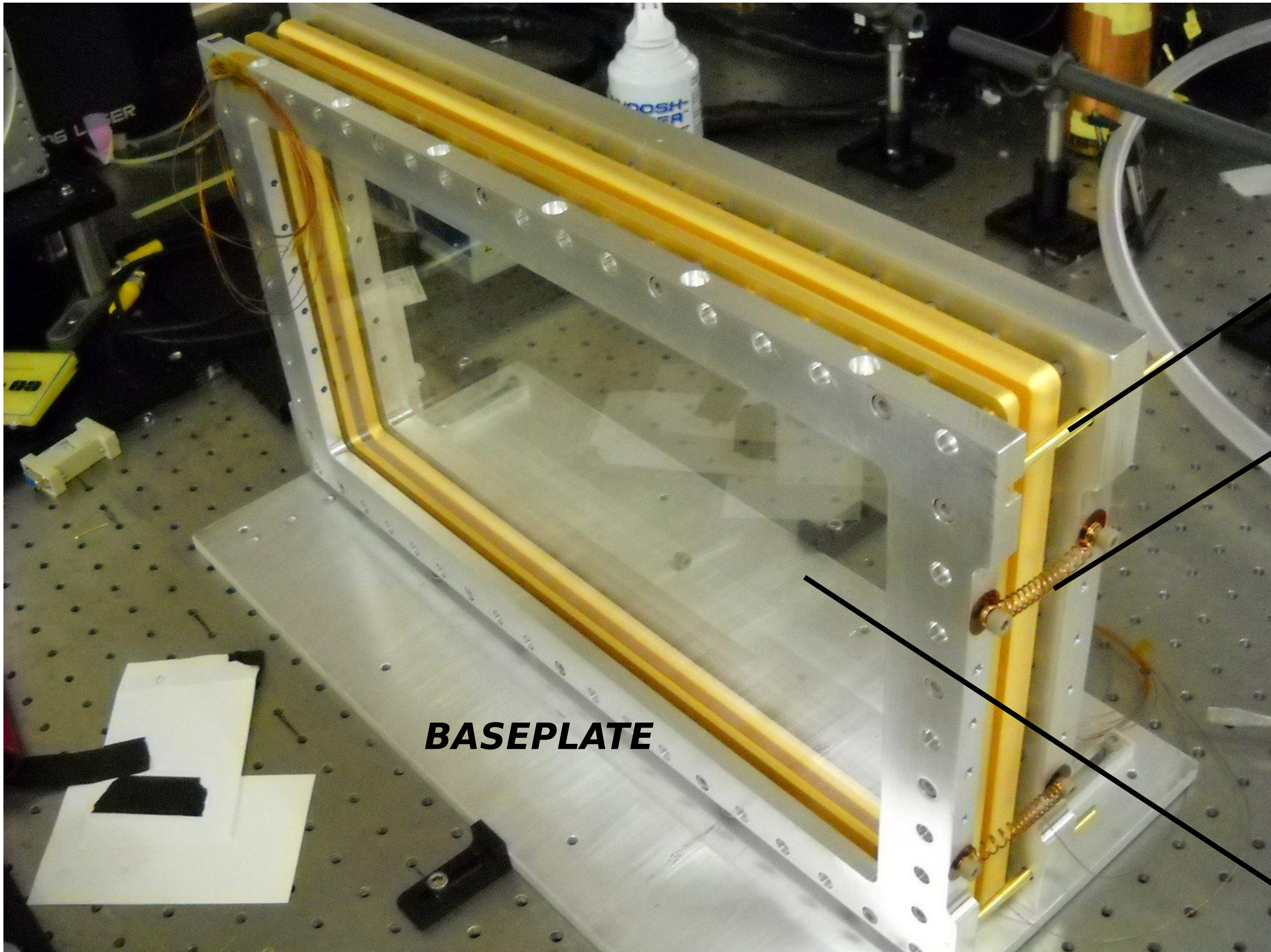
eEDM apparatus: Magnetic shielding



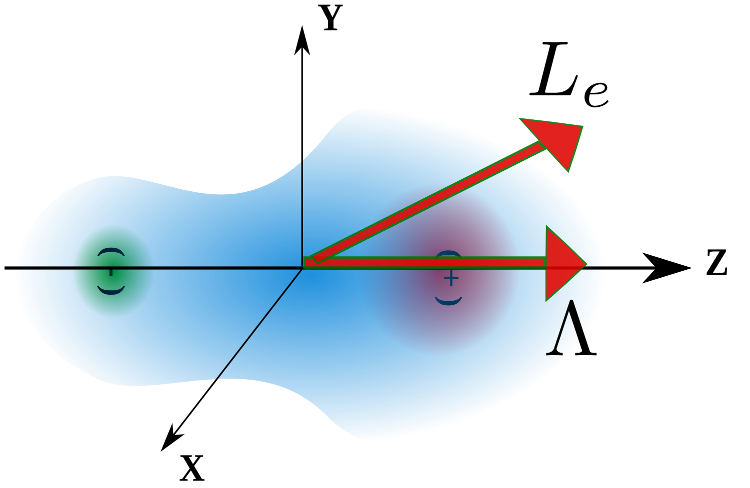
eEDM apparatus: $\mathcal{B}$-field coil

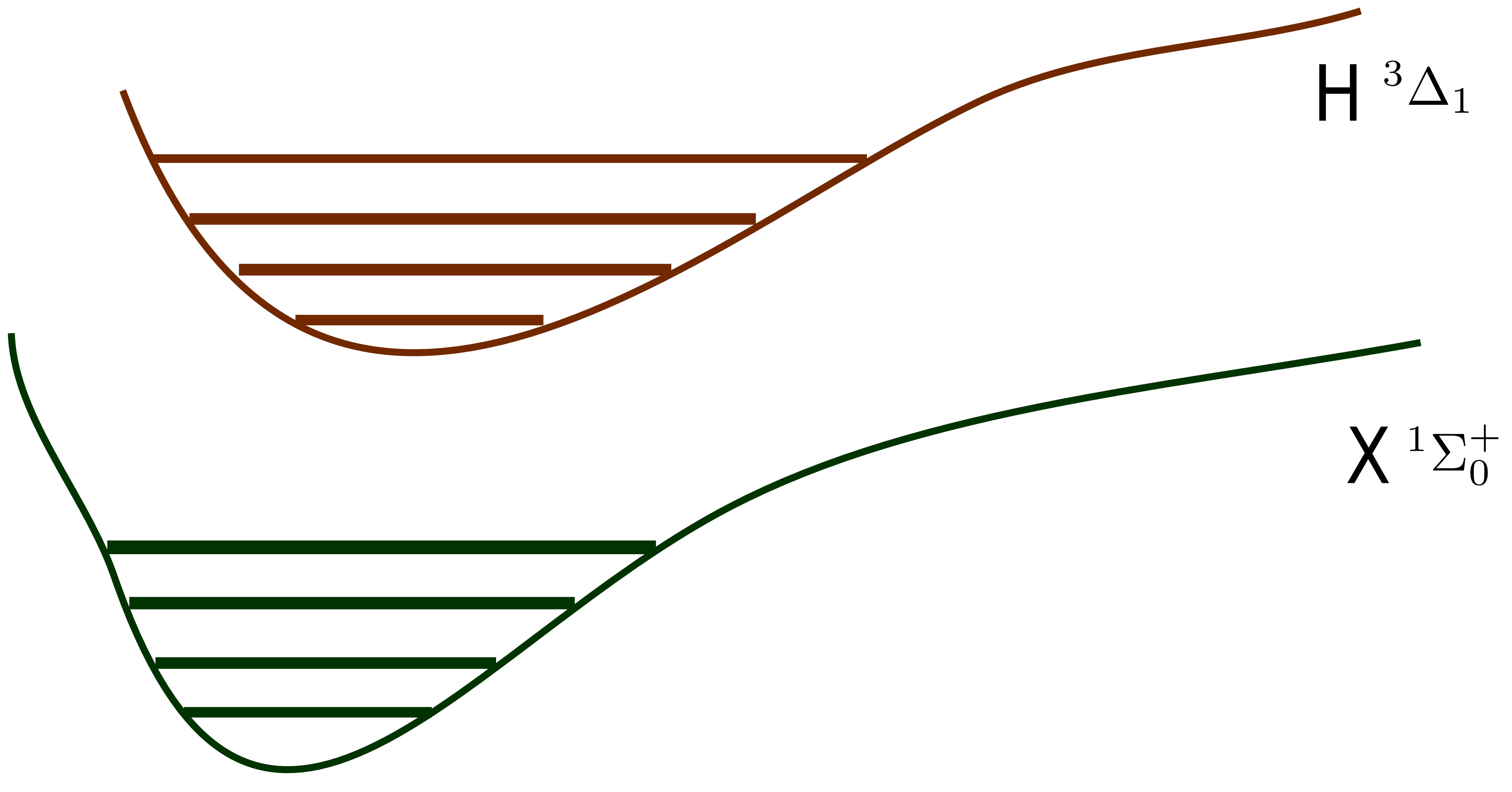


eEDM apparatus: $\mathcal{E}$-field plates



Thorium monoxide (ThO)





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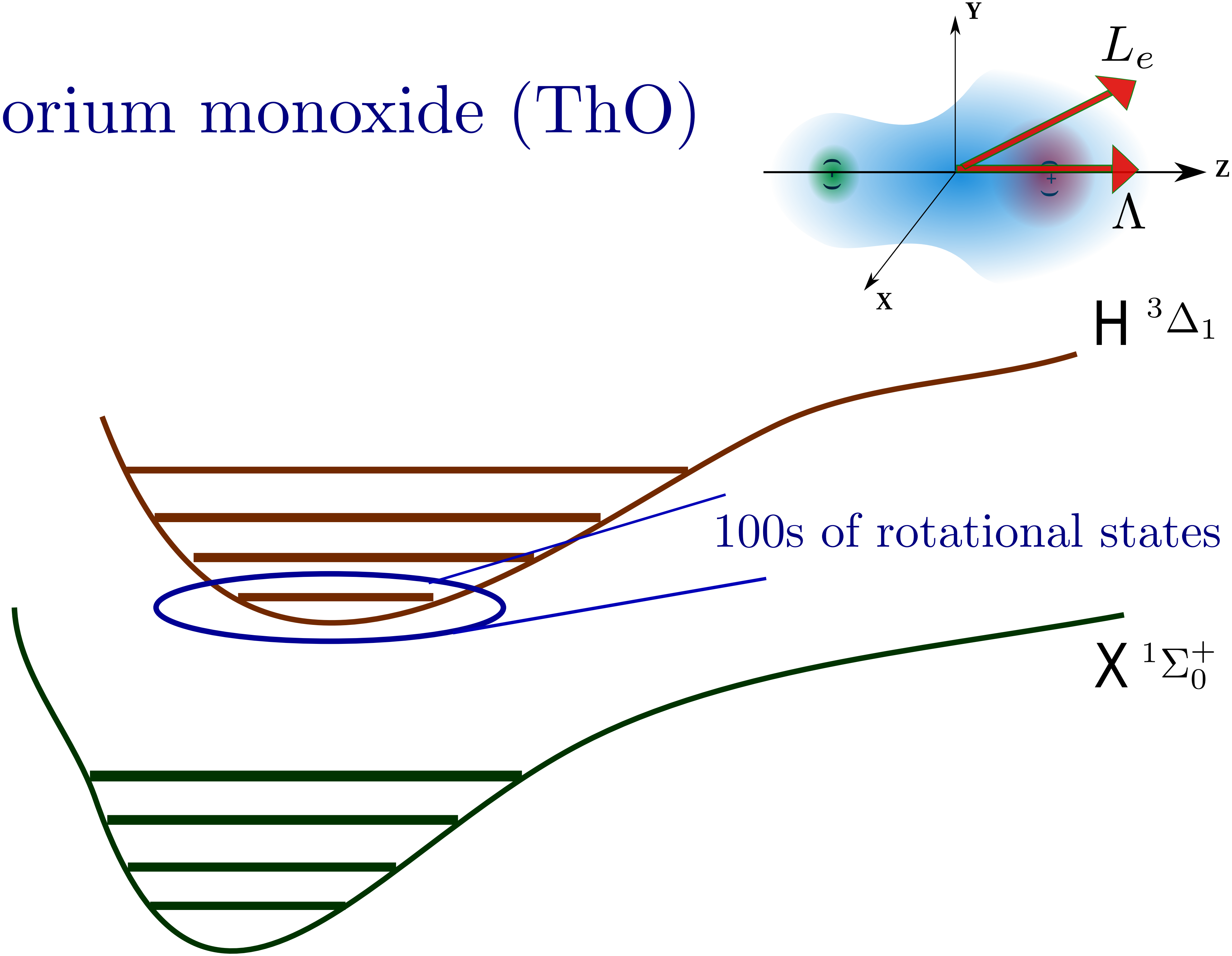

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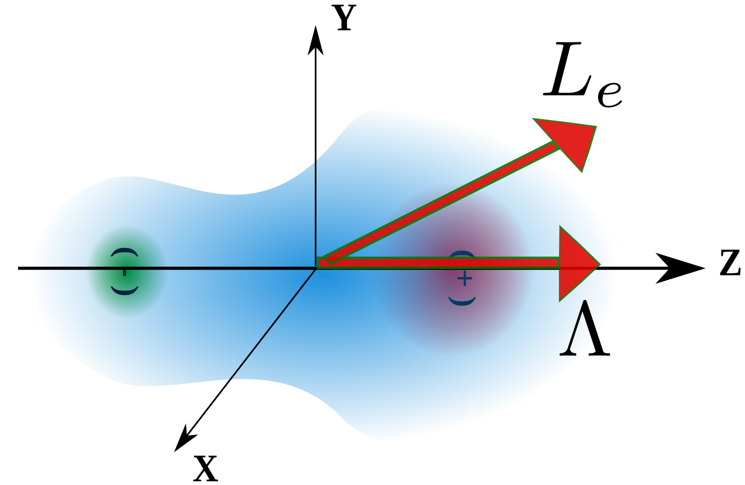
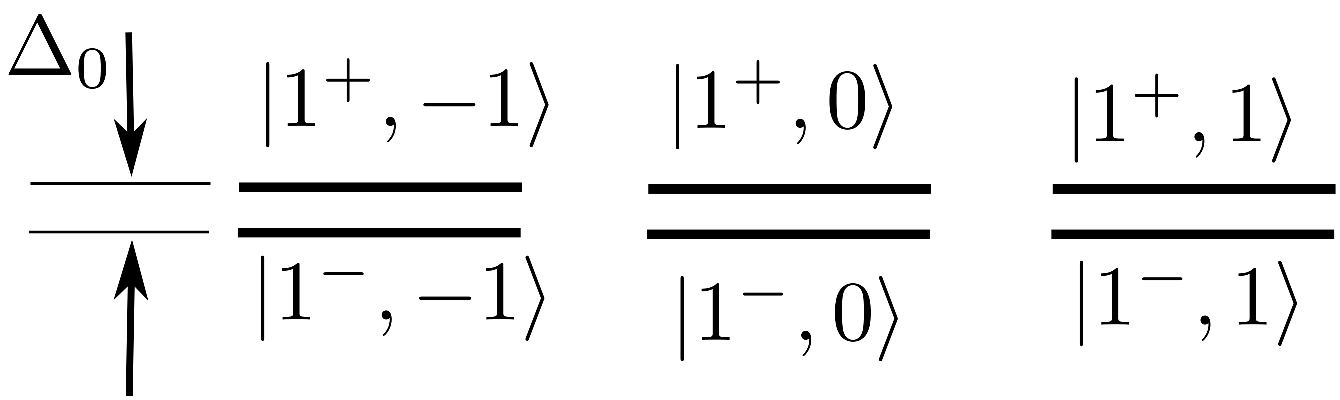


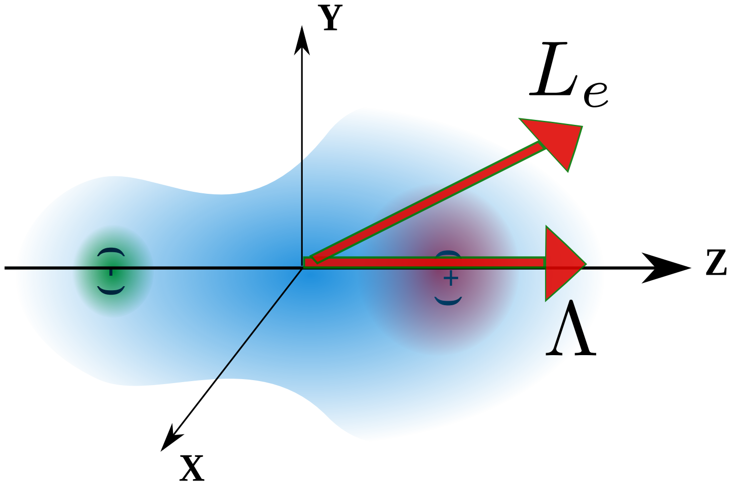
$$\mathcal{E}_{lab} = 0$$

$$|\psi\rangle = |J^p, m_J\rangle$$

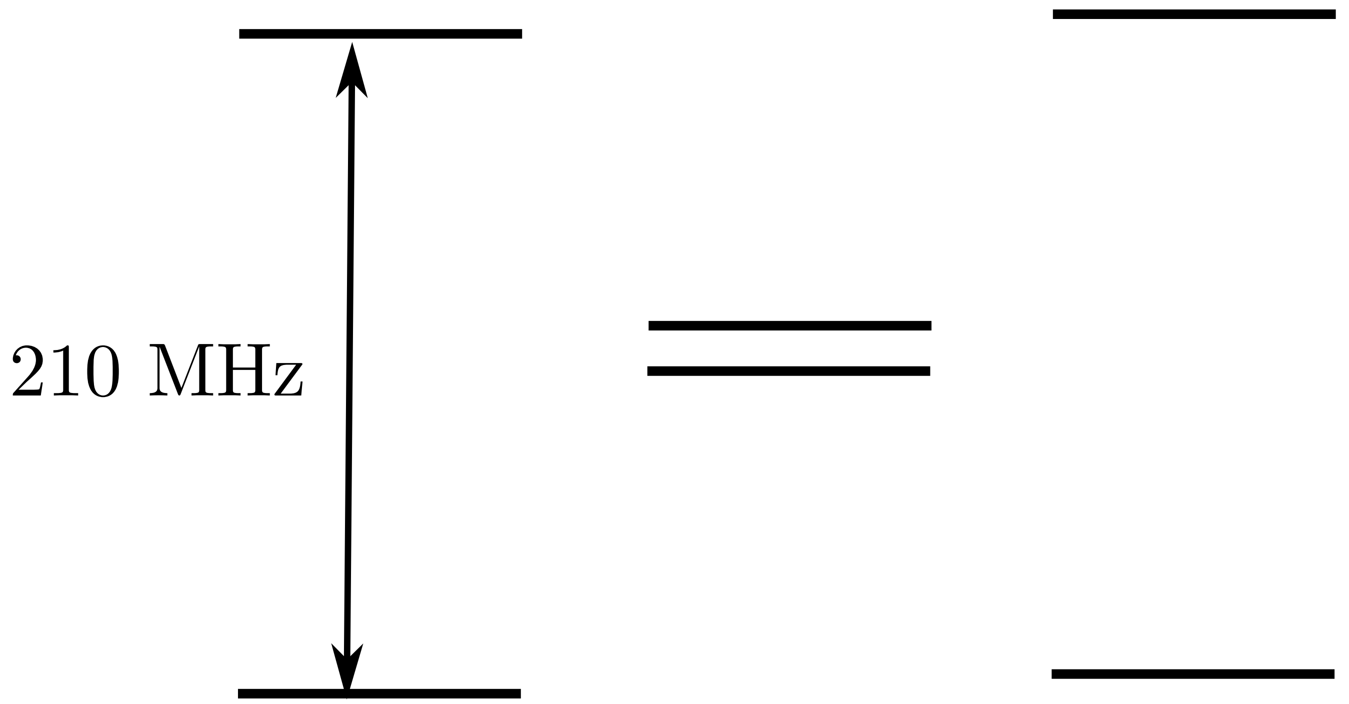


Lowest vibrational, lowest rotational state in $H\ ^3\Delta_1$

Thorium monoxide (ThO)



$$\mathcal{E}_{lab} = 100 \text{ V/cm}$$



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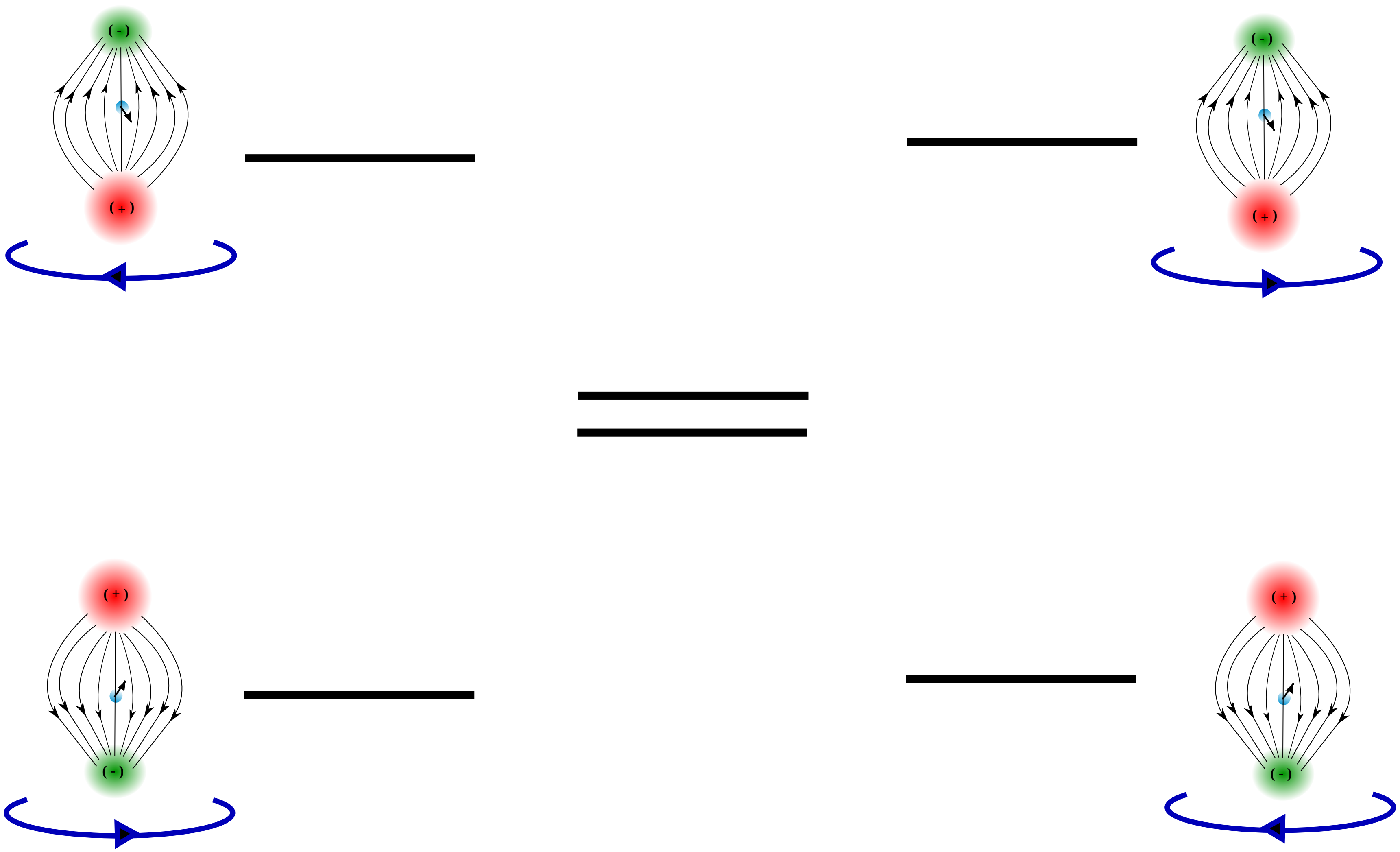
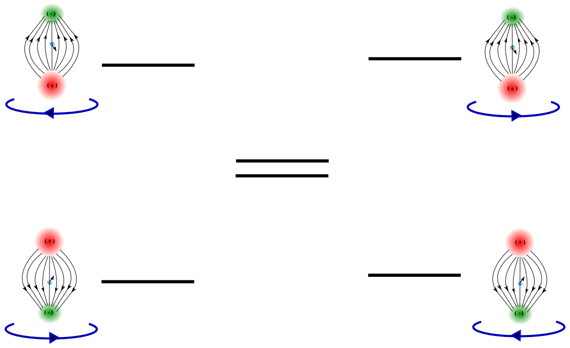
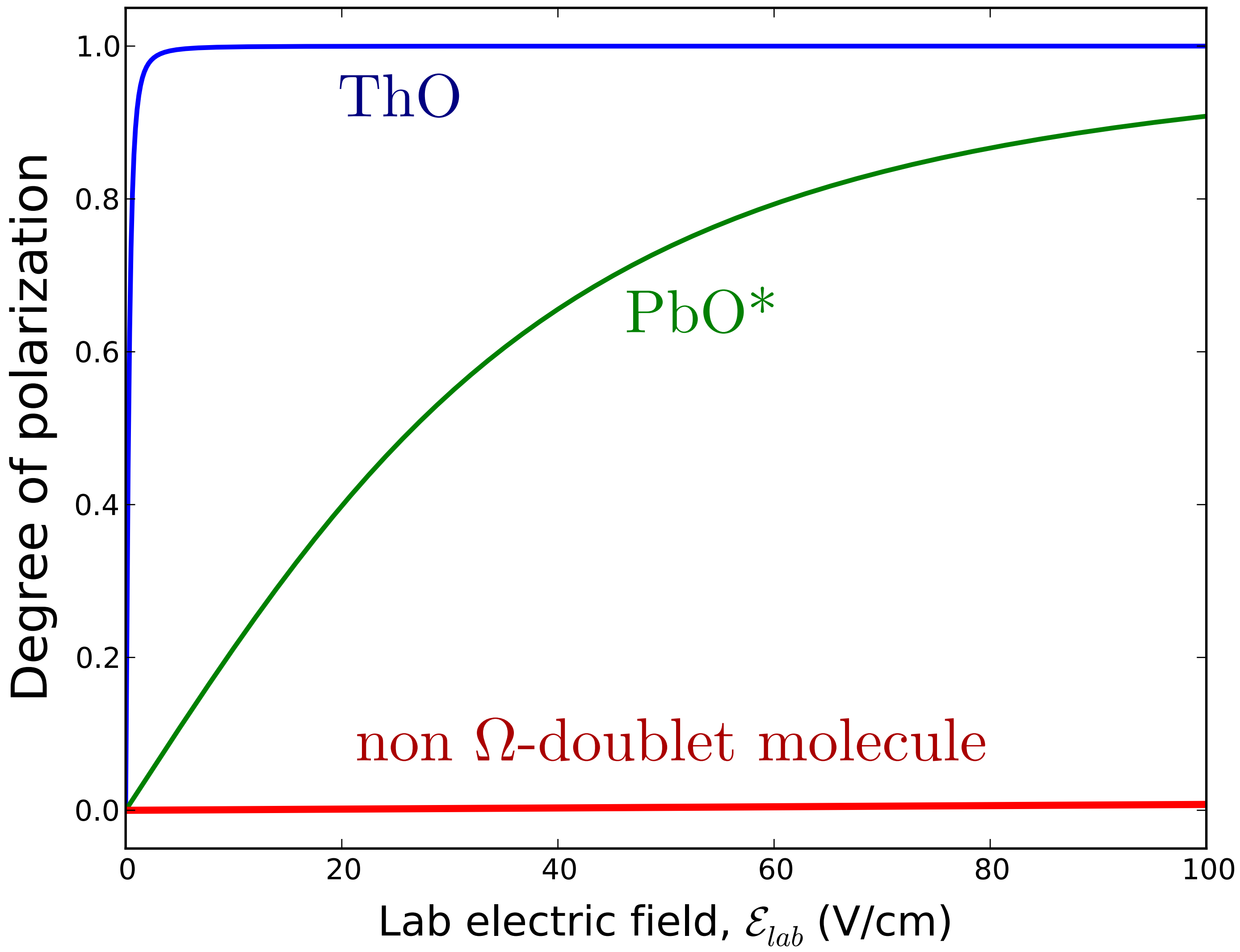
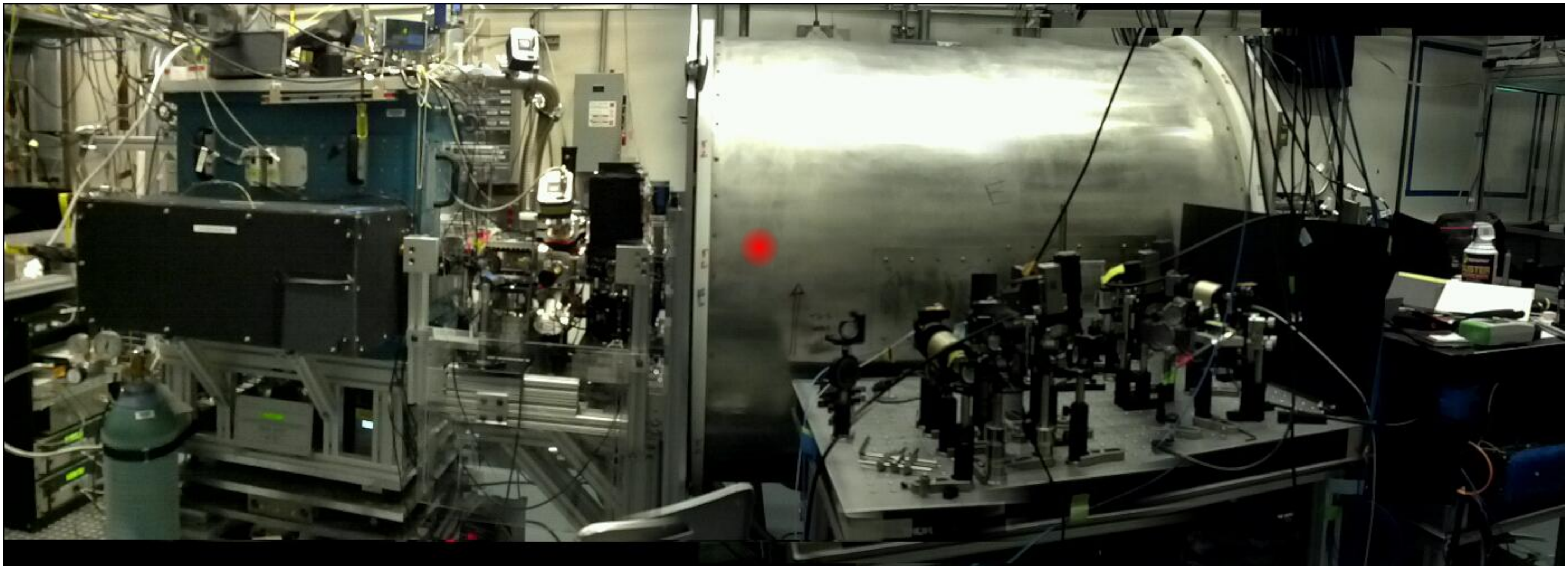


Thorium monoxide (ThO)

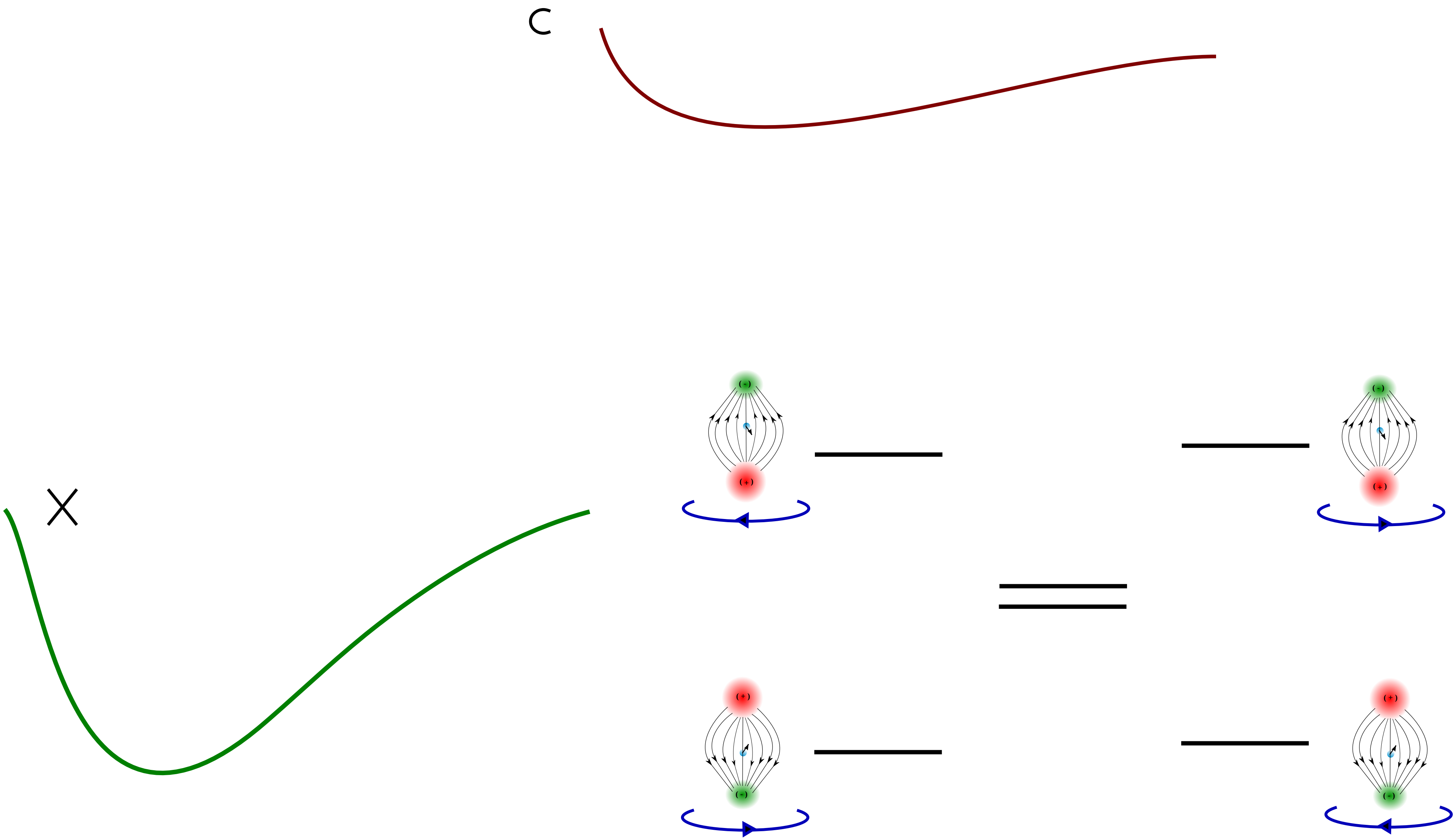




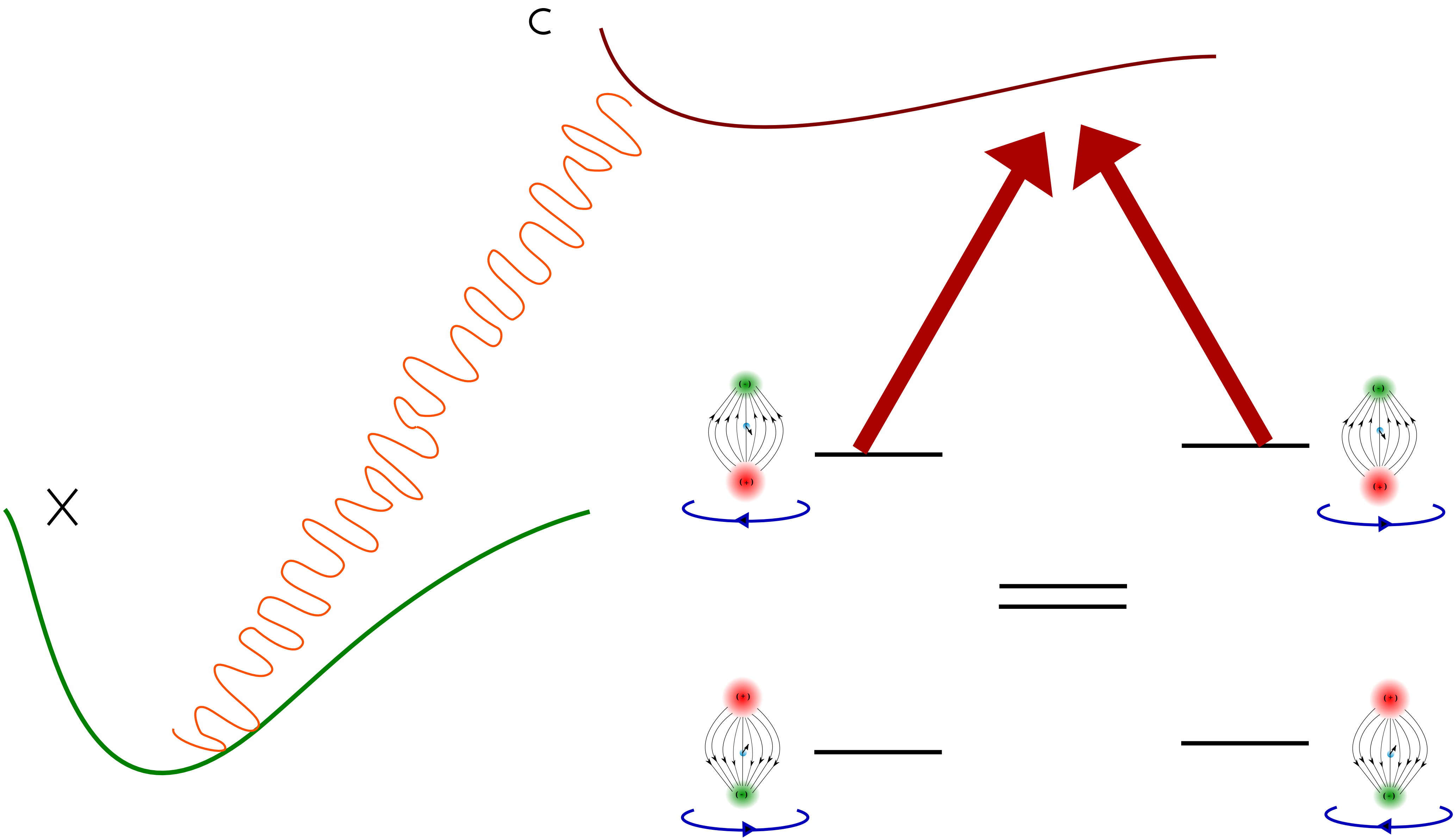


Step 3: Prepare the spin $\perp$ to the $\mathcal{E}$-field

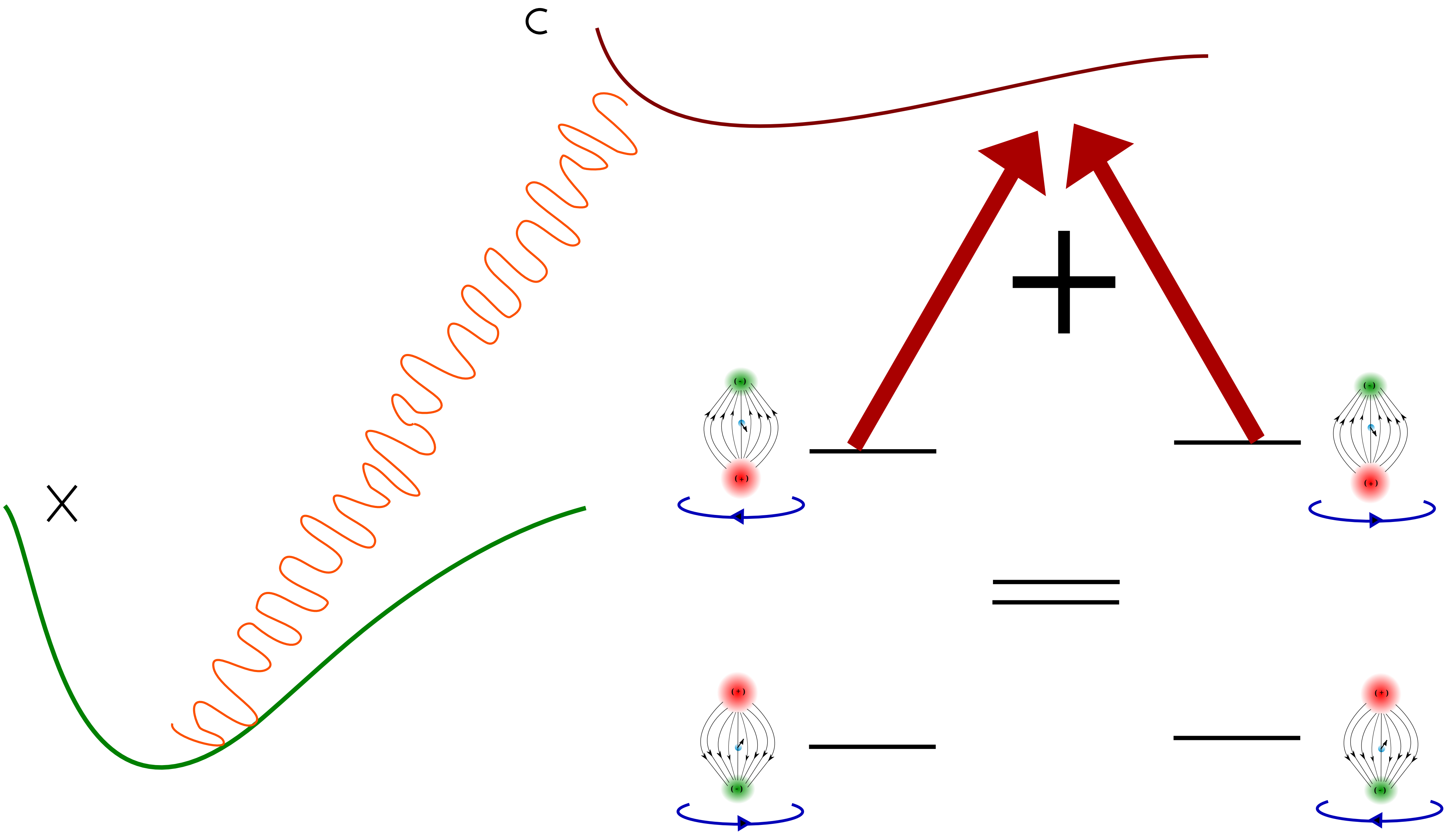
Spin preparation using laser polarization

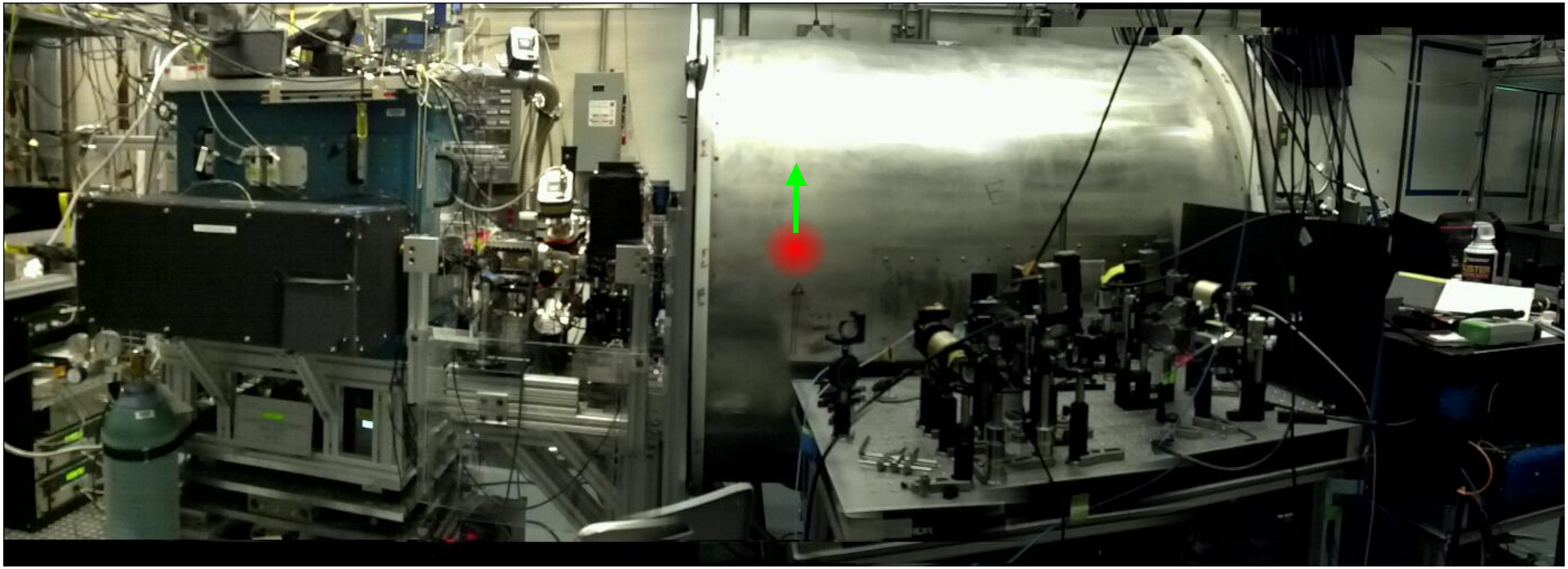


Spin preparation using laser polarization

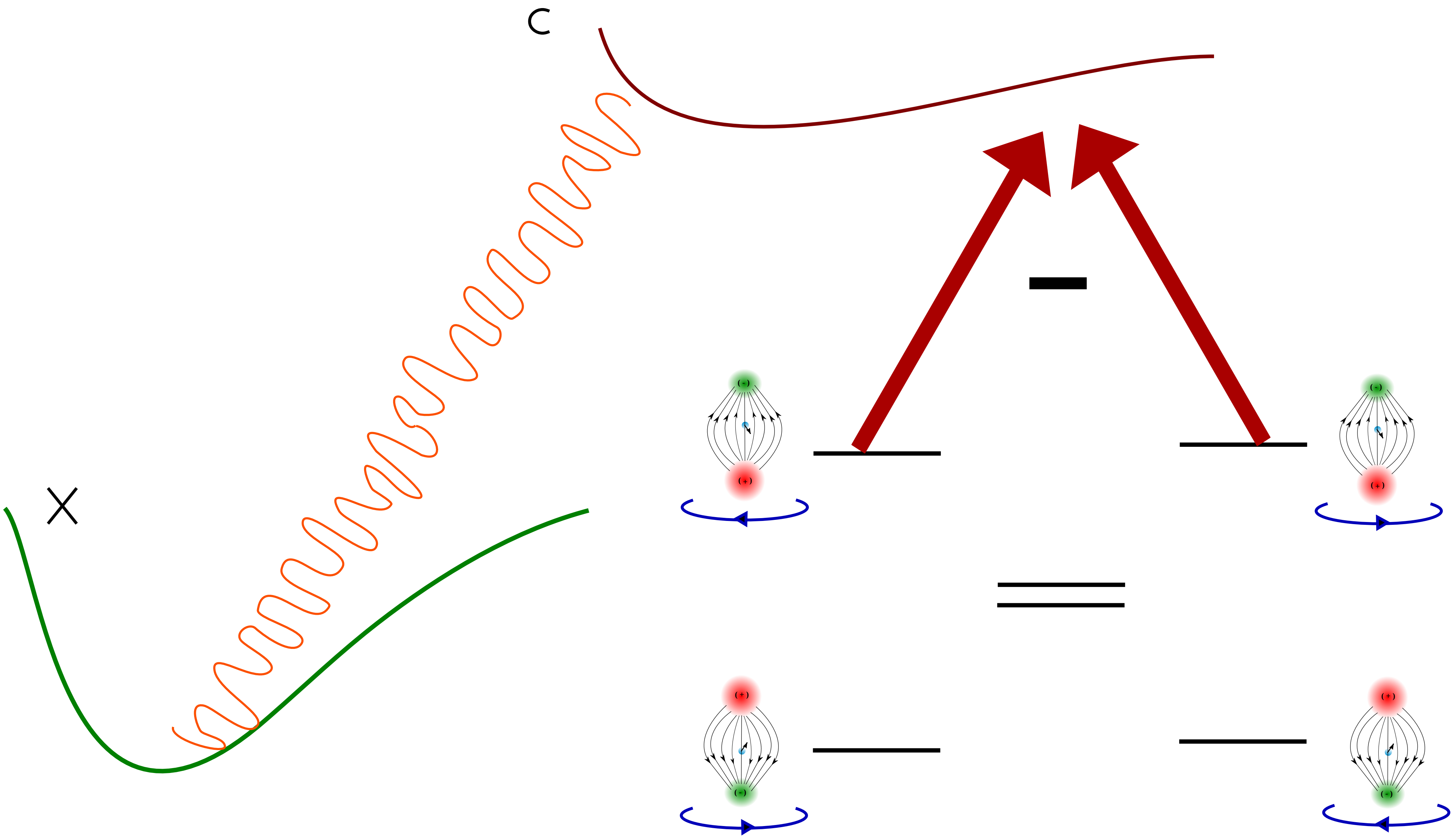


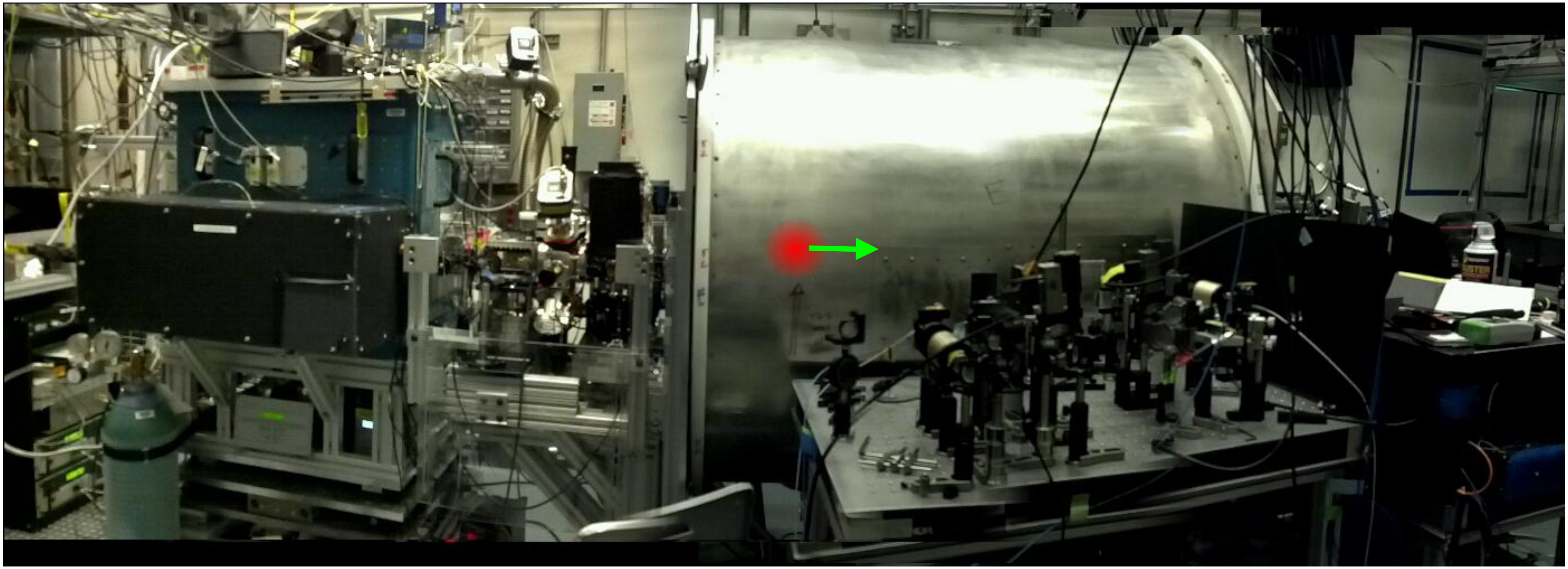
Spin preparation using laser polarization



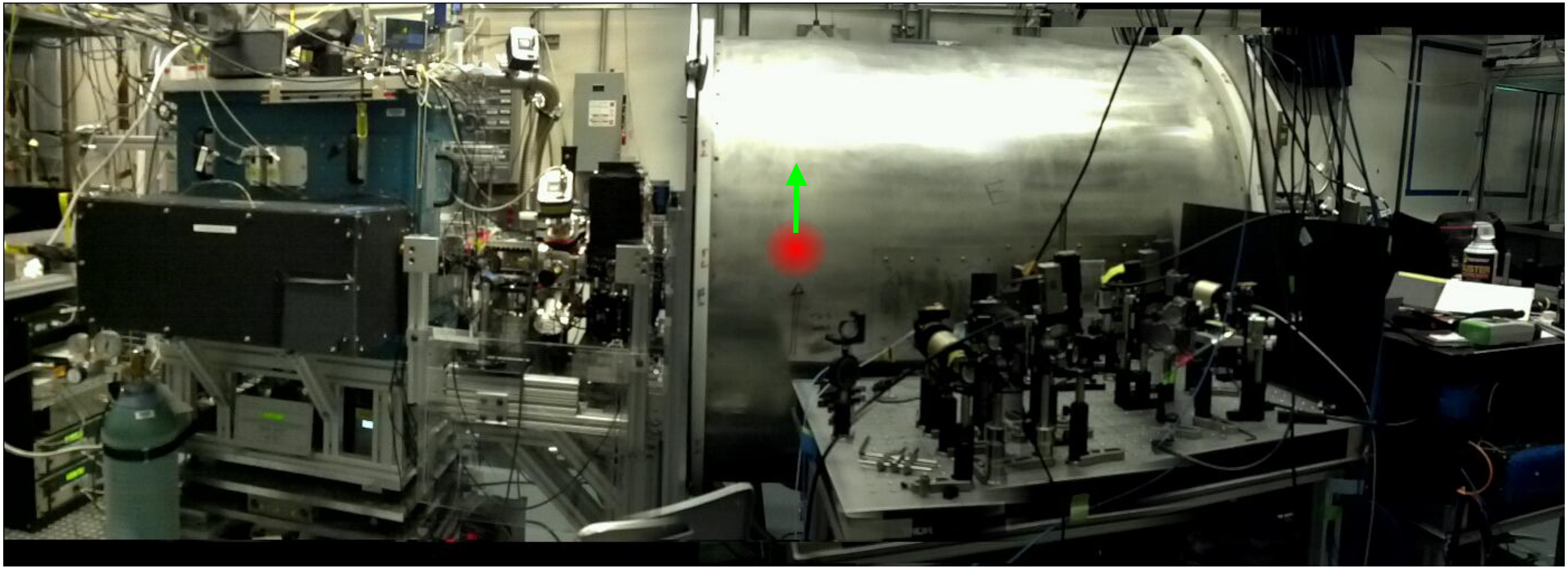


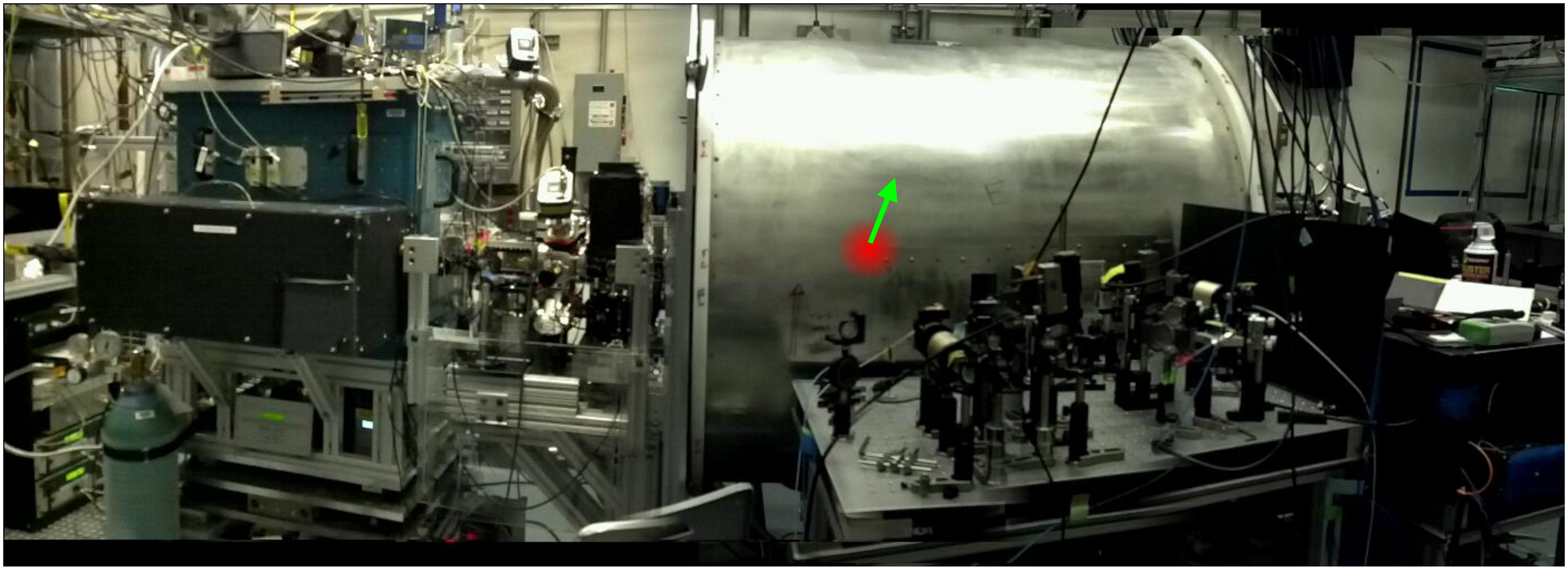
Spin preparation using laser polarization

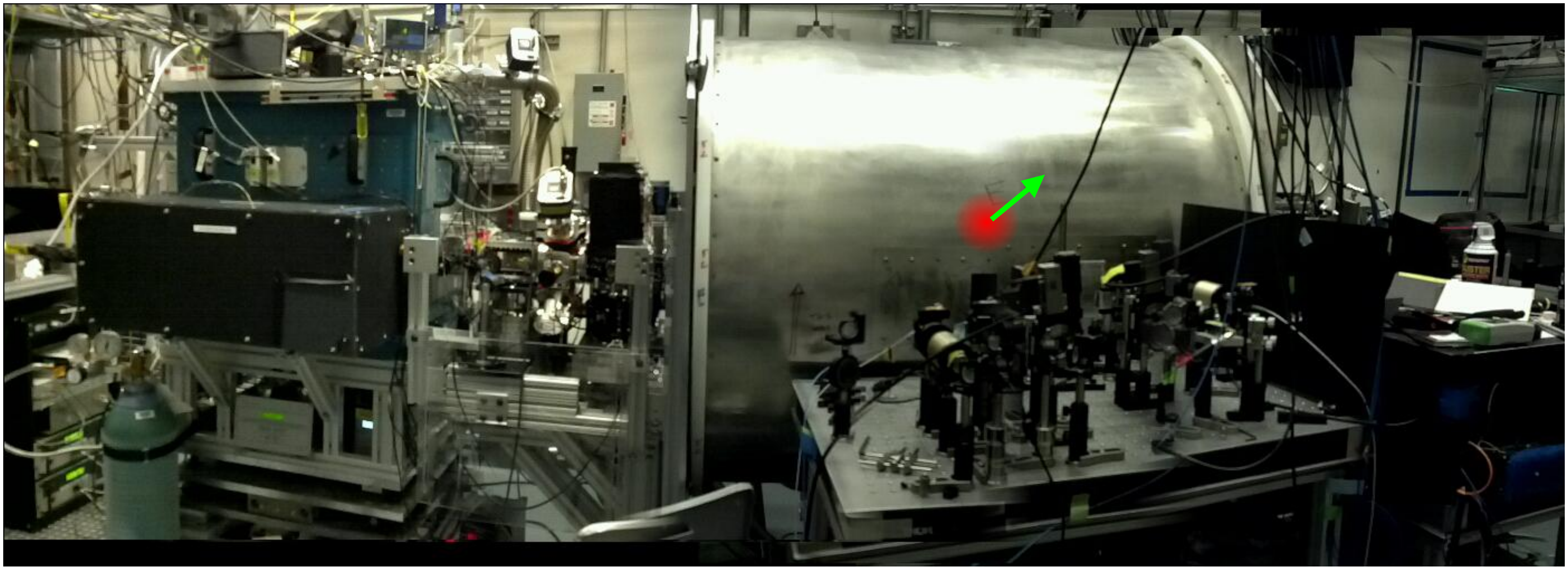


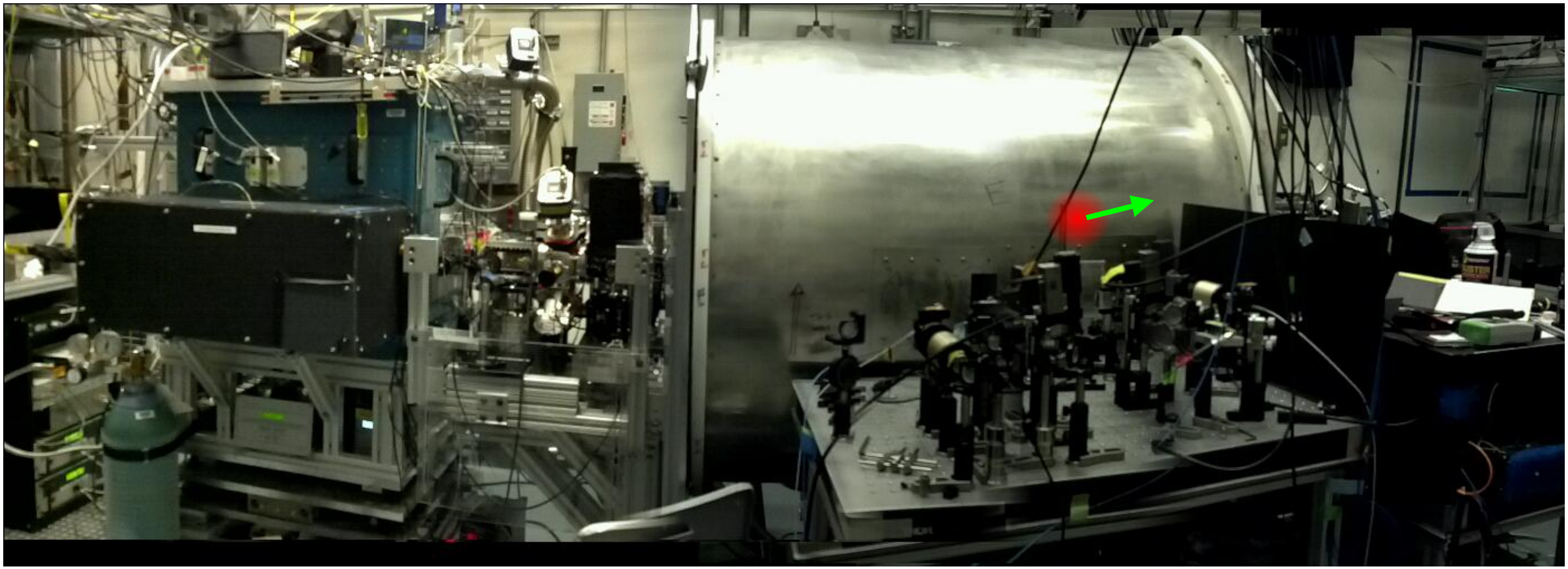


Step 4: Let it precess

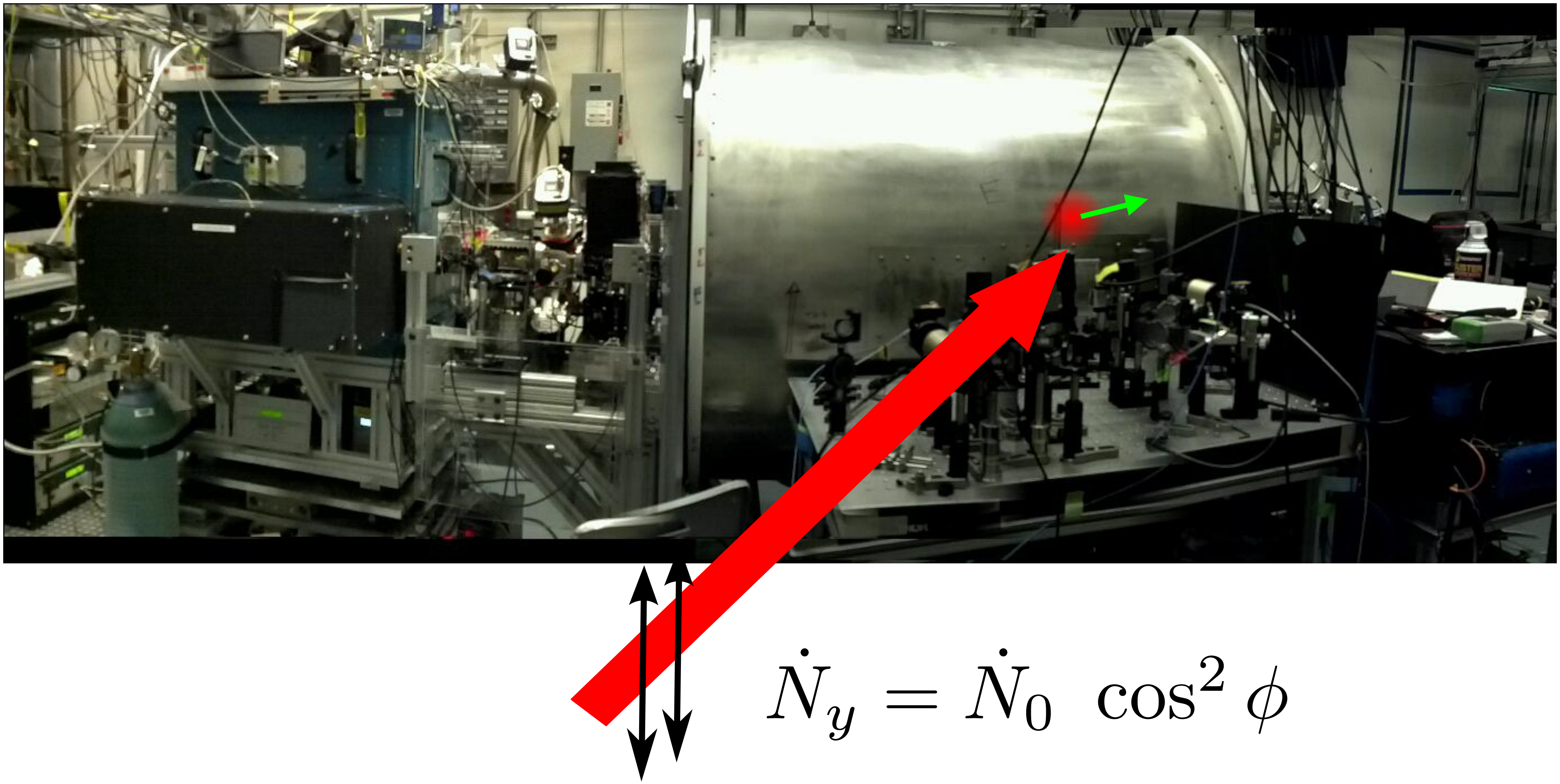




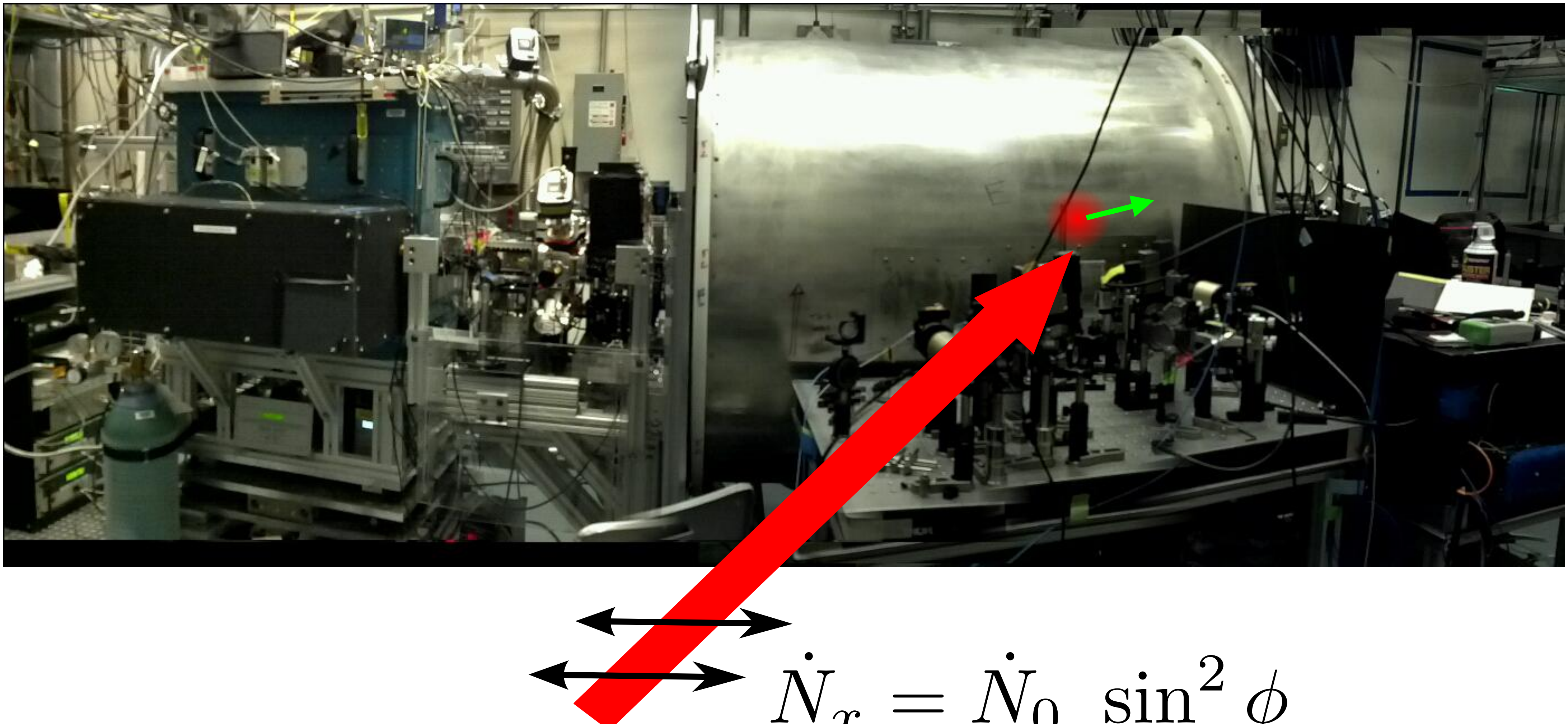




Step 5: See how far the "clock" spun round

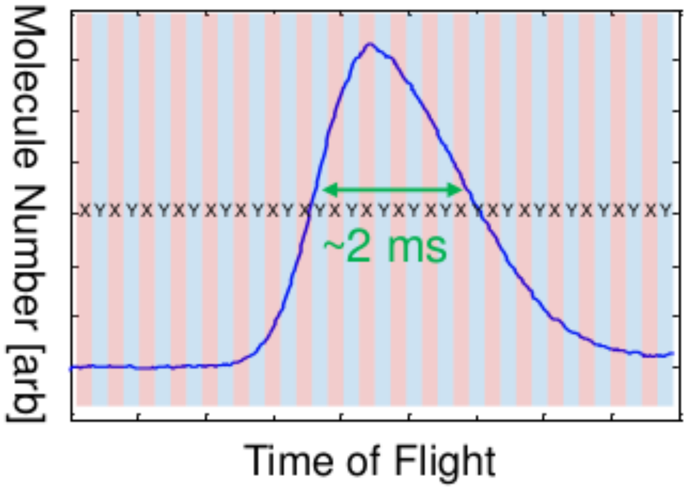


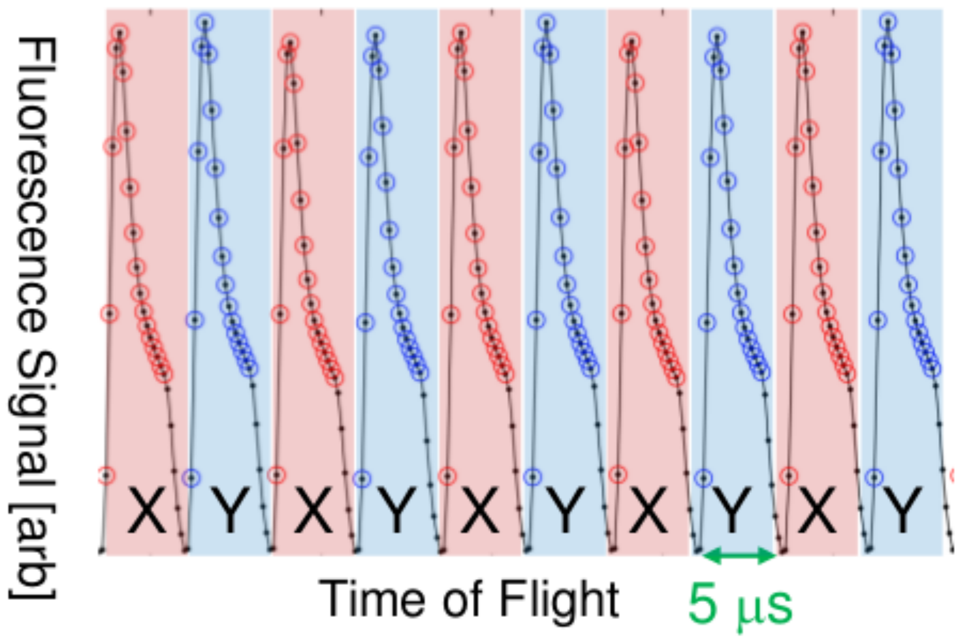
$$\dot{N}_y = \dot{N}_0 \ \cos^2 \phi$$



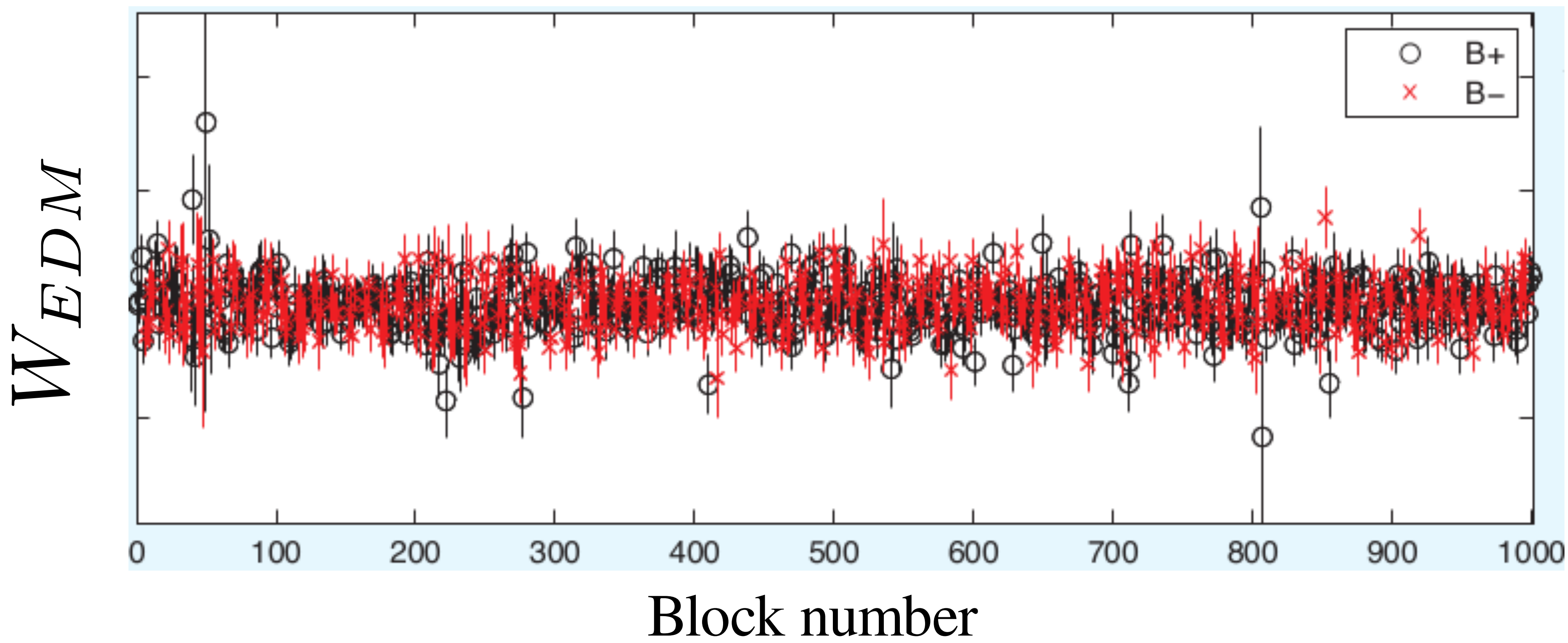
$$\dot{N}_x = \dot{N}_0 \ \sin^2 \phi$$

Fast polarization flips





Spin precession data

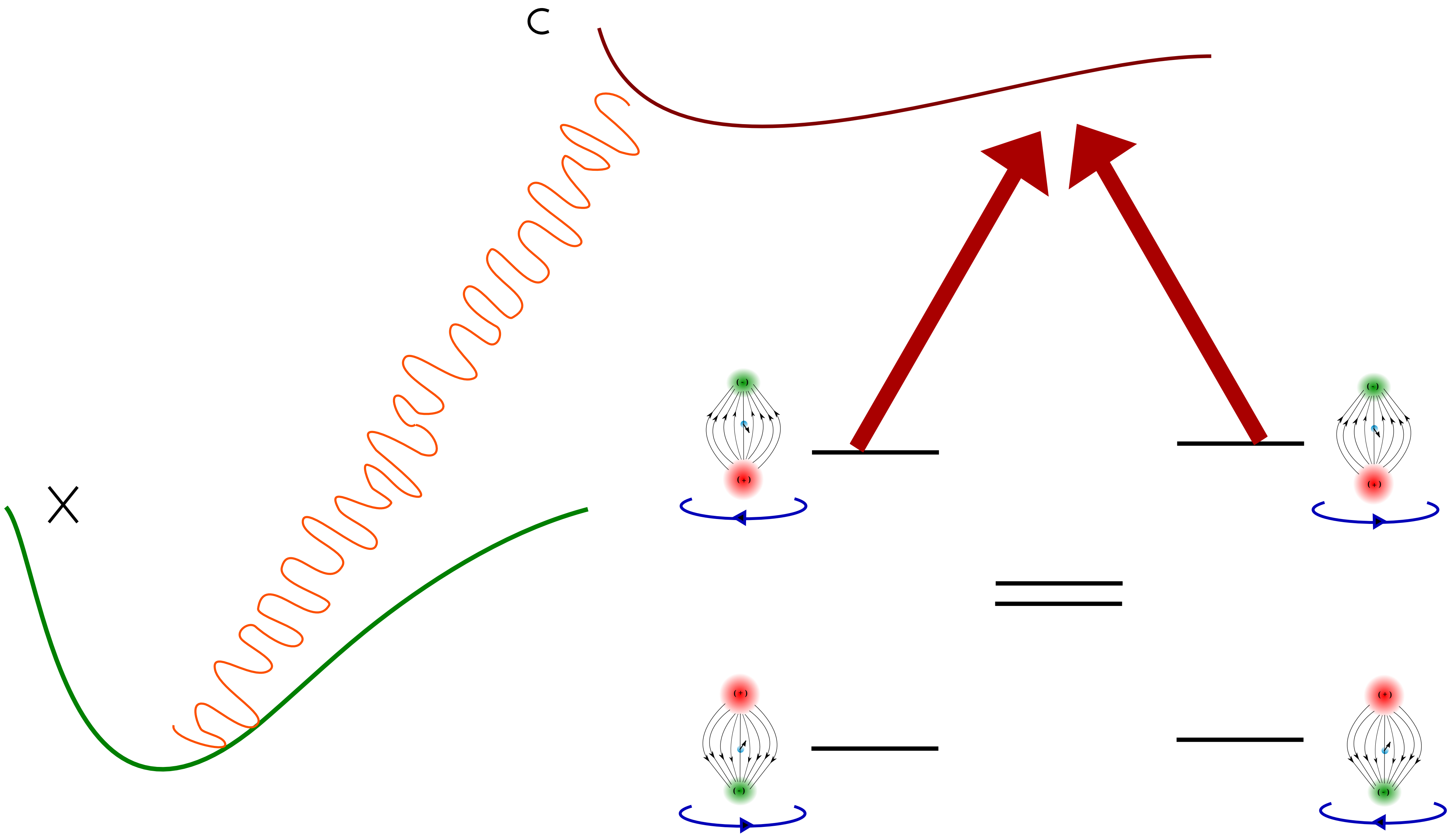


We can obtain $\delta W \sim 2$ mHz
with 1 day of data (10^10 photons)

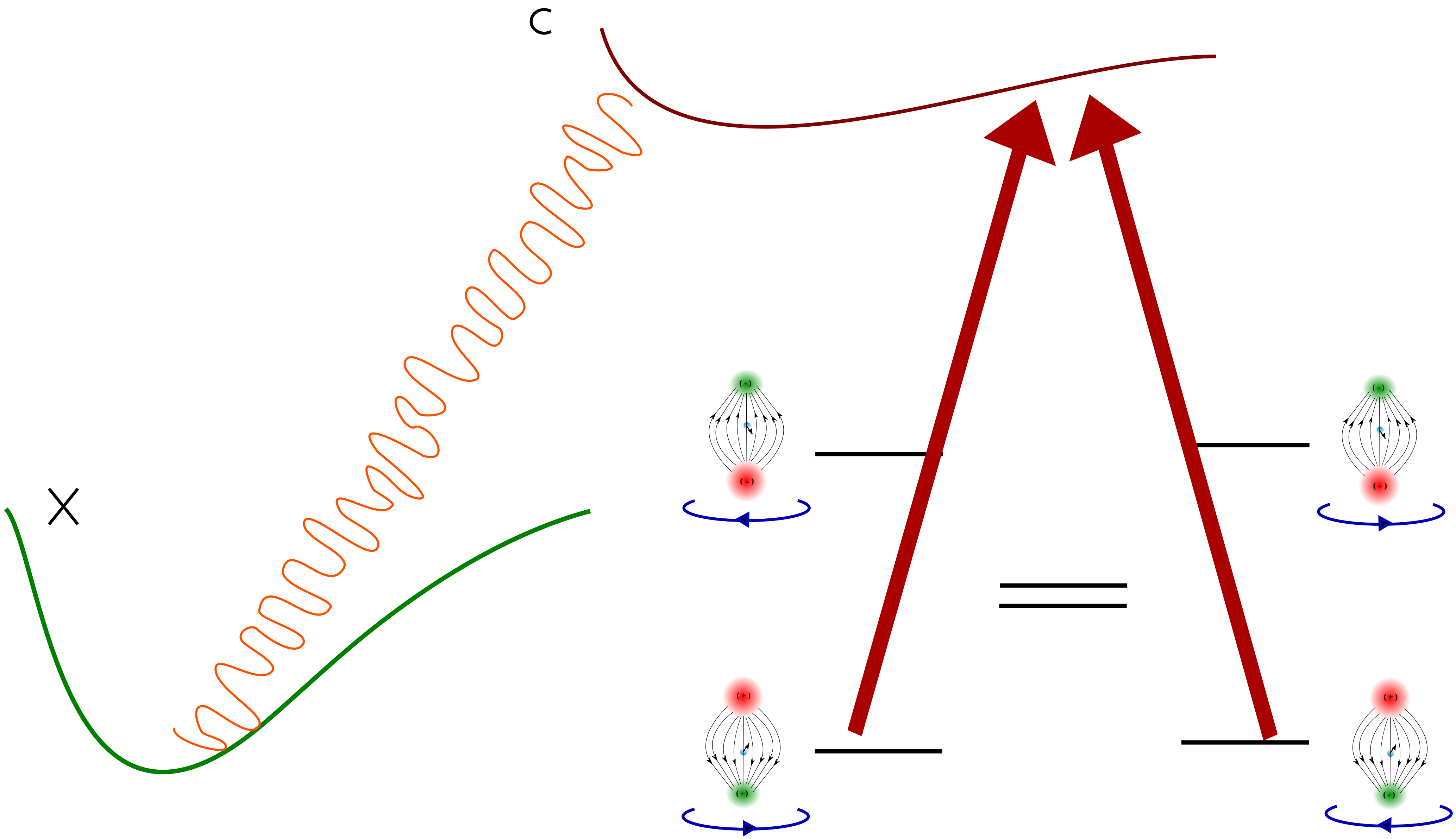
Step 6: Reverse. Repeat.

$$\mathcal{E}_{lab} \longrightarrow -\mathcal{E}_{lab}$$
$$\mathcal{B}_{lab} \longrightarrow -\mathcal{B}_{lab}$$
$$\mathcal{E}_{mol} \longrightarrow -\mathcal{E}_{mol}$$

$\mathcal{N}$ reversal



$\mathcal{N}$ reversal



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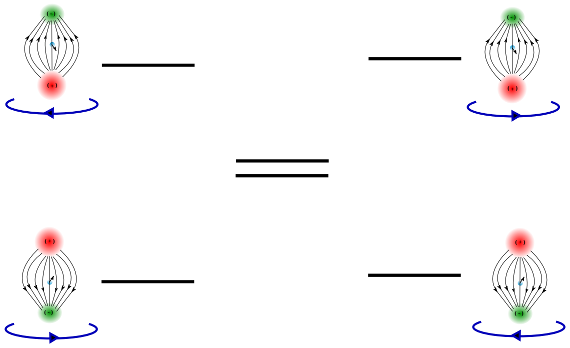
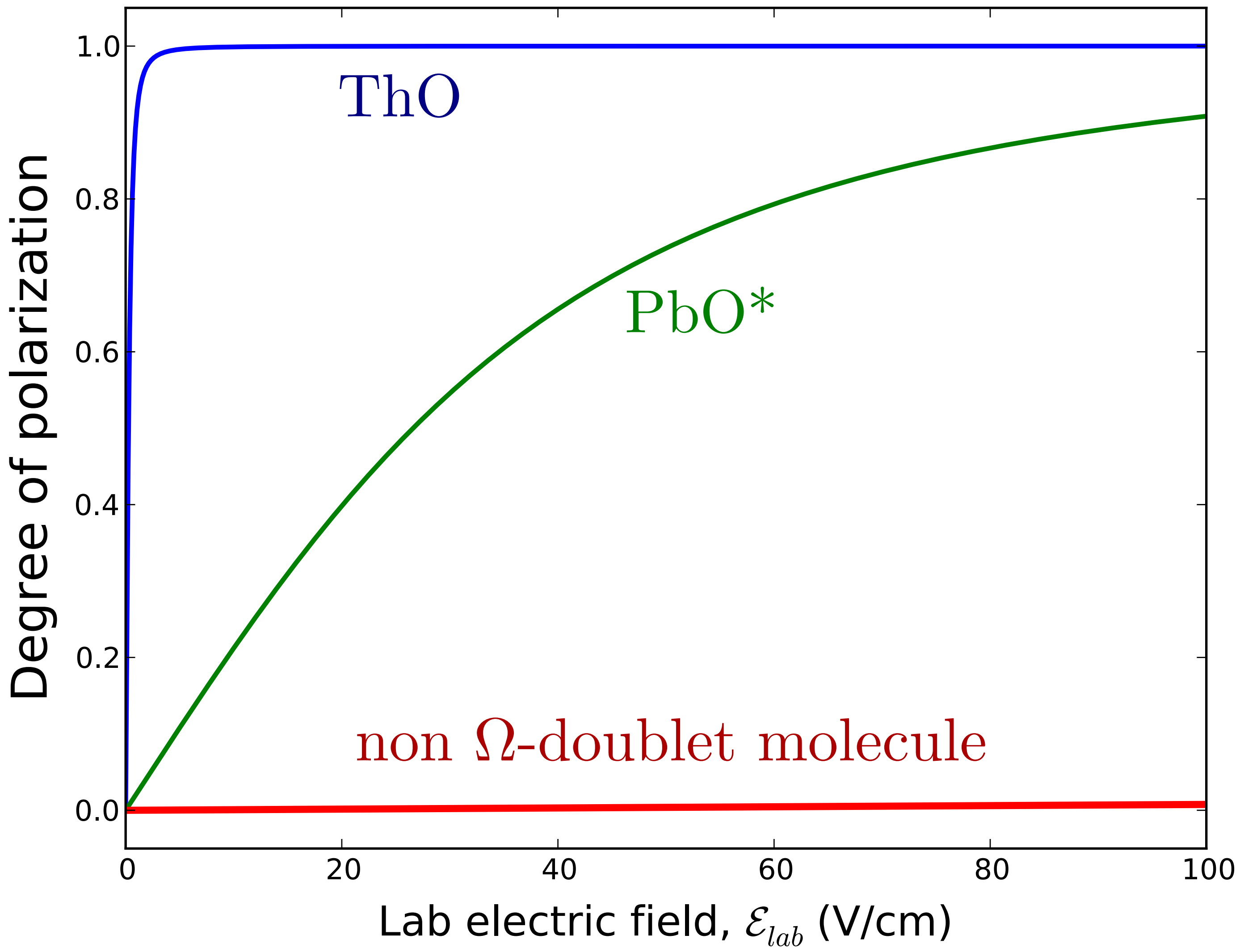
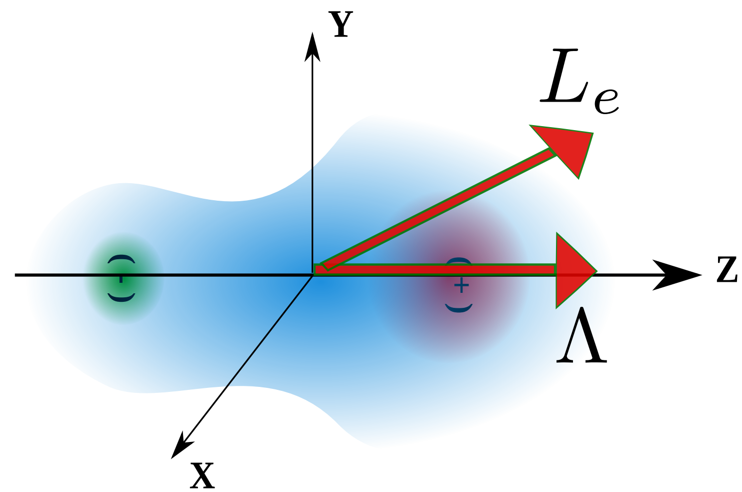




${}^3\Delta_1$ state: suppressed magnetic moment

Configuration: ${}^{2\Sigma+1}\Lambda_\Omega$



$\Lambda = 2$

μ_{orb}

$\Sigma = 1$

μ_{spin}

$\mu \approx 0$

Small amount of spin-orbit mixing makes $\mu \simeq 0.01\ \mu_B$

Systematic effects

	$\mathcal{N}$	$\mathcal{E}$	$\mathcal{B}$
Spin precession in background B-field	+	+	+
Non-reversing B-field	+	+	-
Non-reversing E-field	+	-	+
Leakage current	+	-	-
g-factor difference	-	+	+
g-factor difference x n.r. B-field	-	+	-
EDM term	-	-	+
g-factor difference x leakage B-field	-	-	-

Systematic effects

laser frequency offsets,
laser powers,
laser beam profiles,
purposely added E- and B-field offsets,
purposely added polarization imperfections,
purposely added E- and B-field gradients

... and a lot more ...

Outlook

- Systematic tests
- Electrostatic focusing, rotational cooling (= larger flux)
- Testing a *continuous* ThO beam source (= steadier flux)
- Higher efficiency detection schemes (= more photons)

Publications

A. C. Vutha et al., J. Phys. B 43, 74007 (2010).

N. R. Hutzler et al., PCCP 13, 18976–85 (2011).

A. C. Vutha et al., Phys. Rev. A 84, 4 (2011).