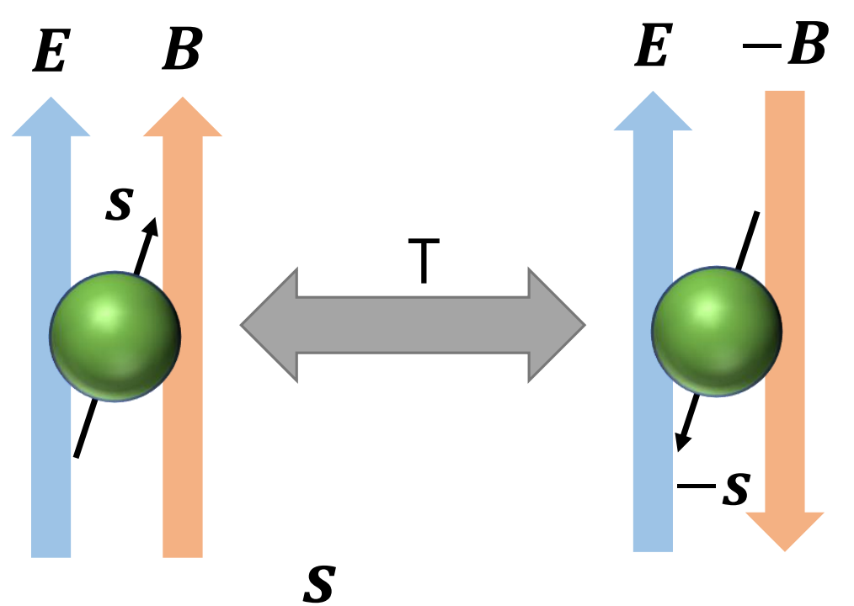
Development of a novel comagnetometer for high-precision measurement of the electron's electric dipole moment using laser-cooled Fr atoms

S. Nagase[(a)], H. Nagahama[(a)], K. Nakamura[(a)], N. Ozawa[(a)], M. Sato[(b)], T. Nakashita[(b)], M. Fukase[(a)], D. Uehara[(a)], Y. Sakemi[(a)]
(a) Center for Nuclear Study, The Univ. of Tokyo. (b) Graduate School of Arts and Sciences, The Univ. of Tokyo.

Introduction

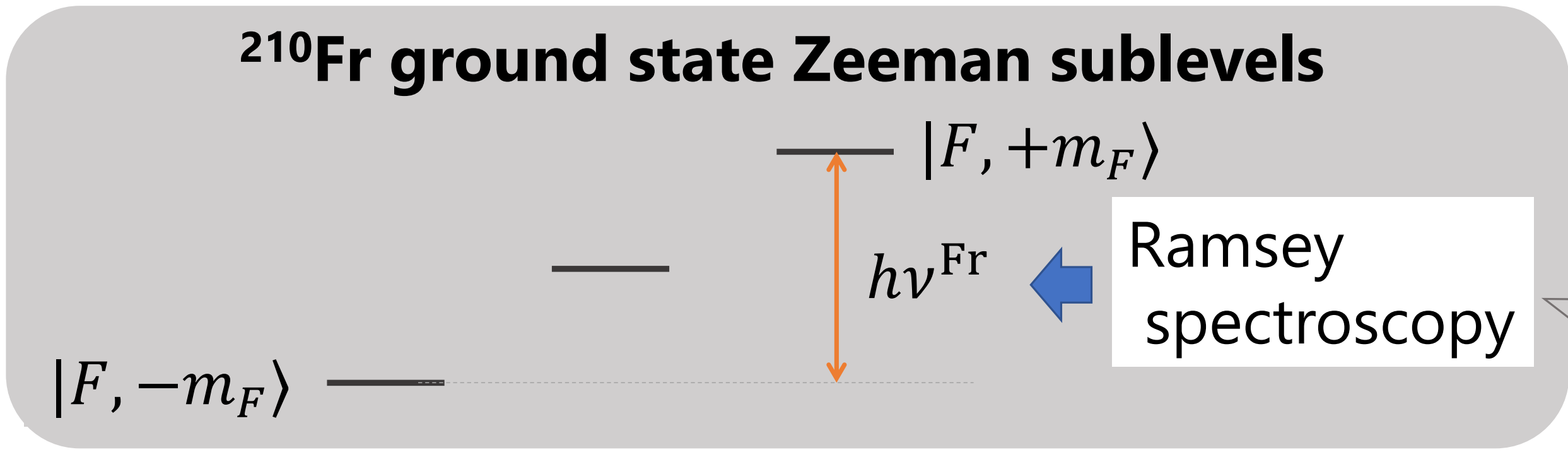
Electron's electric dipole moment (eEDM) : physical quantity of proof that time reversal symmetry is violated
Francium atoms (Fr) : good probe to measure the eEDM
- Large eEDM enhancement factor ($R_{\mathrm{Fr}} = 799$[1])

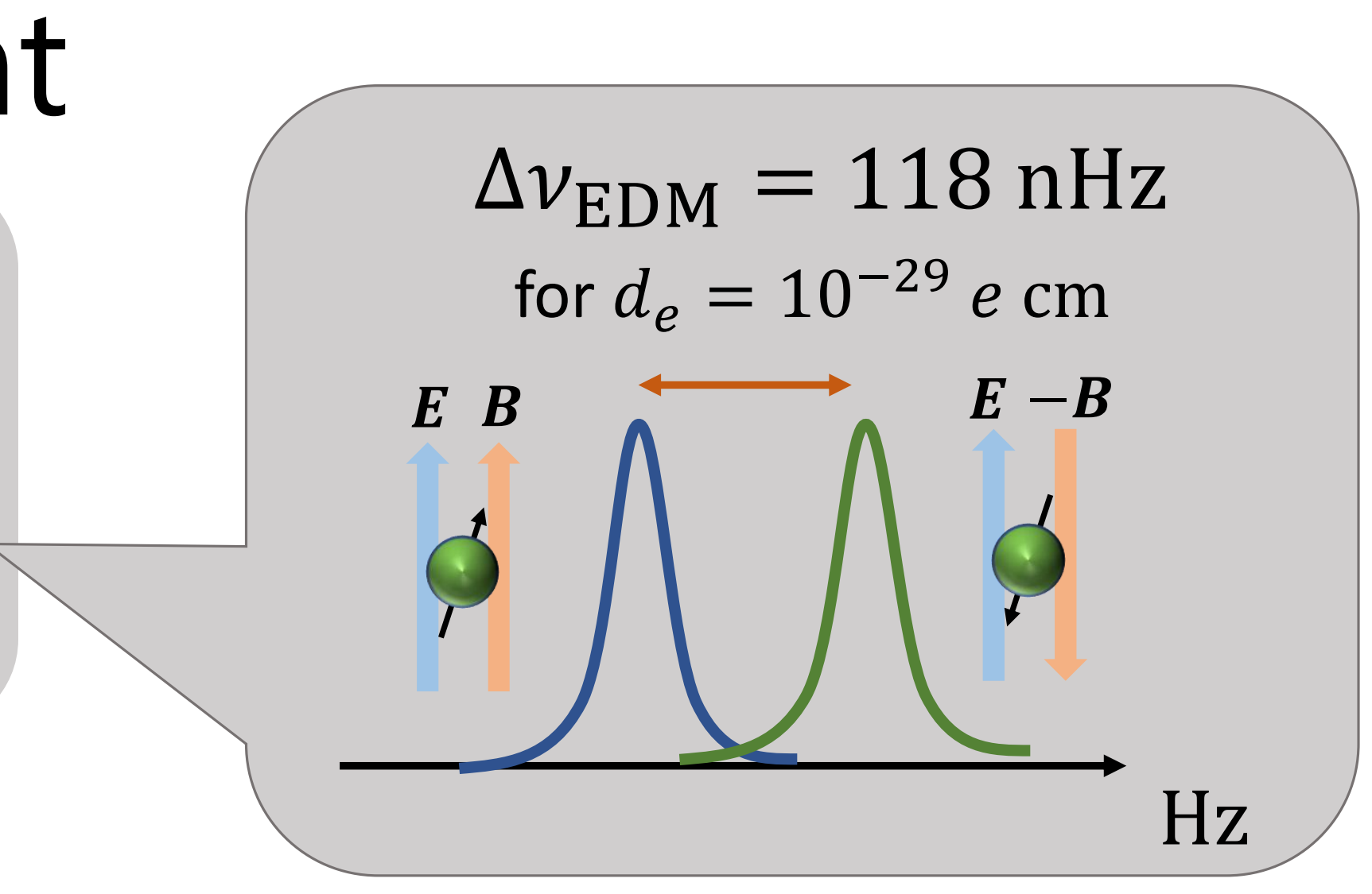
Our goal : detection of the energy shift caused by the eEDM
- The energy shift is detected as a change of the Larmor frequency
- We apply magnetic and electric fields in parallel and antiparallel and detect the frequency difference.

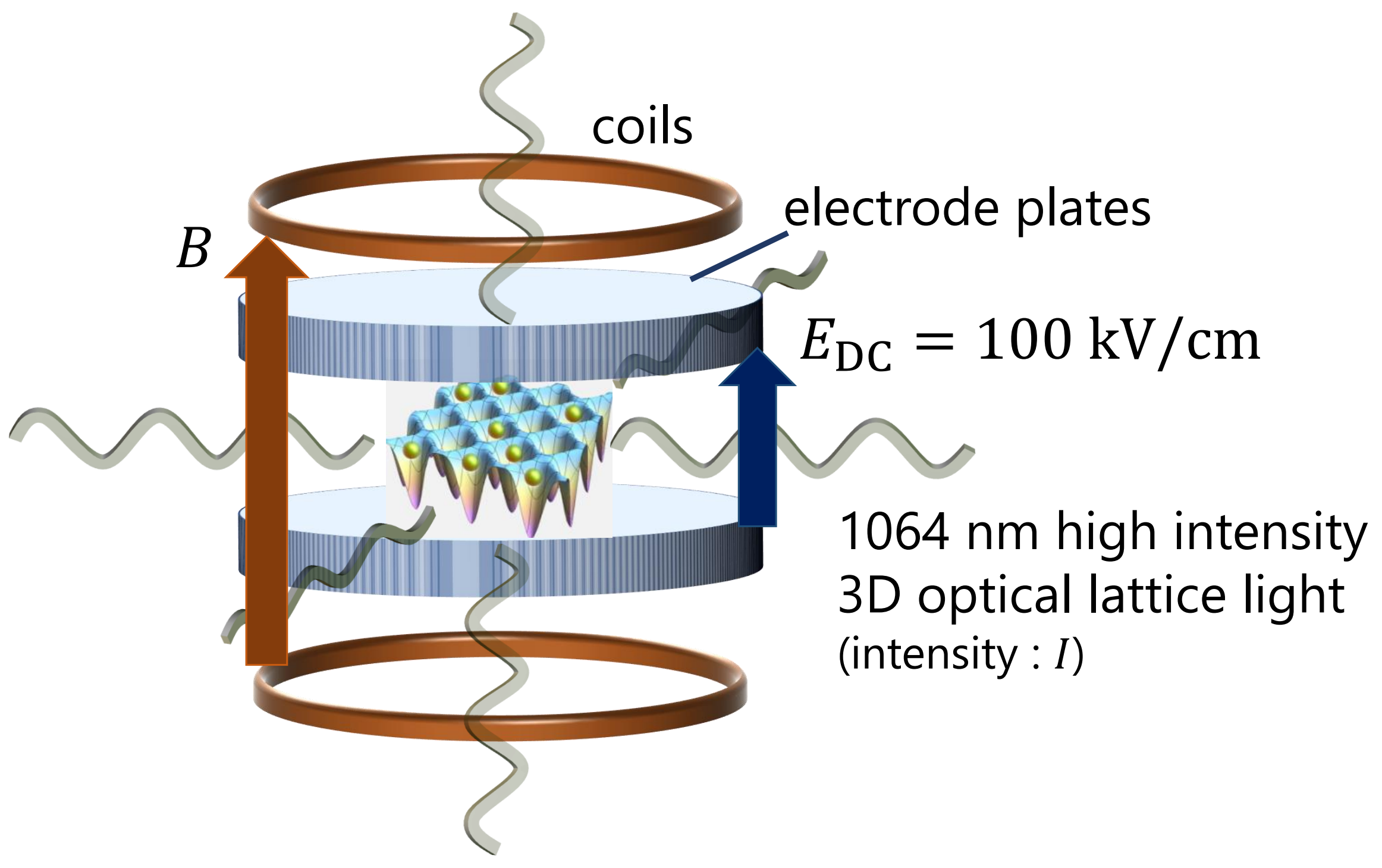


$$\mathcal{H} = -\mu\frac{\boldsymbol{s}}{|\boldsymbol{s}|}\cdot\boldsymbol{B} - d_e\frac{\boldsymbol{s}}{|\boldsymbol{s}|}\cdot\boldsymbol{E} \qquad \mathcal{H} = -\mu\frac{\boldsymbol{s}}{|\boldsymbol{s}|}\cdot\boldsymbol{B} + d_e\frac{\boldsymbol{s}}{|\boldsymbol{s}|}\cdot\boldsymbol{E}$$

Method of Fr-EDM measurement







Our goal : $\delta d_e < 10^{-29}$ e cm (current upper limit [2])
- frequency resolution $\xi = \frac{1}{V}\frac{1}{2\pi T\sqrt{N}} \geq$ **16 μHz**
- shot noise limit $\Delta\nu = \frac{1}{V}\frac{1}{2\pi T\sqrt{Nn}} \geq$ **92 nHz**

$N = 10^6$: atoms trapped
$T = 10$ sec : coherence time
$n = 2000$: the number of measurement
$0 \leq V \leq 1$: Visibility of Ramsey fringe

What we measure [3-5]

$$\nu^{\mathrm{Fr}} = \underbrace{g_F\Delta m_F\mu_B B/h}_{\textbf{Zeeman shift}} + \underbrace{\alpha(\lambda)U\Delta m_F\varepsilon_p}_{\substack{\textbf{vector light shift}\\ \text{(VLC)} \propto I,\,\varepsilon_p}} + \underbrace{\frac{g_F}{g_J}\Delta m_F R_{\mathrm{Fr}}\boldsymbol{d_e}\cdot\boldsymbol{E}_{\mathrm{DC}}/h}_{\textbf{Fr-EDM}} + \underbrace{(\text{collision shift})}_{\Delta P\,\times\,30\ \mathrm{nHz\ for\ Cs\ [3]}} + \underbrace{\left(\mathrm{m}_{\mathrm{F}}^2\ \text{dependence term}\right) + (\text{higher order})}_{\text{disappears for above scheme}}$$

dominant sources of systematic error

ΔP : population difference between $|\mathrm{F},\pm m_F\rangle$
U : trap depth
ε_p: polarization impurity of optical lattice laser beam
α : polarizability
$\beta = \alpha U/I$

$\delta B = \frac{h\xi}{g_F\Delta m_F\mu_B} <$ **16 pG** $\quad \delta(I\varepsilon_p) = \frac{\xi}{\beta\Delta m_F} < \mathbf{1.3\times10^{-3}\ mW/cm^2}$ of stabilities are needed.

for $\Delta m_F = 4$

Principle of dual-species comagnetometer

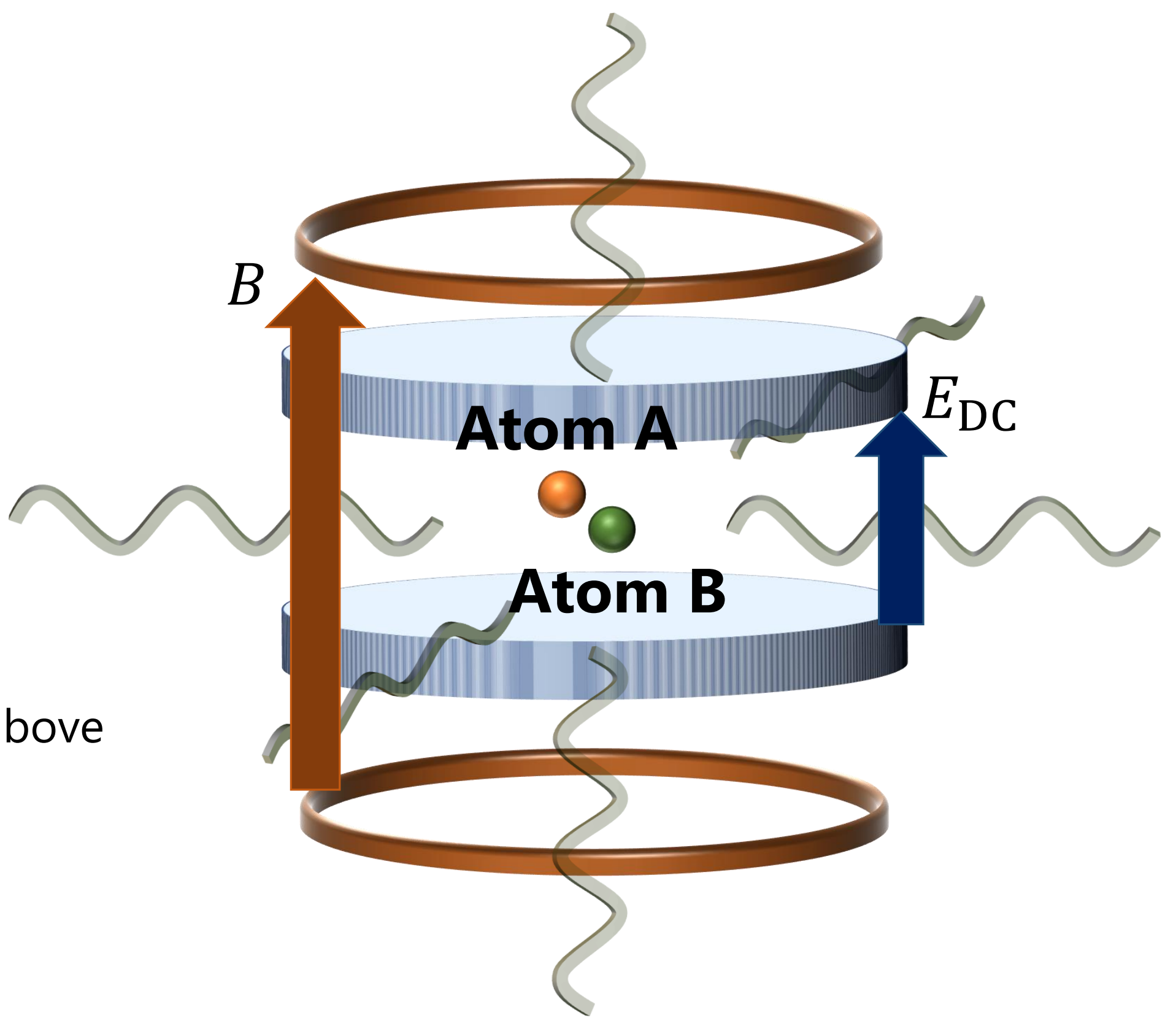
Atom **A** and atom **B** with small eEDM
Simultaneously measure each Larmor frequency

$$\begin{cases}\nu^{\mathrm{A}} = g_F^{\mathrm{A}}\Delta m_F^{\mathrm{A}}\mu_B B/h + \beta^{\mathrm{A}}\Delta m_F^{\mathrm{A}} I\varepsilon_p\\ \nu^{\mathrm{B}} = g_F^{\mathrm{B}}\Delta m_F^{\mathrm{B}}\mu_B B/h + \beta^{\mathrm{B}}\Delta m_F^{\mathrm{B}} I\varepsilon_p\end{cases}$$

We can measure the effects of both independently.

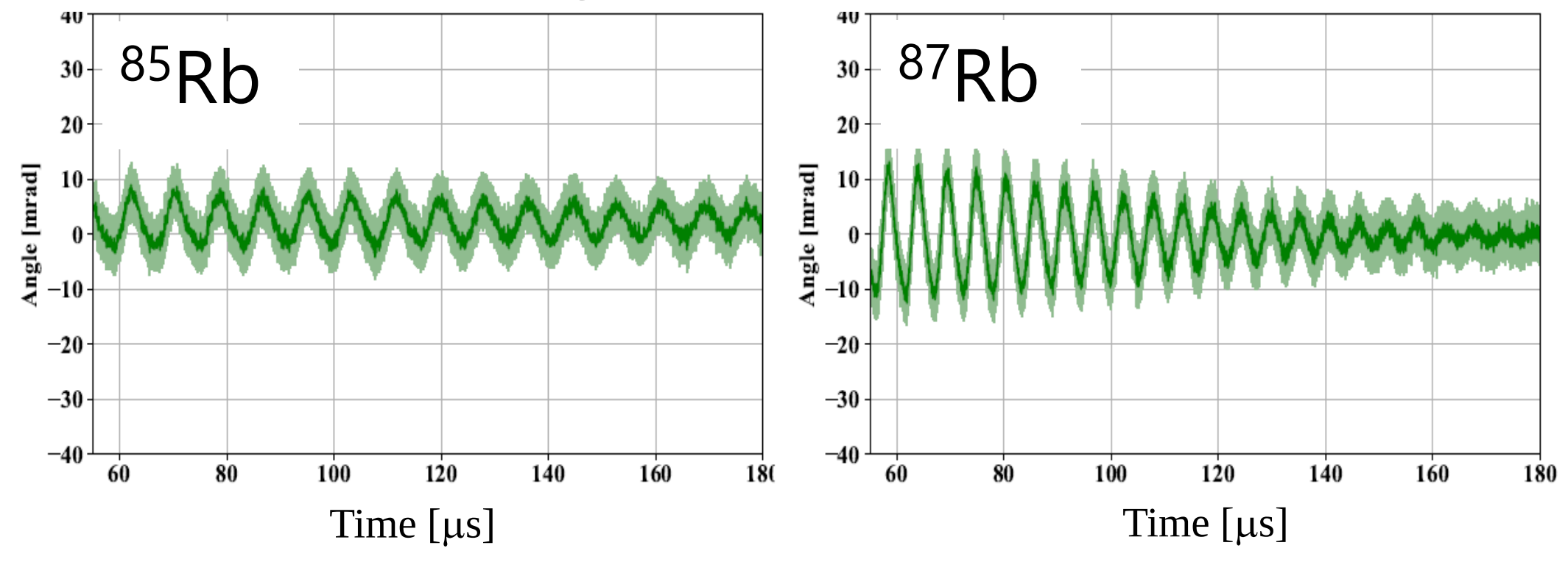
$\delta B = \mathbf{6.3\ pG}$
$\delta(I\varepsilon_p) = \mathbf{2.1\times10^{-3}\ mW/cm^2}$
for ^{87}Rb-^{133}Cs

Assume that ξ and $\Delta\nu$ are equal to above



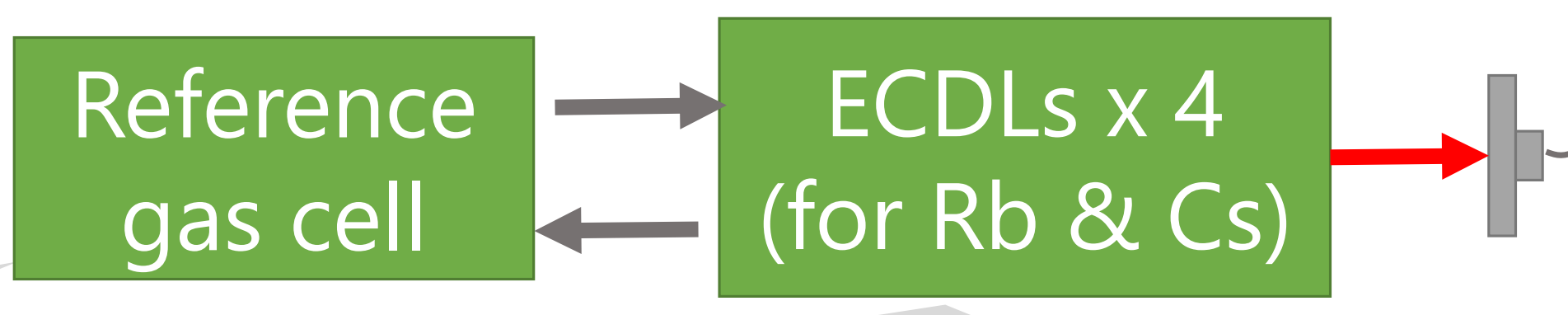
Prototype with ^{85}Rb-^{87}Rb at Tohoku Univ[6]

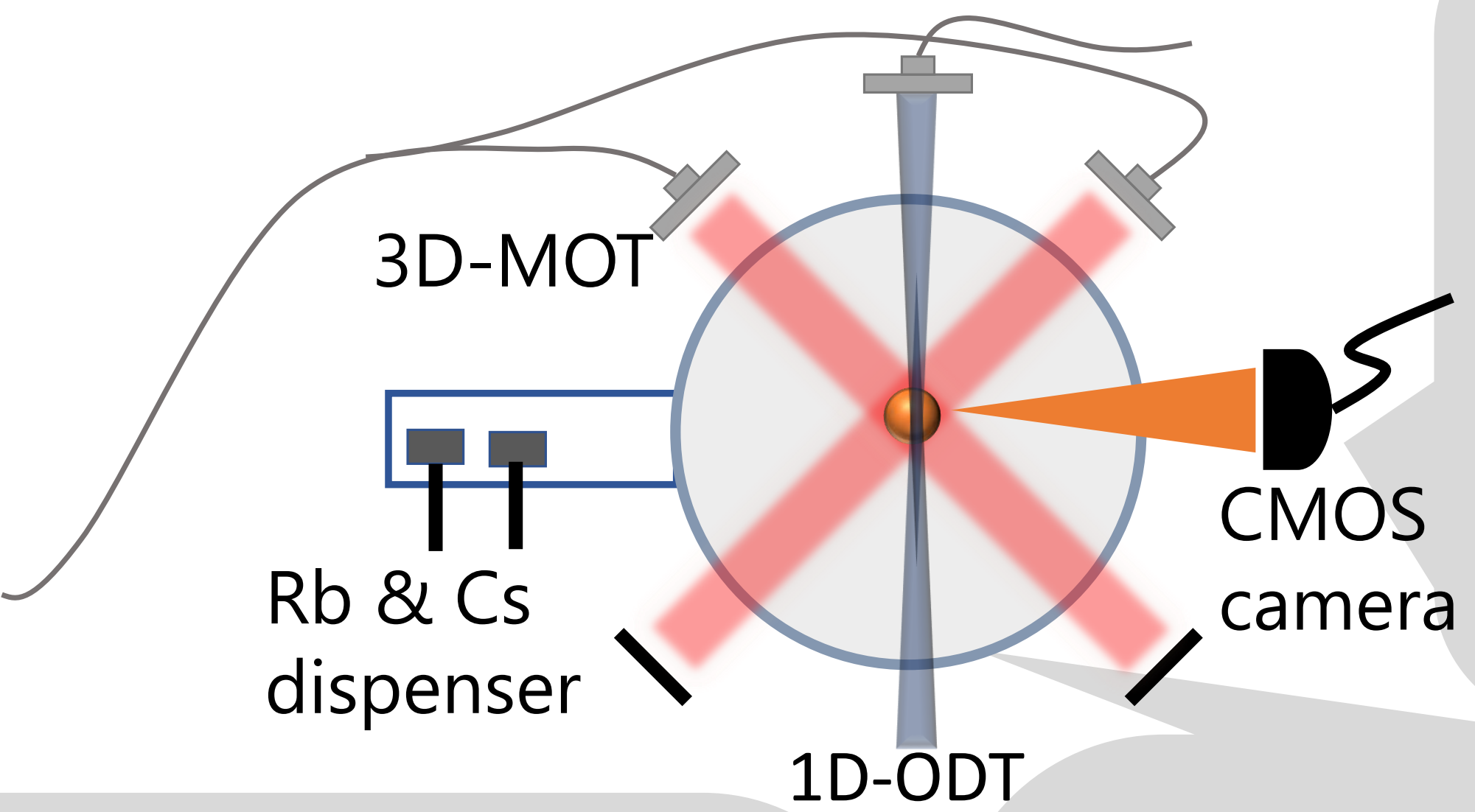
Measurement signal of Larmor precession with paramagnetic Faraday rotation[7].



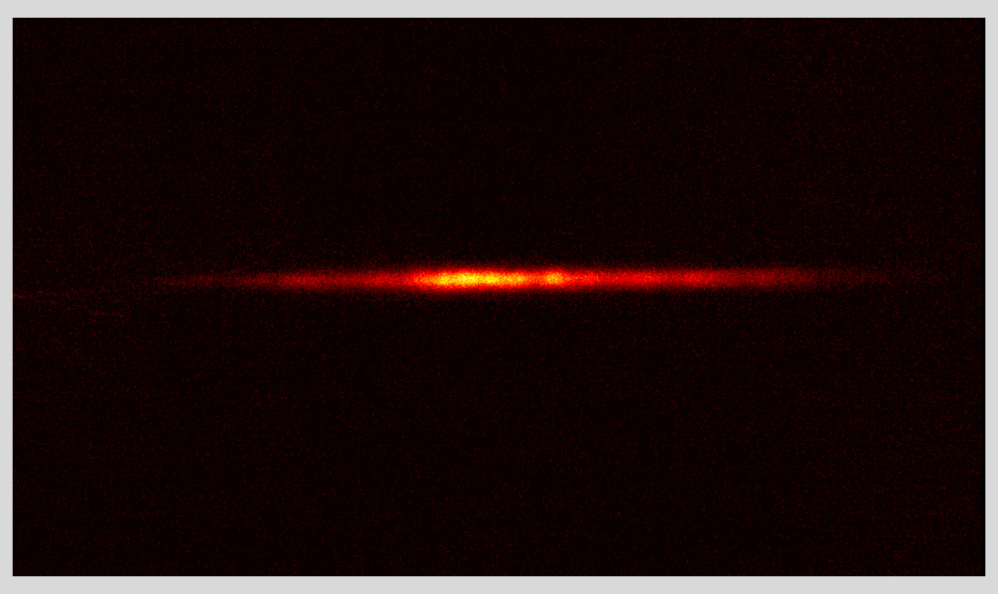
Achieved magnetic field sensitivity < 1 mG
Using Cs and Rb is better to divide Zeeman shift and VLS[6].

Status of ^{87}Rb-^{133}Cs comagnetometer

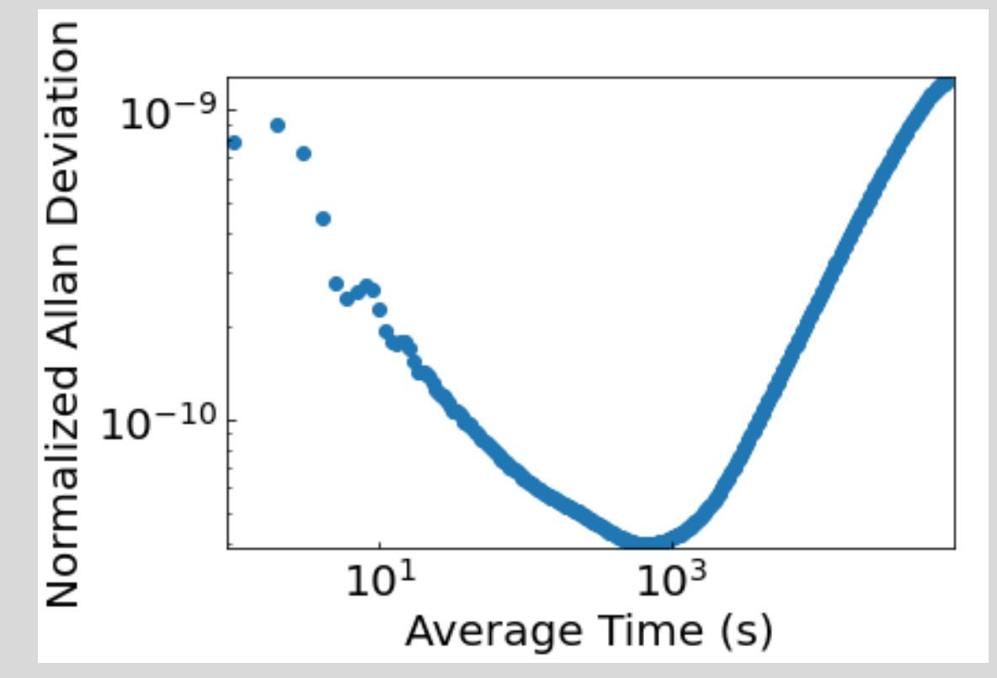




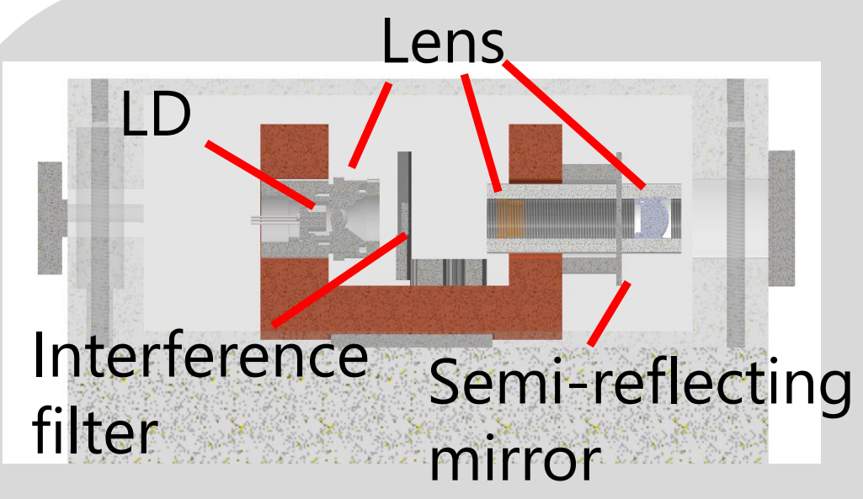
fluorescent image of Rb atoms in the optical dipole trap (ODT)

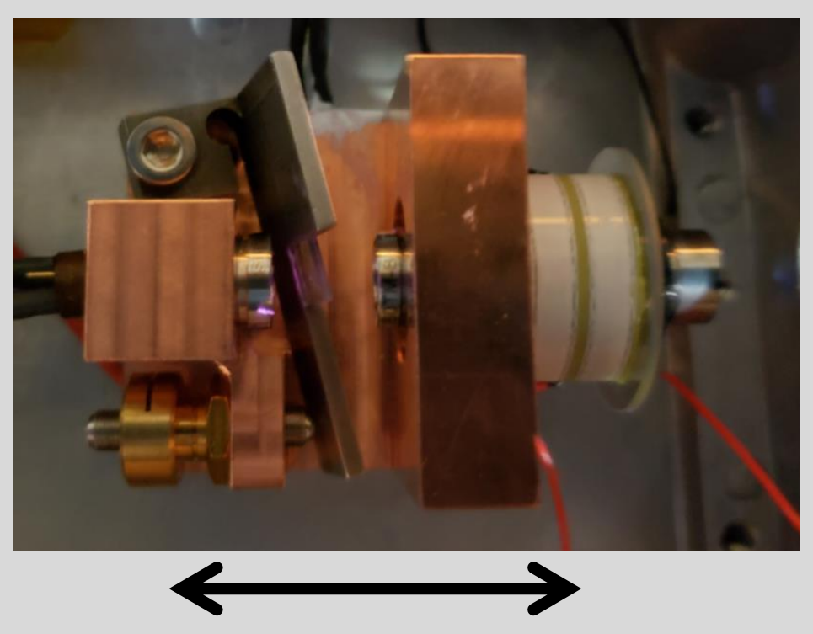


Modulation transfer spectroscopy



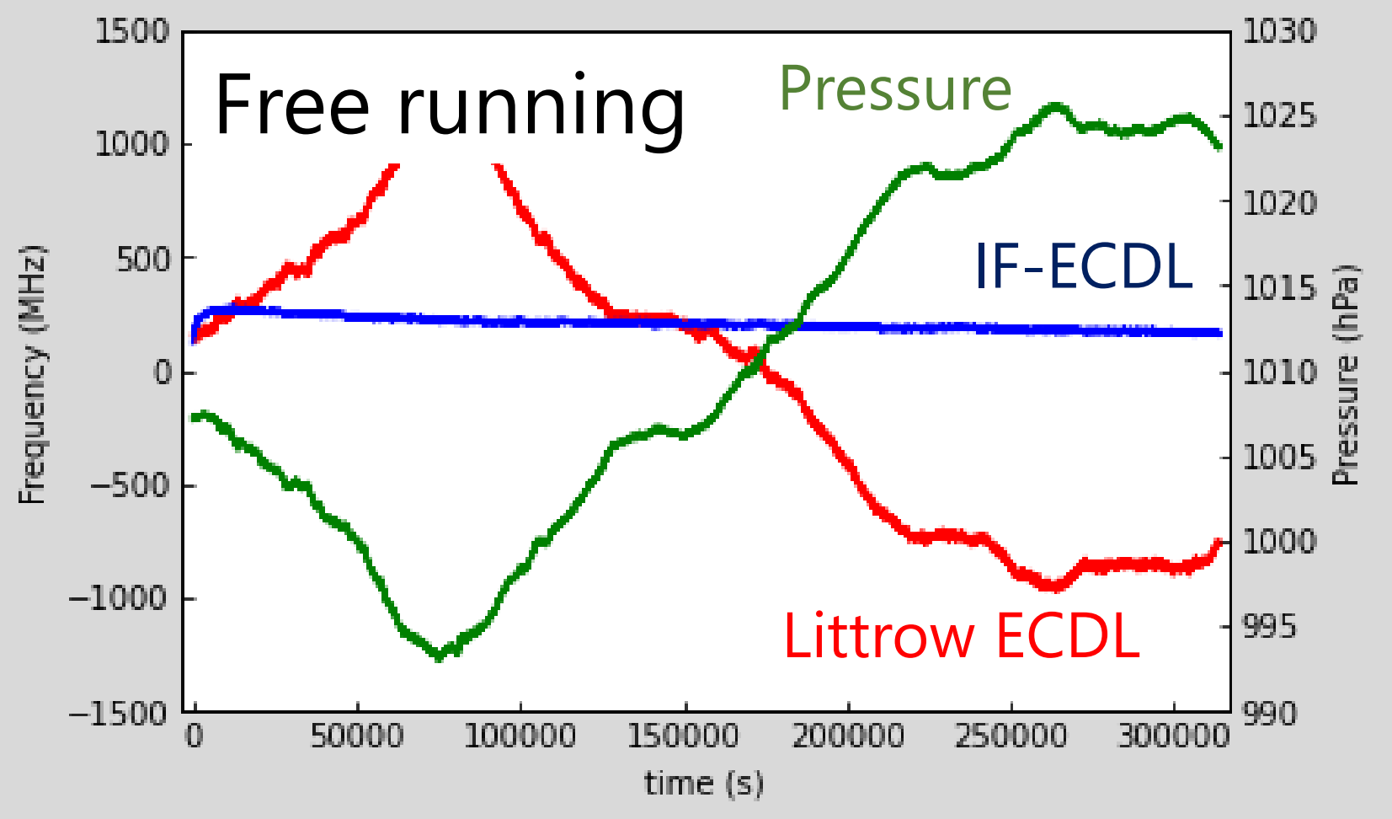
Achieved stable laser source





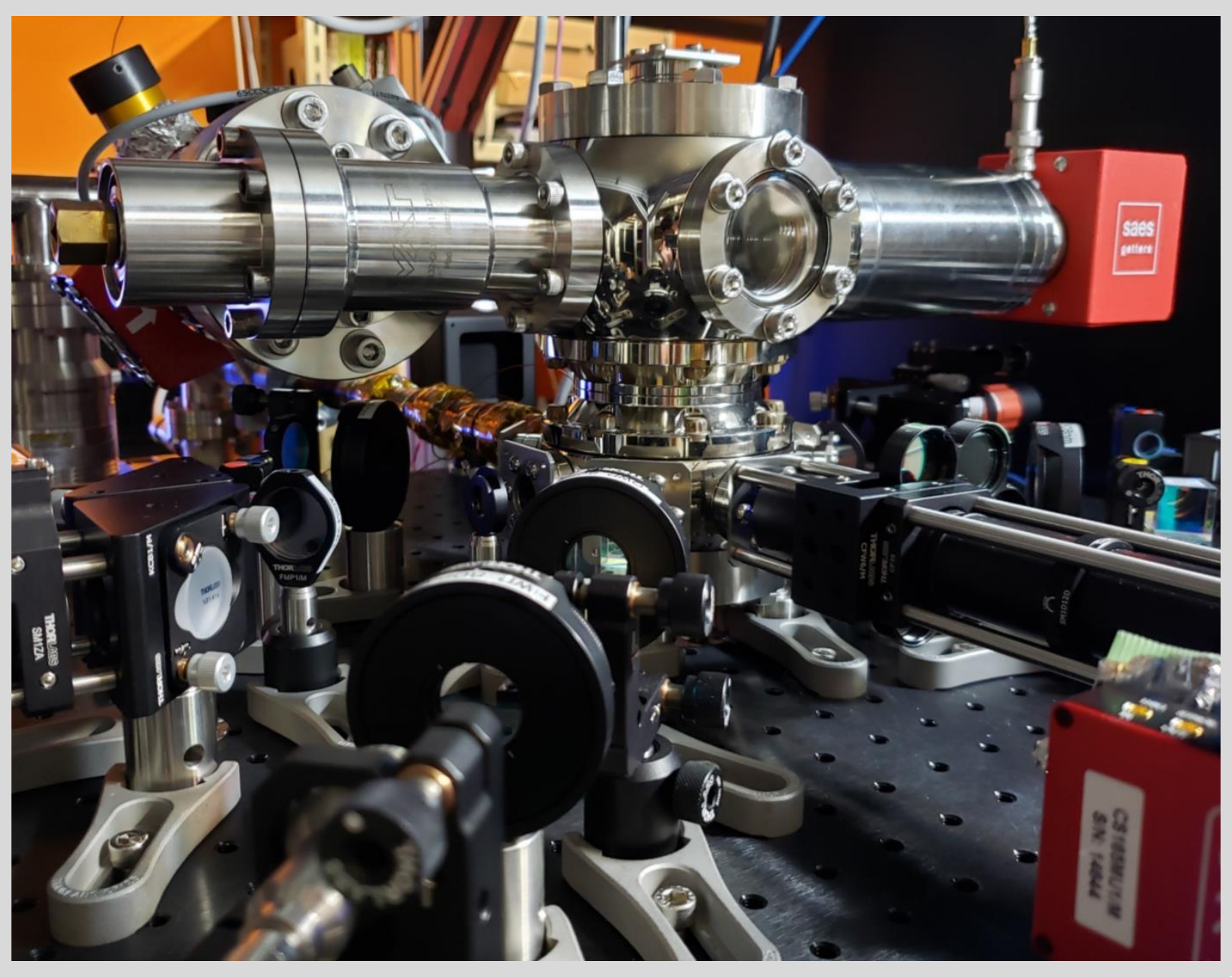
Cavity length ~50 mm

Homemade interference type external cavity diode lasers (IF-ECDL)



Reduce frequency drift with air-tight housing

Magneto-optical trap (MOT) chamber
Achieved ultra high vacuum
($< 1\times10^{-11}$ Torr)



Conclusion

- The magnetic field fluctuation and the polarization and intensity fluctuation of the optical lattice laser beam are dominant sources of systematic error for EDM measurement.
- The basic idea of dual-species comagnetometer to eliminate these errors was introduced.
- Development of the Rb-Cs comagnetometer is ongoing.

[1] N. Shitara *et al.*, J. High Energy Phys. **2021**, 124 (2021).
[2] ACME Collaboration *et al.*, Nature **562**, 355 (2018).
[3] C. Chin, *et al.*, Phys. Rev. A, **63**, 033401 (2001).
[4] M. V. Romails, *et al.*, Phys. Rev. A, **59**, 6 (1999).
[5] K. Zhu, *et al.*, Phys. Rev. Lett. **111**, 243006 (2013).
[6] A. Uchiyama, PhD thesis, Tohoku Univ. (2018).
[7] T. Isayama, *et al.*, Phys. Rev. A, **59**, 6 (1999).