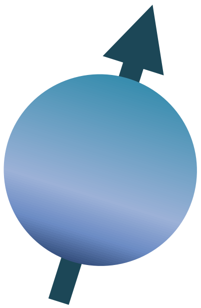
Search for the permanent electric dipole moment of laser cooled francium atom



Cyclotron and Radioisotope Center
Tohoku University
Aiko Uchiyama

Collaboration

Cyclotron and Radioisotope Center (CYRIC), Tohoku University

*Frontier Research Institute for Interdisciplinary Sciences (FRIS), Tohoku University

K. Harada, T. Inoue*, S. Ito, M. Itoh, H. Kawamura*, K. Sakamoto,

K. S. Tanaka, A. Uchiyama, U. Dammalapati, and R. Yoshioka,

Center for Nuclear Study, the University of Tokyo

Y. Sakemi

The University of Tokyo

T. Aoki

RIKEN

K. Asahi

Tokyo Univ. Agri. Tech.

A. Hatakeyama

Okayama University

A. Yoshimi

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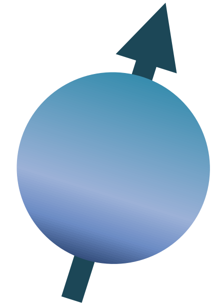
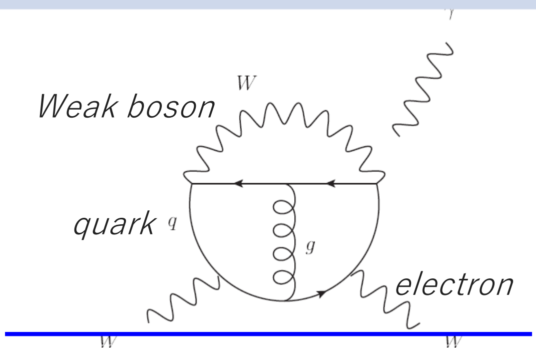
Electron EDM

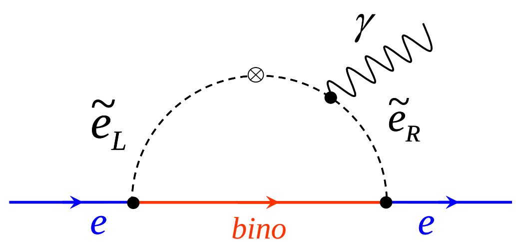


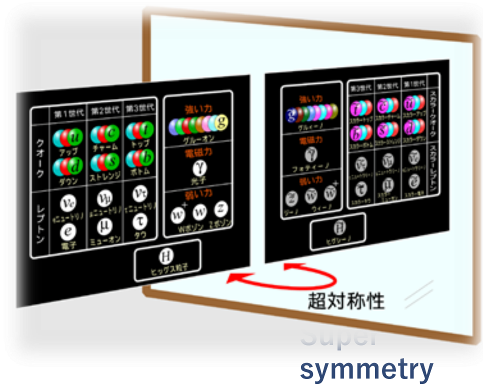
EDM : Permanent **E**lectric **D**ipole **M**oment

Standard Model (SM) :
Higher order loop calculation
$|d_e^{SM}| < 10^{-37}\ e\mathrm{cm}$

Beyond SM :
SUSY particle
$\sim 10^{10}$ times larger than SM







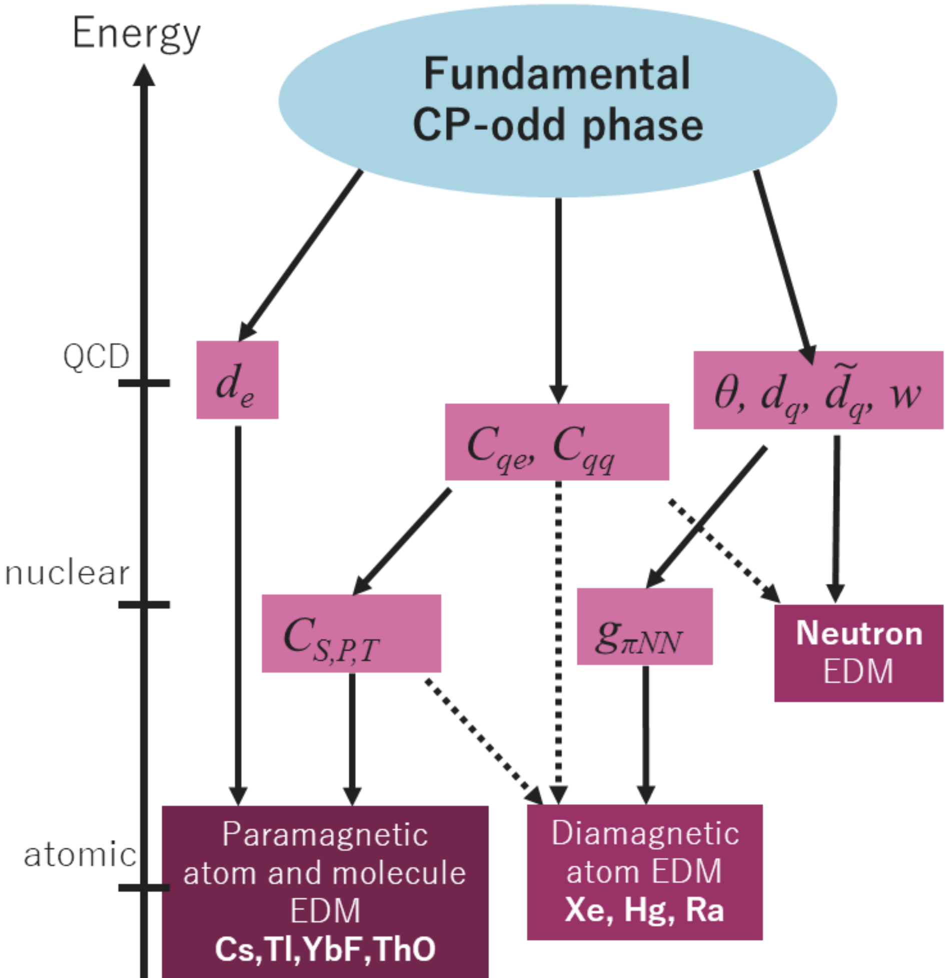
$$d_e \sim e \times \frac{m_e}{M^2} = 10^{-23} e\ \mathrm{cm} \times \left(\frac{1\ \mathrm{TeV}}{M}\right)^2$$

$|d_e| < 10^{-29} e$ cm corresponds to SUSY mass $M > 10^3$ TeV

Pospelov, M. & Ritz,. *Ann. Phys. (N. Y).* **318,** 119–169 (2005).

Sensitive EDM search corresponds to **heavy** SUSY search

The electron EDM search

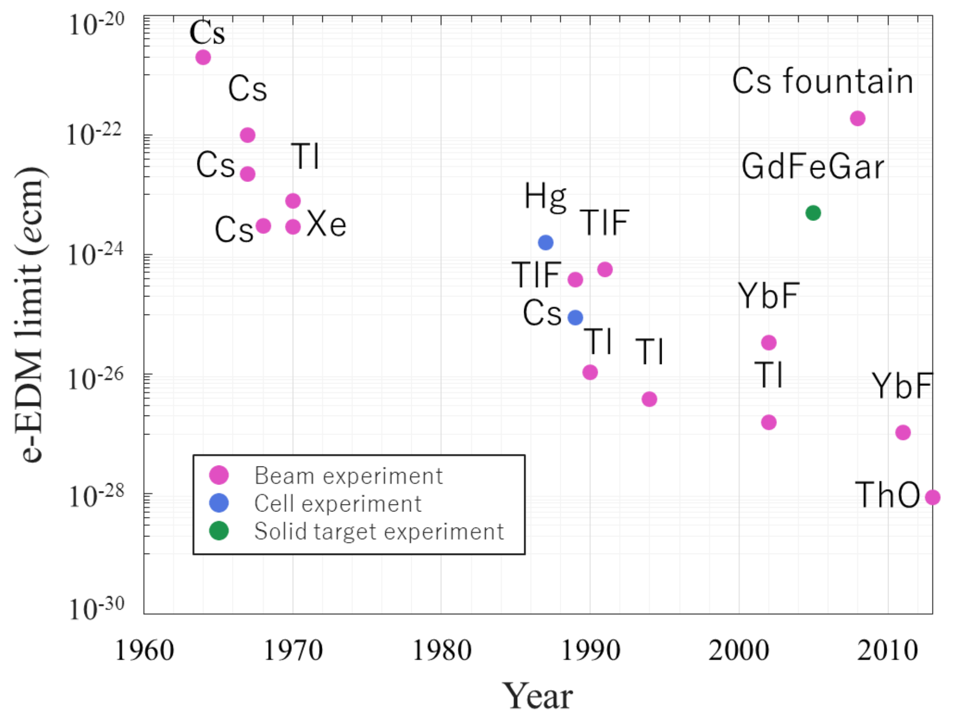


Fr (This talk)

Experimental upper limit

$|d_e| < 8.7 \times 10^{-29}\ e$ cm

The ACME Collaboration *et al.*, Science 343, 269 (2014)



Atomic and molecular **beam experiments** improved electron EDM upper limit

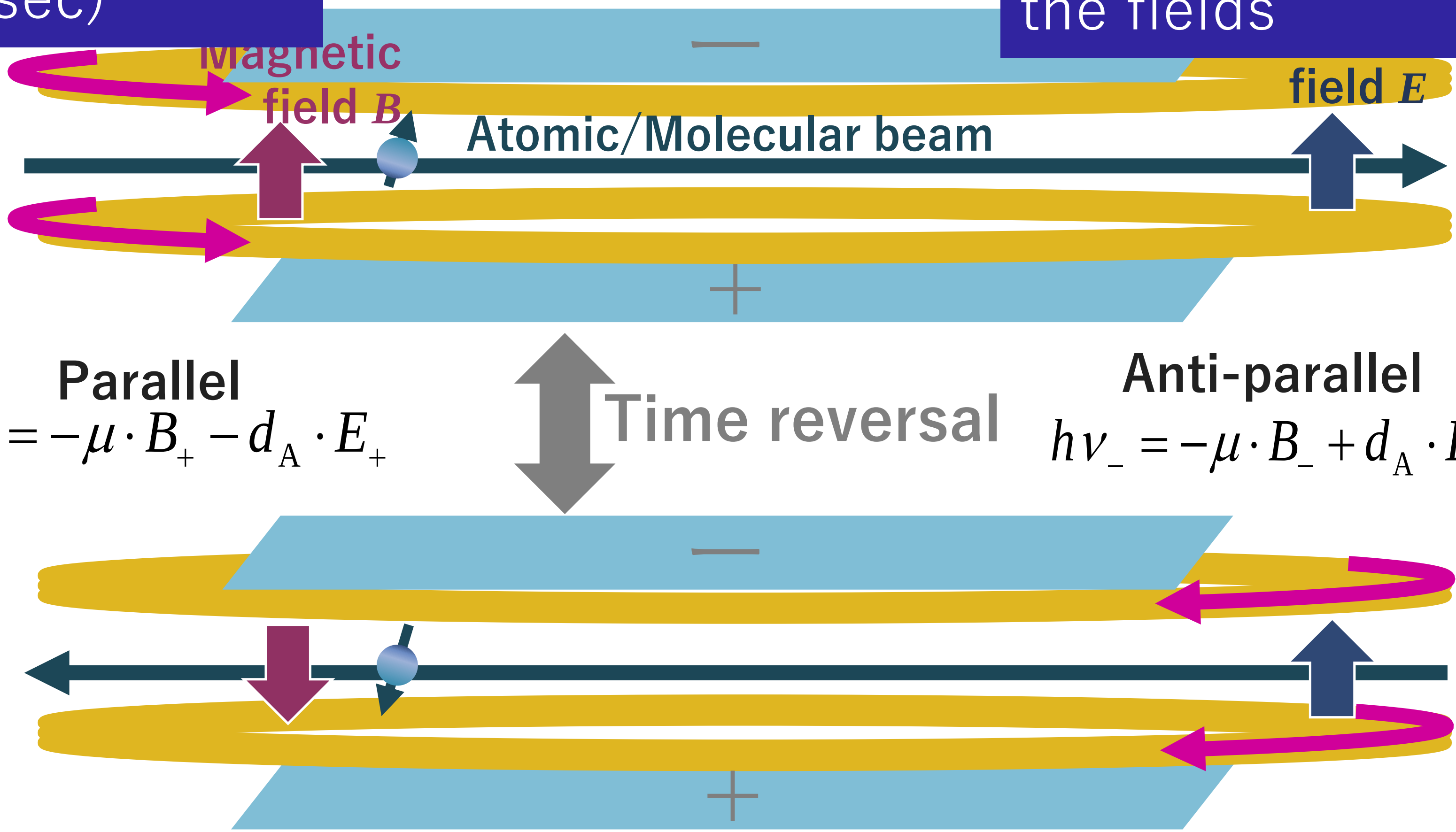
EDM search using beam

Short interaction time (< msec)

$$Rd_e = d_A = -\frac{h(\nu_+ - \nu_-) + \mu(B_+ - B_-)}{E_+ + E_-}$$

μ : magnetic dipole moment

Non-uniformity of the fields



Parallel

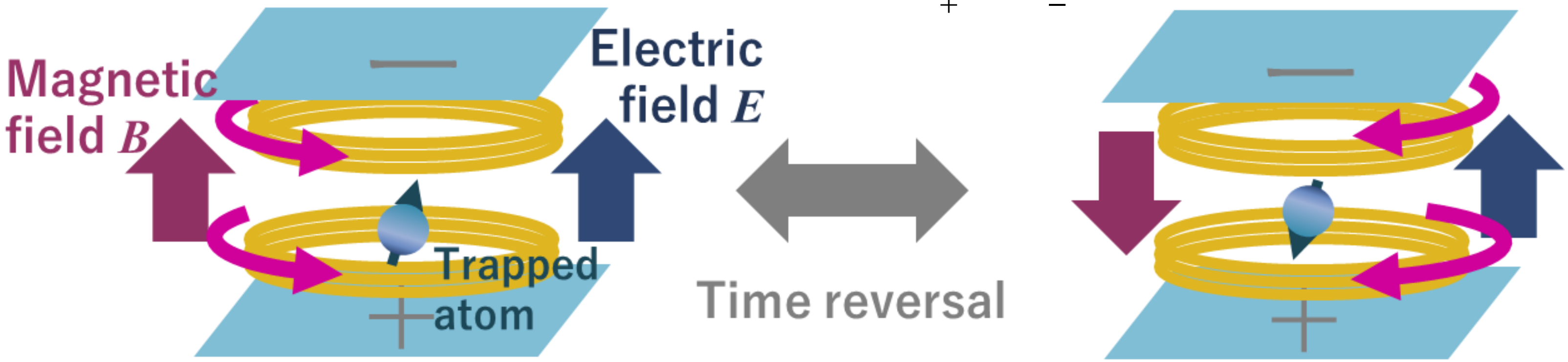
$$h\nu_+ = -\mu \cdot B_+ - d_A \cdot E_+$$

Anti-parallel

$$h\nu_- = -\mu \cdot B_- + d_A \cdot E_-$$

EDM search using trapped atom

$$Rd_e = d_A = -\frac{h(\nu_+ - \nu_-) + \mu(B_+ - B_-)}{E_+ + E_-}$$



Parallel

$$h\nu_+ = -\mu \cdot B_+ - d_A \cdot E_+$$

Anti-parallel

$$h\nu_- = -\mu \cdot B_- + d_A \cdot E_-$$

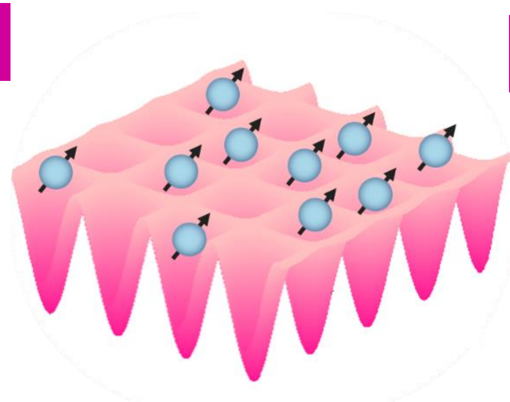
Long interaction time (~sec)

Localization

Slow velocity

- small Doppler effect
- small $v \times E$ effect

Collision



Optical lattice

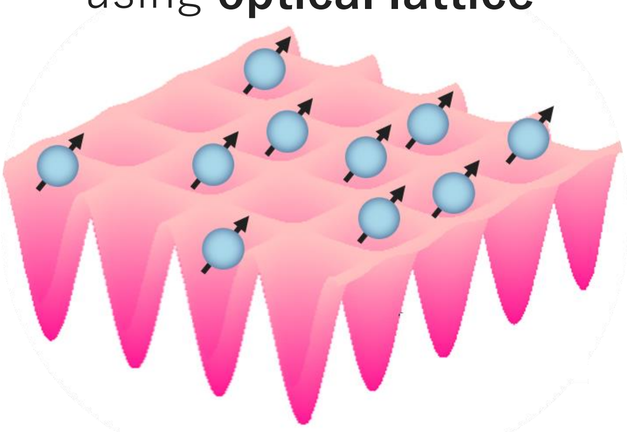
- low collision rate

Francium EDM

Heaviest alkali metal

Availability of laser cooling and trapping

➡ EDM measurement using **optical lattice**

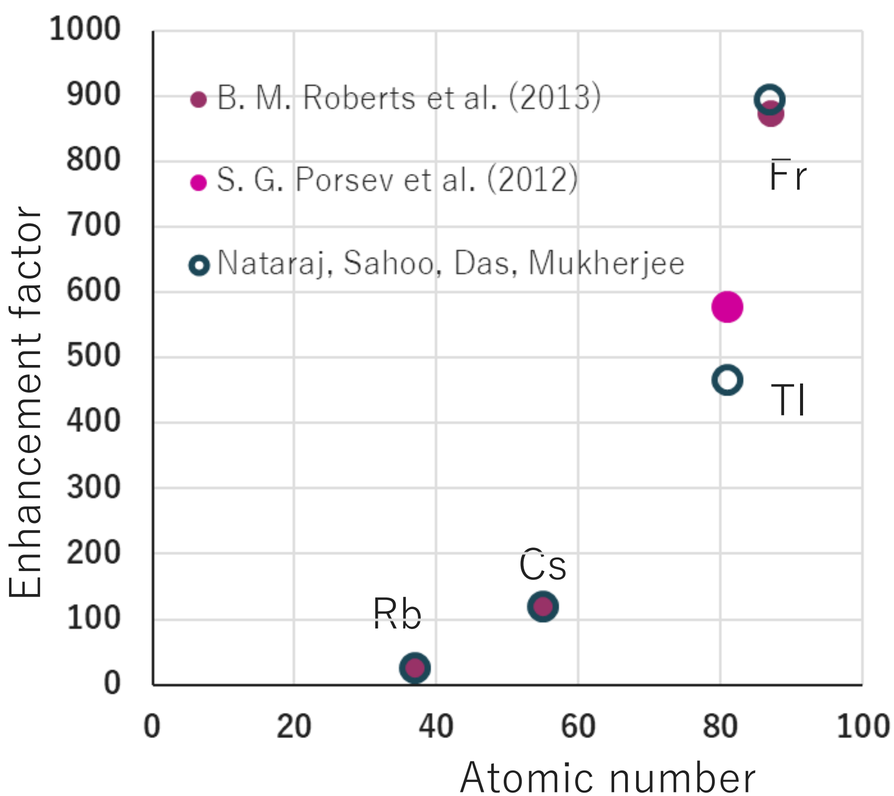


No stable isotope…

^{210}Fr =3.2 min
^{211}Fr =3.1 min
^{212}Fr =20. min

Large enhancement of the electron EDM

Atomic EDM $d_A = R d_e$.



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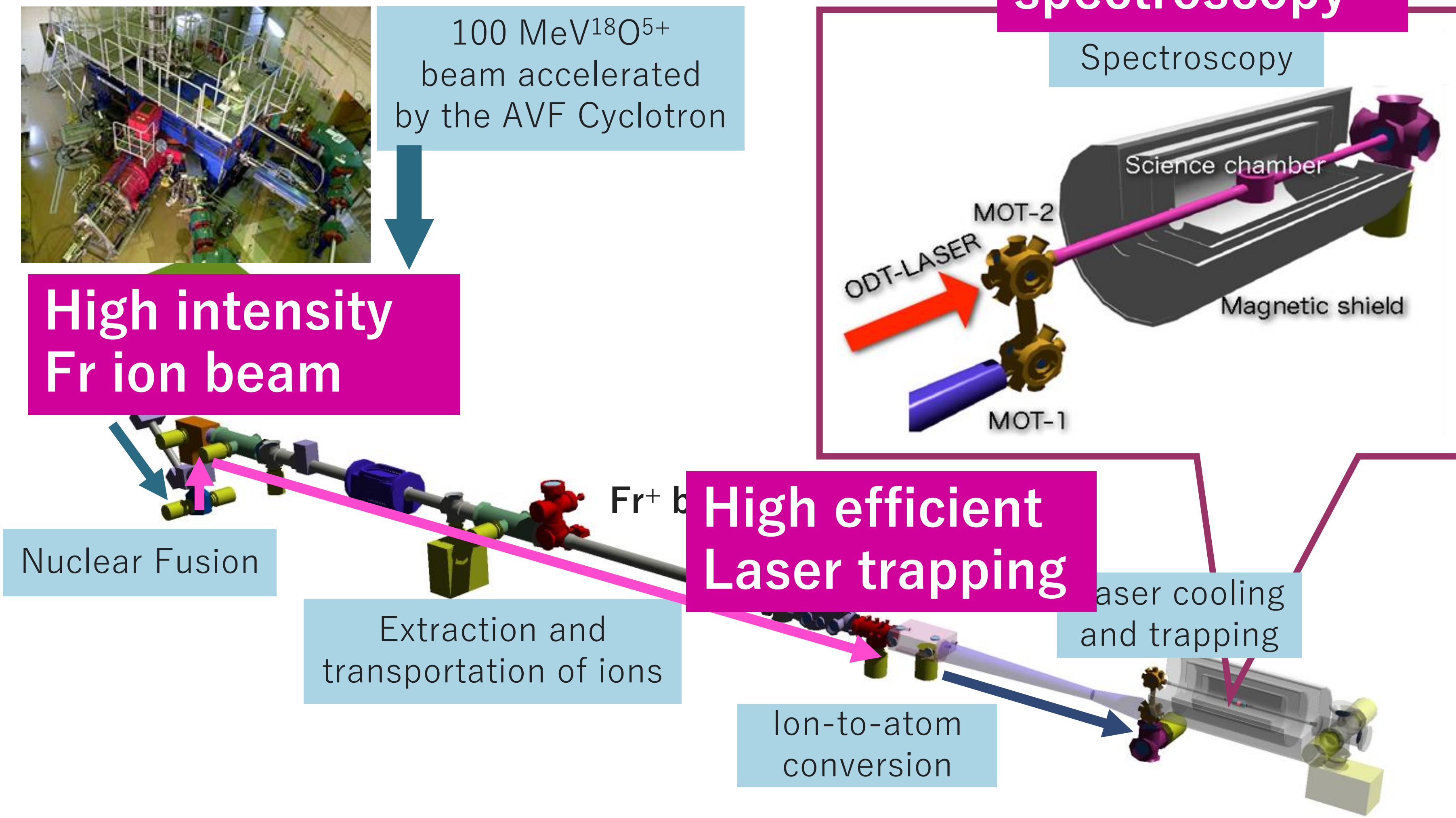
  - Electron permanent electric dipole moment (EDM)
  - Electron EDM search using atoms and molecules
- **Francium EDM project at CYRIC**
  - Laser-cooled francium factory
  - Offline test using rubidium
- **Rubidium magnetometer**
  - Nonlinear magneto-optical rotation (NMOR) effect
- **Conclusion**

Fr-EDM project

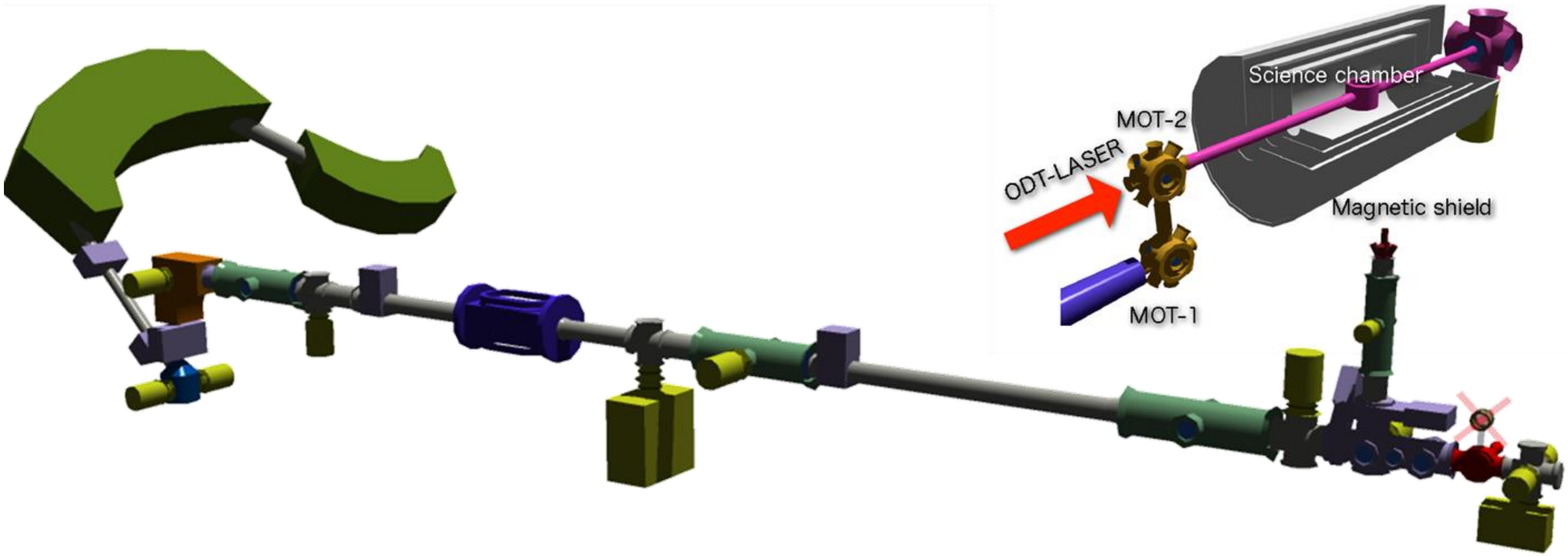


Status of Fr-EDM project

Francium production
- ✔ Fr ion source
- ✔ Ion transportation
- ✔ Ion purification
- ✔ Ion-to-atom conversion

Laser cooling and trapping
- ✔ Magneto-optical trap
- ✔ Optical lattice

Spectroscopy
- ✔ Ramsey's method
- ✔ High voltage system
- ✔ Magnetometer
- Co-magnetometer



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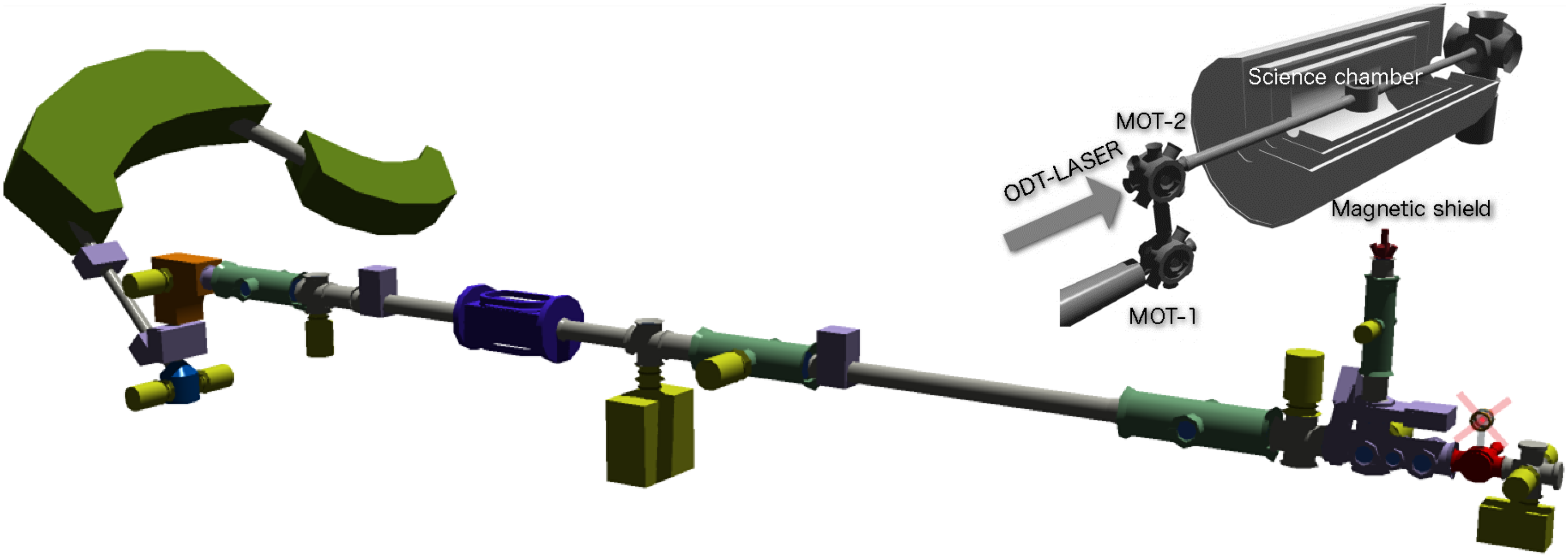
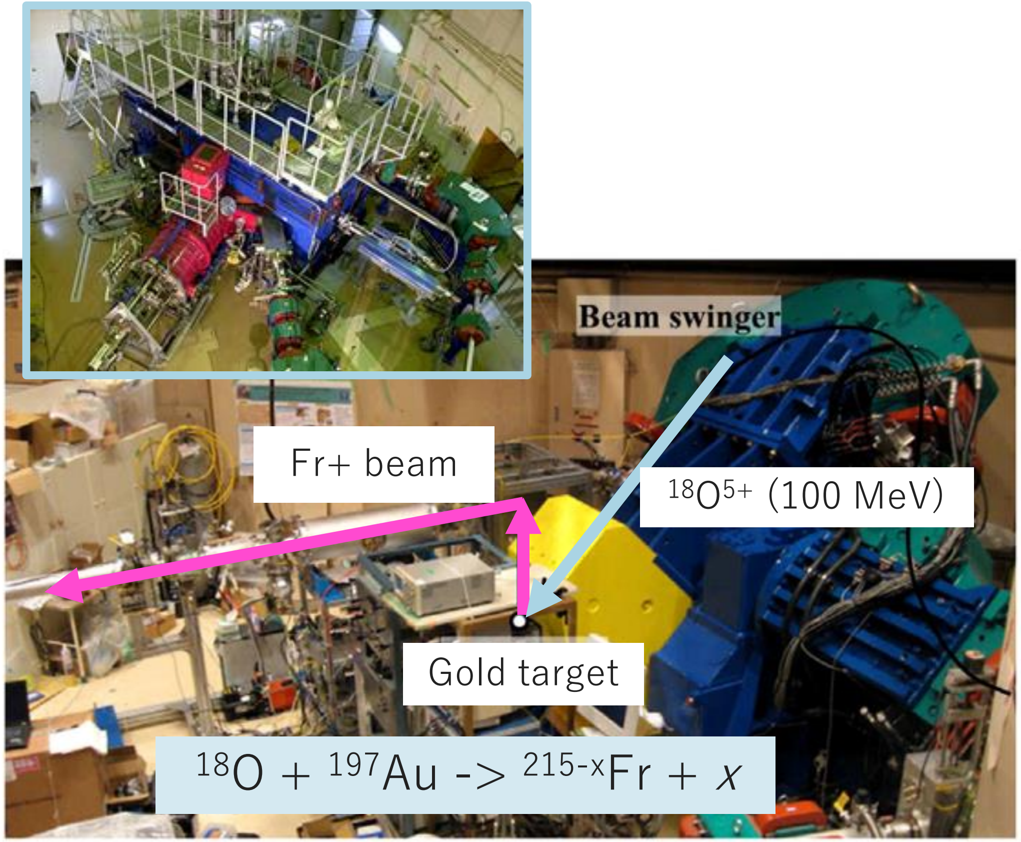


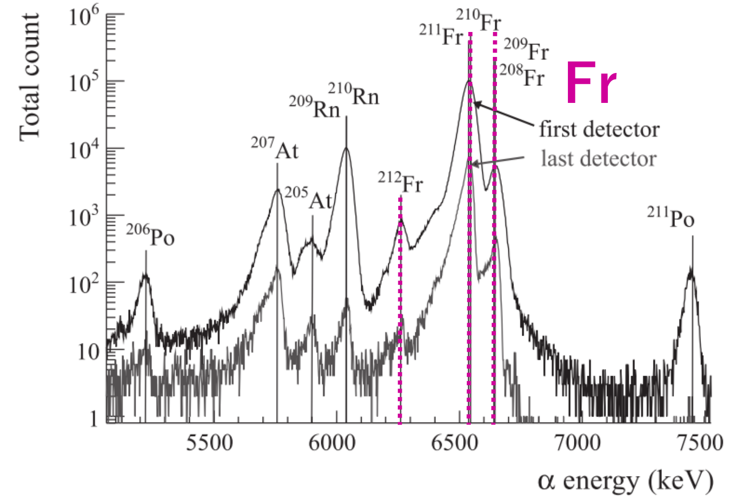
Fr ion source



Maximum ^{210}Fr yield: ~10^6 pps
Extraction efficiency: ~14 %

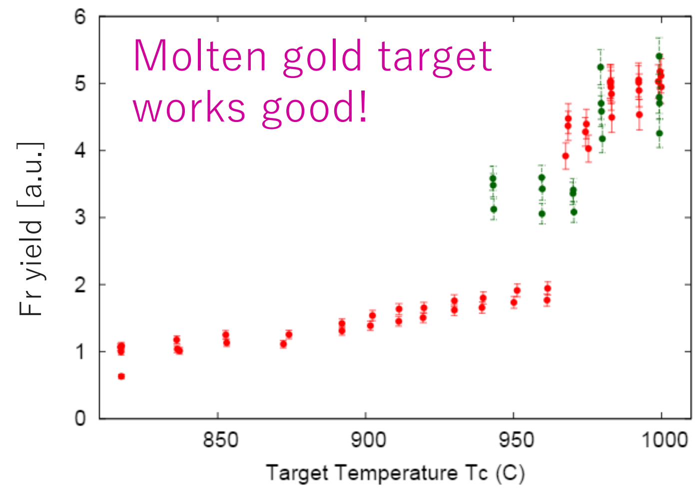
- ✔ Production of sufficient amount of Fr ions
- ✔ Stable operation with **molten gold**

α energy spectrum



Kawamura, H. et al Nucl. Instr. Meth. B 317, 582–585 (2013).

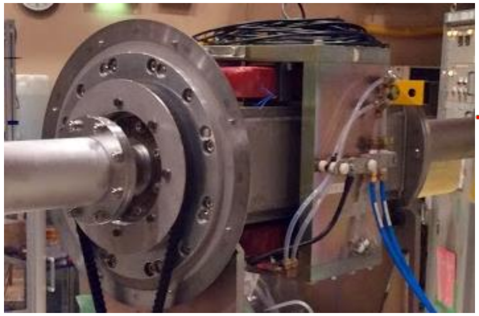
Temperature dependence of Fr yield

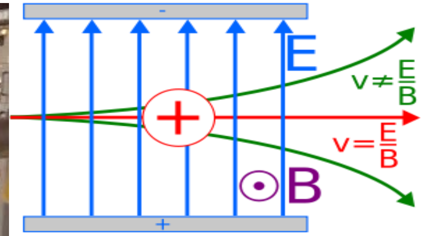


Master thesis Hayamizu (2012).

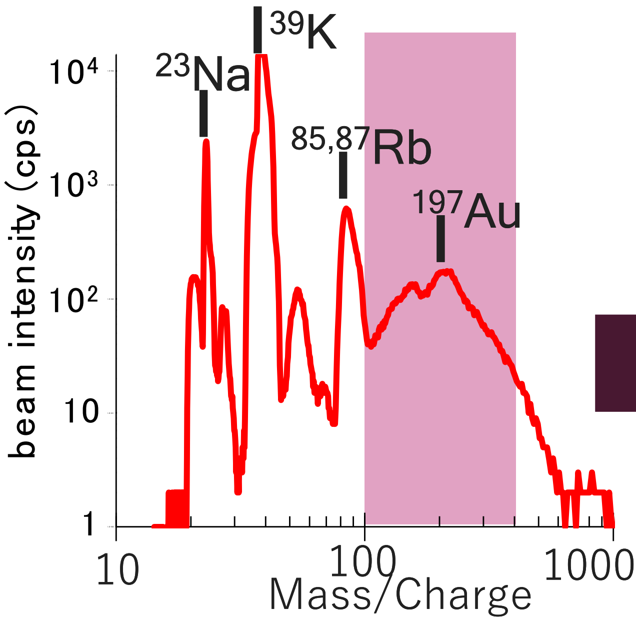
Transportation and purification

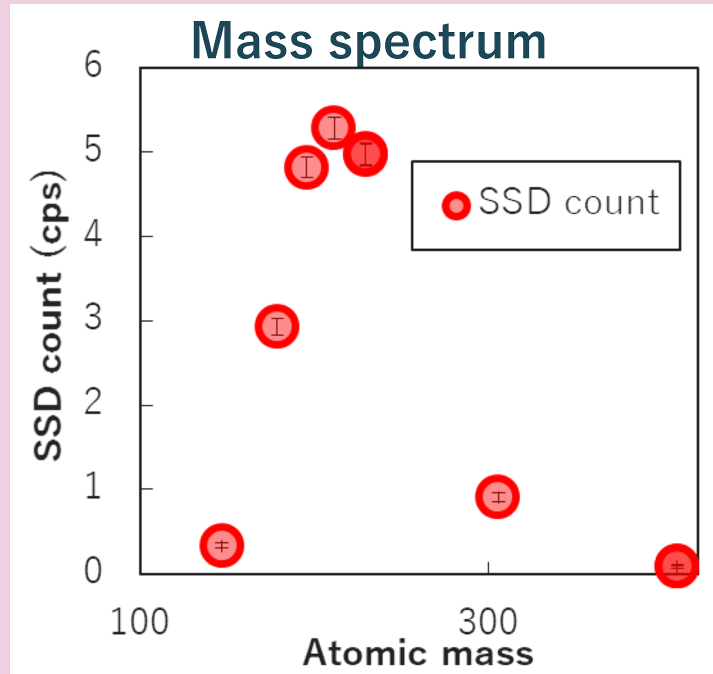
Wien filter





Electric field: E
Magnetic field: B





	Fr purity	Transport efficiency
Without Wien filter	10^{-6}	15%
With Wien filter	10^{-3}	26%

purification

✔ Purification of ion beam

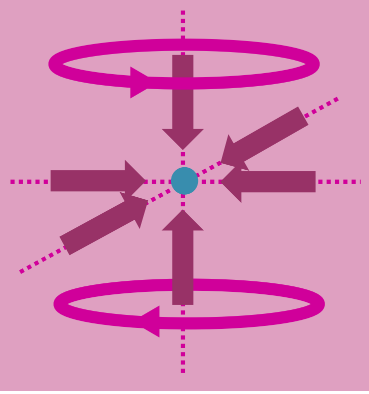
✔ Resolve charges with **high magnetic field operation**
→ **High resolution**

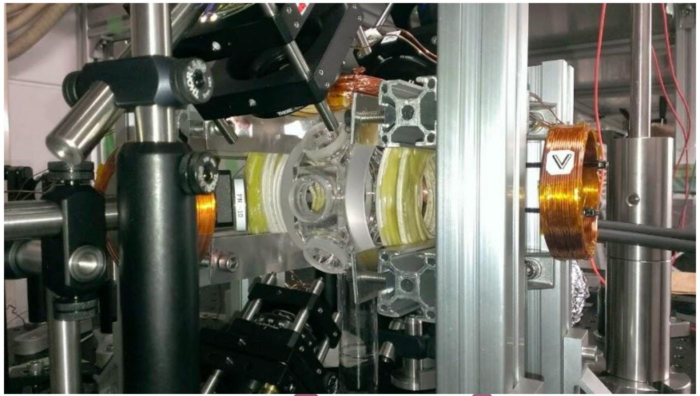
Fr magneto-optical trap (MOT)

Optical molasses:
cooling atom

+

Quadrupole magnetic field:
gathering atom

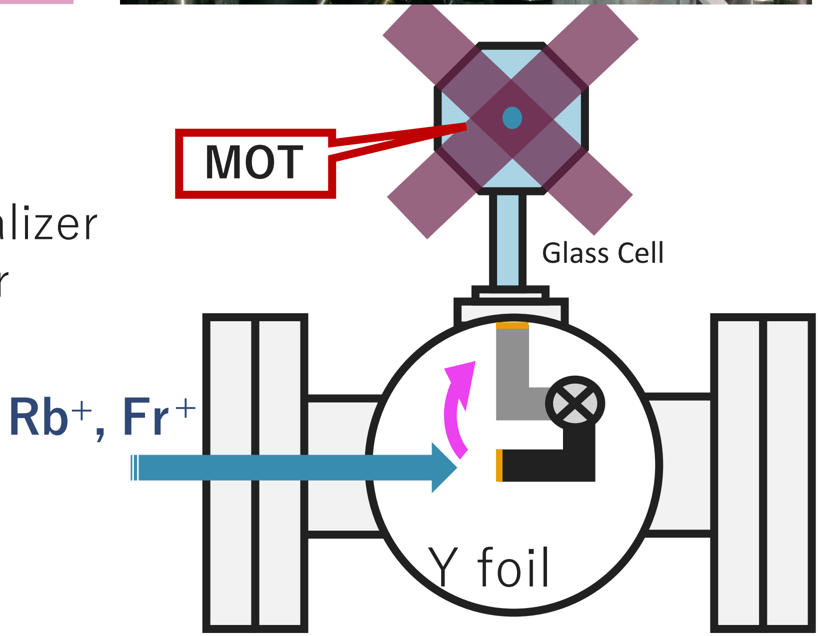




Ion-to-Atom conversion

Ionization potential
Fr: 4.0 eV
Rb: 4.2 eV

Work function
Y: 3.1 eV -> neutralizer
Au: 5.1 eV -> ionizer



- ✔ Neutralization using Y foil

  Efficiency depends on the condition of the target surface

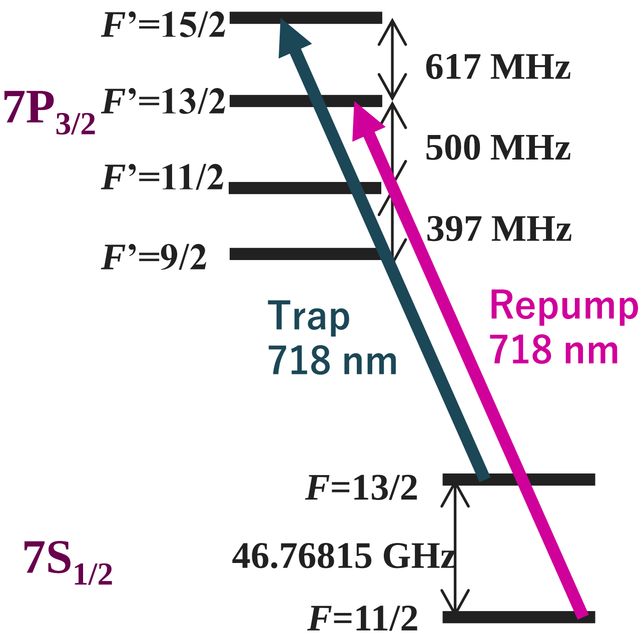
- ✔ To elucidate the **mechanism**

Fr magneto-optical trap (MOT)

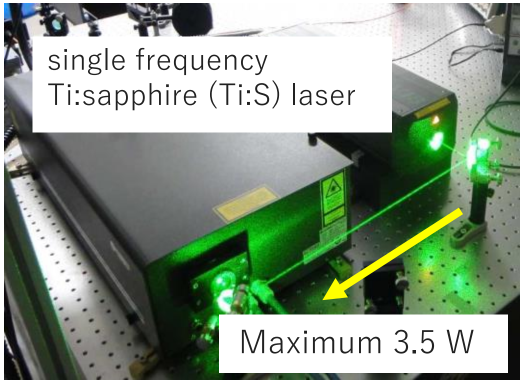
Laser light for Fr-MOT

^{210}Fr Energy Level

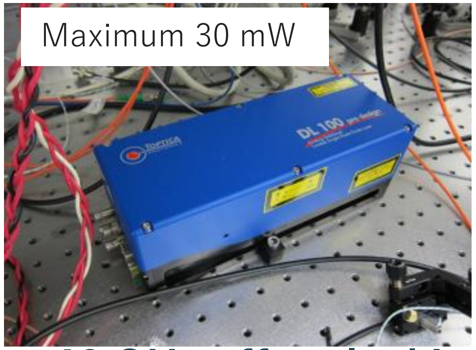
D2 Line



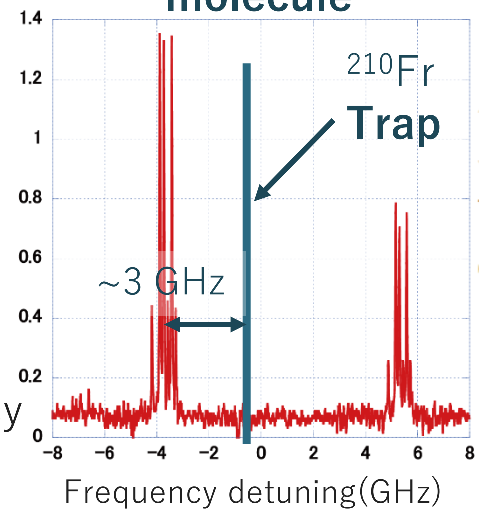
Trapping light



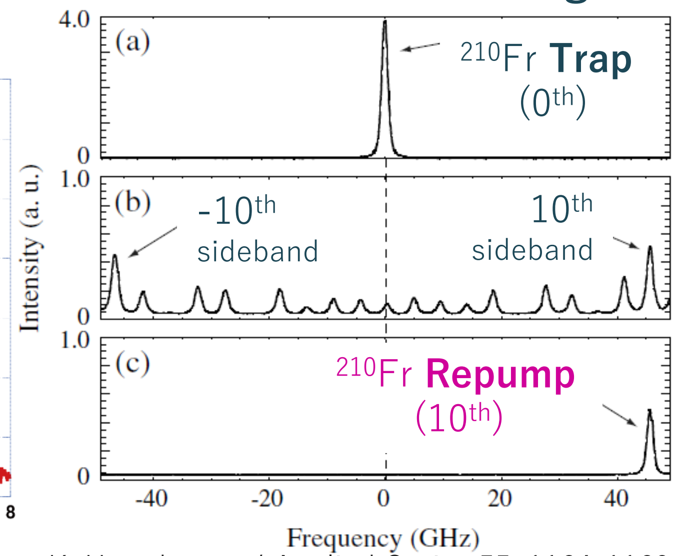
Repumping light



Spectrum of Iodine molecule



46 GHz offset locking



K. Harada, *et al.* Applied Optics 55, 1164-1169 (2016).

- ✔ Two offset locking systems
- ✔ Determination of resonant frequency

precisely for high reproducibility

Status of Fr-EDM project

Francium production
- ✔ Fr ion source
- ✔ Ion transportation
- ✔ Ion purification
- ✔ Ion-to-atom conversion

Laser cooling and trapping
- ✔ Magneto-optical trap
- ✔ Optical lattice

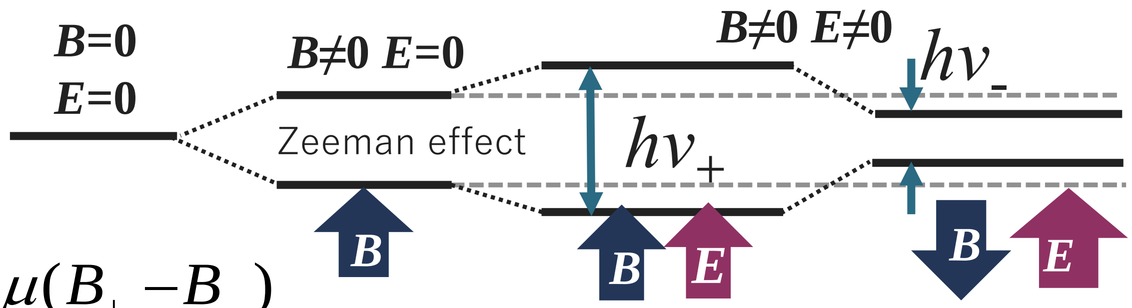
	Resonant wavelength
Rubidium	780 nm
Francium	718 nm

→Rubidium is good for the

Spectroscopy
- ✔ Ramsey's method
- ✔ High voltage system
- ✔ Magnetometer
- Co-magnetometer

EDM measurement

$$h\nu_+ = -\mu \cdot B_+ - d \cdot E_+$$
$$h\nu_- = -\mu \cdot B_- + d \cdot E_-$$



$$\Rightarrow d_{\mathrm{Fr}} = -\frac{h(\nu_+ - \nu_-) + \mu(B_+ - B_-)}{E_+ + E_-}$$

If $\nu_+ = \nu_- = \nu \pm \delta\nu$, $B_+ = B_- = B \pm \delta B$, $E_+ = E_- = E \pm \delta E$

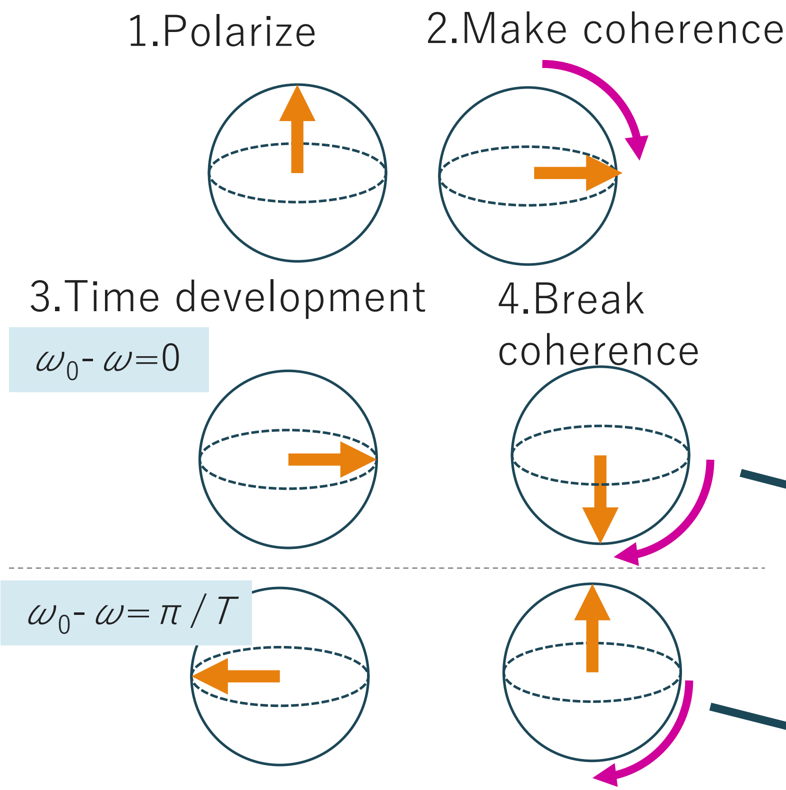
$$\delta d_{\mathrm{Fr}} > \sqrt{2\left(\frac{h}{2E}\right)^2 \delta\nu^2 + 2\left(\frac{\mu}{2E}\right)^2 \delta B^2}$$

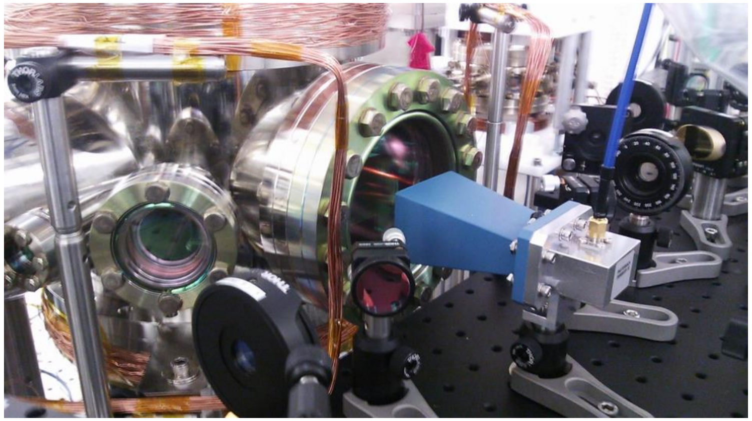
To achieve $\delta d_{\mathrm{Fr}} < 5 \times 10^{-25}\ e\ \mathrm{cm}$

$E > 100$ kV/cm and $\delta\nu < 10\ \mu$Hz, $\delta B < 1$ fT

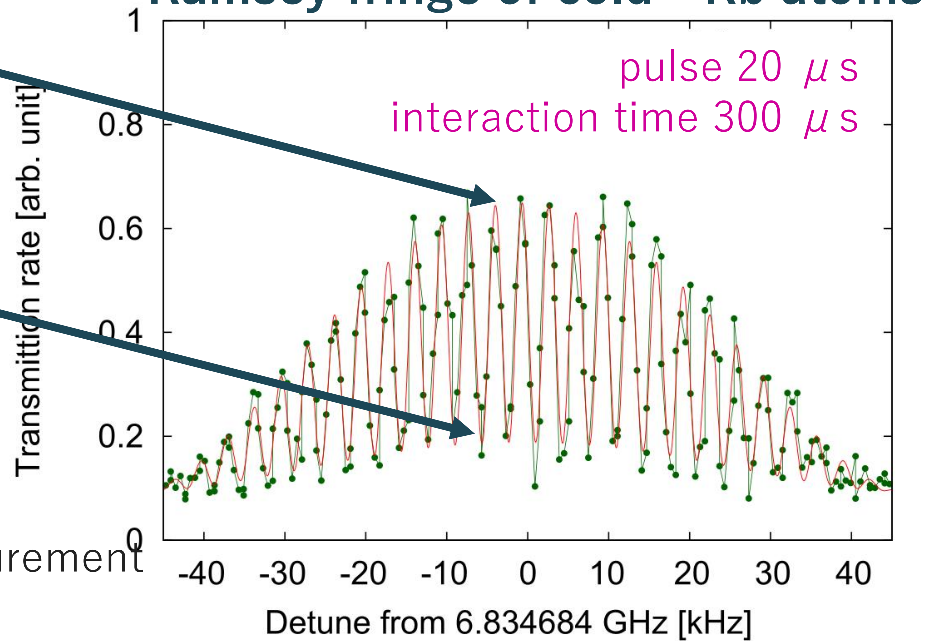
- ✔ Precision spectroscopy (Ramsey's method)
- ✔ High voltage system
- ✔ Magnetometer

Ramsey's method for cold atom





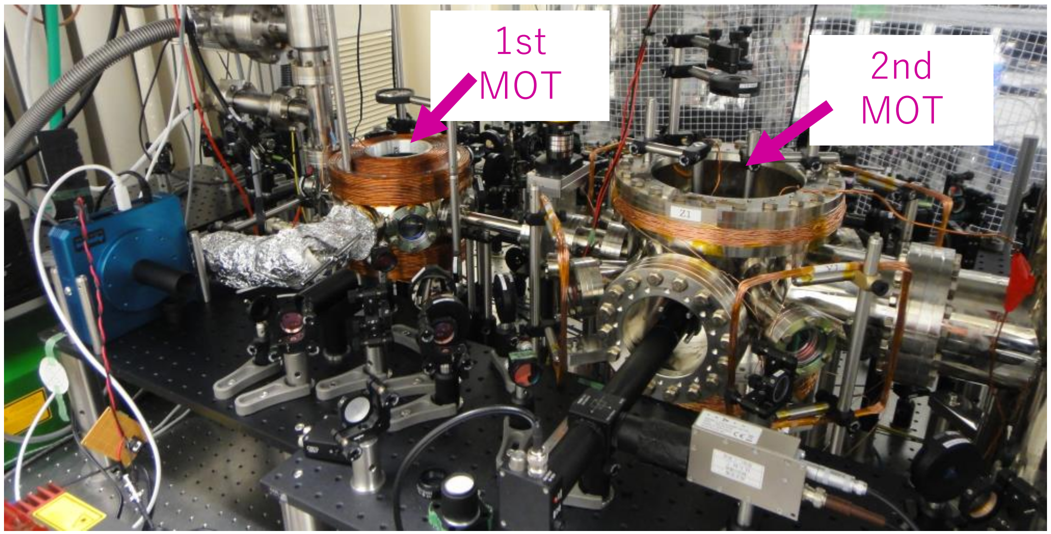
Ramsey fringe of cold ^{87}Rb atoms



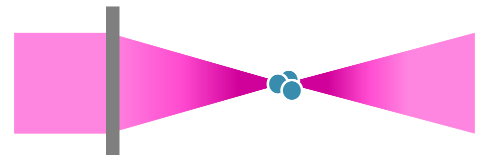
- ✔ Ramsey's method can be used for cold atom
  - Fringe width is now ~ kHz (for ~GHz)
- ✔ Interaction time is **not** enough for EDM measurement

Laser cooling and trapping

Offline laser trapping test using Rubidium (Rb) atoms

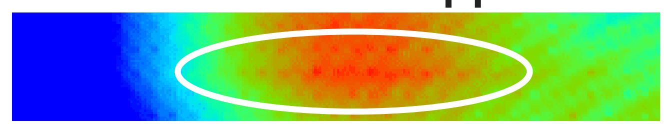


Optical dipole force trap (ODT)

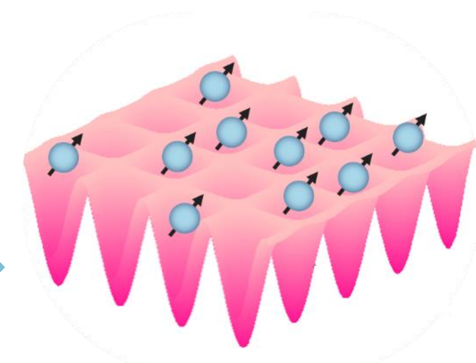


Trap using
AC stark shift

Trapped atom



- ✔ Trapping Rb atoms by ODT
- ✔ Improvement of **loading efficiency**
  - Cooling to lower temperature (Sisyphus cooling)
- ✔ Development toward optical lattice
  - ✔ **High power single mode** fiber laser

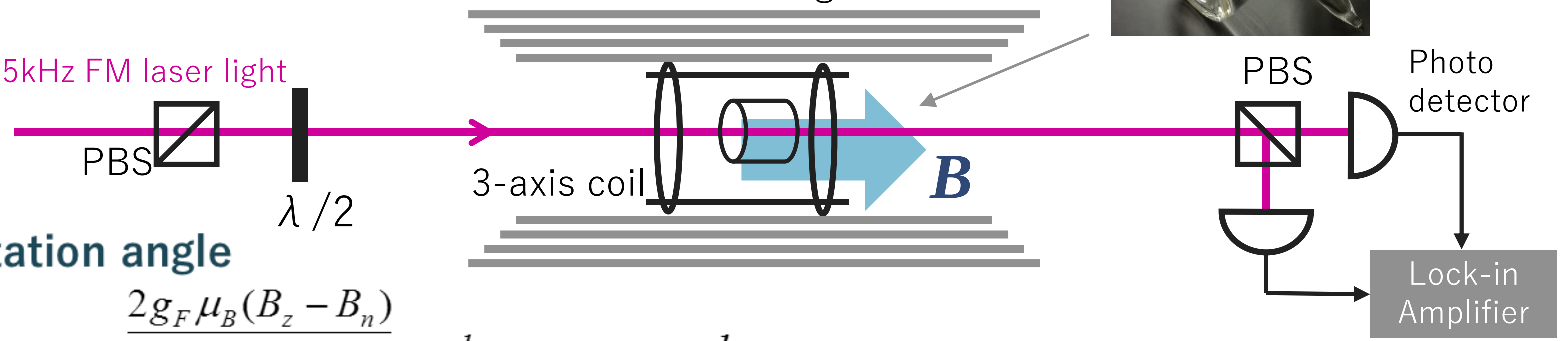


Contents

Rb magnetometer

Non-linear magneto-optical rotation using frequency modulated light (FM-NMOR)

Paraffin coated Rb cell (ϕ 3 cm, l 3 cm)



Rotation angle

$$\theta(B_z) \approx \frac{\dfrac{2g_F\mu_B(B_z - B_n)}{\hbar\Gamma}}{1+\left(\dfrac{2g_F\mu_B(B_z - B_n)}{\hbar\Gamma}\right)^2}\frac{l}{l_0} \qquad B_n = n\frac{h}{g_F\mu_B}\frac{\nu_{\mathrm{Mod.}}}{2}$$

g_F: g factor ,μ_B: Bohr magneton, Γ: relaxation rate

$$\theta \approx \frac{V_S - V_P}{2(V_S + V_P)} \Rightarrow V_S - V_P \approx \frac{g_F\mu_B}{\hbar\Gamma}V_{\mathrm{Amp}}(B_z - B_n)$$

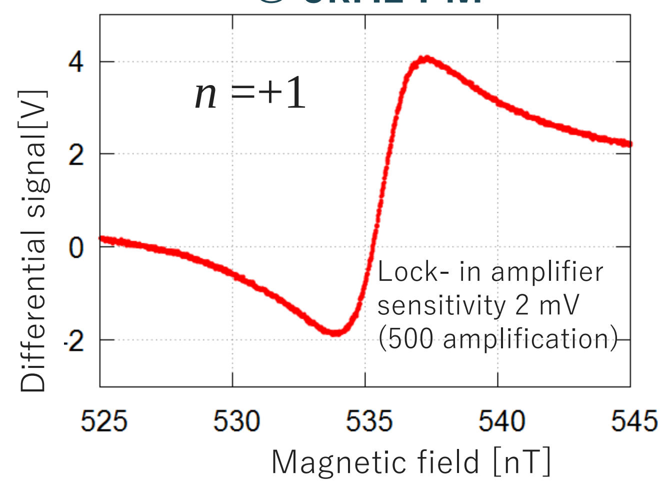
Differential signal is used for the measurement

For high sensitivity

Large slope
Small noise

$$\delta B \sim \left(\frac{\partial V}{\partial B}\right)^{-1}\delta V$$

Differential signal of ^{85}Rb @ 5kHz FM



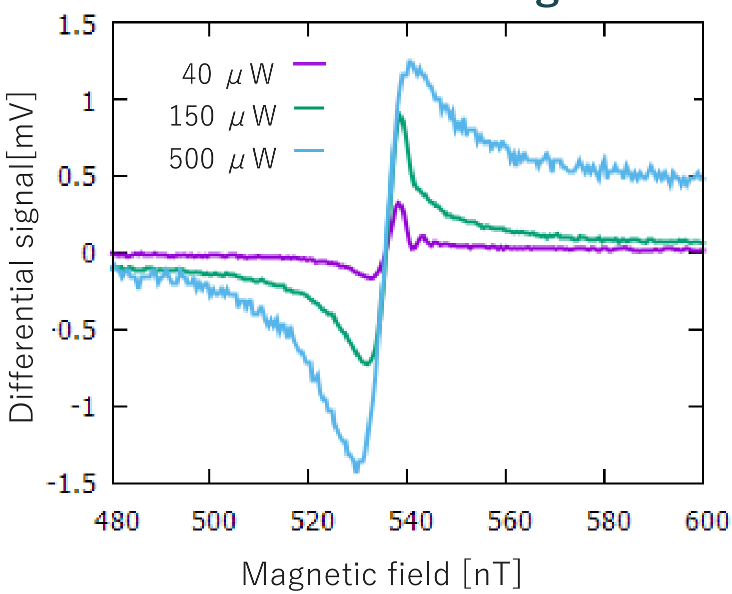
FM-NMOR slope laser intensity dependence

$$\delta B \sim \left(\frac{\partial V}{\partial B}\right)^{-1} \delta V$$

Differential signal (V_S-V_P)

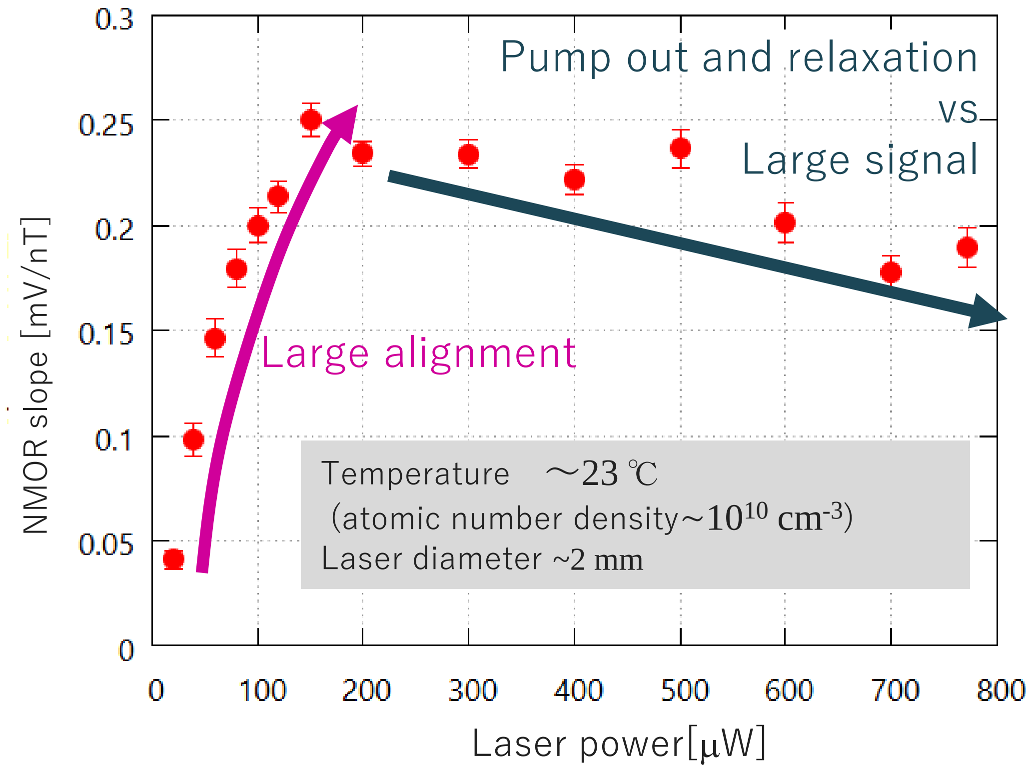
$$V_S - V_P \approx \frac{g_F \mu_B}{\hbar \Gamma} V_{Amp} (B_z - B_n)$$

^{85}Rb n=1 NMOR signals



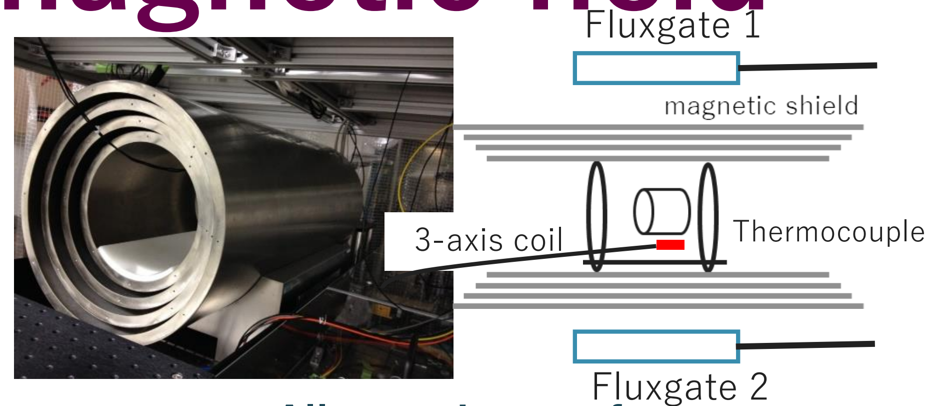
※ 150 μW and 500 μW signals corrected for offset

^{85}Rb n=1 NMOR slope
Laser light power dependence



- ✔ **1.2 GHz** FM width is the best
- ✔ **150 μW** is the best at room temperature
- ✔ **-0.6 GHz** detuning from ^{85}Rb F=3 is the best

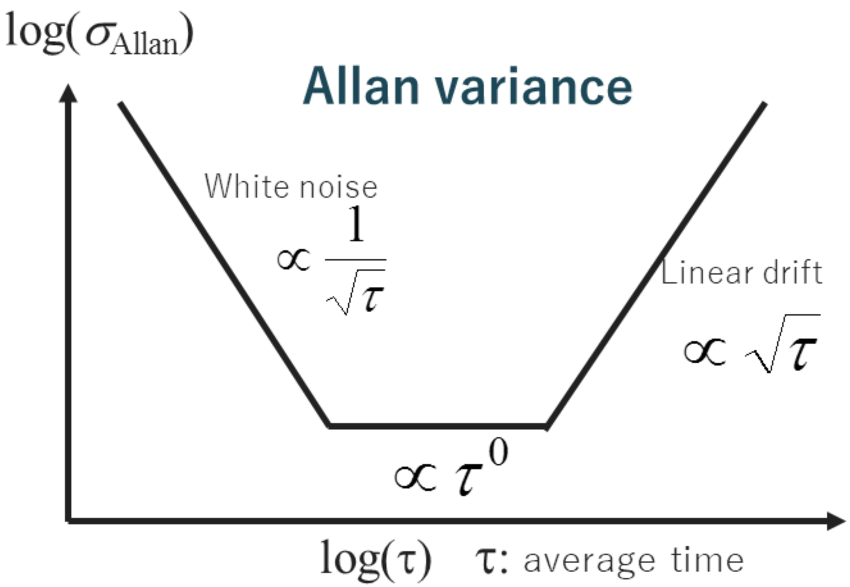
Stability of the magnetic field



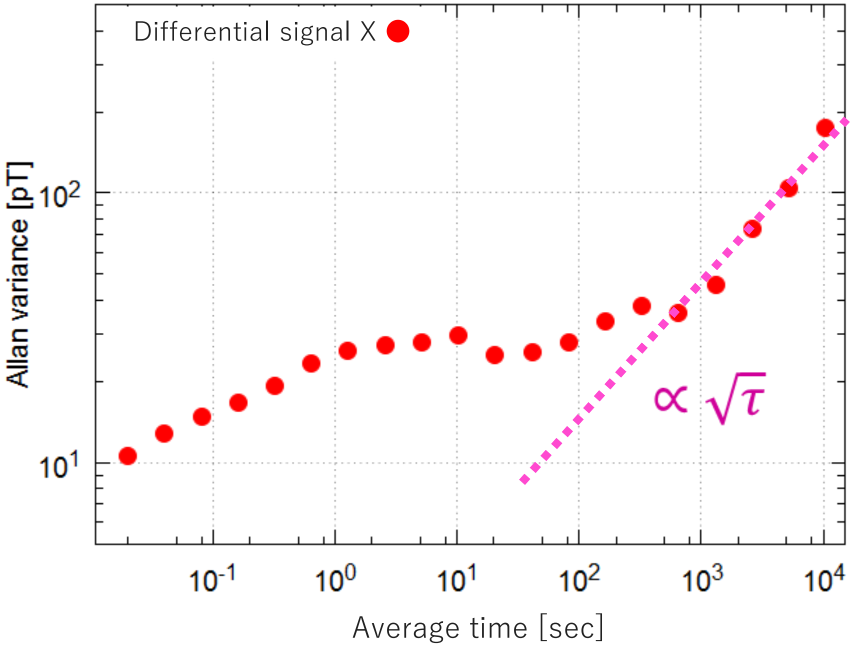
Allan variance $\sigma^2_{\mathrm{Allan}}$

$$\sigma^2_{\mathrm{Allan}}(\tau) = \frac{1}{2(N-1)} \sum_{k=1}^{N-1} \left(\overline{B_k(\tau)} - \overline{B_{k-1}(\tau)} \right)^2$$

$\overline{B_k(\tau)}$: time averaged magnetic field

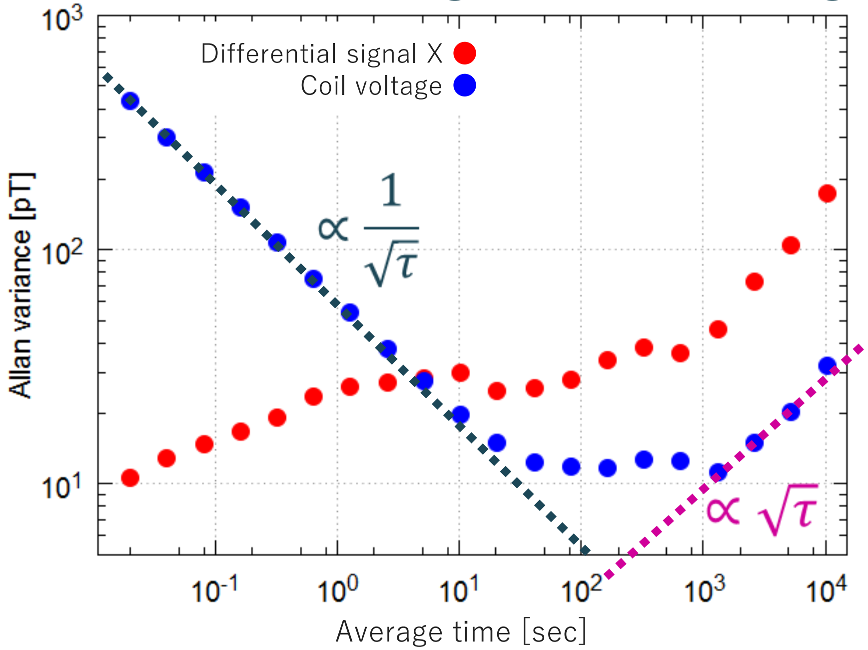


Allan variance of the differential signal

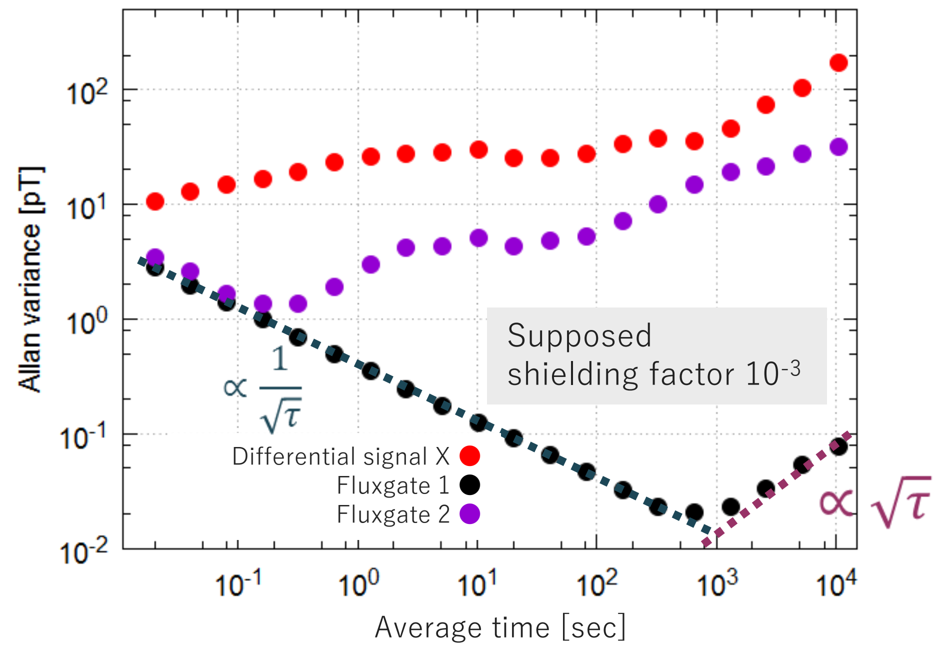


Influence of the external magnetic field

Allan variance of the differential signal and coil voltage



Allan variance of the differential signal and magnetic field outside of the shield



Magnetic field fluctuation is large on one side of the shield ➡ Correction coil is needed

Other effect also contribute

Influence of other parameters

Differential signal V_s-V_p

$$V_S - V_P \approx \frac{g_F \mu_B}{\hbar \Gamma} V_{Amp} (B_z - B_n)$$

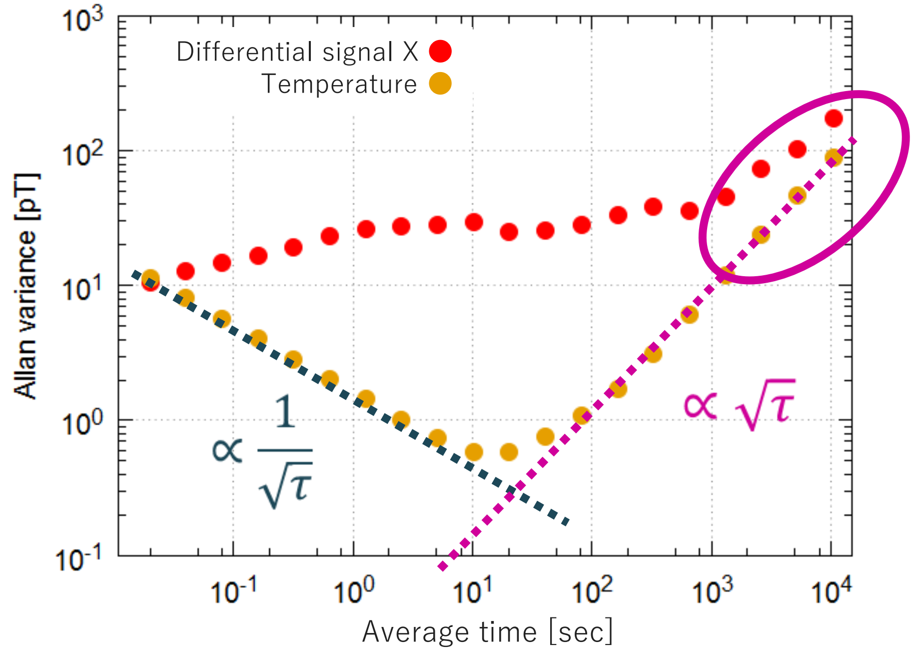
Temperature

-> Atom density
-> Absorption length
-> Amplitude V_{Amp}

-> V_s-V_p

Only Long term fluctuation

Allan variance of the differential signal and temperature



Laser **frequency** and **Intensity**

-> Absorption length and relaxation rate Γ
-> **NMOR slope** $g_F \mu_B V_{Amp} / \hbar \Gamma$

-> V_s-V_p

Contents

Conclusion

- Electron EDM is a good candidate to search for the physics beyond the standard model.
- Fr atom is useful to search for the electron EDM.
- Laser-cooled francium factory is being constructed:
  - Fr ion source
  - Fr transportation and purification
  - Fr ion-to-atom conversion
  - Fr MOT try
- Offline test using rubidium is ongoing:
  - Ramsey's method
  - Laser trapping (MOT, ODT)
  - High voltage system
  - Magnetometer