Development of the magneto-optical trap system for radioactive francium atoms toward an electron electric dipole moment search

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Abstract

The finite value of the electron electric-dipole-moment (eEDM) serves as the signature of violation of both parity (P) and time-reversal (T) invariance.

➡ CP-violation (CPT symmetry is to be preserved.)

The eEDM is a sensitive tool for exploring new physics beyond the Standard Model.

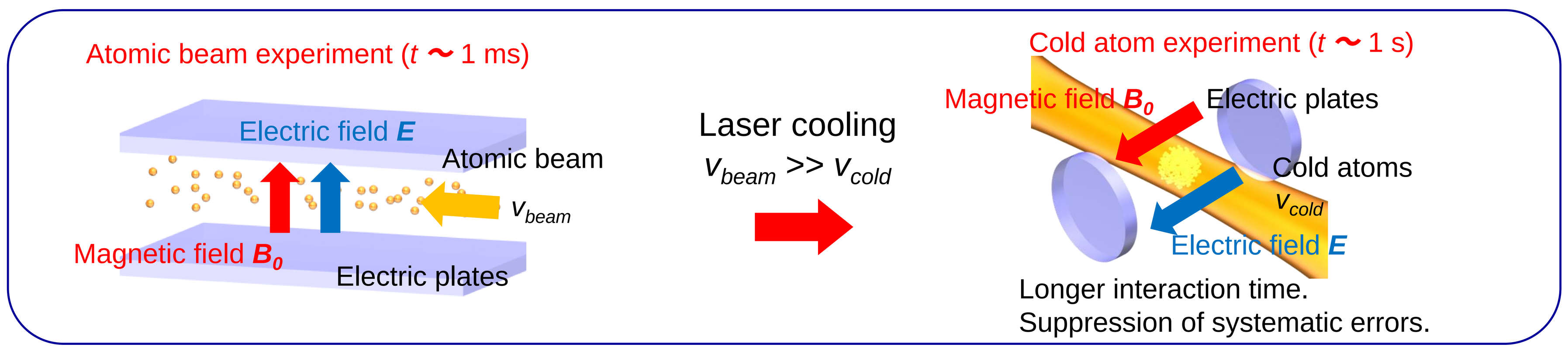
A francium atom is the heaviest alkali element and the enhancement factor of Fr atom for the eEDM is 895. The laser cooling and trapping techniques suppress systematic errors and elongate an interaction time between atoms and an external electric field.

eEDM sensitivity

$$\delta d_e = \underbrace{\frac{hF}{RE}\frac{1}{t} \times \frac{1}{\sqrt{N}}}_{\text{one measurement}} \times \frac{1}{\sqrt{m}}$$

R : Enhancement factor
E : External electric field
t : Interaction time
N : Number of atoms
m = *T* / *t* : number of measurements
T: Total experimental time
F: Total atomic angular momentum

The best limit on eEDM: 8.7 x 10^{-29} *e* cm ; The ACME Collaboration, J. Baron, et al., Science 343, 269 (2014).



The estimated sensitivity of eEDM for Fr atoms in an optical trap,

R = 895 (For Fr atom)
t = 10 s, *N* = 10^7 atoms, *E* = 100 kV/cm
n = 86400 (20 s @ one measurement), F = 13/2

$|d_e| \sim 10^{-29}$ *e* cm

We perform an eEDM search using laser-cooled francium (Fr) atoms.

Magneto-optical trapping (MOT) is performed to trap Fr atoms.

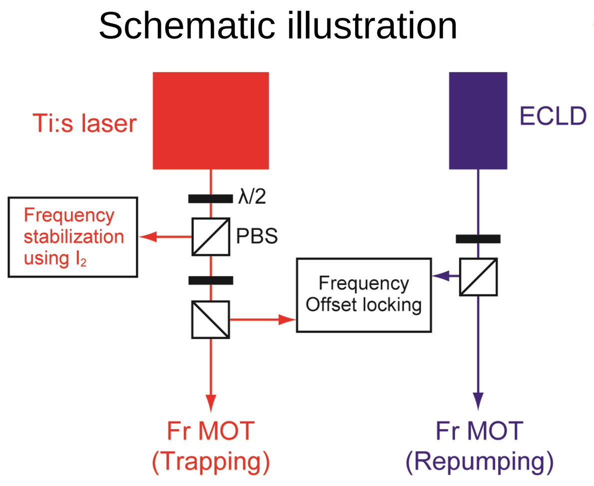
➡ Frequency stabilization of laser sources is needed for MOT.

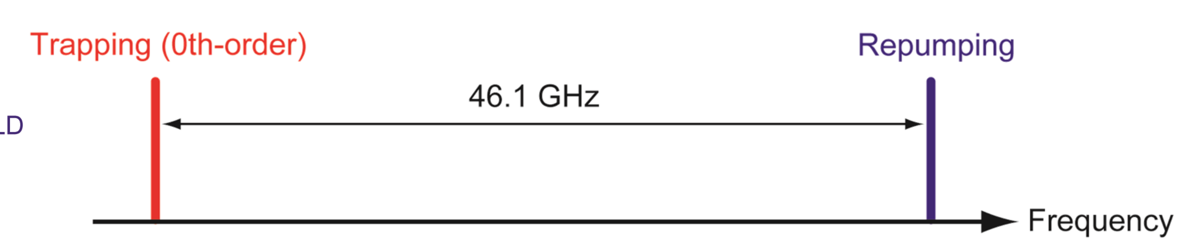
Methods of laser frequency stabilization for radioactive atoms.
◆ Frequency modulation spectroscopy of iodine molecules. ◆ Transfer cavity

1. Frequency offset locking

The technique of frequency offset locking can lock the frequency difference between two laser sources to a constant value. It is used as a frequency stabilization and a method for scanning both lasers simultaneously while keeping the frequency difference constant within a capture range.

Schematic illustration

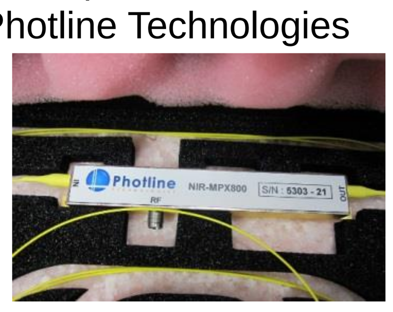


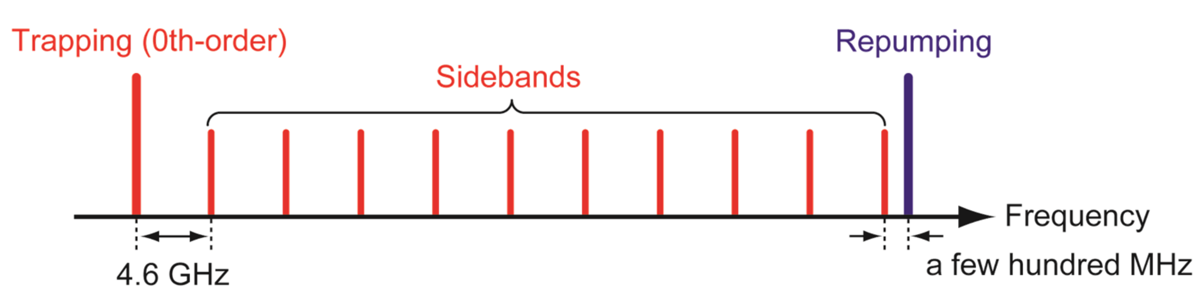


It is tough to keep the beat frequency of 46.1 GHz directly.

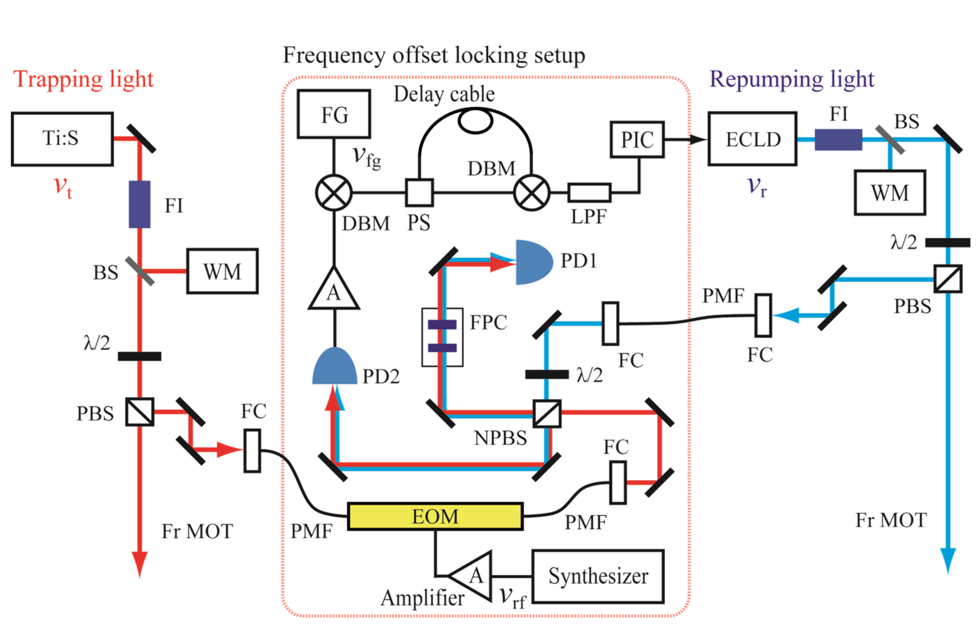
We used an electro-optics modulator (EOM) which can generate 10th-order sidebands.
It enables to detect the beat frequency of a few hundred MHz.

EOM (NIR-MPX-800-LN-05)
Photline Technologies

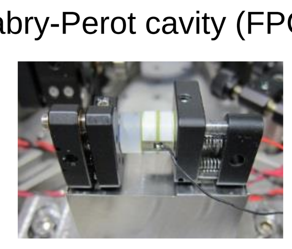




2. Experimental setup for the frequency offset locking



Fabry-Perot cavity (FPC)



- Two mirrors distance : 1.5 mm
- Free Spectrum Range : 100 GHz
- The reflectance of mirror : 99 %

The signal mixed by the DBM is shown as

$$\cos(2\pi\Delta\nu t) \times \cos\{2\pi\Delta\nu(t+\tau)\}$$
$$= \frac{1}{2}[\cos\{2\pi\Delta\nu(2t+\tau)\} + \cos(2\pi\Delta\nu\tau)]$$
$$\Delta\nu = \nu_r - \nu_{10} - \nu_{LO}$$

After LPF, the error signal is obtained.

$$\frac{1}{2}\cos(2\pi\Delta\nu\tau)$$

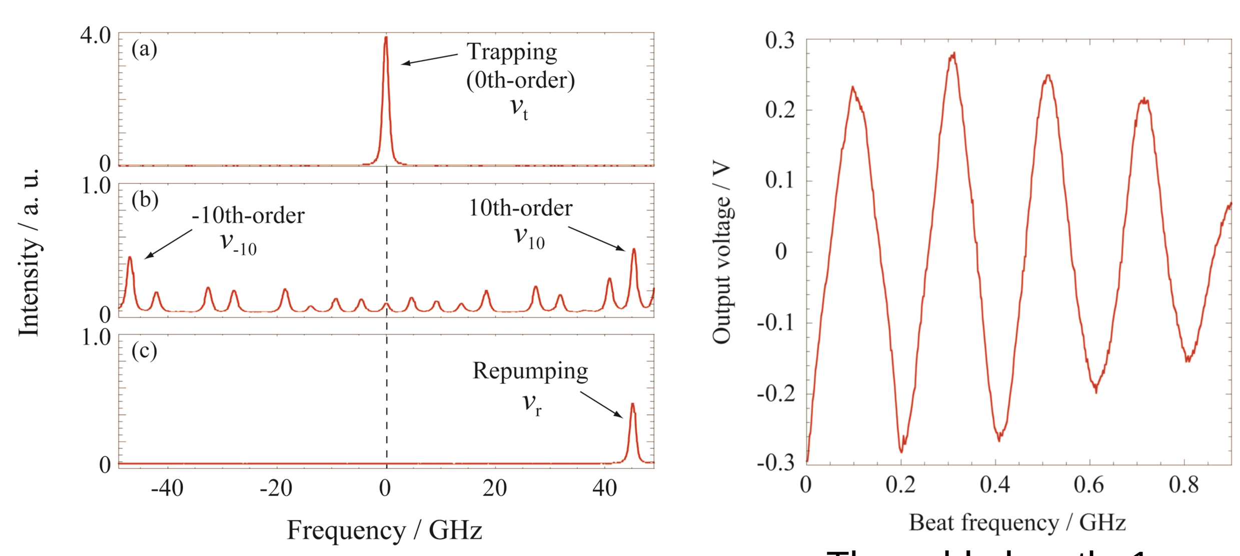
Conclusion

We succeeded in the frequency stabilization using frequency-offset locking with 46 GHz for magneto-optical trapping of Fr atoms.

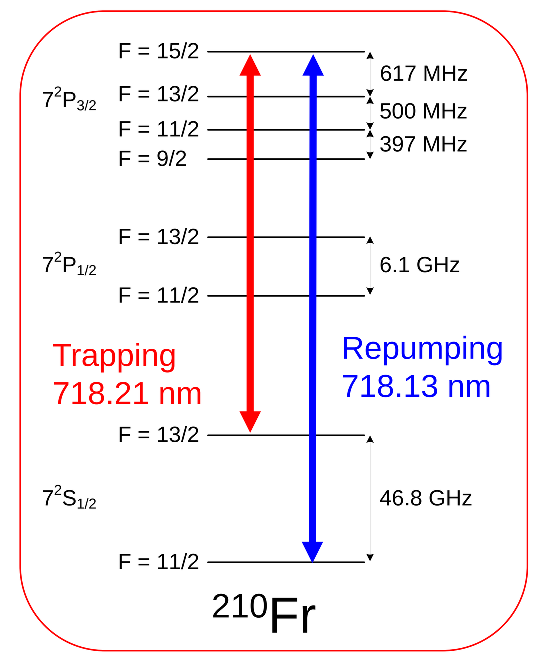
The capture range of more than 2 GHz was achieved when the cable length for the delay was 1 m.

- The error signal was obtained by the delayed self-homodyne detection of the beat signal between 10th-order sideband component and the repumping frequency.
- 10th-order sideband components were generated by EOM which is driven by an RF of 4.6 GHz.

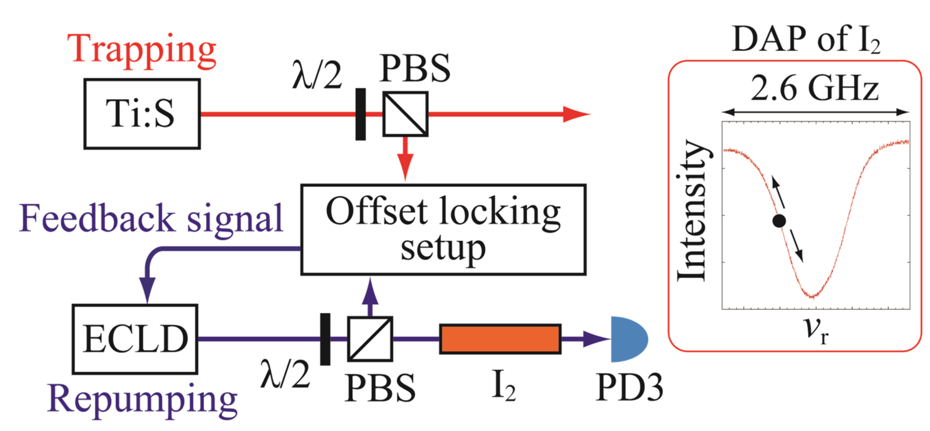
3. Experimental results

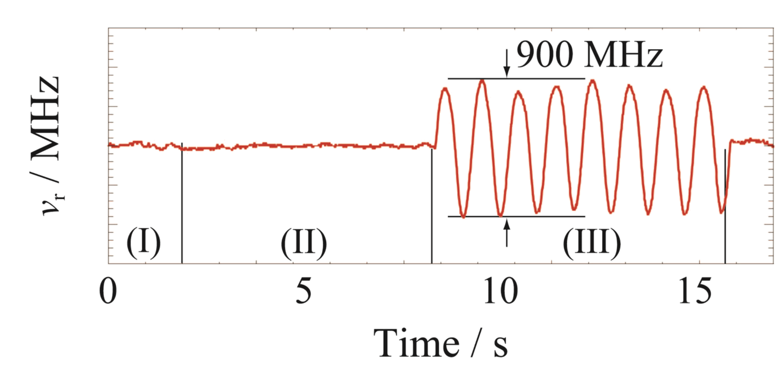


The cable length: 1 m



For confirming whether the frequency difference between the trapping and the repumping lights is locked, we then performed an absorption spectroscopy of I_2.

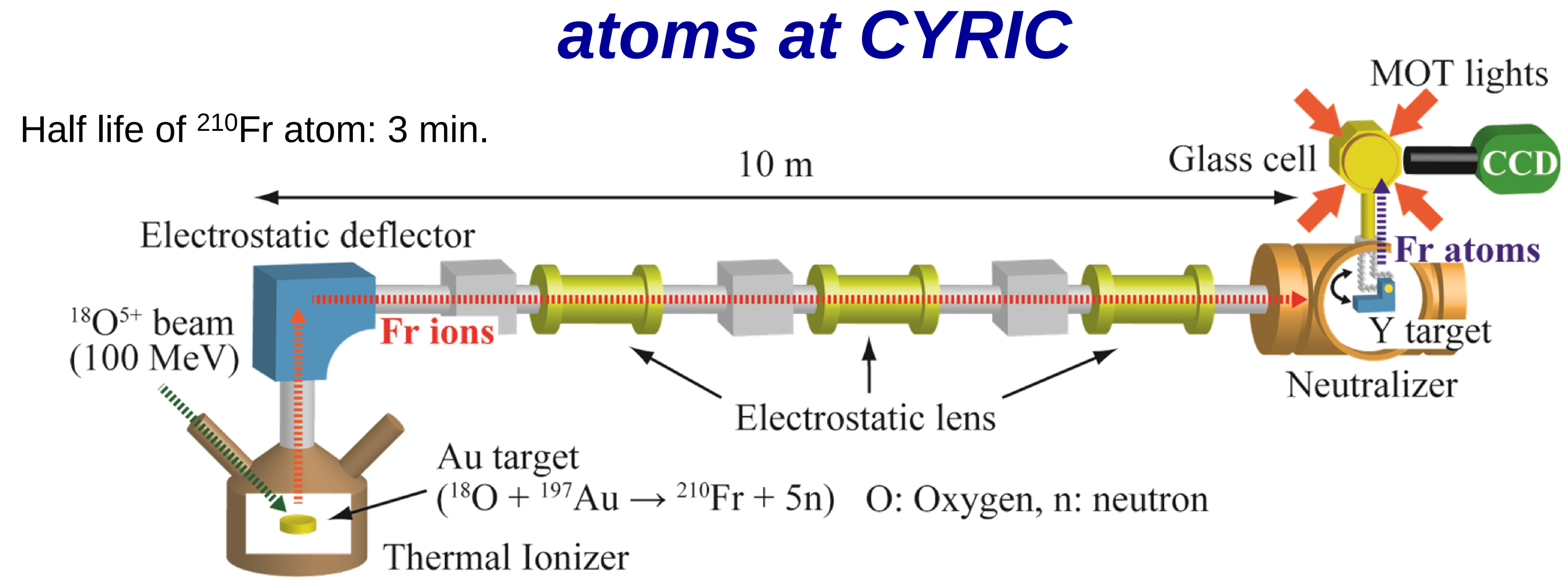




(I) Free running, (II) Locking, (III) Scanning
Maximum capture range : 1.4 GHz

4. Beam line for magneto-optical trapping of Fr atoms at CYRIC

Half life of ^{210}Fr atom: 3 min.



We have succeeded in the verification experiment of the entire apparatus using Rb ion beam and observed the fluorescence of Rb trapped by MOT.

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