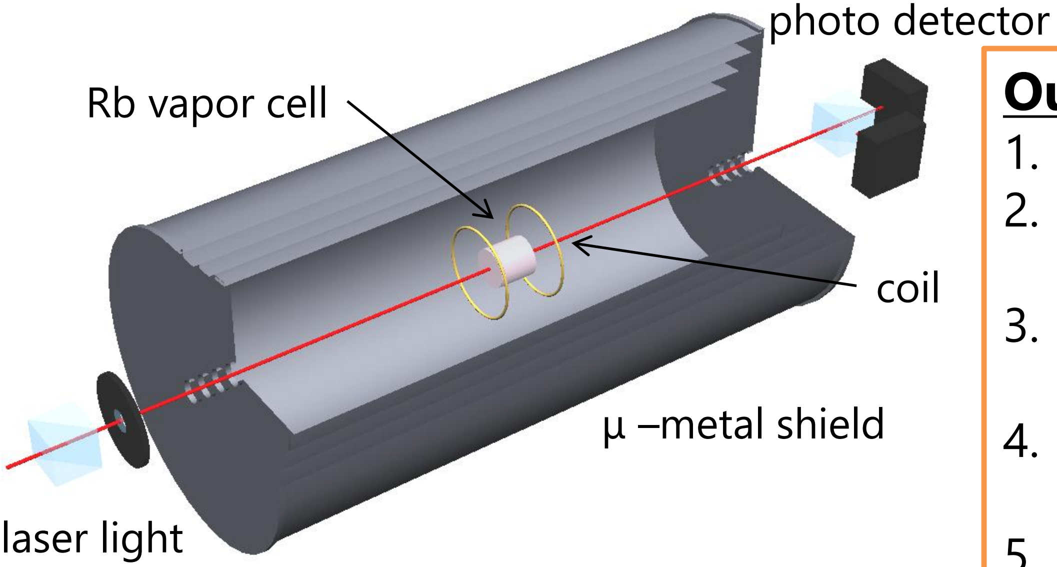
冷却フランシウム原子を用いた 電子EDM探索のためのルビジウム磁力計の開発



Outline:

1. Motivation
2. Nonlinear magneto-optical Rotation (NMOR) effect
3. Frequency modulated (FM) NMOR
4. FM-NMOR spectroscopy for a sensitive magnetometry
5. Summary

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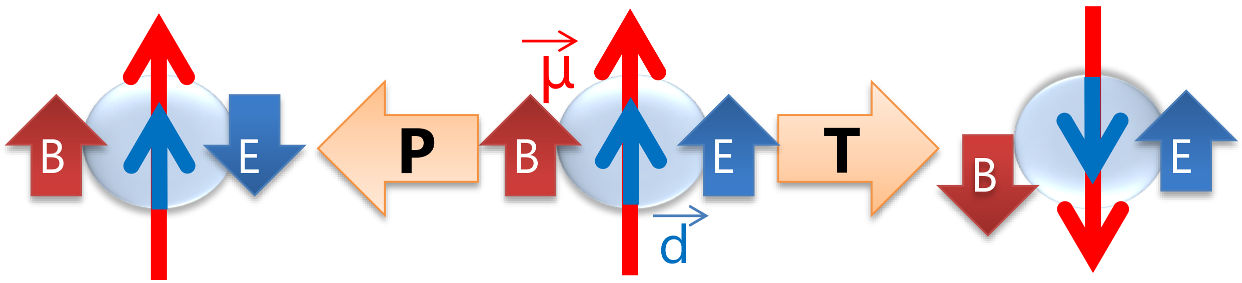
内山愛子

Motivation to study the Rb Magnetometer

-> search for electron permanent electric dipole moment (***e*-EDM**)

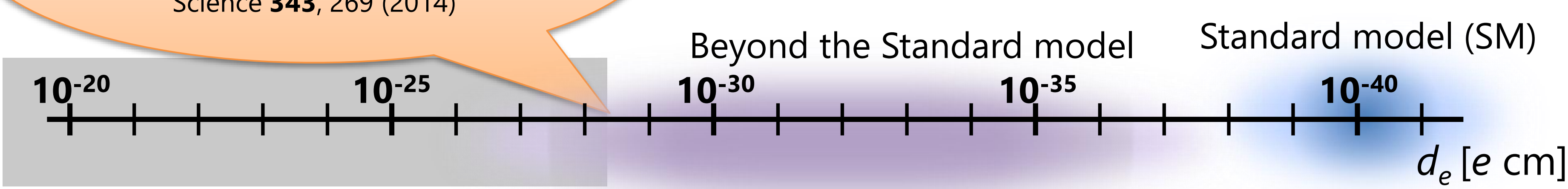
If an elementary particles has the finite size of the permanent electric dipole moment (**EDM**) ($\vec{d}$) along its spin direction, **T** and **P** are violated.



$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

μ: magnetic dipole moment
d: electric dipole moment

Experimental upper limit :
$|d_e| < 8.7 \times 10^{-29}$ *e* cm
The ACME Collaboration *et al.*, Science **343**, 269 (2014)



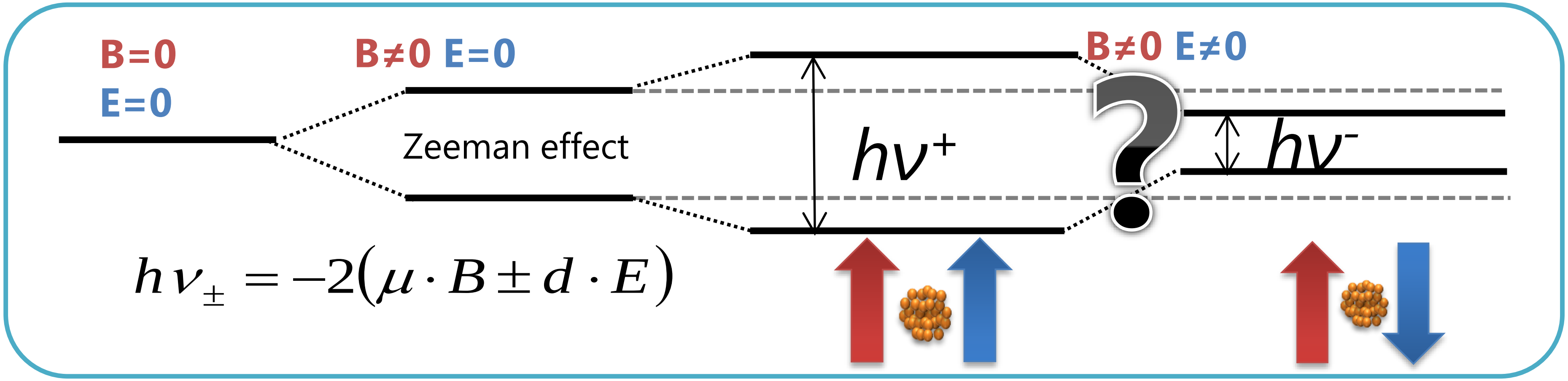
-> EDM can be a probe to test the physics beyond the SM

How to search for the *e*-EDM?

-> measurement of **the energy shifts of atom**

$$d_{\mathrm{Fr}} = R_{\mathrm{Fr}} d_e$$

Francium has **large enhancement factor** R_{Fr}~895 and can be **cooled and trapped** by using laser light.



$$h\nu_{\pm} = -2(\mu \cdot B \pm d \cdot E)$$

d_{Fr}~10^{-26} *e* cm in *E* = 100 kV/cm requires the sensitivity of ***δB*~0.1 fT**

$$\delta B < \frac{E\,\delta d}{\mu}$$

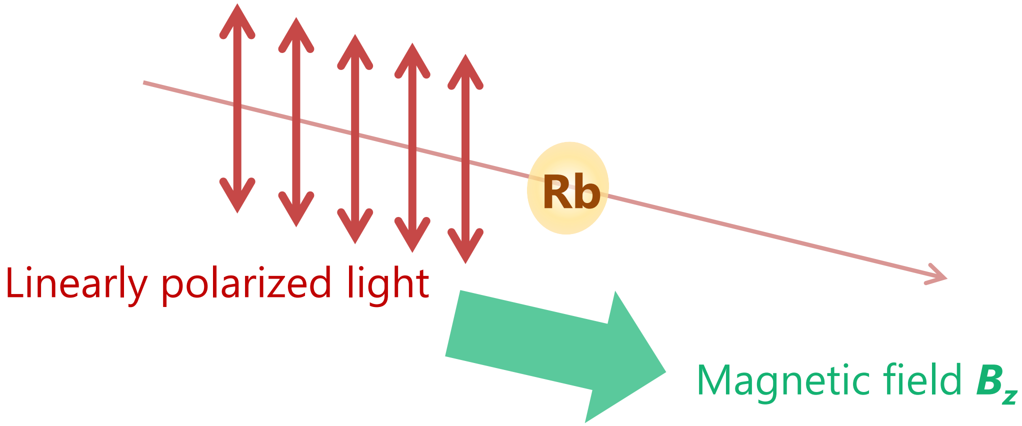
Earth's magnetic field~50 μT

-> precision measurement of magnetic field should be performed and fluctuation of magnetic field should be suppressed.

How to measure the magnetic field?

->using the frequency modulated nonlinear magneto-optical rotation (**FM-NMOR**) effect

1. The linearly polarized light produces an alignment state of Rb atoms.
2. The atomic alignment precesses in the magnetic field.
3. The polarization plane of the light rotates due to an interaction with the atomic alignment.

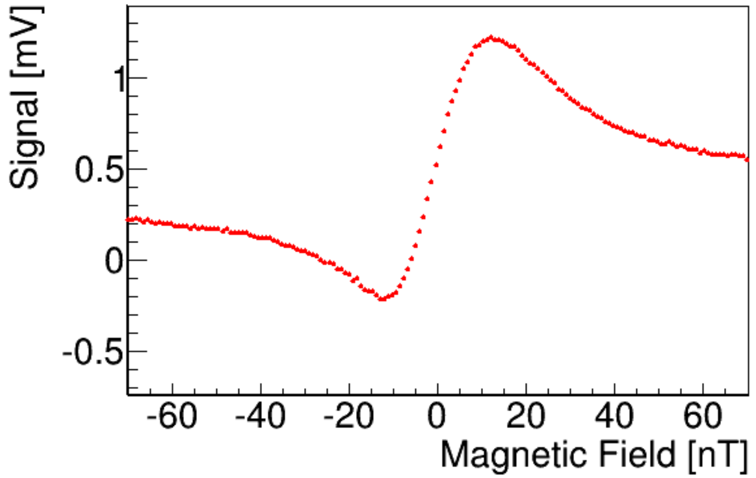


D. Budker *et al.*, Rev. Mod. Phys. 74, 1153 (2002)

Rotation angle:

$$\varphi \approx \frac{\dfrac{2g_F\mu_B B_Z}{\hbar\Gamma}}{1+\left(\dfrac{2g_F\mu_B B_Z}{\hbar\Gamma}\right)^2}\frac{l}{l_0}$$

g_F: Landé g-factor, μ_B: Bohr magneton
l: length of the cell, l_0: absorption length



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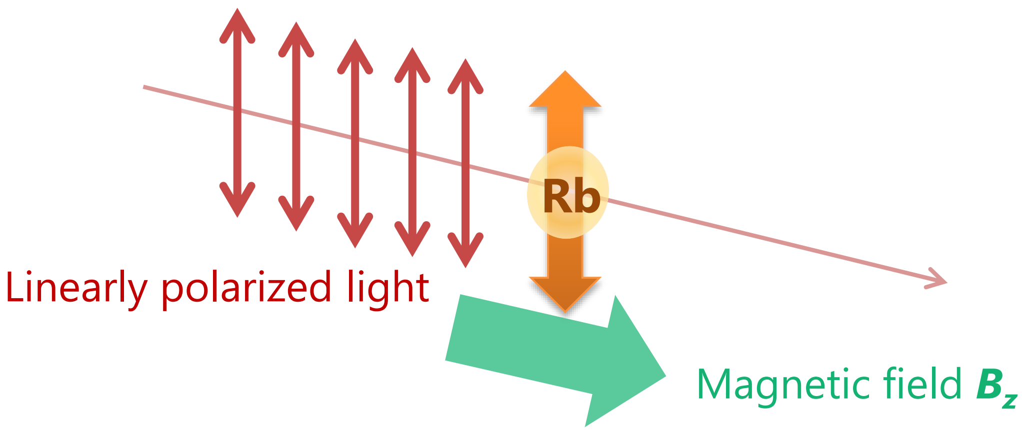

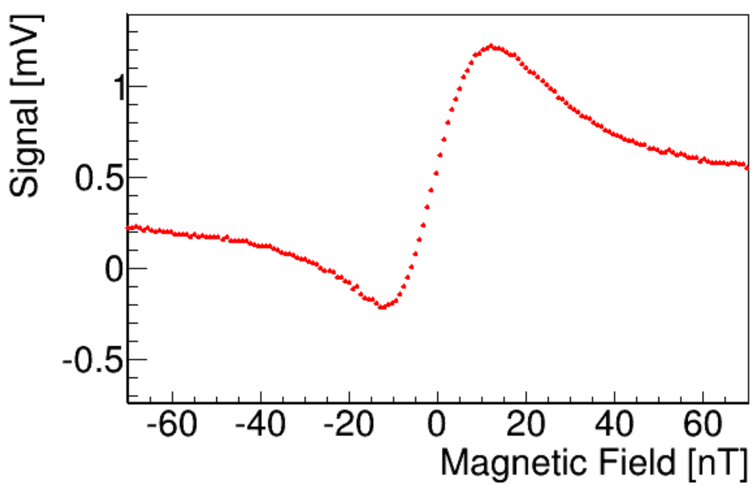

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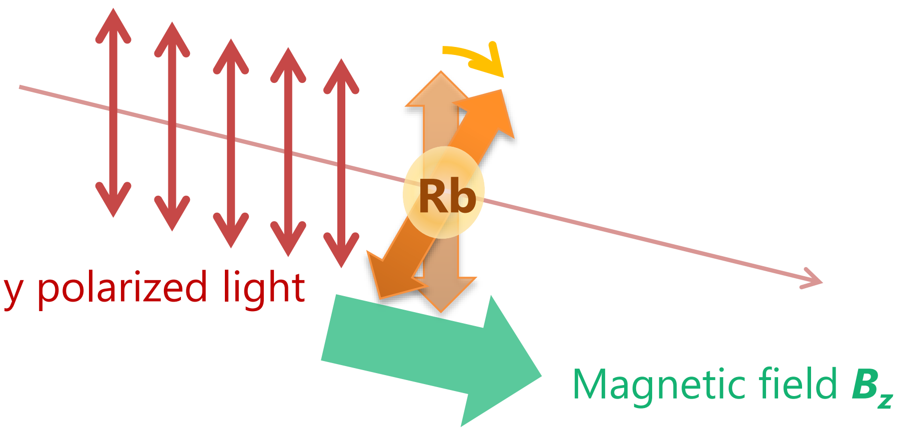

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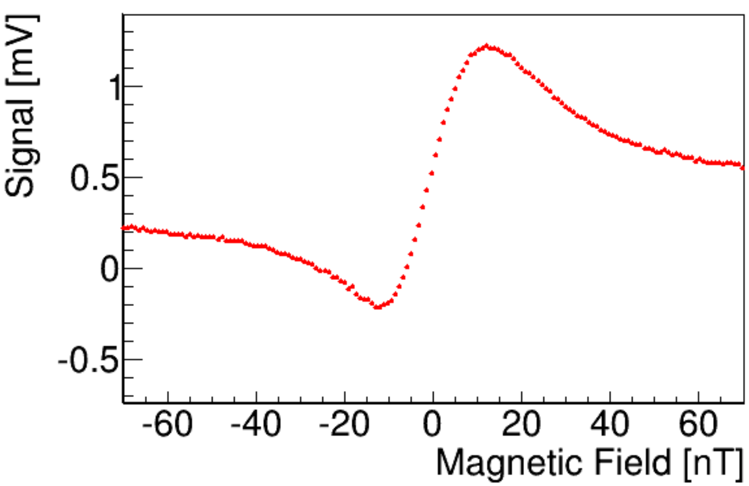

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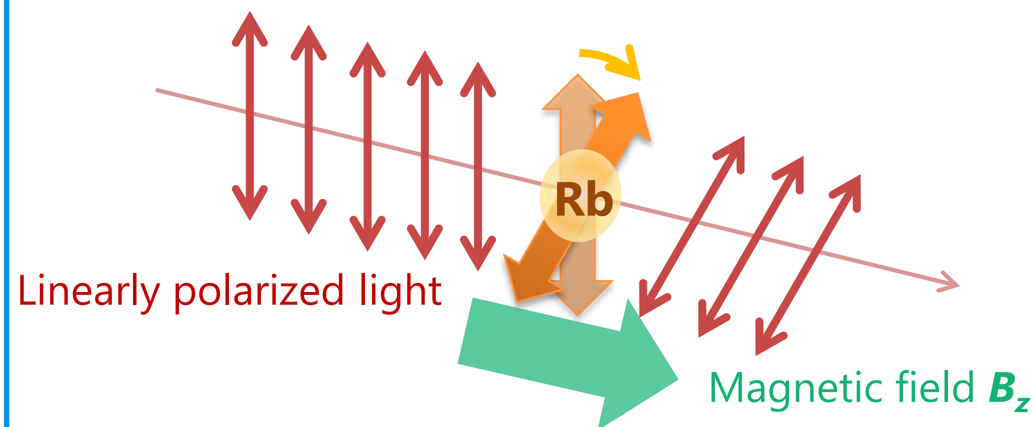

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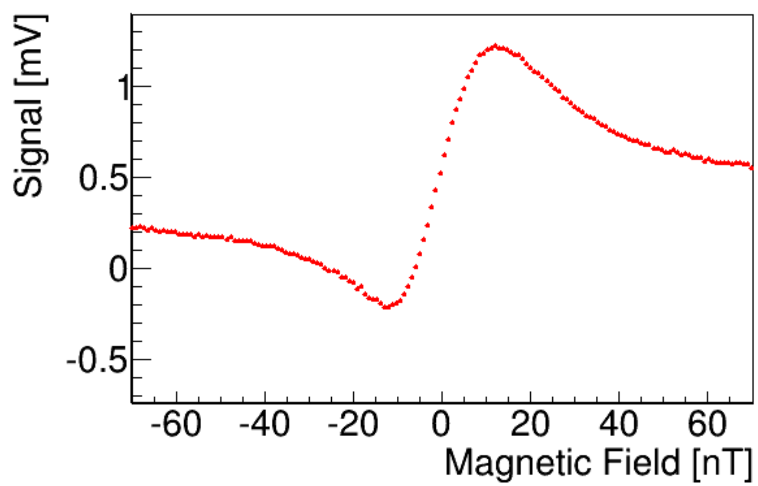
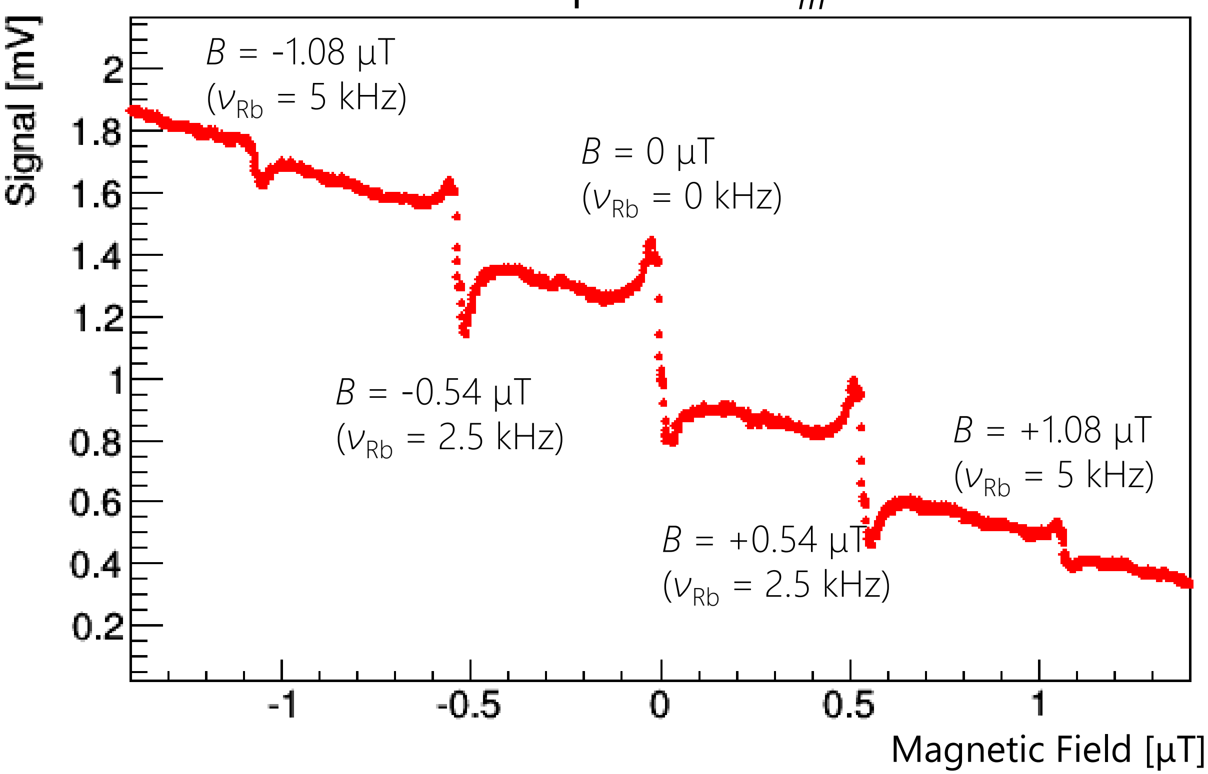


Frequency modulated NMOR (FM-NMOR)

- Modulated light enable to measure **non-zero magnetic fields**.

FM-NMOR spectrum Ω_m =5 kHz



$$n\Omega_m = 2\Omega_L$$

Ω_L : Lamor frequency
Ω_m: modulation frequency

$$\Omega_L = \frac{2m_F g_F \mu_B B}{h}$$

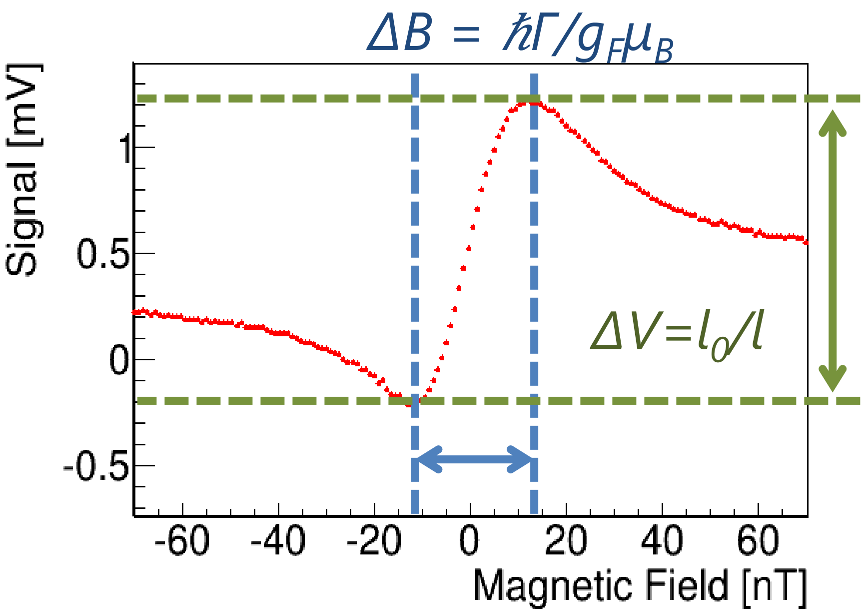
Resonance frequency of FM-NMOR
-> Lamor frequency
-> Magnetic field

What should I do for the sensitive FM-NMOR magnetometer?

-> find the best condition for the FM-NMOR

$$\delta B = \left(\frac{\partial \varphi}{\partial B}\right)^{-1} \delta\varphi, \qquad \frac{\partial \varphi}{\partial B} \propto \frac{\Delta V}{\Delta B}$$

large magnitude of slope = high sensitivity



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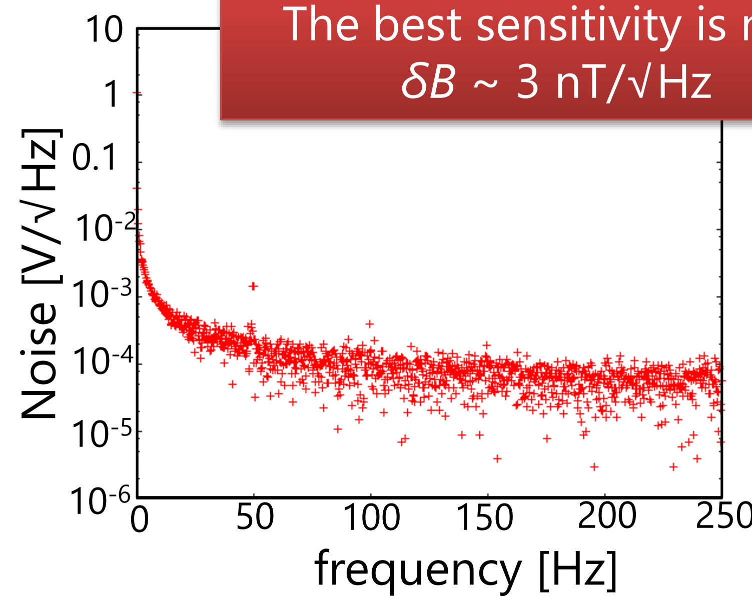
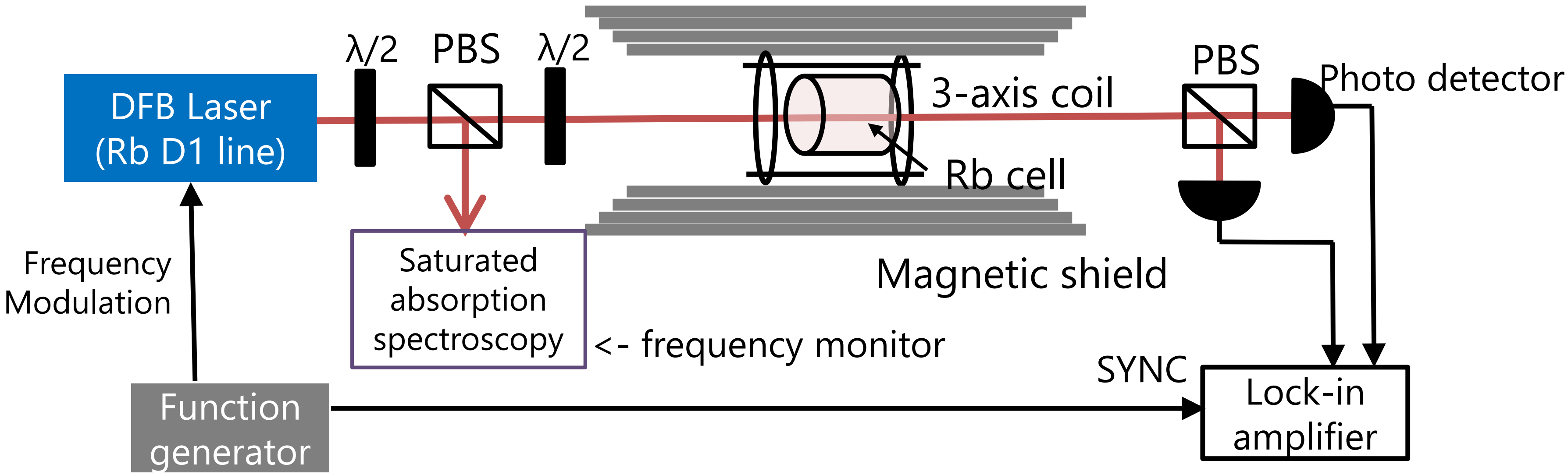
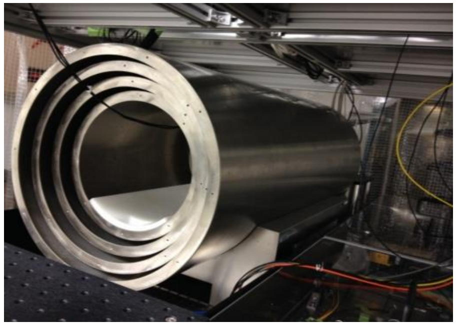


The best sensitivity is now δB ~ 3 nT/√Hz

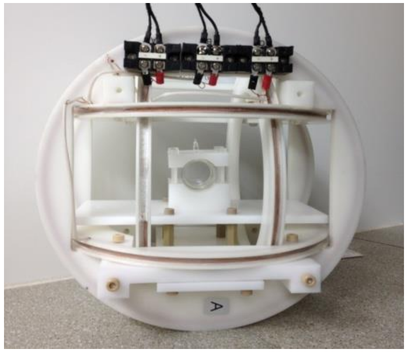
Experimental apparatus



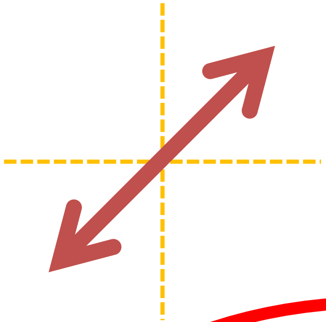
DFB laser

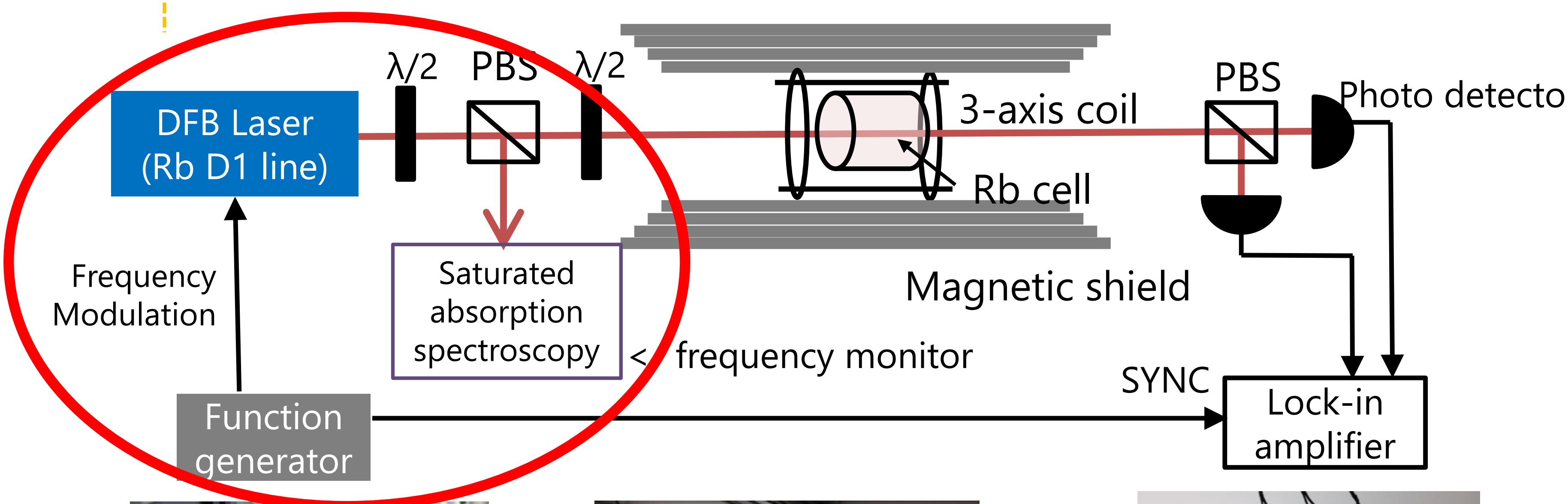


Magnetic shield



3-axis coil and Rb cell





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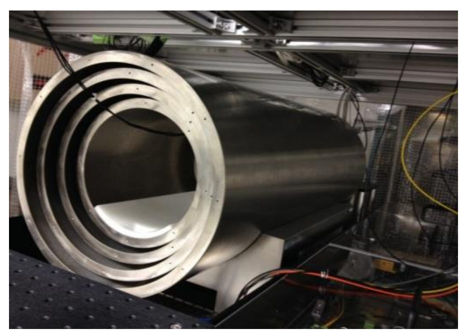
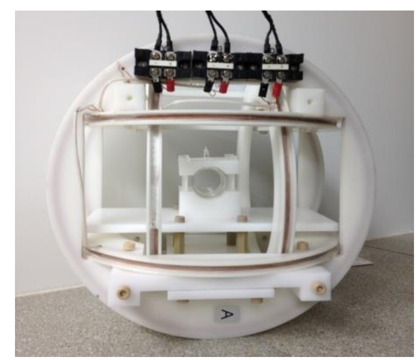


Magnetic shield



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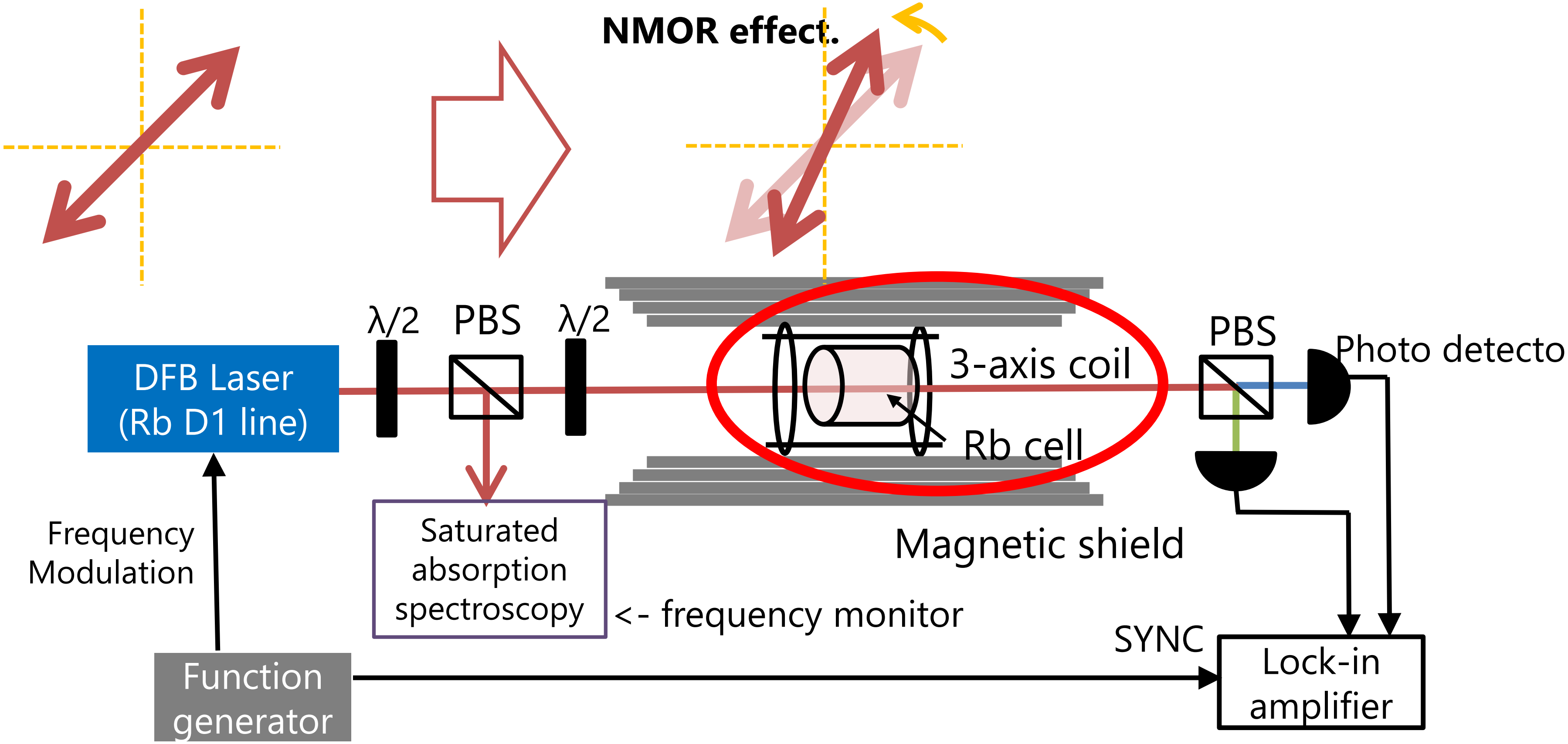

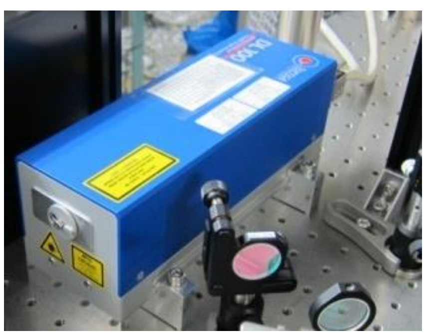

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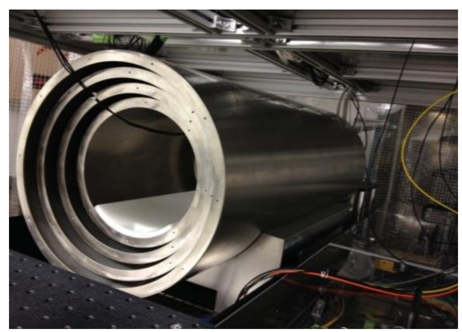

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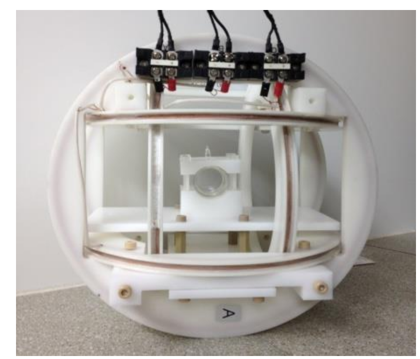

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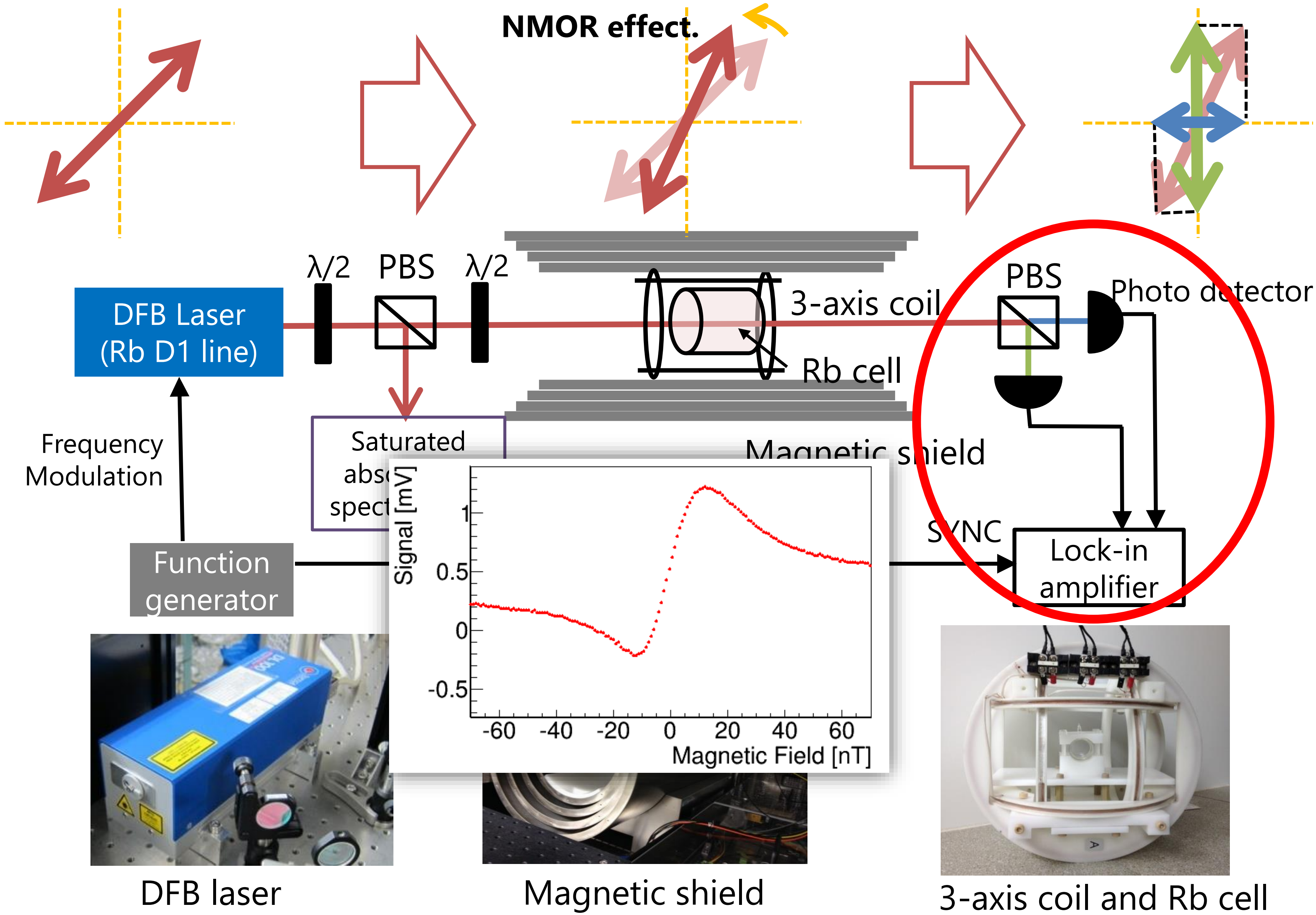
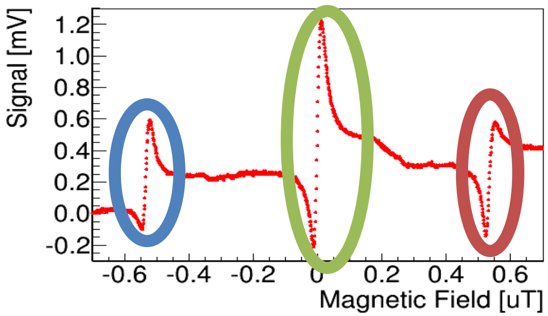
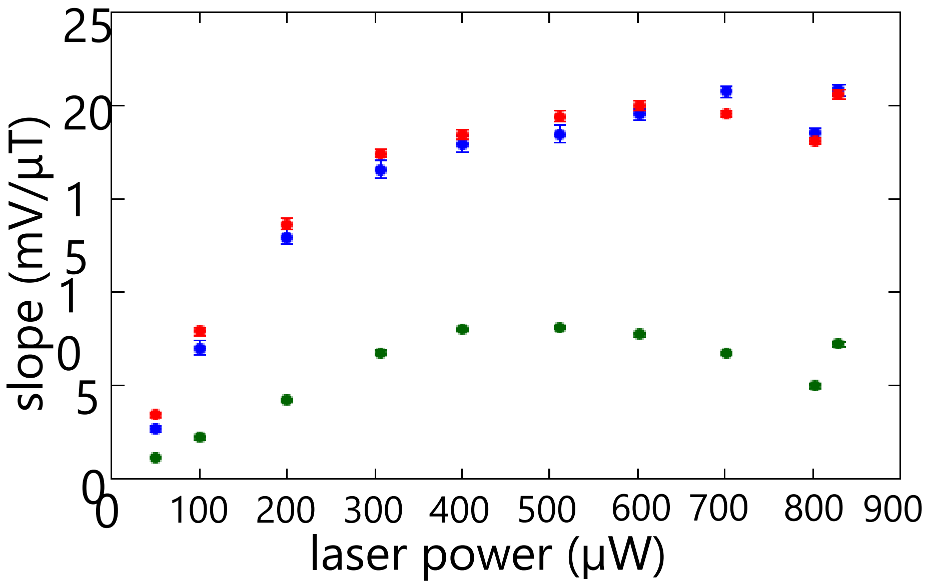

NMOR effect.
λ/2
PBS
λ/2
DFB Laser
(Rb D1 line)
3-axis coil
Rb cell
PBS
Photo detector
Saturated
abs
spect
Magnetic shield
Frequency
Modulation
Function
generator
SYNC
Lock-in
amplifier
Signal [mV]
1
0.5
0
-0.5
-60
-40
-20
0
20
40
60
Magnetic Field [nT]
DFB laser
Magnetic shield
3-axis coil and Rb cell

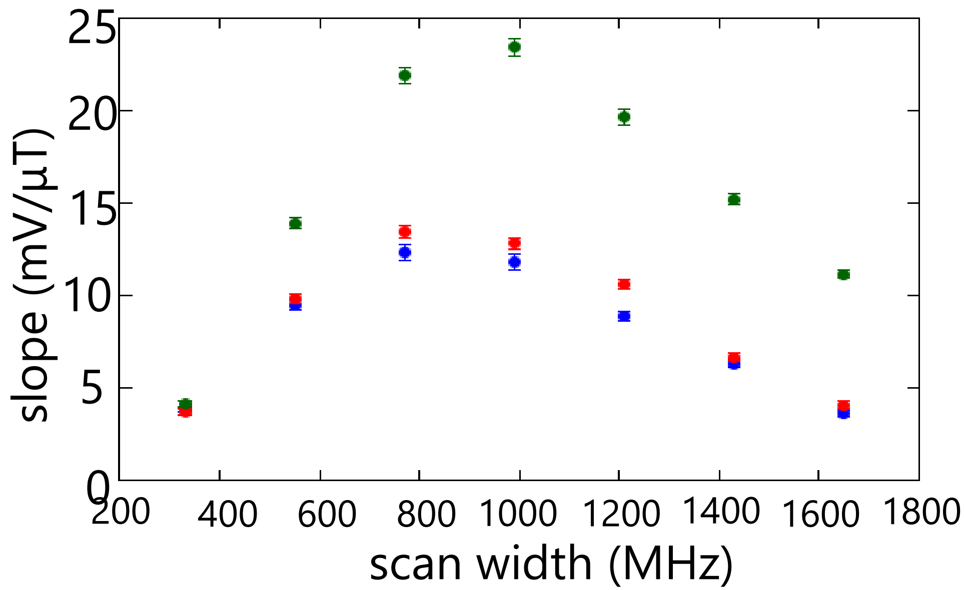
FM parameter dependence

- long coherence time
- large absorption = large alignment

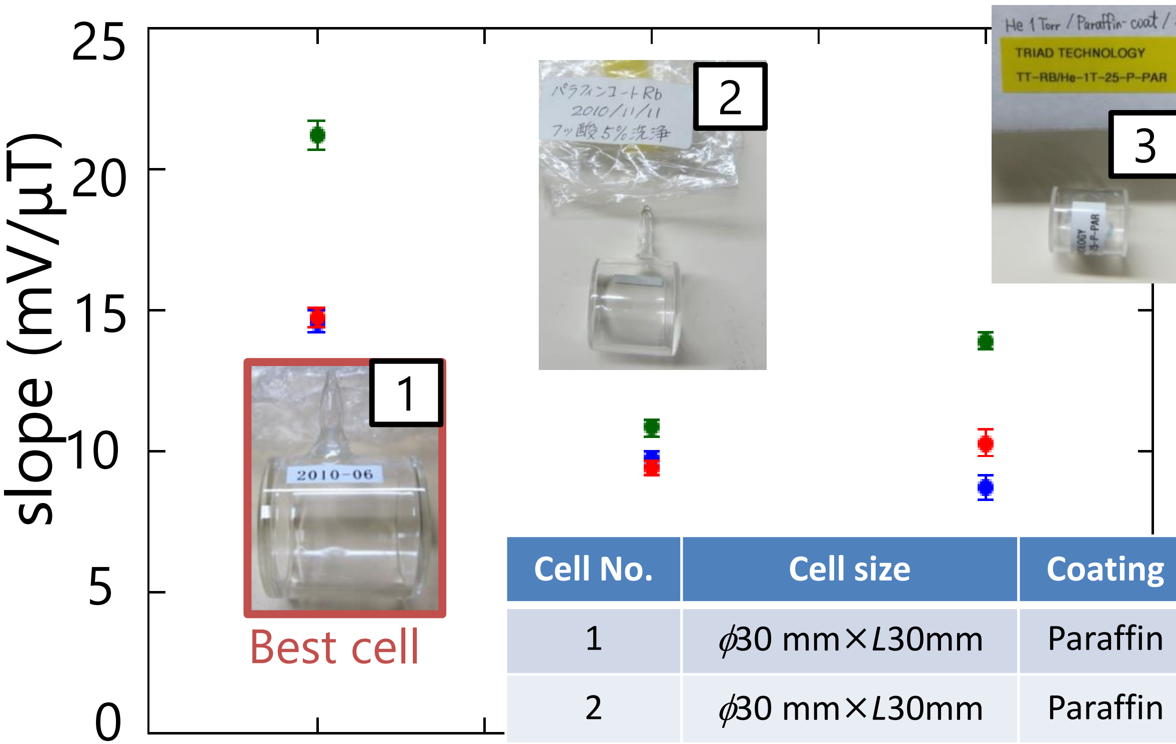
high sensitivity

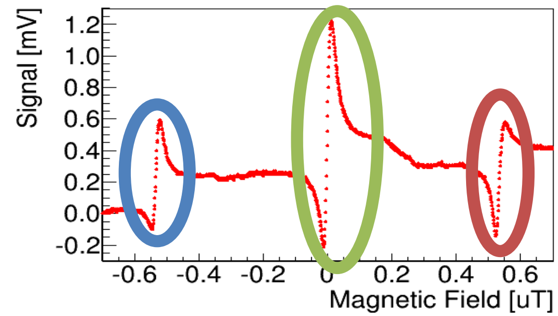






Cell dependence





Cell No.	Cell size	Coating	Cleaning	Buffer gas	NMOR signal
1	ϕ30 mm×L30mm	Paraffin	HNO_3	–	○
2	ϕ30 mm×L30mm	Paraffin	HF	–	○
3	ϕ25mm×L25 mm	Paraffin	?	He 1 torr	○
4	ϕ20mm×L20 mm	Paraffin	HF	–	×
5	ϕ25mm×L25 mm	–	?	N_2 50 torr	×
6	ϕ25mm×L25 mm	–	?	–	×

Summary

The Rb atomic magnetometer based on the FM-NMOR effect was studied for the electron EDM search using the laser cooled Fr atoms.

The dependences on the frequency scan width, the laser power, and the cell production procedure for the field sensitivity were measured.

The best magnetic sensitivity is now 3 nT/√Hz at the present condition.

Collaboration

Cyclotron and Radioisotope Center (CYRIC), Tohoku University

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