Physics of fundamental Symmetries and Interactions – PSI2013
Paul Scherrer Institut, Switzerland, September 9-12, 2013

Experimental Search for atomic EDM in ^{129}Xe using active nuclear spin maser

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Active spin maser

EDM measurement of ^{129}Xe atom

○ Stable isotope
- Number density: $10^{18} \sim 10^{19}$ cm^{-3}

○ Long coherence time
- $T_2 \sim 10^2$ s

○Nuclear spin: 1/2
- Unique Zeeman splitting

Experimental upper limit：

$$|d(^{129}\mathrm{Xe})| < 4.1 \times 10^{-27}\ e\mathrm{cm}$$

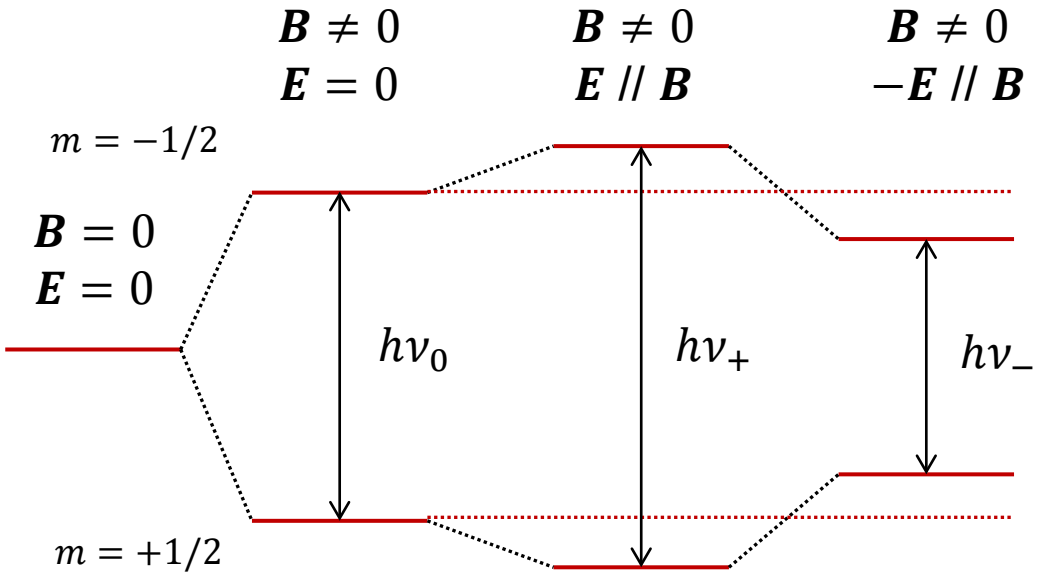
M. A. Rosenberry *et al.*, Phys. Rev. Lett. 86, 22 (2001)

c.f. $|d(^{199}\mathrm{Hg})| < 3.1 \times 10^{-29}\ e\mathrm{cm}$

W. C. Griffith *et al.*, Phys. Rev. Lett. 102, 101601 (2009)

EDM search under 10^{-28}ecm

Principle of EDM measurement

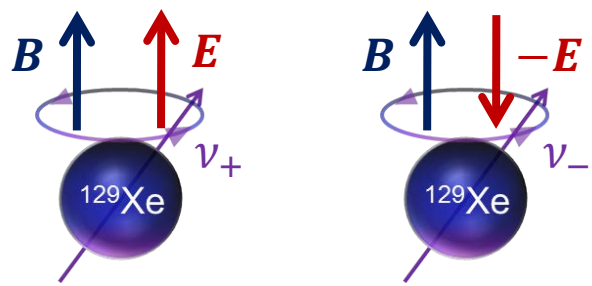


$$H = -\boldsymbol{\mu} \cdot \mathbf{B} - \mathbf{d} \cdot \mathbf{E}$$

Energy level of spin ½ system
($\mu > 0$, $d > 0$)

$$E = -\mu B - dE$$

$$\nu_+ = \frac{2\mu B + 2dE}{h}$$



$$E = -\mu B + dE$$

$$\nu_- = \frac{2\mu B - 2dE}{h}$$

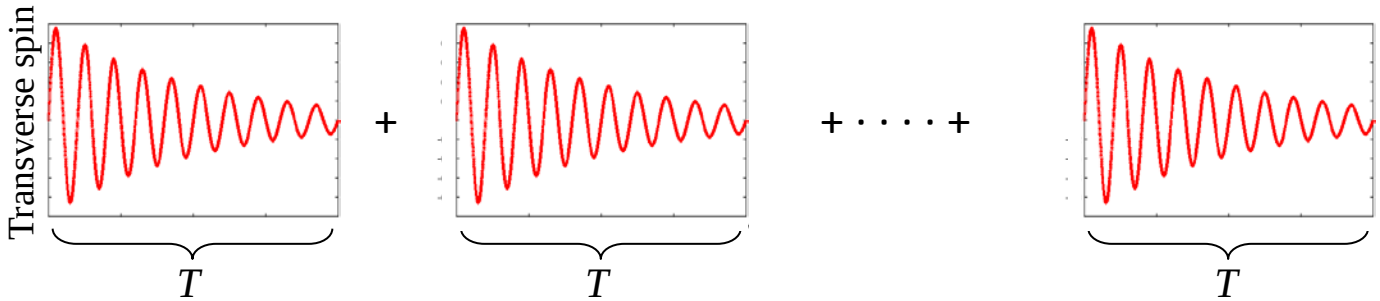
$$\Delta\nu = \nu_+ - \nu_- = \frac{4dE}{h}$$

$d = 10^{-28}$ ecm, $E = 10$ kV/cm

$\Delta\nu = 1$ nHz

How to improve frequency precision?

- Repeat of Free-induction decay (FID) measurements

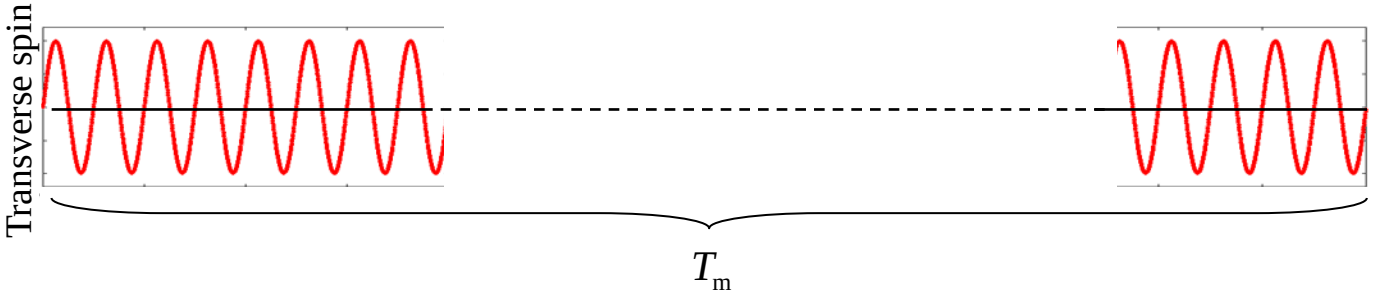


$$\delta\nu_{\text{final}} = \frac{\delta\nu_{\text{ind}}}{\sqrt{n}} \propto \frac{1}{\sqrt{n}}\frac{1}{T\sqrt{T}} = T^{-1}\boxed{T_{\text{m}}^{-1/2}}$$

$T_{\text{m}} = n \times T$

T_{m} : measurement time

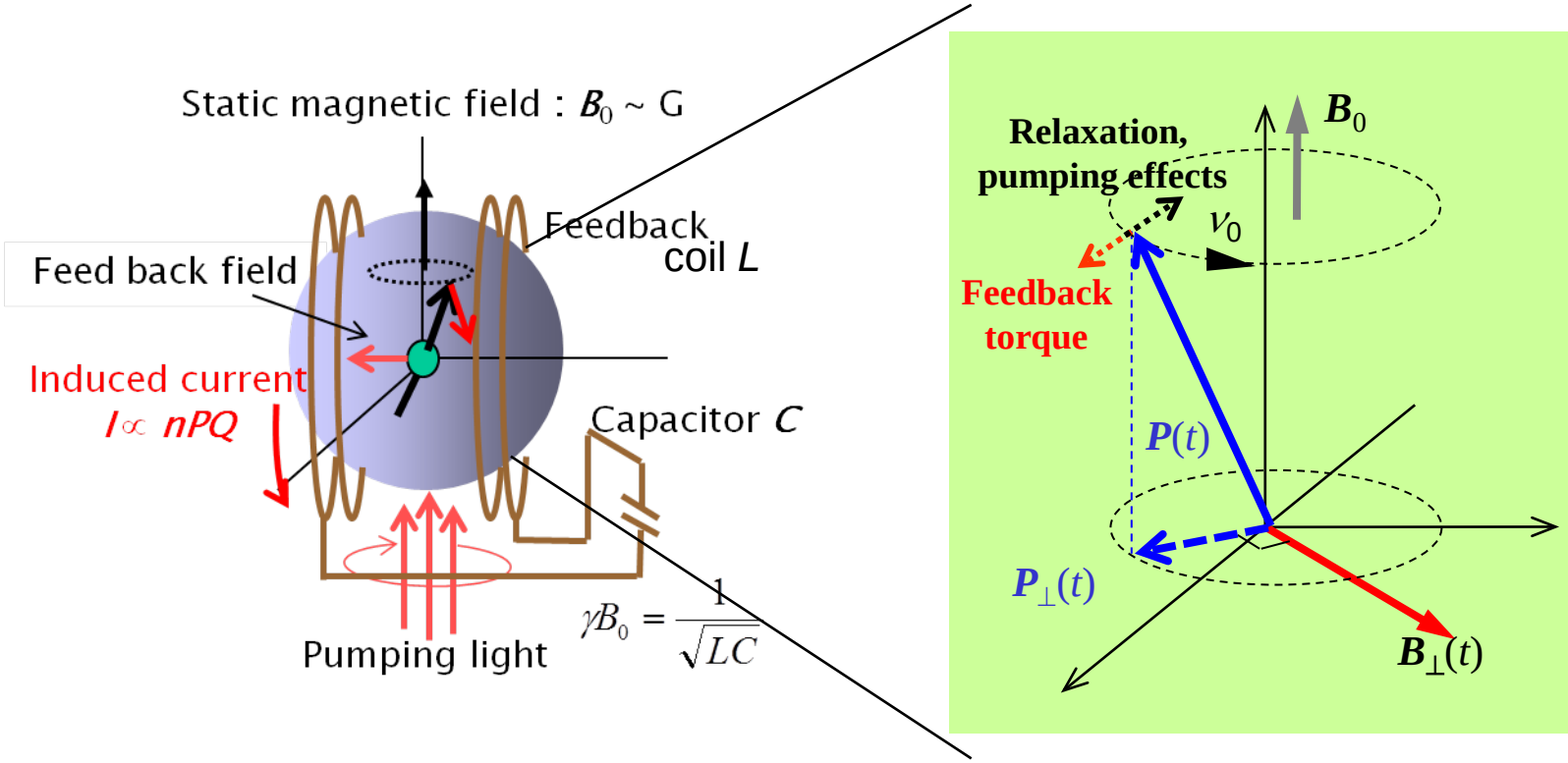
- Consecutive measurement of spin precession



$$\delta\nu_{\text{final}} \propto \frac{\delta\phi}{T_{\text{m}}} = \boxed{T_{\text{m}}^{-3/2}} : \left[\text{Fourier width} : \frac{1}{T_{\text{m}}}\right] \times \frac{1}{\left[\text{data points} : T_{\text{m}}\right]^{1/2}}$$

Long-term measurement

Nuclear-spin maser (spin-coil coupling)



M. G. Richards *et al.*, JPB 21 (1988) 655 : ^{3}He spin maser
T. E. Chupp *et al.*, PRL 72 (1994) 2363 : ^{129}Xe spin maser

Oscillation condition

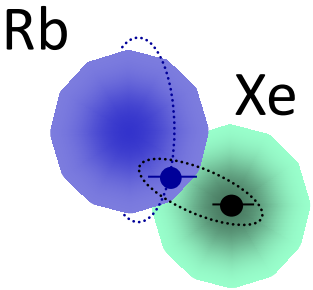
$$\frac{1}{\tau_{RD}} = \frac{1}{2}\gamma^2 \eta \mu_0 \hbar I[n] P_0 Q > \frac{1}{T_2}$$

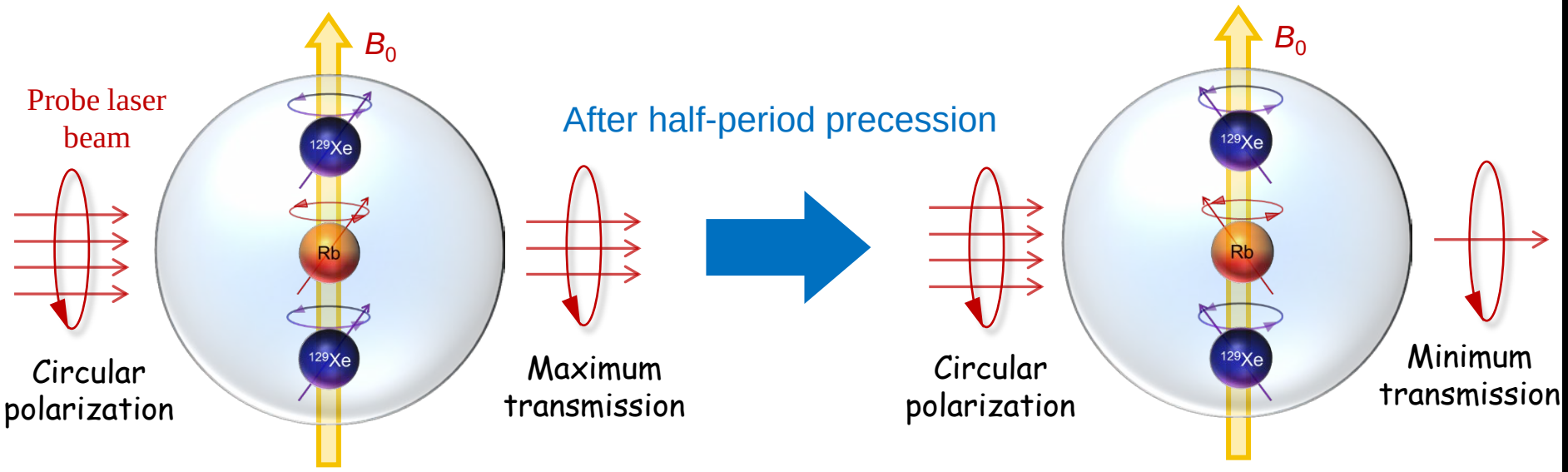
ν ~ kHz (B_0 ~ G)

Strong coupling between nuclear spin and feedback coil

Optical spin detection

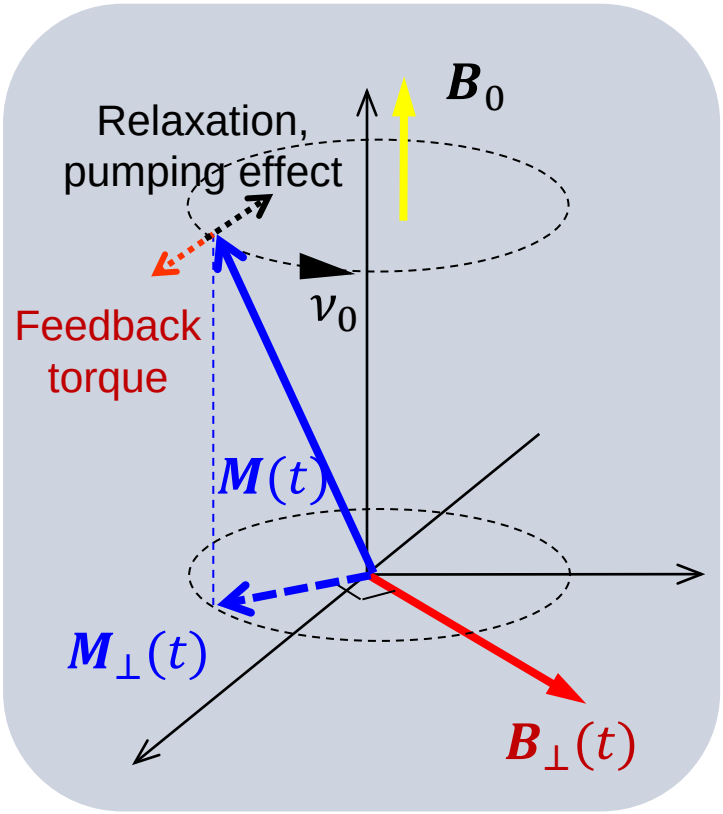
Transverse polarization transfer :
^{129}Xe nuclei → Rb atoms (re-pol)

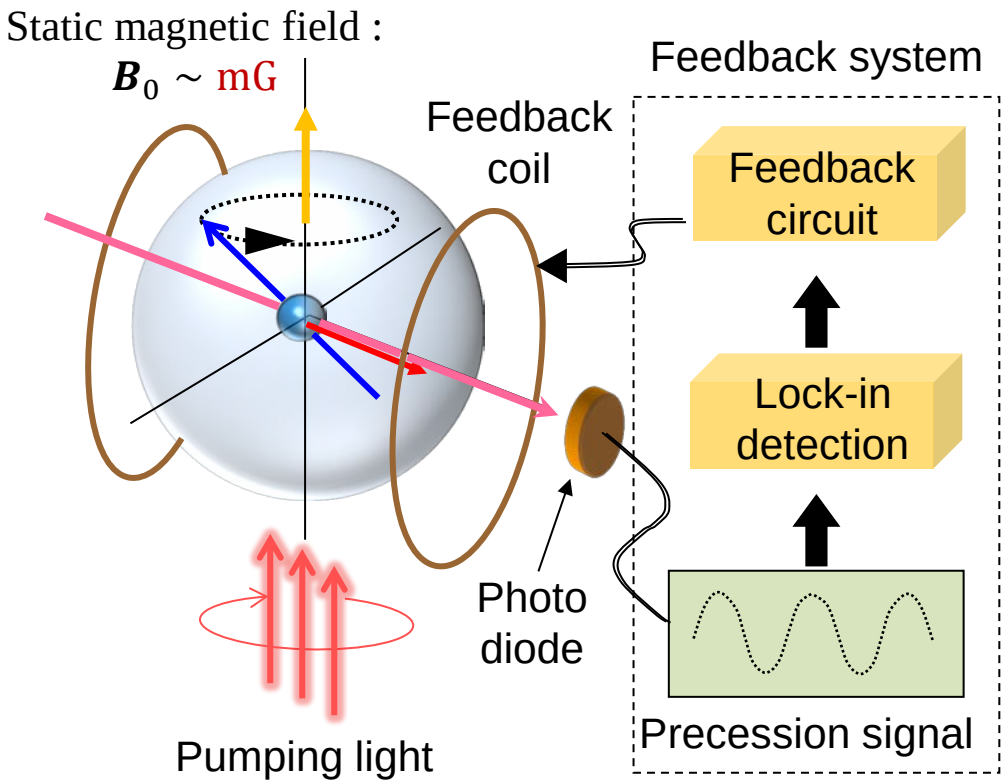




"Active" nuclear-spin maser

"Optically coupled" spin maser
with a feedback field generated by optical spin detection

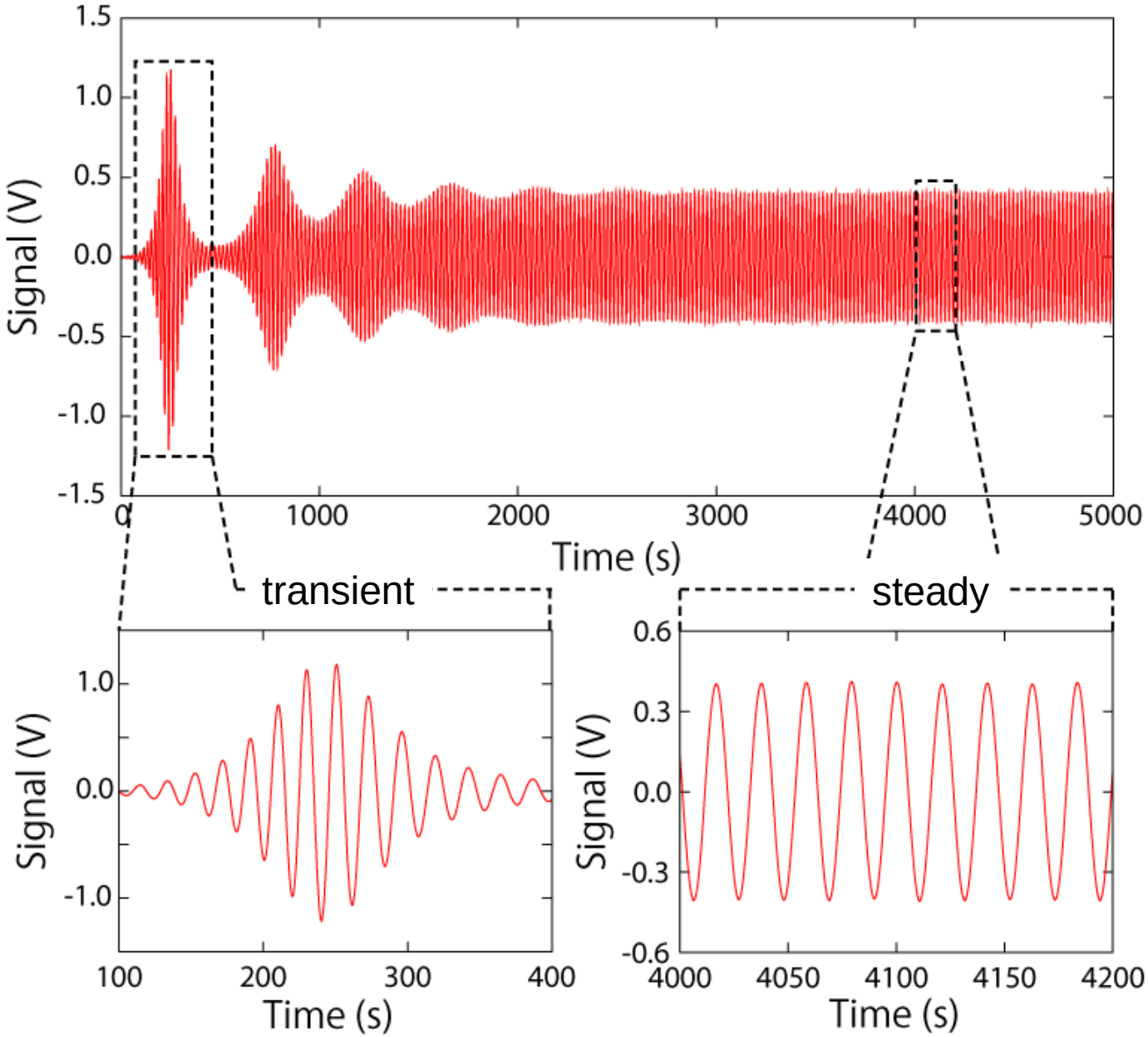




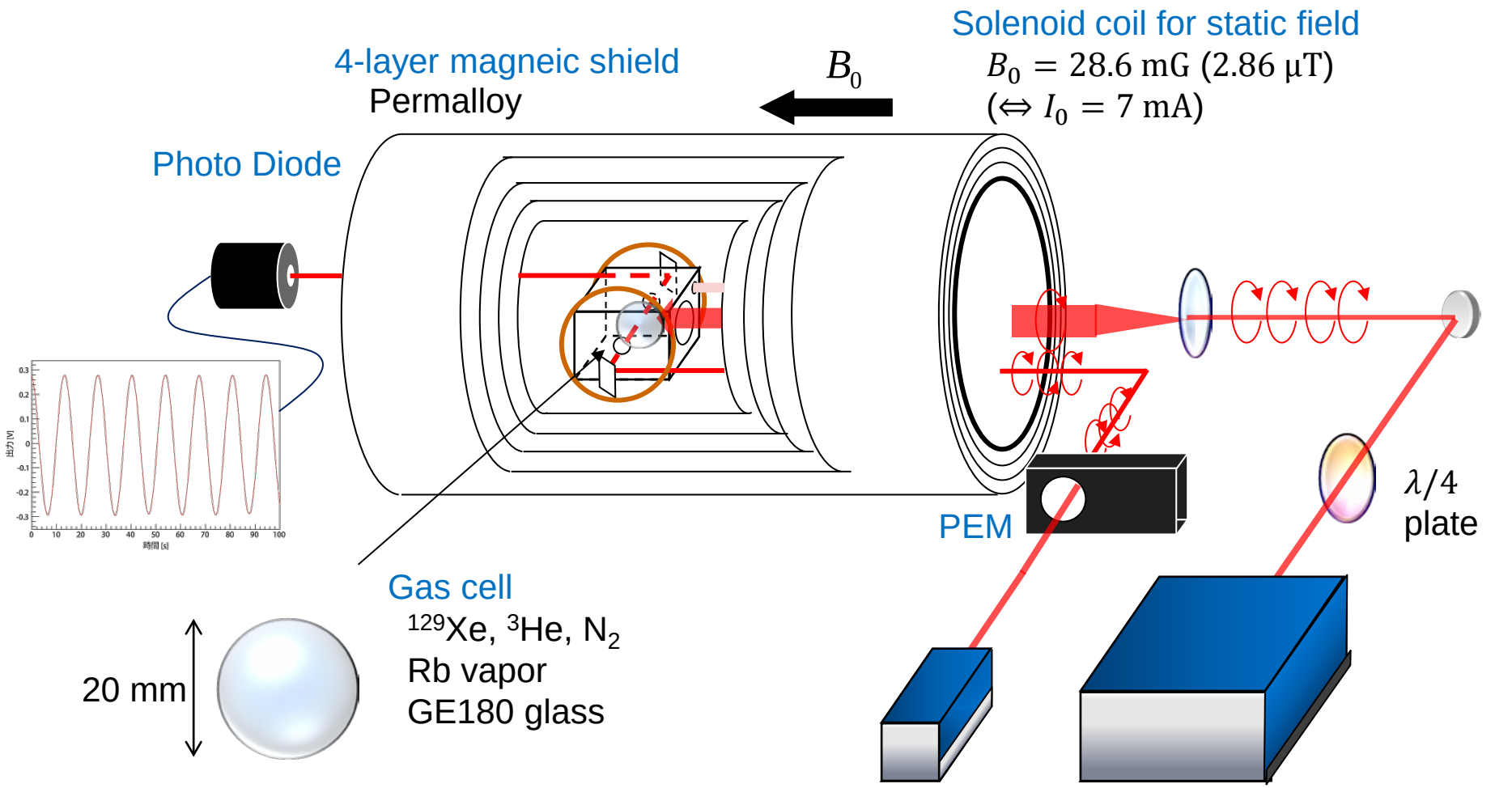
A. Yoshimi *et al.*, Phys. Lett. A 304 (2002) 13.
A. Yoshimi *et al.*, Phys. Lett. A 376 (2012) 1924.

Maser oscillation at low fields (~ mG)
Suppression of drifts in B_0 → Suppression of drifts in ν

Maser oscillation of ^{129}Xe



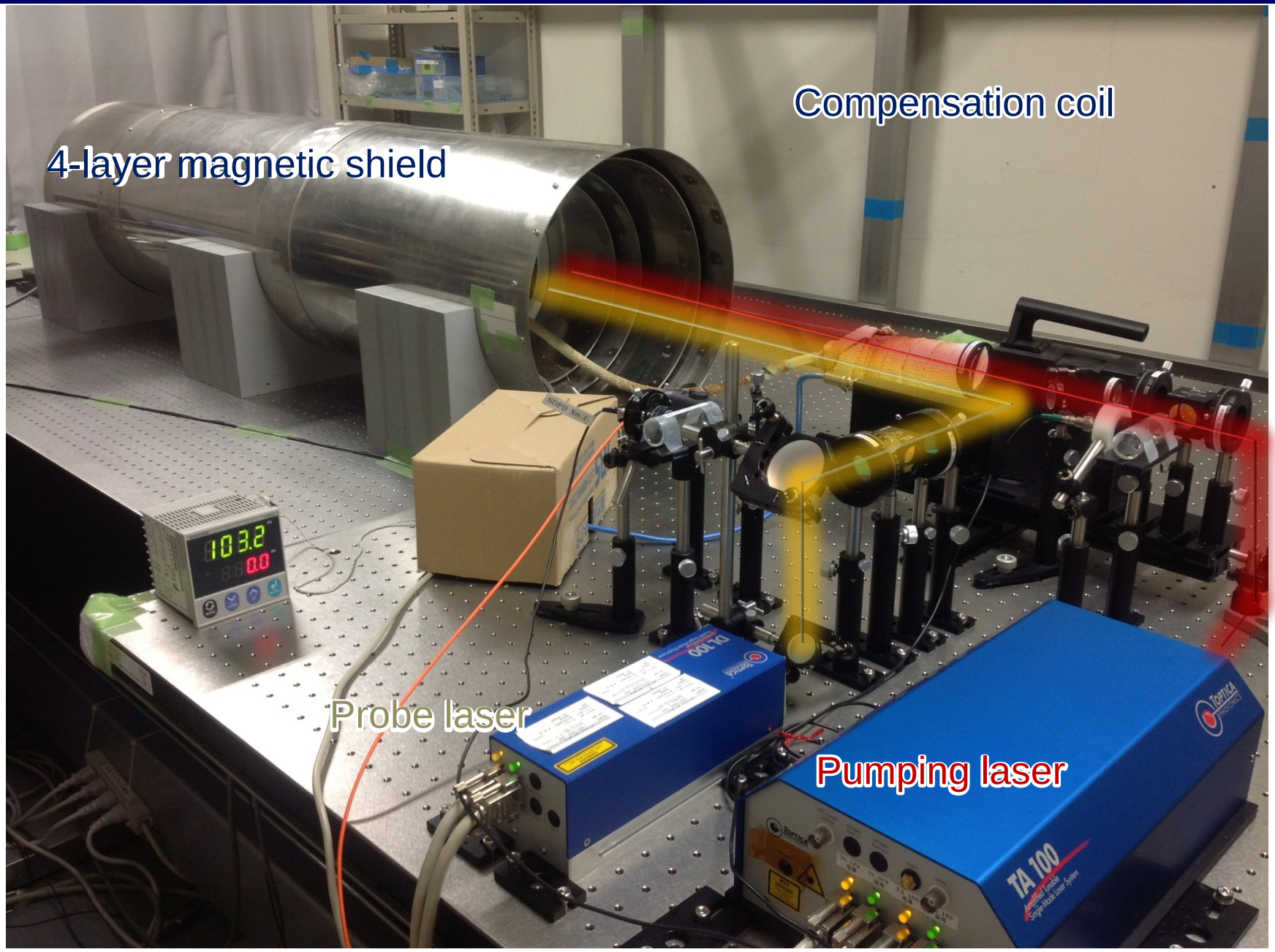
Setup for maser



Probe laser
Wave length：794.76 nm
Width：～10 MHz
Power：10 mW

Pumping laser
Wave length：794.76 nm
（Rb D1 line）
Width：～10 MHz
Power：1 W

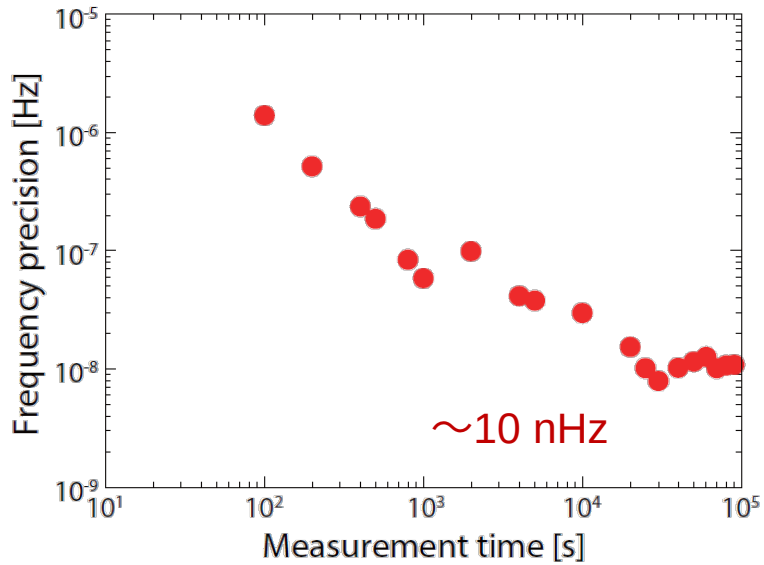
Setup for maser



Long-term frequency drift

Determination precision of averaged frequency

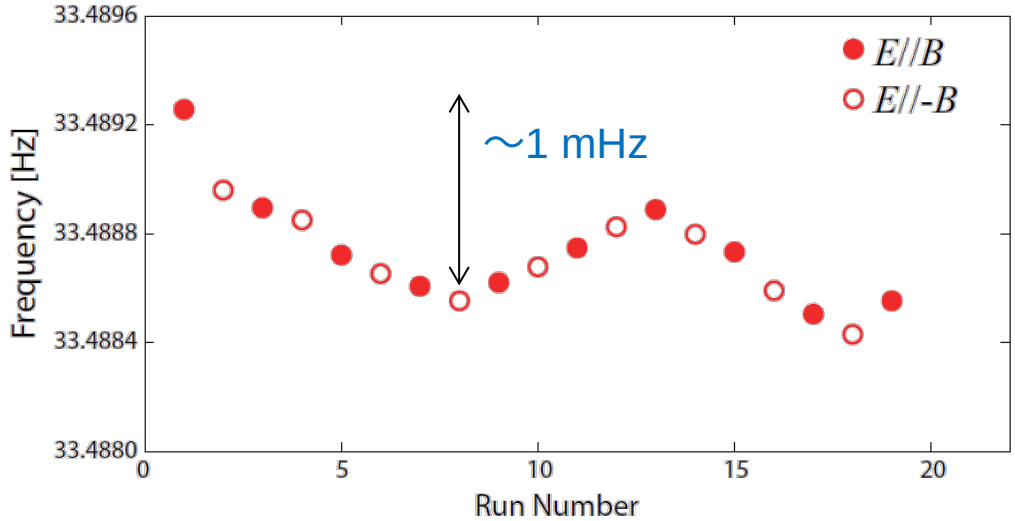
$\Delta\nu \sim 10$ nHz



Long-term frequency drift

Long-term drift in mag. field at cell position

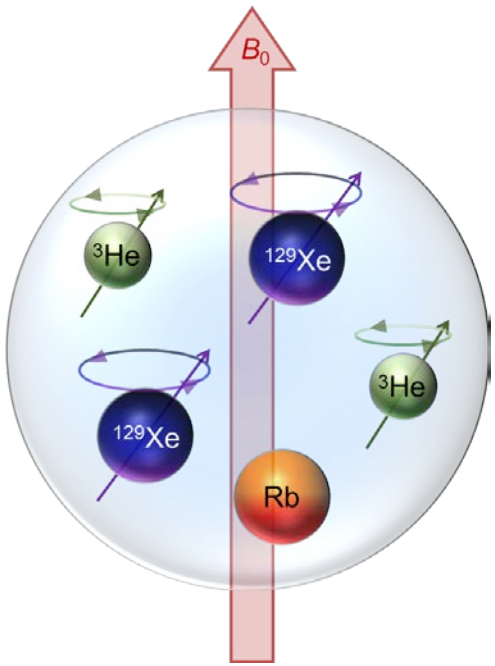
$\delta\nu \sim 1$ mHz



T. Inoue *et al.*, Physica E 43 (2011) 847-850

^{3}He co-magnetometer

Principle of ^{3}He co-magnetometer



- ^{129}Xe frequency: B_0 + EDM

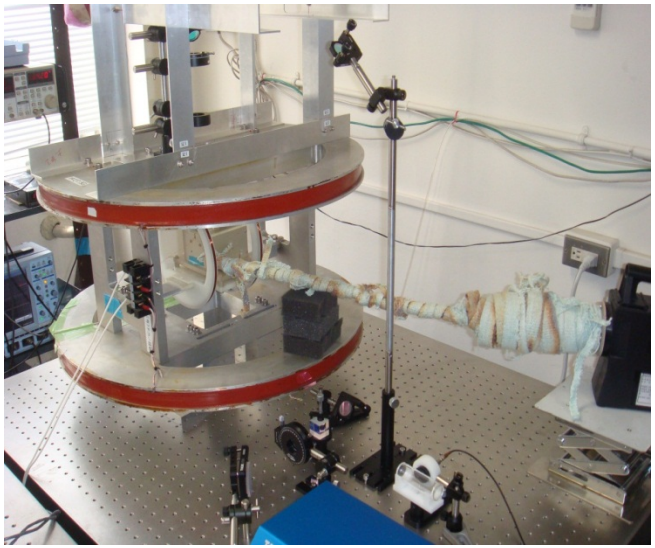
- ^{3}He frequency: B_0

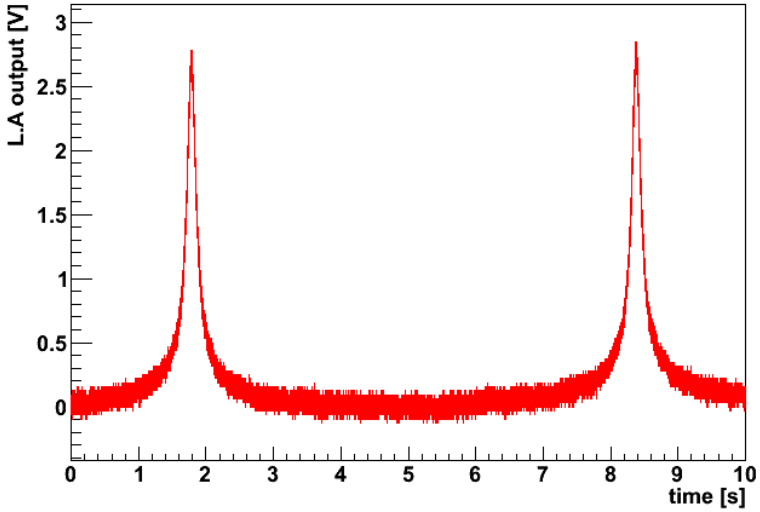
- Negligible EDM in ^{3}He
- *in situ* magnetometry
- Correlation in phase：$\Phi_{\mathrm{Xe}}(t) = \frac{\gamma_{\mathrm{Xe}}}{\gamma_{\mathrm{He}}}\Phi_{\mathrm{He}}(t)$

Spin polarization of ^{3}He

GE180 spherical cell :
Low magnetic impurity
Low leakage of ^{3}He

Checked by AFP-NMR measurement





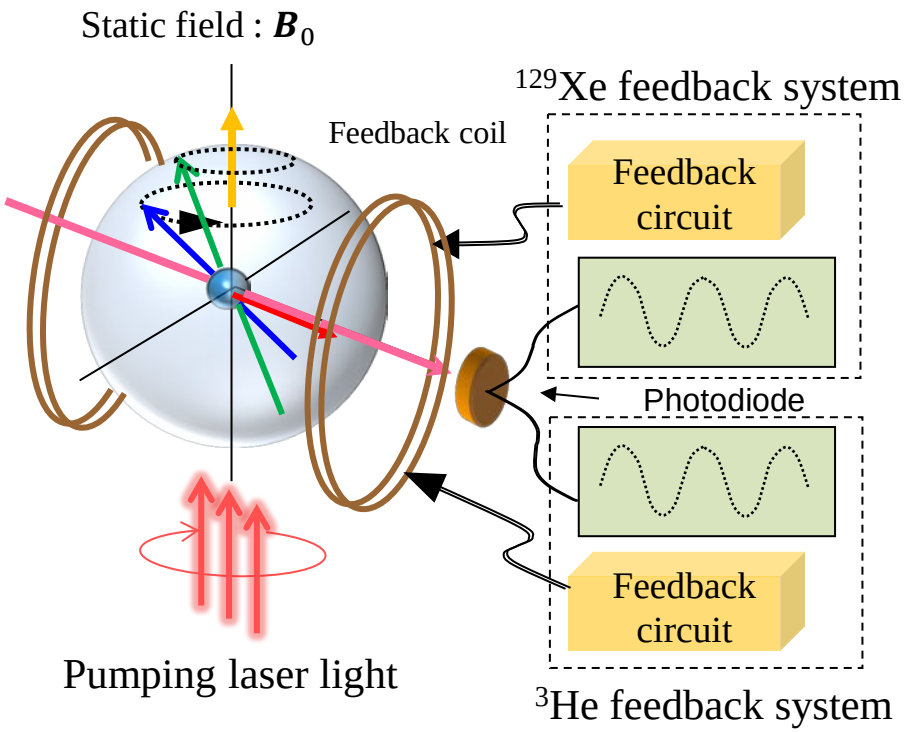
Typically

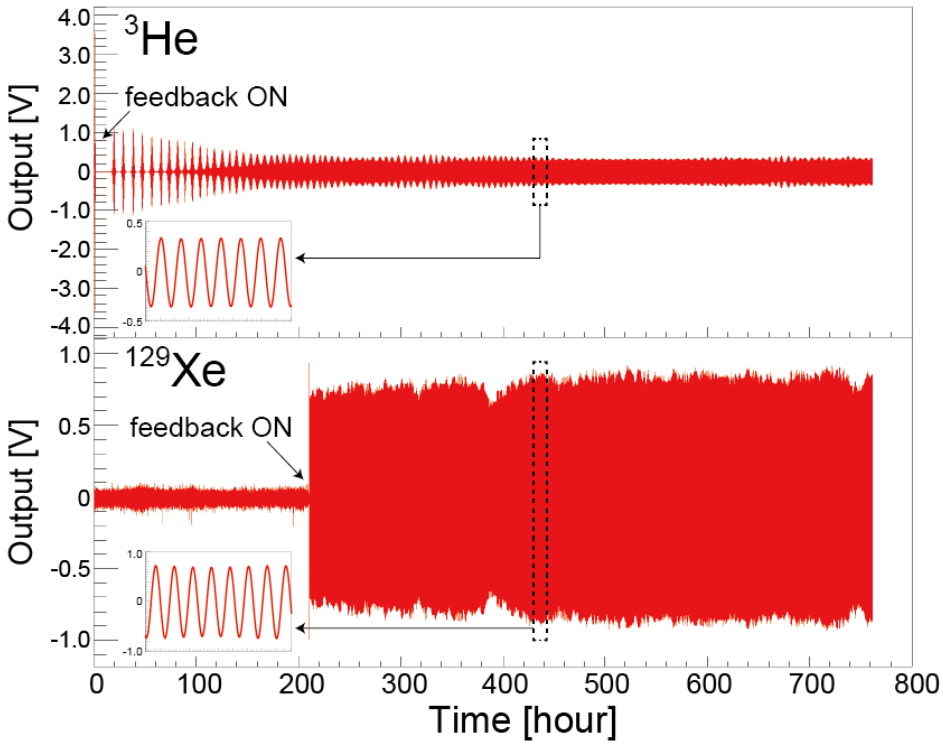
$P(^3\text{He}) = 3\ \%$

$T_1(^3\text{He}) = 50$ hours

at 100 ℃

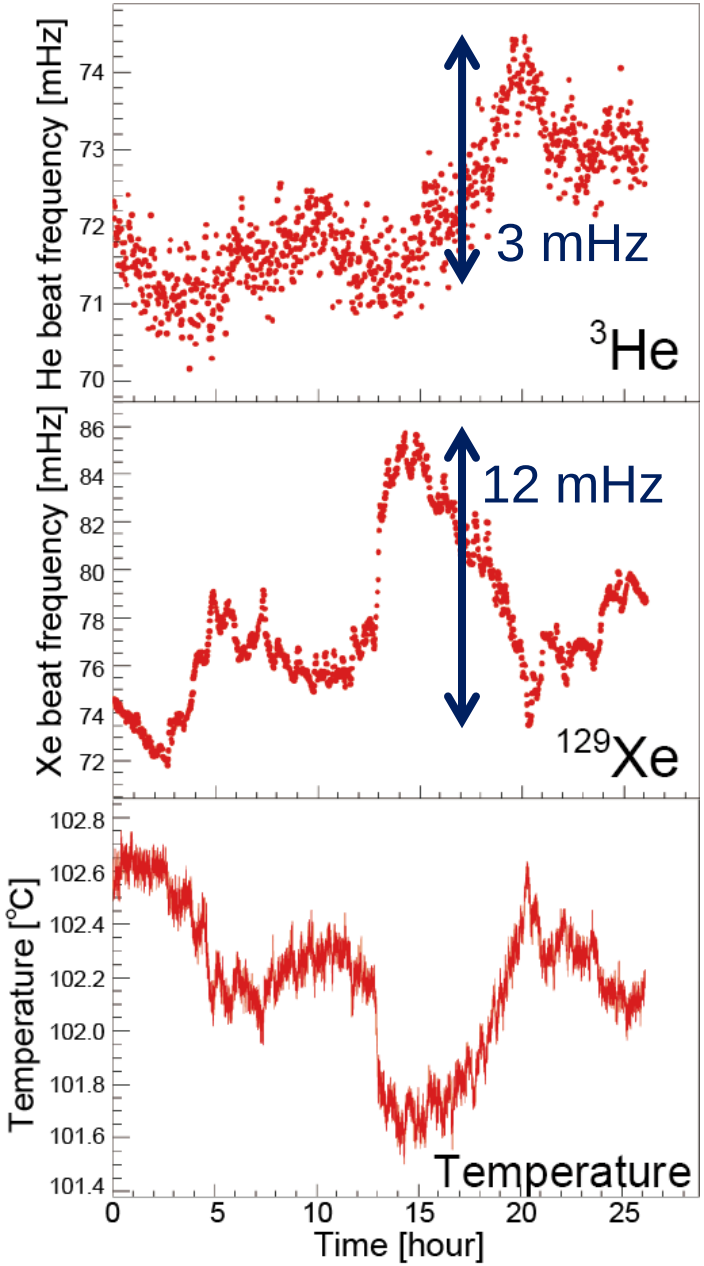
Concurrent operation of $^{129}Xe/^{3}He$ masers





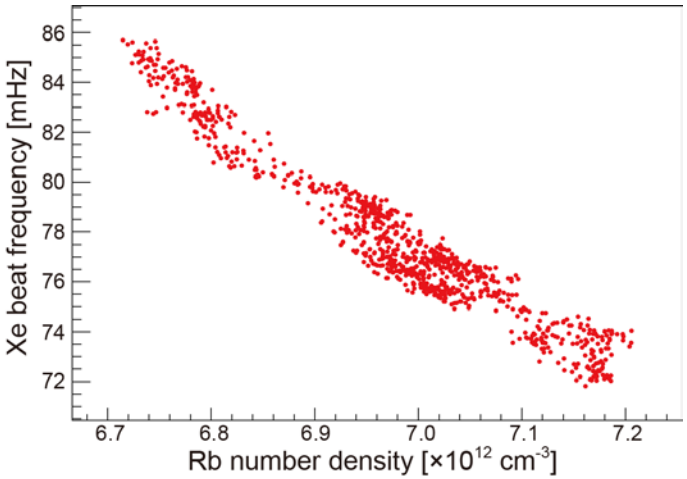
- Spherical GE180 cell (^{129}Xe: 1 Torr, ^{3}He: 470 Torr, N_2: 100 Torr)
- Simultaneous spin detection & individual feedback of $^{129}Xe/^{3}He$
- Succeeded in concurrent maser oscillation
- Determination precision of averaged frequencies for $^{129}Xe/^{3}He$ are both ~100 nHz in 10^6 sec

Correlation of frequency



- No correlation between $\nu(^{129}\mathrm{Xe})$ and $\nu(^{3}\mathrm{He})$
- Larger drift in $\nu(^{129}\mathrm{Xe})$ than $\nu(^{3}\mathrm{He})$

  Cf.) $\dfrac{\gamma_{\mathrm{He}}}{\gamma_{\mathrm{Xe}}} \sim 3$
- Correlated with cell temperature



Frequency shift due to polarized Rb

Frequency shift of $^{129}Xe/^{3}He$
due to contact interaction with polarized Rb

$$\Delta\nu \propto \kappa\,[\mathrm{Rb}]\,P_{\mathrm{Rb}}$$

Rb number density

Rb Polarization

Two-body factor κ_0

$$\begin{cases} \kappa_{0\,\mathrm{Xe-Rb}} = 493(31) & [1] \\ \kappa_{0\,\mathrm{He-Rb}} = 4.52 + 0.00934T & [2] \end{cases}$$

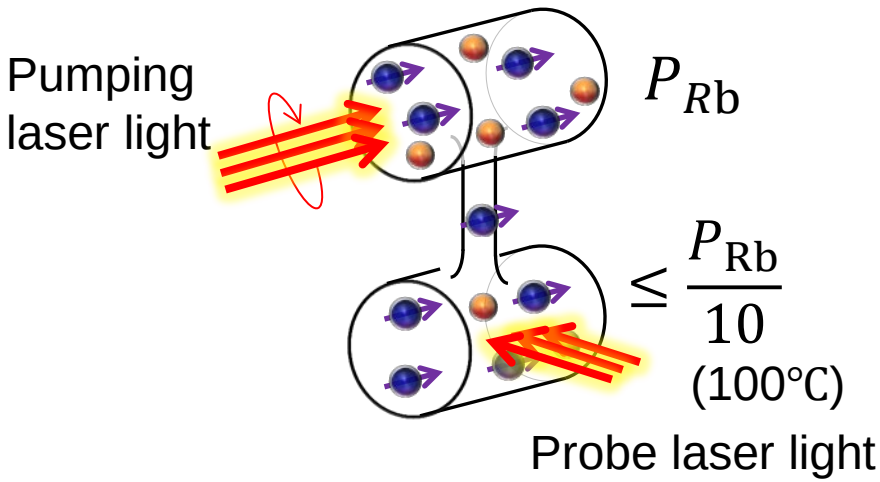
[1] Z. L. Ma *et al.*, Phys. Rev. Lett. 106, 193005 (2011)

[2] M. V. Romalis *et al.*, Phys. Rev. A 58, 3004 (1998)

Frequency shift due to polarized Rb atoms can not be removed by ^{3}He co-magnetometer

Double-cell geometry

Cell is divided into Pumping section & Probe section



Rb number density

$$\Delta\nu_{Rb} \propto \kappa\,[Rb]\,P_{Rb}$$

Rb polarization

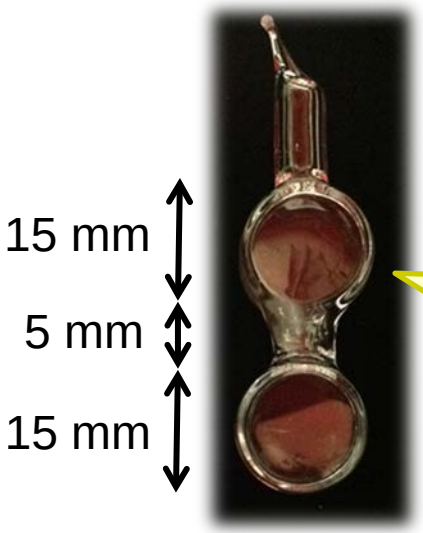
Advantages

- Reduce P_{Rb} at probe section
- Different temperature at pumping part & probe part

Difficulties

- $T_1(^{129}Xe)$ vs diffusion
- Deterioration of maser signal due to reduced P_{Rb}

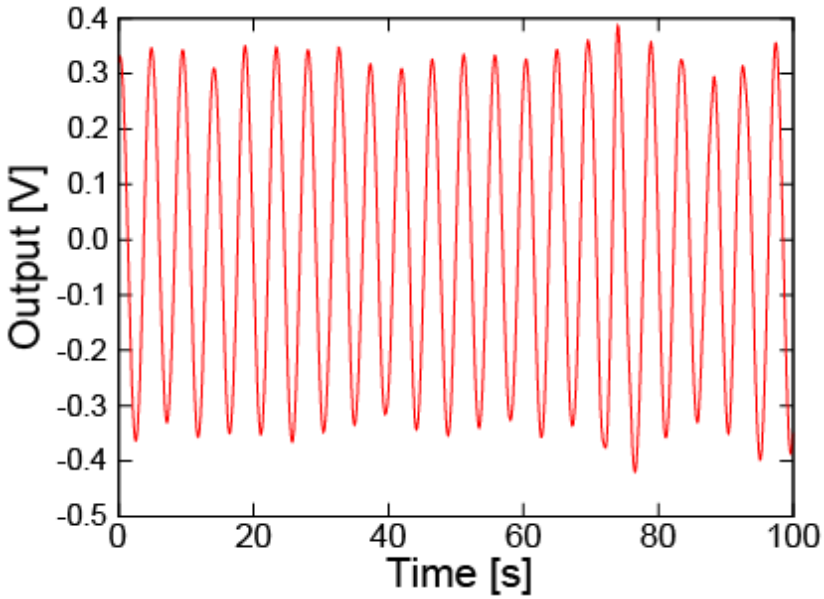
Maser oscillation with double cell



GE180
SurfaSil coated

Xe: 10 Torr/1.33 kPa
He: 470 Torr/62.65 kPa
N_2:100 Torr/13.33 kPa
Rb

^{129}Xe maser oscillation



- ^{129}Xe maser + ^{3}He FID measurements
- Frequency shift is reduced < 1/10 (90 mHz -> 8 mHz)
- Remaining shift due to Rb longitudinal repolarization

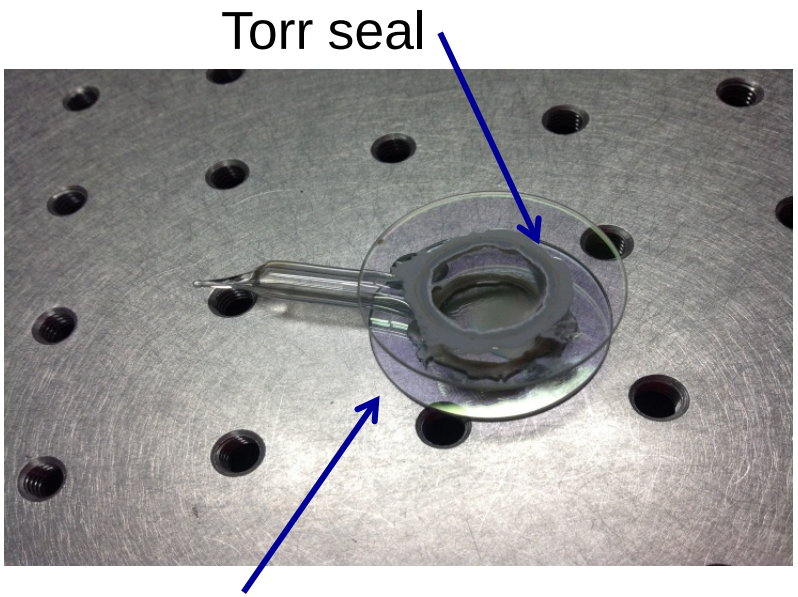
EDM measurement

Electric-field application test

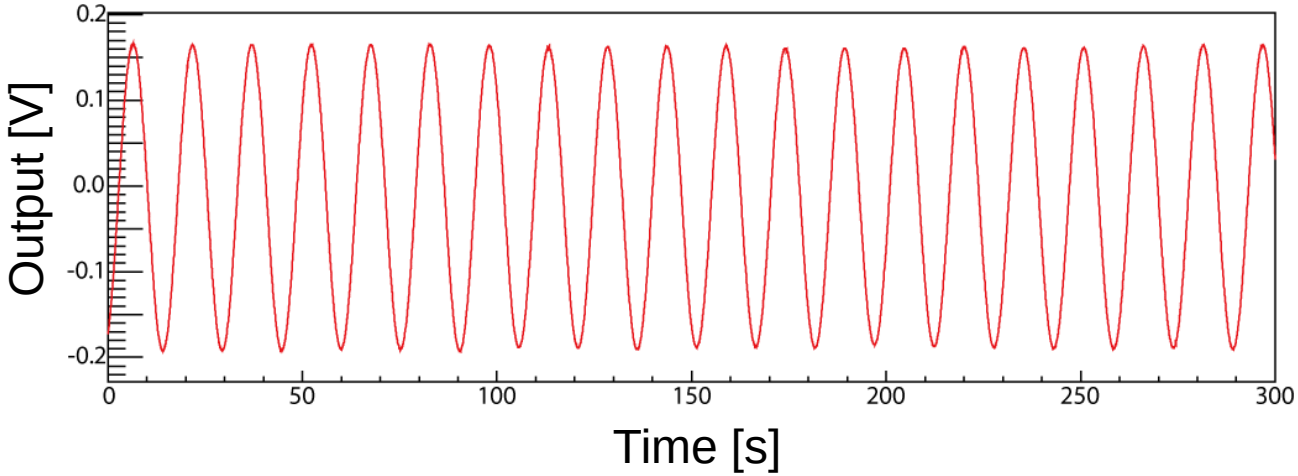
- Gas pressure

^{129}Xe	:	1 Torr
^{3}He	:	470 Torr
N_2	:	100 Torr

- GE180
- SurfaSil coated

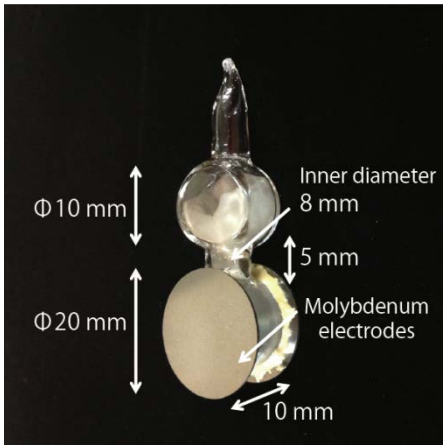


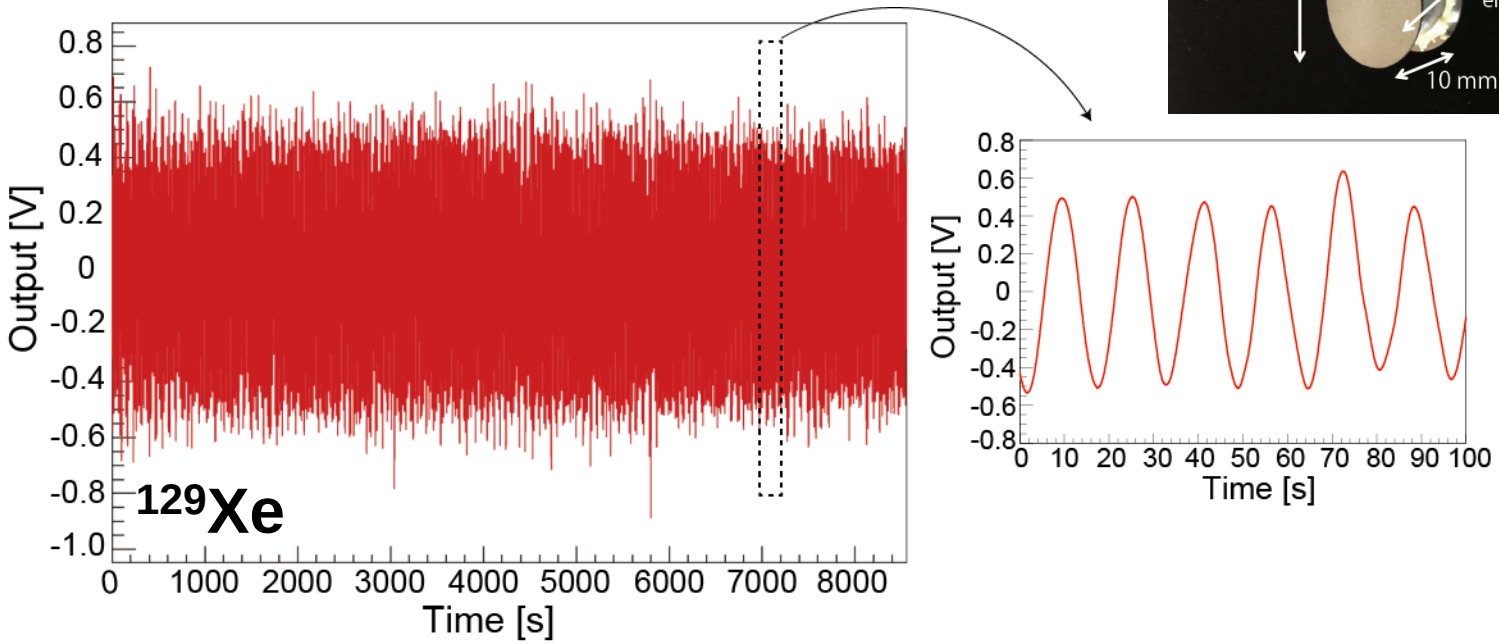
^{129}Xe maser signal @ E = 5 kV/cm (Leak current : 70 pA)



First run of EDM measurement

- Double cell with Mo electrodes
- E = 1.5 kV/cm (Leak current : 620 pA)
- ^{129}Xe maser + ^{3}He FID





First run of EDM measurement using
^{129}Xe active spin maser + ^{3}He co-magnetometer
has been conducted

Future Perspective

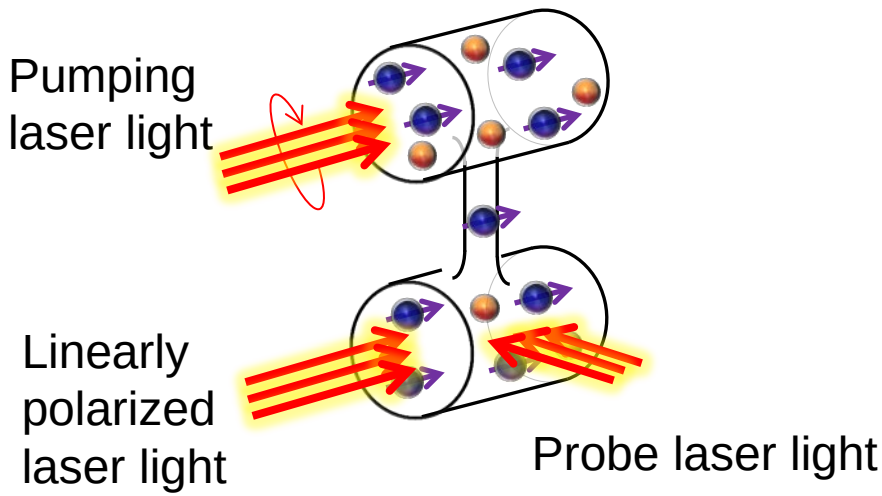
To be improved

- Improvement in ^{3}He polarization
- Improvement in T_2 for ^{3}He
- Reduction of Rb longitudinal polarization

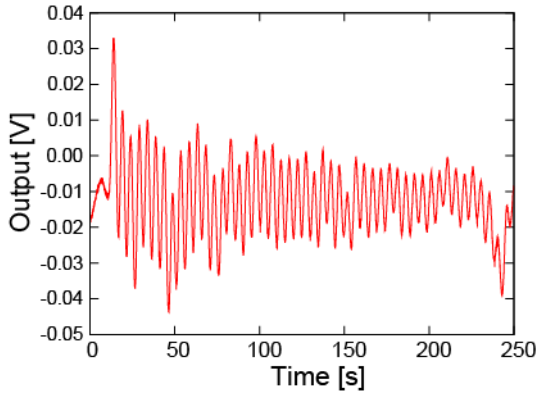
Reduction of Rb longitudinal polarization

Linearly polarized laser light is introduced into probe section

- Destroy Rb longitudinal polarization
- Monitor [Rb] through transmission



- Rb transverse polarization survives



Summary

➢ Active spin maser

- Optical spin detection + artificial feedback
- Determination precision of averaged frequency: ～10 nHz

➢ Incorporation of ^{3}He co-magnetometer

- Concurrent ^{129}Xe/^{3}He maser oscillation
- Frequency shift due to polarized Rb
- Double-cell geometry

➢ EDM measurement

- First trial using active ^{129}Xe maser + ^{3}He co-magnetometer

➢ Future perspective

- Improvement in ^{3}He polarization
- Improvement in T_2
- Reduction of Rb longitudinal polarization