Nuclear spin maser for ^{129}Xe atomic EDM measurement - present status -

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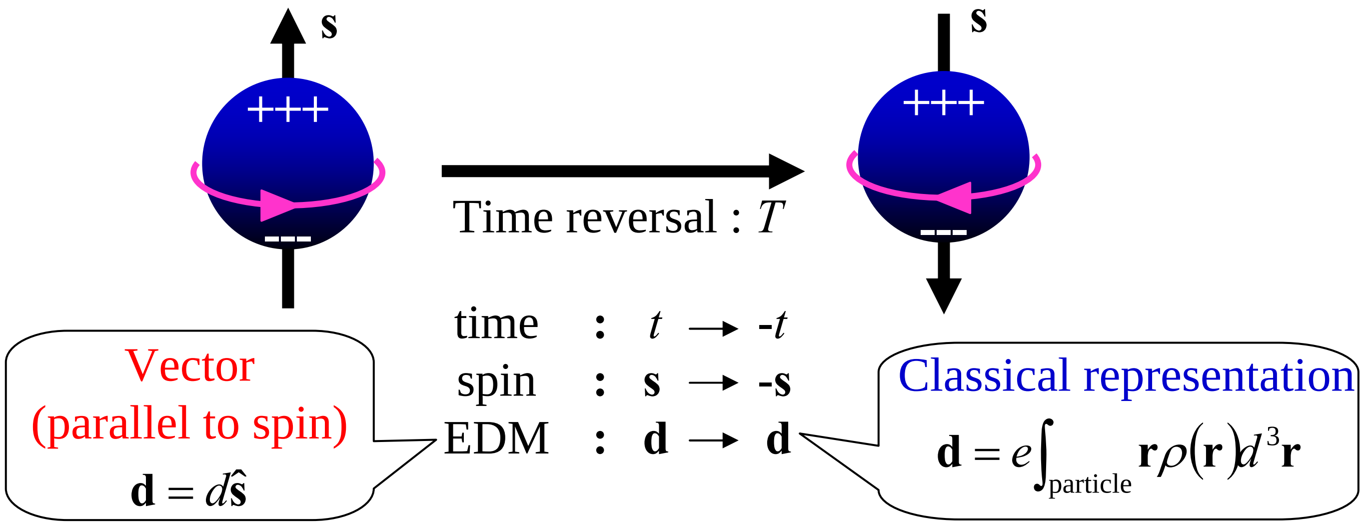
ADVANCED STUDIES INSTITUTE
"SYMMETRIES AND SPIN"
(SPIN-PRAHA-2008)

Electric Dipole Moment (EDM) and time reversal

Non-zero EDM associated with spin is
direct evidence of time reversal symmetry violation



$d \neq 0$: T-violation ➡ CP-violation (by CPT theorem)

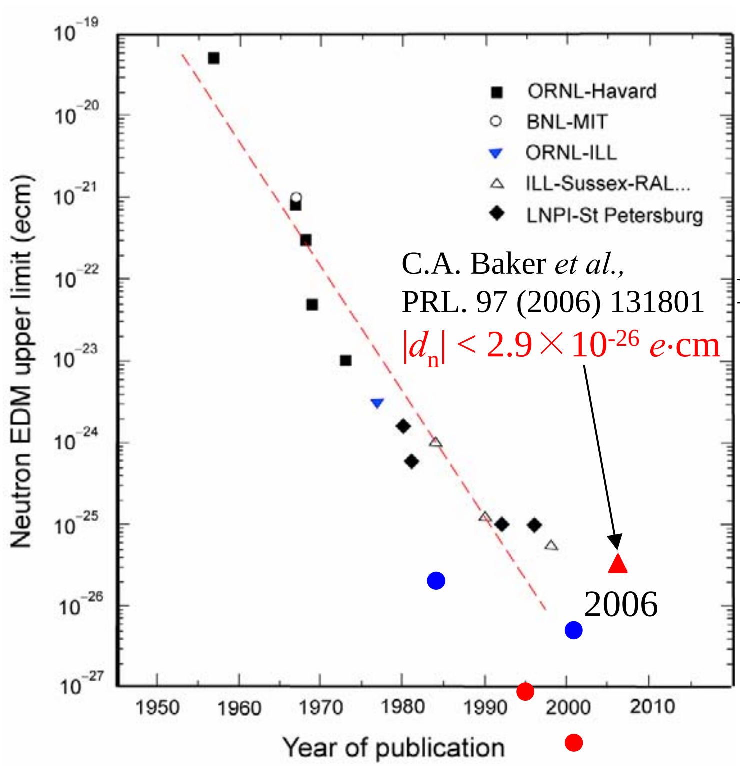
EDM : sensitive to the CP violation beyond SM

Standard Model (SM) : Predicted neutron EDM is by five orders magnitude smaller than the present experimental upper limits.

Beyond SM : Predicted neutron EDMs are detectable in the current experimental condition.

Search for EDM ⟶ Test of the SM and beyond SM

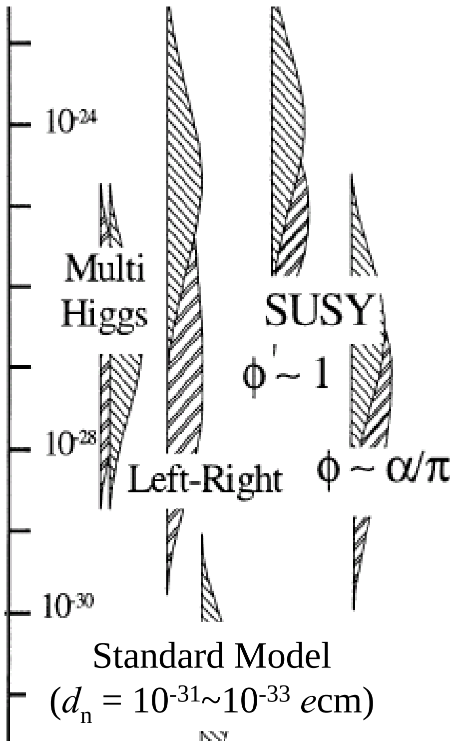
EDM of what?



● $d(^{129}\mathrm{Xe}) < 4.1\times10^{-27}$ ecm (2001)
Rosenberry and Chupp, PRL. 86 (2001) 22

● $d(^{199}\mathrm{Hg}) < 2.1\times10^{-28}$ ecm (2001)
M.V. Romalis *et al.*, PRL. 86 (2001) 2505

Neutron EDM predicted values



Neutron
- Direct measurement of nucleon EDM
- Unstable particle : $\tau_{1/2}$ = 614.8 s
- Low density : $\rho \sim$ 1-100 UCN/cm^{-3}

Diamagnetic Atom
(^{129}Xe, ^{199}Hg, Ra, Rn…)
- Stable particle
- High density : $\rho \sim 10^{10}$-10^{20} cm^{-3}
- Schiff shielding

In an external electrostatic potential, the atomic system consisting of ・non-relativistic, ・point-like, ・charged particles doesn't show an energy shift due to EDM.

→not complete

- EDM induced by the Schiff moment :***S*** of the nucleus

$$d\left(^{129}\mathrm{Xe}\right) = 0.38\times10^{-17}\left(\frac{S}{e\,\mathrm{fm}^3}\right)e\,\mathrm{cm}$$

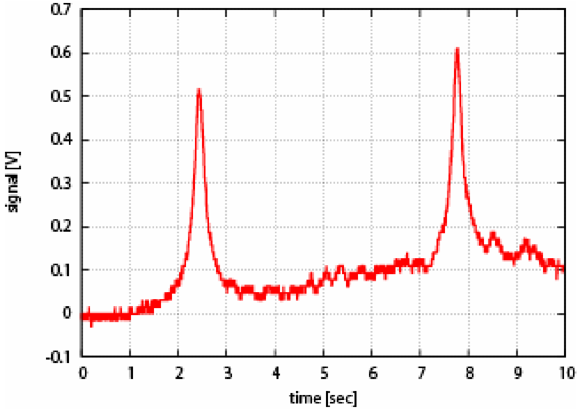
V. A. Dzuba et al., PRA **66**, 012111 (2002)

Why ^{129}Xe atom?

(1)Stable particle

•high density : ~10^{18} – 10^{19} atom/cm^3
 @ room temperature

AFP-NMR signal



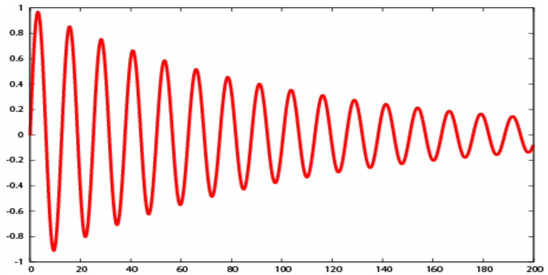
(2)High polarization and long relaxation time

•polarization : $P(^{129}Xe)$ ~ 40% (AFP-NMR)
 @ 180 torr (n ~ 5 × 10^{18} atom/cm^3)

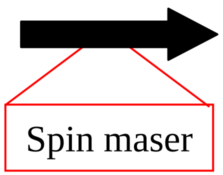
•T_1 ~ 20 min.

(3)A spin maser technique is applicable.

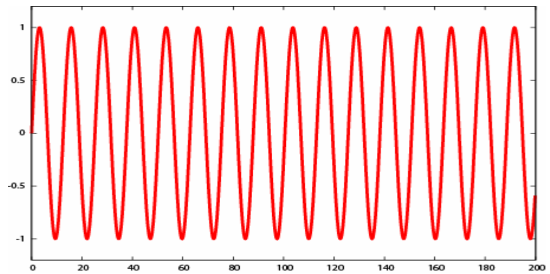
Free precession



$\delta\nu \propto T_m^{-1/2}$



Sustained oscillation (maser oscillation)



$\delta\nu \propto T_m^{-3/2}$

We aim at an experimental search for $d(^{129}Xe)$,
by using "Active" Spin Maser.

Goal; $d(^{129}Xe) = 10^{-28} \sim 10^{-29}$ $e$cm

Principles of experiment

Energy shift according to E direction

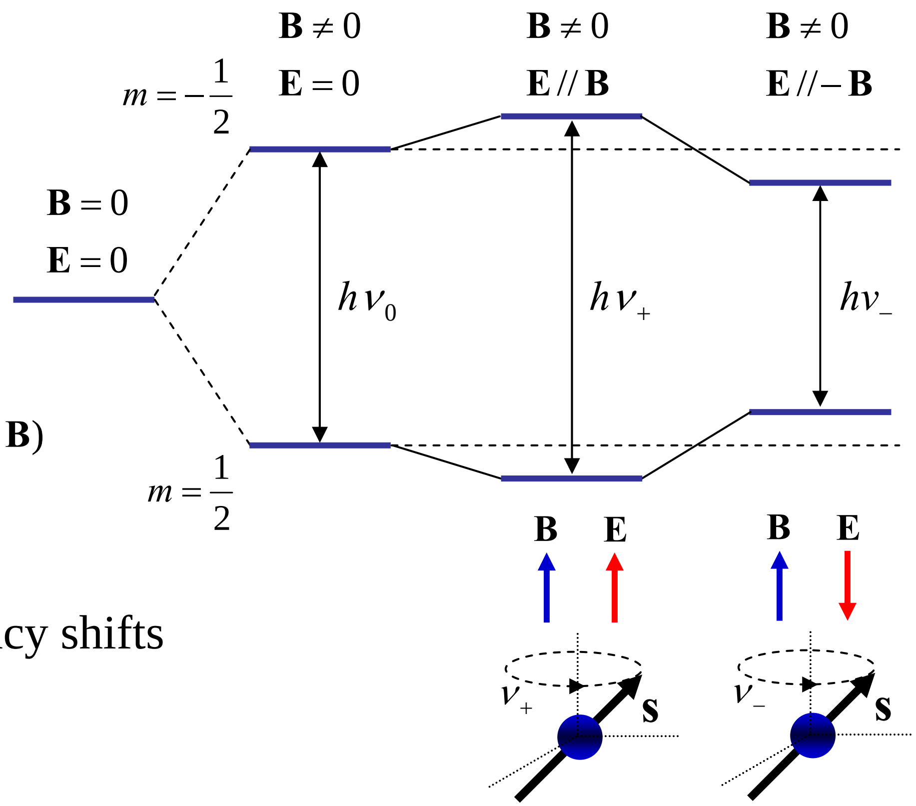
E parallel to B
$H = -\mu B - dE$

E anti-parallel to B
$H = -\mu B + dE$

Small shift of spin precession frequency

$$\nu_+ = \frac{2\mu B + 2dE}{h} \ (\mathbf{E} // \mathbf{B}) \qquad \nu_- = \frac{2\mu B - 2dE}{h} \ (\mathbf{E} // -\mathbf{B})$$

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



EDM measurement
⇨ measurement of difference between frequency shifts

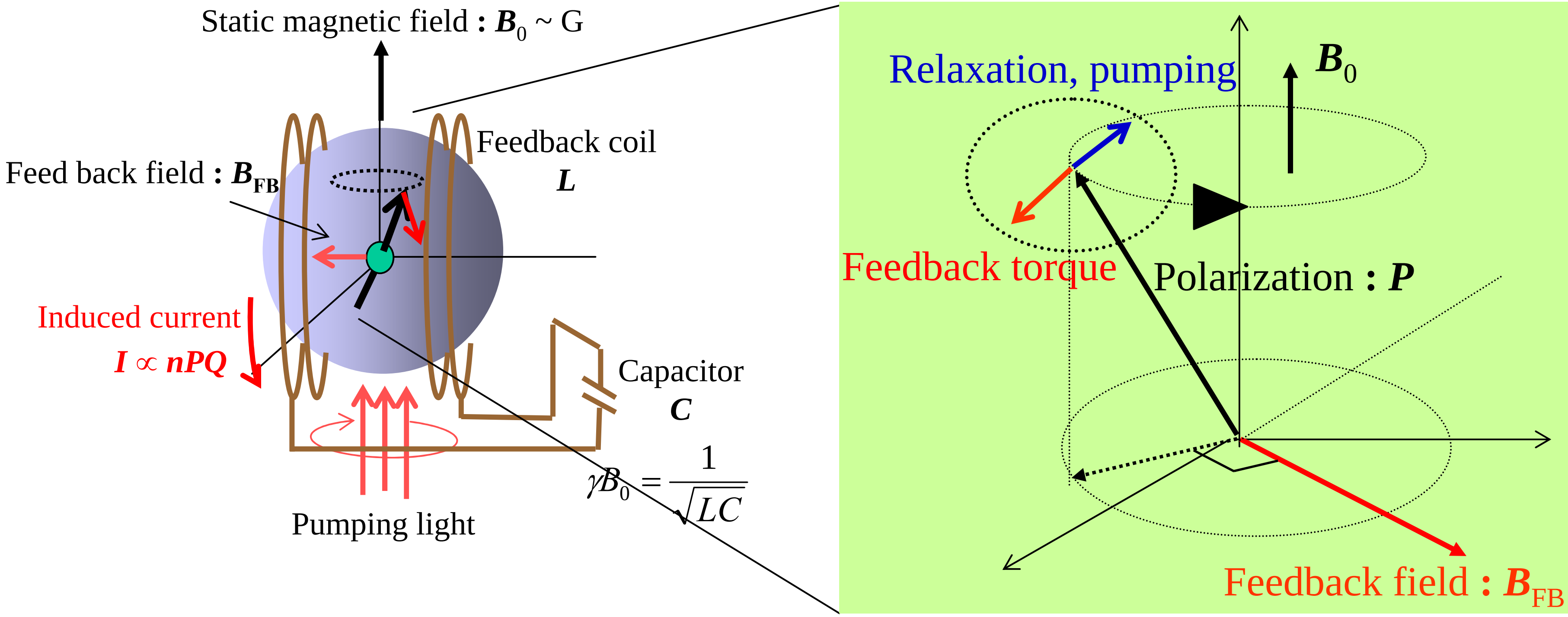
$$\nu_+ - \nu_- = \frac{4dE}{h}$$

Long measurement time of spin precession ➡ spin maser

Conventional (passive) spin maser

M.G. Richards, *JPB* **21** (1988) 665: ^{3}He spin maser
T. Chupp *et al.*, *PRL* **72** (1994) 2363: ^{129}Xe spin maser

Nuclear spin maser : strong coupling between nuclear spins and a feedback coil
⟶ Sustained spin precession



Operation condition

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

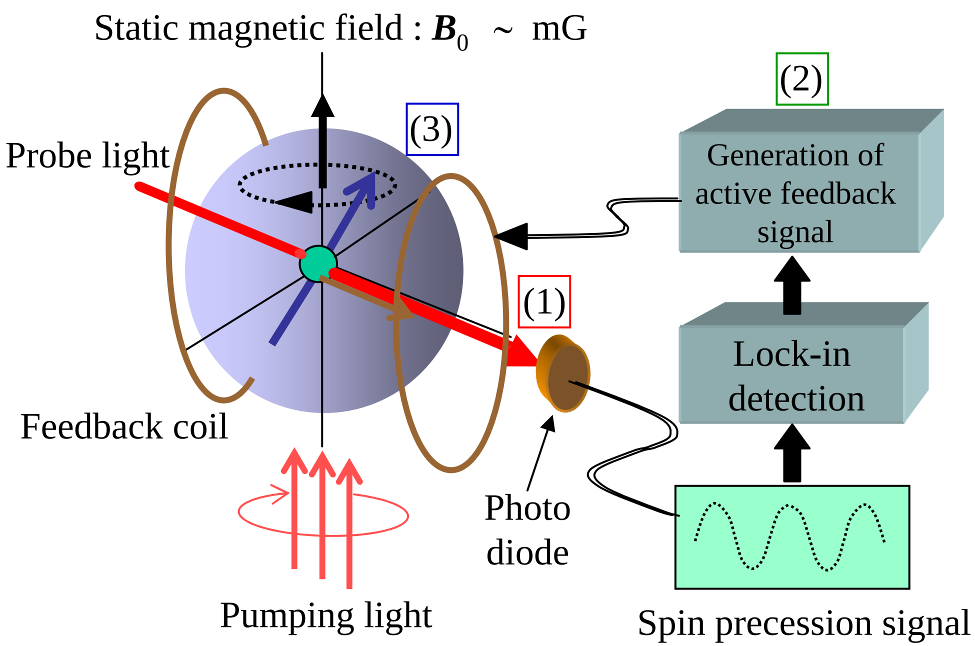
Radiation dumping time   transverse relaxation time

•Large Q-factor : operation frequency ~ kHz
= strong static field (~G)

Large fluctuation in the static field
↓
Large fluctuation in the precession frequency

Active spin maser

A. Yoshimi *et al.*, PLA 304 (2002) 13.



(1)Detection of spin precession without pick-up coil (optical detection of spin precession)

(2)Generation of feedback field by using detected signal (orthogonal to the spin)

(3) Sustained spin precession by active feedback field (maser operation)

Maser operation in low static field (~ mG)

•Small field fluctuation → small frequency fluctuation

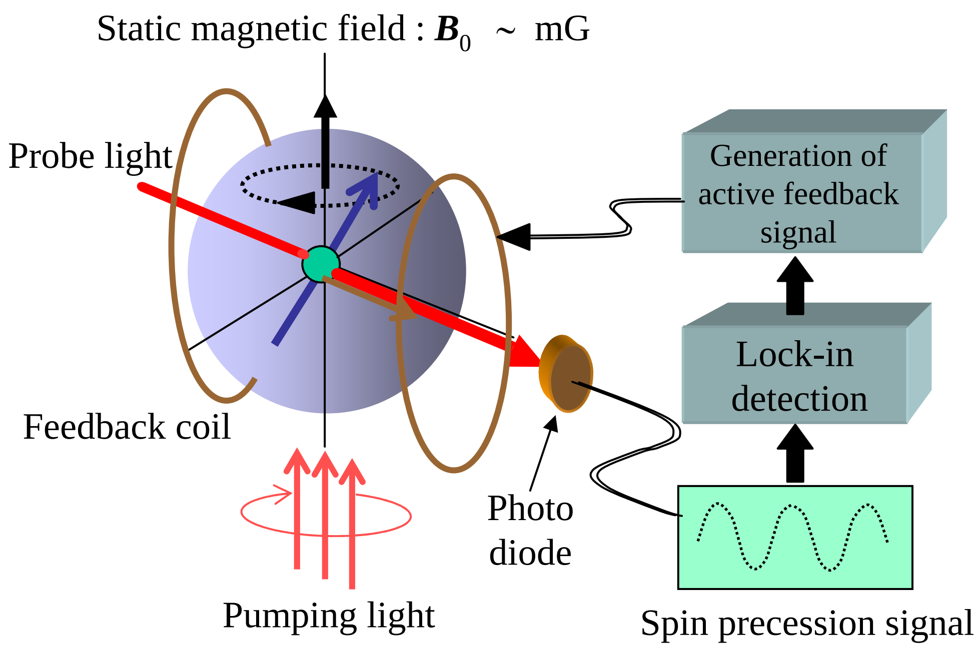
Improvement of experimental setup
·Magnetic shield : 3 layers => 4 layers
·A current source for static magnetic fields: stability 10^{-4} => 10^{-6}

Three key ingredients for active spin maser

(a) Polarization of ^{129}Xe nuclear spin

(b) Optical detection of nuclear spin precession

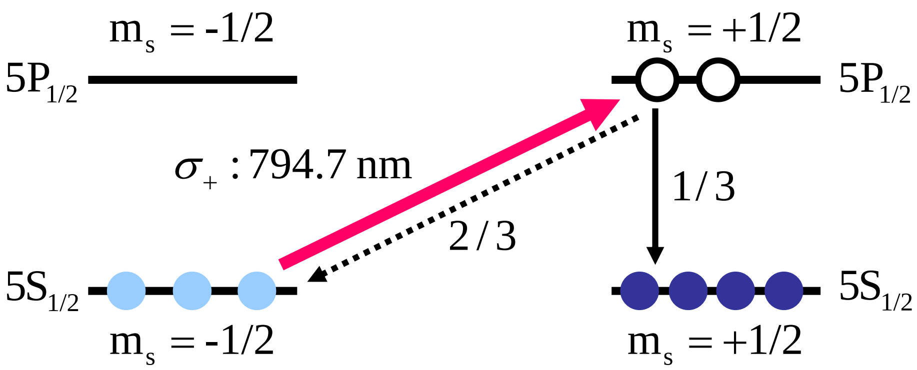
(c) Generation of active feedback field

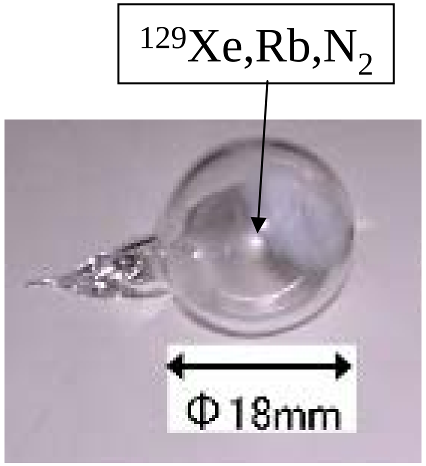


Polarization of ^{129}Xe nuclear spins

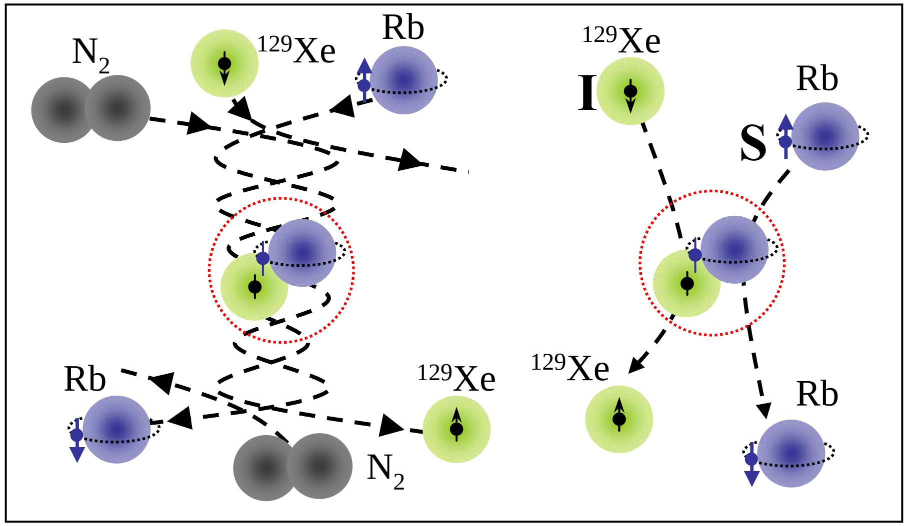
- Atomic polarization of Rb atoms by using optical pumping technique

Selective excitation by circularly polarized light





- Nuclear polarization by spin exchange interaction with Rb atom



•Two body collision with Rb
•Formation of van der Waals molecule with Rb

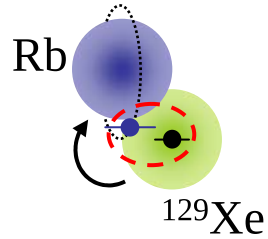
$$P_{Xe} = \frac{\gamma_{se}}{\gamma_{se} + \Gamma_{sd}} P_{Rb}$$

Spin exchange rate

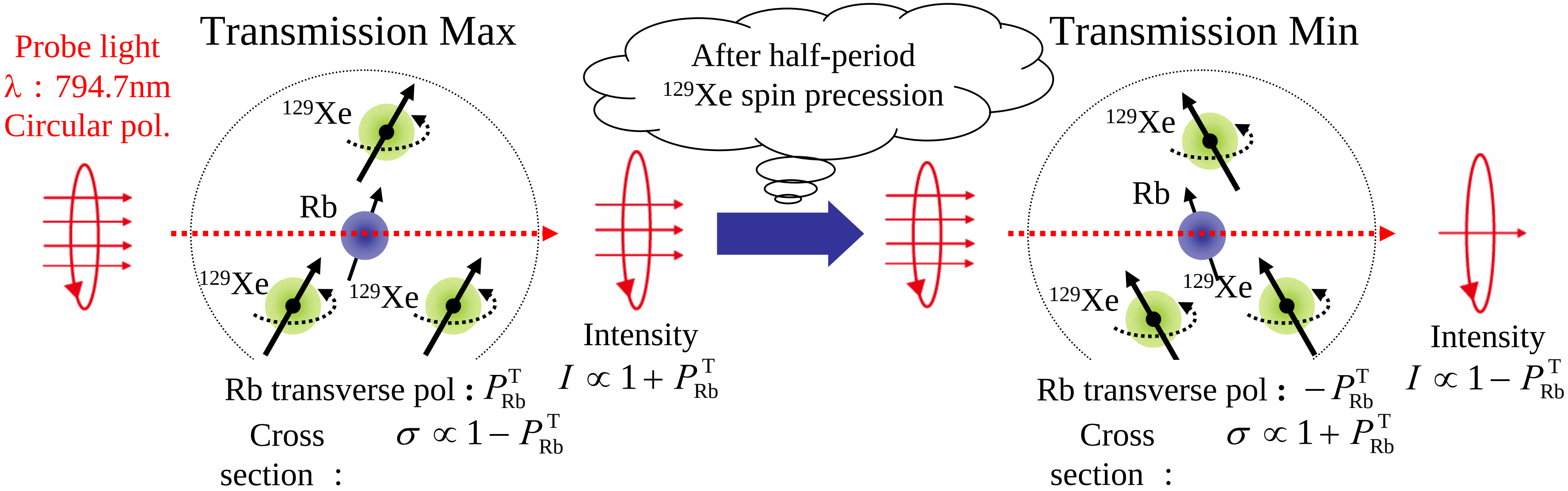
Spin relaxation rate

Optical detection of nuclear spin precession

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



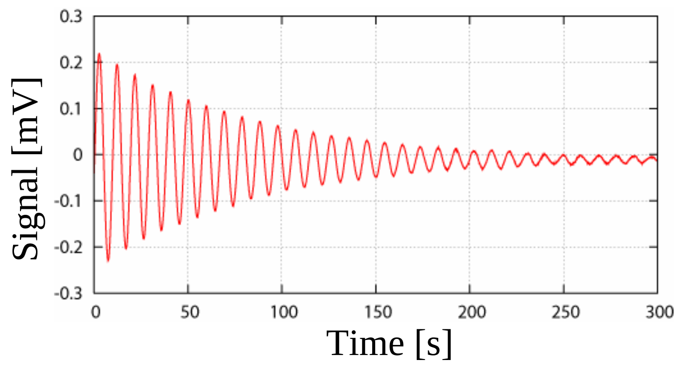
^{129}Xe nuclear spin precession
→Optical detection by probe light (Rb D1 line : 794.7 nm)



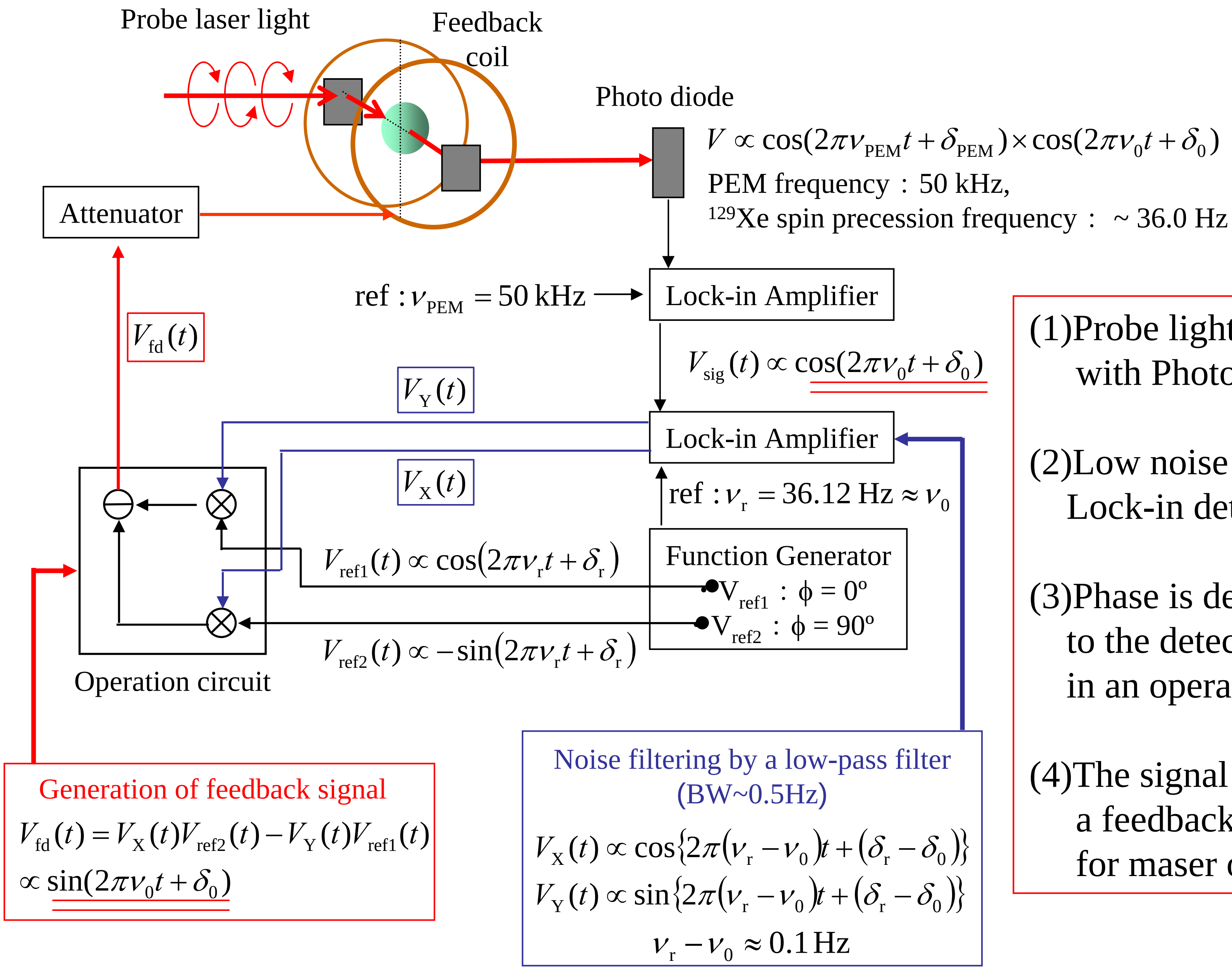
Experiments
→Circular polarization of probe laser is modulated with a photo-elastic modulator (PEM).

- Suppression of Rb transverse polarization
- Phase-sensitive detection by using a Lock-in Amplifier

Typical ^{129}Xe free precession signal



Generation of active feedback field



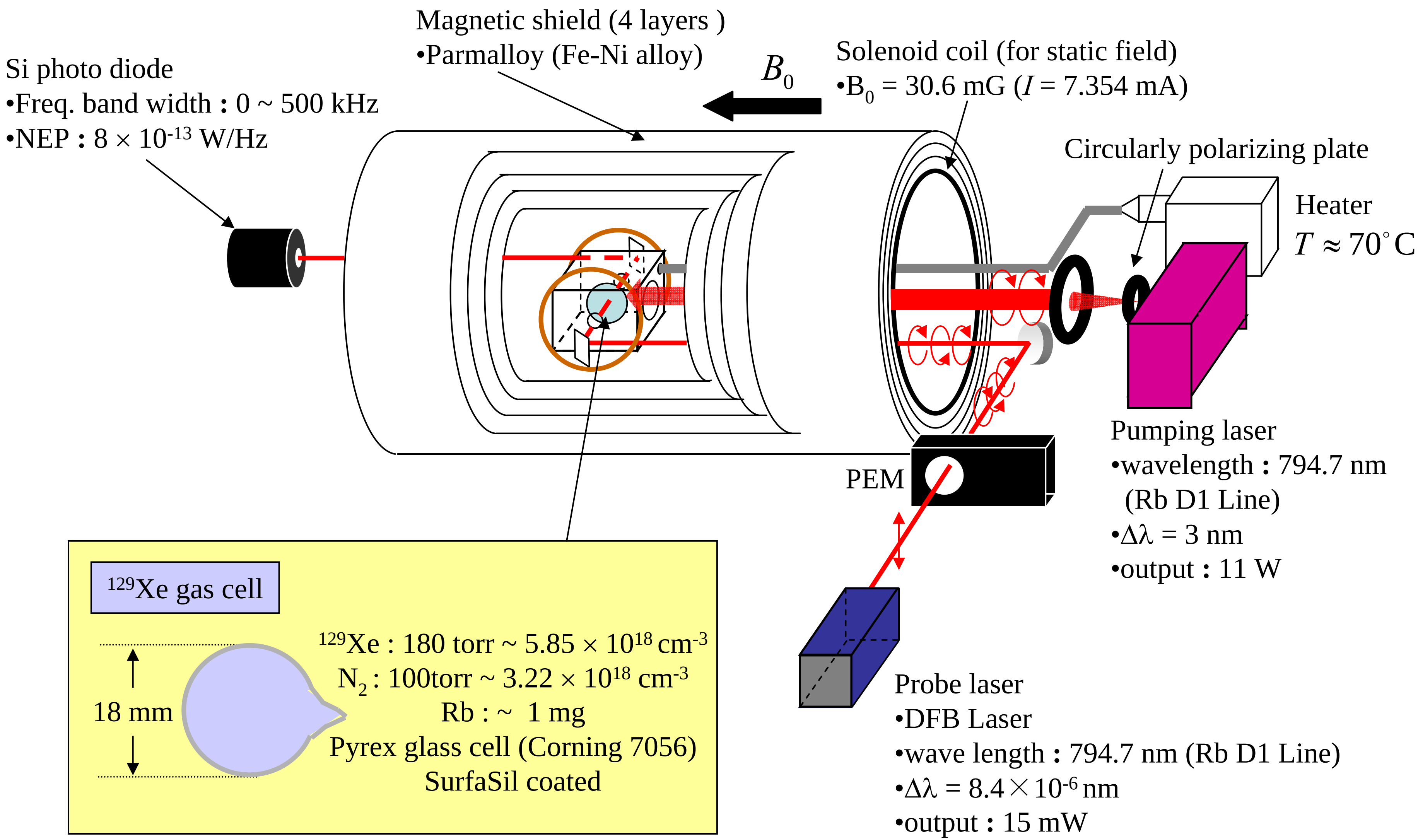
(1)Probe light detection with Photo Diode

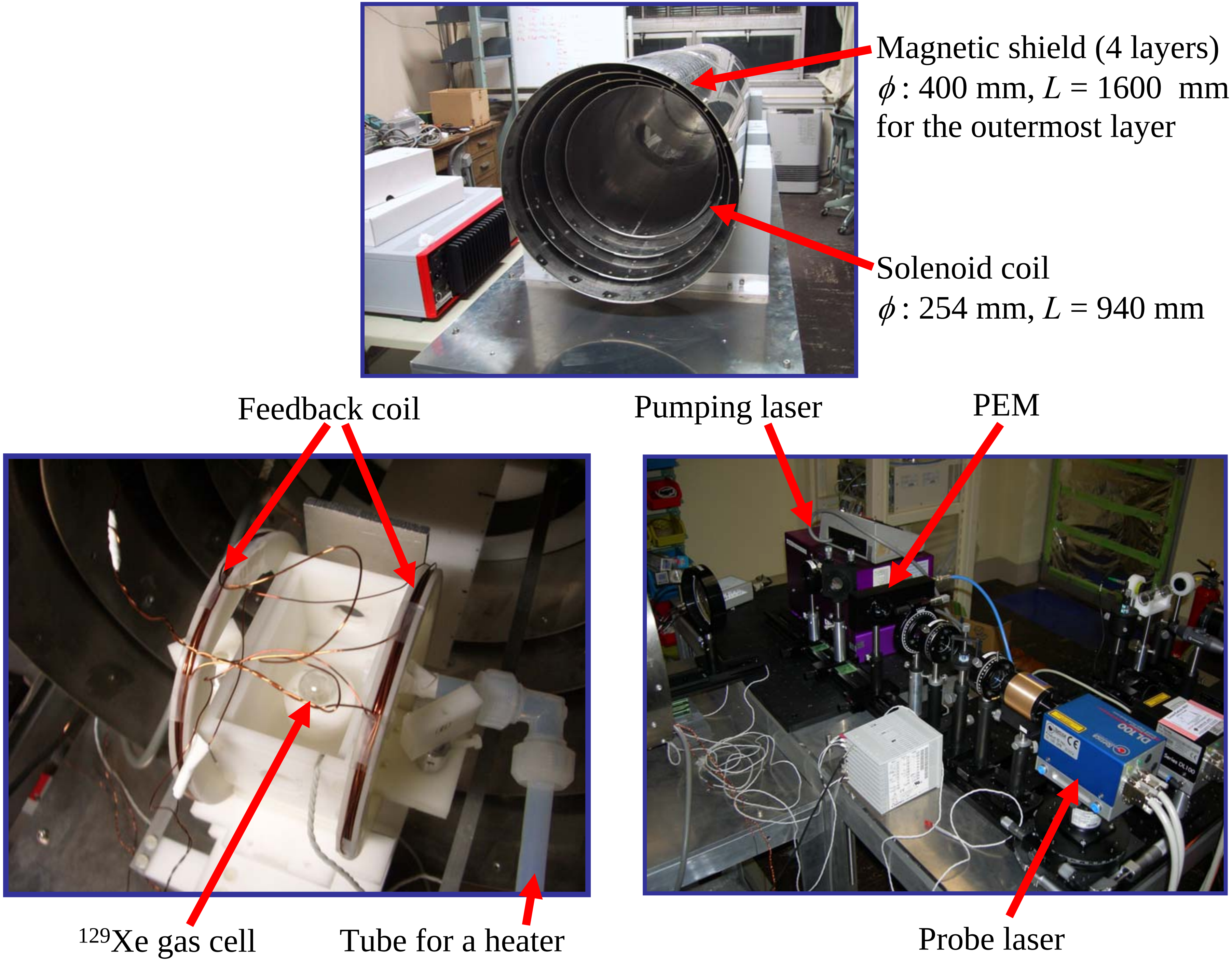
(2)Low noise signals by Lock-in detection

(3)Phase is delayed by 90º to the detected signal in an operation circuit

(4)The signal is applied to a feedback coil for maser operation

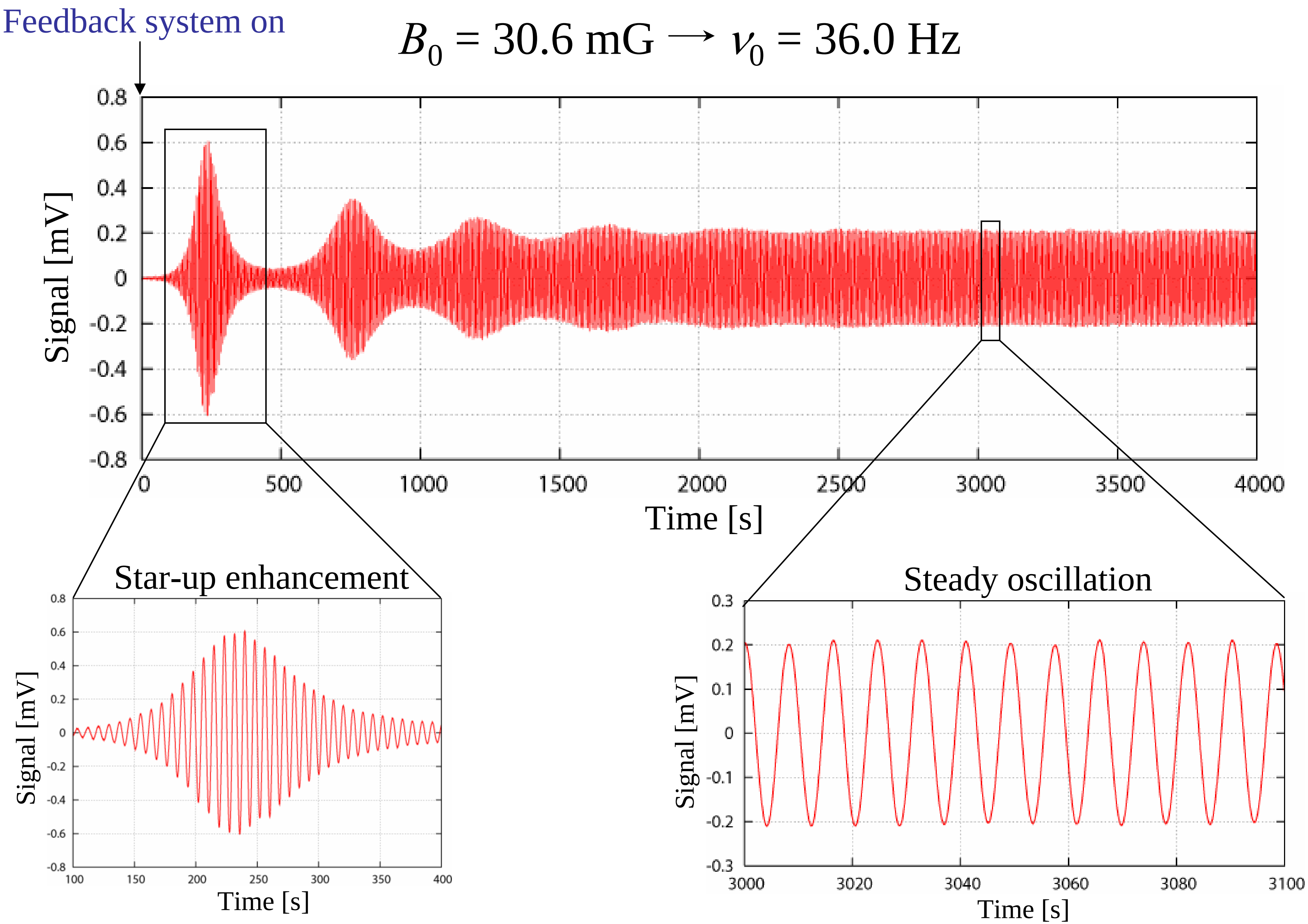
Experimental apparatus




Magnetic shield (4 layers)
ϕ : 400 mm, L = 1600 mm
for the outermost layer
Solenoid coil
ϕ : 254 mm, L = 940 mm
Feedback coil
Pumping laser
PEM
^{129}Xe gas cell
Tube for a heater
Probe laser

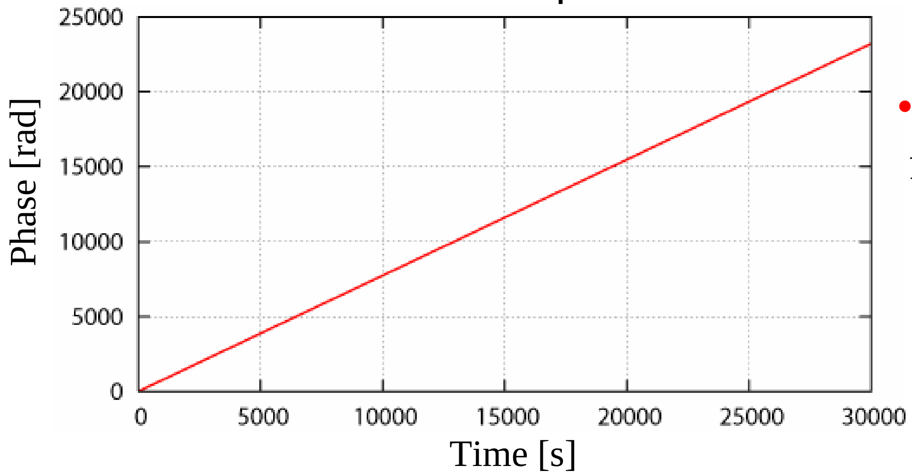
Result : Maser Operation

$B_0 = 30.6\ \text{mG} \longrightarrow \nu_0 = 36.0\ \text{Hz}$



Result on the frequency analysis

Precession phase



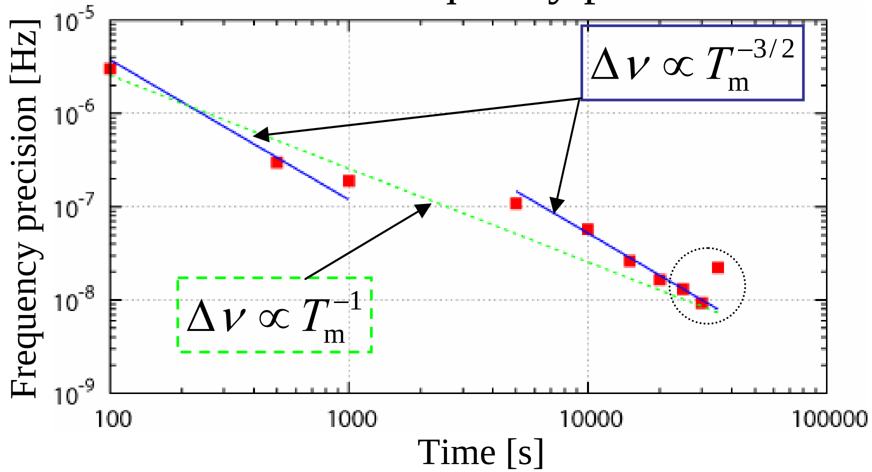
•A linear χ^2fitting was performed on the phase data for 30000 s

➡ frequency precision : 9.3 nHz

➡ EDM precision : 9×10^{-28} $e$cm (E = 10 kV/cm)

$$\nu_{\mathrm{ref}} - \nu_0 = 0.1231150674 \pm 0.0000000093\,\mathrm{Hz}$$

Measured frequency precision



•The frequency precision is not proportional to $T_{\mathrm{m}}^{-3/2}$ (T_{m}:measurement time) simply.

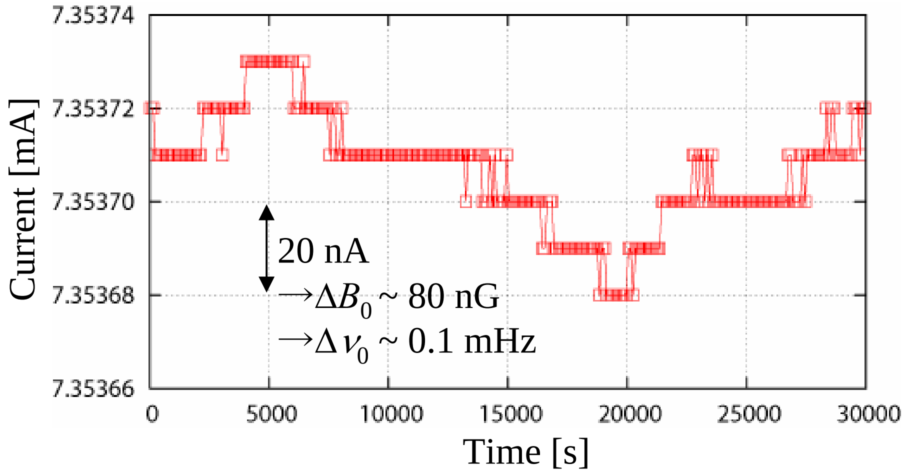
•The frequency precision is getting worse beyond 30000s.

➡ some noises in addition to white noise

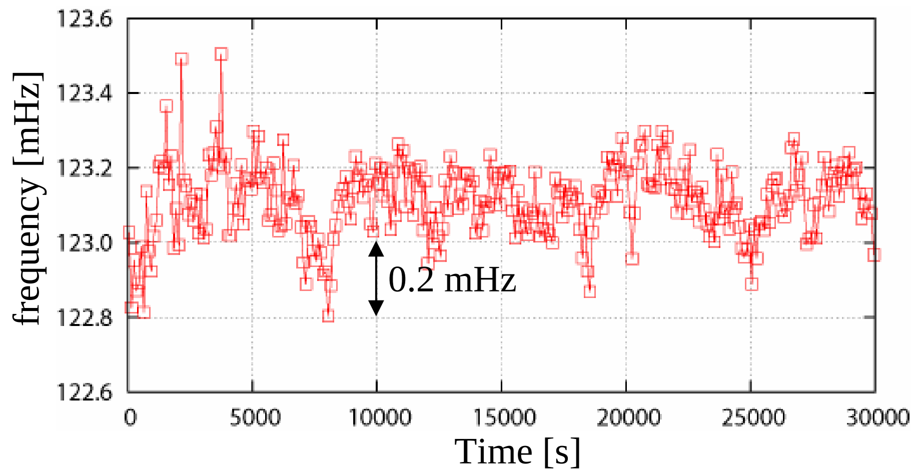
Correlation with the static field current source

• Frequency fluctuation → static field fluctuation → current source fluctuation

Average static field current (100 s)



Average detected frequency (100 s)



$$\frac{\Delta I}{I_{\text{mean}}} = 1\times10^{-6}$$

$$\frac{\Delta \nu_0}{\nu_0} = 3\times10^{-6}$$

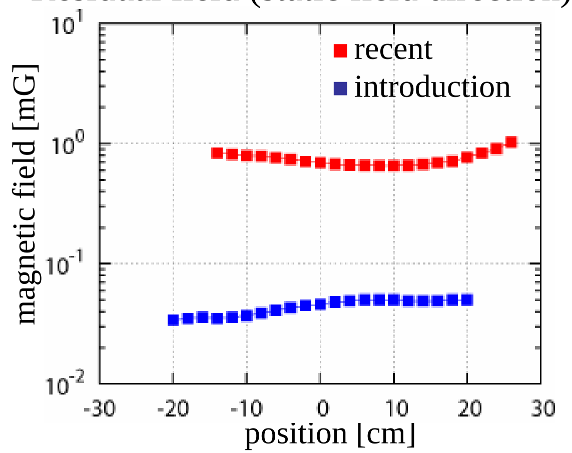
The stability of current source should not be the main source of the frequency fluctuation.

Correlation with environmental magnetic fields

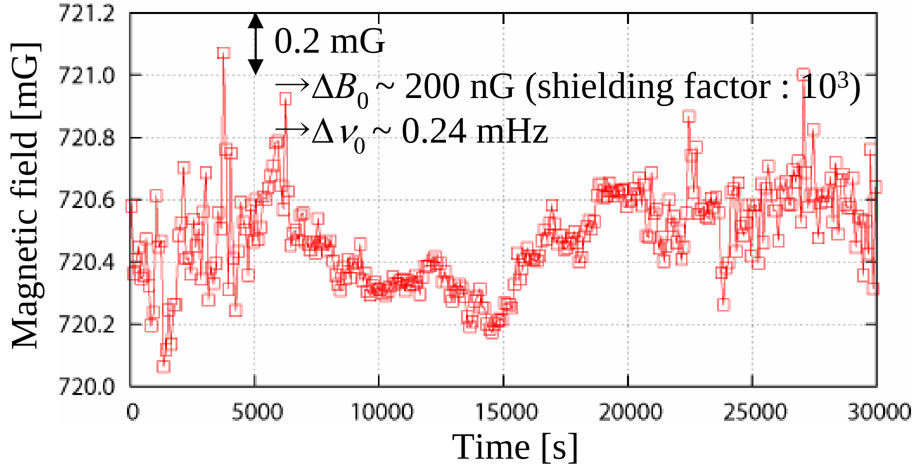
- Static field fluctuation
  → environmental magnetic fields fluctuation in the experimental room

Residual magnetic field in the shield : about 0.7 mG
  → shielding factor : 10^3
  but original : 10^4
  Secular change of magnetic shield

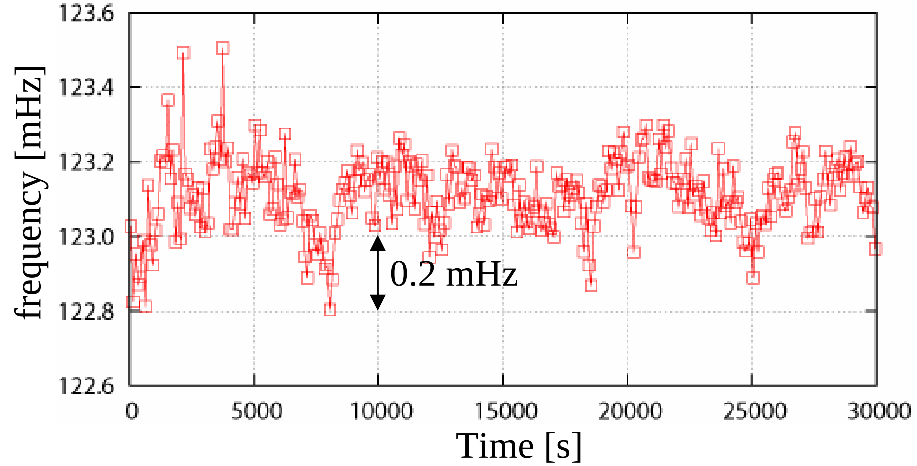
Residual field (static field direction)



Average environmental field (100 s)



Average detected frequency (100 s)



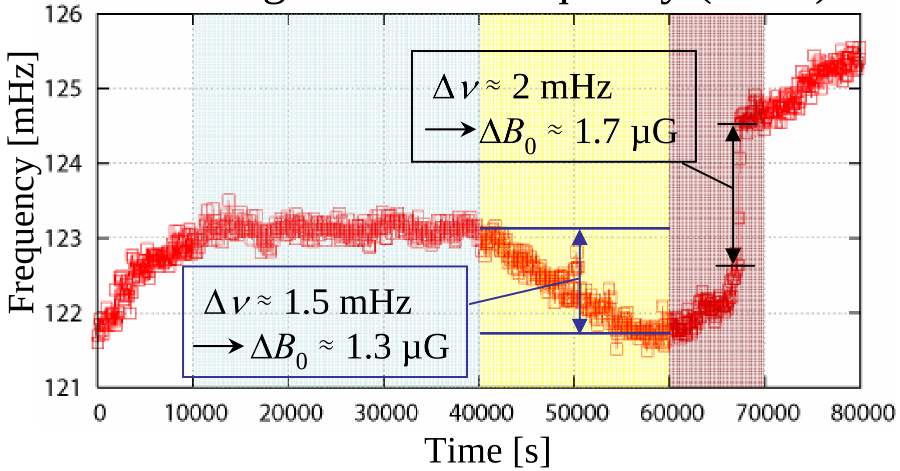
$$\frac{\Delta B_0^{ext}}{B_0} = 5\times10^{-6}$$

$$\frac{\Delta \nu_0}{\nu_0} = 3\times10^{-6}$$

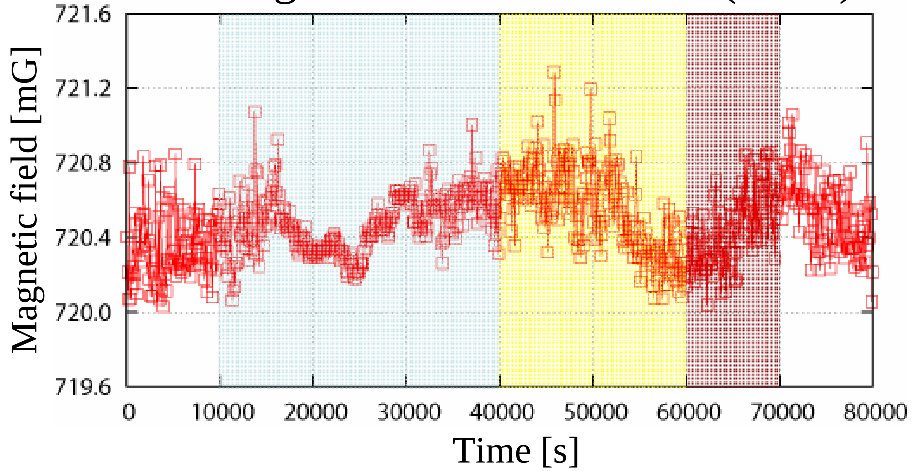
The fluctuation in the environmental magnetic field was the dominant noise source.

Frequency stability for a long term measurement

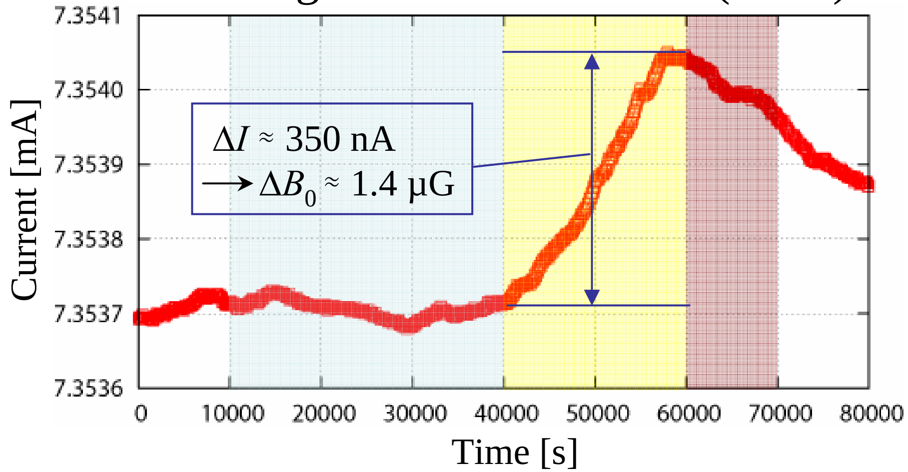
Average detected frequency (100 s)



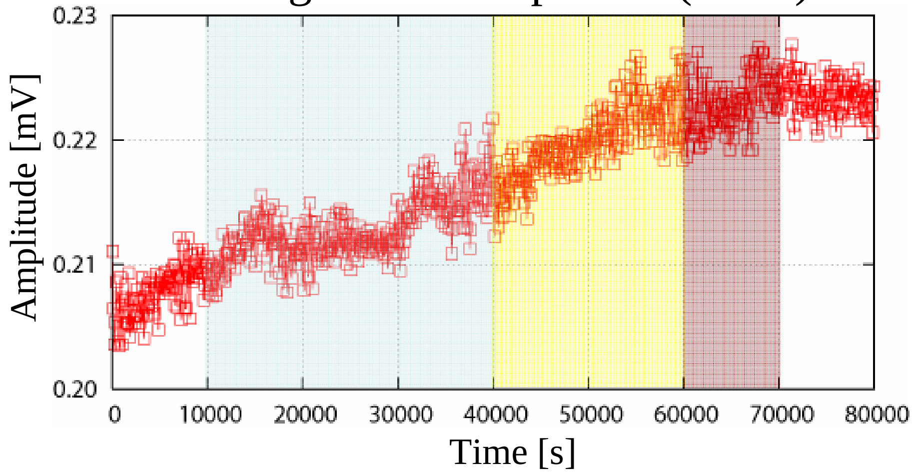
Average environmental field (100 s)



Average static field current (100 s)



Average maser amplitude (100 s)



- Frequency change from 40000 s to 60000 s ⇔ current shift
- Sudden jump of frequency ⇔ no correlation data → accidental magnetization of the shield?

The long term stabilization for the current source and the demagnetization of the shield

Summary

- The active spin maser has been successfully operated in an upgraded experimental apparatus.

- The frequency precision was 9.3 nHz for 30000s measurement time. It corresponds to the EDM precision of 9×10^{-28} *e*cm, when E = 10 kV/cm.

- Due to the secular degradation of the magnetic shield, the fluctuation in the environmental magnetic field is considered the main noise source.

- For a long term stability of the maser frequency, a long term stabilization of current source and the demagnetization of the shield are necessary.

Future prospects

·The introduction of new current source tolerant of the low frequency and thermal noises.

·The demagnetization of the magnetic shield

→ for one day measurement (86400 s)

$$\Delta\nu = 9.3\,\mathrm{nHz} \times \left(\frac{86400}{30000}\right)^{-3/2} = 1.9\,\mathrm{nHz}$$

$$\Rightarrow \quad d(^{129}\mathrm{Xe}) = 2\times10^{-28}\ e\mathrm{cm} \quad (E = 10\,\mathrm{kV/cm})$$

And

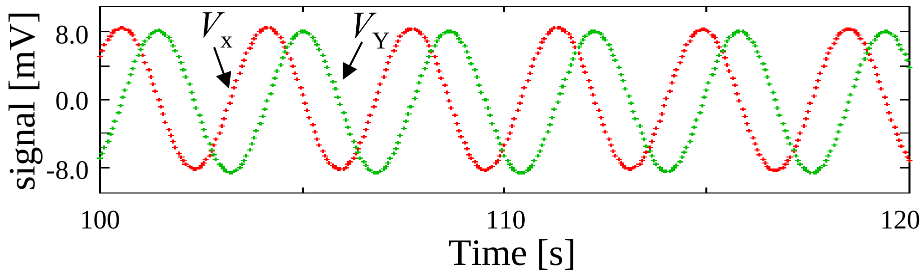
·HV application tests and reduction of leakage current

·Incorporation of a magnetometer ; An optical magnetometer by using the technique of nonlinear magneto-optical rotation with frequency-modulated light (FM NMOR)

➡ ^{129}Xe-EDM precision : $10^{-28} \sim 10^{-29}$ *e*cm

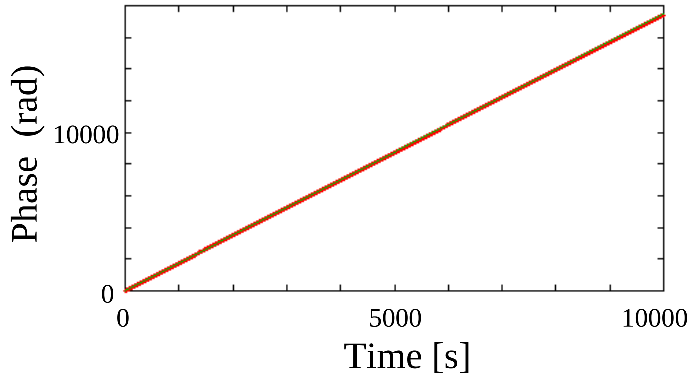
Frequency precision in the previous setup

Lock-in Amplifier outputs



$$\phi(t) = \tan^{-1}\frac{V_X(t)}{V_Y(t)}$$

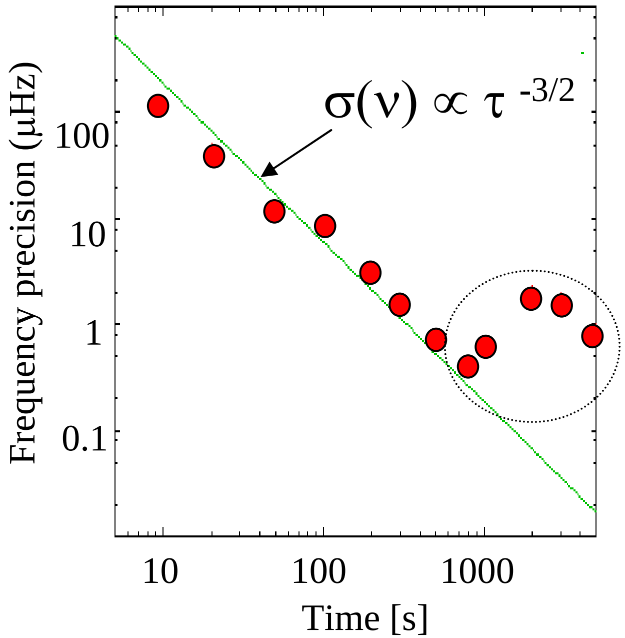
Precession phase



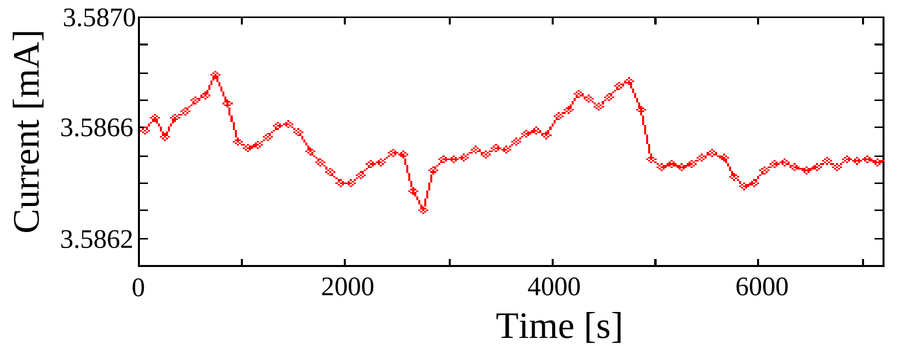
ν = 277.20844 ± 0.00096 mHz

→ **δν = 0.96 μHz**

Measured frequency precision



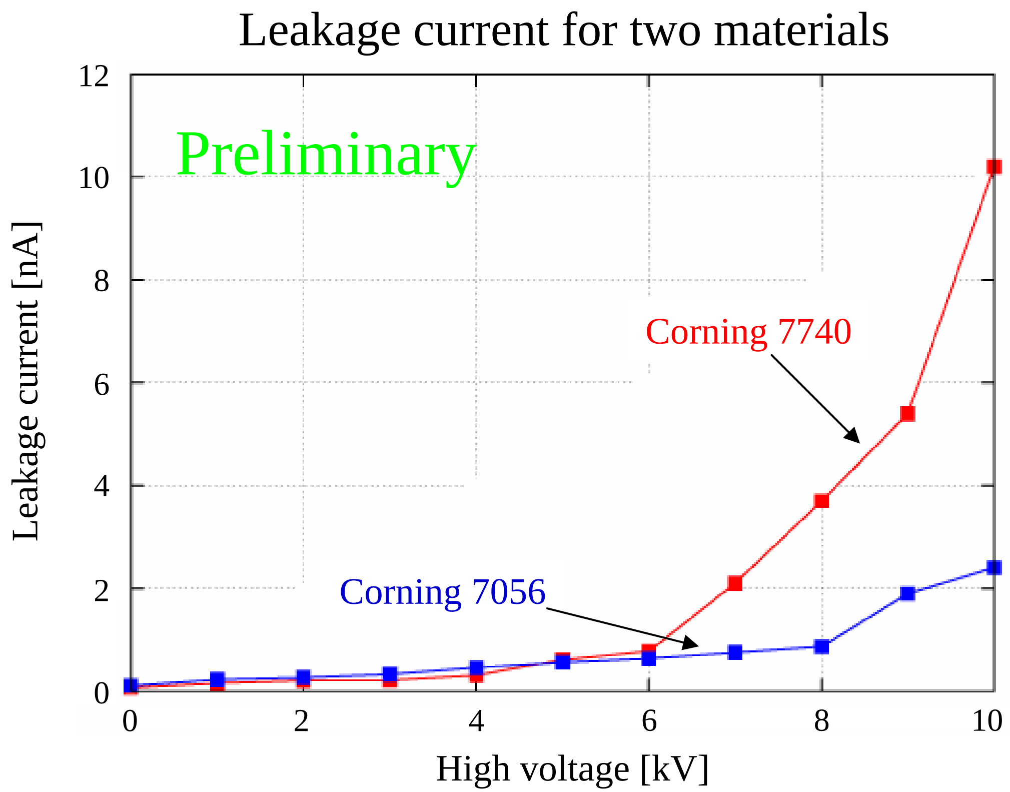
Averaged static field current (stability: 10^{-4})



$\delta I \sim 0.1\ \mu A$ for time scale of 1000 s

(**$\delta B_0 \sim 0.8\ \mu G$, $\delta\nu_0(^{129}Xe) \sim 1$ mHz**)

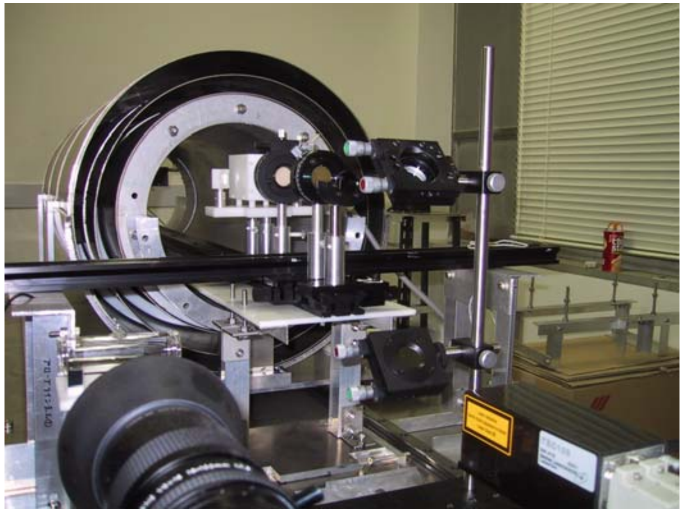
Result : leakage current test (Preliminary)



$$I_{\rm Leak} = 1\,{\rm nA} \Rightarrow B_{\rm Leak} = 0.6\,{\rm nG} \Rightarrow 700\,{\rm nHz} \Rightarrow \Delta d = 7\times 10^{-26}\ e{\rm cm}\ \left(E = 10\ {\rm kV/cm}\right)$$

Optical magnetometer

Fluctuation of magnetic field
→ Main source of frequency noise in spin maser operation

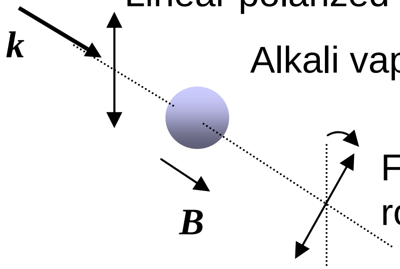


$d_{atom} \approx 10^{-28}\ e\mathrm{cm}$ ═ $\delta\nu \approx 1\,\mathrm{nHz}$ ═ $\delta B \approx 1\,\mathrm{pG}$

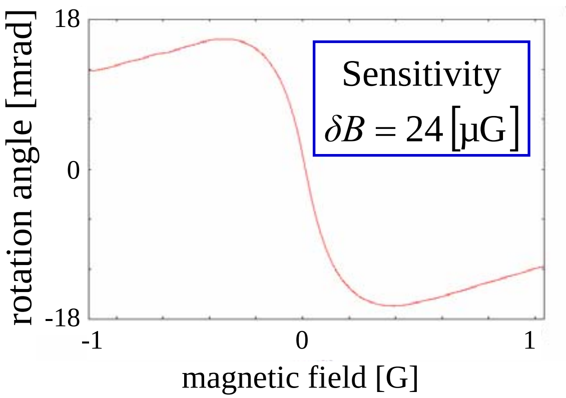
$E = 10\ \mathrm{kV/cm}$

Neutron EDM experiment….. Hg atomic magnetometer
Xe EDM experiment @ Michigan Gr. ….. ^{3}He co-magnetometer

Atomic magnetometer with Rb using magneto-optical rotation

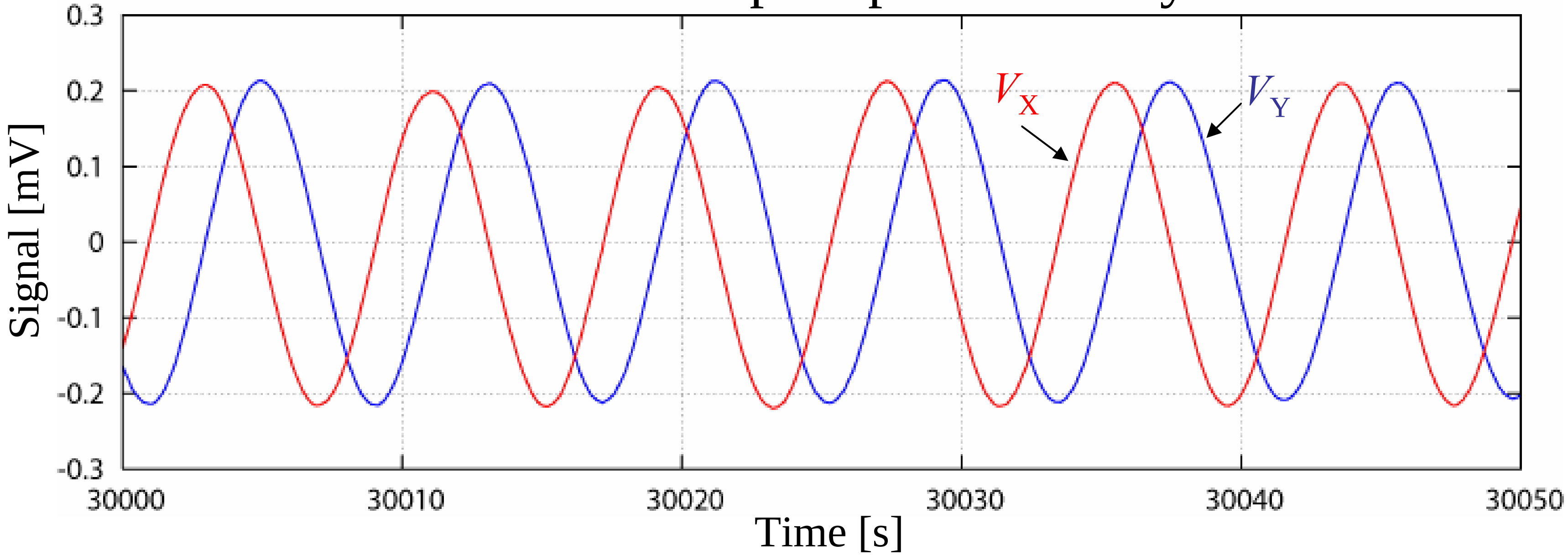


D. Budker et al.,
PRA 62 (2000) 043403.



Analysis about the frequency

Part of Lock-in Amp outputs in steady state



Two Lock-in Amp outputs (V_X, V_Y)

$$V_X(t) = V_{L.A.} \cos[2\pi(\nu_{ref} - \nu_0)t + (\phi_{ref} - \phi_0)]$$

$$V_Y(t) = V_{L.A.} \cos\left[2\pi(\nu_{ref} - \nu_0)t + (\phi_{ref} - \phi_0) - \frac{\pi}{2}\right]$$

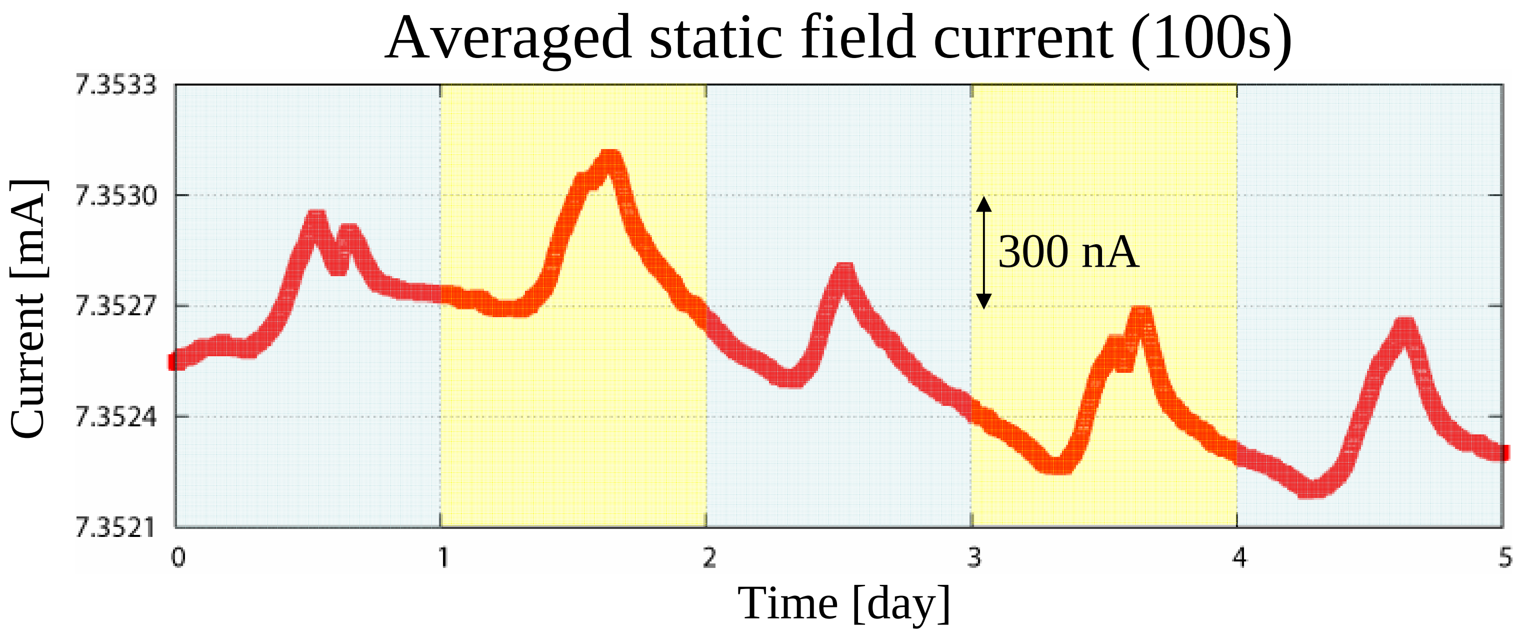
$$= V_{L.A.} \sin[2\pi(\nu_{ref} - \nu_0)t + (\phi_{ref} - \phi_0)]$$

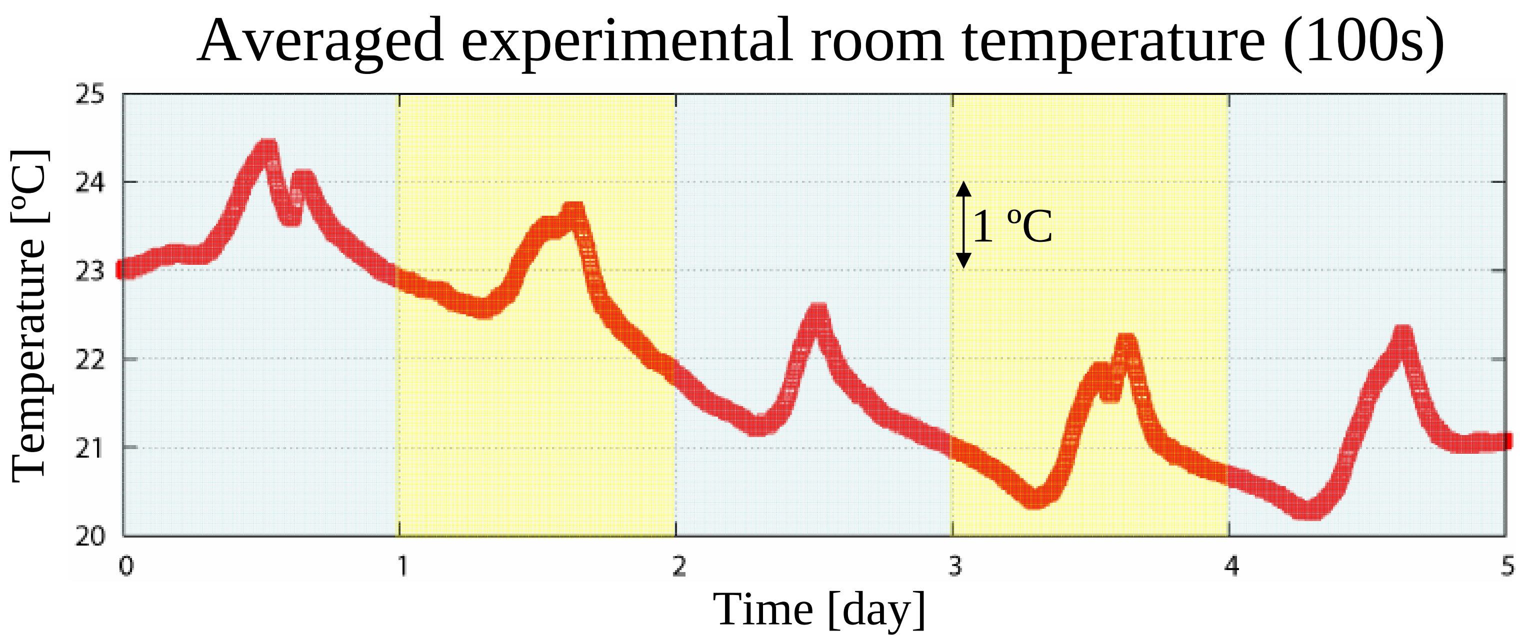
$$\phi(t) = \tan^{-1}\frac{V_Y(t)}{V_X(t)}$$

$$= 2\pi(\nu_{ref} - \nu_0)t + (\phi_{ref} - \phi_0)$$

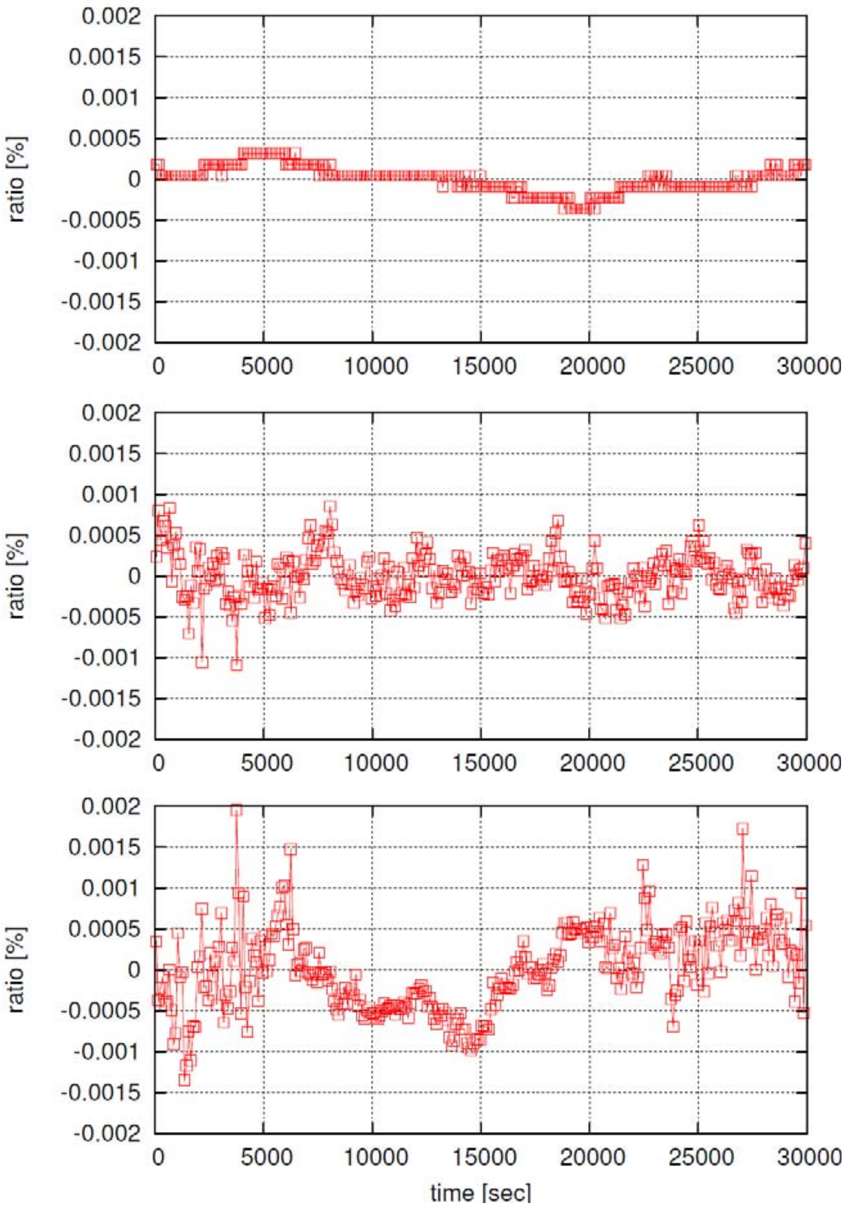
The frequency is decided by the phase data

Temperature dependence of the current source





Deviations for some observables

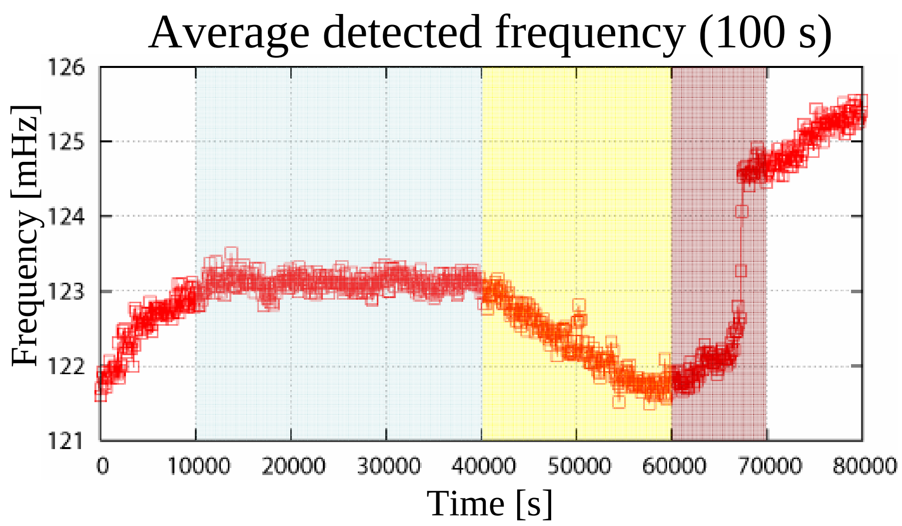


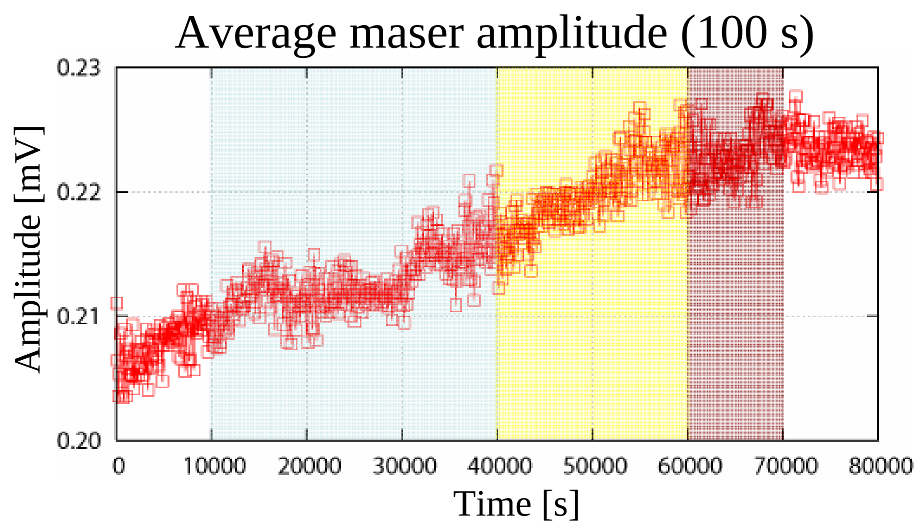
Current

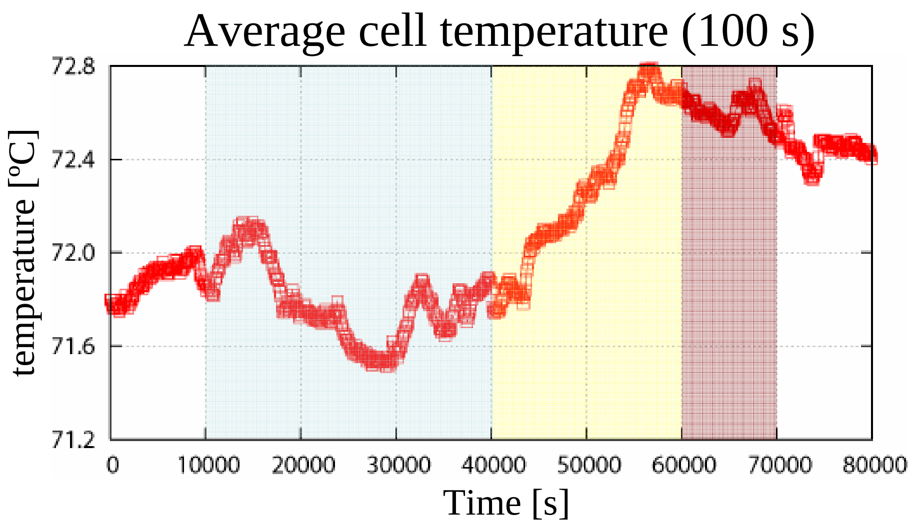
Maser frequency : ν_0

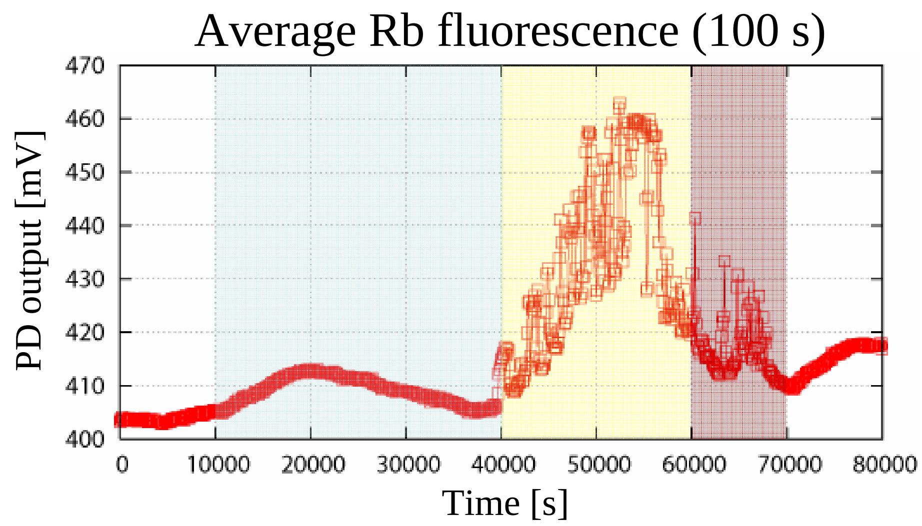
Environmental field
(Shielding factor : 10^3)

Other data


Average detected frequency (100 s)
Frequency [mHz]
126
125
124
123
122
121
0
10000
20000
30000
40000
50000
60000
70000
80000
Time [s]


Average maser amplitude (100 s)
Amplitude [mV]
0.23
0.22
0.21
0.20
0
10000
20000
30000
40000
50000
60000
70000
80000
Time [s]

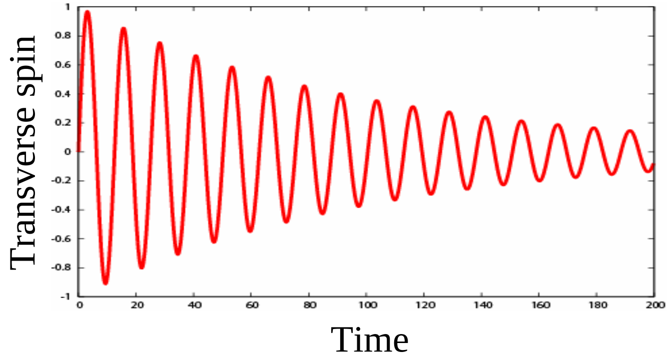

Average cell temperature (100 s)
temperature [ºC]
72.8
72.4
72.0
71.6
71.2
0
10000
20000
30000
40000
50000
60000
70000
80000
Time [s]


Average Rb fluorescence (100 s)
PD output [mV]
470
460
450
440
430
420
410
400
0
10000
20000
30000
40000
50000
60000
70000
80000
Time [s]

Frequency precision

- Normally, spin precession is subject to
  decoherence (or, transverse relaxation)
  due to field inhomogeneity,
  spin-spin interaction,
  …..

Free precession : $\delta\nu \propto T_{\mathrm{m}}^{-1/2}$



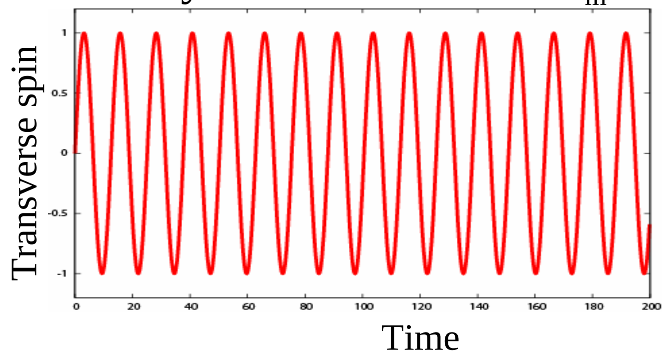
While...

- Accuracy of frequency determination:

$$\sigma_\nu \propto \left[\text{Fourier width } \frac{1}{T_{\mathrm{m}}}\right] \times \frac{1}{\left[\#\text{ of data points } T_{\mathrm{m}}\right]^{1/2}}$$

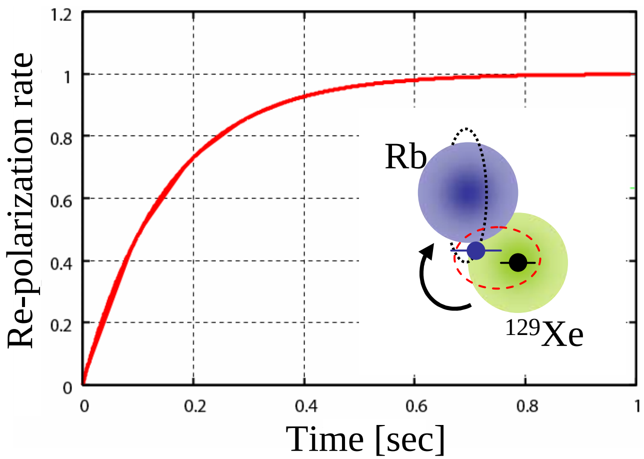
$$\propto \frac{1}{T_{\mathrm{m}}^{3/2}} \quad (T_{\mathrm{m}}\text{ : measurement time})$$

Steady oscillation : $\delta\nu \propto T_{\mathrm{m}}^{-3/2}$



Optical detection of nuclear spin precession

Development of transverse-polarization



Transverse-polarization transfer

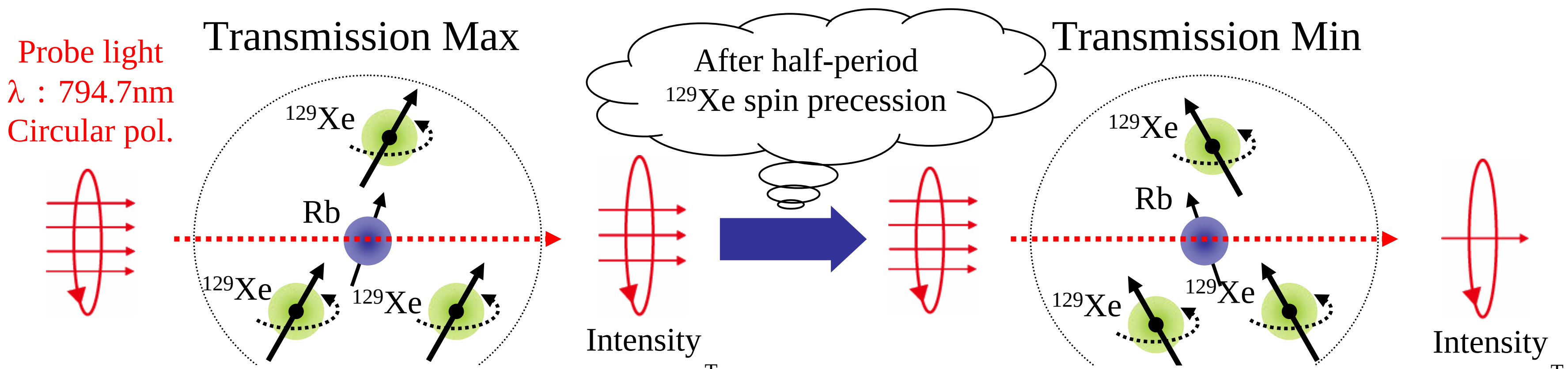
^{129}Xe nuclei ⟶ Rb atoms (re-polarization)

$$\frac{dP_{\mathrm{Rb}}^{\mathrm{T}}}{dt} = \gamma_{\mathrm{se}}^{\mathrm{repol}} P_{\mathrm{Xe}}^{\mathrm{T}} - \Gamma'_{\mathrm{sd}} P_{\mathrm{Rb}}^{\mathrm{T}}$$

$\gamma_{\mathrm{se}}^{\mathrm{repol}}$:re-polarization rate

Γ'_{sd} :re-polarization relaxation rate

$$\nu_0 \leq 1/\gamma_{\mathrm{se}}^{\mathrm{repol}} \sim 1\,\mathrm{kHz} \longrightarrow \nu_0^{\mathrm{exp}} = 36.0\ \mathrm{Hz}$$



Transmission Max

Rb transverse pol : $P_{\mathrm{Rb}}^{\mathrm{T}}$

Cross section : $\sigma \propto 1 - P_{\mathrm{Rb}}^{\mathrm{T}}$

Intensity $I \propto 1 + P_{\mathrm{Rb}}^{\mathrm{T}}$

Transmission Min

Rb transverse pol : $-P_{\mathrm{Rb}}^{\mathrm{T}}$

Cross section : $\sigma \propto 1 + P_{\mathrm{Rb}}^{\mathrm{T}}$

Intensity $I \propto 1 - P_{\mathrm{Rb}}^{\mathrm{T}}$

Maser equation

- Modified Bloch equation

$$\frac{dP_x}{dt} = \gamma(\mathbf{P}\times\mathbf{B})_x - \frac{P_x}{T_2}$$

$$\frac{dP_y}{dt} = \gamma(\mathbf{P}\times\mathbf{B})_y - \frac{P_y}{T_2}$$

spin exchange

$$\frac{dP_z}{dt} = \gamma(\mathbf{P}\times\mathbf{B})_z - \frac{P_z}{T_1} + \boxed{\left(\overline{P}_{Rb} - P_z\right)\gamma_{se}}$$

$$\gamma B_x = \beta\frac{P_y}{P_0},\quad \gamma B_y = -\beta\frac{P_x}{P_0}$$

feedback gain

rotation frame: $\omega_0 = -\gamma B_0$

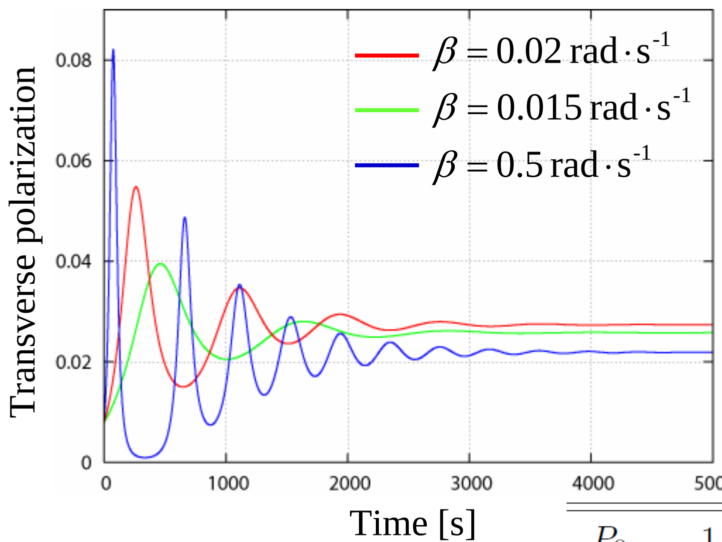
$$\frac{dP_{\mathrm{T}}}{dt} = \left(\beta\frac{P_{\mathrm{Z}}}{P_0} - \frac{1}{T_2}\right)P_{\mathrm{T}}$$

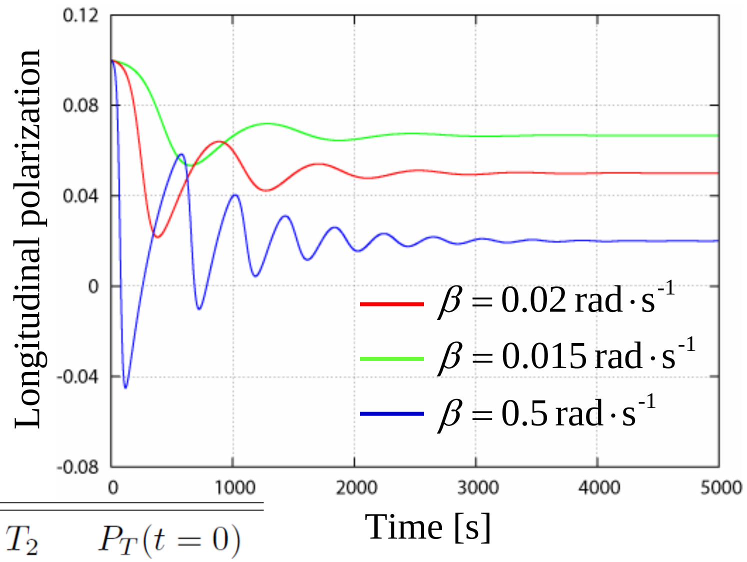
$$\frac{dP_{\mathrm{Z}}}{dt} = -\frac{P_{\mathrm{T}}^2}{P_0\tau_{\mathrm{RD}}} + \frac{P_0 - P_{\mathrm{Z}}}{T_1^*}$$

$$1/T_1^* = 1/T_1 + \gamma_{se}$$

$$P_{\mathrm{T}} = \sqrt{P_x^2 + P_y^2}$$

$$P_{\mathrm{T}}^{\mathrm{eq}} = \frac{P_0}{\beta}\sqrt{\frac{1}{T_1^*}\left(\beta - \frac{1}{T_2}\right)} \neq 0,\quad P_{\mathrm{Z}}^{\mathrm{eq}} = \frac{P_0}{\beta T_2}$$

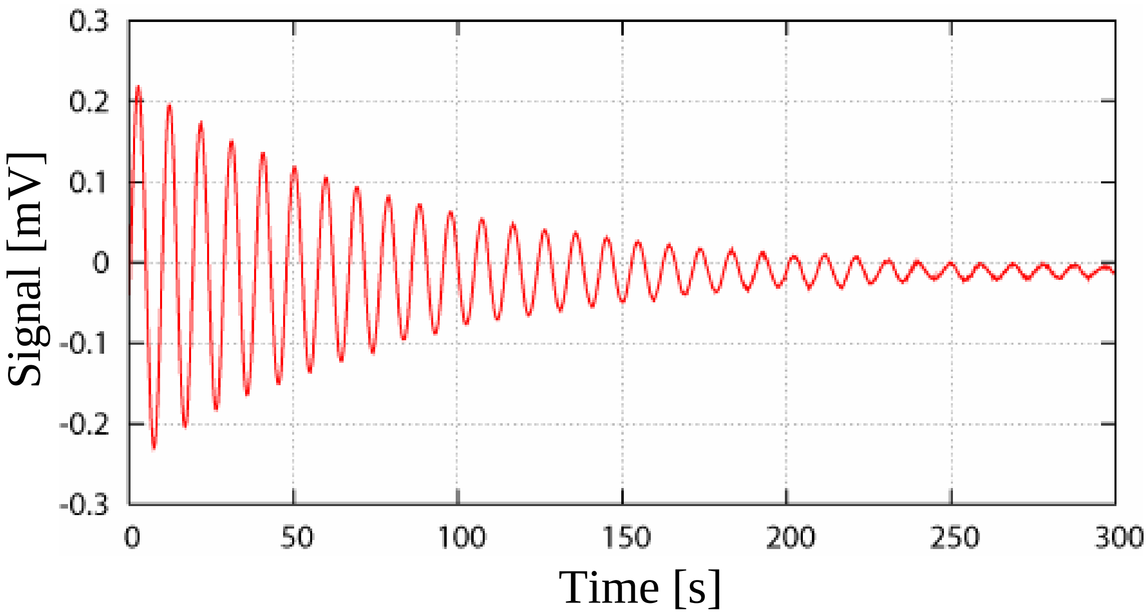




P_0	$1/T_1^*$	T_2	$P_T(t=0)$
0.1	0.003s^{-1}	100s	0.008

Result : T_2 Measurement

- Static magnetic field : B_0 =30.6 mG → ν_0 =36.0 Hz
- ν_0 = 36.0147097 ± 0.0000022 Hz (χ^2 fitting) → $\Delta \nu_0$ =2.2 μHz
- T_2 = 81.8 ± 0.1 s



Atomic EDM induced by finite nuclear size effect

P,*T*-odd interaction between nucleons

J.S.M. Ginges, V.V. Flambaum, Phys. Rep. 397 (2004) 63
V. A. Dzuba et al., PRA **66**, 012111 (2002)

$$\hat{W} = \frac{G}{\sqrt{2}}\frac{\eta}{2m_p}\boldsymbol{\sigma}\cdot\nabla\rho_A(\mathbf{r}) = \eta\frac{G}{2\sqrt{2}m_p}\frac{\rho(0)}{U(0)}\boldsymbol{\sigma}\cdot\nabla U(\mathbf{r})$$

$$\rho = \bar{\psi}\psi + \underline{\underline{\eta\frac{G}{2\sqrt{2}m_p}\frac{\rho(0)}{U(0)}\nabla\cdot(\bar{\psi}\boldsymbol{\sigma}\psi)}}$$

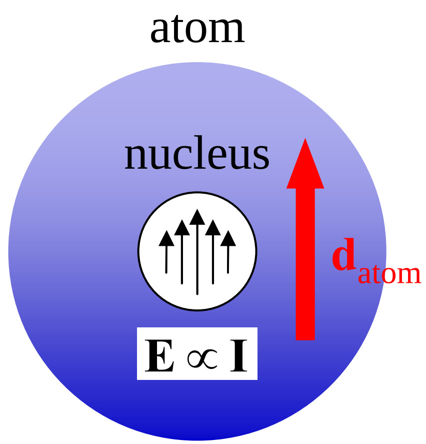
P,*T*-odd nuclear density

Schiff moment

$$\mathbf{S} = \frac{1}{10}\left[e\int_{\text{nucleus}}\mathbf{r}r^2\rho(\mathbf{r})d^3\mathbf{r} - \frac{5}{3}\mathbf{d}\frac{1}{Z}\int_{\text{nucleus}}r^2\rho(\mathbf{r})d^3\mathbf{r}\right]$$

$$\varphi_{\text{Schiff}} = 4\pi\mathbf{S}\cdot\nabla\delta^3(\mathbf{R}) \rightarrow \mathbf{E} = -\nabla\varphi_{\text{Schiff}} \propto \mathbf{I}$$

$$\mathbf{d}_{\text{atom}} = 2\sum_M \frac{\langle 0|\hat{\mathbf{D}}|M\rangle\langle M|\varphi_{\text{Schiff}}|0\rangle}{E_0 - E_M},\quad \hat{\mathbf{D}} = -e\sum \mathbf{r}_i$$



$$d(^{129}\text{Xe}) = 3.8\times10^{-5}\ \text{fm}^{-2}\cdot S(^{129}\text{Xe})$$
$$S(^{129}\text{Xe}) = 1.75\times10^{-8}\eta\ e\text{fm}^3$$
$$\longrightarrow d(^{129}\text{Xe}) = 6.7\times10^{-26}\eta\ \ e\text{cm}$$

$$d(^{199}\text{Hg}) = -2.8\times10^{-4}\ \text{fm}^{-2}\cdot S(^{199}\text{Hg})$$
$$S(^{199}\text{Hg}) = -1.4\times10^{-8}\eta\ e\text{fm}^3$$
$$\longrightarrow d(^{199}\text{Hg}) = 3.9\times10^{-25}\eta\ \ e\text{cm}$$

^{129}Xe, ^{199}Hg EDMs induced by Schiff moment

J.S.M. Ginges, V.V. Flambaum, Phys. Rep. 397 (2004) 63

The largest contribution to the constant η: $\frac{G}{\sqrt{2}}\eta \approx \frac{g\bar{g}_{\pi^0}}{m_\pi^2}$

where g and $\bar{g}_{\pi^0}$ are the constant of the strong and T-odd π meson-nucleon interaction:

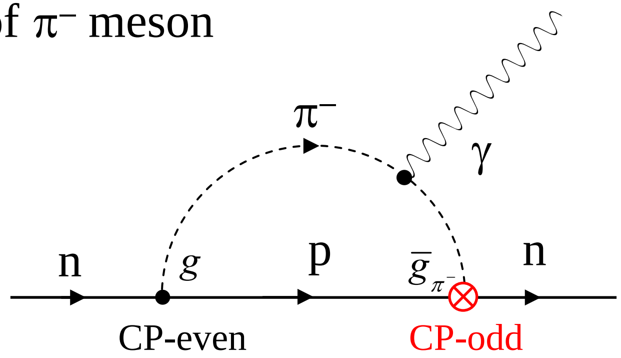
$$\left(g\bar{n}i\gamma_5 n + \bar{g}_{\pi^0}\bar{p}p\right)\pi^0 + \sqrt{2}\left(g\bar{p}i\gamma_5 n + \bar{g}_{\pi^0}\bar{p}n\right)\left(\pi^-\right)^\dagger + \cdots$$

Neutron EDM induced through virtual creation of π⁻ meson

$$d_n = \frac{e}{m_p}\frac{g\bar{g}_{\pi^-}}{4\pi^2}\ln\frac{M}{m_\pi}$$

$$\left|\bar{g}_{\pi^-}\right| = \left|\bar{g}_{\pi^0}\right|$$
$$M \sim m_\rho \sim 770\ \text{MeV}$$

$$d_\text{n} \sim 10^{-22}\eta\ e\text{cm}$$

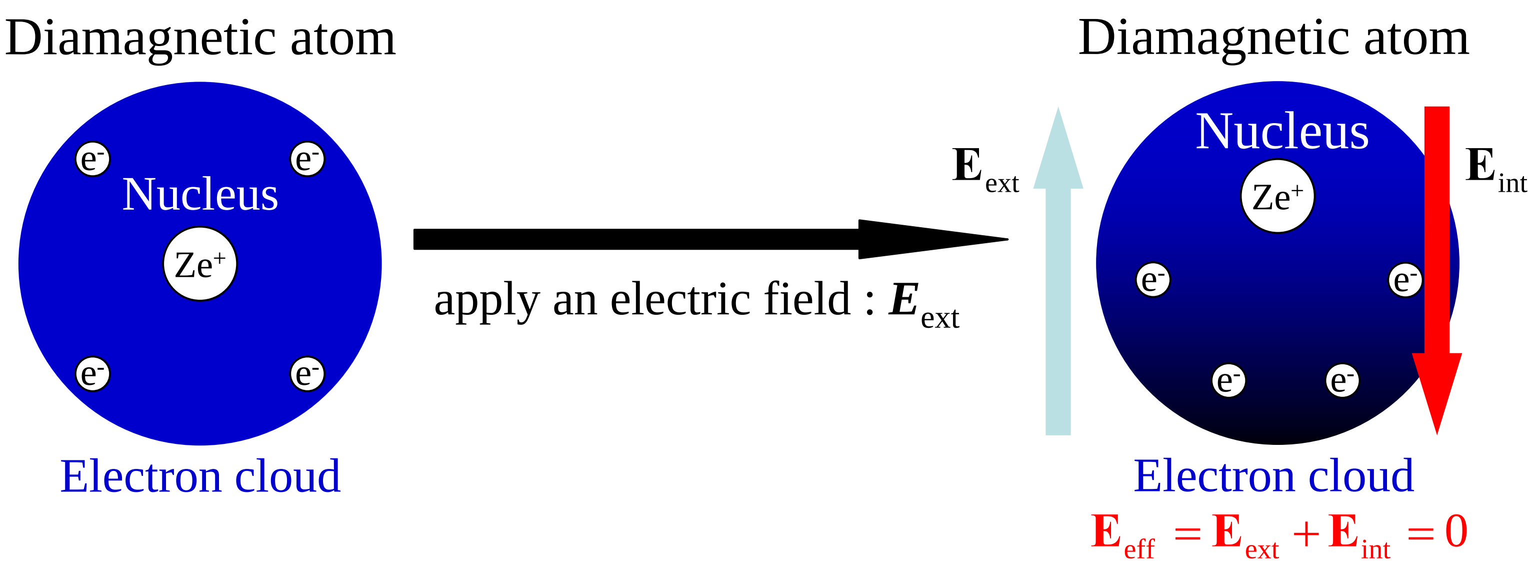


from M. Pospelov, A. Ritz, Ann. Phys. 318 (2005) 119.

$$d\left({}^{129}\text{Xe}\right) \sim 6.7\times10^{-4} d_n$$
$$d\left({}^{199}\text{Hg}\right) \sim 3.9\times10^{-3} d_n$$

Schiff shielding

In an external electrostatic potential,
the atomic system consisted of
・non-relativistic, ・point-like, ・charged
particles doesn't show an energy shift due to EDM,
even if the components of atomic system have the EDMs.



The electron cloud moves to cancel an external electric field
The effective electric field is zero.