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Experimental Search for an EDM in ^{129}Xe Atom

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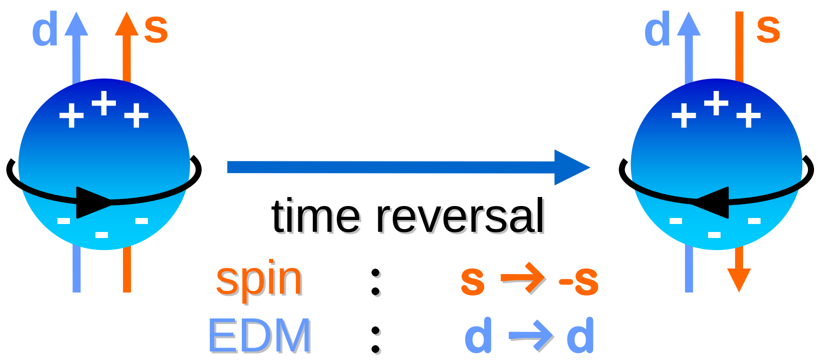
OUTLINE:

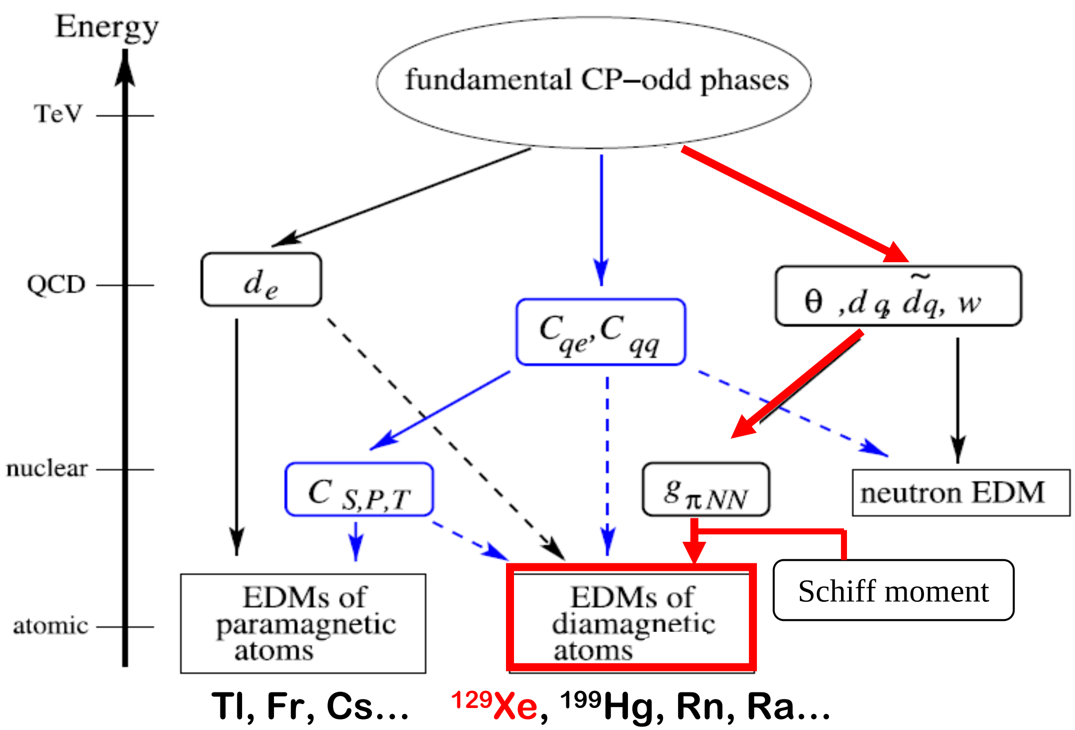
1. Introduction
2. "Optically coupled" spin maser
3. Present status
4. Summary

Electric dipole moment (EDM)



$d \neq 0$: Violation of T
⇒ Violation of CP (CPT theorem)

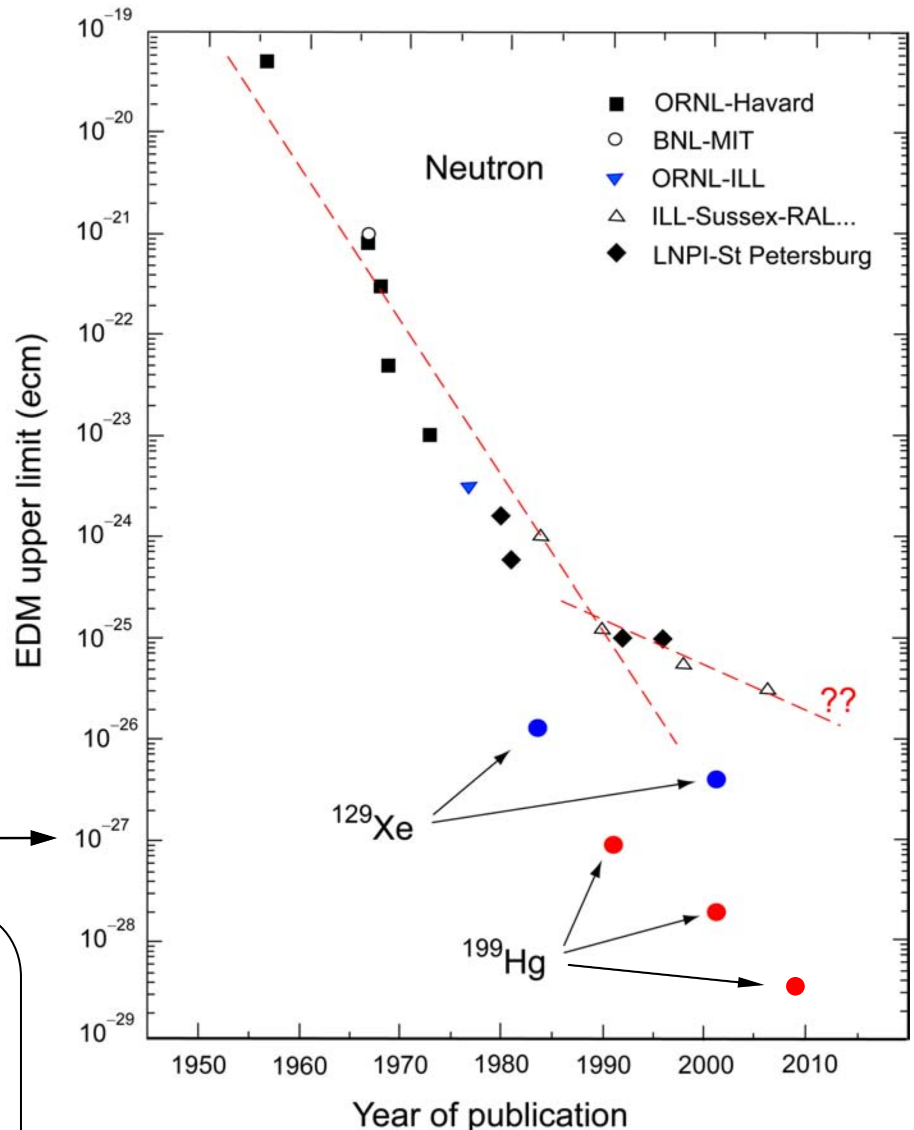
M. Pospelov and A. Ritz,
Annals of Phys. 318, (2005) 119-169



EDM in diamagnetic atoms
(^{129}Xe, ^{199}Hg, Rn, Ra…)

- stable particle
- macroscopic number of particles
- P,T-violating NN interaction
- EDM generated by a nuclear Schiff moment

⇒ Probing new physics in a different facet from those in the neutron and electron EDMs



$d = 10^{-27}$ e·cm
E = 10 kV/cm

$\Delta\nu$ = 10 nHz
($\Delta\omega \approx 1°$ /day)

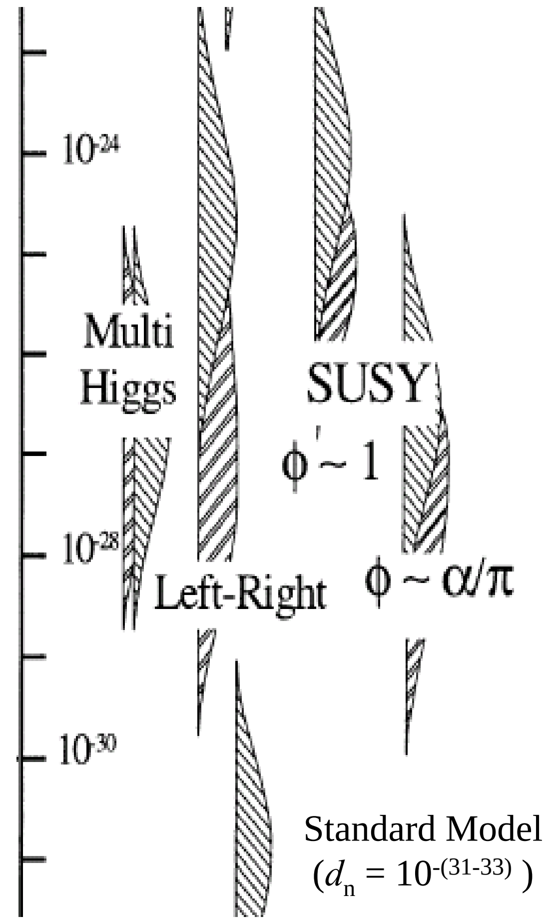
● $d(^{199}\mathrm{Hg}) < 3.1 \times 10^{-29}$ $e$cm

Grifith *et al.*, *PRL* **102** (2009) 101601

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

Rosenberry and Chupp, *PRL* **86** (2001) 22

Neutron EDM predicted values



[Pendlebury and Hinds, *NIM* A **440** (00) 471]

Detection of an EDM

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

Energy shift upon an *E*-field reversal

E // B

$$H = -\mu B - dE$$

E // −B

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

Shift in a precession frequency

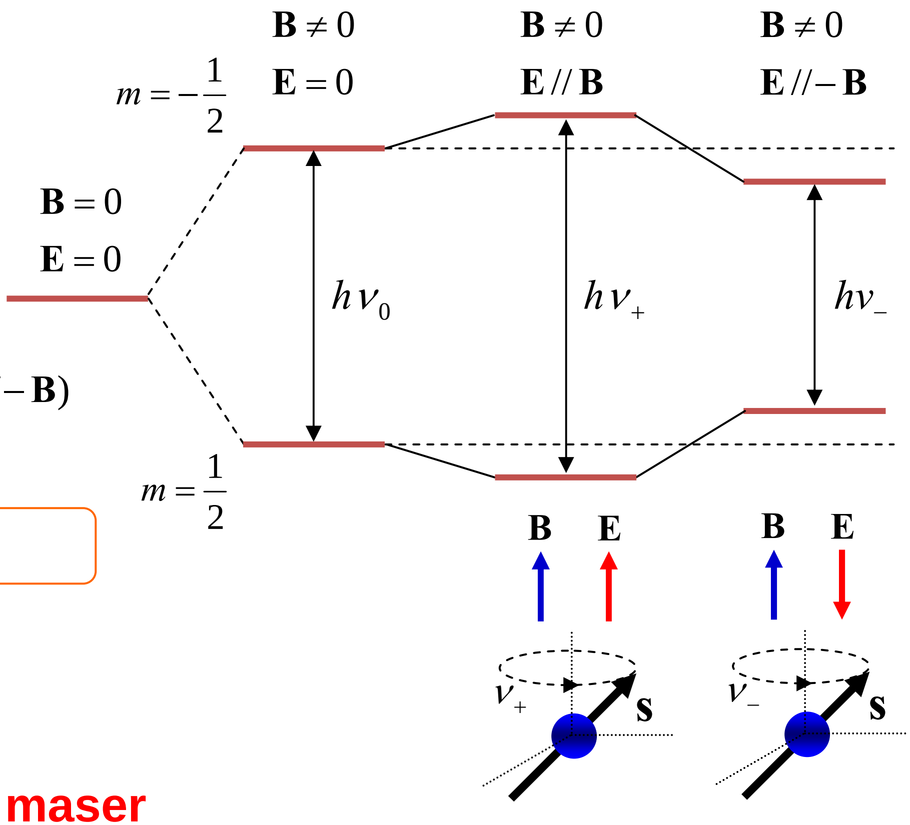
$$\nu_+ = \frac{2\mu B + 2dE}{h}\ (\mathbf{E}/\!/\mathbf{B}) \qquad \nu_- = \frac{2\mu B - 2dE}{h}\ (\mathbf{E}/\!/-\mathbf{B})$$

the difference ⇒ signal of an EDM

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

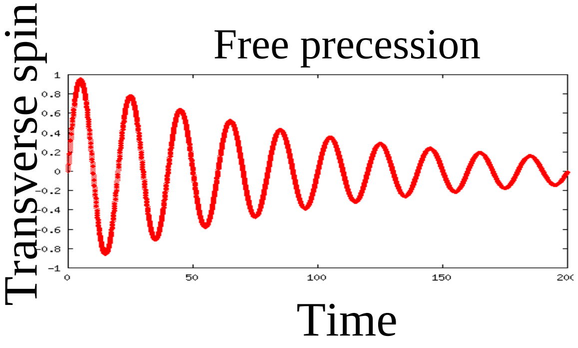
Desires long precession times => Spin maser

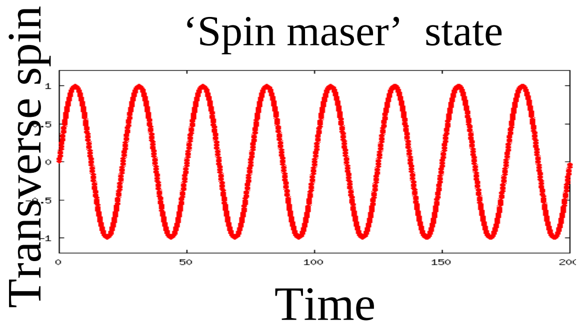
Energy levels for a spin 1/2
(for a case of μ > 0, d > 0)



<u>Key issue for a high-sensitivity EDM detection</u>:

— Realization of a long precession time





Spin maser

- ^{129}Xe polarization vector $\boldsymbol{P} = \langle \boldsymbol{I} \rangle / I$
- Static field $\boldsymbol{B}_0 = (B_x, B_y, B_0)$

- $\boldsymbol{P}$ follows the Bloch equations:

$$\dot{\boldsymbol{P}} = -\gamma \boldsymbol{B} \times \boldsymbol{P} - \frac{1}{T_{1,2}} \boldsymbol{P}$$

or,

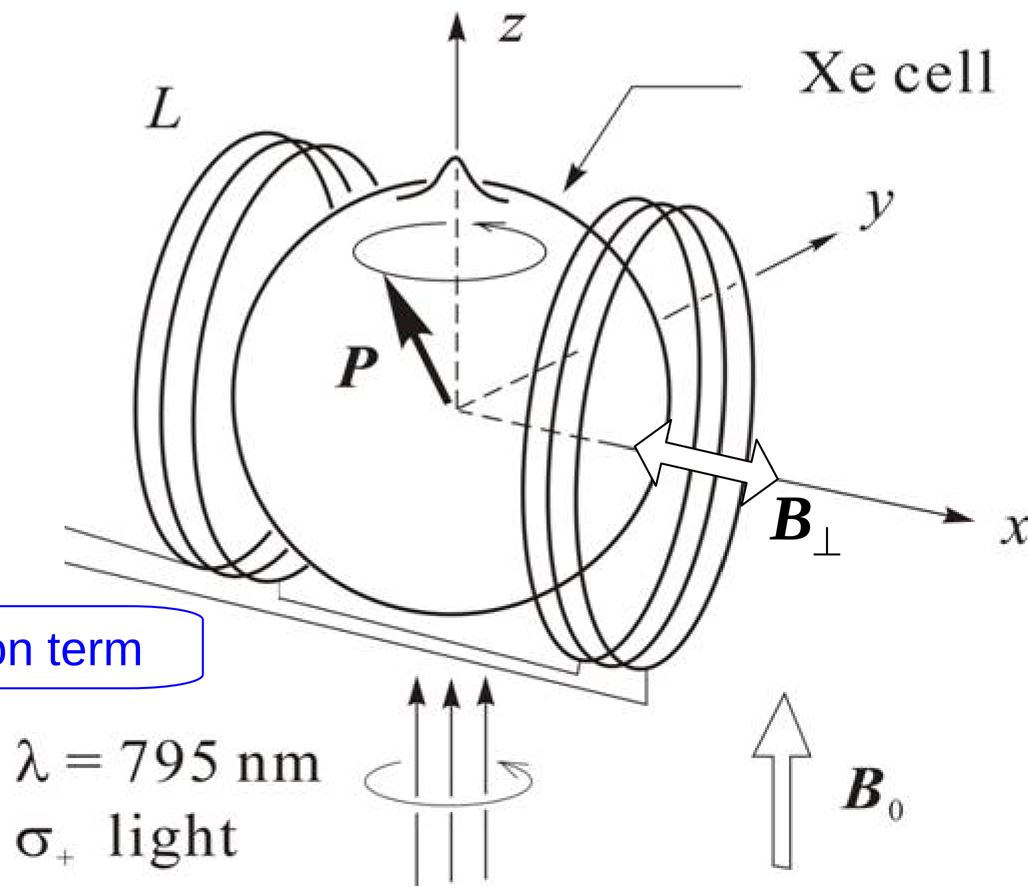
$$\frac{\mathrm{d}P_x}{\mathrm{d}\,t} = \gamma\left(P_y B_0 - P_z B_y\right) - \frac{P_x}{T_2},$$

$$\frac{\mathrm{d}P_y}{\mathrm{d}\,t} = \gamma\left(P_z B_x - P_x B_0\right) - \frac{P_y}{T_2},$$

$$\frac{\mathrm{d}P_z}{\mathrm{d}\,t} = \gamma\left(P_x B_y - P_y B_x\right) - \frac{P_z}{T_1} + \left(P_0 - P_z\right)G.$$

relaxation term

Pumping term

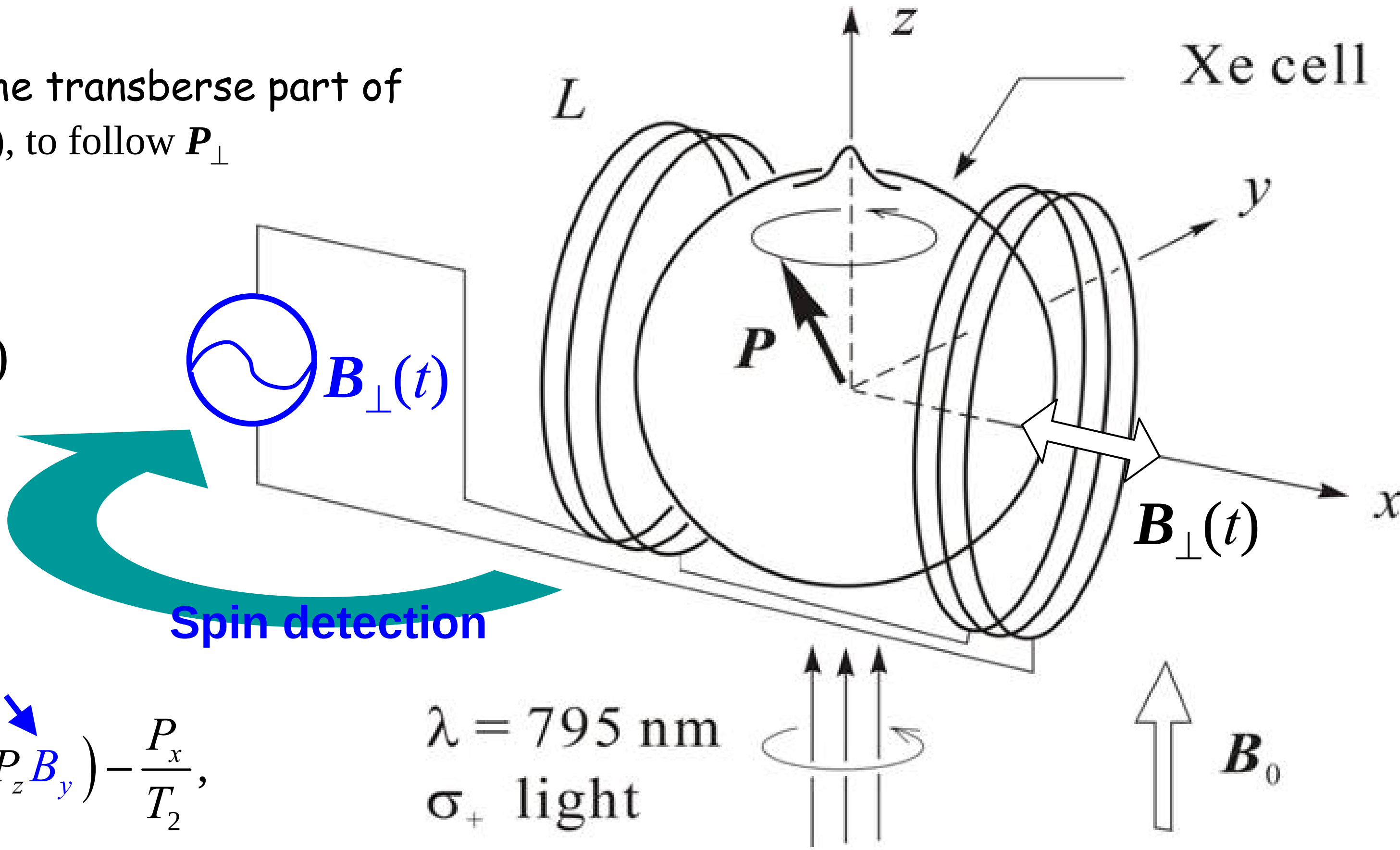


Spin Maser

- Now we devise the transberse part of the $\boldsymbol{B}$ field, $\boldsymbol{B}_\perp(t)$, to follow $\boldsymbol{P}_\perp$

$$B_x(t) \propto P_y(t)$$

$$B_y(t) \propto -P_x(t)$$



$$\frac{\mathrm{d}P_x}{\mathrm{d}\,t} = \gamma\left(P_y B_0 - P_z B_y\right) - \frac{P_x}{T_2},$$

$$\frac{\mathrm{d}P_y}{\mathrm{d}\,t} = \gamma\left(P_z B_x - P_x B_0\right) - \frac{P_y}{T_2},$$

$$\frac{\mathrm{d}P_z}{\mathrm{d}\,t} = \gamma\left(P_x B_y - P_y B_x\right) - \frac{P_z}{T_1} + \left(P_0 - P_z\right)G.$$

$$\frac{\mathrm{d}P_x}{\mathrm{d}\,t} = -\omega_0 P_y + \alpha P_z P_x - \frac{P_x}{T_2}, \qquad (1)$$

$$\frac{\mathrm{d}P_y}{\mathrm{d}\,t} = \omega_0 P_x + \alpha P_z P_y - \frac{P_y}{T_2}, \qquad (2)$$

$$\frac{\mathrm{d}P_z}{\mathrm{d}\,t} = -\alpha\left(P_x P_x + P_y P_y\right) - \frac{P_z}{T_1} + \left(P_0 - P_z\right)G. \qquad (3)$$

$$\left(\begin{aligned} B_x &\equiv \frac{\alpha}{\gamma} P_y \\ B_y &\equiv -\frac{\alpha}{\gamma} P_x \\ \omega_0 &\equiv -\gamma B_0 \end{aligned}\right)$$

Taking (1) + i (2) and setting $P_x(t) + iP_y(t) \equiv e^{i\omega t}\tilde{P}_\perp(t)$

$$\frac{\mathrm{d}\tilde{P}_\perp}{\mathrm{d}\,t} = \left[\left(\alpha P_z - \frac{1}{T_2}\right) - i\left(\omega - \omega_0\right)\right]\tilde{P}_\perp, \qquad (4)$$

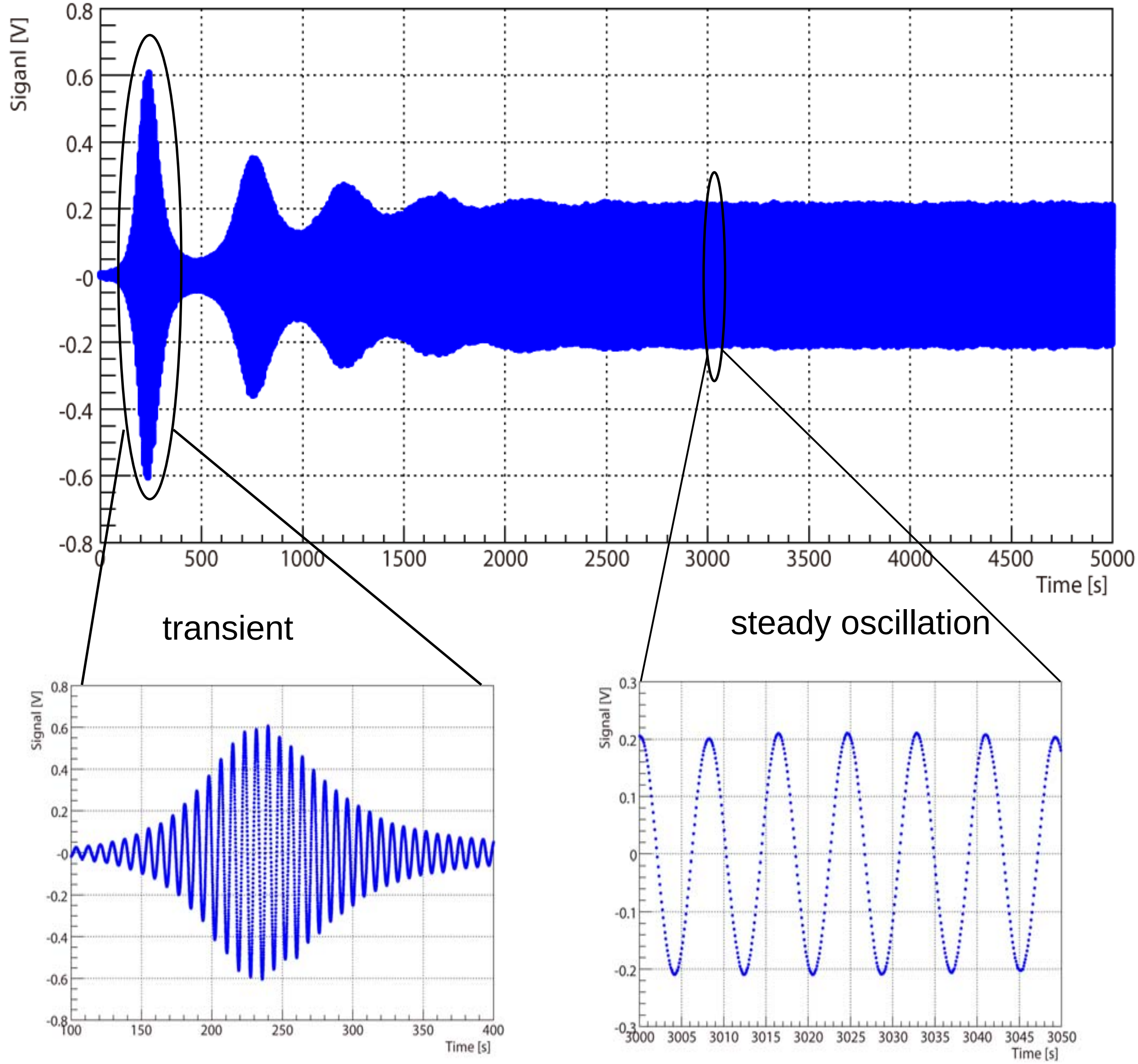
$$\frac{\mathrm{d}P_z}{\mathrm{d}\,t} = -\alpha\left|\tilde{P}_\perp\right|^2 - \frac{P_z}{T_1} + \left(P_0 - P_z\right)G. \qquad (3')$$

The steady state solutions $\left(\frac{\mathrm{d}\tilde{P}_\perp}{\mathrm{d}\,t} = 0 \ \text{ and } \ \frac{\mathrm{d}P_z}{\mathrm{d}\,t} = 0\right).$

- Trivial solution: $\tilde{P}_\perp^{\,\mathrm{eq}} = 0, \quad P_z^{\,\mathrm{eq}} = \frac{GT_1}{GT_1 + 1} P_0$

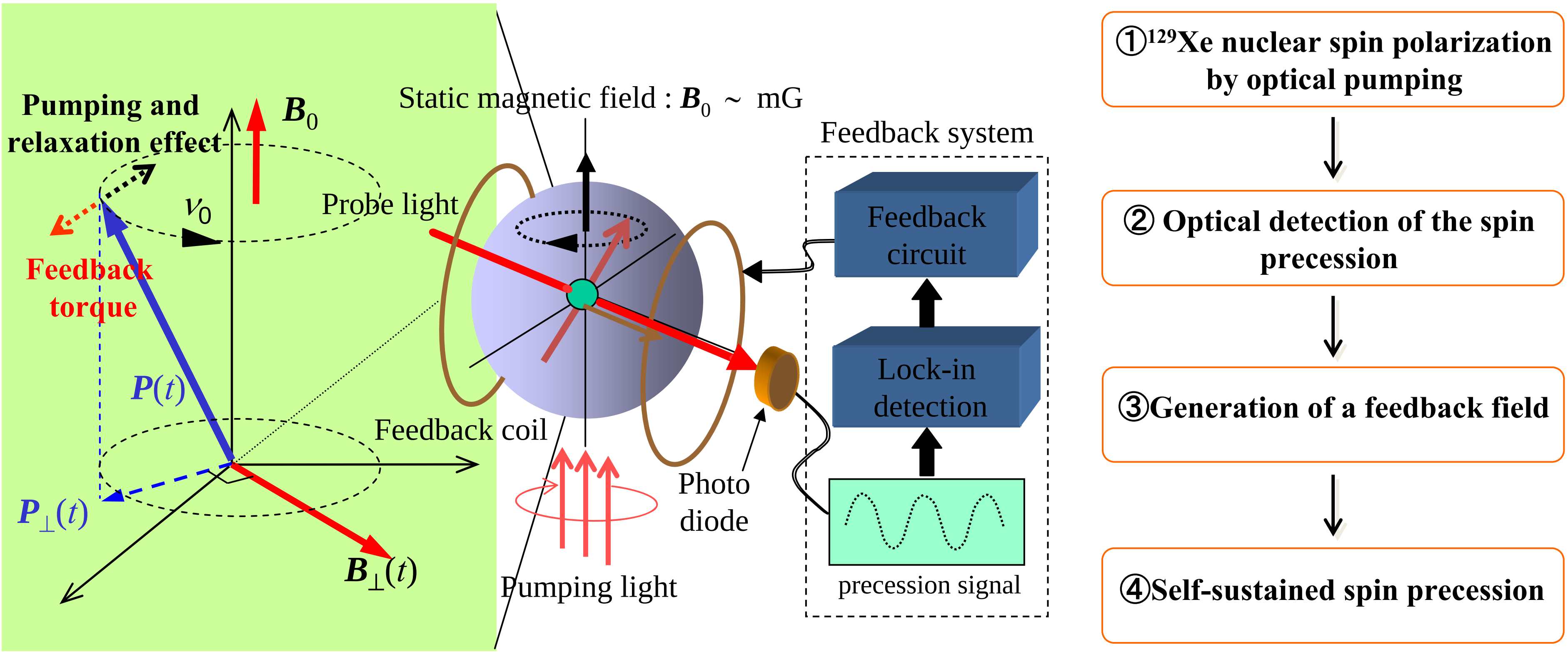
- Non-trivial solution: $$\boxed{\left|\tilde{P}_\perp\right|^{\mathrm{eq}} = \sqrt{\frac{G}{\alpha}\left(P_0 - \frac{1 + 1/GT_1}{\alpha T_2}\right)}, \quad P_z^{\,\mathrm{eq}} = \frac{1}{\alpha T_2}, \quad \text{with} \quad \omega = \omega_0.}$$

Maser oscillation



Spin maser

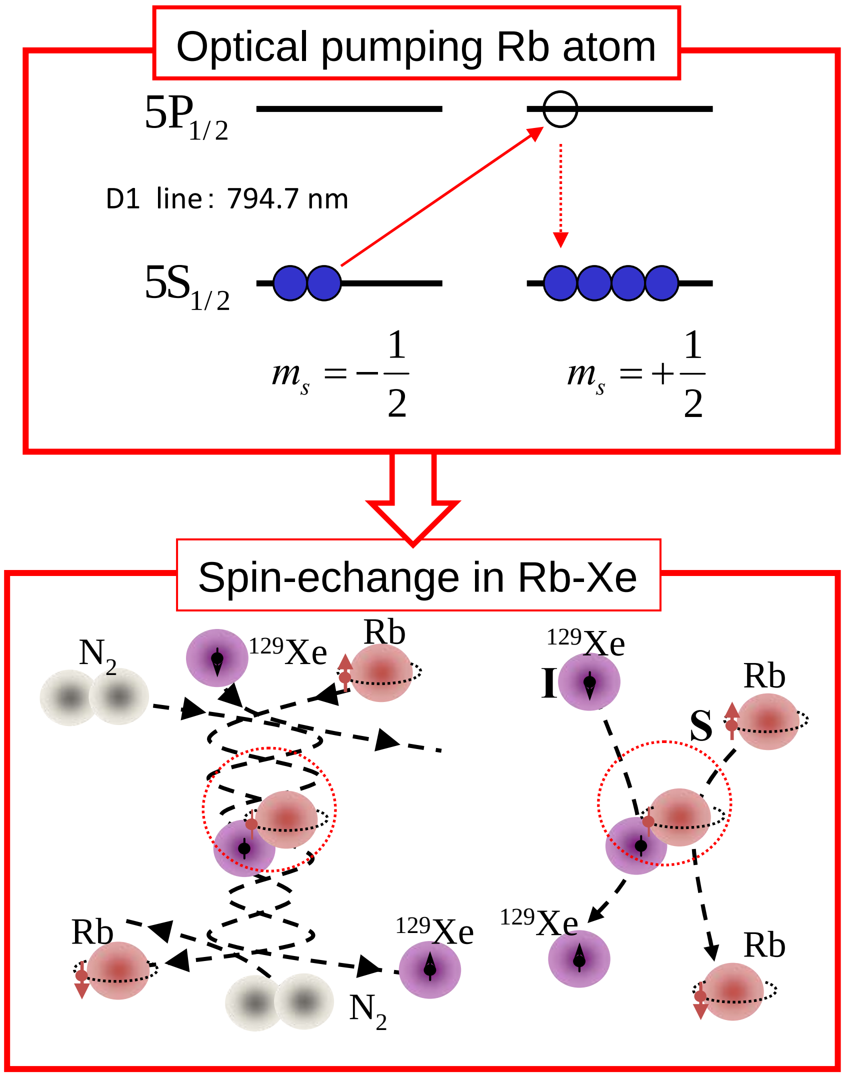
"Optically coupled" spin maser
with a feedback field generated from optical spin detection



Realization of maser oscillation at very low fields (≤ mG)
Suppression of drifts in the B_0 field => Suppression of drifts in ν

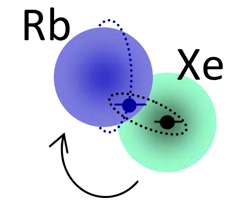
Spin polarization of ^{129}Xe and Optical detection of nuclear precession

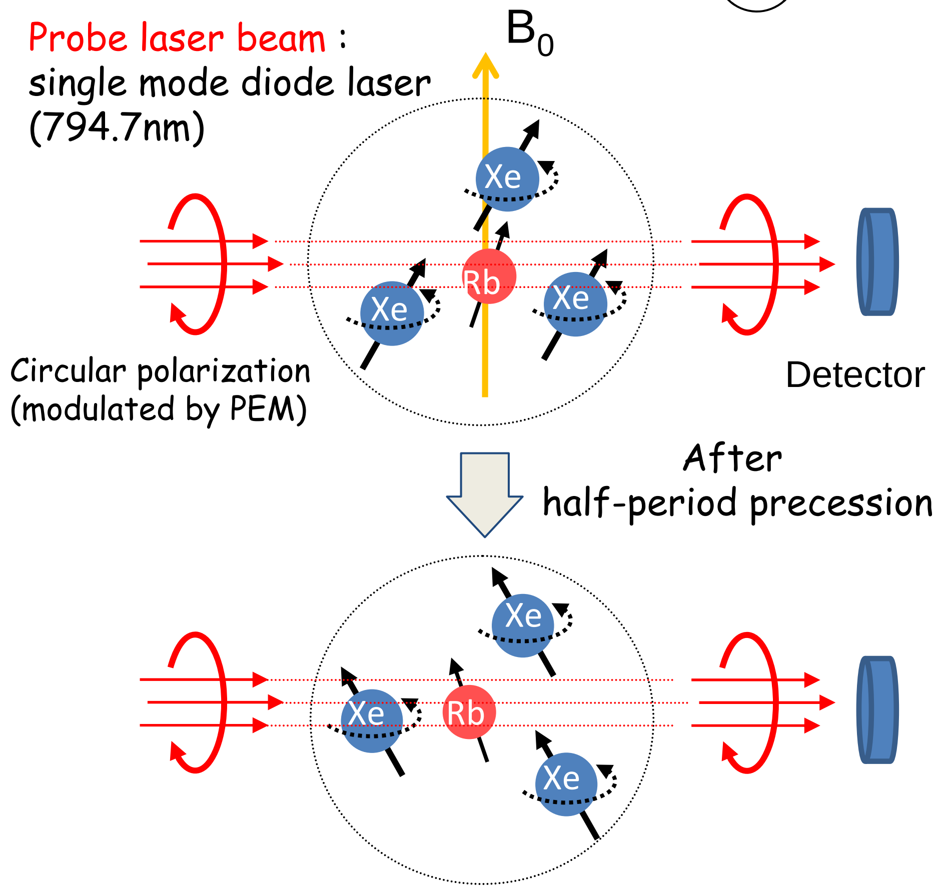
Spin polarization of ^{129}Xe



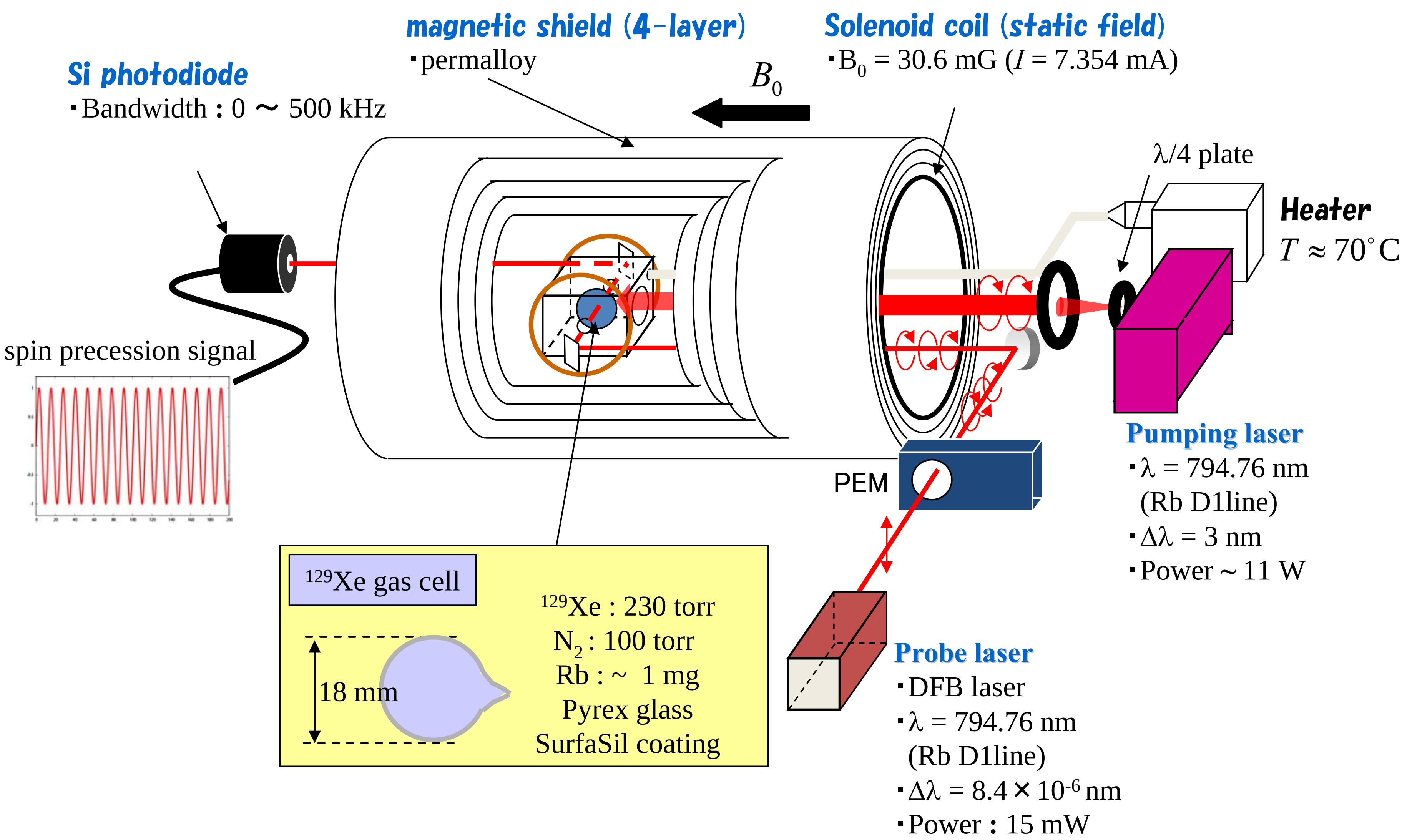
Detection of precession of ^{129}Xe

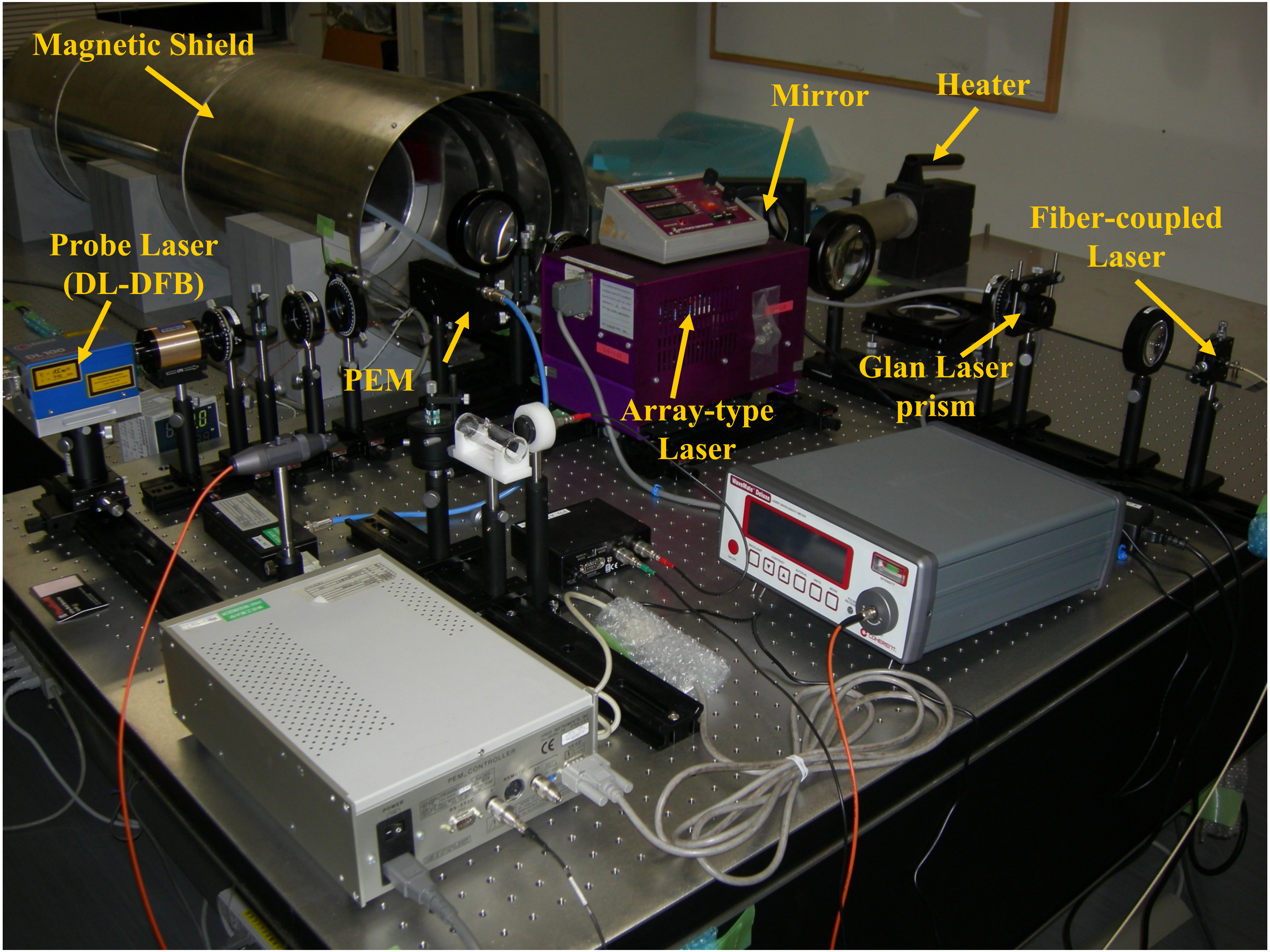
Transverse polarization transfer :
^{129}Xe nuclei → Rb atoms (re-pol)

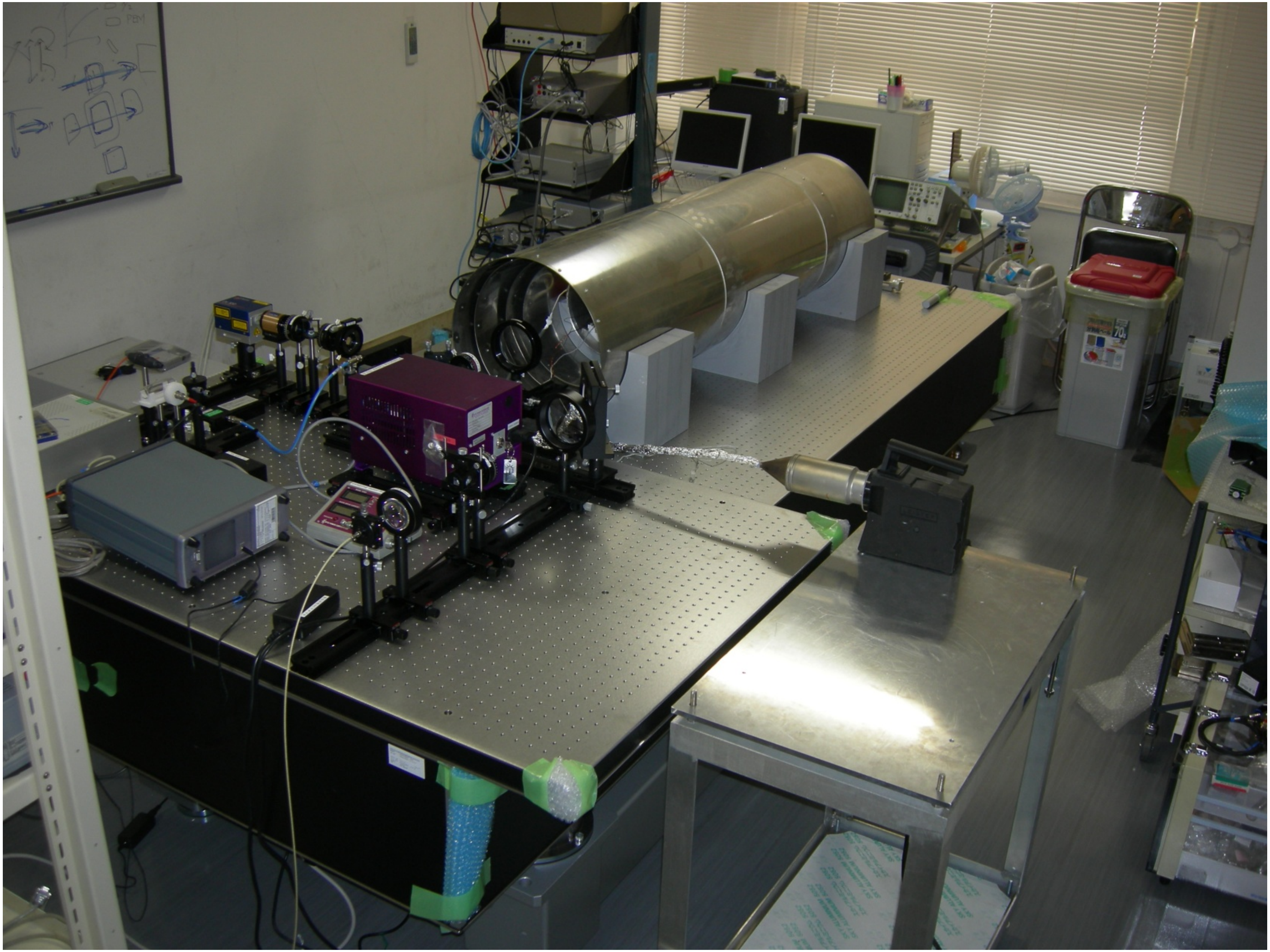




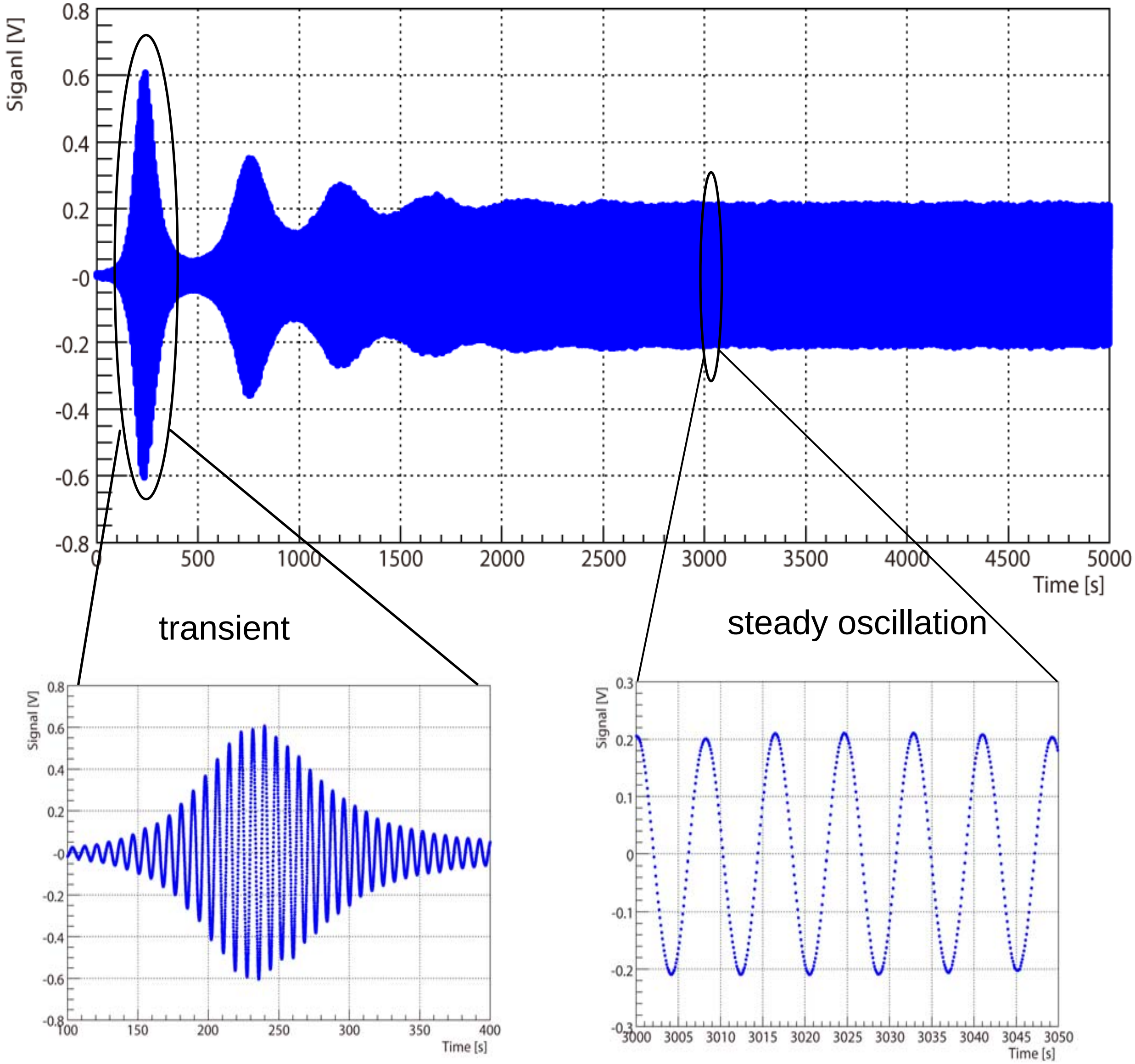
Setup for the maser experiment



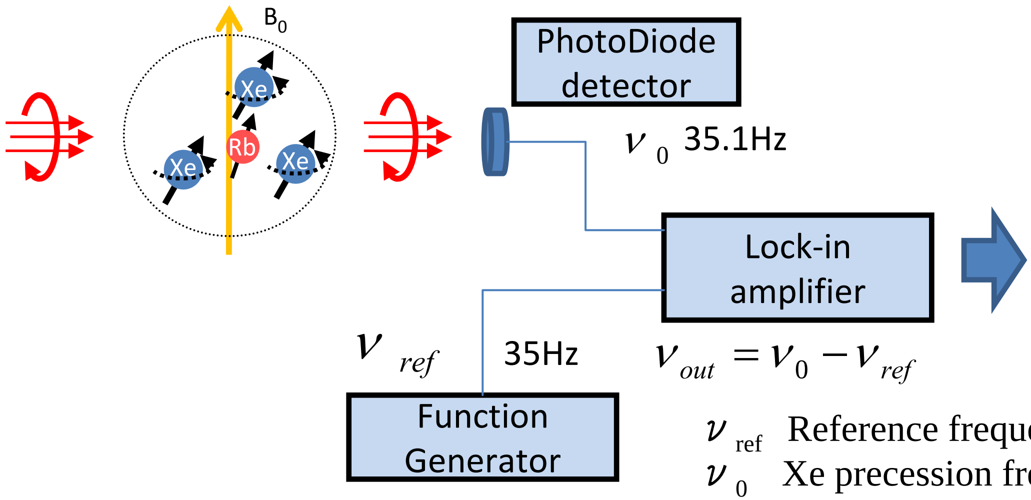

Magnetic Shield
Mirror
Heater
Probe Laser
(DL-DFB)
Fiber-coupled
Laser
PEM
Glan Laser
prism
Array-type
Laser



Maser oscillation

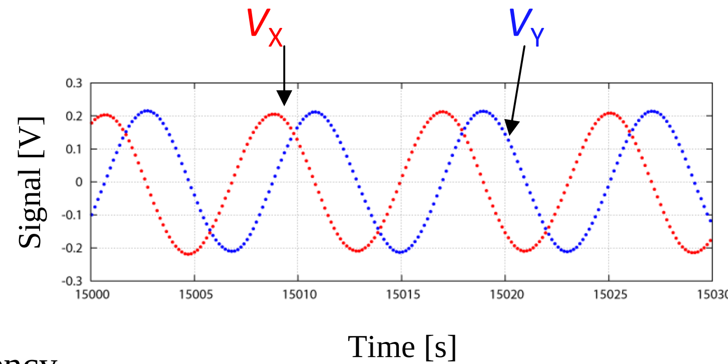


Frequency determination



$\nu_{\rm ref}$ Reference frequency
ν_0 Xe precession freq.

Lock-in Amplifier output



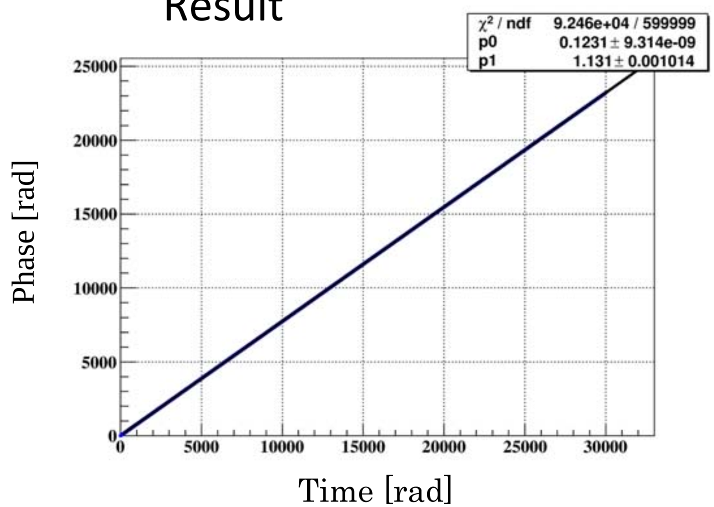
- Lock-in amplifier output signals

$$V_X = \cos(2\pi(\nu_{\rm ref} - \nu_0)t + (\phi_{\rm ref} - \phi_0))$$
$$V_Y = \sin(2\pi(\nu_{\rm ref} - \nu_0)t + (\phi_{\rm ref} - \phi_0))$$

- Phase

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

Result



fitting function

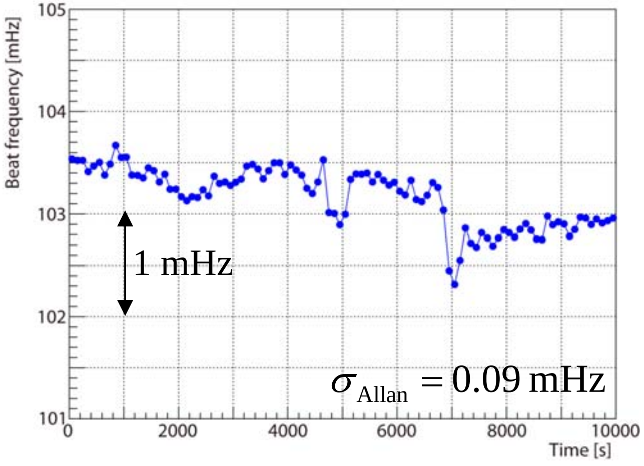
$$\boxed{f(x) = 2\pi a x + b}$$

$\Delta a =$ 9.3×10^{-9} Hz
freq. precision

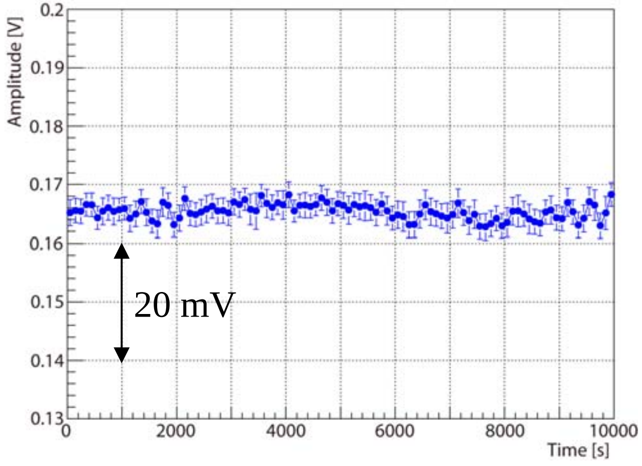
Frequency and amplitude fluctuations

Array-type laser

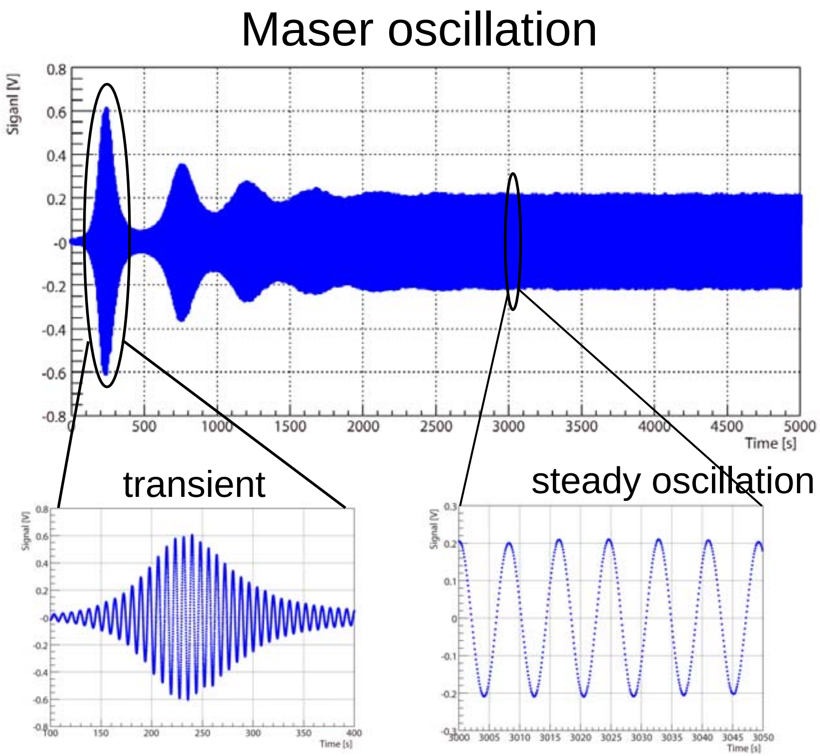
Frequency variation (100 sec)

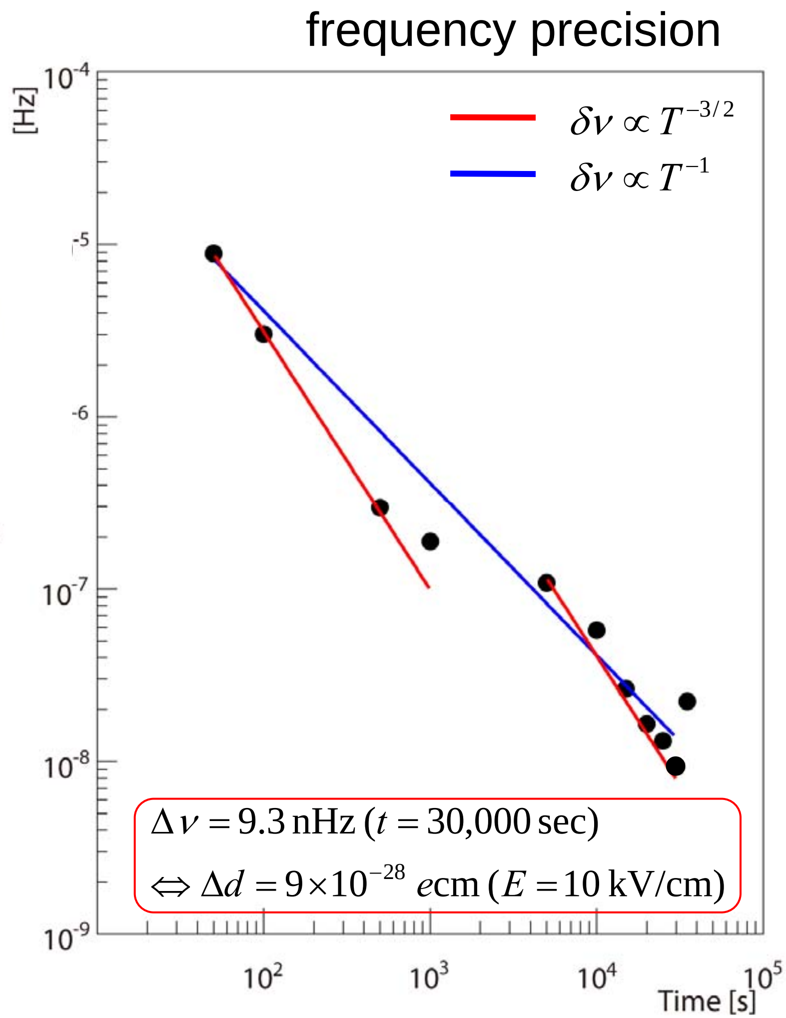


Amplitude variation (100 sec)



Spin maser

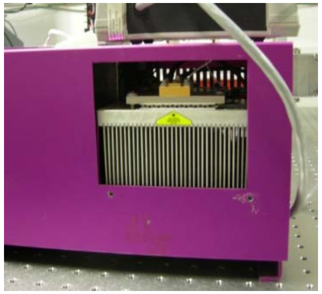

Maser oscillation
Siganl [V]
Time [s]
transient
steady oscillation


frequency precision
[Hz]
$\delta\nu \propto T^{-3/2}$
$\delta\nu \propto T^{-1}$
$\Delta\nu = 9.3\,\mathrm{nHz}\ (t = 30{,}000\ \mathrm{sec})$
$\Leftrightarrow \Delta d = 9\times10^{-28}\ e\mathrm{cm}\ (E = 10\ \mathrm{kV/cm})$
Time [s]

Ongoing developments

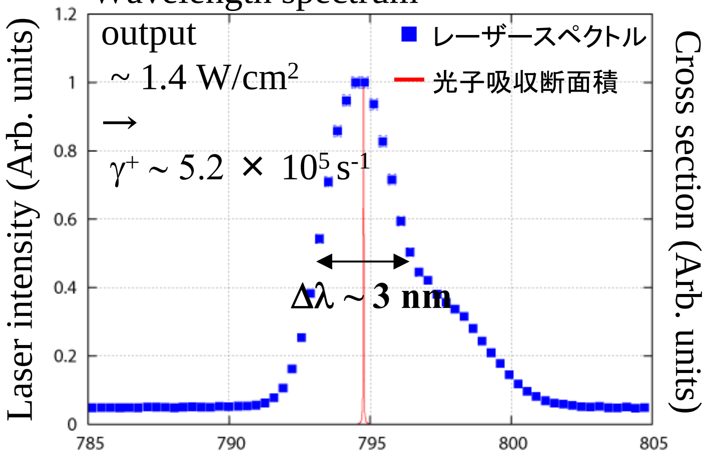
- Pumping laser
- Polarization in double cell
- B_0 stabilization
- Simulation study of frequency precision
- Magnetometry

Pumping lasers

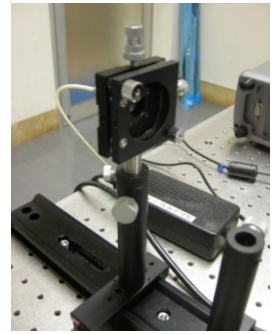


Array-type laser
・OPC-A018-795-CSPS/L
(OPTO POWER
CORPORATION)

Wavelength spectrum



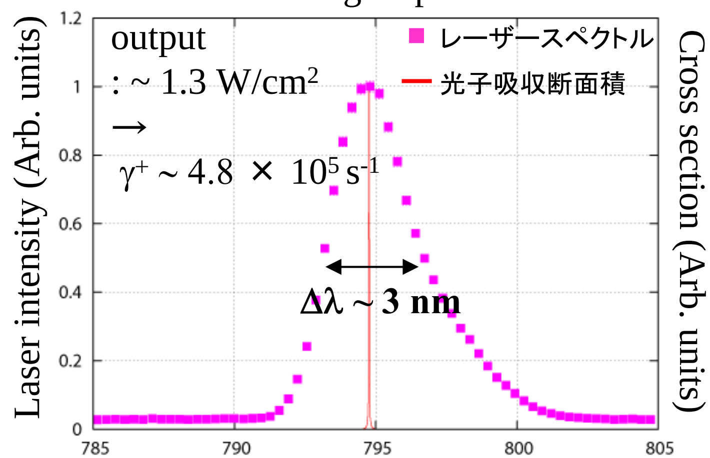
メーザー発振テスト



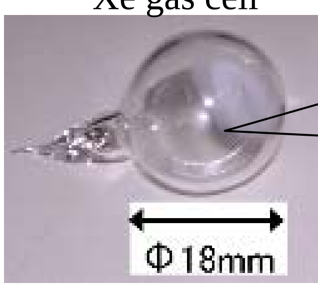
Fiber-coupled laser
・ FAP800 (COHERENT)
=> **broad illumination**

- Pol. homogeneous over the cell

Wavelength spectrum



^{129}Xe gas cell

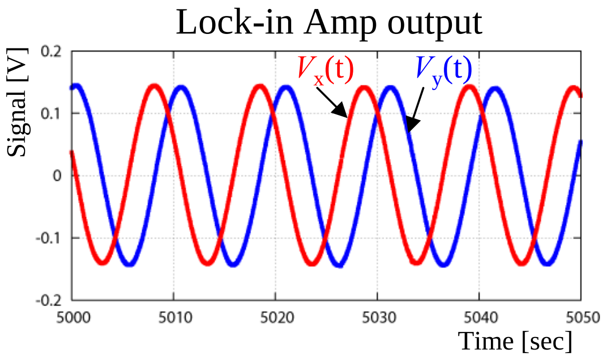


^{129}Xe : 230 torr
N_2 : 100 torr
Rb ~ 1 mg

Pressure broadening
Xe : 18.9 ± 0.5 GHz/amg
N_2 : 17.8 ± 0.3 GHz/amg

$$\Rightarrow \left.\begin{array}{l} \bullet\ \Gamma \sim 7.5\ \text{GHz} \\ \bullet\ \Delta\lambda \sim 3\ \text{nm} \end{array}\right\} \text{効率} : \sim 0.5\ \%$$

Result : drifts in amplitude



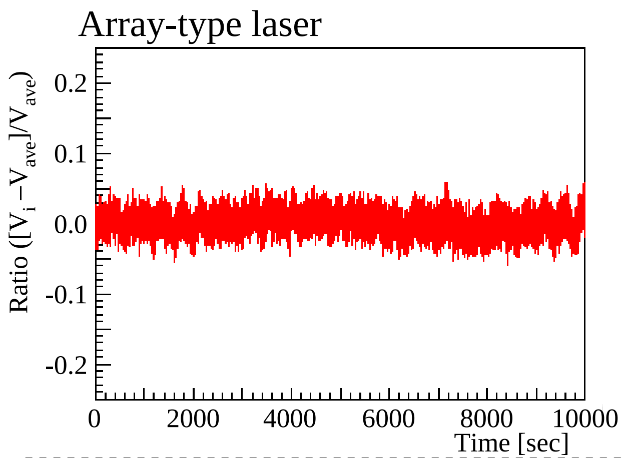
Lock-in Amp output

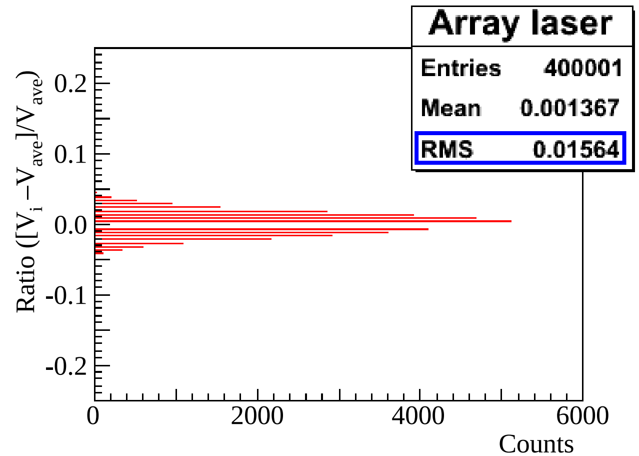
$$V_x(t) = V_{\text{amp}} \cos\left[2\pi(\nu_{\text{Xe}} - \nu_{\text{ref}})t + (\phi_{\text{Xe}} - \phi_{\text{ref}})\right]$$

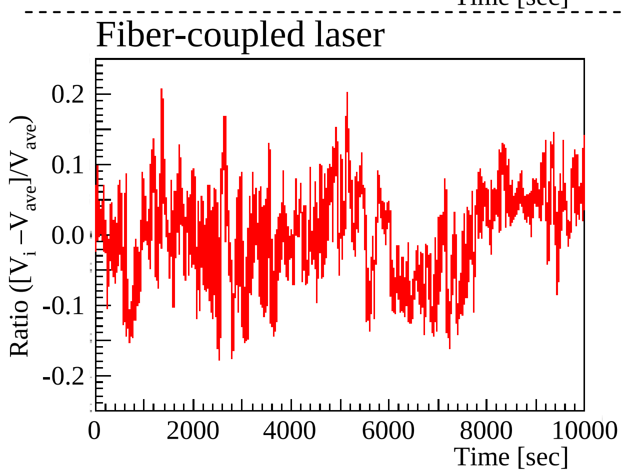
$$V_y(t) = V_{\text{amp}} \cos\left[2\pi(\nu_{\text{Xe}} - \nu_{\text{ref}})t + (\phi_{\text{Xe}} - \phi_{\text{ref}}) - \pi/2\right]$$

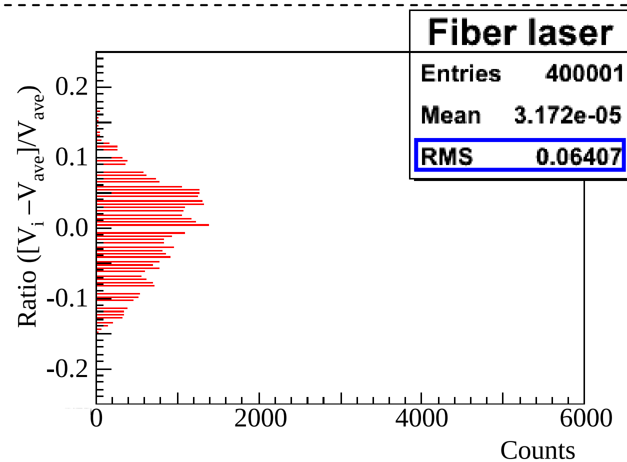
$$= V_{\text{amp}} \sin\left[2\pi(\nu_{\text{Xe}} - \nu_{\text{ref}})t + (\phi_{\text{Xe}} - \phi_{\text{ref}})\right]$$

$$\Rightarrow V_{\text{amp}} = \sqrt{V_x^2(t) + V_y^2(t)}$$





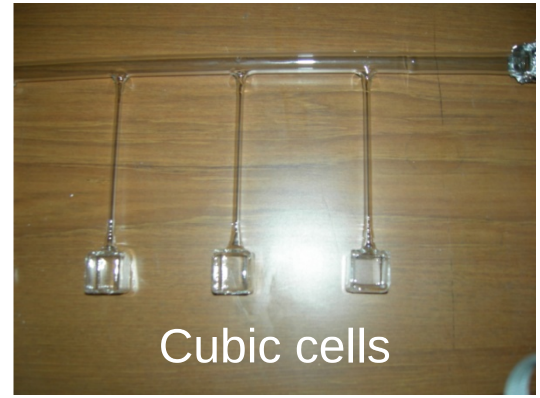


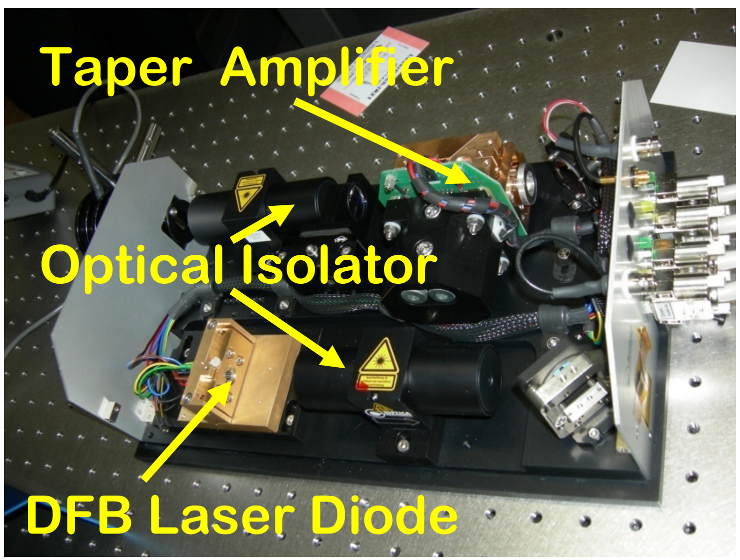


~ 4 times worsened

Future

Spherical cell
•good symmetry
•Reflection
⇒ lowering of the pumping efficiency?





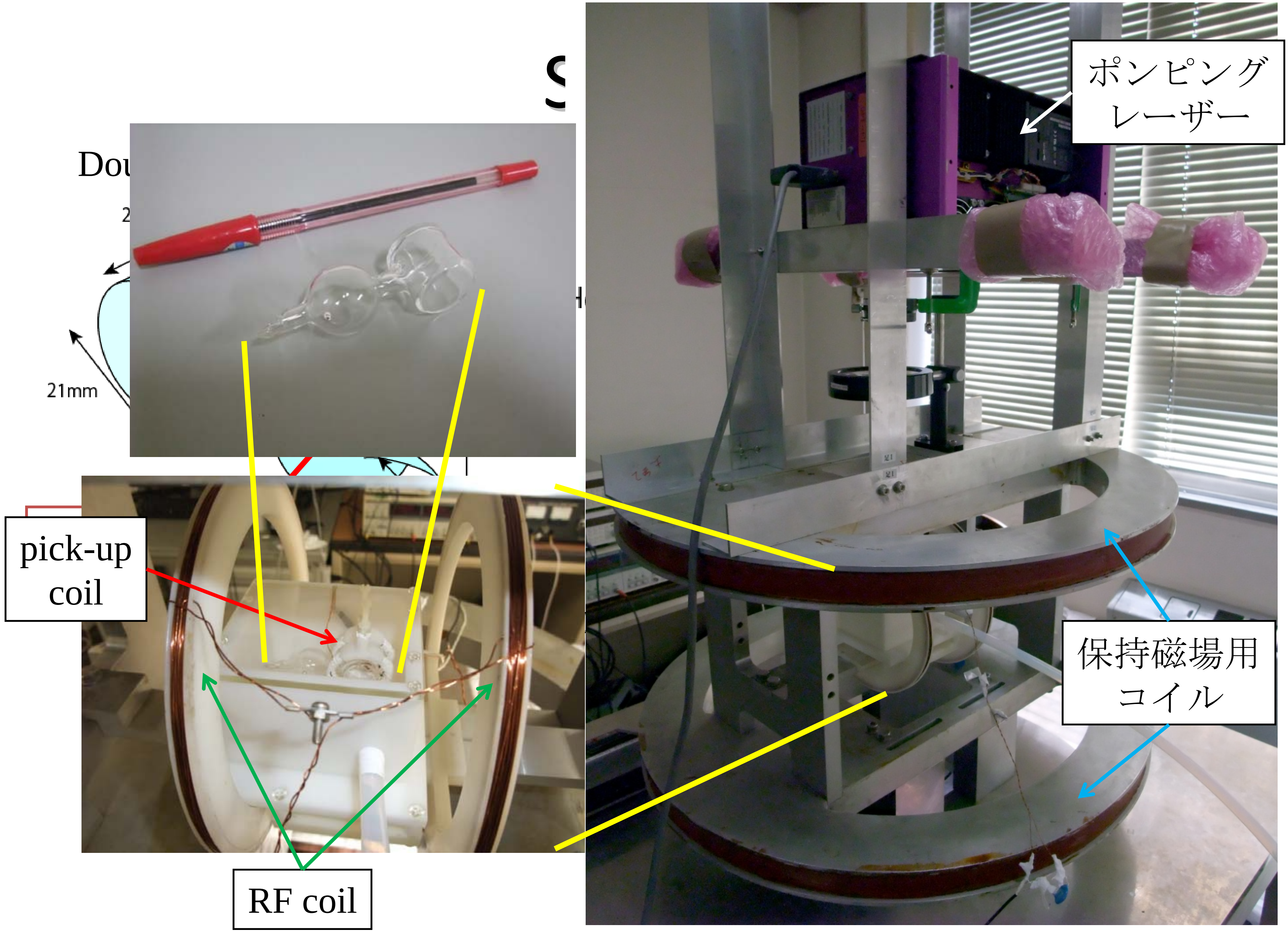
Introduction of a narrow-line laser
(TA DFB, TOPTICA)

Power : ~ 430 mW
line width : ~ 4MHz
(cf. pressure broadening ~ 7.5 GHz)

20 times enhanced pumping efficiency

$$\boxed{\gamma^{+} \sim 10^{7}\ \mathrm{sec}^{-1}}$$

=> suppression of amplitude fluctuations


ポンピング
レーザー
保持磁場用
コイル
pick-up
coil
RF coil
21mm

Determination of poraization

^{129}Xe magnetization M

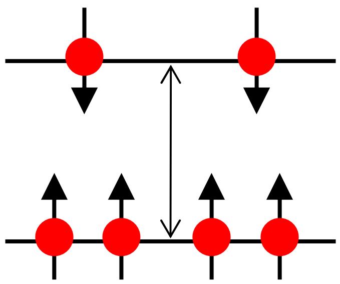
$$M \propto \gamma P N \propto V$$

$$P_{\mathrm{Xe}} = P_{\mathrm{p}} \times \frac{\gamma_{\mathrm{p}}}{\gamma_{\mathrm{Xe}}} \times \frac{V_{\mathrm{Xe}}}{V_{\mathrm{p}}} \times \frac{N_{\mathrm{p}}}{N_{\mathrm{Xe}}}$$

P : Polarization
k : Boltzmann constant
B_0 : Holding field
γ :Gyromagnetic ratio
T_k : Temperature
V : Signal
N : Number density

Proton (in water) spin polarization

$m_z = -\frac{1}{2}$



$m_z = +\frac{1}{2}$

$$N_- = N e^{-\frac{E_-}{kT}}$$

$$E_- = \tfrac{1}{2}\gamma\hbar B_0$$

$$N_+ = N e^{-\frac{E_+}{kT}}$$

$$E_+ = -\tfrac{1}{2}\gamma\hbar B_0$$

$$P_{\mathrm{p}} = \frac{N_+ - N_-}{N_+ + N_-} = \tanh\left(\frac{\gamma_{\mathrm{p}}\hbar B_0}{2kT_k}\right) = 3.06 \times 10^{-9}$$

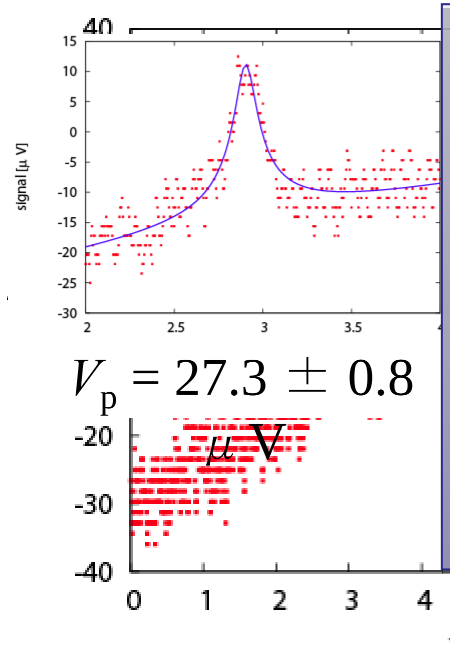
B_0 = 0.869 [mT]
γ_{p} = 2.675 × 10^8 [rad/T・s]
T_k = 290.5 [K]

Result

Calibration for ^{129}Xe spin polarization

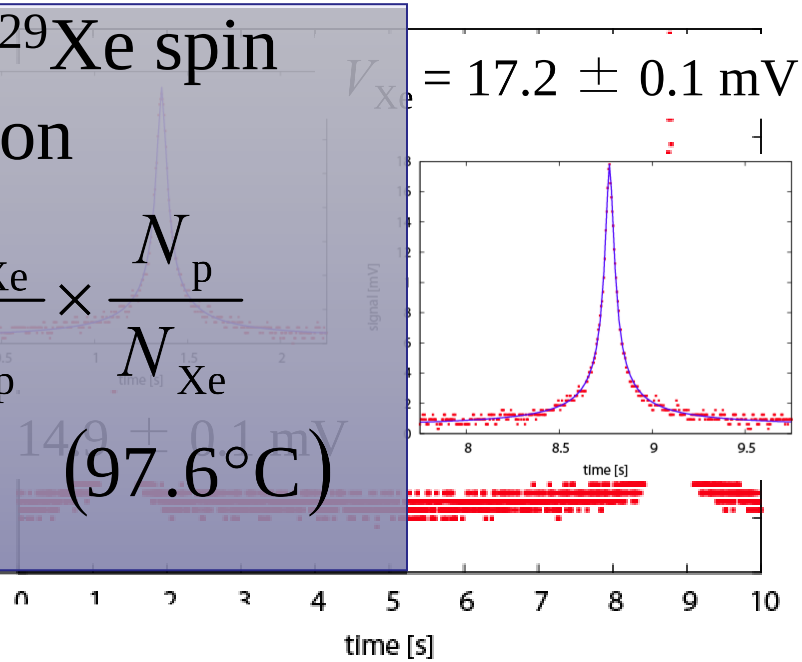
$$P_{Xe} = P_p \times \frac{\gamma_p}{\gamma_{Xe}} \times \frac{V_{Xe}}{V_p} \times \frac{N_p}{N_{Xe}}$$

$$= 23.5 \pm 1.2\% \quad (97.6°C)$$



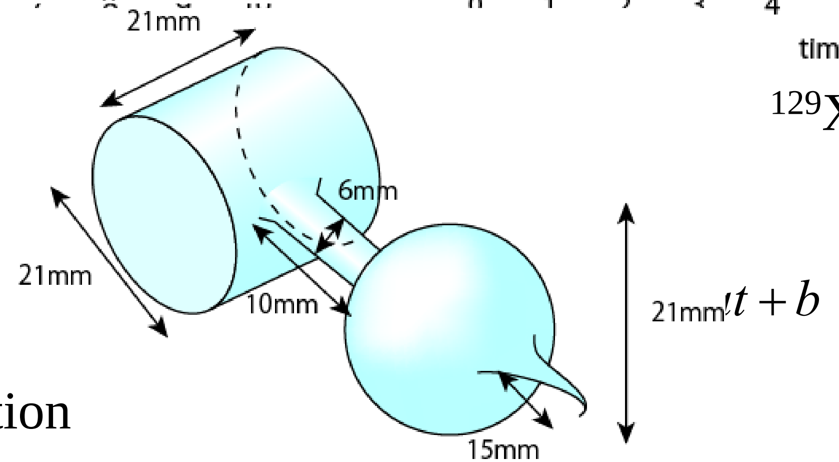
$V_p = 27.3 \pm 0.8$ μV

NMR signal from protons in water



$V_{Xe} = 17.2 \pm 0.1$ mV

^{129}Xe NMR signal



Fitting function

$t + b$

Cell test bench

Current problems

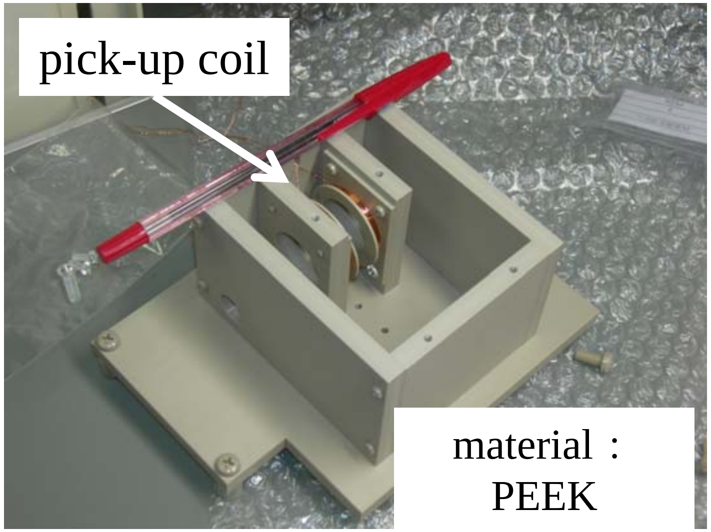
pick-up coil 固定されていない
→測定の再現性が低い, 調整が困難, 振動に弱い

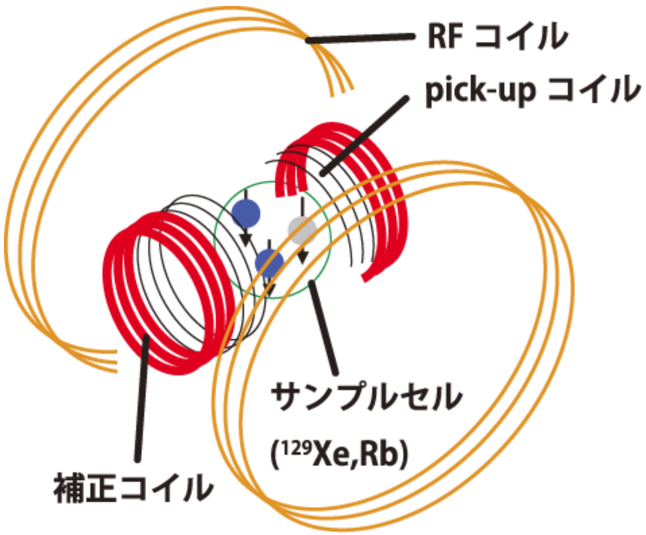
pick-up coil が振動
→NMRシグナルと同じ周波数であるRFシグナルを検出
→ノイズの発生

New system

- Incorporation of anti-vibration system
- Orthogonality adjustment mechanism for pick-up coil

High-precision, high-reproducibility assesment system for ^{129}Xe cells

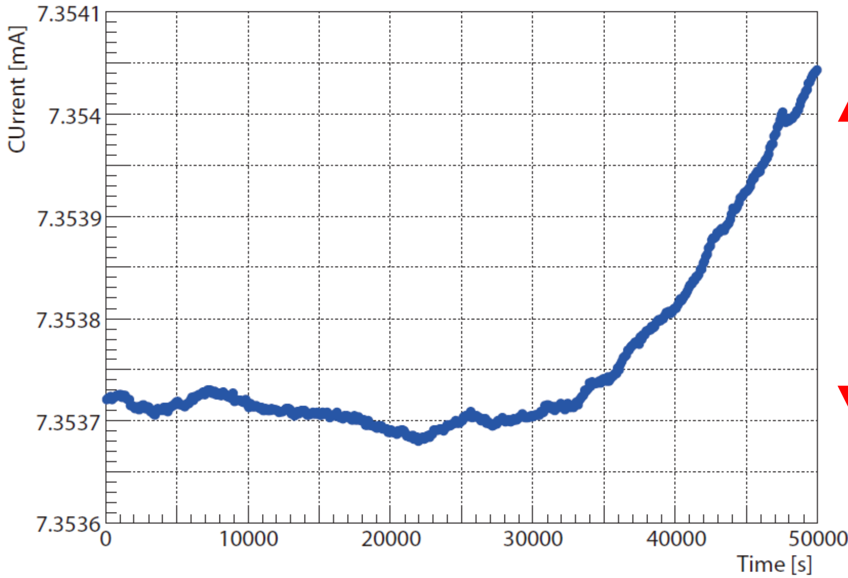




trim coil

Drifts in frequency and solenoid current

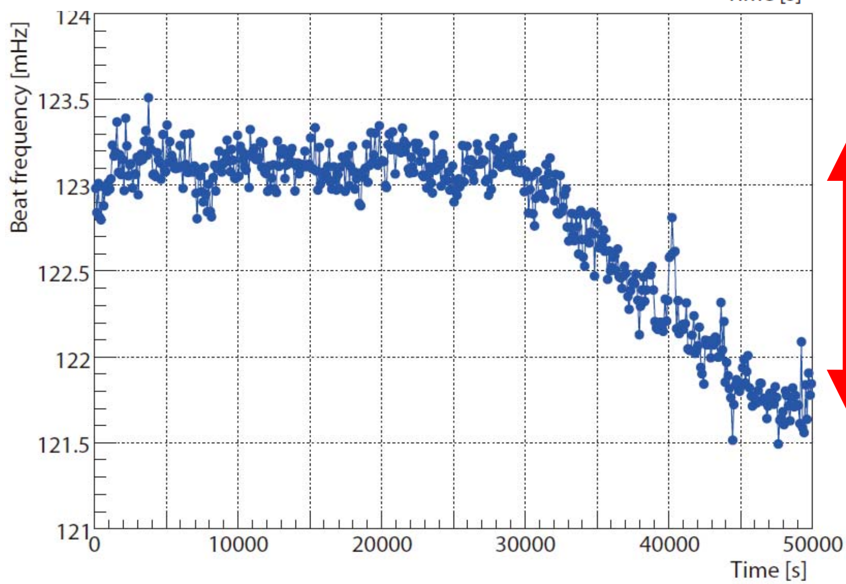
Solenoid current



300nA,
~40ppm

Drifts in frequency mostly stems from drift in the solenoid current

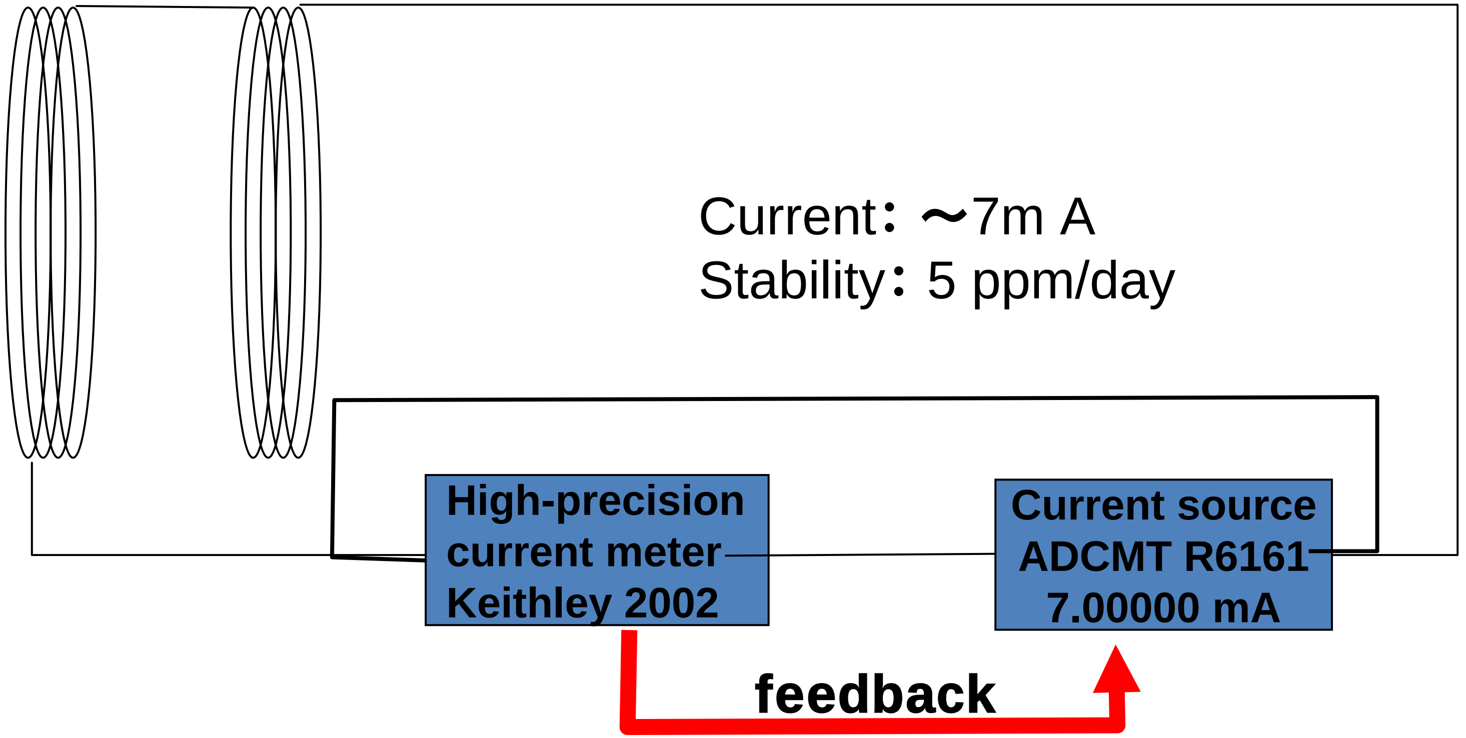
Precession frequency



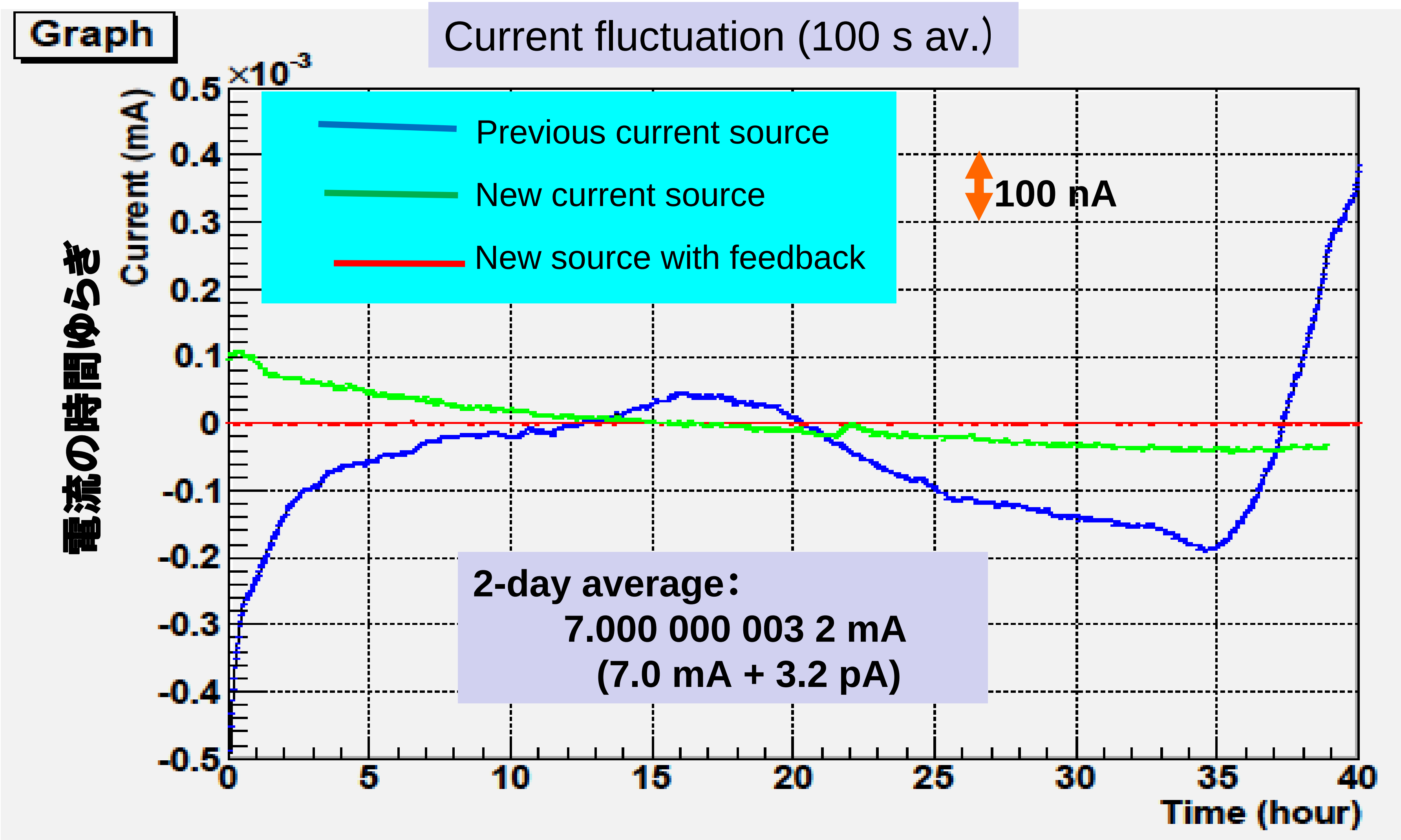
1.5mHz
~40ppm

Current stabilization

- New current source ADCMT R6161
- Deviation from the preset value (7 mA) is fedback



Stability of solenoid current



Simulation study of the frequency precision

Incorporate the phase and amplitude fluctuations of the maser signal.

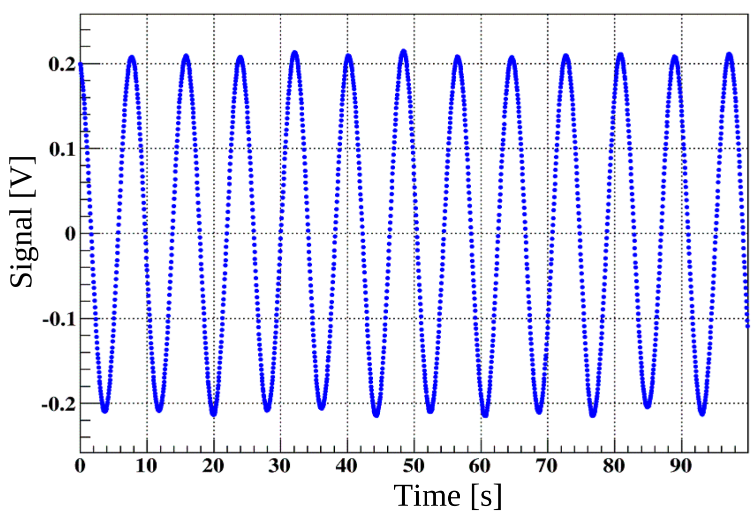
$$V_x = A\sin\theta$$

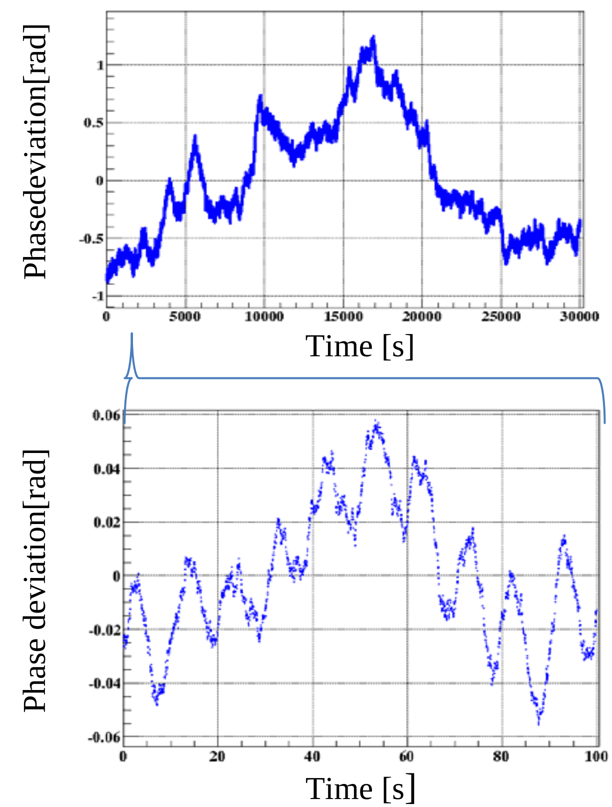
$$A = A_0 + \varepsilon(t)$$

$$\theta_n = \theta_{n-1} + 2\pi\nu\Delta t + \phi_{fluc} + \phi_{peri}$$

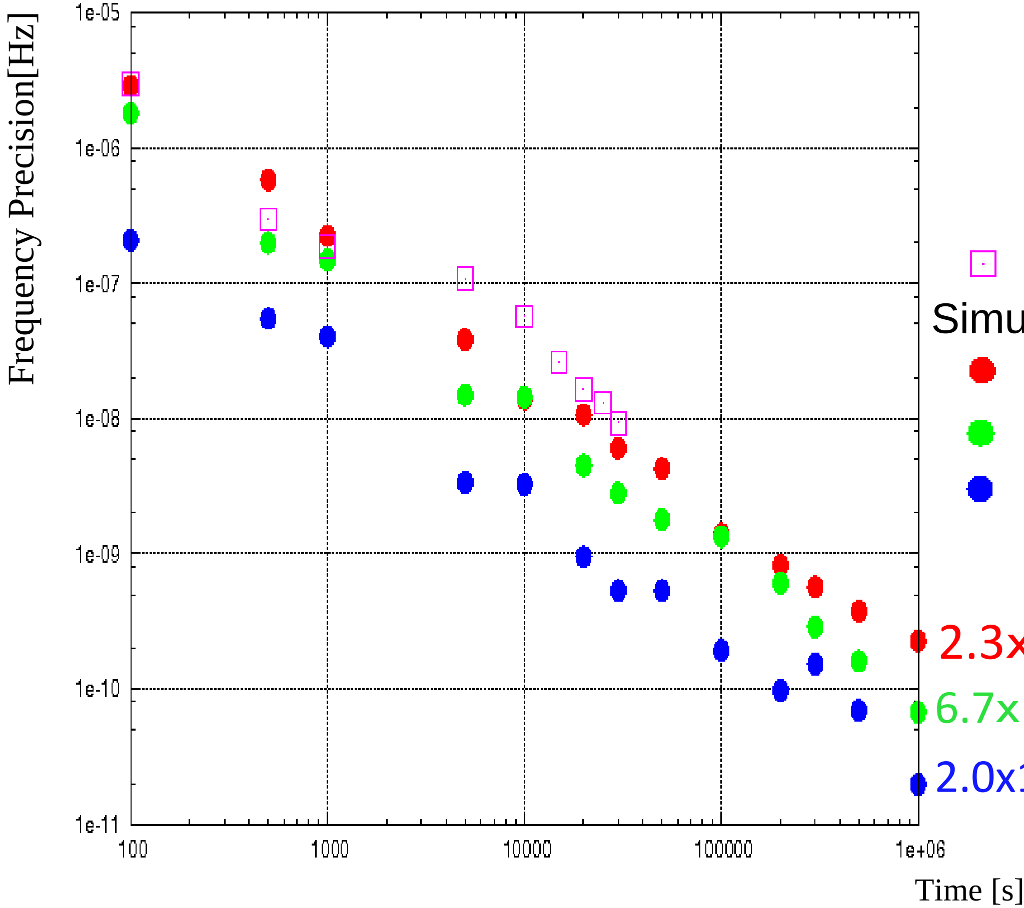
A : シグナル振幅
ε : 振幅のゆらぎ

ν : 測定周波数
ϕ_{fluc} : 位相ゆらぎ
ϕ_{peri} : 周期変動





Simulation results



Half a day 1day 12days

$$V_x = A\sin\theta$$
$$A = A_0 + \varepsilon(t)$$
$$\theta_n = \theta_{n-1} + 2\pi\nu\Delta t + \phi_{fluc} + \phi_{peri}$$

Experiment

Simulation

- σ_A , σ_ϕ , $\sigma_{\phi\ \pi\varepsilon\rho}$ ≈ the experiment
- σ_A σ_ϕ ≈ the experiment, $\sigma_{\phi\ \mathrm{peri}}$ ≈ ×0.5
- σ_A , σ_ϕ , $\sigma_{\phi\ \pi\varepsilon\rho}$ ≈ ×1/10

$2.3\mathrm{x}10^{-10}$ Hz

$6.7\mathrm{x}10^{-11}$ Hz

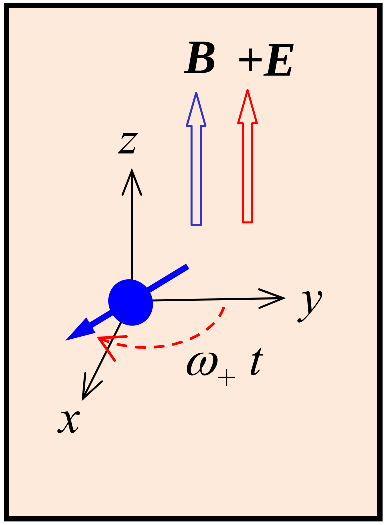
$2.0\mathrm{x}10^{-11}$ Hz

←$1.9\mathrm{x}10^{-30}$ *e*cm (E=10kV)

Should reach a 10^{-10} Hz precision in a 2-day measurement !!

Magnetometry ; Non-linear MagnetoOptical Rotation (NMOR) on Rb atoms

Field precision required in EDM measurements



$$\delta d_A \sim 10^{-28}\ ecm$$

@ E=10kV/cm

↓

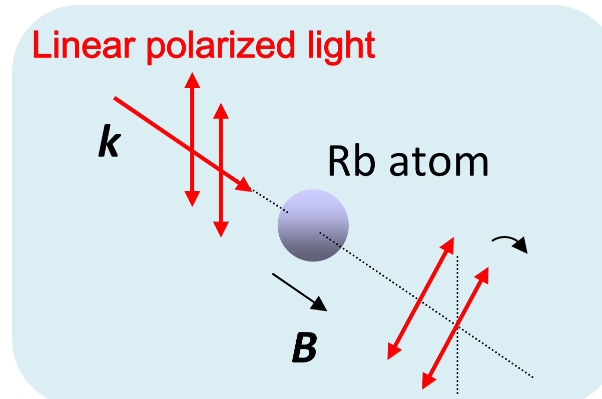
Required frequency precision

$$\delta f \approx 1\,\mathrm{nHz}$$

↓

Field $$\delta B \approx 1\,\mathrm{pG}$$

Resonant optical rotation in Rb vapor (NMOR; Nonlinear Magneto-Optical Rotation)



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

$$\delta B \sim 1\,\mathrm{pG}/\sqrt{\mathrm{Hz}}$$

Optical Pumpingmagnetometers (Rb, Cs) : 30 pG/ √Hz

Magnetometry with SQUID:

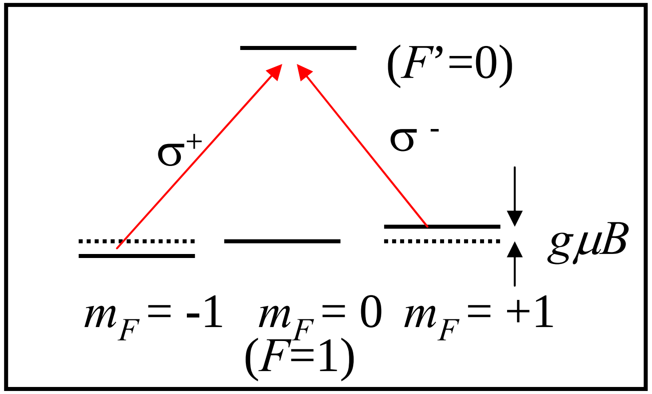
2-3 fT/ √Hz = 20-30 pG /√Hz @ He temp.
50-60 fT/ √Hz = 0.5 – 0.6 nG/ /√Hz @ liq. N_2 temp.
High-Q resonator → 0.08 fT/√Hz = 0.8 pG /√Hz

Advantages:

- Narrow width
- Operation at room temp.
- low field

NMOR

直線偏向光と原子の相互作用

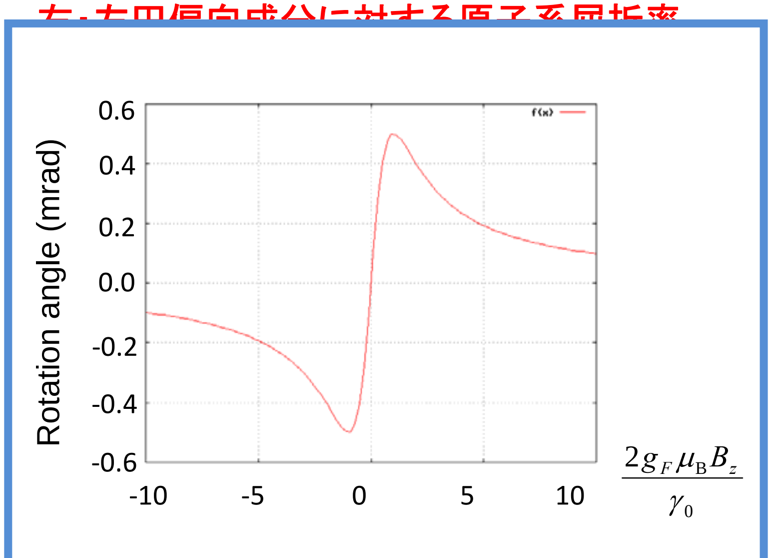


原理

1) 直線偏向光 により原子は alignment 状態になる
　　→ 原子集団の蒸気は linear dichroism を持つ

2) 原子 alignment が磁場の周りを歳差運動する
　　→ dichroism の軸が回転する

3) 回転する dichroic 軸を持つ原子と入射直線偏光ビームとの相互作用で偏光面が回転する

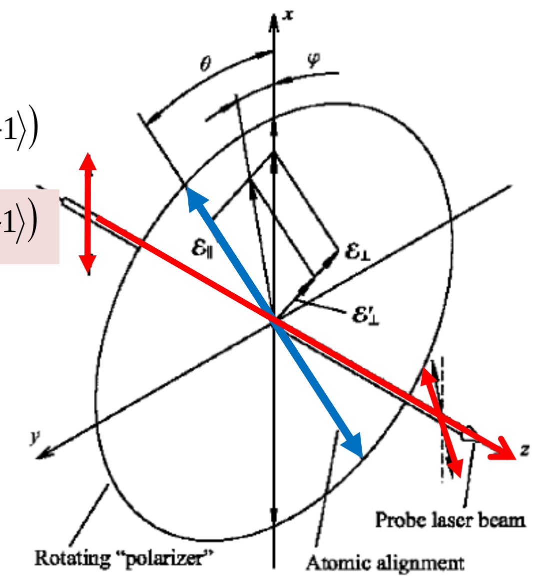


基底状態

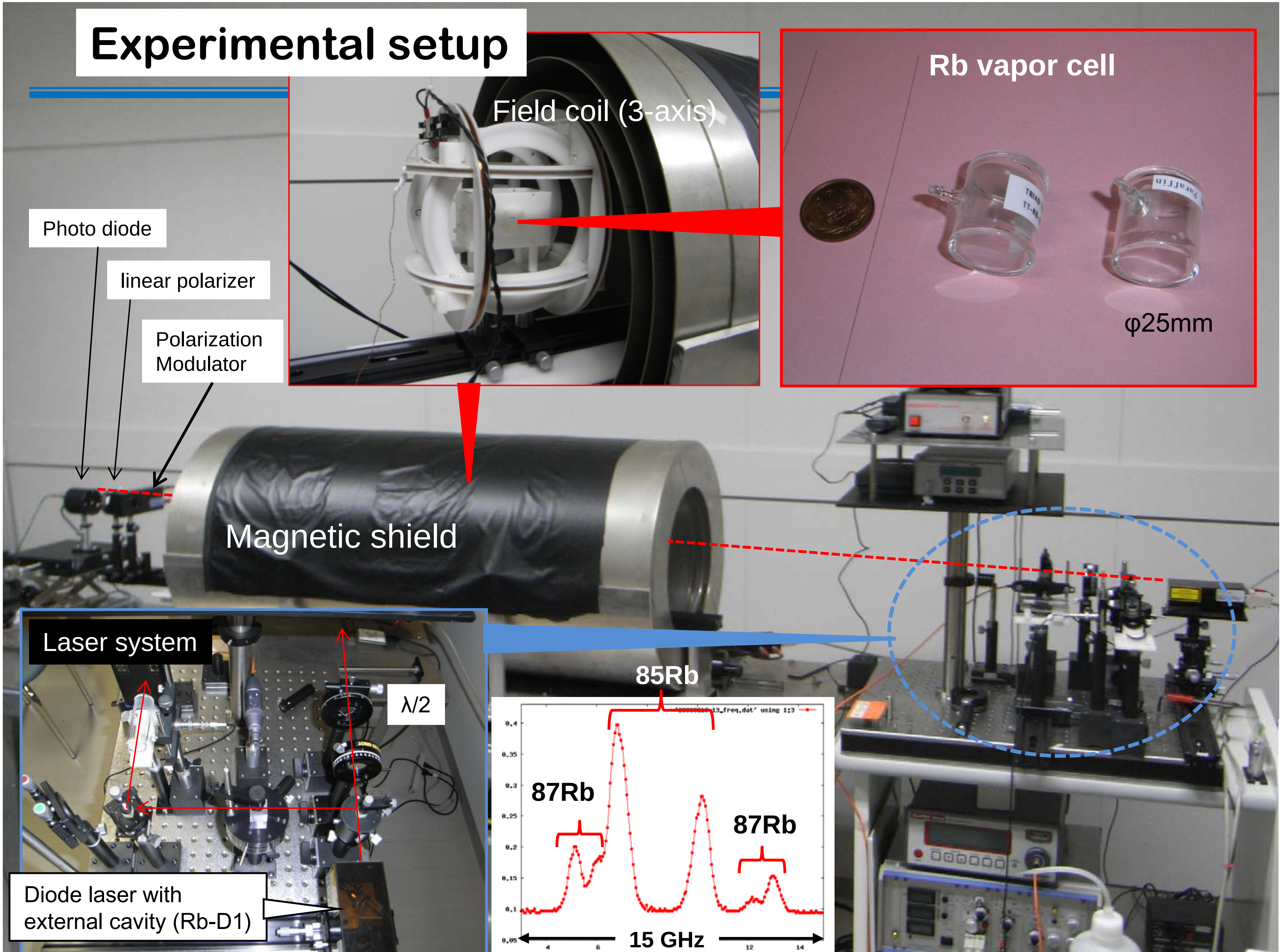
$$|+\rangle = \frac{1}{\sqrt{2}}\left(|m_F = +1\rangle + |m_F = -1\rangle\right)$$

$$|-\rangle = \frac{1}{\sqrt{2}}\left(|m_F = +1\rangle - |m_F = -1\rangle\right)$$

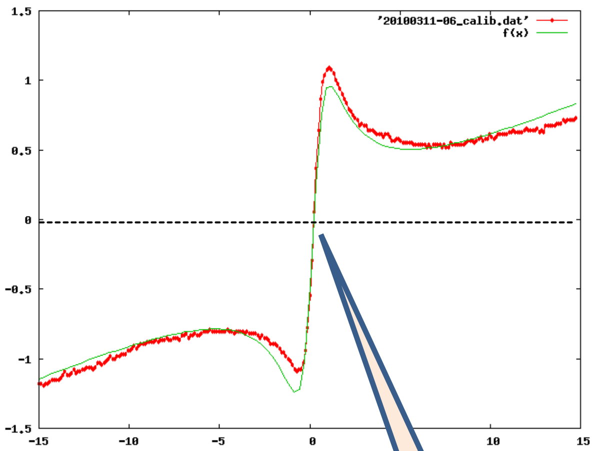
$$|0\rangle = |m_F = 0\rangle$$



Experimental setup



Sensitivity



Field sensitivity at present

Slope at 0G : $\dfrac{\partial \phi}{\partial B_z} = 2.4 \text{ rad / G}$

$$\phi_{\text{noise}} = 0.003 \text{ mrad}$$

$$\rightarrow \delta B = \phi_{noise} \left(\frac{\partial \phi}{\partial B_z} \right)^{-1} = -1.2 \times 10^{-6} [\text{G}]$$

Fitting function:

$$\varphi = \underbrace{\frac{\dfrac{2g_F \mu_B B_z / \hbar}{\gamma}}{1 + \left(\dfrac{2g_F \mu_B B_z / \hbar}{\gamma} \right)^2}}_{\text{Coherence effect}} \frac{l}{2l_0} + \underbrace{aB_z + b}_{\text{Transit effect}}$$

fitting

$$\frac{2g_F \mu_B / \hbar}{\gamma} = 1.146 \pm 0.024$$

$$(\gamma / 2\pi)^{-1} = \frac{1}{1.29 \times 10^2 [\text{s}^{-1}]} = 7.8 \, [\text{ms}]$$

Rb coherence time : ~ 8 ms

Already **1/400** times narrower compared to the transit effect-NMOR
Coherence time much longer than this is realizable.

"NMOR with 1s line-width was observed"
D. Budker et al.,PRA 62 (2000) 043403.

Residual magnetic (transverse) field
Coating procedure …..

Summary

- Precession of ^{129}Xe spins is maintained for unlimitedly long times, by application of a feedback field generated from optically detected spins. The merit of this optically coupled spin maser as a scheme for the EDM search is the capability of operation at very low B_0 fields, as mG or below.
- Frequency precision presently reached is 9.3 nHz, which corresponds to an EDM sensitivity of 9×10^{-28} ecm (E=10kV/cm).
- There still are drifts/fluctuations in the maser frequency that are correlated with ambient temperature and noises. Improvements and further developments are under progress.
  - Reinforcement of ^{129}Xe polarization by introducing a narrow-line high-power TA-DFB pumping laser
  - Stabilization of solenoid current
  - Stabilization of cell temperature by means of a heat transfer fluid GALDEN
  - Cell development for the E-field application
  - Magnetometry with NMOR
  - Shell-model calculation of ^{129}Xe Schiff moment (Yoshinaga and Higashiyama)