High-sensitivity atomic magnetometer for neutron EDM Experiment

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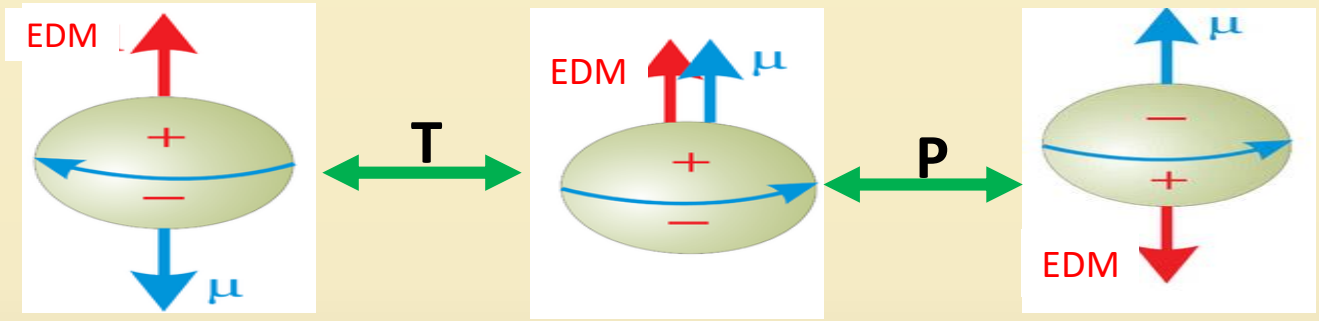
Motivations to measure neutron EDM

Andrei Sakharov conditions[1]:

- Non-conservation of baryon number B
- Violation of C-symmetry and therefore CP
- Interactions away from thermodynamic equilibrium

- EDM violates T symmetry
  --- deeply connected to CP violation and the matter-antimatter asymmetry of the universe



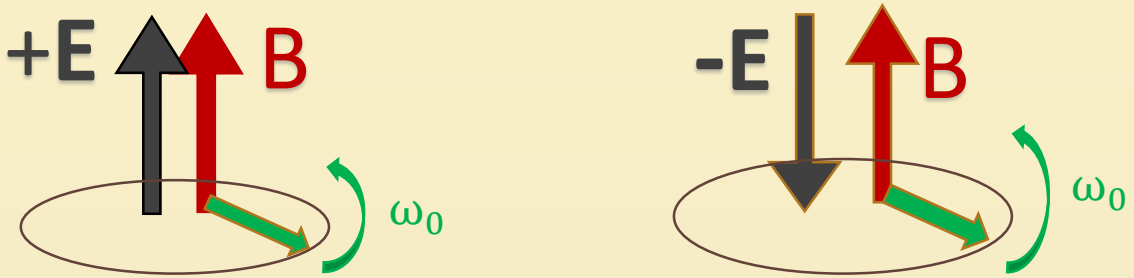
Current best upper limit[2] on the nEDM experiment is 3.0×10^{-26} e-cm

The nEDM experiment at TRIUMF is aiming at the 10^{-27} e-cm level

1. http://www.jetpletters.ac.ru/ps/1643/article_25089.shtml.
2. J. M. Pendlebury et al.Phys. Rev. D 92, 092003(2015)

Principle of nEDM measurement

- Ramsey's method of separated oscillatory fields



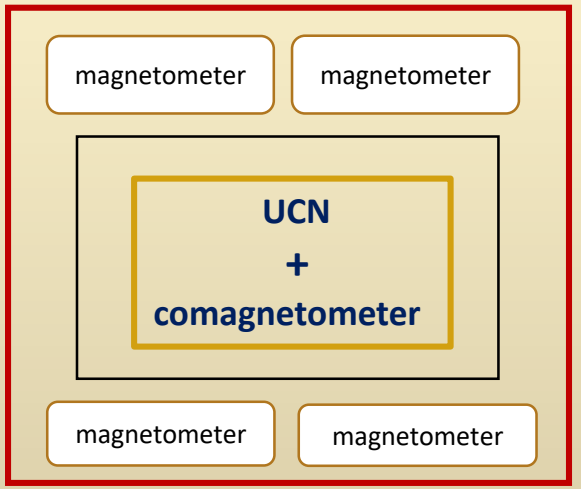
$$h\omega_0{}^{\uparrow\uparrow} = \left|2\mu_n B^{\uparrow\uparrow} + 2d_n \mathrm{E}\right| \qquad h\omega_0{}^{\uparrow\downarrow} = \left|2\mu_n B^{\uparrow\downarrow} - 2d_n \mathrm{E}\right|$$

$$d_n = \frac{h(\omega_0{}^{\uparrow\uparrow} - \omega_0{}^{\uparrow\downarrow}) - 2\mu_n(B^{\uparrow\uparrow} - B^{\uparrow\downarrow})}{4E} = \frac{h(\omega_0{}^{\uparrow\uparrow} - \omega_0{}^{\uparrow\downarrow})}{4E}$$

$$B^{\uparrow\uparrow} \approx B^{\uparrow\downarrow}$$

Goals:

- Precision $\delta d_n = 10^{-25}$ e-cm / 100 s.
- Measurement of field at 16 fT over 100 s
- Field stability at 1-10 pT over 100 s.



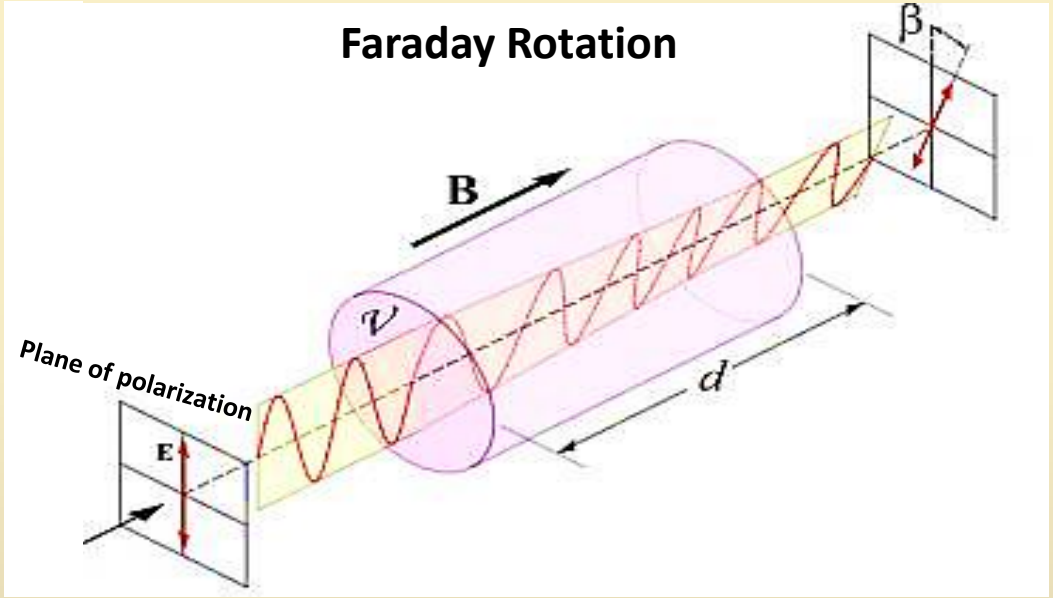
- **Requires to make use of highly sensitive magnetometers**

Nonlinear Magneto-optical Rotation(NMOR)

- Faraday rotation is a linear effect because rotation is independent of light intensity.

- When linearly polarized light interacts with an atomic transition in the presence of a magnetic field, the polarization angle of the light can be rotated. When the rotation angle depends on the light intensity, the effect is called nonlinear magneto-optical rotation (NMOR).

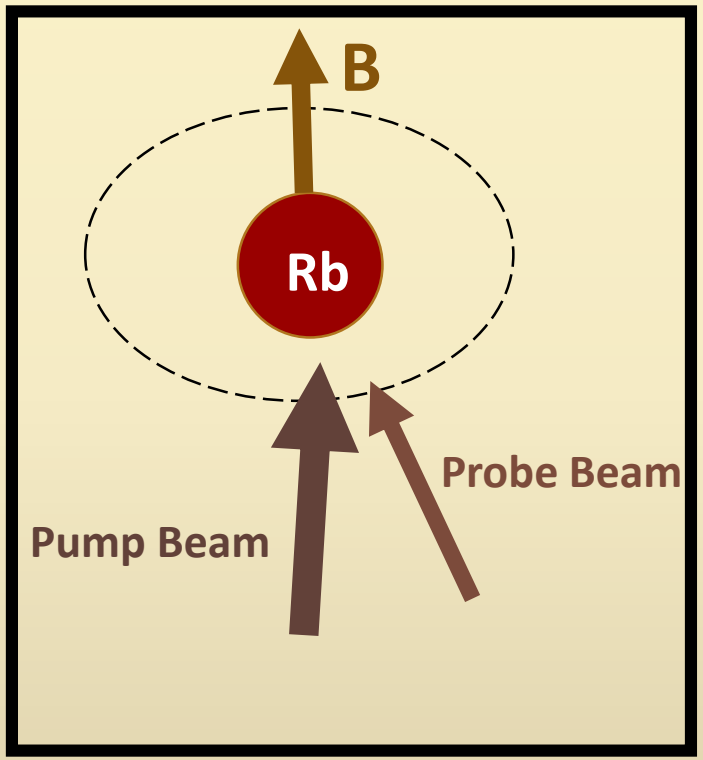
- NMOR magnetometry depends on the induced birefringence of alkali vapour in a magnetic field



https://en.wikipedia.org/wiki/Faraday_effect

NMOR based Rb magnetometer

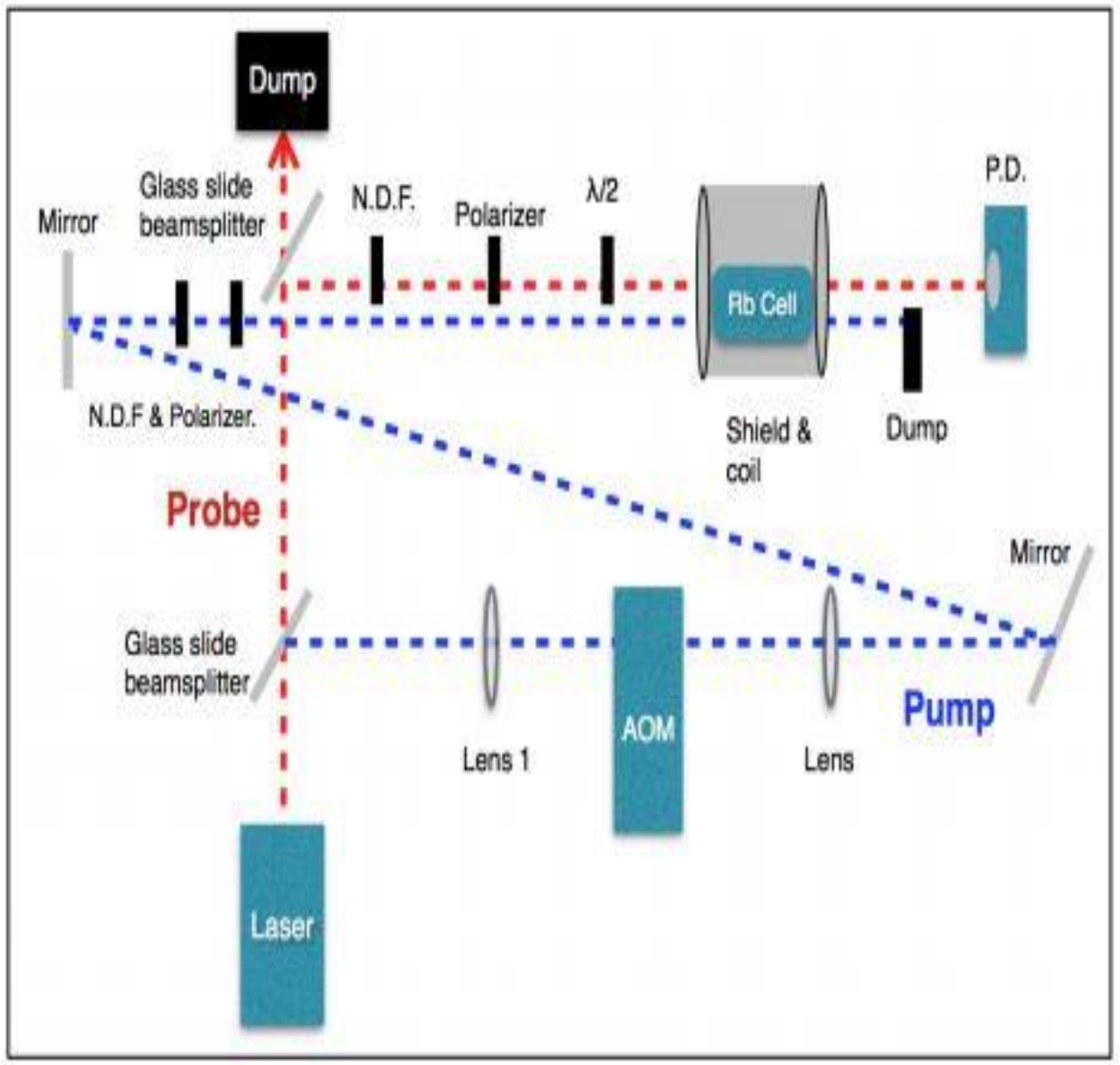
- Based on induced birefringence of alkali vapour in a magnetic field.

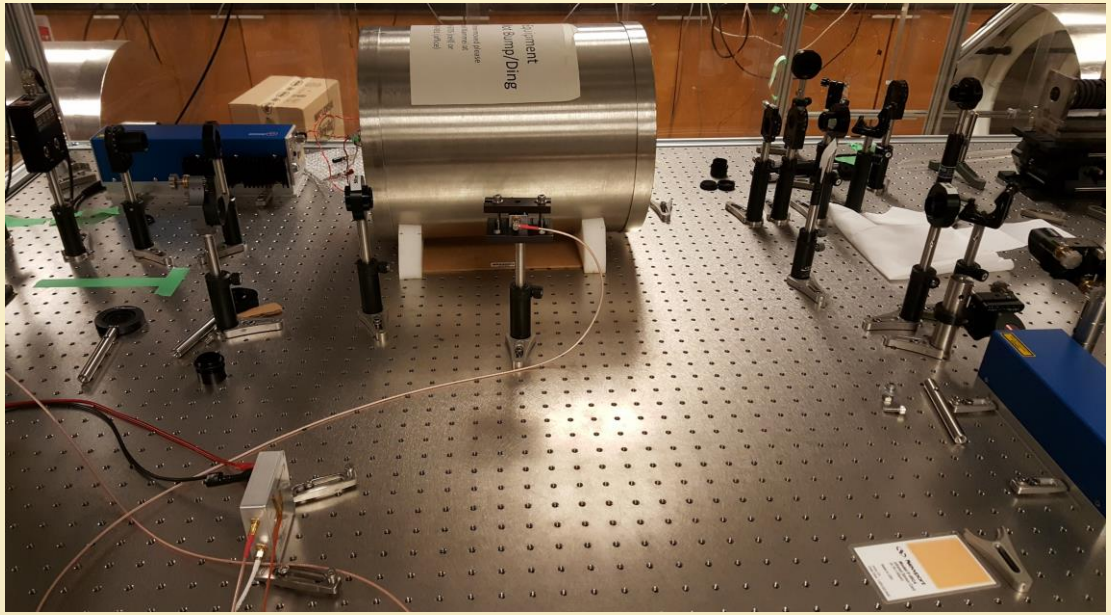


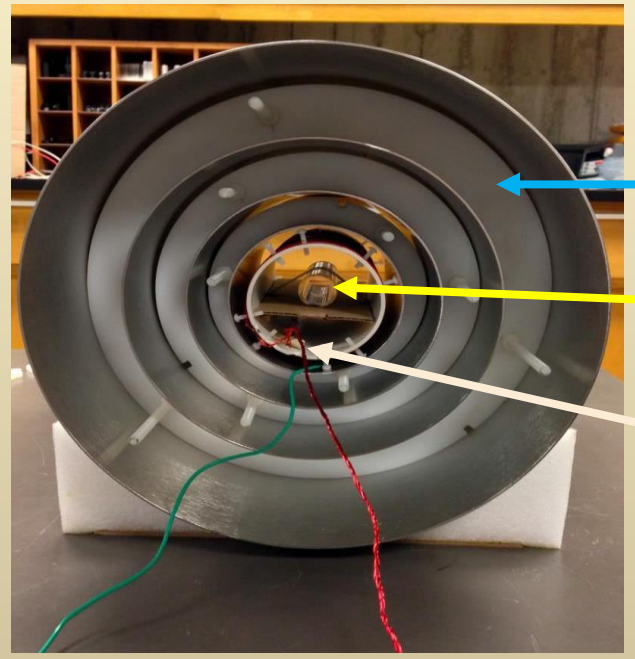
How does it work ?

- Resonant light polarizes Rb atoms via optical pumping. Magnetic moments of the atoms are oriented with respect to the axis of alignment.
- Aligned magnetic dipole moments experience a torque and precess around the axis of the field at the Larmor frequency and medium becomes birefringent
- Optical polarization rotation of a probe beam is used to measure magnetic field

Apparatus







Four-layer μ-metal magnetic shielding

Rb vapor cell

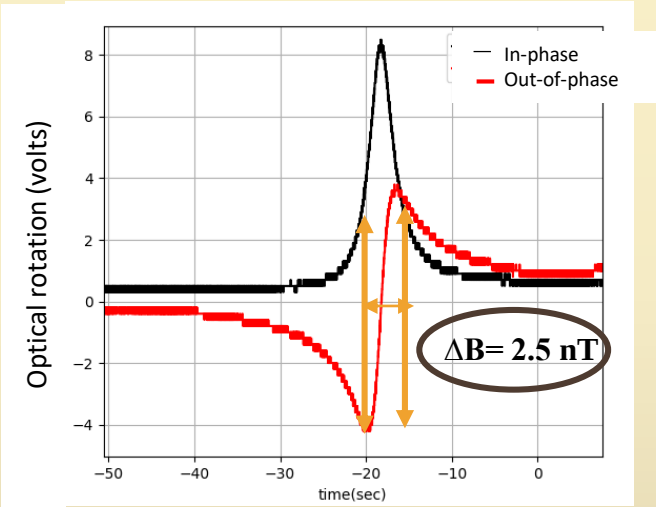
Coil

Operation Modes of Atomic Magnetometer

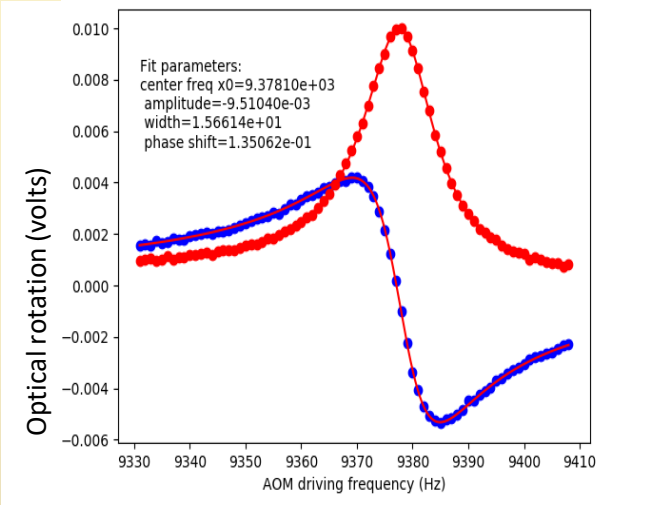
- Continuous oscillation mode

  - pump Rb atoms continuously

NMOR with Amplitude-Modulated Light



NMOR with Frequency-Modulated Light



- possibility of pulling the measured frequency toward the moduation frequency (a systematic effect)
- possibility of increased long-term instability

- Free Induction Decay(FID) mode

  - Free of probe and pump light induced light shifts so best for long-term stability

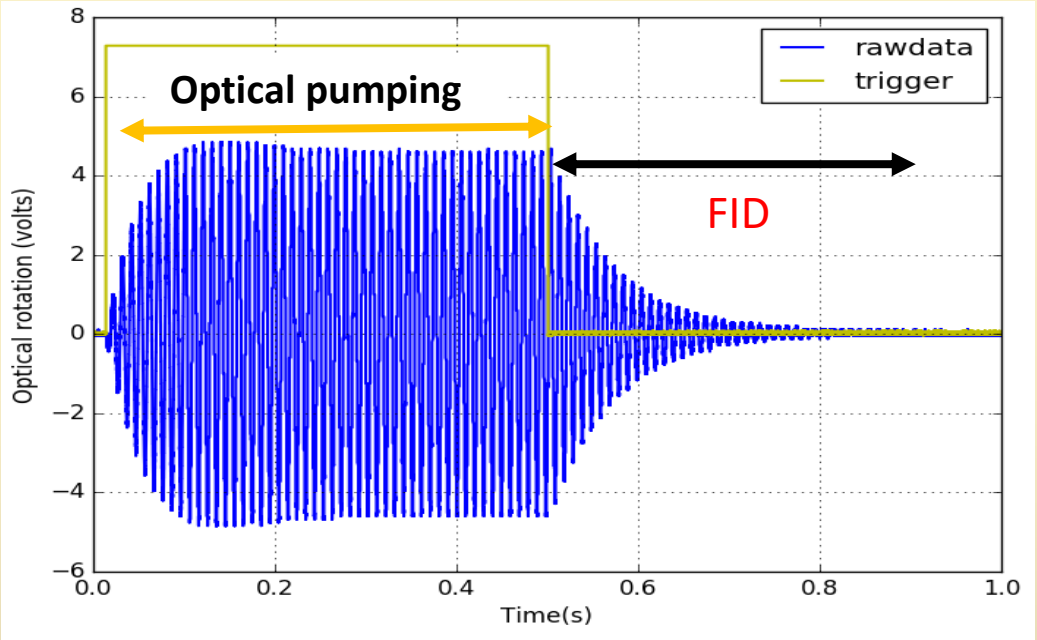
Free induction decay (FID)

Experimental procedure:

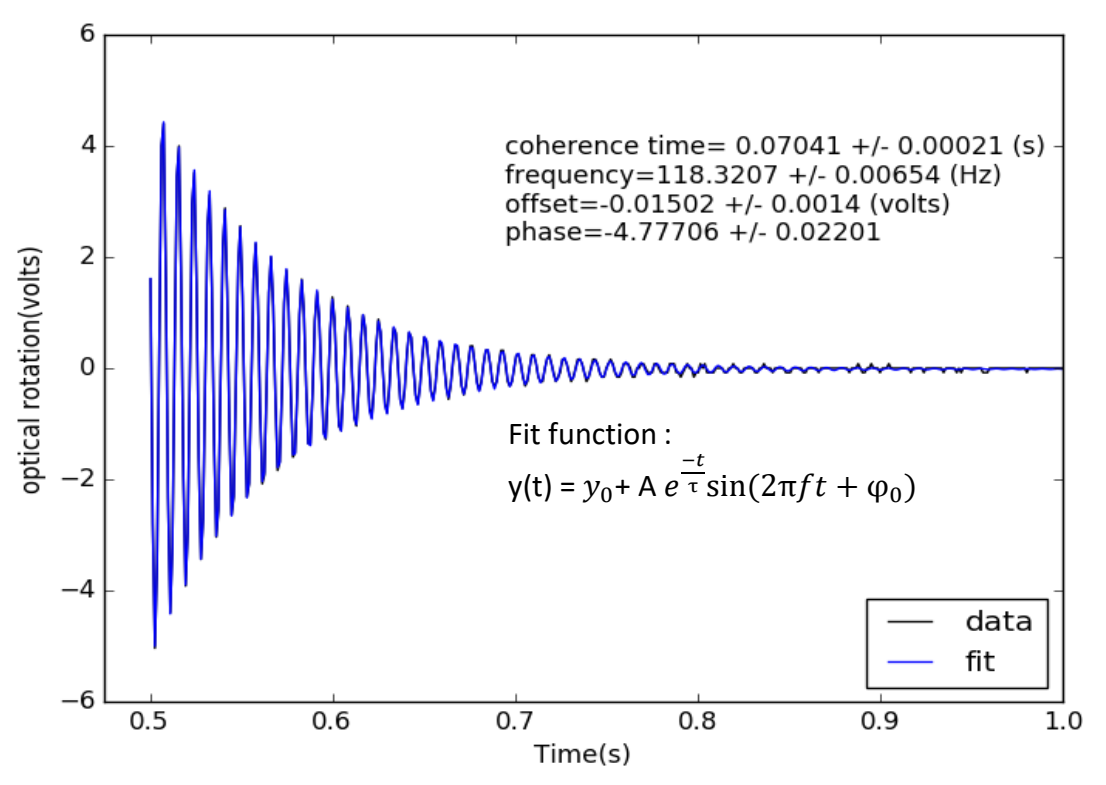
1. Rb atoms inside the cell is excited once and afterwards the decaying processes of the excited atoms is observed. A function generator is used to delivered the pump pulses which are necessary for pumping during a FID measurement.

2. Pumping is done for a very short time interval and the coherence decay takes place fast.

3. The reference signal on the lock-in amplifier has further to be set slightly off resonance (~ 100 Hz) in internal frequency mode in order to properly record the FID.



Single FID measurement



How do I calculate the magnetic field and uncertainty in magnetic field?

$$Magnetic\ field, B = \frac{f}{2\gamma}$$

$$Uncertainty, \Delta B = \frac{\Delta f}{2\gamma}$$

For Rubidium
$\gamma = 4667\ Hz/\mu T$

- Larger amplitude & longer coherence time indicate better frequency precision.

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Field Stability Measurement

Operating field B = 0.2 µT

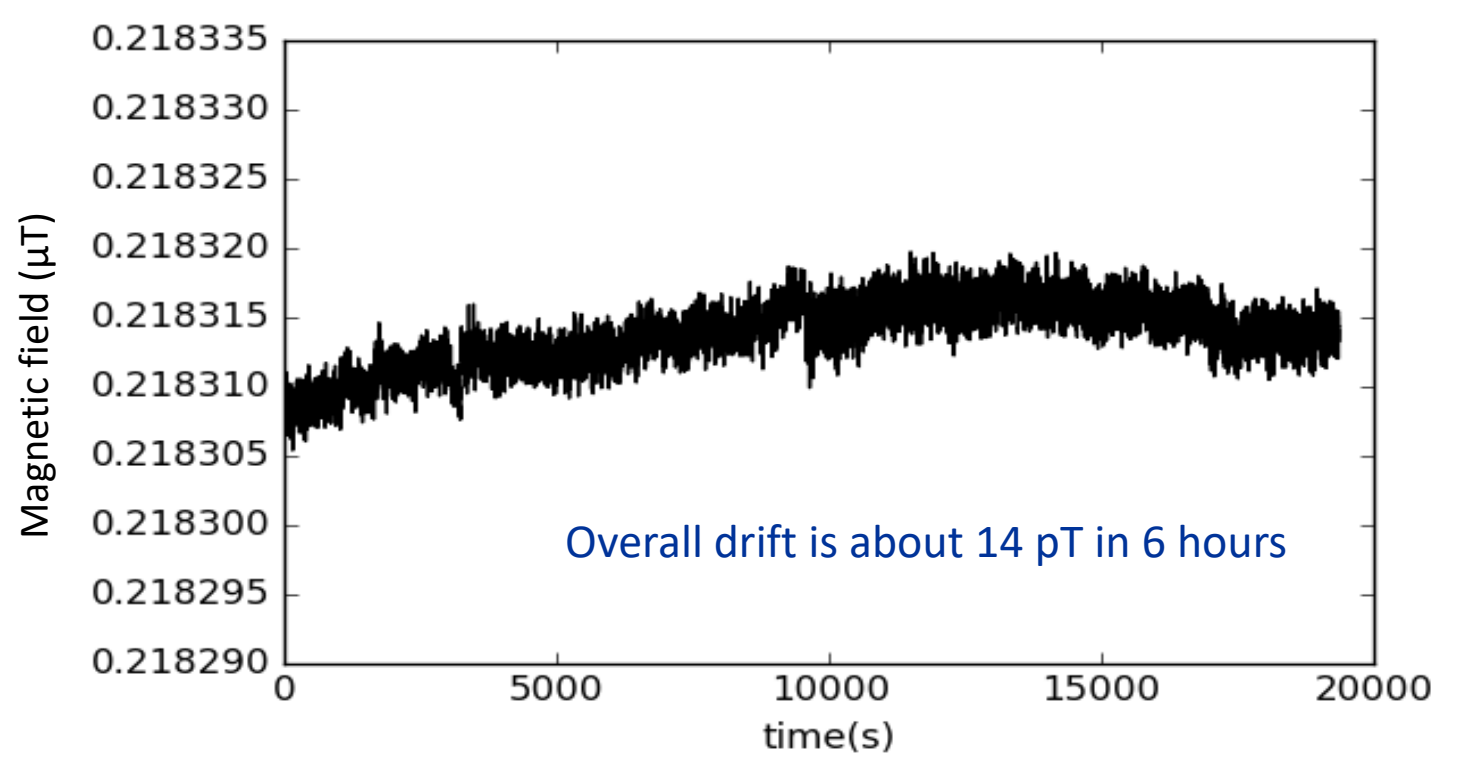


Figure: Results of about 6 hours recordings B-field vs. time

Goals:

- Field stability at 1-10 pT over 100 s.
- Field measurement about 16 fT / 100 s

Current status

- Observed field stability is about 4 pT /100 s

Next steps to do……

Factors affecting long-term measurements :

- Magnetometer effects
  - laser stability

- Magnetic effects
  - degaussing, temperature, coil current, mechanical stability.

Conclusion

- Non-zero nEDM would provide clues to the Baryogenesis puzzle .
- TRIUMF nEDM sensitivity goal is 10^{-27} e-cm.
- Observed field stability ~ 4 pT over 100 s.
- Need improvement in magnetometry for precise understanding of the magnetic field behavior inside the EDM chamber.

Thank You


NSERC
CRSNG

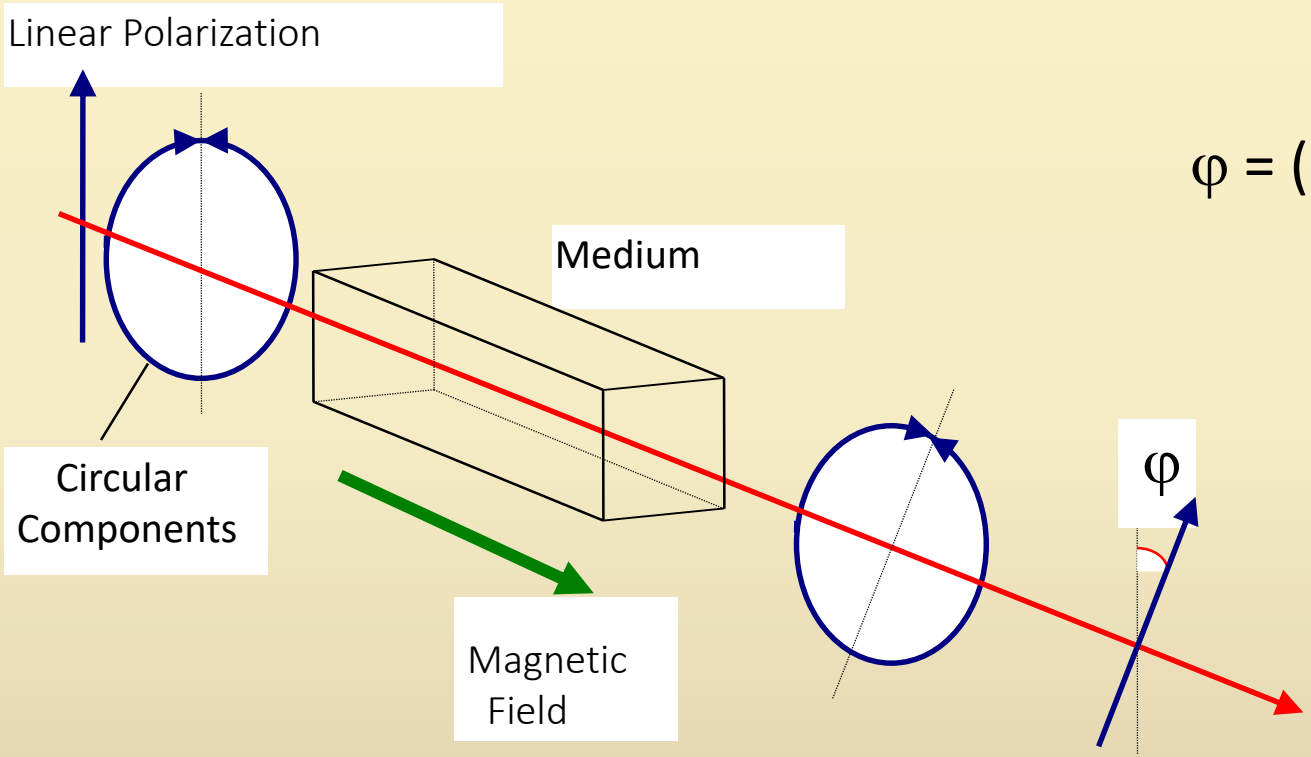

CINP
ICPN
Canadian Institute of Nuclear Physics
Institut canadien de physique nucléaire


TRIUMF

Precession, $\delta d_n \simeq \frac{1}{\sqrt{N_{meas}}} * (\delta d_n)_{per\ meas}$

$$optical\ rotation, \varphi \simeq \frac{{}^{2g\mu B}/_{\hbar\gamma_{rel}}}{1+({}^{2g\mu B}/_{\hbar\gamma_{rel}})^2} * \frac{l}{l_0}$$

Linear Magneto-Optical (Faraday) Rotation

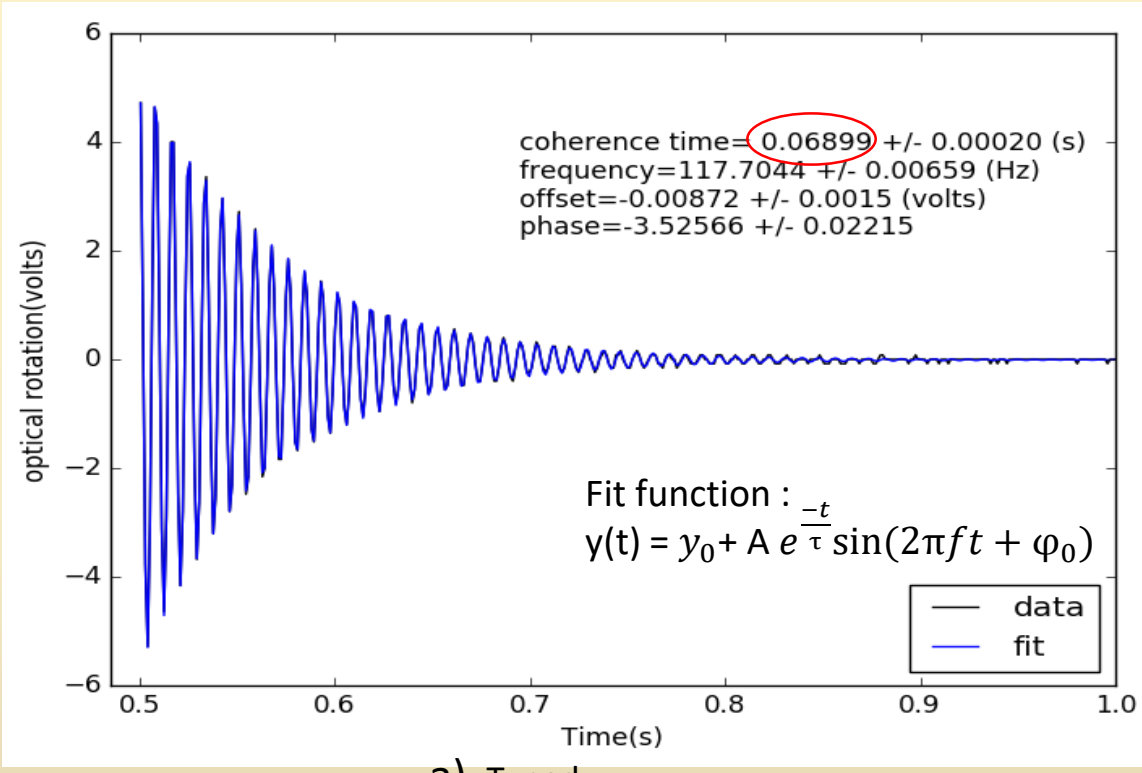


$$\varphi = (n_+ - n_-)\frac{\omega_0 l}{2c} = (n_+ - n_-)\frac{\pi l}{\lambda}$$

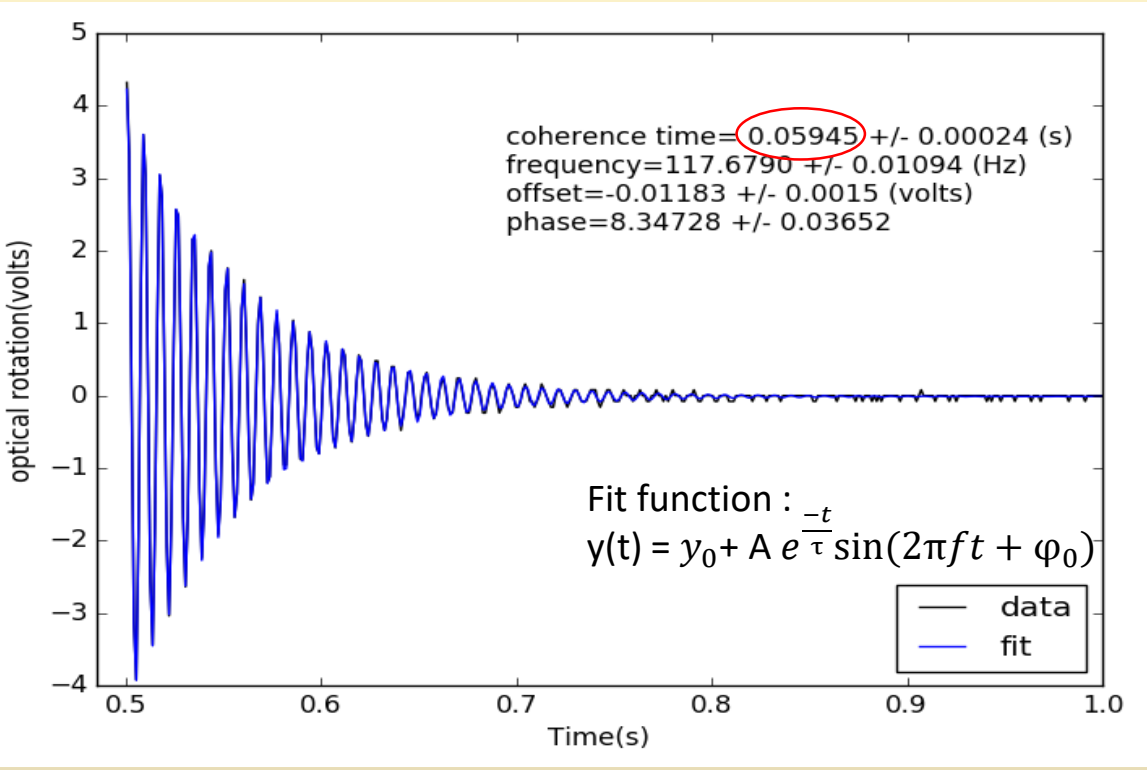
Free induction decay (FID) at 0.2 µT magnetic field

Laser Tuning affects coherence time?

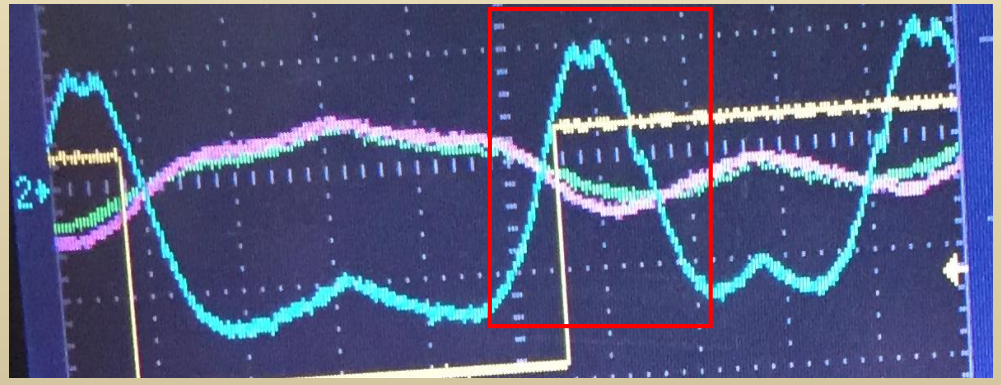
- Laser wavelength is tuned to transition frequency of Rb atom

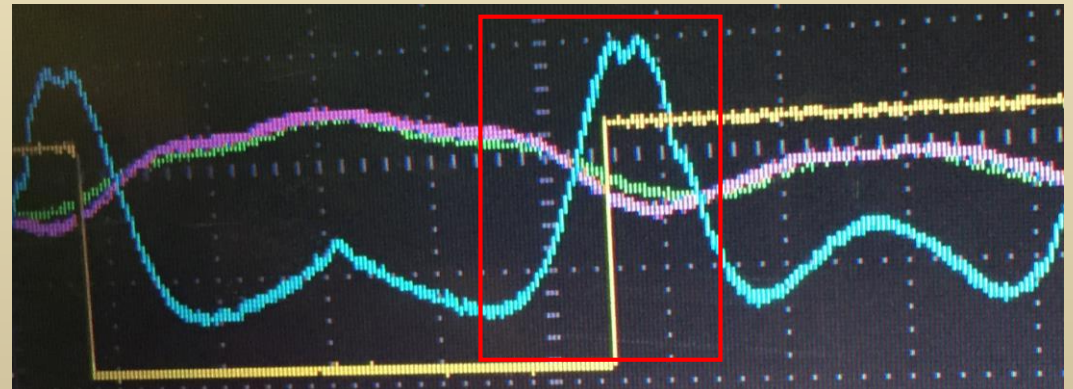


a) Tuned

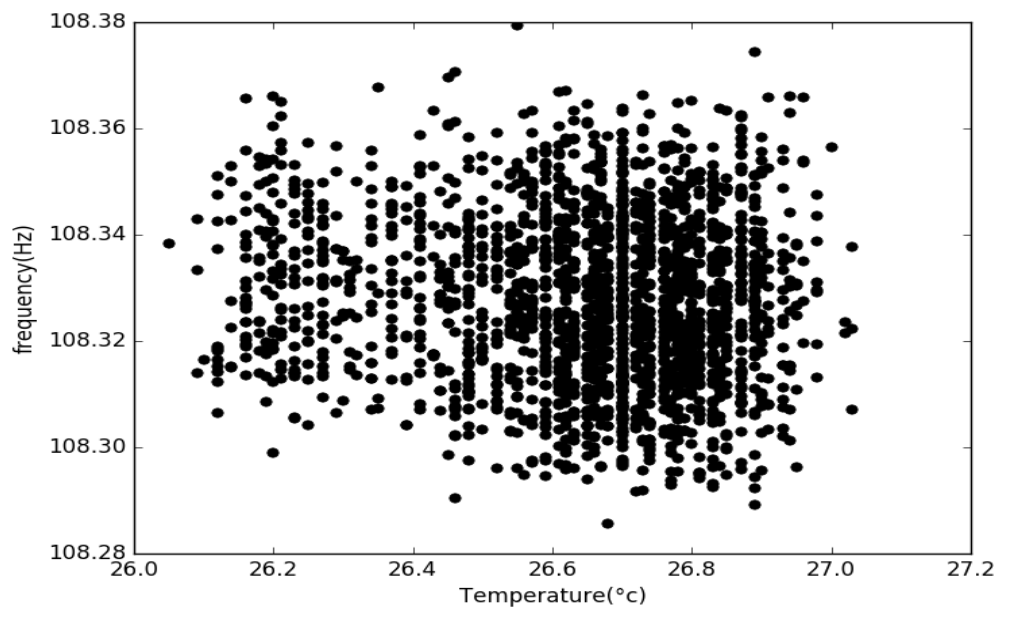


b) Slightly detuned

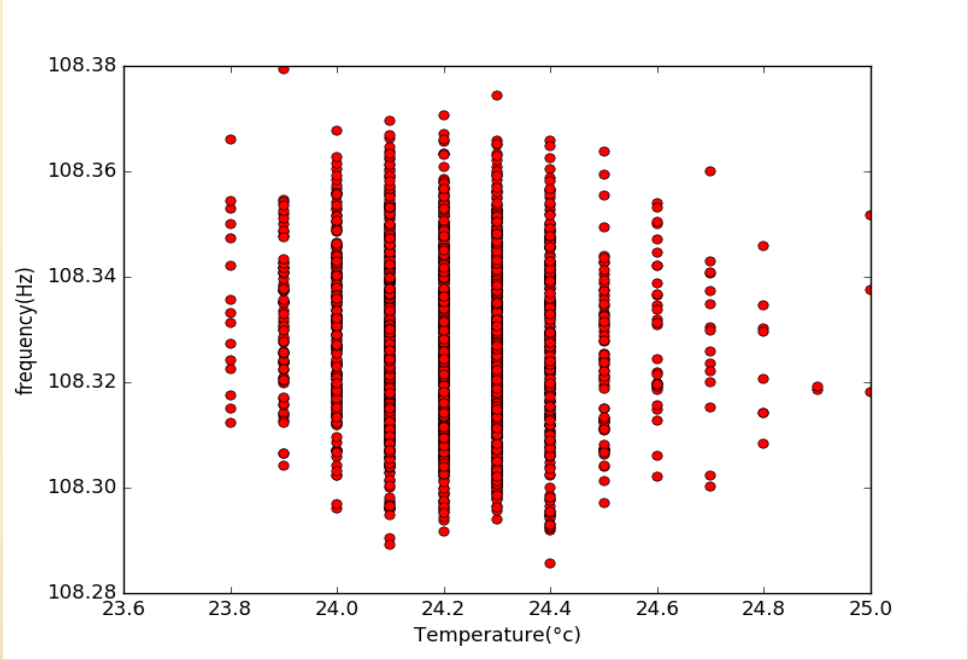




Does frequency/magnetic field depends on temperature?



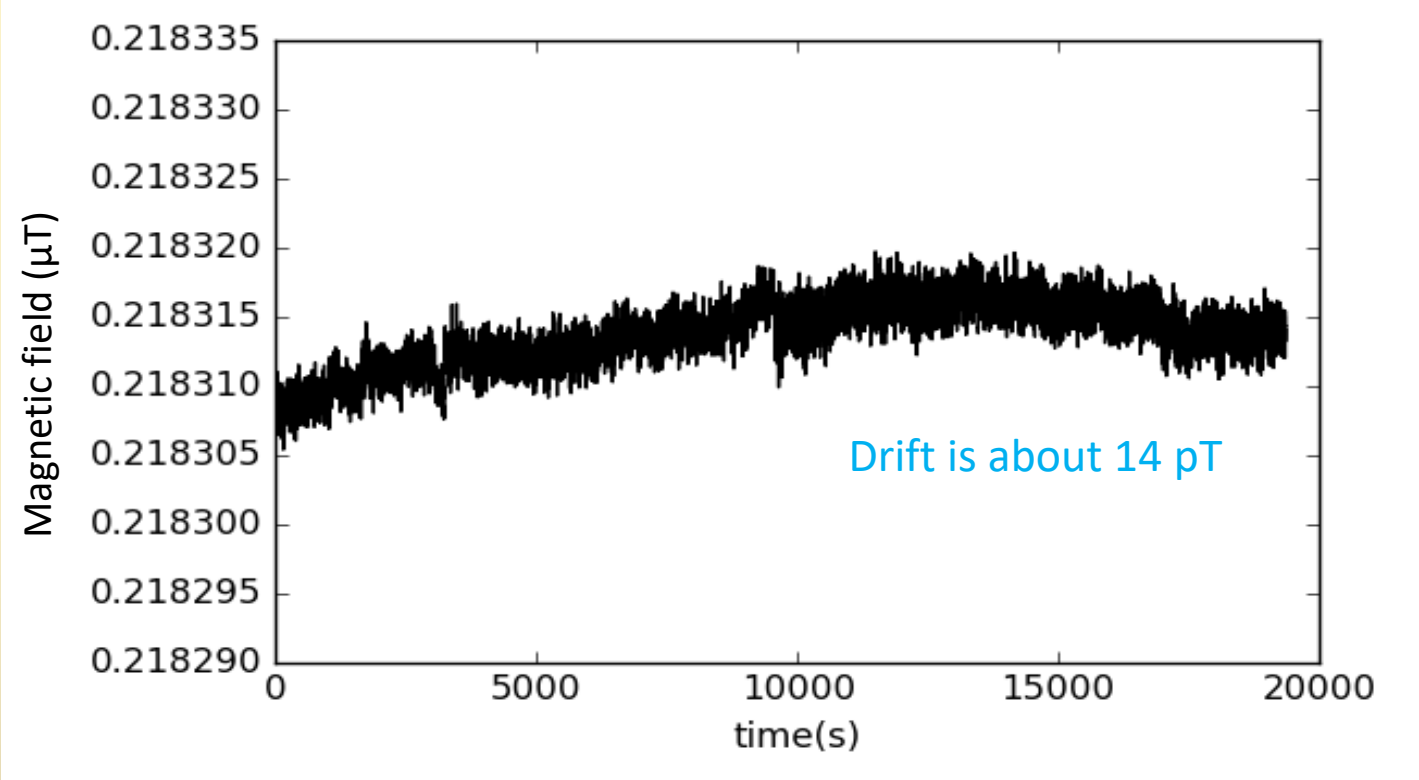
a) FID frequency vs. room temperature

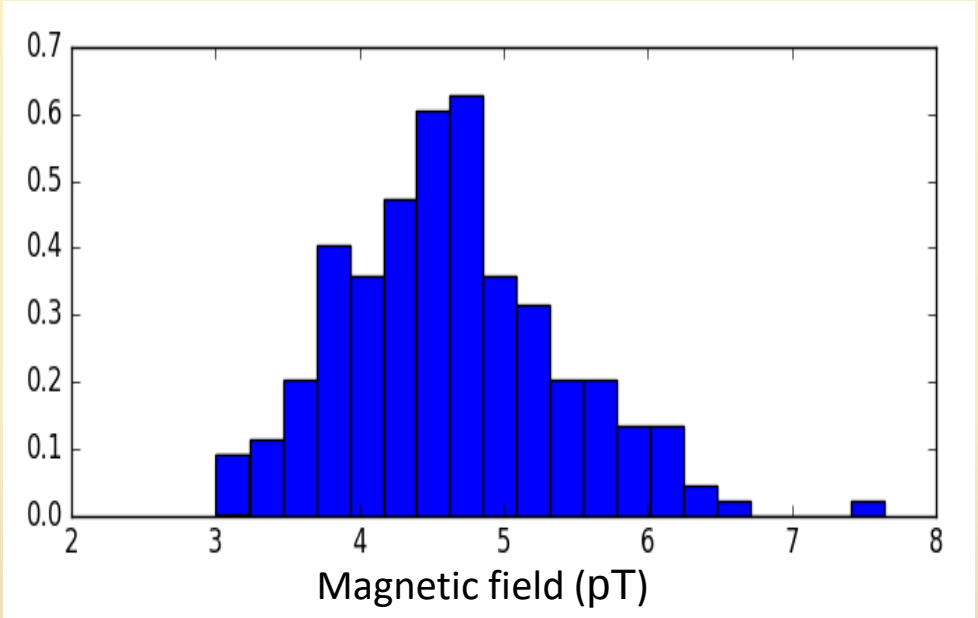


b) FID frequency vs. temperature near shield

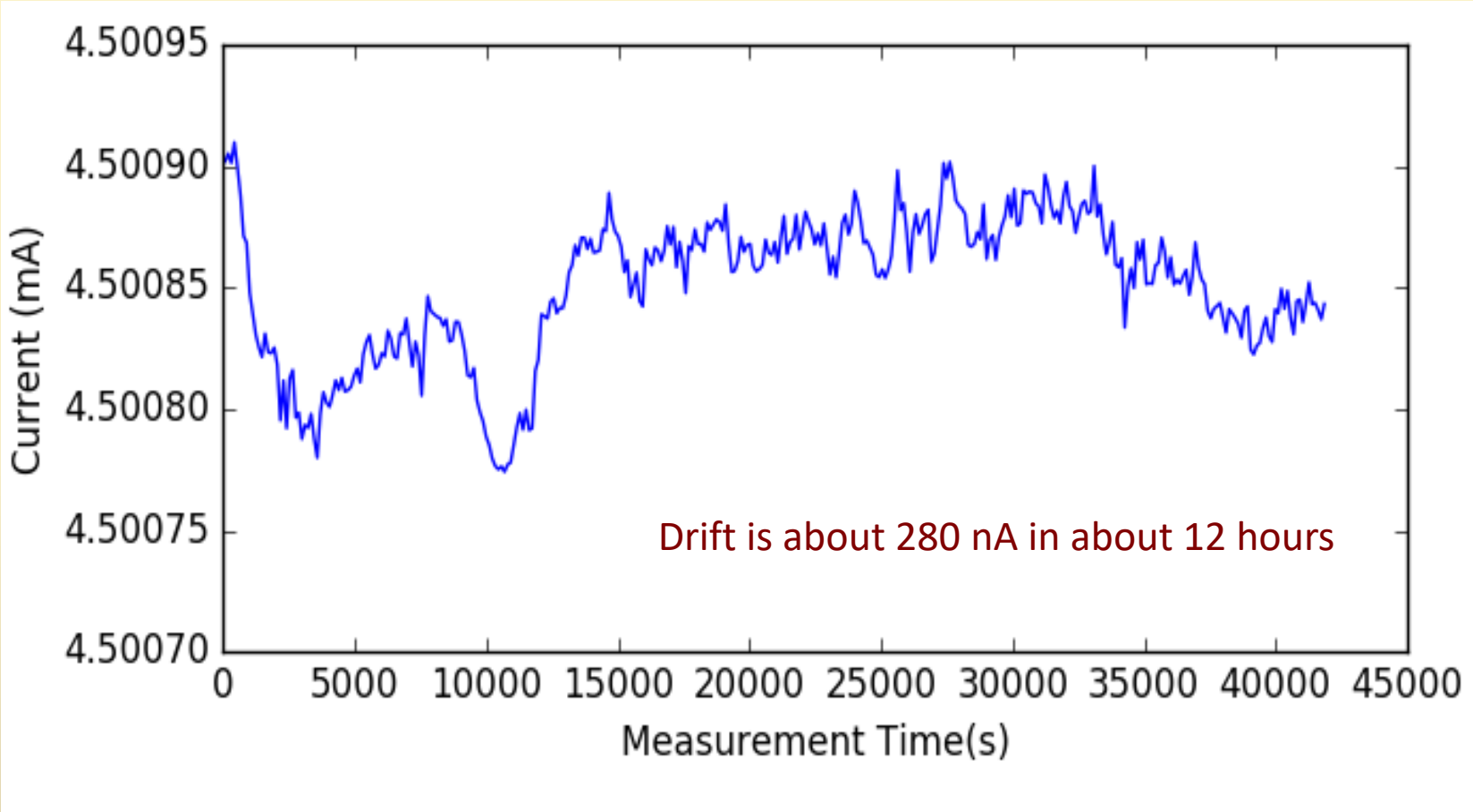
Some atomic magnetometers

- Spin Exchange Relaxation Free (SERF) Magnetometer
- Nonlinear Magneto Optical Rotation (NMOR) Magnetometer
- Chip Scale Atomic Magnetometer(CSAM)

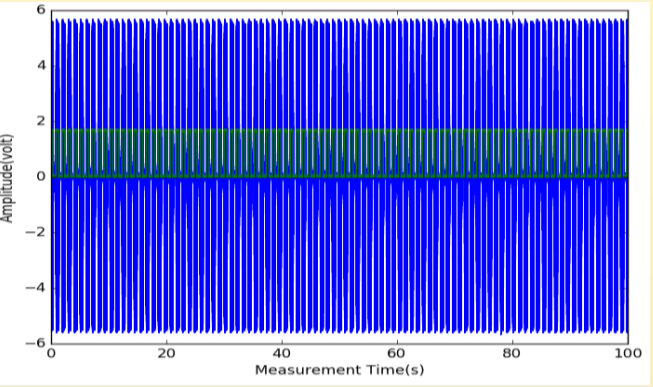

0.218335
0.218330
0.218325
0.218320
0.218315
0.218310
0.218305
0.218300
0.218295
0.218290
Magnetic field (μT)
0
5000
10000
15000
20000
time(s)
Drift is about 14 pT


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
2
3
4
5
6
7
8
Magnetic field (pT)

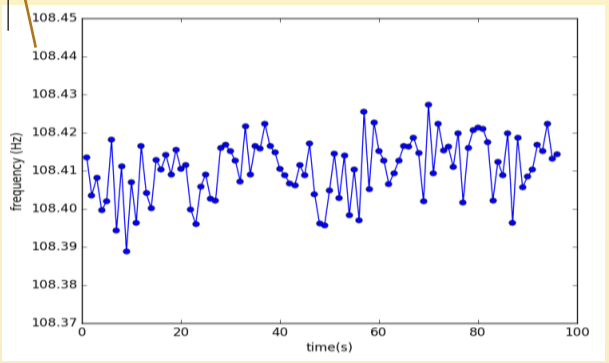
Stability measurement of power supply

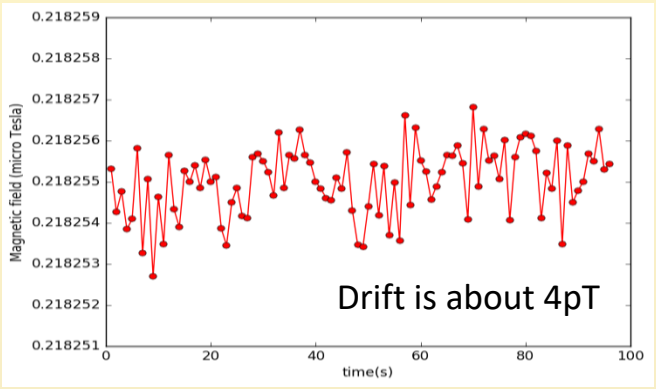


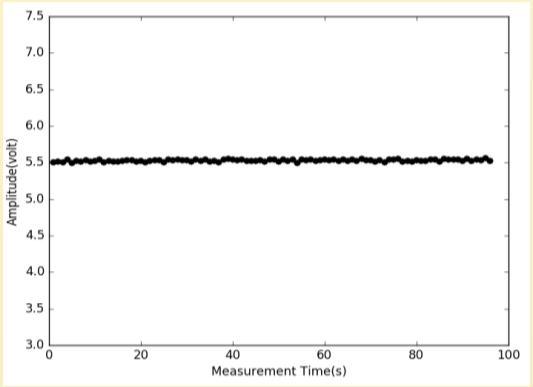
Raw data

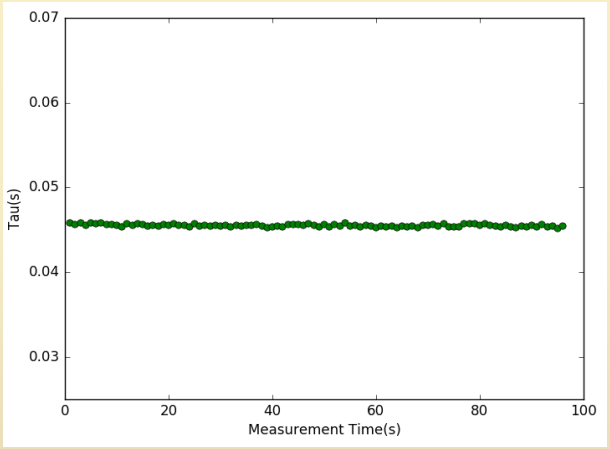


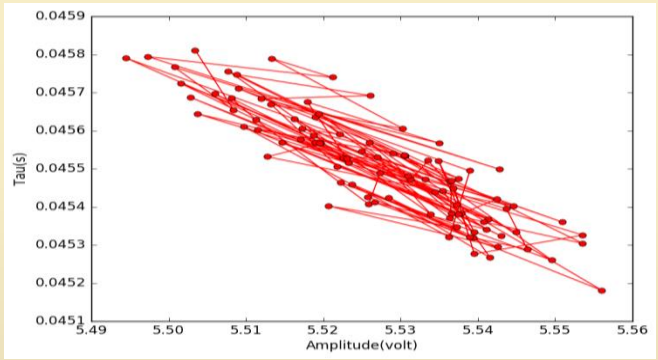
Perfectly tunned

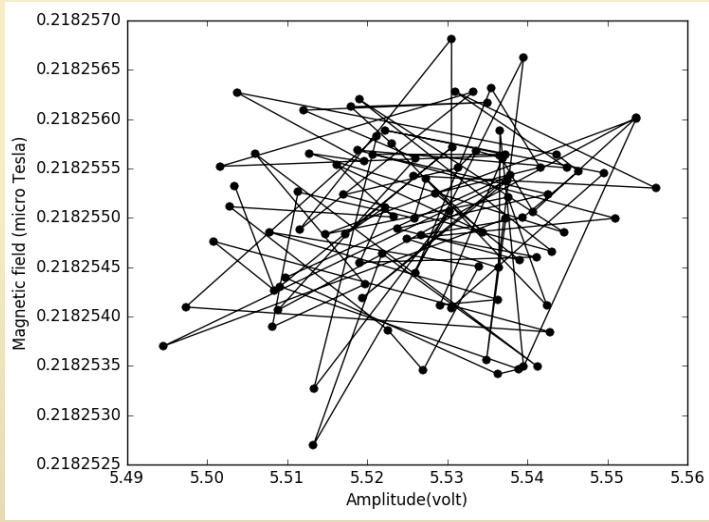


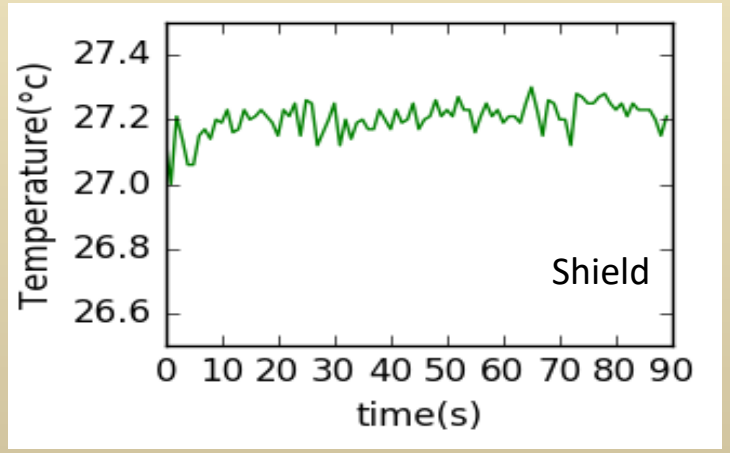


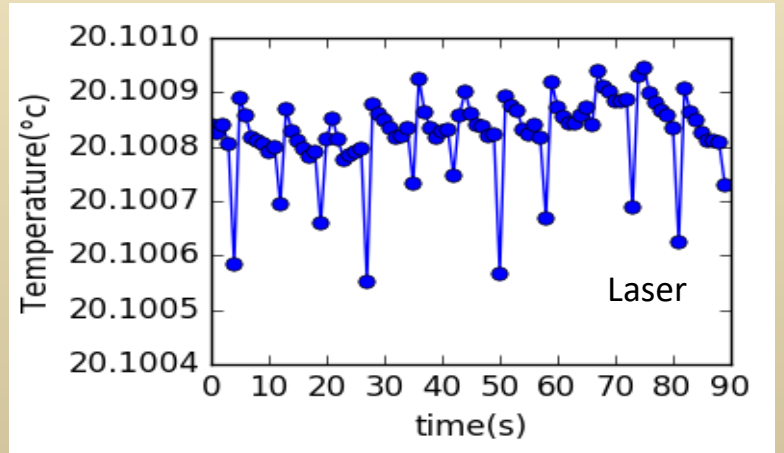




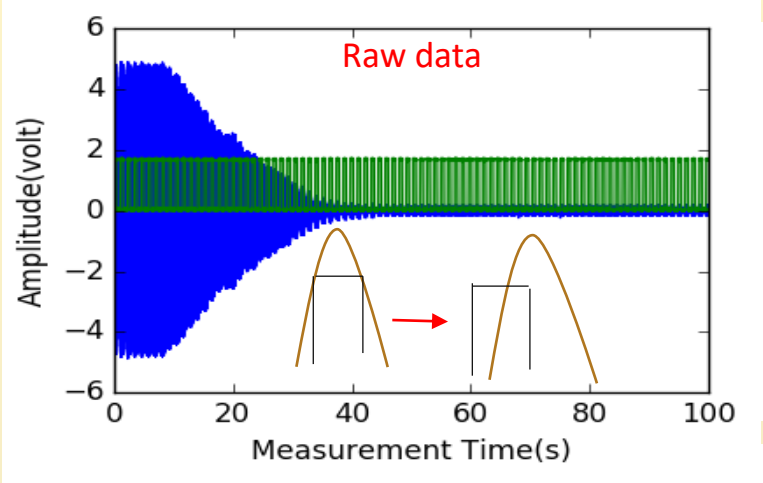


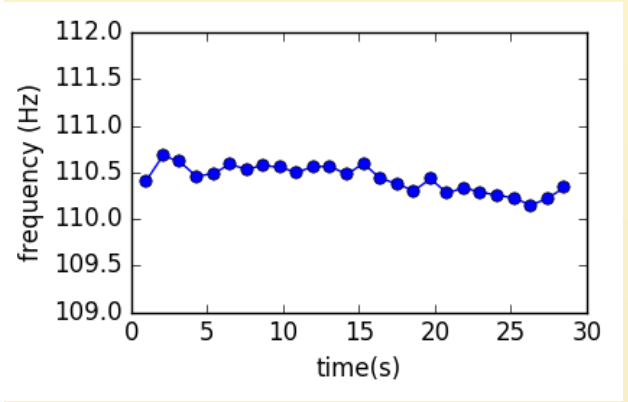


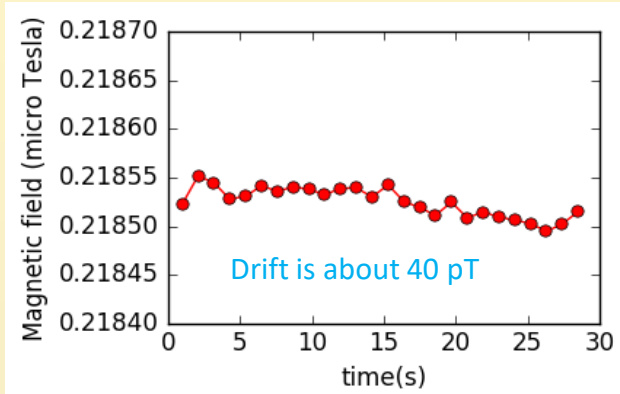


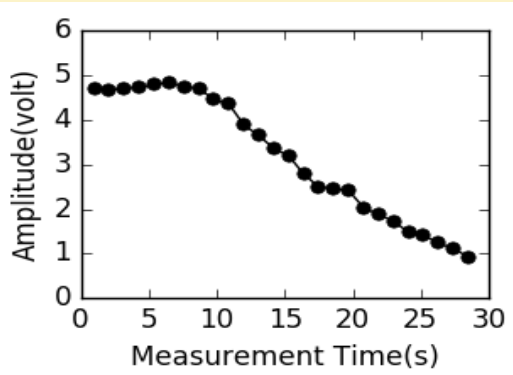


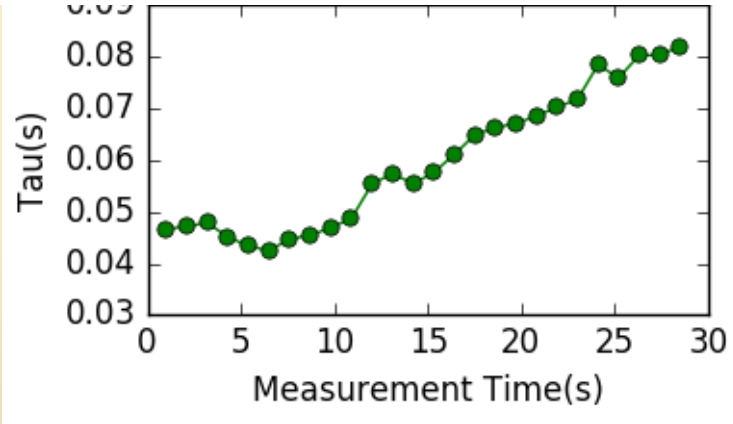
Moved Left from perfect tuning

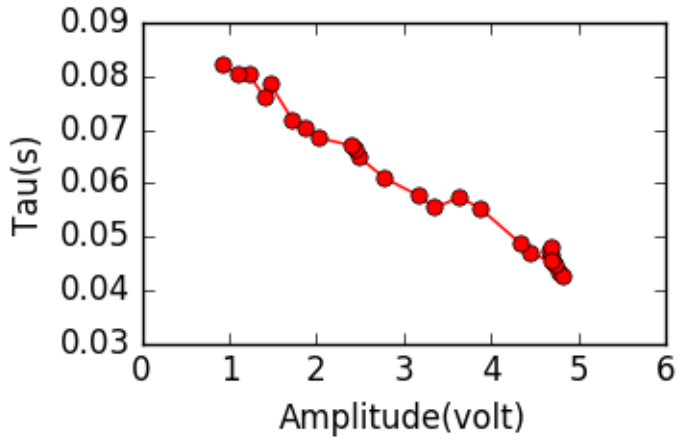


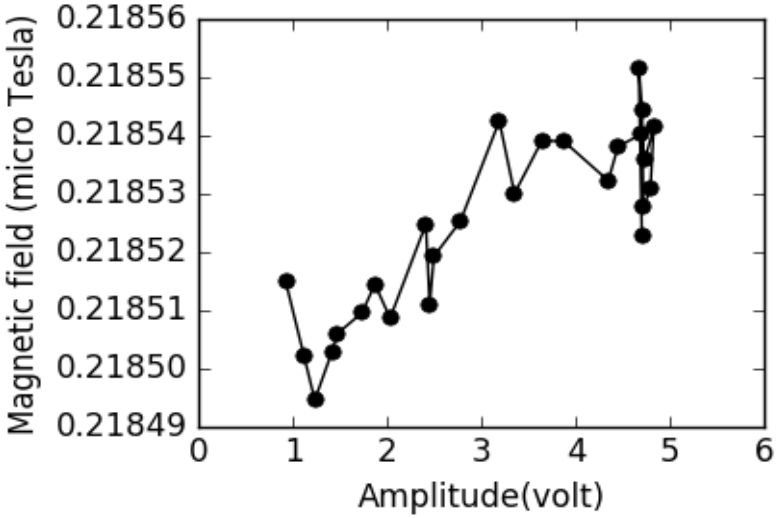


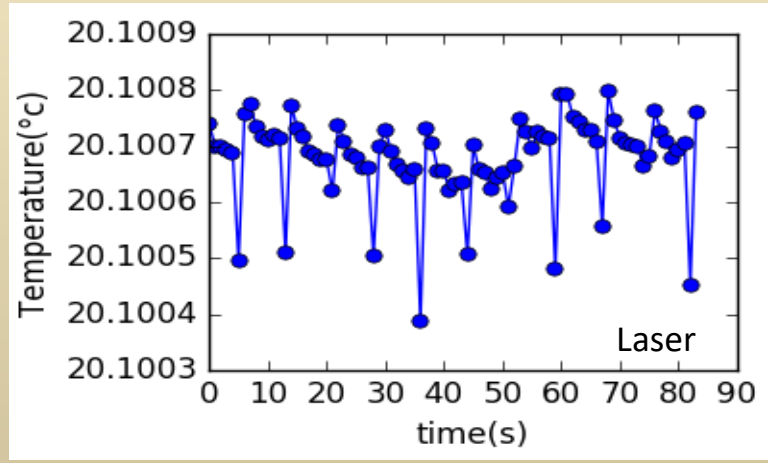


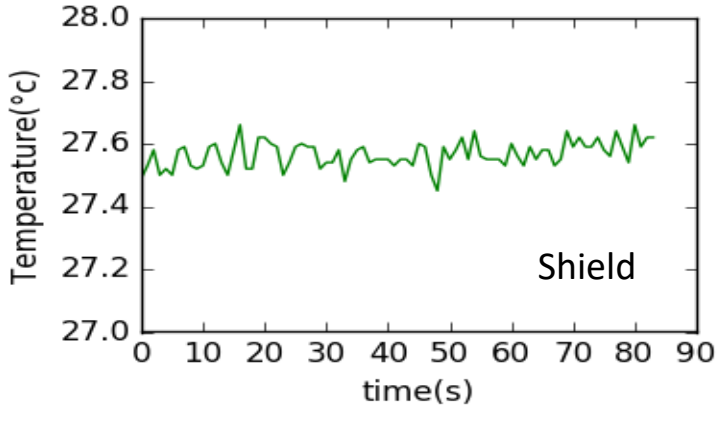












Moved right from perfect tuning