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Title: Ultra-sensitive Magnetic Microscopy with an Atomic Magnetometer

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Ultra-sensitive Magnetic Microscopy with an Atomic Magnetometer

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Postdoc Summer Seminar

Research goals

- Many applications in neuroscience and other fields require a high-resolution, high-sensitivity magnetic microscope.

- Magnetoecephalography (MEG): a diagnostic technique for studying the brain through measurements of magnetic fields produced by neural currents.

- Current MEG can only measure averages over large numbers of neurons (10^4 to 10^5)

- High-resolution magnetometery, capable of detecting a few neurons;
  - Full understanding of brain function
  - Direct imaging of the structure and composition of proteins and molecules

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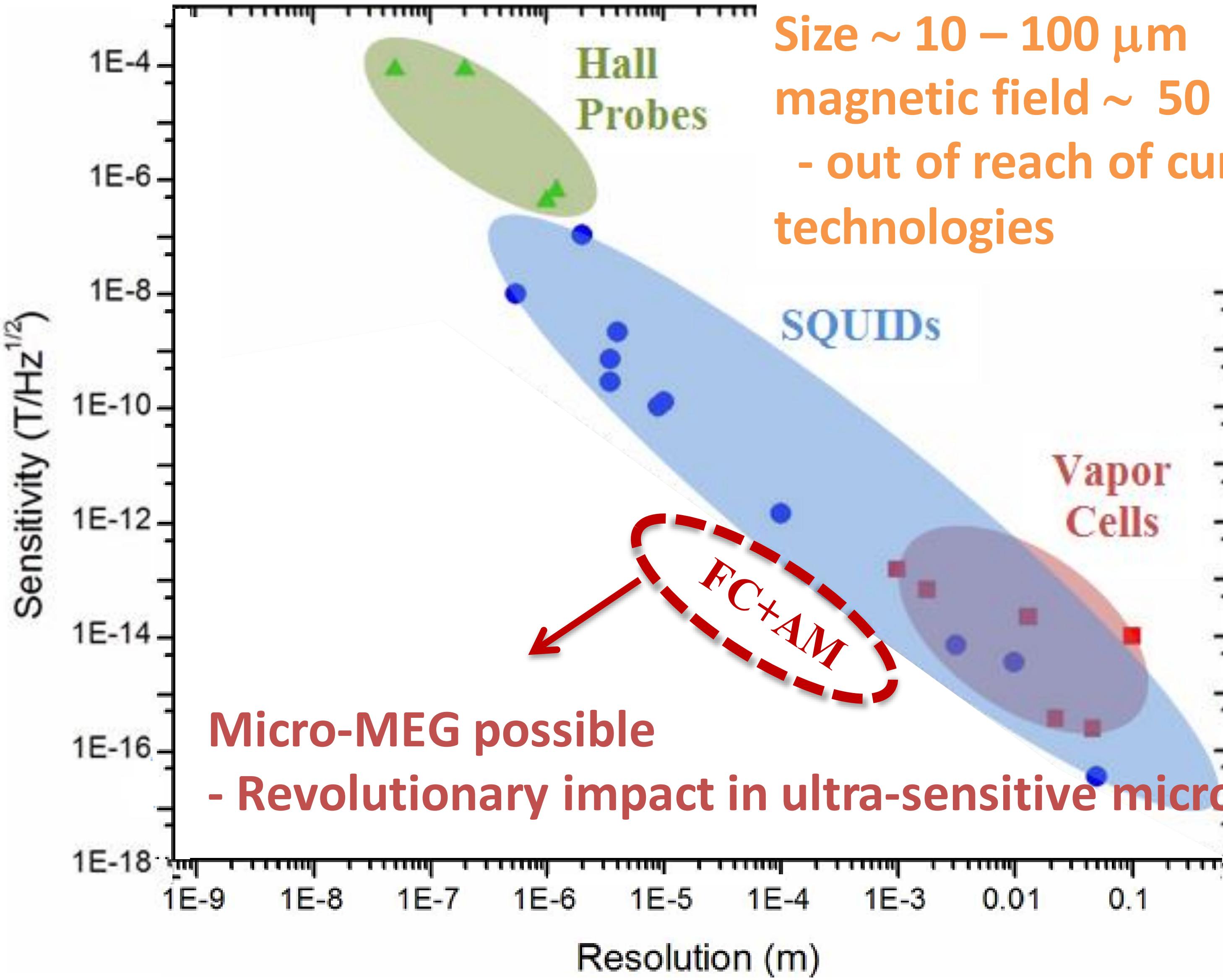
Research goals

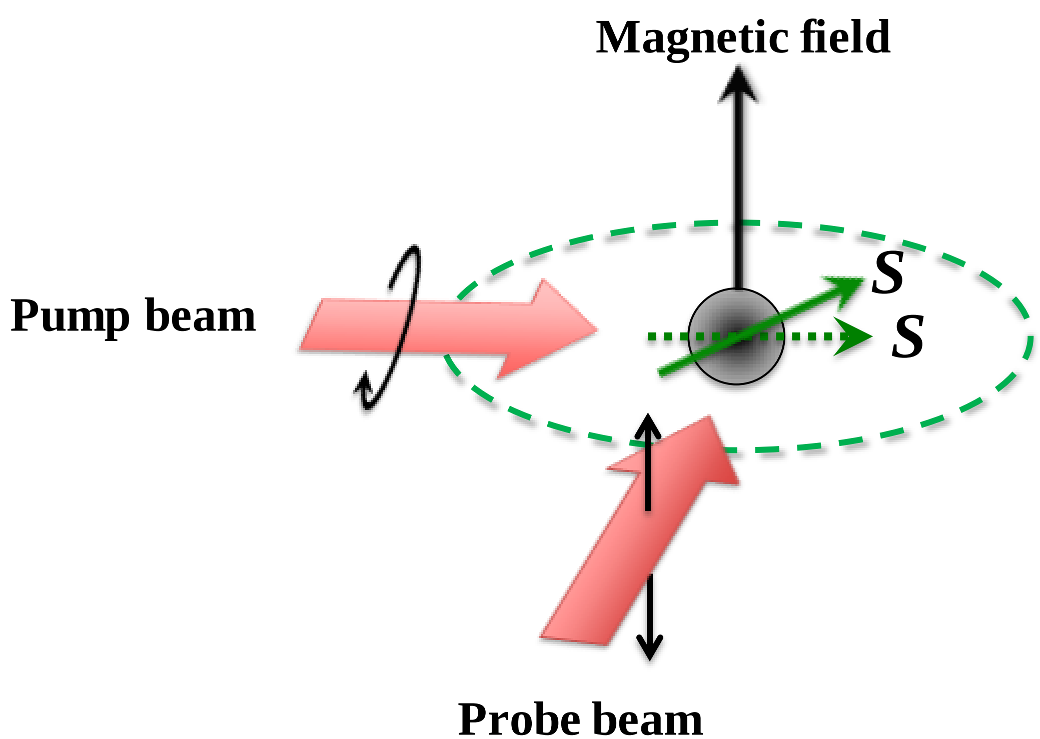
Single neuron :
Size ~ 10 – 100 μm
magnetic field ~ 50 pT
- out of reach of current technologies



Micro-MEG possible
- Revolutionary impact in ultra-sensitive microscopy

Atomic Magnetometer

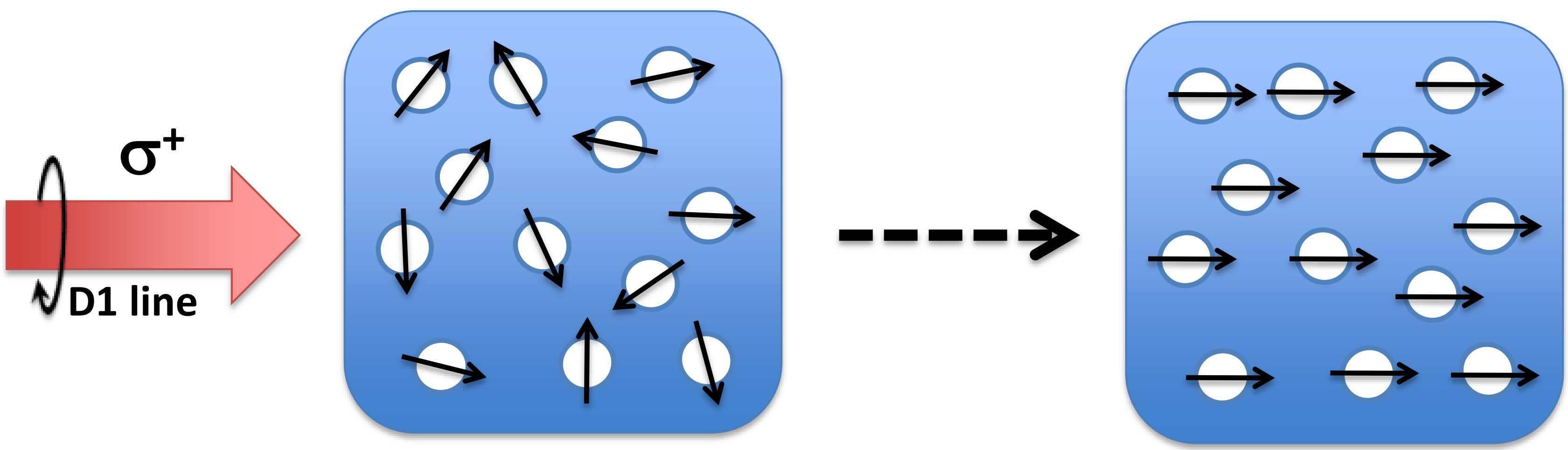
- **Atomic magnetometer:**
  - ➢ **based on lasers and alkali-metal (Cs, Rb, K) vapor cells**
  - ➢ **the most sensitive non-cryogenic magnetic-field sensor.**
- **Alkali-metal: a single unpaired electron in the outer energy shell that can be easily manipulated.**



Principle of atomic magnetometer

1. Optical pumping

Polarizing spins



$n \sim 10^{13}/cm^3$ at $150^\circ C$

Comparison to thermal polarization (P_T) :

$$P_T = \tanh\left(\frac{0.5 g_s \mu_B B}{k_B T}\right)$$

$g_s \approx 2$: Dirac g – factor, μ_B = Bohr magneton

k_B = Boltzmann constant

$P_T = 10^{-7}$ with 0.5 G, $P_T = 0.02$ with 10 T

$P \approx 1$ by optical pumping

(1 W → 10^{18} photons/cc, 1 mW is enough for pumping

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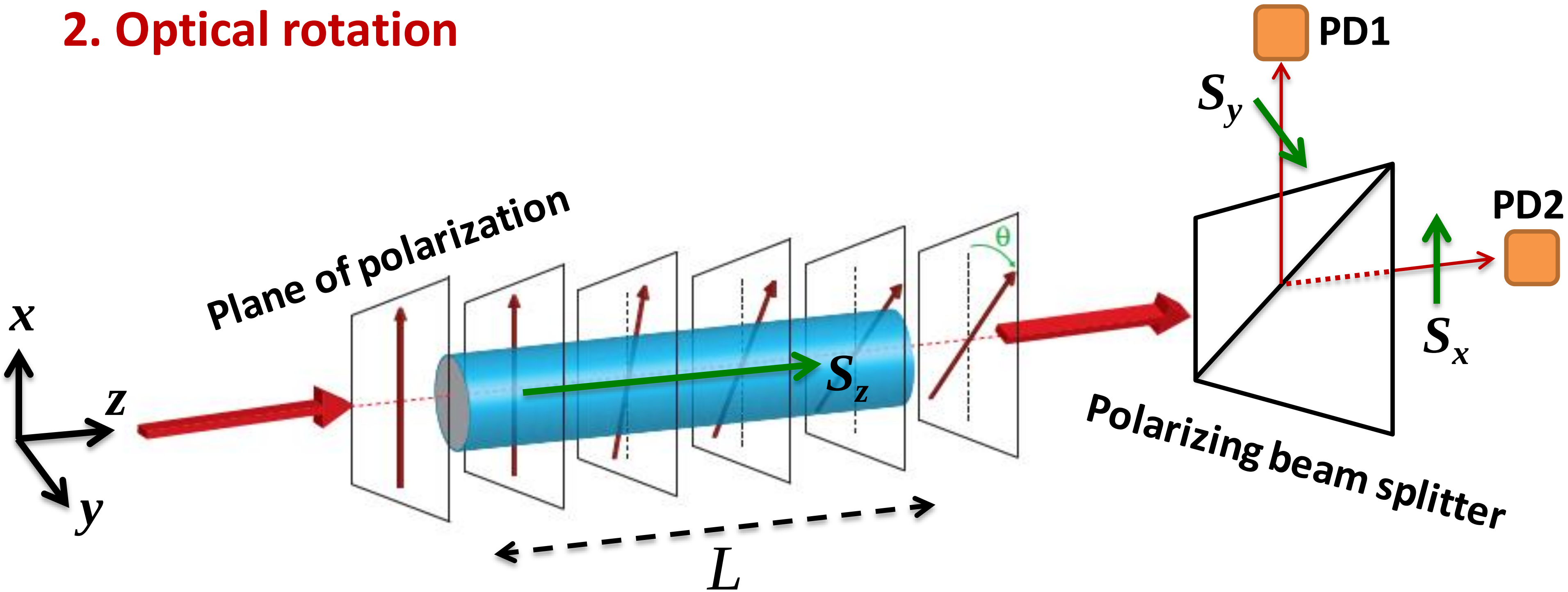
Principle of atomic magnetometer

2. Optical rotation



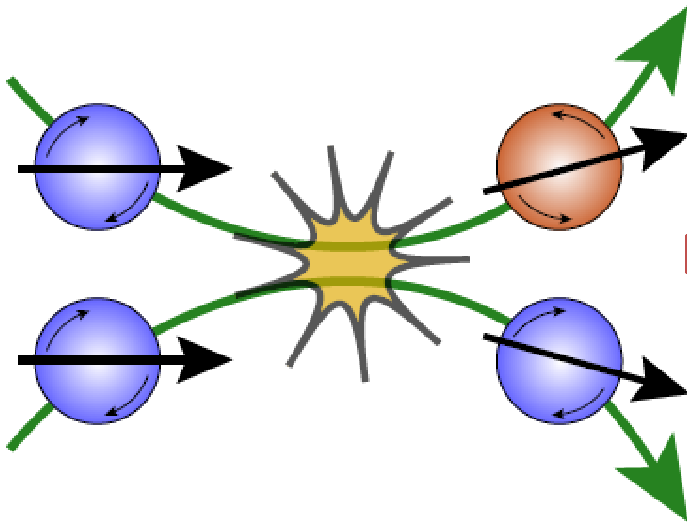
$$\theta \sim LnS_z$$

Optical rotation angle is proportional to the polarization component along the direction of probe beam propagation.

Probe signal at PD : $I_1 = I_0 \sin^2\theta,\ I_2 = I_0 \cos^2\theta$

SERF magnetometer

Fundamental Limitation of AM: Spin-exchange collisions.



Decoherence
(short T_2)

Breakthrough: Spin-Exchange Relaxation-Free (SERF) magnetometer

- In the regime of high density (strong spin-exchange, strong signal) and low magnetic field, spin-exchange collisions do not depolarize the spins.
- Only SERF magnetometer can achieve subfemtotesla sensitivity in low frequency

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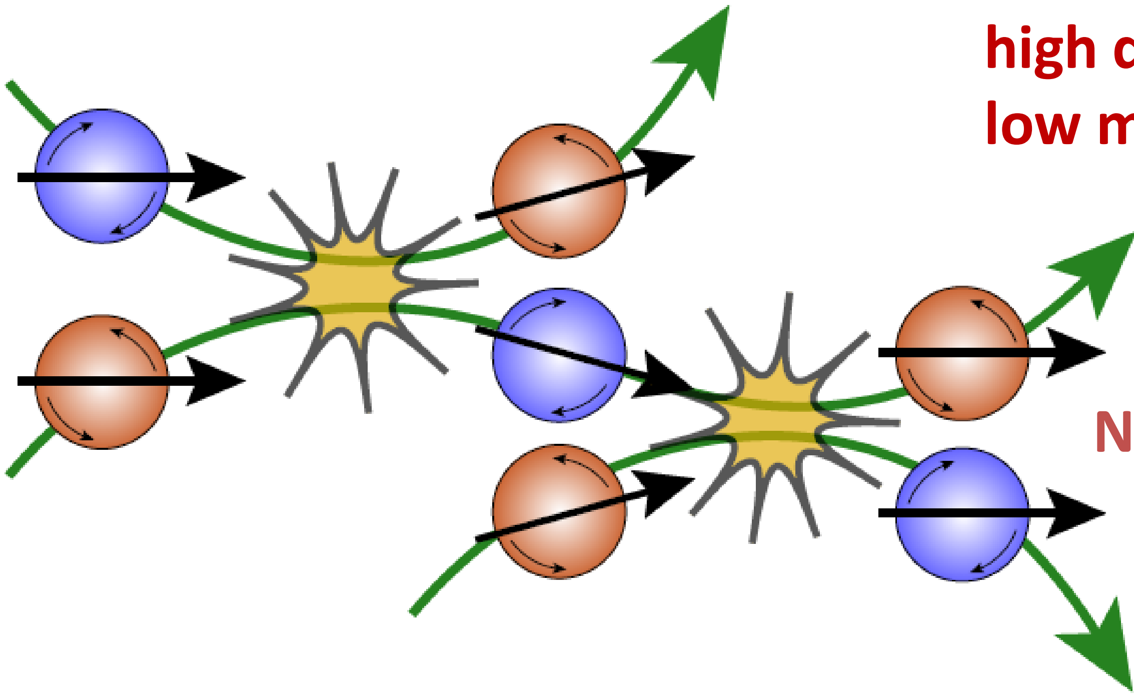
SERF magnetometer



high density,
low magnetic field

NO decoherence

Spin-exchange collision rate >> precession frequency

SERF magnetometer eliminates spin-exchange relaxation !

First demonstrations of the SERF magnetometer (PRL V. 89, p.130801, 2002):

1. Pump and probe beams were orthogonal (most optimal configuration)
2. Sensitivity ~ 10 fT/Hz$^{1/2}$
3. Less convenient for miniaturization and cost reduction

SERF Magnetometer Response

Bloch equation describes the response of the SERF magnetometer to magnetic fields:

$$\frac{d\vec{S}}{dt} = \gamma\vec{S}\times\vec{B} + R(S_0\hat{z} - \vec{S}) - \frac{\vec{S}}{T_2}$$

S : electron spin polarization vector,
R: optical pumping rate
S_0: equilibrium electron spin polarization
$\gamma = 2\pi\times 7\,\mathrm{GHz/T}$

Steady state solution, dS/dt =0 :

$$S_x = S_0\frac{-\beta_y + \beta_x\beta_z}{1+(\beta_x^2+\beta_y^2+\beta_z^2)}, \quad S_y = S_0\frac{\beta_x + \beta_y\beta_z}{1+(\beta_x^2+\beta_y^2+\beta_z^2)},$$

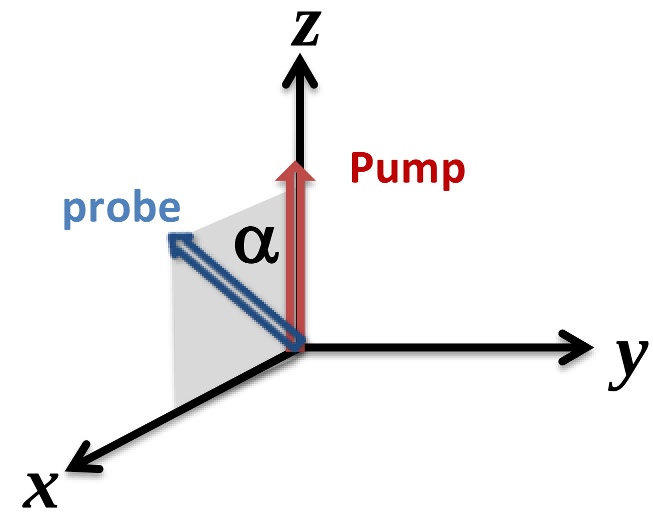
$$S_z = S_0\frac{1+\beta_z^2}{1+(\beta_x^2+\beta_y^2+\beta_z^2)},$$

$$\vec{\beta} = \frac{\gamma\vec{B}}{R+T_2^{-1}}$$

dimensionless magnetic field components

SERF Magnetometer Response

Magnetometer signal proportional to the component of the electron spin in the probe propagation direction:



$$S_{probe} = S_x \sin\alpha + S_z \cos\alpha$$

$$= S_0 \left[\frac{(-\beta_y + \beta_x \beta_z)\sin\alpha + (1+\beta_z^2)\cos\alpha}{1+(\beta_x^2+\beta_y^2+\beta_z^2)} \right]$$

First case: α is not small

$$S_{probe} \approx S_0 \left[\frac{(-\beta_y + \beta_x \beta_z)\sin\alpha}{1+(\beta_x^2+\beta_y^2+\beta_z^2)} \right]$$

Maximum value when α is π/2

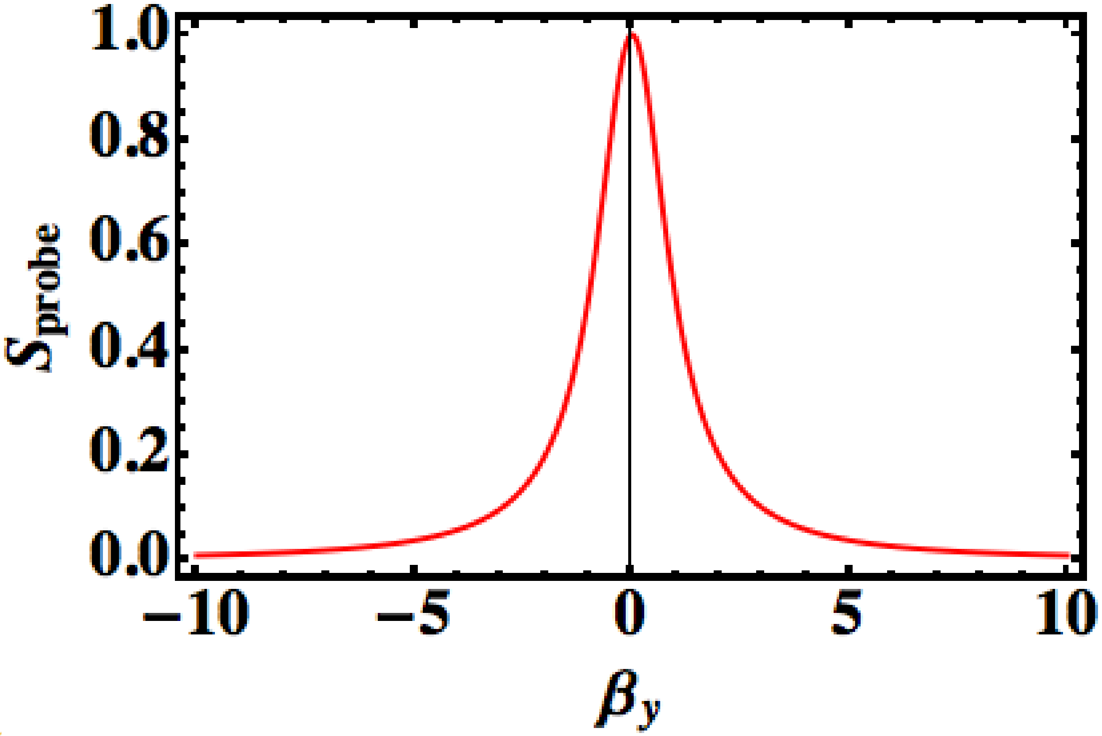
This case is the traditional perpendicular probe-pump orientation, but we are interested in almost parallel beam probe-pump orientation

SERF Magnetometer Response

Second case: α is very small (nearly parallel beams configuration)

$$S_{probe} \approx S_0\left[\frac{(1+\beta_z^2)\cos\alpha}{1+(\beta_x^2+\beta_y^2+\beta_z^2)}\right] \approx S_0\left[\frac{1}{1+(\beta_x^2+\beta_y^2)/(1+\beta_z^2)}\right]$$

Example:



For maximum response to a oscillating field:

$$\frac{\partial S_{probe}}{\partial \beta_y} = \max$$

SERF Magnetometer Response

Second case: α is very small

$$S_{probe} \approx S_0 \left[\frac{(1+\beta_z^2)\cos\alpha}{1+(\beta_x^2+\beta_y^2+\beta_z^2)} \right] \approx S_0 \left[\frac{1}{1+(\beta_x^2+\beta_y^2)/(1+\beta_z^2)} \right]$$

- **Maximum response to a oscillating field in *y* direction:**

$$\frac{\partial S_{probe}}{\partial \beta_y} = 0.65 S_0 \quad \text{at } \boxed{\beta_x = \beta_z = 0, \beta_y = 1/\sqrt{3}}$$

Optimal fields

Decreased by a factor of 1.5 compared to the perpendicular beams

- **Maximum response to a oscillating field in *z* direction:**

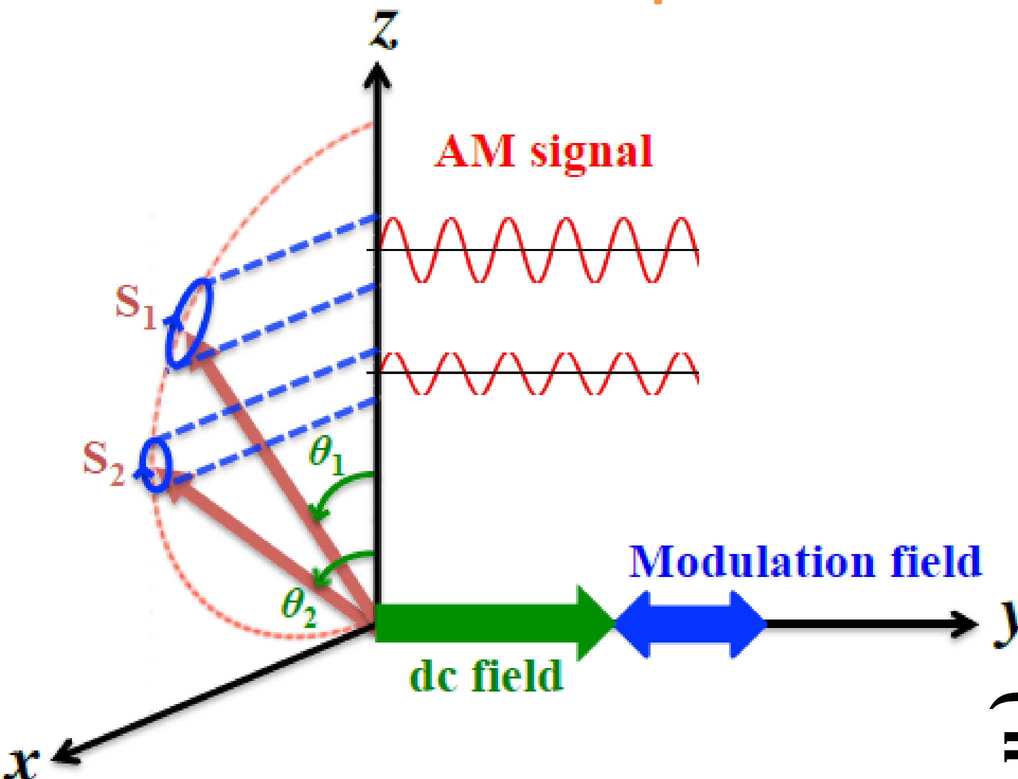
$$\frac{\partial S_{probe}}{\partial \beta_z} = 0.25 S_0 \quad \text{at } \boxed{\beta_z = 1,\ \beta_x^2 + \beta_y^2 = 2}$$

Optimal fields

Decreased by a factor of 2 compared to the perpendicular beams

SERF Magnetometer Response

Visualization of the optimization to the y component:



$$\theta = \tan^{-1}(S_x / S_z) = \tan^{-1} \beta_y^{dc}$$

$$\text{Magnitude} = \sqrt{S_x^2 + S_y^2 + S_z^2}$$

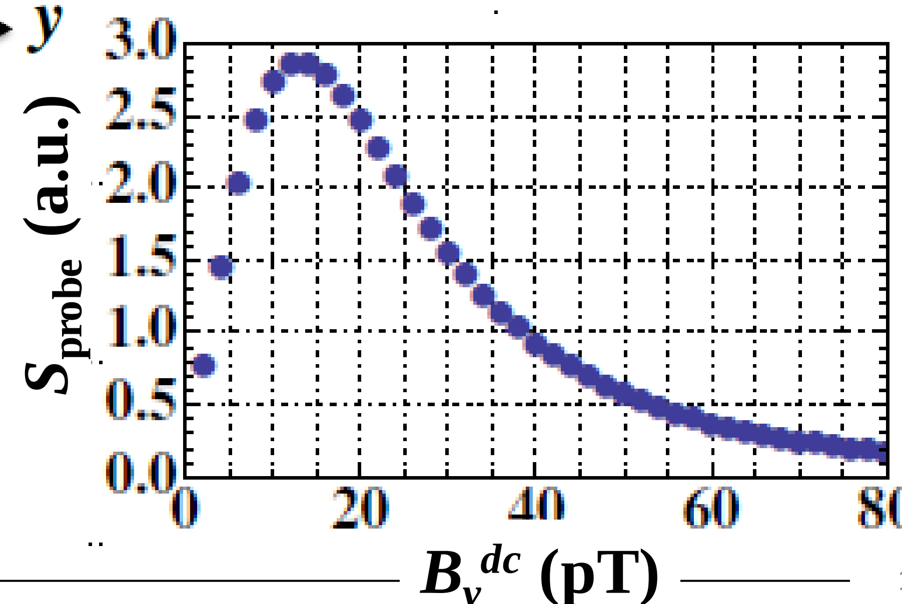
$$= S_0 / \sqrt{1 + (\tan\theta)^2}$$

Optimal angle:

$$\theta = \tan^{-1}(1/\sqrt{3}) = 30^\circ$$

$$\vec{\beta} = \frac{\gamma \vec{B}}{R + T_2^{-1}}, R + T_2^{-1} = 1$$

$$B_y^{dc} = (\beta_y = 1/\sqrt{3}) / \gamma = 13\,\text{pT}$$



Resolution of SERF magnetometer

The fundamental sensitivity limit is due to shot-noise:

$$\delta B = \frac{1}{\gamma\sqrt{NT_2Vt}}$$

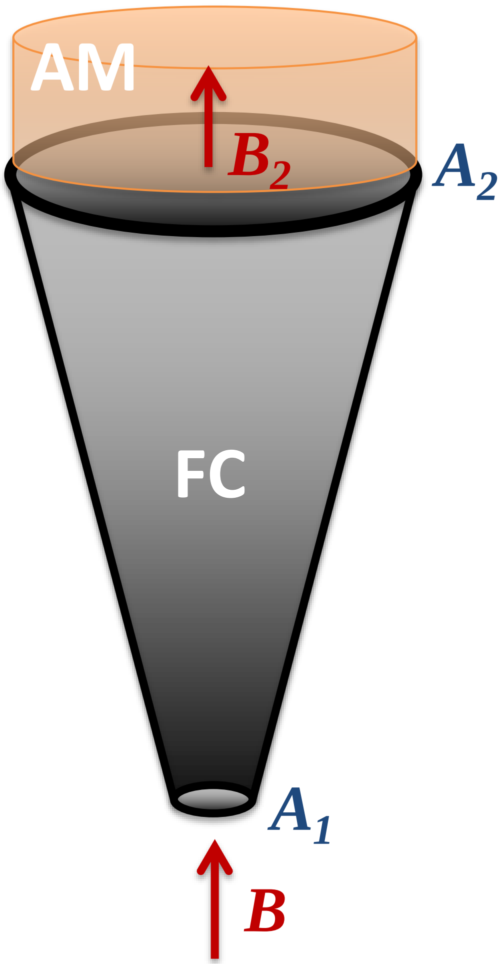
N = the number of active atoms
V = the cell volume,
t = the measurement time

Higher sensitivity $\rightarrow$ lower resolution
Example: 1 fT/Hz$^{1/2}$ $\rightarrow$ cm-scale resolution
(Nature V. 422, p.596, 2003)
70 fT/Hz$^{1/2}$ $\rightarrow$ mm-scale resolution
(Nat. Photonics V. 1, p.649, 2007)

How to reach high resolution, high sensitivity?

- **Instead of reducing cell dimensions to micron size, a flux concentrator expands the microscopic magnetic distribution to match the dimensions of AM operating with high sensitivity.**

FC + AM system



Magnetic field of interest

AM measured B_2:

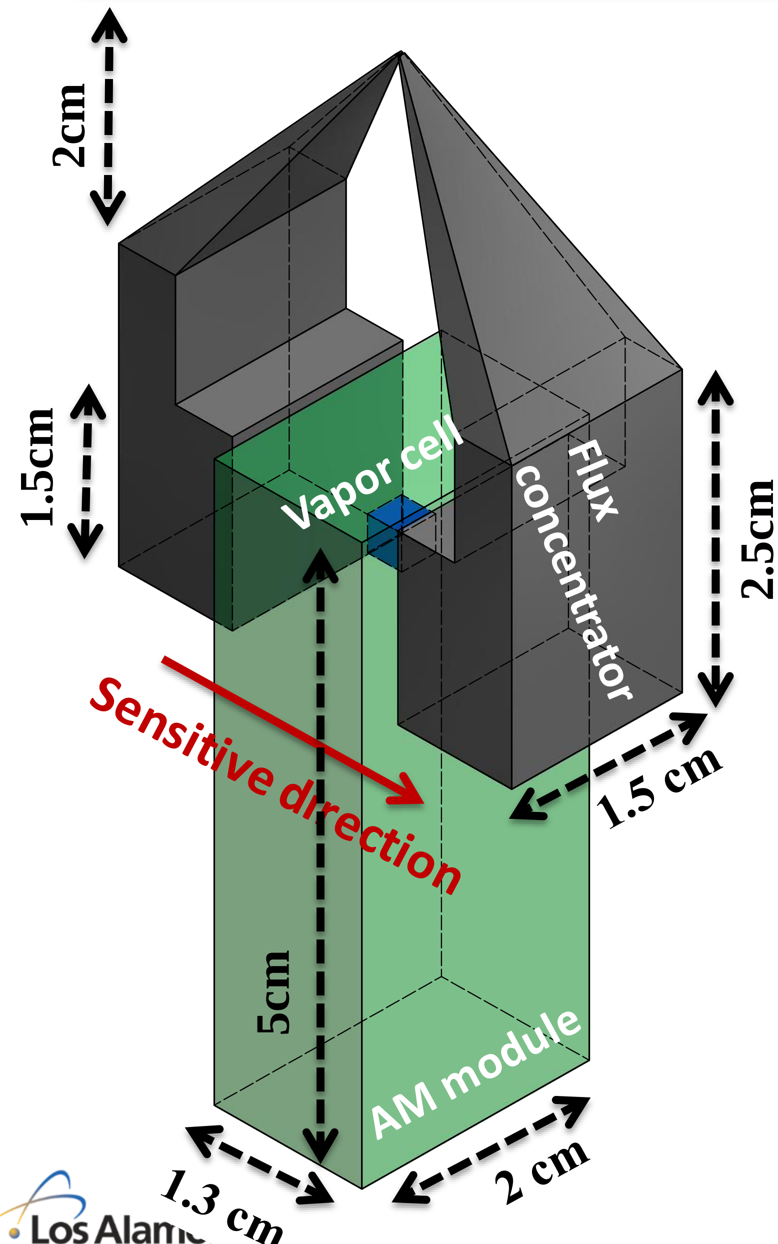
$$B_2 = B\frac{A_1}{A_2}$$

Sensitivity of a FC+AM system composed of an AM with 1 fT sensitivity and 5 mm channel and an FC with 100 μm resolution:

$$B = B_2\frac{A_2}{A_1} = 1\,\mathrm{fT}\frac{\pi\left(\frac{5\mathrm{mm}}{2}\right)^2}{\pi\left(\frac{100\mu\mathrm{m}}{2}\right)^2} = 2.5\,\mathrm{pT}$$

→ **Suitable for detecting a single neuron**

Design of a single channel FC+AM system



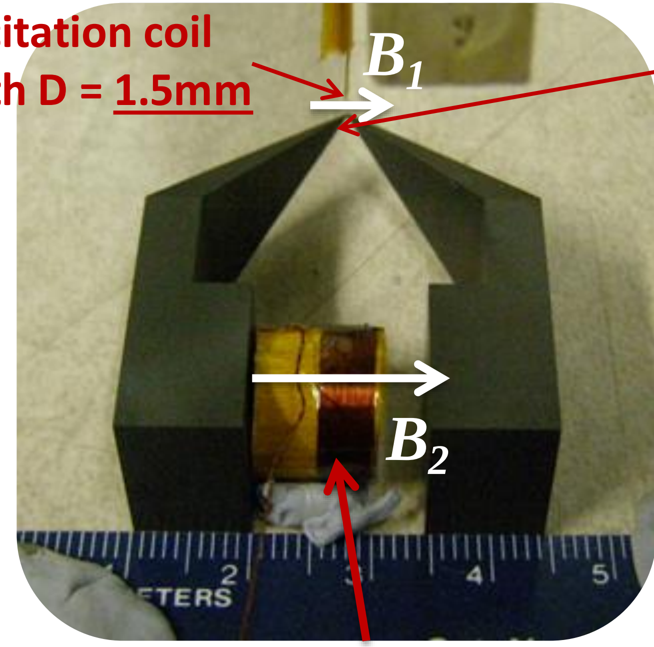
Flux concentrator:

- Constructed from non-conductive MnZn ferrites to avoid large Johnson noise.
- Noise from MnZn ferrite ~ fT level
- μ ~ 6500

Atomic magnetometer:

- Commercial integrated AM
- Vapor cell size: 3mm×3mm× 3mm
- Sensitivity ~ 10 fT level (it can be improved to ~ 1 fT level).

Test of field transfer on FC



Excitation coil with D = 1.5mm

Gap between ferrite tips = 2 mm

Sensing coil with D = 11.6 mm, 20 turns

Field at the excitation coil, $B_1 = \frac{\mu_0 I}{D}$

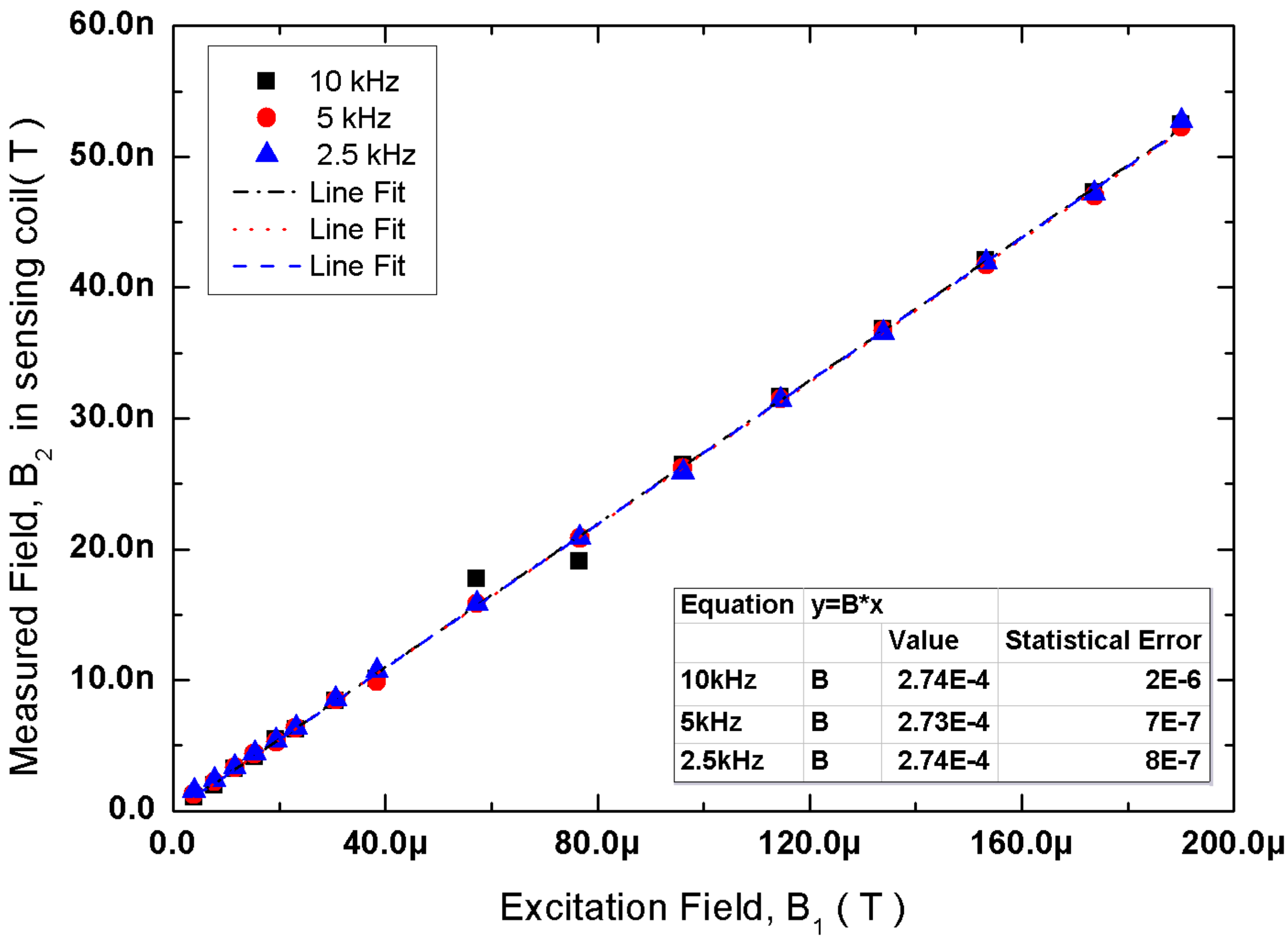
Field at the sensing coil, $B_2 = \frac{V}{NA\omega}$

Field transfer coefficient : $k = \frac{B_2}{B_1}$

Sensitivity of FC + AM system = (Sensitivity of AM)/k

Ideal $k = 9.4 \times 10^{-3}$

Test of field transfer on FC

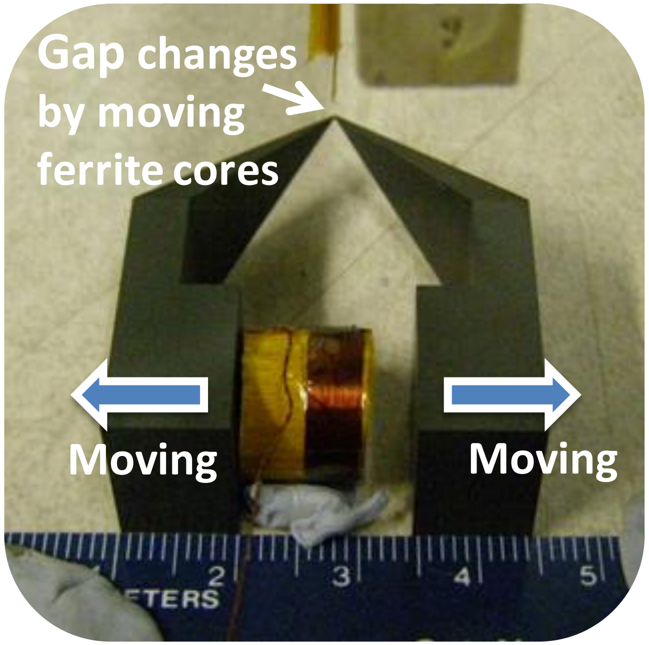


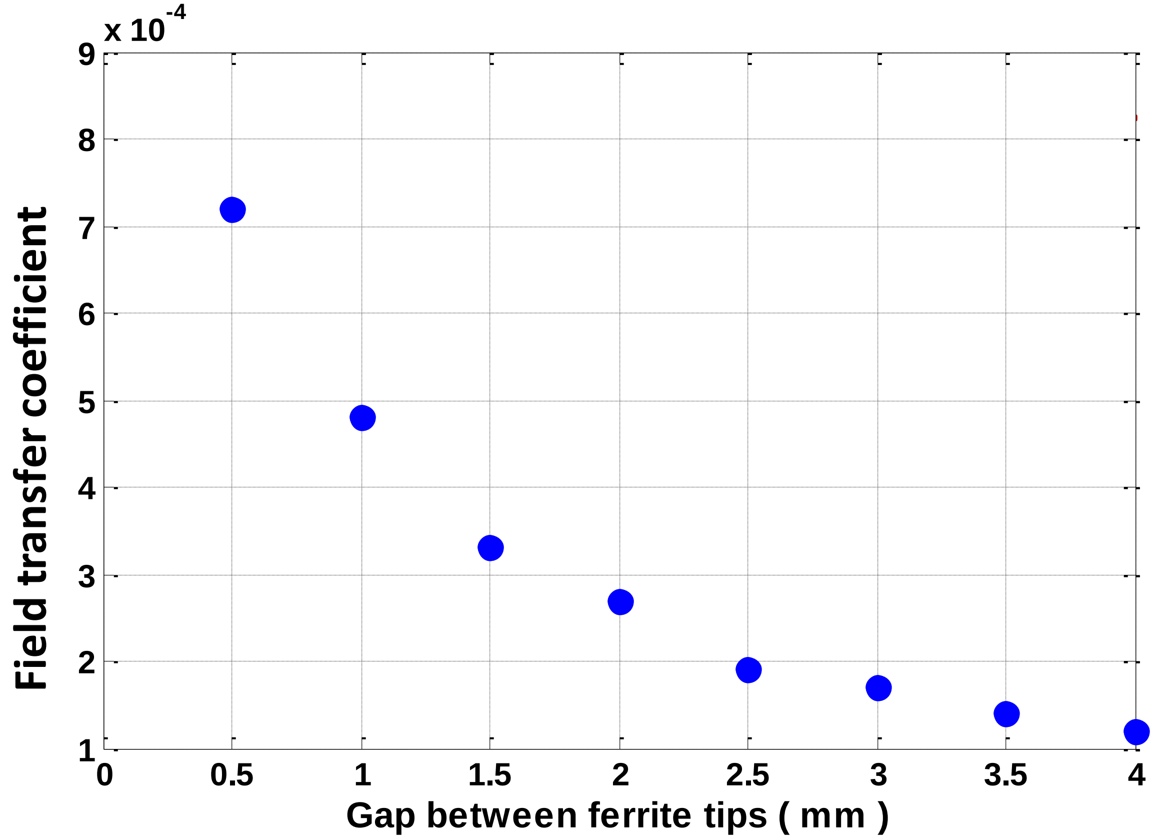
$k = 2.74 \times 10^{-4}$

Sensitivity of FC + AM system

$= 1\,\mathrm{fT}/k = 3.6\,\mathrm{pT}$

Test of field transfer on FC

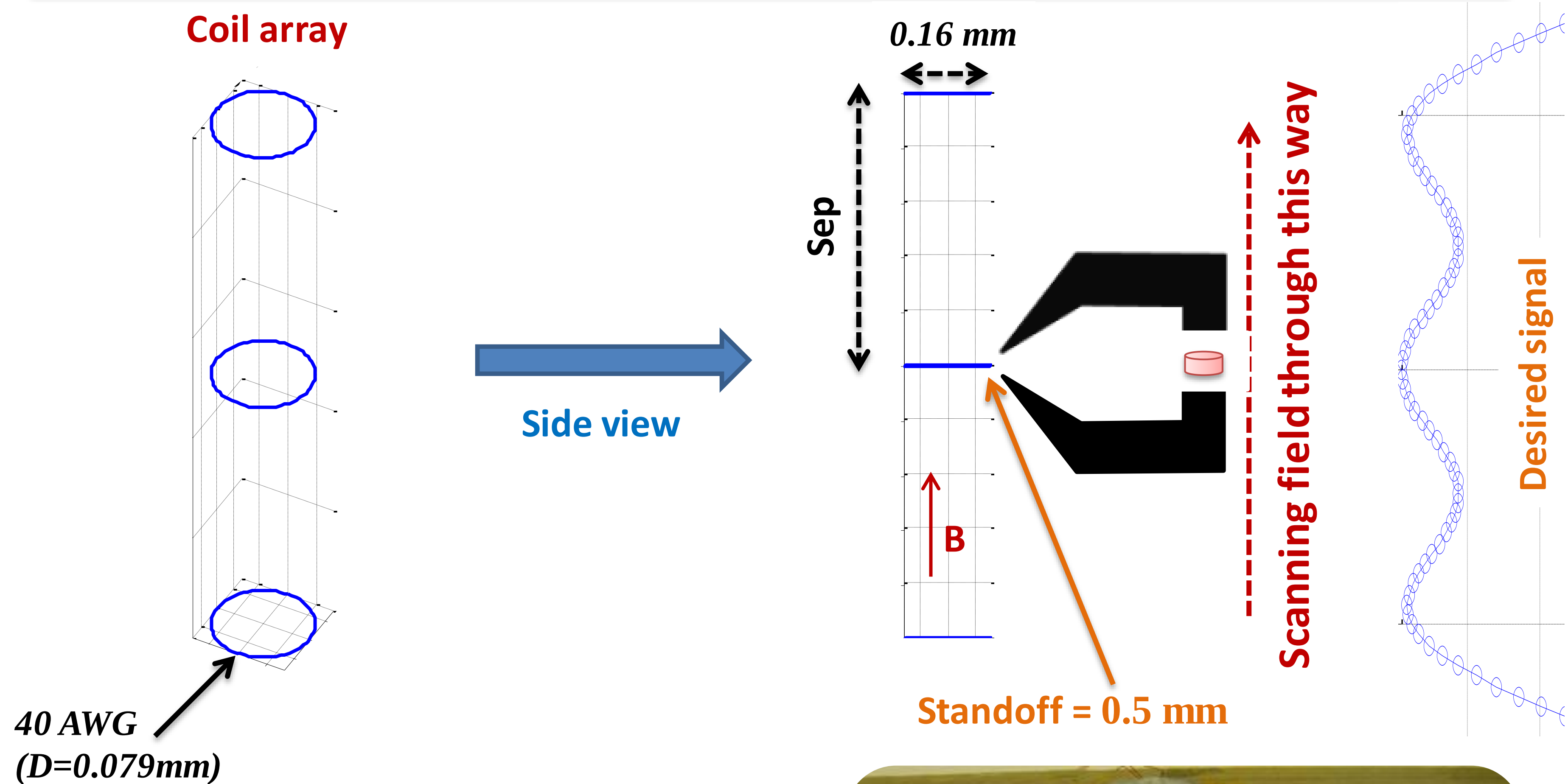




Field transfer improves with smaller gap between ferrite tips

- more flux is collected by ferrite

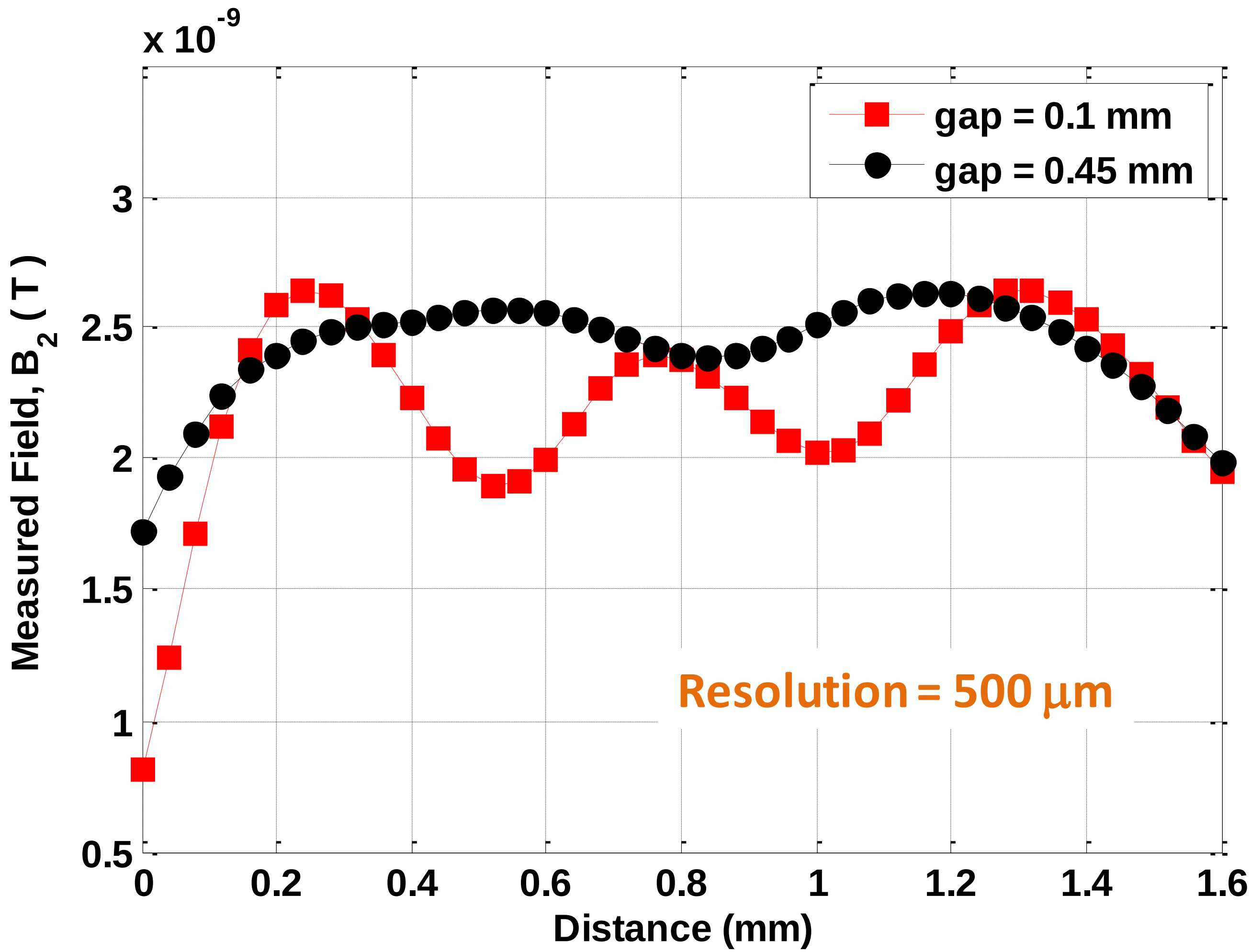
Test of resolution



- Change the distance between the coils for resolution tests
- Flux concentrator can see three peaks of the field?

Test of resolution

- Gap between ferrite tips changed
- Measuring three peaks means the resolution of 500 μm.



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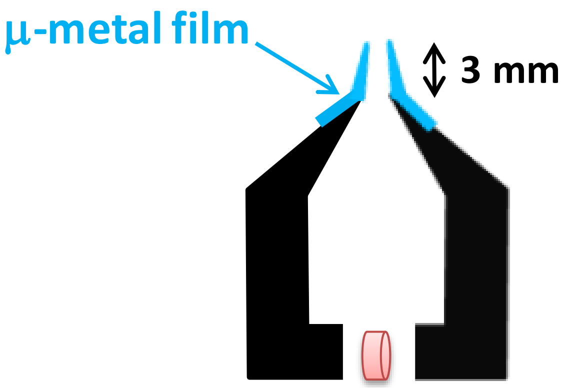
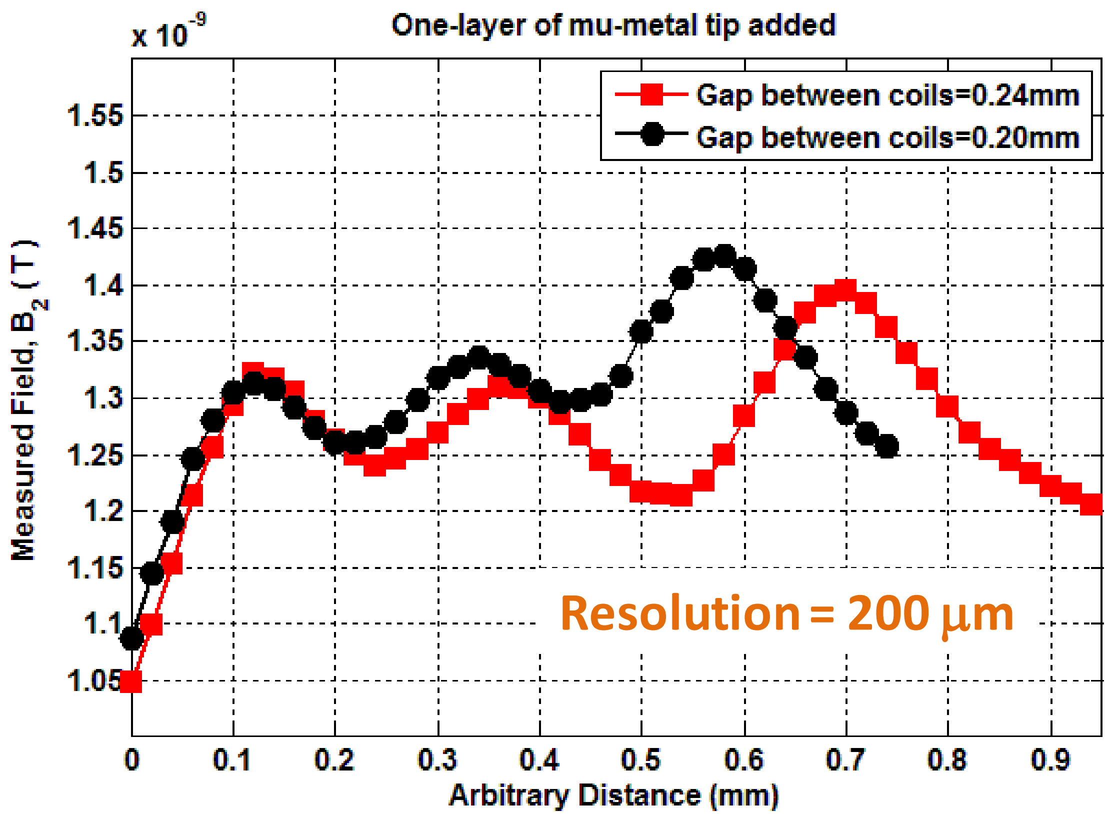
Test of resolution



- **For higher resolution, a sharp μ-metal film (one layer) is attached on the ferrite tips**
- **Gap of the ferrite tips ~ 0.1mm**

- **The distance between excitation coils is ~ <u>0.2 mm and 0.3 mm.</u>**



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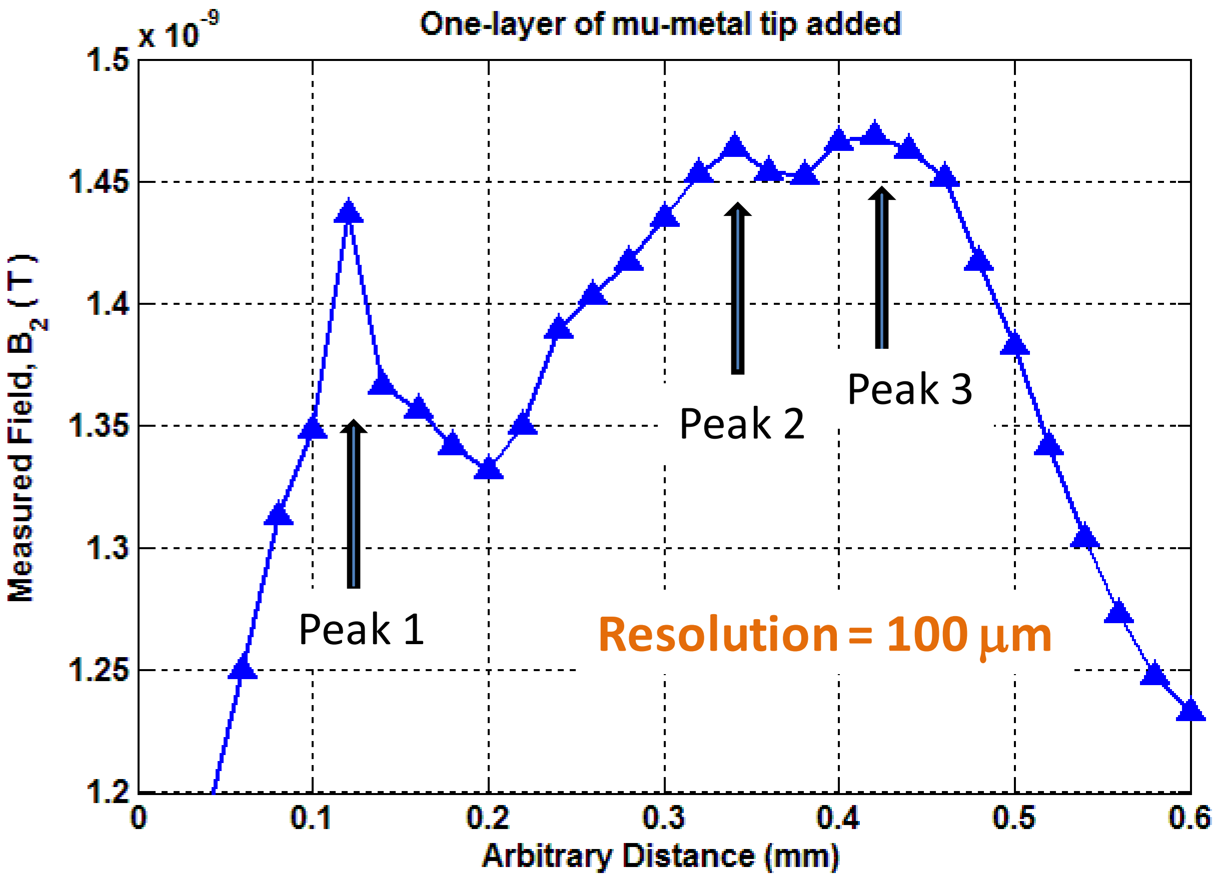
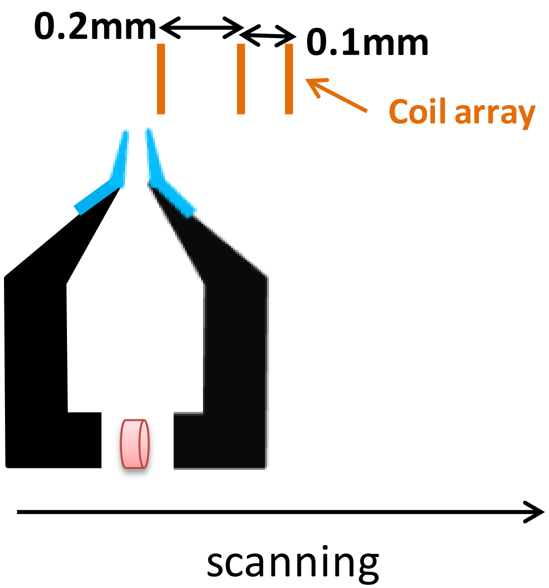
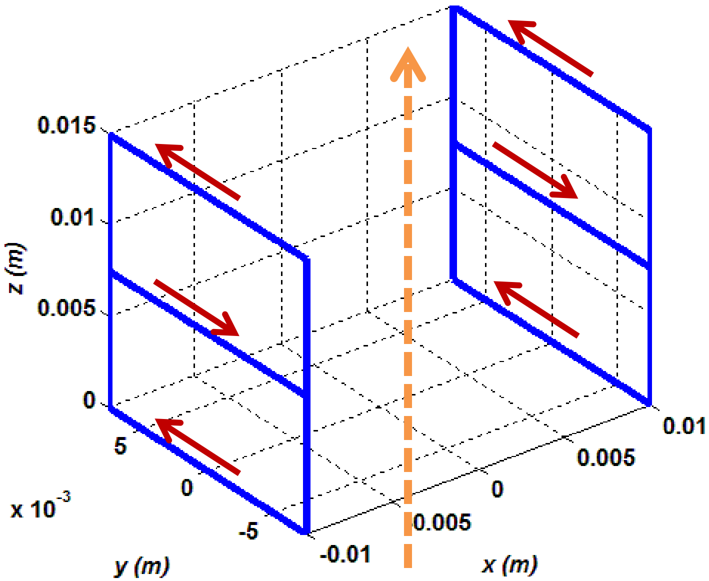
Test of resolution

- The distance between excitation coils is ~0.2 mm and ~0.1 mm.
- Gap of the mu-metal tips ~ 0.1mm

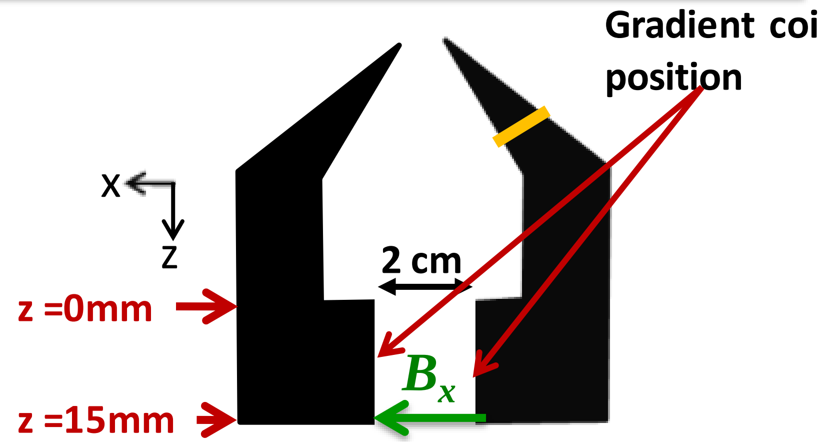


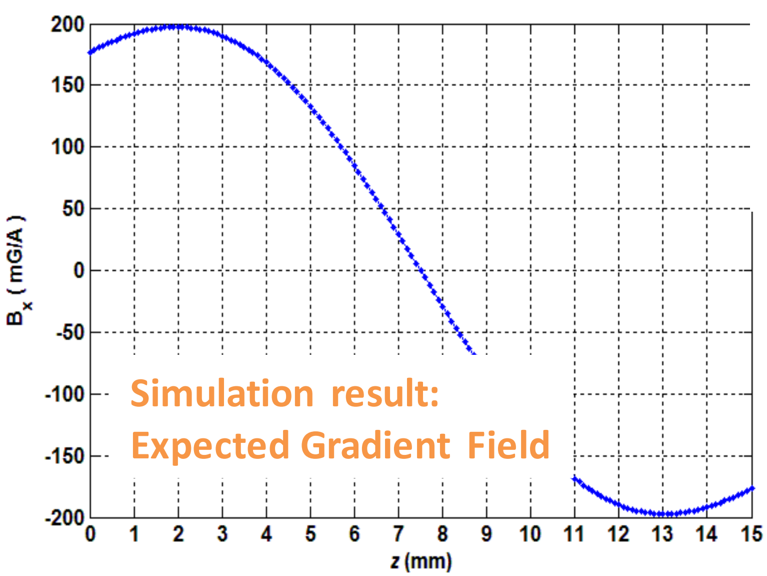


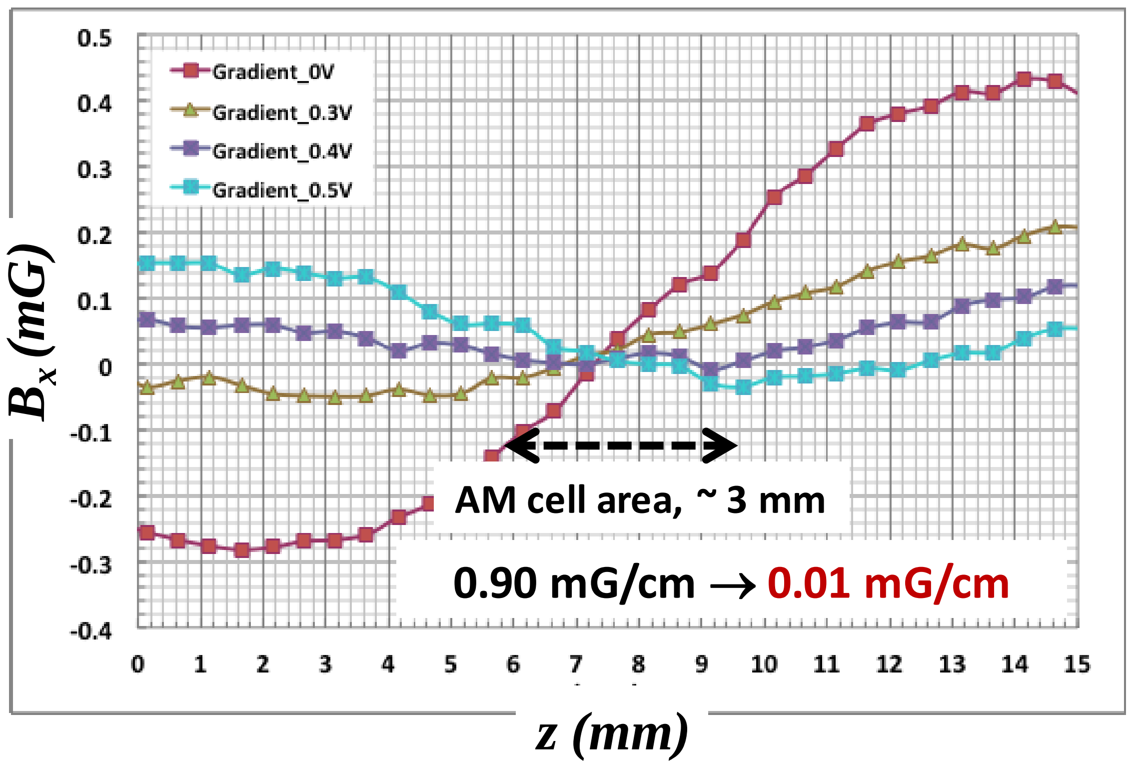
Gradient cancellation



Direction of scanning B_x



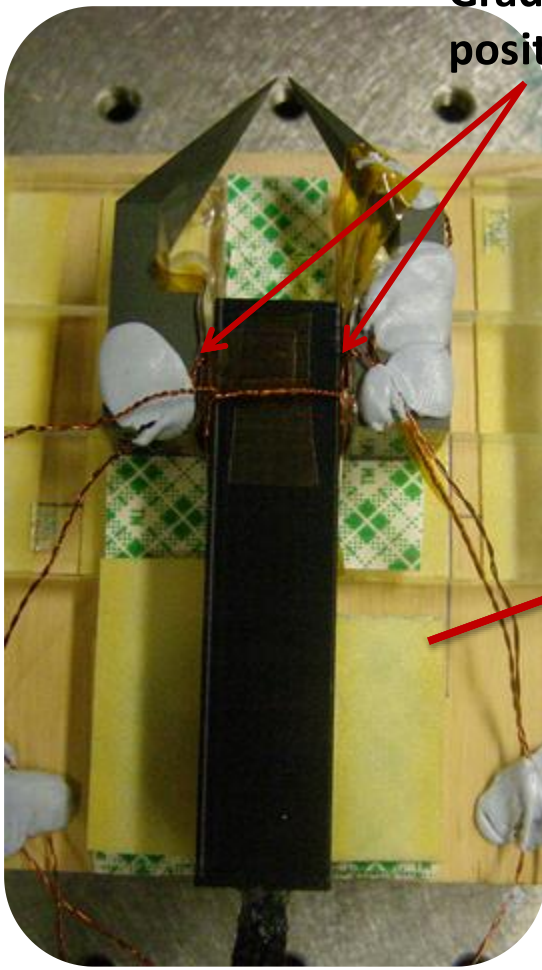


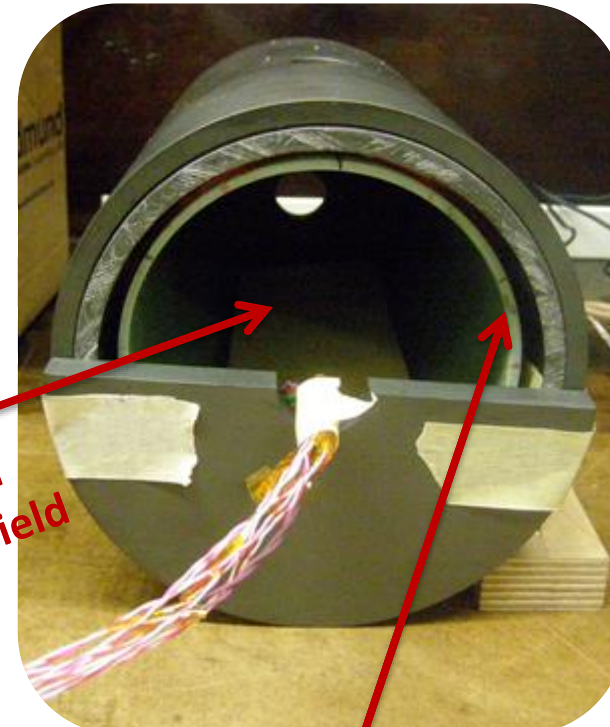


Test of AM performance

Gradient coil position

One layer of mu-metal shied is not shown





The assembly placed inside the ferrite shield

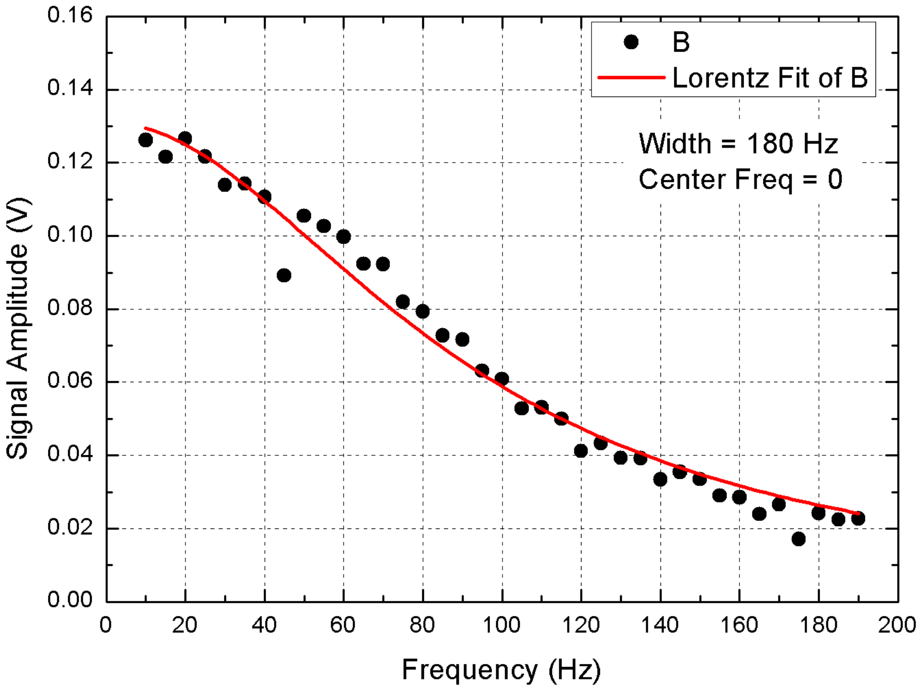
There are 3 axes compensation coil and 5 gradient compensation coil

FC +AM system

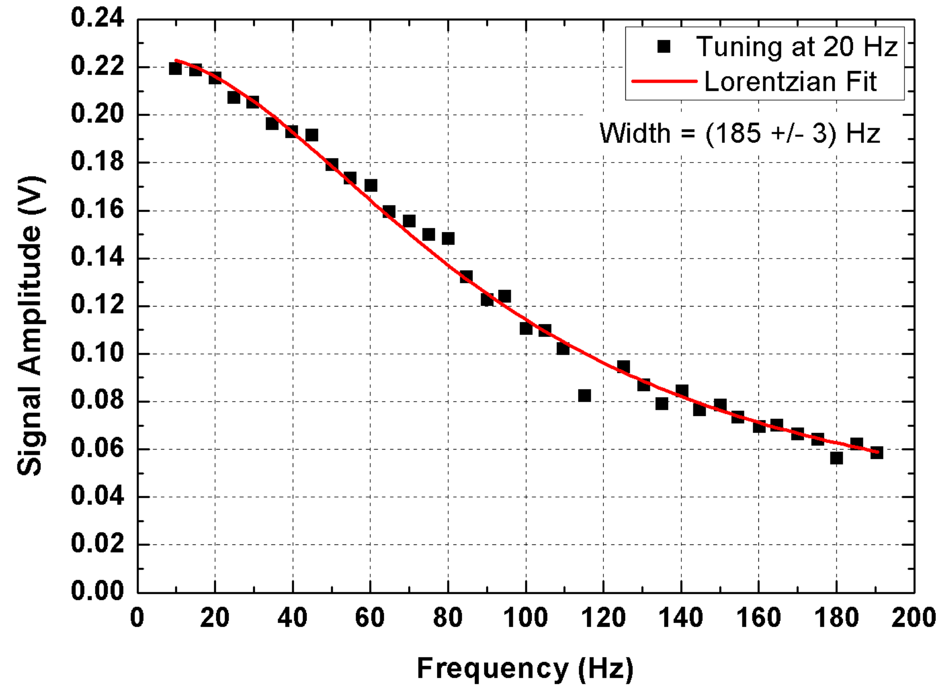
Note: these coils cannot compensate the gradient on FC!

Test of AM performance

Ideal case with shielding



WITH FC in shielding



- **Flux concentrator doesn't deteriorate AM's performance.**
- **The gradient compensation coil on the flux concentrator is important to get best AM's performance.**

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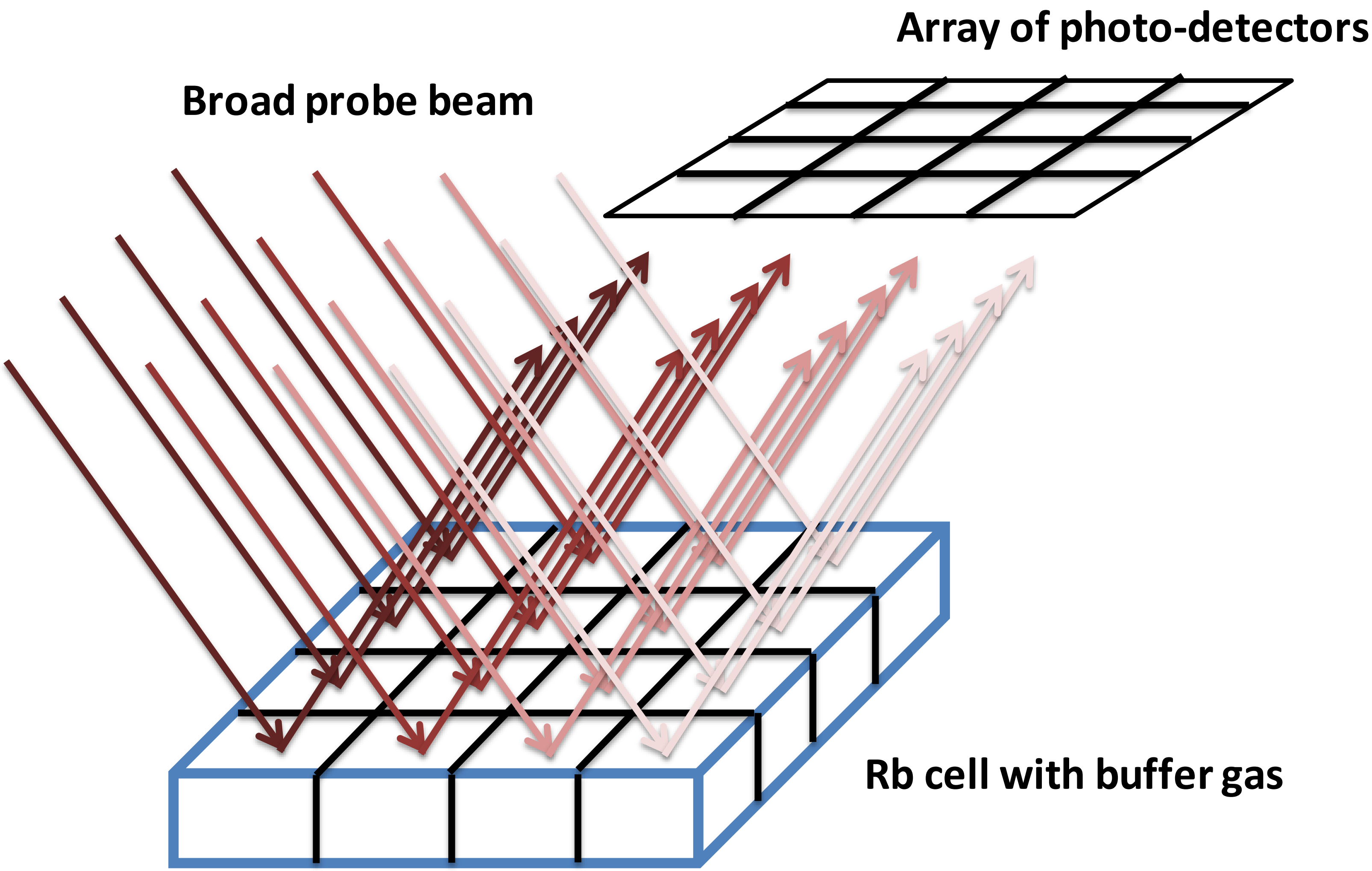
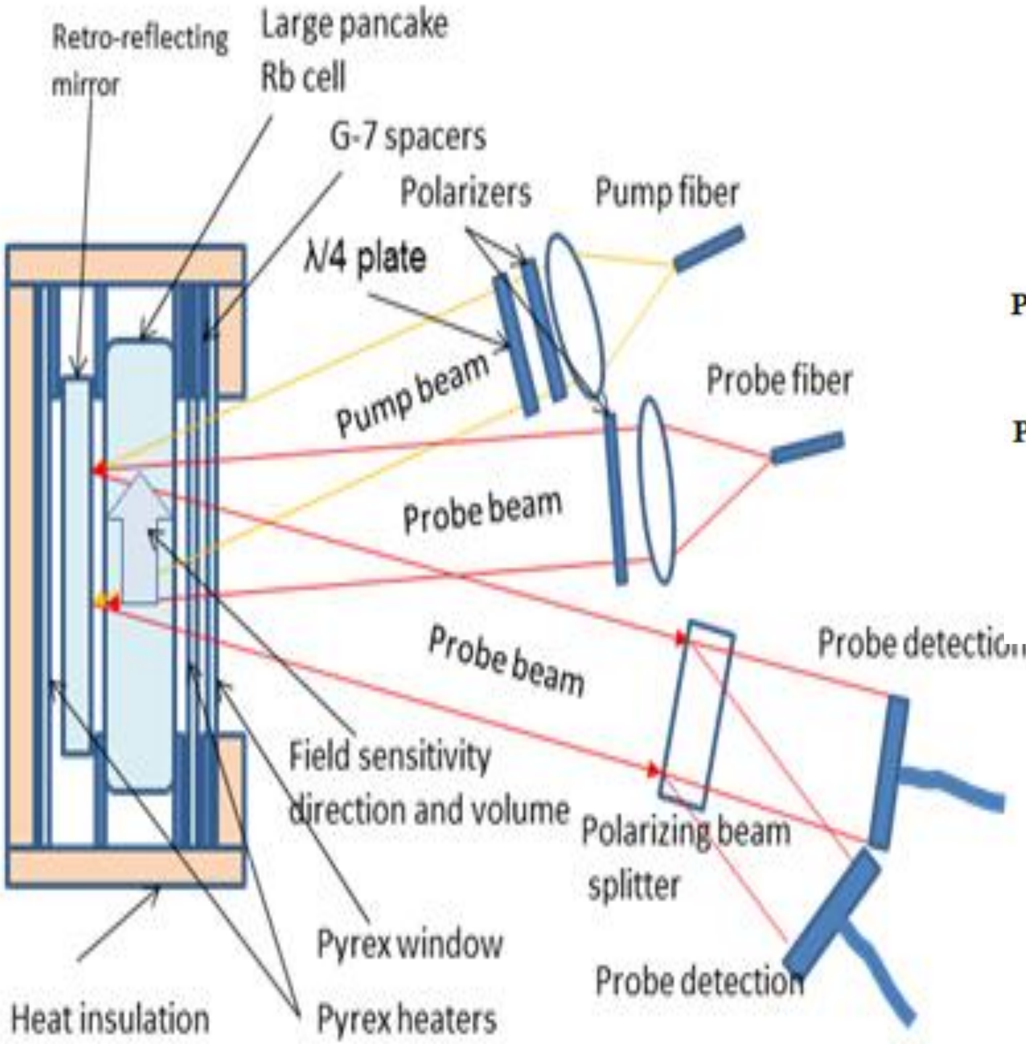
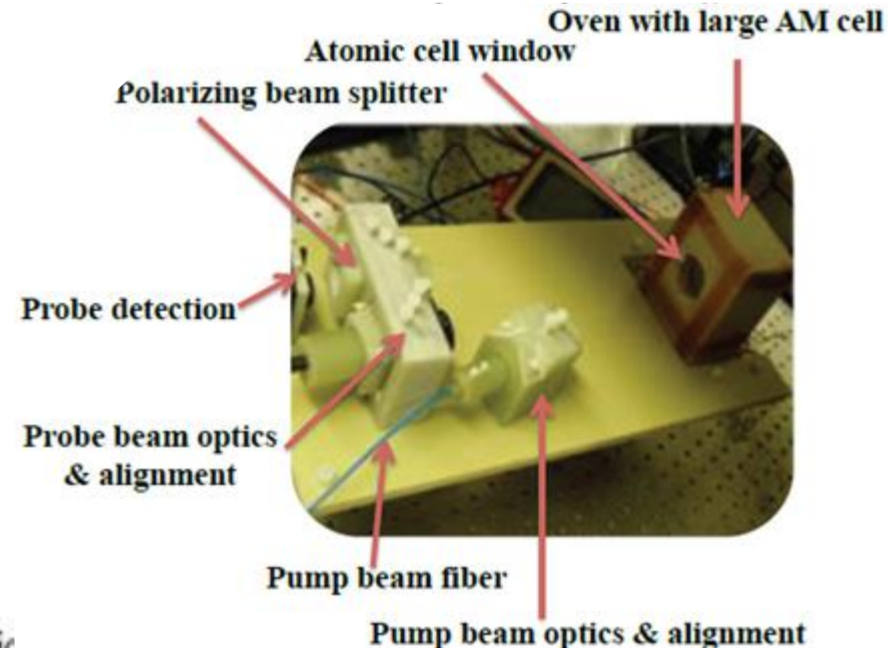
Idea of Multi-channel AM

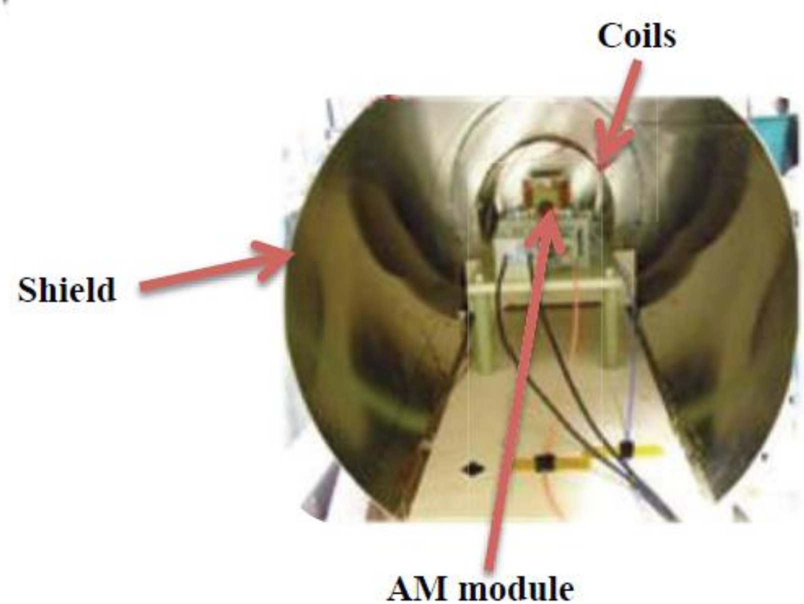


2D multi-channel is possible with Large Rb cell with a buffer gas and broad beams instead of 16 individual cells and beams.

Prototype multi-channel AM







Advantage of using fibers: Flexible AM design

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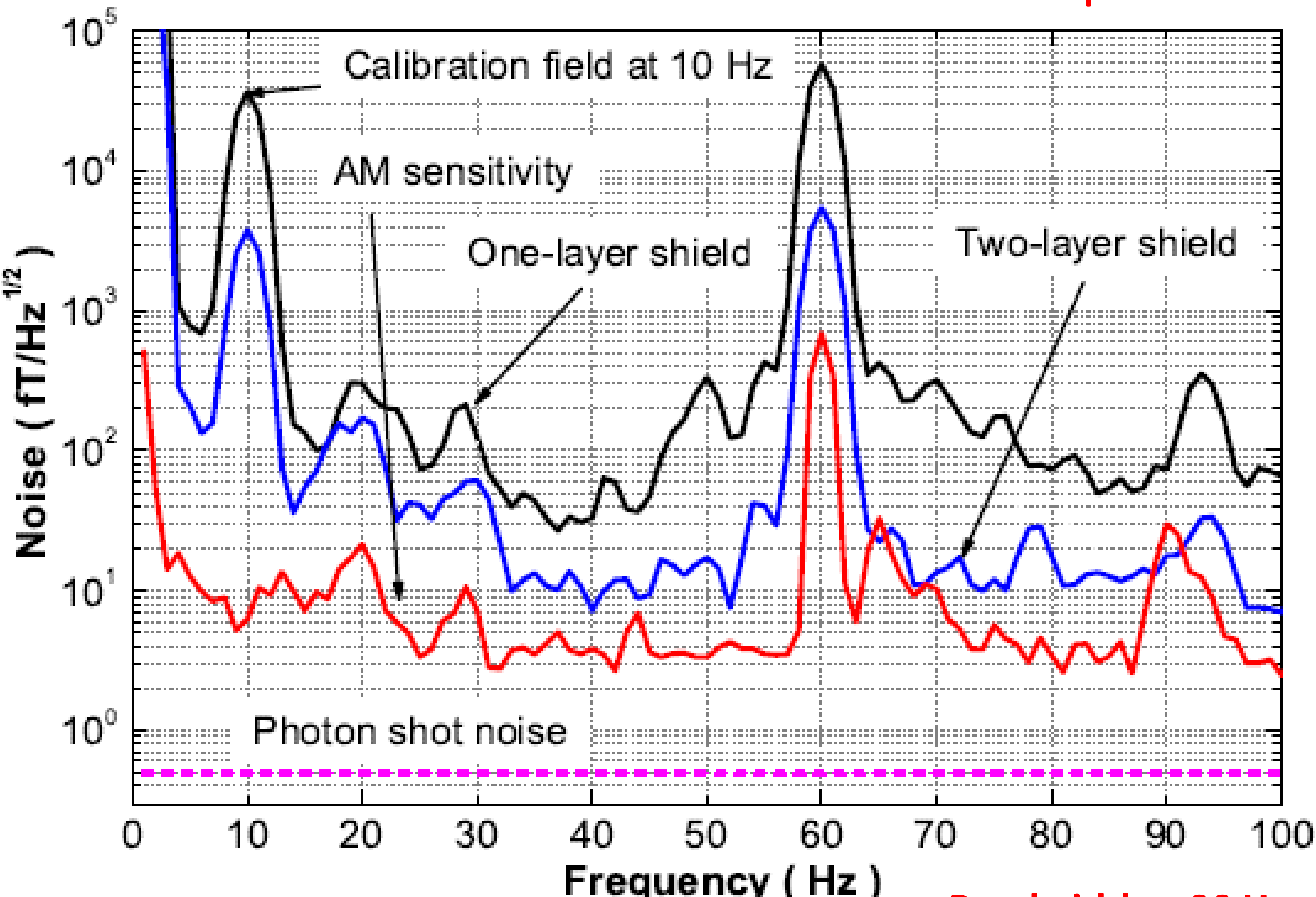
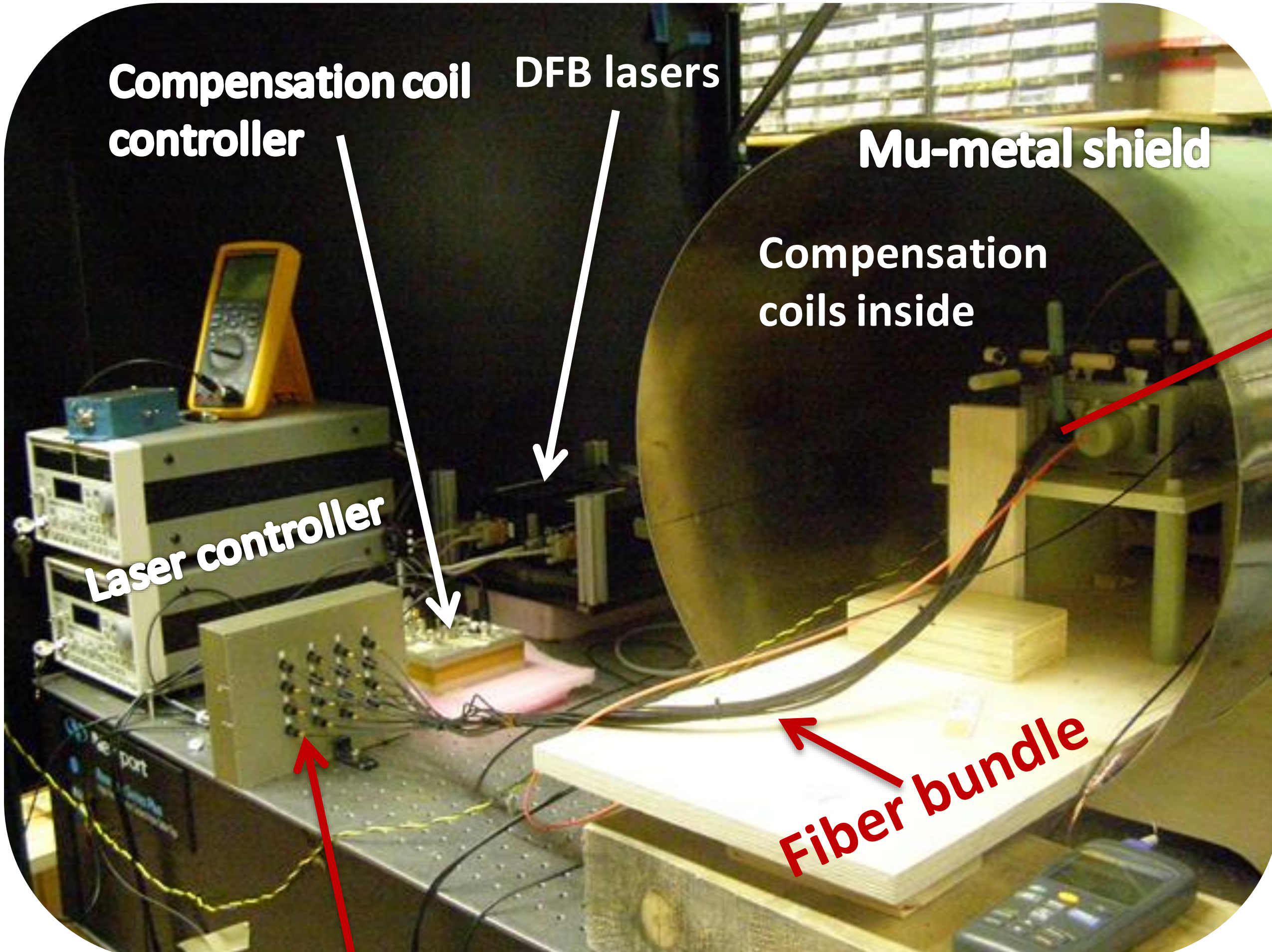
Feasibility proof in single channel

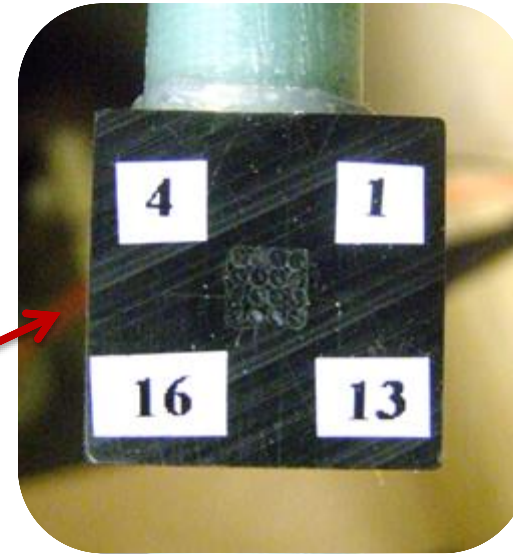
Cell temperature ~ 150 °C



Bandwidth ~ 90 Hz

Configuration of multi-channel AM system



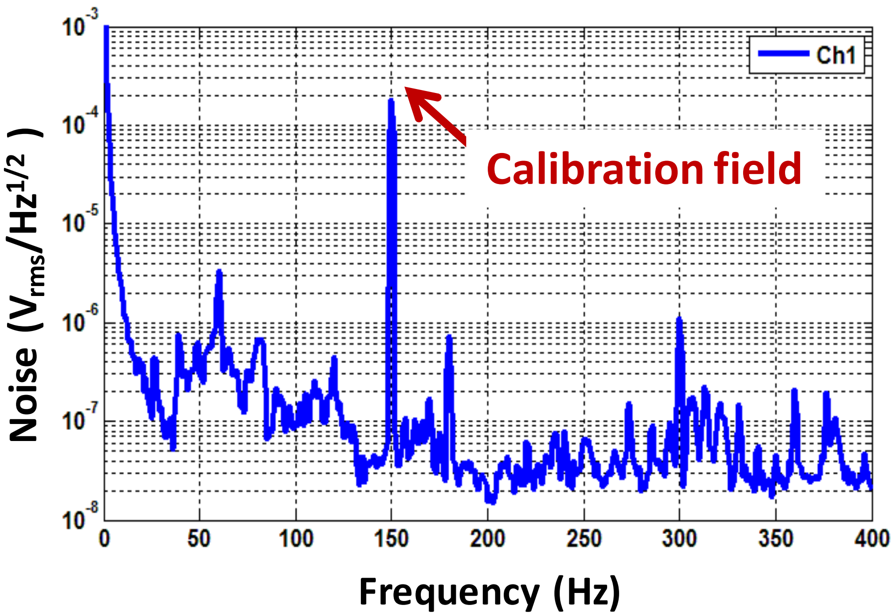


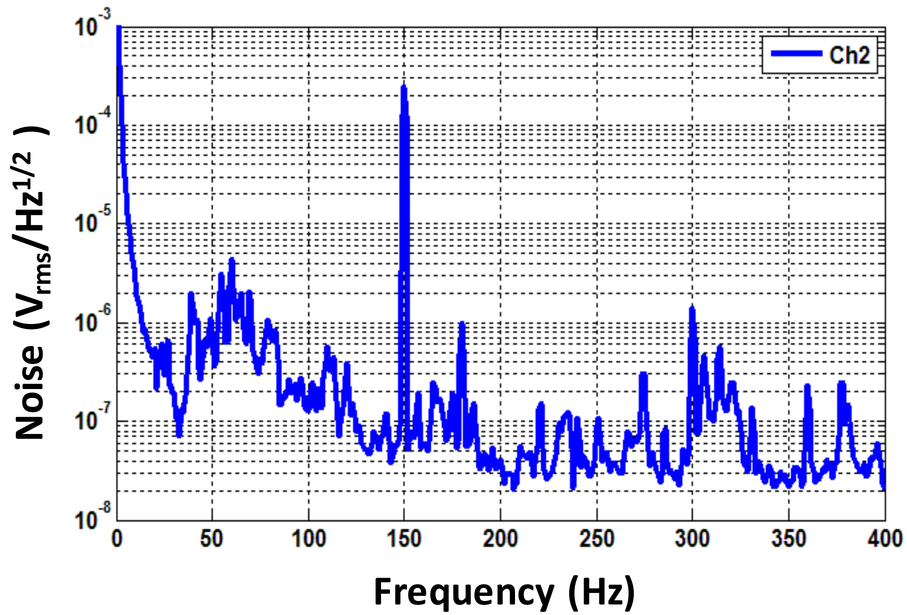
4×4 channels

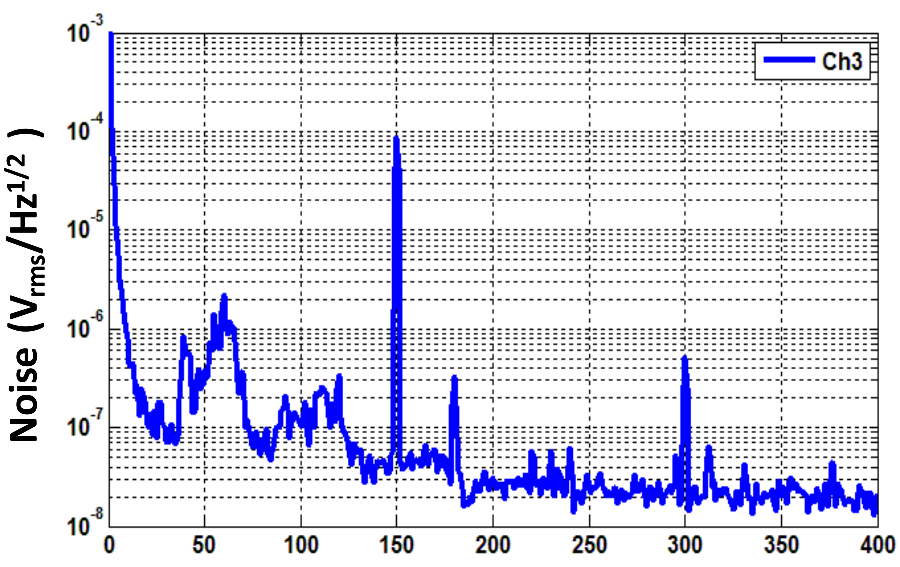
16 channels photodiodes array

For shielding:
One layer of mu-metal shield
One ferrite box

Preliminary sensitivity test





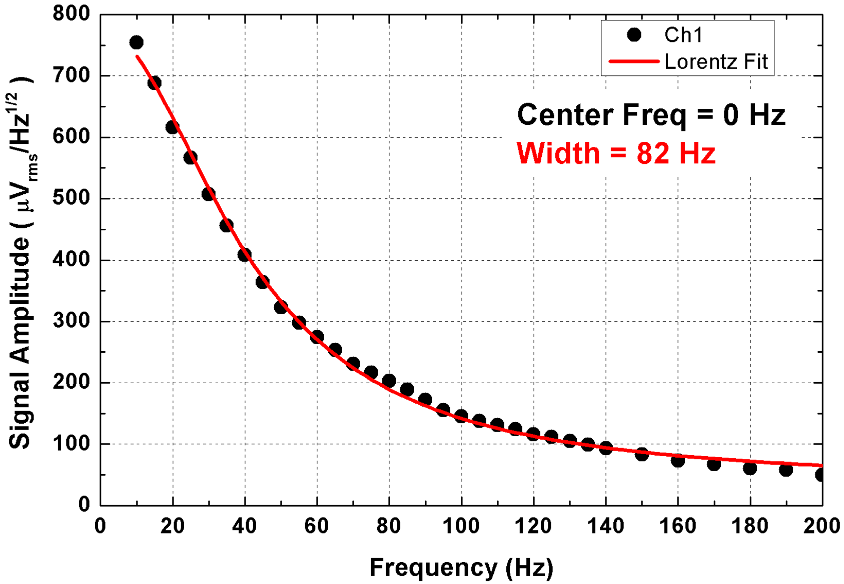


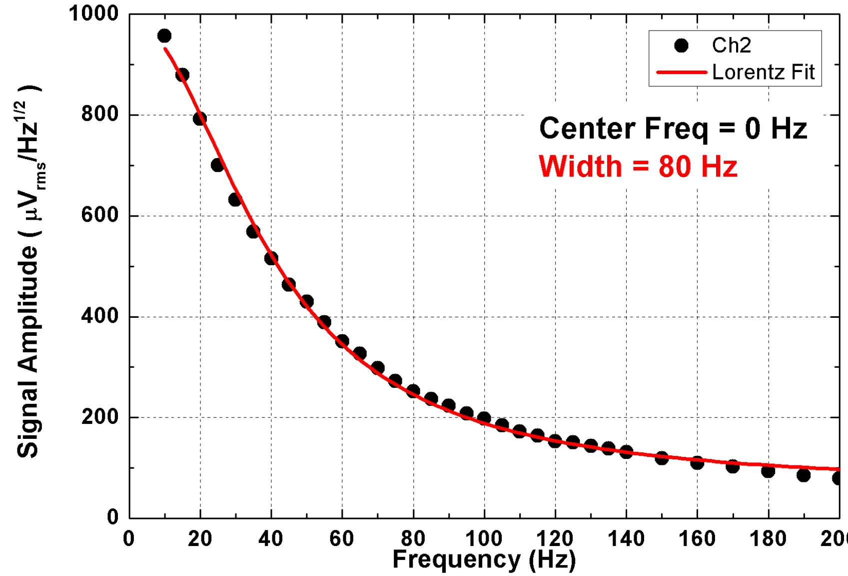
SNR of each channel : 4000 to 100

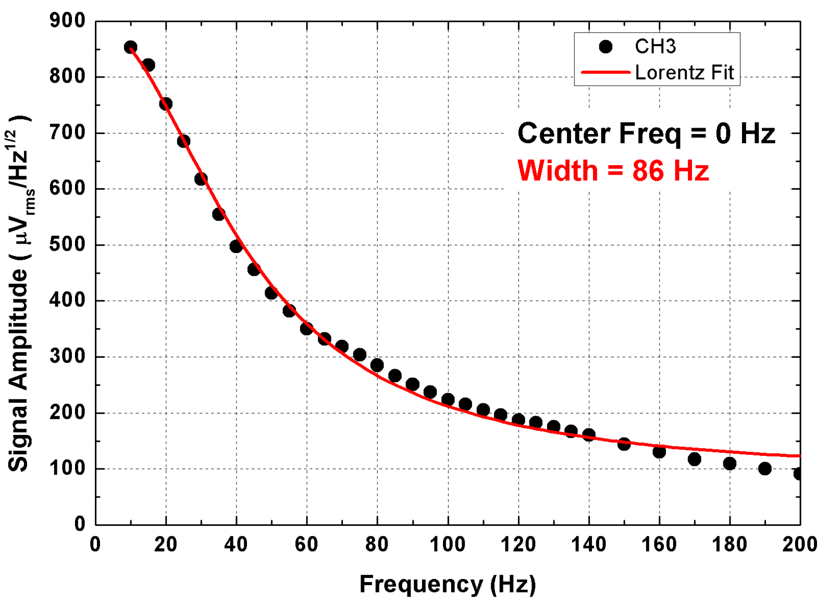
Field sensitivity of each channel: 50 fT/Hz$^{1/2}$ to 2000 fT/Hz$^{1/2}$

The beam is not uniform?
Intensity attenuation in fiber?

Bandwidth of each channel

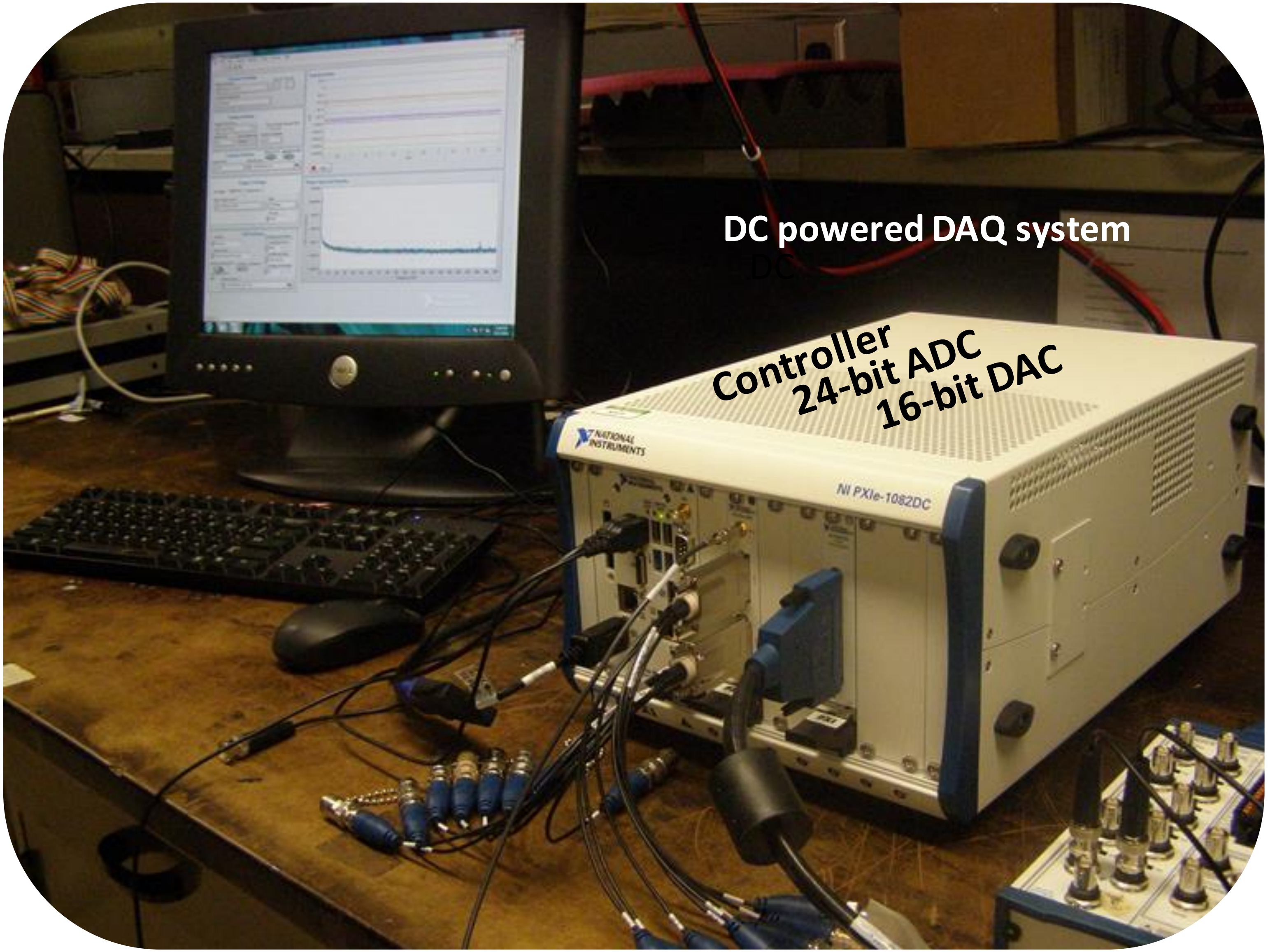




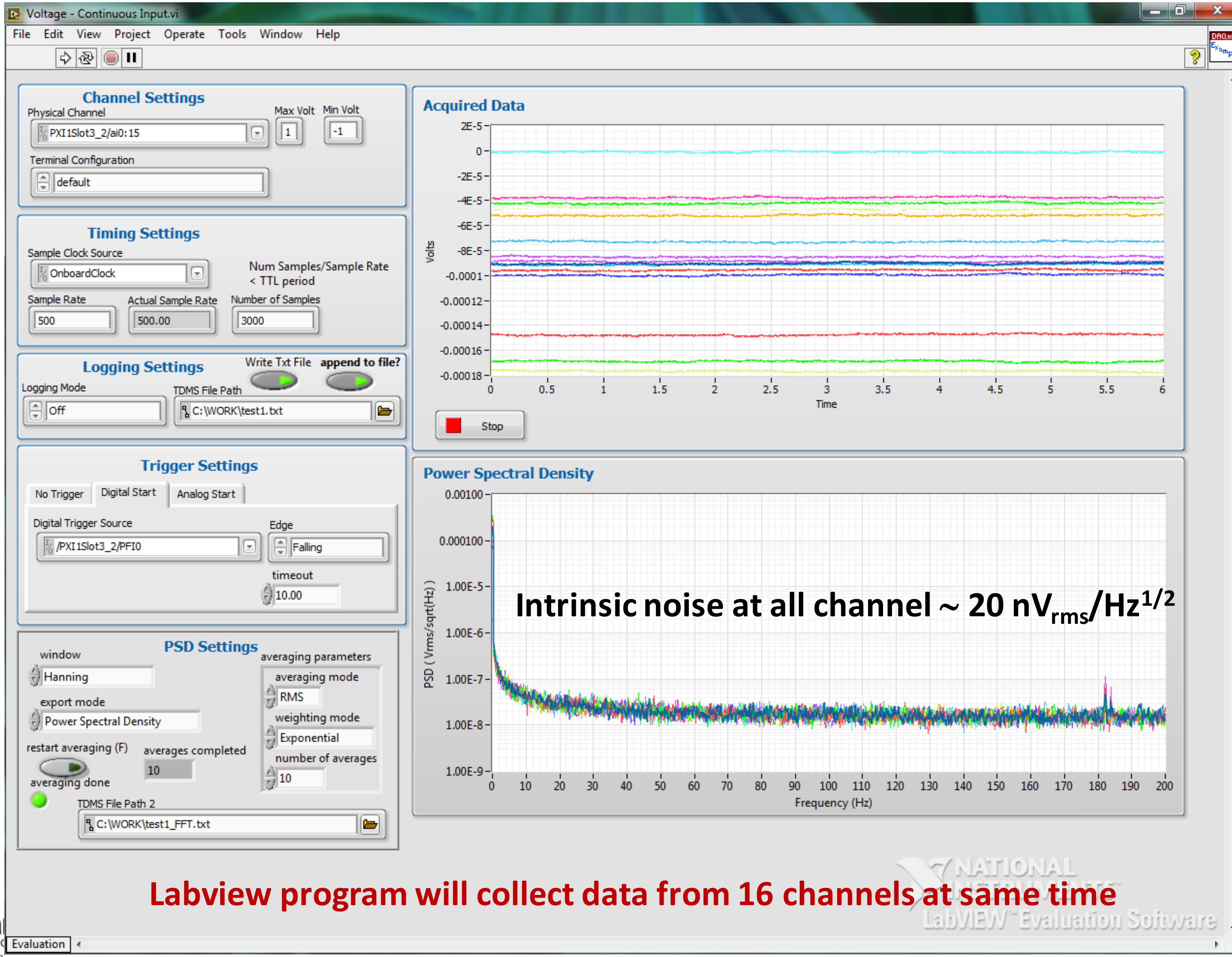


The bandwidth of each channel is good, around 80 Hz

16 channels DAQ system



16 channels DAQ system



Intrinsic noise at all channel ~ 20 $nV_{rms}/Hz^{1/2}$

Labview program will collect data from 16 channels at same time

future work

- Application of the FC+AM system to detection of magnetic nanoparticles which in turn are very important for detection of target molecules in national security, medical diagnostics, and other application areas.
  - ➢ Better AM will be delivered in a week

- Improvement of the multi-channel AM system and keep checking its performance
  - ➢ Place a small coil on the vapor cell and measure the field distribution with 16 channels at same time.
  - ➢ Check the performance of a 4×4 photodiode array