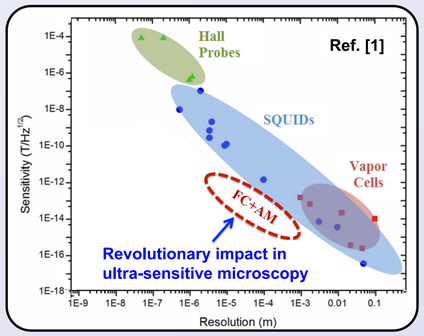
Magnetic Microscopic Imaging with Atomic Magnetometers and Flux Guides for Magnetic Biomarker Applications

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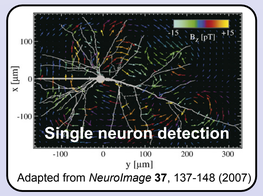
Introduction

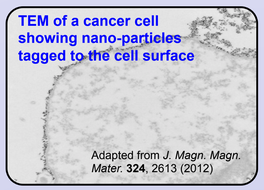
➢ **State-of-the-art in magnetic microscopy:**



- Most sensitive sensors, superconducting quantum interference devices (SQUID) or atomic magnetometer (AM) are with sensitivities below **1 fT/Hz$^{1/2}$** when the sensor size (thus, the resolution) is on the order of a **centimete**r.
- Hall probes have **micrometer scale** resolution, however with sensitivity on the order of **nT/Hz$^{1/2}$**.

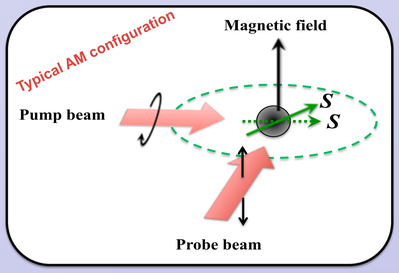
- Many applications require both high resolution and high sensitivity:
  - **Single neuron detection:**
    - ✧ Important to understand the structure and function of the brain at different scales.
    - ✧ Single neurons have dimensions of order of **10 – 100 μm** and are thought to produce **~ 10 pT** magnetic field at a 100 μm stand-off, which is out of reach of current technologies.
  - **Magnetic nano-particle detection:**
    - ✧ Valuable in many fields of medicine and biophysics.
    - ✧ Magnetic imaging of tagged nano-particles to cancerous cells will greatly improve diagnostics and treatment of cancer at an early stage.





➢ **We propose to combine a cm-size atomic magnetometer operating in the spin-exchange relaxation-free (SERF) regime and high permeability flux guides (FGs) to realize an ultra-sensitive, high-resolution FG-AM magnetic microscope:**

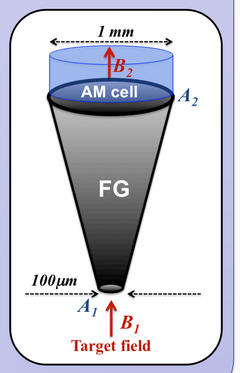
- Atomic Magnetometer:
  - Based on lasers and alkali-metal (Cs, Rb, K) vapor cells
  - The most sensitive non-cryogenic magnetic-field sensor
  - Light is used to manipulate alkali-metal atomic spins and detect the magnetic field



- **Concept of FG-AM magnetic microscope:**
  - An FG directs the flux from a microscopic magnetic distribution to the cell of the AM operating with high sensitivity ➔ to enhance the spatial resolution at the FG tip

e.g. 1-mm AM with a 5 fT sensitivity and a FG with a 100-μm tip will have sensitivity:

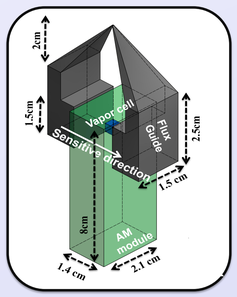
$$\delta B_1 = \delta B_2 \frac{A_2}{A_1} = 5\ \text{fT}\ \frac{\pi(1\text{mm}/2)^2}{\pi(100\mu\text{m}/2)^2} = 0.5\ \text{pT}$$

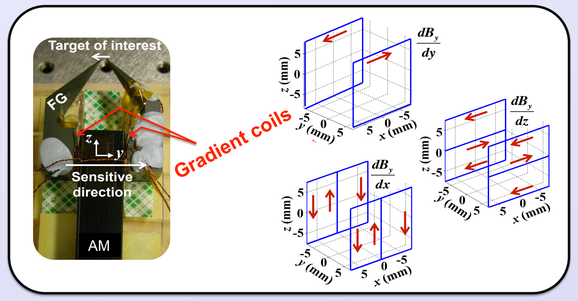


Suitable for detecting a few neurons and localizing sources with 100 micron accuracy!

FG-AM Microscope

➢ **Prototype FG-AM microscope [2]:**

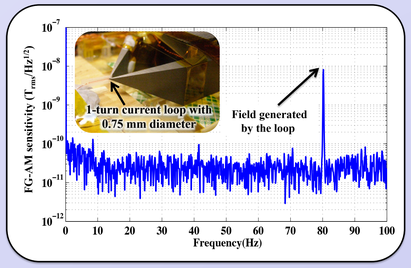




- Flux Guides:
  - Made of an electrically poorly conductive, high permeability (6500 at 10 kHz) MnZn (MN60) ferrite in order to avoid large magnetic Johnson noise.
  - The gap between tips - 50 μm
- Atomic magnetometer:
  - Commercially available; sensor head – 1 cm (3x3x3 mm^3 Rb vapor cell)
  - Intrinsic sensitivity – 20 fT/Hz$^{1/2}$

➢ **Sensitivity and resolution study:**

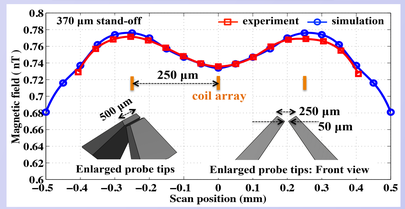
- Sensitivity was experimentally investigated by placing a small 0.75 mm-diameter current loop between the tips and detecting a field generated by the loop with FG-AM.



  - The field transfer coefficient of the FGs, the ratio of the measured field to the generated field, is 8.7×10^{-4}, which results in the sensitivity to a target object of **23 pT/Hz$^{1/2}$.**

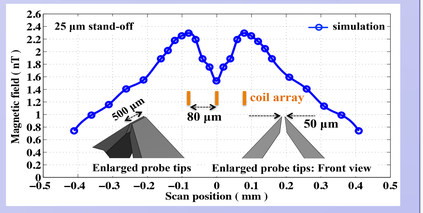
- Resolution was experimentally (left) and numerically (for the same geometry, left, and optimized geometry, right) investigated by scanning the position of an array of 3 coils (D=0.75 mm, 80-μm wire, current reversed in the middle) at specific stand-off distances from the probe tips.

Experimental prototype



- **Best resolution of 250 μm (limited by the upper tip gap of 250 μm) that the FG-AM of the manufactured FG tips shape could achieve.**
- **Sensitivity 23 pT/Hz$^{1/2}$**

Resolution with optimized FGs

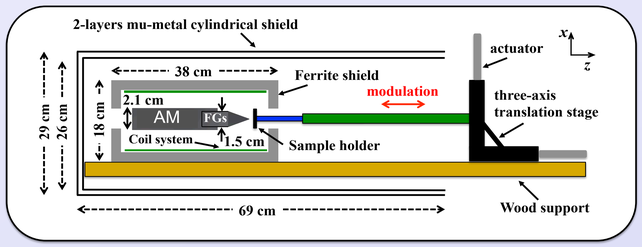


- **Improved resolution of 80 μm using optimized FGs with the sharper tips.**
- **Improved FG-AM sensitivity to a target source located at the probe tips with a better AM at 10 fT/Hz$^{1/2}$ (now commercially available): 8.1 pT/Hz$^{1/2}$**

- **Demonstrated resolution and sensitivity of FG-AM: 250 μm and 23 pT/Hz$^{1/2}$**
- **Simulated resolution and sensitivity for more optimal geometry: 80 μm and 8.1 pT/Hz$^{1/2}$**

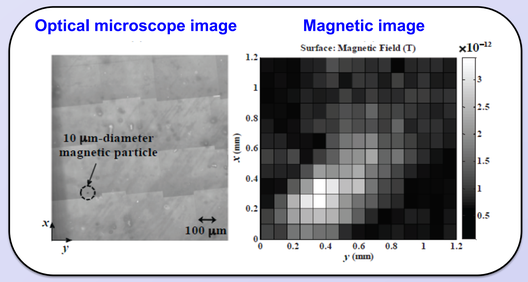
Magnetic Microscopic Imaging

➢ **Schematic of an experimental setup for 2D magnetic micro-imaging:**



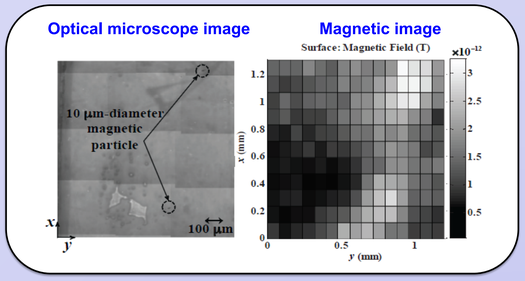
- Located a magnetic sample on the sample holder near the probe tips and moved it with respect to the tips using motorized translation stages.
- Introduced a modulation generated by the actuator, which converts DC signals to AC signals, to improve the signal-to-noise ratio.

➢ **Magnetic micro-particle imaging [3]:**



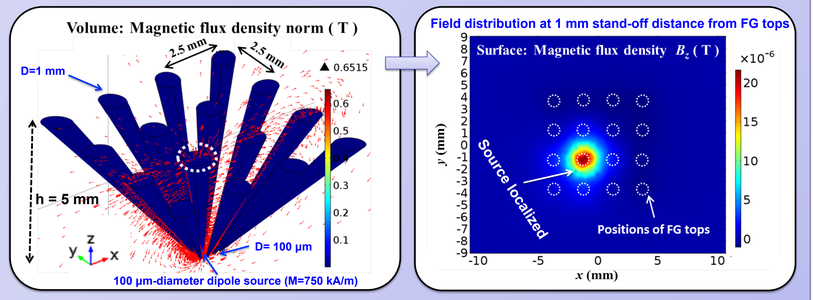
Imaging a single 10-micron magnetic particle

Imaging two 10-micron magnetic particles 1 mm apart



Magnetic imaging provides huge contrast for small magnetic particles.

➢ **2D array of FGs for parallel magnetic imaging [4]:**



- FG array **localizes** the magnetic source well and the crosstalk between FGs can be well neglected.
- Field transfer coefficient (field at 1mm stand-off from FG top/field at FG bottom) is 2.8x10^{-4}, corresponding to **19 pT/Hz$^{1/2}$** with a 5 fT/Hz$^{1/2}$ AM.

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[2] Young Jin Kim and Igor Savukov, "Ultra-sensitive Magnetic Microscopy with an Optically Pumped Magnetometer", *Nature Scientific Reports* ***6****, 24773 (2016)*

[3] Y. J. Kim, I. Savukov, J.-H. Haung, and P. Nath, "Magnetic Microscopic Imaging with an Optically Pumped Magnetometer and Flux Guides", *Applied physics letters* ***110****, 043702 (2017)*

[4] Igor Savukov and Young Jin Kim, "High-resolution magnetic imaging with an array of flux guides", *2017 IEEE Sensors Applications Symposium, 1-4 (2017)*