Weak Magnetic Field Measurement with MTJ Sensor using Lock-in Amplification Technique

Lam Tsz Lok

The Chinese University of Hong Kong

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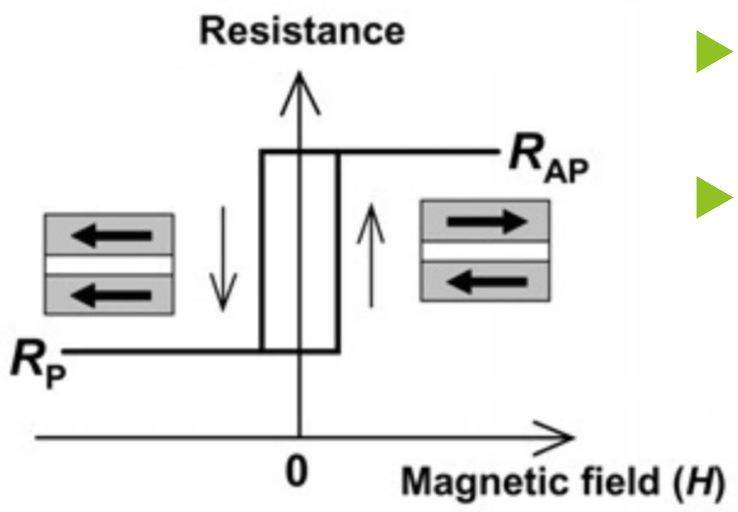
Introduction – What is MTJ Sensor?

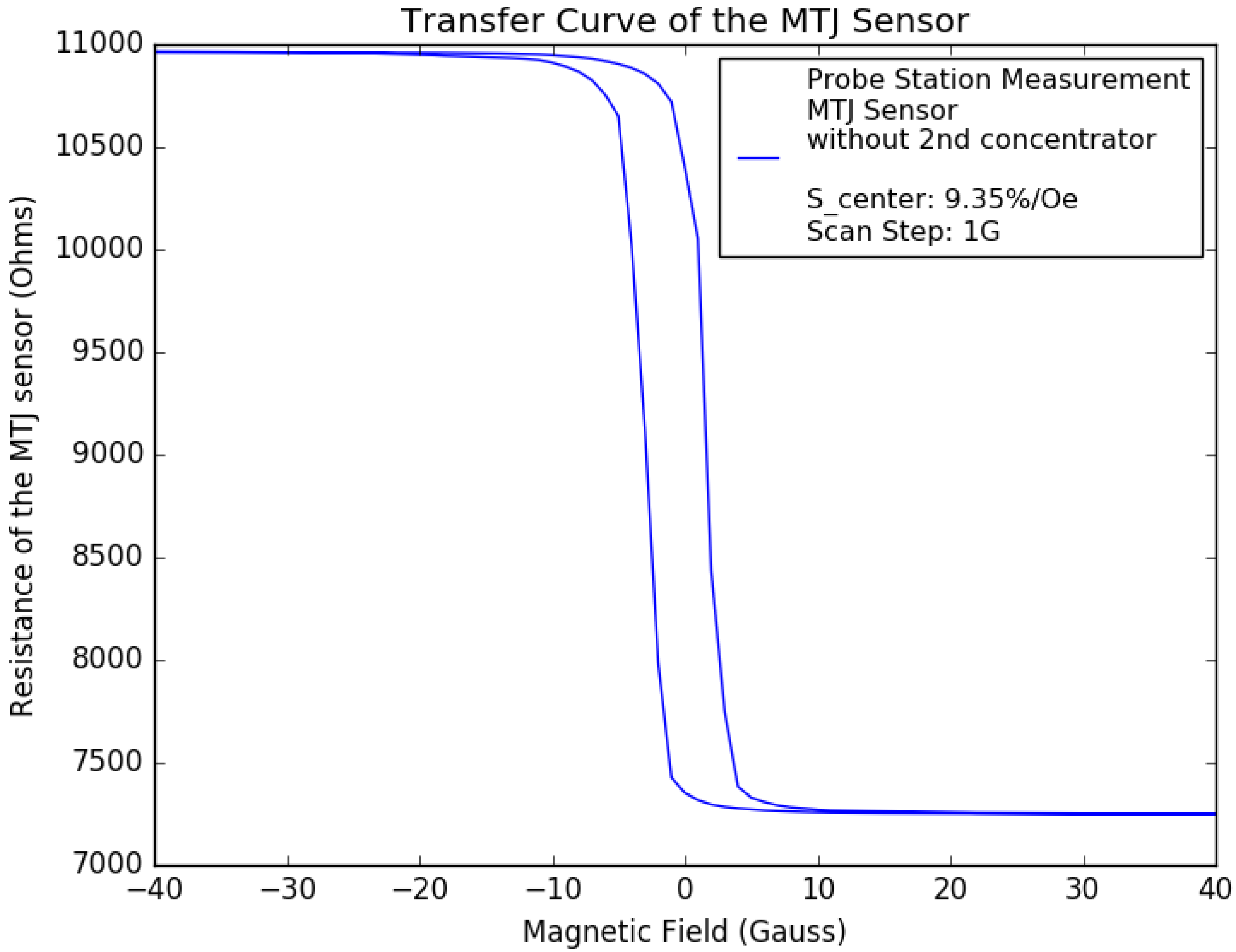
- MTJ: Magnetic Tunneling Junctions
- A non-magnetic layer sandwiched by two ferromagnetic layers called free layer and pinned layer



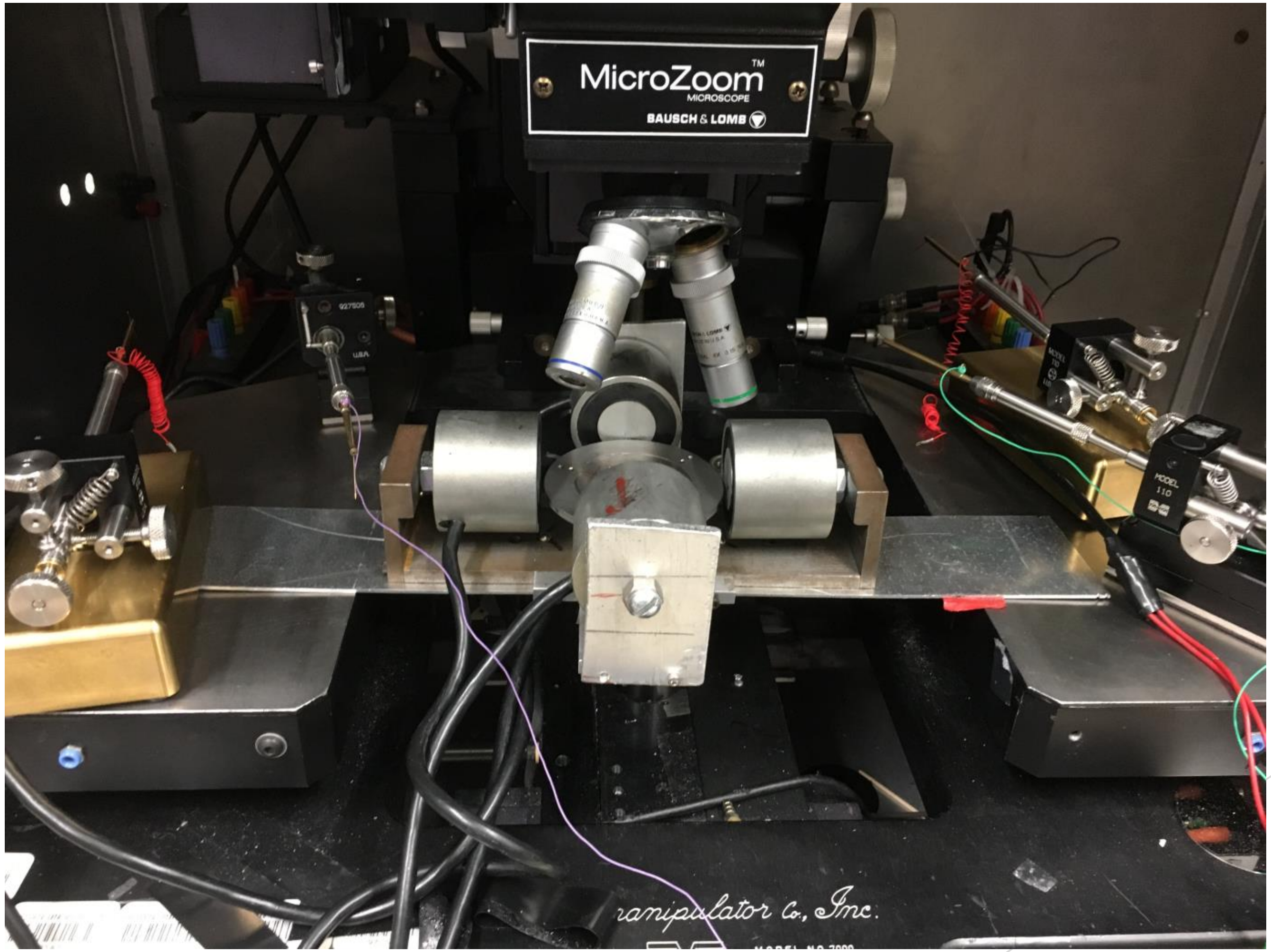
- Magnetoresistance (MR) $= \frac{R_{\uparrow\downarrow}-R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}}$
- Sensitivity $= \frac{1}{R_{\uparrow\uparrow}+R_{\uparrow\downarrow}} \frac{R_{\uparrow\downarrow}-R_{\uparrow\uparrow}}{B_{sat}}$

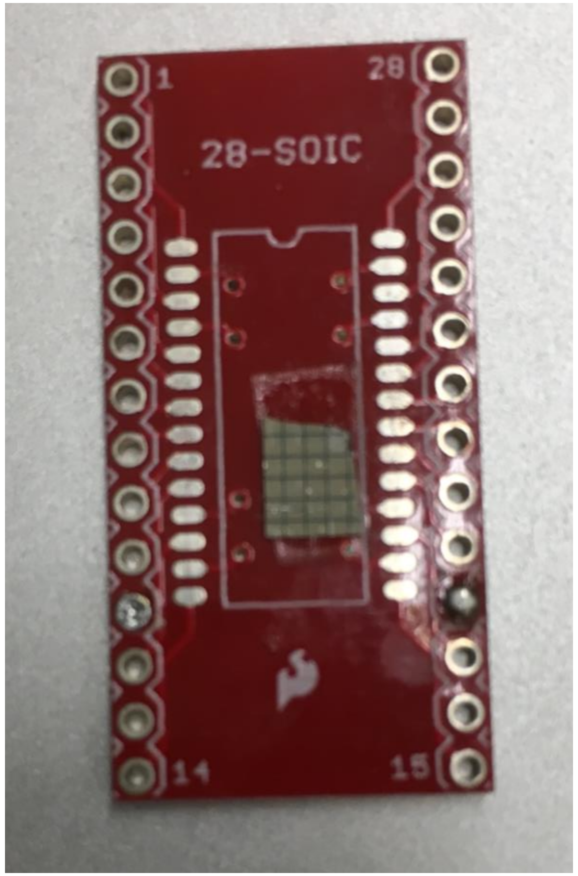
Fig.1. Magnetoresistance curve (transfer curve) of a MTJ sensor

Transfer Curve



Measurement of Transfer Curve – Probe Station





The MTJ sensor on the chips

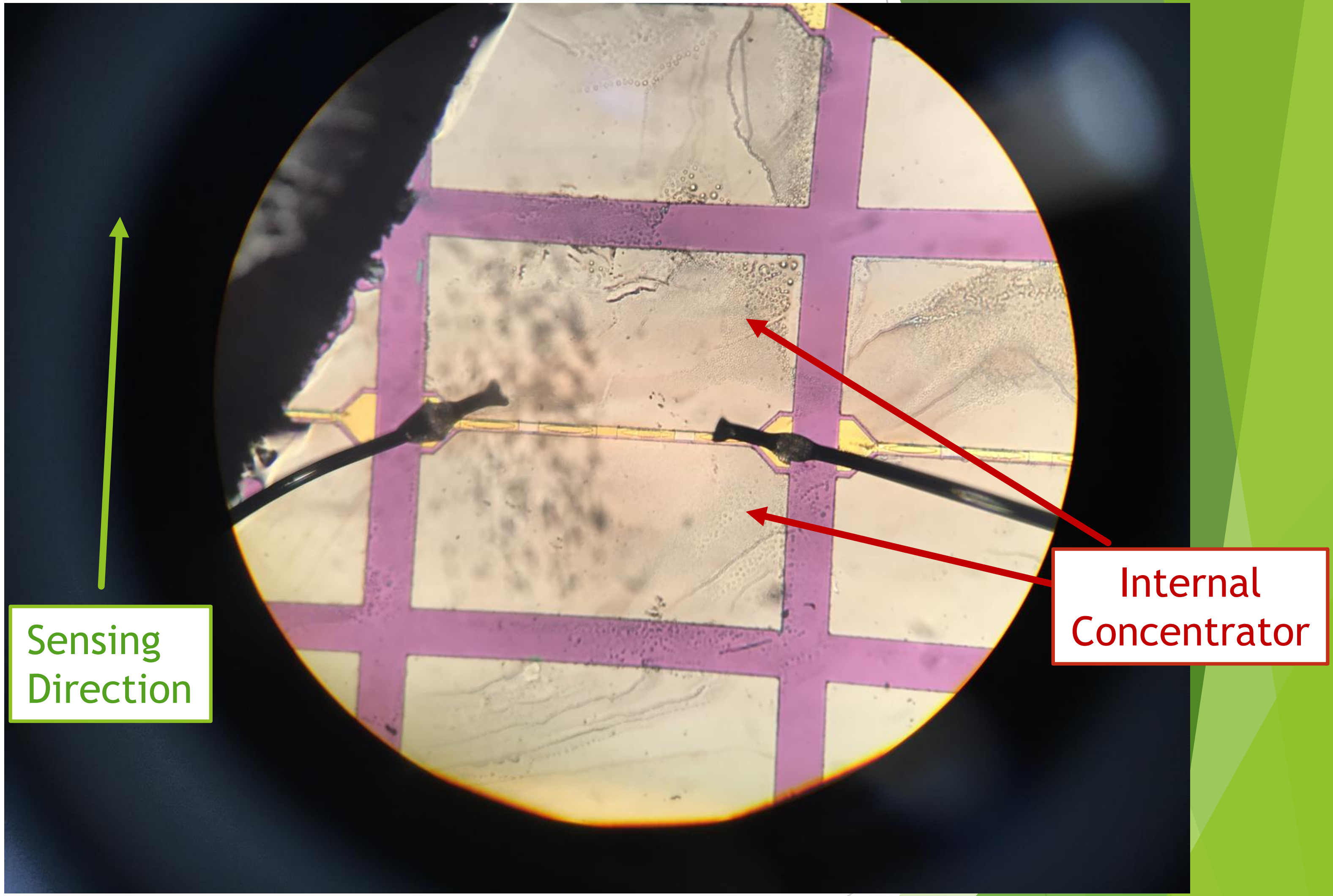


Image of a MTJ array

Noise Source in MTJ System

1. Johnson Noise:

$$S(f) = \frac{4Rhf}{e^{\frac{hf}{k_B T}} - 1} \approx 4Rk_BT \qquad \left(for\ f \ll \frac{k_BT}{h}\right)$$

2. Shot Noise:

$$S_I = 2eIR^2$$

3. Flicker Noise (1/f noise):

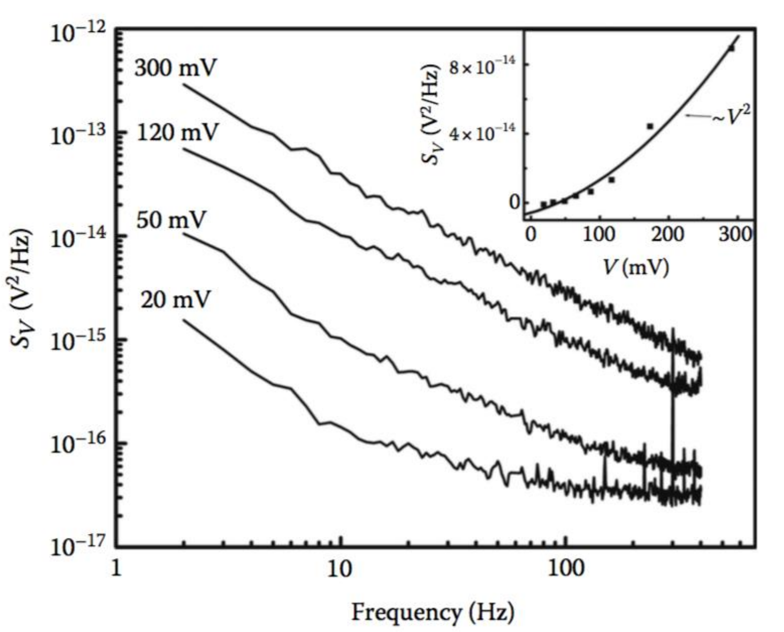
$$S_F(f) = \frac{\alpha V^2}{Af}$$

α : Hooge parameter

A : the junction area

V : voltage across the sensor

R : resistance across the sensor



Noise Voltage Spectrum in frequency domain

Aim of the Project

- Direct Measurement of Weak AC Magnetic Field (down to ~100pT) using Lock-in Amplification Technique.
- Reproduce the Noise Voltage Spectrum in frequency domain

Lock-in Amplification Technique

- Compare the reference waveform and the signal waveform
- Lock the frequency and the phase of the signal
- Powerful tools to eliminate background noise (e.g. Earth B-field)
- Signal Recovery 7265 Dual Phase Lock-in Amplifier

Experimental Setup

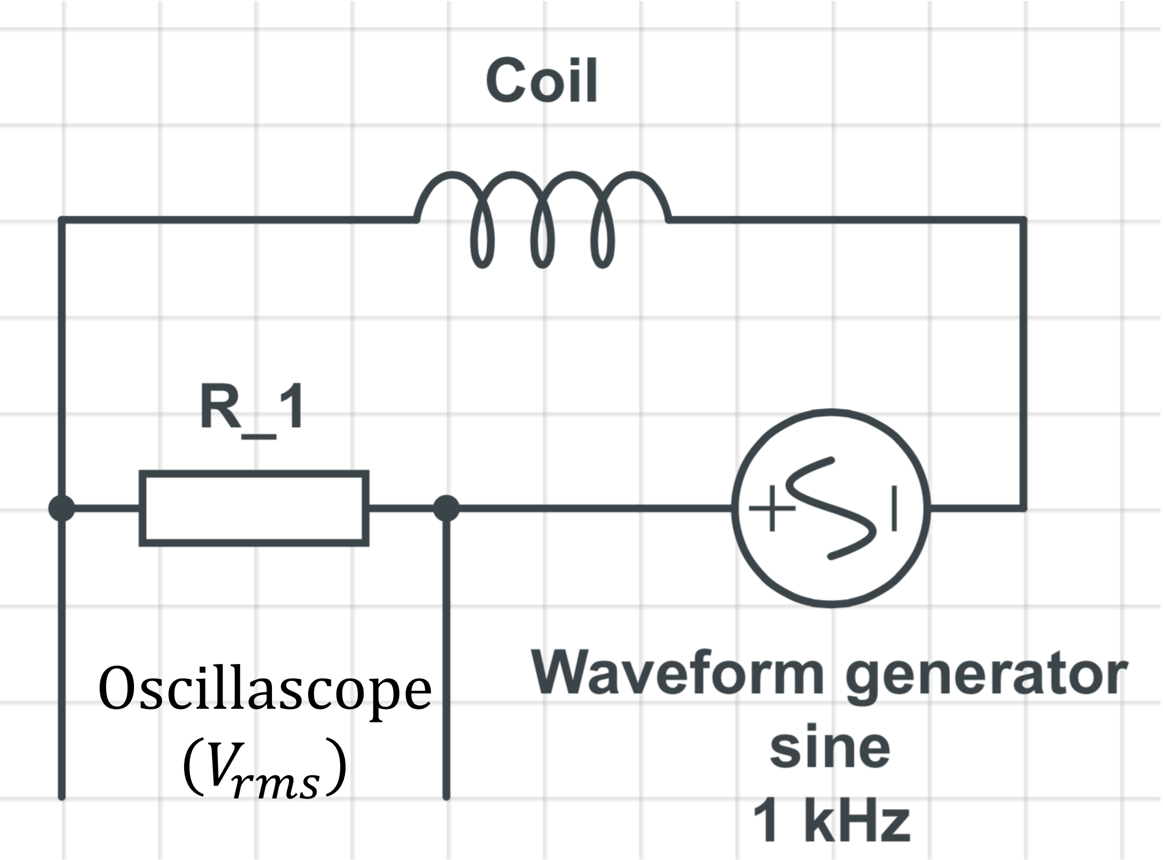


Fig. 2. Coil circuit

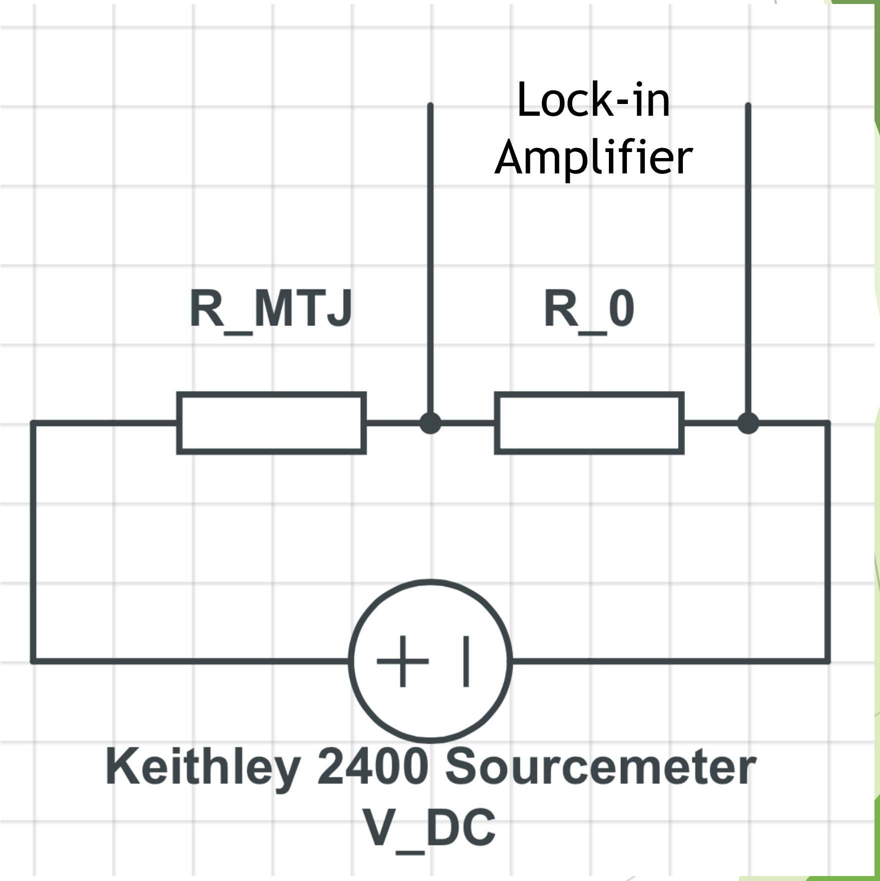


Fig. 3. The MTJ Sensor circuit

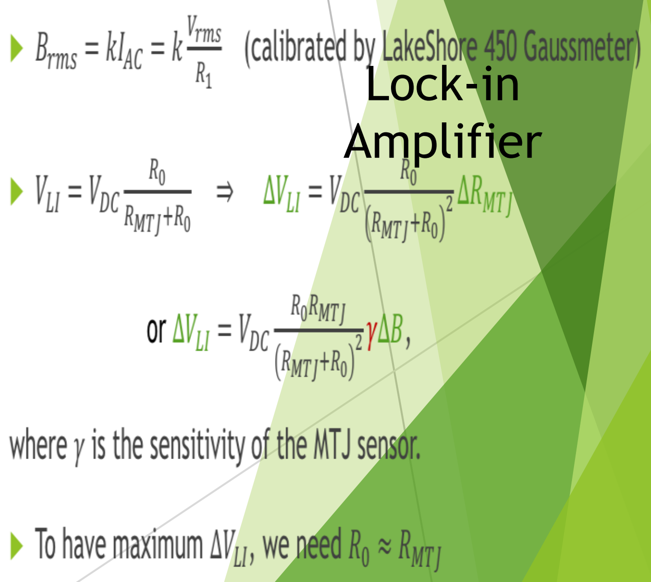
Formula

- $B_{rms} = kI_{AC} = k\frac{V_{rms}}{R_1}$ (calibrated by LakeShore 450 Gaussmeter)
- $V_{LI} = V_{DC}\frac{R_0}{R_{MTJ}+R_0} \Rightarrow \Delta V_{LI} = V_{DC}\frac{R_0}{(R_{MTJ}+R_0)^2}\Delta R_{MTJ}$

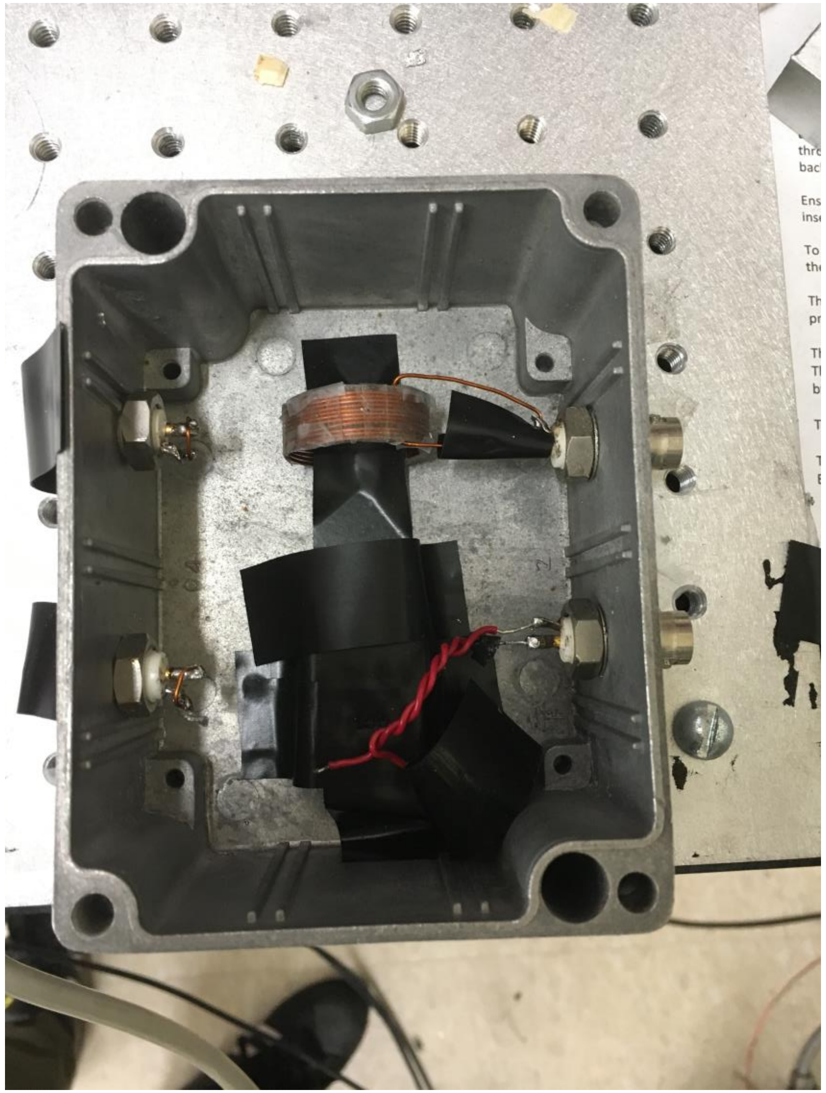
  or $\Delta V_{LI} = V_{DC}\frac{R_0 R_{MTJ}}{(R_{MTJ}+R_0)^2}\gamma\Delta B$,

where γ is the sensitivity of the MTJ sensor.

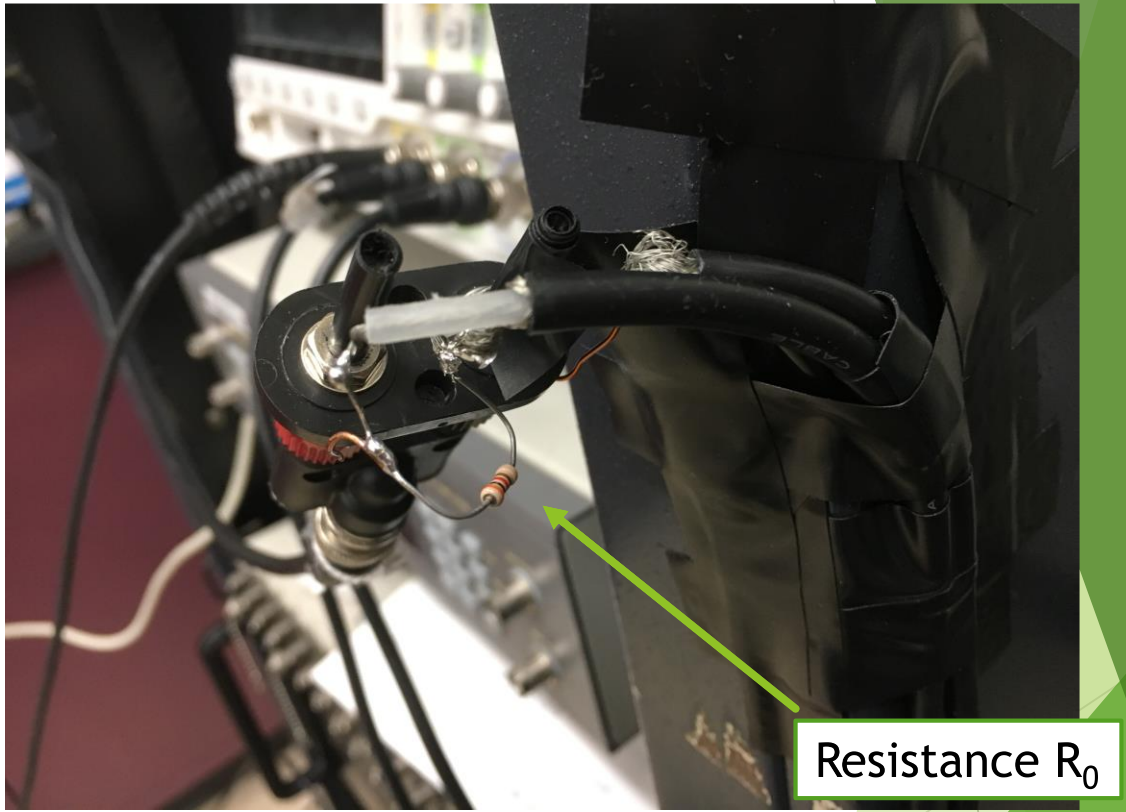
- To have maximum ΔV_{LI}, we need $R_0 \approx R_{MTJ}$



Lock-in Amplifier

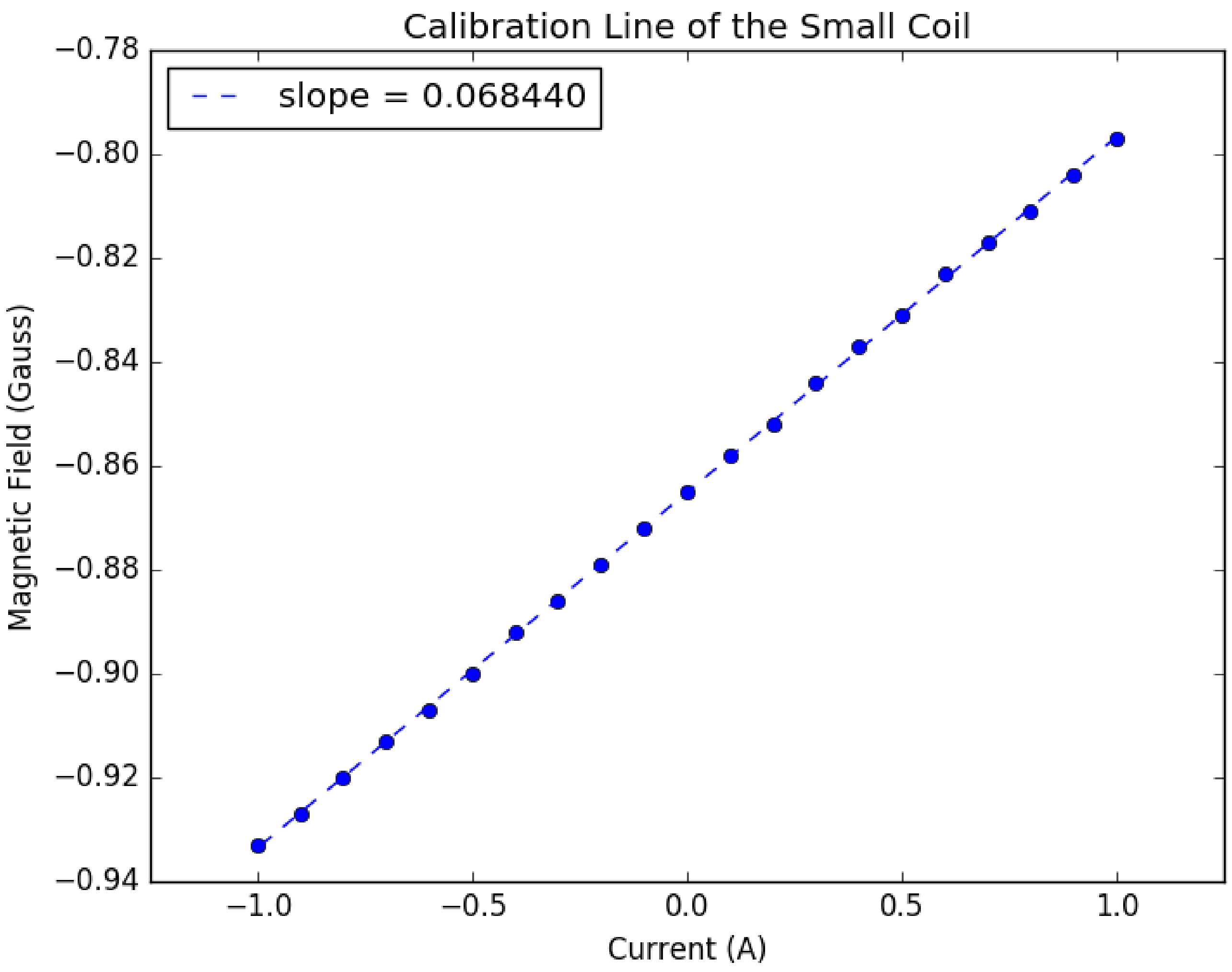


The metal box containing the small coil

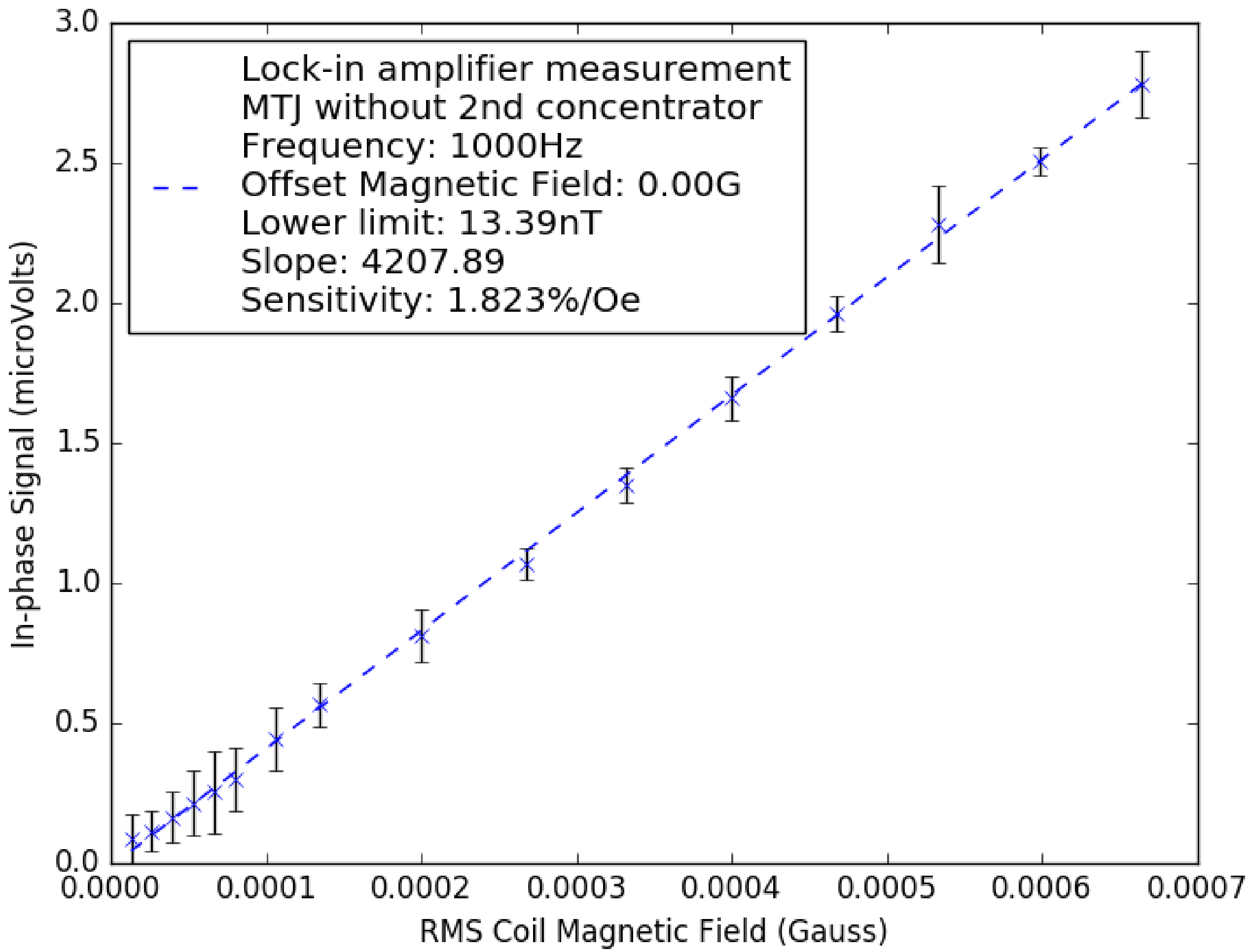


The picture of the resistance R_0

Calibration Line of Small Coil

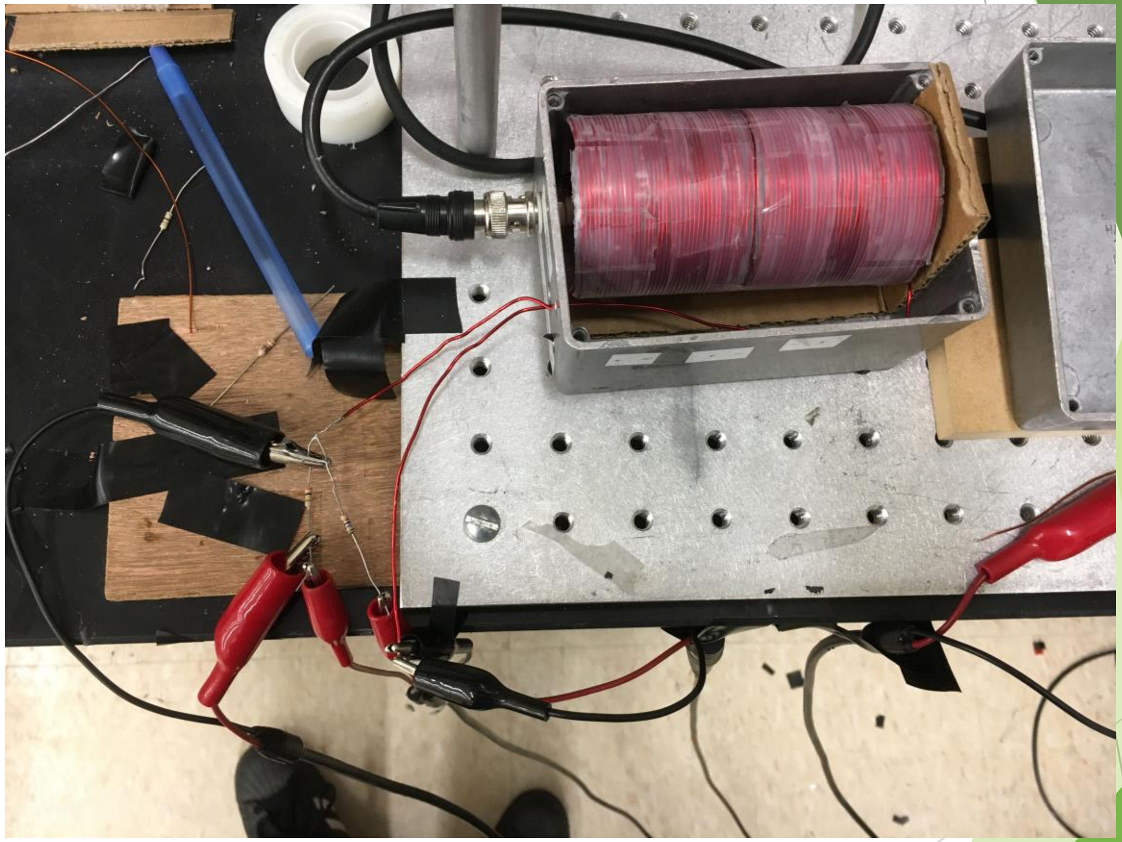


Result – In-phase Signal VS Magnetic Field (without external concentrator)



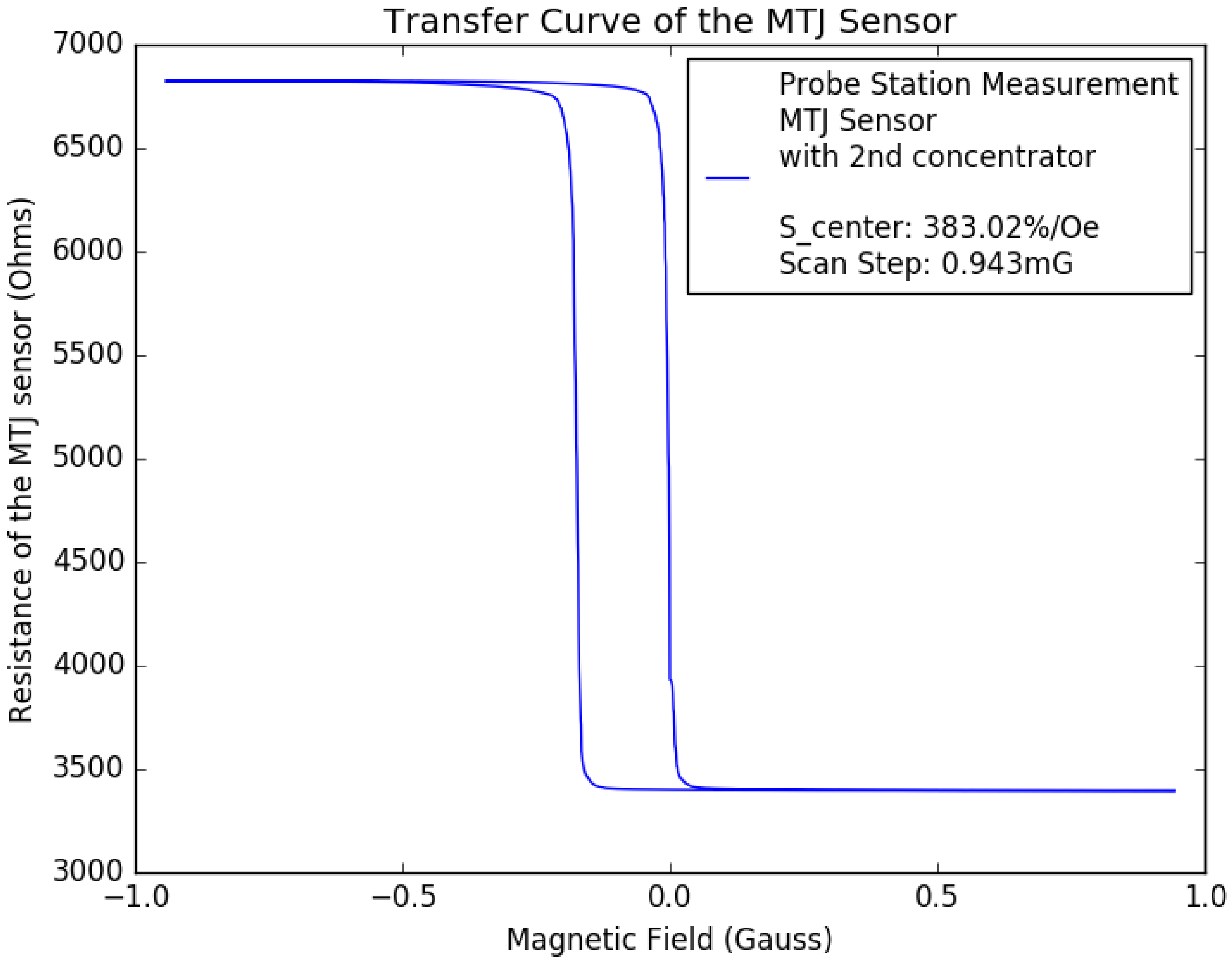
External Concentrator

The MTJ sensor
with 2nd concentrator

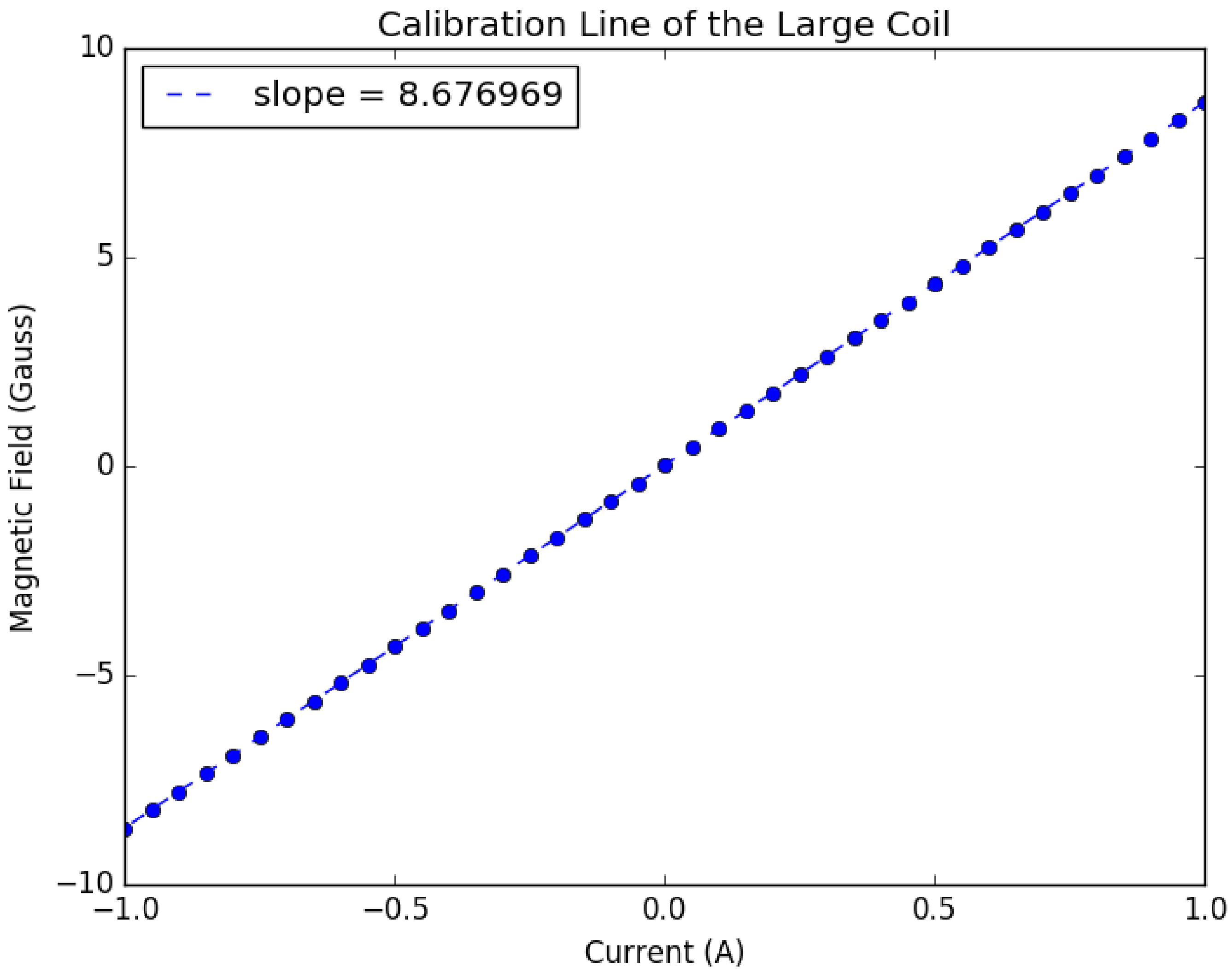


The setup for large coil

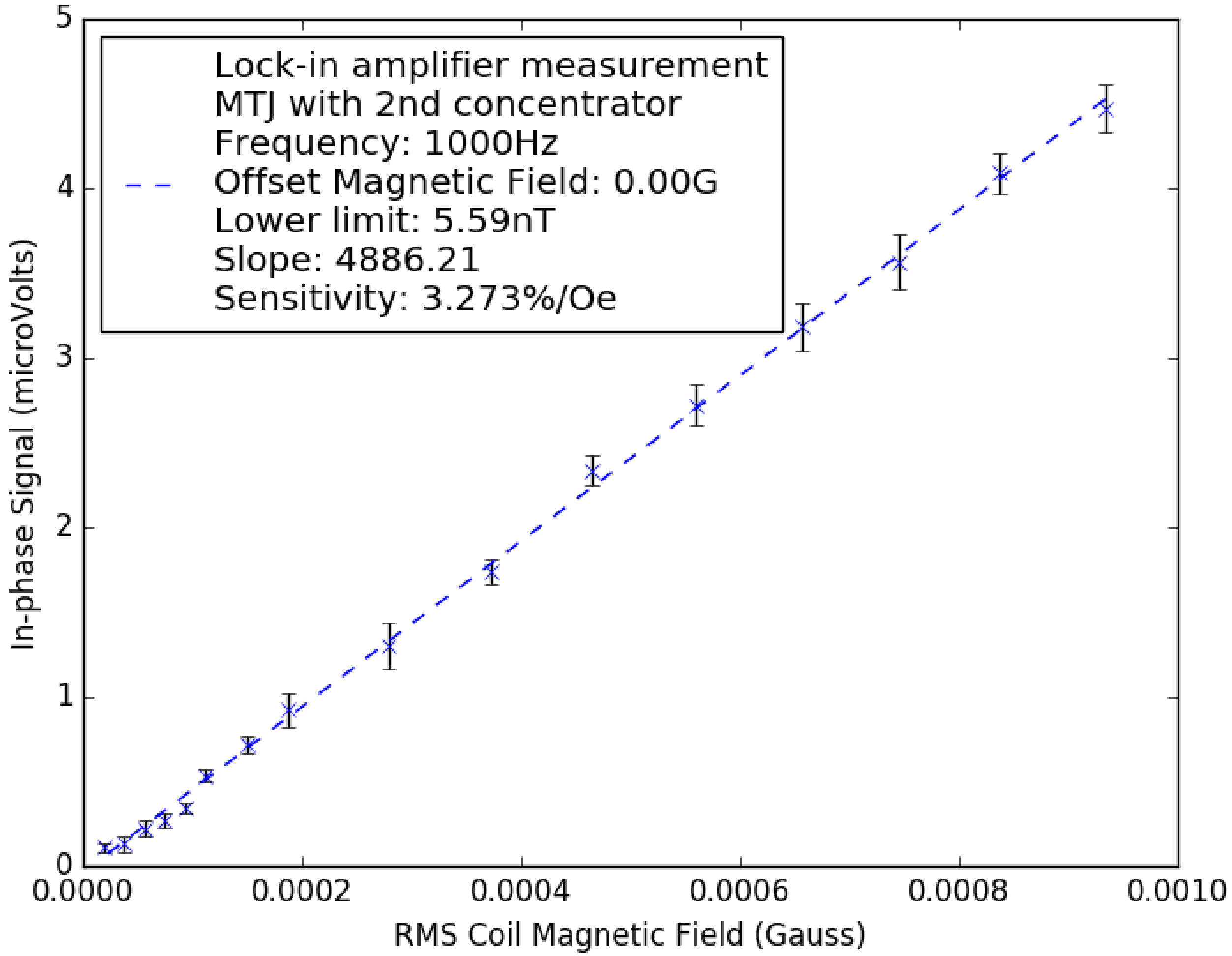
Transfer Curve of the MTJ Sensor (with External Concentrator)



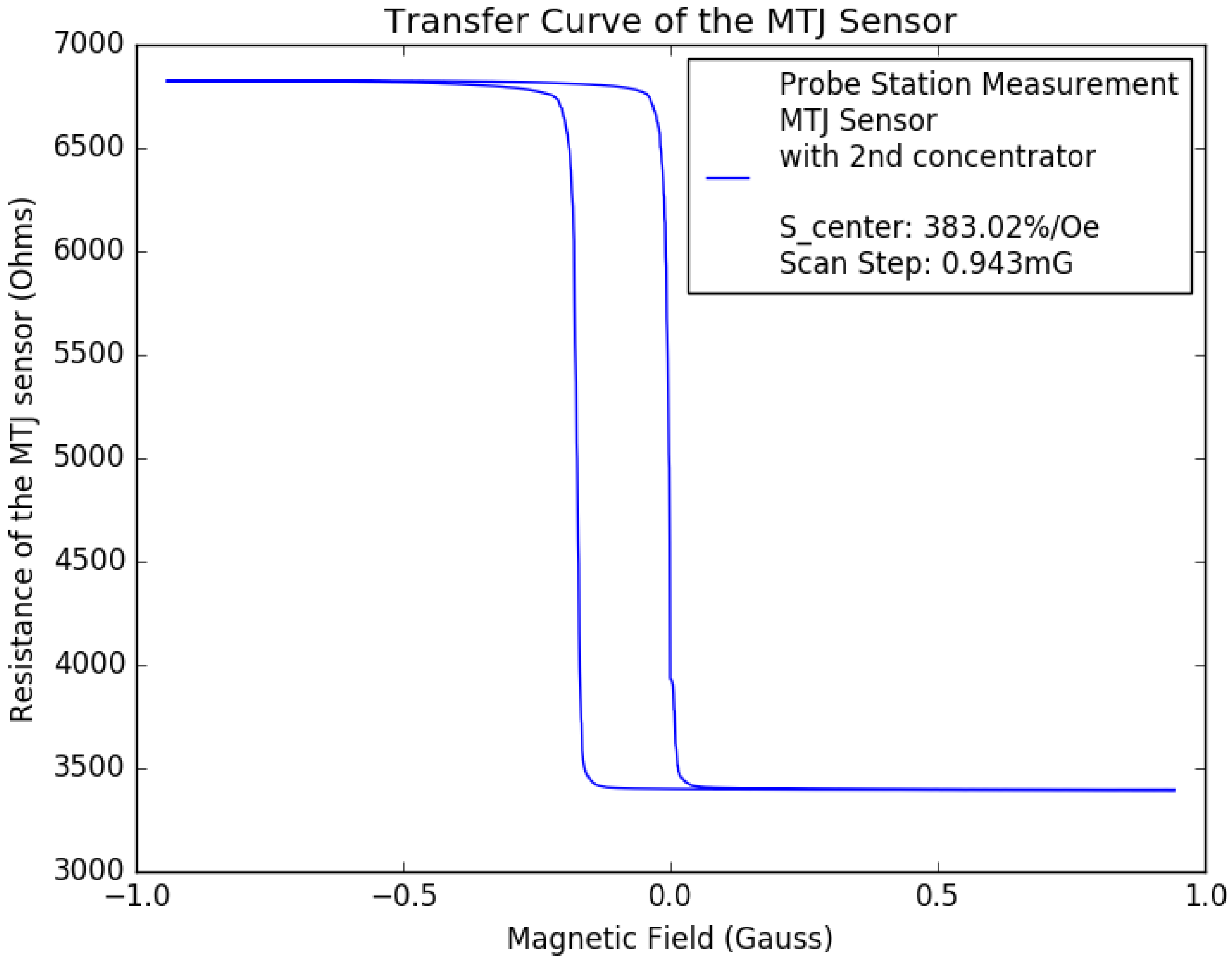
Calibration Line of Large Coil



Result – In-phase Signal VS Magnetic Field (with external concentrator)



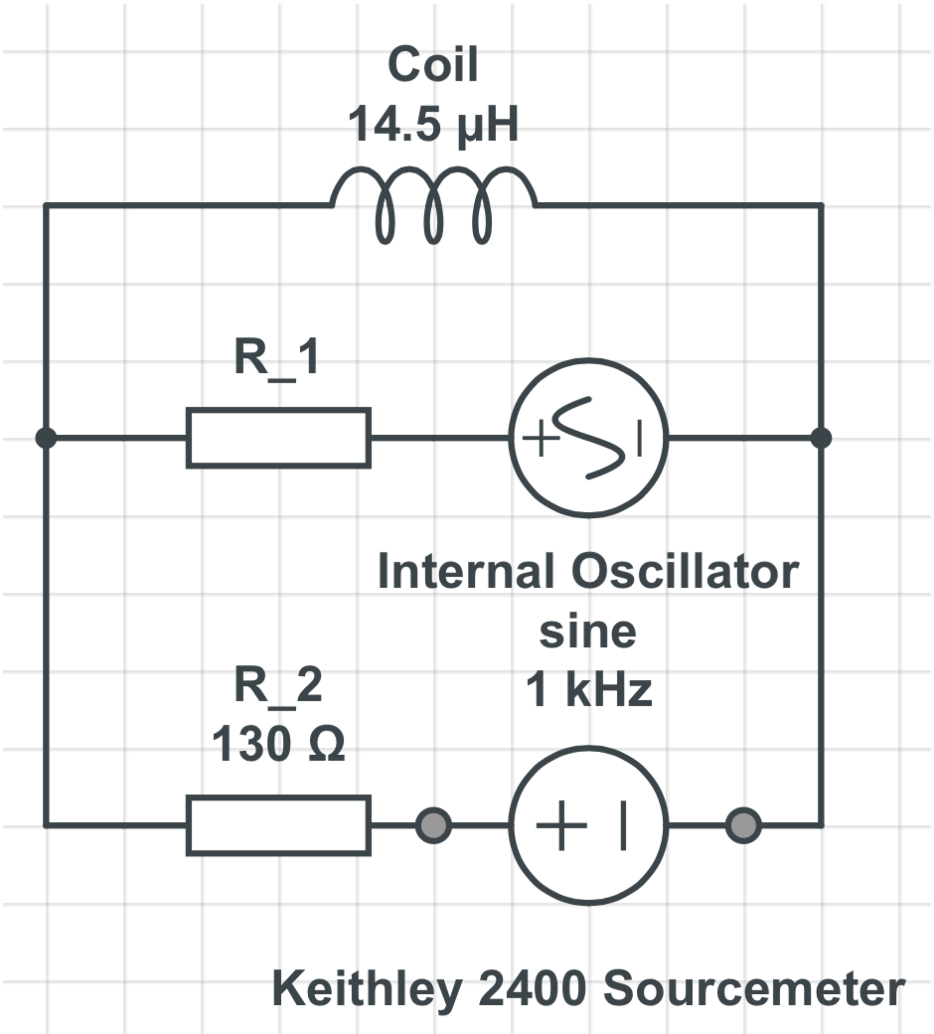
Transfer Curve of the MTJ Sensor (with External Concentrator)



We need to add an offset Magnetic Field to get the maximum sensitivity!

Challenge:
Small AC Magnetic Field
($\sim 1\mu A$ for $\sim 900pT$)
+
Large DC Magnetic Field
(~12mA for 0.104mG)

Experimental Setup 2

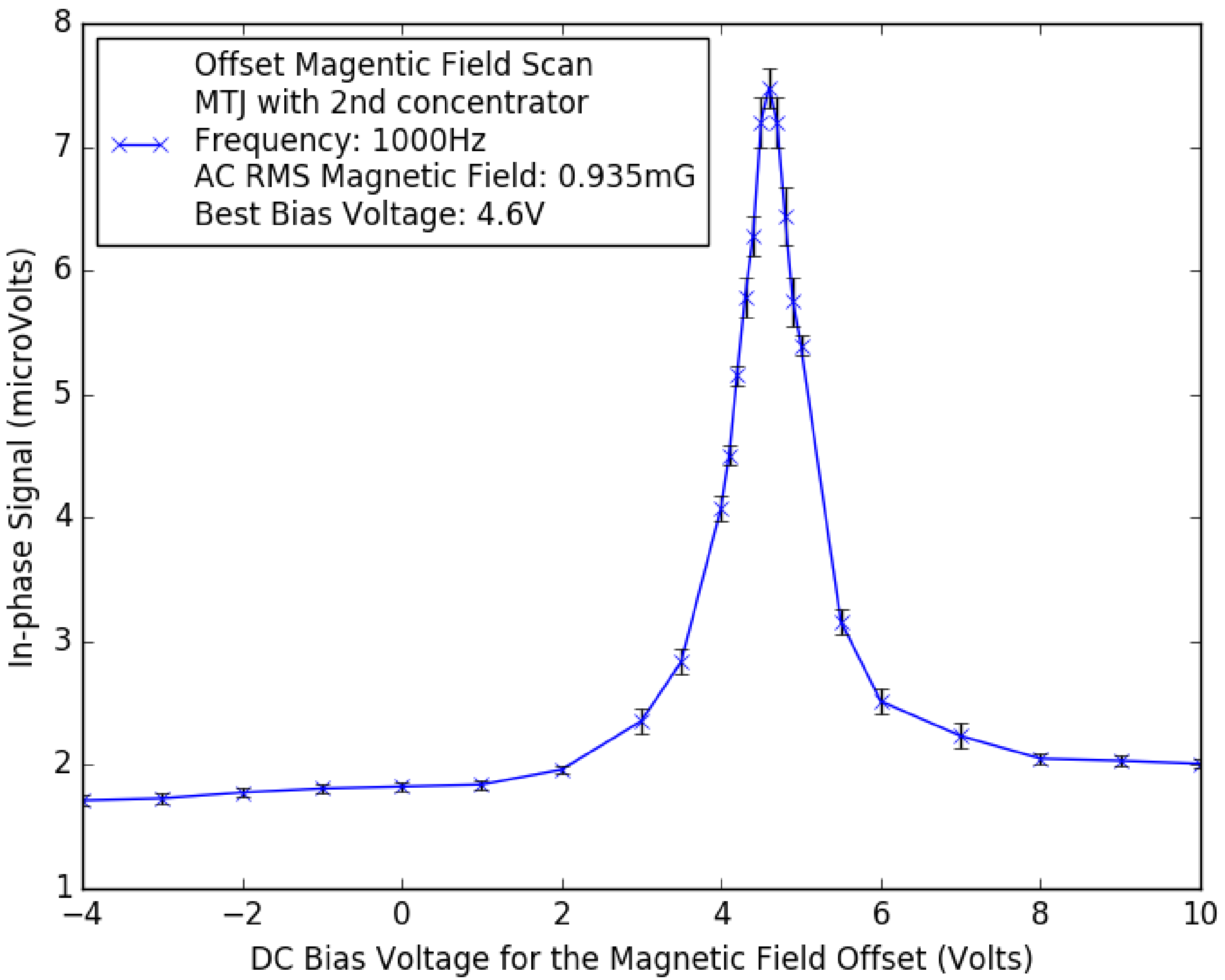


The coil circuit

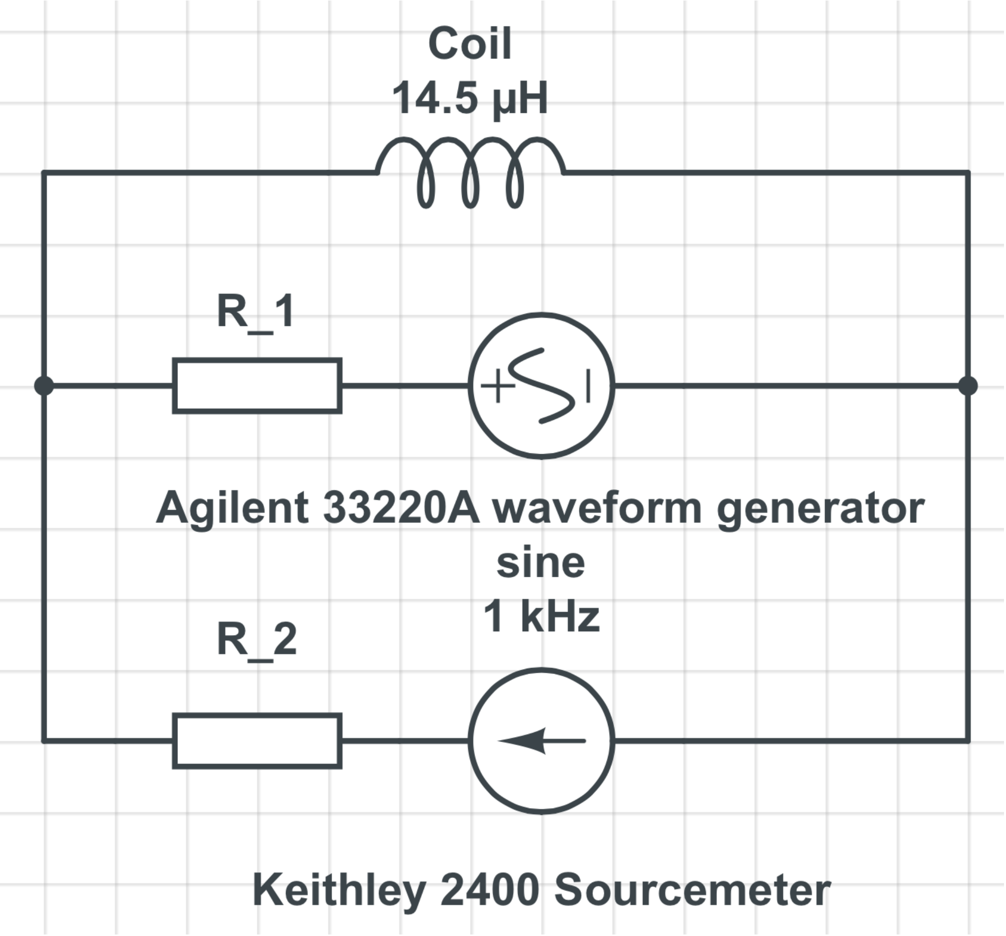
- For impedance of coil << R_1, R_2

$$I_{coil} \approx I_{DC} + I_{osc}$$

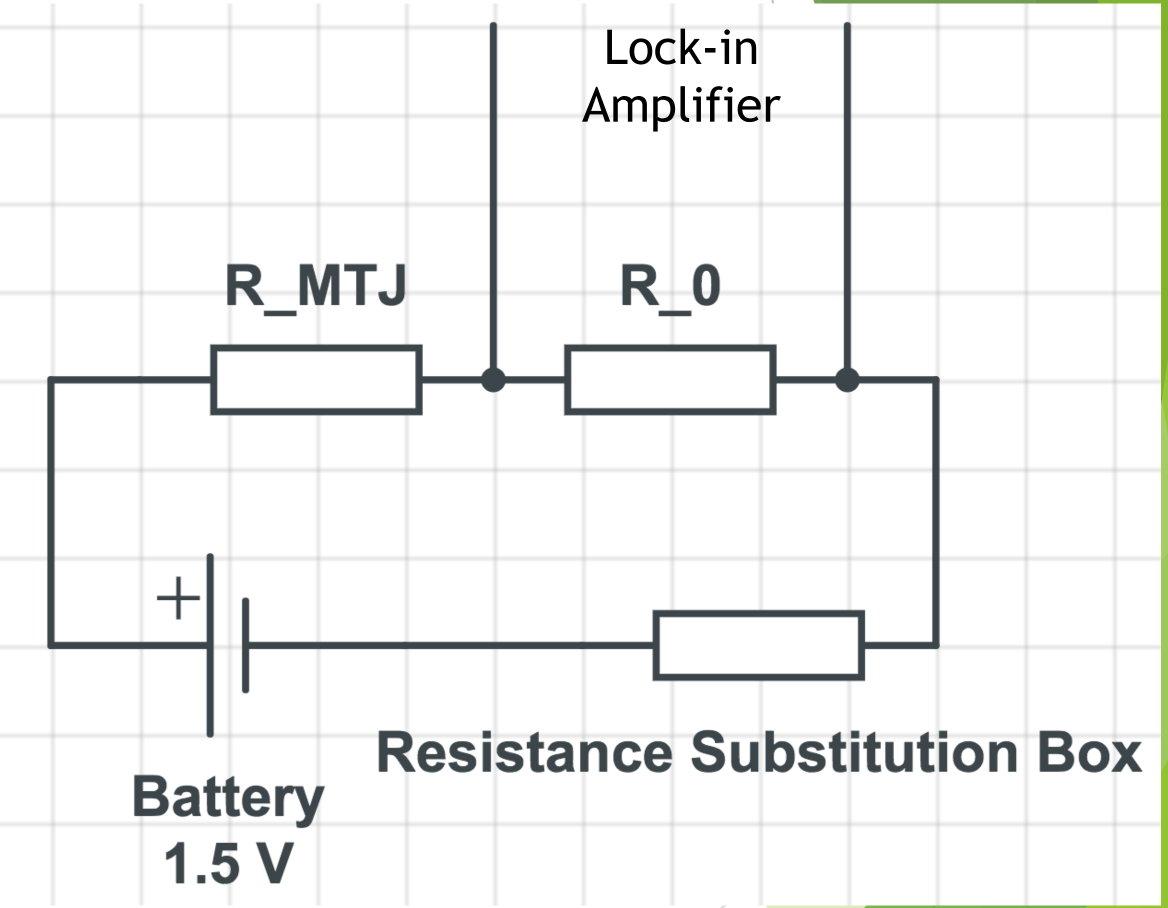
Result – Signal VS Bias Voltage for Magnetic field



Experimental Setup 3

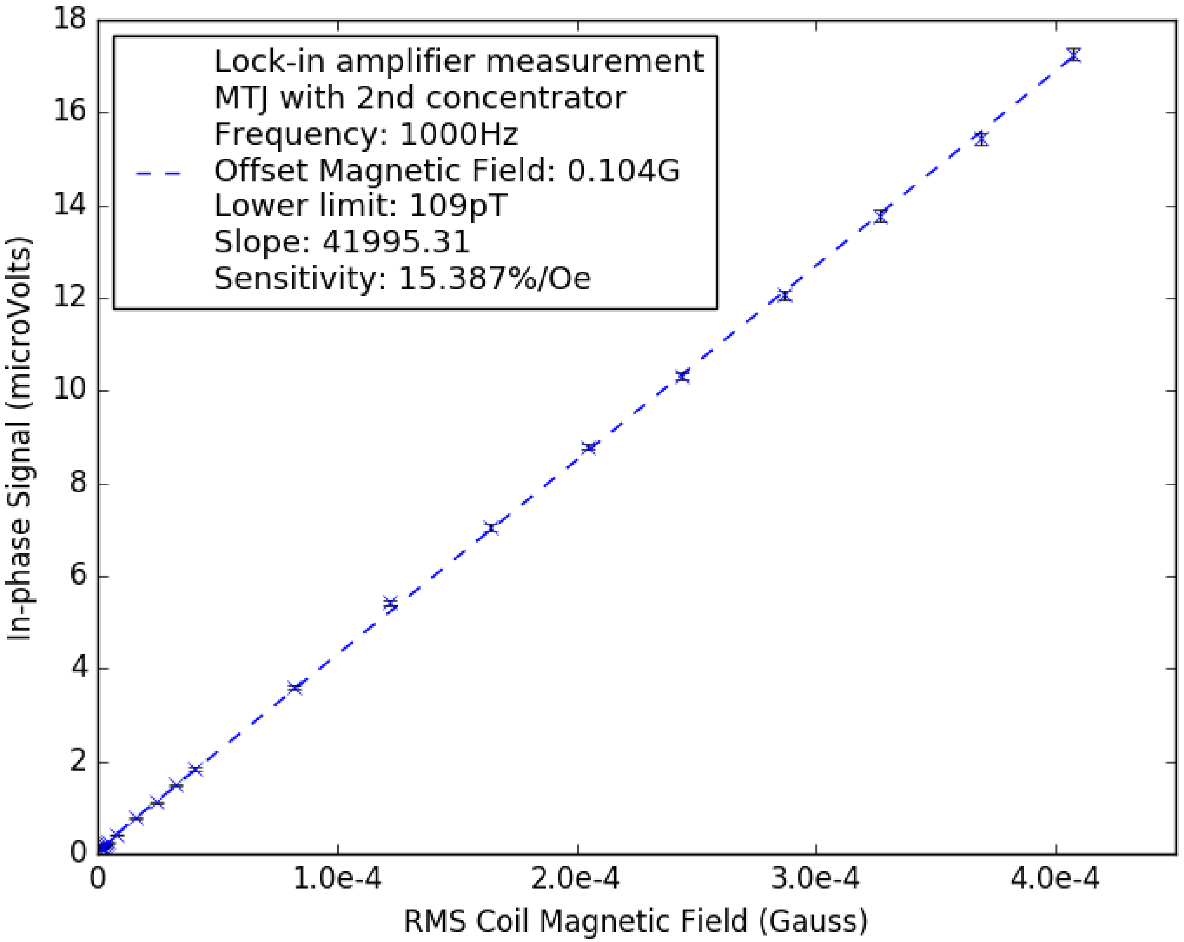


The coil circuit



The MTJ sensor circuit

Result – In-phase Signal VS Magnetic Field
(with external concentrator & Best B-field Offset)



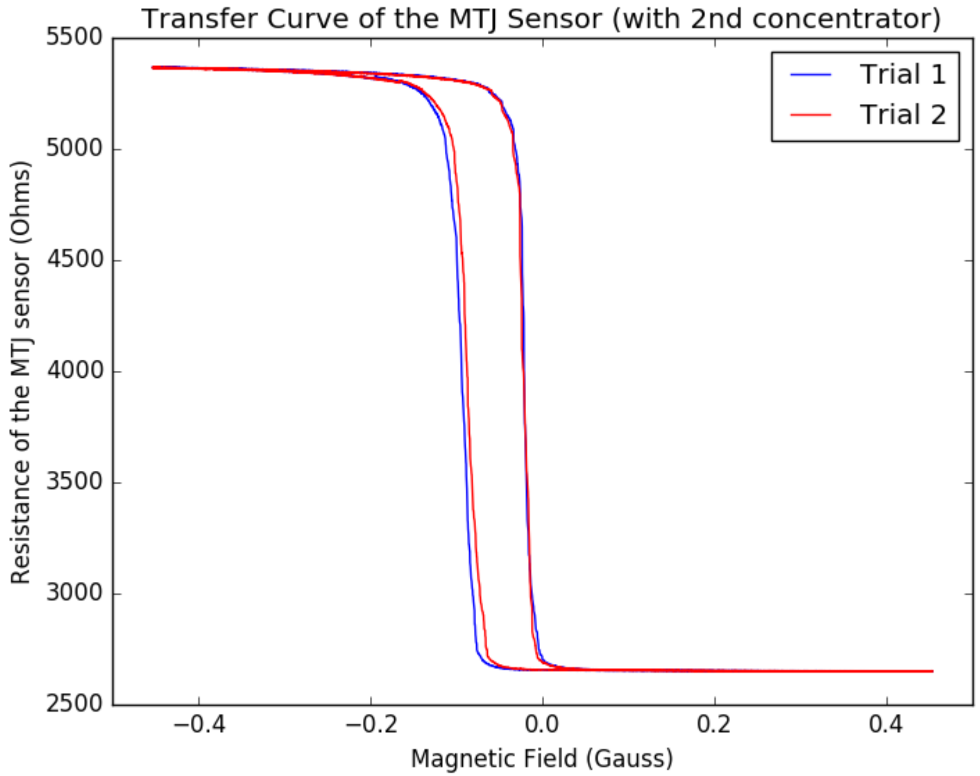
Problem:

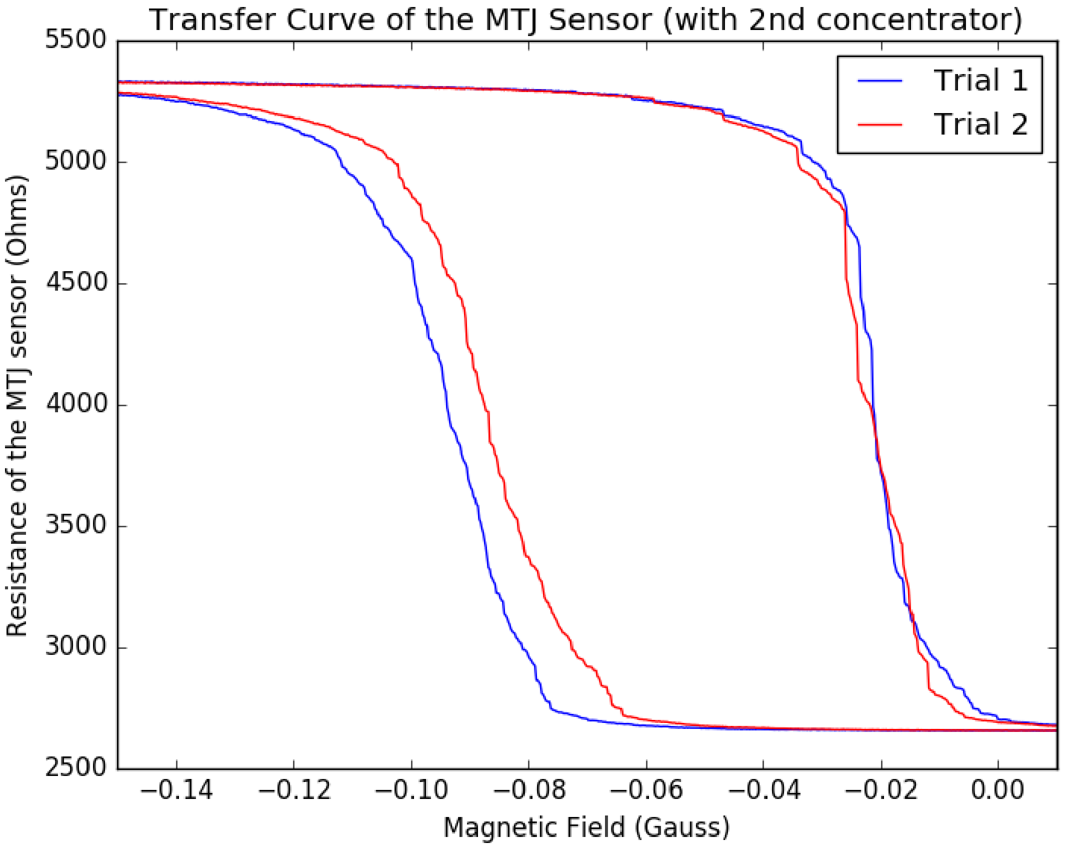
$\sim 78nV$ background noise appears when the AC voltage input for the coil is turned off.

It could come from the shot noise from the battery, but another measurement should be done to identify the source of the background noise.

Potential Problems 1

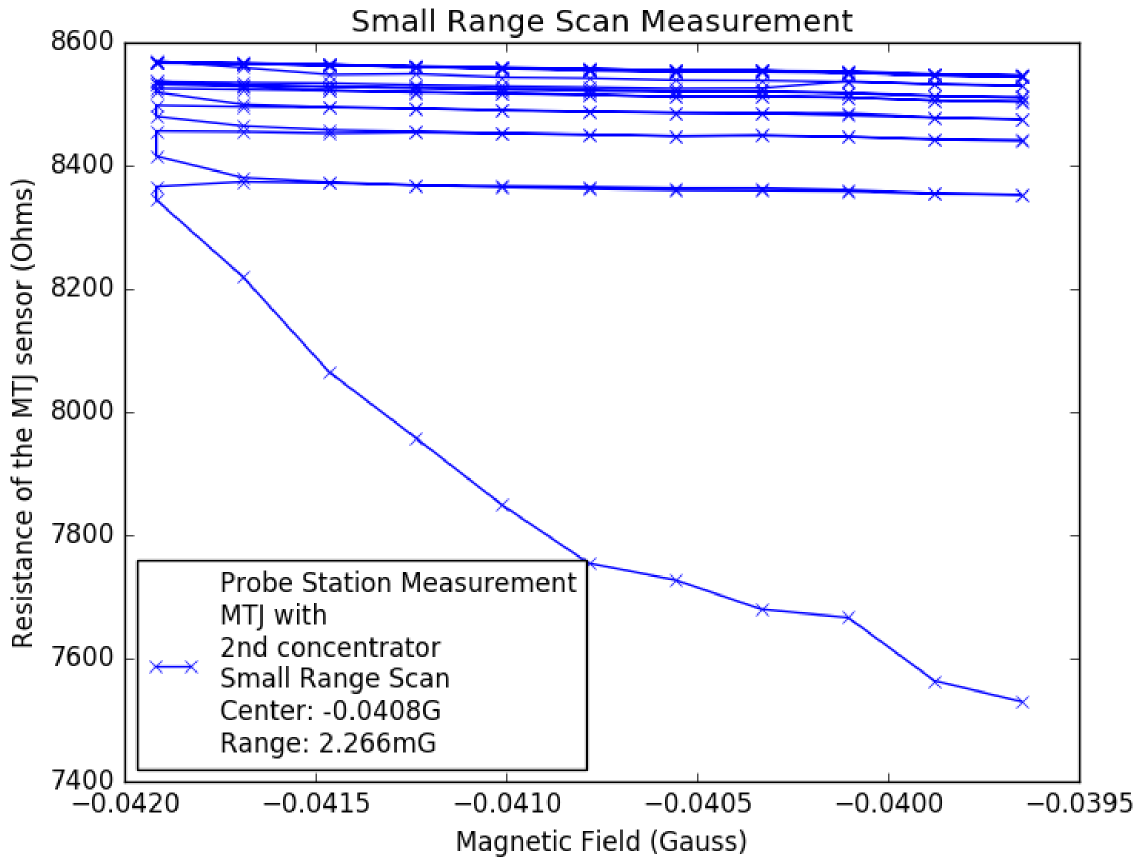
- Unstable state at the most sensitivity region

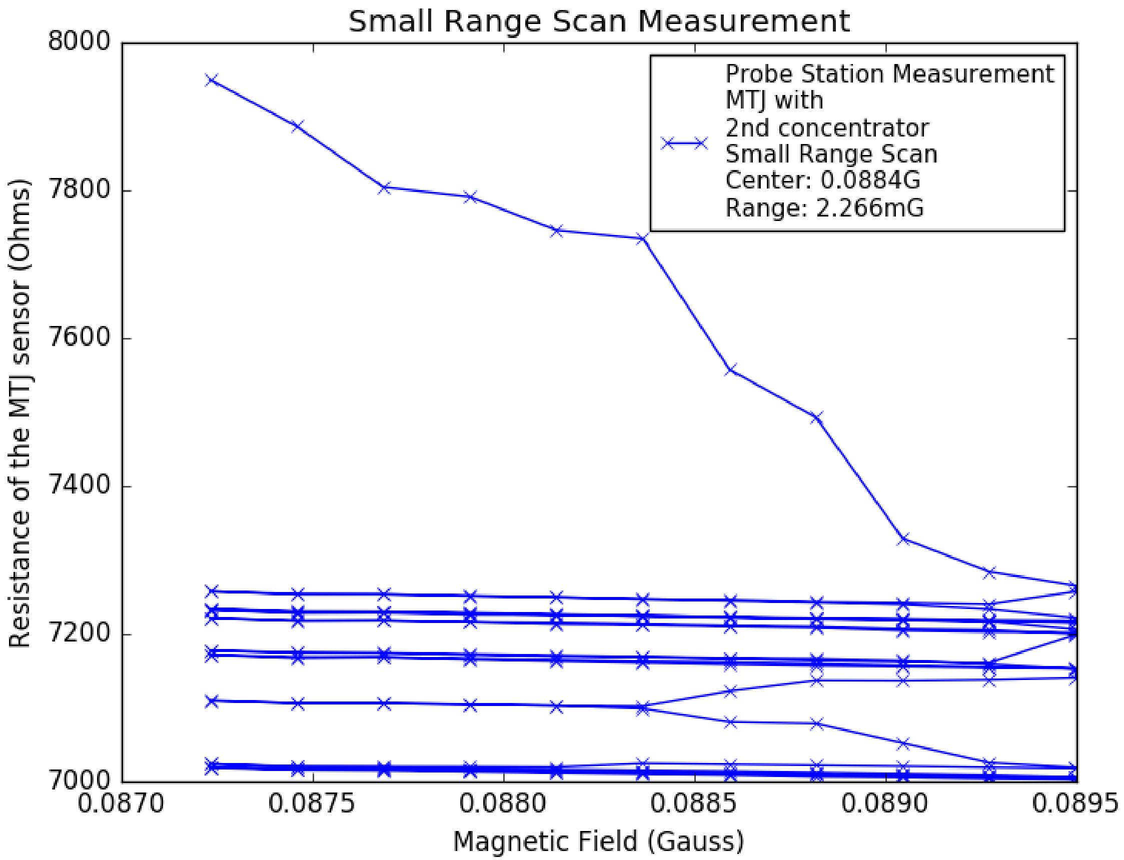




Potential Problem 2

- For small magnetic domain scan, the high sensitivity in large domain transfer curve cannot be reproduced.





Conclusion and Future Work

- Succeed to Measure $109pT$ AC Magnetic Field at 1000Hz Frequency.

- Future work:
  1. Continue the measurement at different frequency.
  2. Identify the source of the $\sim 78nV$ background noise.
  3. Use Helmholtz Coil to further investigate the potential problems.

Acknowledge

- Gratitude to my supervisor Prof. Gang Xiao
- Special Thanks to Gary and Shu Wang
- Physics Department of CUHK, Prof. Chu