Optimizing Hybrid Ferromagnetic Metal-Ferrimagnetic Insulator Spin-Hall Nano-Oscillators

a micromagnetic study

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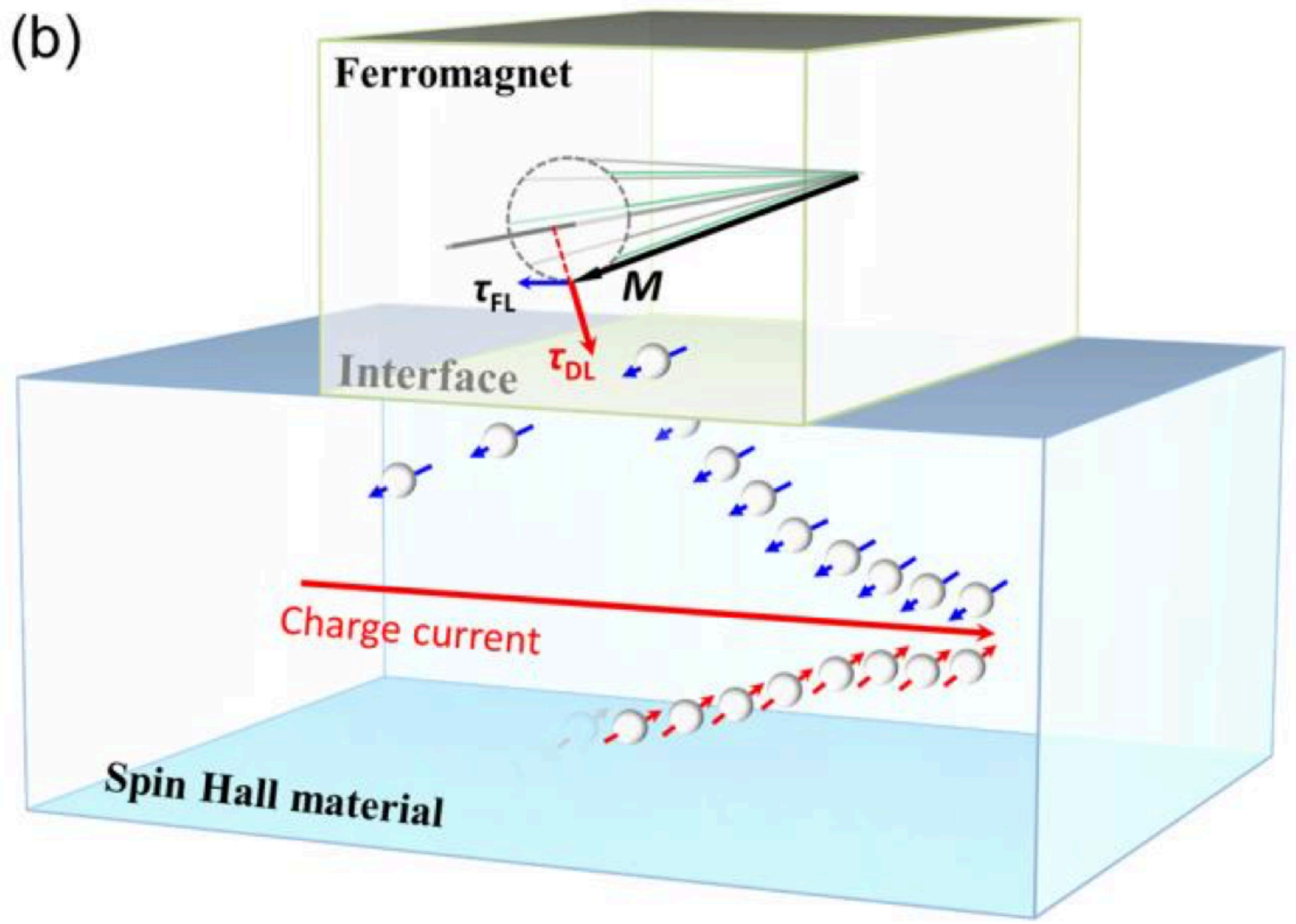
11.2023

Spin-Hall Nano-Oscillator (SHNO)



Lijun Zhu, Daniel C. Ralph, Robert A. Buhrman; Maximizing spin-orbit torque generated by the spin Hall effect of Pt. *Appl. Phys. Rev.* 1 September 2021; 8 (3): 031308.

Electric Current $\xrightarrow{\text{Heavy Metal}}$ Spin Orbit Coupling → Spin-Dependent Deflection → Transverse Spin Current → Spin Accumulation → Spin Transfer Torque → Precession of the Magnetization of Adjacent Ferromagnetic Layer → **Microwave Generation**

Hybrid Spin-Hall Nano-Oscillators (SHNO)

Previous work — Set up

Permalloy (Py) ferromagnetic-metal nanowire and low-damping ferrimagnetic insulator (FI)

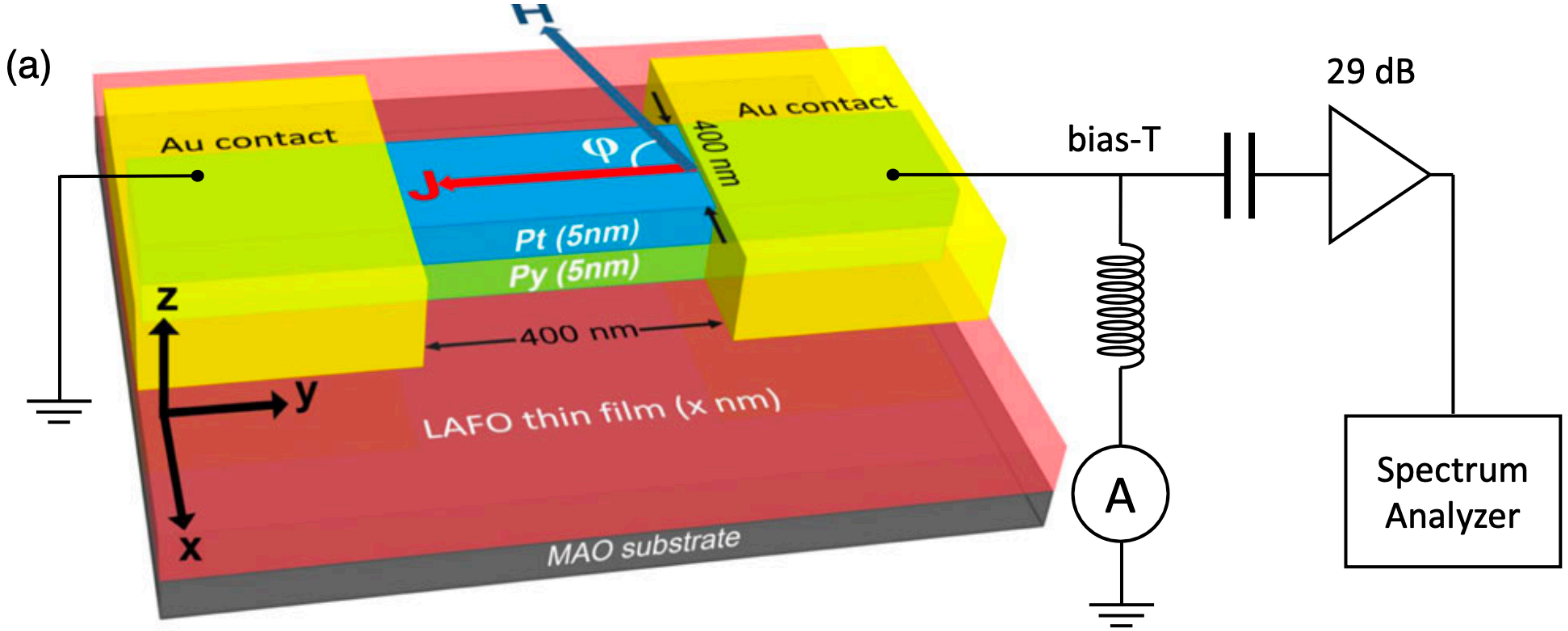
$\phi = 70^{\circ}$

Pt = Platinum

Py = Permalloy ferromagnetic-metal

LAFO = Low-damping ferrimagnetic insulator (epitaxial lithium aluminum ferrite)

MAO = $MgAl_2O_4$

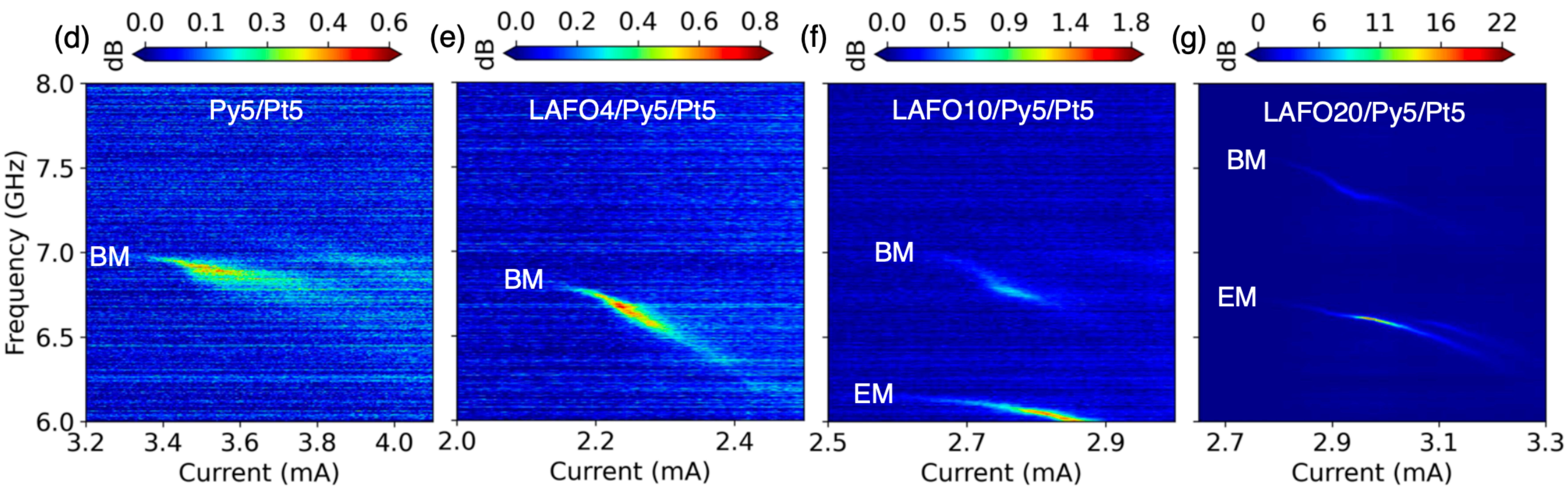


Schematic of the hybrid SHNO device and power spectral density (PSD) measurement setup. Ren, H., Zheng, X.Y., Channa, S. *et al.* Hybrid spin Hall nano-oscillators based on ferromagnetic metal/ ferrimagnetic insulator heterostructures. *Nat Commun* **14**, 1406 (2023).

Hybrid SHNO

Previous work — Observations

Enhanced auto-oscillation amplitude of spin-wave modes

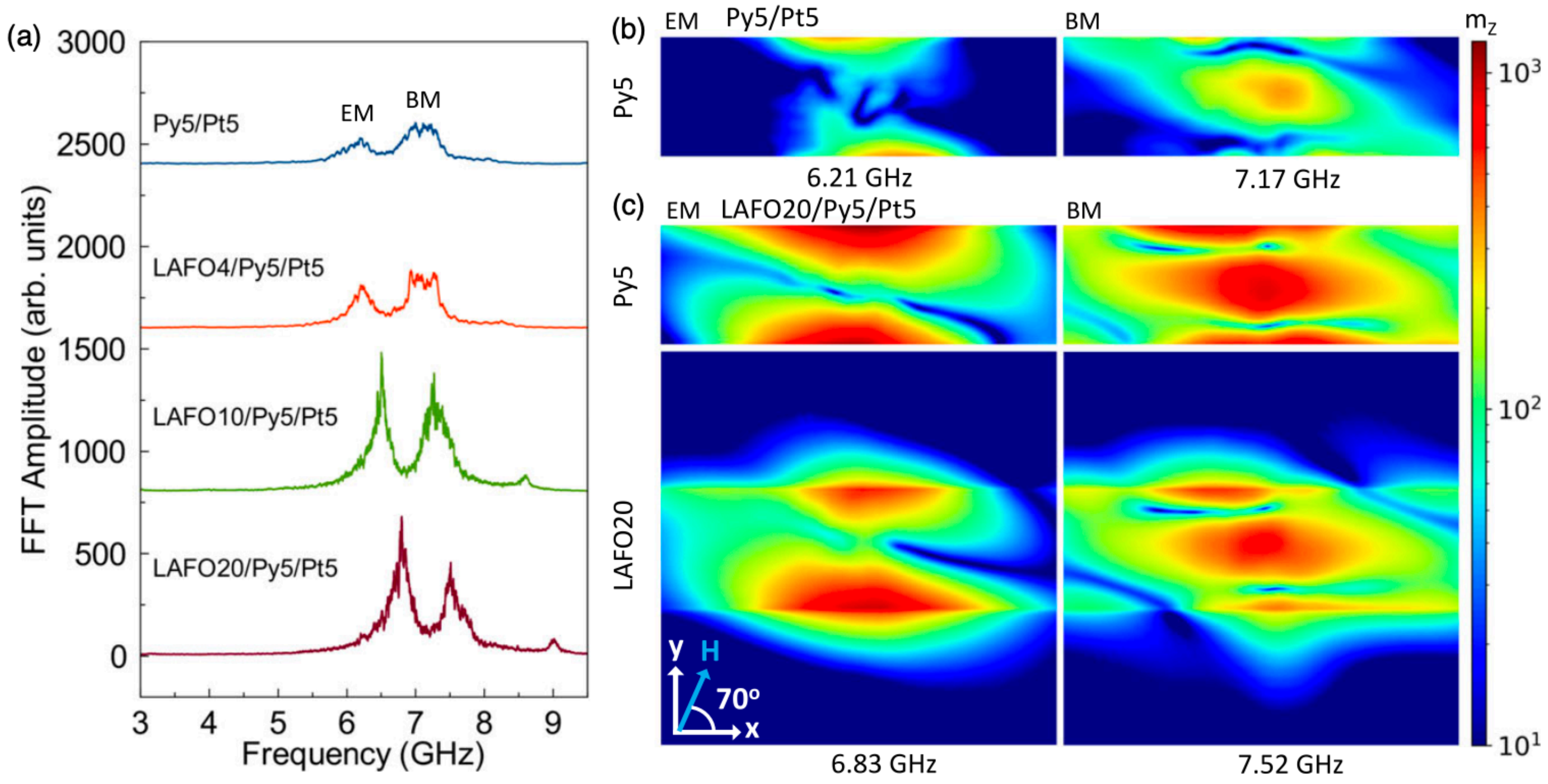


ST-FMR Measurement. Power spectral density (PSD) as a function of bias current at fixed field H = 0.0817 T for φ = 70˚.

- I_{th} drops dramatically between Py5/Pt5 & LAFO/Py5/Pt5
- I_{th} slowly increases with LAFO thickness
- Edge Mode (EM) gradually becomes dominant
- Peak amplitude & quality factor for LAFO/Py5/Pt5 significantly higher than Py5/Pt5

Hybrid SHNO

Previous work — Observations



Micromagnetic Modeling. FFT amplitude spectrum as a function of frequency from micromagnetic simulations of different devices; Top view of spatial FFT images

- Larger larger oscillation amplitude compare to only Py5/Pt5
- Area of EM & BM expands; Amplitude of EM & BM increased
- EM gradually becomes dominant
- Consistent with ST-FMR measurement

Hybrid SHNO

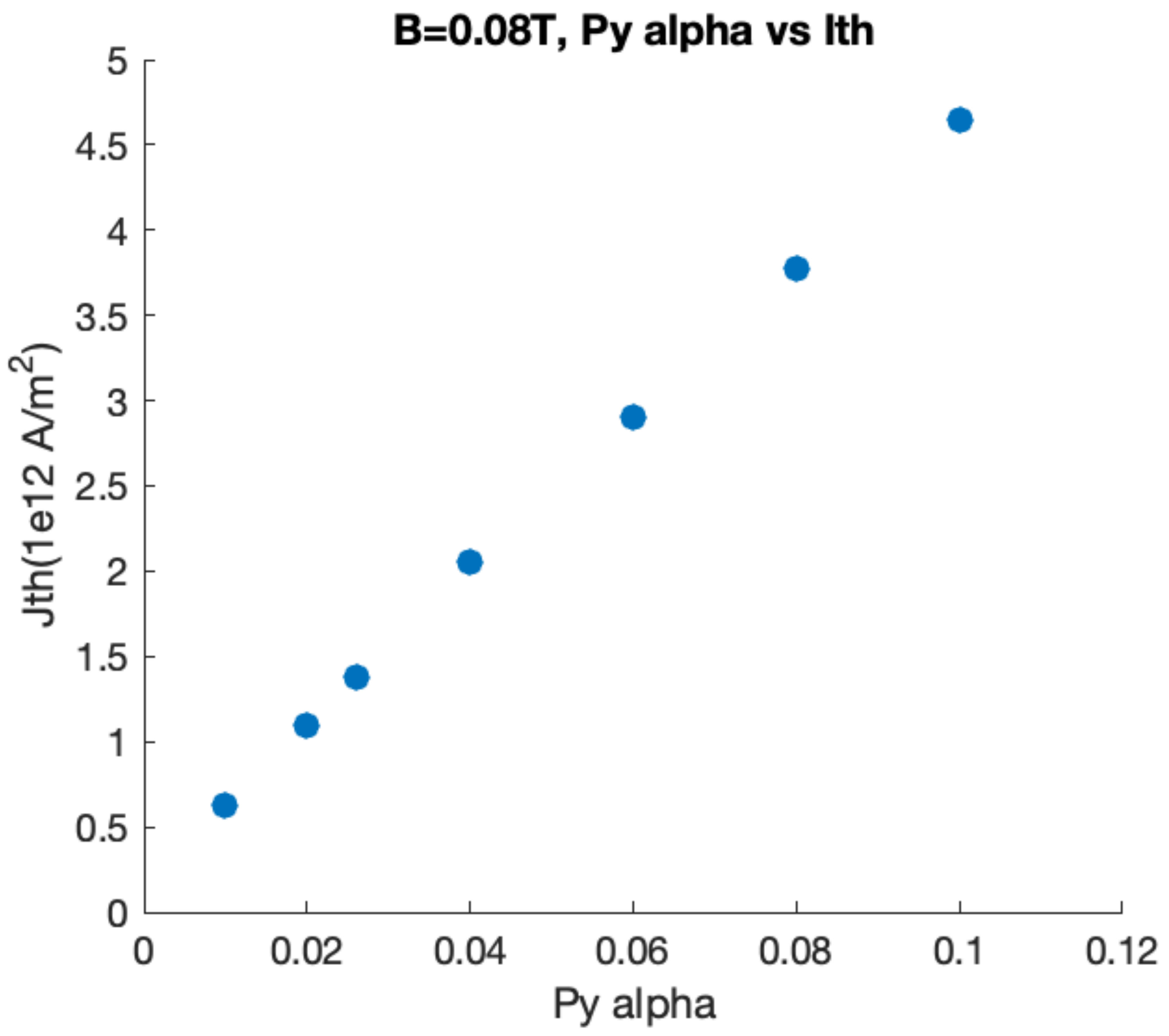
Questions & Methods

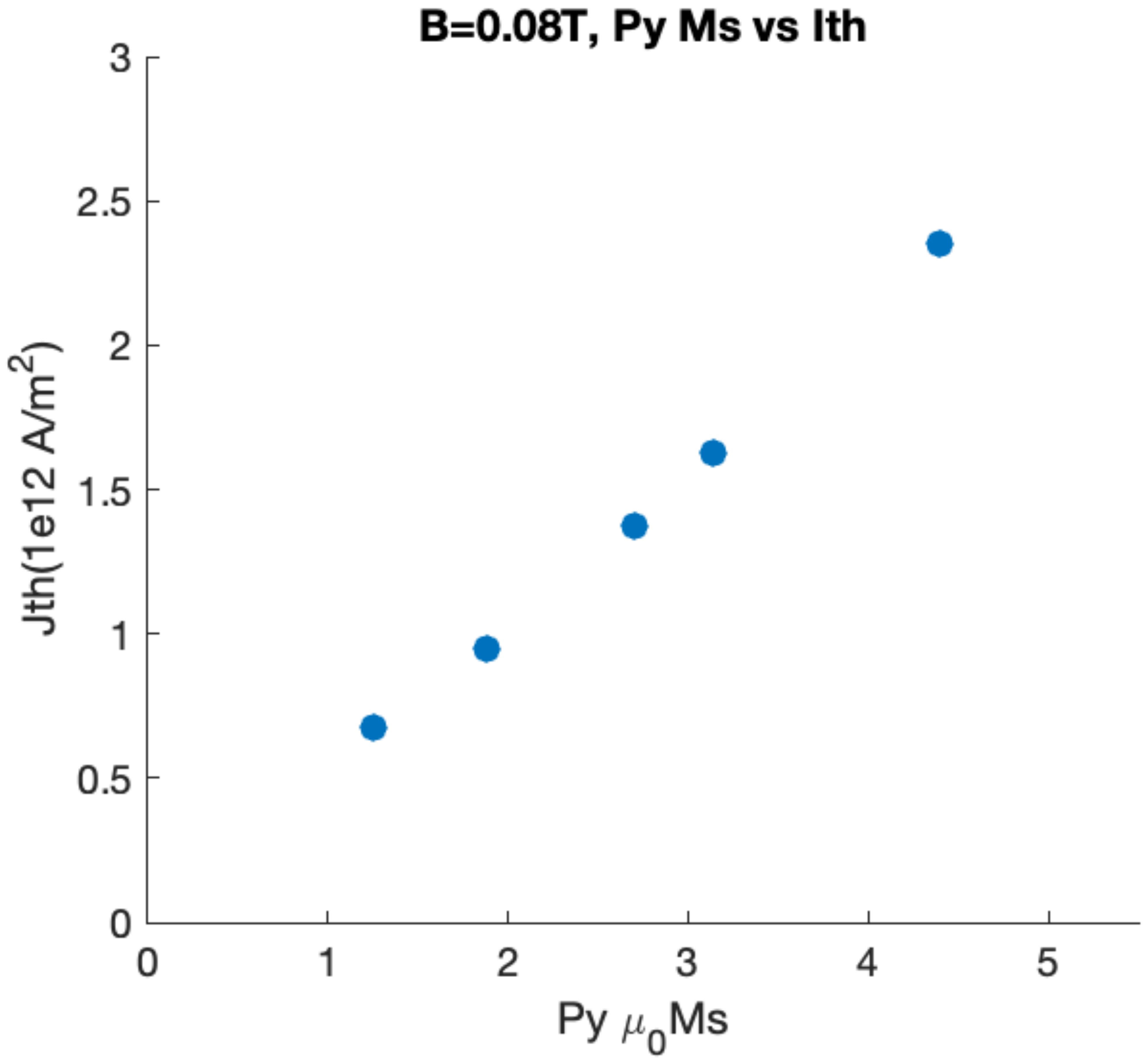
- What causes this drop in I_{th}?
- What causes drastic increased output amplitude when increase the thickness of LAFO layer?
- What is the relationship between material properties and resulting oscillation characteristics? How to enhance the power emission and quality factor of SHNO even more?

We use micromagnetic modeling to explore the relationship between the threshold current & output power and material parameters of the FI (thickness, magnetic anisotropy, Gilbert damping constant(α), and saturation magnetization(Ms), exchange scale).

Py/Pt Only Simulations Test (MuMax3)

J_{th} vs Py α / J_{th} vs Py Ms

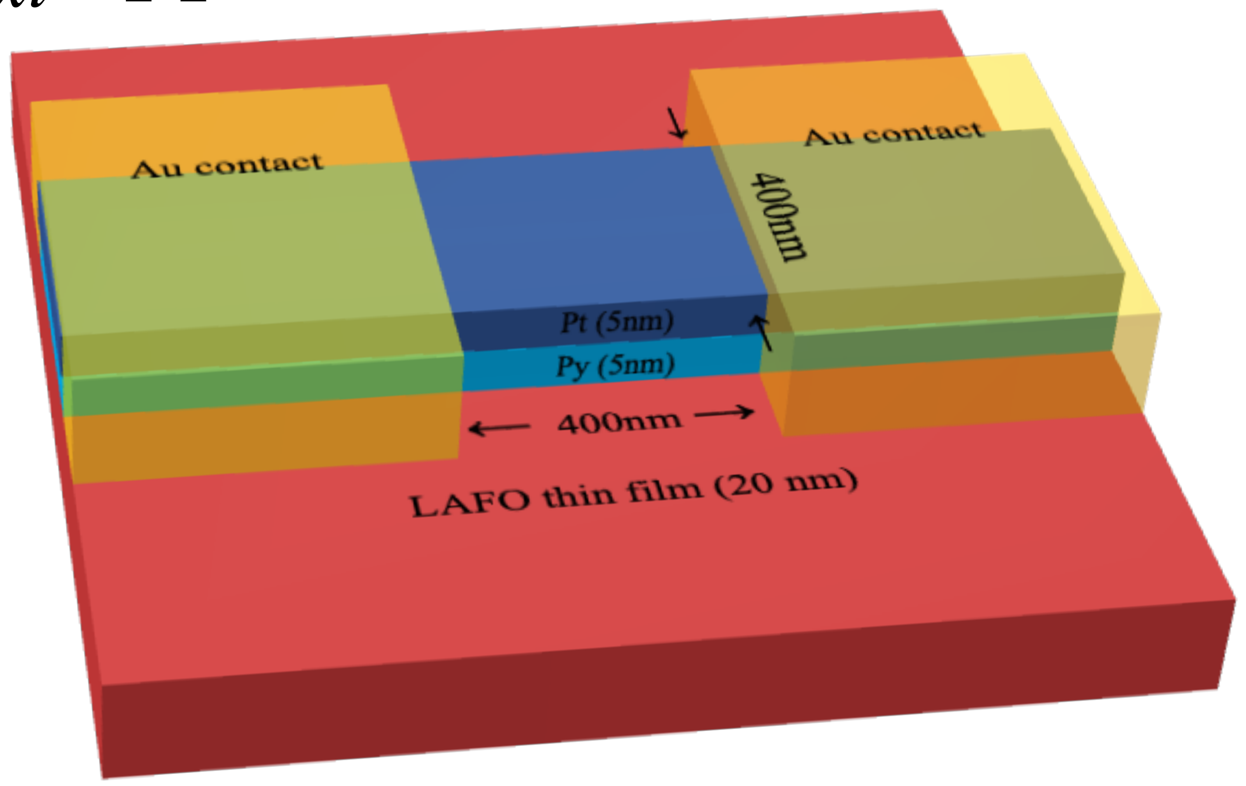


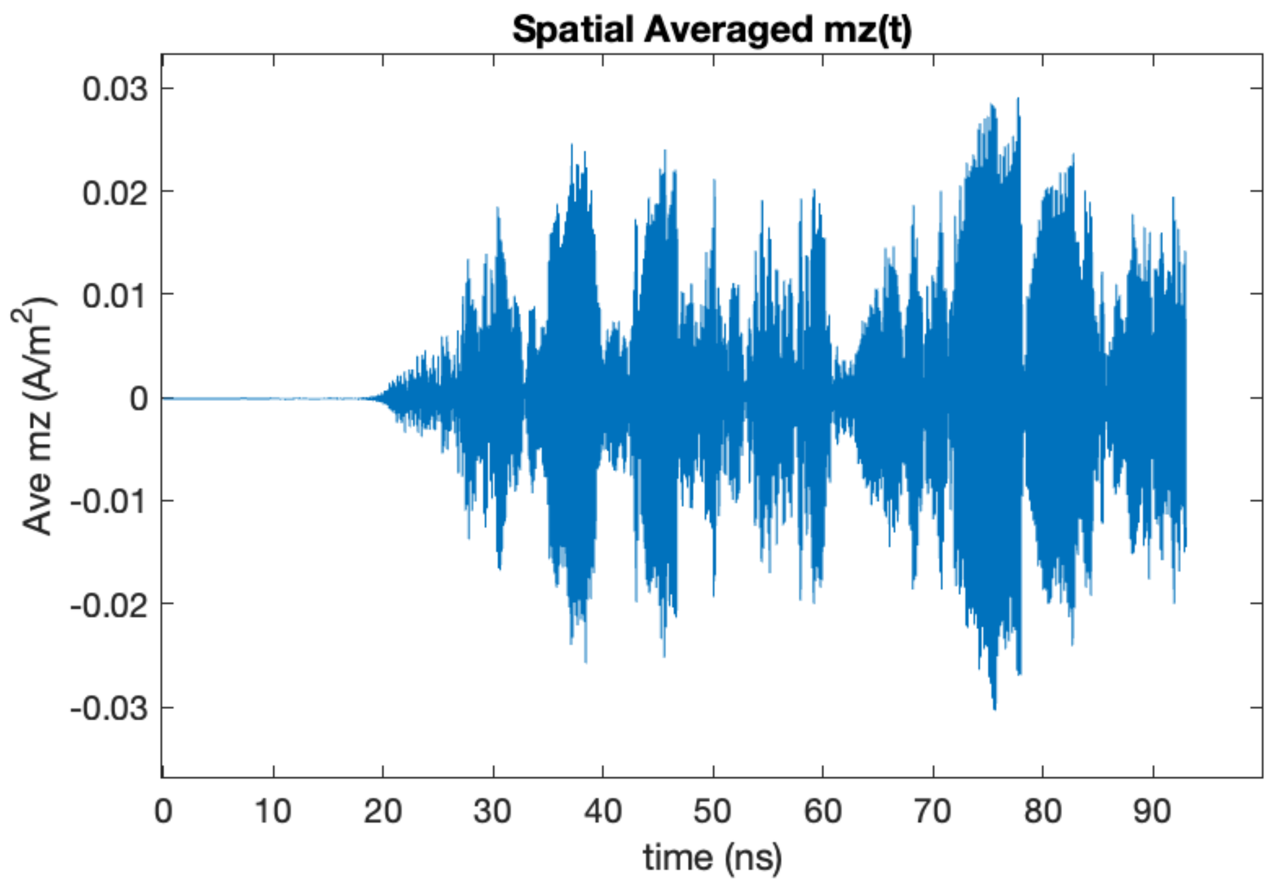


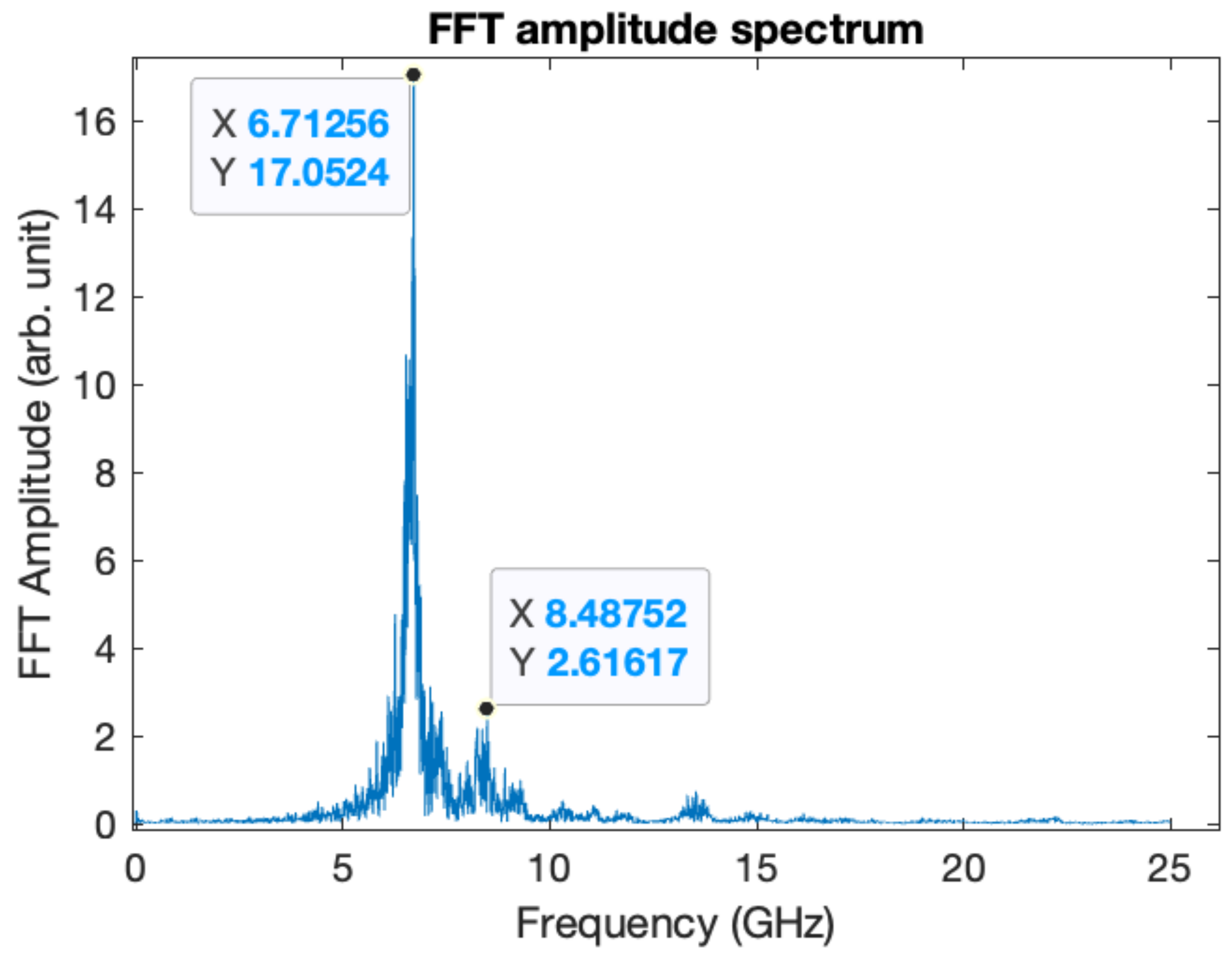
EM & BM frequency/output power vs LAFO saturation magnetization M_s

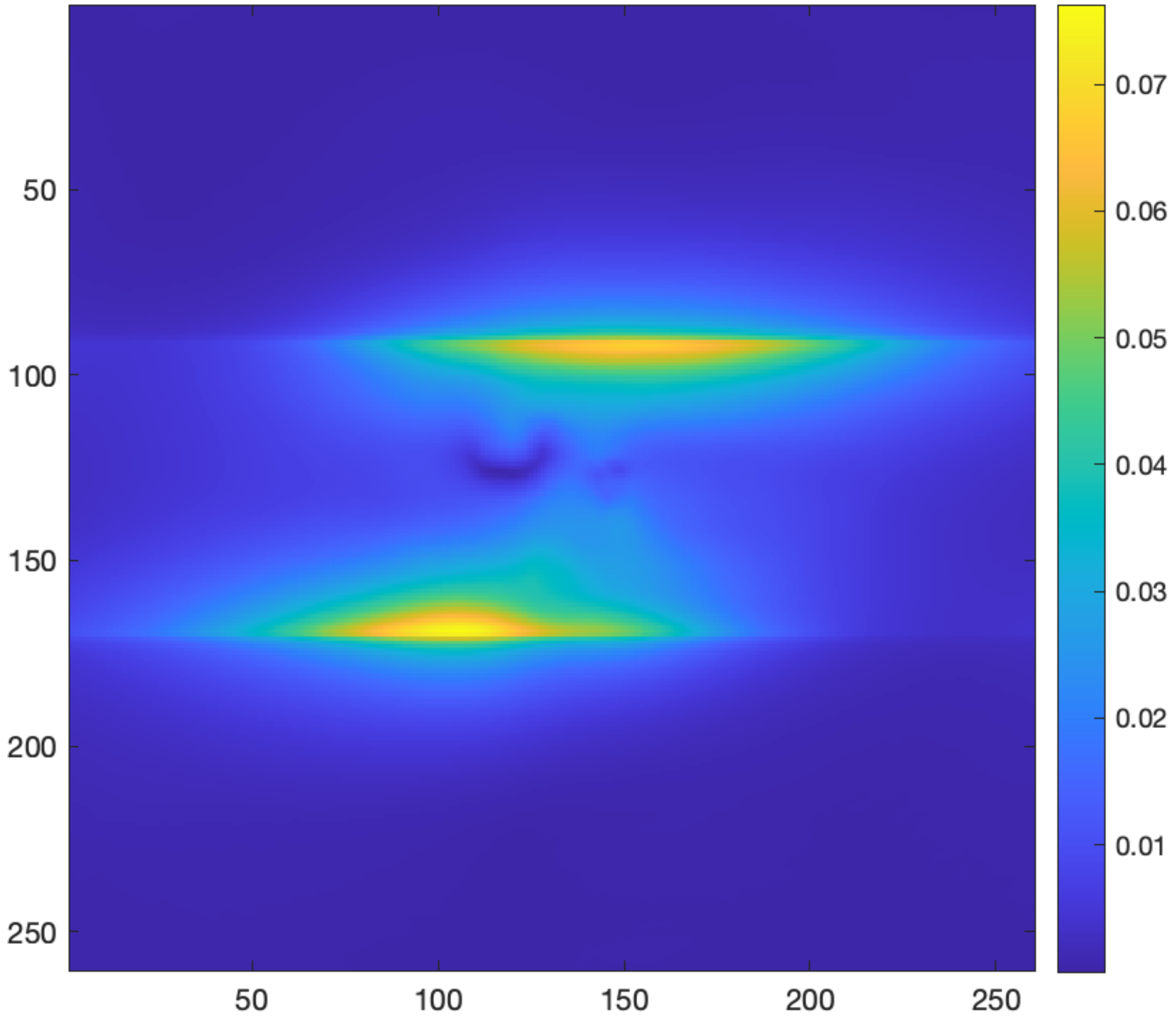
Keep the following variables constant:

- LAFO thickness 20nm
- Current density $-2.02 \times 10^{12} A/m^2$
- $\alpha_{LAFO} = 10^{-3}$
- $\alpha_{Py} = 2.6 \times 10^{-2}$
- $Ku_1 = -3.17 \times 10^4 J/m^3$
- $\mu_0 M_{eff,LAFO} = 0.94T$
- $B_{ext} = 0.08T$
- H_{ext} applied at 70°



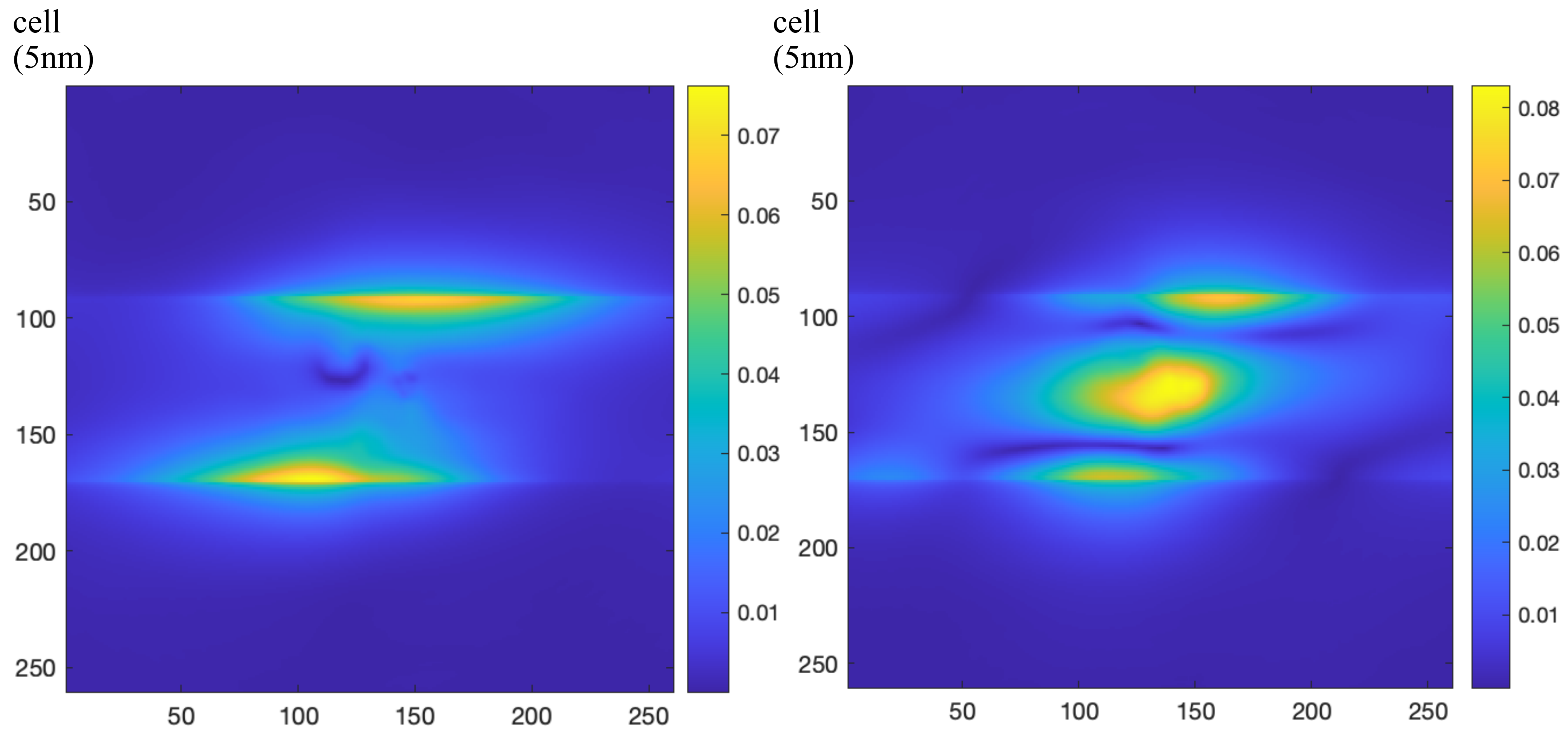




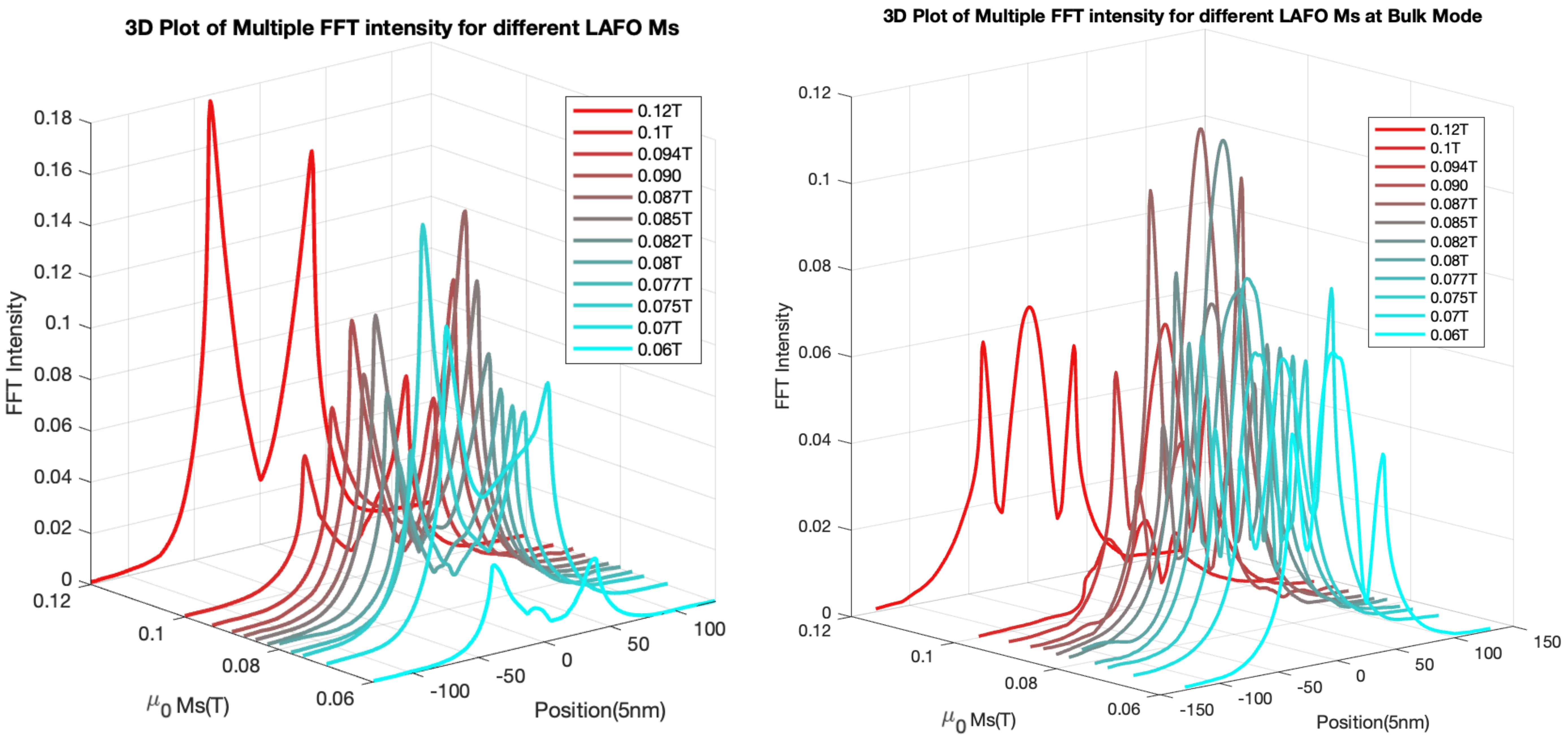


Top view of spatial FFT images of the LAFO layer of a LAFO20/Py5/Pt5 device. This particular example illustrates when LAFO $\mu_0 M_s = 0.0775T$, applied current density $-2.02 \times 10^{12} A/m^2$, spatial FFT at 6.72GHz.

EM & BM frequency/output power vs LAFO saturation magnetization M_s



Top view of spatial FFT images of EM(left) & BM(right) of the LAFO layer in LAFO20/Py5/Pt5 device. This particular example illustrates when LAFO Ms = 775G, applied current density $-2.02 \times 10^{12} A/m^2$, spatial FFT at 6.72GHz.

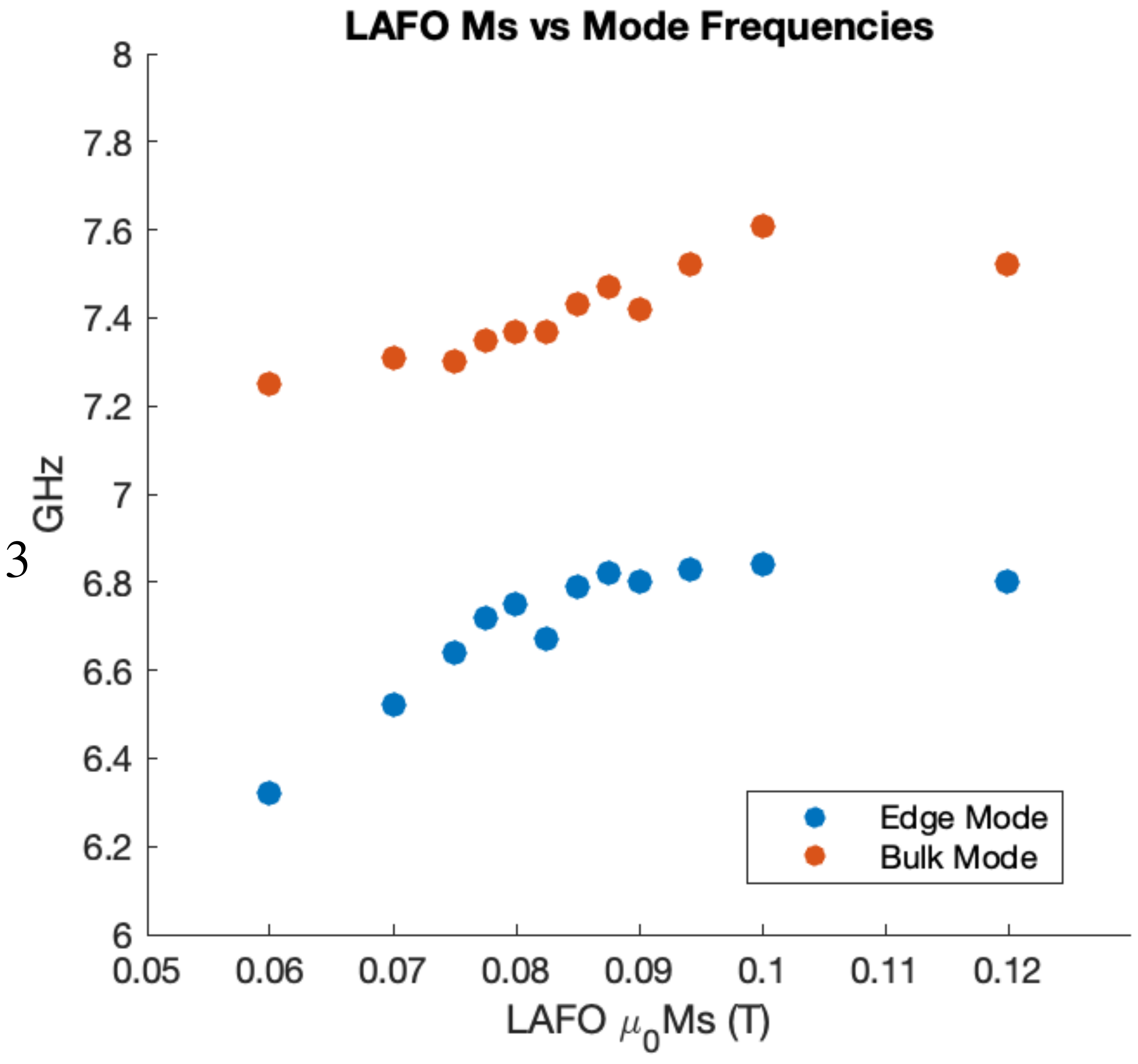


3D diagram of the EM(left) & BM(right) power emission amplitude distribution for different LAFO M_s. Each data point on each line is obtained by finding the maximum emission amplitude at that horizontal coordinate of LAFO

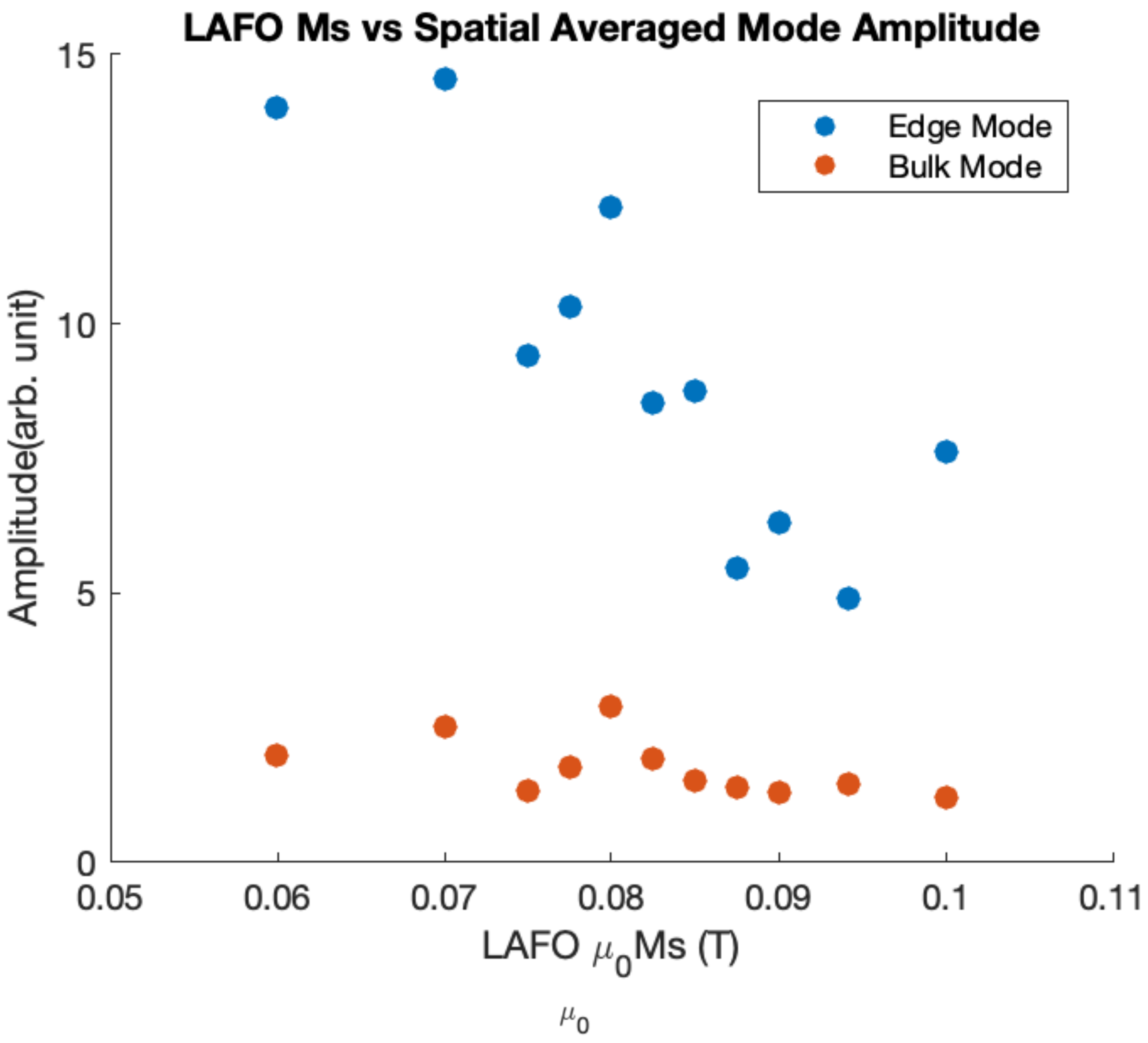
EM & BM frequency/output power vs LAFO saturation magnetization M_s

Keep the following variables constant:

- LAFO thickness 20nm
- Current density $-2.02 \times 10^{12} A/m^2$
- $\alpha_{LAFO} = 10^{-3}$
- $\alpha_{Py} = 2.6 \times 10^{-2}$
- $Ku_1 = -3.17 \times 10^4 J/m^3$
- $\mu_0 M_{eff,LAFO} = 0.94T$
- $B_{ext} = 0.08T$
- H_{ext} applied at 70°



EM & BM frequencies for different LAFO M_s.

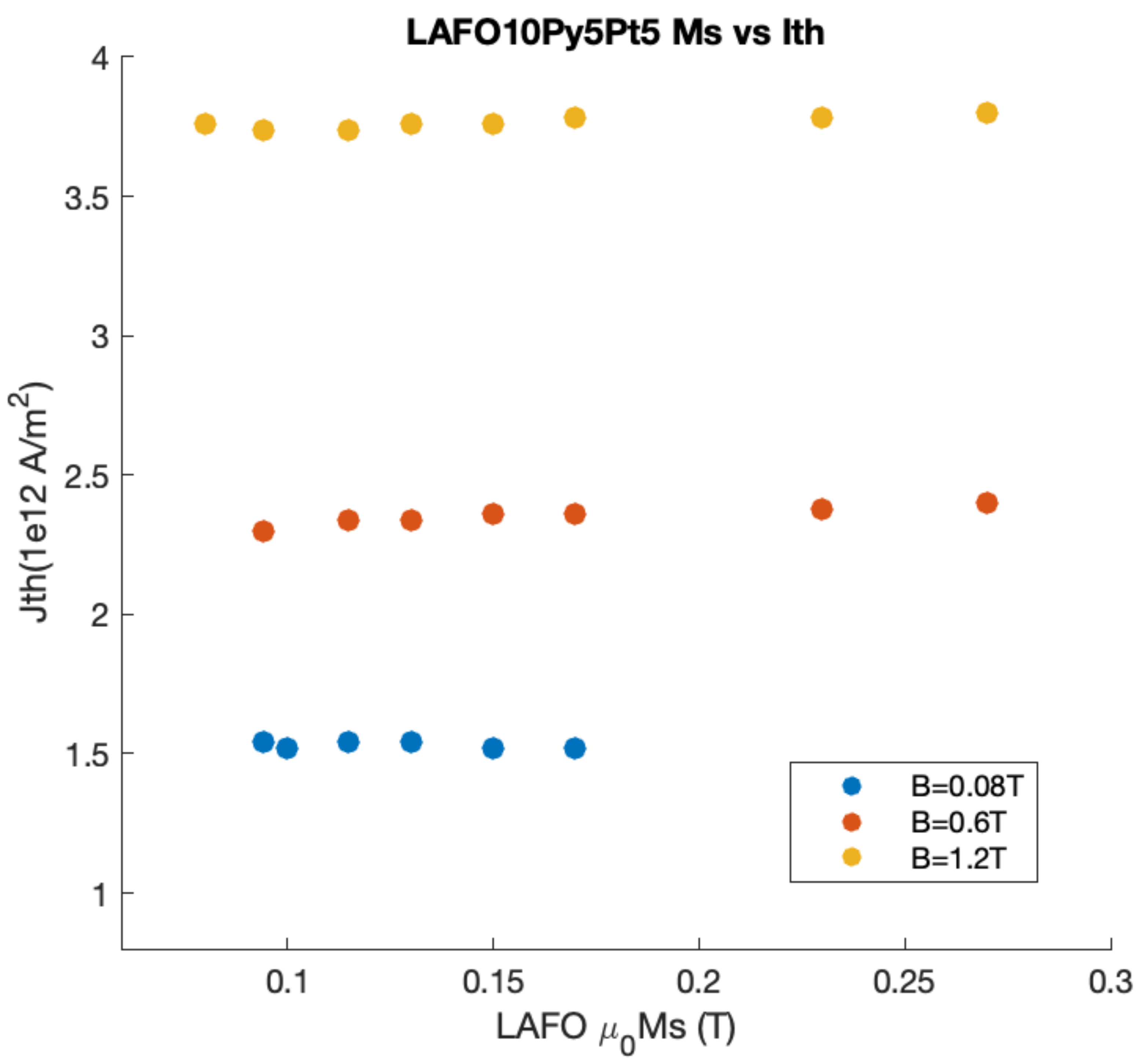


Maximum EM & BM spatial averaged power emission amplitude for different LAFO M_s.
$I = -2.02 \times 10^{12} A/m^2$

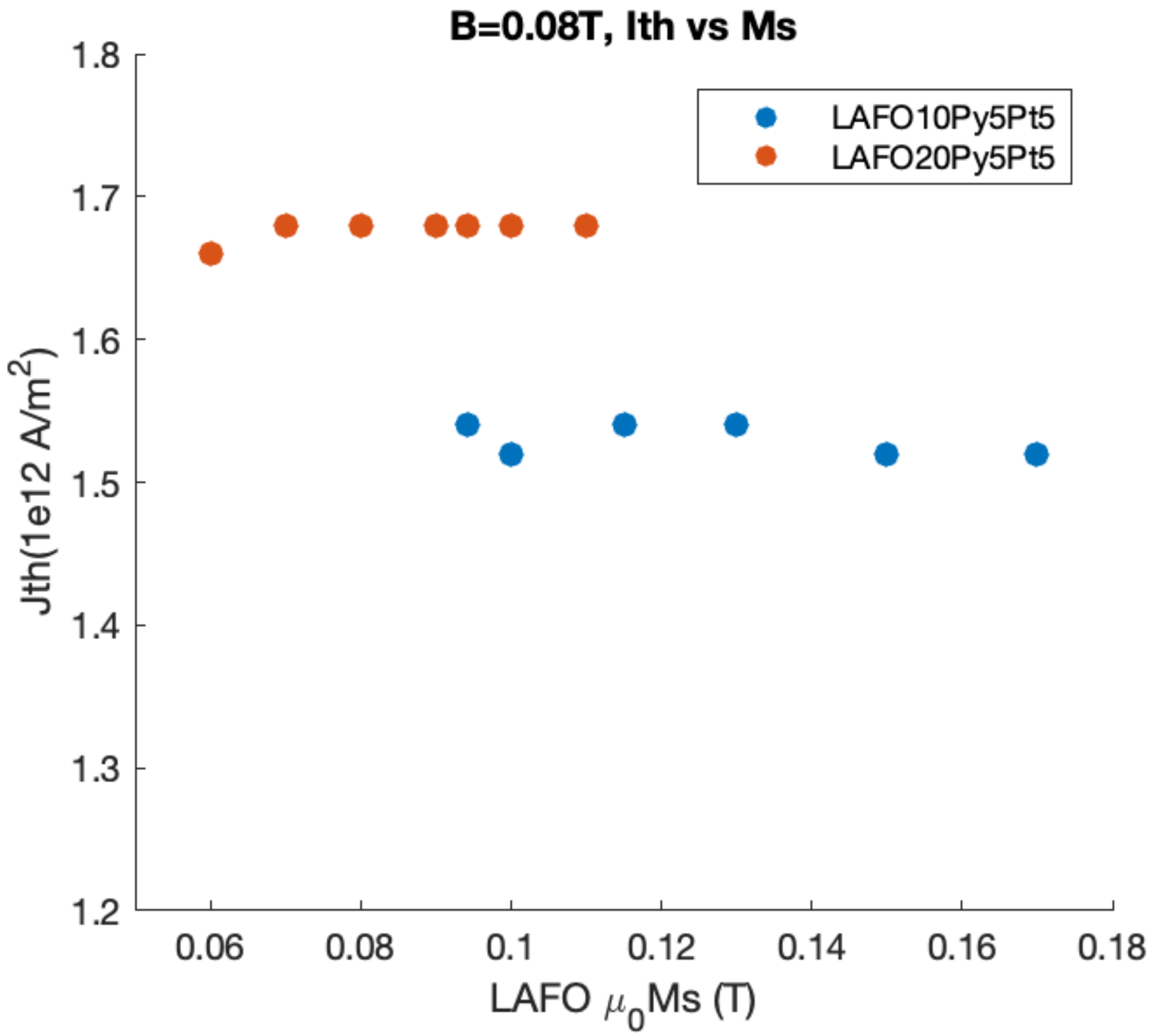
I_{th} vs LAFO M_s

Keep the following variables constant:

- $\alpha_{LAFO} = 10^{-3}$
- $\alpha_{Py} = 2.6 \times 10^{-2}$
- $Ku_1 = -3.17 \times 10^4 J/m^3$
- $\mu_0 M_{eff,LAFO} = 0.94T$
- H_{ext} applied at 70°



I_{th} for LAFO10/Py5/Pt5 with different LAFO M_s at three different external field strength

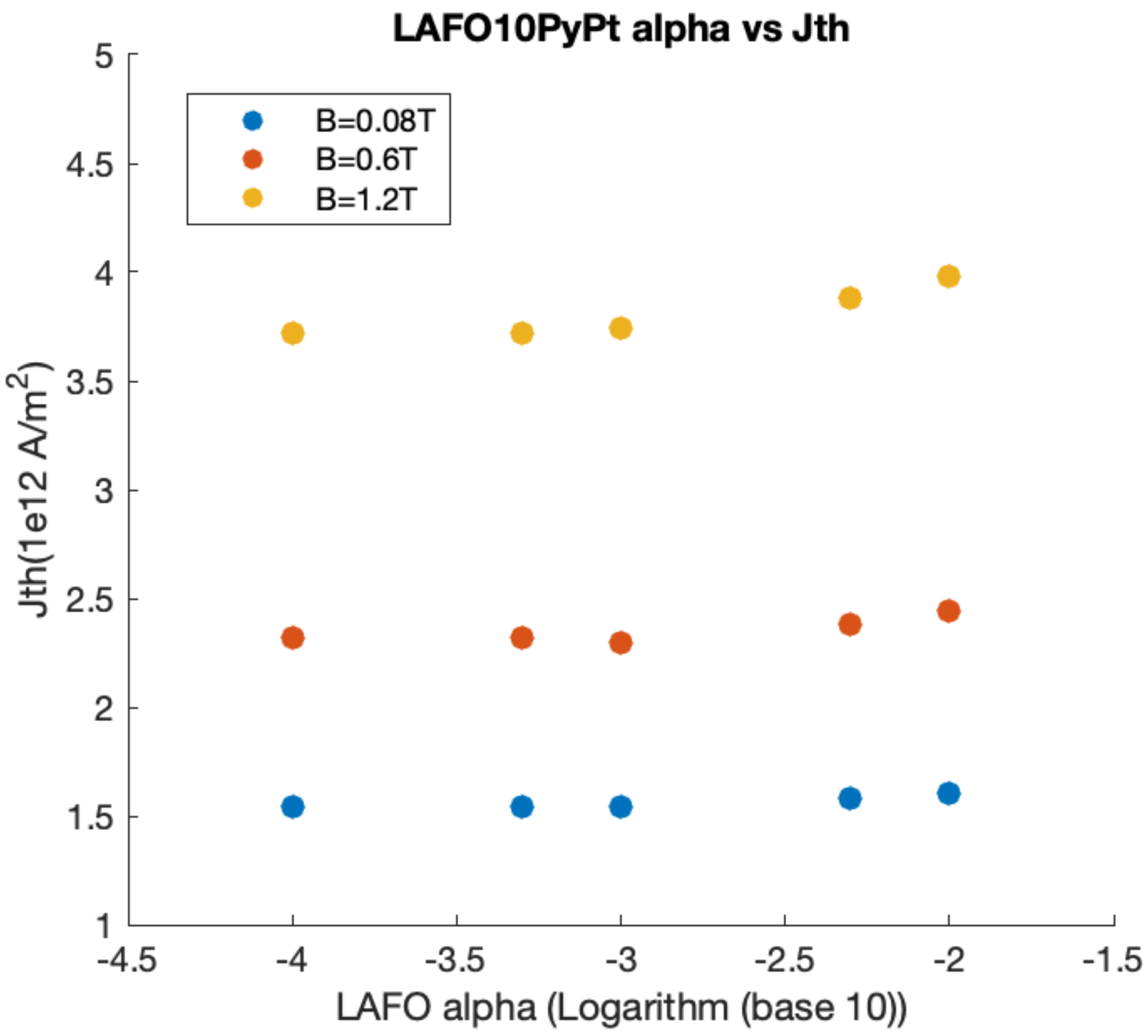


Comparison between the I_{th} for LAFO10/Py5/Pt5 and LAFO20/Py5/Pt5 with different LAFO M_s at $B_{ext} = 0.08T$

I_{th} vs LAFO Damping Constant α

Keep the following variables constant:

- LAFO thickness 10nm
- $\alpha_{Py} = 2.6 \times 10^{-2}$
- $Ku_1 = -3.17 \times 10^4 J/m^3$
- $\mu_0 M_{eff,LAFO} = 0.94T$
- $\mu_0 M_s = 0.0942T$
- H_{ext} applied at 70°

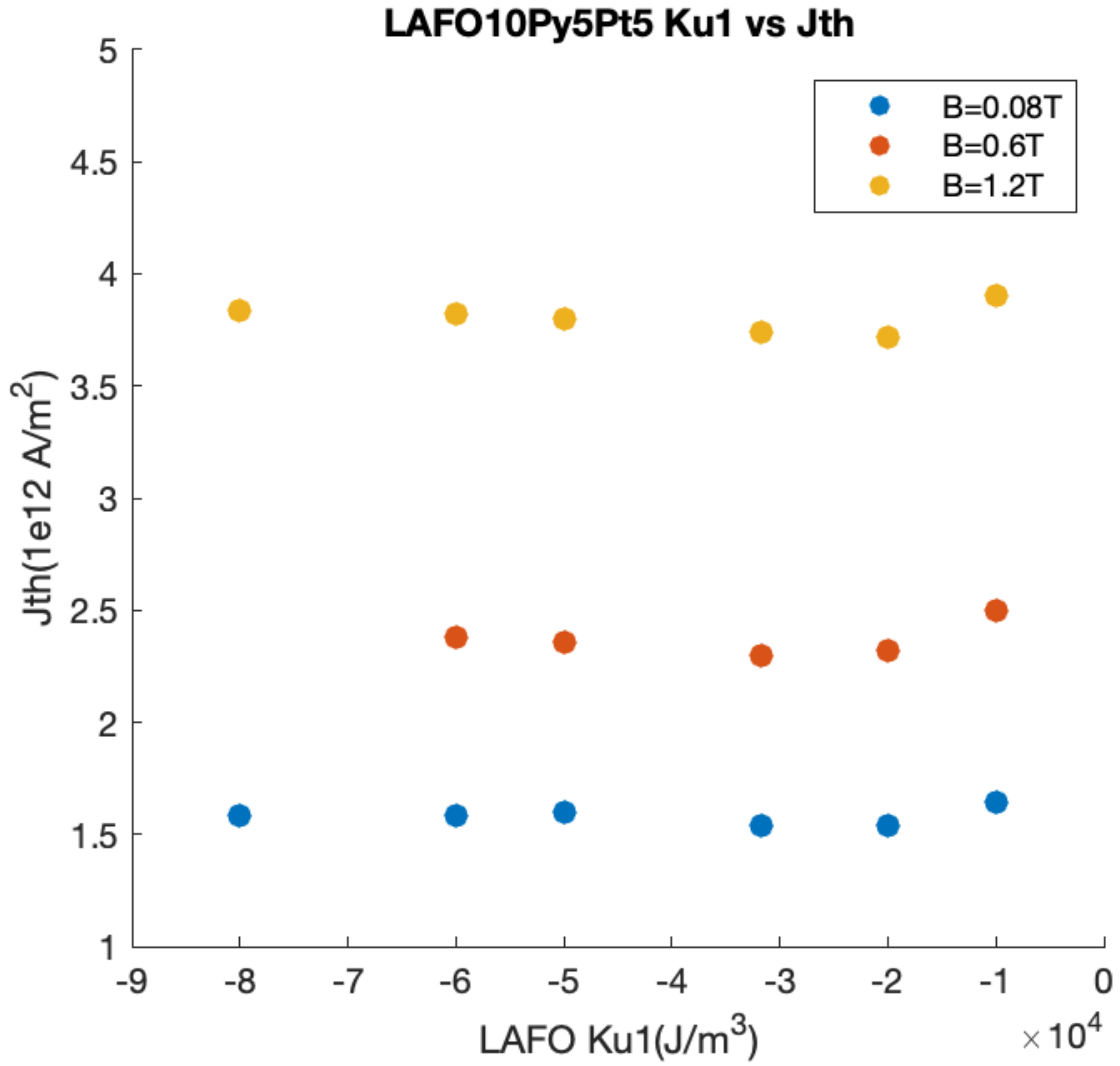


I_{th} for LAFO10/Py5/Pt5 with different α_{LAFO} at three different external field strength, LAFO $\mu_0 M_s = 0.0942T$. The α_{LAFO} axis is in logarithmic scale

I_{th} vs LAFO magnetic anisotropy Ku_1

Keep the following variables constant:

- LAFO thickness 10nm
- $\alpha_{LAFO} = 10^{-3}$
- $\alpha_{Py} = 2.6 \times 10^{-2}$
- $\mu_0 M_{eff,LAFO} = 0.94T$
- $\mu_0 M_s = 0.0942T$
- H_{ext} 70° respect to current

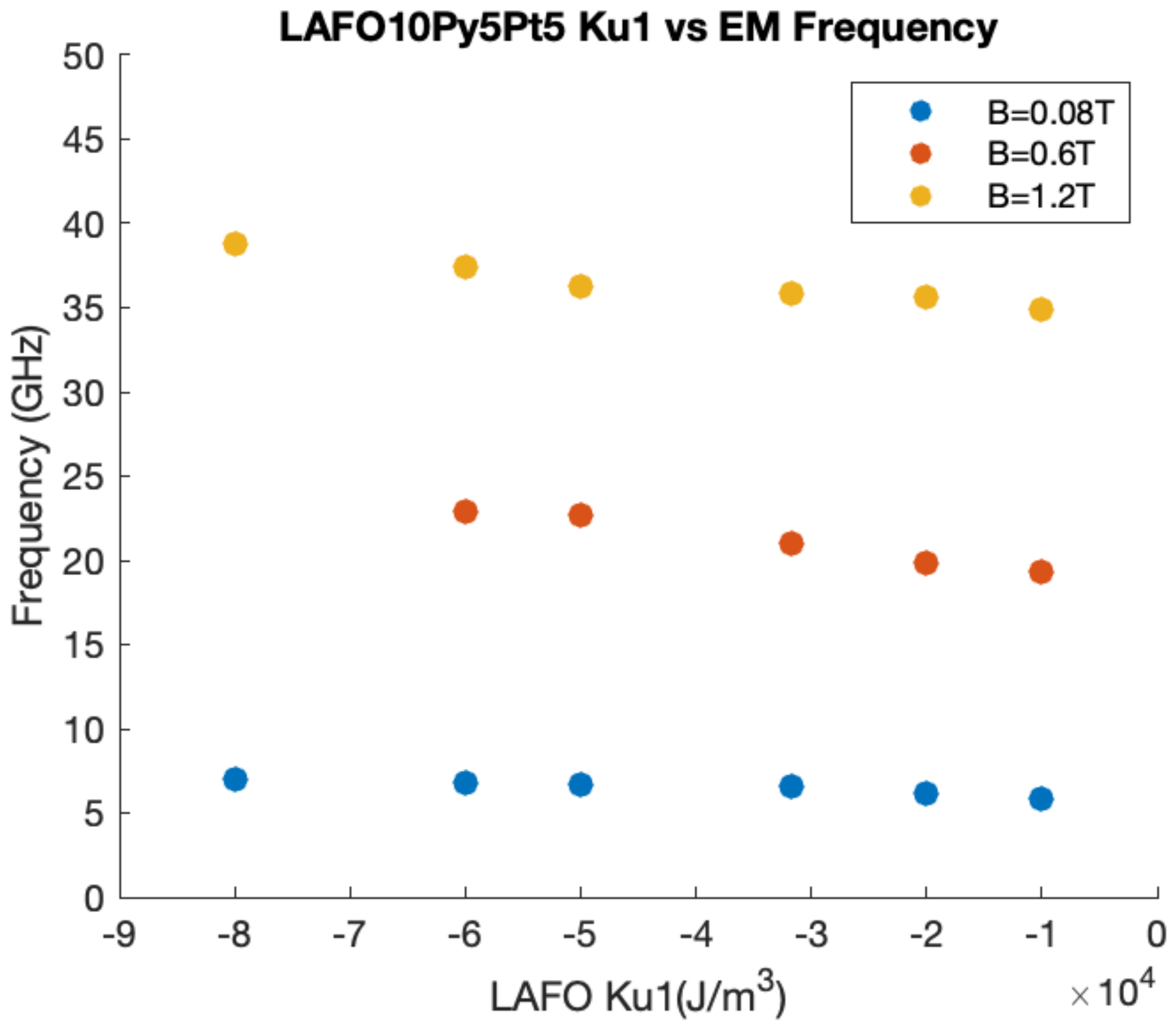


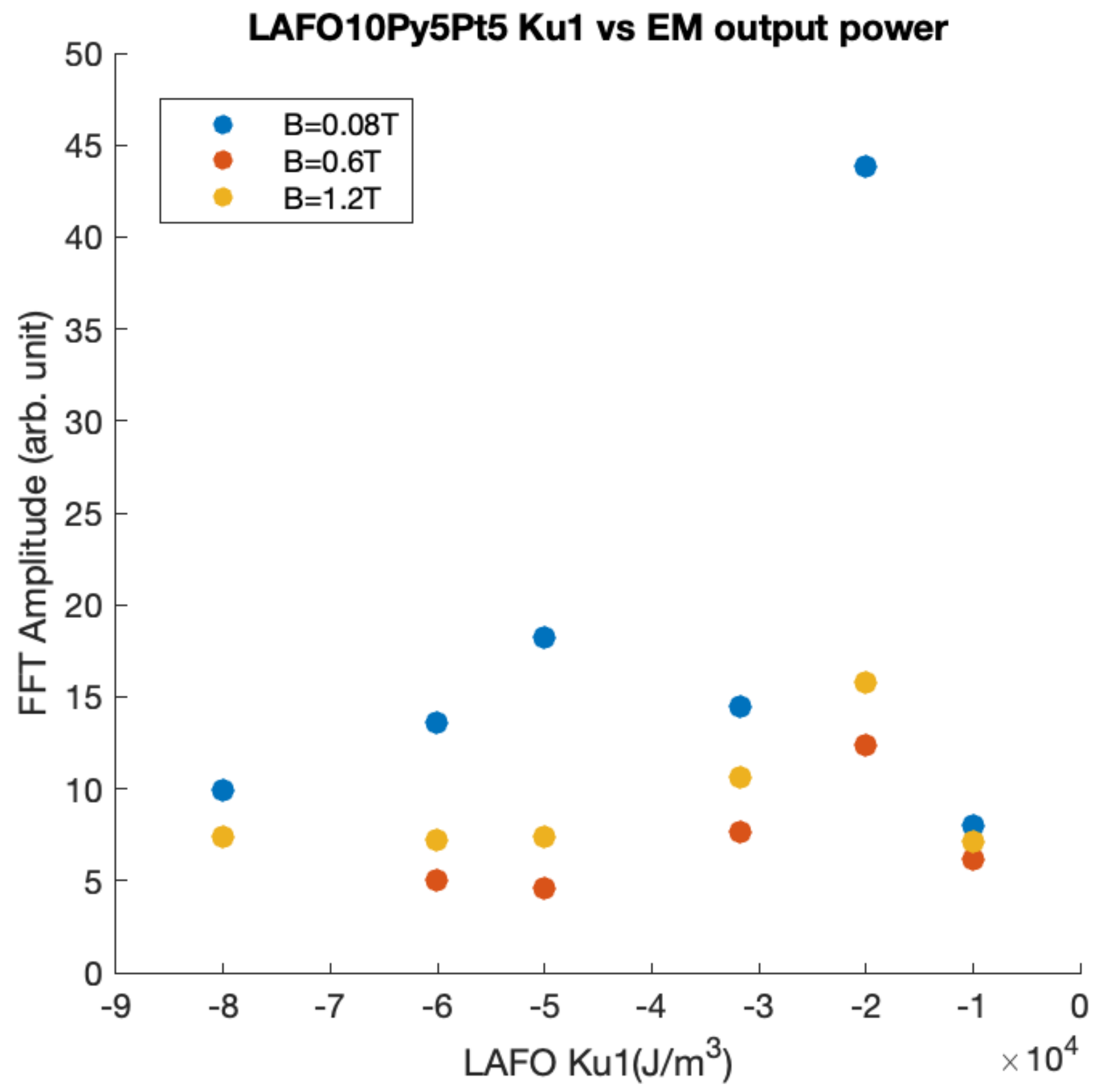
I_{th} for LAFO10/Py5/Pt5 with different $Ku_{1,LAFO}$ at three different external field strength, LAFO $\mu_0 M_s = 0.0942T$, $\alpha_{LAFO} = 10^{-3}$.

EM & BM frequency/output power at 1.2 times I_{th} vs LAFO Ku_1

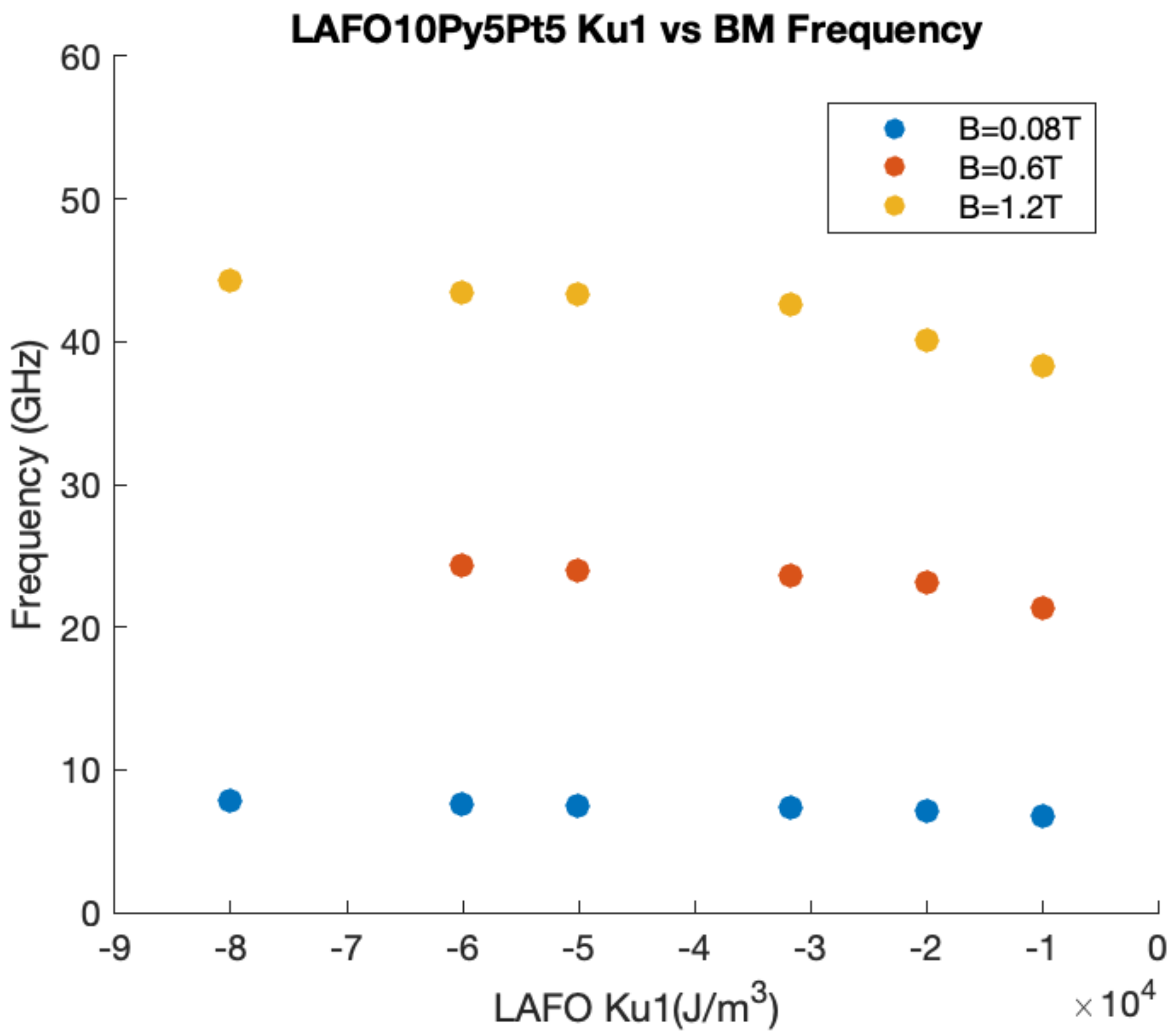
Keep the following variables constant:

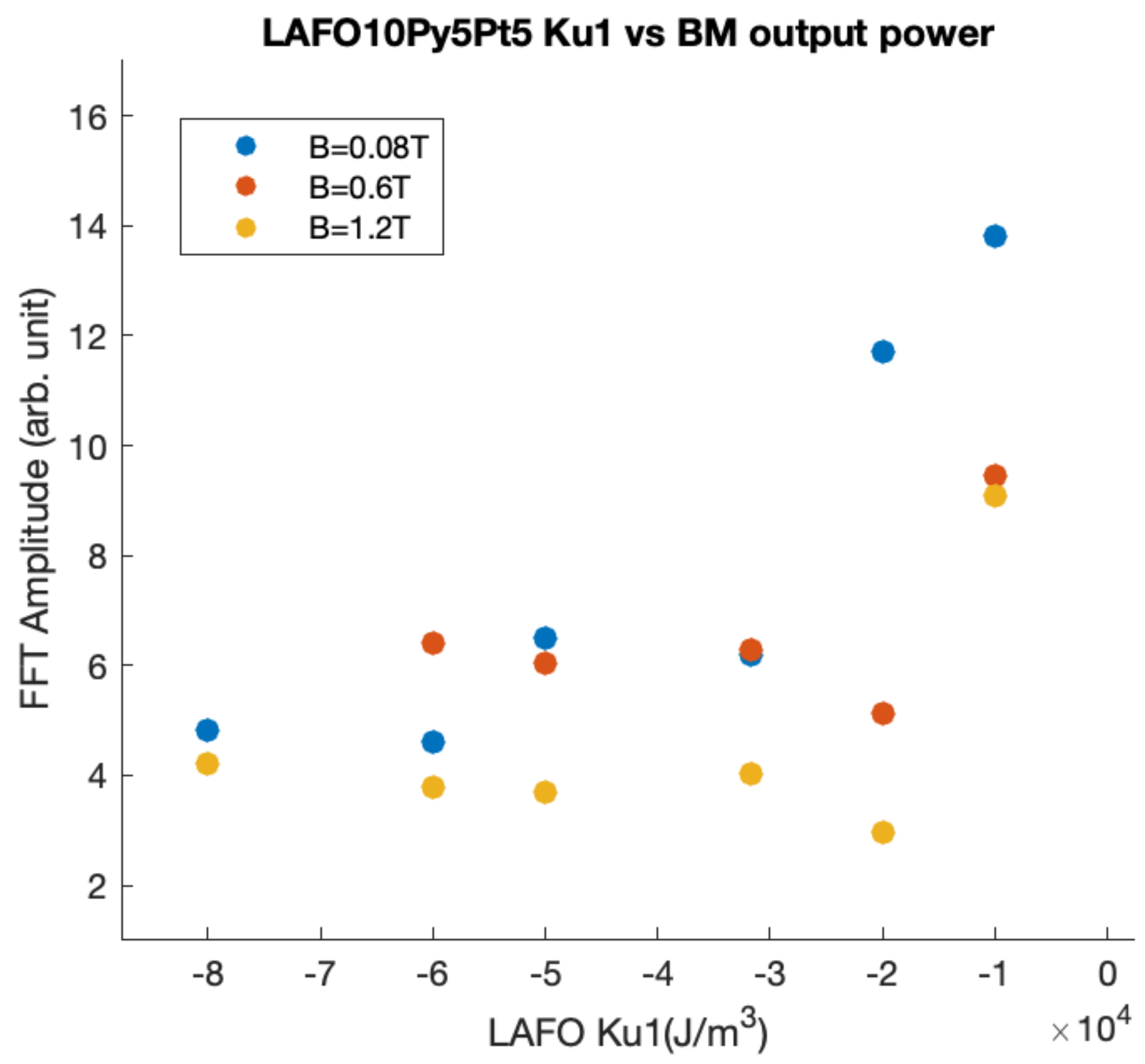
- LAFO thickness 10nm
- $\alpha_{LAFO} = 10^{-3}$
- $\alpha_{Py} = 2.6 \times 10^{-2}$
- $\mu_0 M_{eff,LAFO} = 0.94T$
- $\mu_0 M_s = 0.0942T$
- H_{ext} 70° respect to current





EM



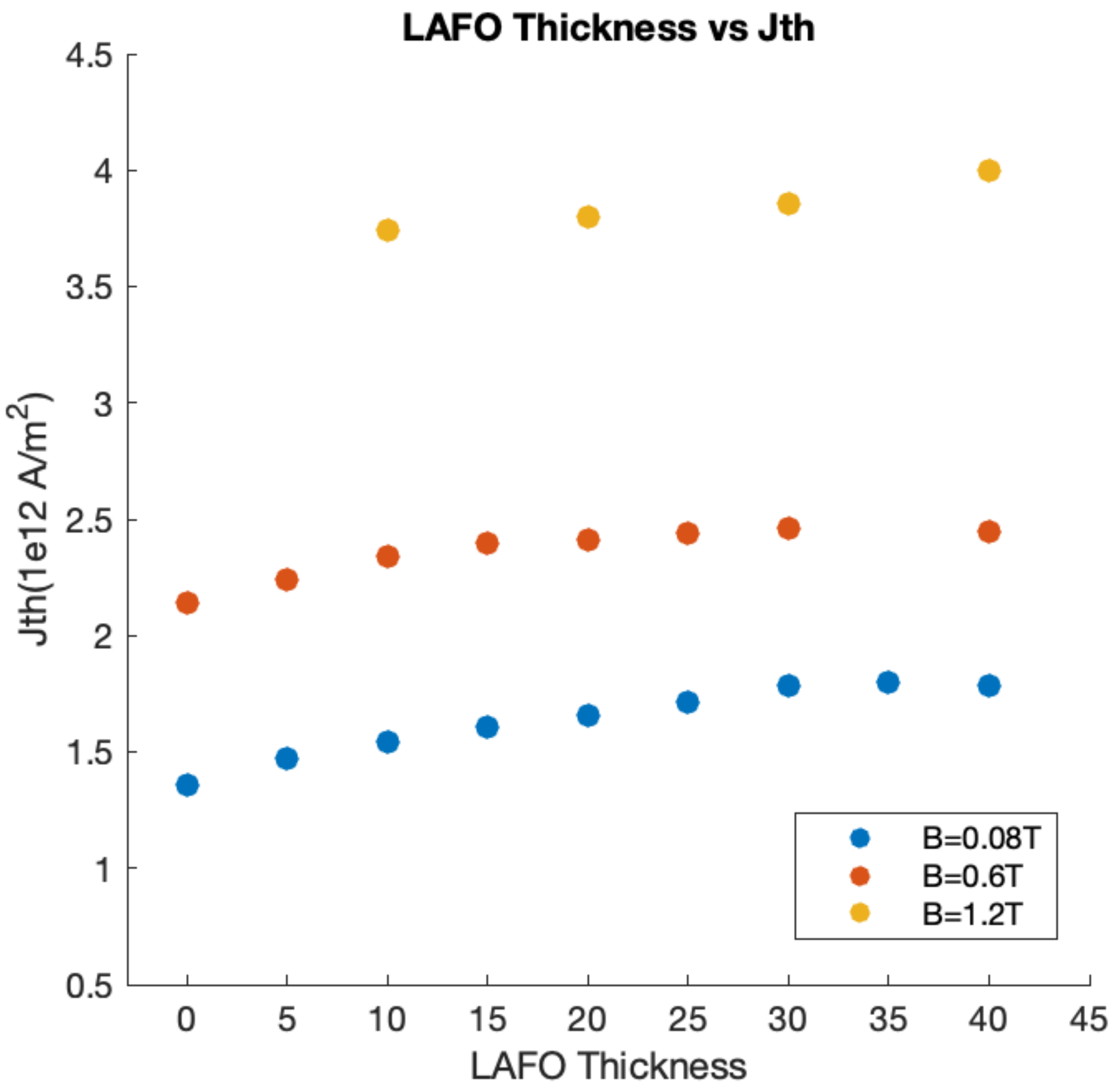


BM

I_{th} vs LAFO thickness

Keep the following constant:

- $\alpha_{LAFO} = 10^{-3}$
- $\alpha_{Py} = 2.6 \times 10^{-2}$
- $\mu_0 M_{eff,LAFO} = 0.94T$
- $\mu_0 M_s = 0.0942T$
- $Ku_1 = -3.17 \times 10^4 J/m^3$
- H_{ext} applied at 70°



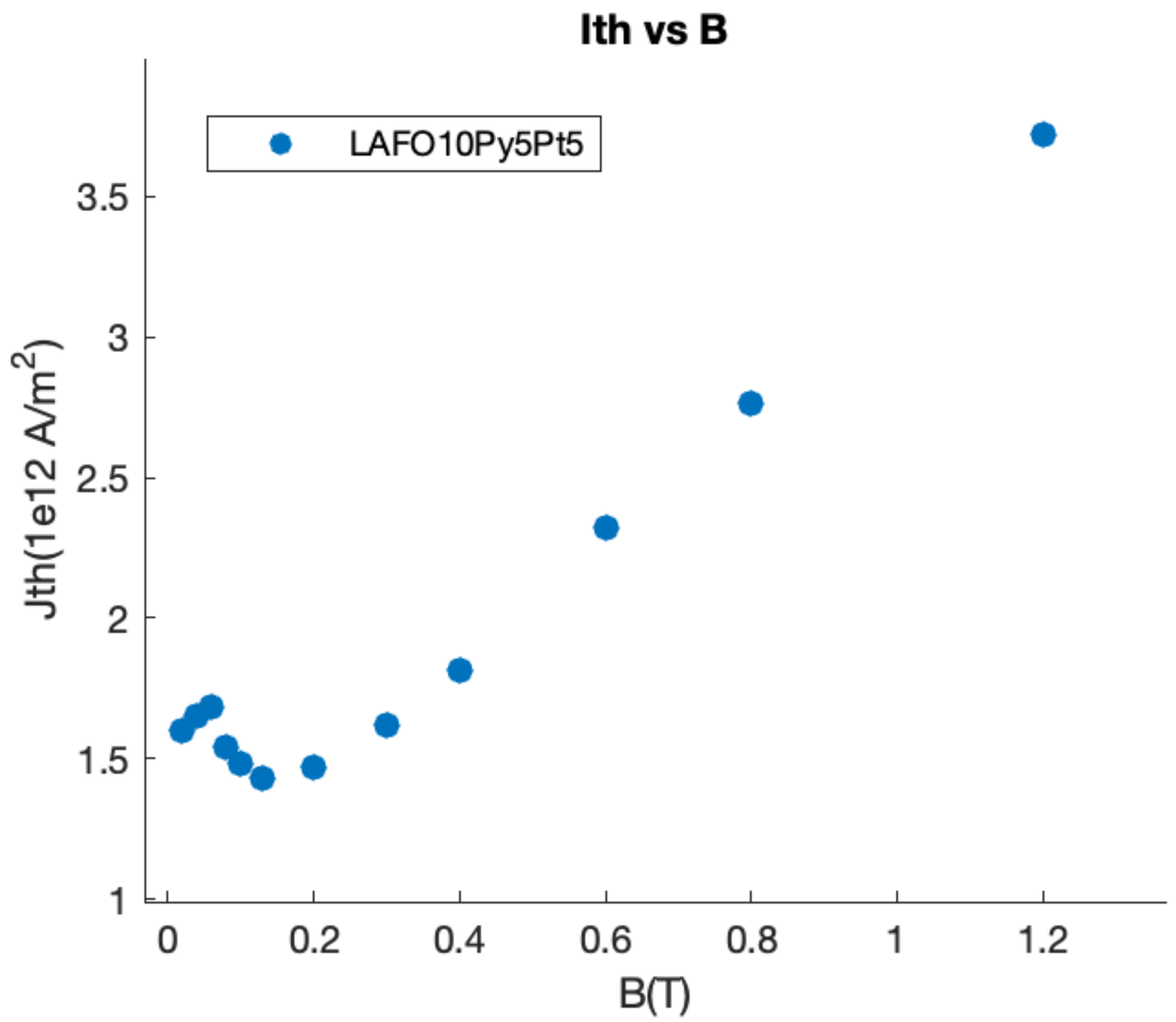
Saturated?

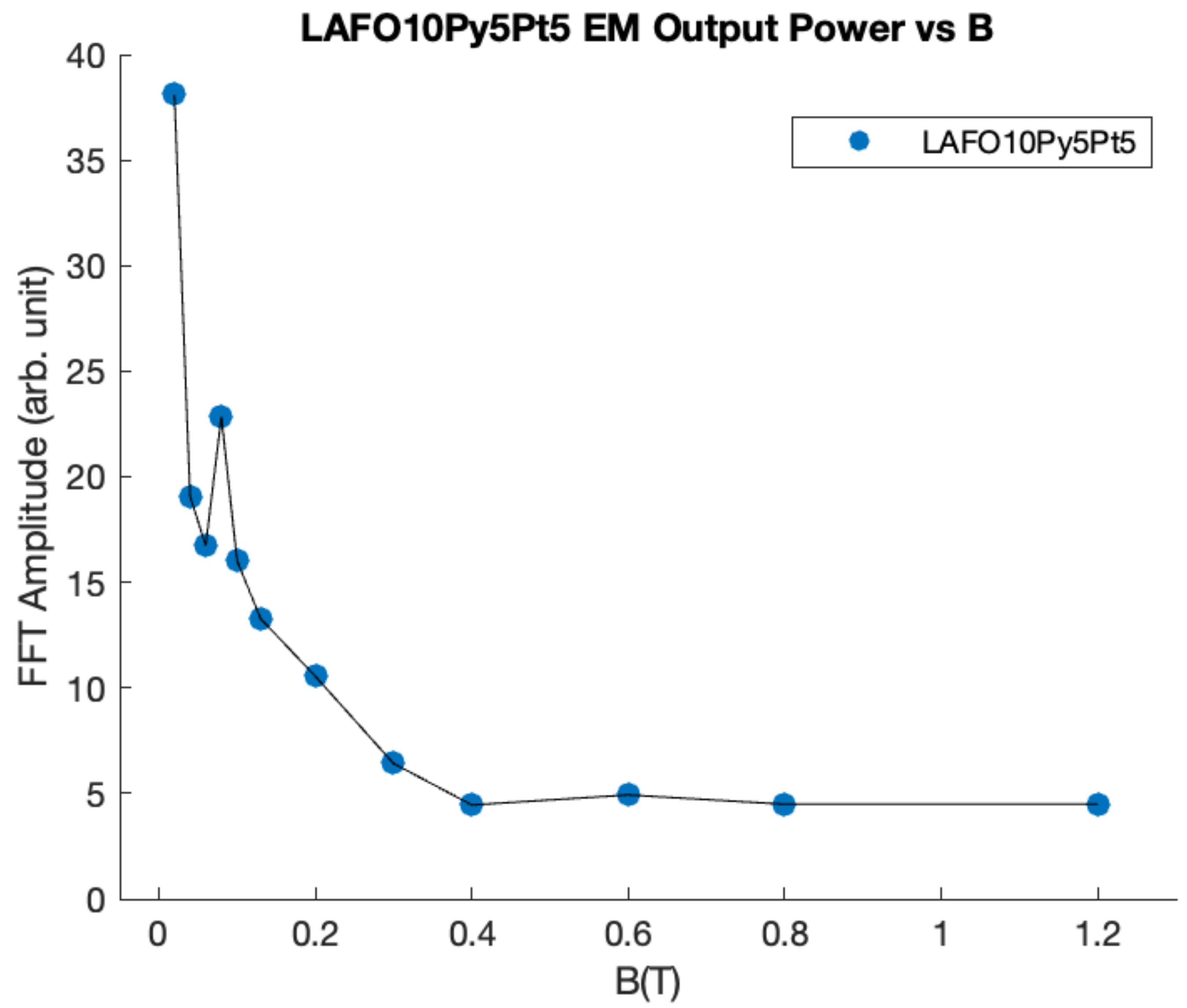
I_{th} for LAFOx/Py5/Pt5 with different LAFO thickness at three different external field strength, LAFO $\mu_0 M_s = 0.0942T$, $\alpha_{LAFO} = 10^{-3}$, $Ku_1 = -3.17 \times 10^4 J/m^3$.

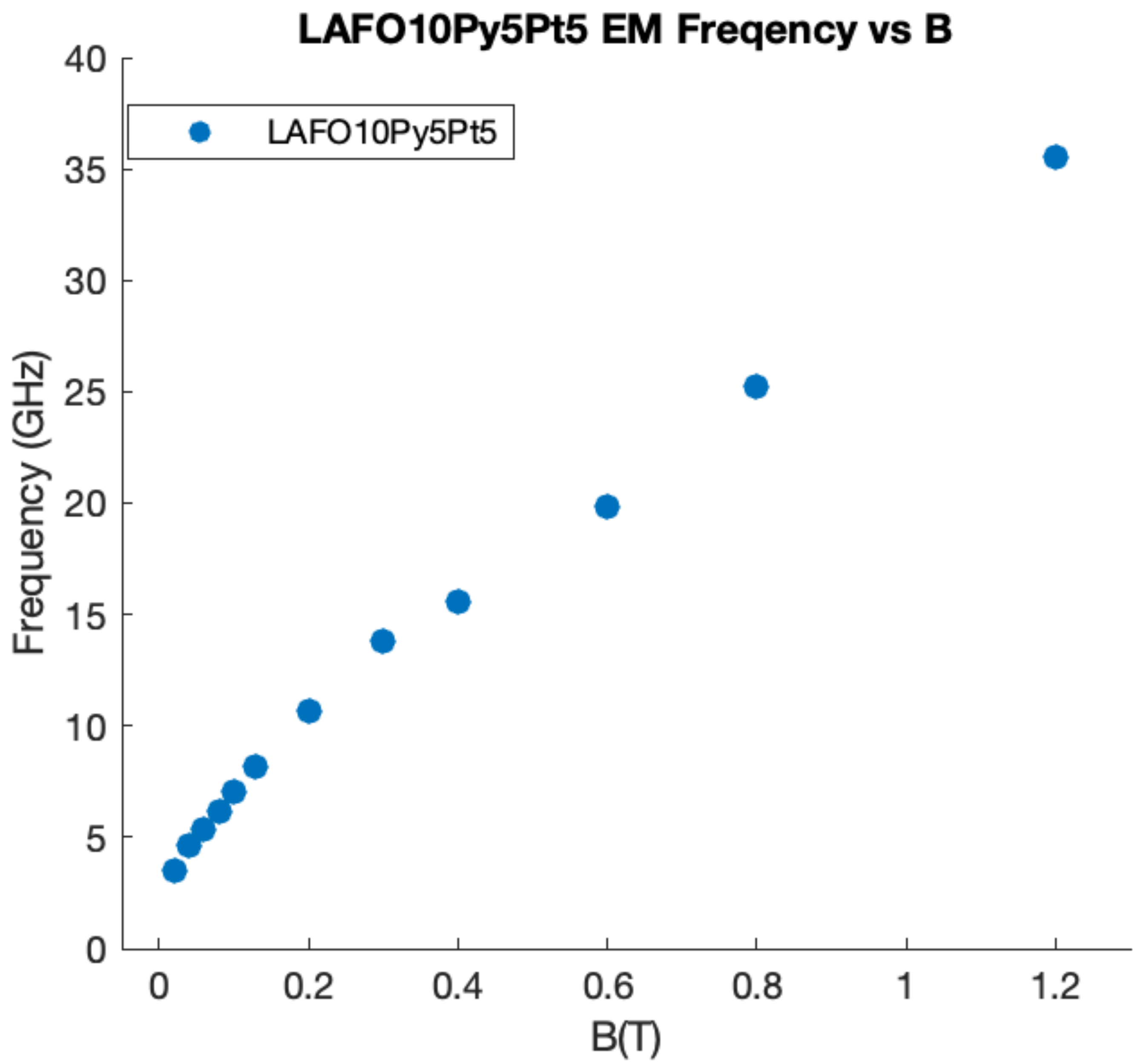
I_{th} & EM at $1.2I_{th}$ vs External Field B

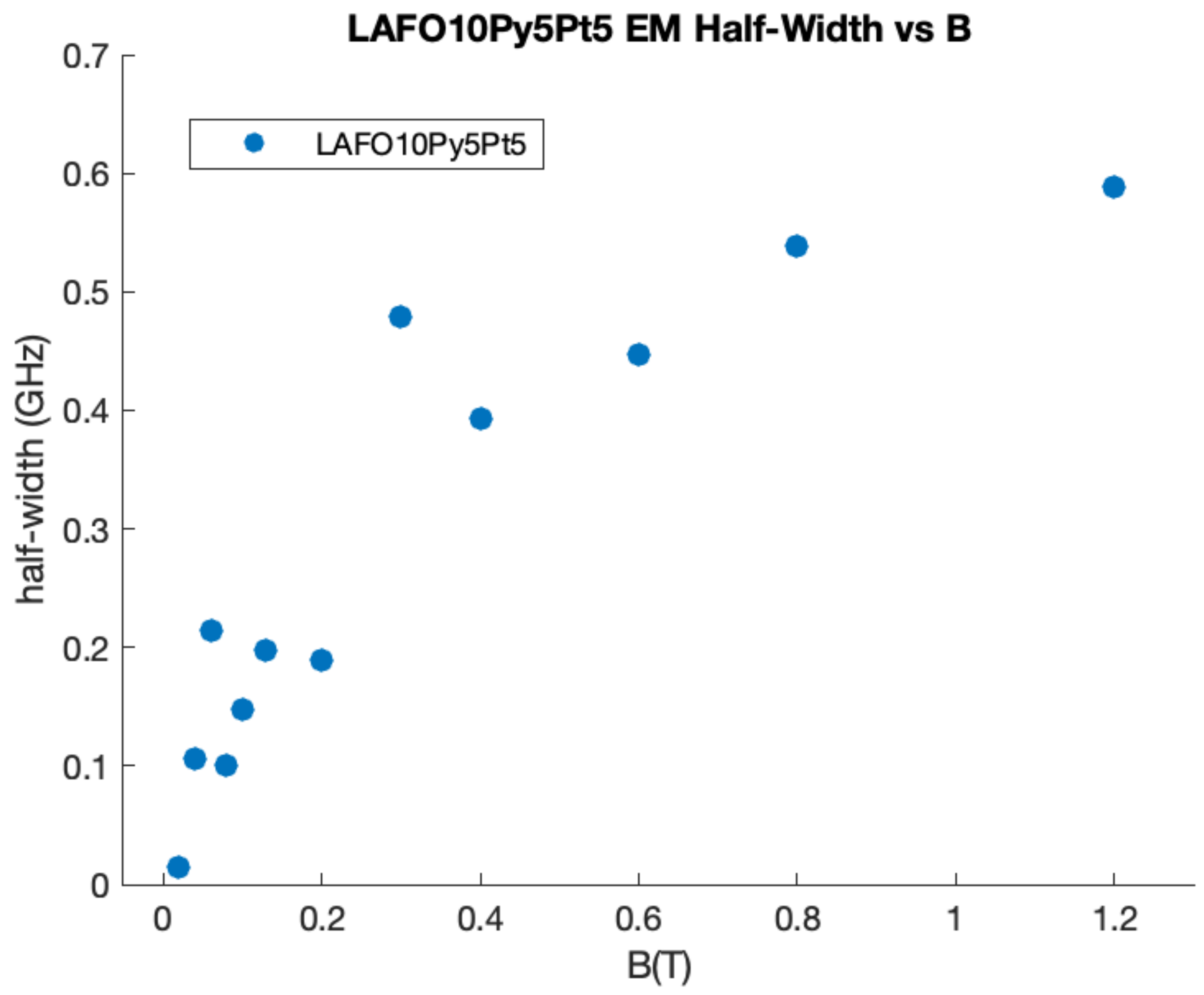
Keep the following constant:

- LAFO thickness 10nm
- $\alpha_{LAFO} = 10^{-3}$
- $\alpha_{Py} = 2.6 \times 10^{-2}$
- $\mu_0 M_{eff,LAFO} = 0.94T$
- $\mu_0 M_s = 0.0942T$
- $Ku_1 = -2 \times 10^4 J/m^3$
- H_{ext} applied at 70°





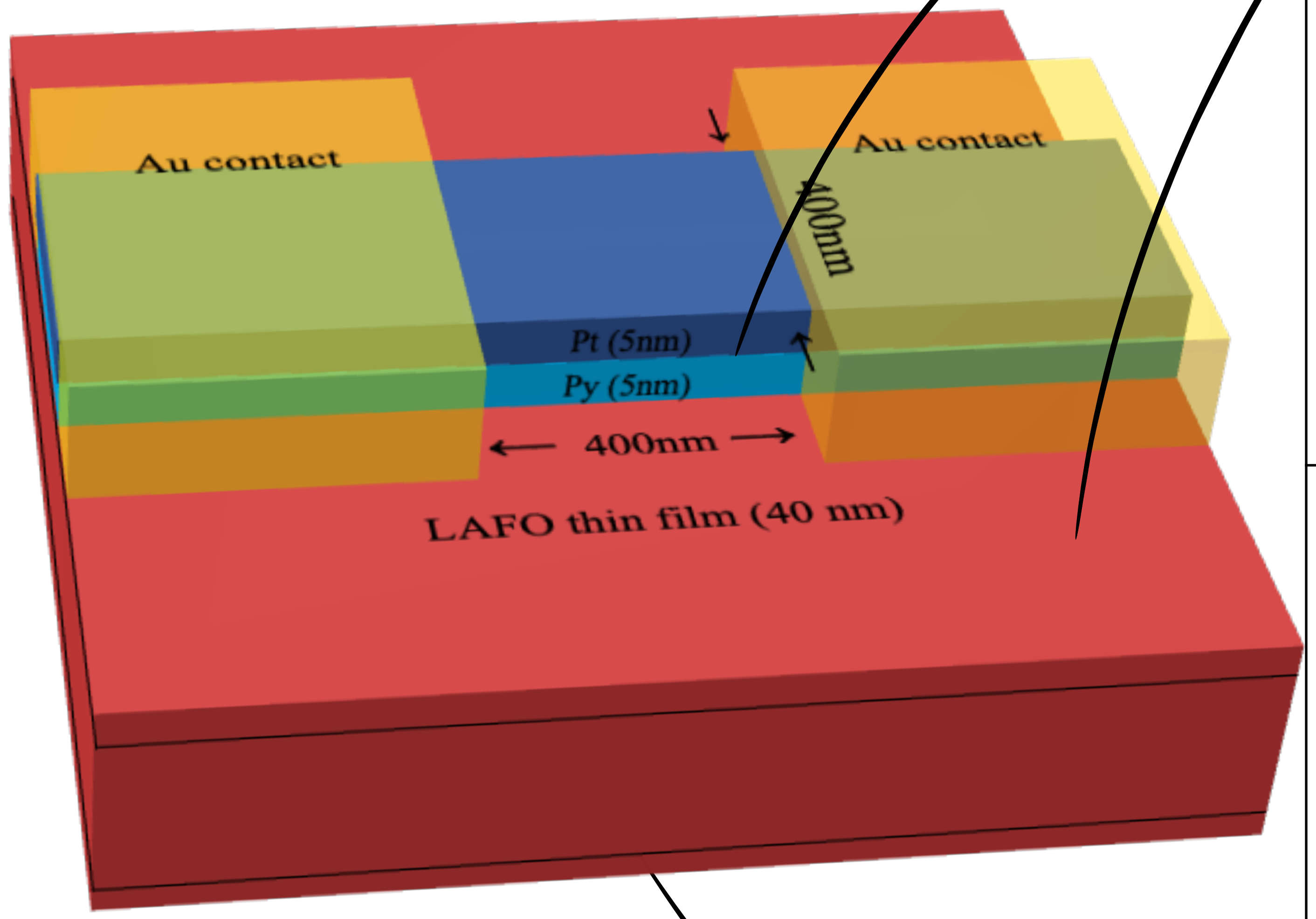


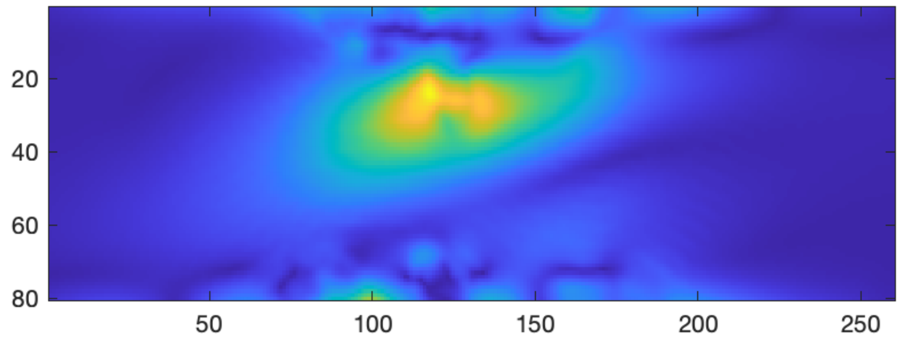
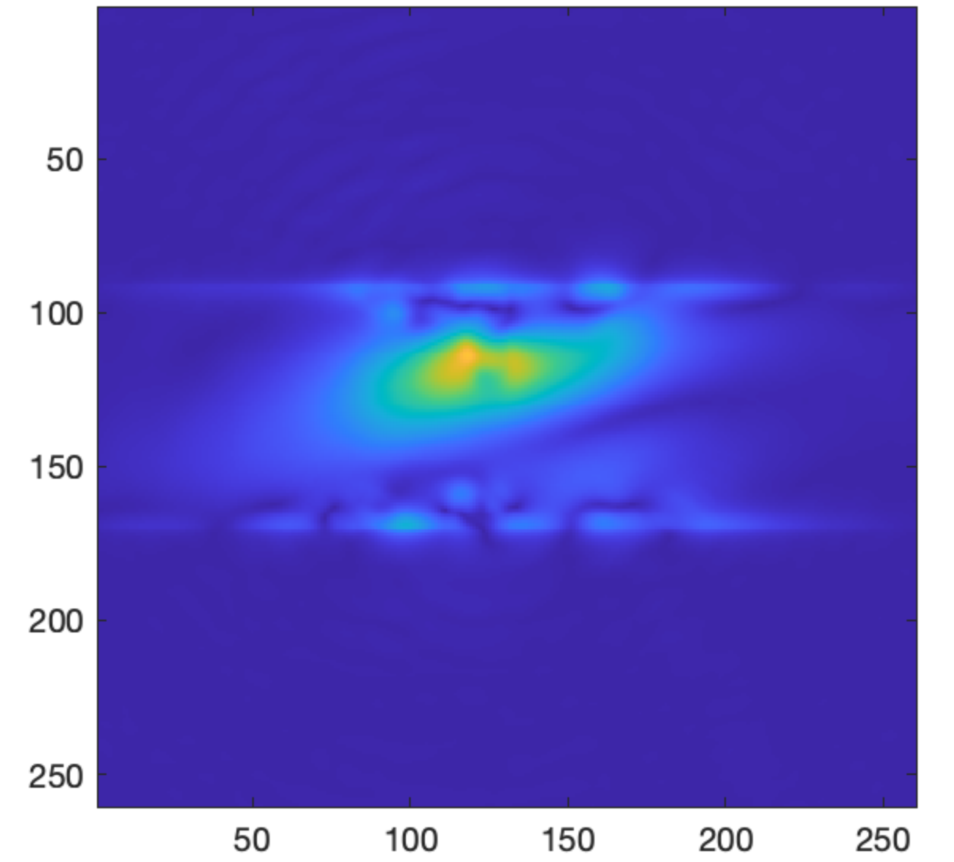
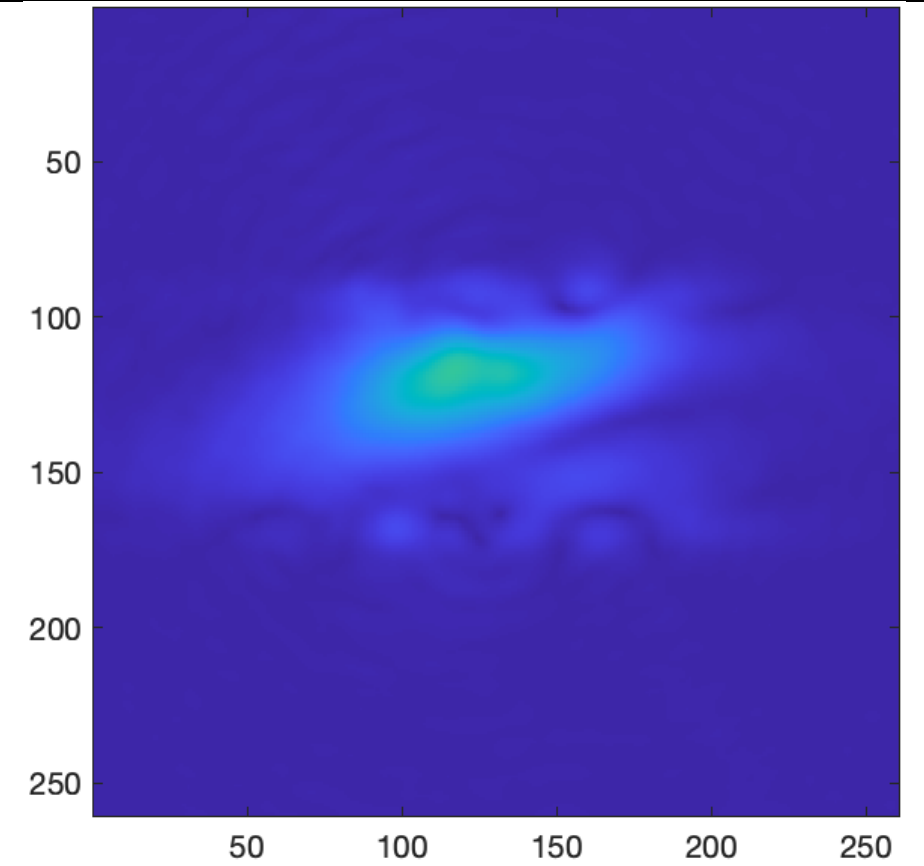
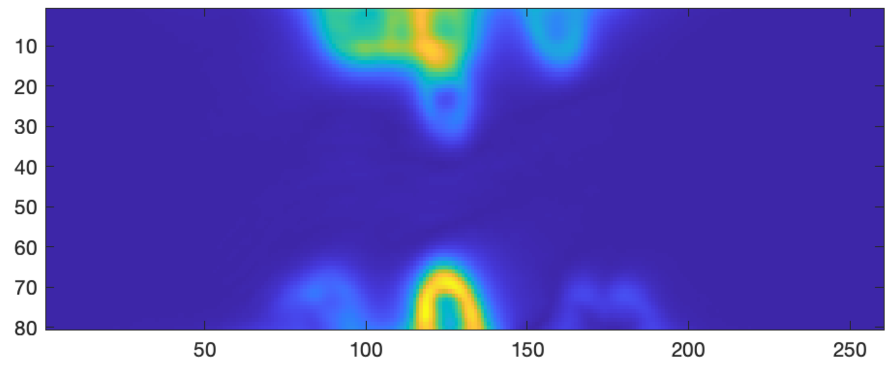
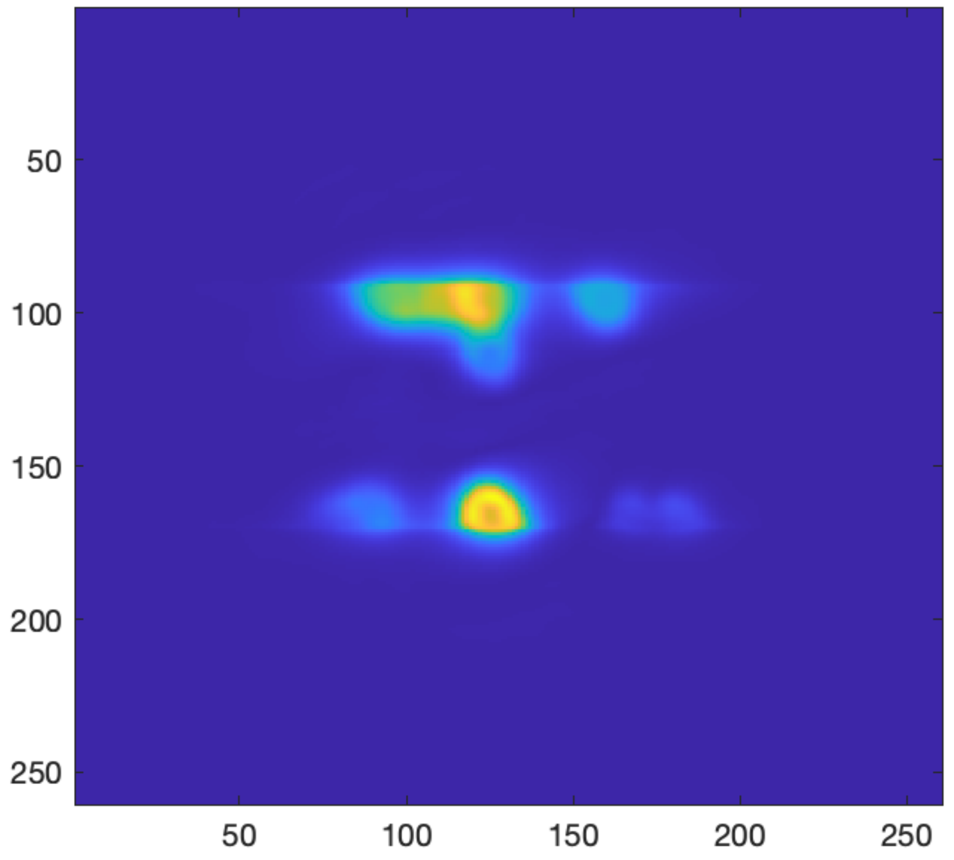
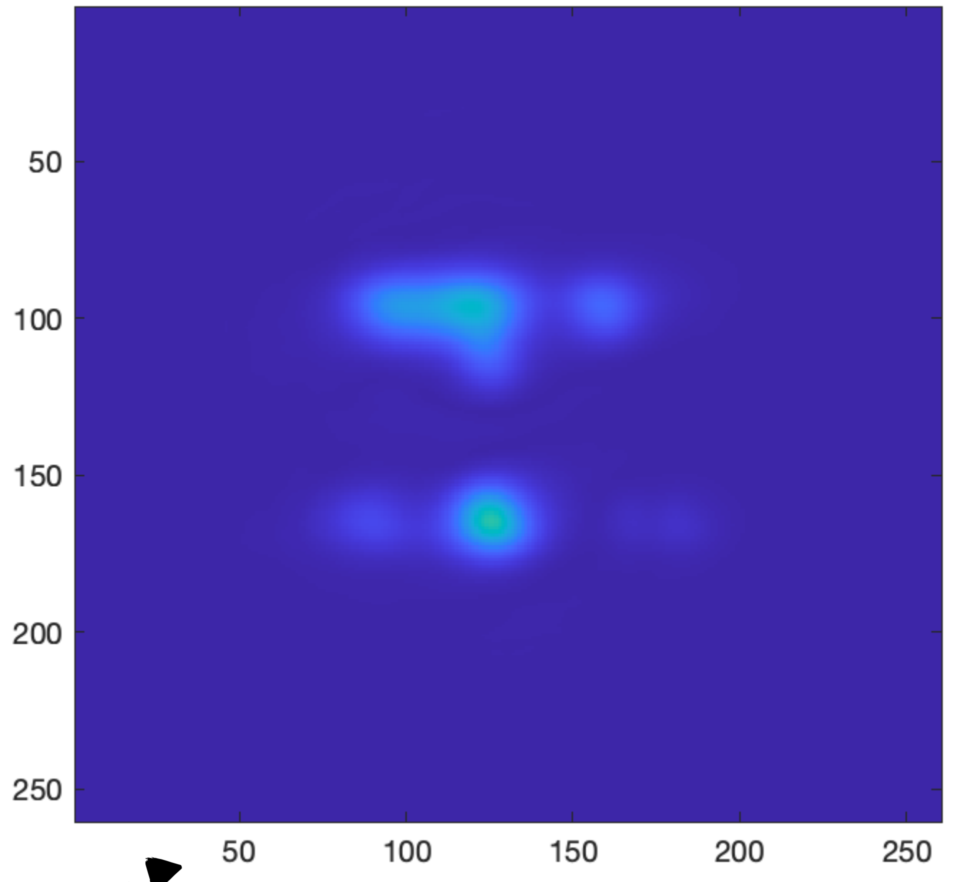


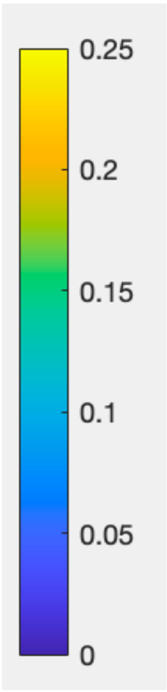
Micromagnetic Simulation (MuMax3)

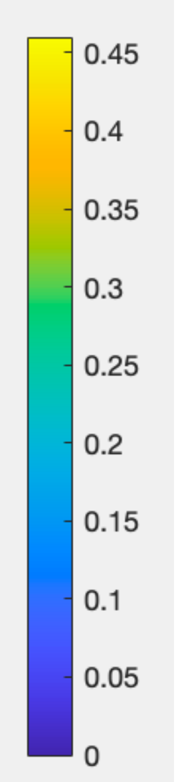
Spin Wave Propagation

LAFO40/Py5/Pt5, at 1.2 times I_{th}



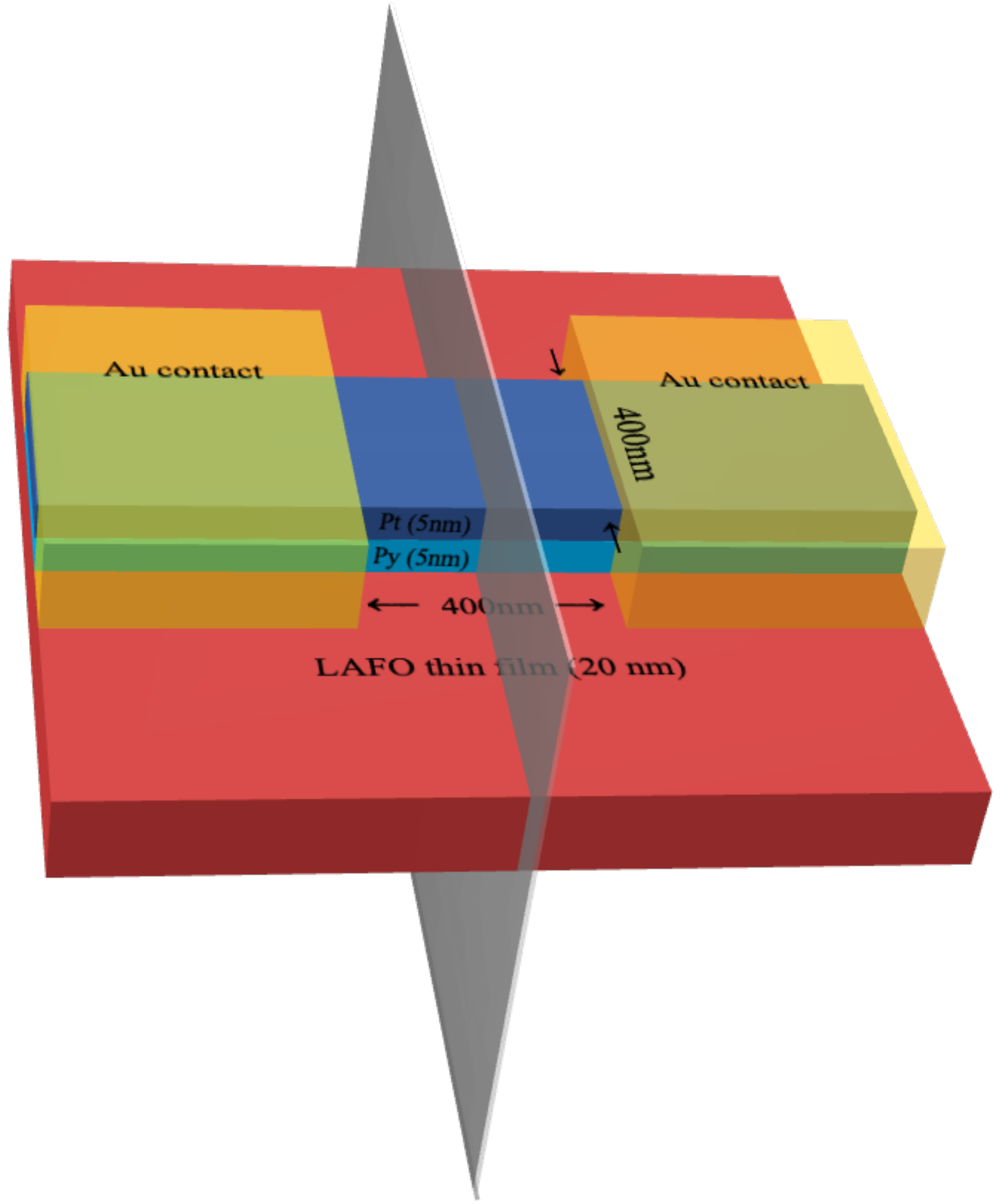
	Py layer (5nm)	Top LAFO Layer (5nm)	Bottom LAFO Layer (5nm)
BM (25.4 GHz)			
EM (21.7 GHZ)			

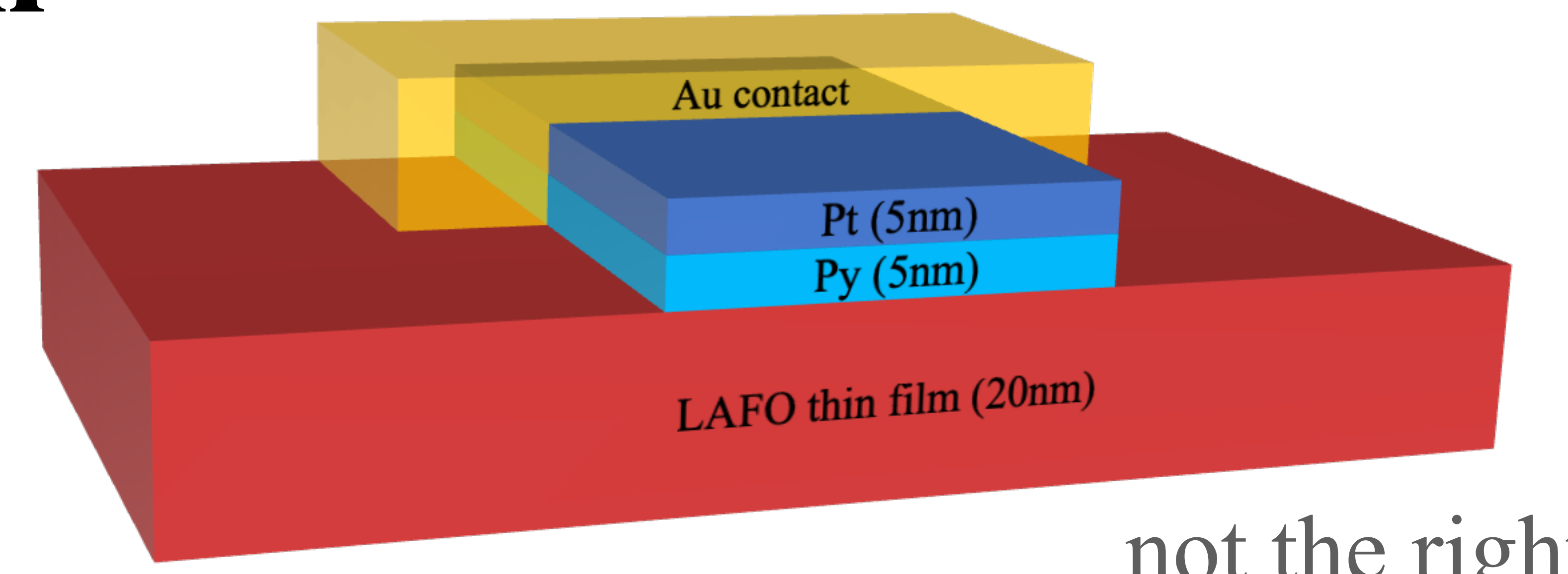




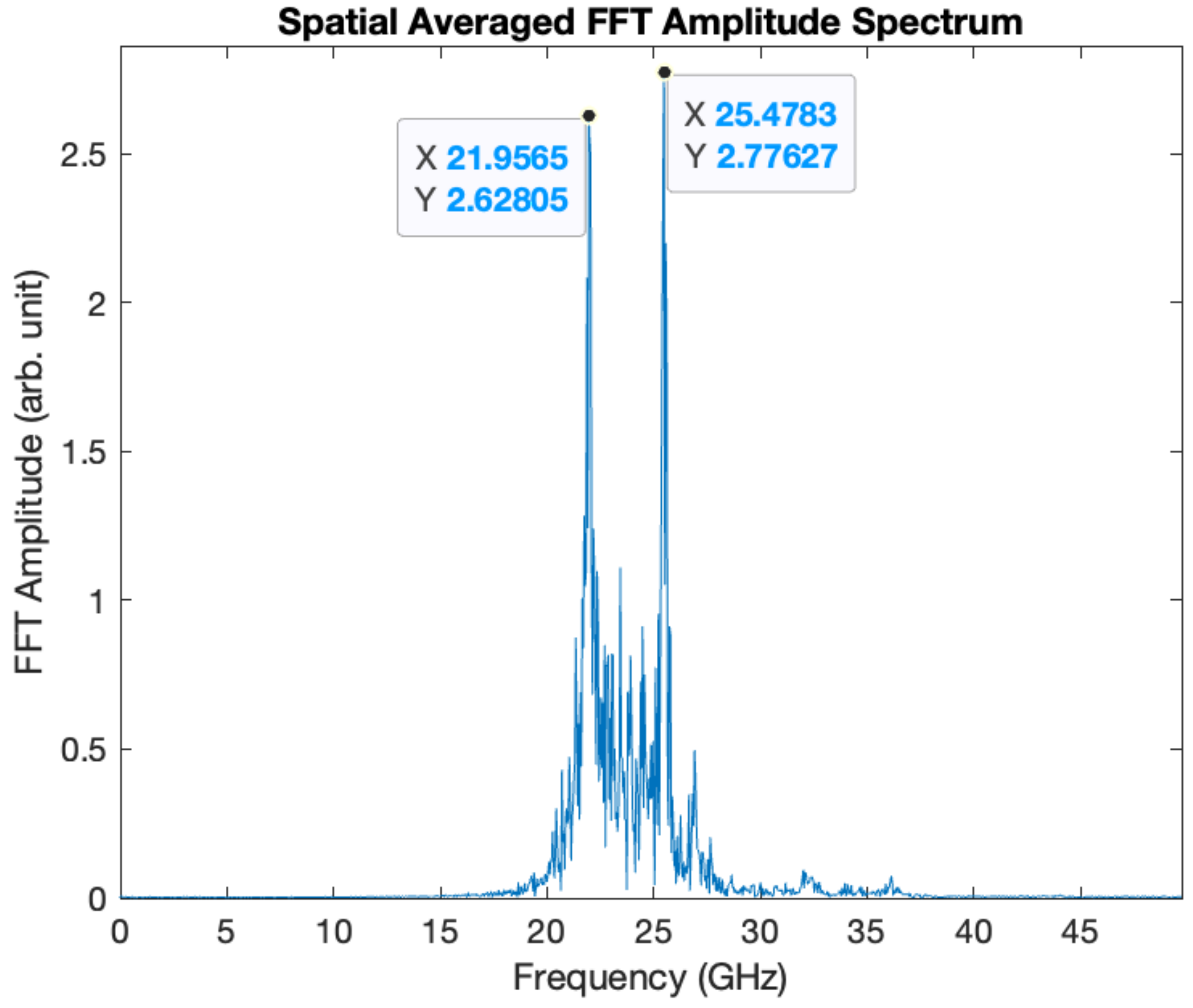
Micromagnetic Simulation (MuMax3)

Spin Wave Propagation



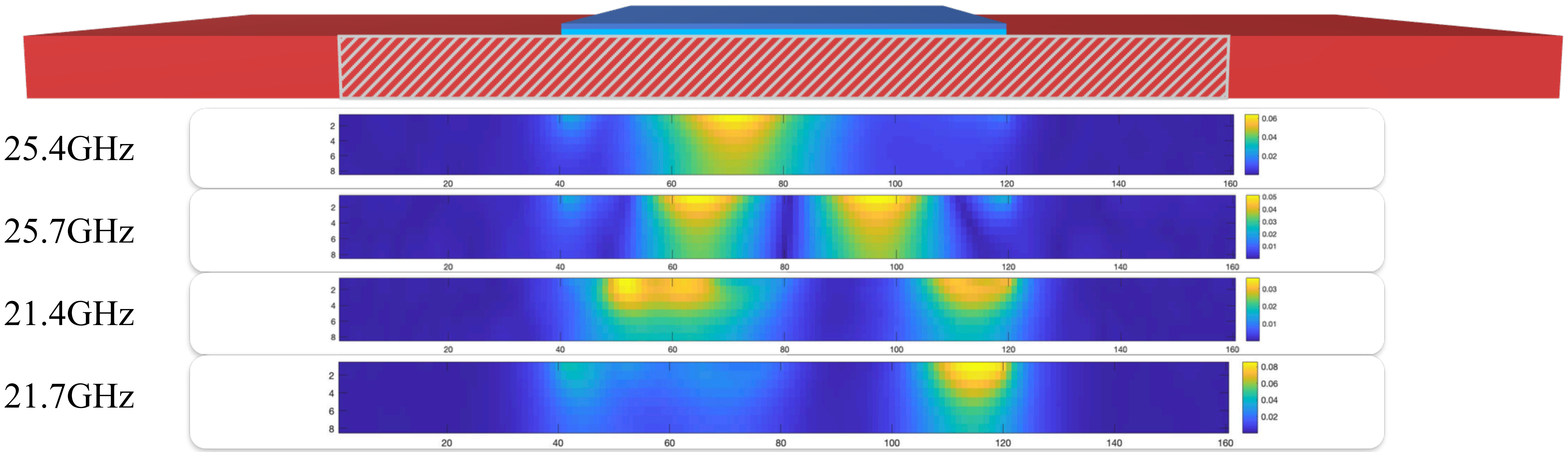


not the right scale



Cross-section FFT

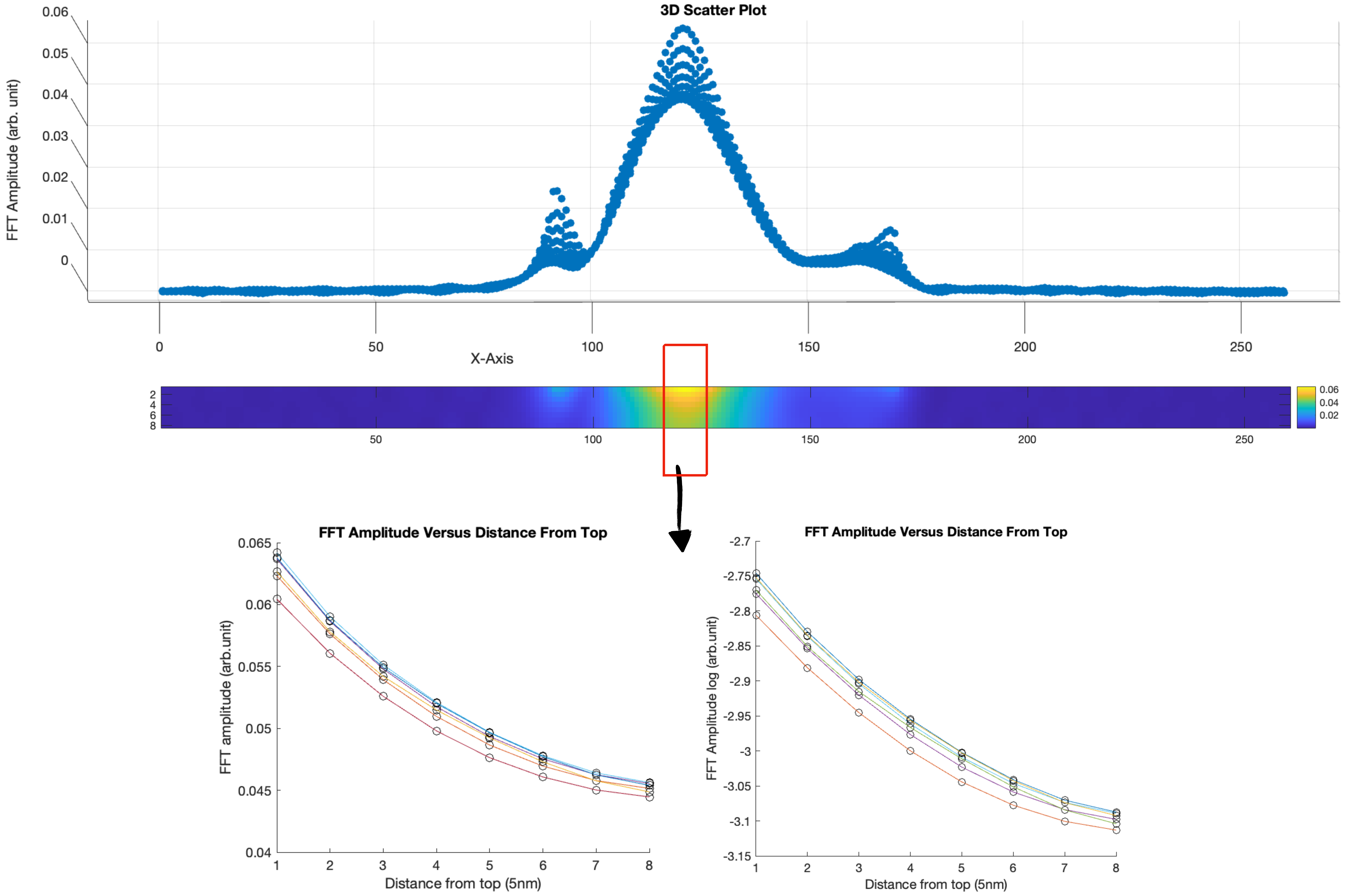
“correct” scale for LAFO40/Py5/Pt5

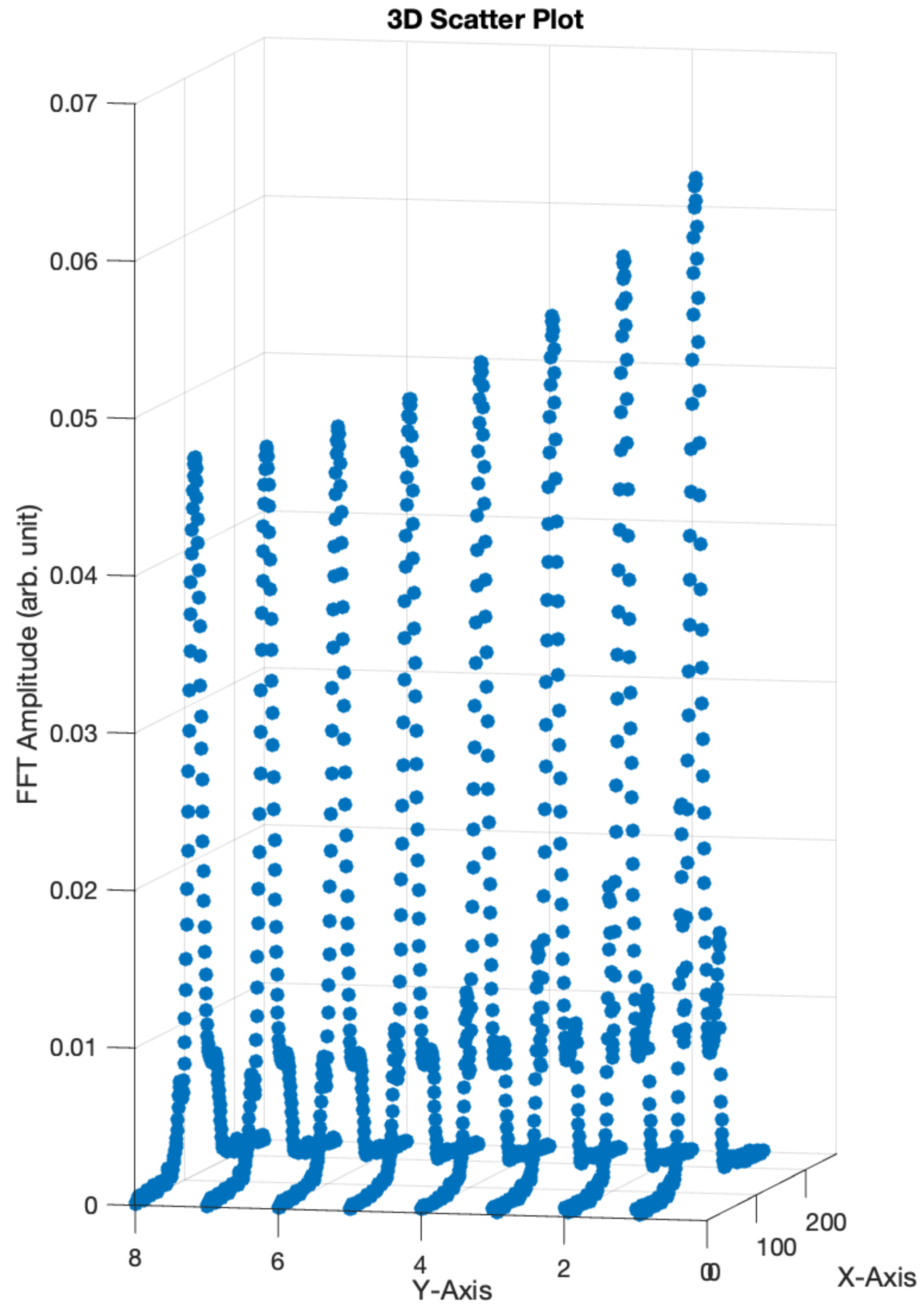


LAFO40/Py5/Pt5, cross-section spatial FFT image at four different frequencies.

Micromagnetic Simulation (MuMax3)

Spin Wave Propagation

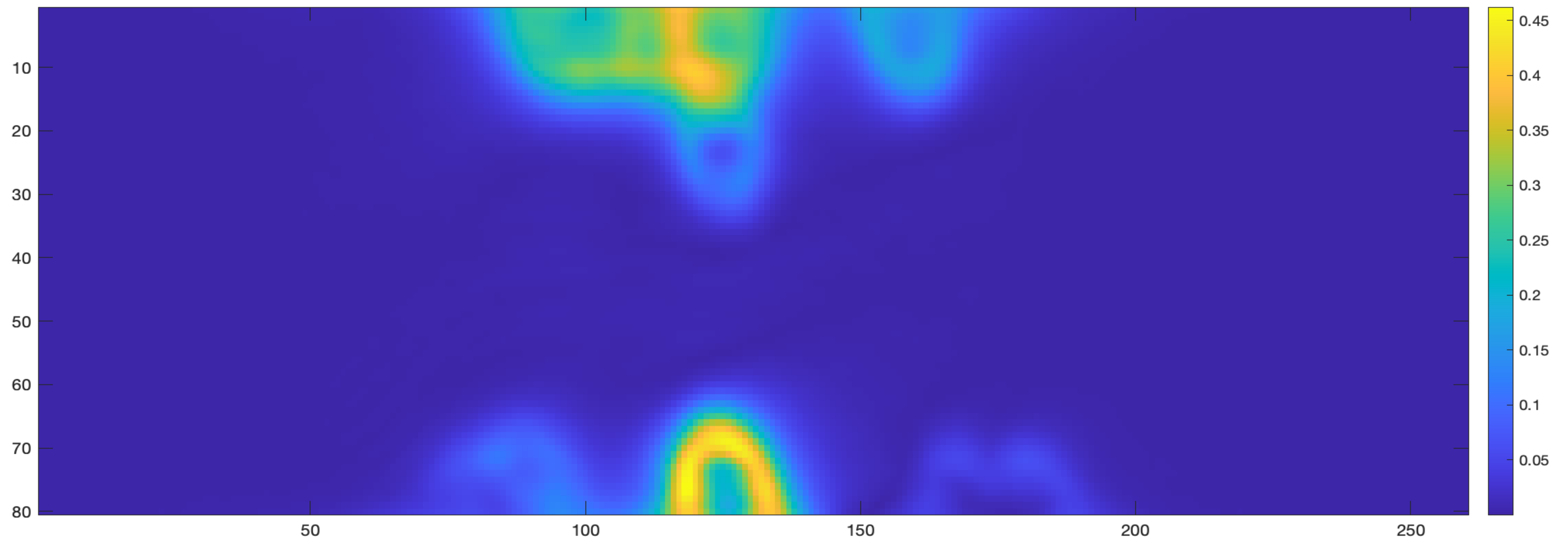




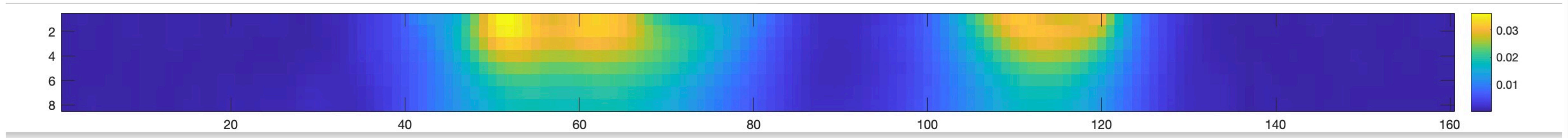
Micromagnetic Simulation (MuMax3)

Spin Wave Propagation — an interesting observation

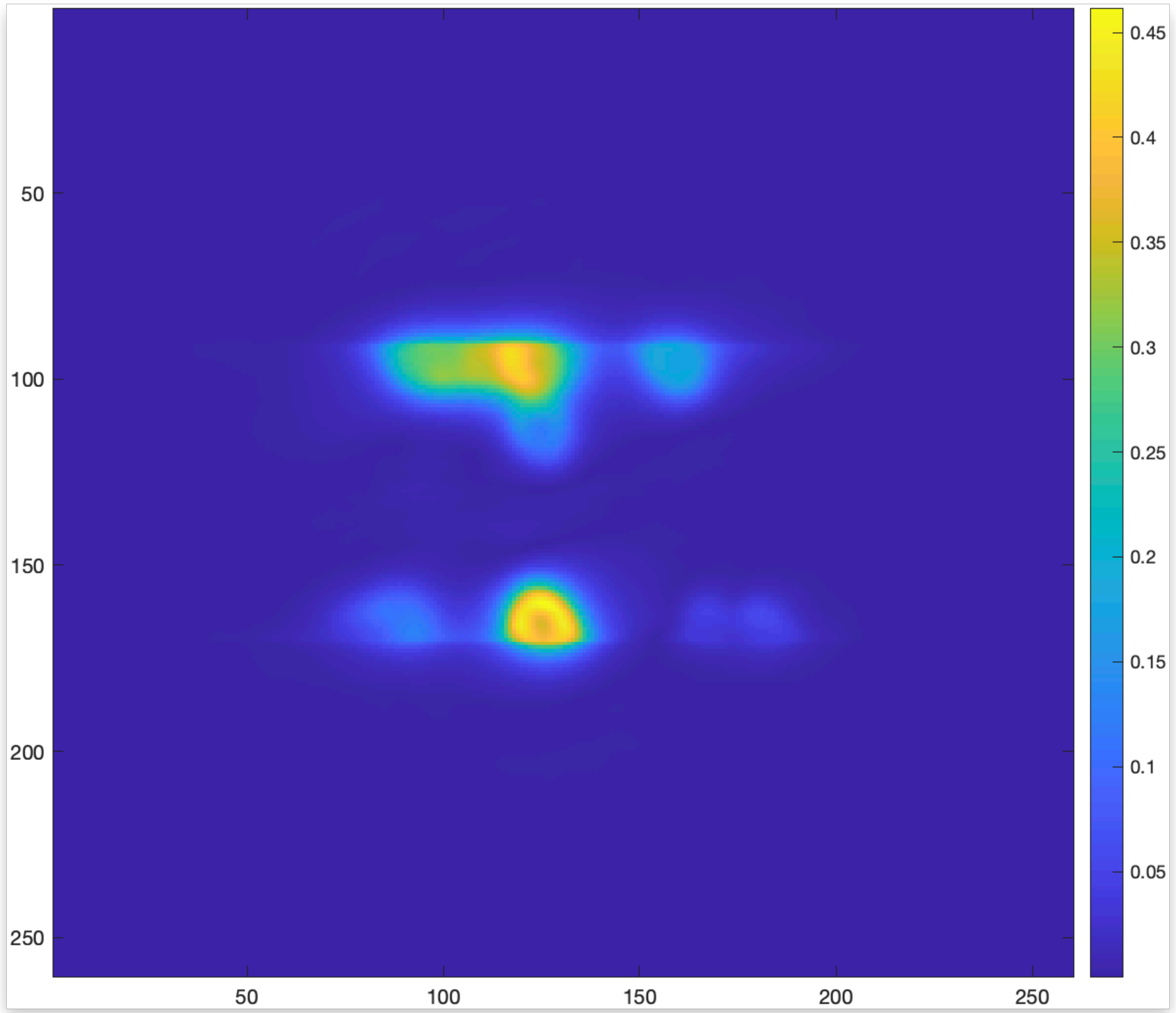
Hemisphere shape (only occur at higher LAFO thickness, 40nm in this case)



Top View of Py



Cross Section View of LAFO



Top Down View of LAFO