

Interfacial Control of Spin-Wave Dynamics in Magnetic Heterostructures

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CMCL members:

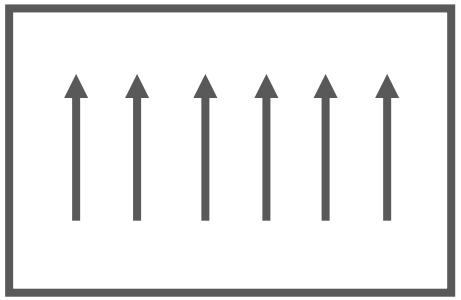
- Ms. Riya Mehta (PhD student)
- Ms. Archana (PhD student)
- Ms. Tanya Sarma (PhD student)
- Ms. Naintara (PhD student)
- Mr. Ishaan Parsad (UG)



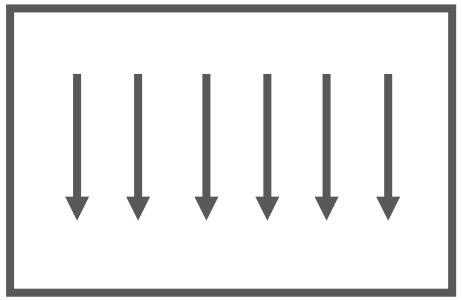


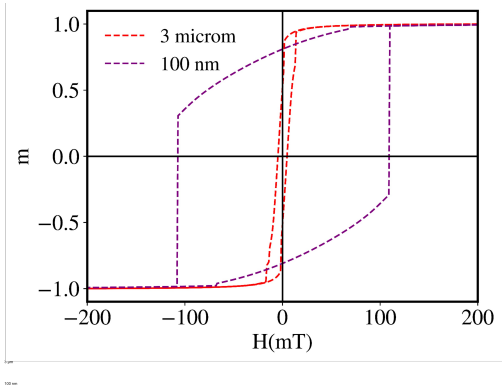
Today's Magnetic Hard Disc

State : 1



State : 0





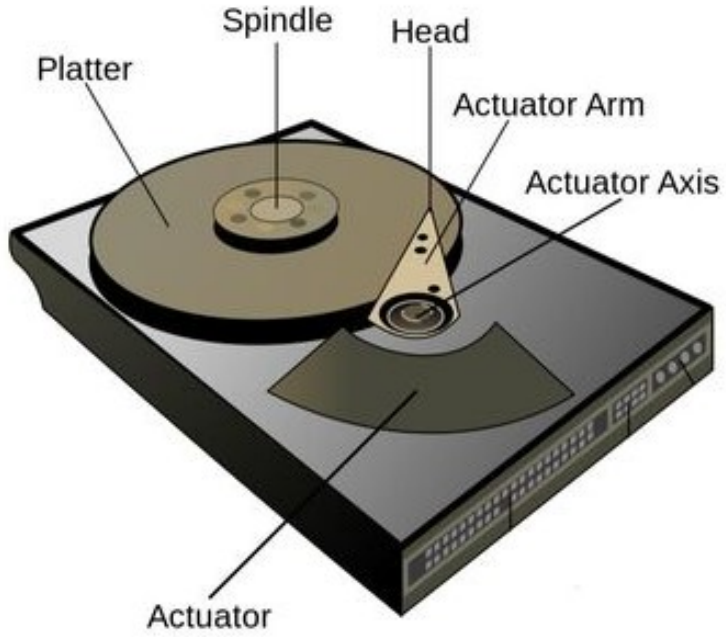


3 micron

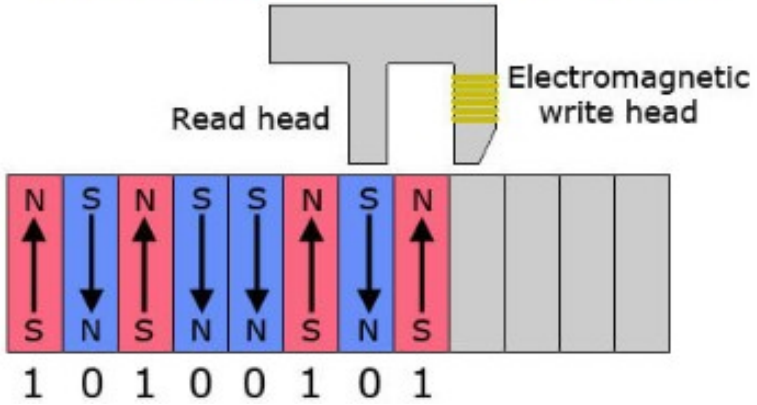


100 nm

$K_U V >> K_B T$

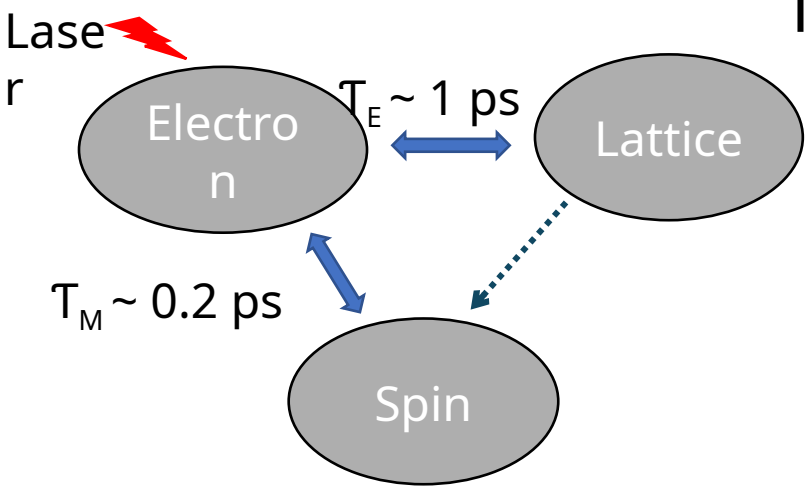


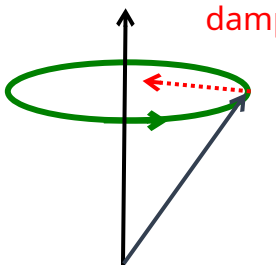
Hard drive read/write head

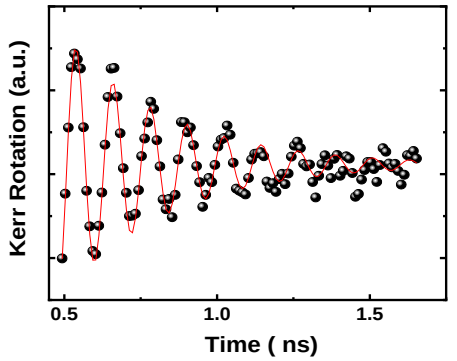


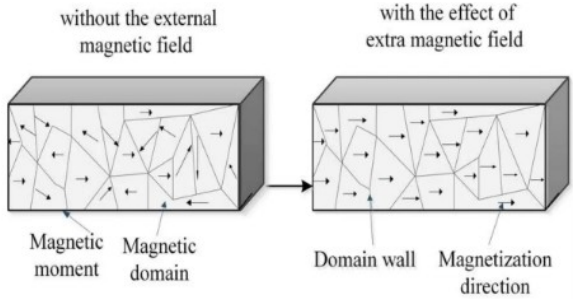
It is a non-volatile and non-destructive read out memory, which is based on a magnetic anisotropy energy to retain information and the principle of magnetoresistance to retrieve information

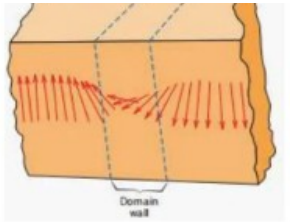
Time Scale of Magnetization







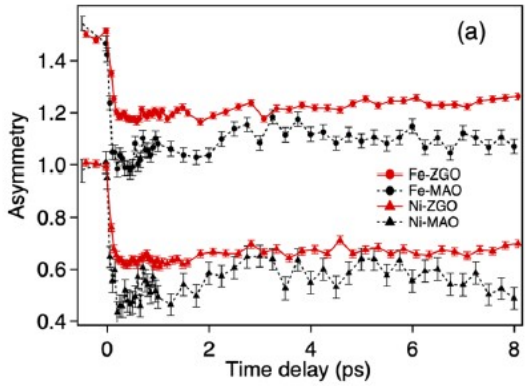




Femto ps ns ms

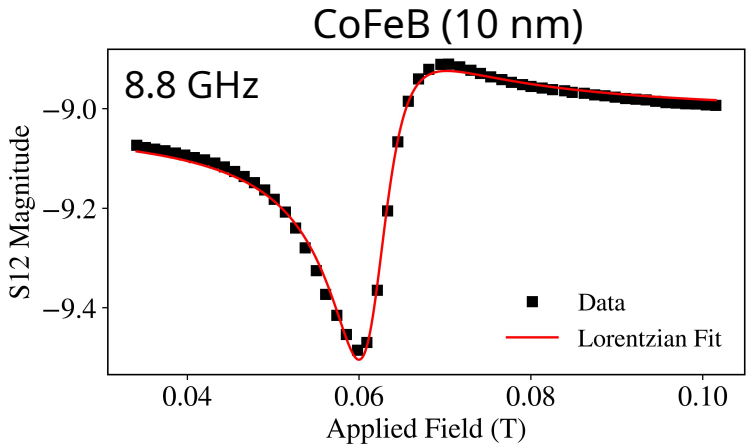
Timescale of magnetization dynamics

Ultrafast dynamics

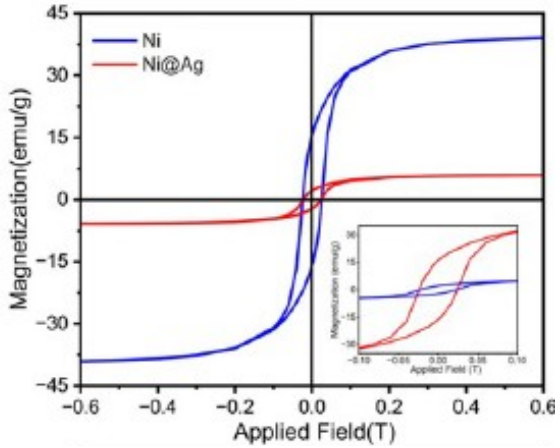


S. Saha et. al. Appl. Phys. Lett. 127, 222406 (2025)

Spinwave dynamics



Hysteresis phenomena



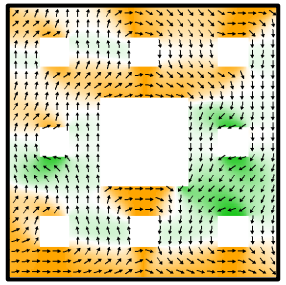
Archana et. al. J. Phys. D: Appl. Phys. 59 25500 (2026)

Research Overview – CMCL, Ashoka University

Simulation

Magnetic Fractals





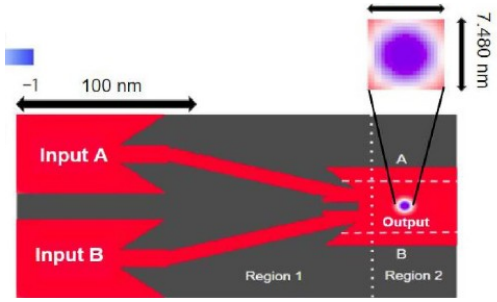
Riya Mehta and Susmita Saha, Phys. Rev. Applied **24**, 054034 (2025)

R. Mehta, et. al J. Phys.: Condens. Matter 36, 443003 (2024)

R. Mehta, et. al J. Phys.: Condens. Matter 35, 324002 , (2023)

J. Zhou, et. al Phys. Rev. B 105, 174415 (2022)

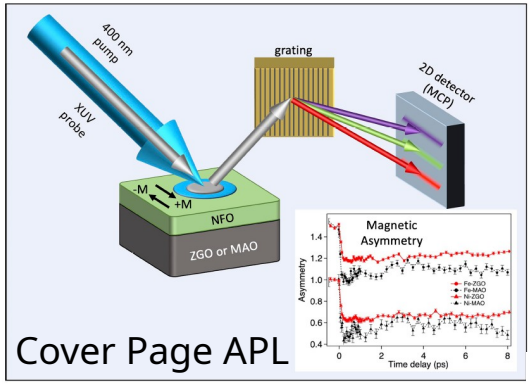
Magnetic Skyrmions



S. Wats and S. Saha, Journal of Physics D: Applied Physics 57, 245001 (2024)

Experiment

Time domain magnetization dynamics



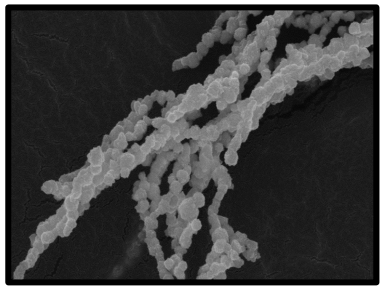
Cover Page APL

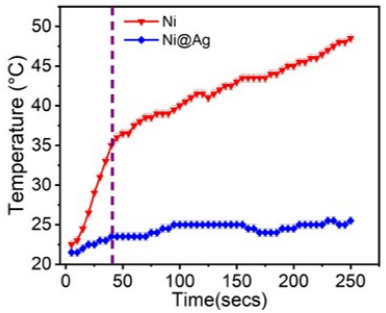
R. Gupta et al. Phys. Rev. B 108,064427 (2023)

S. Saha et. al. Appl. Phys. Lett. 127, 222406 (2025)

S. Saha et. al. J. Vac. Sci. Technol. A 42, 012702 (2024)

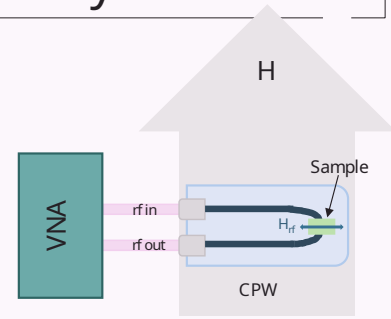
Applications of nanomagnet in bioscience and energy



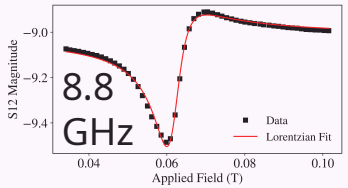


Archana et. al. J. Phys. D: Appl. Phys. 59 25500 (2026)

Frequency domain magnetization dynamics

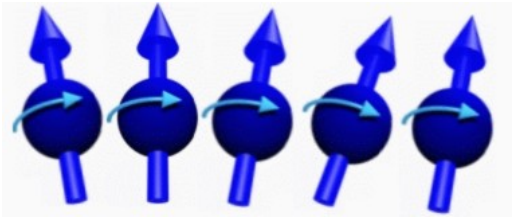


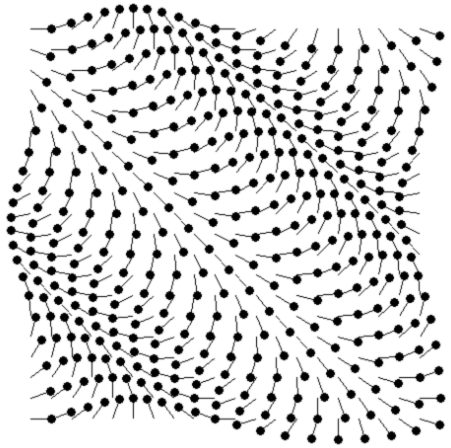
CoFeB (10 nm)



Spinwaves

Excitation



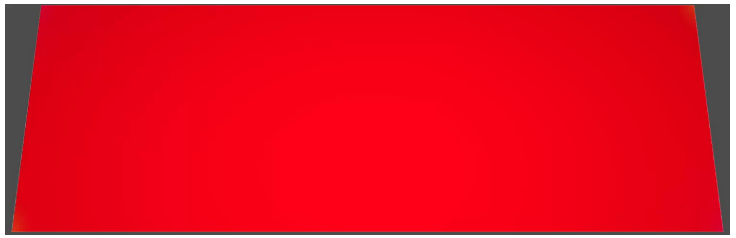


Advantage of spinwaves:

- Wavelength is much shorter than light waves operating at the same frequency range : **Device miniaturization**
- As no charge flows : **Joule heating free**
- **External control** by varying geometrical of physical parameters like magnetic field, lattice constant etc.

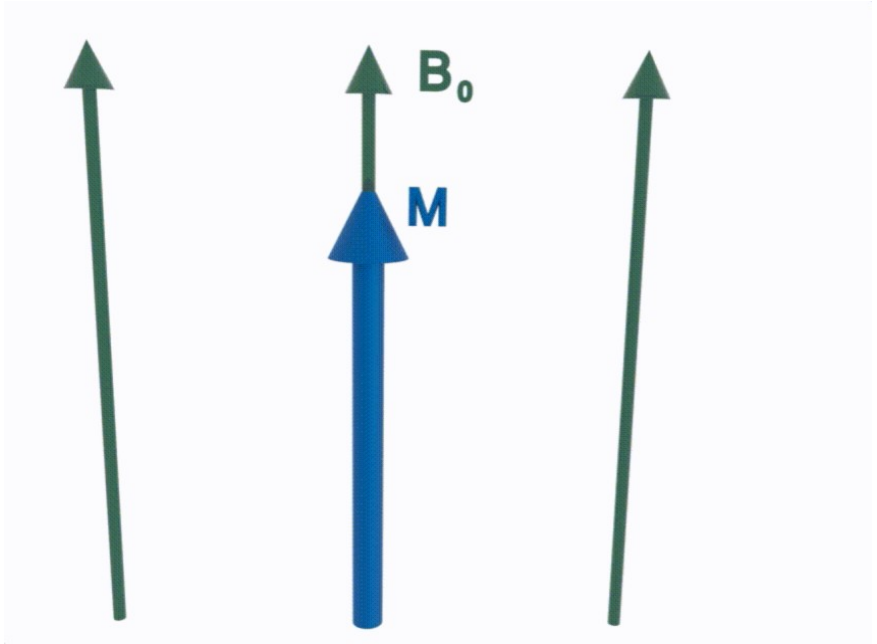
Application of Spinwave

Excite spinwaves by using optical (Laser) or electrical excitation



Detected the spinwaves in time scale (**femtosecond to nanosecond**) or in frequency scale (**GHz to THz**)

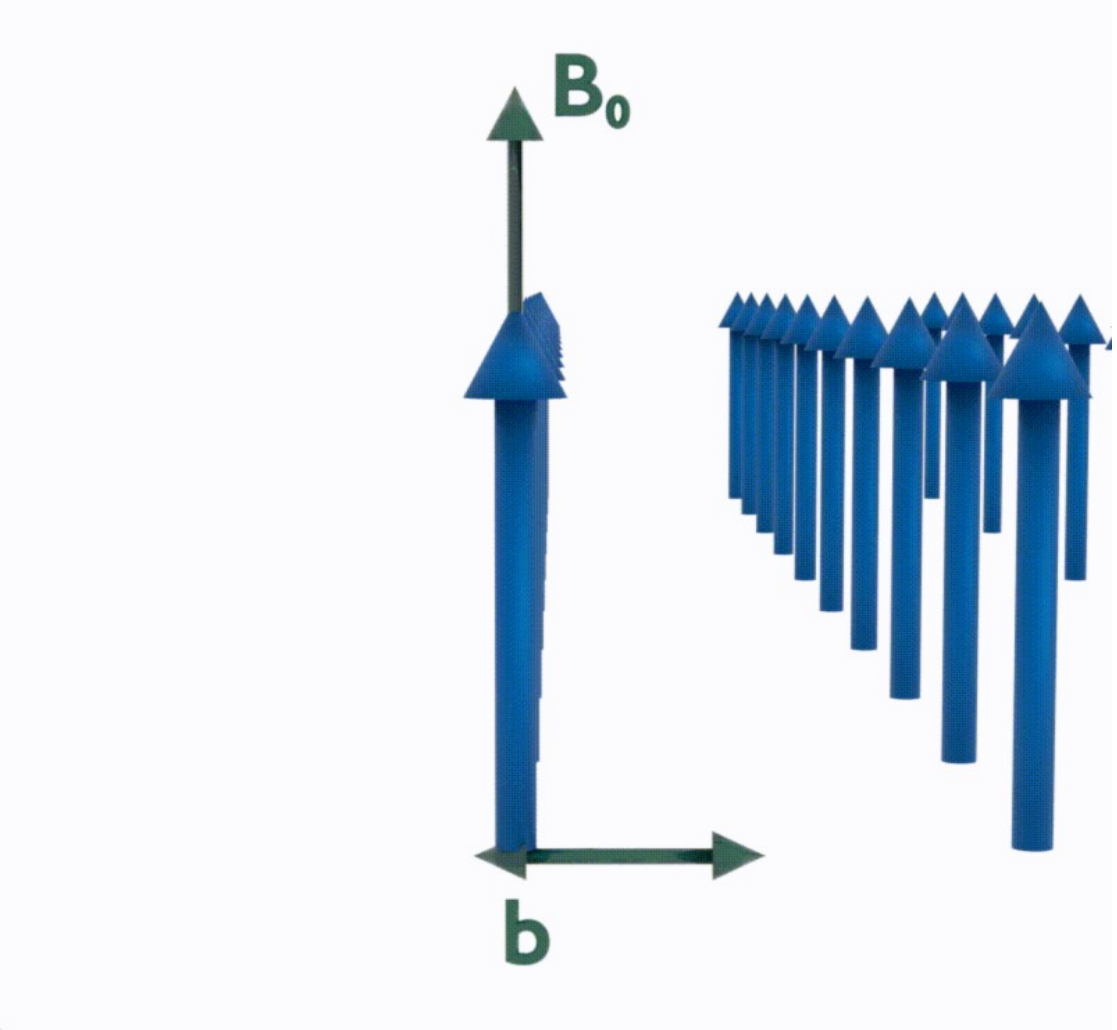
Spinwave and LLG equation



Gilbert Damping

$$\frac{dM}{dt} = -\gamma M \times B_{eff} + \frac{\alpha}{|M|}\left(M \times \frac{dM}{dt}\right)$$

Gyromagnetic ratio



Credit: Dr. D. Bozhko

Giant Magneto Resistance (GMR)

Giant Magnetoresistance (GMR) : *Resistance depends on spin alignment*

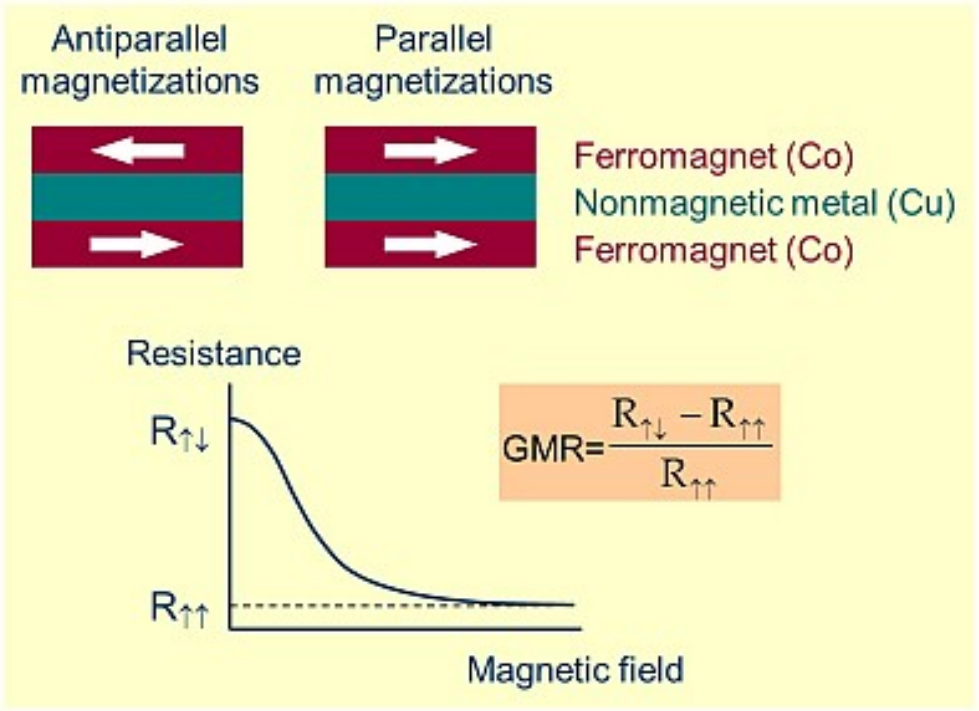
Nobel Prize in 2007



Peter Grünberg



Albert Fert



It occurs in thin layered structures made of alternating ferromagnetic and non-magnetic conductive layers (e.g., Fe/Cr multilayers).

- When magnetic layers are parallel, electron scattering is low → low resistance.
- When magnetic layers are antiparallel, scattering is high → high resistance.

Thus, a small magnetic field can produce a large change in resistance.

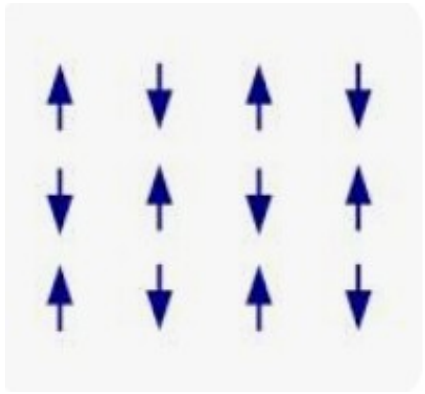
Why It Is Important?

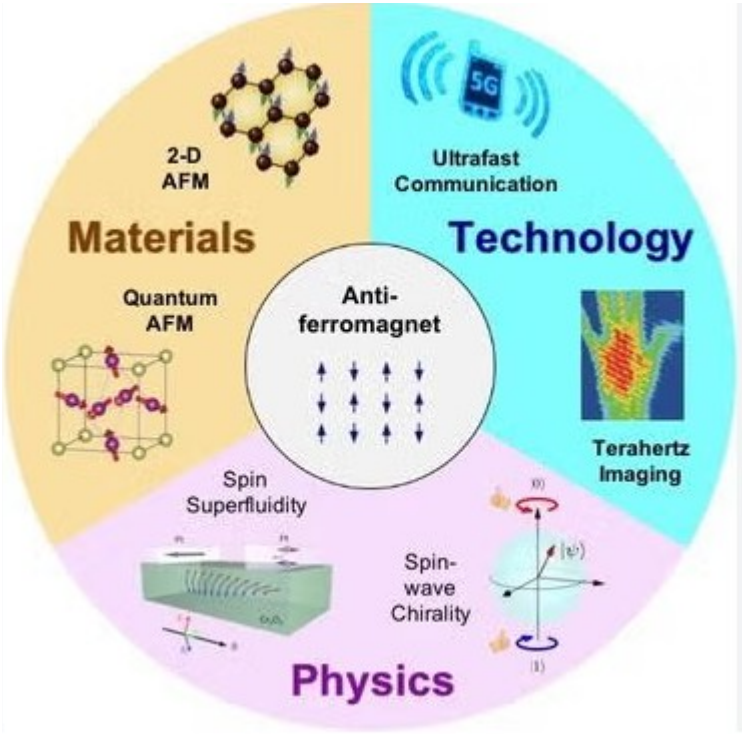
GMR revolutionized data storage technology.

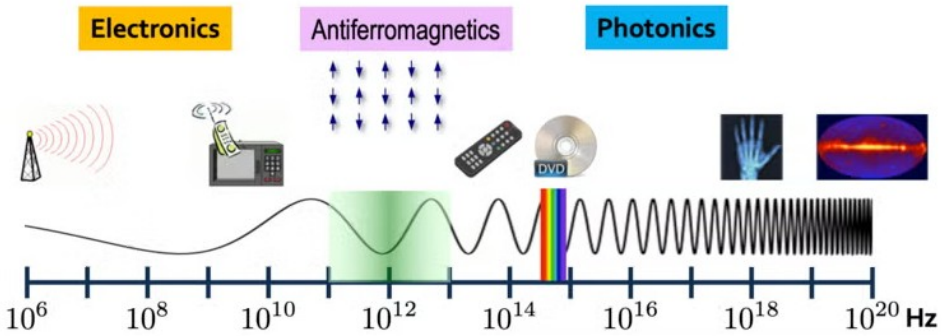
•Used in hard disk read heads

•Enabled massive increase in storage density

Antiferromagnet







Antiferromagnetic Spintronics

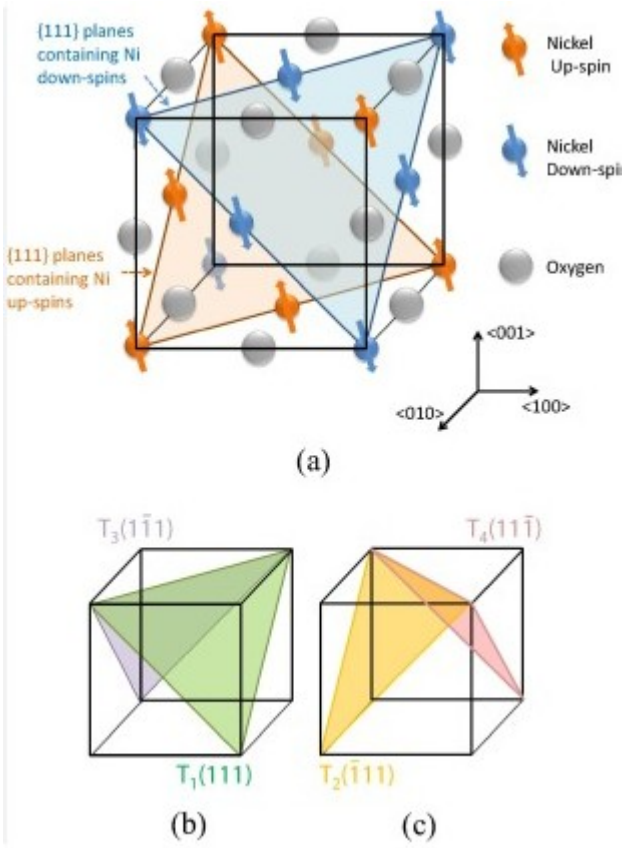
Key Properties of Antiferromagnets:

- **Zero Net Magnetism:** Neighboring spins point exact opposite ways (up and down) and cancel each other out.
- **Néel Temperature :** The critical limit where thermal energy destroys the internal opposite spin pattern, turning the material into a regular paramagnet above this point.
- **External Field Resistance:** Because they lack an outer magnetic footprint, they are robust against outside magnetic disturbances.

Core Advantages

- **No stray fields**: Neighboring tracks do not interfere with each other.
- **High speed**: Switching and spin dynamics operate in the terahertz range.
- **Field safety**: External magnets cannot easily erase stored

CoFeB/NiO (t)/CoFeB : Heterostructure



J. Magn. Magn. Mater, 449, 415-422, (2018)

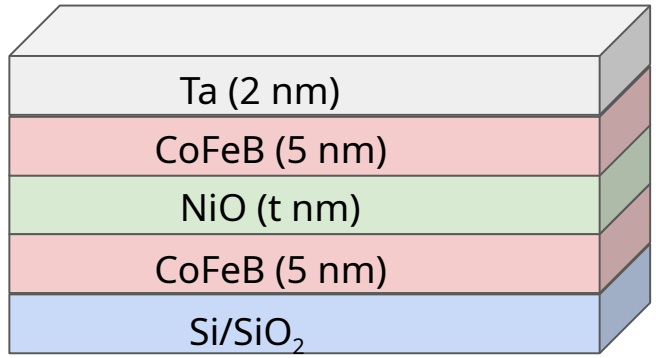
Key Properties of NiO :

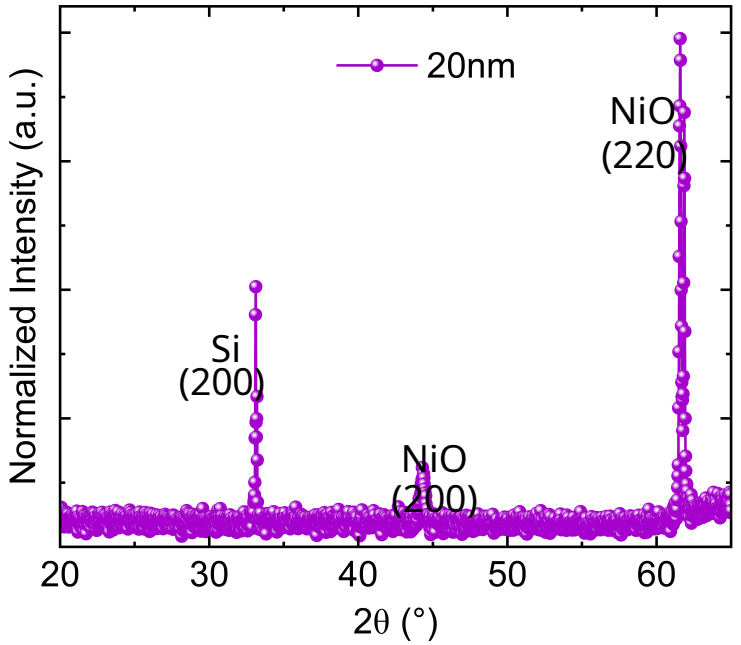
•**Néel Temperature** NiO undergoes a phase transition into an antiferromagnetic ordered state at approximately **523 K to 525 K.**

•**Magnetic Structure:** Within the individual <111> planes of its FCC-like crystal structure, the magnetic moments of adjacent Ni^{2+} ions align ferromagnetically. However, successive <111> planes alternate in opposite directions, cancelling out the net macroscopic magnetization.

•**Superexchange Interaction:** The antiparallel alignment is dictated by strong **180° Ni–O–Ni superexchange interaction**.

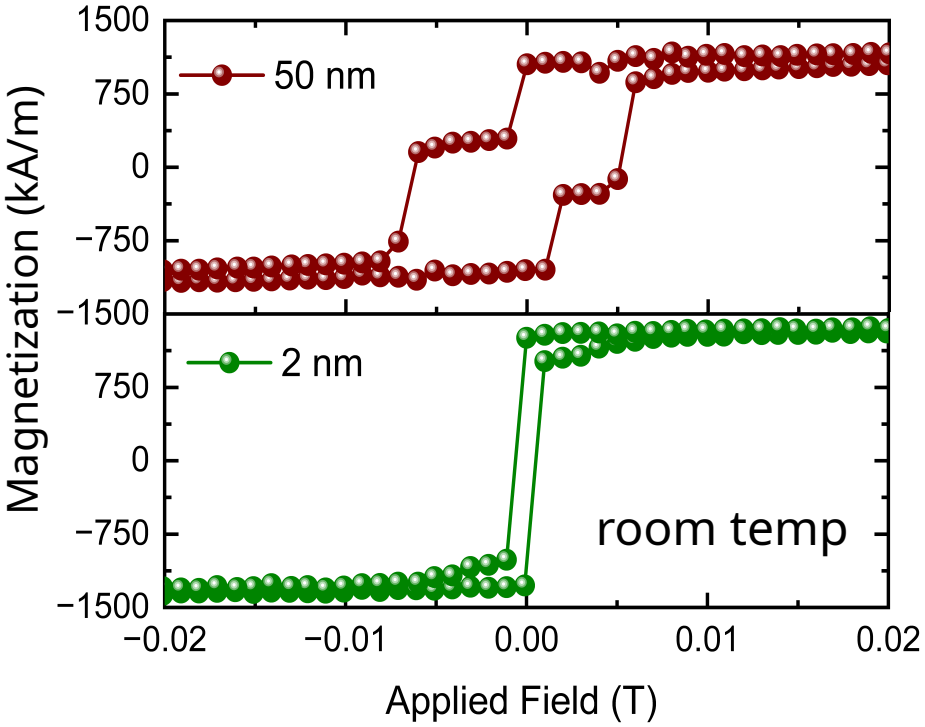
•**Resonance Frequency:** Because its internal exchange fields are exceptionally strong, NiO exhibits ultrafast spin dynamics with natural resonance modes operating in the **Terahertz (THz) domain** (~1.07 THz and 140 GHz), vastly outperforming traditional gigahertz (G ferromagnet.

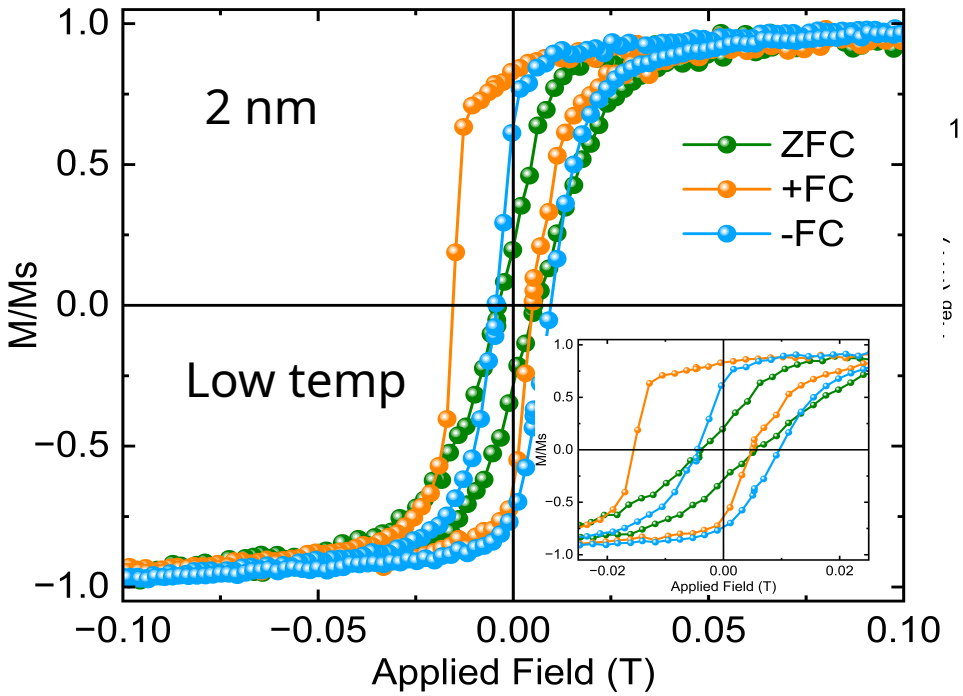


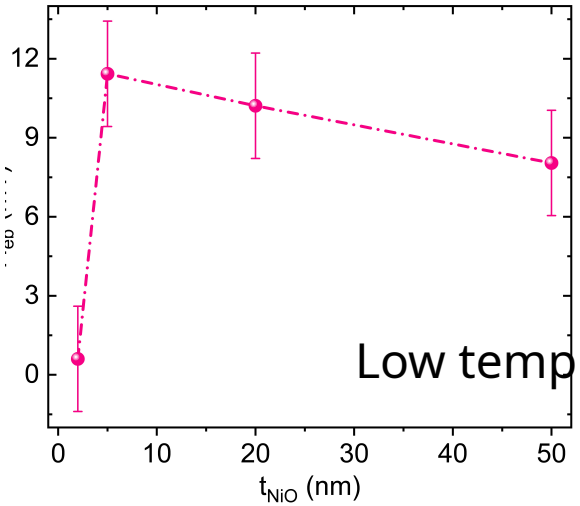


- The face centered cubic phase of NiO.
- No Peak for CFeB as it is an amorphous

Static Magnetic properties of CoFeB/NiO (t)/CoFeB Heterostructure

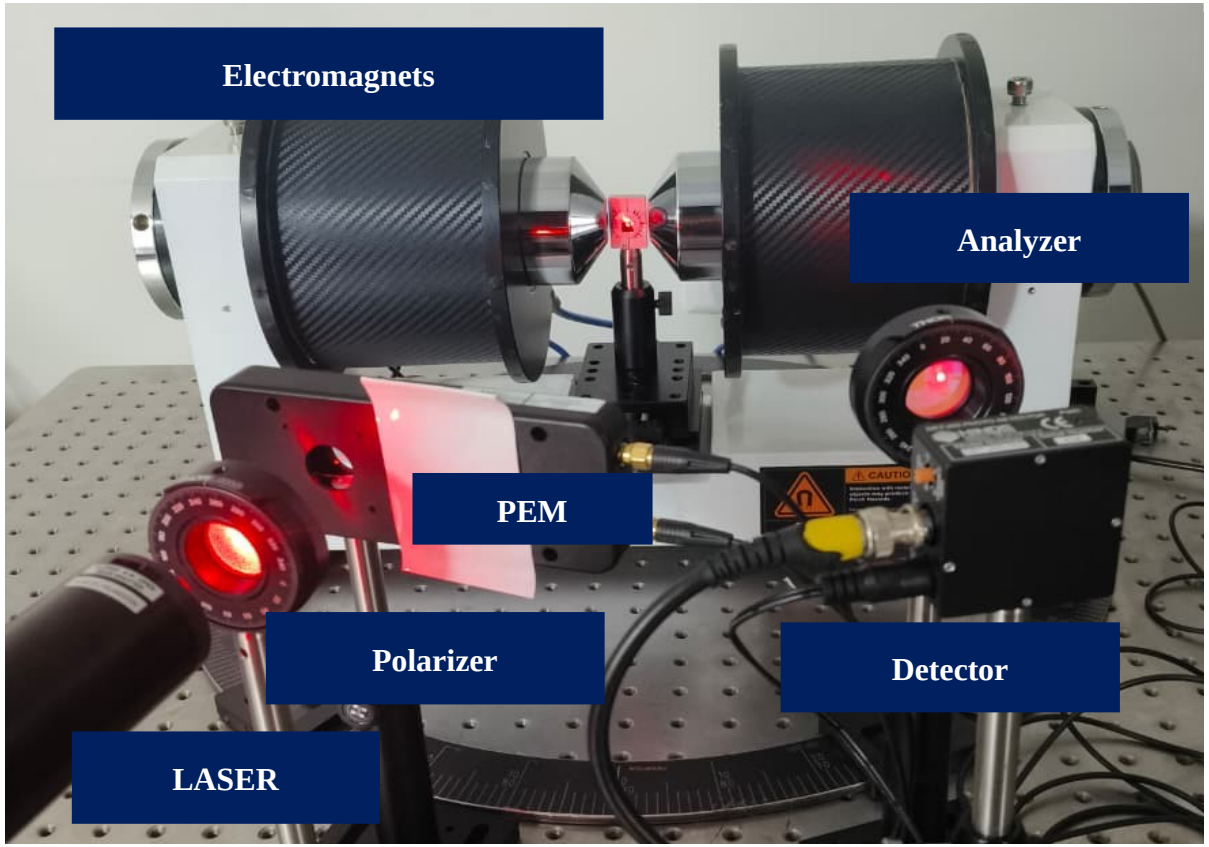


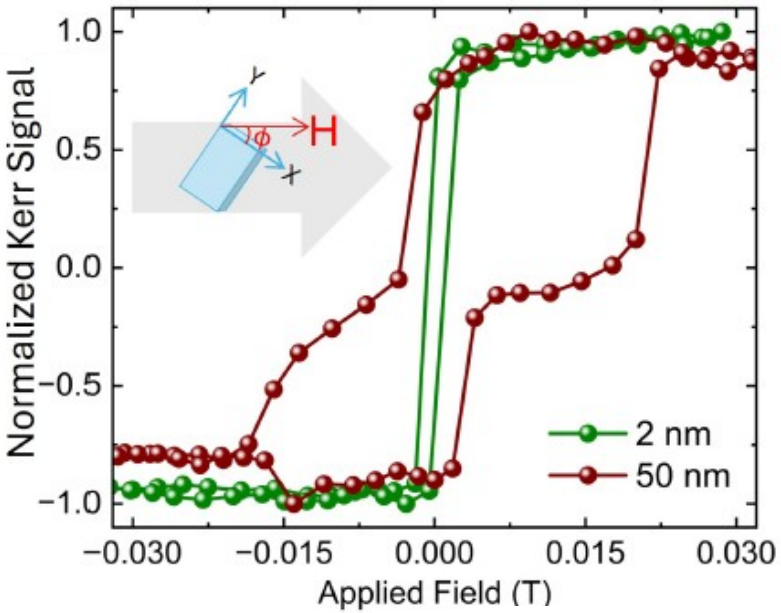


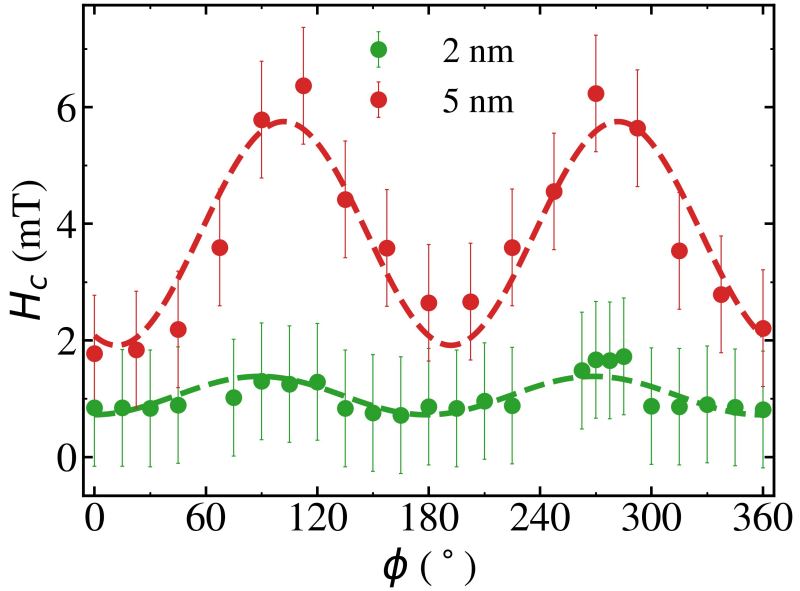


- t_{NiO} = 2 nm : Single hysteresis
- t_{NiO} = 50 nm : a kink appears in the hysteresis
- An anisotropy is observed with the introduction of NiO
- No exchange bias is observed at room temp
- FC and ZFC shows the presence of an exchange bias in the system

Static Magnetic properties of CoFeB/NiO (x)/CoFeB Heterostructure

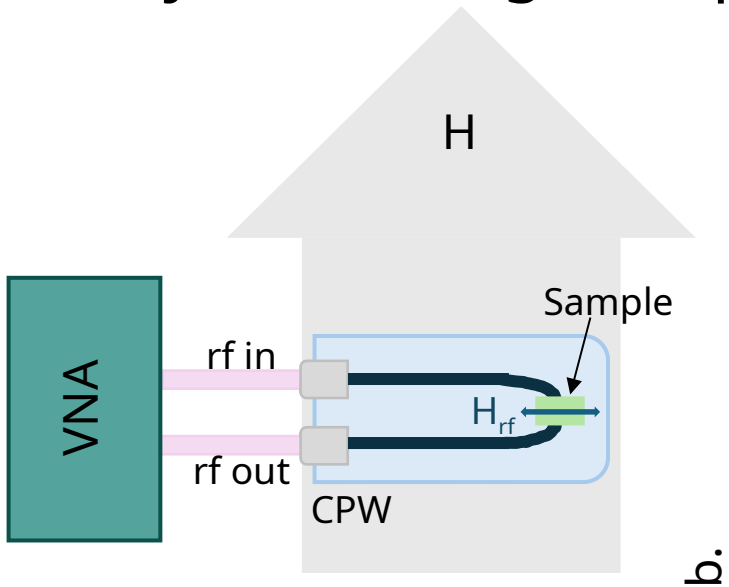






- The coercivity shows a presence of two-fold anisotropy at room temperature

Dynamic Magnetic properties of CoFeB/NiO (x)/CoFeB Heterostructure

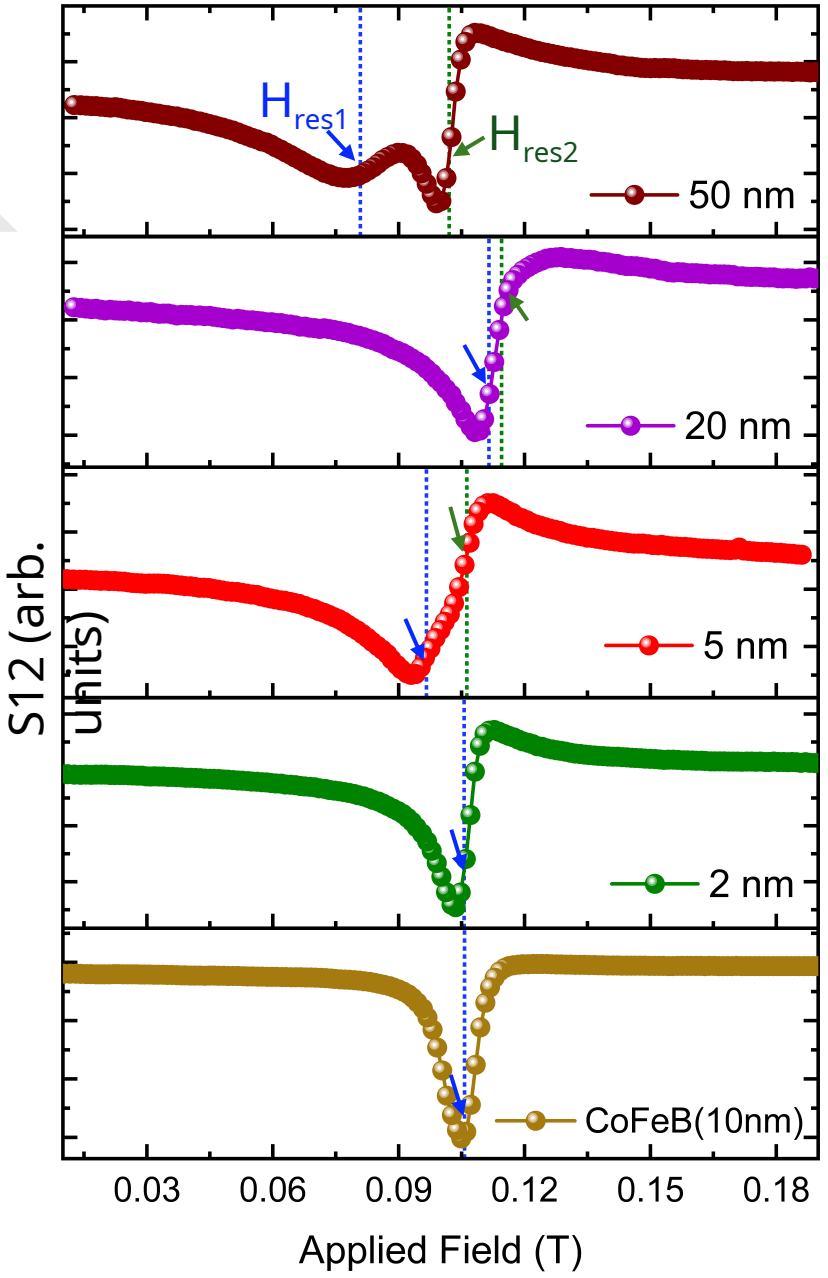


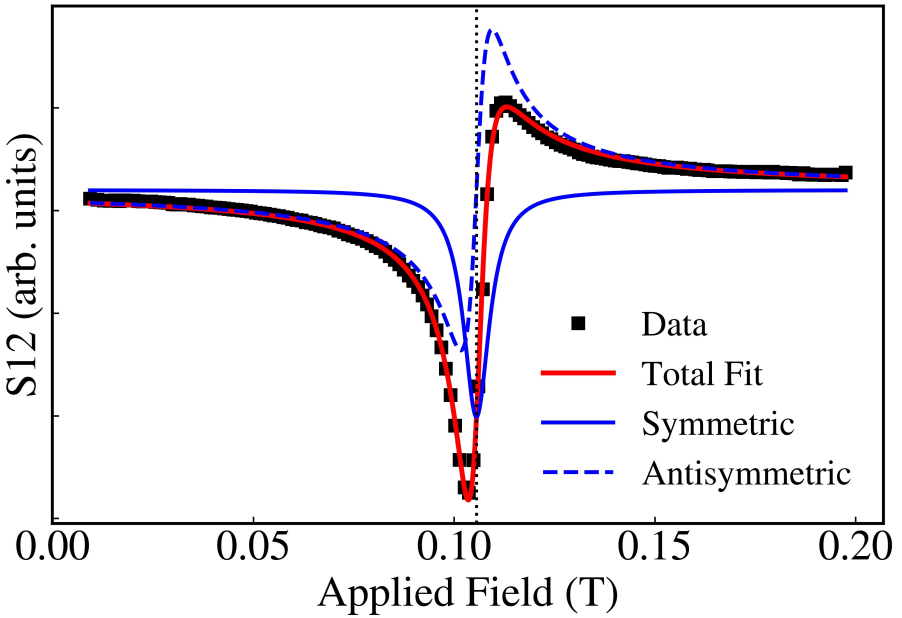
$$S_{12} = \sum_{i=1}^{2} \left[A_i \frac{(\Delta H_i)^2}{(H - H_{res_i})^2 + (\Delta H_i)^2} + B_i \frac{(H - H_{res_i})\Delta Hi}{(H - H_{res_i})^2 + (\Delta Hi)^2} \right] + offset$$

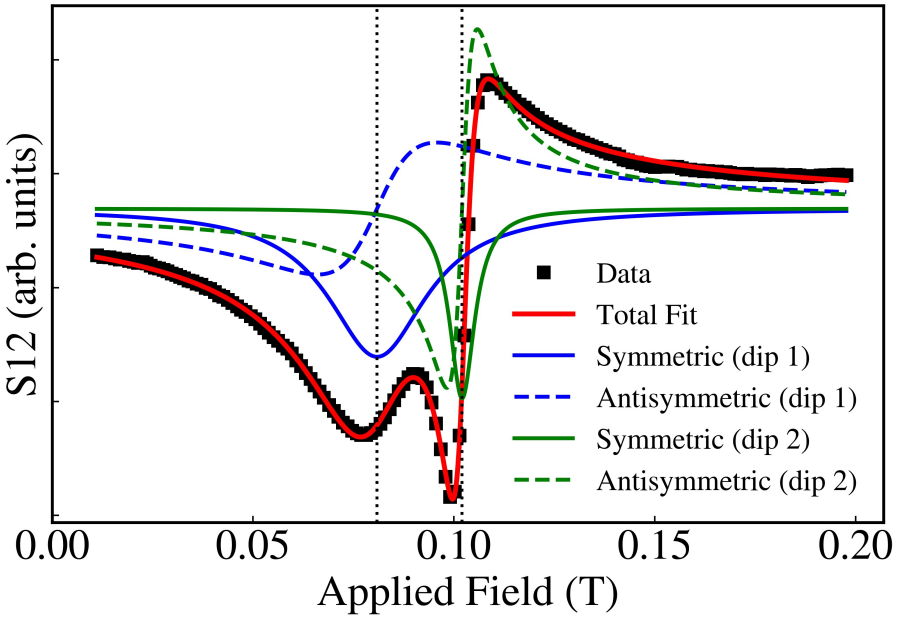
ΔH: The halfwidth at the half maxima

H_{res}: The resonance field,

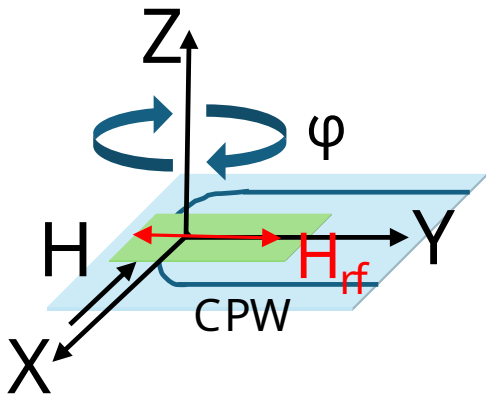
$A$and B: coefficients of symmetric and asymmetric parts

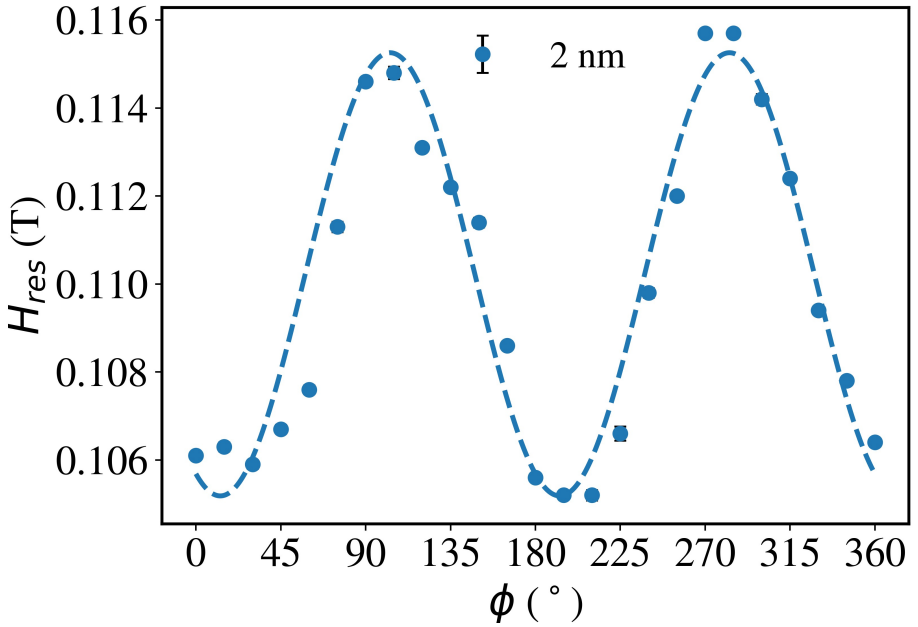


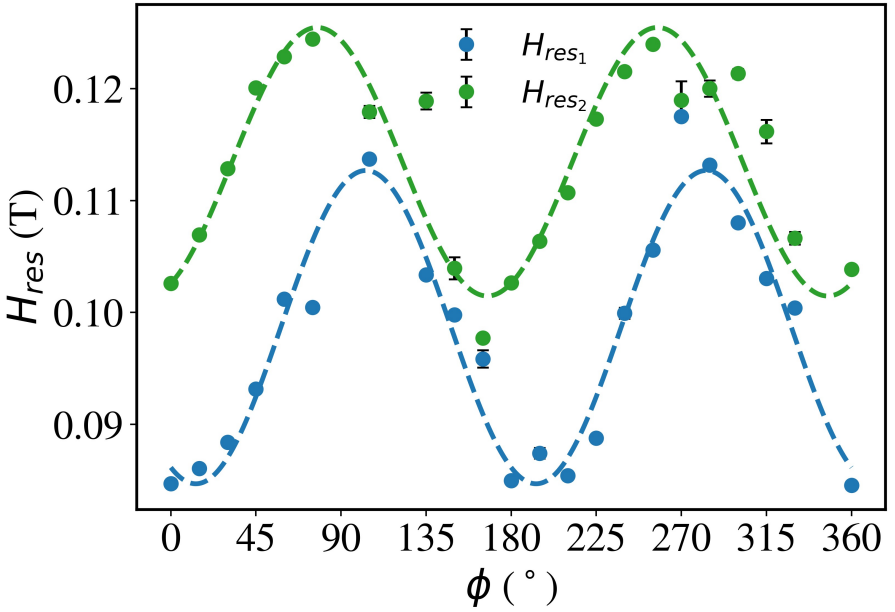




Probing the Two-fold Anisotropy in CoFeB/NiO (x)/CoFeB Heterostructure





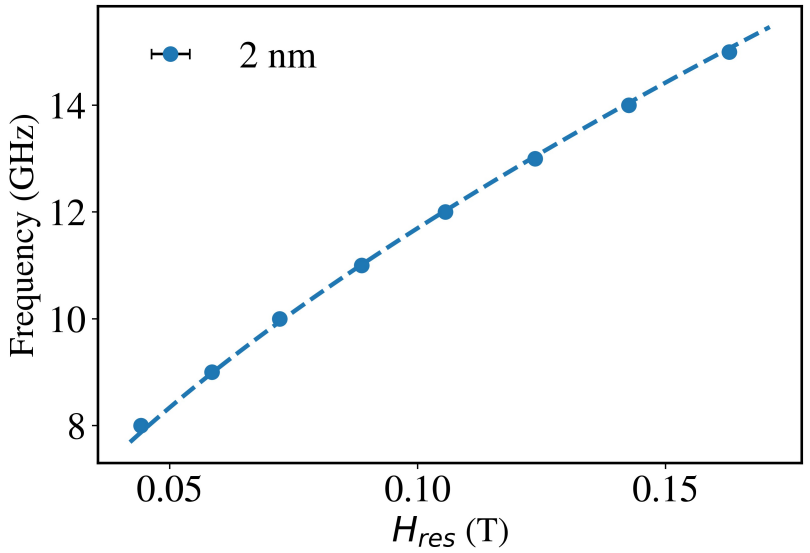


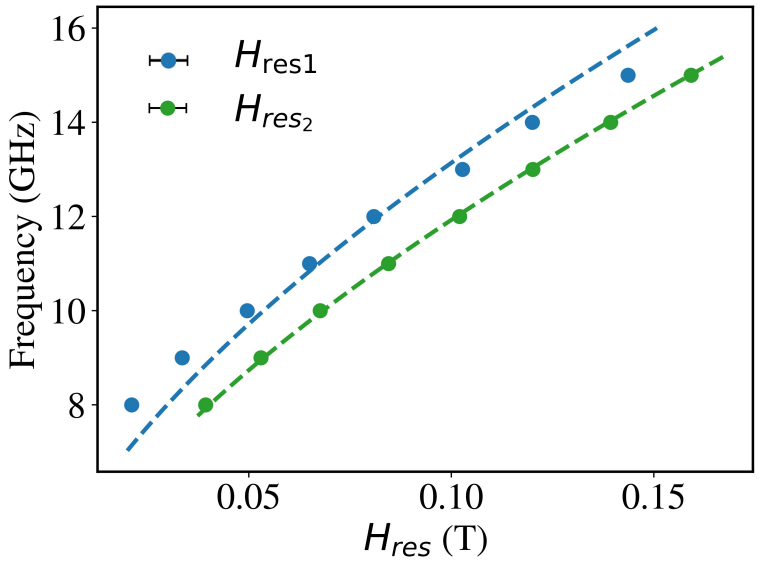
$$H_{res} = H_0 - H_k Cos2(\phi - \phi_0)$$

- For t_{NiO} = 2 nm : Both the FM layer exhibit same interfacial anisotropy
- For t_{NiO} = 50 nm : Both the FM layer exhibit different interfacial anisotropy

t_{NiO} (nm)	H_k (mT)	V
2	5.03 ± 0.017	
5	H_{res1} : 15.0 ± 0.03 H_{res2} : 13.0 ± 0.026	
20	H_{res1} : 9.12 ± 0.023 H_{res2} : 13.3 ± 0.114	
50	H_{res1} : 14.0 ± 0.054 H_{res2} : 12.0 ± 0.016	

Comparison of Effective Saturation Magnetization

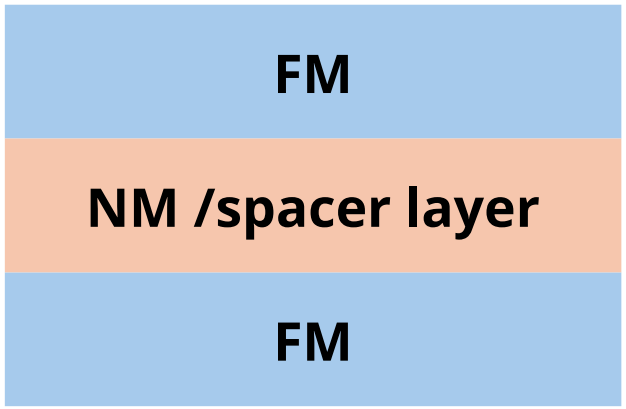




Kittel formula $$f_{FMR} = \frac{\gamma}{2\pi}\sqrt{(H_{res} + H_k)(H_{res} + H_k + 4\pi M_{eff})}$$

t_{NiO} (nm)	H_k (mT)	VSM M_{eff} (kA/m)	FMR M_{eff} (kA/m)
2	5.03 ± 0.017	1393.4 ± 73.15	H_{res1} : 1239.29 ± 0.002
5	H_{res1} : 15.0 ± 0.03 H_{res2} : 13.0 ± 0.026	1223.6 ± 72.1	H_{res1} : 1224.55 ± 0.015 H_{res2} : 1138.11 ± 0.011
20	H_{res1} : 9.12 ± 0.023 H_{res2} : 13.3 ± 0.114	922.9 ± 55.8	H_{res1} : 1113.56 ± 0.007 H_{res2} : 1006.15 ± 0.04
50	H_{res1} : 14.0 ± 0.054 H_{res2} : 12.0 ± 0.016	1186.5 ± 110.8	H_{res1} : 1486.76 ± 0.019 H_{res2} : 1200.34 ± 0.003

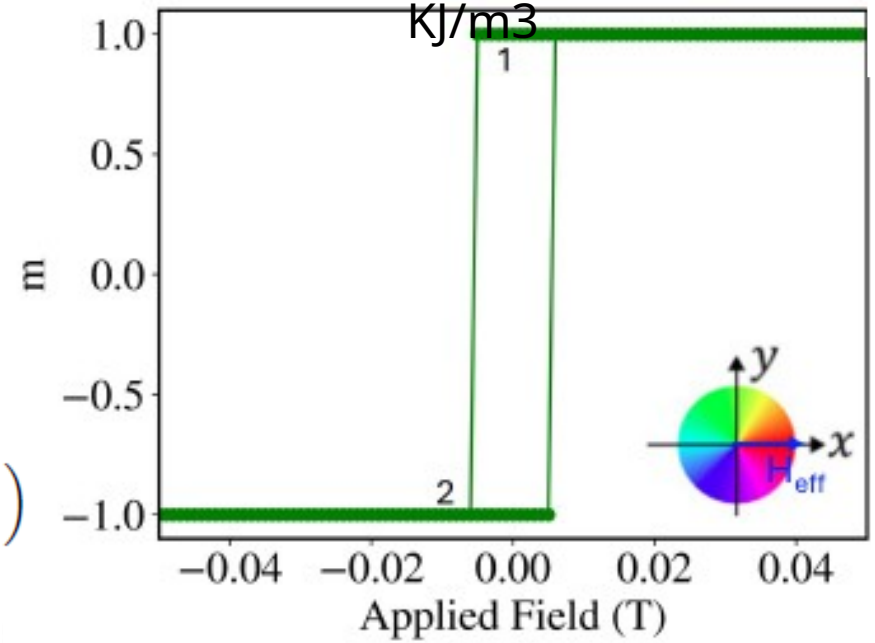
Micromagnetic Simulation



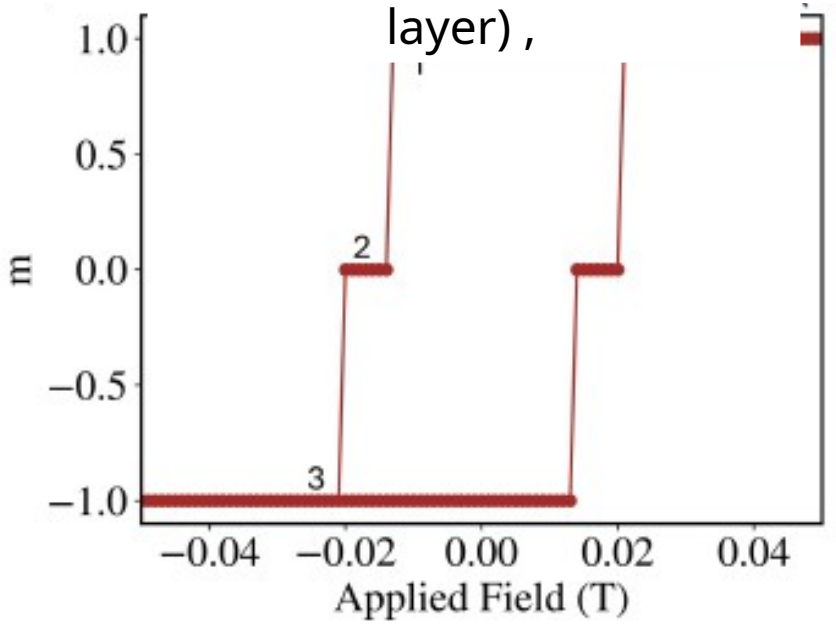
$$\frac{d\mathbf{m}}{dt} = -\gamma(\mathbf{m} \times \mathbf{H}_{eff}) + \alpha\left(\mathbf{m} \times \frac{d\mathbf{m}}{dt}\right)$$

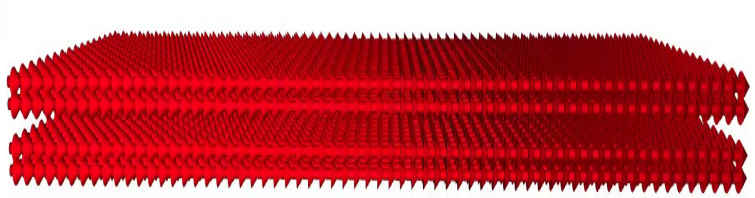
$$\mathbf{H}_{eff} = \mathbf{H}_{ext} + \mathbf{H}_{demag} + \mathbf{H}_{ex} + \mathbf{H}_{anis}$$

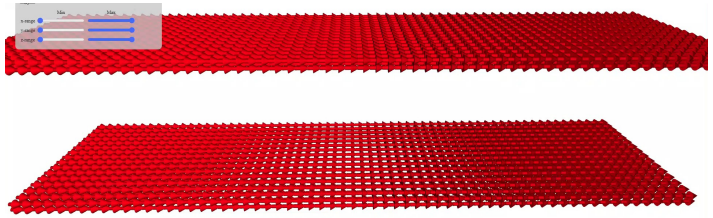
t = 2 nm, K_{eff} = 3.1 KJ/m3



t = 50 nm and
K_{eff} = 10 KJ/m³ (top layer)
K_{eff} = 7 KJ/m³ (bottom layer) ,







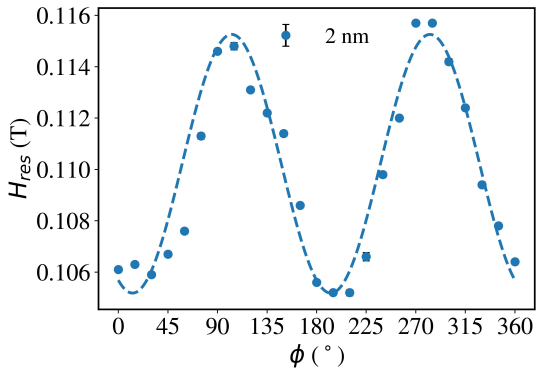
Conclusions

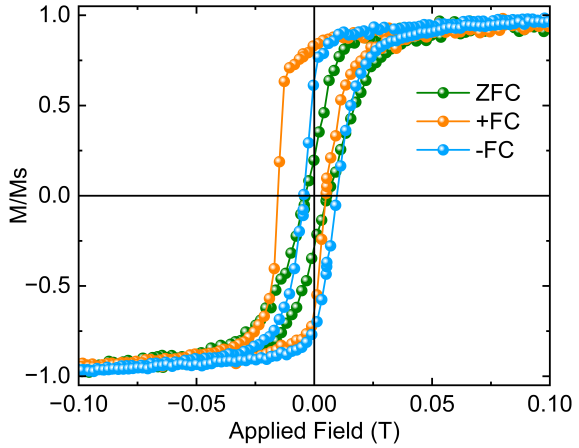
Experiment : Time scale : ns range

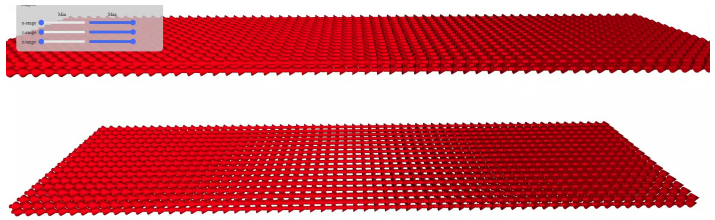
Magnetic trilayers : CoFeb/NiO (x)/CoFeB

Static and Dynamic Magnetic Properties of CoFeB/NiO/CoFeB Trilayers with Varying NiO Thickness

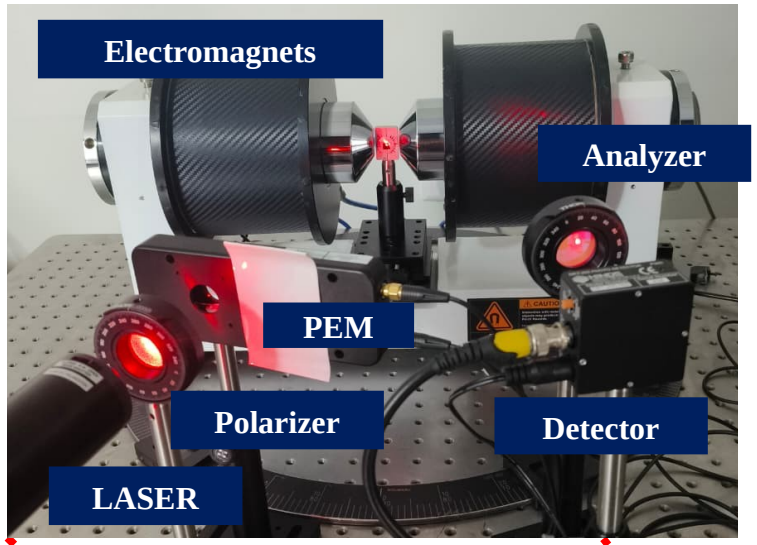
- Spinwave dynamics of CoFeB/ NiO (x)/CoFeB trilayer system modified with the thickness of the NiO spacer layer
- An exchange bias is observed for these trilayer film at low temperature [~2 K]
- An interfacial anisotropy for top and bottom FM layer is probed by both MOKE and FMR measurement and the value of the anisotropy is different for thicker NiO spacer layer

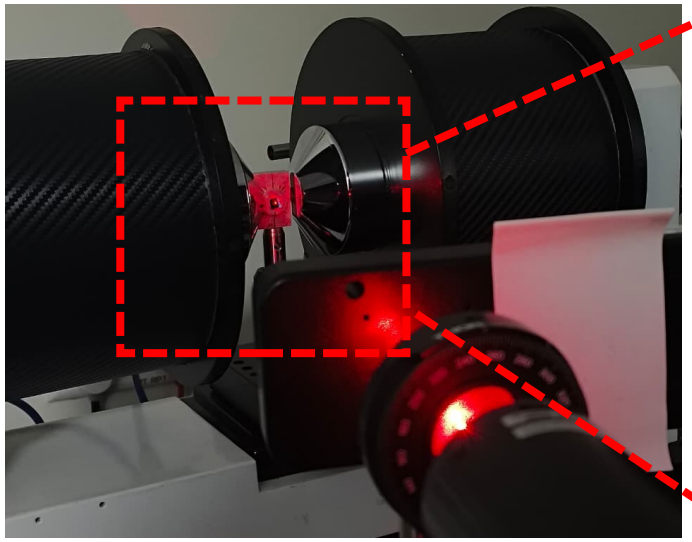


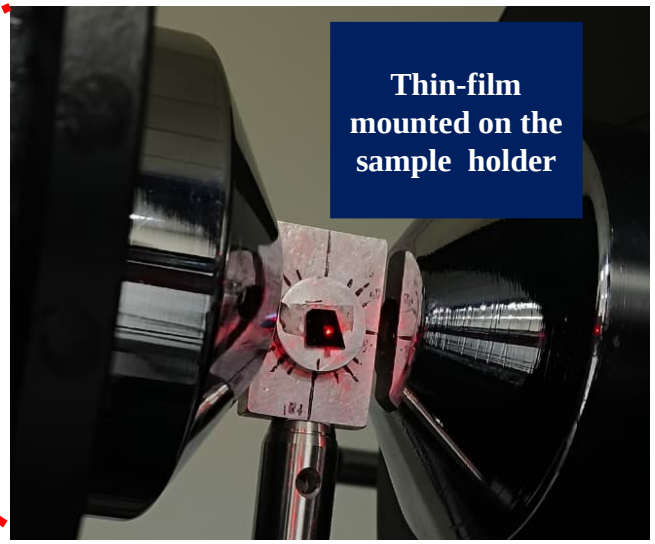


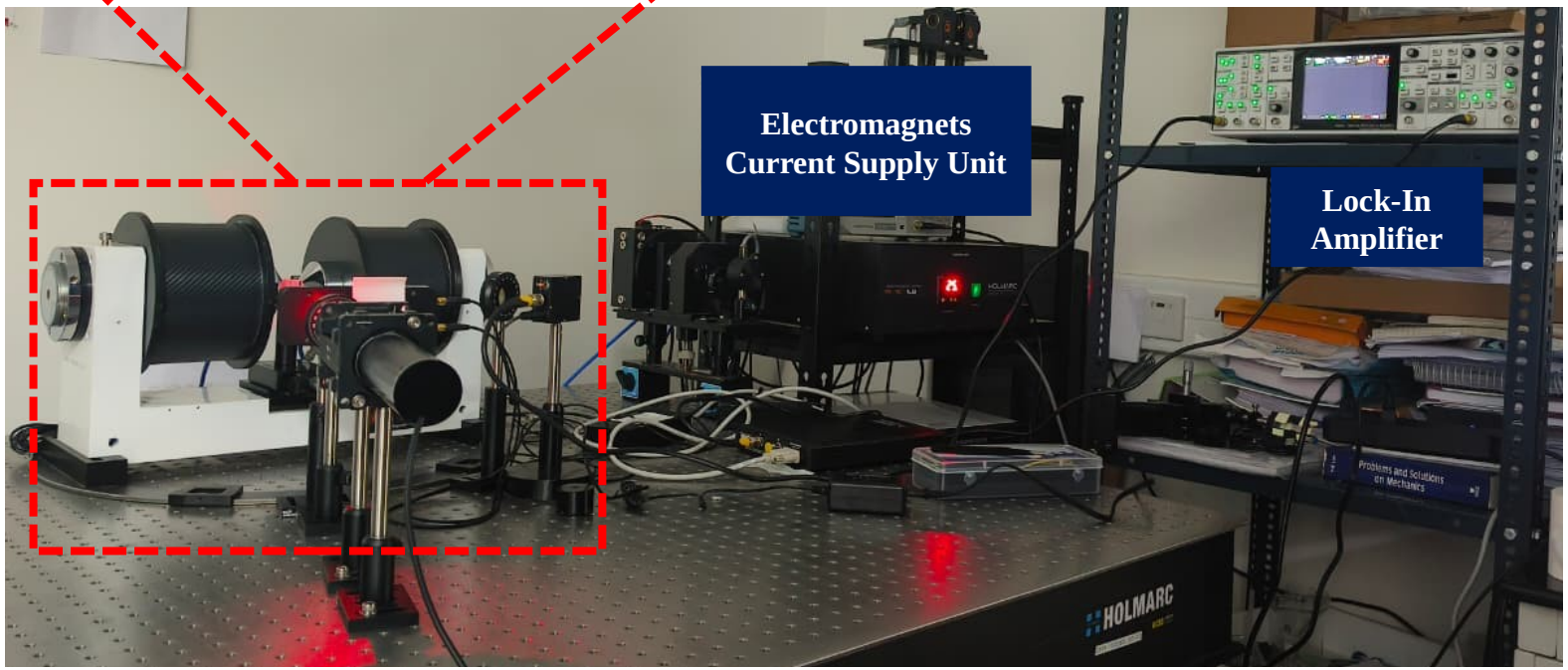


Magneto Optical Kerr Microscope (MOKE) set up present at Ashoka University

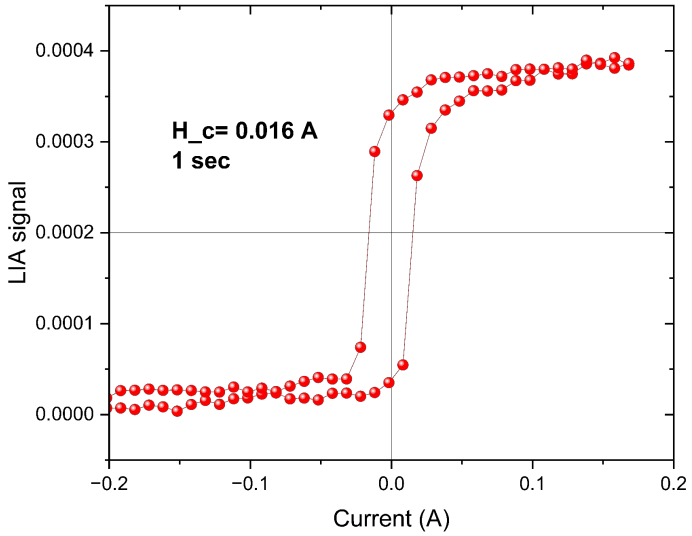




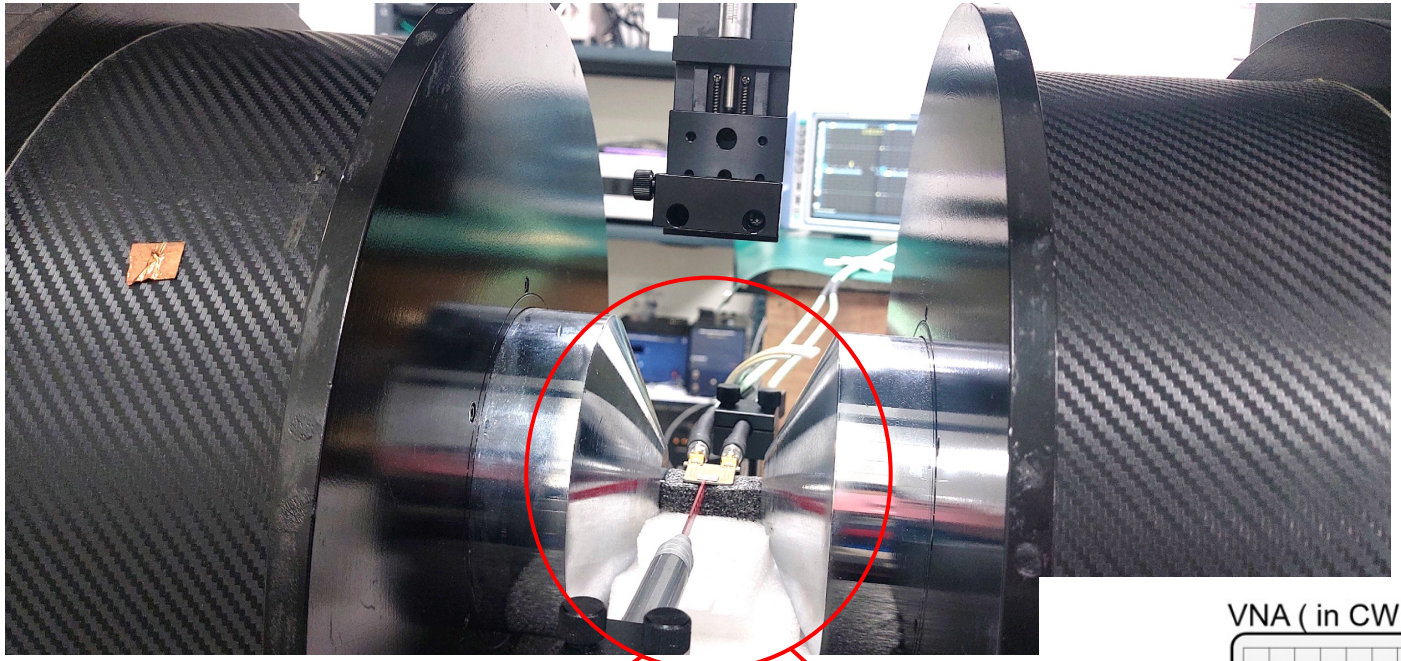


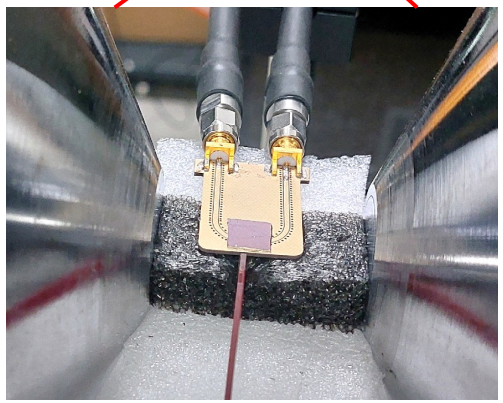


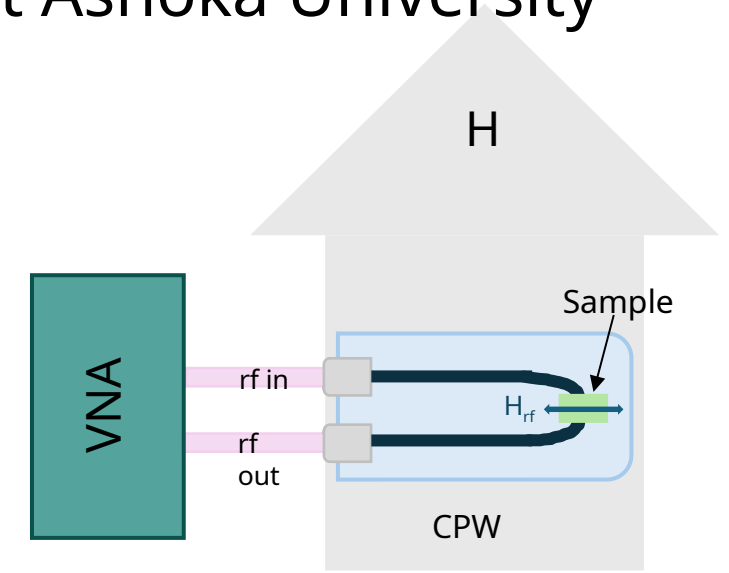
MOKE loop from NiFe (10 nm) Film

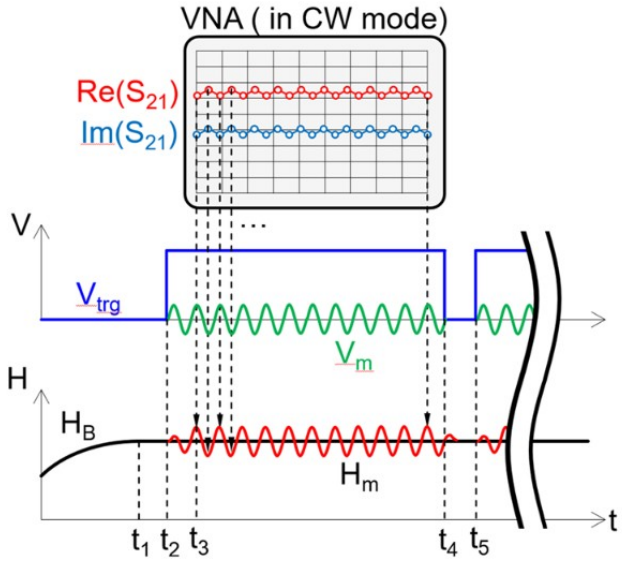


Ferromagnetic resonance (FMR)Set up at Ashoka University

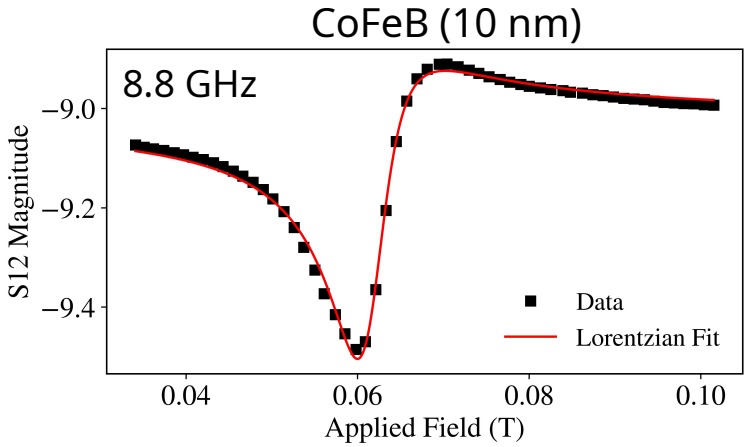






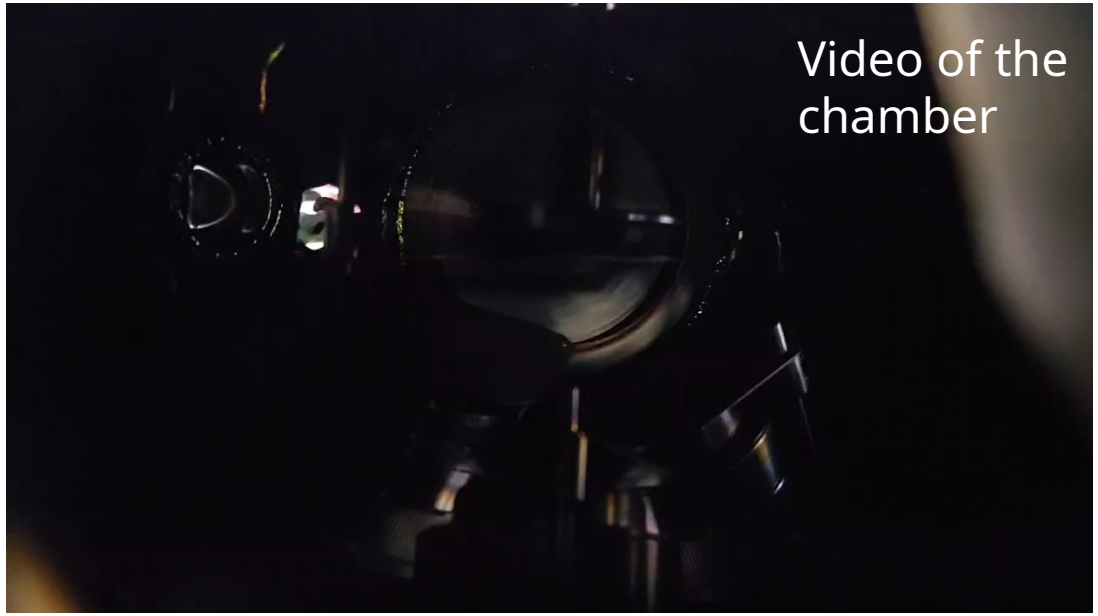


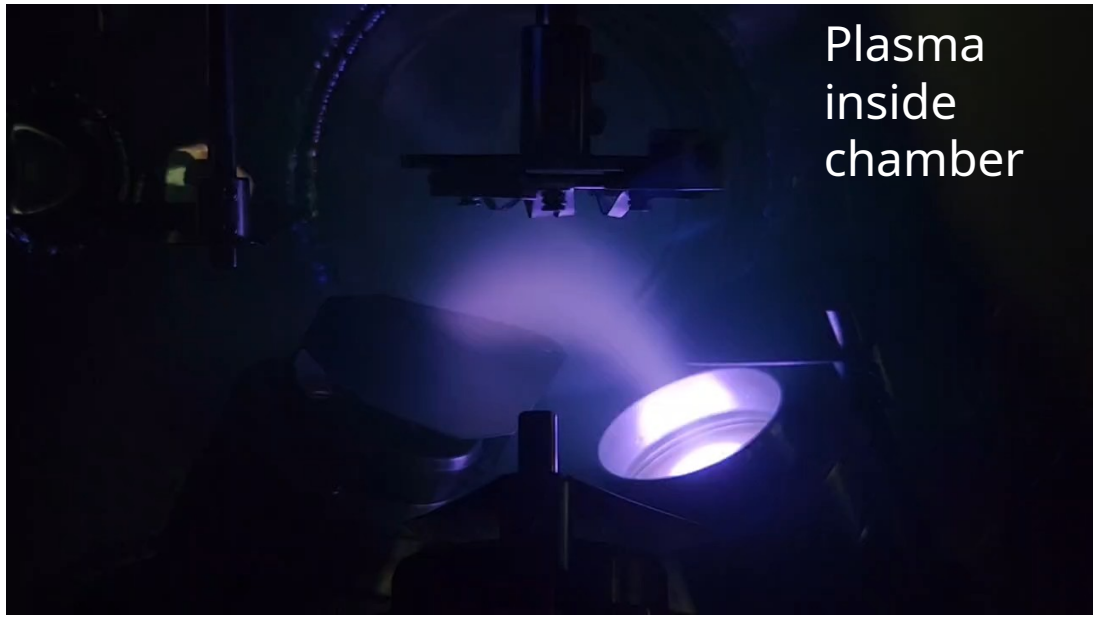
Raw FMR data

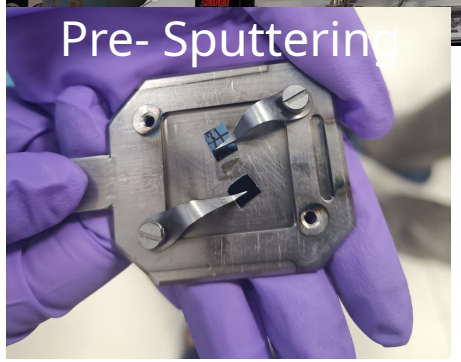


RF/DC Magnetron Sputtering Unit at Ashoka University



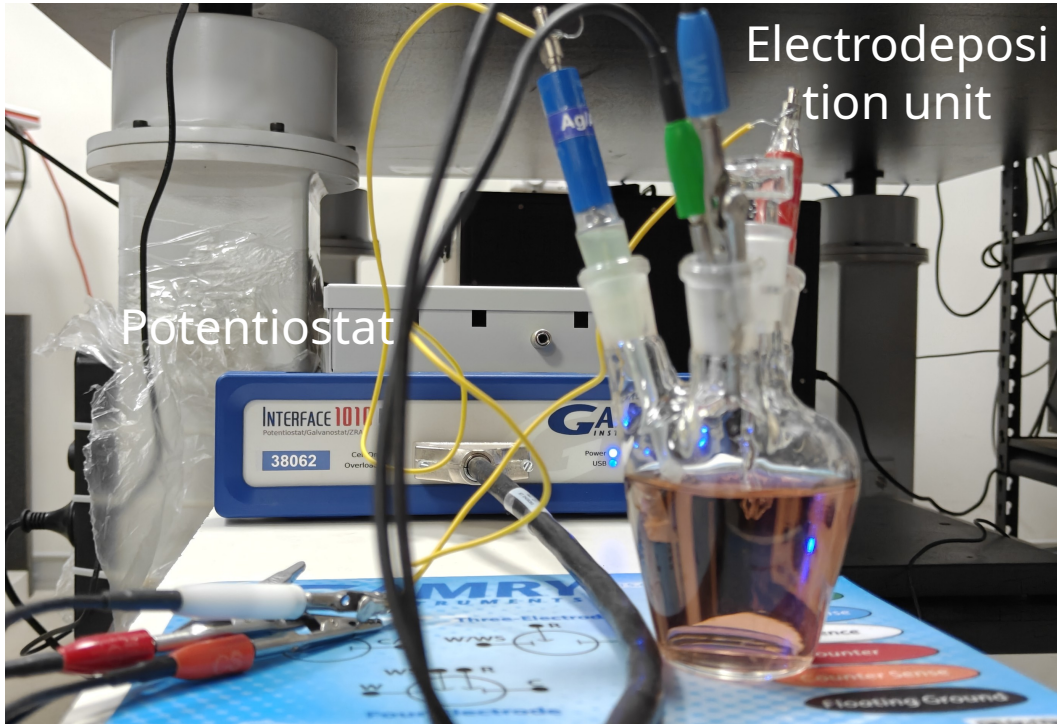


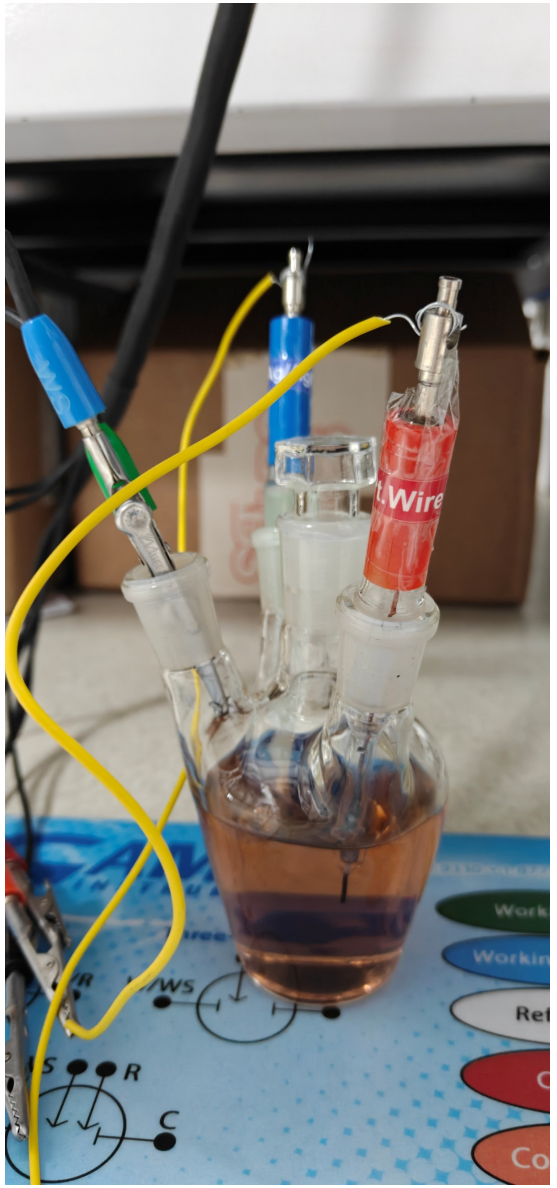




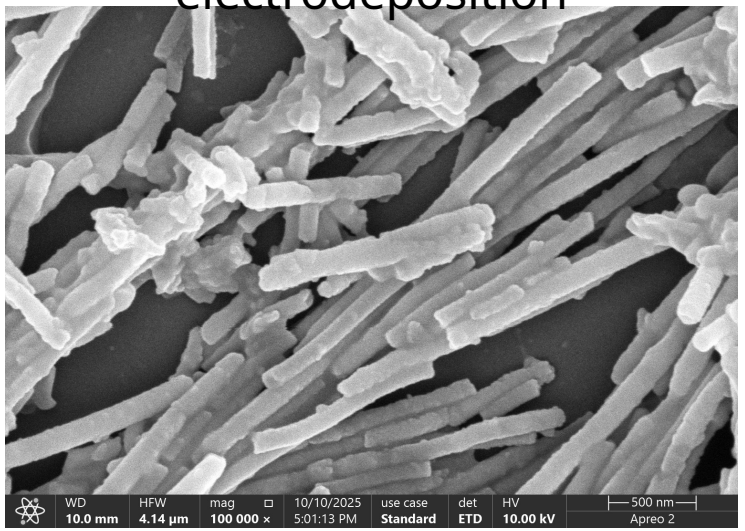


Electro-deposition Technique





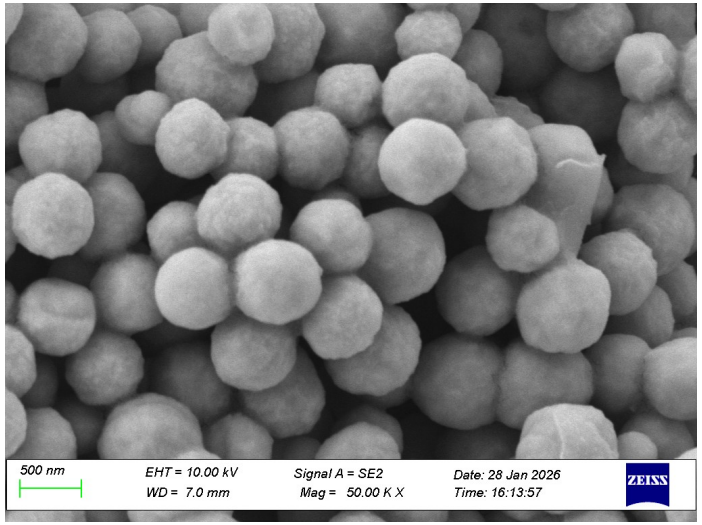
Magnetic nanowire deposited by electrodeposition

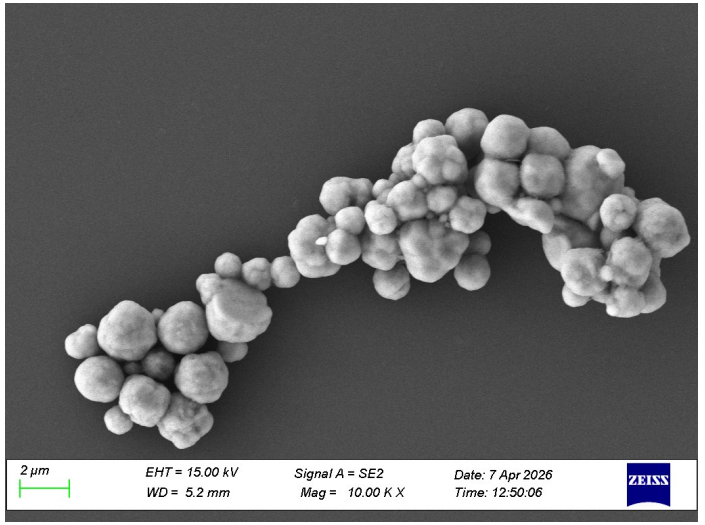


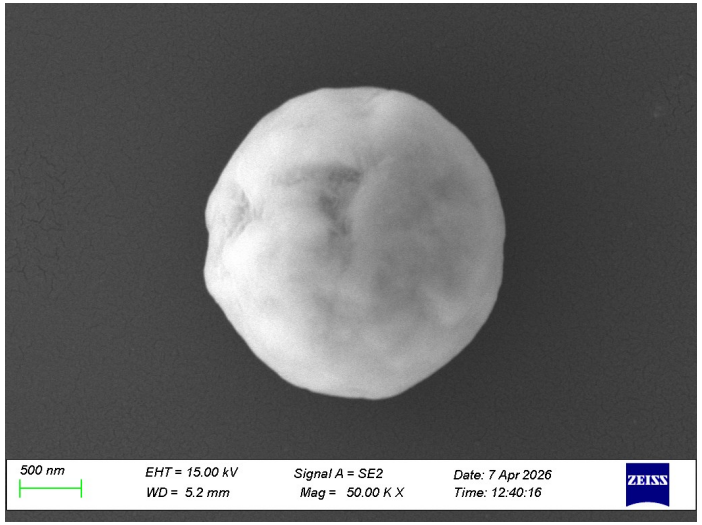
Synthesis of Magnetic Nanoparticles











Thank You