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Exchange Stiffness Constant Determination using Multiple-Mode FMR Perpendicular Standing Spin Waves

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International Spintronics network – 5 Dec. 2022

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Spintronics for data storage, sensing and computation

THz Spintronics

Dynamics (FMR)

High anisotropy $L1_0$ alloys (FePt and MnAl)

Skyrmions

Multifunctional Exchange springs (FeRh)

Magnetic tunnel junctions

Thin film fabrication, advanced characterization and simulation

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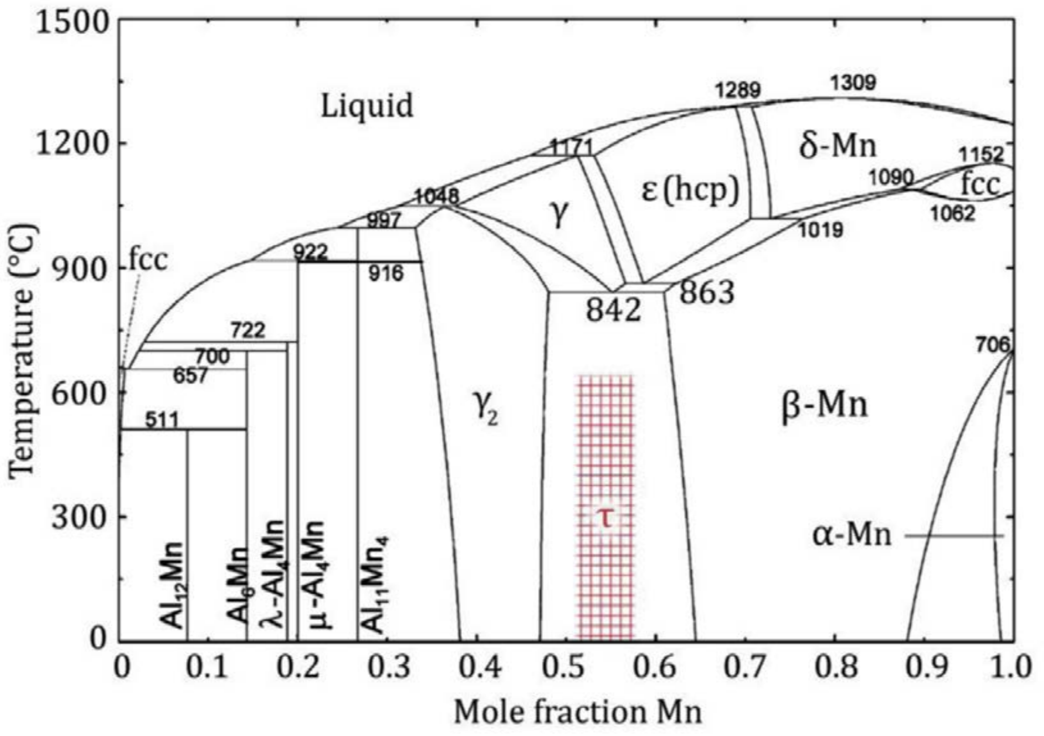
Fabrication of MnAl in Metastable $L1_0$ Phase

- Key advantages:
  - High anisotropy and Ms
  - Very low magnetic damping factor
  - Low cost materials
- Narrow composition window, 50 to 60 at. % Mn
- Brittleness of Mn causes issues with target manufacture
- Two approaches taken:
  - Alloy target sputtering
  - Elemental target co-sputtering
- Composition is a main hurdle and is measured using HAXPES



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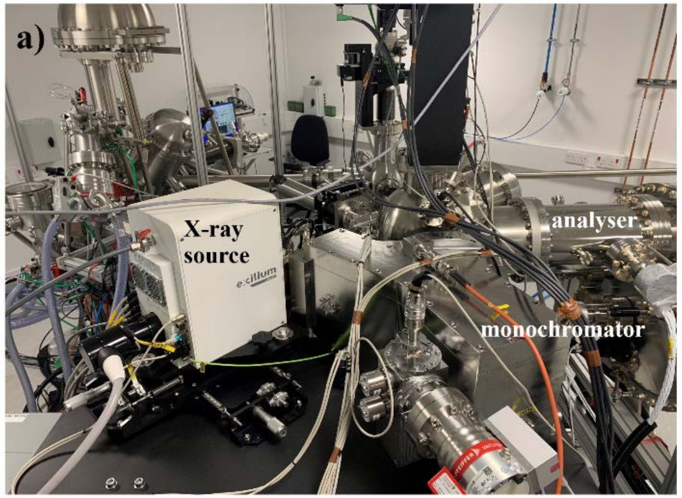
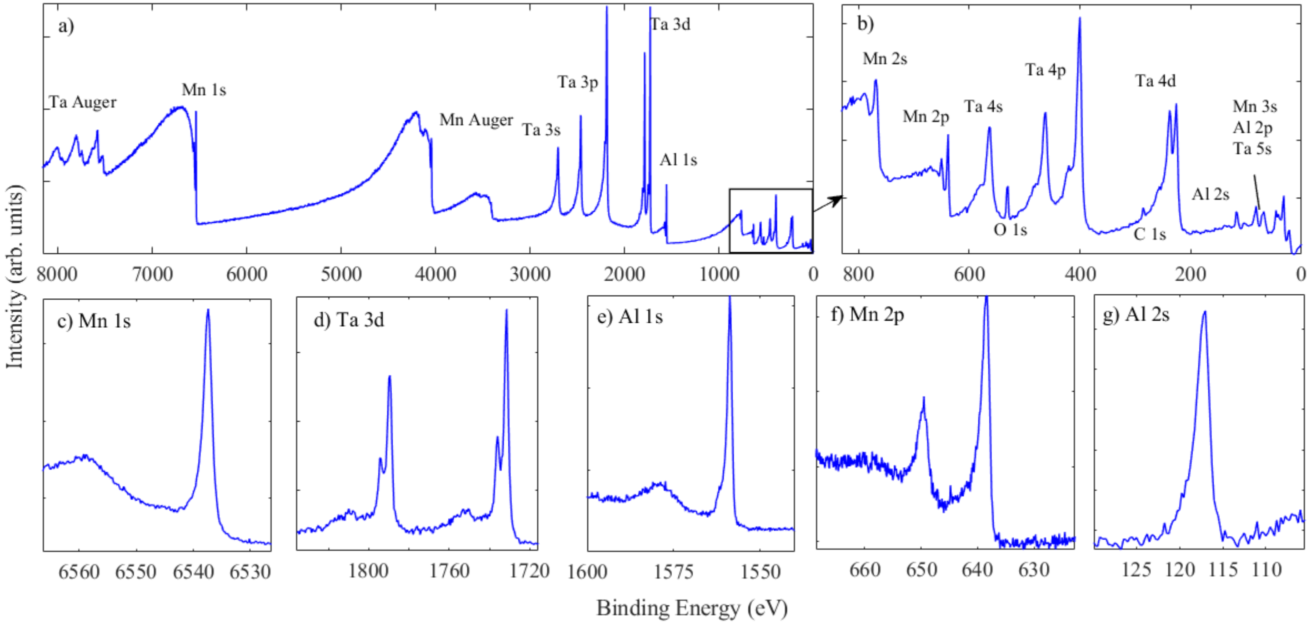
HAXPS at Royce in Manchester

- Ga metal jet X-ray source (Excillum) – 70 keV / 250 W
- EW4000 electron energy analyser capable of measuring photoelectrons with kinetic energies up to 12 keV



- Focused X-ray beam ~ 50 x 50 µm at the sample position giving three orders of magnitude greater flux than traditional lab sources
  - Enables HAXPES measurements to be undertaken on reasonable timescales
- Co-deposited MnAl thin film capped with a *ca.* 5 nm Ta surface layer. Measurements were performed with grazing incidence in transmission mode.



a) HAXPES survey spectrum
b) low binding energy region
c) High resolution spectra of Mn 1s, d) Ta 3d, e) Al 1s, f) Mn 2p, and g) Al 2s

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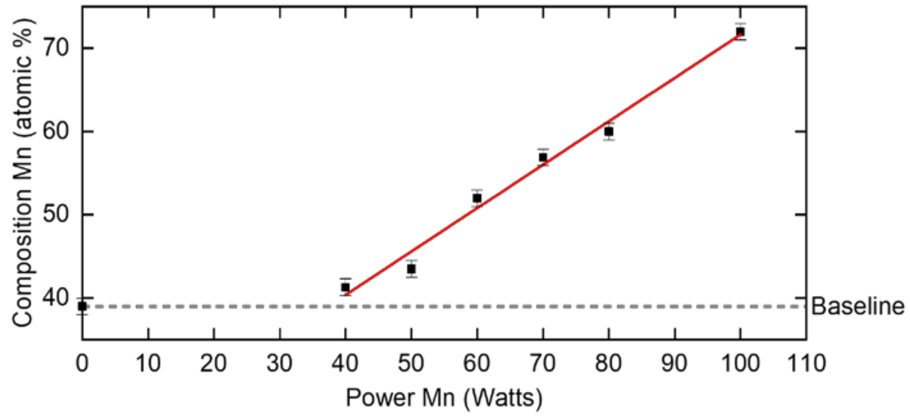
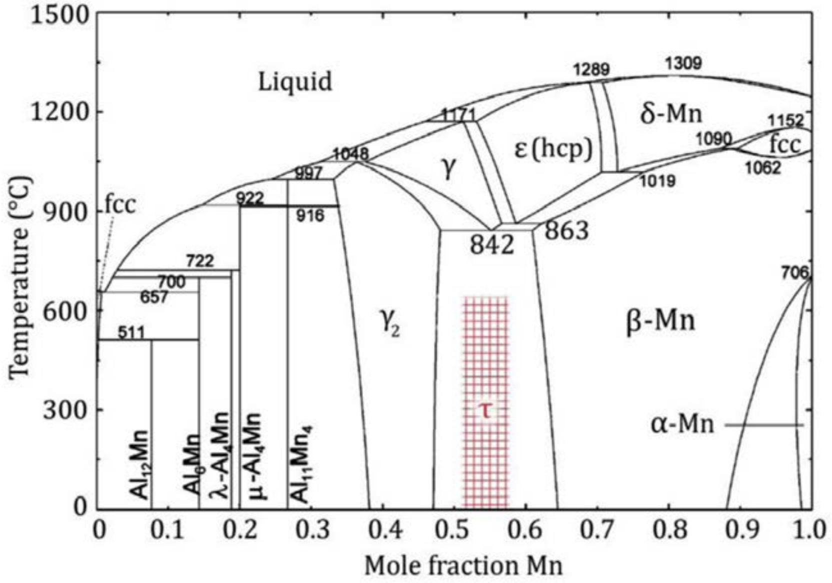
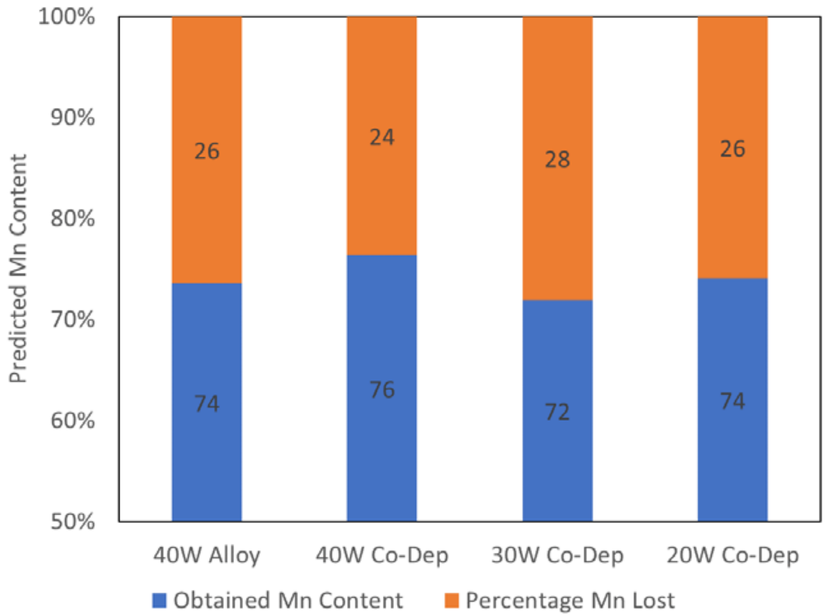
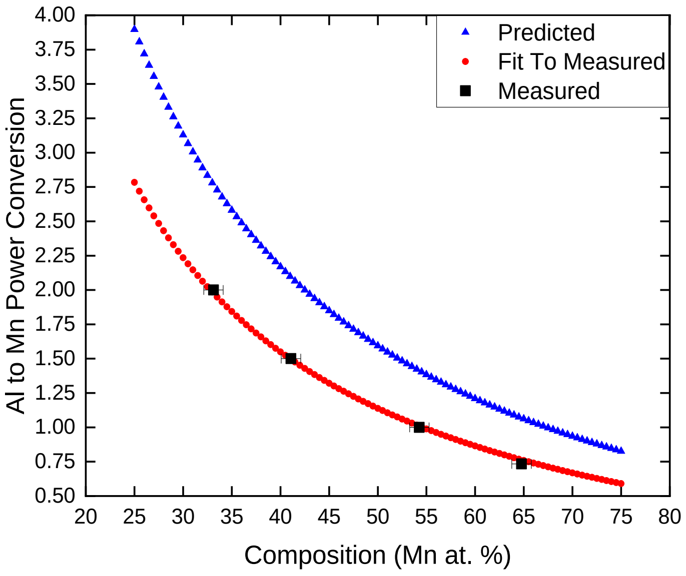
Characterising MnAl thin film fabrication

- **Alloy Target:**
  - Alloy composition 52% Mn
  - Sample composition 39% Mn
  - Corrected by co-depositing with Mn
- **Co-Deposition:**
  - Predicted from individual rate of deposition using XRR









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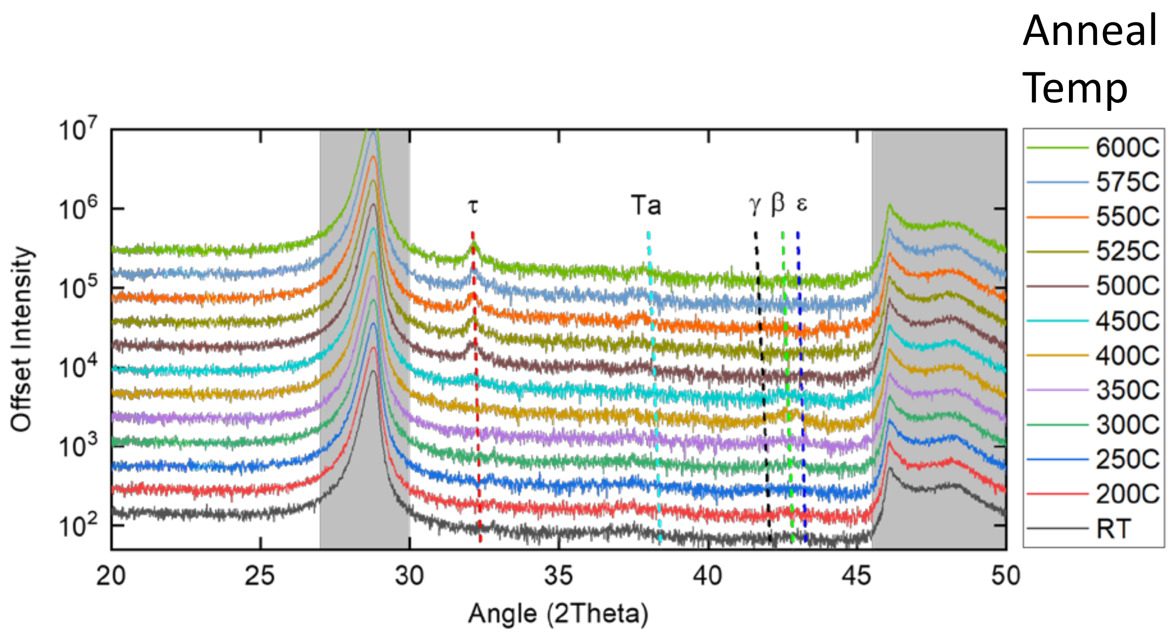
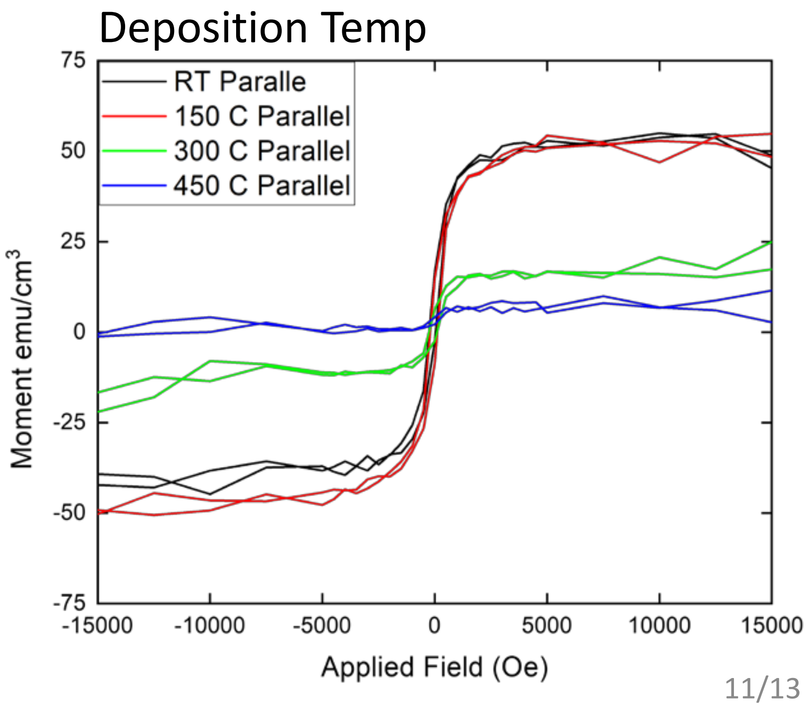
Properties of MnAl Films

- XRD/XRR used to characterise ordering
- Partial $L1_0$ phase ordering achieved
- β, γ, ε phases reduces Ms with deposition temperature
- Surface roughness increases with temperature from 0.8 to 4 nm above 450°C





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Harry Waring

Yu Li

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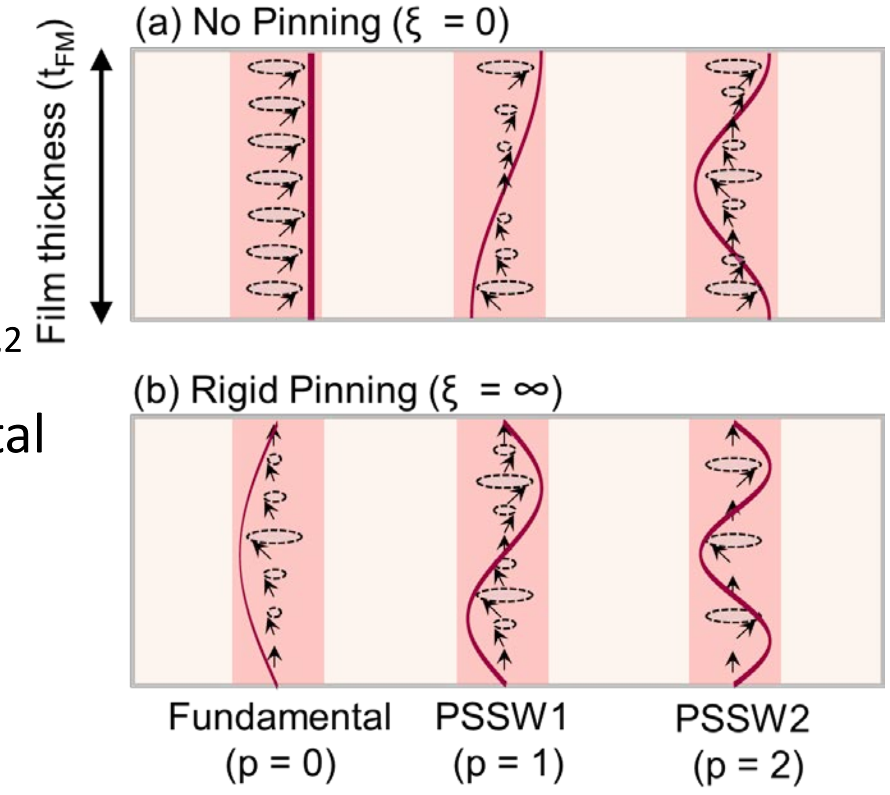
Exchange Constant and PSSWs

- The exchange (stiffness) constant A_{ex} is one of the fundamental properties of magnetically ordered materials[1,2]
- The determination of A_{ex} remains a challenging experimental measurement[1]
- Enhanced knowledge of Aex is key for increasing fundamental knowledge and application of magnetisation dynamics[3]



- Perpendicular Standing Spin Waves (PSSWs) are higher order spin excitations that arise due to the constraints of film thickness[3]
- Aex determined from different PSSW resonances analyzed using rigid pinning model (proposed by Kittel) can vary[3,4]

Exchange Constant

$$A_{ex} \sim \frac{J_{ex} S^2 Z_c}{a_0}$$

where

J_{ex} is exchange integral

Z_c is number of atoms per unit cell

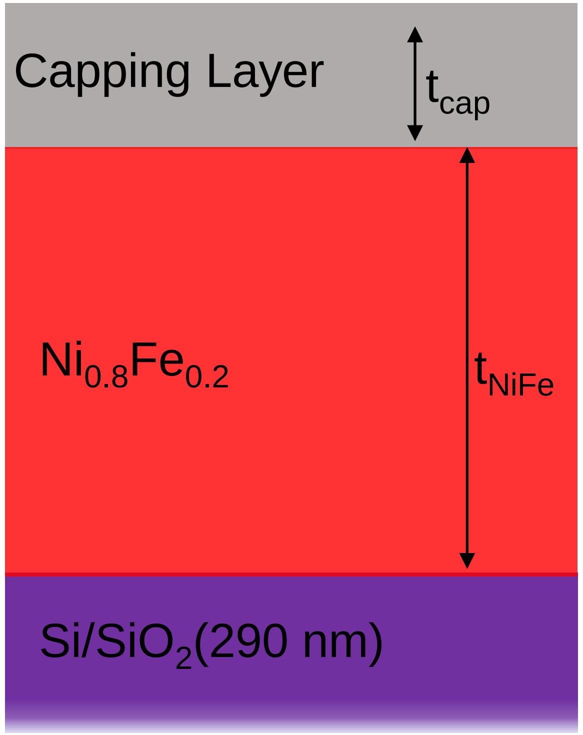
a_0 is lattice parameter

S is total spin quantum number of multi-electron system

[1] J. M. D. Coey, *Magnetism and Magnetic Materials* (2010).
[2] T. Thomson, *Metallic Films for Electronic, Optical and Magnetic Applications: Structure, Processing and Properties* (2013), pp. 454–546
[3] I. S. Maksymov and M. Kostylev, Phys. E Low-Dimensional Syst. Nanostructures **69**, 253 (2015).
[4] J. BenYoussef et al., J. Magn. Magn. Mater. **202**, 277 (1999).

Our Investigation

- We explored the impacts varying both the thickness of ferromagnetic (FM) layer and capping layer material on the measured A_{ex} using experiment and simulation (Mumax^3)[1]
- Thin films were fabricated using magnetron sputtering
- $Ni_{0.8}Fe_{0.2}$ (permalloy[2]) was studied as FM material
  - Thickness of FM layer (t_{NiFe}) was varied between 23 nm and 86 nm
- Capping layer materials explored:
  - Uncapped (formed Fe_2O_3/NiO cap) -> Antiferromagnetic
  - Pt -> Proximity Magnetized
  - Ta -> Nonmagnetic



[1] A. Vansteenkiste et al., AIP Adv. **4**, (2014).
[2] G. Nahrwold et al., J. Appl. Phys. **108**, 013907 (2010).

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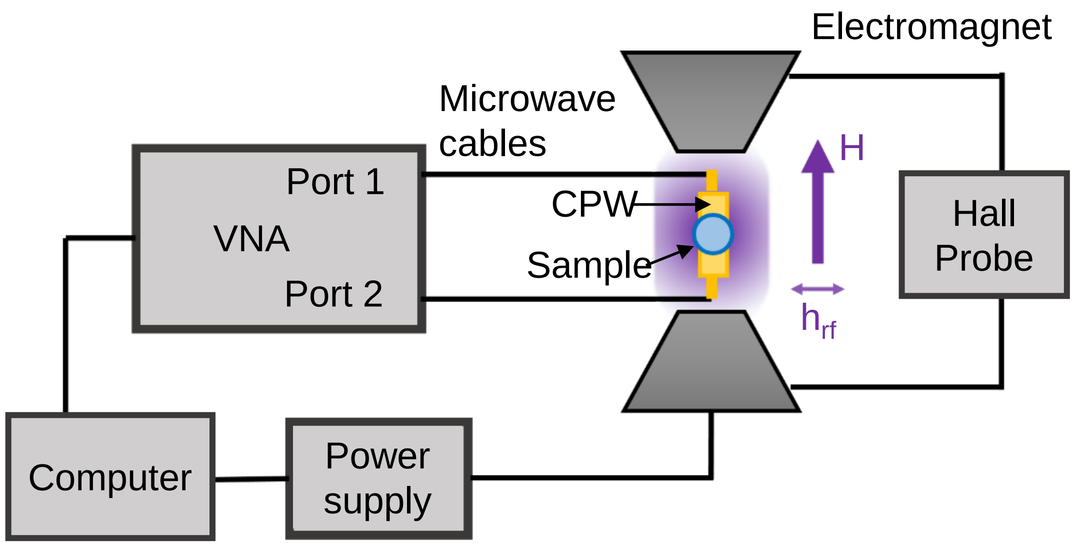
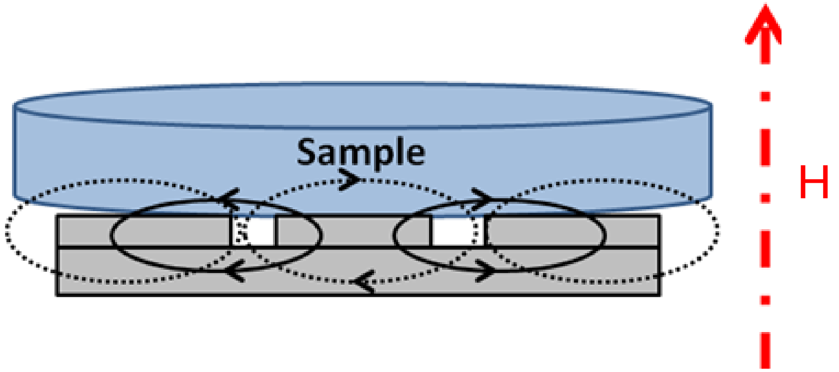
PSSW Measurement

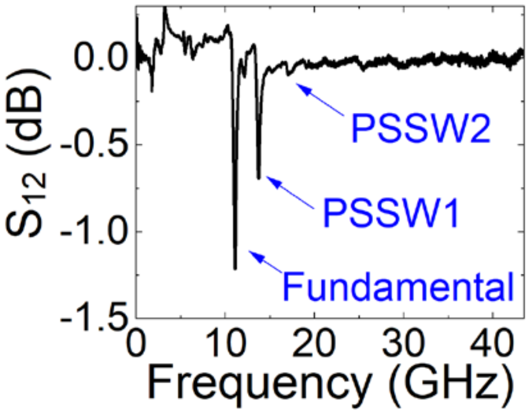
- Vector Network Analyser – Ferromagnetic Resonance (VNA-FMR) spectroscopy was used to measure the spin wave
- Sample placed "flip-chip" on waveguide
- VNA S_{12} parameter used to measure mm-wave absorption
- dc magnetic field applied perpendicular to sample
- Room temperature measurement





PSSW Measurement/Interpretation

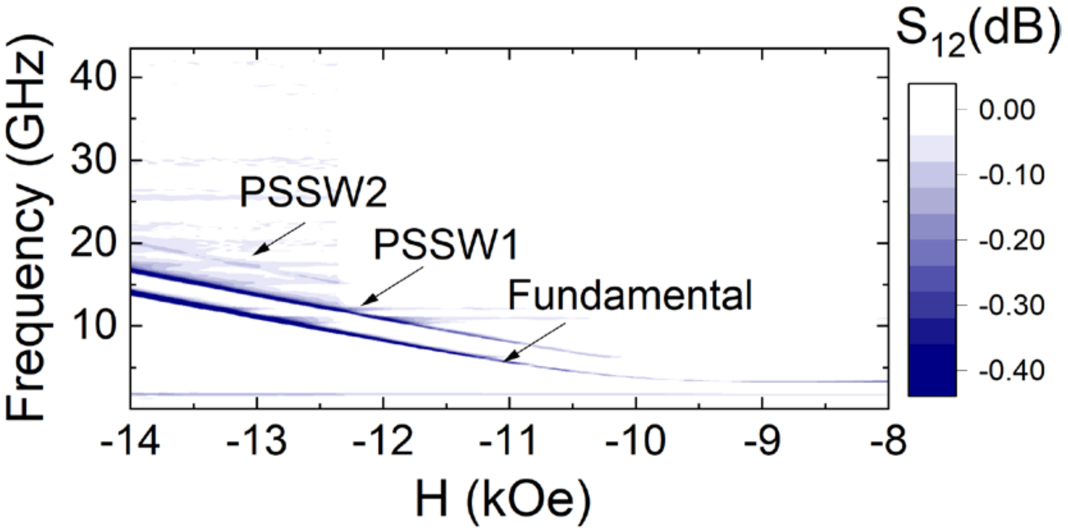
- Vector Network Analyser – Ferromagnetic Resonance (VNA-FMR) spectroscopy was used to measure the spin wave spectra with two PSSW modes detected in addition to FMR mode
- For the proper determination of A_{ex} the boundary conditions considered for analysis of the data is crucial
- Historically, the spin-wave resonance in thin magnetic films has been described on the basis of several models[1,2,3]



Kittel Model of Rigid Surface Pinning

- Spins are pinned at the surface, giving rise to PSSW excitations
- $$f_{PSSW} = \frac{\gamma}{2\pi}\left(H - 4\pi M_s + \frac{2A_{ex}}{M_s}\frac{p^2\pi^2}{t_{NiFe}^2}\right)$$

f_{PSSW} is PSSW frequency
H is external field



[1] C. Kittel, Phys. Rev. **110**, 1295 (1958)
[2] P. E. Wigen et al., Phys. Rev. Lett. **9**, 206 (1962).

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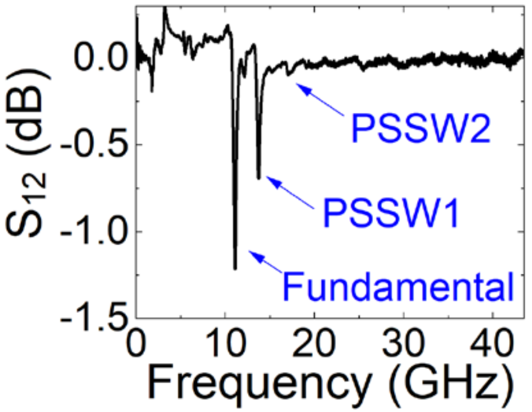
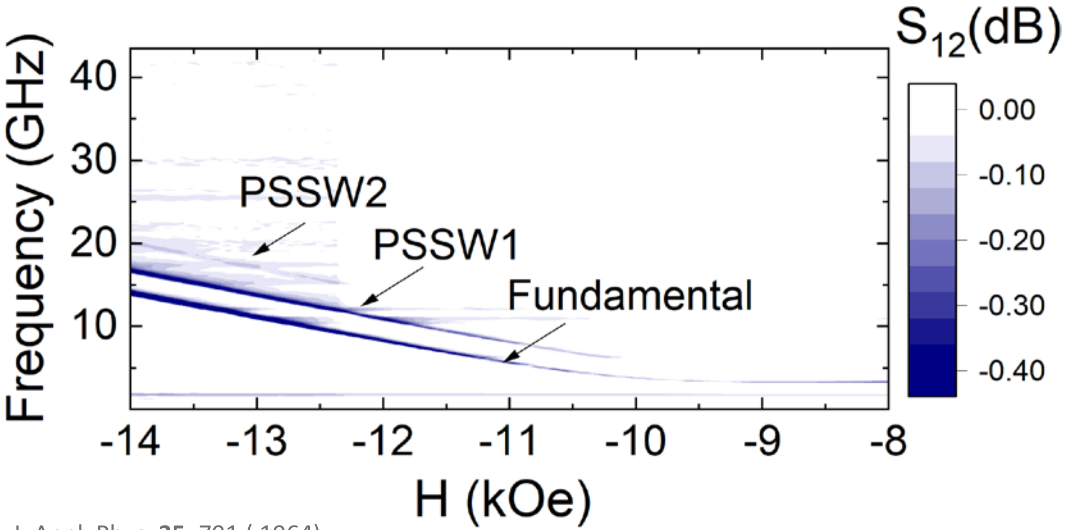


Generalised Wavevector Surface Pinning Model

- ❖ Spins are pinned at the surface, giving rise to PSSW excitations
- ❖ $f_{PSSW} = \frac{\gamma}{2\pi}\left(H - 4\pi M_s + \frac{2A_{ex}}{M_s} k_p^2\right)$

K_p is mode (starting at p =1)
δ is pinning parameter 0 < δ < 1
λ is wavelength

$$k_p = (p_k + \delta) = \frac{2\pi}{\lambda_p}$$



[1] C. F. Kooi at al., J. Appl. Phys. **35**, 791 (1964).
[2] H. Puszkarski, Prog. Surf. Sci. **9**, 191 (1979).
[3] A. Maksymowicz, Phys. Rev. B. **33**, 6045 (1986).

Interpretation of Spectra: Analytic Models

- Rigid surface pinning of the PSSW modes assumed
- Frequency of PSSWs related to external field with[1]

$$f_{PSSW} = \frac{\gamma}{2\pi}\left(H - 4\pi M_s + \frac{2A_{ex}}{M_{Eff}}\frac{p^2\pi^2}{t_{NiFe}^2}\right)$$

- **Striking result:**
  - Resonance data could not be fitted using a single A_{ex}
  - Analysis instead necessitates the introduction of an effective exchange constant $A_{ex,eff}$
  - $A_{ex,eff}$ varies with thickness, capping layer material and mode number p
- Inconsistent with physical expectation exchange constant is single valued for a FM material

Uncapped

Pt capped

Ta capped

[1] I. S. Maksymov and M. Kostylev, Phys. E Low-Dimensional Syst. Nanostructures **69**, 253 (2015).

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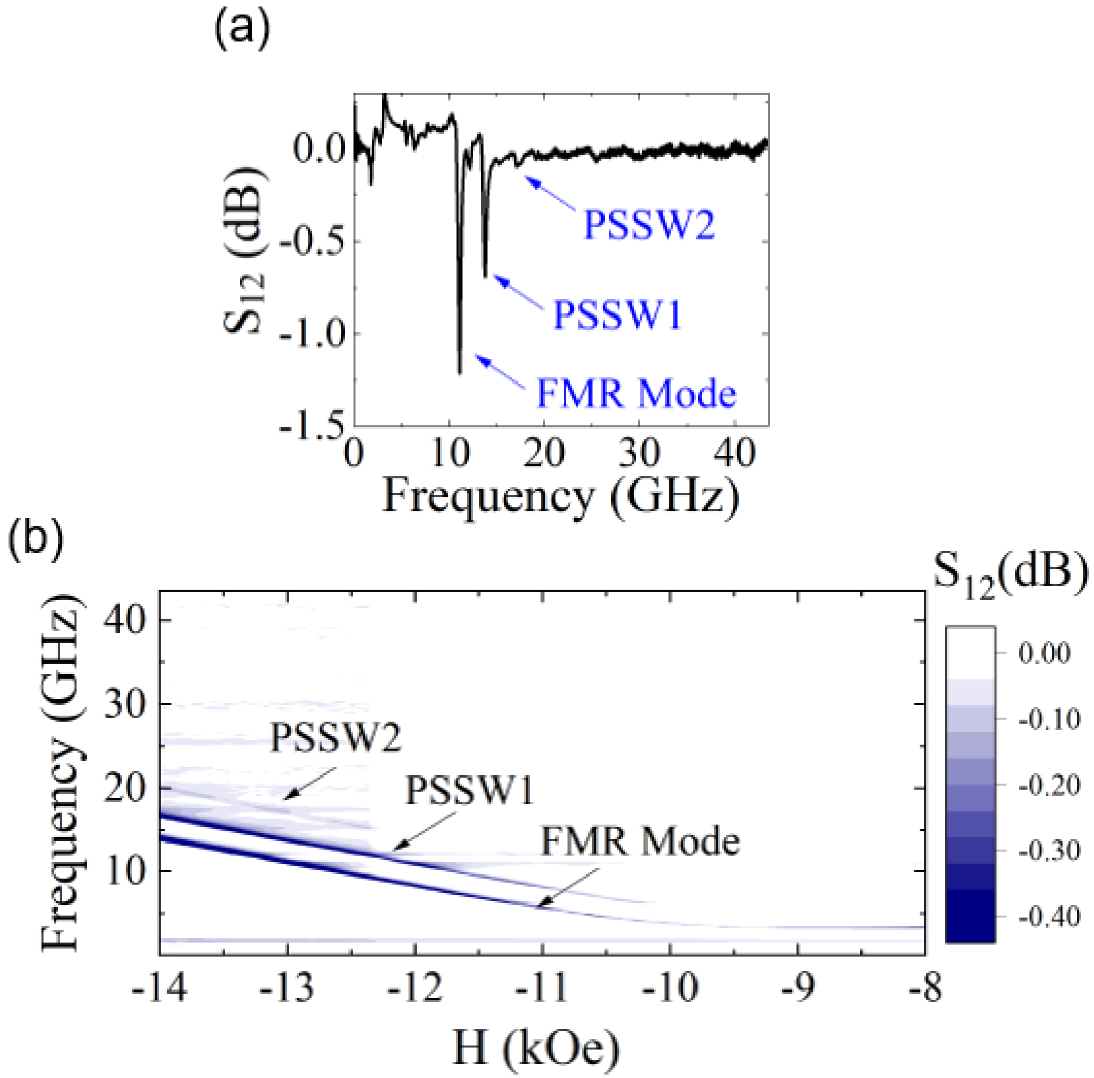
Wigen Model of Dynamic Pinning

- A surface layer of a few monolayers where the internal field differs from the bulk
- Leads to a *dynamic pinning* phenomena
- Simulations needed to explore this case



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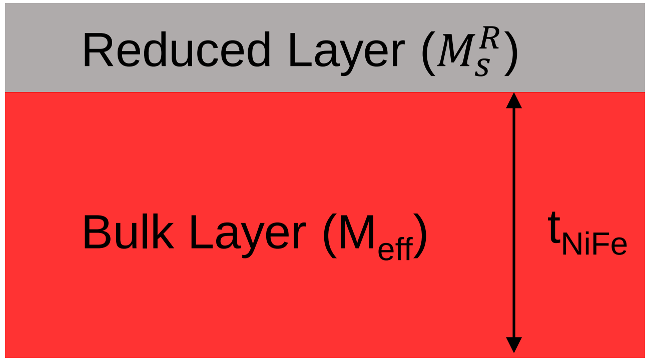
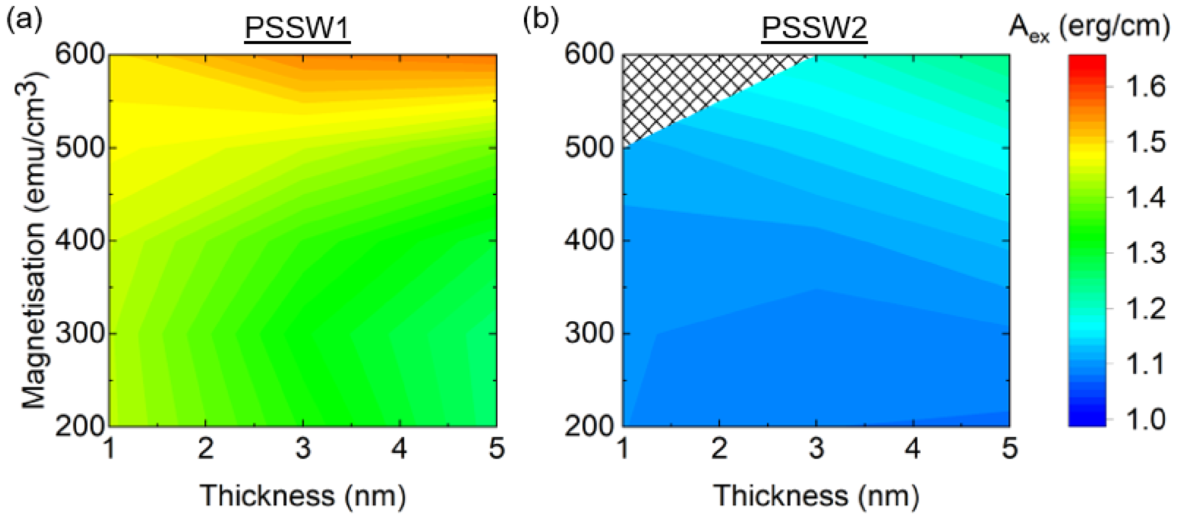
[2] P. E. Wigen et al., Phys. Rev. Lett. **9**, 206 (1962).
[3] C. F. Kooi et al., J. Appl. Phys. **35**, 791 (1964).

Interpretation of Spectra: Dynamic Pinning

- Performed Mumax^3 simulations[1] to model DP model
- Magnetic parameters chosen to be consistent with NiFe
  - Gilbert damping, α = 0.001 (to ensure high signal to noise)
  - A_{ex} = 1 to 1.6 x 10^{-6} erg/cm[2]
- Dynamic Pinning of spin waves is assumed
  - Generated through a surface layer of a few monolayers with a different magnetisation than the bulk
  - The Ta and Pt capped samples were simulated using reduced layer parameters $M_S^R \leq 500$ emu/cm^3 and t^R=5 nm (region of insensitivity ⟶)
  - The uncapped NiFe films, the approach of modelling antiferromagnets as detailed by De Clerq et al. was followed [3]



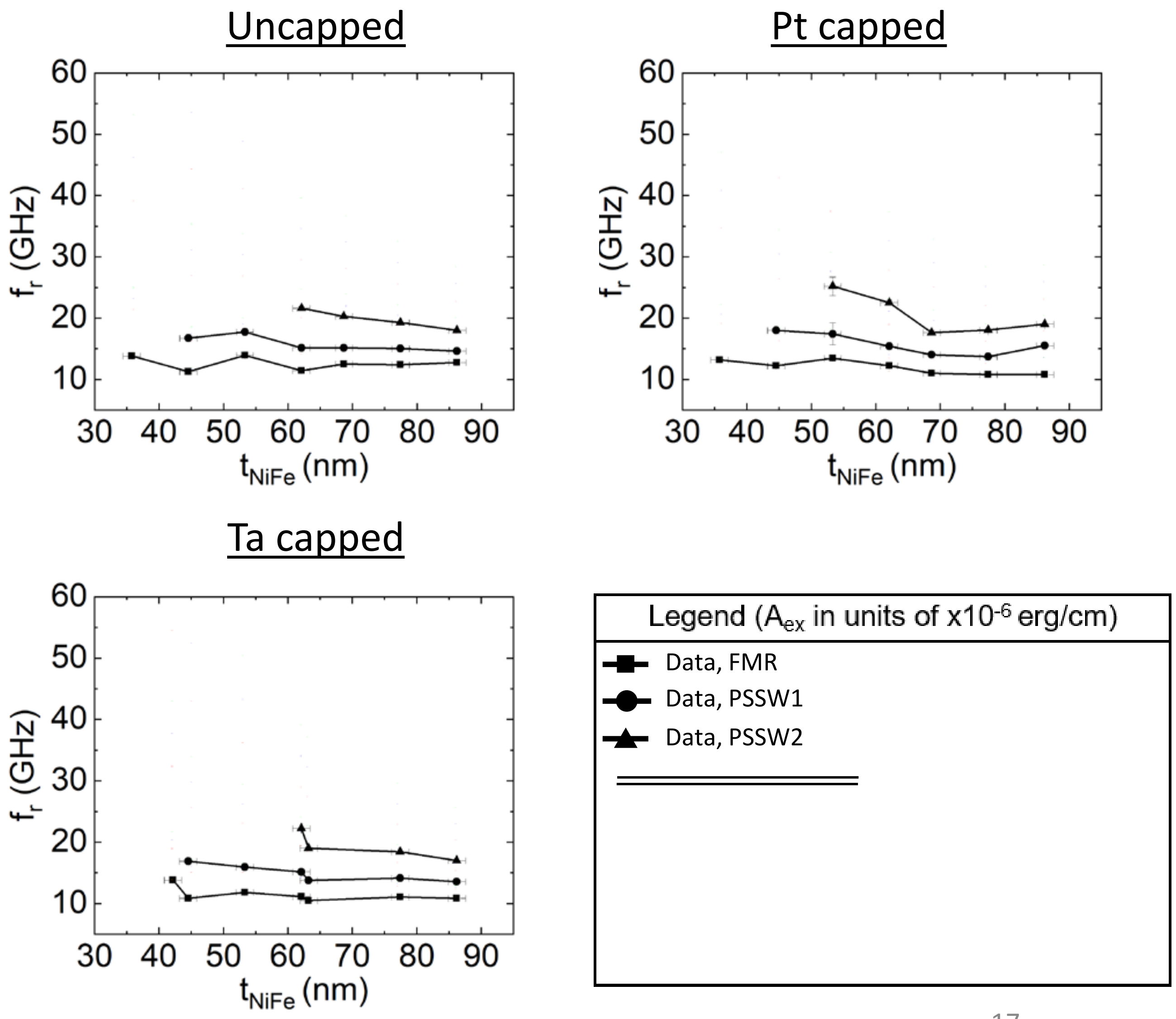


Sensitivity of the extracted A_{ex} for a Pt capped NiFe film with t_{NiFe} = 55 nm from comparison of simulation and experiment using a) PSSW1 and b) PSSW2. The hatched region in b) shows the conditions where a PSSW could not be observed in the simulation.

[1] A. Vansteenkiste et al., AIP Adv. **4**, 107133 (2014).
[2] J. M. D. Coey, *Magnetism and Magnetic Materials* (2010).
[3] J. De Clercq et al., J. Phys. D. Appl. Phys. **50**, 425002 (2017).

Interpretation of Spectra: Dynamic Pinning

- Dynamic Pinning of spin waves is assumed
  - Generated through a surface layer of a few monolayers with a different magnetisation than the bulk
- Performed Mumax^3 simulations to simulate DP model
- Magnetic parameters chosen to be consistent with NiFe
- DP model reproduces experimentally measured resonant frequencies of the PSSW modes



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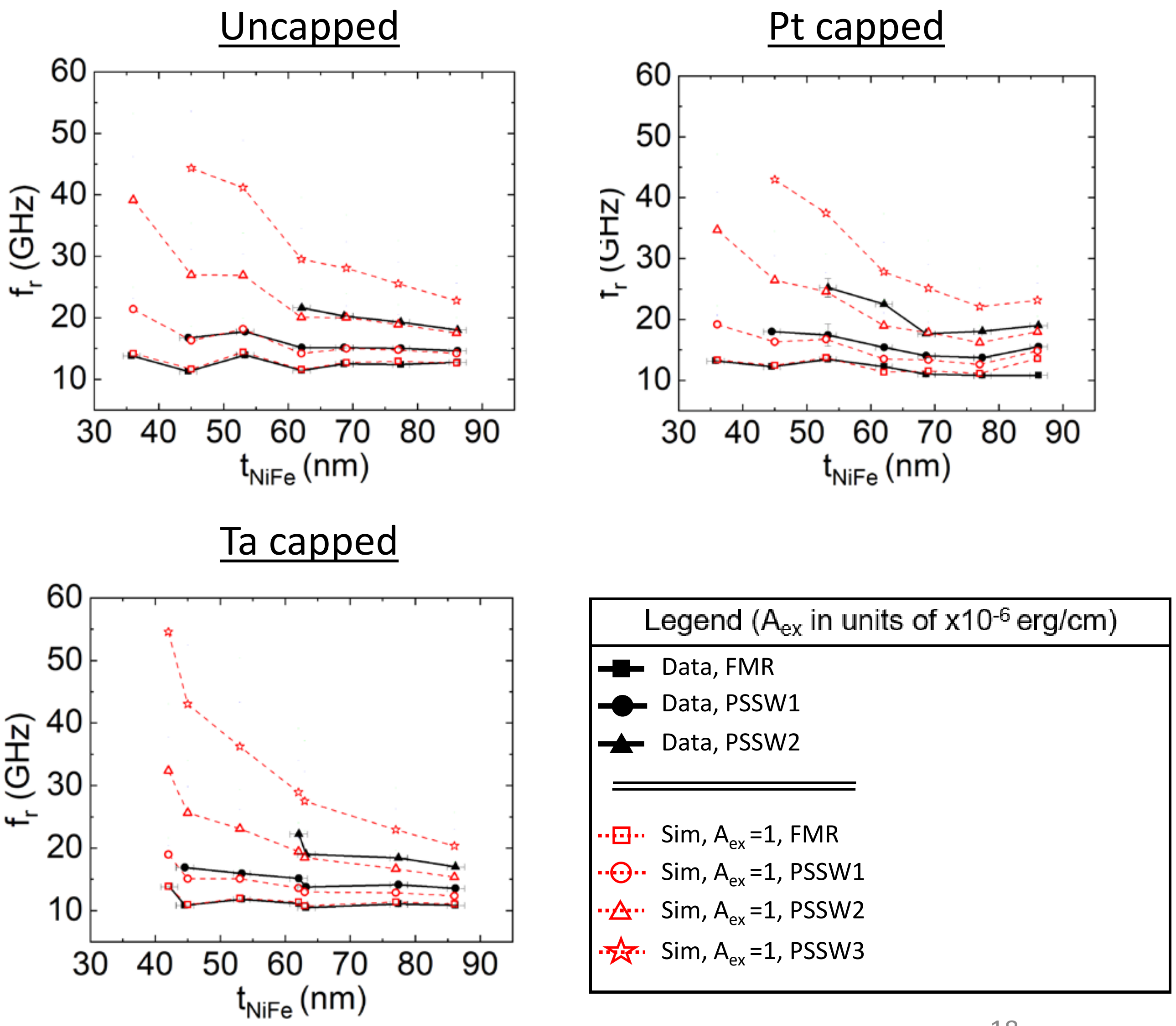

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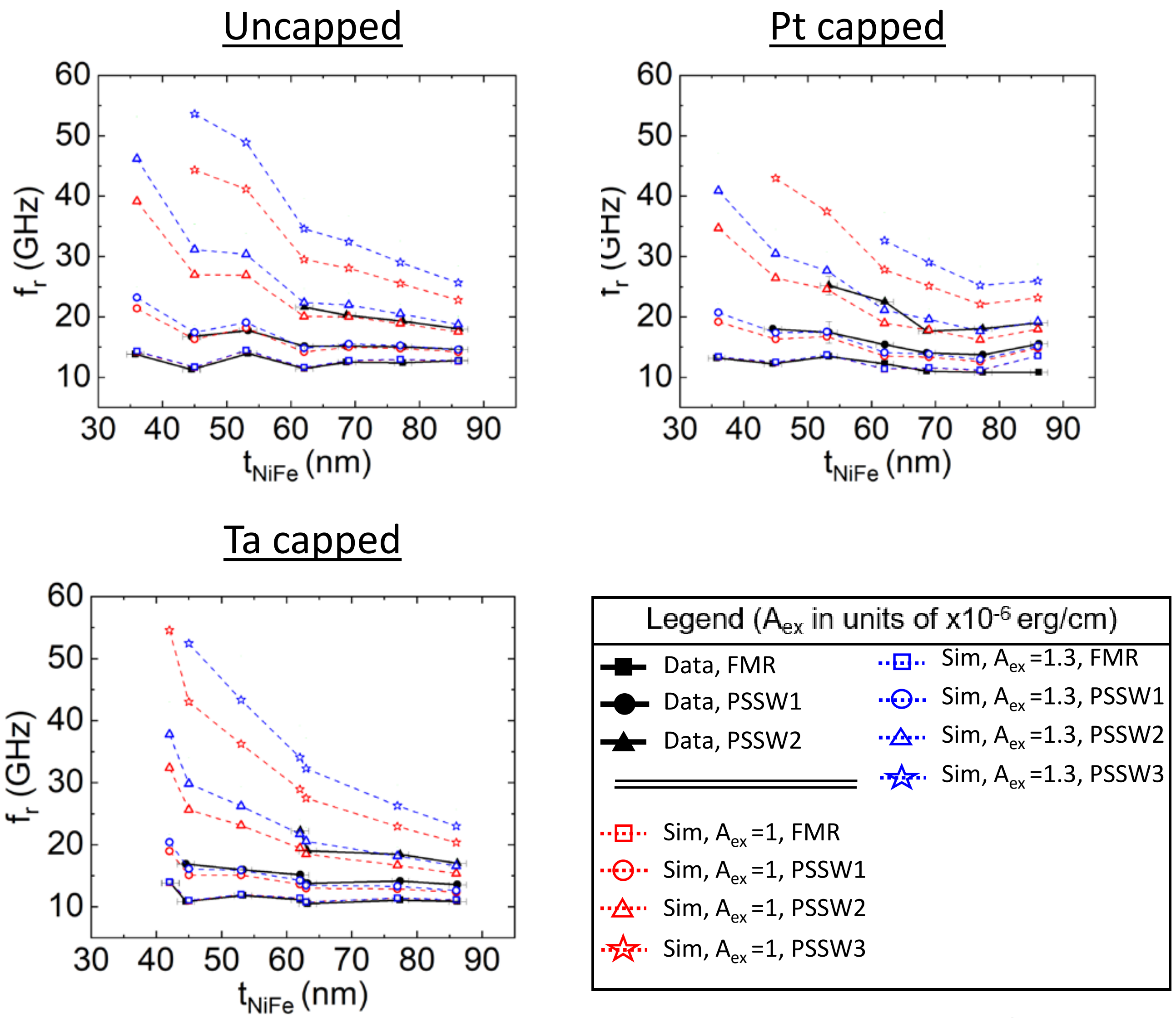

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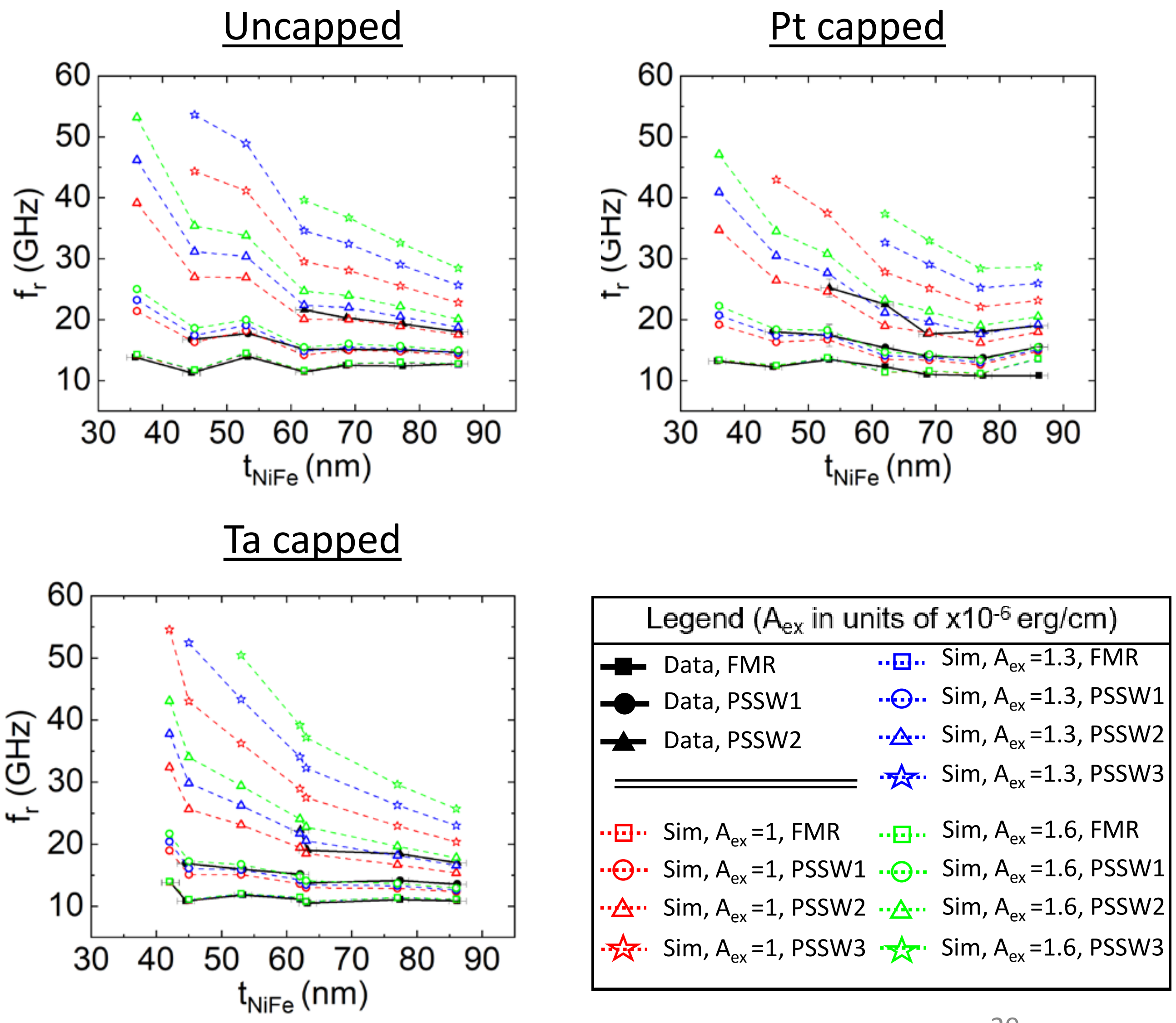

Determination of A_{ex}

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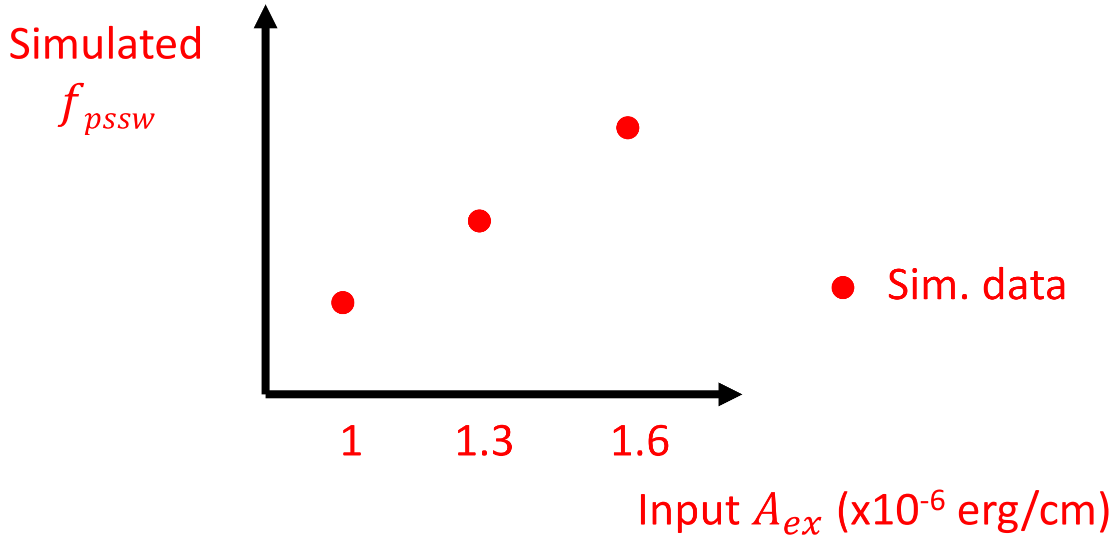

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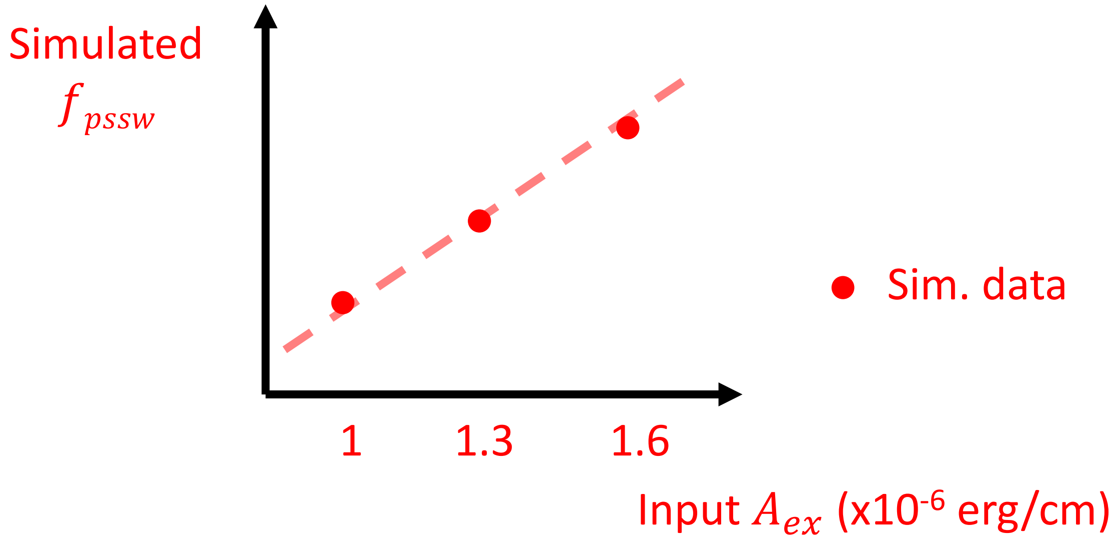

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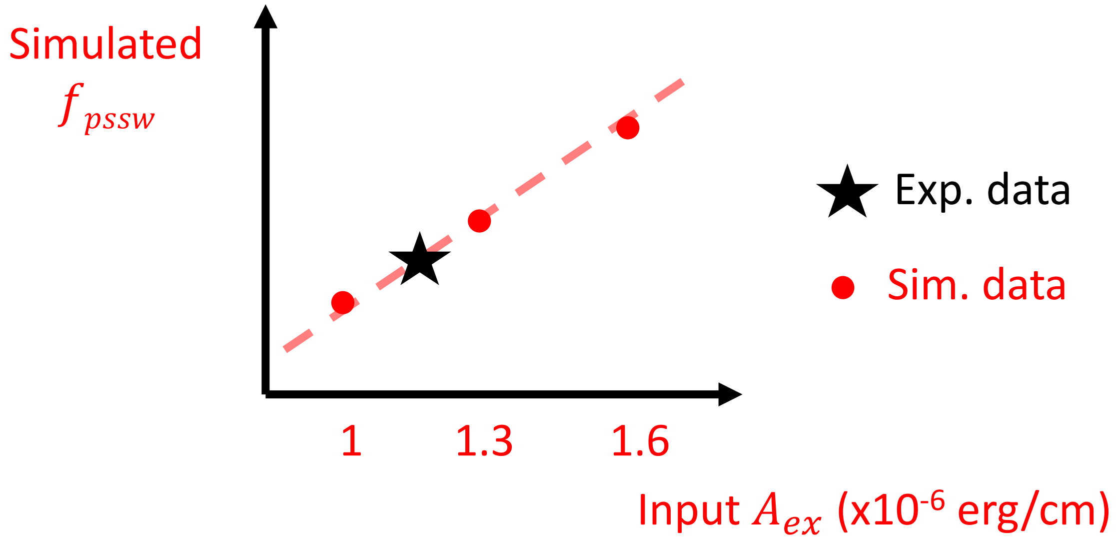


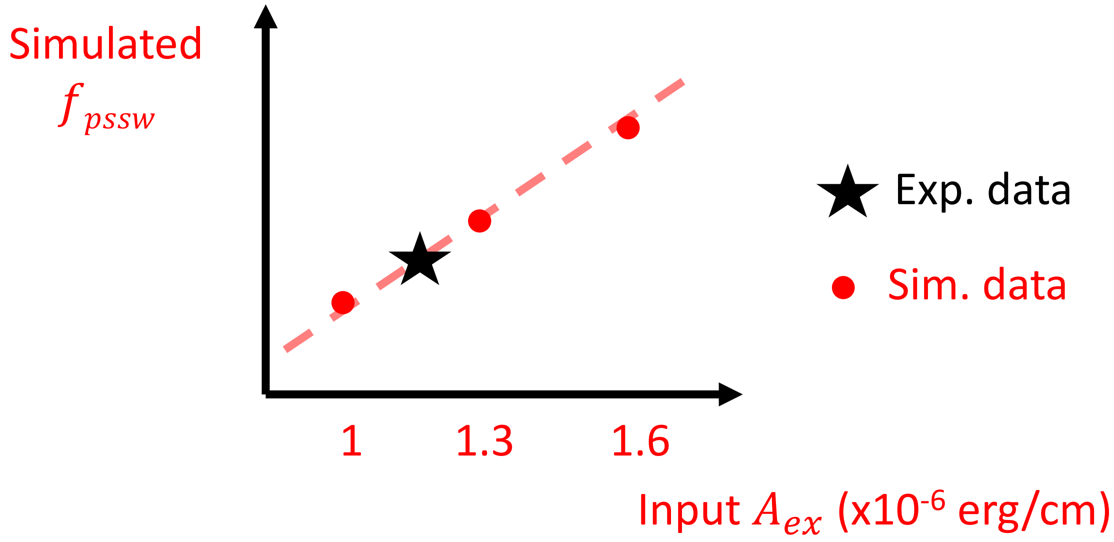
Determination of A_{ex}

- The optimal A_{ex} in each capping layer case was determined by comparing simulation and experimental measurement

- The variation of the determined A_{ex} from utilising different selections of PSSW modes was investigated

- Shorter wavelength PSSWs provided
  - Greater consistency across the range of capping layer materials explored.
  - Agreement with literature value
  - Similar to findings of $A_{ex,\,eff}$

- These data indicate extracted A_{ex} possesses a slight dependency on capping layer material



	A_{ex} (x10^{-6} erg/cm)			
Capping Layer	PSSW1 (t$_{NiFe}$ <55 nm)	PSSW1	PSSW2	All modes
Uncapped	1.0±0.2	1.2±0.2	1.1±0.1	1.12 ±0.16
Pt Capped	1.4±0.2	1.6±0.3	1.2±0.2	1.4±0.2
Ta Capped	1.4±0.1	1.7±0.3	1.3±0.2	1.5±0.2

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Summary

- The dynamic properties of a series of NiFe thin films with differing layer thickness and capping layers have been explored with PSSWs measured.
- A simple analysis based on Kittel model of Surface Pinning to extract a single value of A_{ex} is unable to describe the resonant frequencies of the measured PSSWs
- The Dynamic Pinning model proposed by Wigen is able to fully reproduce the experimental data
- Our results suggest that shorter wavelength, higher order PSSWs (eg. PSSW2) are less affected by the changes in dynamic pinning which we hypothesise is due to the larger angle between the spins compromising the PSSWs
- These data support the utility of using PSSWs to determine A_{ex} but show that care must be taken when applying this approach to the complex structures needed for spintronic devices.

<u>Take-away message</u>
The structure in which the layers where the exchange constant is being investigated can influence the measured exchange constant with more consistent values being obtained from an analysis of short-wavelength PSSWs

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- The whole NEST team →
- The Funding agencies
- Our collaborators everywhere:

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Questions