How to set up FMR sweeps based on static/conventional magnetometry data

Using SI units here: B [tesla] = μ_0(H+M)

<u>For purposes of setting up initial FMR sweeps:</u>

We can roughly estimate things easily by taking:

- $\gamma/2\pi$ ~ 28 GHz/T (pure spin gyromagnetic ratio)
- expressing $\mu_0 H$ and $\mu_0 M$ in units of tesla (1 T = 10 kOe); sometimes we drop the μ_0 prefactor but the units of H or M in tesla mean that it is implied
- M_S can be calculated from M(H) loop from SQUID, knowing film thickness and area, and using conversion:
  M_S[tesla] = M_S[emu/cm3] / 796

Remember that the Kittel resonance condition reverts to the Larmor precession formula in the absence of anisotropies:

$$f = \gamma\mu_0/2\pi * H$$

and the discussion below is about solving the equation of motion for spins in the presence of various anisotropies relative to the direction of applied field:

- Demag field $H_D = -N_d M$ where N_d is the demag factor (N = 1 for thin film is assumed below)
- In-plane anisotropy field H_K^{in} which is the preference for moment to point along one direction in the plane of the film. This is usually very small in materials like CoFeB and NiFe.
- Perpendicular Uniaxial anisotropy field $H_K^\perp = 2K_U/\mu_0 M_S$
  - In our convention here, $H_K^\perp > 0$ tends to point moment out of plane
  - if $H_K^\perp$ is large enough, namely larger than the demagnetization field, then $M_{EFF} = M_S - H_K^\perp < 0$, indicating we have PMA film
  - If $H_K^\perp = 0$ this implies an easy plane anisotropy: the material wants the moment to lie in the plane, but this does not specify any particular direction in-plane (that is specified by H_K^{in})
  - One can also have a tilted anisotropy in which $H_K^\perp$ is not enough to completely bring the magnetization out of plane.

Applied field Out of Plane (OOP) of film:

$$f_{RES} = \frac{\gamma\mu_0}{2\pi}(|H_{RES}| + H_K^\perp - M_S) = \frac{\gamma\mu_0}{2\pi}(|H_{RES}| - M_{EFF})$$

So, an $H_K^\perp > 0$ adds to the applied field, while the demag field $H_D = -M_S$ needs to be overcome in order to bring the moment out of plane and produce a strong resonance ($f_{RES} > 0$). Note that H_K and M_S cannot be separated in OOP FMR measurements, so in our examples below we express the combined M_{EFF} .

- M_{EFF} is directly measured in SQUID M(H) data along hard-axis:
  - PMA film: hard axis is in-plane, so in-plane saturation field = $H_K^\perp - M_S = -M_{EFF}$
  - IMA film: hard axis is out-of-plane, so OOP saturation field = $M_S - H_K^\perp = M_{EFF}$

Applied Field In Plane (IP) of film:

$$f_{RES} = \frac{\gamma\mu_0}{2\pi}\sqrt{\left(M_{EFF} + \mathrm{H}_K^{in} + |H_{RES}|\right)\left(\mathrm{H}_K^{in} + |H_{RES}|\right)}$$

H_K^{in} : in-plane anisotropy field; i.e., anisotropy between directions X and Y in the plane of film. $H_K^{in} > 0$ means it is collinear with external field.

The first term in the square root is the field seen trying to get the moment out of plane, and again M_{EFF} appears since it is the total perpendicular anisotropy (competition between demag and uniaxial anisotropies).

The second term in the square root is for the in-plane direction that is perpendicular to the external field.

We recover the familiar textbook Kittel equations for OOP and IP (Kittel's Intro to Solid State Physics, 5th Ed.) by ignoring $H_K^{\perp}$ and H_K^{IN} .

Translating these equations to PhaseFMR software:

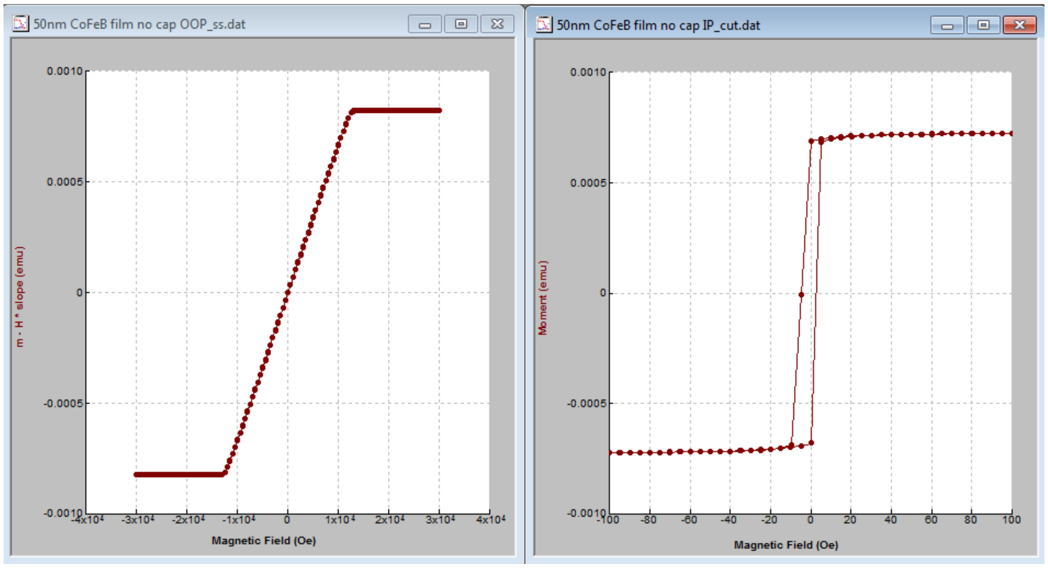
PhaseFMR	here	comments
IP M_S	**M_{EFF}**	Software doesn't know about $H_K^{\perp}$ so it is included in reported M_S
IP H_K	**H_K^{IN}**	
OOP M_S	**M_S**	You can manually enter an HK (=$H_K^{\perp}$) in the software; we choose to leave that H_K=0 so that reported M_S is M_{EFF}
OOP H_K	**$H_K^{\perp}$**	

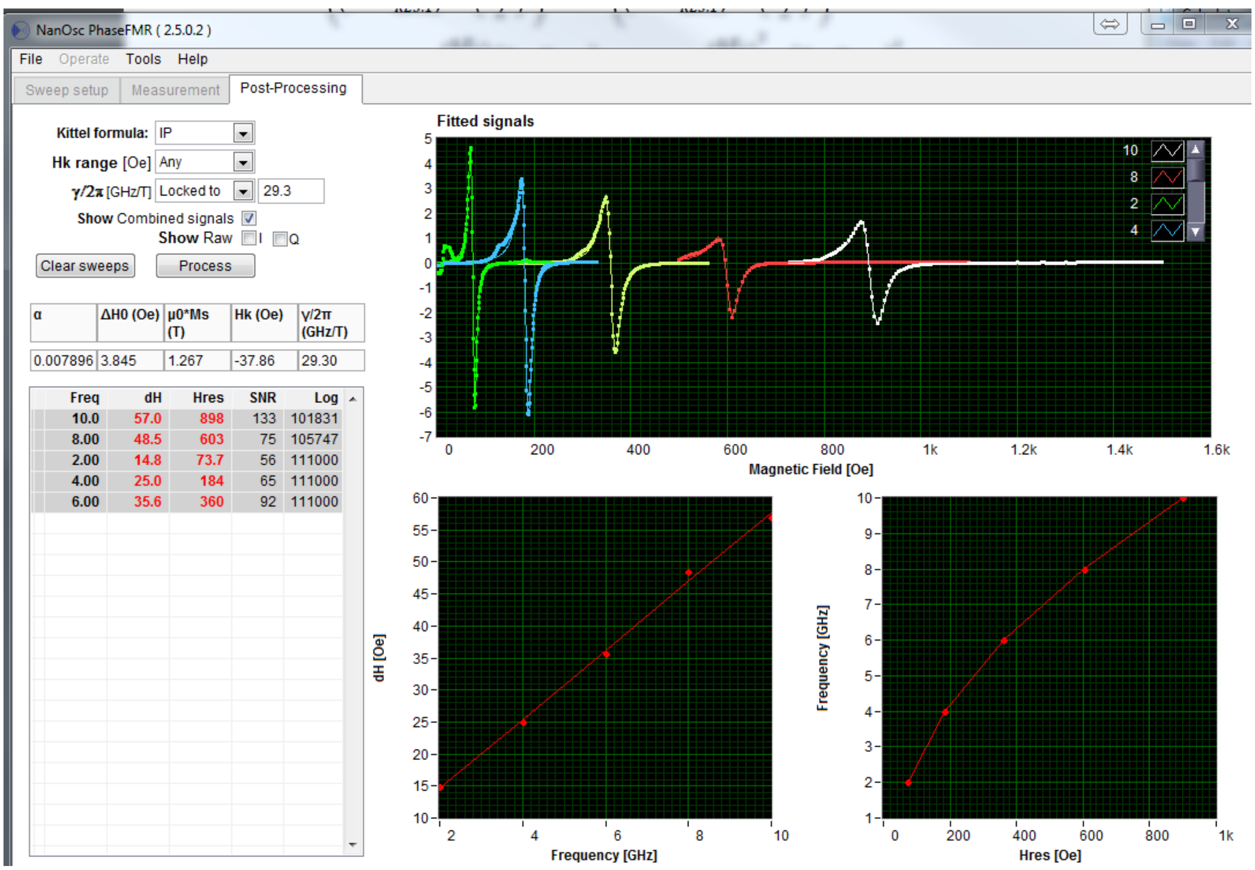
IP Example for IMA CoFeB film (50nm thick)

From SQUID: OOP saturation field = $\mu_o M_{EFF}$ = 1.32 T

From FMR: $\mu_o M_{EFF}$ = 1.267 T ($\gamma/2\pi$ = 29.3 GHz/T taken from Shaw(2015))

(HK_{in} may be due to magnet remanence?)



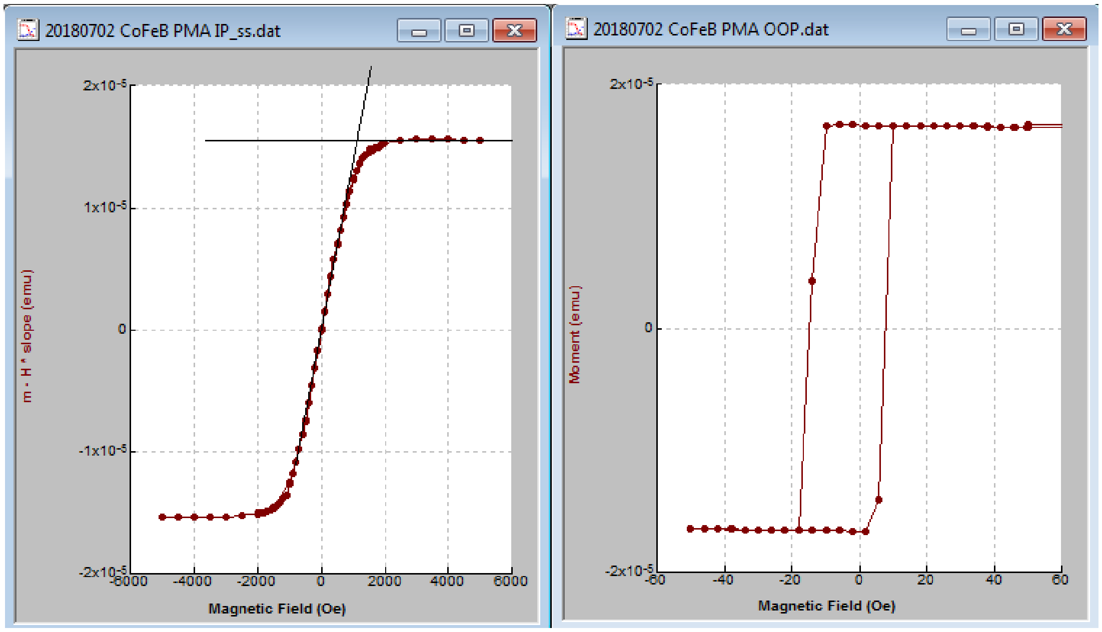


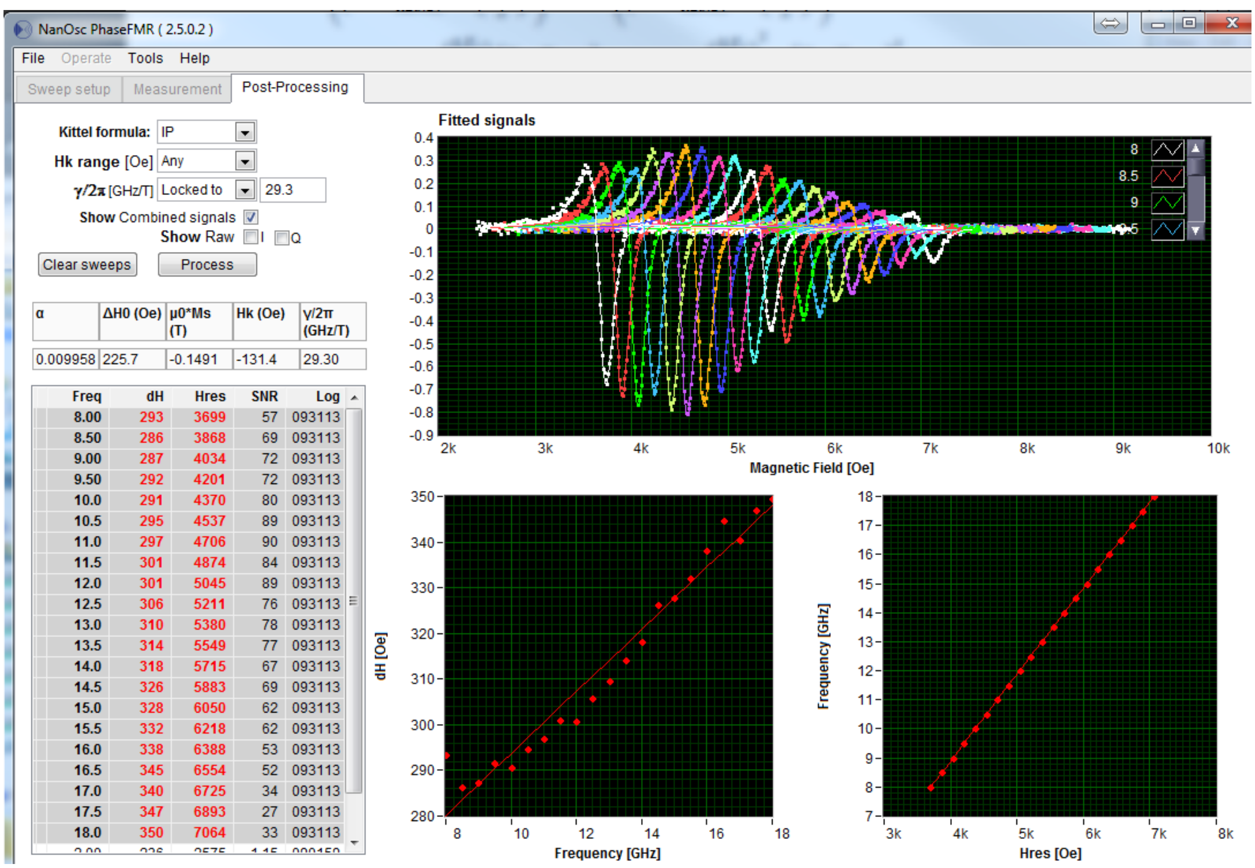
IP Example for PMA CoFeB film:

From SQUID: IP saturation field = - $\mu_o M_{EFF}$ = 0.154 T

From FMR: $\mu_o M_{EFF}$ = $\mu_o M_S$ (in PhaseFMR) = -0.15 T

Reminder: in PhaseFMR below, H_K is actually H_K^{in} because we're doing IP analysis.



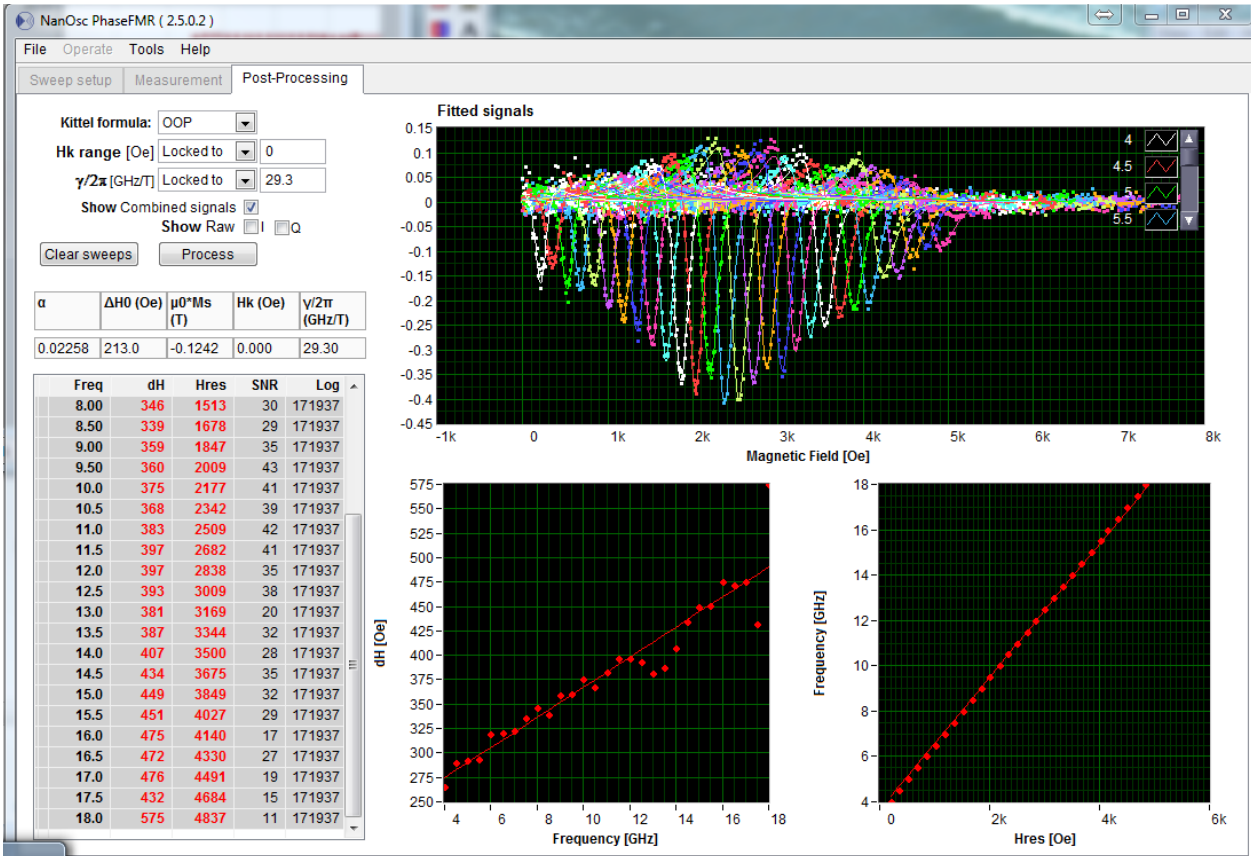


<u>OOP Example for PMA CoFeB film (same one as above):</u>

From SQUID: IP saturation field = $-\mu_o M_{EFF} = 0.154$ T

From FMR: $\mu_o M_{EFF} = -0.124$ T

(Agreement not good, may need to remeasure: we need to resolve this before publishing as an app note)

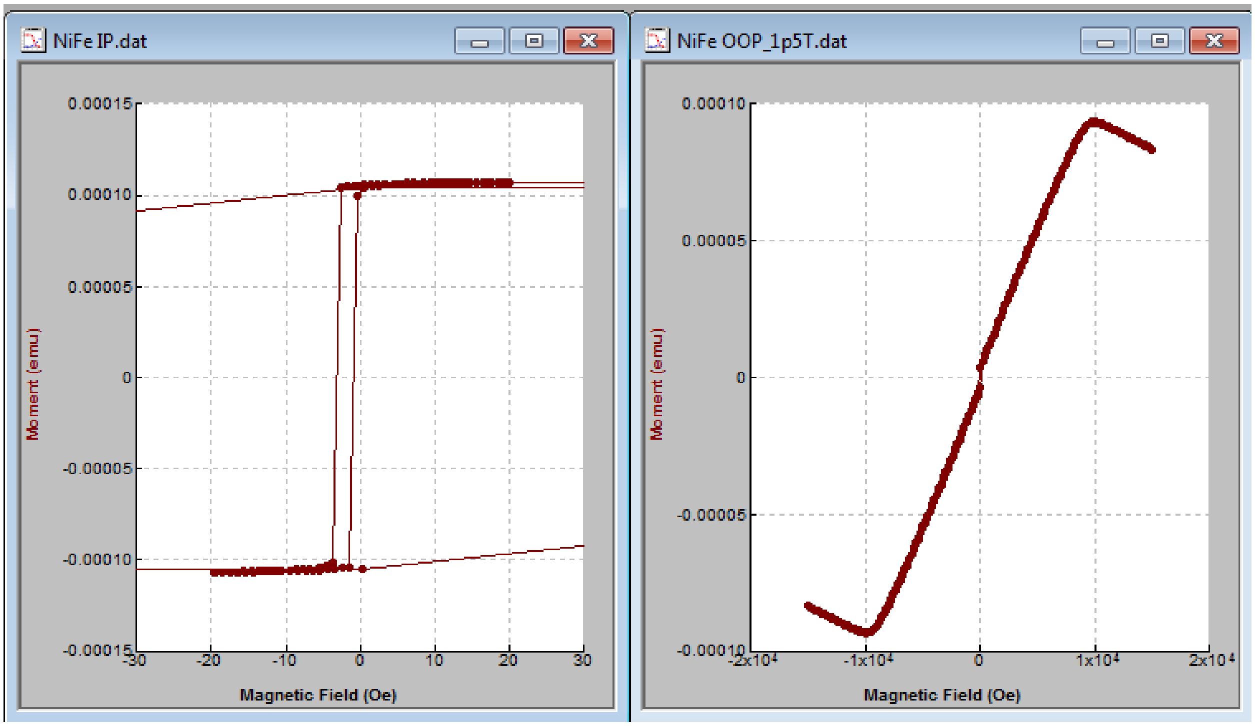


IP Example for Permalloy reference sample NiFe 10nm / Ta 5nm (sent in CryoFMR User Kit):

Measured in-plane in “hard” direction (Sharpie line is perp. to H_{DC}); fitted $H_K < 0$ validates this

From SQUID: OOP saturation field = $\mu_o M_{EFF}$ = 0.91 T (intersect lines from 0-0.6 T and 1.1-1.5T)

From FMR: $\mu_o M_{EFF}$ = 0.90 T



Sweep setup | Measurement | Post-Processing

Kittel formula: IP

Hk range [Oe] Any

γ/2π [GHz/T] Fitted

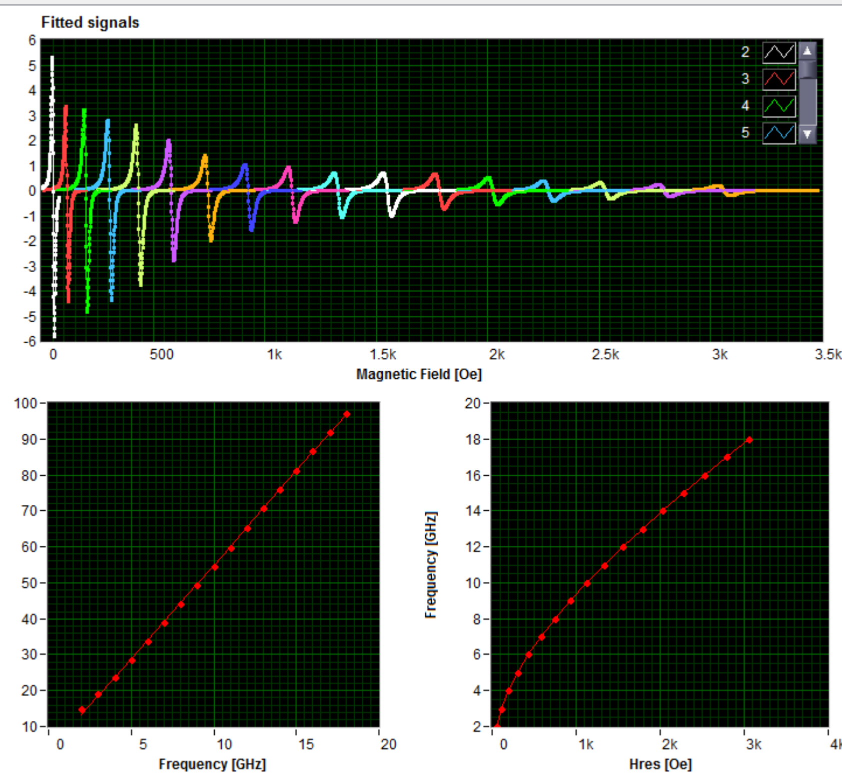
Show Combined signals ☑

Show Raw ☐ I ☐ Q

Clear sweeps | Process

α	ΔH0 (Oe)	μ0*Ms (T)	Hk (Oe)	γ/2π (GHz/T)
0.007702	2.946	0.9042	-2.490	29.59

Freq	dH	Hres	SNR	Log
2.00	14.9	52.7	93	205532
3.00	19.2	115	194	205532
4.00	23.7	200	317	205532
5.00	28.5	308	424	205532
6.00	33.7	436	562	205532
7.00	38.8	584	697	205532
8.00	44.1	749	828	205532
9.00	49.3	930	961	205532
10.0	54.5	1126	1129	205532
11.0	59.8	1334	1291	205532
12.0	65.2	1555	1540	205532
13.0	70.6	1785	1684	205532
14.0	75.9	2025	1498	205532
15.0	81.2	2273	1675	205532
16.0	86.5	2529	1285	205532
17.0	91.8	2792	840	205532
18.0	97.1	3060	856	205532



<u>OOP Example for Permalloy reference sample</u>