Heating properties of Fe_3O_4 nanoparticles dispersed in agarose

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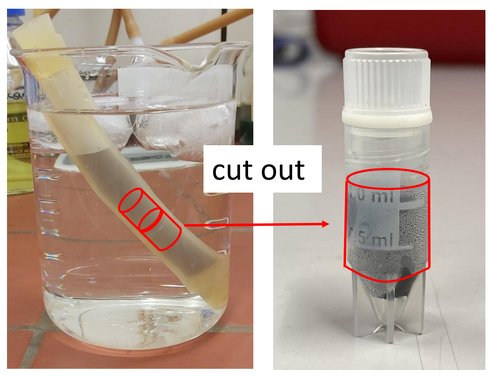
Motivation

Magnetic particle hyperthermia (MPH) has emerged as a promising therapeutic method for local treatment of cancer cells. Therefore, magnetic nanoparticles (MNPs) are exposed to an external alternating magnetic field in such a way that lethal temperatures for the tumor cell of at least 41°C-45°C are reached. The heating properties of MNPs are strongly dependent on the intrinsic parameters such as particle structure and size, as it significantly influences the domain state of the particles and therefore the magnetic behavior.
Additionally, external factors such as magnetic field amplitude and frequency also play a major role. Magnetite exhibits excellent magnetic properties besides its biocompatibility, which is why further investigations are required [1].

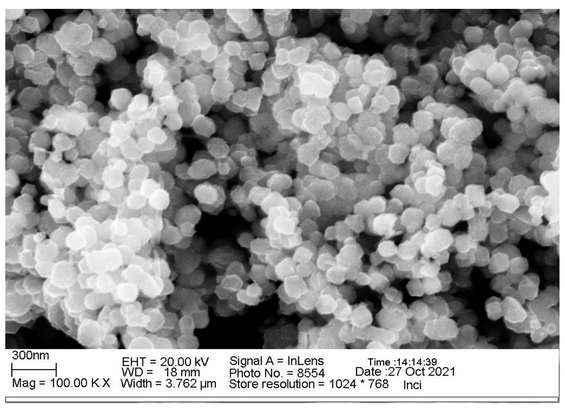
Sample preparation

Batch	Sample name	C_{NP} in $\frac{mg}{ml}$	$C_{Agarose}$ in $\frac{mg}{ml}$
1	H03	7.22	10
1	H04	7.22	10
2	H05	4.49	10
2	H06	4.49	10
3	H07	7.2	10
3	H08	7.2	10
4	H09	16.81	10
4	H10	16.81	10
5	H11	13.02	10
5	H12	13.02	10
6	H13	9.16	5
6	H14	9.16	5
7	H15	12.43	15
7	H16	12.43	15

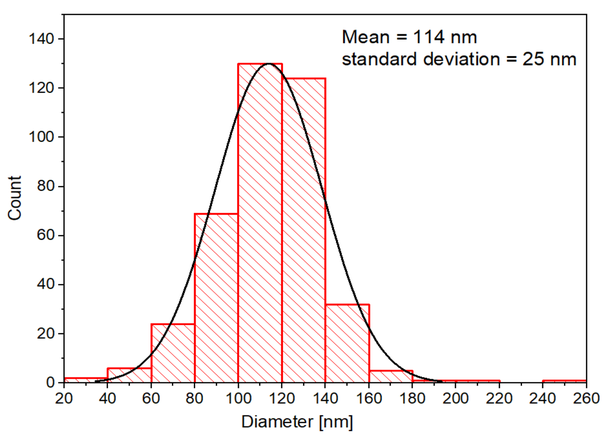


- Two samples per batch
- Homogeneous concentration profile
- Fe_3O_4 NP concentration determined by **PPMS:** *Physical Property Measurement System*

SEM characterization [3]



Size distribution of 400 MNPs



$$r_{\ single \rightarrow multi\ domain} \approx 9\frac{\sqrt{AK_u}}{\mu_0 M_S^2} \approx 45.2\ nm$$

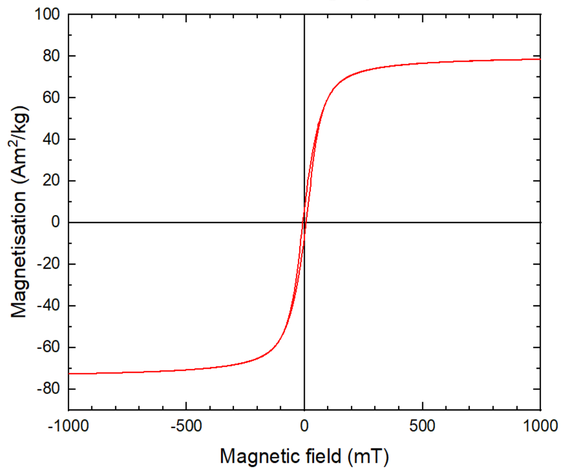
$$r_{\text{superparamagnetism}} \approx \left(\frac{9k_BT}{K_u}\right)^{\frac{1}{3}} \approx 7.2\ nm$$

$$r_{particle} = 57\ nm$$

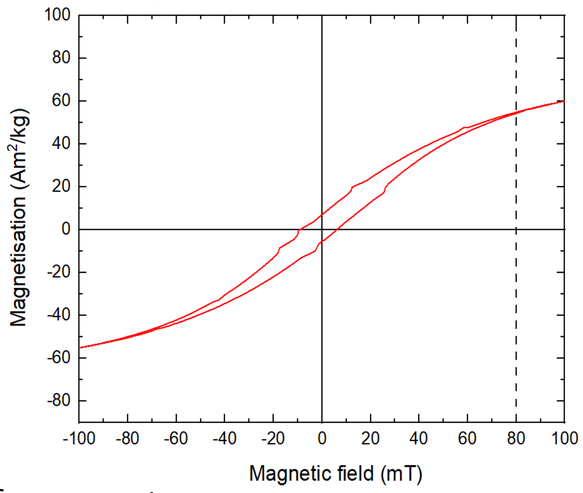
- MNPs are mainly multi domain
- Heating effect due to hysteresis loss
- Neel, Brown relaxation may take place due to size distribiution

Magnetic properties

Hysteresis of Fe_3O_4 powder



Enlarged representation of hysteresis



- Hysteresis curve indicates a multi domain ferromagnet
- Saturation magnetization M_S=79.6 Am^2/kg
- Coercivity: $\mu_0 H_C$= 8.4 mT (H_C= 6.7 kA/m)
- Irreversibility point at 80 mT

References

[1] B. Mehdaoui et al., Adv. Funct. Mater., 21: 4573-4581 (2011)
[2] Silvio Dutz, Rudolf Hergt Nanotechnology 25: 452001 (2014)
[3] O'Handley, Robert C. Modern magnetic materials: principles and applications. Wiley, (2000)
[4] E. Myrovali et al. ACS Applied Materials & Interfaces 13: 21602–21612 (2021)
[5] S. Ota et al., J. Magn. Magn. Mater., 538: 168313 (2021)

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Conclusion

- Ferromagnetic mostly multi domain Fe_3O_4 NPs with mean diameter of 114 nm
- Heating temperature up to 60°C
- Mean SLP≈140 W/g , which is within the range of commercially available NPs [5]
- Concentration of agarose and therefore viscosity has no influence on heating effect
- SLP is proportional to frequency
- No observation of a constant exponent α as predicted → reaching irreversibility point with increasing magnetic field

Specific loss power mathematical principles [2]

- For $H < H_c$: $SLP \propto f\ H^{\alpha=3}$
- For $H > H_c$: $SLP \propto f\ \left(1 - \left(\frac{H_c}{H}\right)^{\alpha=5}\right)$

We expect: $\alpha \leq 3$

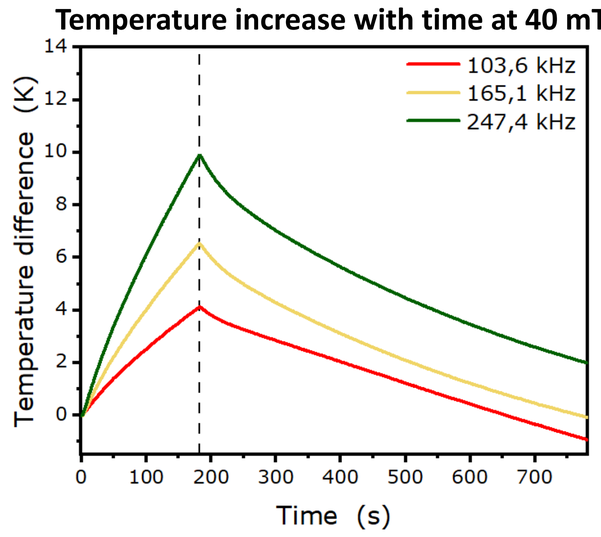
Initial Slope Methode → adiabatic approach

$$SLP = \frac{C}{m_{MNP}}\frac{\Delta T}{\Delta t}$$

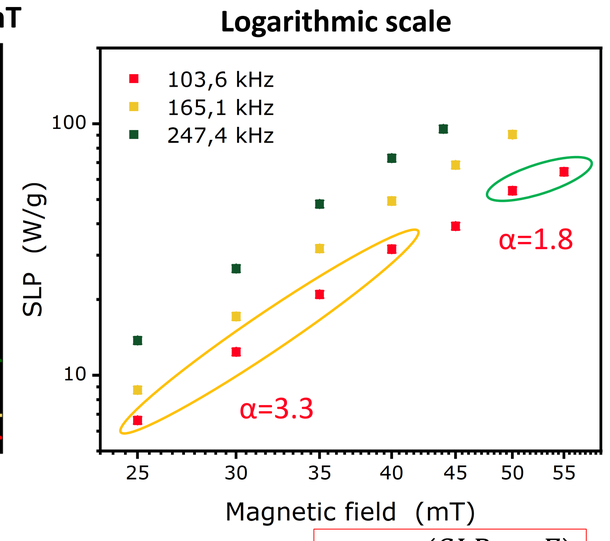
SLP results

Sample H05: C_{NP}=4.5 mg/ml & $C_{Agarose}$=10 mg/ml

Temperature increase with time at 40 mT



Logarithmic scale

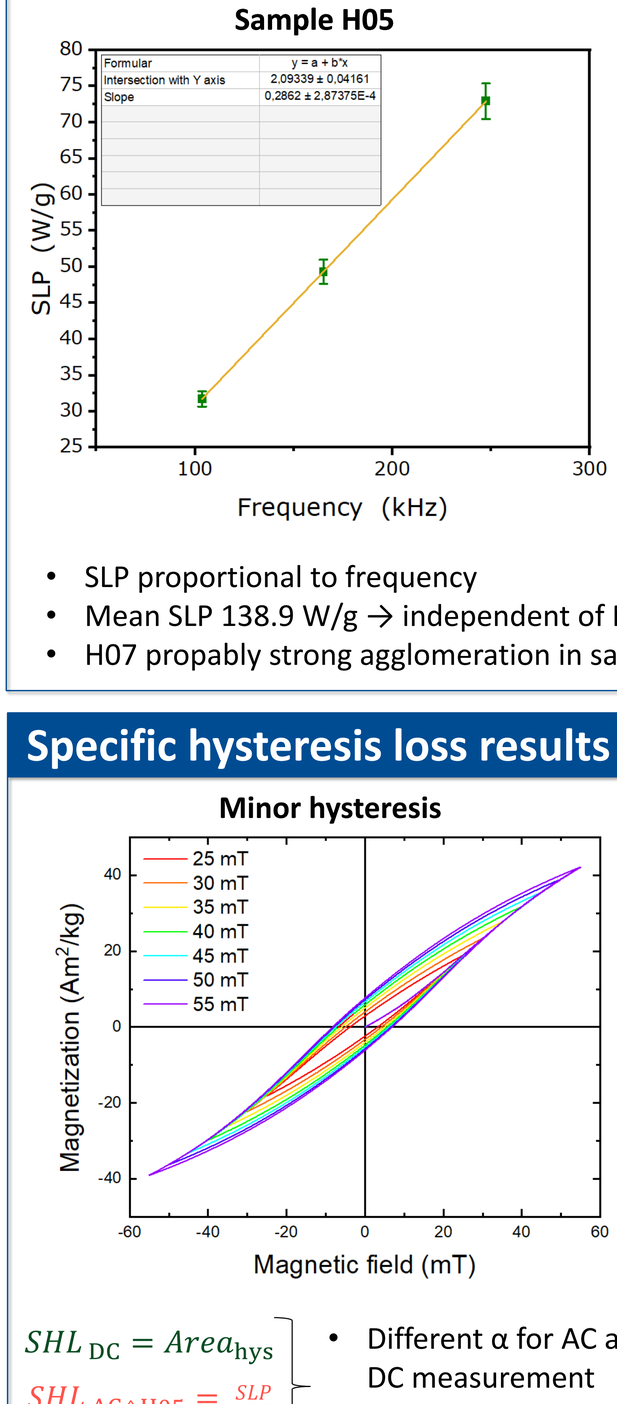


- No constant exponent α
- No stable temperature in measurement device, due to cooling, which effects SLP at low magnetic fields more

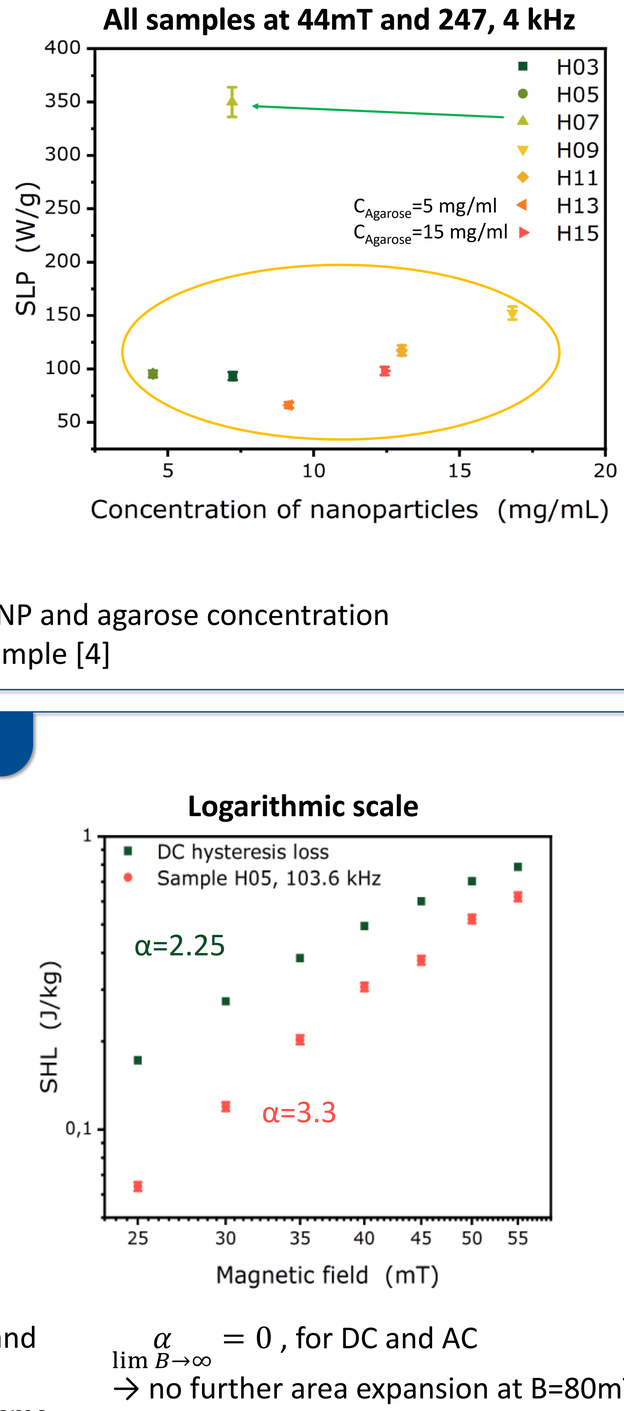
$$\alpha = \frac{ln\left(\frac{SLP_2 - F}{SLP_1 - F}\right)}{ln\left(\frac{H_2}{H_1}\right)}$$

Influence of frequency and agarose concentration on SLP

Sample H05



All samples at 44mT and 247, 4 kHz



- SLP proportional to frequency
- Mean SLP 138.9 W/g → independent of NP and agarose concentration
- H07 propably strong agglomeration in sample [4]

Specific hysteresis loss results

Minor hysteresis

Logarithmic scale

$$SHL_{\text{DC}} = Area_{\text{hys}}$$

$$SHL_{\text{AC}\triangleq\text{H05}} = \frac{SLP}{f}$$

- Different α for AC and DC measurement
- Unknown mechanisms may have an influence

$$\lim_{B\to\infty} \alpha = 0$$, for DC and AC
→ no further area expansion at B=80mT
→ saturation