Dynamics of a magnetic nanoparticle with cubic anisotropy in a viscous liquid

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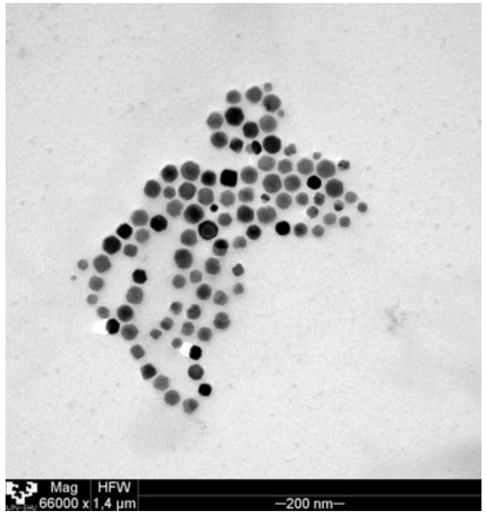
Importance of bacterial magnetosomes

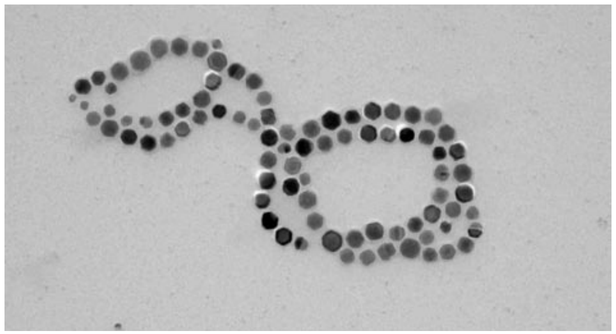
1. Nanoparticles of the best quality:

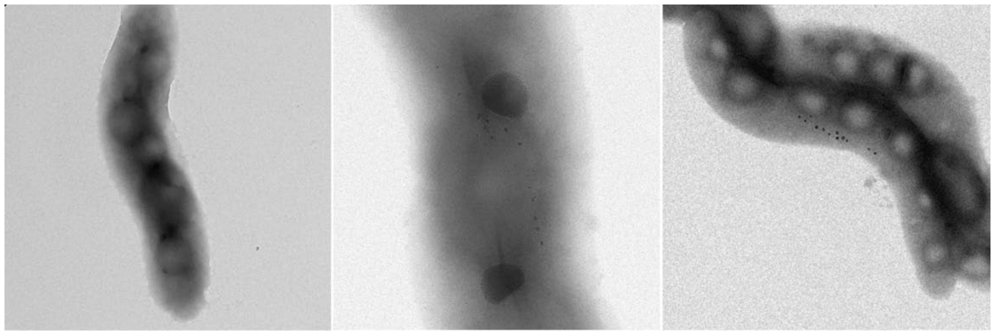
- a) perfect crystalline structure
- b) narrow size distribution
- c) quasi-spherical shape
- d) biocompatibility



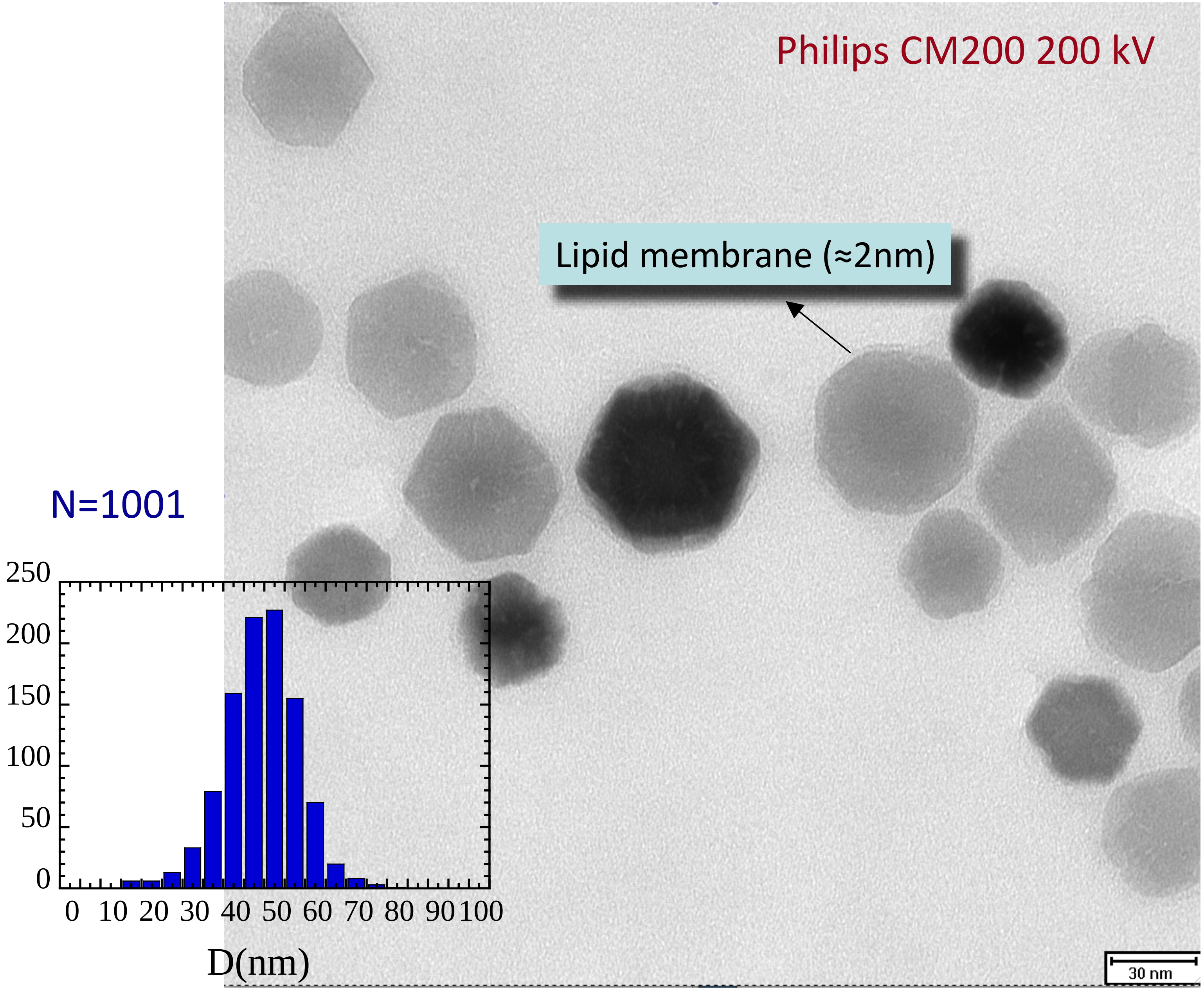
2. Promising applications in biomedicine:

- a) targeted drag delivery
- b) magnetic nanoparticle hyperthermia
- c) sintering of biocompatible polymers

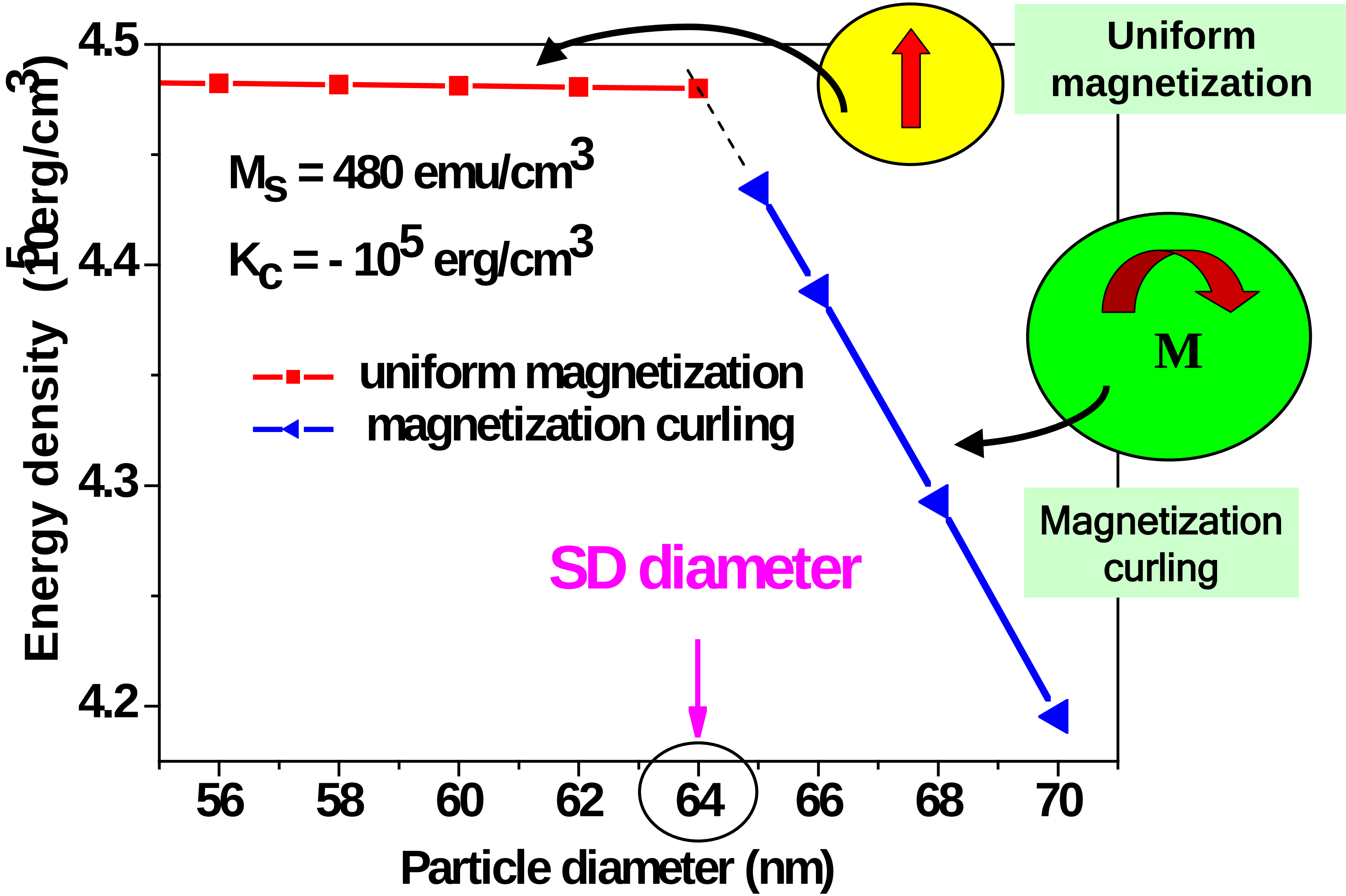




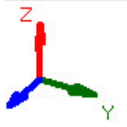
TRANSMISSION ELECTRON MICROSCOPY



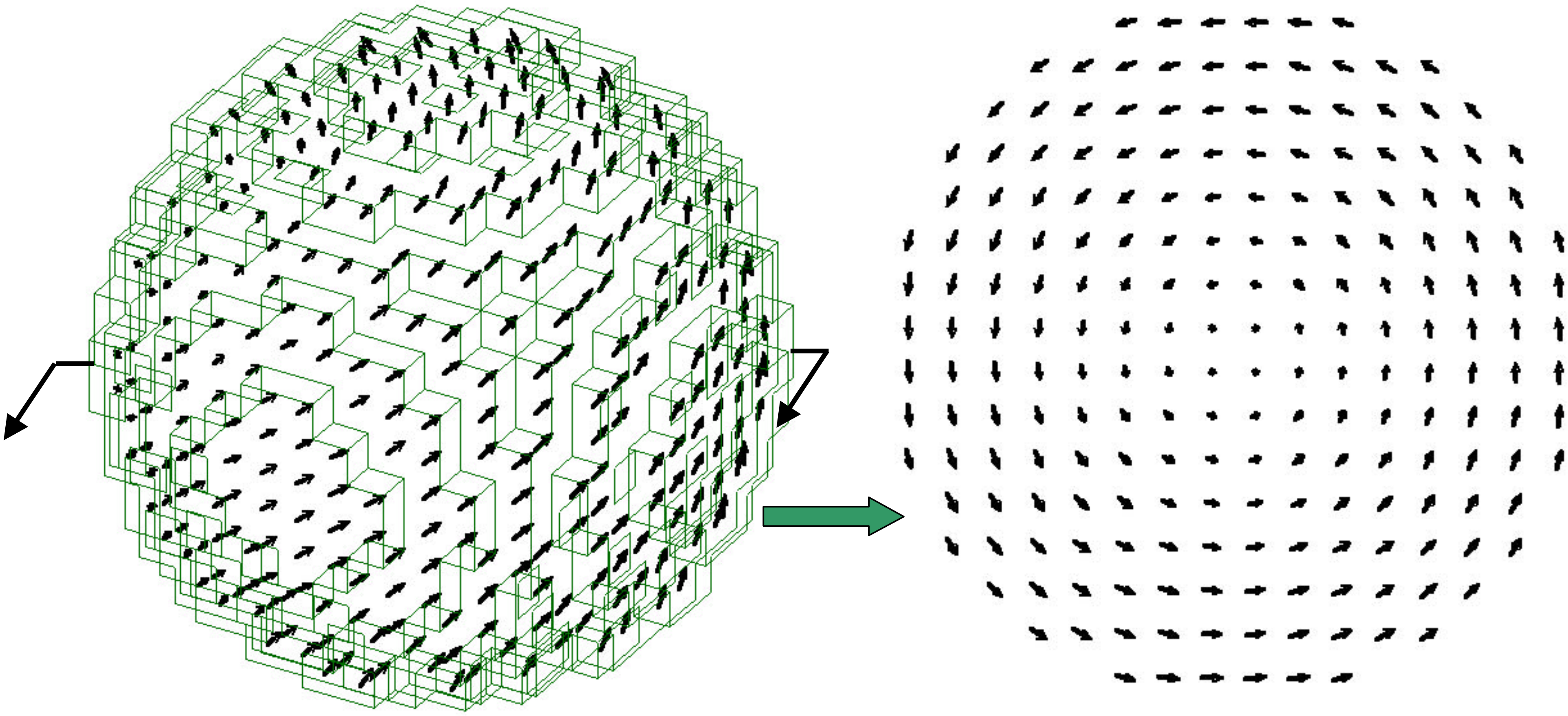
Magnetic diagram of the lowest energy states



Micromagnetic numerical simulation, $D > d_c$

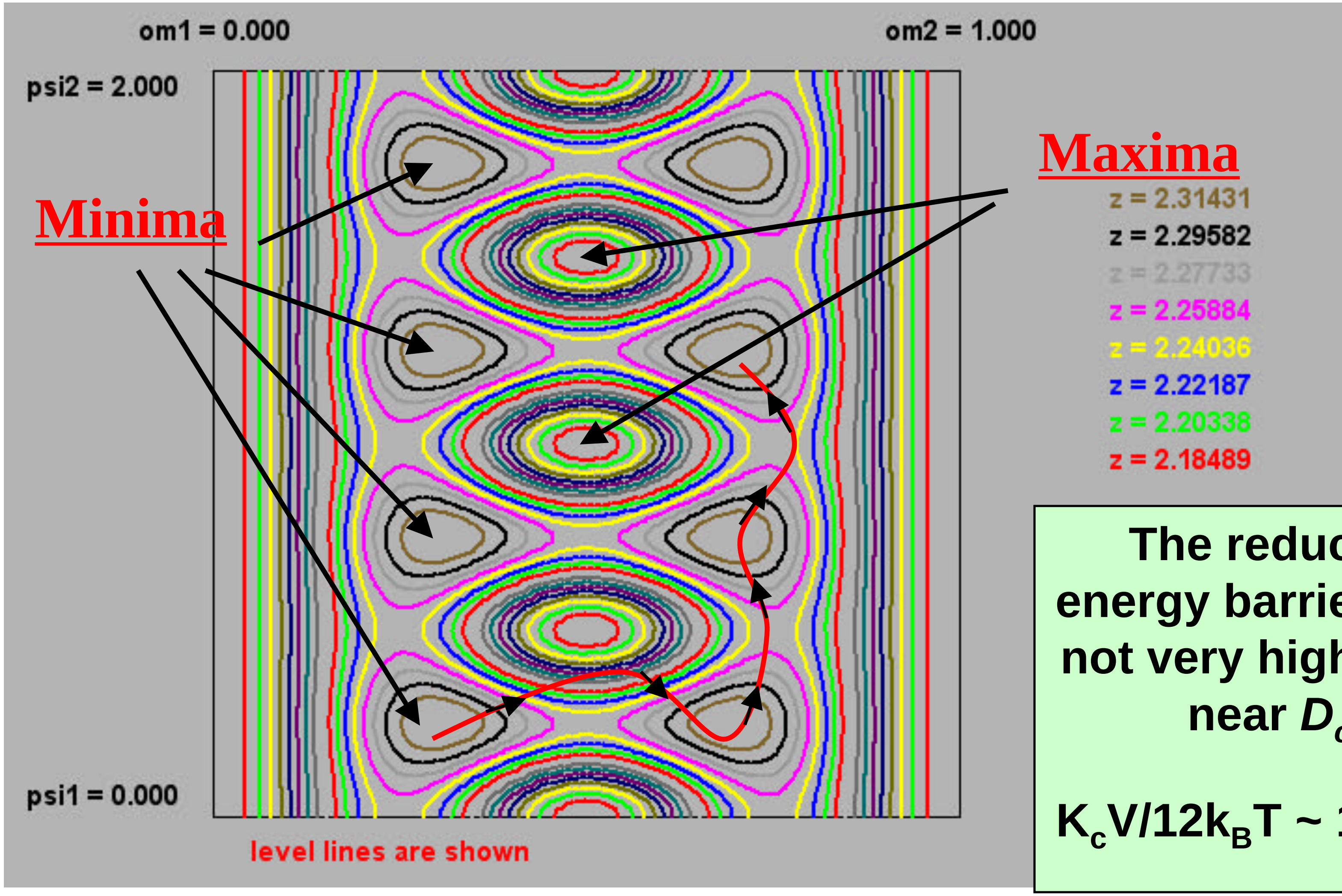


$K = -10^5$ erg/cm^3 $M_s = 480$ emu/cm^3



Magnetization curling in magnetosomes with $D = 68$ nm $> d_c$
Reduced particle magnetic moment equals $\langle M_z \rangle / M_s = 0.77$.
Magnetosomes single domain diameter is estimated to be 64 nm.

Energy landscape for a cubic anisotropy nanoparticle ($K_c < 0$)

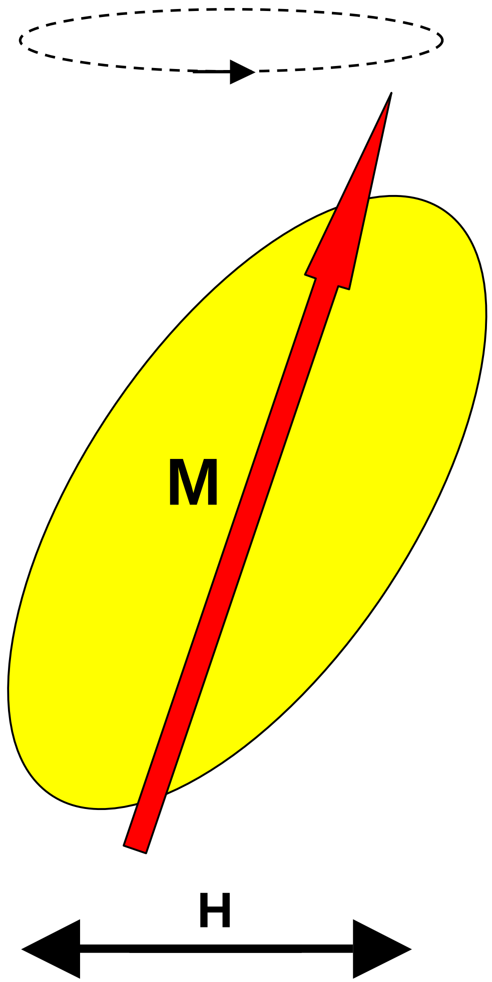


The reduced energy barriers are not very high even near D_c

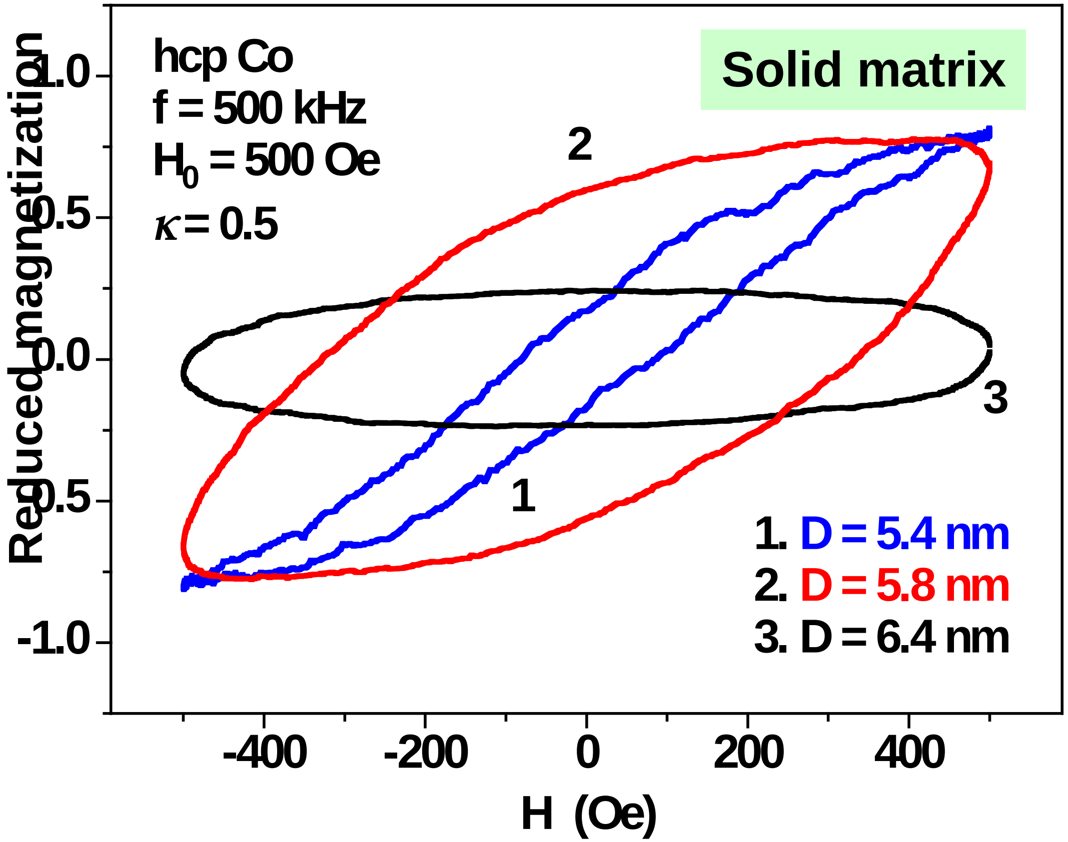
$K_cV/12k_BT \sim 10 - 40$

The largest single-domain nanoparticles are prone to superparamagnetism!

Magnetic nanoparticles can generate heat in alternating magnetic field



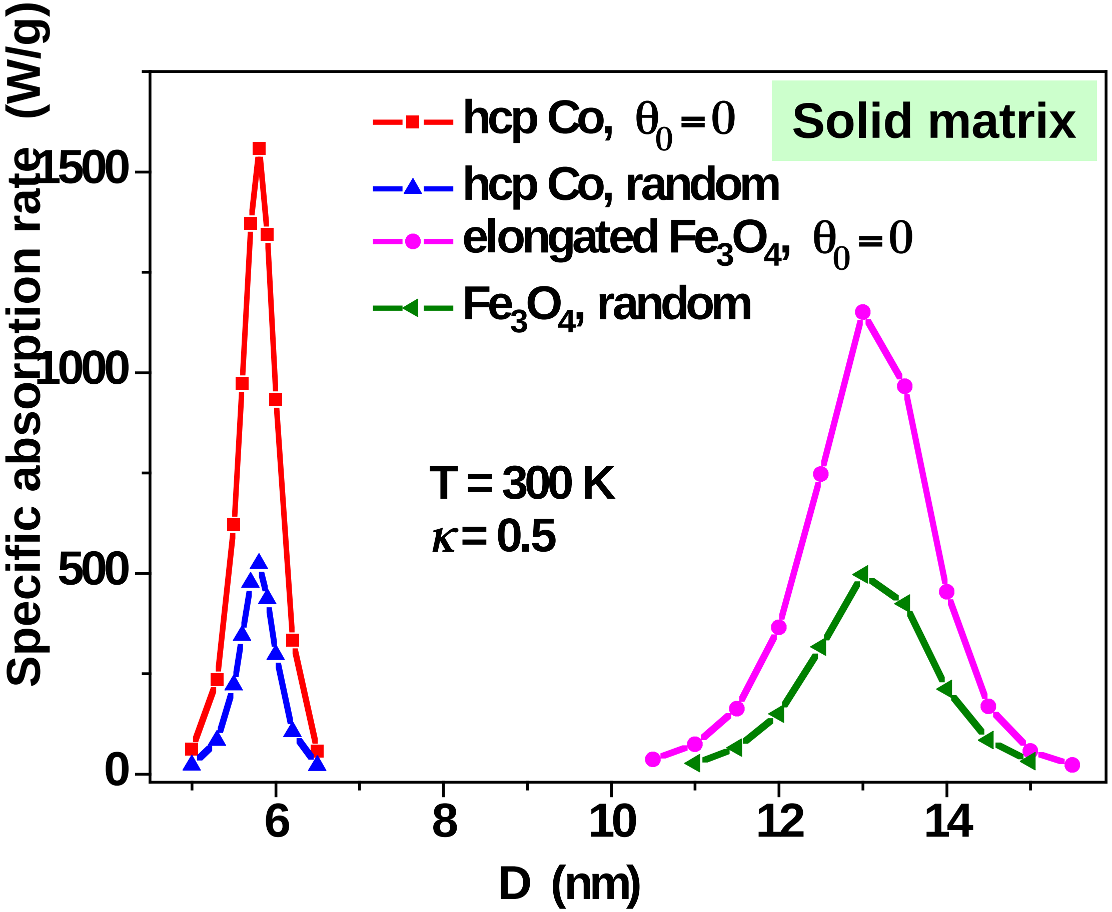
AC magnetic field

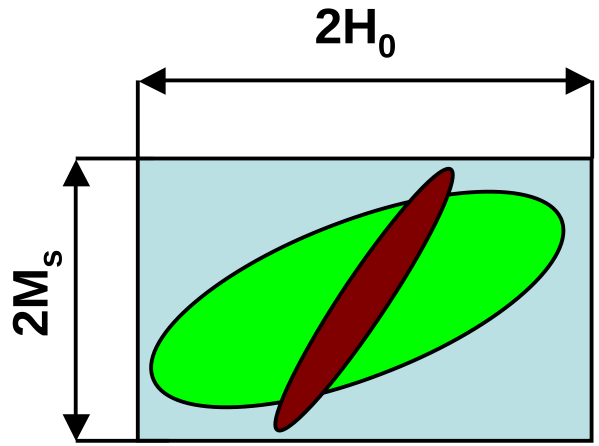


Evolution of the hysteresis loops of oriented assembly of Co nanoparticles as a function of particle diameter.

N.A. Usov, J. Appl. Phys. 107, 123909 (2010)

Specific absorption rate for a dilute assembly in a solid matrix





Maximal hysteresis loop area

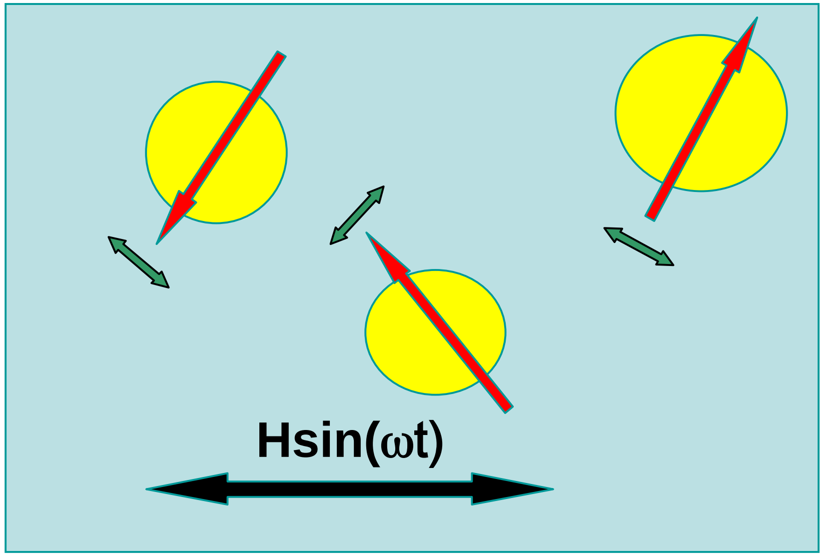
$A_{max} = 4H_0M_s$

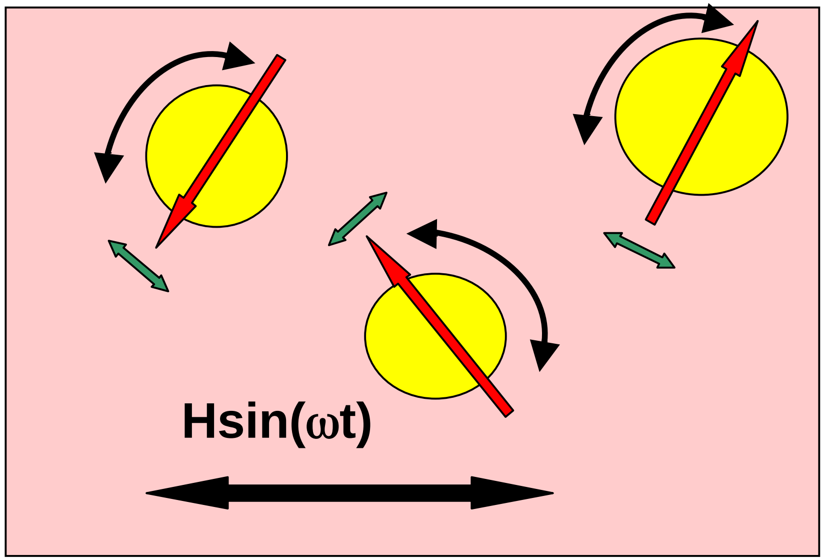
$SAR = A*f/\rho$

Specific absorption rate of oriented and non-oriented assemblies of Co nanoparticles (f = 500 kHz, H_0 = 200 Oe) and elongated Fe_3O_4 nanoparticles (f = 400 kHz, H_0 = 120 Oe) as the functions of the particle diameter.

N.A. Usov, J. Appl. Phys. 107, 123909 (2010)

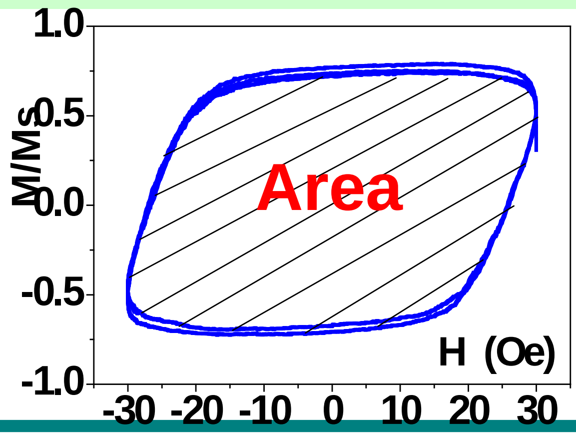
Neel - Brown and Debay (Brownian) relaxation processes





Magnetic nanoparticles in a <u>solid matrix</u>:
no particle rotation as a whole.

Magnetic nanoparticles in a <u>liquid</u>:
particle rotations + moment oscillations.



Important!

$$SAR = A^*f/\rho$$

The hysteresis loop area is the only measure for the energy losses for the both processes!

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Heat dissipation mechanism of magnetite nanoparticles in magnetic fluid hyperthermia

Makoto Suto[a], Yasutake Hirota[b], Hiroaki Mamiya[c], Asaya Fujita[d], Ryo Kasuya[a], Kazuyuki Tohji[a], Balachandran Jeyadevan[a,*]

The Néel (τ_N) and Brownian (τ_B) magnetic relaxation times of a particle are given by the following equations:

$$\tau_N = \tau_0 \exp\frac{KV_M}{kT} \quad (1)$$

$$\tau_B = \frac{3\eta V_H}{kT} \quad (2)$$

$$\tau = \frac{\tau_B \tau_N}{\tau_B + \tau_N} \quad (3)$$

where τ_N is the Néel relaxation time, τ_B the Brown relaxation time τ the effective relaxation time, $\tau_0 = 10^{-9}$ s, K the anisotropy

From Eqs. (6) and (9b) the power dissipation is expressed as

$$P = \pi\mu_0\chi_0 H_0^2 f \frac{2\pi f\tau}{1+(2\pi f\tau)^2}. \quad (14)$$

Oversimplified analysis

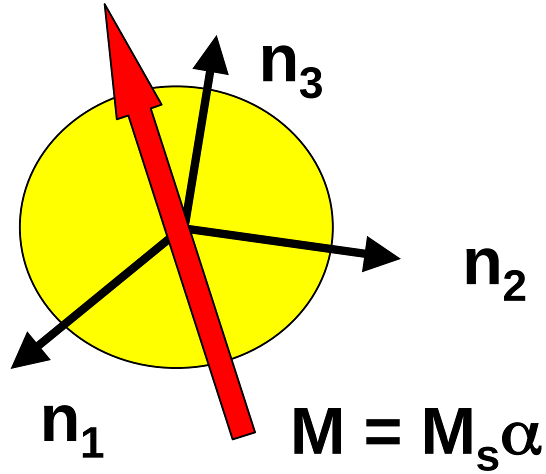
$$\tau = \frac{\tau_N \tau_B}{\tau_N + \tau_B} \quad ???$$

Total energy of a magnetic nanoparticle of cubic anisotropy

$$W = K_c V\left((\vec{\alpha}\vec{n}_1)^2(\vec{\alpha}\vec{n}_2)^2 + (\vec{\alpha}\vec{n}_1)^2(\vec{\alpha}\vec{n}_3)^2 + (\vec{\alpha}\vec{n}_2)^2(\vec{\alpha}\vec{n}_3)^2\right) - M_s V\vec{\alpha}\vec{H}_0 \sin(\omega t)$$

$$\frac{d\vec{n}_i}{dt} = [\vec{\omega}, \vec{n}_i]$$

Kinematics relation



Mechanical rotation equation

Regular torque

$$I\frac{d\vec{\omega}}{dt} + \xi\vec{\omega} = \vec{N}_m + \vec{N}_{th}$$

White noise torque

Stochastic Landau-Lifshitz equation

Effective magnetic field

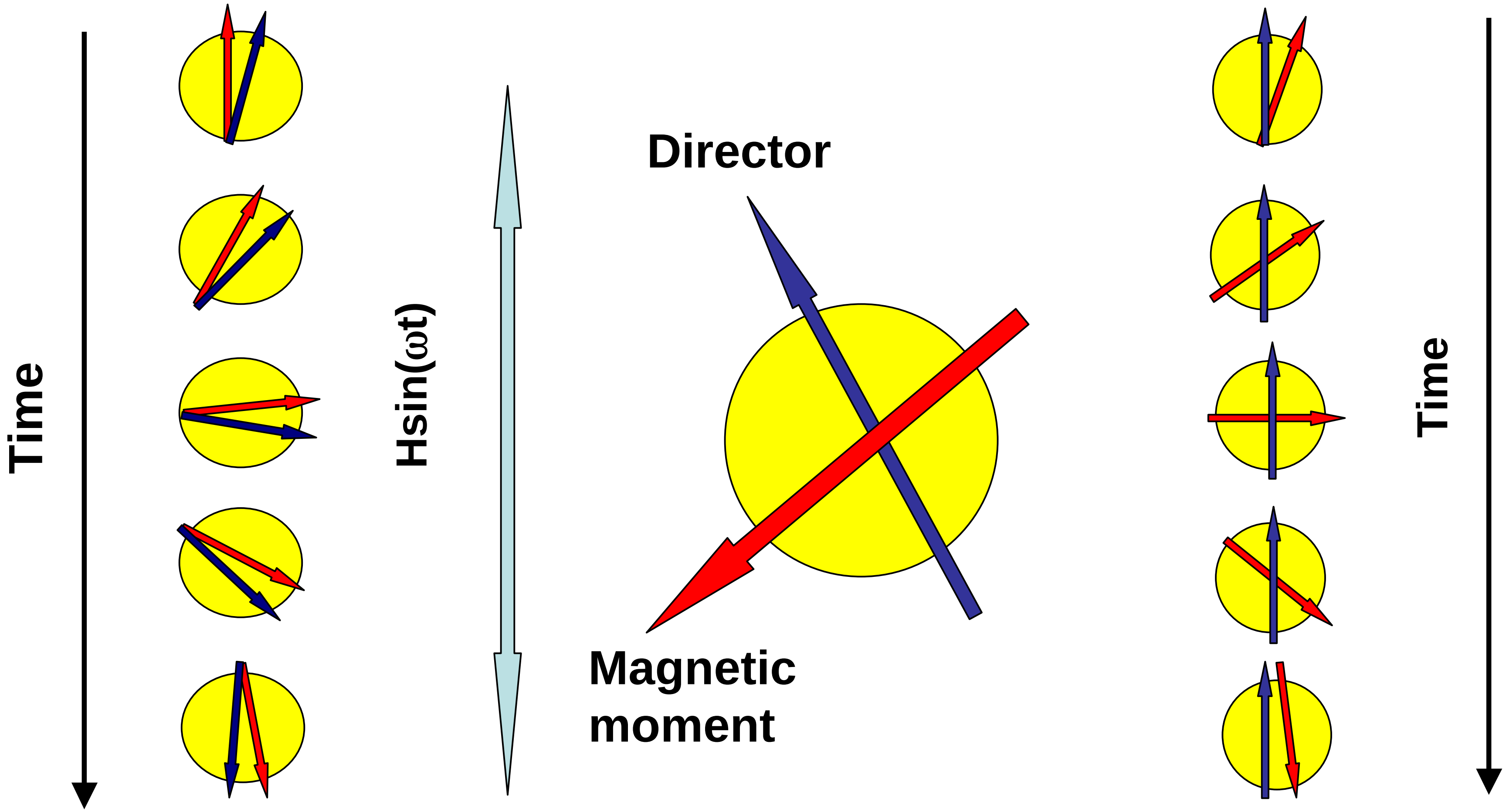
White noise field

$$\frac{\partial\vec{\alpha}}{\partial t} = -\gamma_1\left[\vec{\alpha}, \vec{H}_{ef} + \vec{H}_{th}\right] - \kappa\gamma_1\left[\vec{\alpha}, \left[\vec{\alpha}, \vec{H}_{ef} + \vec{H}_{th}\right]\right]$$

Magneto-dynamics (no or small thermal fluctuations)

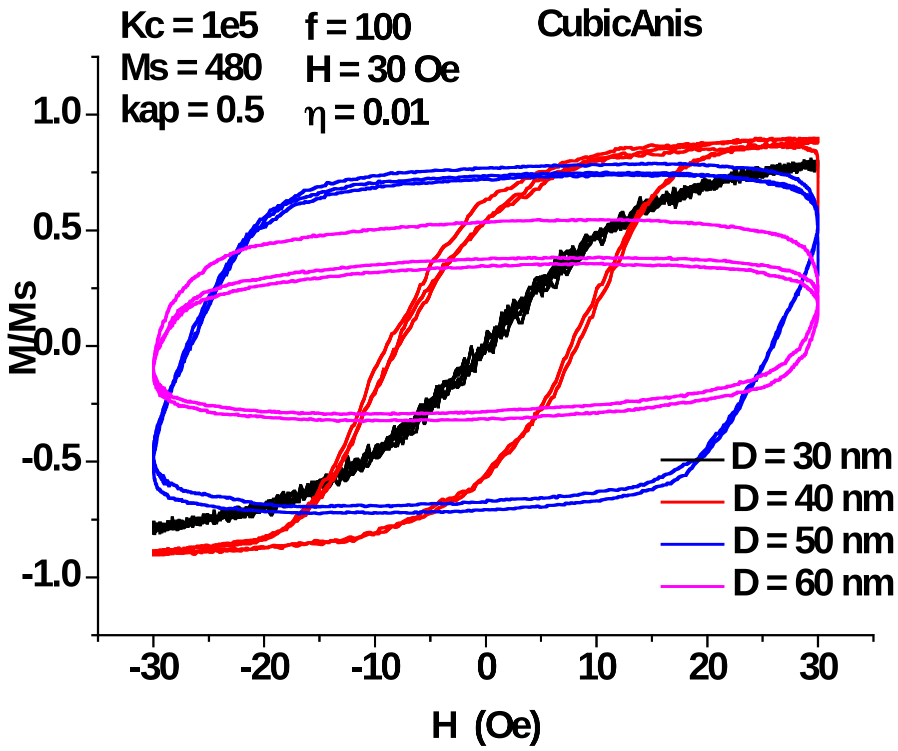
Viscous regime, $H_0 < H_k$

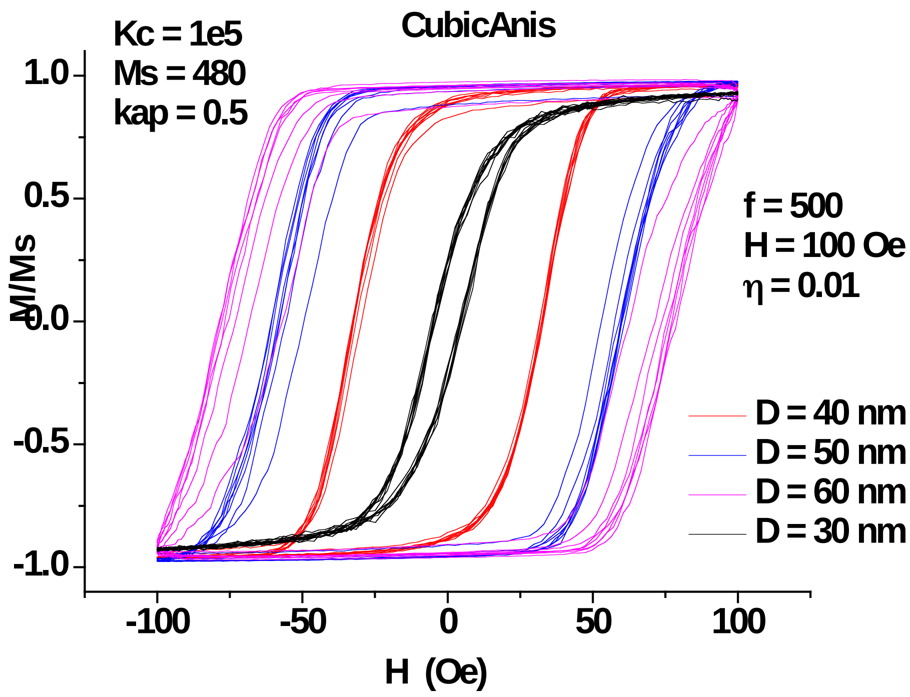
Magnetic regime, $H_0 > H_k$



Thermal fluctuations can modify these regimes significantly!

Numerical simulation results for magnetosomes





Hysteresis loops of a dilute assembly of magnetosome like nanoparticles in a water solution as a function of the particle diameter.

At H_0 = 30 Oe, f = 100 kHz maximal SAR = 207 W/g is found for D = 45 nm

At H_0 = 100 Oe, f = 500 kHz maximal SAR = 1860 W/g is ontained for D = 60 nm!

Maximal SAR values obtained up to now:

R. Herdt, et. al., J. Magn. Magn. Mater. 293 (2005) 80.
SAR = 960 W/g for measurements at f = 410 kHz, H_0 = 125 Oe (magnetosomes)

E. Alphandéry, et. al., J. Phys. Chem. C 115, 18 (2011).
SAR = 1200 W/g for measurements at f = 108 kHz, H_0 = 880 Oe (magnetosomes)

B. Mehdaoui, et. al., Adv. Funct. Mater. 21, 4573 (2011)
SAR = 3000 W/g for measurements at f = 274 kHz, H_0 = 730 Oe (metallic iron nanoparticles)

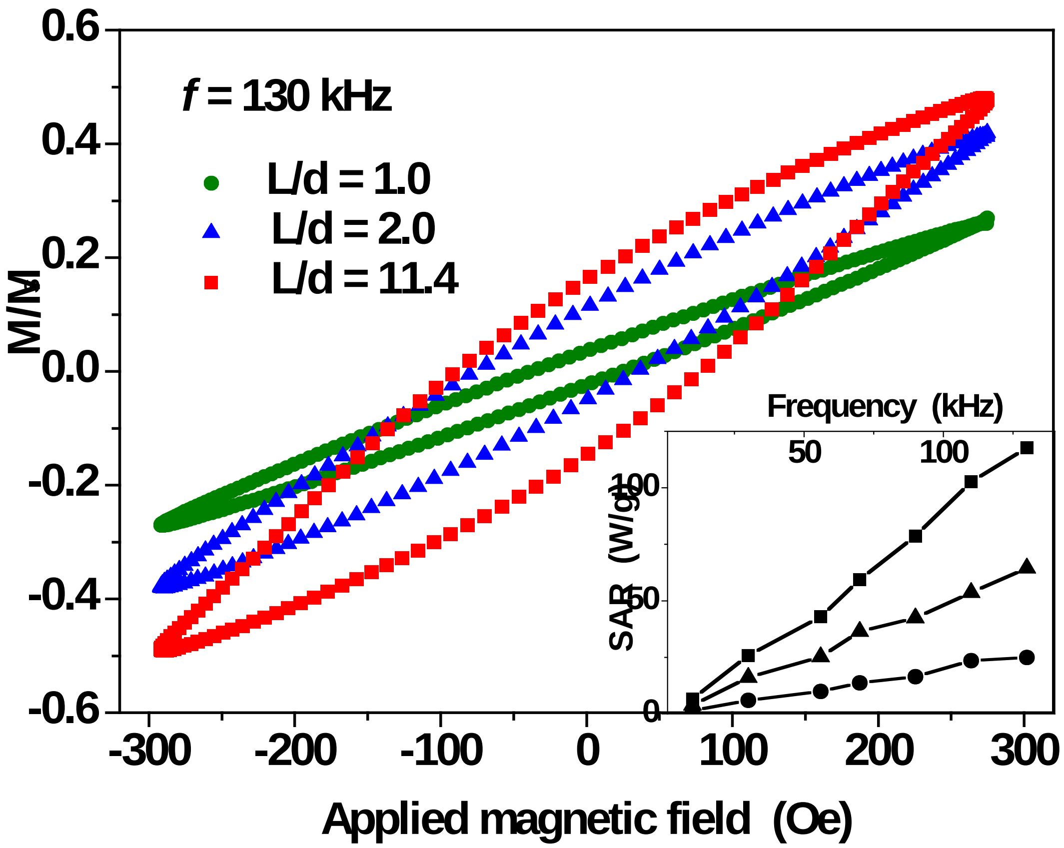
Unsolved problems

1) **For magnetosomes – existence of chains and clusters**

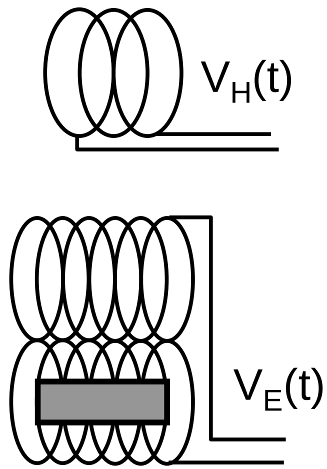
2) **For dense assemblies – influence of magnetostatic interactions**

3) **General problem: nature of effective magnetic anisotropy for a nanoparticle?**

Influence of a demagnetizing factor of a whole sample on a SAR for a dense nanoparticle assembly



S. A. Gudoshnikov,
B. Ya. Liubimov,
N. A. Usov
AIP Advances 2, 012143 (2012)



Hysteresis loops of Fe_3O_4 nanoparticles for samples with various aspect ratio L/d at a frequency f = 130 kHz and field strength H_0 = 280 Oe. Inset shows SAR as a function of the frequency for the same samples.

Summary - Conclusions

1. Particles with cubic type of magnetic anisotropy can provide significant SAR values at low alternating magnetic field amplitudes

2. The highest SARs ~ 1 kW/g are obtained up to now for bacterial magnetosomes

3. Behavior of a particle in a liquid media differs from that in a solid matrix! Interpretation is more complicated!

4. Magnetostatic interactions (in particular, demagnetizing field of a whole sample) make great Influence on a SAR value!

Thank you for your attention!