ENHANCED AND SUPER-LOCALISED MAGNETIC HYPERTHERMIA

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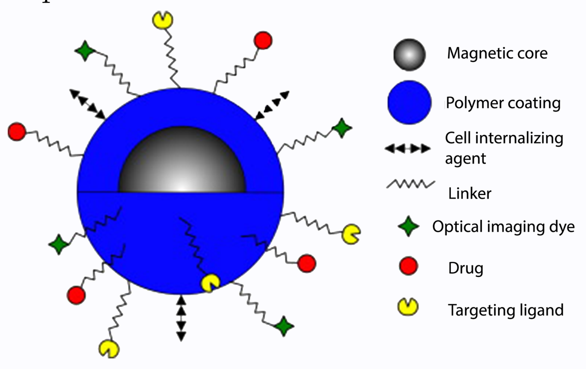
ABSTRACT

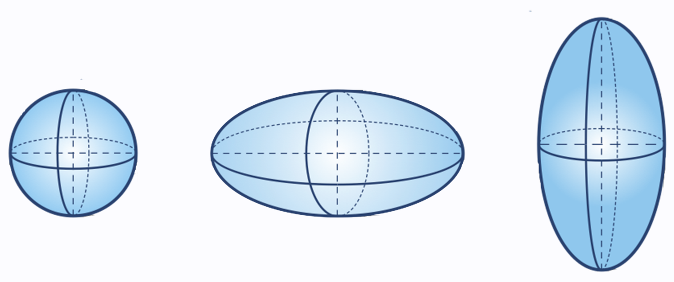
Single-domain ferromagnetic nanoparticle system can be used to transfer energy from a timedependent magnetic field into their environment. This local heat generation, i.e., magnetic hyperthermia, receives applications in cancer therapy which requires the enhancement of the energy loss. A possible way to improve the efficiency is to chose a proper type of applied field, e.g., a rotating instead of an oscillating one. Our goal is to demonstrate that the efficiency of magnetic hyperthermia is drastically increased by the combination of a static and rotating applied fields which has great importance since it is easy to realise in practice. Furthermore it can be used to "super-localise" the heat transfer: in case of an inhomogeneous applied static field, tissues are heated up only where the magnitudes of the static and rotating fields reach the required ratio (e.g. it should be one for isotropic nanoparticles).

MAGNETIC NANOPARTICLE (MNP)

Physical properties of magnetic nanoparticles:

- diameter $\sim 10\text{nm} - 200\text{nm}$
- single domain
- $T < T_{\text{Curie}}$ and $T_{\text{Curie}} \sim 44\,^\circ\text{C}$
- biocompatible external coating
- $m = 2.7 \times 10^{-21}$ kg
- $V = 5 \times 10^{-25}$ m^3
- shape anisotropy: λ_{eff}
  - $\lambda_{\text{eff}} = 0$ spherical (isotropic) nanoparticle
  - $\lambda_{\text{eff}} < 0$ oblate (lens shape) nanoparticle
  - $\lambda_{\text{eff}} > 0$ prolate (cigar shape) nanoparticle





$\lambda_{\text{eff}} = 0$ $\lambda_{\text{eff}} < 0$ $\lambda_{\text{eff}} > 0$

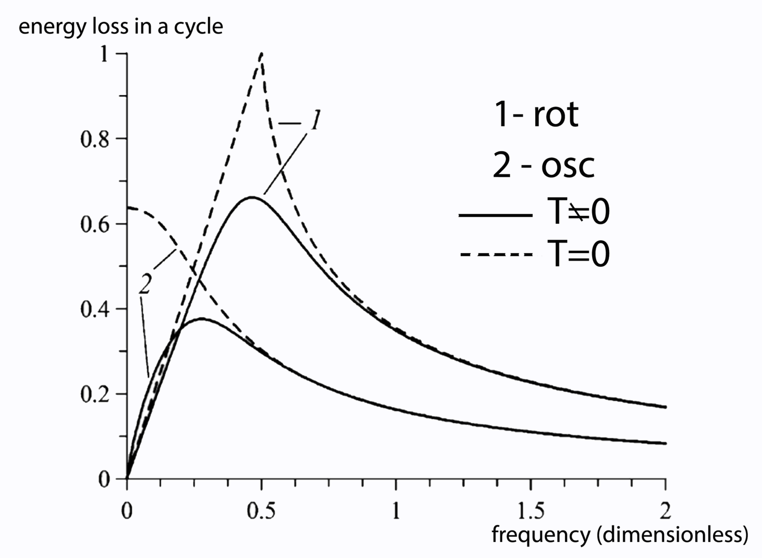
GOAL OF THE RESEARCH

MNP + applied field = heat generation

OUR GOAL: IMPROVE EFFICIENCY!

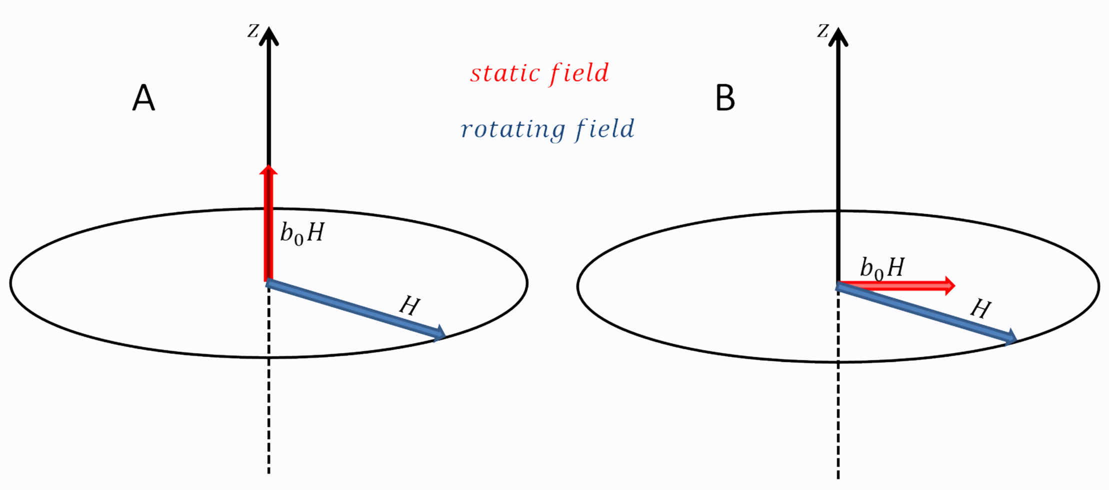
→ by a new type of external field

- isotropic case, $T = 0$: rotating field $\leq$ oscillating field [1]
- isotropic case, $T \neq 0$: rotating field $\simeq$ oscillating field [2]
- $T = 0$: anisotropic rotating $\leq$ isotropic rotating [3,4]



ALWAYS THE OSCILLATING IS THE BEST?

⇒ **OUR PROPOSAL: static + rotating field**



Two cases are considered: $(T = 0)$

A) $b_0 \perp$ rotating field **?** rotating field $(b_0 = 0)$

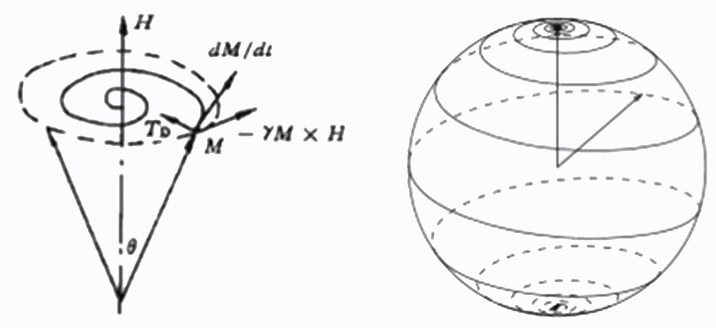
B) $b_0 \parallel$ rotating field **?** rotating field $(b_0 = 0)$

LANDAU-LIFSHITZ-GILBERT (LLG) EQUATION

The **deterministic** Landau-Lifshitz-Gilbert equation has been used to investigate the nonlinear dynamics of magnetization and the specific loss power in magnetic nanoparticles in case of a fixed particle approach with uniaxial anisotropy driven by a rotating magnetic field.

LLG equation: describe the dynamics of a single-domain magnetic nanoparticle. It does not change the saturation magnetic moment $|\mathbf{m}| = m_S$, so the unit vector $\mathbf{M} = \mathbf{m}/m_S$ is introduced and the LLG reads as

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{M} = -\gamma'[\mathbf{M} \times \mathbf{H}_{\text{eff}}] + \alpha'[[\mathbf{M} \times \mathbf{H}_{\text{eff}}] \times \mathbf{M}]$$



$\gamma' = \mu_0\gamma_0/(1 + \alpha^2)$

$\alpha' = \alpha\mu_0\gamma_0/(1 + \alpha^2)$ where α is the dimensionless damping factor

$\gamma_0 = 1.76 \times 10^{11}$ Am^2/Js is the gyromagnetic ratio of the electron spin

$\mu_0 = 4\pi \times 10^{-7}$ Tm/A (or N/A^2) is the permeability of free space

Rotating, static magnetic field and the effect of anisotropy:

$$\text{A)} \quad \mathbf{H}_{\text{eff}} = \mathrm{H}_0\,(\cos(\omega t), \sin(\omega t), \lambda_{\text{eff}}\mathrm{M}_z + \mathrm{b}_0)$$

$$\text{B)} \quad \mathbf{H}_{\text{eff}} = \mathrm{H}_0\,(\cos(\omega t) + \mathrm{b}_0 + \lambda_{\text{eff}}\mathrm{M}_z, \sin(\omega t), 0)$$

ω is the angular frequency

M_z is the z-component of the magnetization vector

λ_{eff} is the anisotropy parameter

b_0 stands for the static stabilising field

Set of dimensionless parameters typical for hyperthermia: introducing $t_0 = 0.5 \times 10^{-10}$s and $\omega_L = H_0\gamma'$ and $\alpha_N = H_0\alpha'$.

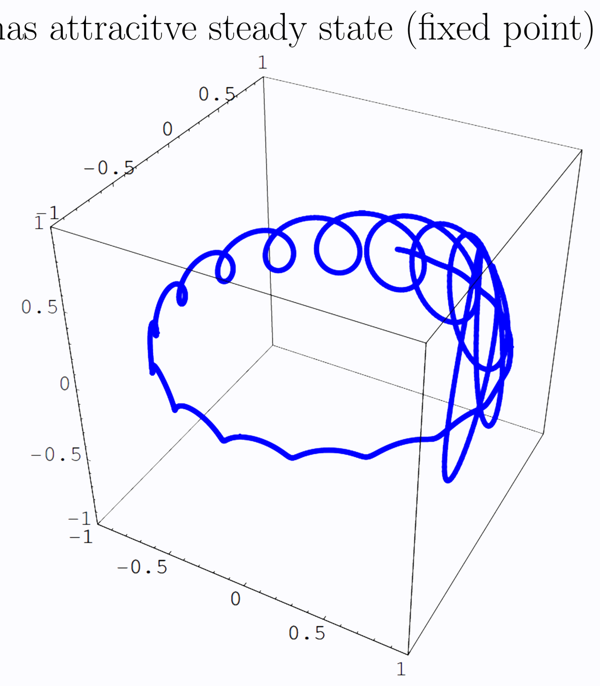
$$\omega \to \omega t_0 = 2.5 \times 10^{-5}, \qquad \omega_L \to \omega_L t_0 = 0.2, \qquad \alpha_N \to \alpha_N t_0 = 0.02.$$

Loss energy in a single cycle:

$$E = \mu_0 m_S \int_0^{\frac{2\pi}{\omega}} \mathrm{d}t \left(\mathbf{H}_{\text{eff}} \cdot \frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t}\right)$$

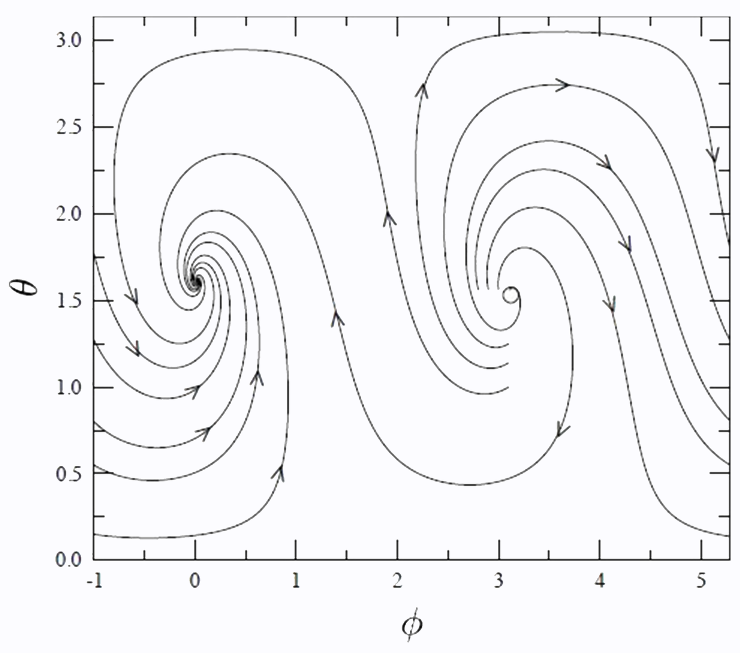
STEADY STATE SOLUTION

LLG equation has attracitve steady state (fixed point) solutions.



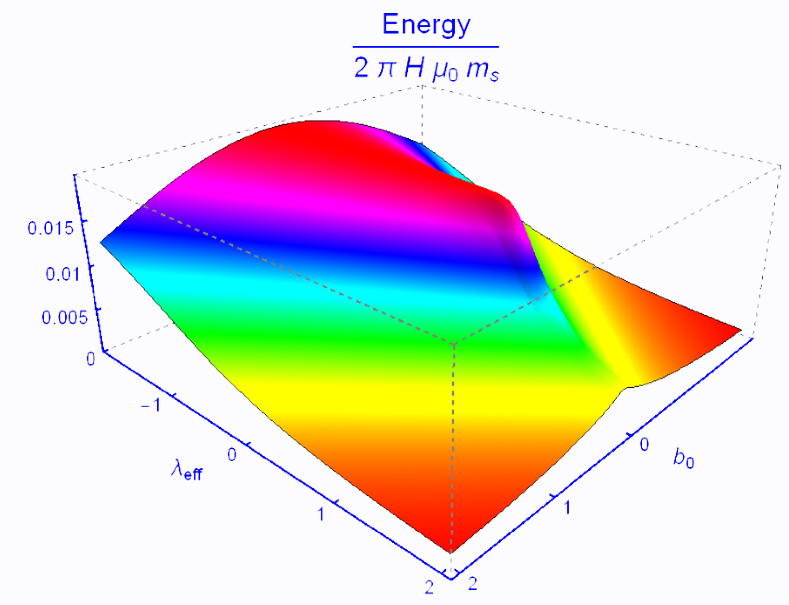
laboratory frame

We can rewrite LLG equation in polar coordinates in a rotating frame (M, θ, φ) → but M = constant.



rotating frame

A) STATIC FIELD PERPENDICULAR TO THE PLANE OF ROTATION

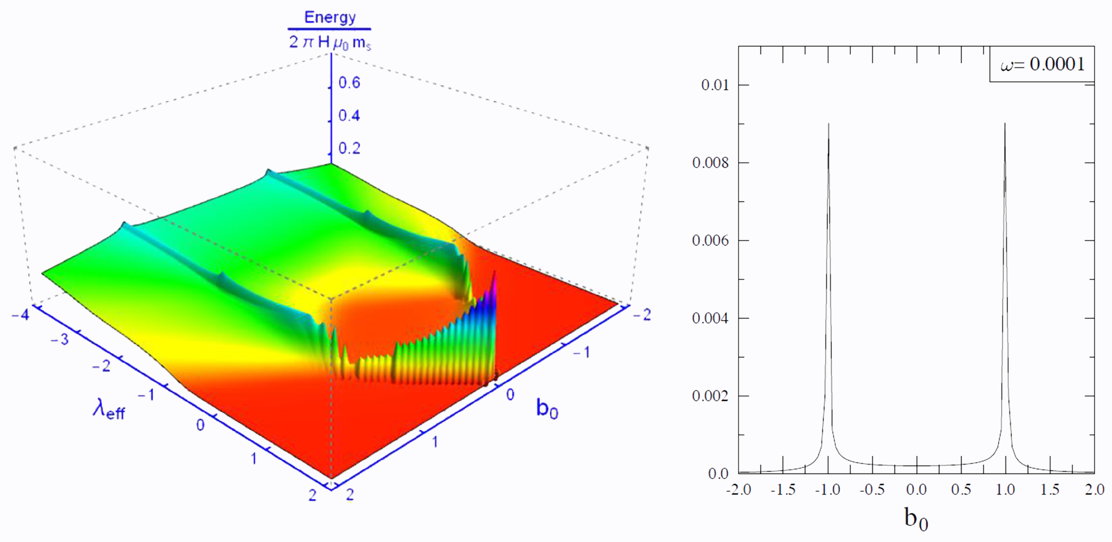


Any static field (b_0) decreases the energy loss!

NEGATIVE RESULT

B) STATIC FIELD IN THE PLANE OF ROTATION

No fixed point solutions, but attractive limit cycles! The energy loss depends on the strenght of the static applied field and the anisotropy. https://youtu.be/v5z_HB1WzCc



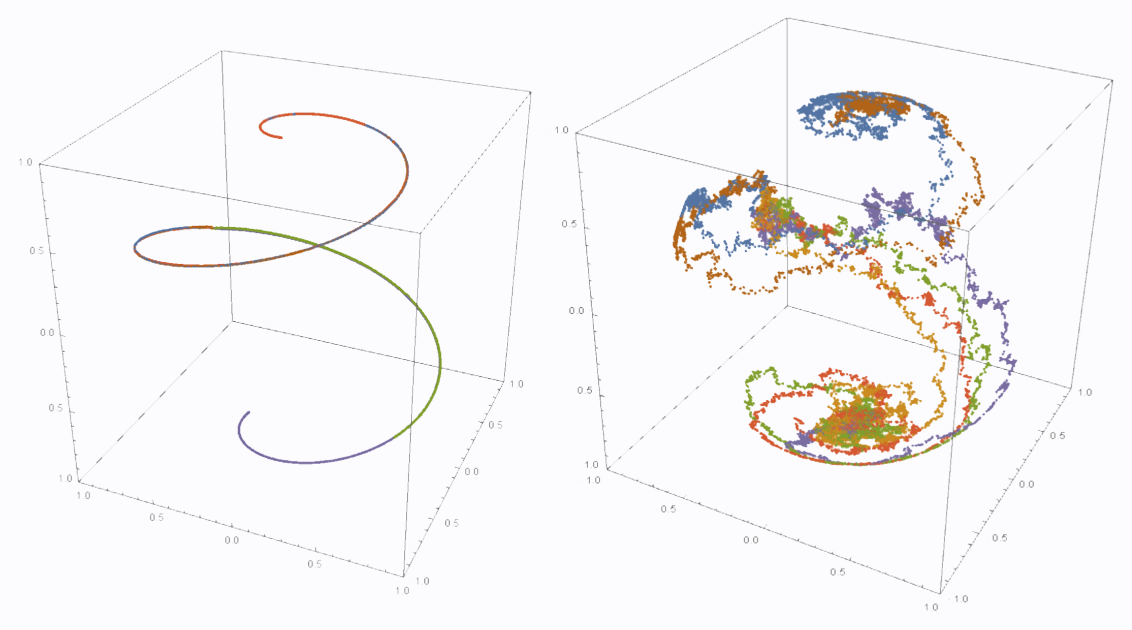
The energy loss has a very large maximum. [5] $(\lambda_{\text{eff}} = 0)$

$$\Rightarrow \qquad |b_0| + \frac{1}{2}\lambda_{\text{eff}} - 1 = 0$$

⇒ This can be used to **"SUPER-LOCALISE"** the heat transfer.

POSITIVE RESULT

STOCHASTIC LLG RESULT



$T = 0$ $T \neq 0$

Thermal effects do not modify significantly the deterministic result.

SUMMARY

If the static applied field is in the plane of rotation and the magnitudes of the static and rotating fields have a certain ratio (should be the same for isotropic case)

⇒ significant increase in the energy loss/cycle is observed;

⇒ it can be used to "super-localise" and enhanced the heat transfere!

List of references

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