The effect of trapezoidal wave rise-time on power dissipation for magnetic hyperthermia

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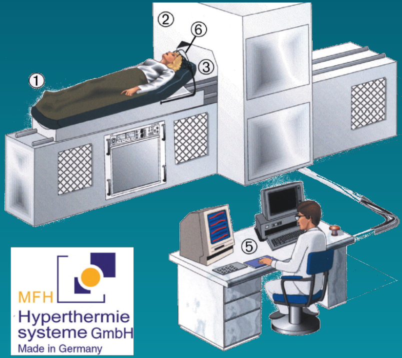
Magnetic hyperthermia

A novel therapy for treating tumours

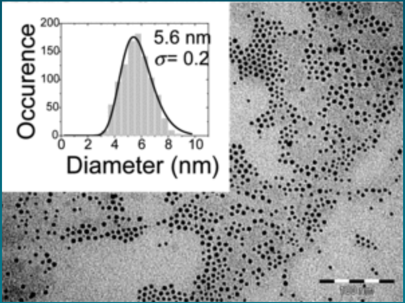
- Localised heating from magnetic losses
- Thermoablation of tissue above 45C
- Improves effectiveness of radiotherapy



[1] Jordan, A., et al.. J Magn Magn Mater (2001)

Required particle properties

- Magnetic properties
- Nontoxic and biocompatible
- High specific heating rates
- Operable at low fields



Use single domain magnetic nanoparticle iron oxides / ferrites

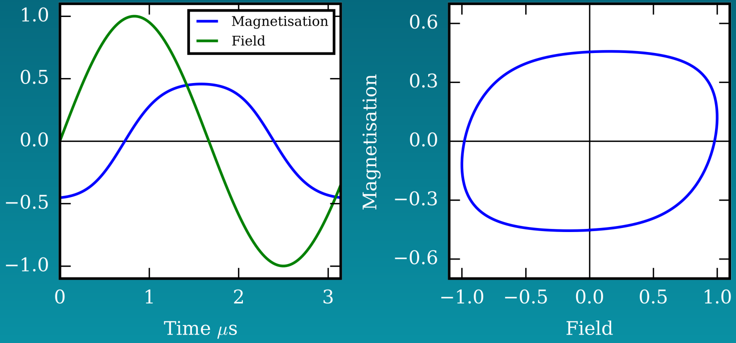
Optimum particle size and applied field characteristics?

[2] Mehdaoui, B., et al.. Adv Func Mater (2011)

Magnetic particle losses

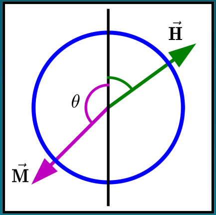
Obtained from hysteresis loop area (neglecting Brownian rotation):

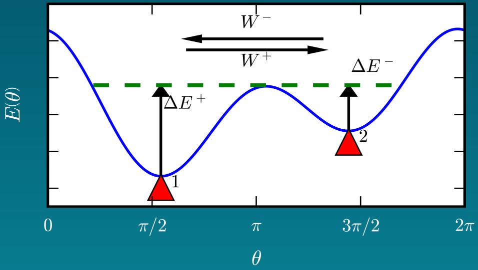
$$\mathrm{SPL} = f V^{-1} \int_{h_{\min}}^{h_{\max}} 2Km\,\mathrm{d}h$$



Simulating MNP dynamics

Jump process limit of the LLG dynamics





Stoner-Wohlfarth model and master equation

$$E = E_{\mathrm{SF}}\left(\theta, \vec{\mathbf{H}}(t)\right) \qquad \frac{\mathrm{d}}{\mathrm{d}t}\vec{\mathbf{p}}(t) = W(t)\vec{\mathbf{p}}(t)$$

$$W^{\pm}(t) = f_0 e^{-\Delta E^{\pm}(t)/k_B T} \qquad M(t) = p_1(t)M_1 + p_2(t)M_2$$

[3] Carrey, J., et.al.. J. App. Phys. (2011)

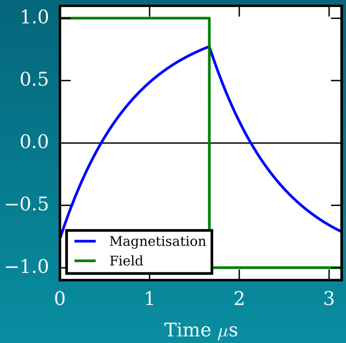
Simulating the MH curve

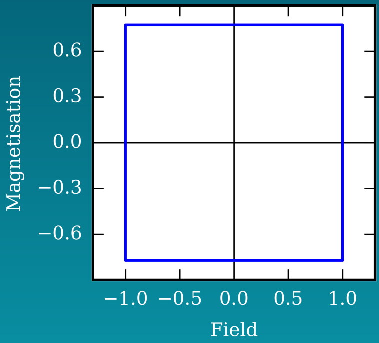
Data: Particle properties, temperature, external field
Result: Time dependent magnetisation

while *solution is not periodic* $M(t_0) \neq M(t_N)$ **do**
    $\vec{\mathbf{p}}(t_0) \leftarrow \vec{\mathbf{p}}(t_N)$;
    for t_n *in one field cycle* **do**
        Compute $H(t_n)$;
        Compute $W_\pm(H(t_n))$;
        Compute $\mathrm{d}\vec{\mathbf{p}}/\mathrm{d}t$ at t_n;
        Compute $\vec{\mathbf{p}}(t_n)$ with RK4;
        Compute $M(t_n)$;
    end
    Store $\vec{\mathbf{p}}(t_N)$;
end

Square waveforms lead to degeneracy

$$\mathrm{SPL} = f V^{-1} \int_{h_{\min}}^{h_{\max}} 2Km\,\mathrm{d}h$$



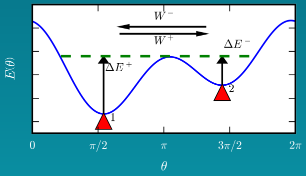


An alternative calculation of SPL

Applies to arbitrary applied field waveforms

$$\mathrm{SPL} = fV^{-1}\int_0^T \left[E^+(t) - E^-(t)\right]\frac{\mathrm{d}p_1(t)}{\mathrm{d}t}\mathrm{d}t$$

- Integral can be solved numerically
- Closed form solution for square waveform
- **No explicit dependence on** H



[4] McPhail, M., et.al.. *In review* (2016)

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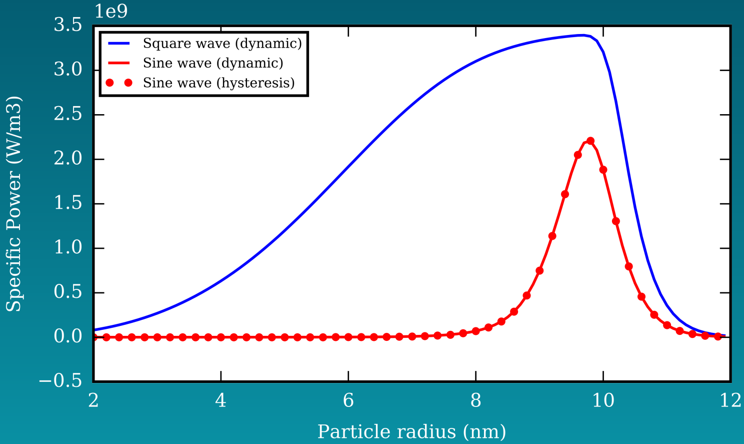
Conditions for validity

- Steady-state periodic
- $H < H_c$
- Time reversal symmetry
- Master equation applies

[4] McPhail, M., et.al.. *In review* (2016)

Results for a single (aligned) particle

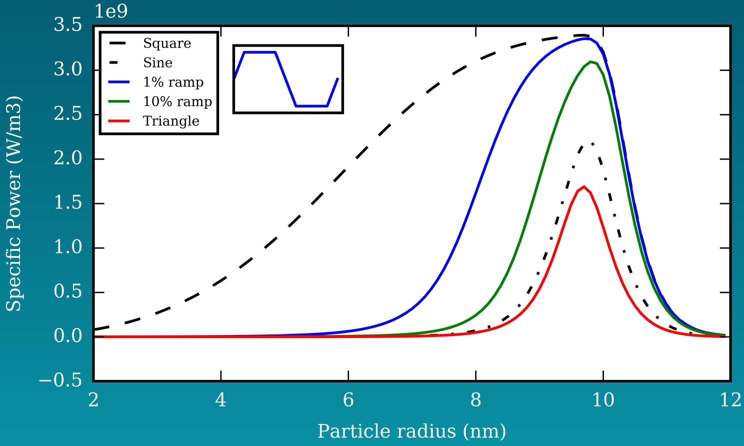
Square wave harmonics target smaller particles



$T = 298\text{K}, K = 11k\text{kJ/m}^3, h = 0.13, f = 300\text{kHz}$

Applied trapezoidal waveform

Harmonics quickly diminish



$T = 298\text{K}, K = 11\text{kJ/m}^3, h = 0.13, f = 300\text{kHz}$

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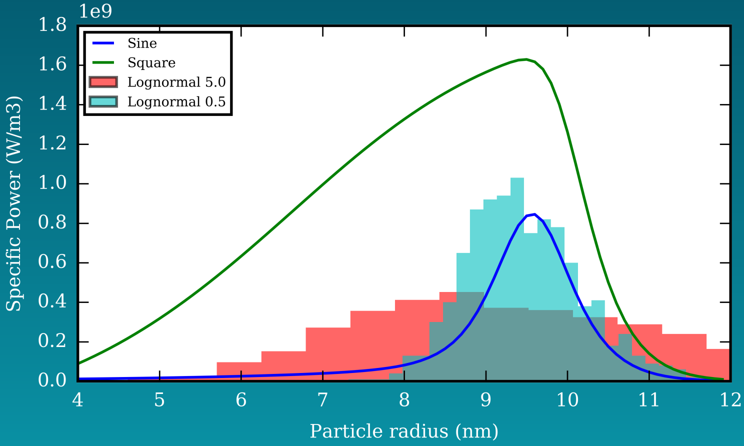
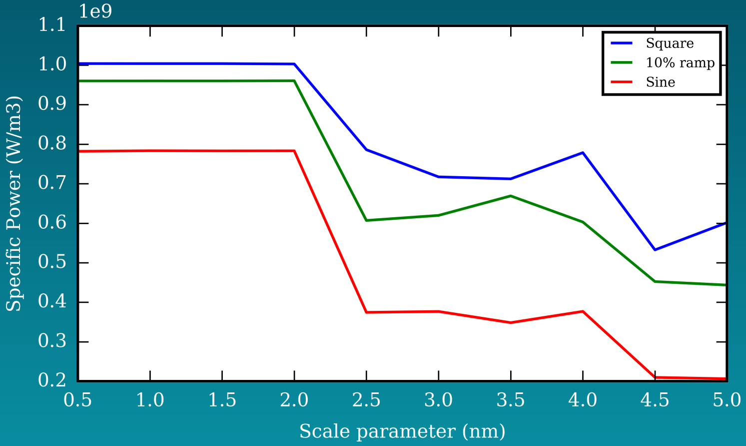
A realistic particle ensemble

Lognormal size and uniform anisotropy axis distributions



$T = 298\text{K}, K = 11\text{kJ/m}^3, h = 0.13, f = 300\text{kHz}, \alpha = 0.1, M_s = 350\text{kA/m}$

Applied waveforms of equal power



$T = 298\text{K}$, $K = 11\text{kJ/m}^3$, $h = 0.13$, $f = 300\text{kHz}$, $\alpha = 0.1$, $M_s = 350\text{kA/m}$, $\bar{r} = 9.5\text{nm}$

Conclusions

- We have introduced an alternative formulation to compute the SPL obtained in an applied square wave.
- The square waveform can target a large range of particle sizes.
- Good SPL can be achieved with broad particle distributions and trapezoidal waves.

Questions?

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