Impact of local SPIO concentration on the Magnetic Particle Imaging signal

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Recently, Magnetic particle imaging (MPI) has been presented as a new imaging method that potentially offers 3D real-time imaging of the concentration distribution $c(\boldsymbol{x})$ of superparamagnetic iron oxide (SPIO) particles in biological systems at high spatial resolution [1].

A sample containing SPIOs at concentration c is exposed to a harmonically oscillating magnetic field $H(t)(O(10\, mT/\mu_0))$ at frequency ω_0. The MPI signal is the Fourier spectrum of the response field, which contains higher harmonics $N \cdot \omega_0$, due to the nonlinear magnetization curve $M(H,c)$ of the sample in the range of the field strength mentioned above.

In essence, $M(H,c)$ transposes input to output and therefore is the key quantity to calculate the MPI signal for a known configuration. For tomographic purposes, the quantity $c(\boldsymbol{x})$ has to be reconstructed from the MPI signal. Hence, the quality of the theory describing the impact of concentration c on the magnetization curve is essential for the image reconstruction.

Recent authors only considered Langevin's single particle model of paramagnetism (SPM) for reconstruction [e.g. 2]. Hence, magnetic inter particle coupling was neglected until now, which can be done for $c < 0.2\, mol/l$. When particles agglomerate in cell vesicles, as is the case for SPIO labeled markers, concentrations much higher than $0.2\, mol/l$ are reached.

Besides SPM, we use second order modified mean field theory (MMF2), which includes particle coupling in ferrofluids [3]. Magnetization curves $M(H,c)$ simulated with MMF2 theory are close to reality [4]. *Figure 1* particularly shows rising nonlinearity of the magnetization curve with increasing SPIO concentration. For $c \to 0$, MMF2 converges to SPM. *Figure 2* shows the variation of the single higher harmonics of the MPI signal in an 1D MPI experiment, while increasing the concentration of a rectangular sample of constant width: the MMF2 curves show that not only the amplitudes, but also the ratio of the harmonics change with increasing concentration. As expected, the SPM curves show no change. Hence, image reconstruction in MPI using Langevin's single particle model leads to deviations from the true distribution of concentrations.

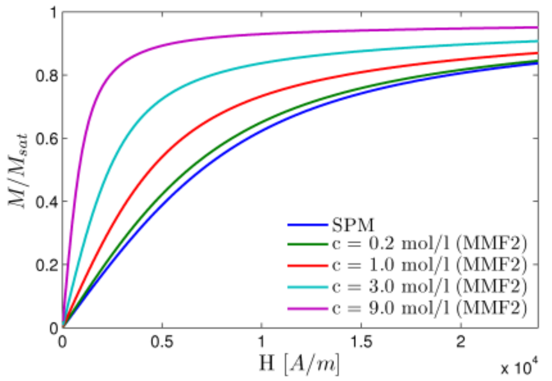

Figure 1: ***Normalized Magnetization curves calculated for SPIO samples (consisting of Magnetite particles with diameter $d = 15\, nm$) with different concentrations c using MMF2 and SPM theory. M_{sat} is the saturation magnetization of the corresponding sample.***

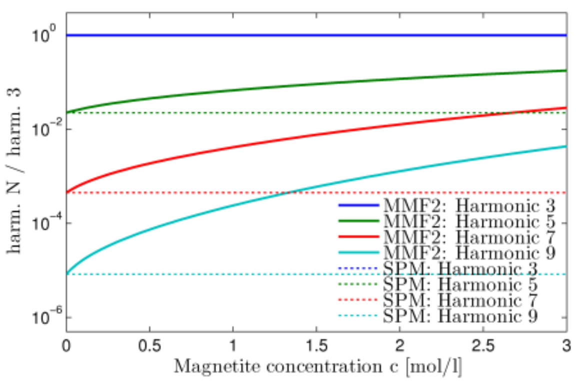

Figure 2: ***Normalized MPI signal amplitudes of a simulated 1D experiment in dependence of c, which is the height of a rectangular SPIO sample $c(x)$ (consisting of Magnetite particles with $d = 15\, nm$). The amplitudes of harmonics $N = 3; 5; 7; 9$ are normalized to $N = 3$. The MPI signal was acquired and analyzed using MMF2 and SPM theory separately.***

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[2] **Rahmer et al**: *Signal encoding in magnetic particle imaging: properties of the system function*; BMC Medical Imaging 2009, 9:4
[3] **A. O. Ivanov, O. B. Kuznetsova**: *Magnetic properties of dense ferrofluids: An influence of interparticle correlations*; Phys. Rev. E 64, 041405 (2001)
[4] **Ivanov et al**: *Magnetic properties of polydisperse ferrofluids: A critical comparison between experiment, theory, and computer simulation*; Phys. Rev. E 75, 061405 (2007)