Magnetic Susceptometry Imaging with Robust Atomic Magnetometers

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Atomic magnetometers (AM) are compact magnetic field sensors based on the optical detection of spin precession in a magnetized atomic gas. AMs perform best in highly homogeneous fields and in a magnetically silent environment. An unshielded environment, or the presence of field gradients in excess of a few nT/mm rapidly degrade the magnetometer performance (sensitivity). For this reason, the deployment of conventional AMs in biomedical imaging techniques that rely on rapidly varying strong magnetic field gradients is quite challenging. In applications based on magnetic nanoparticles (MNP) [1], such as Magnetic Particle Imaging (MPI) [2] and Magnetorelaxometry (MRX)[3], MNPs have to be magnetized by fields of a few ten mT in order to produce detectable nonlinear induction. Moreover, in scanning imaging modalities the MNPs are exposed additionally to gradients of a few T/m.

We have investigated and implemented ways to overcome those limitations and have demonstrated a coil system and an AM design allowing MNP imaging by MPI. This dedicated magnetometry system – of suitable size for small animal applications – features a high bandwidth and a high sensitivity based on feedback operation of a pump-probe variant of the M_x scheme in Cs. We have designed a compact self-shielding magnetic system, suppressing – at the nearby AM position – by three orders of magnitude the stray components of the fields and gradients needed to magnetize the MNPs and to encode their spatial distribution (Fig. 1, left). We deployed a heated, diffusion-limited Cs buffer gas cell with a mm^3-scale sensing volume that minimizes the inhomogeneous broadening of the magnetic resonance line by the fringe fields. We have optimized the resonance amplitude by varying the atomic density, light power, and deploying a repumping laser beam to compensate for hyperfine losses of pumped state population, thus keeping the sensitivity in the few pT range (Fig. 1, right top) in presence of the nearby mT field and T/m gradient sources.

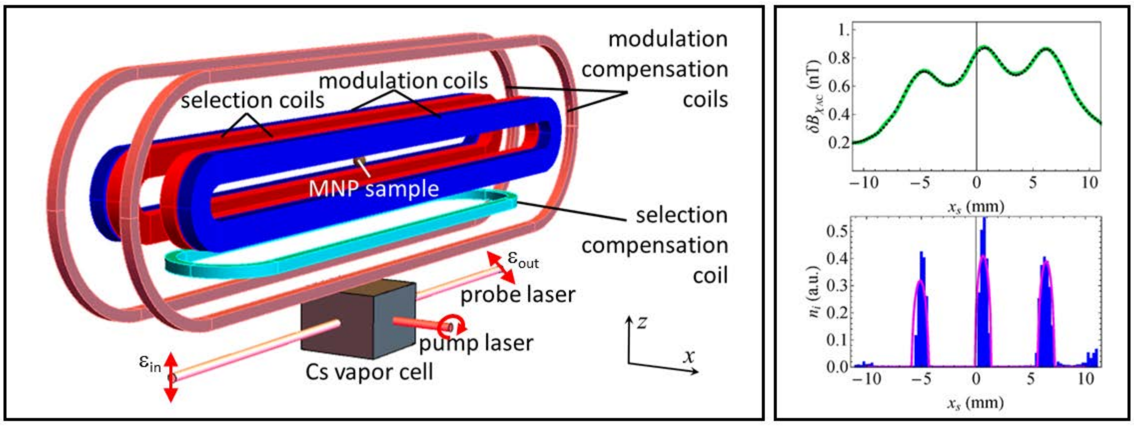

Fig. 1: Left: Sketch of the experimental set-up for performing MPI measurements on MNPs with a Cs AM. Right: Example of a 1D MPI scan of a structured MNP sample (top) and deconvoluted MNP density distribution (bottom).

In order to extract the spatial distribution of the MNPs (Fig. 1, right bottom) from the signal patterns recorded by the AM (Fig. 1, right top), we have developed efficient (off-line) data analysis routines deploying simulated annealing techniques. With the presented system we have recorded 1D mechanical (Fig. 1, right), 1D magnetic, and hybrid 2D magneto-mechanical scanned images of MNP distributions in up to a 20×40 mm^2 phantom, using the standard Resovist MNP agent.

References

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