Magnetic Particle Imaging (MPI) is a new imaging diagnostic technique. This new imaging method was developed by researchers from Philips Imaging laboratory in 2003. The first results of their works on Magnetic Resonance Imaging (MRI) was implemented with high spatial and time resolution, ruling PET, combined with high spatial and time resolution. Therefore, MPI is a method simple and scalable. Although the third MPI applications are quite unique. Magnetic nanoparticles, some of which are quite unique, can be applied to research properties of superparamagnetic nanoparticles in a field of 100 nm and coated with biocompatible polymers.

Superparamagnetic nanoparticles are used as a tracer. The core of such particles is usually manufactured from superparamagnetic iron oxide (SPION) (Fig. 1). It is a form of inorganic iron oxide that is biodegradable.

Table 1: Comparison of parameters of various molecular imaging modalities.

| Modality            | Spatial Resolution | Time Resolution | Sensitivity |
|---------------------|--------------------|-----------------|-------------|
| PET                 | 1 mm               | 1 s             | 10^3 mol/L  |
| MRI                 | 1 mm               | 1 min           | 10^3 mol/L  |
| MPI                 | 0.1 mm             | 1 s             | 10^10 mol/L |
| SPECT               | 1 cm               | 1 min           | 10^6 mol/L  |

The increased attention regarding this modality is result of research institutes commenced since that publication some research institutions commenced MPI in Poland. The main achievement of this technique is the development of new magnetic nanoparticles.

**Keywords:** nanoparticles, superparamagnetic iron oxide, tomography, molecular imaging.
magnetization changes and excitation signal, which is stronger by about six orders of magnitude.

**Fig. 2.** Magnetization signals, signals induced in receiving coil and their amplitude spectra for medium excited with sinusoidal signal depending on the magnetization curve: linear medium (top) and nonlinear medium - superparamagnetic nanoparticles (bottom)

![Images of magnetic signals and spectra](image1)

If nanoparticles magnetization curve was linear, separation of this signal would be impossible (Fig. 2). However, as the magnetization curve is nonlinear signal from nanoparticles contains harmonics of excitation frequency (Fig. 3). It is possible to separate those high frequencies by filtering out excitation frequency (broadband method) or by measurement of each harmonic separately (narrowband method). Through analysis of this harmonics signals for example particles concentration can be estimated.

Localization of the tracer can be achieved by application of gradient magnetic field, which cause nearly all nanoparticles to undergo saturation thus preventing them from contributing in signal generation, except those in small volume near the zero magnetization field strength, called field free point (FFP). In such circumstances magnetization signal induced in receiving coil originates only from particles in FFP [3]. To scan whole imaged volume FFP can be moved. There are two known procedures of scanning using this method of localization – frequency mixing method (excitation frequency much higher than movement of FFP) and driving field method (high frequency movement of FFP used as exciting field) [2]. Time resolution of imaging is highly dependent on applied scanning process.

2. Research conducted in Division

In Nuclear And Medical Electronics Division research on model of tomographic scanner for nanoparticles imaging are being carried out since 2011. In the wake previous studies, conducted under statutory works, one dimensional nanoparticles scanner was created. Presently system for nanoparticles spectroscopy is being developed. Furthermore, numerical calculation MATLAB toolbox is being written that will allow simulation of MPI measurement system, generation of simulated measurement result of such systems and reconstruction of MPI images from both artificial and real data.
2.1. Magnetic Nanoparticles Scanner

MPI scanner developed in Nuclear And Medical Electronics Division allows one dimensional imaging of nanoparticles concentration [4] (Fig. 4 and 5). It is designed for research of small objects. Current acquisition system employs narrowband detection method using lock-in amplifier and mix frequency method for field free point displacement. Particles are excited with signal of 10 kHz frequency and 8 mT of amplitude. Gradient coils generate field of about 1 T/m strength. Field of view of the scanner has about 30 mm diameter. Using this setup first real measurements were conducted [7] (Fig. 7). The phantoms with the chambers for water solution of nanoparticles with 0.5 mol/L concentration (Fig. 6) were used in the experiments. The phantoms were made using 3D printing technology.

Fig. 4. Measurement setup for one dimensional MPI scanner. On the left side, equipment used for generation of excitation signal and gradient field (function generator, power supply, audio power amplifier). In the middle, MPI scanner gentry containing coils and cooling system. On the right side, equipment used in acquisition setup (lock-in amplifier and oscilloscope).

Fig. 5. MPI scanner gentry. View of gradient coils and receiving coil.

Fig. 6. CT image of phantom with three chambers filled with ferrofluid. Phantom was printed in 3D printing technology and use for MPI scanner research.

2.2. Magnetic Nanoparticles Spectroscopy

Magnetic Nanoparticles Spectroscopy (MPS) allows measurement of harmonic spectra of magnetization signal of magnetic nanoparticles. It is used for research of properties of nanoparticles, for example particle diameter or magnetization curve estimation. Magnetic particles spectrometer may be considered a zero dimensional MPI scanner. To acquire the spectra of magnetization signal harmonics only detection of magnetization signal is necessary. In this case gradient coils are irrelevant. Signal from whole volume is acquired and afterwards amplitude and phase of each harmonic is measured or calculated by Discrete Fourier Transform from signal. Set of amplitudes and phase angles of all harmonics in function of frequency is called magnetic particle spectrum and is unique for specific nanoparticles batch. First trial measurements of amplitude and phase angle spectra of nanoparticles using modified MPI scanner model (Fig. 8) were conducted in Division (Fig. 9 and 10). Development of new magnetic particles spectroscopy is planned in the near future.

Fig. 7. Measurement along X axis of scanner of magnetic response of 60 nm nanoparticles dispersed in water in three chamber phantom. “Zero” position corresponds to center of the FOV of the scanner. Amplitude of 5th harmonic measured by lock-in amplifier is proportional to concentration of nanoparticles.

Fig. 8. Scheme of MPS setup, using narrowband detection method. It is in fact MPI scanner setup without driving and gradient coils. In this configuration signal is acquired from whole volume.
Fig. 9. Magnetic moment spectrum of FeraSpin™ XL nanoparticles at a field strength of 8 mT/μ0

Fig. 10. Phase angle spectrum of FeraSpin™ XL nanoparticles at a field strength of 8 mT/μ0

2.3. Numerical Simulation Toolbox

The last important project connected to MPI developed in Division is work on program for numerical calculations. MPIsim software is written in MATLAB. When completed this toolbox will be ideal scientific help for designing new models of the MPI scanner or coils setups or for verification of results of real measurements. Its first module will allow simulation of magnetic field generated by coils of the scanner [5, 6], including gradient field, driving field and excitation field (Fig. 11 and 12). Second part will be used for simulation of 1D/2D/3D MPI measurements (Fig. 15), which theoretical with allow numerical estimation of system function of analyzed scanner. Last function of the program will be reconstruction of MPI images and particles concentration distribution. Using this toolbox it will also be possible to numerical calculation of magnetic particles spectra (Fig. 13) and estimation of particle magnetization curve, from both simulated and real data (Fig. 14). This feature will allow not only estimation of magnetic parameters of nanoparticles but also may lead to better theory describing superparamagnets behavior.

Fig. 11. Comparison of result of simulation and real measurement of Z-component of magnetic induction of field generated by gradient coils of MPI scanner model

Fig. 12. Distribution of Z-component of magnetic induction of field generated by gradient coils of MPI scanner model. Computed in MPIsim toolbox

Fig. 13. On the left side, signal induced by changing magnetization of nanoparticles in receiving coil calculated in MPI toolbox. On the right side, amplitude harmonic spectrum of this signal
3. Conclusions

Magnetic Particles Imaging is a very promising molecular imaging technique with wide range of potential applications. Its progress will surely contribute to expansion of knowledge in both fields of electronics and medicine. Due to this rezone it became one of the main topics of interest in the Nuclear And Medical Electronics Division. Past results motivate us to continue work in this field. Probable next step will be extension of functionality of current MPI scanner model to 2D or 3D imaging, which in turn will allow further research in this new imaging technique.

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