

# Differential magnetometry on Fe<sub>2</sub>O<sub>3</sub> nano-clustered particles

Leon Abelmann <sup>a,b\*</sup>, Melissa van de Loosdrecht <sup>b</sup>, Bennie ten Haken <sup>b</sup>,  
Lijun Pan <sup>c</sup>, Bum Chul Park <sup>c</sup>, Young Keun Kim <sup>c</sup>

<sup>a</sup> KIST Europe, Saarbrücken, Germany

<sup>b</sup> University of Twente, Enschede, The Netherlands

<sup>c</sup> Department of Materials Science, Korea University, Seoul, Korea

\* Corresponding author, email: [l.abelmann@kist-europe.de](mailto:l.abelmann@kist-europe.de), [ykim97@korea.ac.kr](mailto:ykim97@korea.ac.kr)

## I. Introduction

Modern contrast agents for Magnetic Particle Imaging consist of clusters of superparamagnetic iron-oxide particles, rather than individual particles [1,2]. These multi-granule nanoclusters (MGNCs) have the advantage that the size of clusters can be increased, without sacrificing the superparamagnetic response that is necessary to avoid magnetic attraction and unwanted agglomeration.

Previously, we have investigated the suitability of these nanoclusters for Magnetic Particle Imaging [3]. In this contribution we optimize these particles for use in differential magnetometry, a technique that can for instance be applied to detect sentinel lymph nodes in laparoscopic procedures [4].

## II. Material and Methods

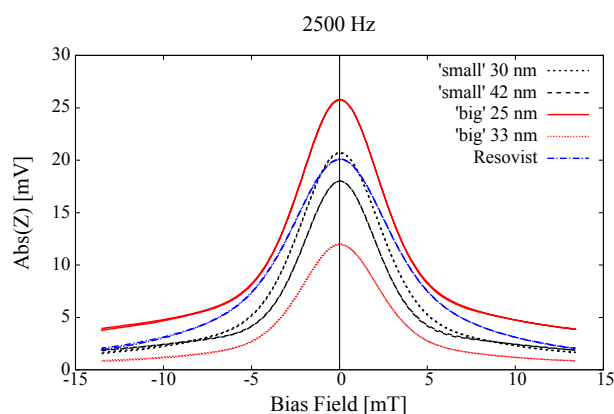
This type of magnetic multi-granule nanoclusters (MGNCs) can be easily formed by the simple reaction of FeCl<sub>3</sub> in ethylene glycol, which serves as both the solvent and reductant, in the presence of sodium acetate [5]. By adjusting the process conditions, the granule size as well as the number of granules can be adjusted. Two formulations were used, one with an average granule size of 15 nm, and one with 23 nm. The average number of granules per cluster was varied so that the cluster size varies from an average diameter of 25 to 43 nm. The smallest clusters with the bigger granules are composed of only one or two granules.

The magnetic response for differential magnetometry was measured by a home built susceptometer (superparamagnetic quantifier, SpaQ), with a drive field of 1.3 mT at a frequency of 2.5 kHz. The sample volume was 200±10 µL of a 1 mg(Fe)/mL suspension. The bias field was applied with a maximum value of 14 mT.

## III. Results

Fig. 1 shows a subset of the range of suspensions investigated. The label “small” (black curves) refers to granules in the order of 15(2) nm, the label “big” (red curves) to granules of about 23(3) nm, as measured by transmission electron microscopy. Of each formulation, two different cluster sizes are shown (continuous and dashed lines). As can be observed, the signal varies considerably with formulation as well as cluster size. The effect of cluster size appears to be much stronger when using bigger granules. Even with this first initial parameter sweep, we can reach signals that are 20% higher than a commercial solution (Resovist™, Bayer Schering Pharma GmbH) with identical iron content. It should be noted however that the commercial solution was in water, whereas our suspensions are still in ethanol. (Suspensions in water have been prepared, and will be shown at the conference).

The maximum peak height and width of the particle response function at half the maximum signal are shown in table 1. The width of the Resovist curve is significantly larger than that of the nanocluster suspensions.

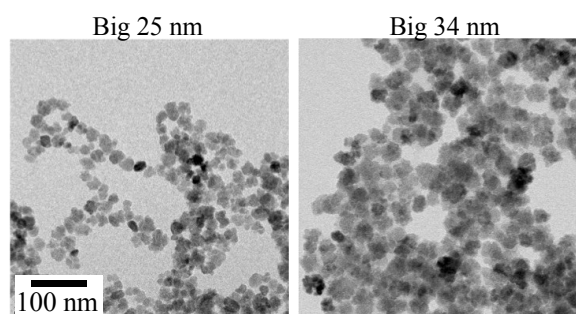


**Figure 1:** Particle response function for multi-granule nanocluster suspensions with variation in size of the granules (black and red curves) as well as the diameter of the total cluster. For comparison, Resovist with identical iron content is shown in blue.

	Peak (mV)	FWHM (mT)
<b>Small 30 nm</b>	10±1	2.90±0.05
<b>Small 42 nm</b>	9±1	2.62±0.05
<b>Big 25 nm</b>	13±1	2.92±0.05
<b>Big 34 nm</b>	6±1	2.77±0.05
<b>Big 43 nm</b>	7±1	2.53±0.05
<b>Resovist</b>	10±1	3.55±0.05

**Table 1:** Peak signal at 0 mT and width at half maximum for suspensions with different granule size (“small” vs “big”) and cluster size. For comparison, Resovist with identical iron content is shown.

Fig. 2 shows the transmission electron microscopy image of the suspension with the highest signal (“Big” 25 nm) and the lowest signal (“Big” 34 nm). Apart from the size, there is no apparent difference. Also the coercivities of both suspensions are identical (0.9 kA/m), indicating that the origin of the signal difference might be related to the hydrodynamic radius. Further research is in progress.



**Figure 2:** Transmission electron micrograph of the suspension with the highest (left) and the lowest signal (right)

## IV. Conclusions

When using multi-granule nanoclusters, one can tune the size of the granules relatively independently from the size of the clusters. This offers an extra degree of freedom in tuning magnetic particles for differential magnetometry and Magnetic Particle Imaging. We have shown that the highest signal can be obtained when using bigger granules, but that the relation between cluster size and magnetic signal increases when using big granules.

These promising first results encouraged us to realize suspensions in water by proper surface modification of the nanoclusters, and to further optimize their response.

## REFERENCES

- [1] F. Ahrentorp, A. Astalan, J. Blomgren, C. Jonasson, E. Wetterskog, P. Svedlindh, A. Lak, F. Ludwig, L.J. Van Ijzendoorn, F. Westphal, C. Gruttner, N. Gehrke, S. Gustafsson, E. Olsson, and C. Johansson.

- Effective particle magnetic moment of multi-core particles. *Journal of Magnetism and Magnetic Materials*, 380:221–226, 2015. doi:10.1016/j.jmmm.2014.09.070.
- [2] D. Schmidt, F. Palmetshofer, D. Heinke, U. Steinhoff, and F. Ludwig. A phenomenological description of the MPS signal using a model for the field dependence of the effective relaxation time. *IEEE Transactions on Magnetics*, 51(2), 2015. doi:10.1109/TMAG.2014.2345192.
- [3] Pan, L., Park, B. C., Ledwig, M., Abelmann, L., & Kim, Y. K. (2017). Magnetic Particle Spectrometry of Fe<sub>3</sub>O<sub>4</sub> Multi-granule Nanoclusters. *IEEE transactions on magnetics*, 53(11), [5101004]. DOI: 10.1109/TMAG.2017.2701904
- [4] Pouw, J. J., Grootendorst, M., Klaase, J. M., van Baarlen, J., & ten Haken, B. (2016). Ex vivo sentinel lymph node mapping in colorectal cancer using a magnetic nanoparticle tracer to improve staging accuracy: a pilot study. *Colorectal disease*, 18(12), 1147–1153. DOI: 10.1111/codi.13395
- [5] J. Cha, J.S. Lee, S.J. Yoon, Y.K. Kim, and J.-K. Lee. Solid-state phase transformation mechanism for formation of magnetic multi-granule nanoclusters. *RSC Advances*, 3(11):3631–3637, 2013. doi:10.1039/c3ra21639j.