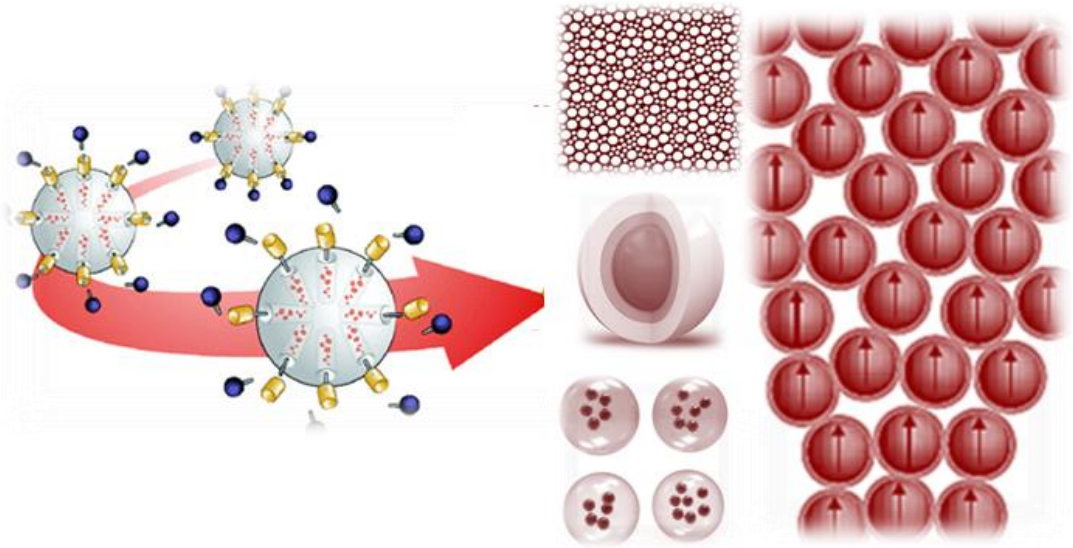
Aristotle University of Thessaloniki

Physics Department



Particle and field controls to increase hyperthermia efficiency

Magna Charta

Magnetic

nanostructure

Characterization

Technology & Applications

Dr Eirini Myrovali

Introduction

Synthesis

Morphology & Magnetic Features

Magnetic Hyperthermia

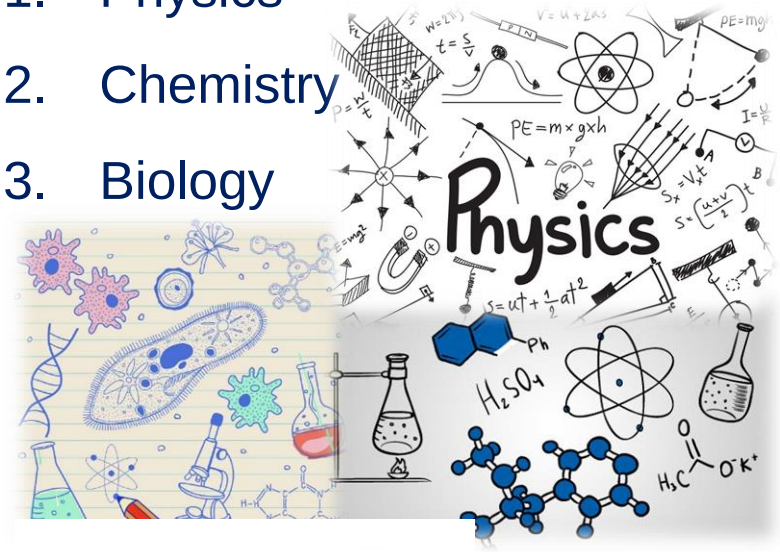
Conclusions

Introduction

Particle and field controls to increase hyperthermia efficiency

Nanotechnology includes the understanding of the fundamental:

1. Physics
2. Chemistry
3. Biology

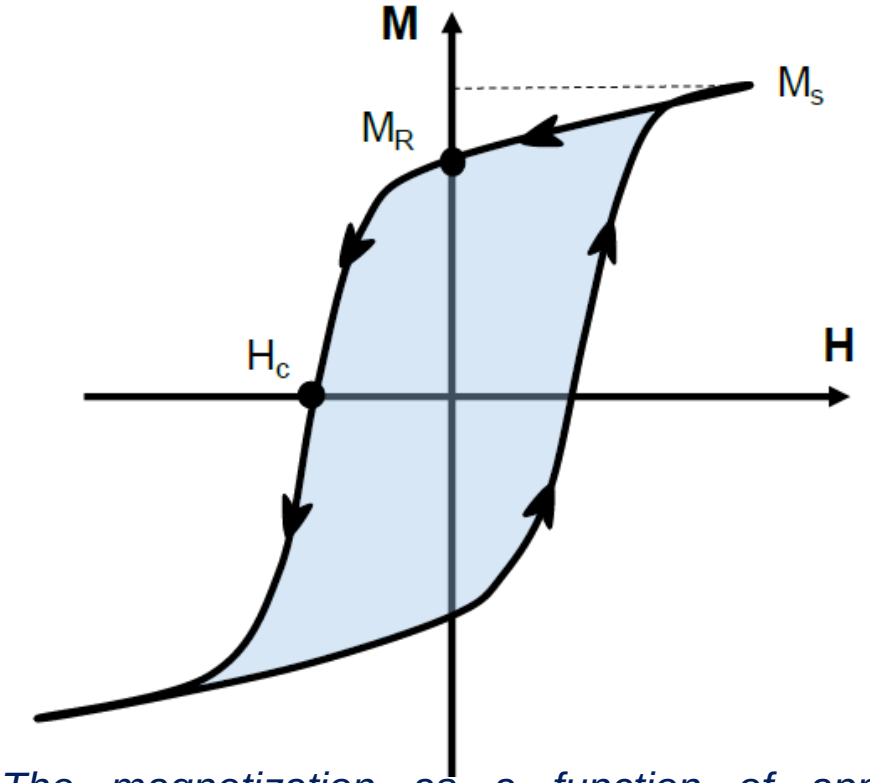


- Nanotechnology may be able to create **many new materials** and **devices** with a vast range of applications.
- A nanoparticle is usually defined as a particle of matter that is between 1 and 100 nanometres (nm) in diameter.
- Magnetic nanoparticles belong to the group of nanotechnology-based materials with an impact in fields of analytical chemistry, biosensing, and nanomedicine.

Why are magnetic nanoparticles so important ??

Magnetic features

Magnetic nanoparticles are classified by their response to an externally applied magnetic field.



The magnetization as a function of applied magnetic field. Typical hysteresis loop area of MNPs with the characteristic features.

The magnetization raises with the field until it reaches the maximum value. This value is called **saturation magnetization** M_s because all the magnetic dipoles are aligned in an external magnetic field. **Remanent magnetization** M_R exists when the applied field is zero. Remanent magnetization can be removed by applying a field in the opposite direction to the applied field. This field is called **coercive field** H_c.

Magnetic features

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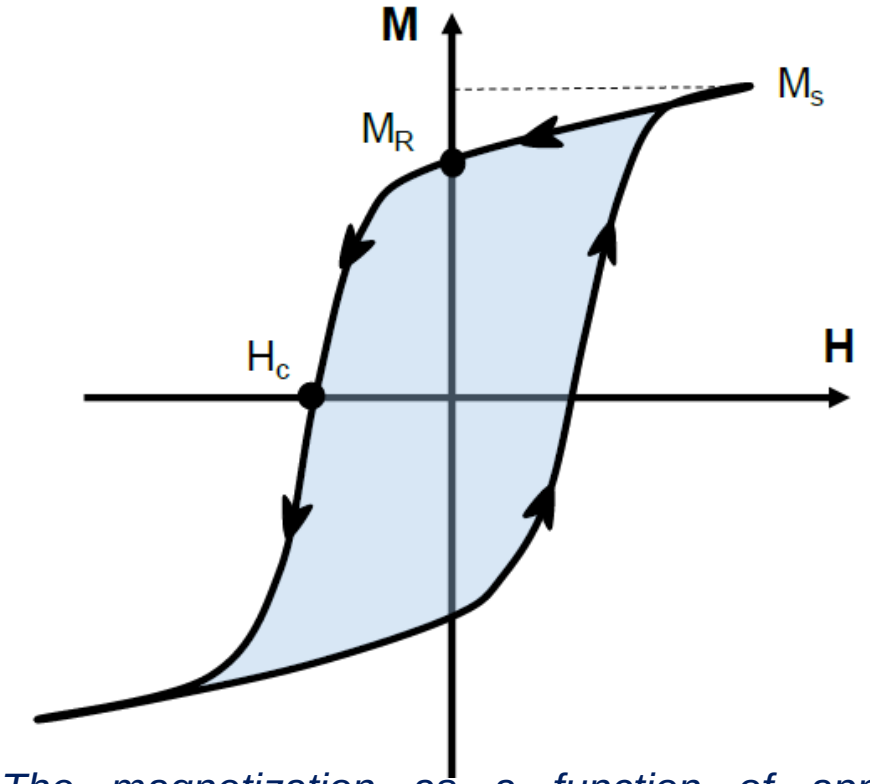
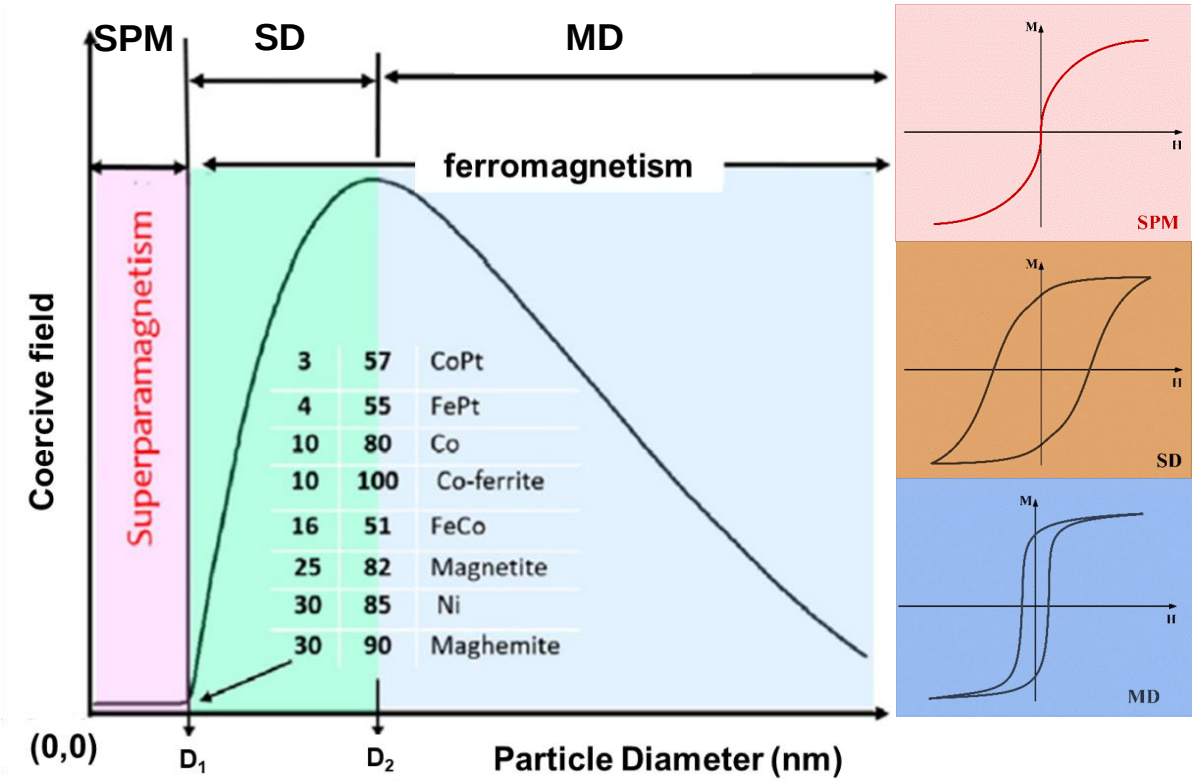
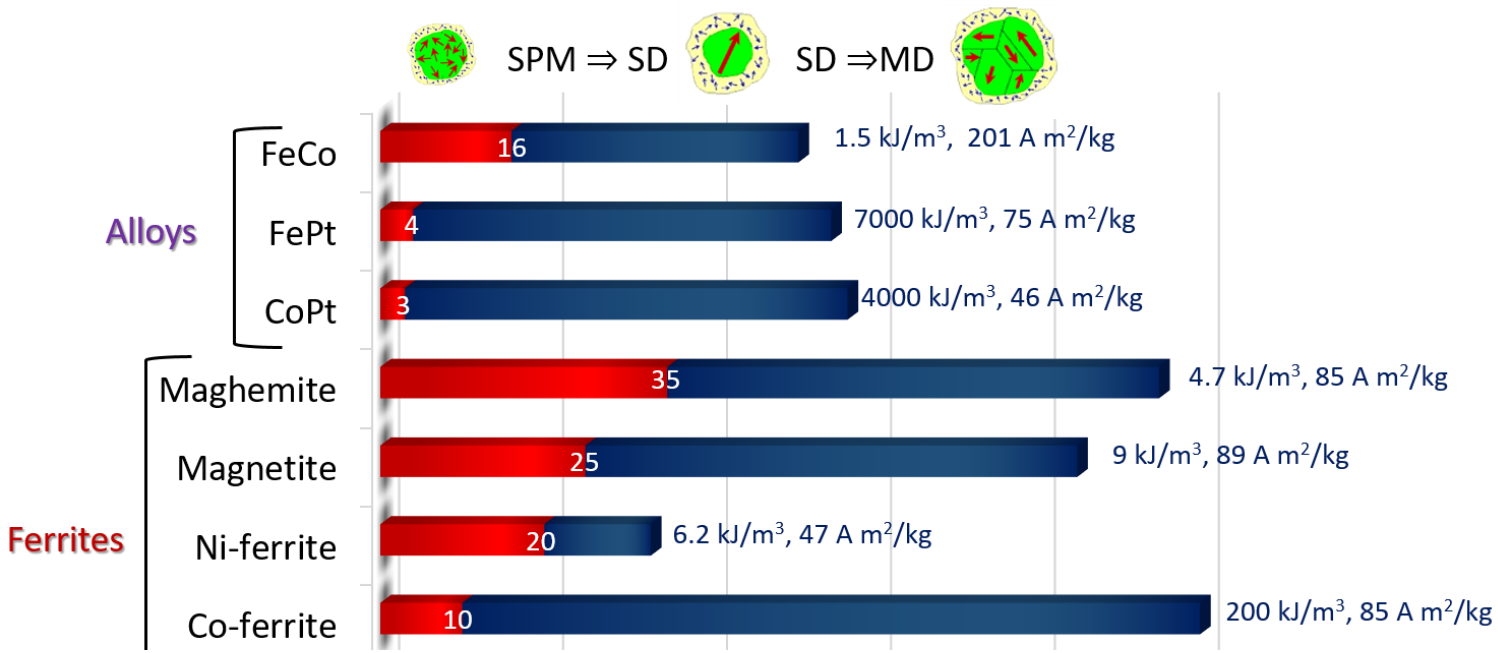


The magnetization as a function of applied magnetic field. Typical hysteresis loop area of MNPs with the characteristic features.



Introduction

Particle and field controls to increase hyperthermia efficiency



✓ The key in nanotechnology research is the ability to **manipulate nanomaterials** in order to take advantage of their **special properties.**

Iron oxide nanoparticles are receiving much attention due to great perspectives of magnetic properties. They have emerged as one of the primary nanomaterials for biomedical applications due to their:

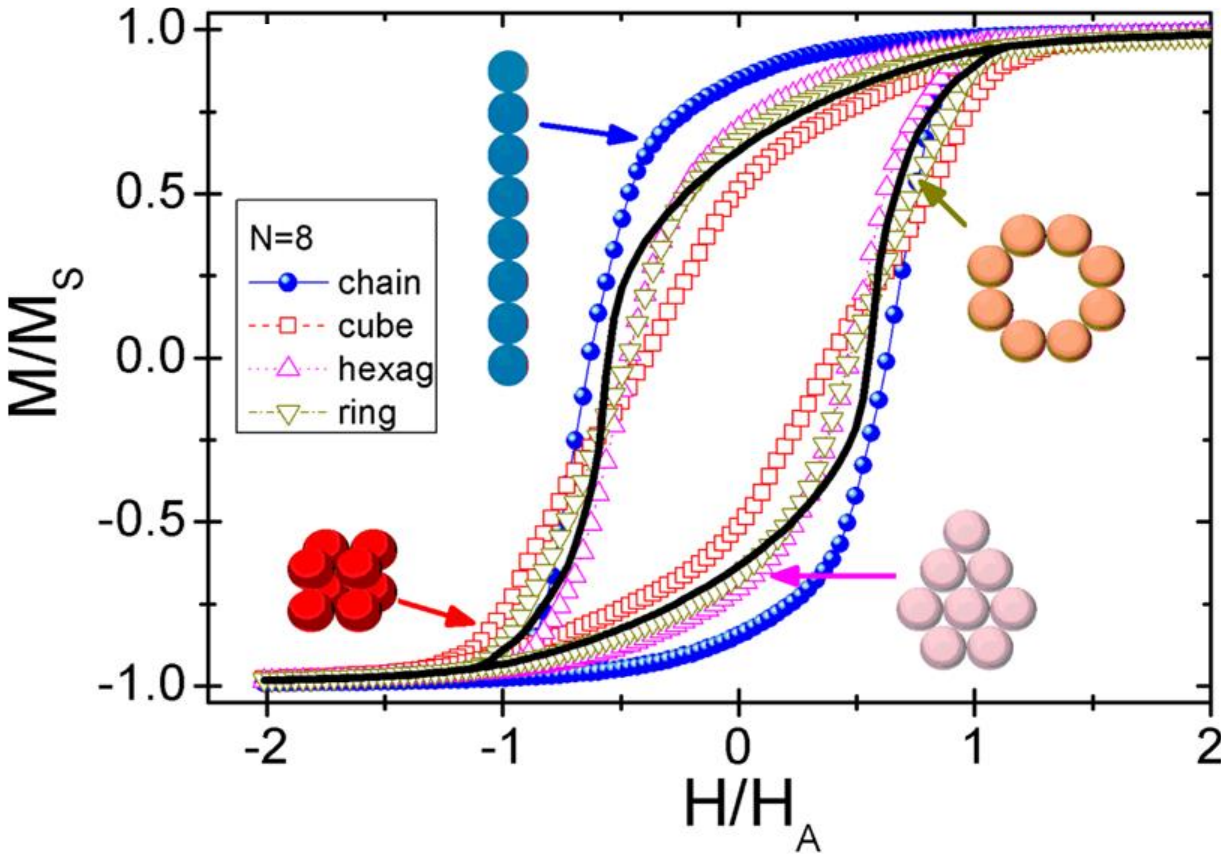
1. Long blood retention time
2. Biodegradability
3. Low toxicity

✓ The **size** and the **shape** play a crucial role in magnetic features.

Introduction

Particle and field controls to increase hyperthermia efficiency

Chain-organized magnetic structuring often exhibits properties which do not exist in randomly aggregated MNPs because they allow the selective modification of their inter- or intra-particle interactions.



Recently, oriented MNPs have driven a tremendous interest for a wide range of applications such as:

1. Spintronics (for high-density magnetic data storage)
2. Water treatment
3. Biomedical applications

There is significant interest in embedding chain in **biomedical applications**, such as magnetic resonance imaging (MRI) or magnetic particle hyperthermia (MPH).

Serantes, D. et al. “The Journal of Physical Chemistry C” 118.11 (2014): 5927-5934.

Introduction

Particle and field controls to increase hyperthermia efficiency

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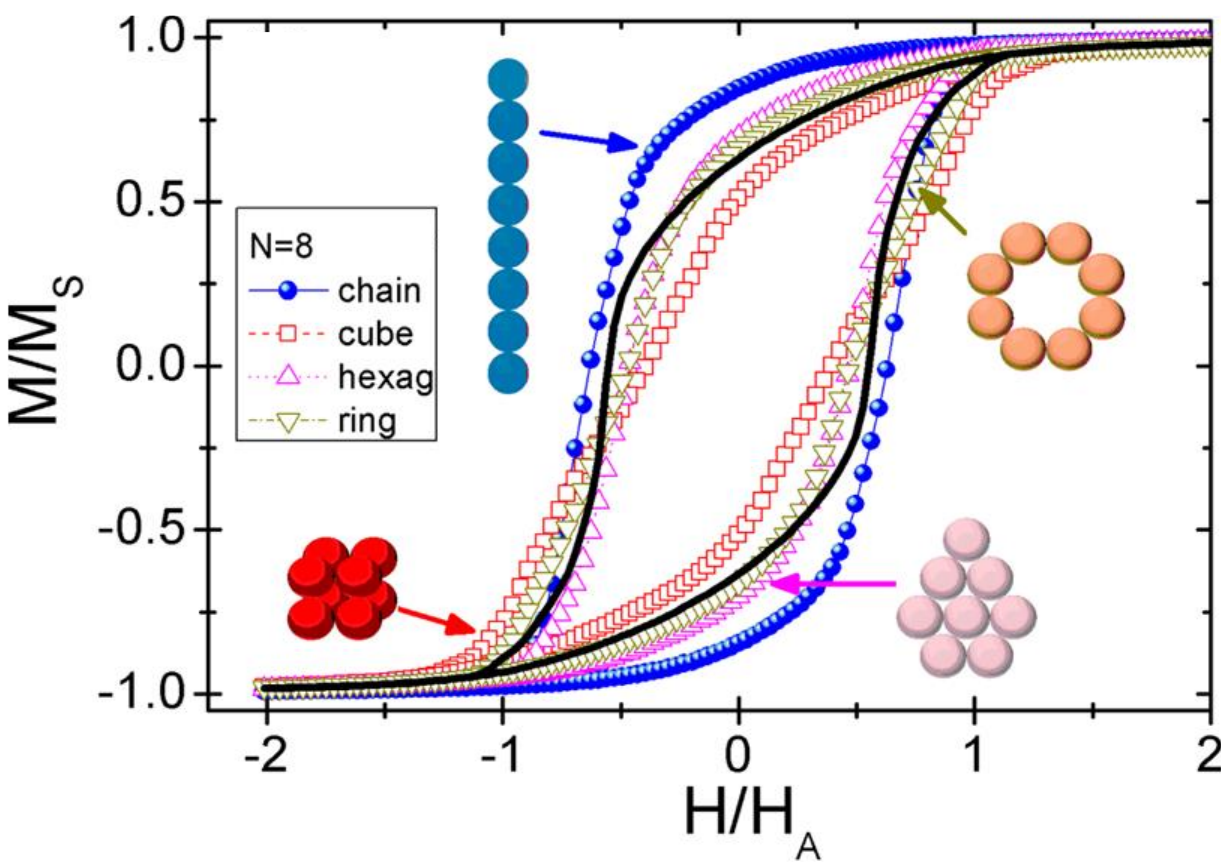
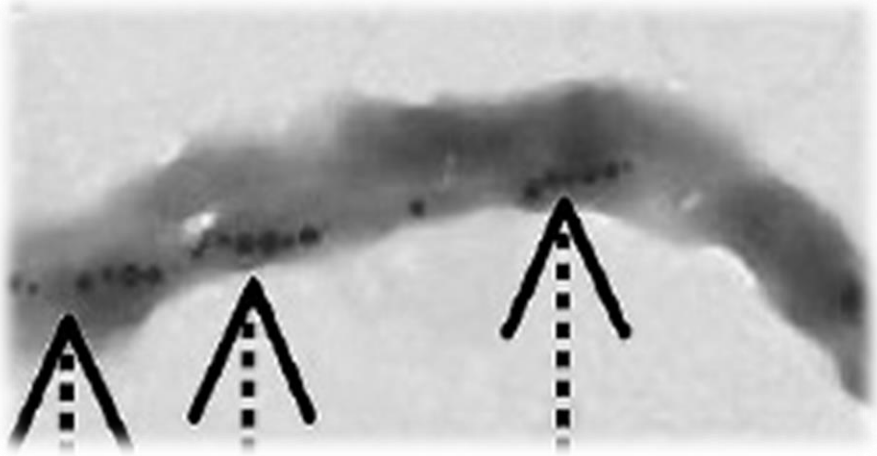


Serantes, D. et al. “The Journal of Physical Chemistry C” 118.11 (2014): 5927-5934.

One of the most fascinating processes in nature is self-assembly. Self-assembly is a process in which nanoparticles are organized autonomously into patterns or structures due to magnetic interactions **without human intervention.**

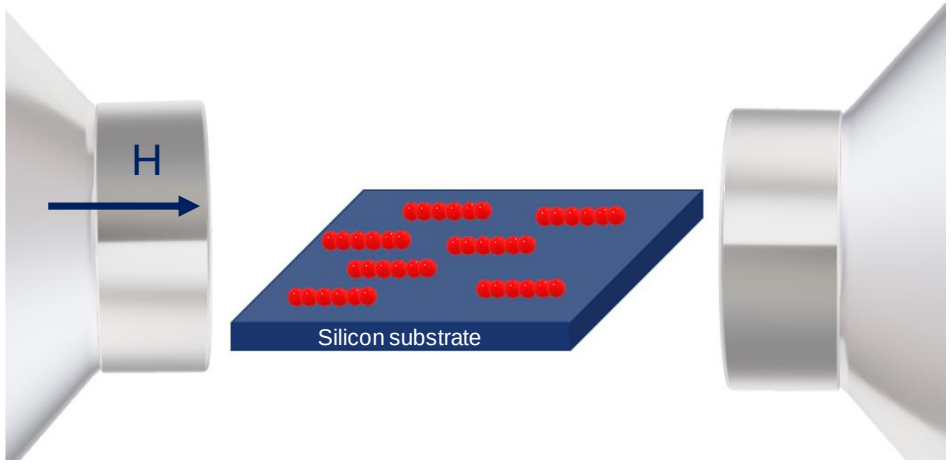


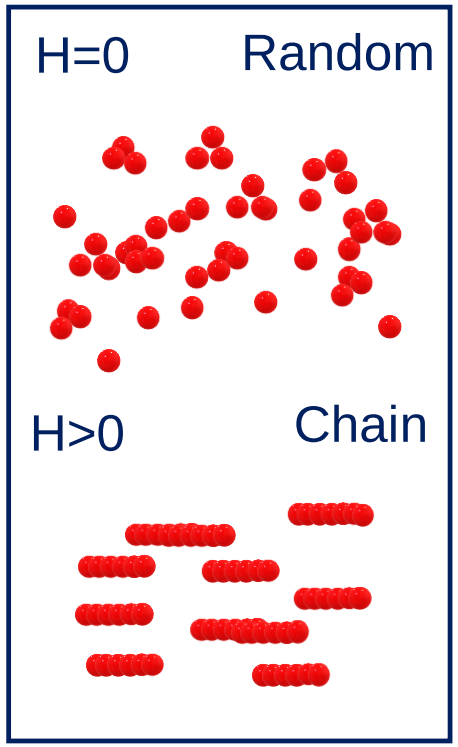
Alphandéry, E. et al. “Acs Nano” 3.6 (2009): 1539-1547.

Introduction

Particle and field controls to increase hyperthermia efficiency

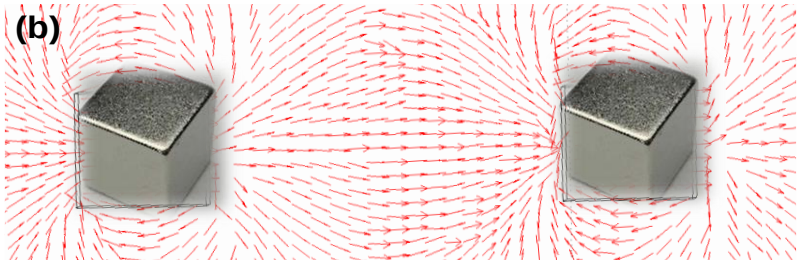
Chain formation has also been reported to create micro-nanostructures assembled by iron oxide nanoparticles by using an **artificial magnetic field**.



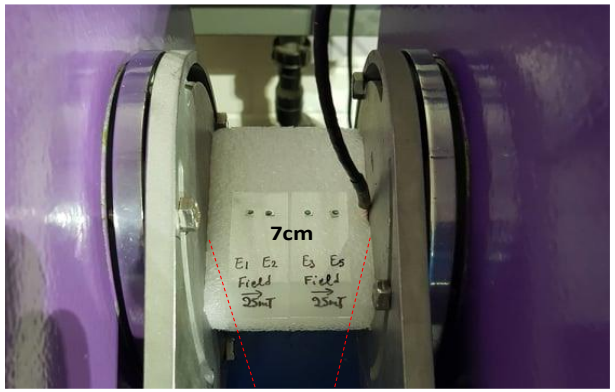


Magnets NdFeB

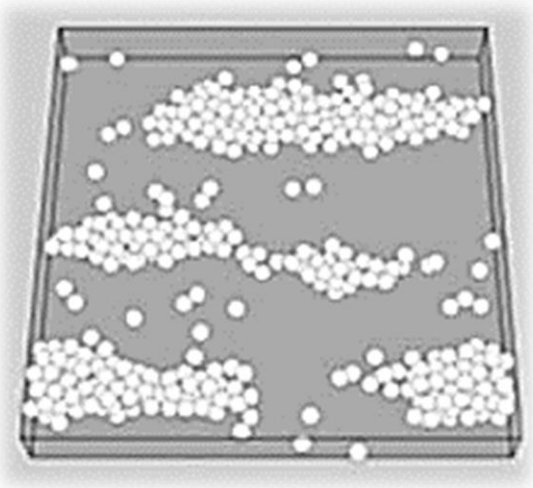
40 mT



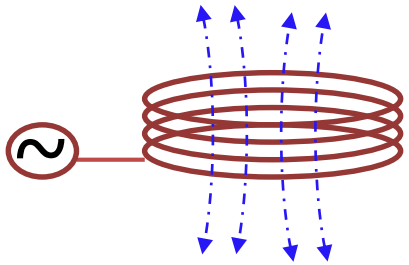
> 40 mT



Electromagnets



Hyperthermia measurements



AC magnetic field

Optimize the chain formation varying:

1. Particle Size

2. External field

Optimize the heating efficiency of Fe_3O_4 chain arrays

Content

Particle and field controls to increase hyperthermia efficiency

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Magnetic Features

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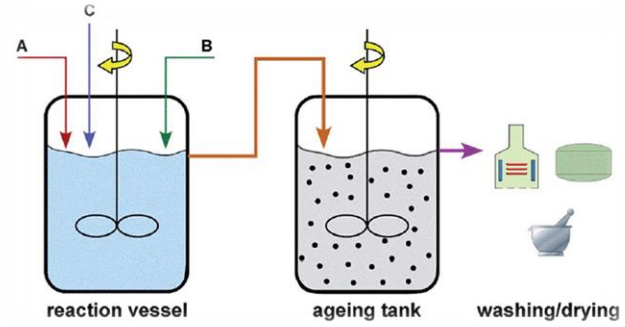
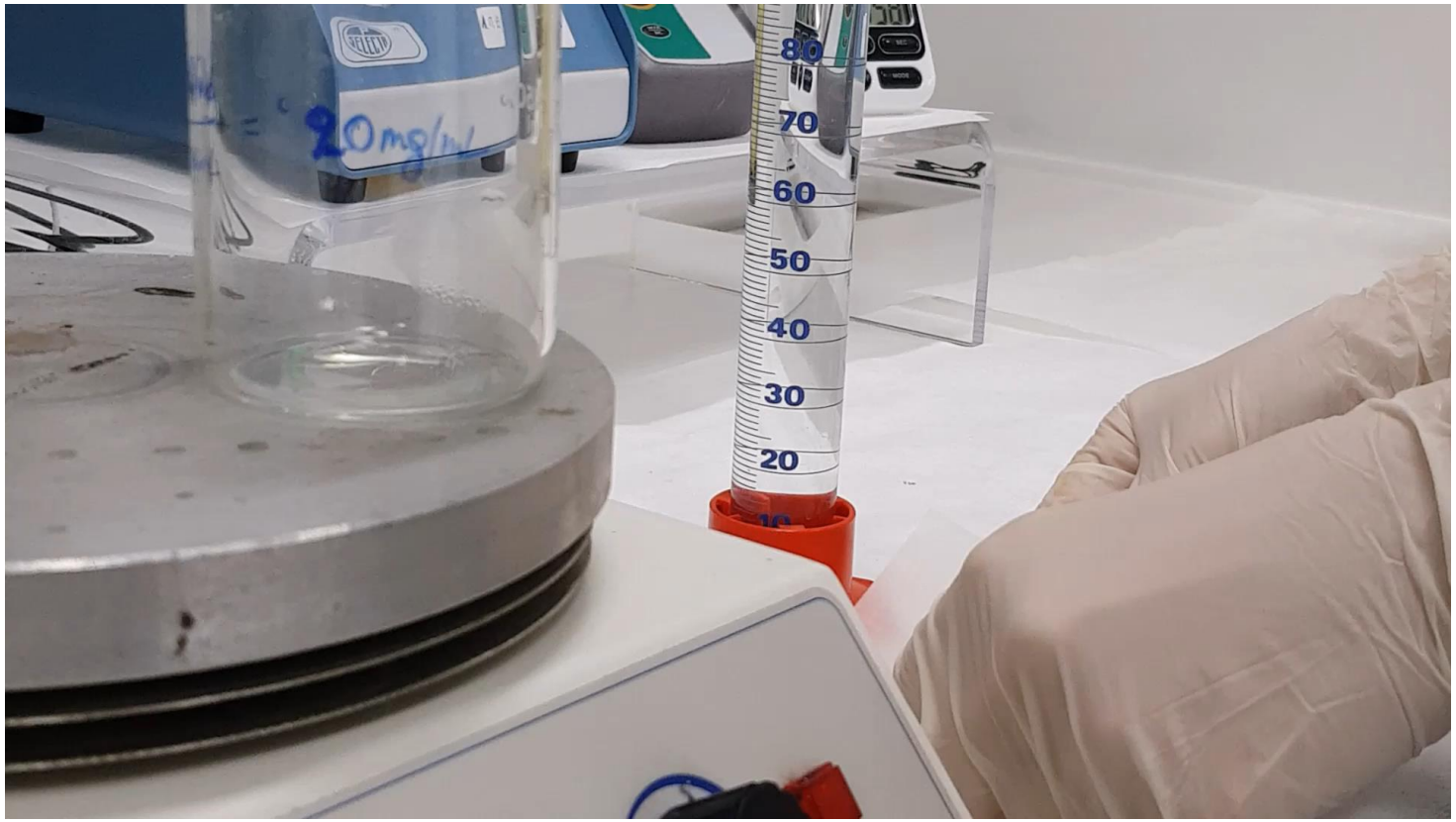
Synthesis

Particle and field controls to increase hyperthermia efficiency

Co-precipitation synthesis



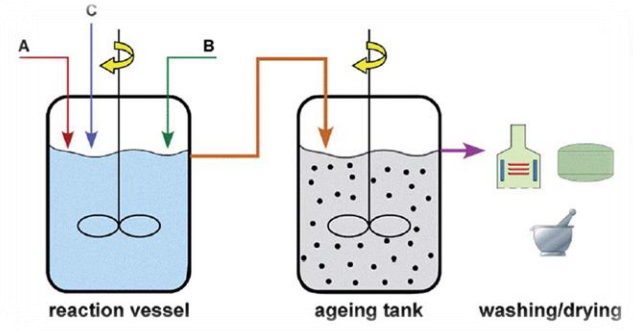


- Agarose gel content mimics the microstructure of hard tissues, while lower content gels have porosities similar to soft tissues such as the human brain.
- Stabilize the MNPs

Synthesis

Particle and field controls to increase hyperthermia efficiency

Co-precipitation synthesis



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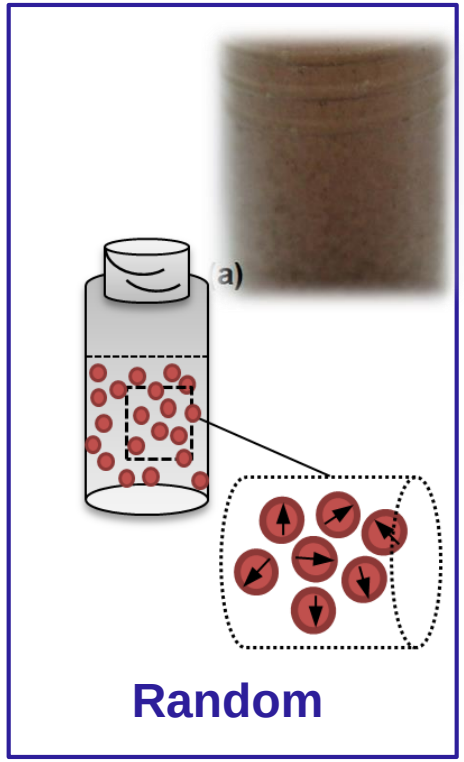
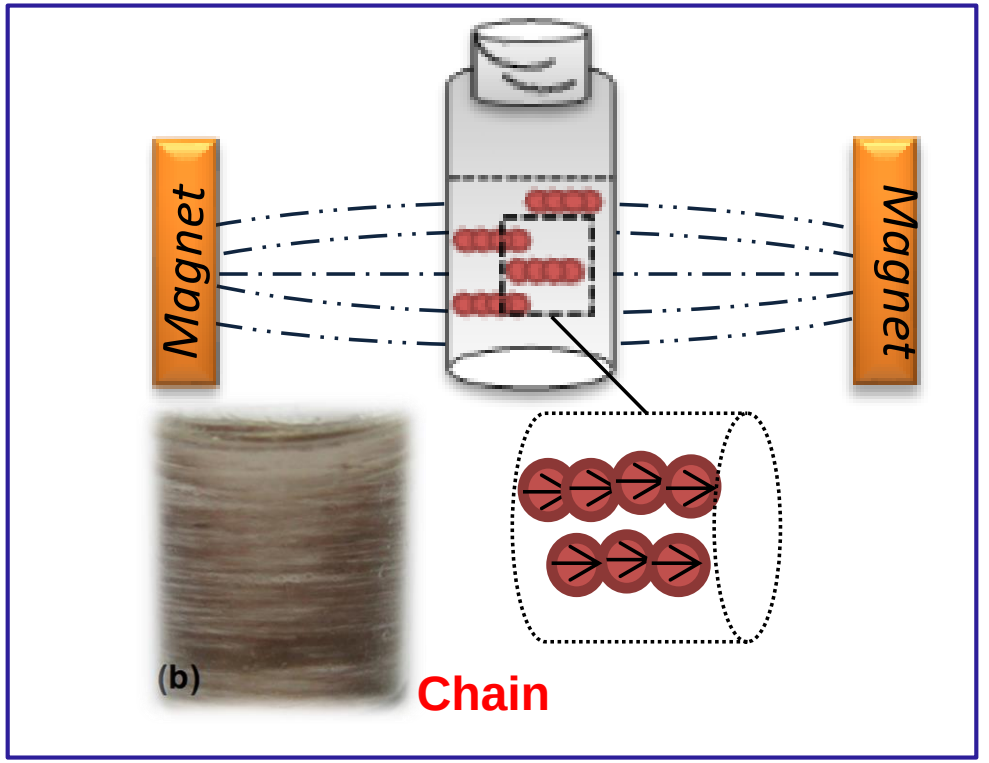
- Stabilize the MNPs



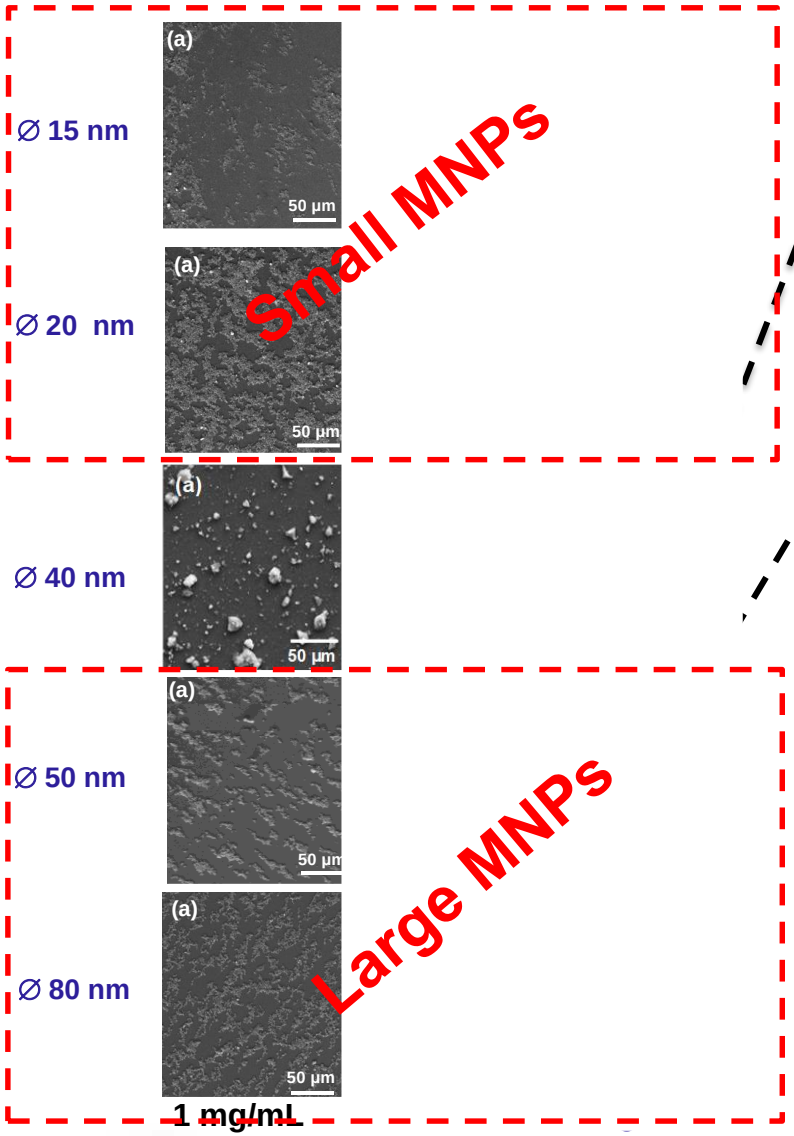


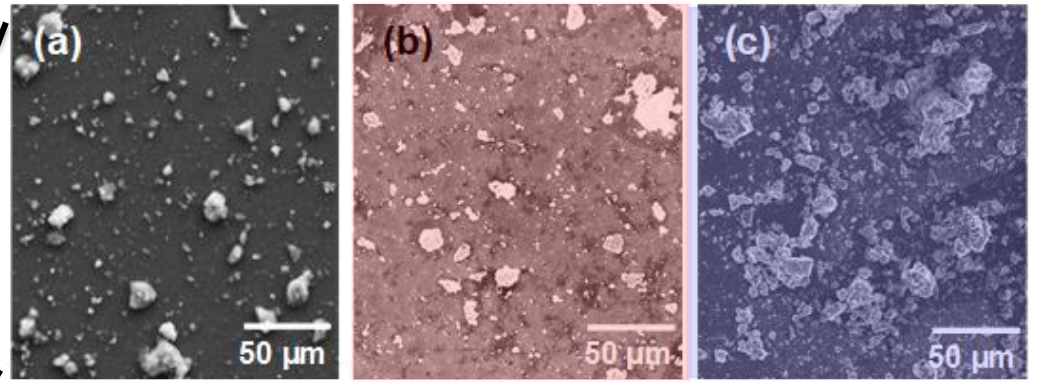
Myrovali, E. et al., Scientific reports 6 (2016): 37934.

Morphology & Magnetic Features

Particle and field controls to increase hyperthermia efficiency

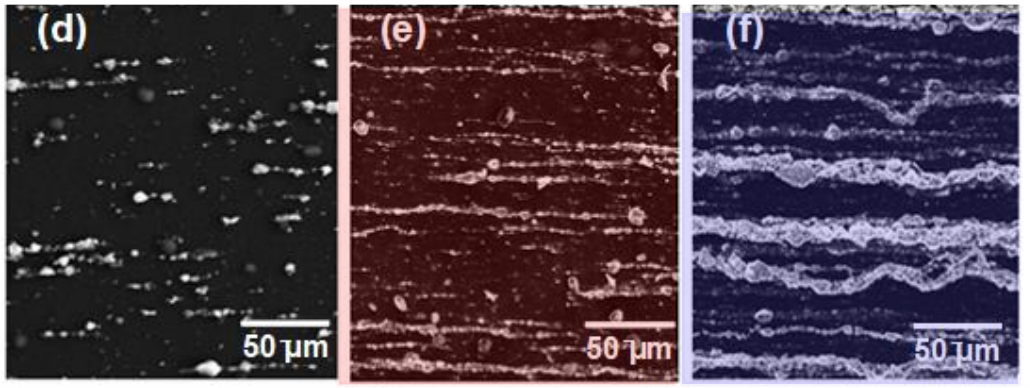
Size dependence





External applied field 40 mT

∅ 40 nm



The MNPs are not oriented and are localized in inhomogeneous island-like structures. That means, the MNPs tend to gather forming groups, also known as aggregates, i.e. bigger clusters due to the absence of coatings.

Successful formation of chains

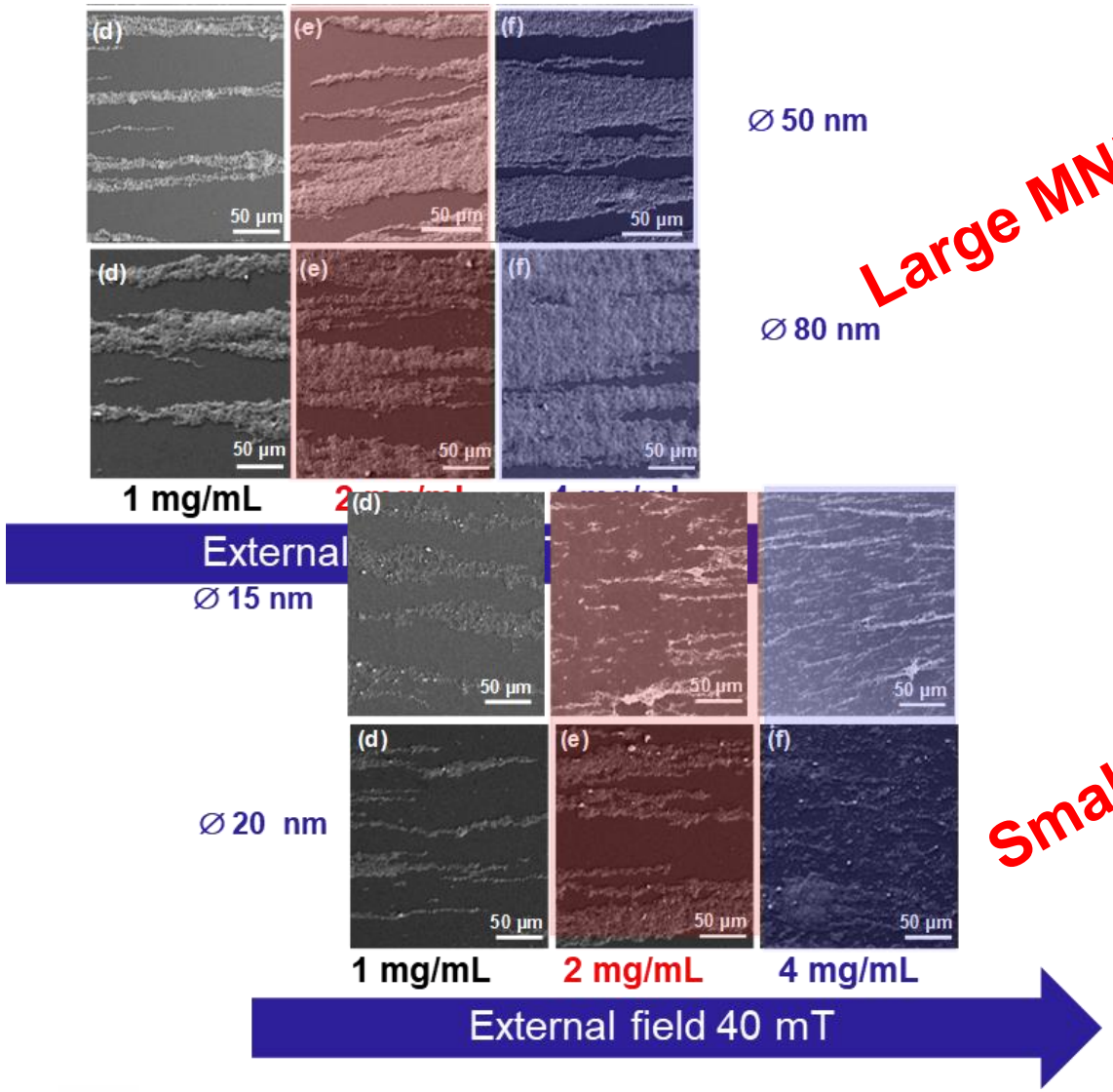
→ length
→ the inter-chains distances

Myrovali, E. et al., Scientific reports 6 (2016): 37934.

Morphology & Magnetic Features

Particle and field controls to increase hyperthermia efficiency

Size dependence



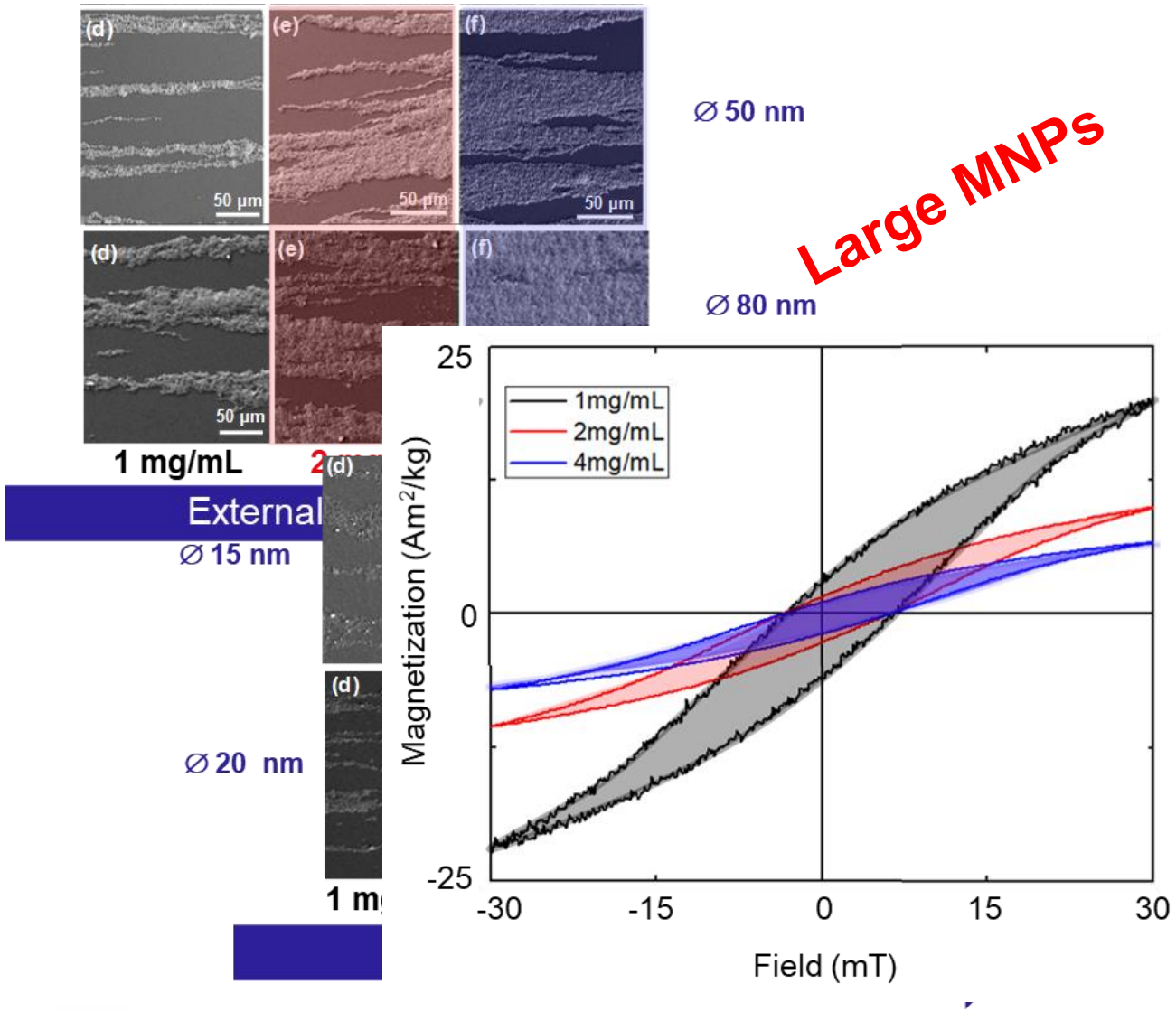
- ✓ In the smaller concentration of 1 mg/mL there are longer chains as compared to higher concentration 4 mg/mL.
- ✓ Chains are formed with short distances between them when the concentration increases.

- ✓ There are well formed chains.
- ✓ The chains remain separated even in the highest concentration (4mg/mL).
- ✓ The **concentration MNPs plays a crucial role in generating chains** with tunable **width** and **length**. The attractive forces enhance when nanoparticle size and concentration increase.

Morphology & Magnetic Features

Particle and field controls to increase hyperthermia efficiency

Size dependence

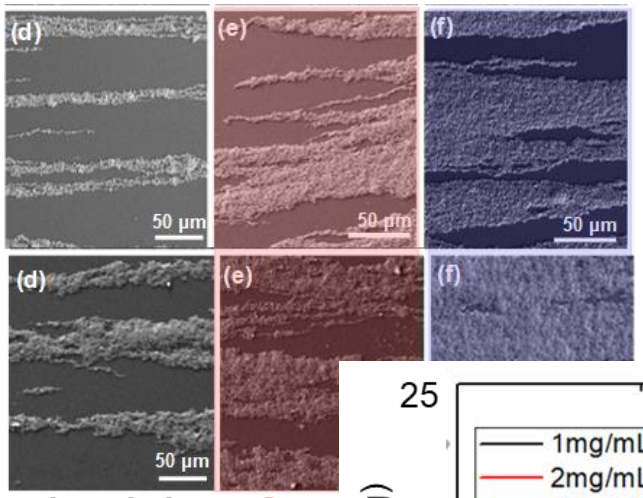


- ✓ In the smaller concentration of 1 mg/mL there are longer chains as compared to higher concentration 4 mg/mL.
- ✓ Chains are formed with short distances between them when the concentration increases.
- ✓ The coercive field does not exhibit any variation when the concentration increases from 1 mg/mL to 4 mg/mL.
- ✓ The magnetization increases faster in low concentration 1 mg/mL as compared to higher concentration 4 mg/mL.

Morphology & Magnetic Features

Particle and field controls to increase hyperthermia efficiency

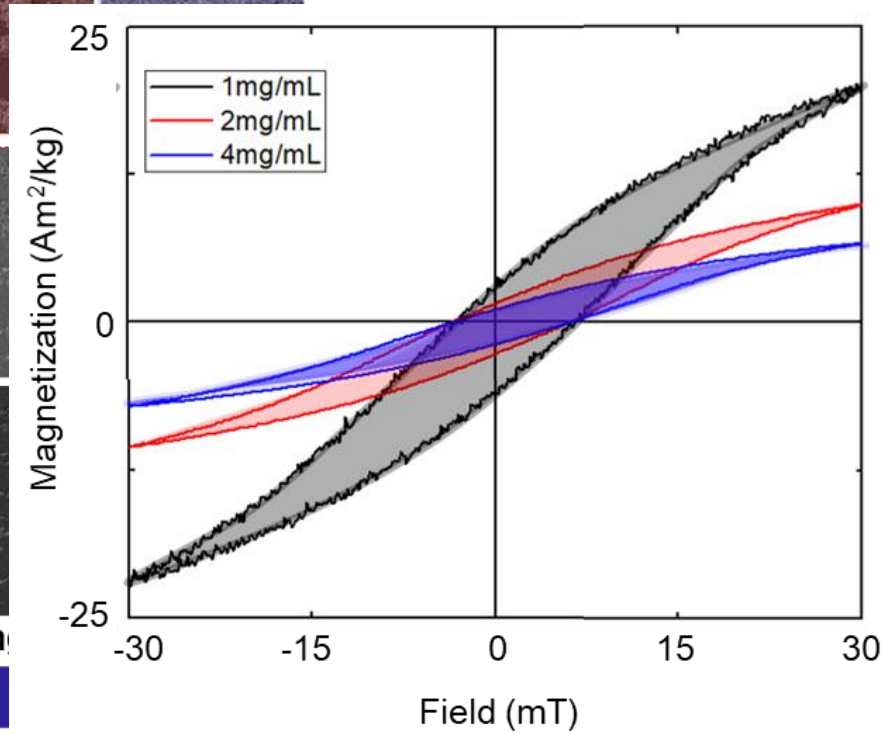
Size dependence



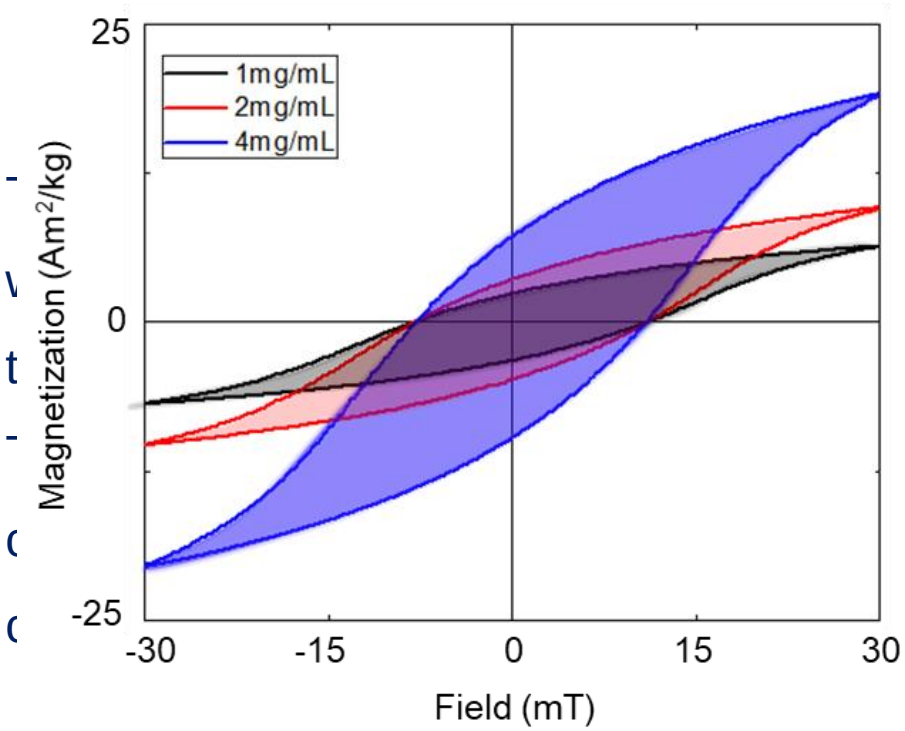
∅ 50 nm

Large MNPs

∅ 80 nm



✓ On the contrary, the magnetization has a significant increase when the concentration rises up to 4 mg/mL in small MNPs.



✓ -

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v

g/mL

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✓ -

low

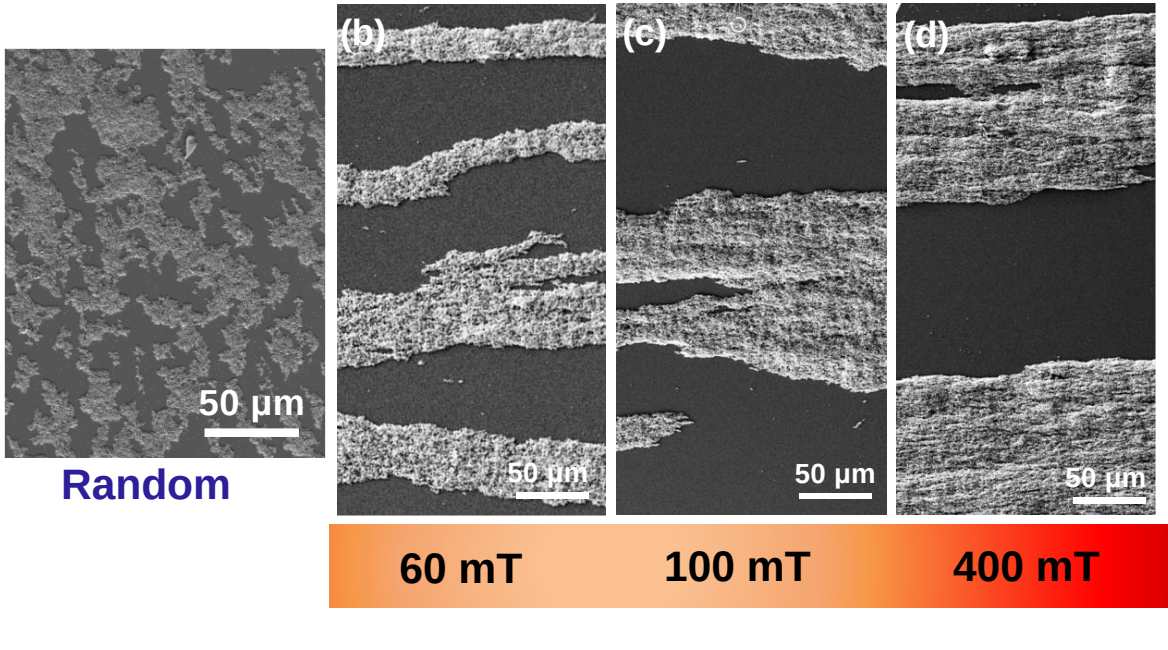
gher

Morphology & Magnetic Features

Particle and field controls to increase hyperthermia efficiency

Field dependence

∅ 80 nm – 4 mg/mL



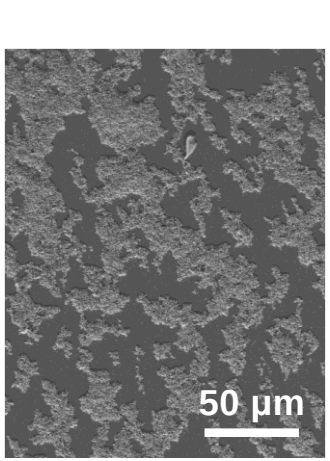
- ✓ A small increase in the field raises the length and thickness of the chains; as a result, we have well-formed chains, and more space opens up between them.
- ✓ By applying even bigger fields, i.e. 100 mT, chains turn into wider arranged areas. Chains become wider and denser linear structures appear in a strong magnetic field of 400 mT.
- ✓ By increasing the strength of the applied field, the attractive interactions rise between the chains, creating longer and wider chains due to dipolar interactions.

Morphology & Magnetic Features

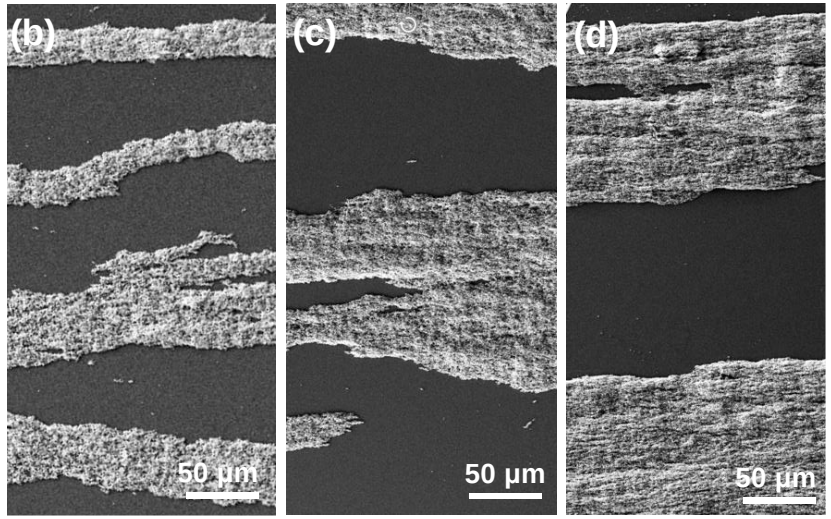
Particle and field controls to increase hyperthermia efficiency

Field dependence

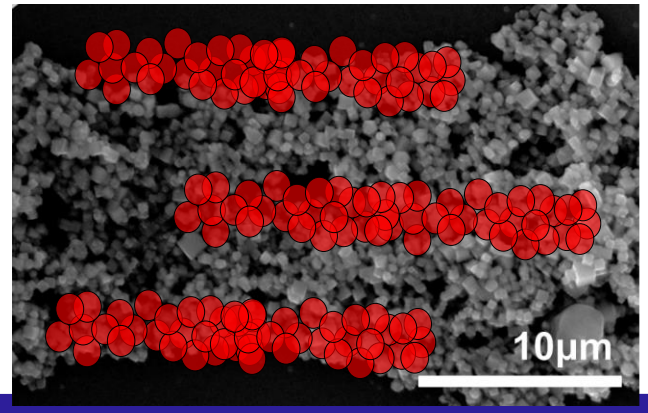
∅ 80 nm – 4 mg/mL



Random



60 mT **100 mT** **400 mT**



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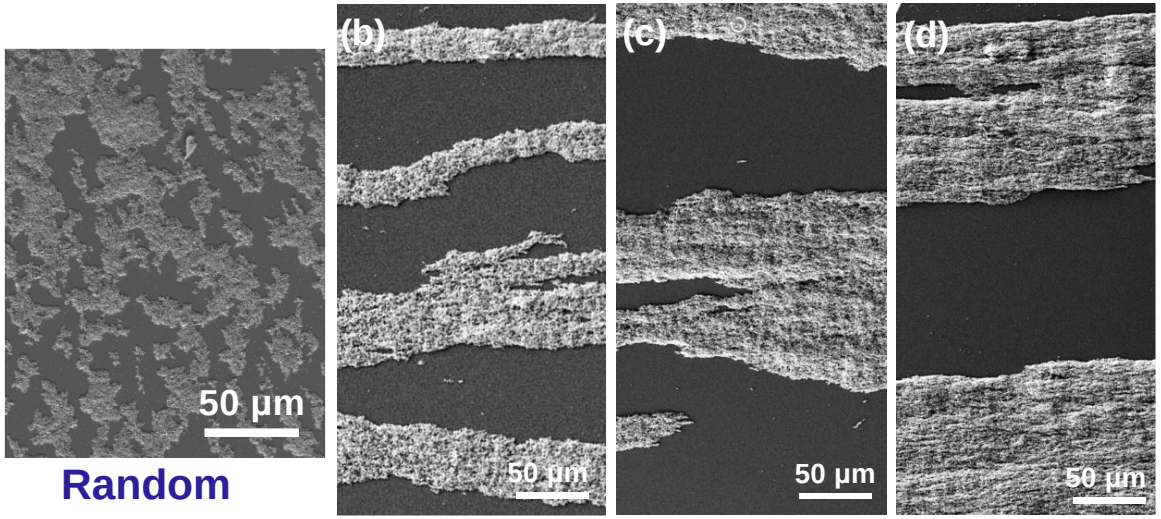
- ✓ By applying even bigger fields, i.e. 100 mT, chains turn into wider arranged areas. Chains become wider and denser linear structures appear in a strong magnetic field of 400 mT.
- ✓ By increasing the strength of the applied field, the attractive interactions rise between the chains, creating longer and wider chains due to dipolar interactions.
- ✓ MNPs start interacting with one another and create a long chain agglomerate structure with **core-to-core** structure.

Morphology & Magnetic Features

Particle and field controls to increase hyperthermia efficiency

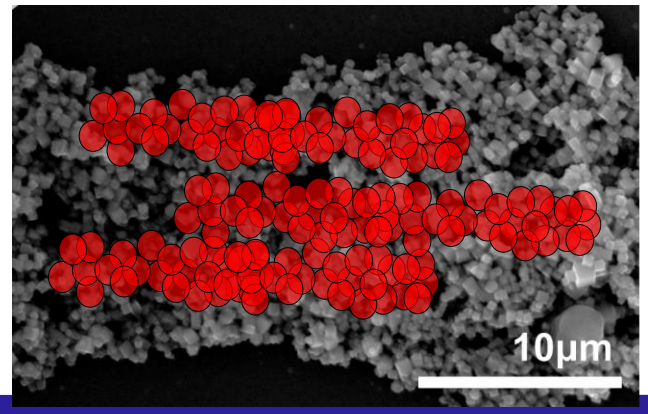
Field dependence

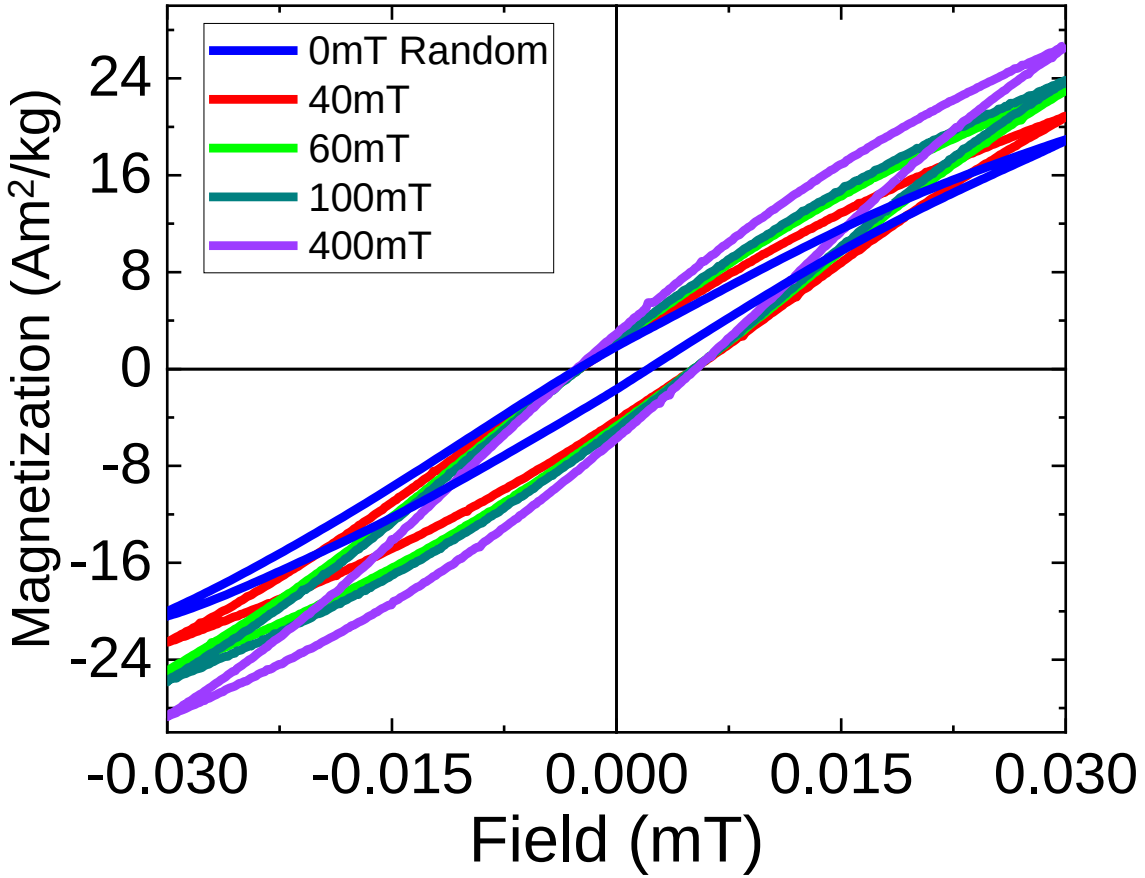
∅ 80 nm – 4 mg/mL



Random

60 mT **100 mT** **400 mT**





The magnetization values (Mr, Ms) and coercivity field increase depending on the external applied field as compared to the random one. Chain formation enhances the collective magnetic properties.

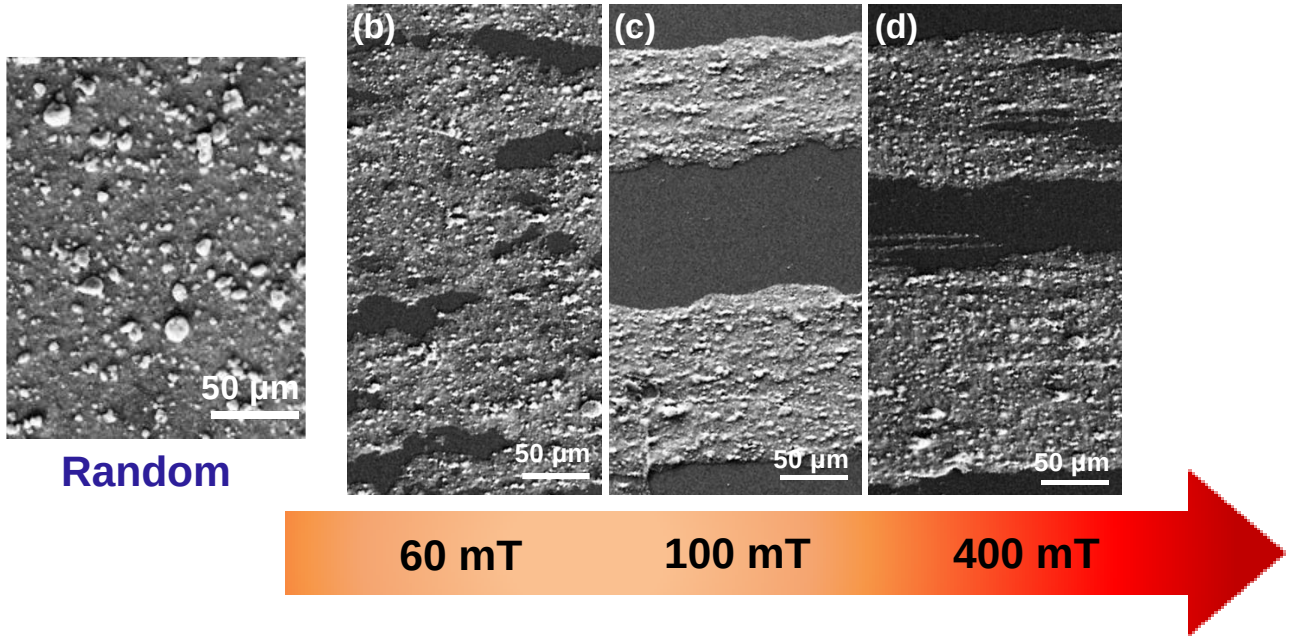
Morphology & Magnetic Features

Particle and field controls to increase hyperthermia efficiency

Field dependence

∅ 15 nm – 4 mg/mL

✓ Well-formed chains and more space opens up between them.

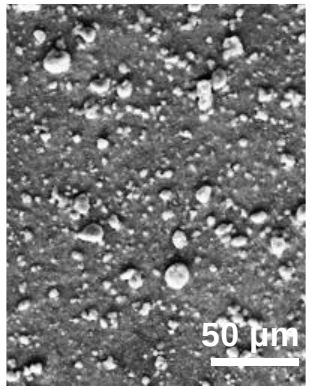


Morphology & Magnetic Features

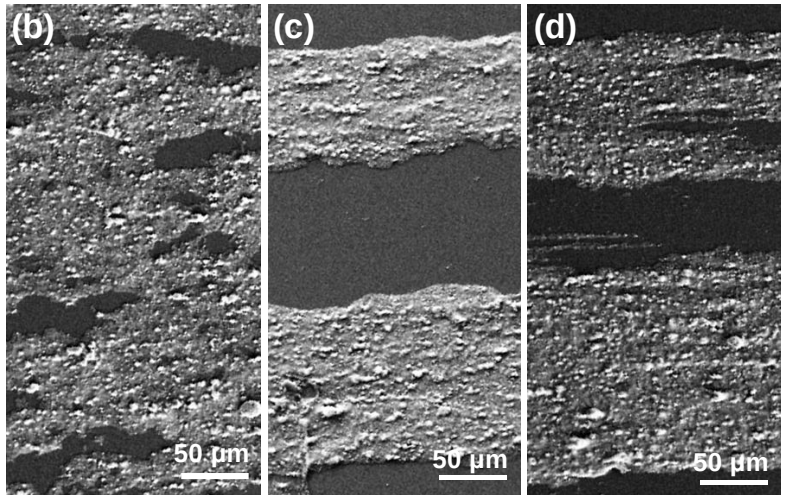
Particle and field controls to increase hyperthermia efficiency

Field dependence

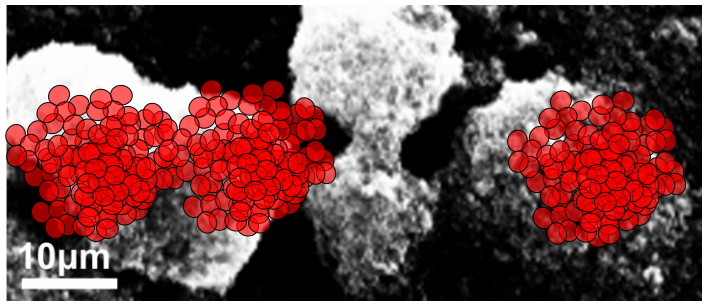
∅ 15 nm – 4 mg/mL



Random



60 mT **100 mT** **400 mT**



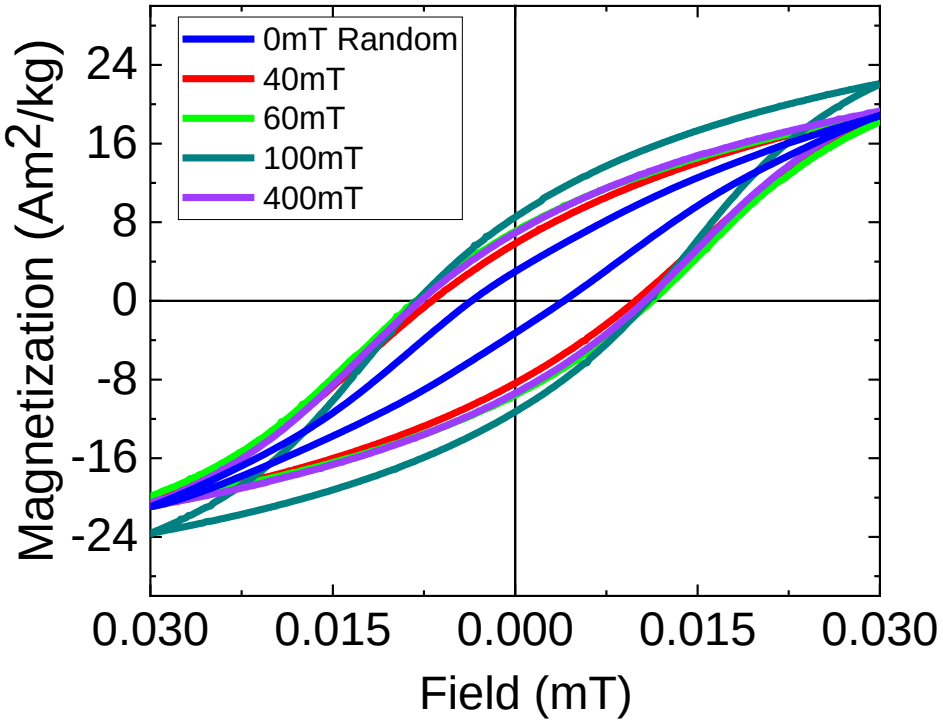
✓ Well-formed chains and more space opens up between them.

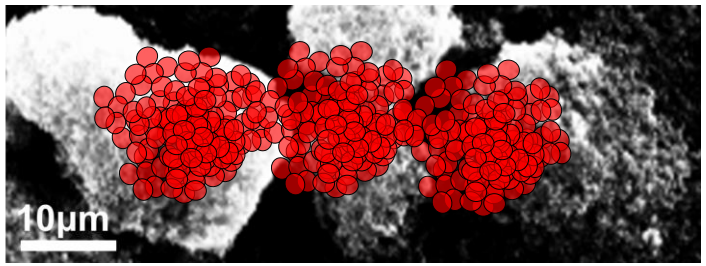
- Such phenomenon can be explained by **cluster to cluster** form.
- A cluster consits of a large number of particles. That means a cluster is composed of several cores per particle and present strong magnetic interactions.
- By increasing the strength of the applied field, the attractive interactions rise between the chains, creating longer and wider chains due to dipolar interactions.
- Thus, the chain structure separates because there are strong dipolar interactions.

Morphology & Magnetic Features

Particle and field controls to increase hyperthermia efficiency

Field dependence





- ✓ The magnetization values (M_r, M_s) and coercivity field increase depending on the external applied field as compared to the random one.
- ✓ In small MNPs the loops become increasingly **wider** and **square**r as compared to the large MNPs.
- ✓ These results indicate that the magnetic properties could be attributed to the **connection between the chains**.
- ✓ That means, **cluster-to-cluster** formation could be implied stronger dipolar interactions than **core to core** formation because a cluster behaves as ferromagnetic core.

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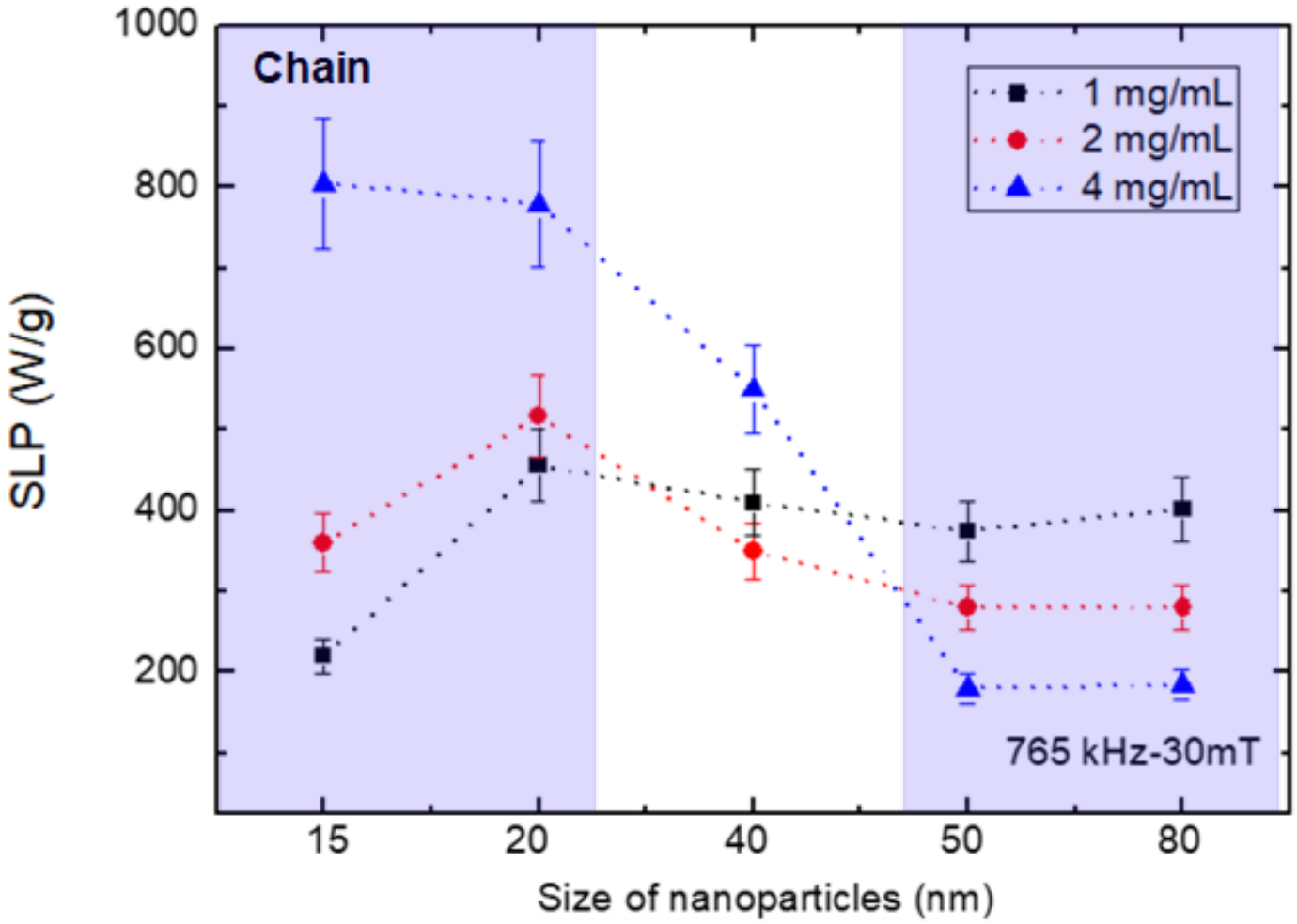
Magnetic hyperthermia

Particle and field controls to increase hyperthermia efficiency

765 kHz – 30 mT



Small MNPs

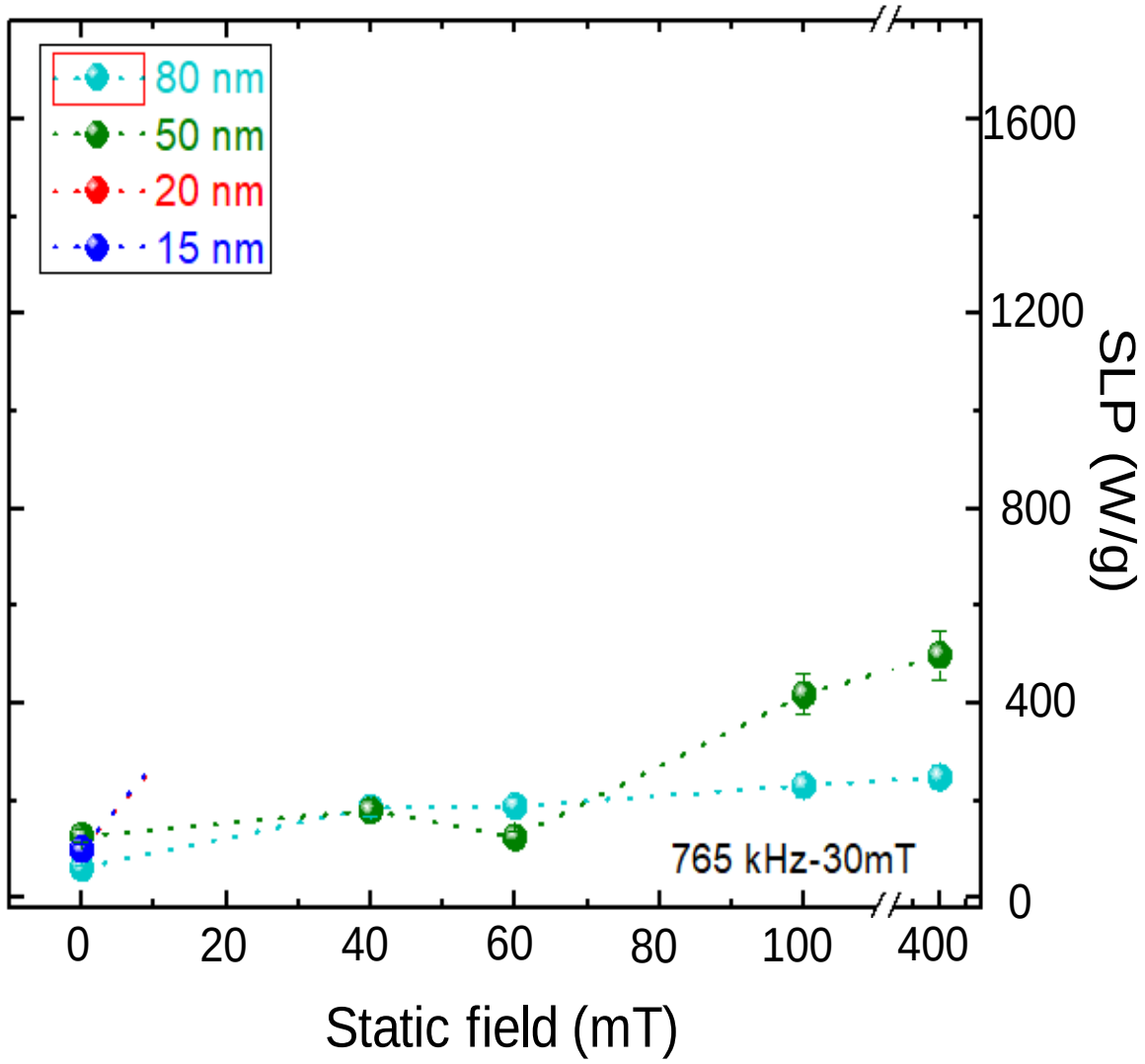
- ✓ Increasing the concentration increases the thermal efficiency of the nanoparticles.
- ✓ C ↑, small and many chains.

Large MNPs

- ✓ Reducing the concentration increases the thermal efficiency of the nanoparticles.
- ✓ C ↓, chain formation.

Magnetic hyperthermia

Particle and field controls to increase hyperthermia efficiency

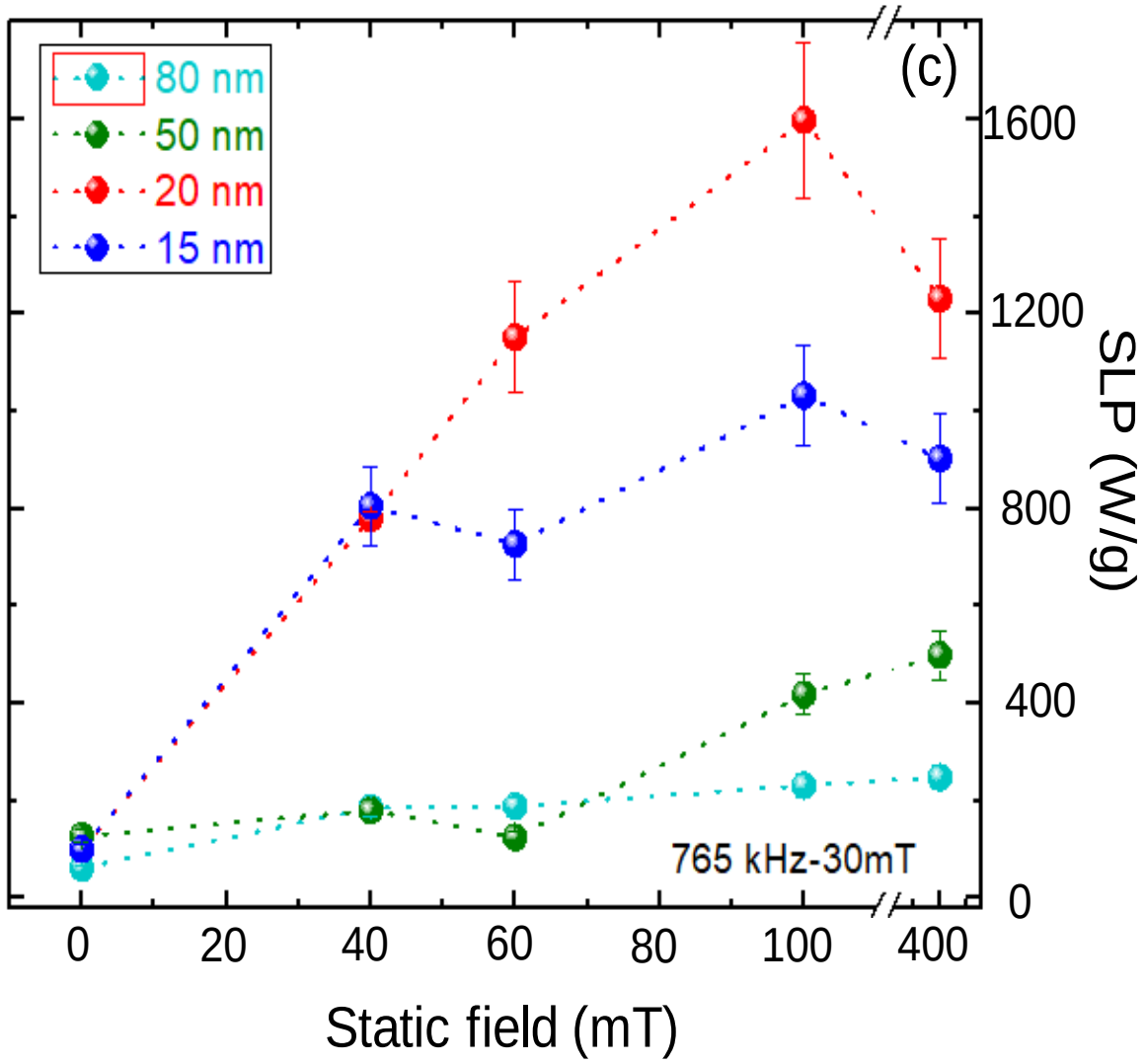


Large MNPs

- ✓ As the field increases, the value of SLP increases.
- ✓ The results are in good agreement with the SEM images and the magnetic characterization.

Magnetic hyperthermia

Particle and field controls to increase hyperthermia efficiency



Large MNPs

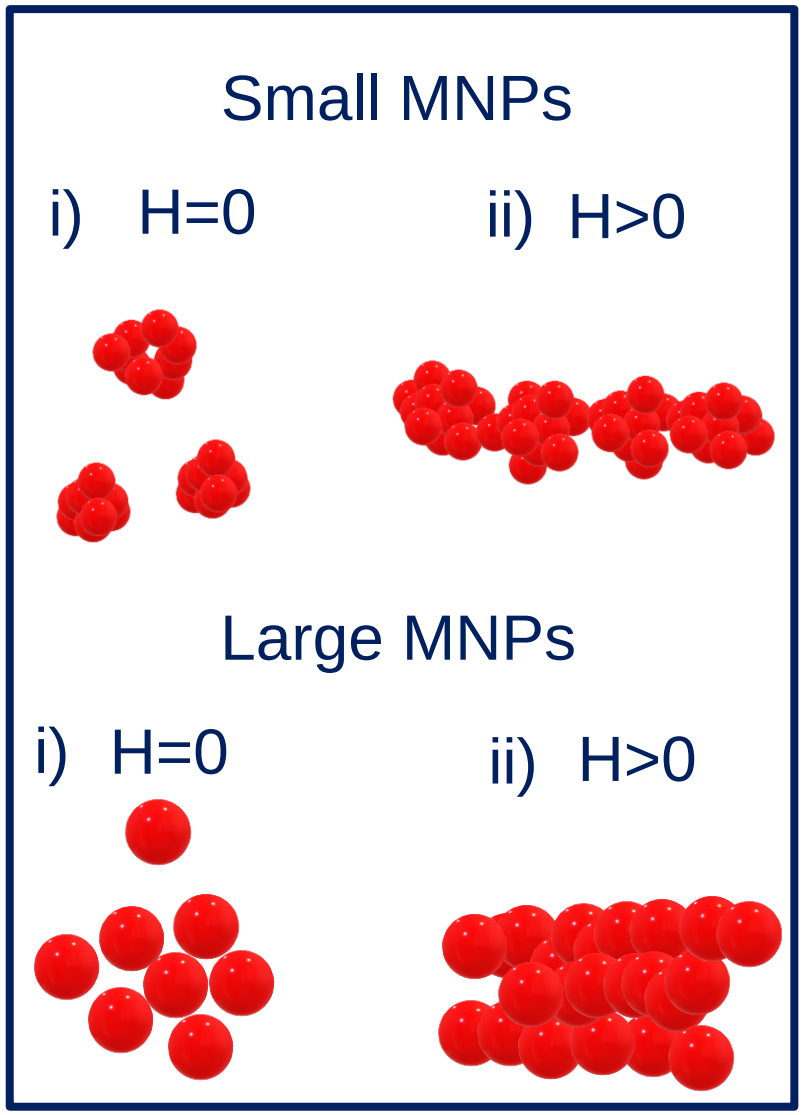
- ✓ As the field increases, the value of SLP increases.
- ✓ The results are in good agreement with the SEM images and the magnetic characterization.

Small MNPs

- ✓ The heating efficiency increases eightfold as compared to random.
- ✓ These results indicate that the magnetic properties could be attributed to the connection between the chains. That means, **cluster-to-cluster** formation could be implied stronger dipolar interactions than core to core formation because a cluster behaves as ferromagnetic core.

Conclusions

Particle and field controls to increase hyperthermia efficiency



- ✓Successfully chain formation depends on the size and the field.
- ✓Cluster to cluster formation increases the magnetic properties.
- ✓The chain formation revealed the enhanced thermal response.
- ✓The chain formation promise to open new ways to design nanocrystalline magnetic materials.

MagnaCharta Group members

Particle and field controls to increase hyperthermia efficiency

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Thank you for your attention!!

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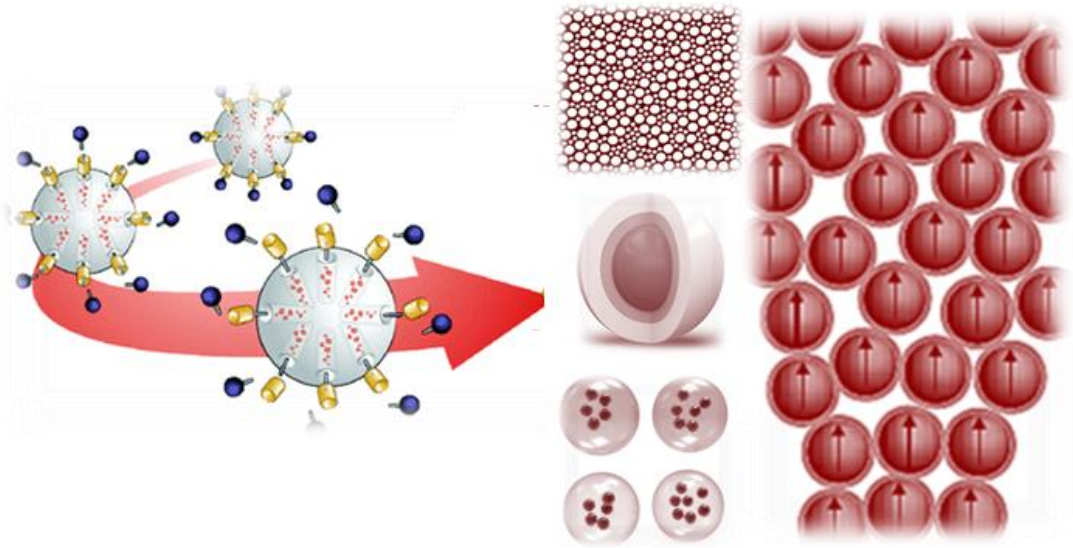

Particle and field controls to increase hyperthermia efficiency

Magna Charta

Magnetic

nanostructure

Characterization

Technology & Applications

Dr Eirini Myrovali