



THE HENRYK NIEWODNICZAŃSKI  
INSTITUTE OF NUCLEAR PHYSICS  
POLISH ACADEMY OF SCIENCES

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# **Composite particles based on Cu and Fe synthesized by Pulsed Laser Melting in Liquid**

Oliwia Polit

Department of Magnetic Materials and Nanostructures

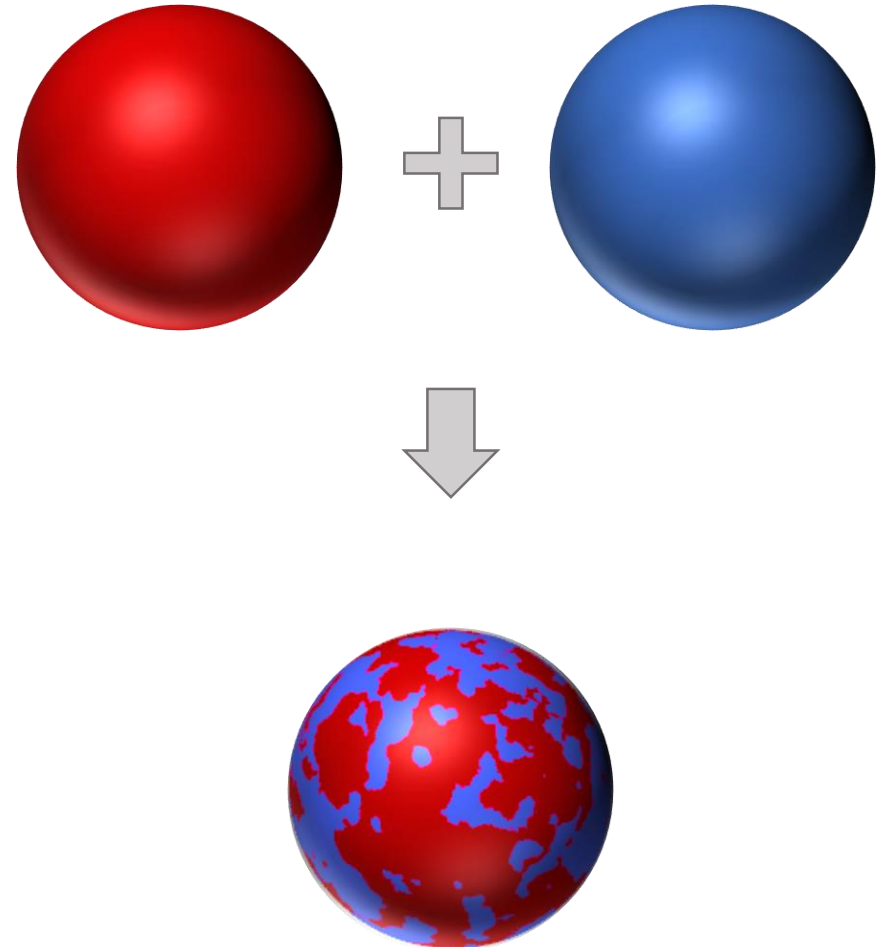
# Motivations

## Composite particles

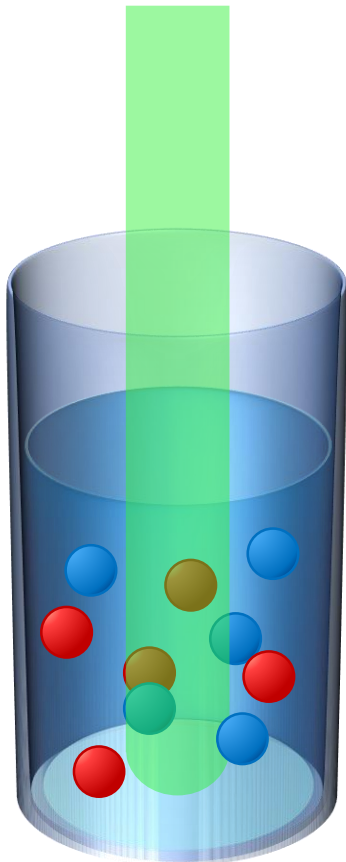
- Multifunctionality
- Enhanced properties
- Novel function

## Fundamental research

## Method development (Pulsed Laser Melting in Liquid)

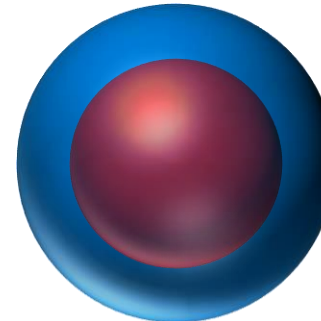


## Pulsed Laser Melting in Liquid



Important parameters:

- Materials
- Molar ratio
- Laser fluence
- Wavelength
- Irradiation time
- Solvent
- Laser frequency



Advantages:

- Easy
- Under room temperature and pressure
- No toxic agents
- No surfactants
- Flexible particle modification
- Complex composites in single-step process

## Materials for our studies



+



## Materials for our studies

Raw nanoparticles  
5 nm / 30 nm



Raw nanoparticles  
40 nm



+



ethanol/  
ethyl acetate

# Irradiation

Material:  $\text{Fe}_3\text{O}_4 + \text{Cu}$

Size of Cu NPs: 40 nm

Size of  $\text{Fe}_3\text{O}_4$  NPs: 5 or 30 nm

Molar ratio Fe:Cu: 1:1, 1:3 and 3:1

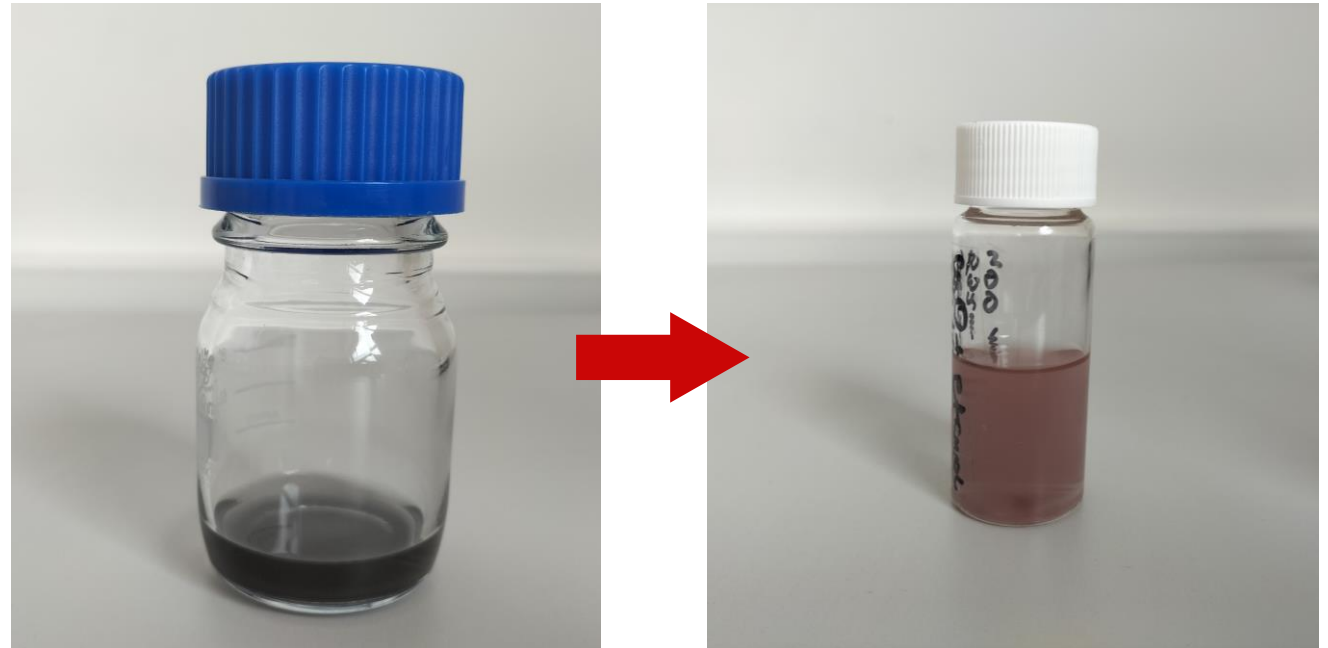
Laser fluence: 200 or 300  $\text{mJ/pulse}\cdot\text{cm}^2$

Wavelength: 532 nm

Frequency: 10 or 33 Hz

Irradiation time: 1 h

Solvent: ethanol or ethyl acetate



# Irradiation

Material:  $\text{Fe}_3\text{O}_4 + \text{Cu}$

Size of Cu NPs: 40 nm

Size of  $\text{Fe}_3\text{O}_4$  NPs: 5 or 30 nm

Molar ratio Fe:Cu: 1:1, 1:3 and 3:1

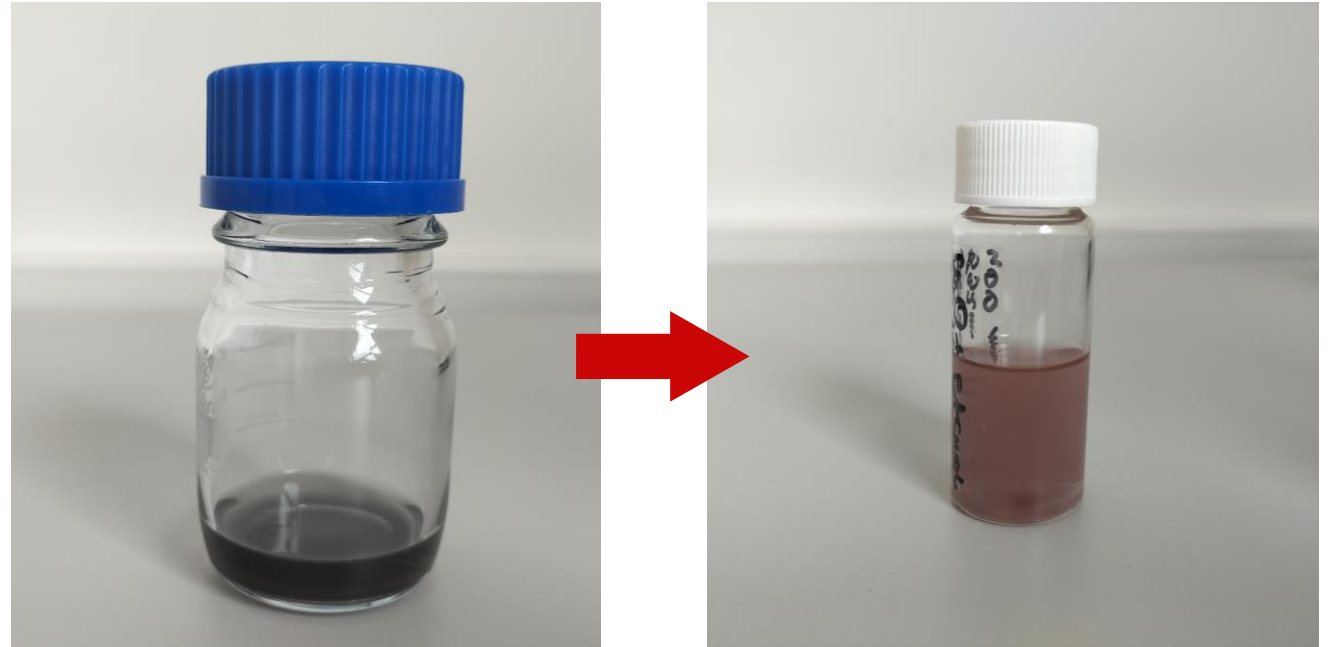
Laser fluence: 200 or 300  $\text{mJ/pulse}\cdot\text{cm}^2$

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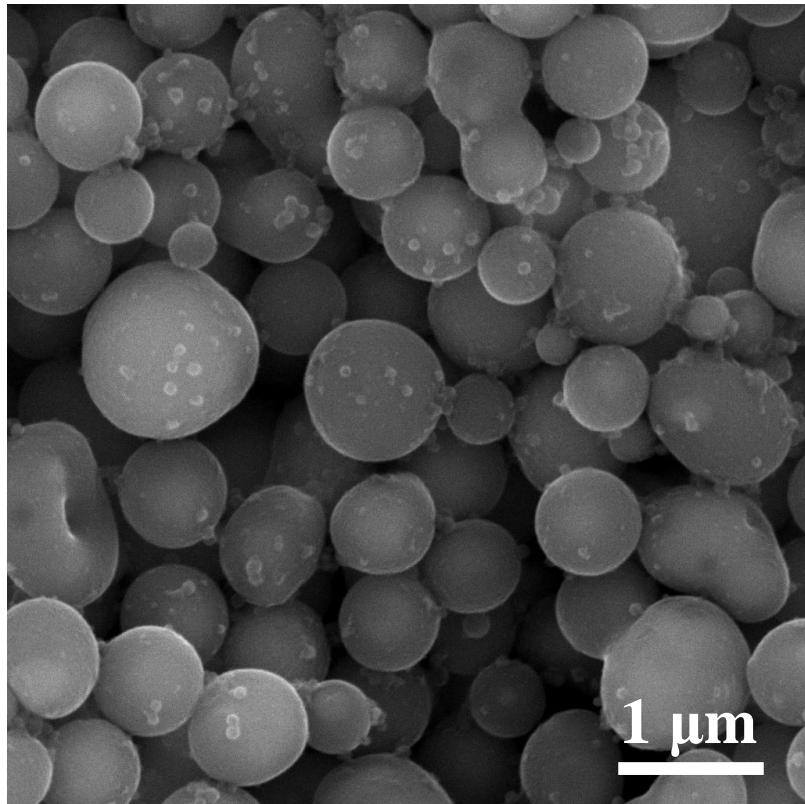
Irradiation time: 1 h

Solvent: ethanol or ethyl acetate



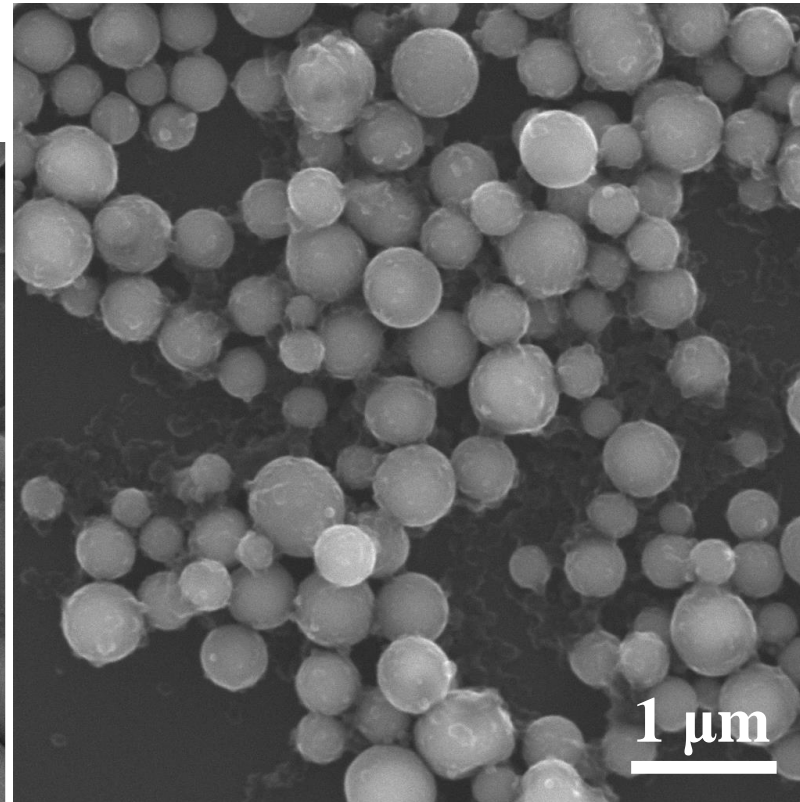
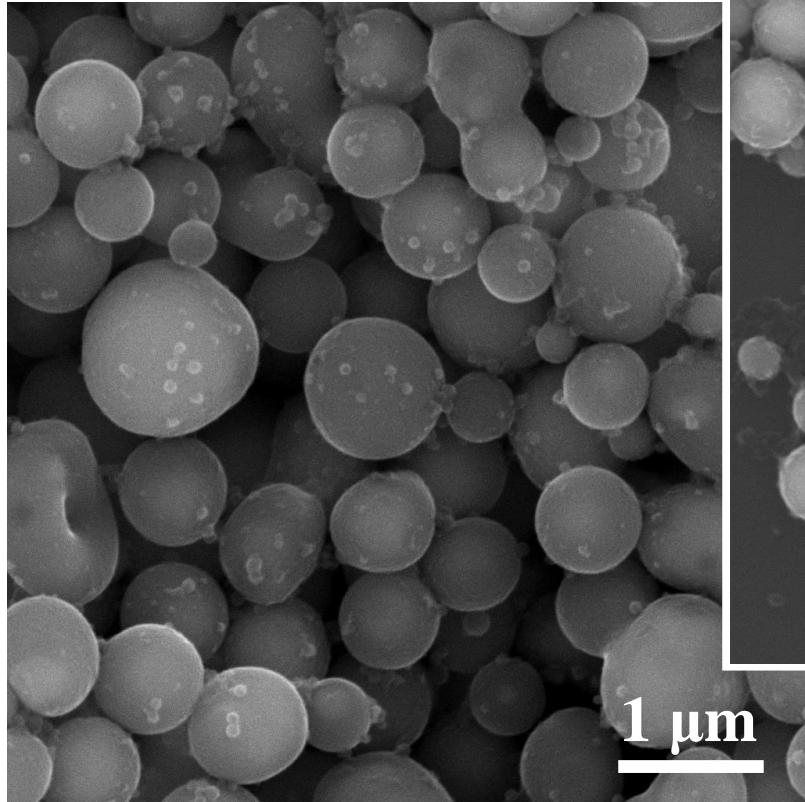


# Results

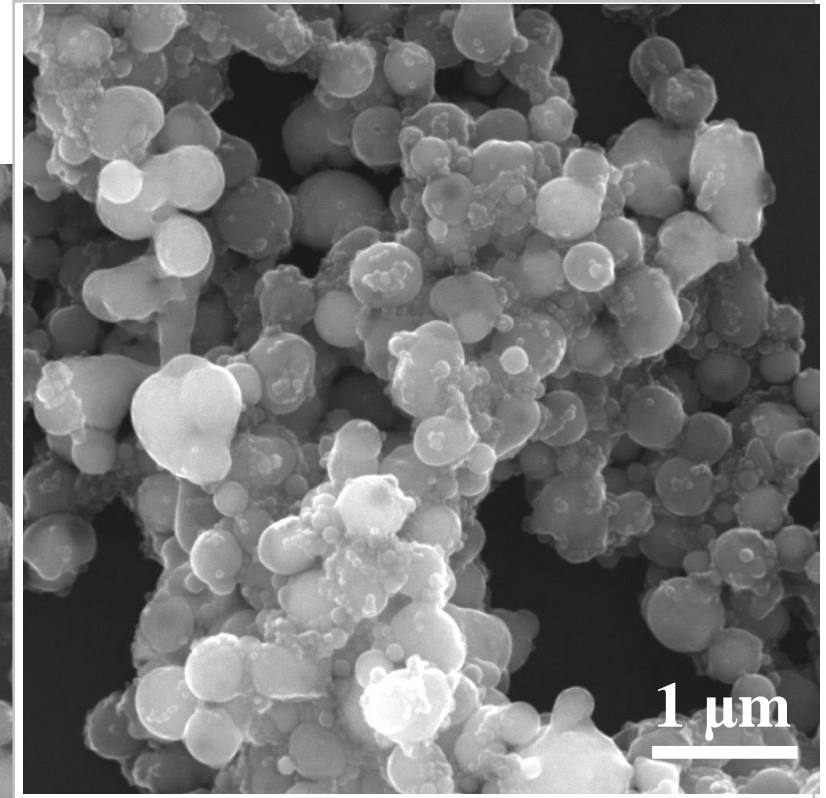
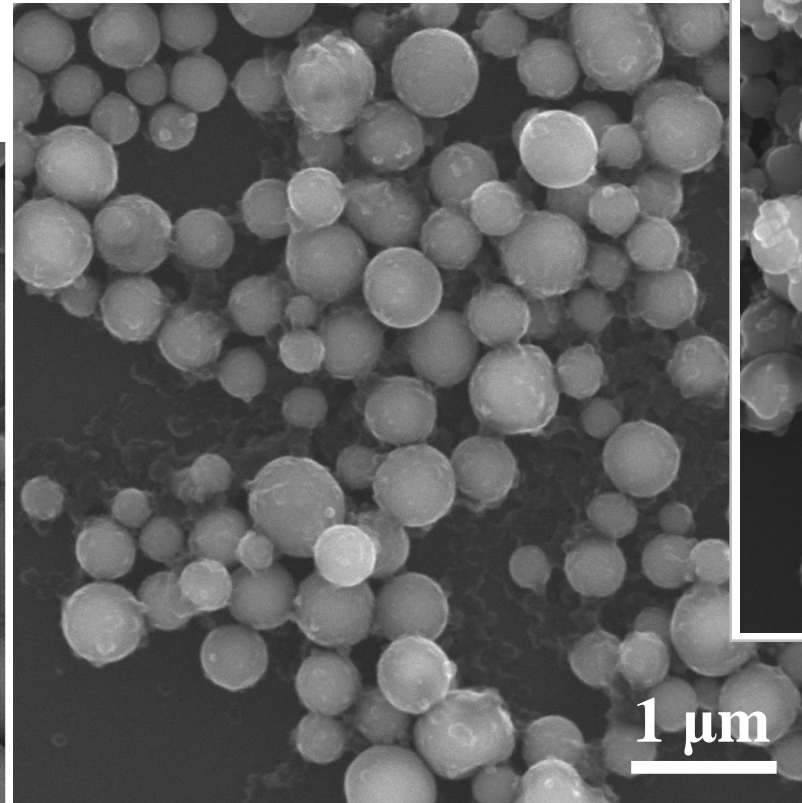
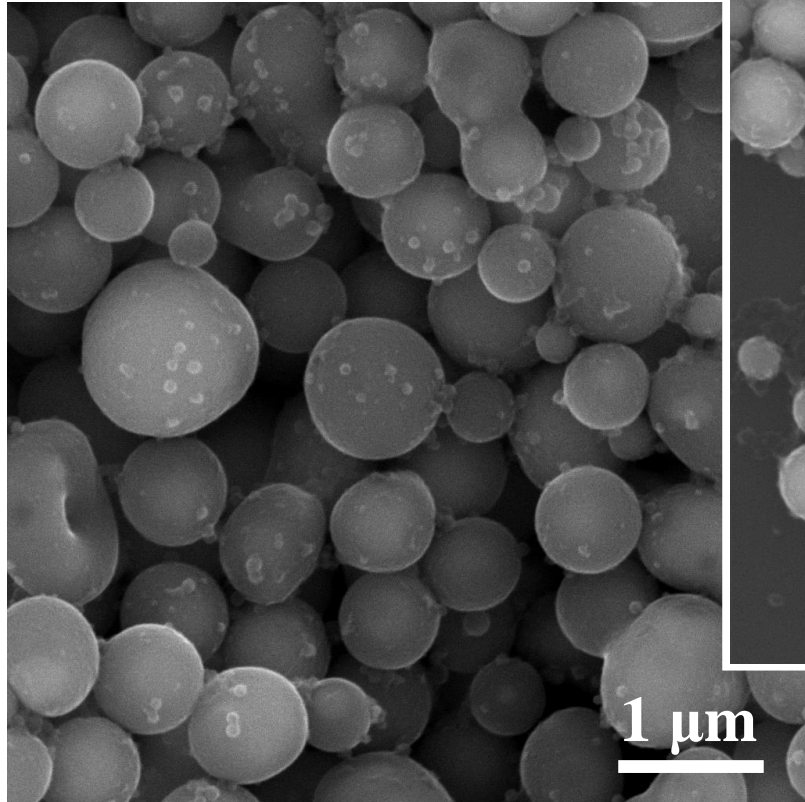




# Results



# Results





## Comparison of results for various parameters

- Laser fluence: **200** or **300 mJ/pulse·cm<sup>2</sup>**
- Size of Fe<sub>3</sub>O<sub>4</sub> NPs: **5** or **30 nm**
- Frequency: **10** or **33 Hz**
- Solvent: **ethanol** or **ethyl acetate**

## Laser fluence

Material:  $\text{Fe}_3\text{O}_4 + \text{Cu}$

Size of Cu NPs: 40 nm

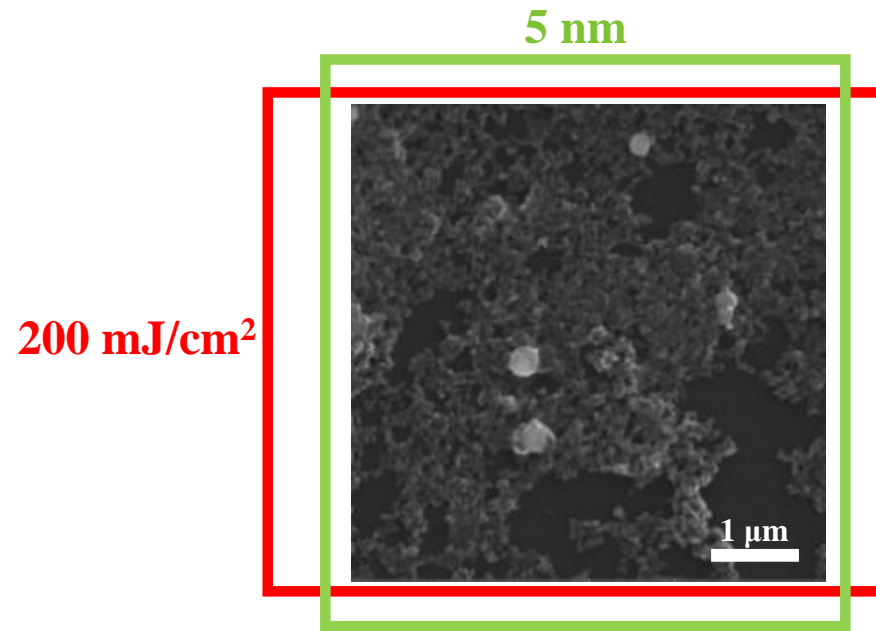
Molar ratio Fe:Cu: 1:1

Wavelength: 532 nm

Frequency: 10 Hz

Irradiation time: 1 h

Solvent: ethanol



## Laser fluence

Material:  $\text{Fe}_3\text{O}_4 + \text{Cu}$

Size of Cu NPs: 40 nm

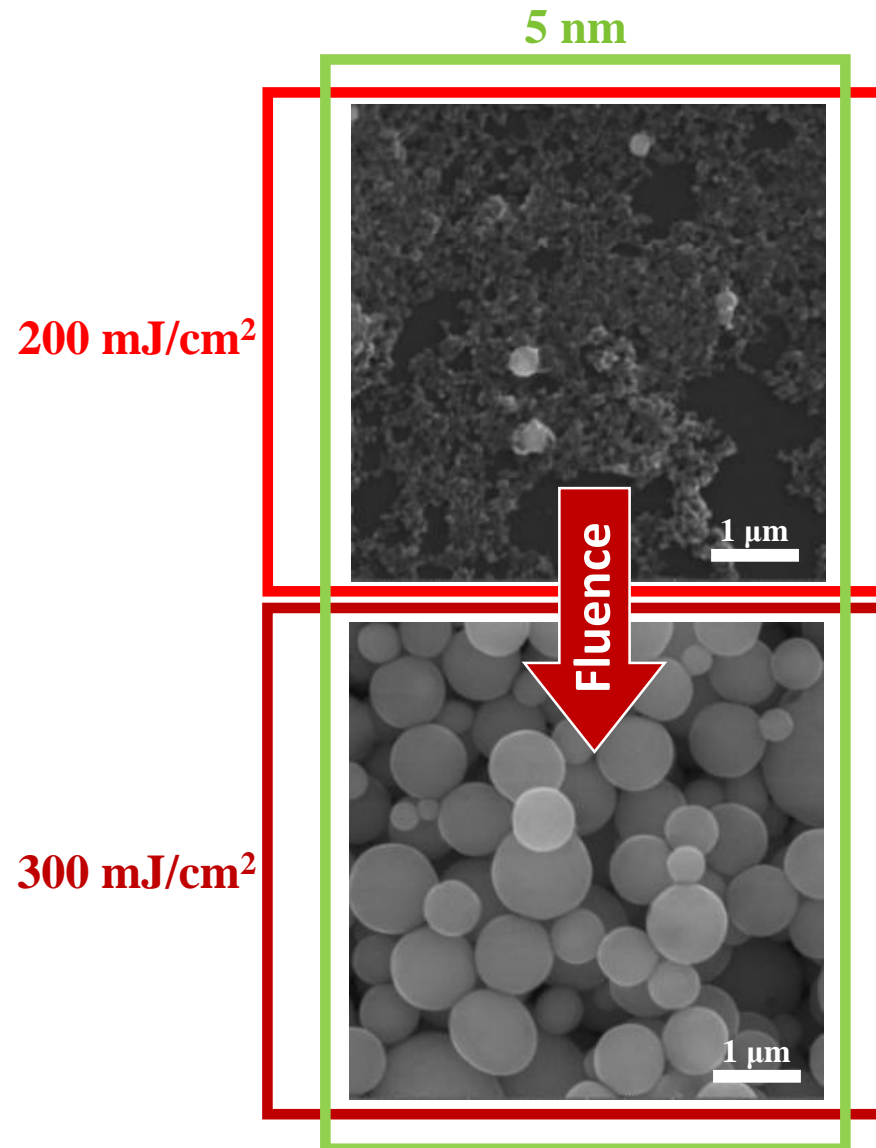
Molar ratio Fe:Cu: 1:1

Wavelength: 532 nm

Frequency: 10 Hz

Irradiation time: 1 h

Solvent: ethanol



## Size of $\text{Fe}_3\text{O}_4$

Material:  $\text{Fe}_3\text{O}_4 + \text{Cu}$

Size of Cu NPs: 40 nm

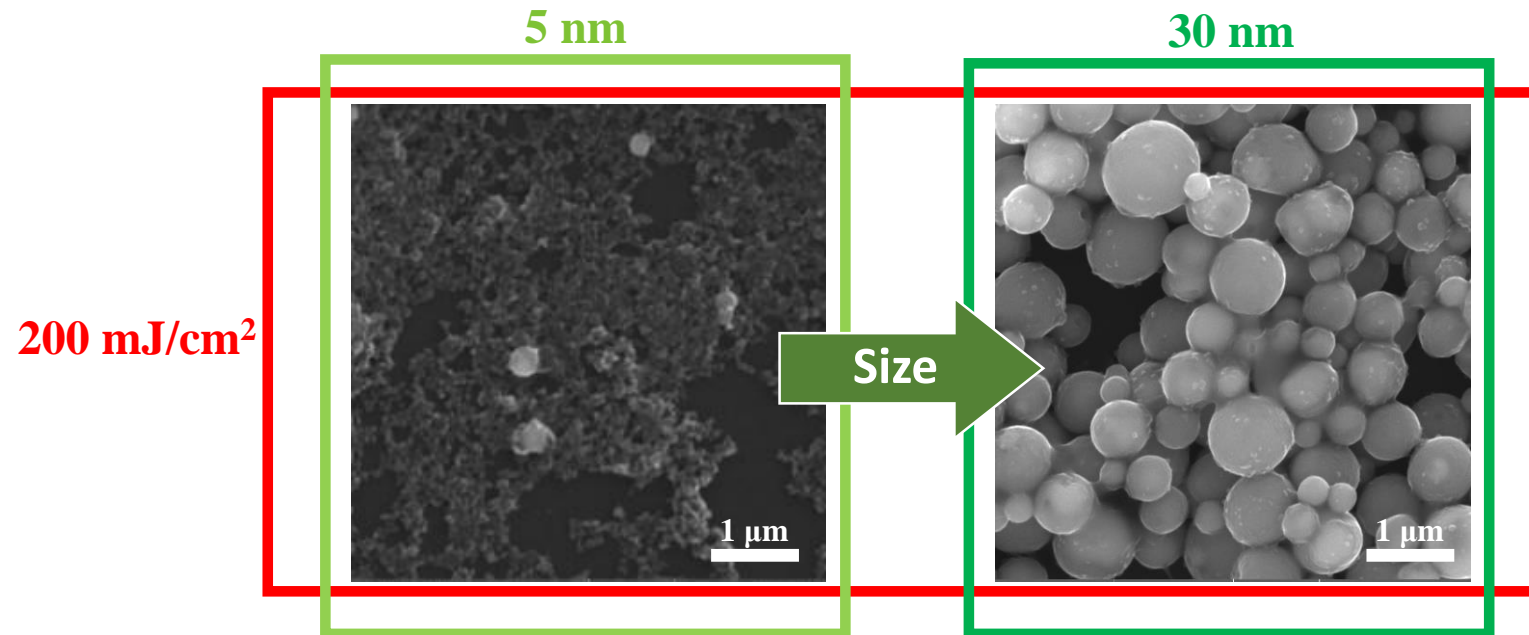
Molar ratio Fe:Cu: 1:1

Wavelength: 532 nm

Frequency: 10 Hz

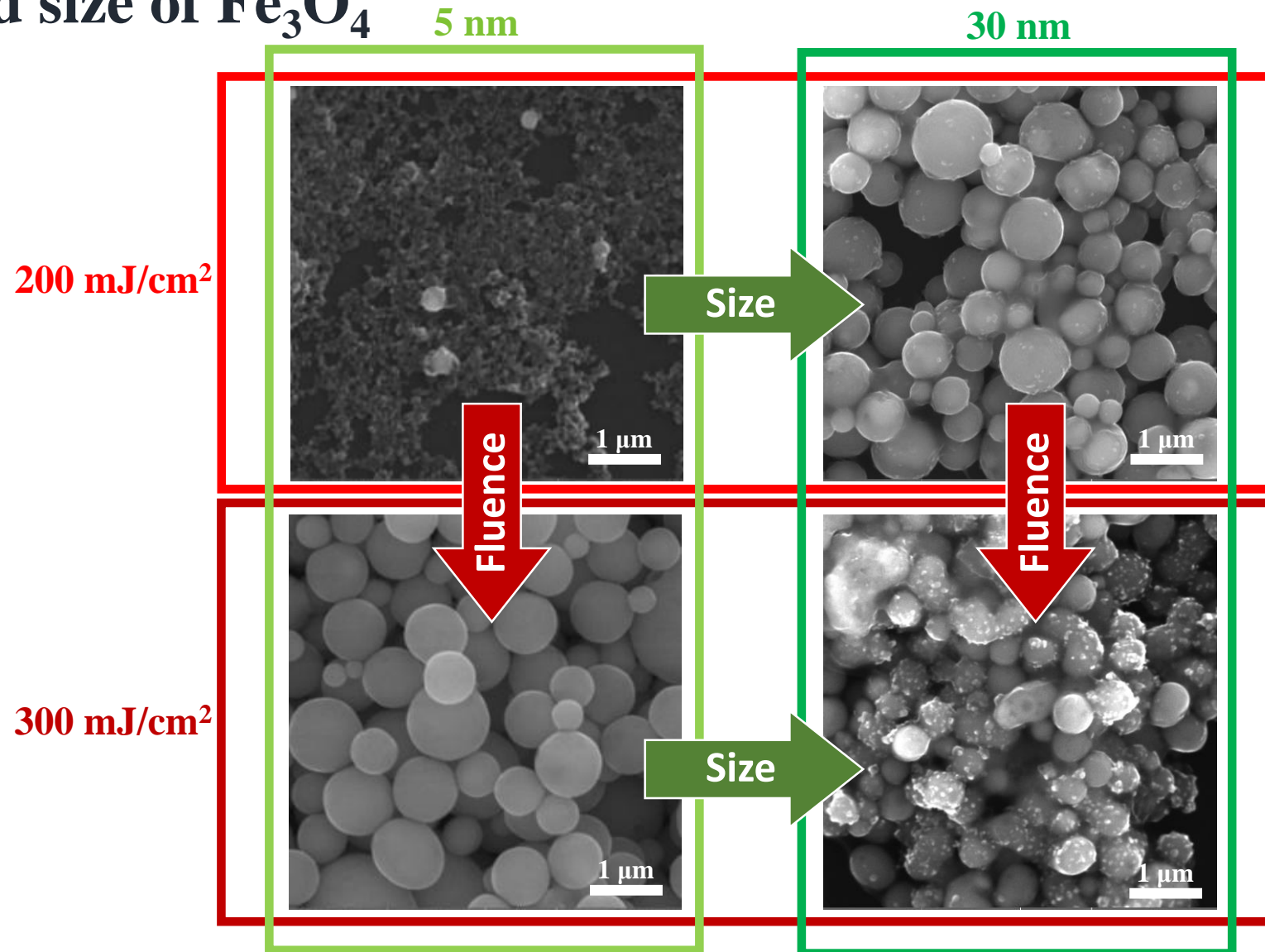
Irradiation time: 1 h

Solvent: ethanol



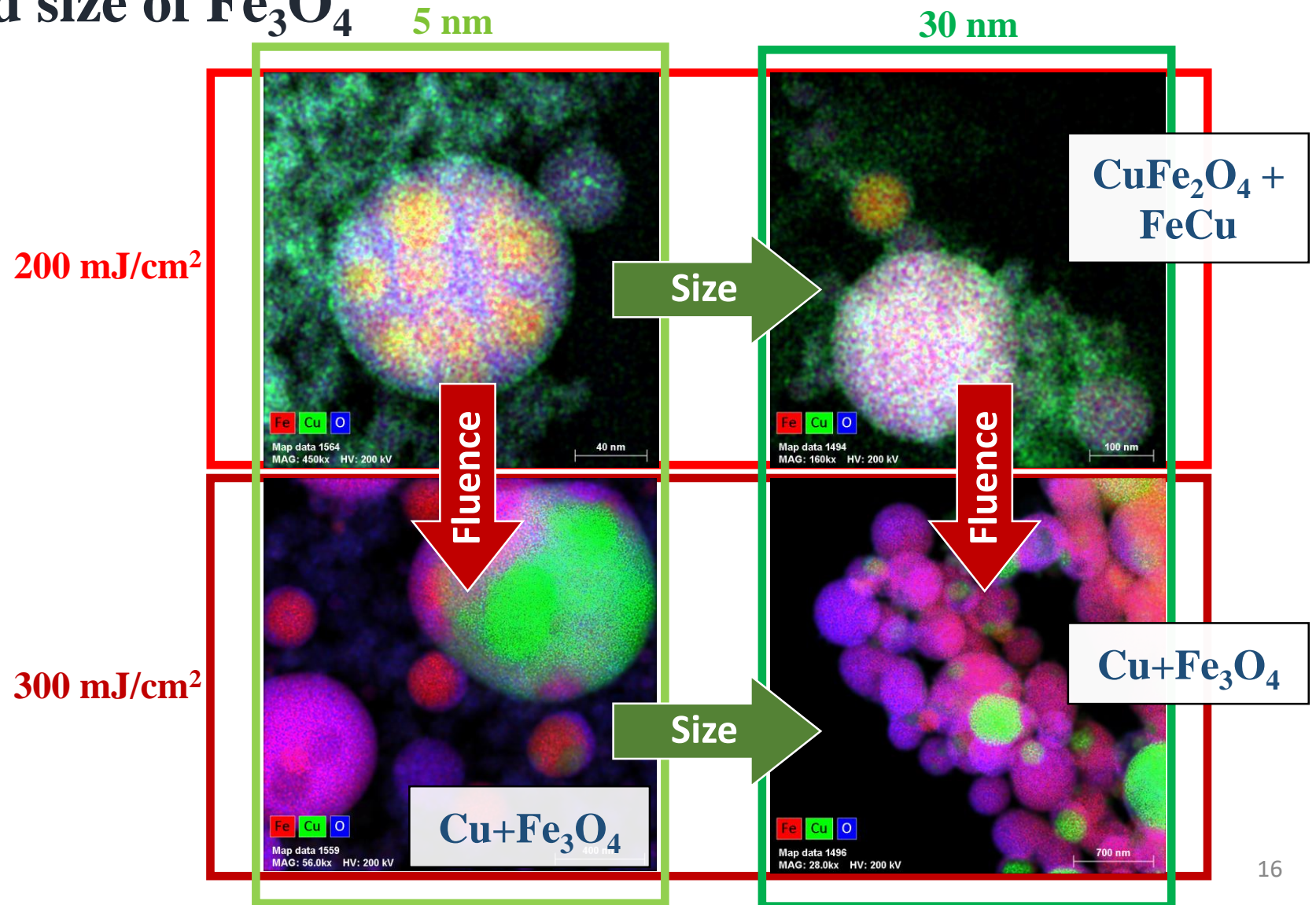
## Laser fluence and size of $\text{Fe}_3\text{O}_4$

Material:  $\text{Fe}_3\text{O}_4 + \text{Cu}$   
Size of Cu NPs: 40 nm  
Molar ratio Fe:Cu: 1:1  
Wavelength: 532 nm  
Frequency: 10 Hz  
Irradiation time: 1 h  
Solvent: ethanol



# Laser fluence and size of $\text{Fe}_3\text{O}_4$

Material:  $\text{Fe}_3\text{O}_4 + \text{Cu}$   
 Size of Cu NPs: 40 nm  
 Molar ratio Fe:Cu: 1:1  
 Wavelength: 532 nm  
 Frequency: 10 Hz  
 Irradiation time: 1 h  
 Solvent: ethanol





## Laser fluence, solvent

Material:  $\text{Fe}_3\text{O}_4 + \text{Cu}$

Size of Cu NPs: 40 nm

Size of  $\text{Fe}_3\text{O}_4$  NPs: 30 nm

Molar ratio Fe:Cu: 1:1

Size of  $\text{Fe}_3\text{O}_4$  NPs: 30 nm

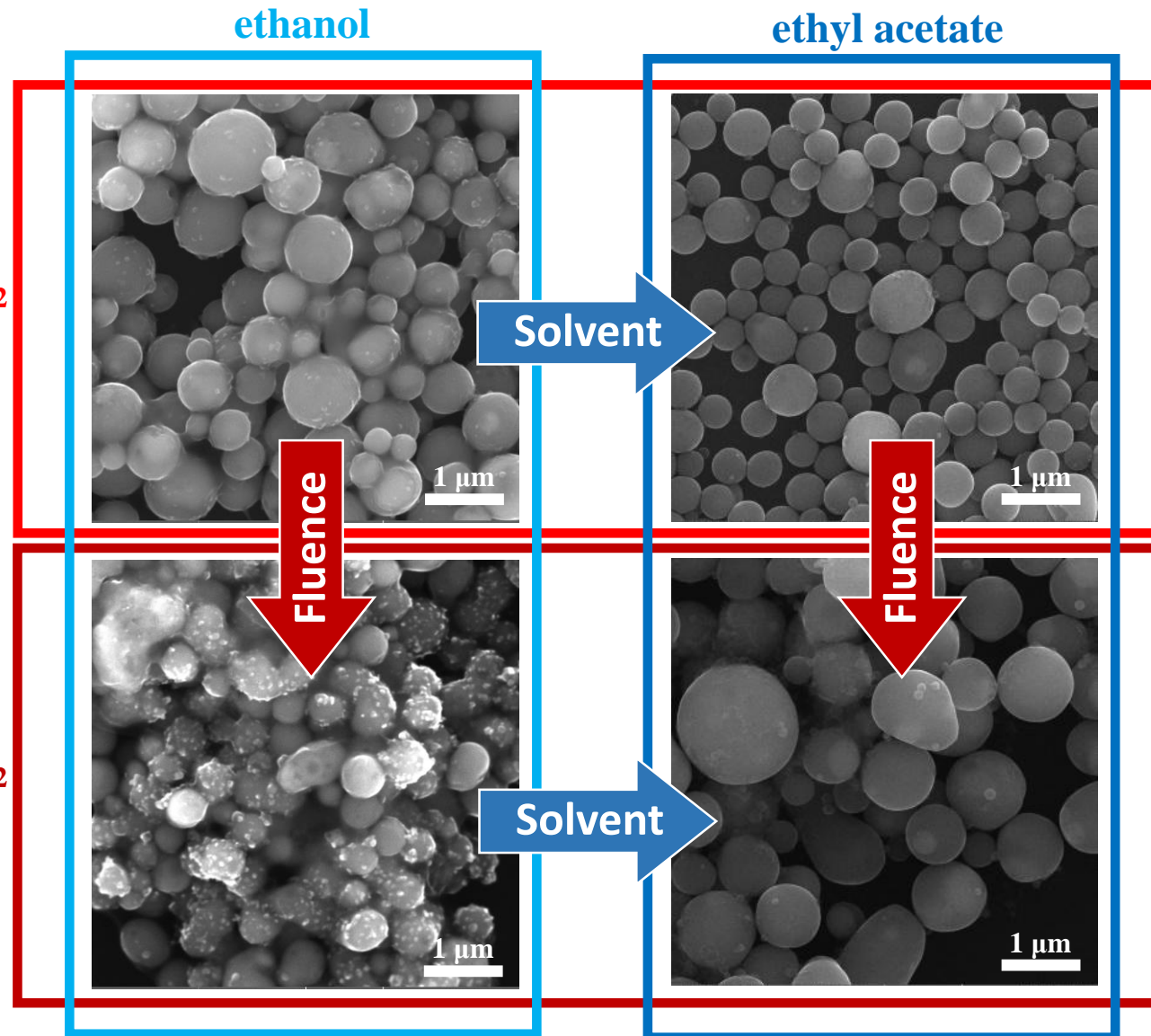
Wavelength: 532 nm

Frequency: 10 Hz

Irradiation time: 1 h

**200 mJ/cm<sup>2</sup>**

**300 mJ/cm<sup>2</sup>**



## Laser fluence, solvent

Material:  $\text{Fe}_3\text{O}_4 + \text{Cu}$

Size of Cu NPs: 40 nm

Size of  $\text{Fe}_3\text{O}_4$  NPs: 30 nm

Molar ratio Fe:Cu: 1:1

Size of  $\text{Fe}_3\text{O}_4$  NPs: 30 nm

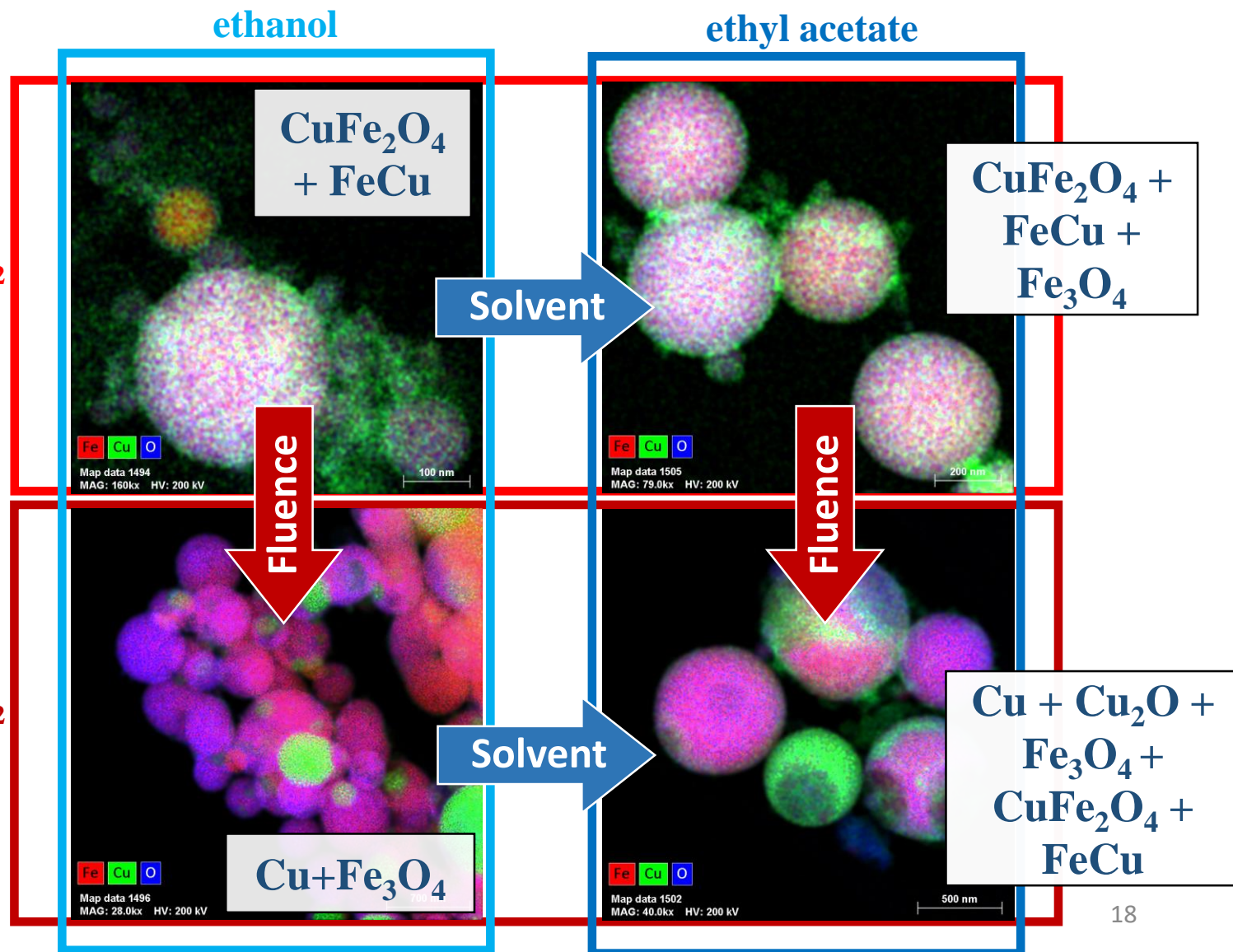
Wavelength: 532 nm

Frequency: 10 Hz

Irradiation time: 1 h

**200 mJ/cm<sup>2</sup>**

**300 mJ/cm<sup>2</sup>**



# Laser frequency

Material:  $\text{Fe}_3\text{O}_4 + \text{Cu}$

Size of Cu NPs: 40 nm

Size of  $\text{Fe}_3\text{O}_4$  NPs: 5 nm

Molar ratio Fe:Cu: 3:1

Laser fluence:

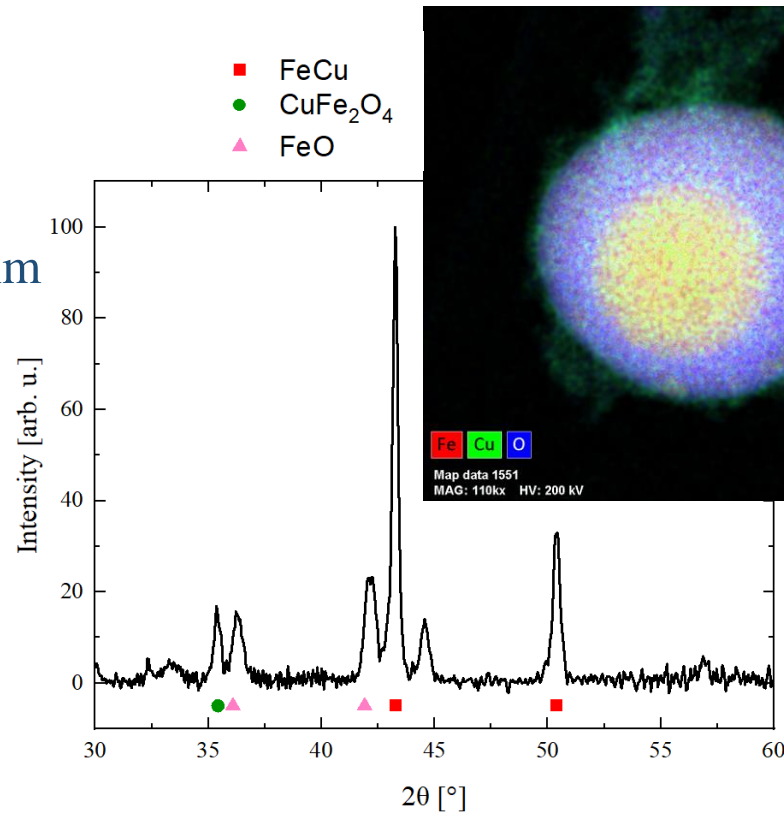
225 mJ/pulse·cm<sup>2</sup>

Wavelength: 532 nm

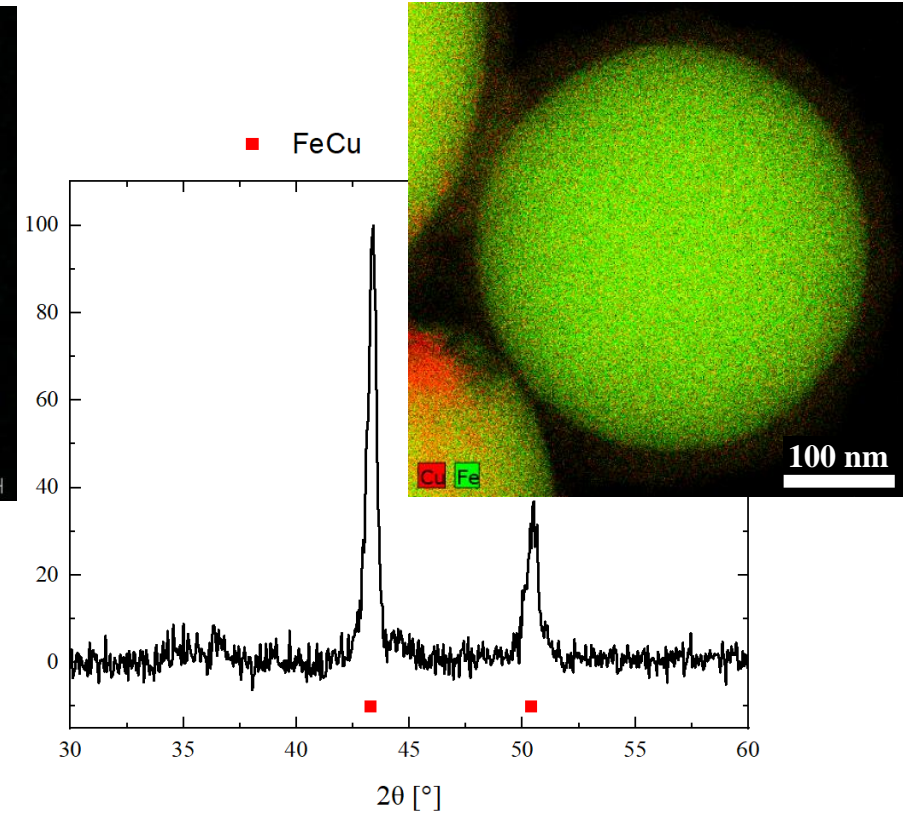
Frequency: 10 Hz

Irradiation time: 1 h

Solvent: ethanol



10 Hz



33 Hz

# Magnetic properties

Material:  $\text{Fe}_3\text{O}_4 + \text{Cu}$

Size of Cu NPs: 40 nm

Size of  $\text{Fe}_3\text{O}_4$  NPs: 30 nm

Molar ratio Fe:Cu: 1:1

Laser fluence:

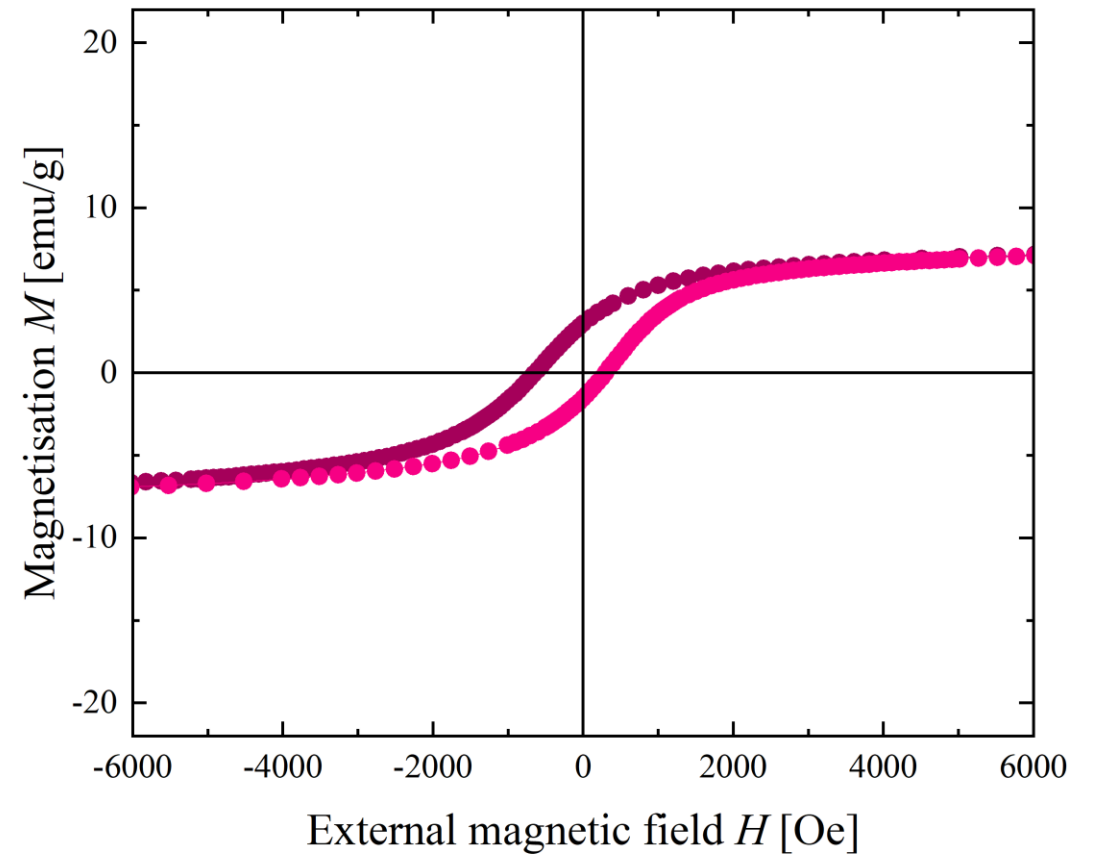
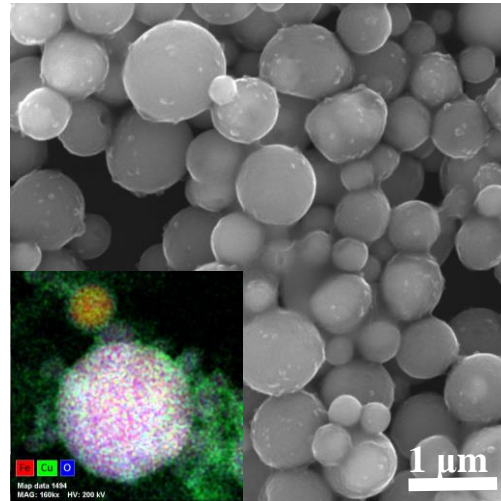
200 mJ/pulse·cm<sup>2</sup>

Wavelength: 532 nm

Frequency: 10 Hz

Irradiation time: 1 h

Solvent: ethanol



# Magnetic properties

Material:  $\text{Fe}_3\text{O}_4 + \text{Cu}$

Size of Cu NPs: 40 nm

Size of  $\text{Fe}_3\text{O}_4$  NPs: 30 nm

Molar ratio Fe:Cu: 1:1

Laser fluence:

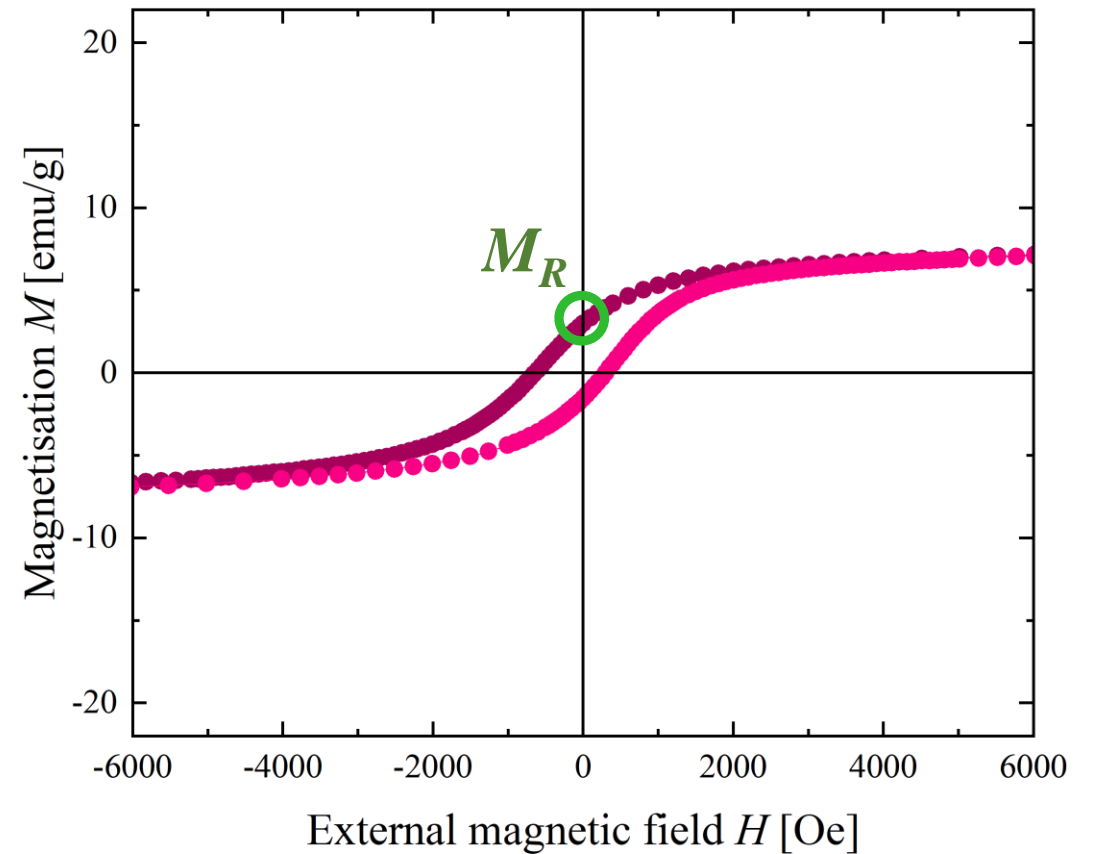
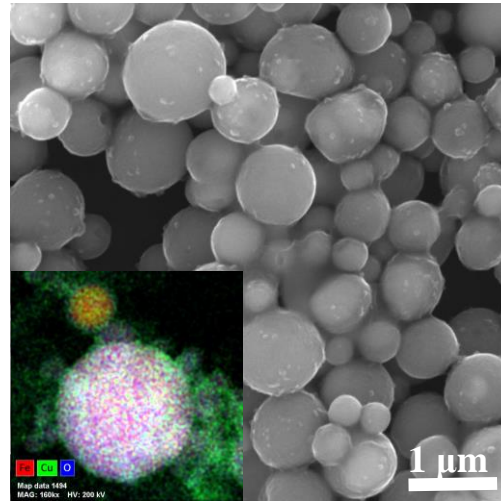
200 mJ/pulse·cm<sup>2</sup>

Wavelength: 532 nm

Frequency: 10 Hz

Irradiation time: 1 h

Solvent: ethanol



# Magnetic properties

Material:  $\text{Fe}_3\text{O}_4 + \text{Cu}$

Size of Cu NPs: 40 nm

Size of  $\text{Fe}_3\text{O}_4$  NPs: 30 nm

Molar ratio Fe:Cu: 1:1

Laser fluence:

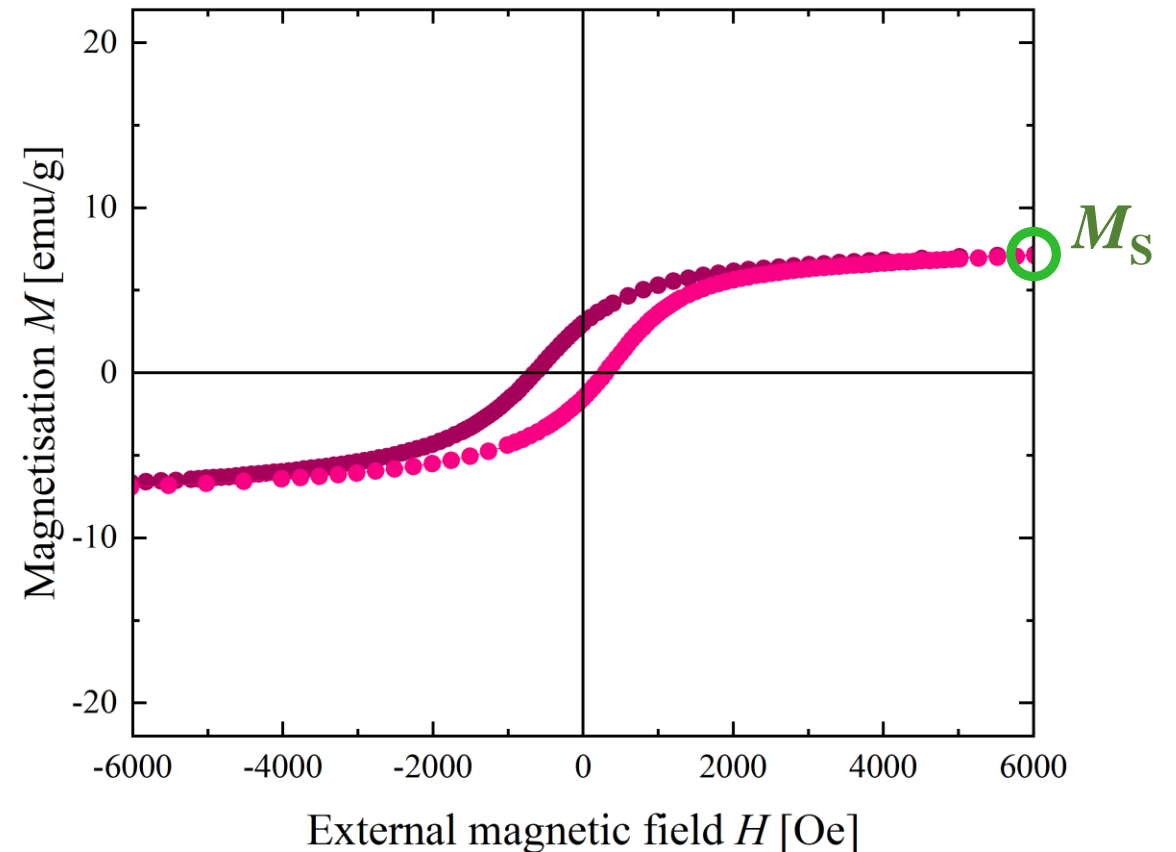
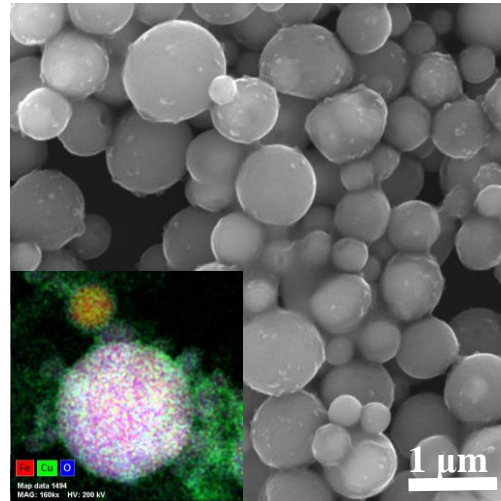
200 mJ/pulse·cm<sup>2</sup>

Wavelength: 532 nm

Frequency: 10 Hz

Irradiation time: 1 h

Solvent: ethanol



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Material:  $\text{Fe}_3\text{O}_4 + \text{Cu}$

Size of Cu NPs: 40 nm

Size of  $\text{Fe}_3\text{O}_4$  NPs: 30 nm

Molar ratio Fe:Cu: 1:1

Laser fluence:

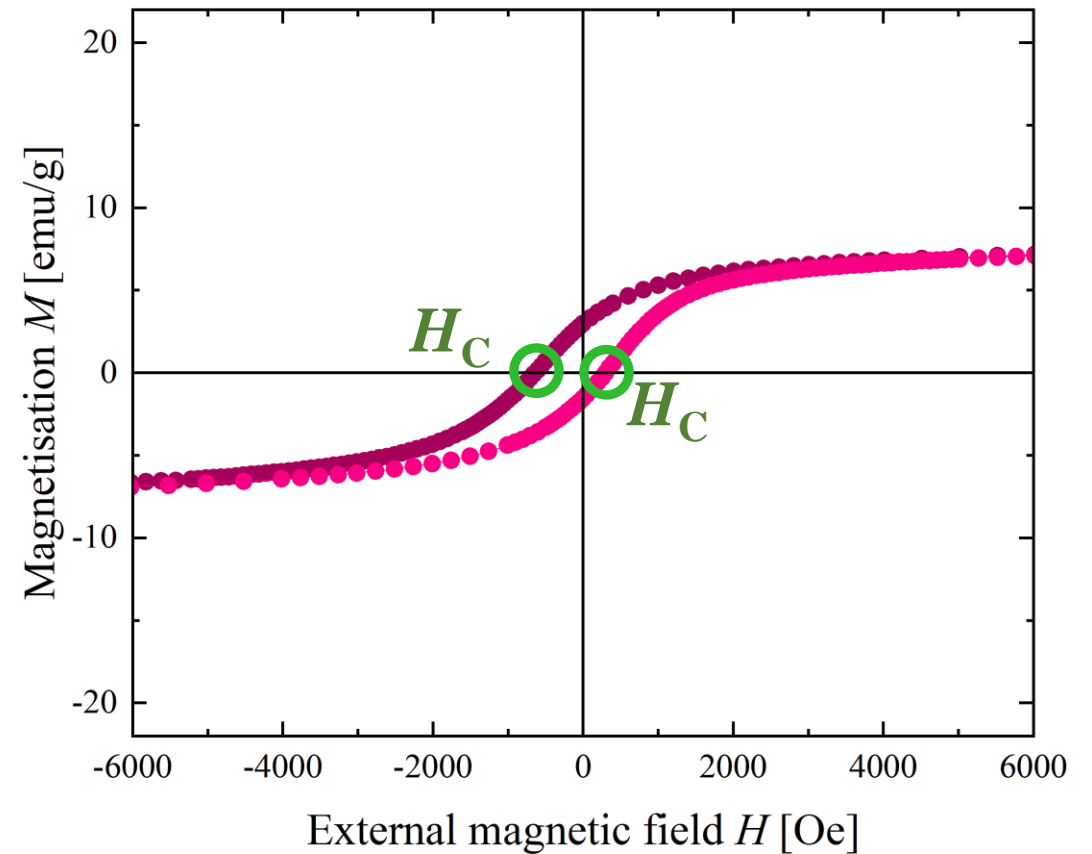
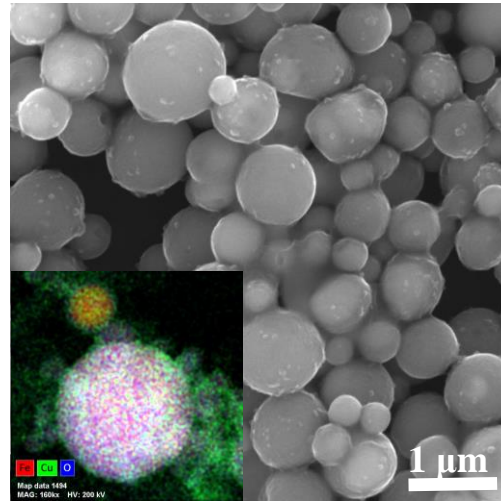
200 mJ/pulse·cm<sup>2</sup>

Wavelength: 532 nm

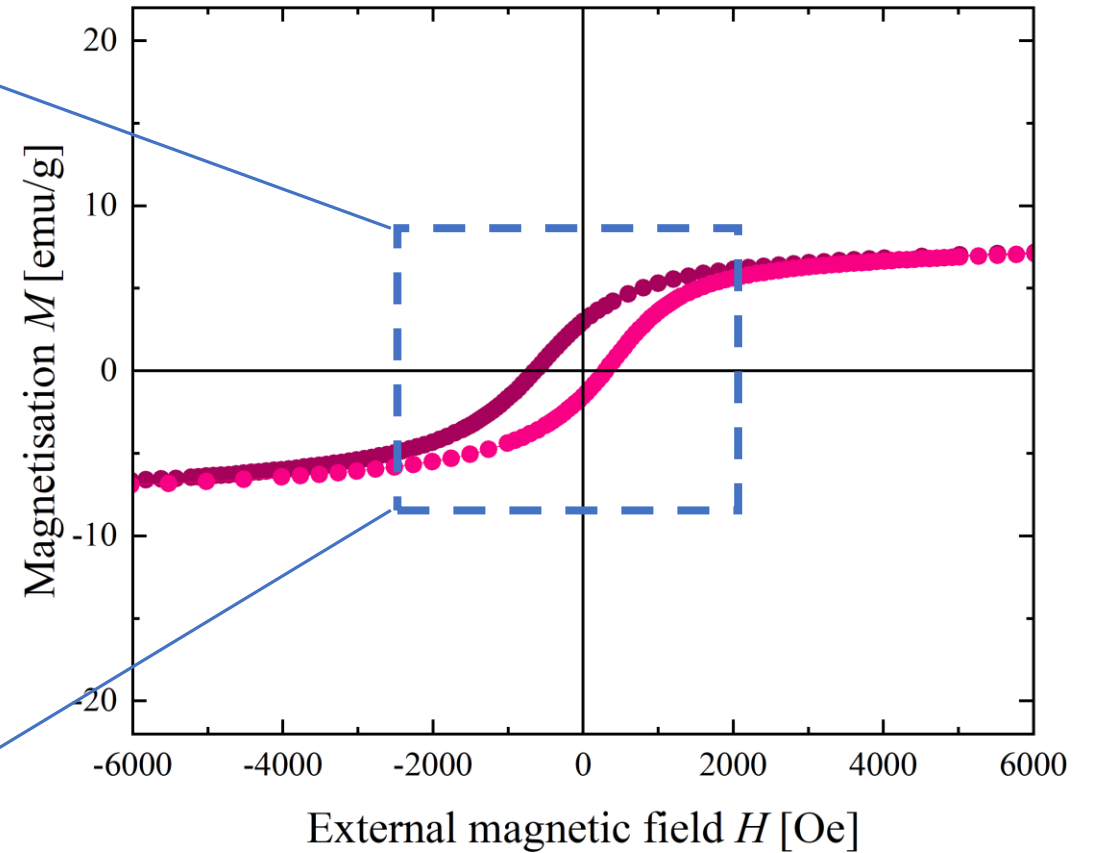
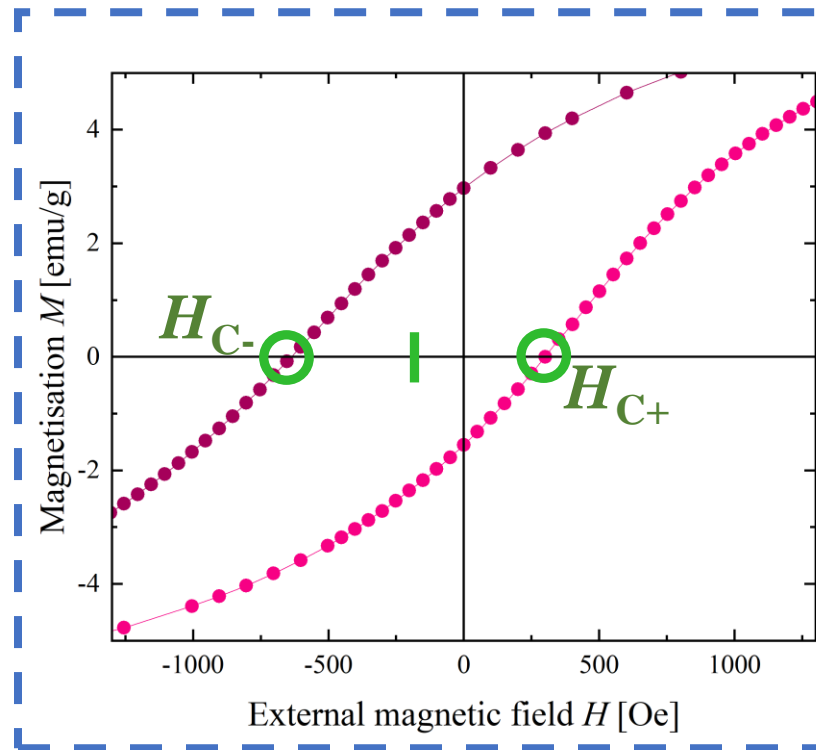
Frequency: 10 Hz

Irradiation time: 1 h

Solvent: ethanol

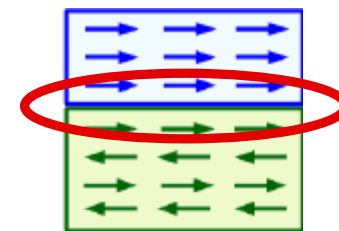
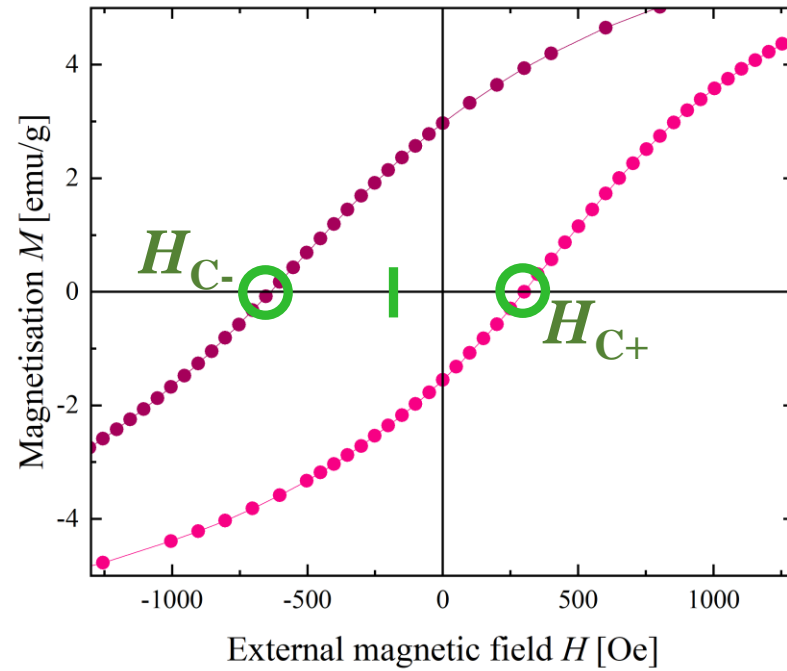


# Exchange bias effect



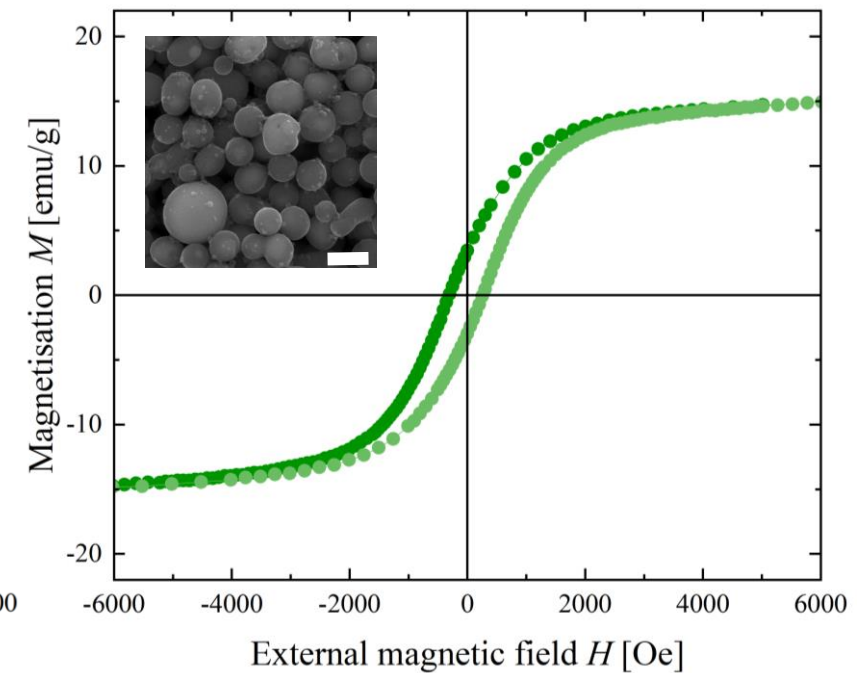
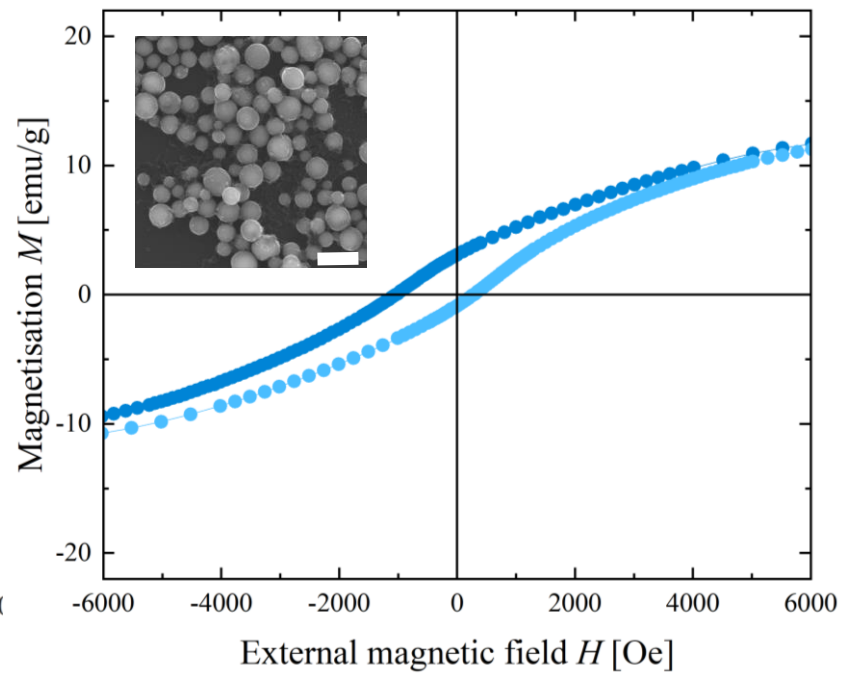
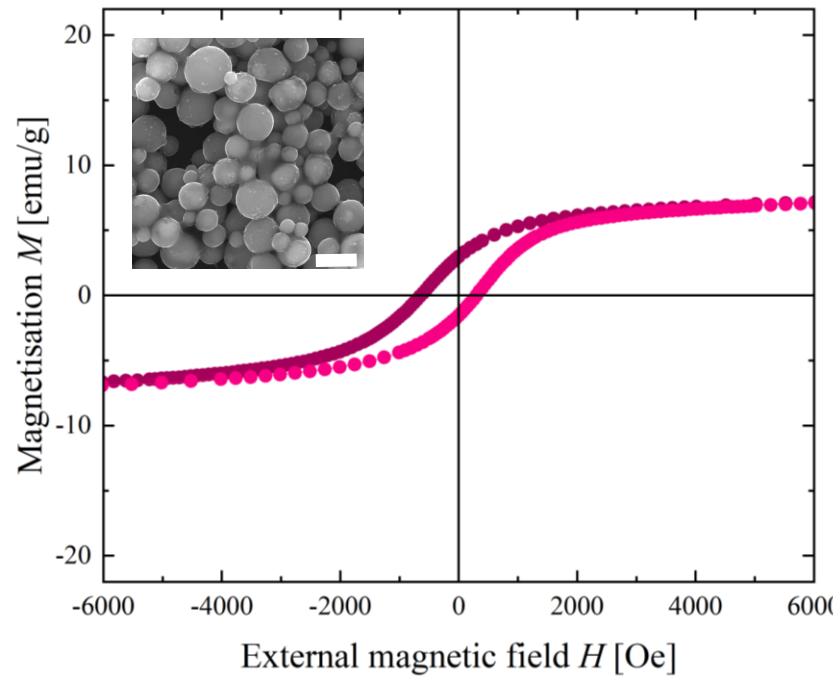


# Exchange bias effect



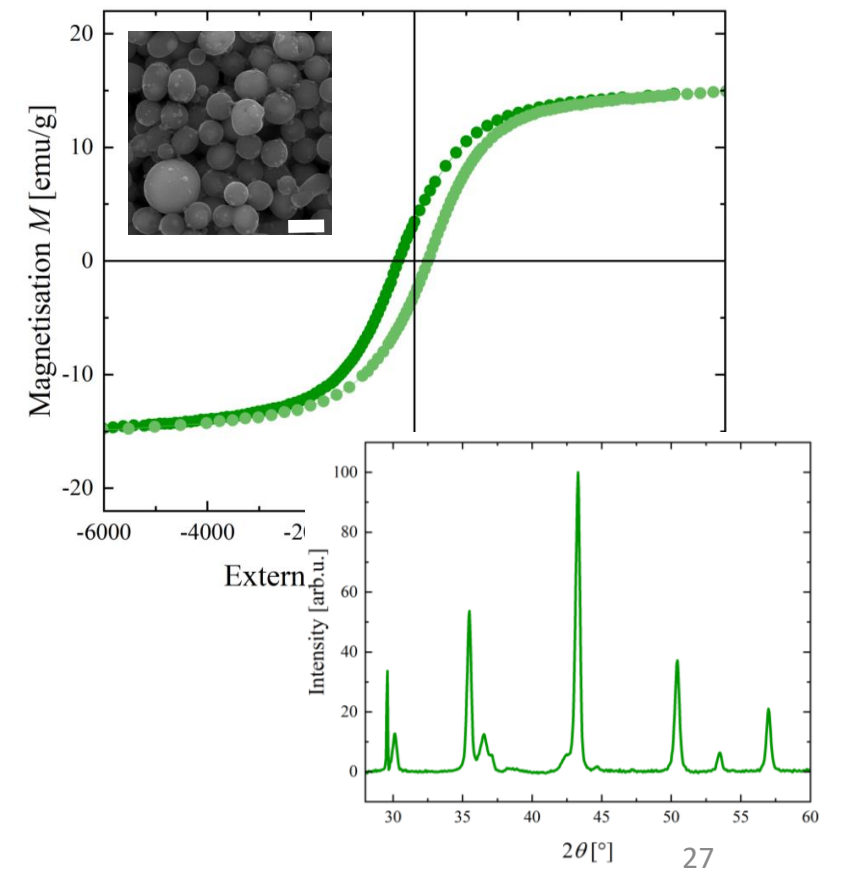
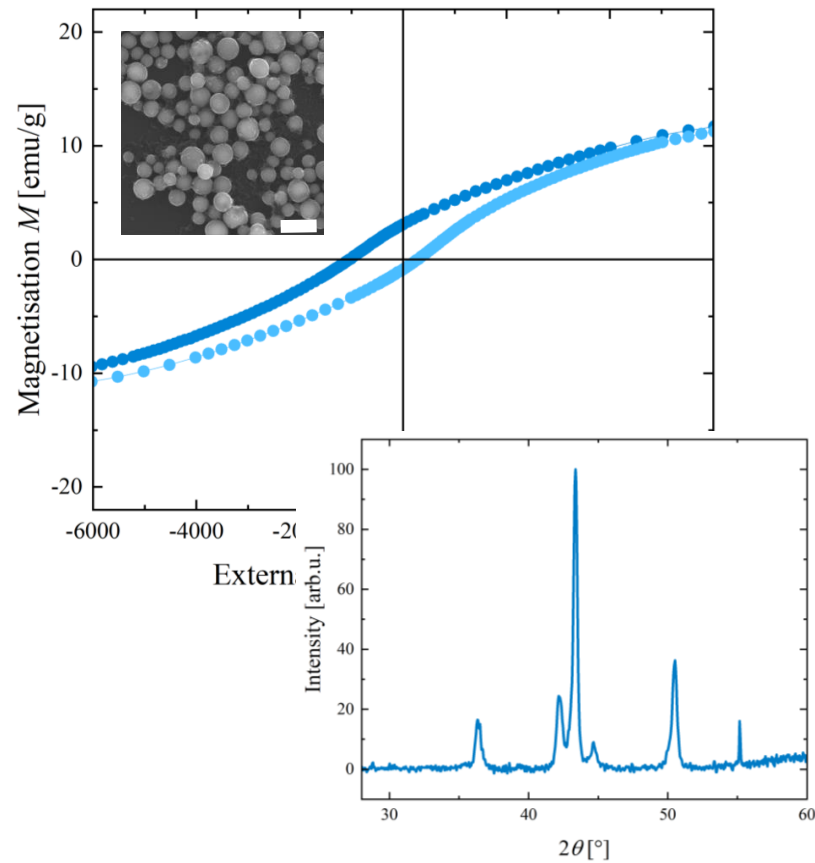
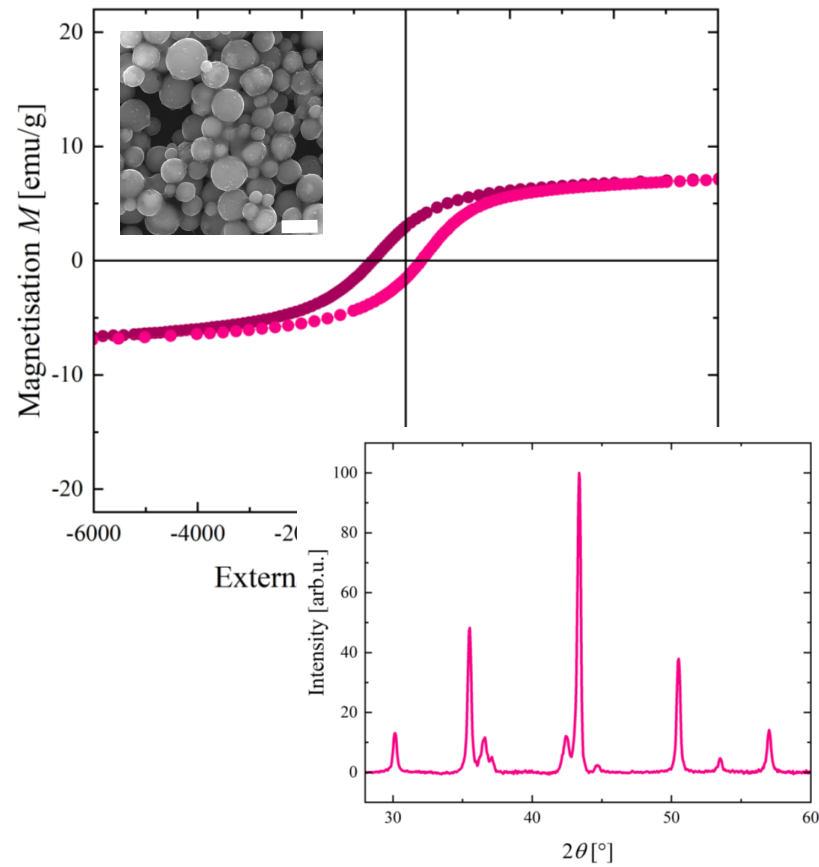
Ferromagnet  
+  
Antiferromagnet

# Magnetic properties for 3 different samples

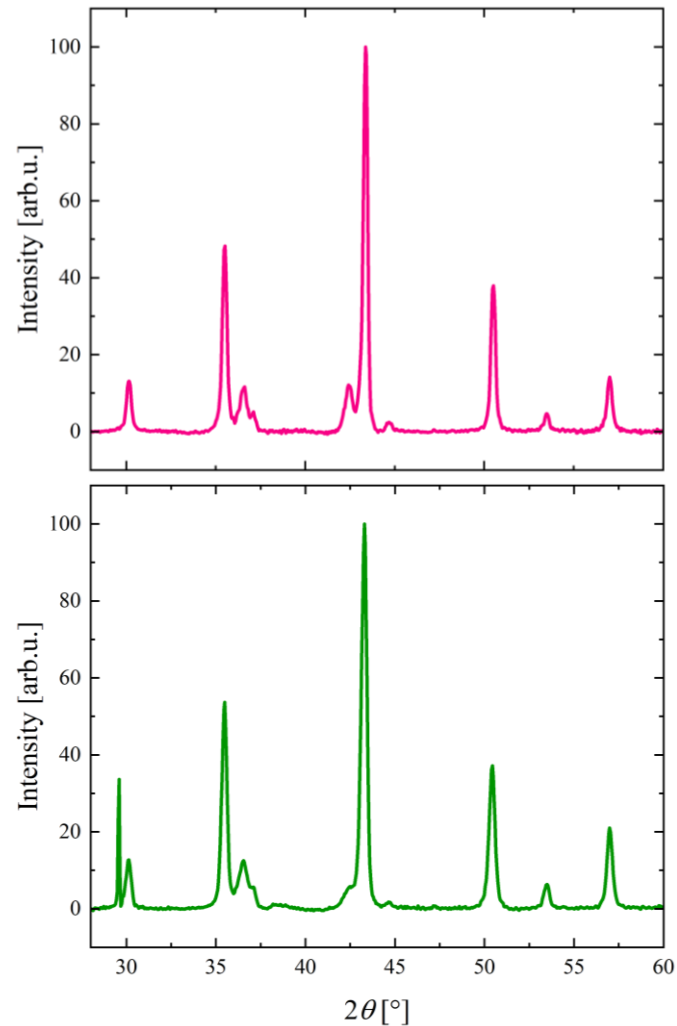
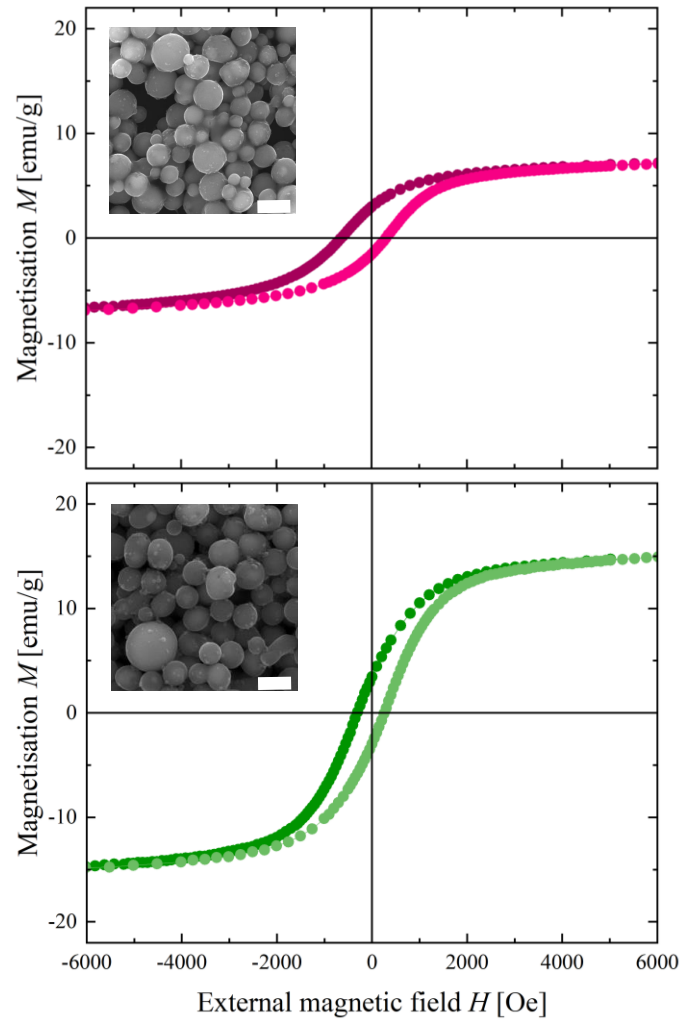




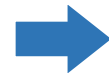
# Magnetic properties for 3 different samples



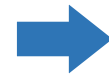
# Magnetic properties for 3 different samples



## Summary



bigger particles

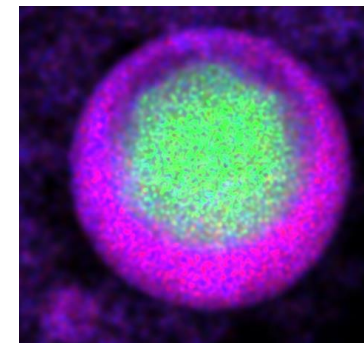
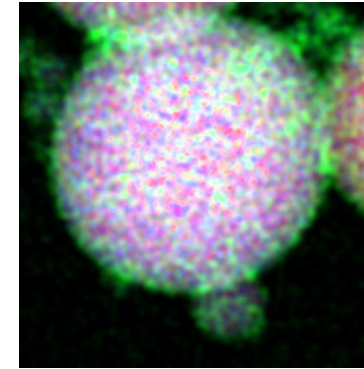


less oxidised components



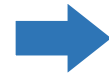
componet separation

Higher  
fluence

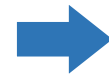


## Summary

Different  
size of raw  
NPs



different fluence



structural changes



different agglomeration

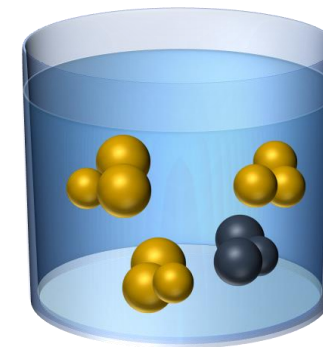
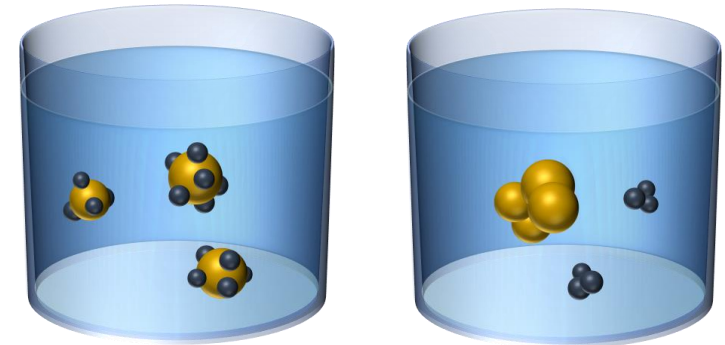


Different  
solvent



different oxidation state

From agglomeration to mechanism of  
composite formation

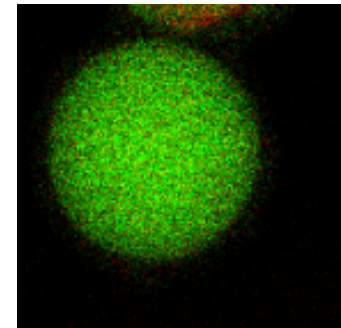
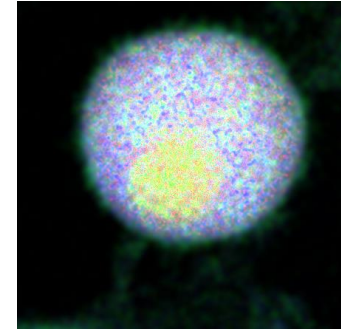


## Summary

Higher  
frequency

➔ less oxidised components

➔ more even components distribution

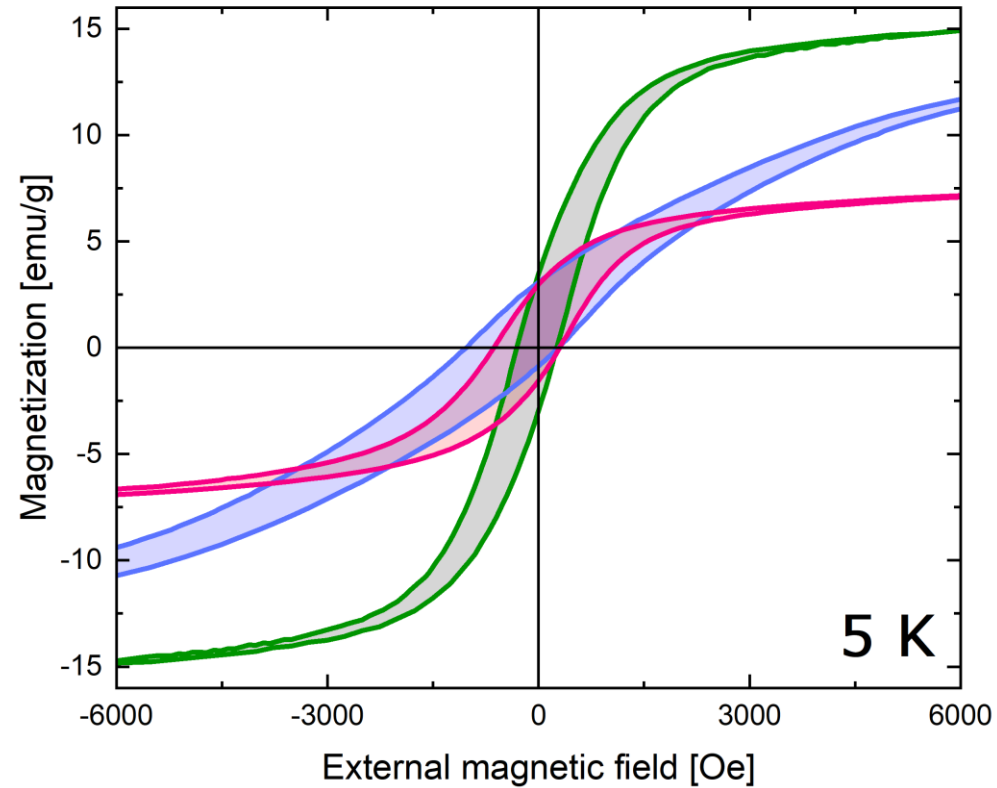


## Summary

Change of parameters  
of synthesis



Modulation of magnetic  
properties





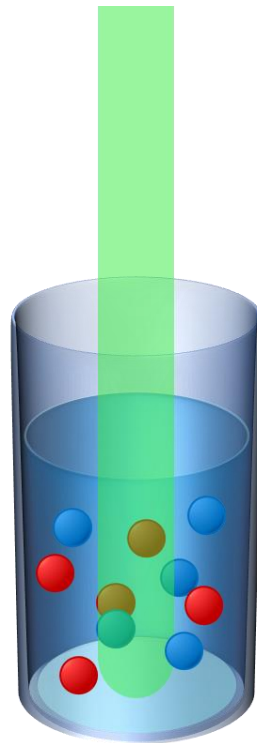


**Thank you for attention!**

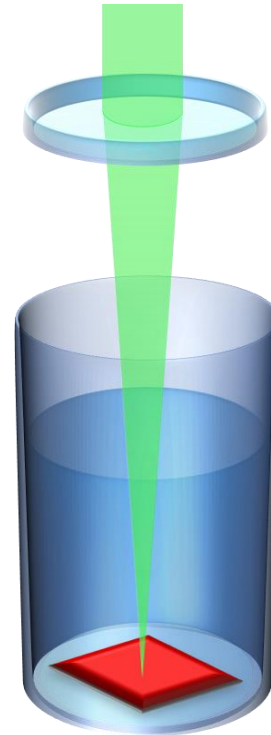
## Group of Pulsed Laser Irradiation in Liquid methods

Important parameters:

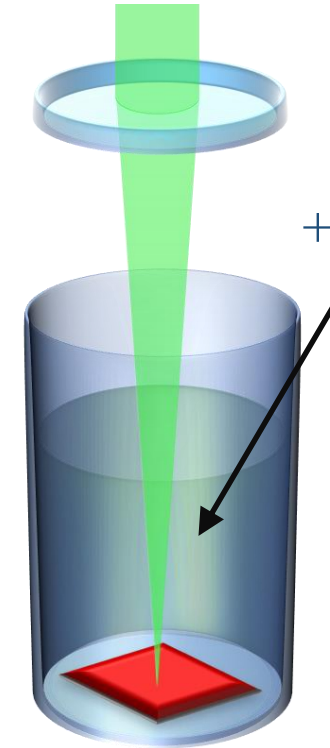
- Materials
- Molar ratio
- Laser fluence
- Wavelength
- Irradiation time
- Solvent
- Laser frequency
- ...



**Pulsed Laser Melting  
in Liquid**

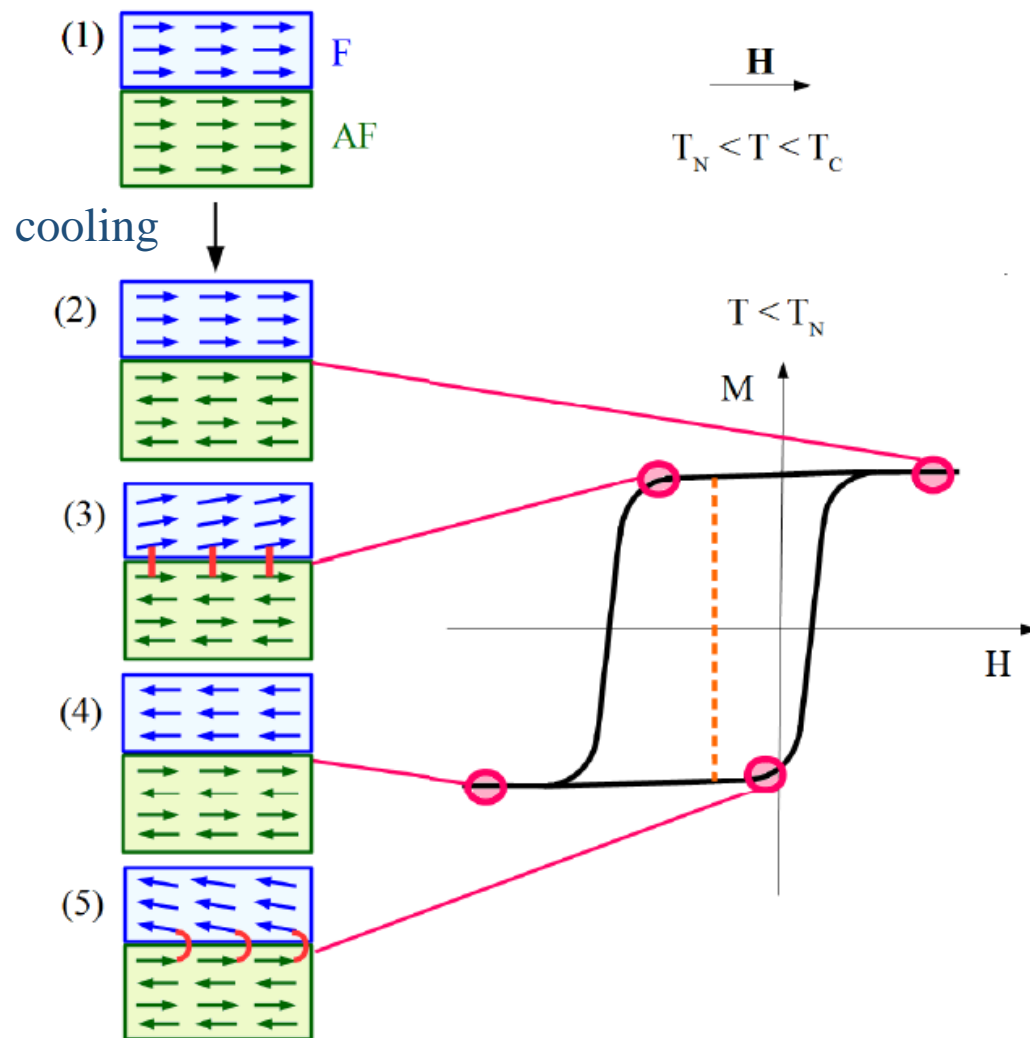


**Pulsed Laser Ablation  
in Liquid**



**Reactive Laser Ablation  
in Liquid**

# Exchange bias



## Molar ratio Fe:Cu

Material:  $\text{Fe}_3\text{O}_4 + \text{Cu}$

Size of Cu NPs: 40 nm

Size of  $\text{Fe}_3\text{O}_4$  NPs: 5 nm

Laser fluence:

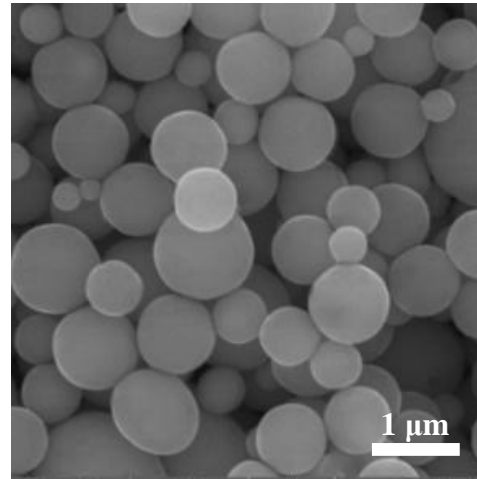
300 mJ/pulse·cm<sup>2</sup>

Wavelength: 532 nm

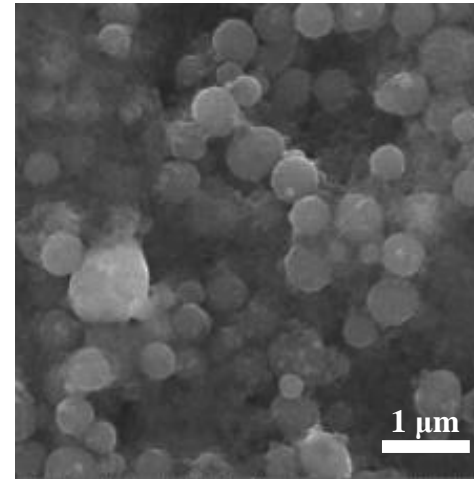
Frequency: 10 Hz

Irradiation time: 1 h

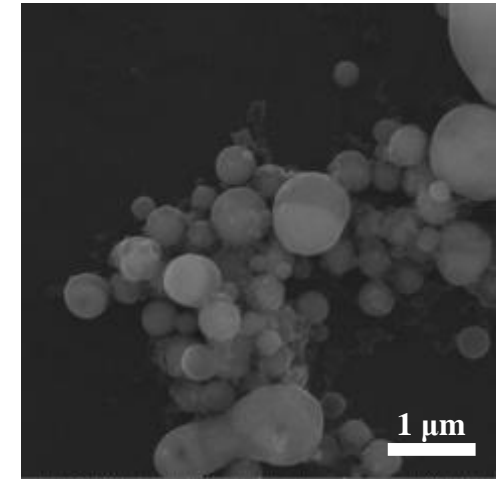
Solvent: ethanol



1:1



1:3



3:1

## Molar ratio Fe:Cu

Material:  $\text{Fe}_3\text{O}_4 + \text{Cu}$

Size of Cu NPs: 40 nm

Size of  $\text{Fe}_3\text{O}_4$  NPs: 5 nm

Laser fluence:

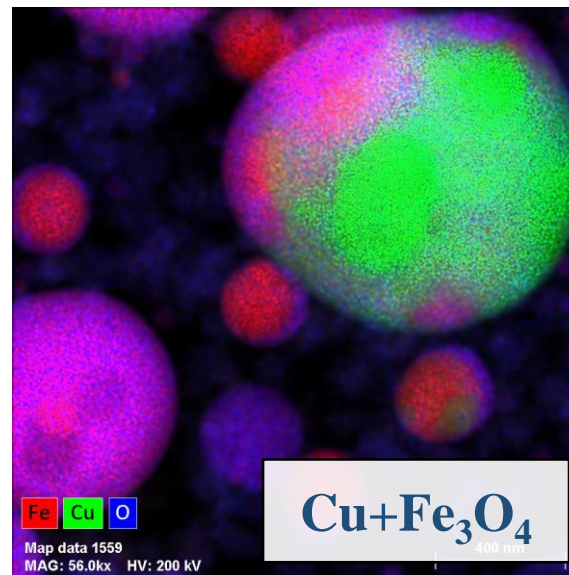
300 mJ/pulse·cm<sup>2</sup>

Wavelength: 532 nm

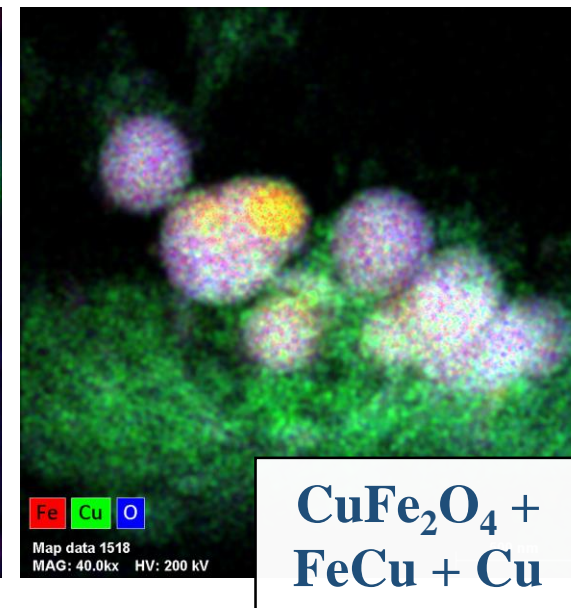
Frequency: 10 Hz

Irradiation time: 1 h

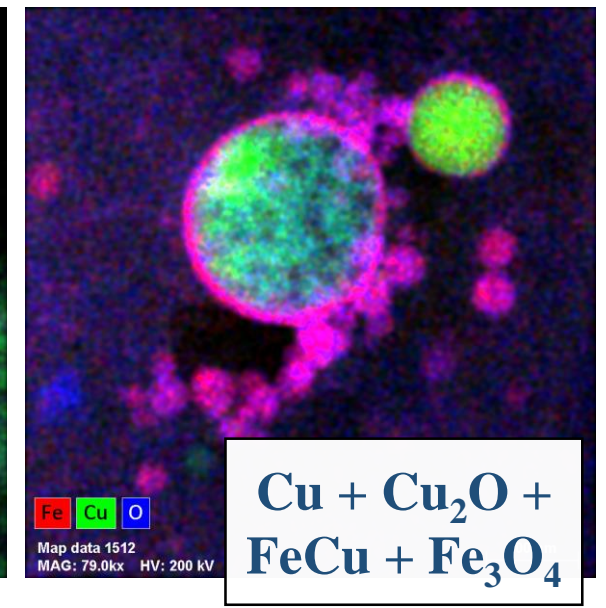
Solvent: ethanol



1:1



1:3



3:1