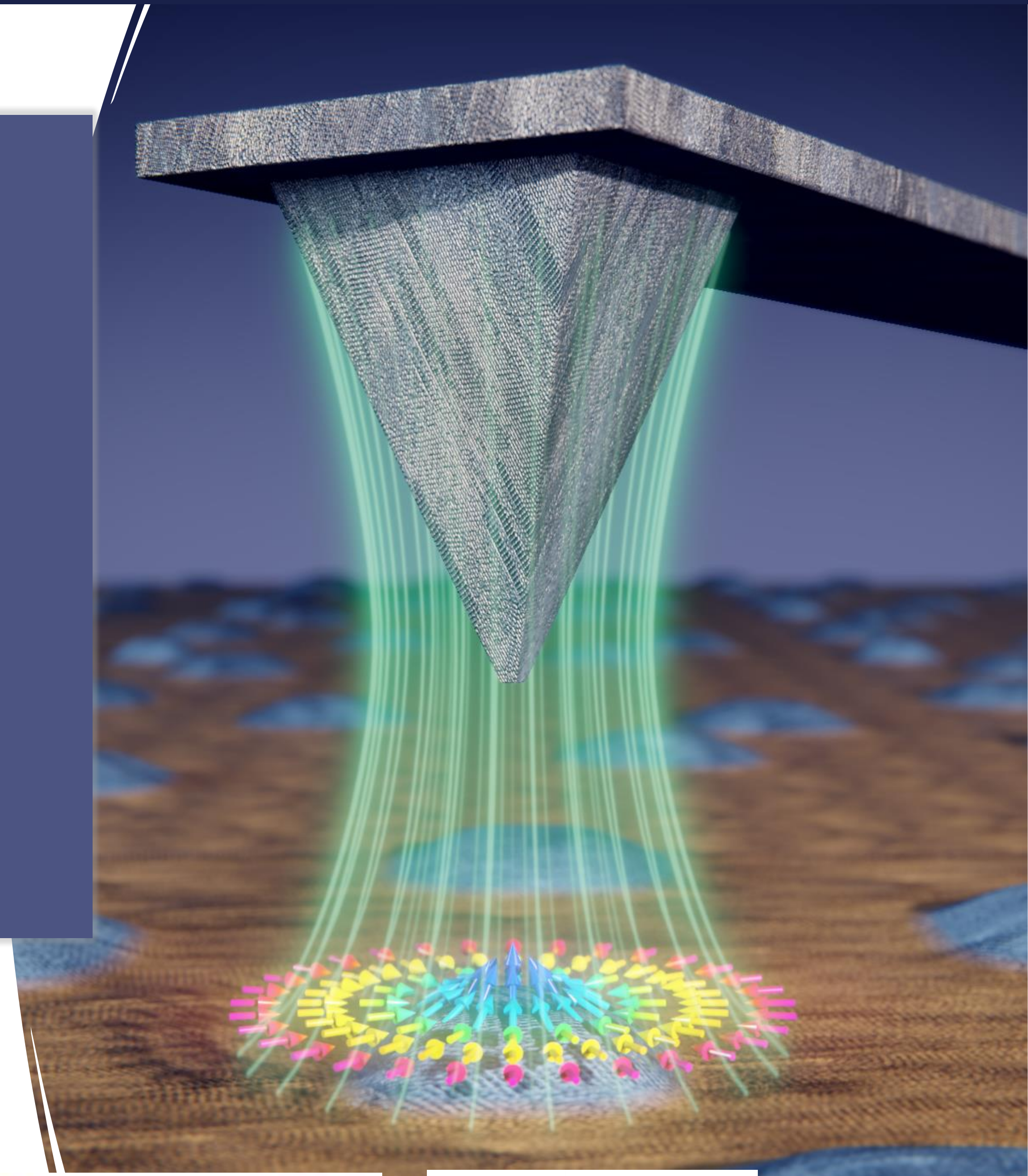
Magnetic Force Microscopy for Biomaterials



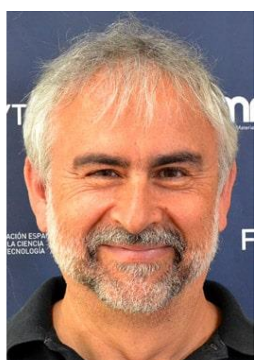
MIRIAM JAAFAR
miriam.jaafar@uam.es

UAM Universidad Autónoma de Madrid
IFIMAC Condensed Matter Physics Center
icmm
CSIC Consejo Superior de Investigaciones Científicas

Thank you...

Agustina Asenjo

Manuel Vázquez



Rafael Pérez del Real

Oksana Fesenko

Eider Berganza

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

icmm

IMN micro nano

iqfr

ICMAB

UAM
Universidad Autónoma de Madrid

BCMATERIALS

icma
Instituto de Ciencia de Materiales de Aragón

INMA
INSTITUTO DE NANOCIENCIA Y MATERIALES DE ARAGÓN

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

unizar

Universidad del País Vasco
Euskal Herriko Unibertsitatea

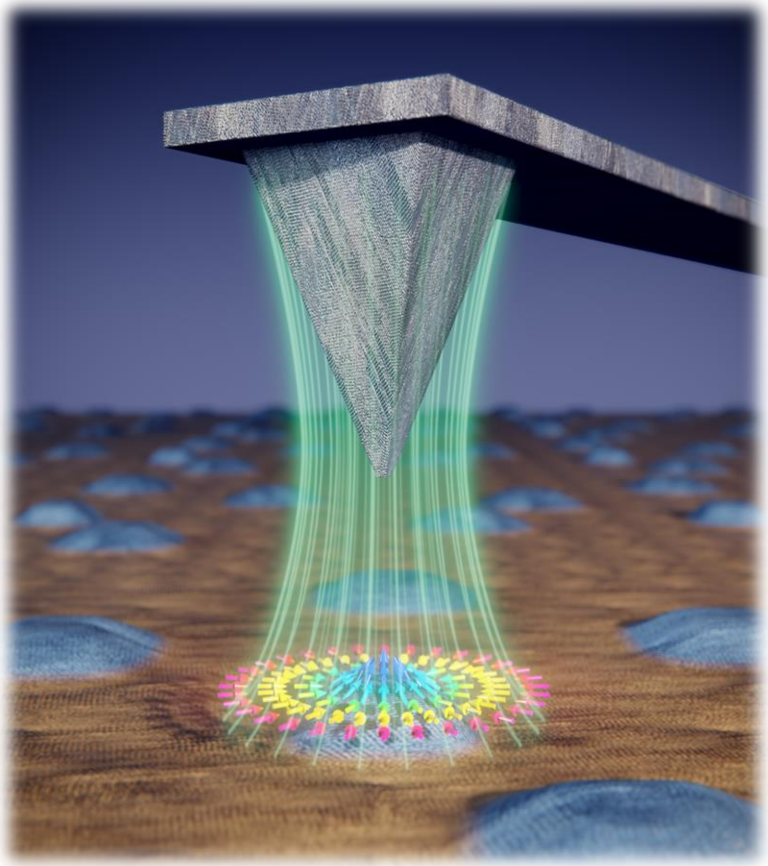
UNIVERSIDAD COMPLUTENSE MADRID

UNIVERSITAT DE BARCELONA

Universidad de Oviedo

Scope

- Introduction
- Co- Virus like particles
- MFM in liquids
- Special MFM probes
- Some applications
- Conclusions



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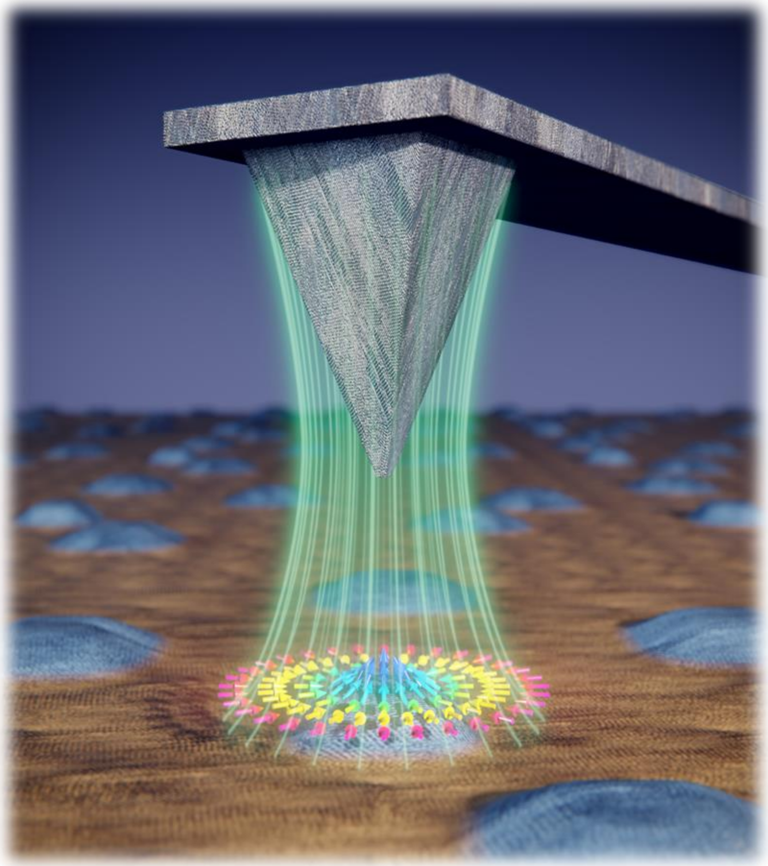
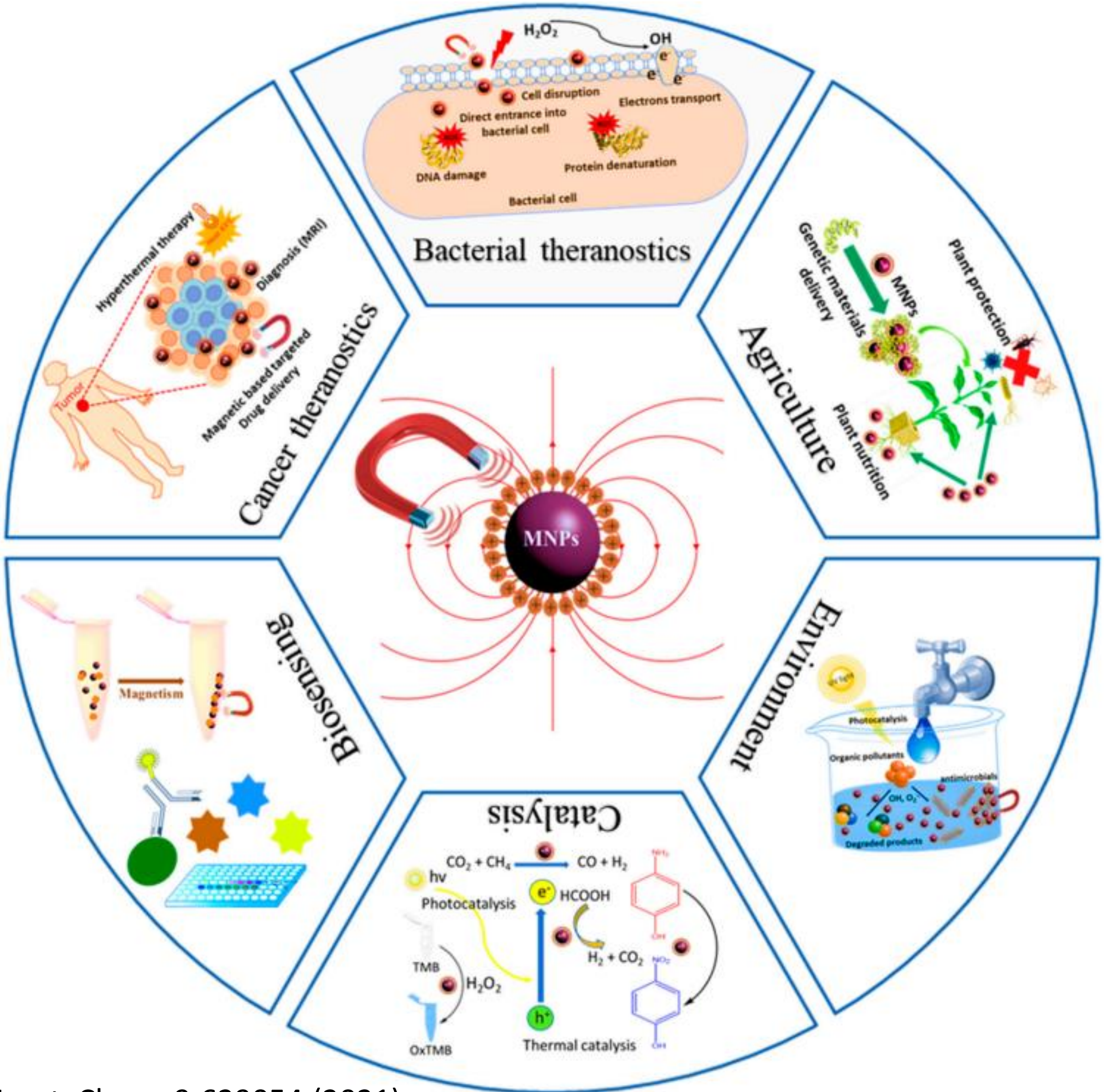
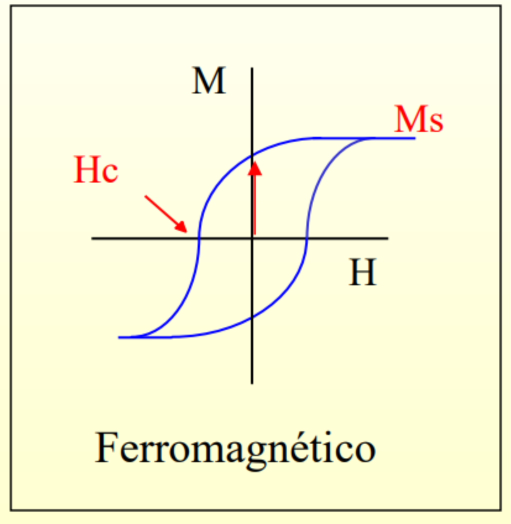
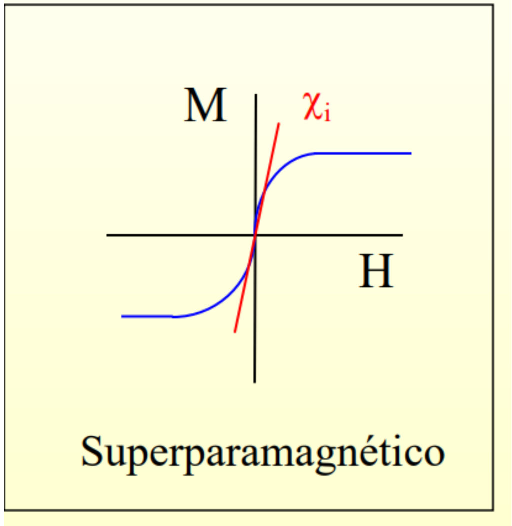


Motivation: Magnetism & Biology







Front. Chem. 9:629054 (2021)

The importance of characterization

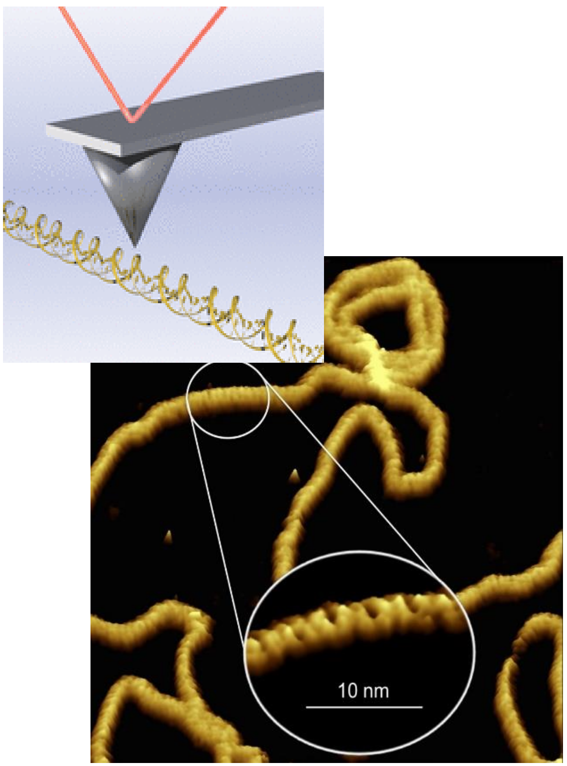
Significant advances in science require the development of new theories, new fabrication techniques, but also accurate characterization methods.

- High spatial resolution
- High sensitivity
- Complementary information

How can SFM help in the characterization of biomaterials?

Motivation: Scanning Force Microscopy & Biology

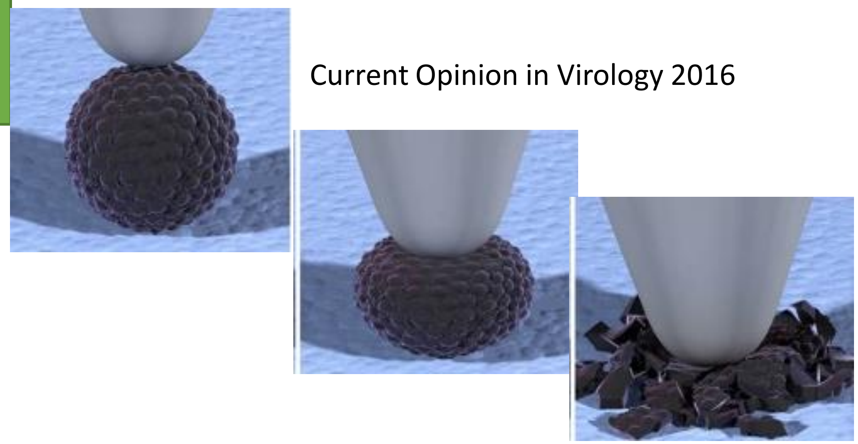
IMAGING and MANIPULATING nanostructures in physiological conditions on a single molecule level.



A. Pyne et al., Small 2014 P.Ares et al., Nanoscale 2016

STUDY MECHANICAL PROPERTIES

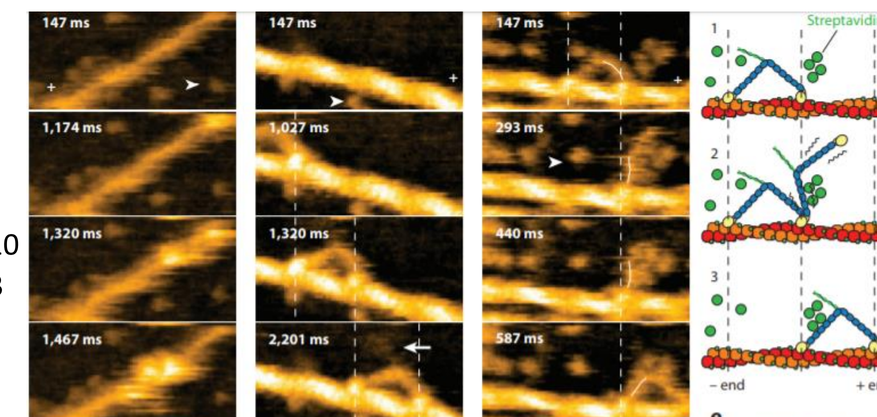
A.P.Perrino and R. García



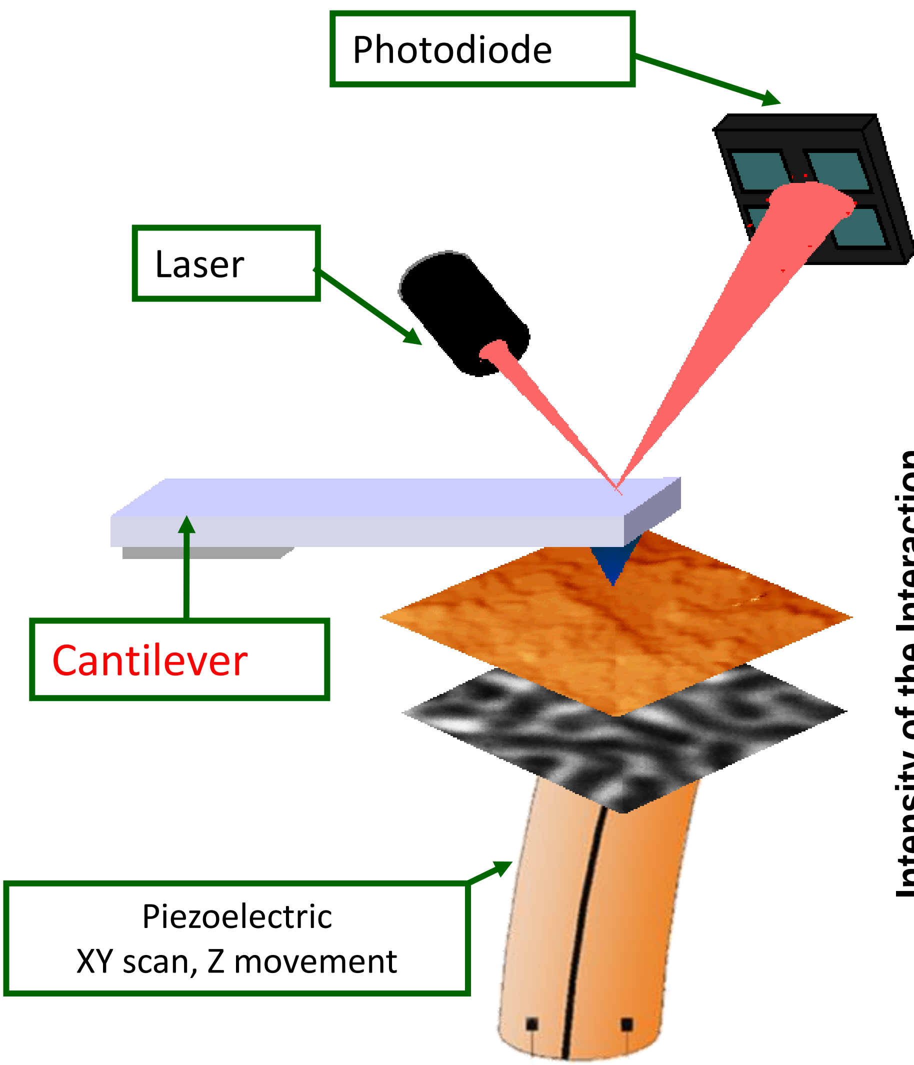
Current Opinion in Virology 2016

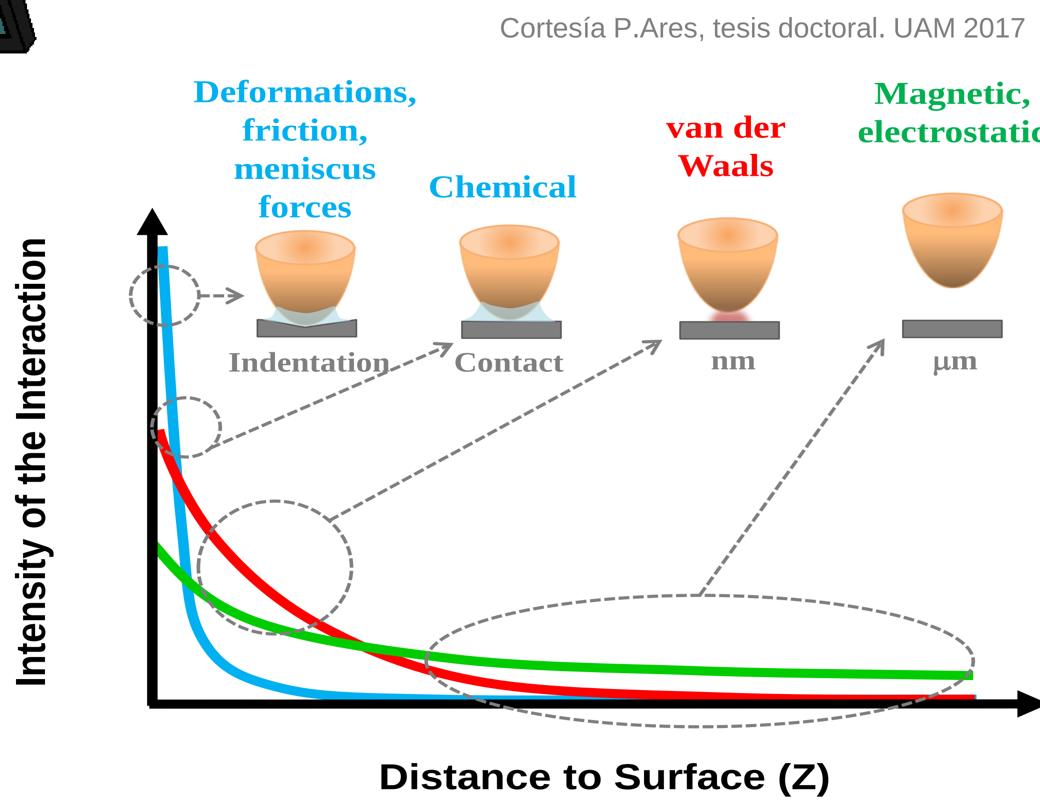
VISUALIZE THE STRUCTURE DYNAMICS AND DYNAMIC PROCESSES

Kodera et al. Nature, 2010
Annu. Rev. Biophys. 2013



Scanning Force Microscopy



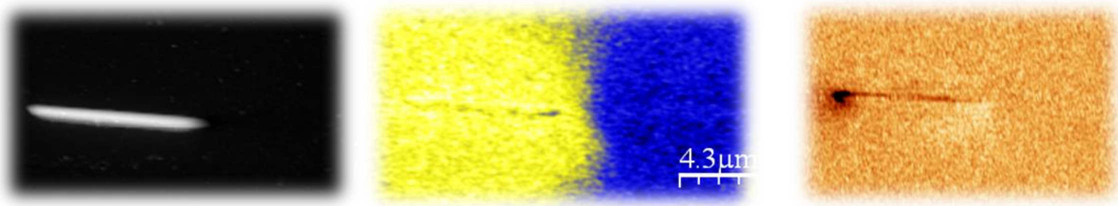


Motivation: SFM in magnetism

Appl. Phys. Lett. **50**, 1455 (1987)
J. Appl. Phys. **62**, 4293 (1987)

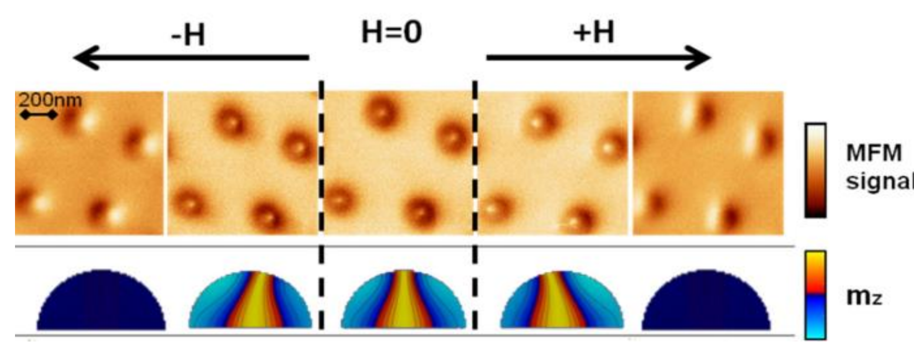
MAGNETIC FORCE MICROSCOPY

- Low cost technique.
- Lateral resolution better than 20nm
- Additional information (3D topo,...)
- To study individual elements
- Magnetization reversal process



Topography Electrostatic properties Magnetic properties

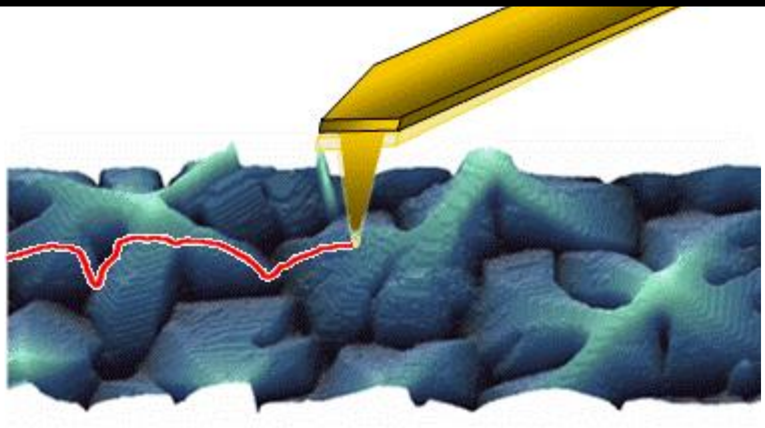
M. Jaafar *et al. Beilstein J. Nanotechnol.* 2011, *2, 552–560*



E. Berganza et al. *Nanoscale*, 2020

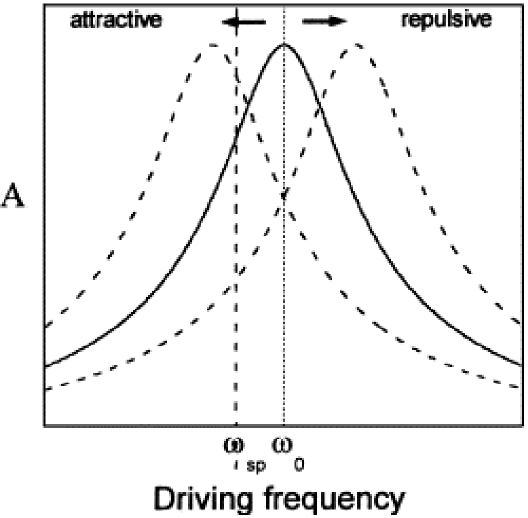
Magnetic Force Microscopy: Dynamic modes

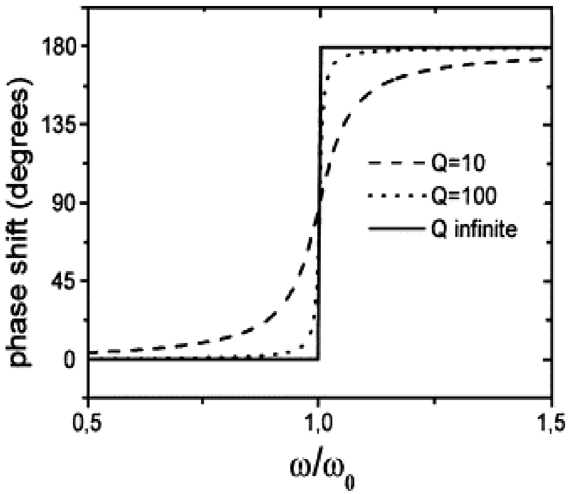
DYNAMIC MODES



$$\Delta A = \frac{A_0 Q}{2k} \frac{\partial F_z^{\,medium\ range}}{\partial z}$$

$$\Delta \omega \propto \frac{\omega_0}{2k} \frac{\partial F_z^{\,long\ range}}{\partial z}$$





MFM signal = frequency shift

$$F_{magnetic} = m_{tip} \bullet \nabla H_{sample}$$

Magnetic Force Microscopy: Dynamic modes

DYNAMIC MODES

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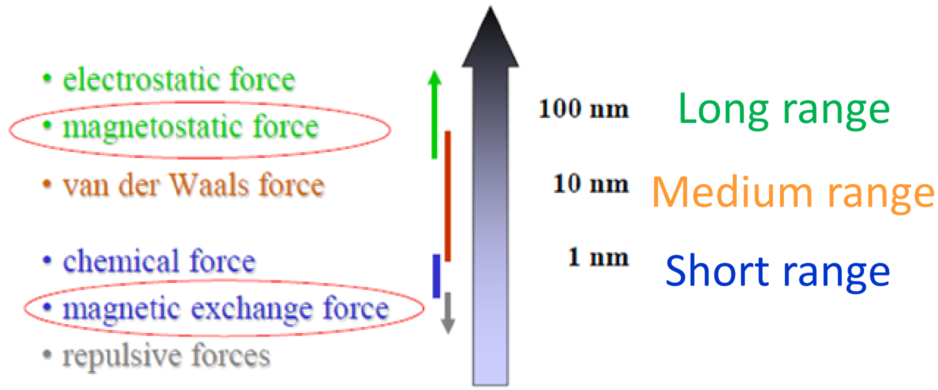
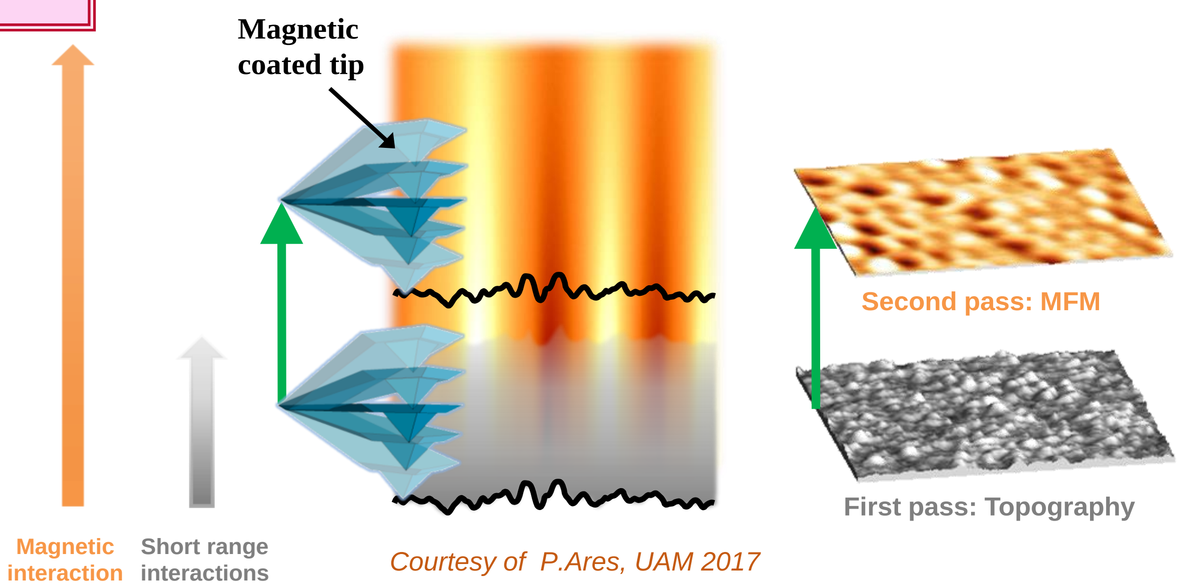




Courtesy of P.Ares, UAM 2017

MFM signal = frequency shift

$$F_{magnetic} = m_{tip} \bullet \nabla H_{sample}$$

Motivation: MFM from magnetism to biomagnetism

Frontiers of magnetic force microscopy
O. Kazakova et al. J. Appl. Phys. 125, 060901 (2019)

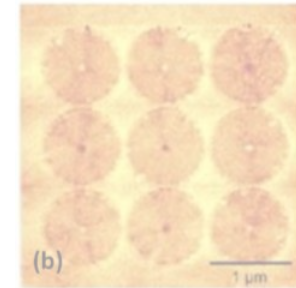
Classical ferromagnetic samples

Data storage

Thin films:

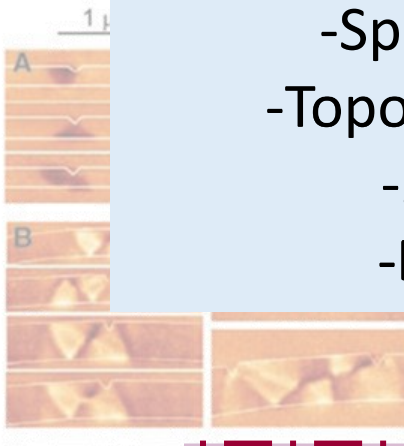
ures→

e



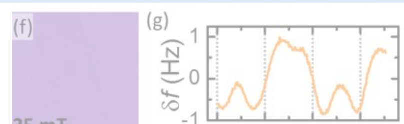
Ono et al. Science 2000

Ferromagnetic domains- Domain Wall movement

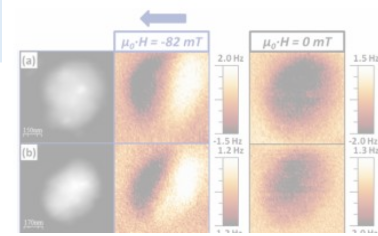


S. P. Pa

Science 32



Nanoparticles



C. Moya et al. Nanoscale, 2015,7, 17764-17770

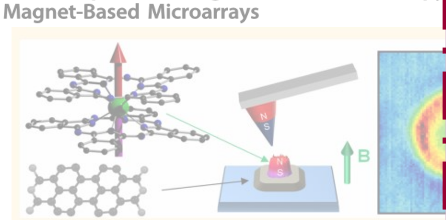
Molecular magnets

NANO LETTERS

DOI: 10.10

Nano Le

Low-Temperature Magnetic Force Microscopy
Magnet-Based Microarrays



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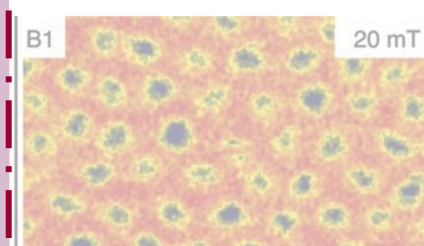
13)



CHALLENGES….
-Antiferromagnets
-Spin-caloritronics
-Topological insulators
-2D materials
-**Biomaterials**

- ✓ *Resolution*
- ✓ *Sensitivity*
- ✓ *Different environments*
- ✓ *Quantitative information*

Motivation: MFM from magnetism to biomagnetism

PROBE-ENGINEERING

Customized probes are used to perform very specific tasks and push the limits of commercial MFM systems →

- ✓ to achieve a higher resolution
- ✓ to reduce/increase probe–sample interaction→ High **sensitivity** but without disturbing the magnetic structure of the samples
- ✓ to be able to combine different scanning modes.
- ✓ Working in different environments (**liquids**)

- ✓ *Resolution*
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Motivation: MFM from magnetism to biomagnetism

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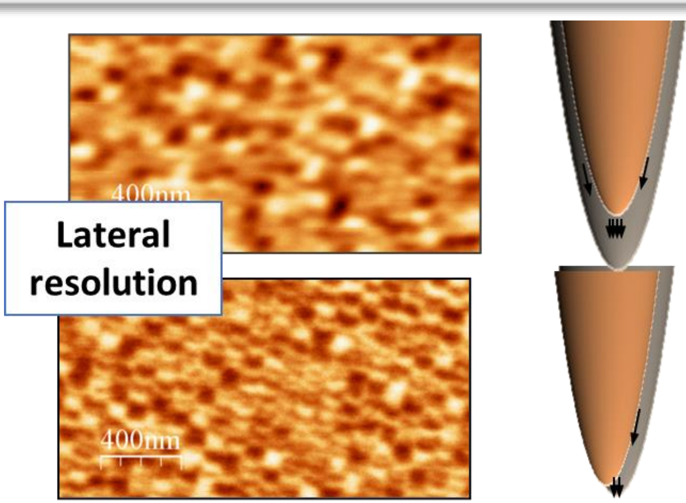
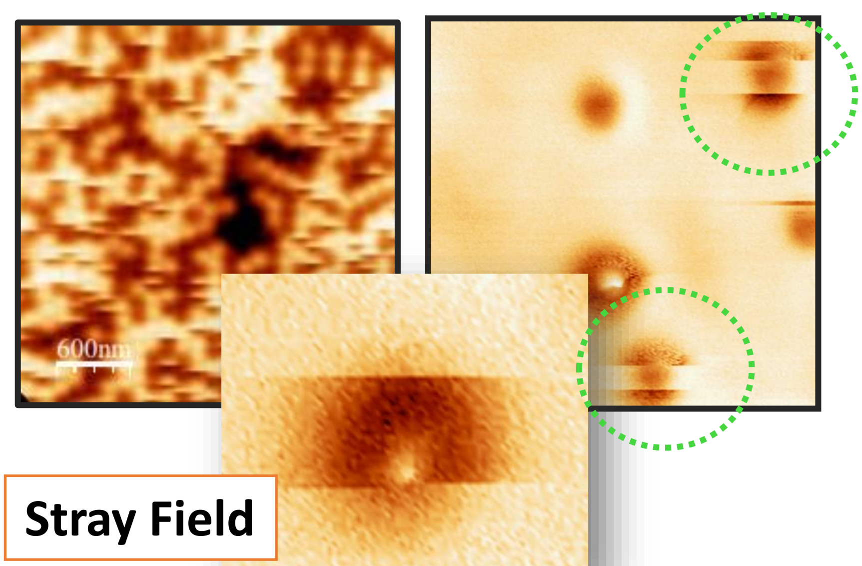


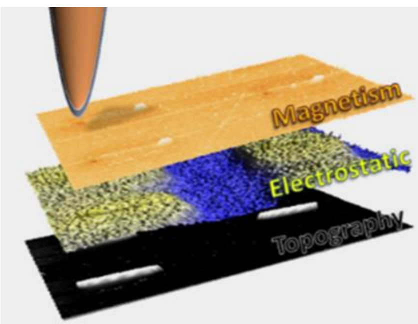
O. Iglesias –Freire, **M. Jaafar** et al .Beilstein J. Nanotechnol., **7**, 1068–1074 (2016)

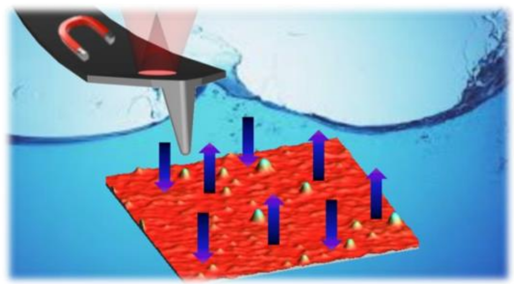


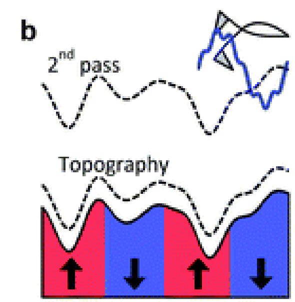
Motivation: MFM from magnetism to biomagnetism

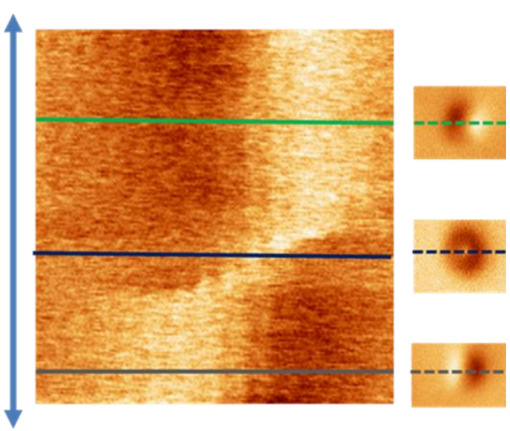
NON STANDARD OPERATION MODES

- ✓ to achieve a higher resolution: measure as close as possible
- ✓ to be able to combine different scanning modes→ Complementary information
- ✓ Working in different environments (**liquids**)

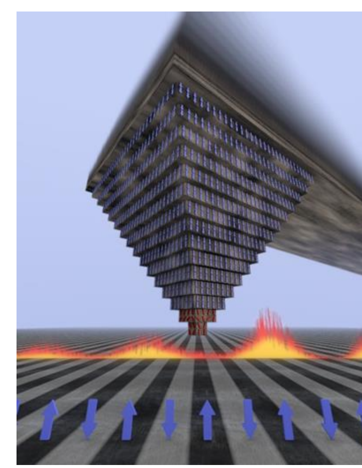








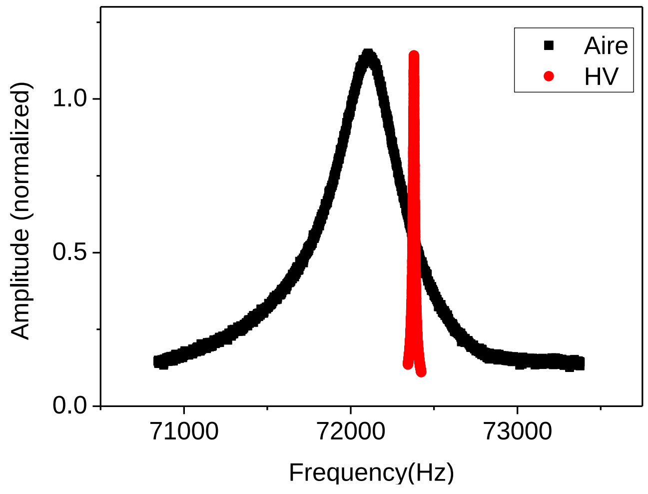
- ✓ *Resolution*
- ✓ *Sensitivity*
- ✓ *Different environments*
- ✓ *Quantitative information*

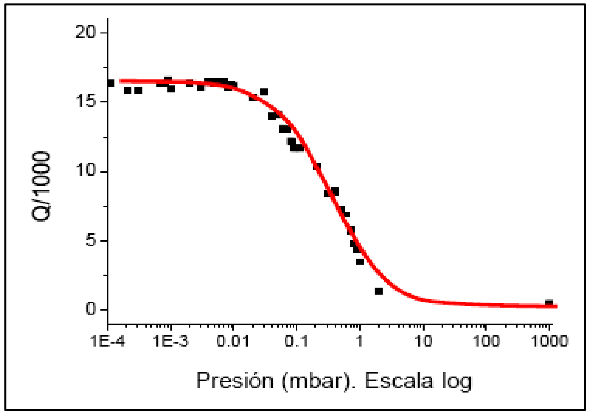


Imaging biological samples under physiological conditions by Magnetic Force Microscopy

$$\text{SENSITIVITY} \propto \sqrt{Q}$$

Q(liquid)~5
Q(air)~200
Q(vacuum)~ 10000



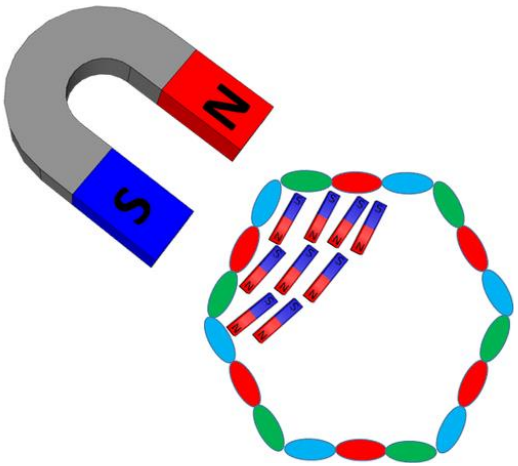


Experiments in liquids
(*Low Q*)

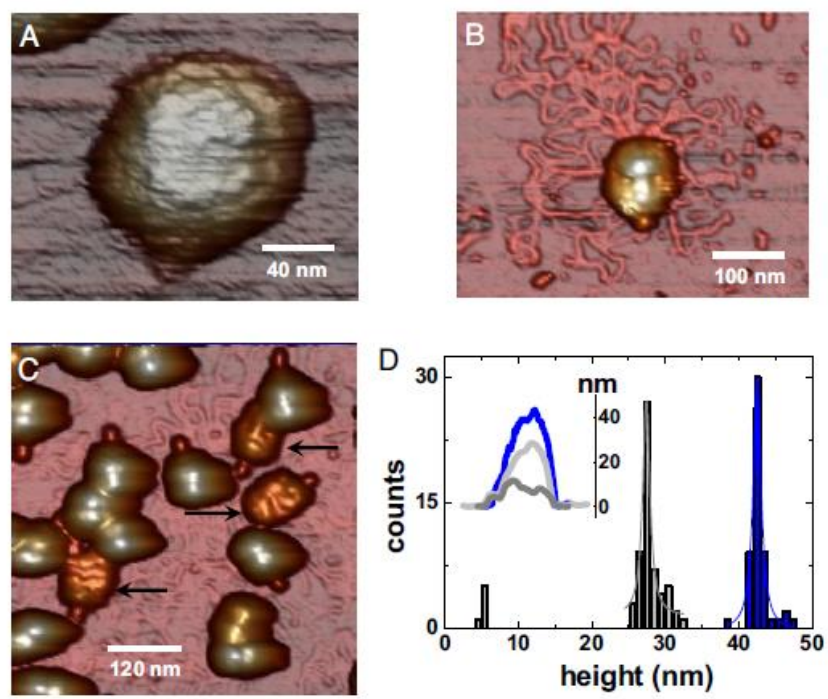
Experiments at ambient conditions
(Medium Q)

Experiments in HV/UHV
(*High Q*)

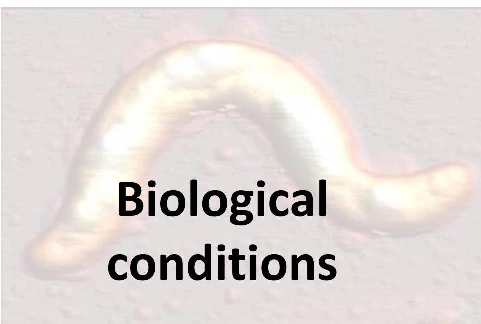
Imaging biological samples under physiological conditions by Magnetic Force Microscopy



For certain samples, measuring in physiological media will be critical



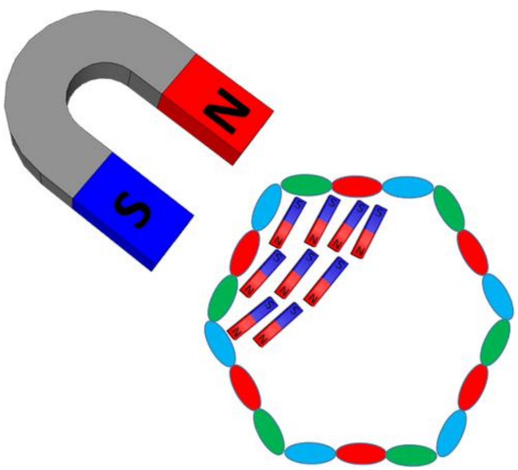
Experiments in liquids
(*Low Q*)



Desiccation effects on ϕ29 viruses

C. Carrasco *et al.*, PNAS. 2009

Co-Virus like particles

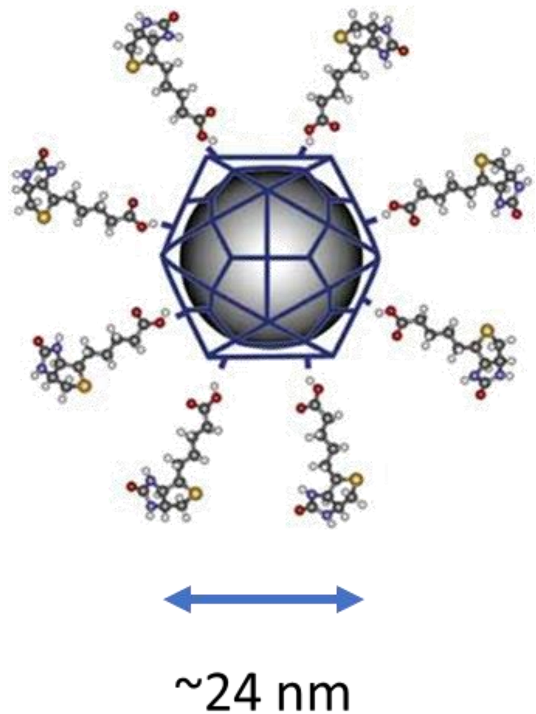


Aljabali, A. A. A.; Sainsbury, F.; Lomonossoff, G. P.; Evans, D. J.. Small 2010, 6 (7), 818–821.

Virus capsids have been suggested as promising templates for building up nanometric-sized magnetic clusters by taking advantage of their inner cavity as a **nanoreactor**

UNIVERSITY OF Hull

In collaboration withc Prof. David Evans, Dr. P.J. de Pablo

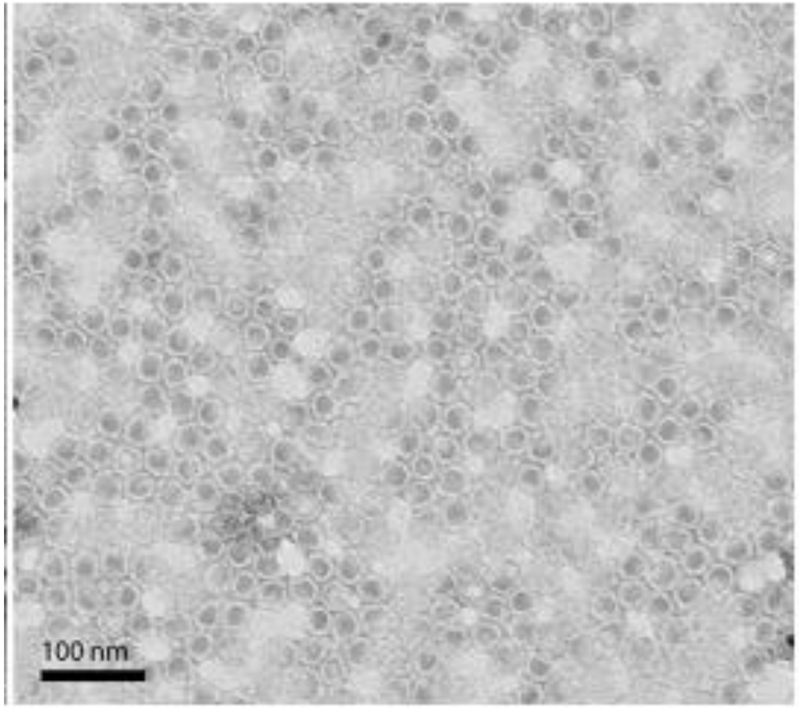


To move closer toward the development of virus like particles (VLPs) for such applications as magnetic hyperthermia treatments, it is essential to investigate the magnetic moment of individual particles because they are required to be easily manipulated by magnetic fields.

Is it possible to analyze the metallic cluster grown inside the virus capsid with MFM?

Co-Virus like particles

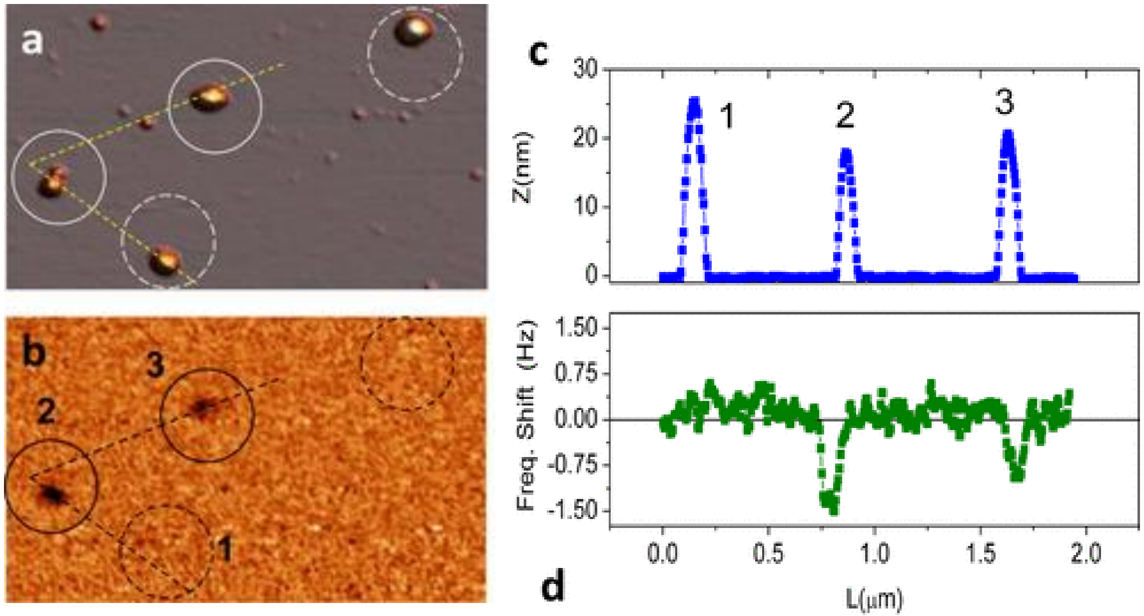
- Electron microscopy imaging provides a **comparison between empty (eVLPs) and loaded viruses (Co-VLPs)** by the different contrast inside the particles
- Unmodified particles were invisible under transmission electron microscopy (TEM).
- The TEM data suggested that the **virus cages are completely filled with metallic cobalt**



M. JAAFAR et al., ACS Appl. Mater. Interfaces. 6, pp. 20936 – 20942 (2014).

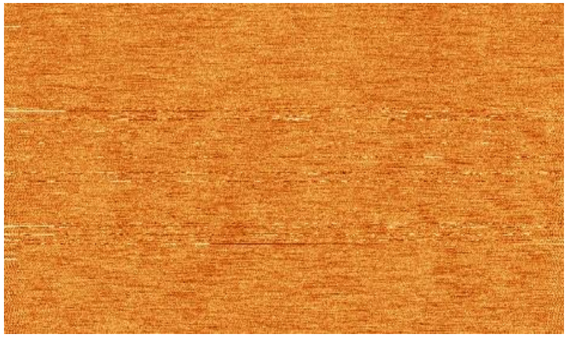
Co-Virus like particles

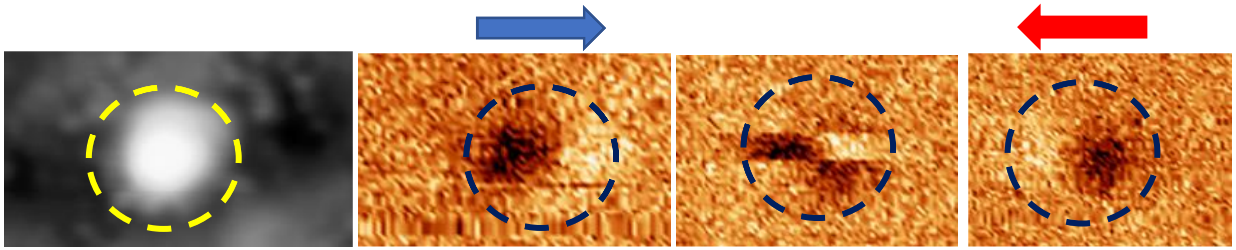
Magnetic nanoparticles



Control Experiment: CoNps are of similar size→ we expected to find similar magnetization values in the case of solid filling of Co-VLPs.

Co-Virus like particles:



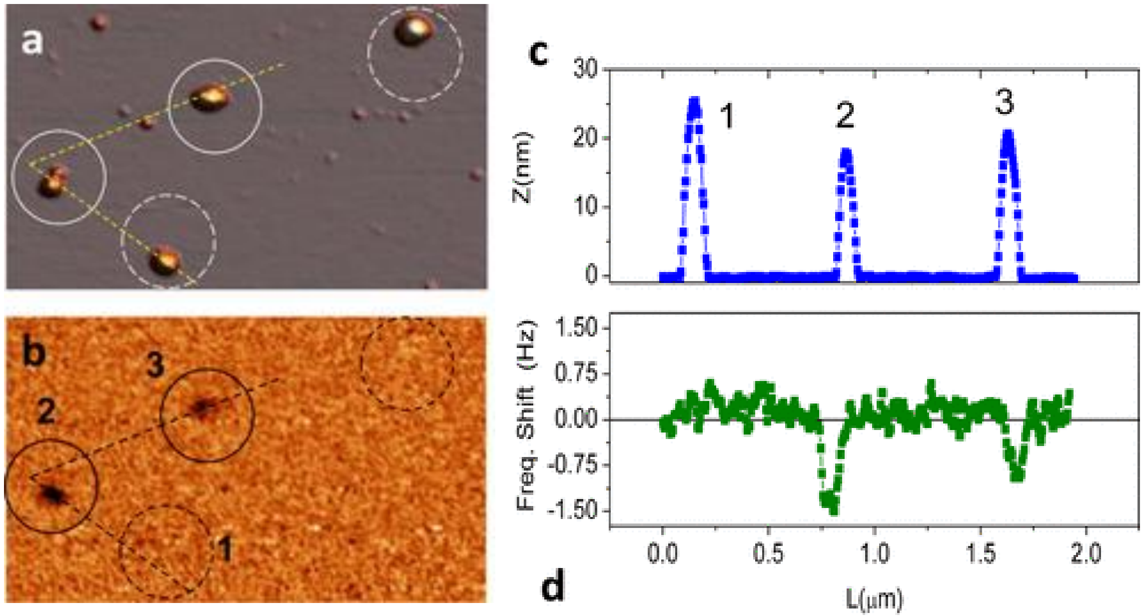


Variable Field Magnetic Force Microscopy Measurements

M. JAAFAR et al., ACS Appl. Mater. Interfaces. 6, pp. 20936 – 20942 (2014).

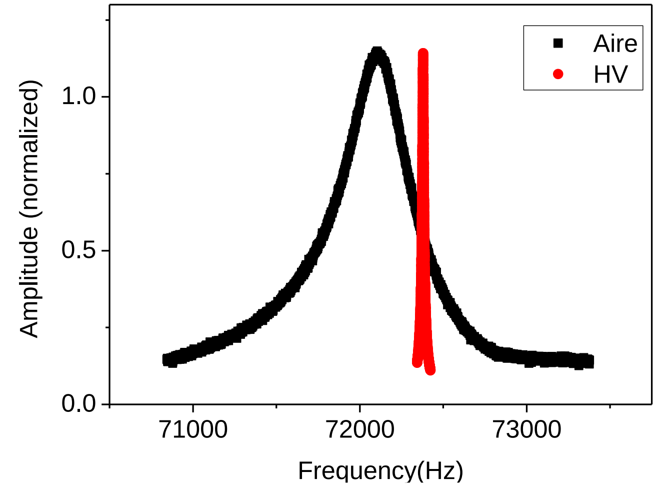
Co-Virus like particles

Magnetic nanoparticles



Q(air)~200

Q(vacuum)~ 10000

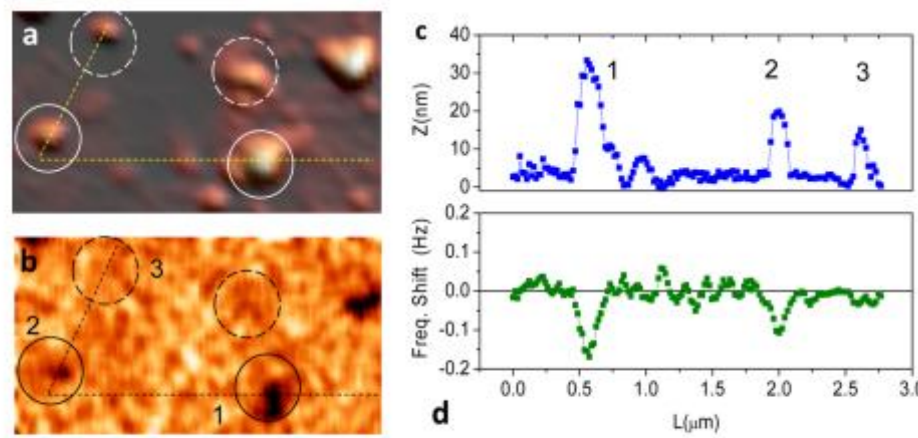


$$\text{sensitivity} \propto \sqrt{Q}$$

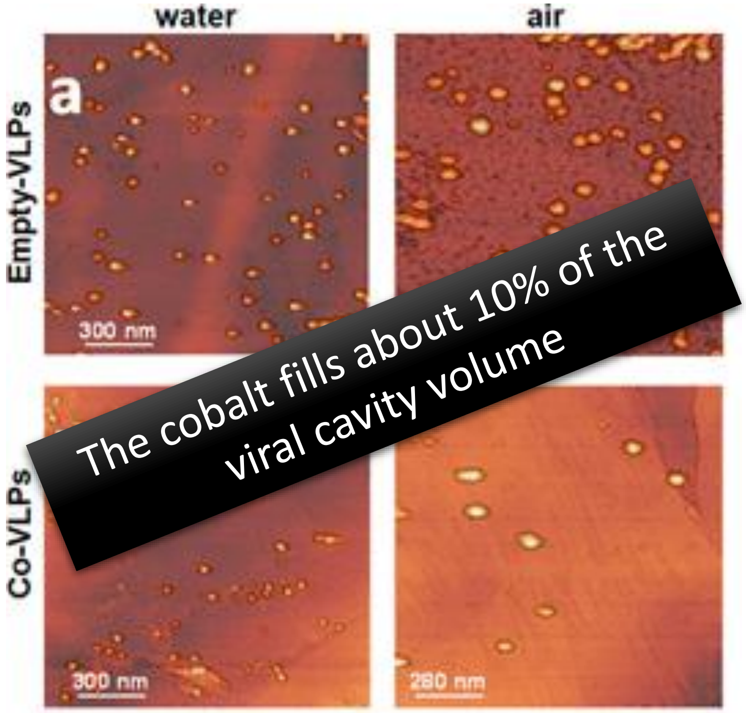
Co-Virus like particles:

Co-VLP signal is ~8 times lower than that of the commercial CoNP, indicating that the amount of the magnetic Co inside virus particles is less than expected.

-Co-VLPs have about 8 times less Co than commercial Co-Nps??.

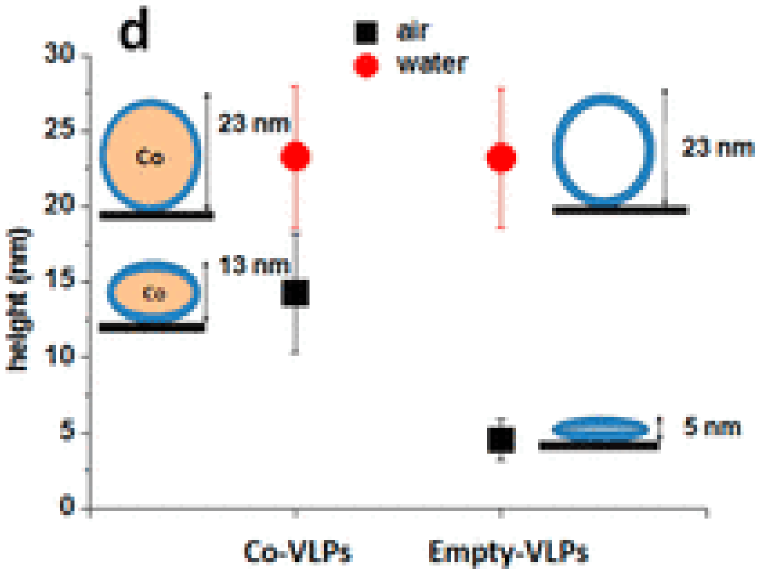


Co-Virus like particles



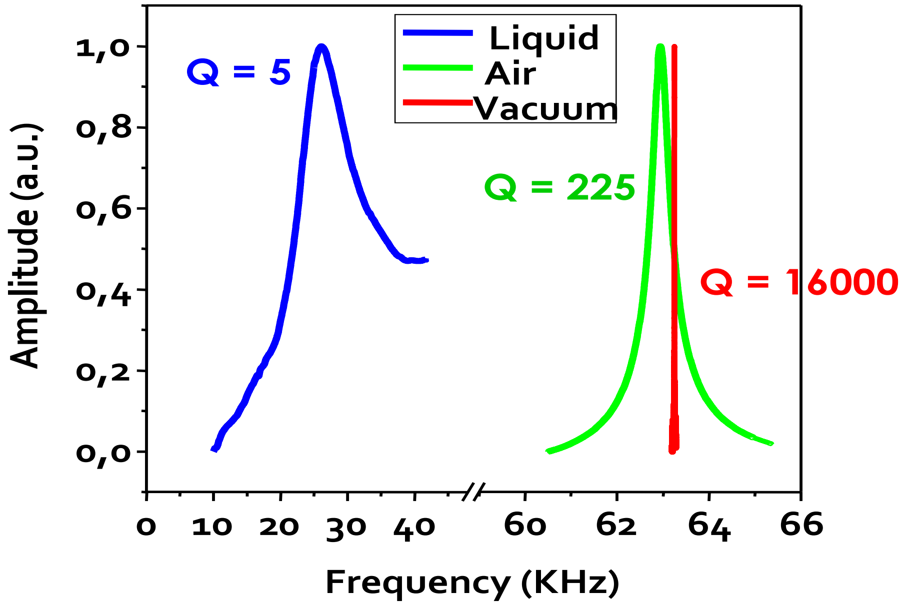
- Protein shells are severely affected by dehydration.
- In particular, virus structures are prone to collapse
- The difference between heights observed for collapsed Co-VLP and eVLP (~9 nm) establishes a top limit for the size of the cobalt cluster inside the viruses.

Biological specimens can dramatically **change their properties** when studied far away of physiological conditions→ it is important of being able to develop MFM measurements in liquid media



M. JAAFAR et al., ACS Appl. Mater. Interfaces. 6, pp. 20936 – 20942 (2014).

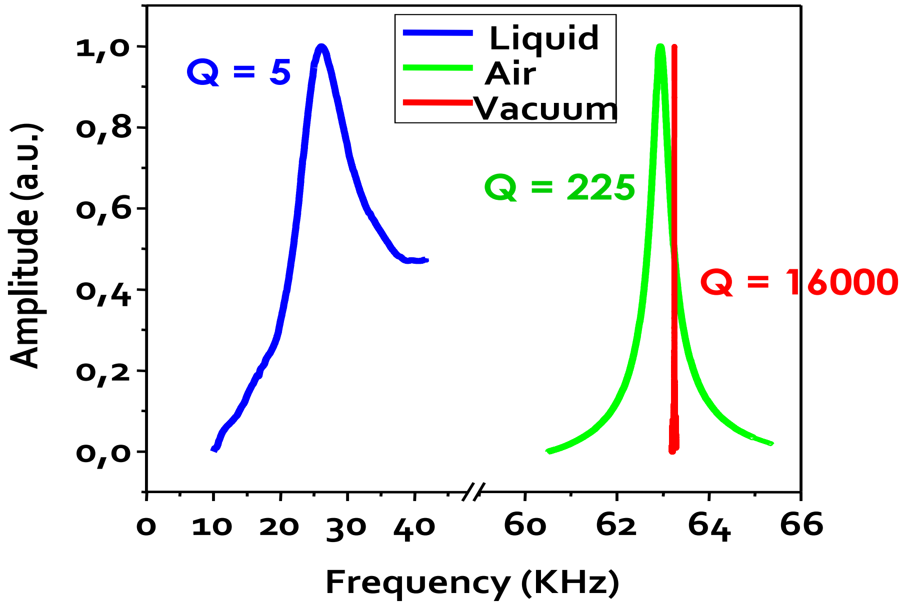
MFM in liquids

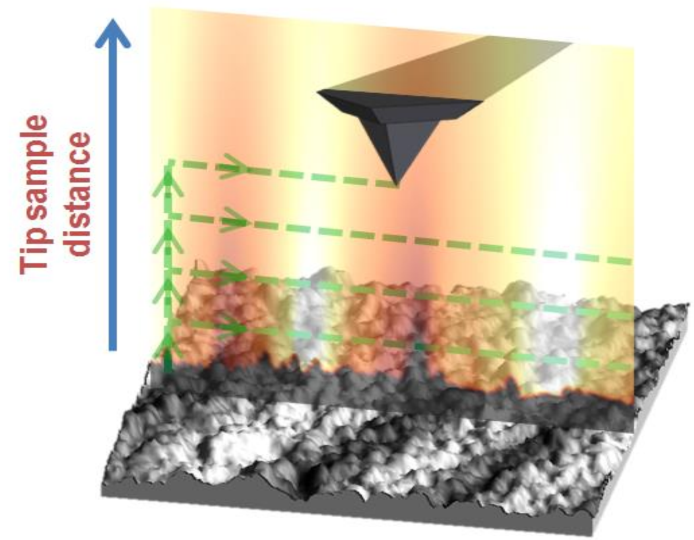


- The difficulty in developing MFM for detecting magnetic interactions in liquids as a consequence of the **high damping forces on the cantilever**, which are several times greater than in air.
- This is the origin of the **low quality factor Q** of the cantilever resonance characteristic of liquid measurements.
- This low Q results in a **significant loss of sensitivity in the MFM signal**.

P. Ares, **M. Jaafar**, A. Gil, J. Gómez-Herrero and A. Asenjo,
Small 11 (36) 4731-6 (2015)

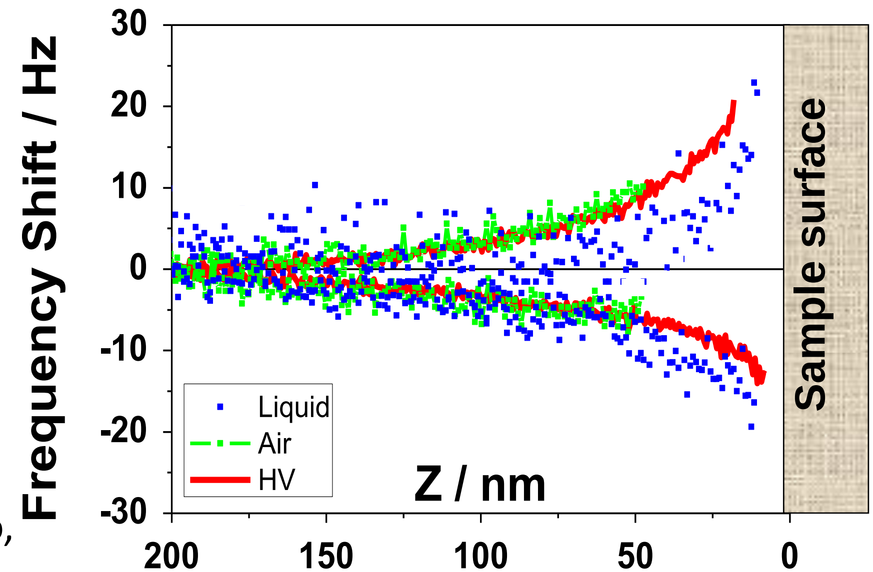
MFM in liquids





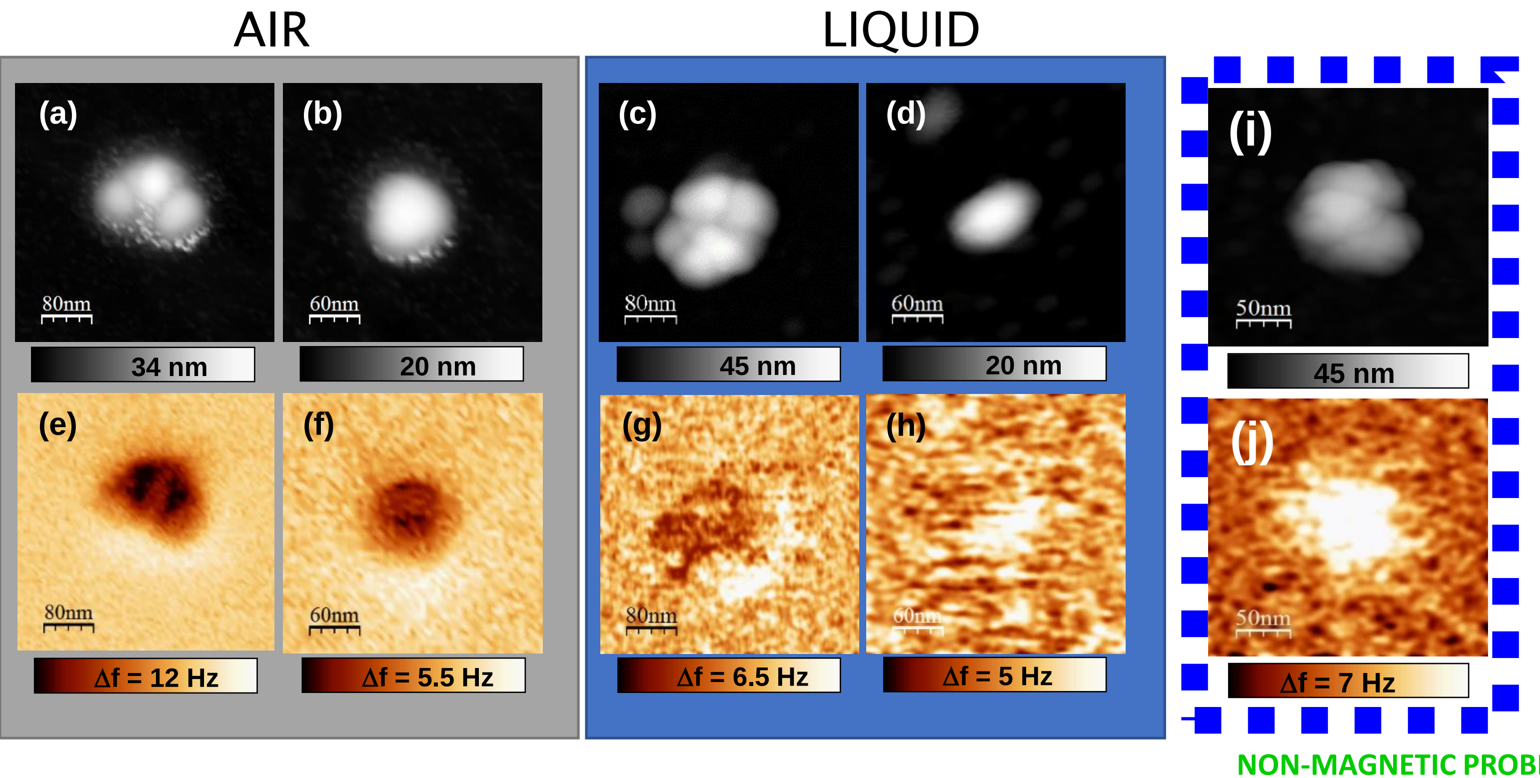
HV signals are the cleanest ones, whereas the liquid signals are the noisiest.

But… it can be observed that in both vacuum and liquid, where the attractive forces are much lower than in air, the **magnetic signal can be detected with the tip very close to the sample** (tip sample distances <10 nm), in contrast to air conditions



P. Ares, **M. Jaafar**, A. Gil, J. Gómez-Herrero and A. Asenjo, **Small** 11 (36) 4731-6 (2015)

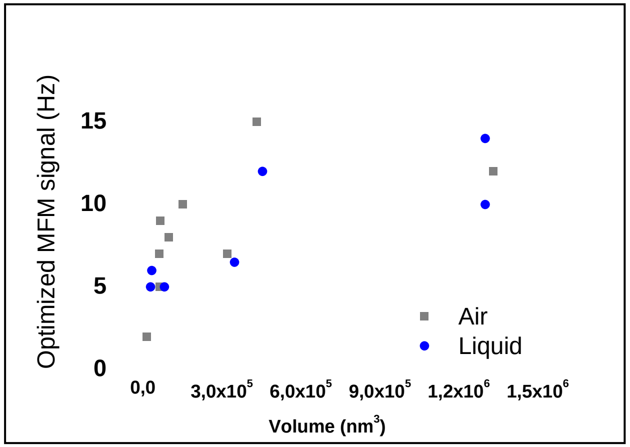
MFM in liquids. Fe_3O_4 nanoparticles



Cubic NPs, 30 nm side, courtesy of P. Morales, ICMM-CSIC

$$\sqrt{\frac{f_{0,liq}/Q_{liq}}{f_{0,air}/Q_{air}}} \sim 4.5$$

$$\frac{\left[\text{Signal}/\mathit{noise}\right]_{liquid}}{\left[\text{Signal}/\mathit{noise}\right]_{air}} \sim 5$$



P. Ares, **M. Jaafar**, A. Gil, J. Gómez-Herrero and A. Asenjo, **Small** 11 (36) 4731-6 (2015)

MFM in biomaterials: special probes

To improve the sensitivity we need specific cantilevers, NOT OFFERED by the companies

$$\delta\omega = -\frac{1}{2}\frac{\omega_0}{k}\frac{\partial F}{\partial z}$$

R. García and R. Pérez, Surface Science Reports (2002)

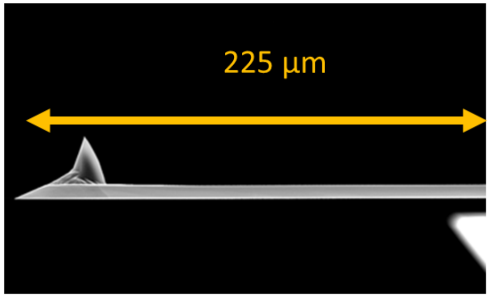
Higher sensitivity requires ω_0/k as high as possible

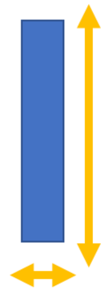
The noise increases for softer cantilevers

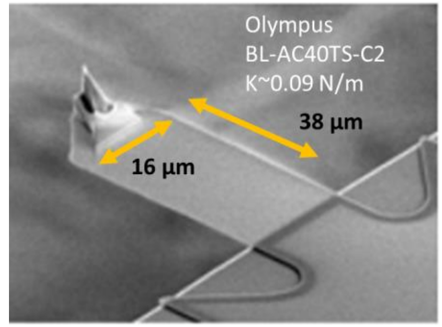
$$\sqrt{1/_{kQ}}$$

The adhesion of the magnetic coating to the AFM probe is and additional handicap

MFM in biomaterials: special probes







Regarding the noise → $\sqrt{\frac{(kQ)_N}{(kQ)_l}} \sim 7$

With standard MFM probes: Nanosensors PPP-MFMR:
$f_0 \sim 26$ kHz, $k \sim 2.8$ N/m, $Q \sim 3$ $\Rightarrow$ $(\omega_0/k)_N \sim 6\times10^4$ rad.N/s.m

With, for example, specific probe for liquids: Olympus biolevers *Olympus BL-AC40TS-C2* (Non magnetic):
$f_0 \sim 25$ kHz, $k \sim 0.09$ N/m, $Q \sim 2$ $\Rightarrow$ $(\omega_0/k)_l \sim 1.7\times10^6$ rad.N/s.m

→ $\frac{(\omega_0/k)_l}{(\omega_0/k)_N} \sim 29$

Theoretical Signal to noise ratio improvement:

29/7 ~ 4

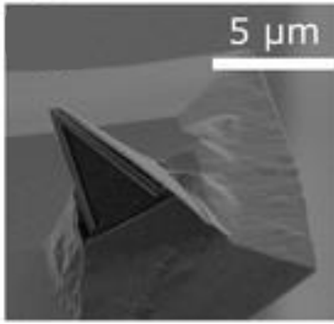
Custom made MFM probes

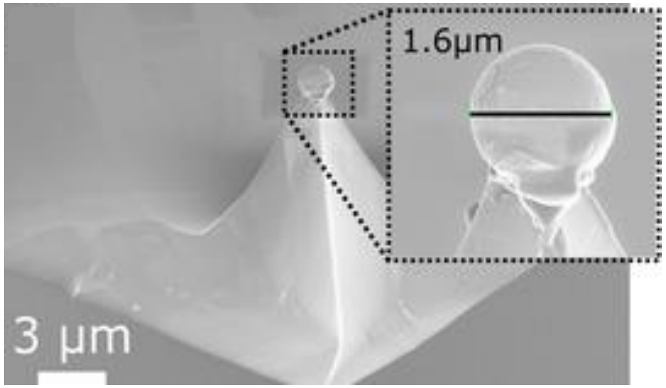
Different trends can be identified:

(i) customized *magnetic coatings*, where the magnetic properties of the material are varied

(ii) probes with magnetic *adhered structures*, such as Fe-filled carbon nanotubes (CNTs) or magnetic beads

(iii) MFM probes with *fabricated nanostructures*





Wolny et al., J. Appl. Phys. **108**, 1 (2010)

Belova et al., Rev. Sci. Instrum. **83**, 93711 (2012).

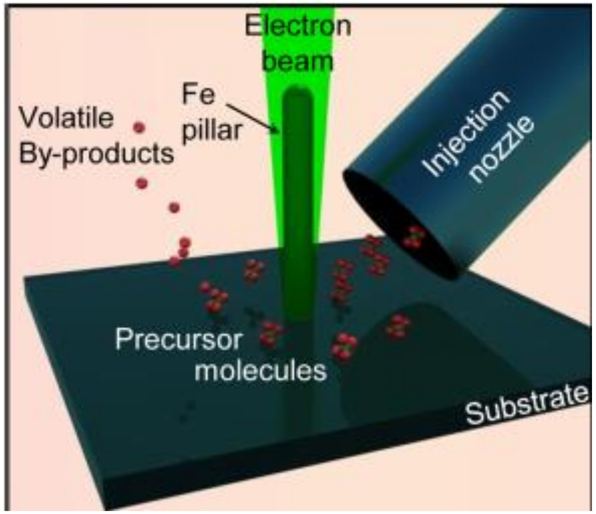
Corte-León et al., J. Magn. Magn. Mater. **400**, 225–229 (2016)

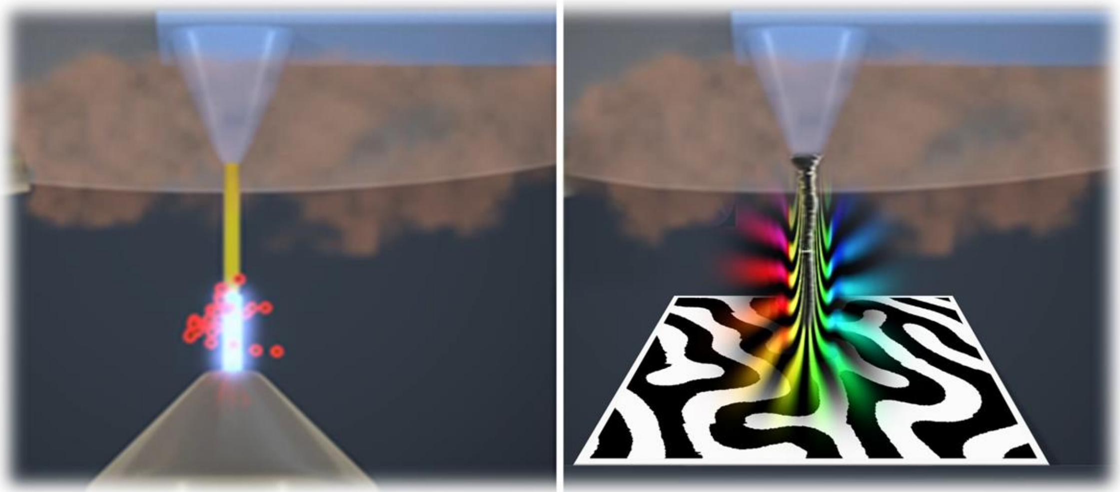
O. Iglesias –Freire, et al .Beilstein J. Nanotechnol., **7**, 1068–1074 (2016)

Puttock et al., IEEE Trans. Magn. **53**, 1–5 (2017)

Custom made MFM probes. FEBID

Magnetic nanorods growth by Focused Electron Beam Induced Deposition onto non magnetic probes





De Teresa et al.
J. Phys. D: Appl. Phys. 49 (2016) 243003

3D nanorods have been fabricated using commercial Helios Nanolab 600 and 650 Dual Beam systems

Precursor gases: Co2(CO)8 and Fe2(CO)9
Electron beam voltage in the range of 3 to 30 kV.
Range of current: 50-100 pA (Co) and 43-86 pA (Fe)

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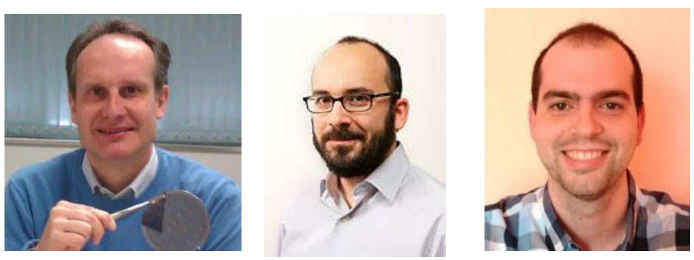

J.M. de Teresa, C. Magén, J.P. Navarro

Custom made MFM probes. FEBID

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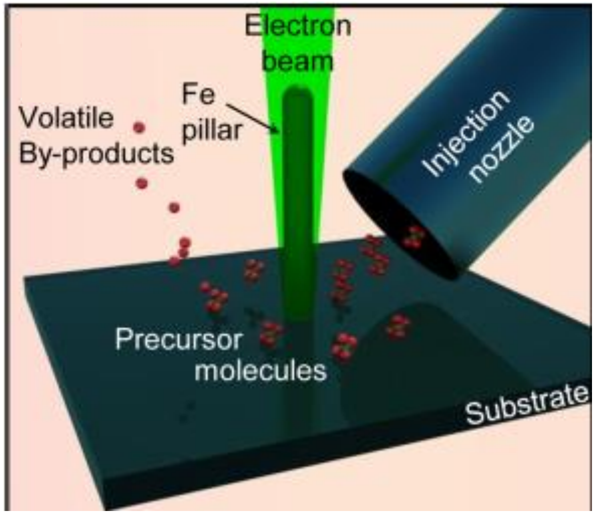
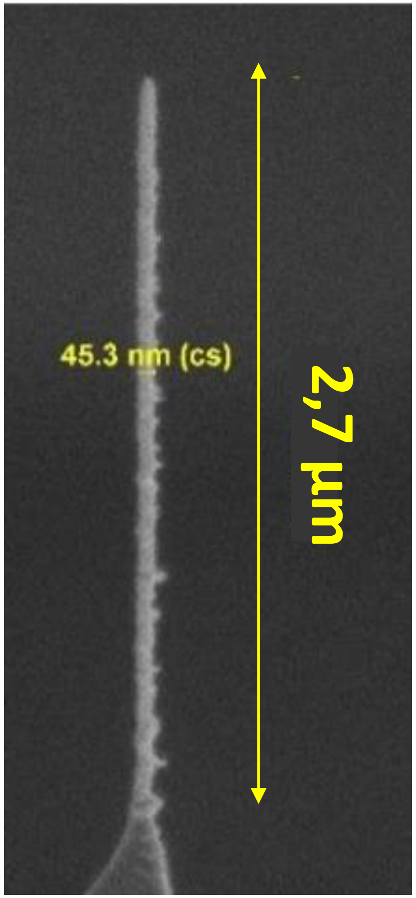
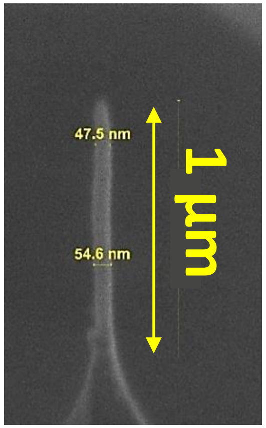


Material
Geometrical parameters
Different cantilevers





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J.M. de Teresa, C. Magén, J.P. Navarro

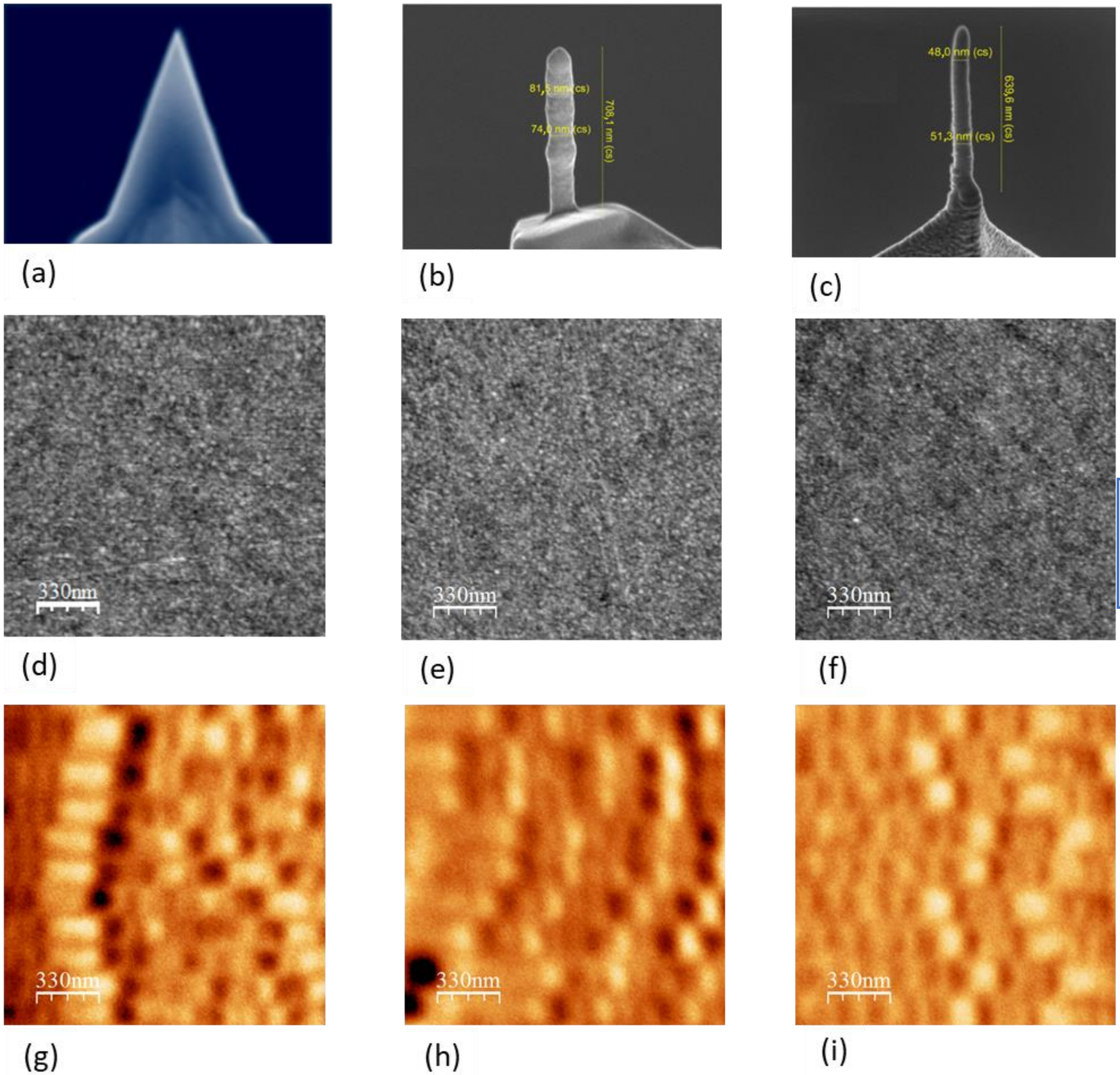
Custom made MFM probes. FEBID

Commercial MFM probe | Co nanorod | Fe nanorod

Reference sample: comercial hard disk

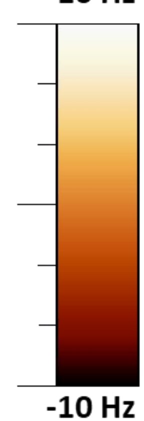
Topography

MFM



- Different materials: Co, Fe, Core-Shell (metallic content around 80%)
- Control on the stray field

- **Optimal behaviour in liquids**



Ambient conditions

M. Jaafar et al. Nanoscale, 2020, 12, 10090

MFM in biomaterials: special probes

Custom made **BIOLEVER MFM probe**

Fe Nanorods

patent ES2711860

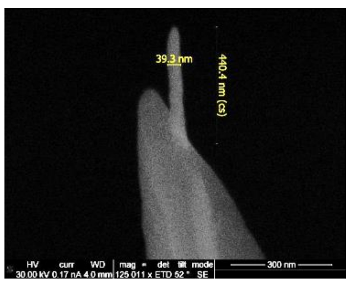
PREMIO INVENCIÓN OEPM

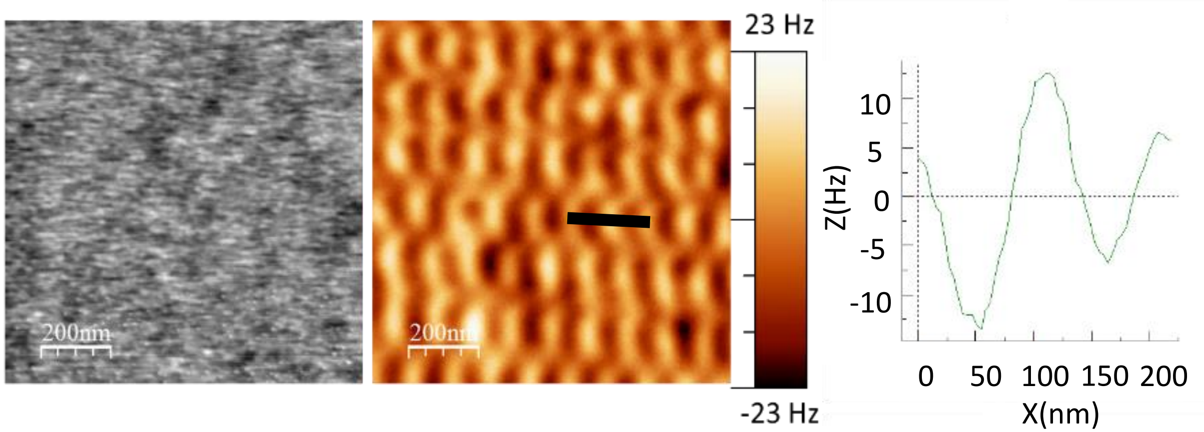
Oficina Española de Patentes y Marcas

2022

Biolevers
K~ 0,1 N/m

AIR





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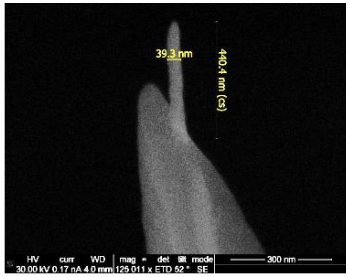
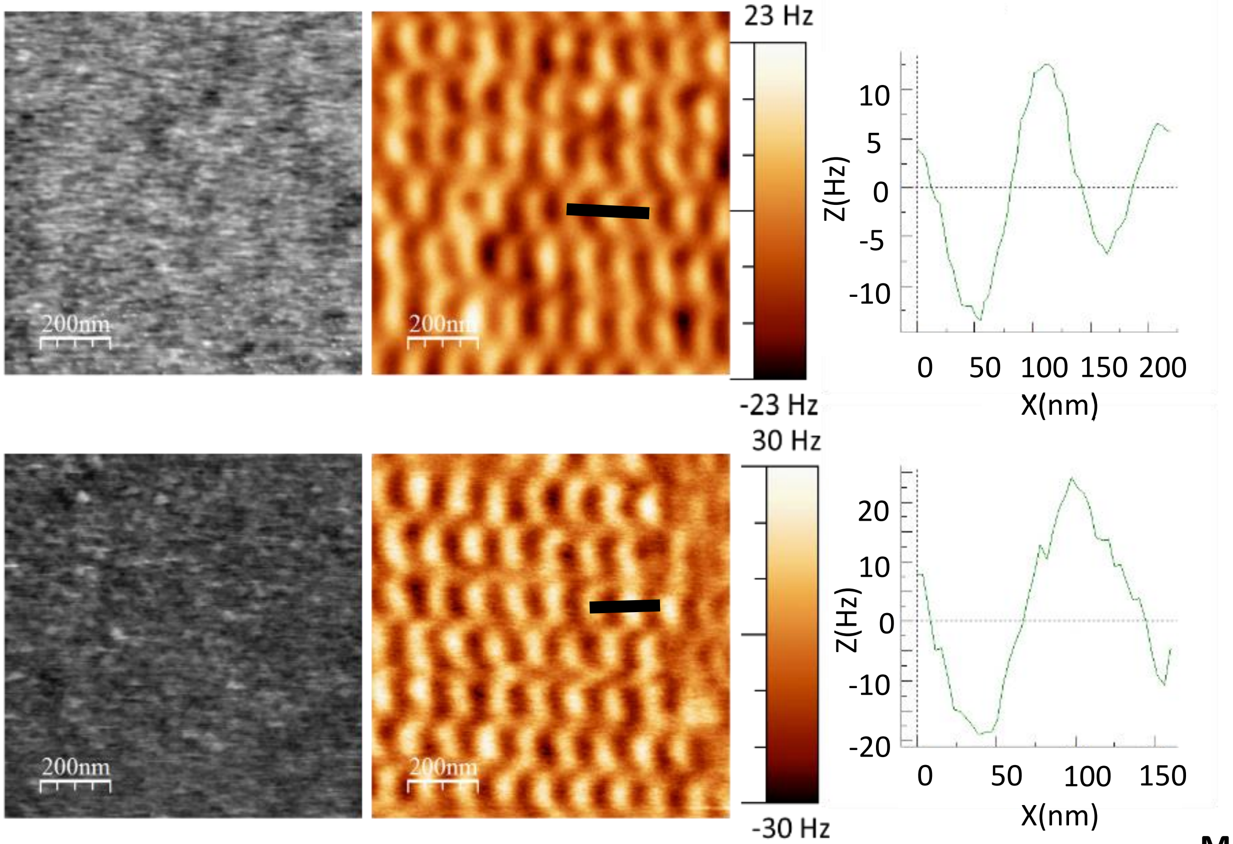


AIR

WATER

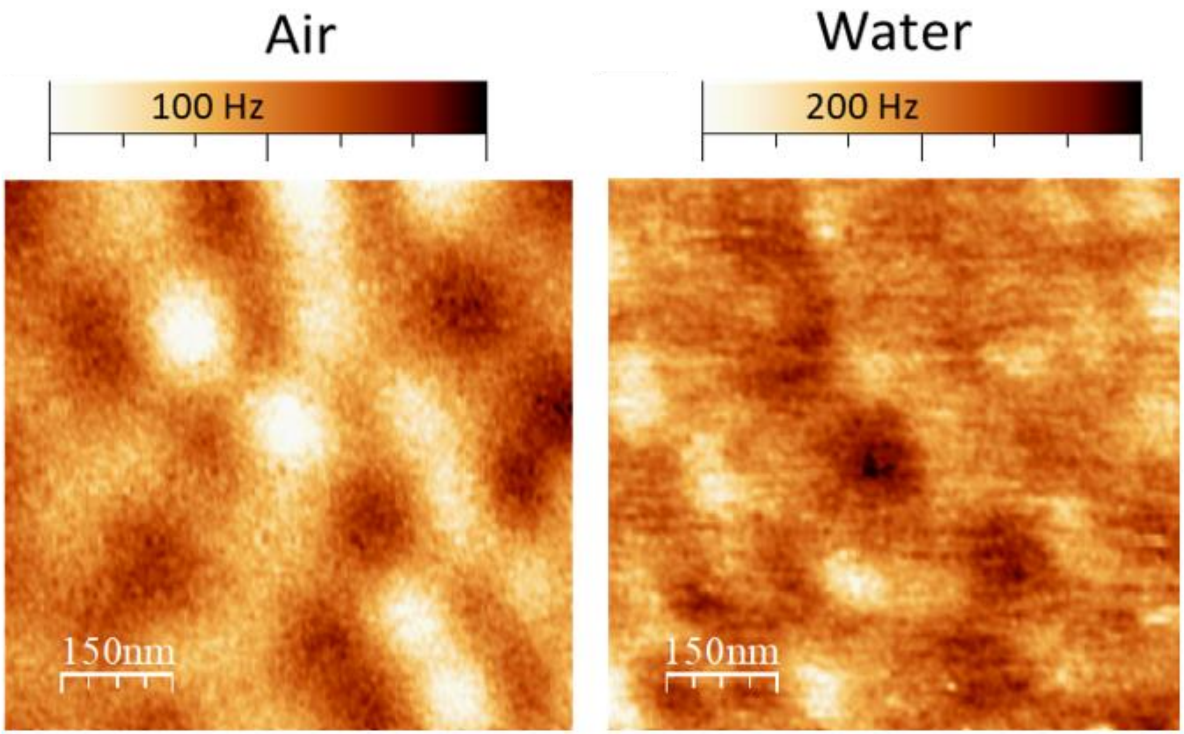


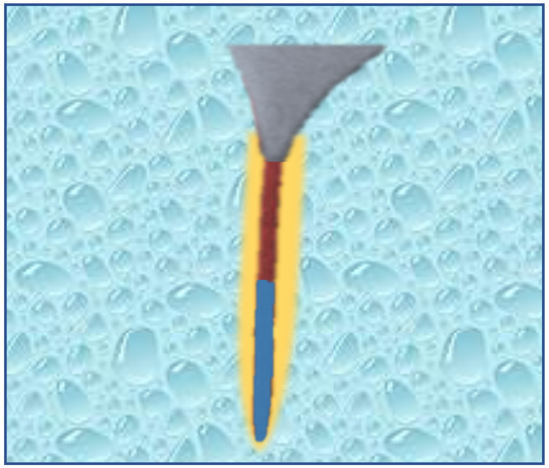
M. Jaafar et al.
Nanoscale, 2020, 12, 10090

MFM in biomaterials: special probes

Custom made **BIOLEVER MFM probe**

Core-Shell Nanorods





Minimizing the degradation of the magnetic properties due to surface oxidation

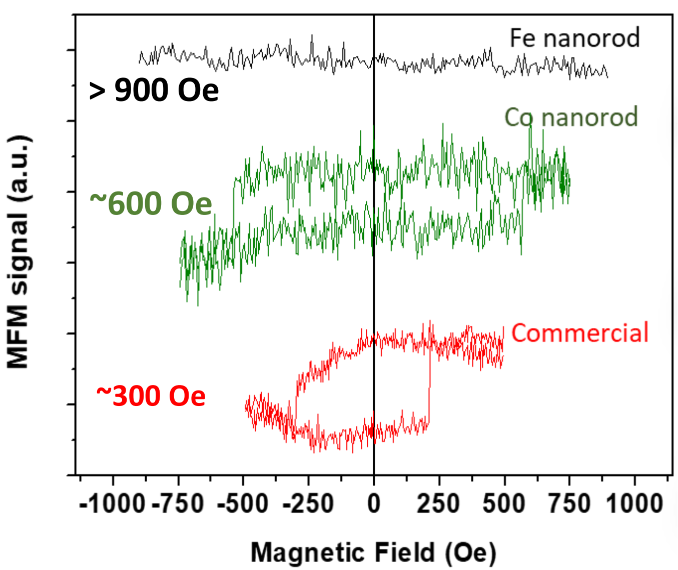
M. Jaafar et al.
Nanoscale, 2020, 12, 10090

Custom made MFM probes. FEBID

High aspecto ratio: advantages

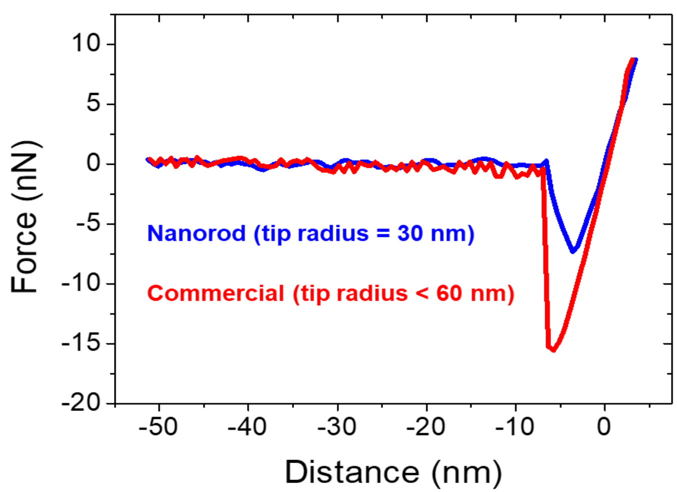
INCREASING THE COERCIVE FIELD →

The high-aspect ratio achievable in FEBID nanorod tips makes them magnetically harder than the commercial ones, reaching coercive fields higher than 900 Oe.



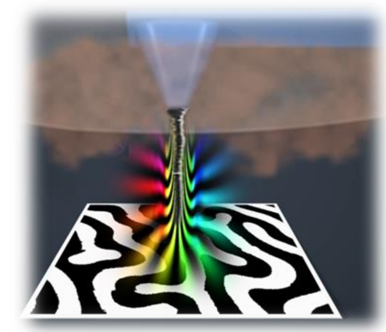
LOWER VAN DER WAALS INTERACTION→

It allows measuring the magnetic properties of the sample **much closer to its surface**



CONFINED MAGNETIC STRAY FIELD→

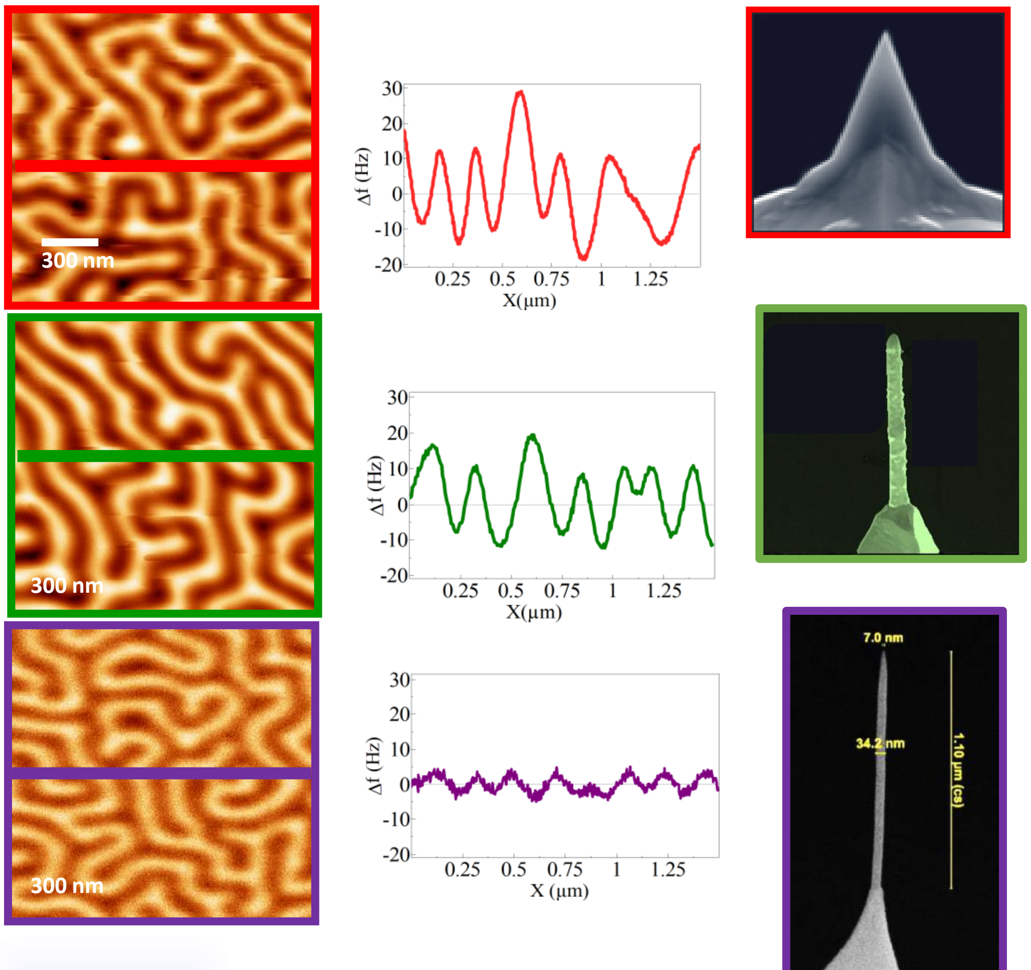
The shape of the nanorods produces a very confined magnetic stray field, whose interaction with the sample is extremely localized and perpendicular to the surface, with negligible in-plane components.



M. Jaafar et al. Nanoscale, 2020, 12, 10090

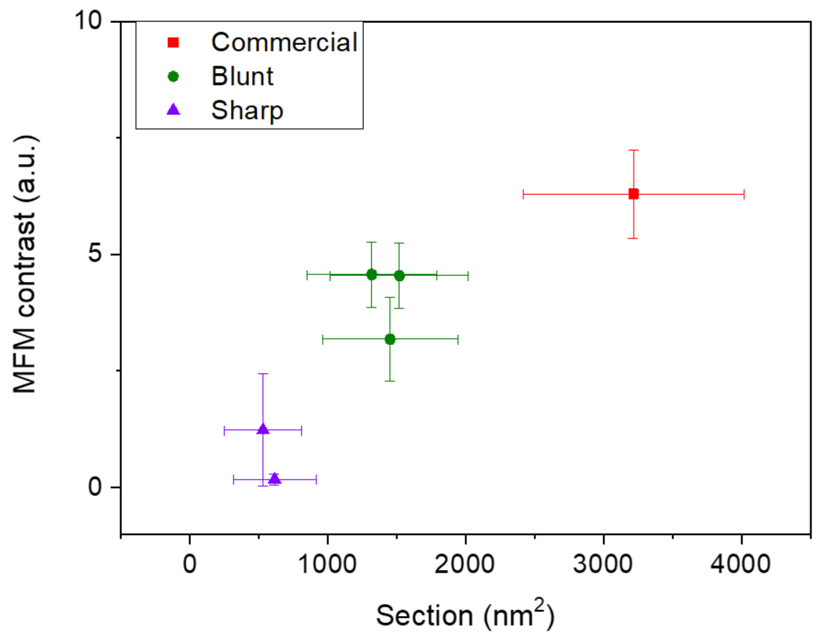
Custom made MFM probes. FEBID

CUSTOMIZATION OF THE TIP STRAY FIELD



FePd multilayer REFERENCE SAMPLE

The frequency shift is proportional to the magnetic moment of the tip.

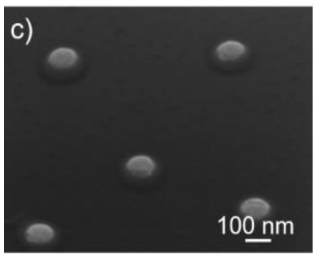


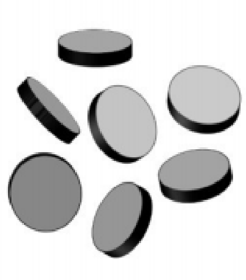
M. Jaafar et al. Nanoscale, 2020, 12, 10090

Some challenges in MFM: Biomaterials

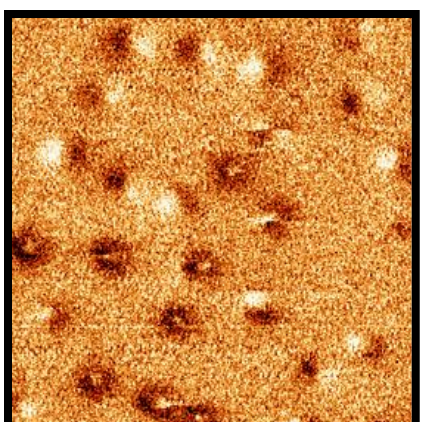
Sub-100 nm diameter nanodots (magneto-mechanical actuators)

In collaboration with
M Goiriena-Goikoetxea, A García Arribas, M.L. Fdez- Gubieda





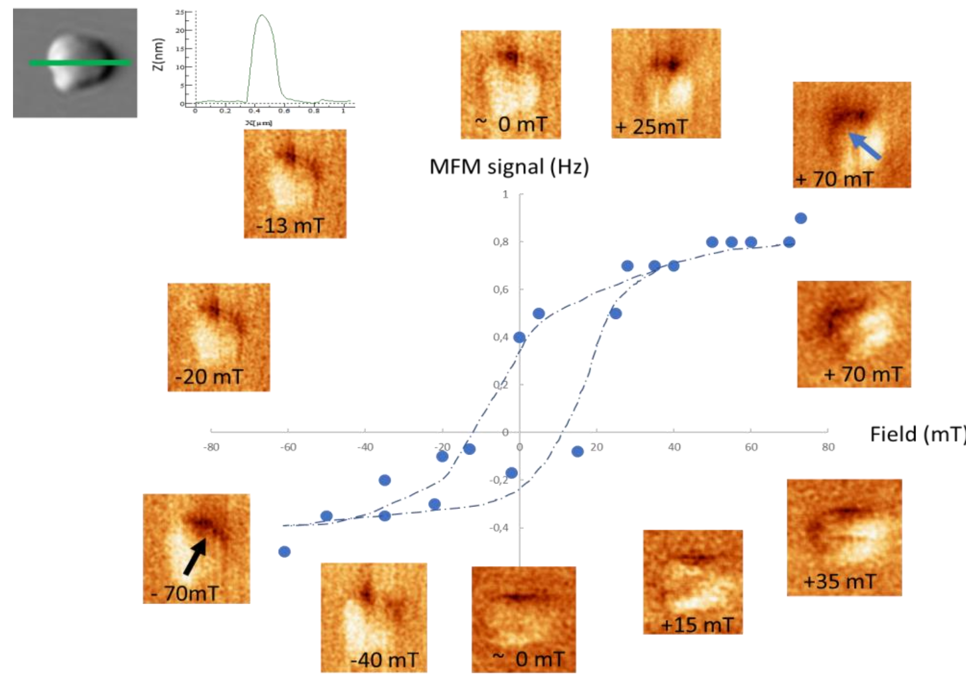
M Goiriena-Goikoetxea, et al.
Applied Physics Reviews 7 (1), 011306 (2020)



Nanoscale, 2017,9, 11269-11278
Nanoscale, 2020, 12, 18646-18653

Magnetic Nanoheaters (Multishell Nanoarchitecture)

In collaboration with
G. Singh, C. Tejera, S. Gallego, D. Martínez – Martín



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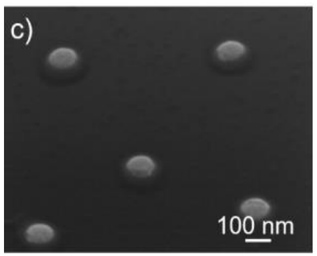

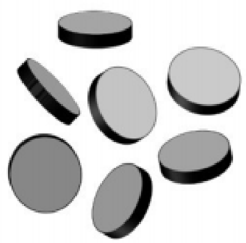

M Goiriena-Goikoetxea, et al.
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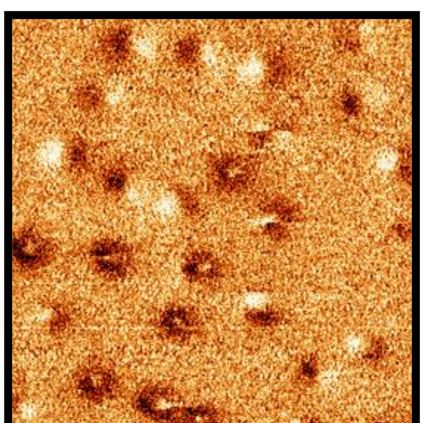

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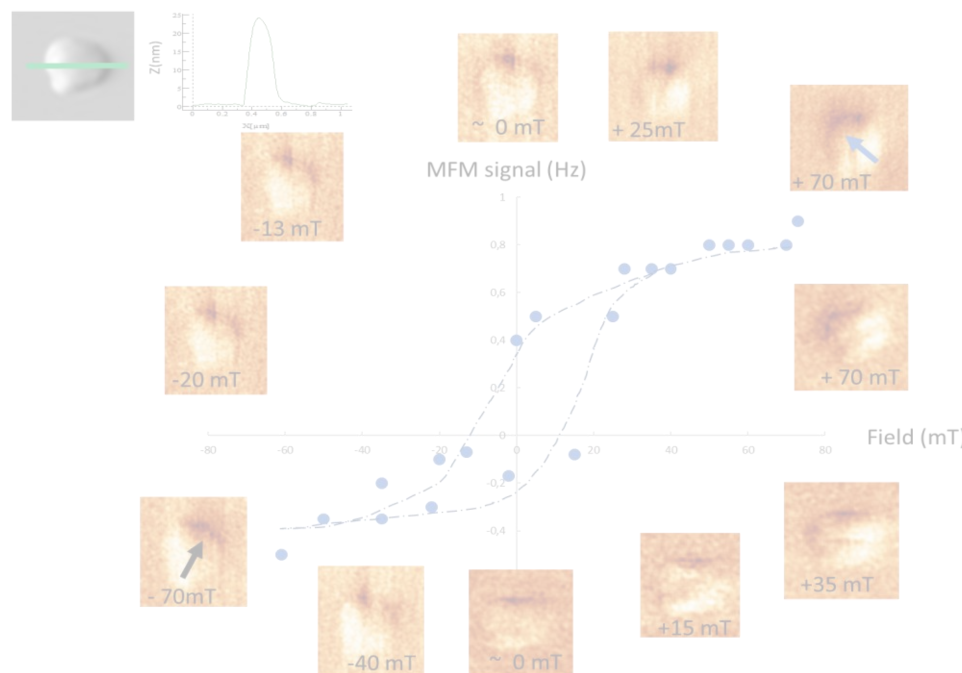
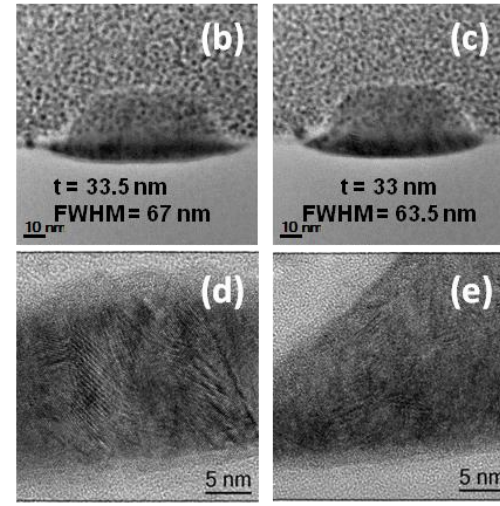


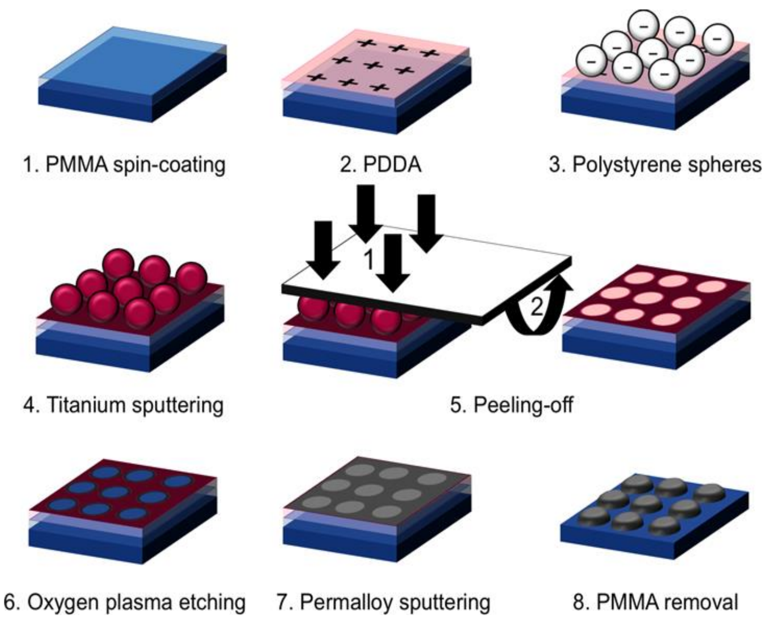
Spin configurations in Sub-100 nm diameter Py hemispherical shaped nanodots

In collaboration with
M. Goiriena – Goikoetxea, A. García –Arribas, K. Y. Guslienko. M.L. Fdz- Gubieda.



Permalloy (Py) sub-100 nm diameter particles (nanodots) with ***no uniaxial magnetic anisotropy or DMI***
The nanodots possess a domed shape

Fabrication: Hole Mask Colloidal Lithography



Goiriena M. et al. *Nanotechnology* **27,** (2016).

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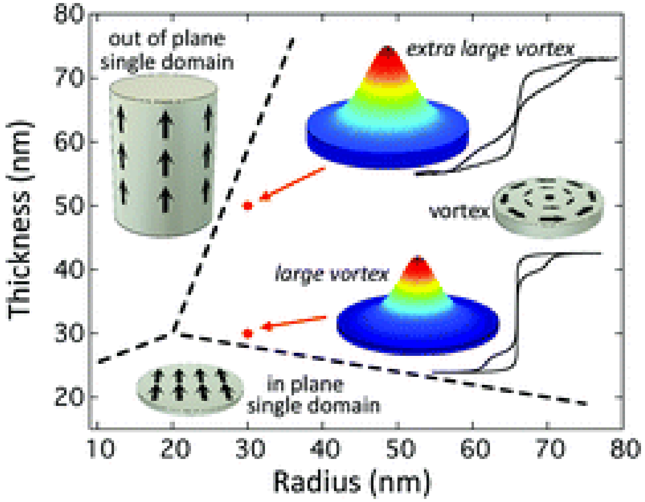
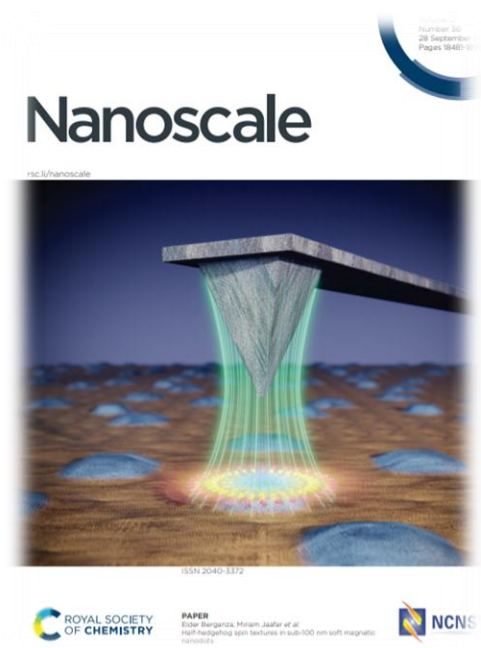
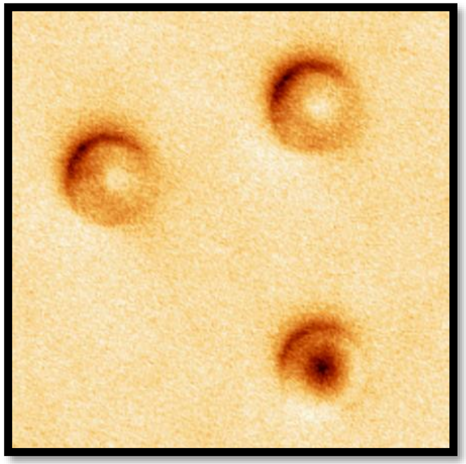
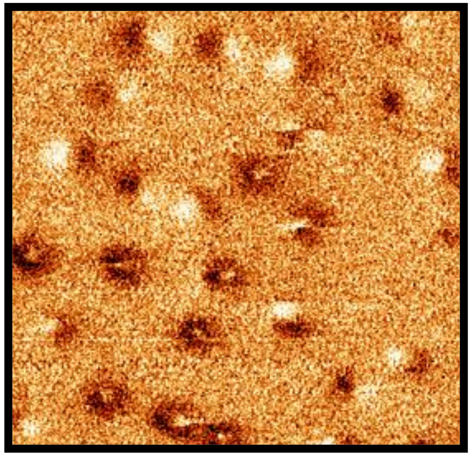


M. Goiriena-Goikoetxea, …, ***M. Jaafar****…et al. Nanoscale,9, 11269-11278 (****2017****)*

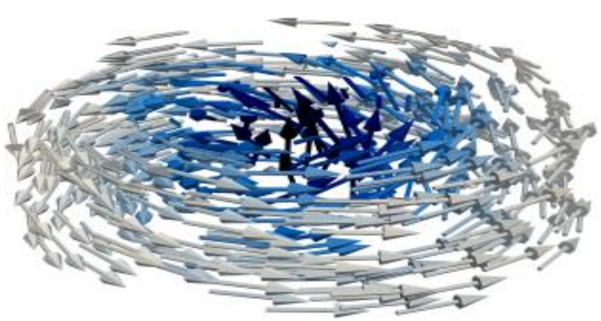


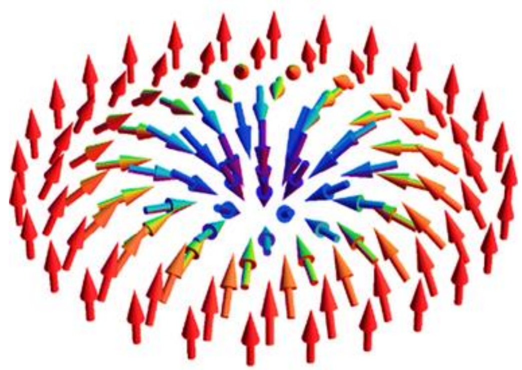
E. Berganza, ***M. Jaafar*** *et al.*
Nanoscale, 2020, **12**, 18646-18653



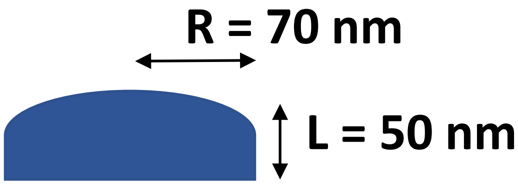


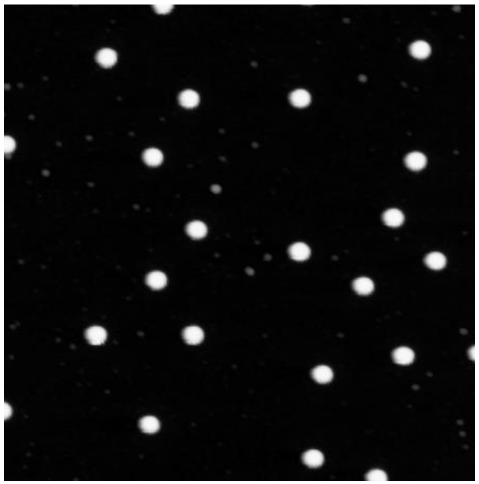
VORTEX *vs* *SKYRMION*

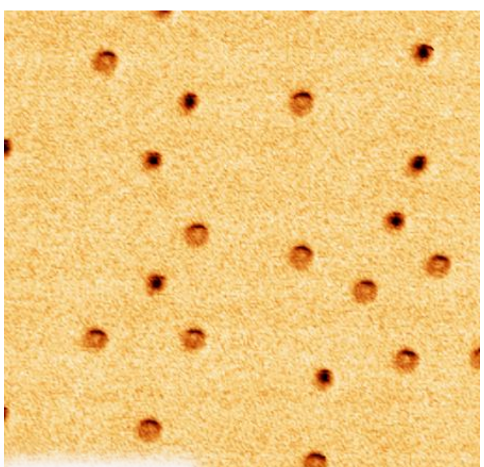


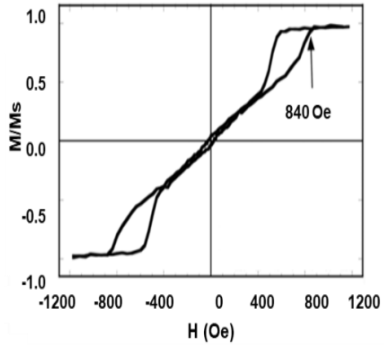


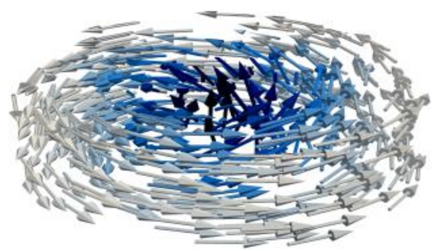
Spin configurations in Sub-100 nm diameter Py hemispherical shaped nanodots

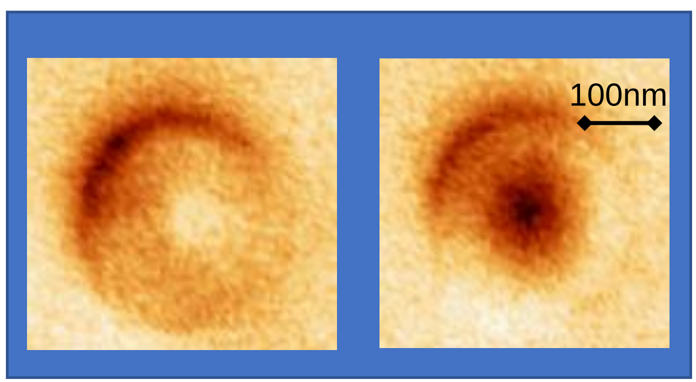




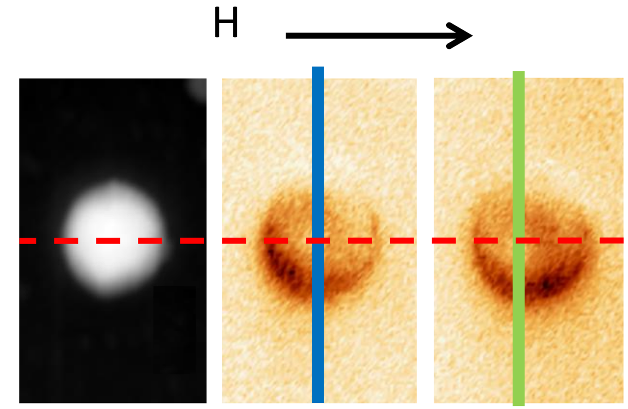


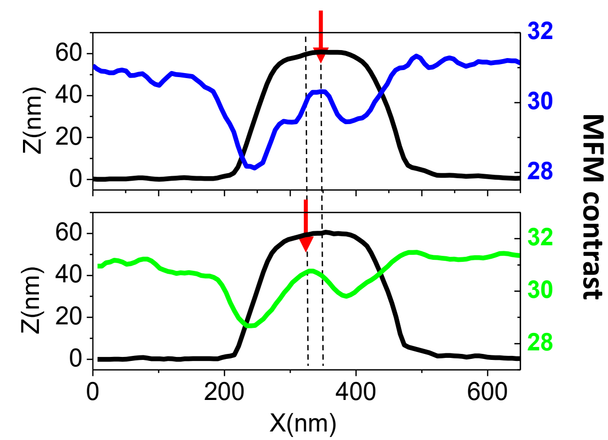






Core displacement perpendicular to field





*M. Goiriena-Goikoetxea, ..., **M. Jaafar**...et al. Nanoscale,9, 11269-11278 (**2017**)*

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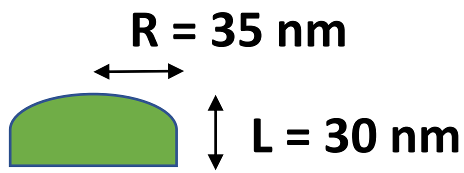
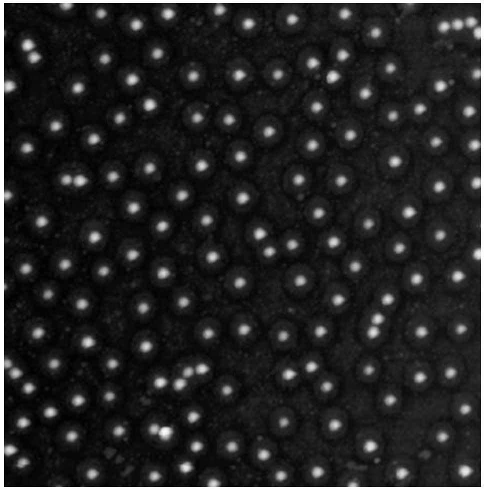
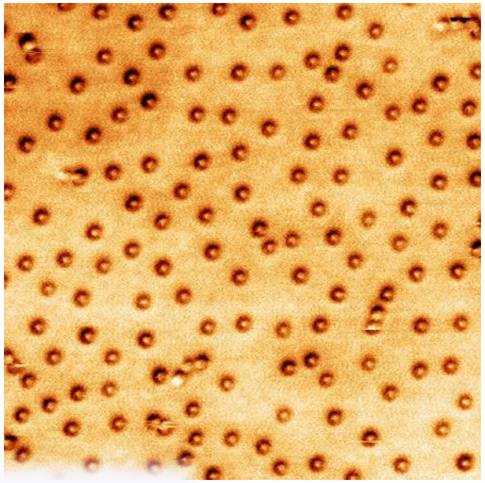
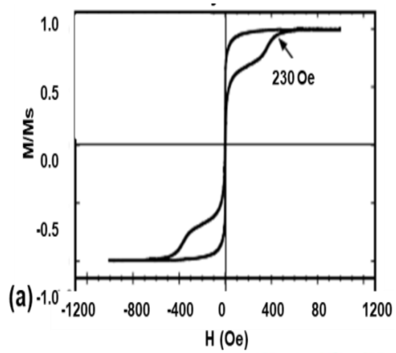
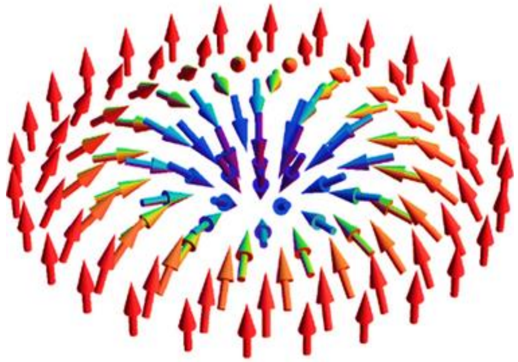


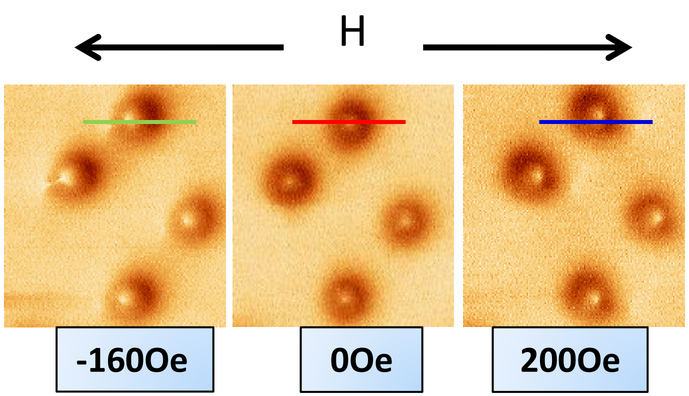


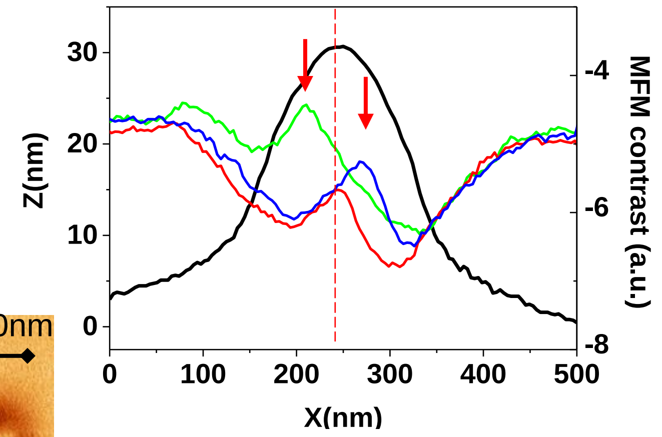


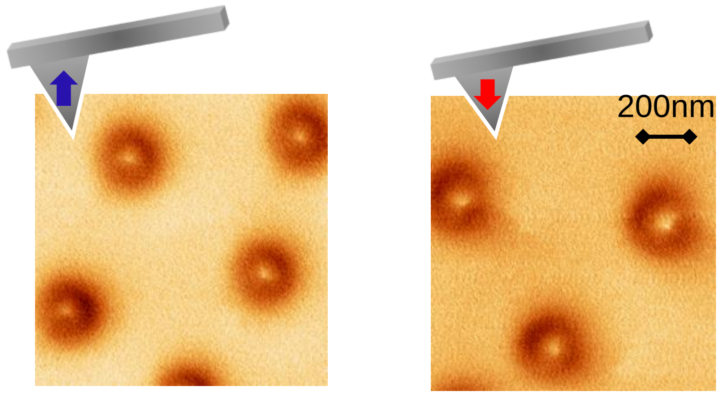




Core displacement parallel to field



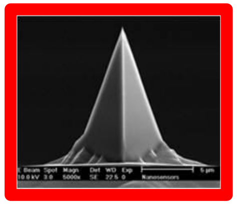
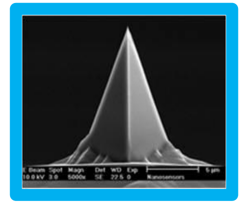
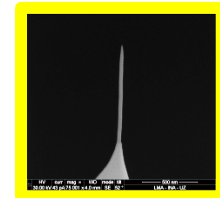


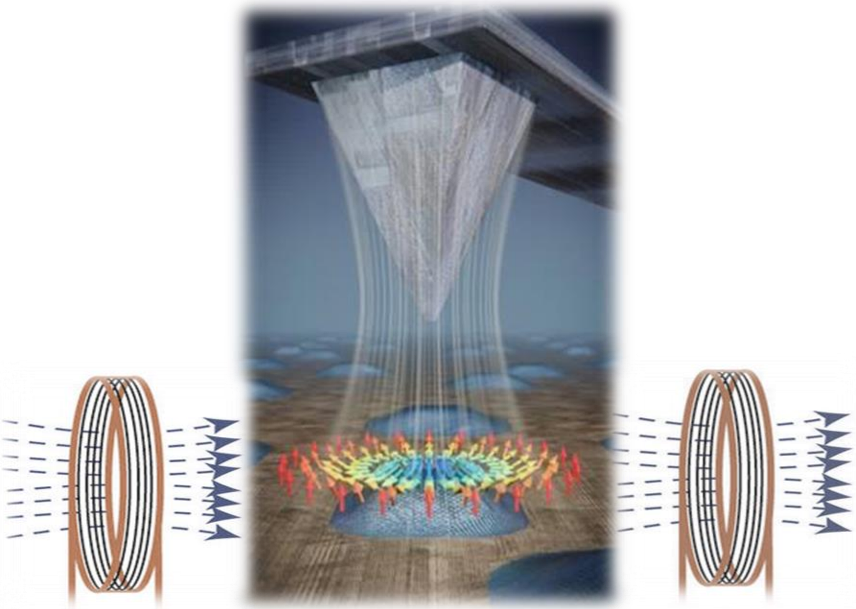


No change in the core contrast!!!

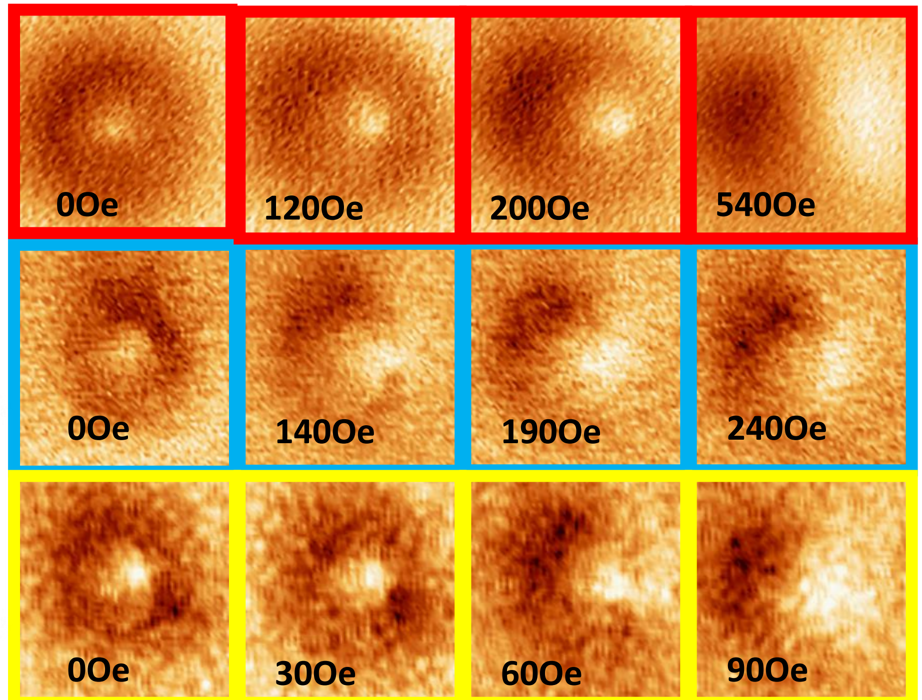
E. Berganza, **M. Jaafar** et al. *Nanoscale*, 2020, **12**, 18646-18653

Spin configurations in Sub-100 nm diameter Py hemispherical shaped nanodots

Tip category	High moment	Medium moment	Very Low moment
SEM Image	1 	2 	3 



VF-MFM (in-plane field)



1

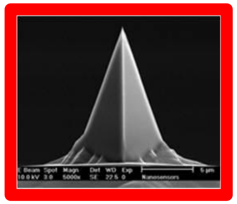
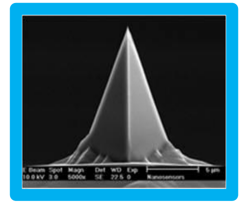
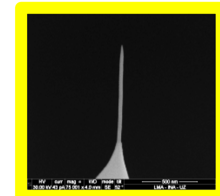
2

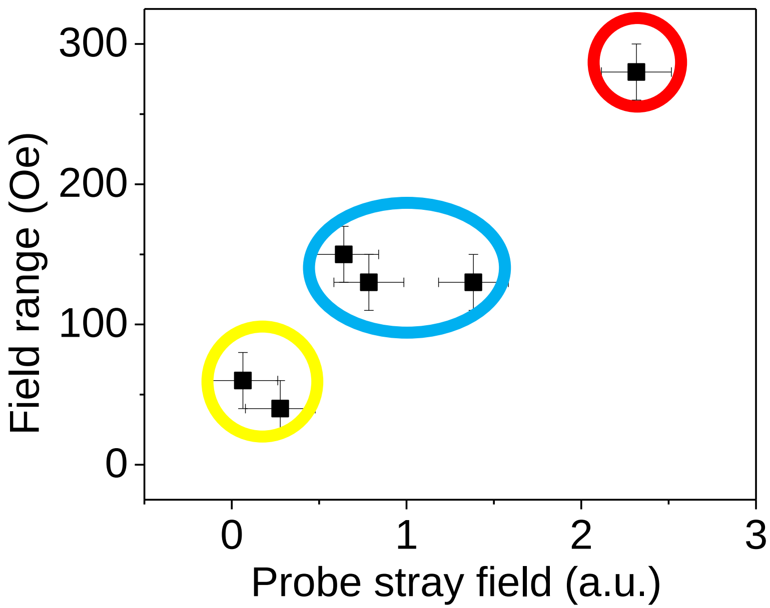
3

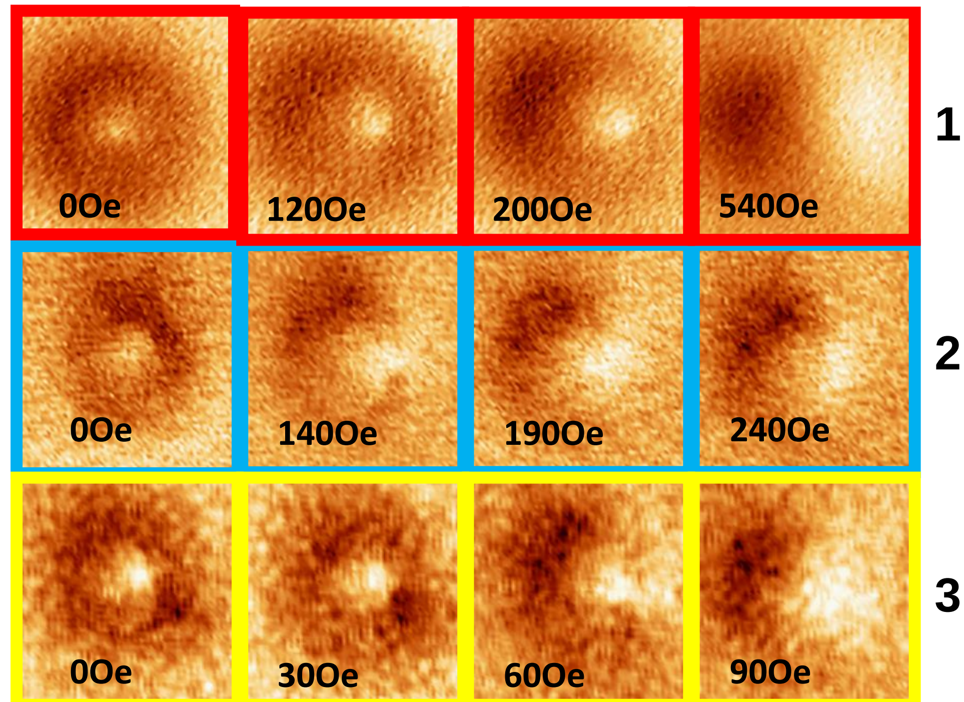
E. Berganza , **M. Jaafar** et al. Nanoscale, 12, 18646-18653 (2020)

E. Berganza, J.A. Fdz- Roldán, **M. Jaafar** et al. Sci. Rep. 12, (2022) 3426

Spin configurations in Sub-100 nm diameter Py hemispherical shaped nanodots

Tip category	High moment	Medium moment	Very Low moment
SEM Image	1 	2 	3 

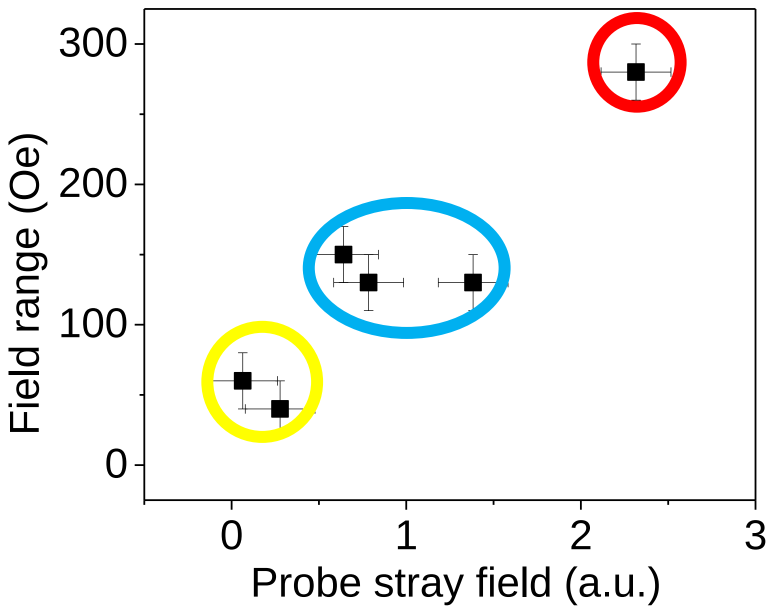


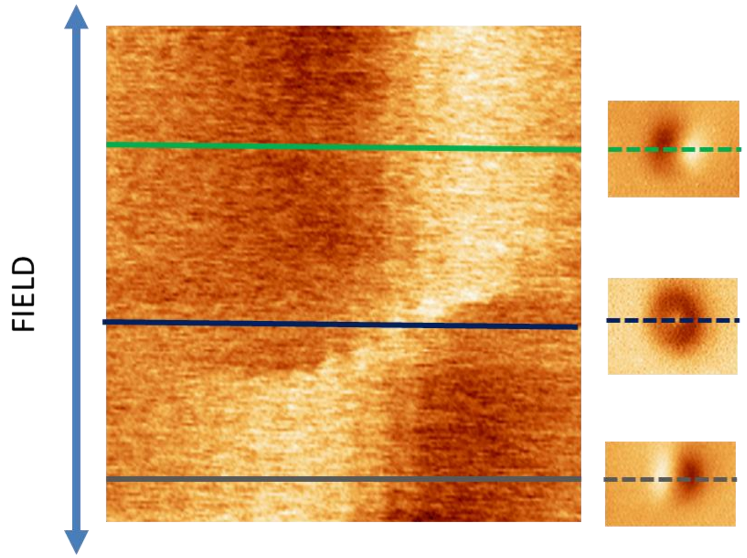


E. Berganza , **M. Jaafar** et al. Nanoscale, 12, 18646-18653 (2020)
E. Berganza, J.A. Fdz- Roldán, **M. Jaafar** et al. Sci. Rep. 12, (2022) 3426

Spin configurations in Sub-100 nm diameter Py hemispherical shaped nanodots

- Non-chiral hedgehog skyrmions are induced and further stabilized by the magnetic field coming out from the MFM probe in soft magnetic nanodots in absence of DMI and perpendicular anisotropy. High resolution MFM imaging and VF-MFM are used to characterize them.
- Analytical calculations and micromagnetic simulations confirmed the existence of metastable Néel skyrmions in permalloy nanodots even without external stimuli in a certain size range.



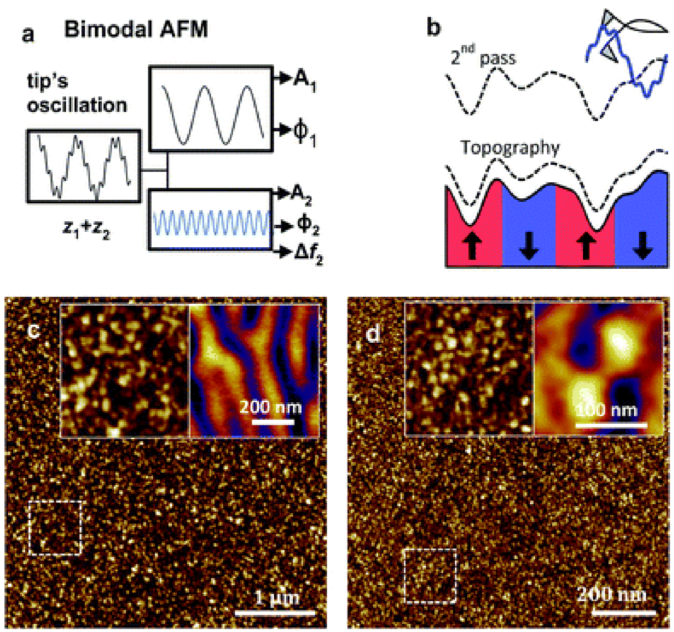


E. Berganza , **M. Jaafar** et al. Nanoscale, 12, 18646-18653 (2020)
E. Berganza, J.A. Fdz- Roldán, **M. Jaafar** et al. Sci. Rep. 12, (2022) 3426

Some challenges in MFM: BIOMATERIALS

Non standard operation modes

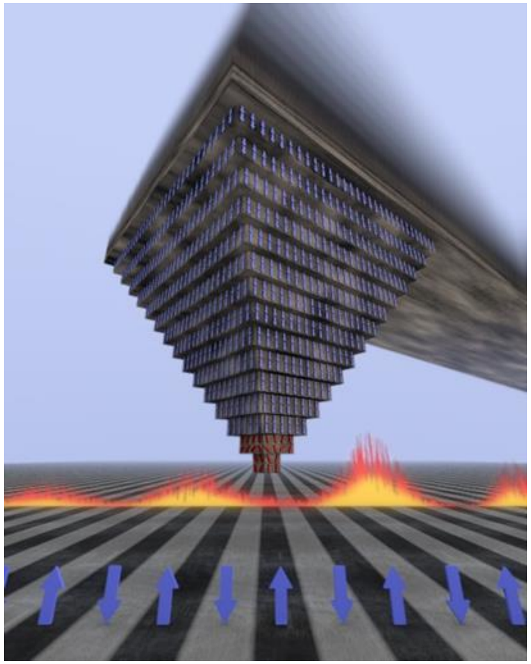
Multifrequency: Bimodal MFM



Gisbert V.G., C. Amo, **M. Jaafar** et al. Nanoscale 13 , 2026- 2033 (2021)

M. Jaafar, A. Asenjo. Appl. Sci. 2021, 11, 10507.

Magnetic Dissipation Force Microscopy



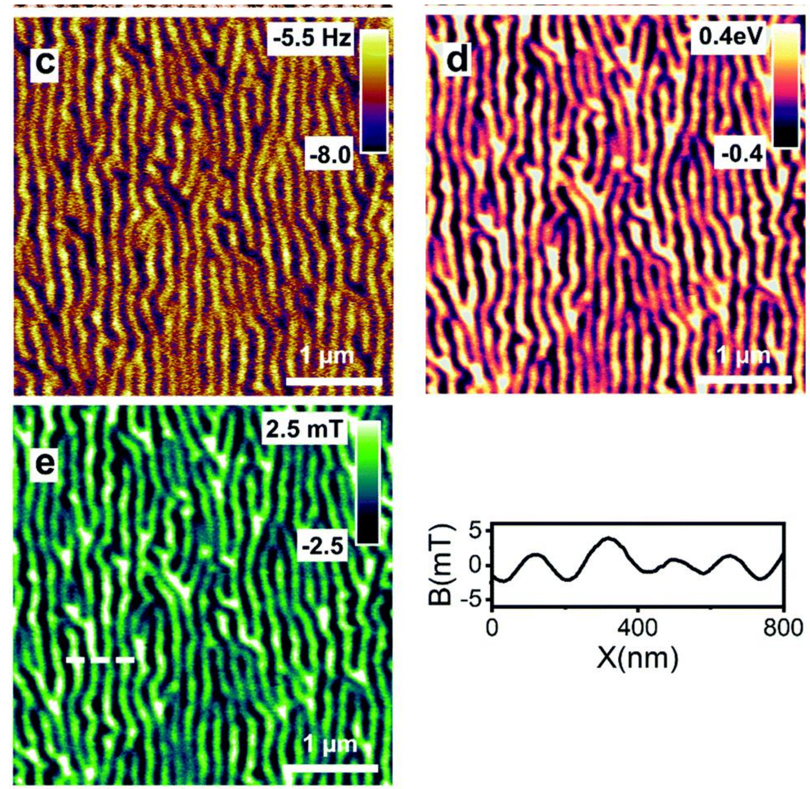
M. Jaafar et al.
Nanoscale, 2016, 8, 16989–16994

BIMODAL MFM

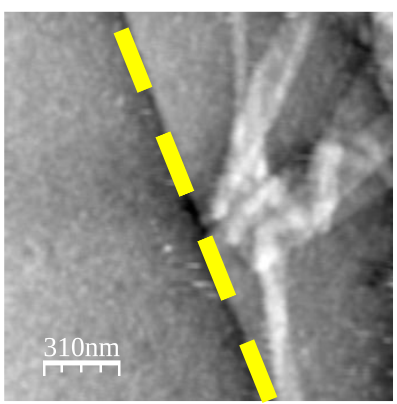
Quantitative imaging in MFM

Bimodal MFM has recently been used for **quantitative imaging** with high-spatial resolution

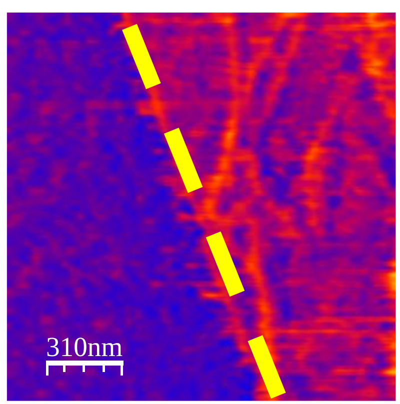
Gisbert V.G., Amo C.A., **Jaafar M.**, Asenjo A., Garcia R.
Nanoscale 13 , 2026- 2033 (2021)



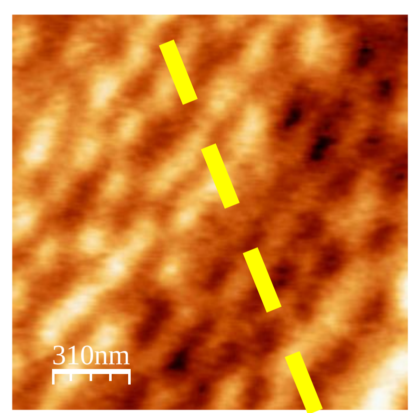
Sub -Surface magnetic contrast



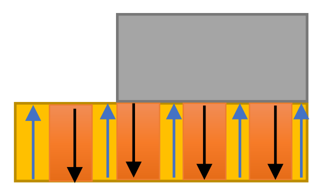
MECHANICAL PROPERTIES



MAGNETIC PROPERTIES

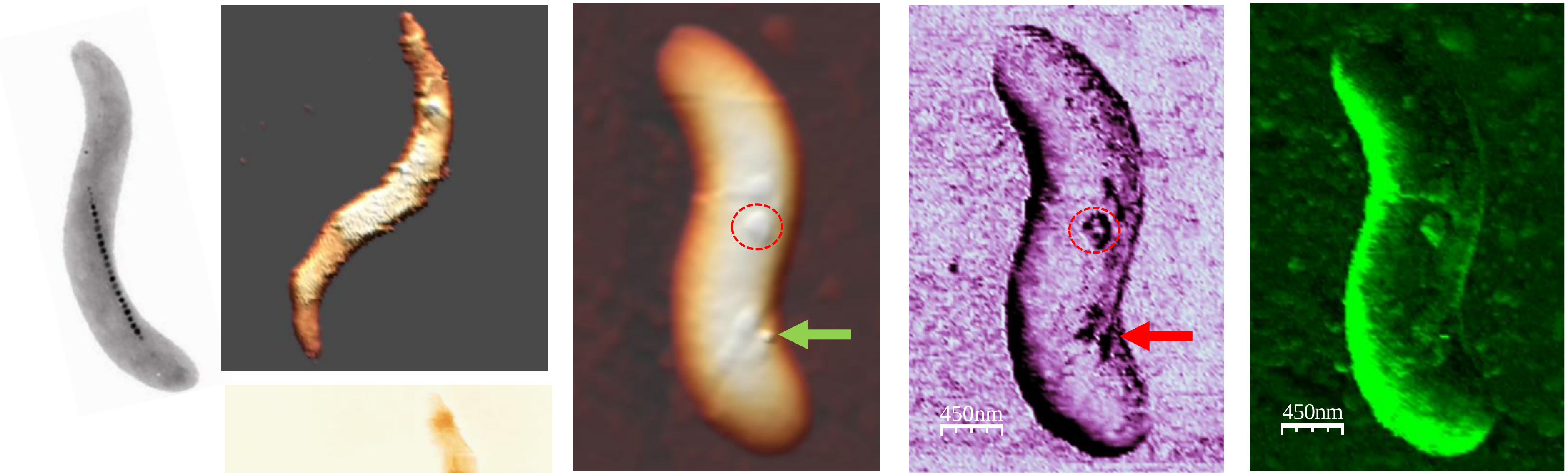


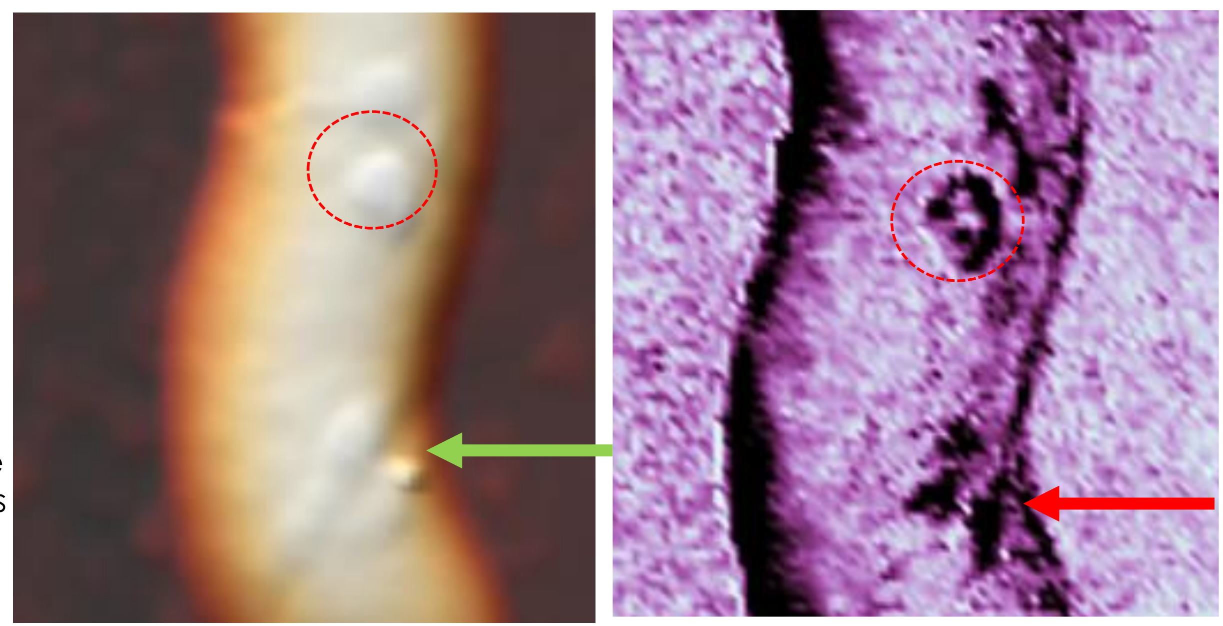
Non Magnetic material



Magnetic material

Bimodal MFM: Sub-Surface contrast





This contrast seem to be a nanomechanical effect that enable the identification of the magnetic properties of the particles (similar than C. Dietz et al, Nanotechnology 22 (2011) 125708)

Work in progress

In collaboration with of M. L. Fernández-Gubieda's group. UPV

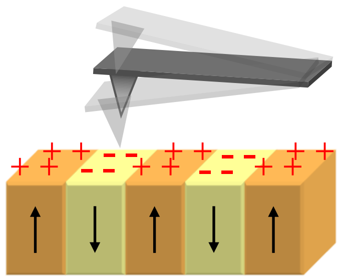
MAGNETIC DISSIPATION FORCE MICROSCOPY

•**Magnetic dissipation Force Microscopy** studies tip-induced magnetization changes in the sample.

Cantilever oscillating

Low field

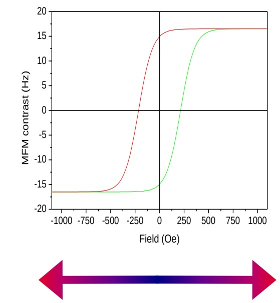
High field



+

“High” stray field

+



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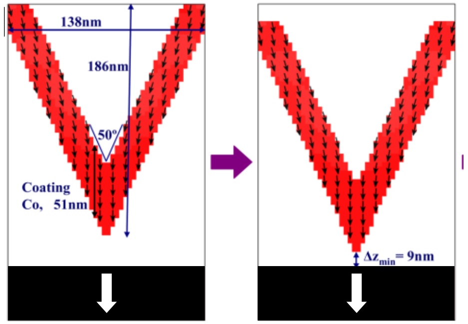
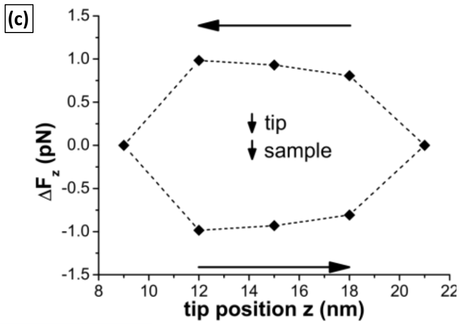
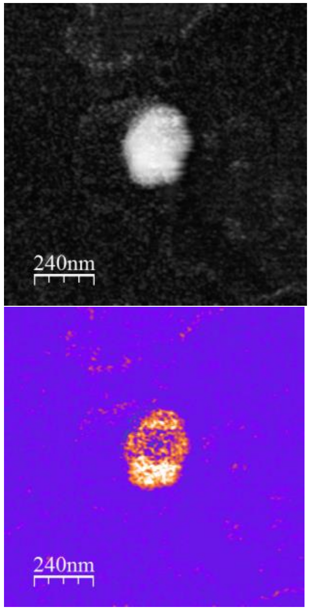
M. Jaafar et al. Nanoscale,8, 16989-16994 (2016)





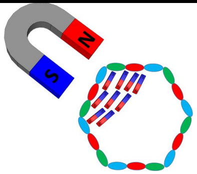
- Power losses of **few fW** → sudden rotations of spins at the apex
- Lateral resolution **below 10 nm** is achieved



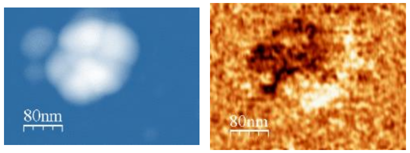
In collaboration with J. Rivas, M. P. Morales

Conclusions

Non standard MFM imaging is a useful technique to study emerging Bio magnetic materials and structures (often extremely demanding in terms of resolution, sensitivity, and physical environment).

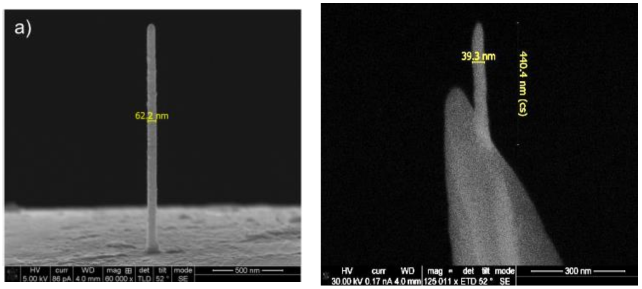


ACS Appl. Mater. Interfaces. 6, pp. 20936 – 20942 (2014).



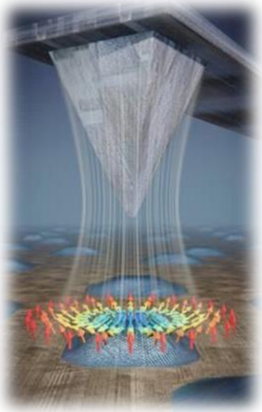
MFM in liquids **Small** 11 (36) 4731-6 (2015)

We have studied magnetic **nanoparticles in liquid**. We can distinguish the magnetic domains in this kind of samples.



Custom made MFM probes: Nanoscale, 12, 10090 (2020)

Custom made bio-MFM probes are the best option to **improve the quality** of the magnetic signal in liquid.



Nanoscale,8, 16989-16994 (2016)
Nanoscale,9, 11269-11278 (2017)
Nanoscale, 12, 18646 (2020)
Nanoscale 13, 2026- 2033 (2021)
Sci. Rep. 12, 3426(2022)

All these examples demonstrate why MFM remains a powerful characterization tool.

In collaboration with

Dr. Agustina Asenjo

Dr. Eider Berganza

icmm

CSIC

Consejo Superior de Investigaciones Científicas

Prof. M Vázquez

Dr. Rafael P. del Real

Dr. Oksana Fesenko

UAM Universidad Autónoma de Madrid

IFIMAC Condensed Matter Physics Center

Prof. J. Gómez-Herrero

Dr. P. Ares

unizar

Prof. J. M. de Teresa

Dr. C. Magén

Dr. J.P. Navarro

cnrs

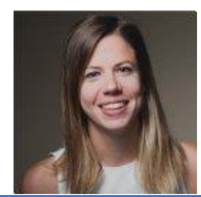
Prof. E.Snoeck

Dr. C. Gatel

Dr. A. Masseboeuf

eman ta zabal zazu

UPV EHU



Prof. M.L. Fdez- Gubieda

Dr. A García Arribas

Dr. M Goiriena-Goikoetxea

Prof. K. Guslienko

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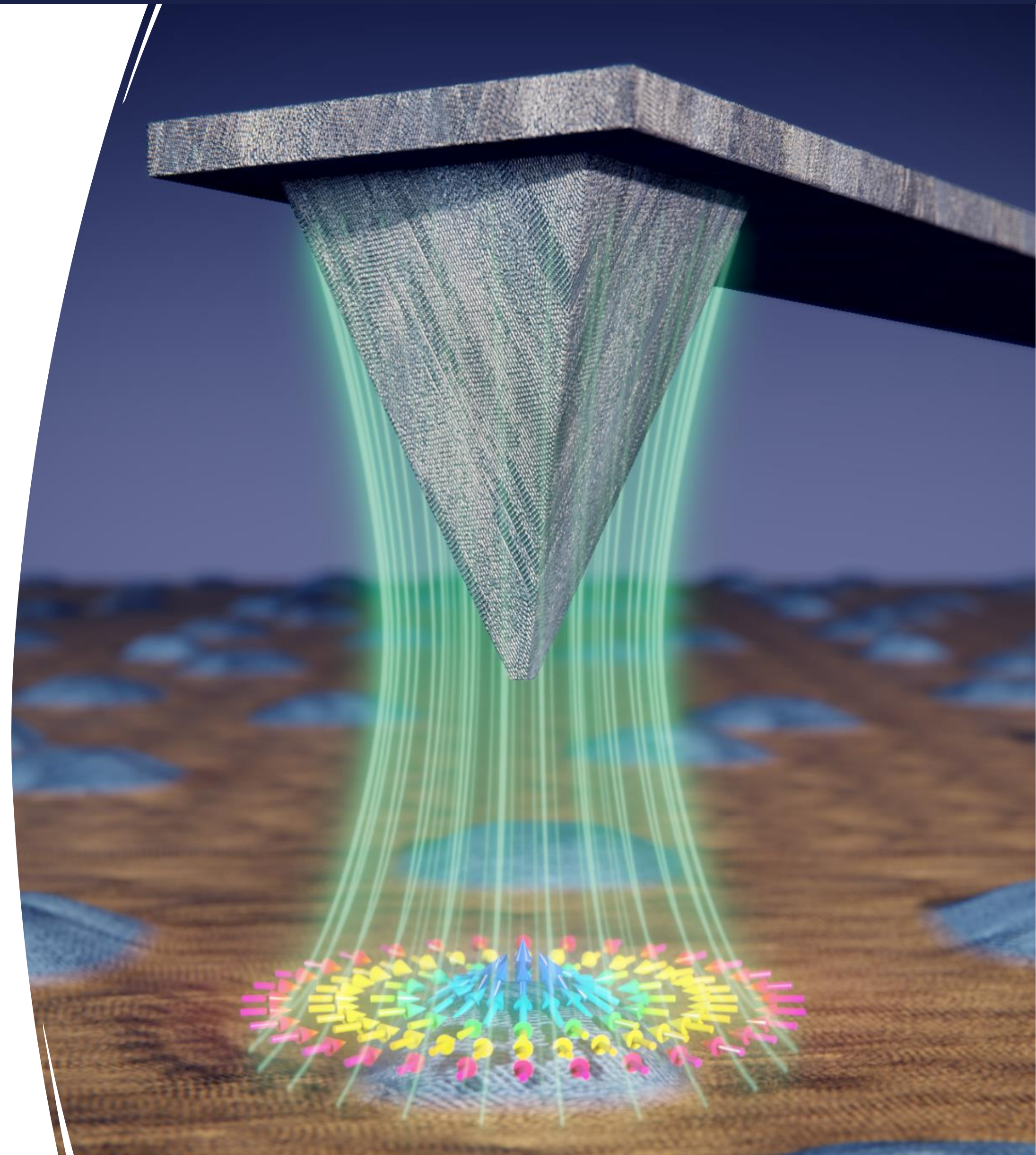
UAM Universidad Autónoma de Madrid

SI1/PJI/2019- 00055

THANK YOU FOR YOUR ATTENTION

miriam.jaafar@uam.es



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