CEMAG
Club Español de Magnetismo

"Recent advances in magnetism at the nanoscale"

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INMA Universidad Zaragoza CSIC Consejo Superior de Investigaciones Científicas LMA

Magnetism in nanostructures and applicactions

Nanofabrication y advanced microscopies

(ILL año1987)

Outline

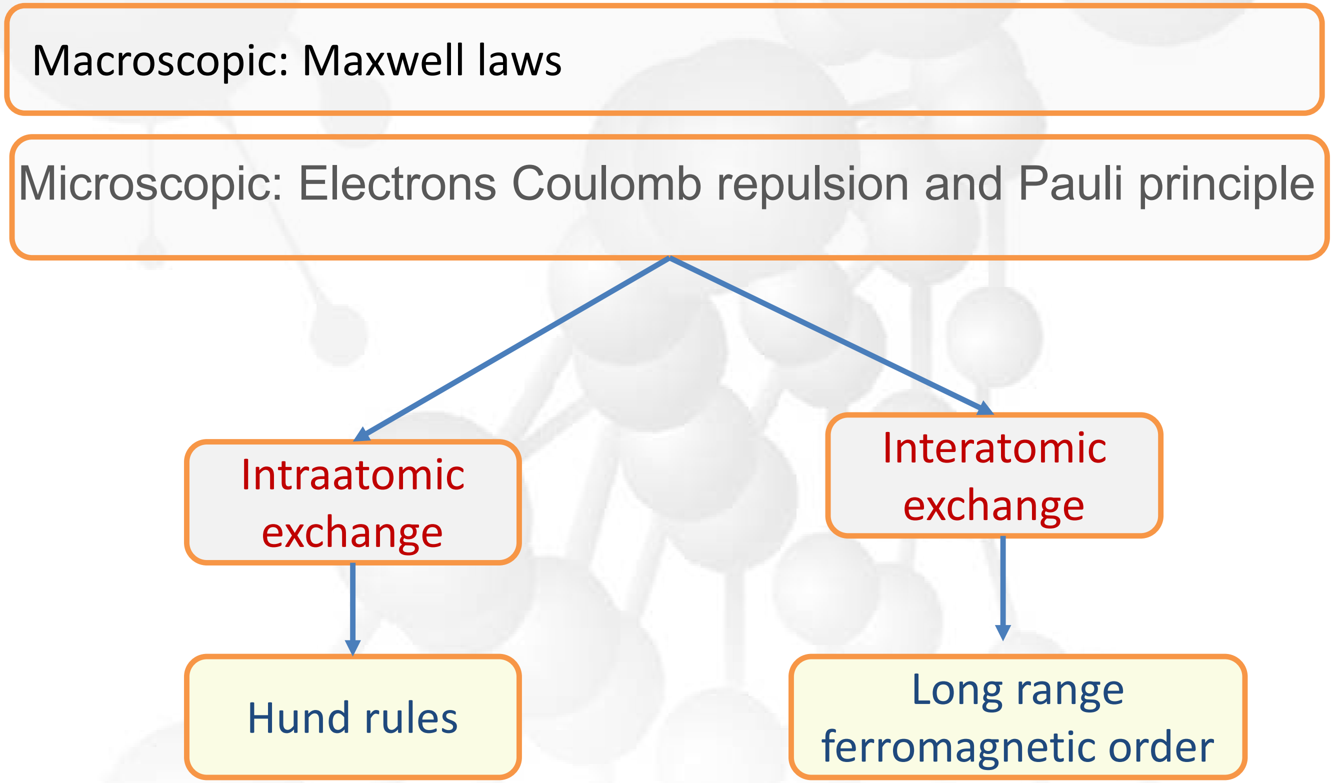
- Introduction: Magnetic quasiparticles and spin currents
- Magnetic polarons in manganites
- Thin film multilayers and the emergence of new thermospin effects
- Magnetic nanoparticles as nanoheaters and ultrasound emitters
- Conclusions

Introduction

- -Exchange interaction
- -Magnetic quasiparticles
- -Spin currents

Exchange interaction

Magnetism constitutes a unique scenario to study the condensed matter from a macro-meso and microscopic point of view



Macroscopic: Maxwell laws

Microscopic: Electrons Coulomb repulsion and Pauli principle

Intraatomic exchange

Hund rules

Interatomic exchange

Long range ferromagnetic order

Going to the smallest: Quasiparticles

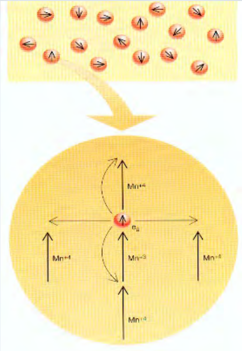
Magnetic quasiparticles: emergent nano-objets resulting from collective excitations

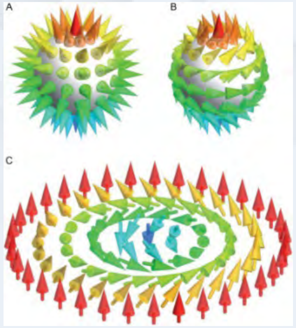
Magnon

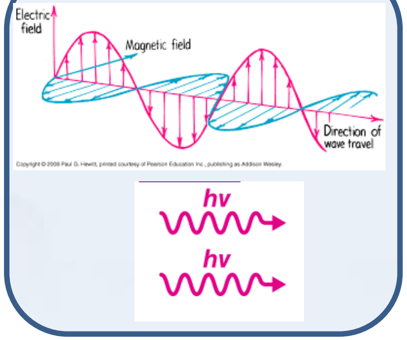
Magnetic polaron

Skyrmion

Photon







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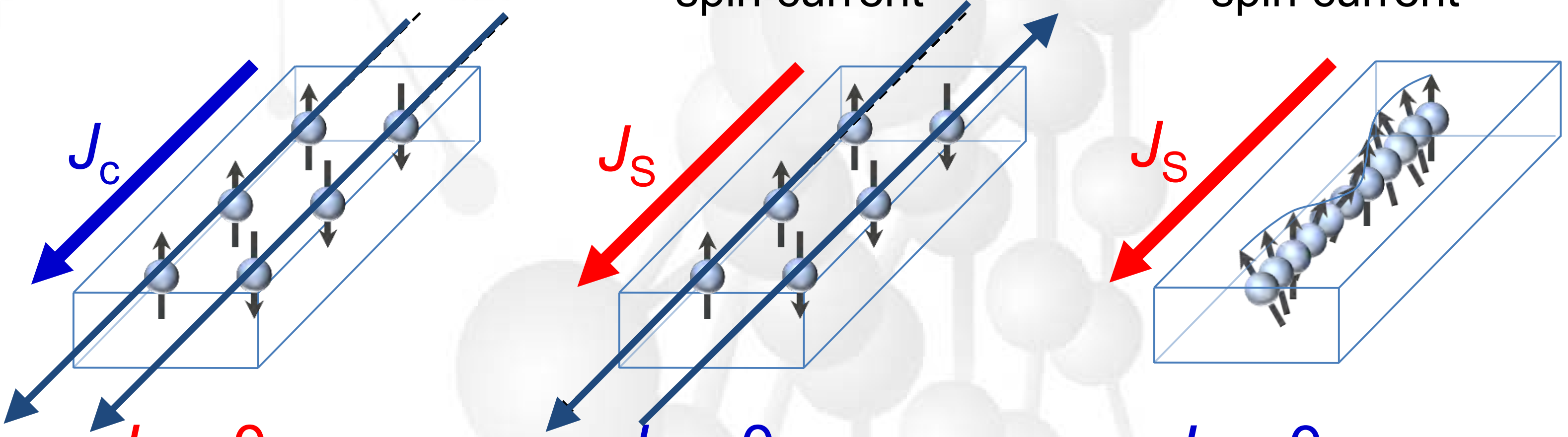
Charge and spin currents

J_c: charge current

J_S: spin current

Conduction-electron spin current

Spin wave (magnons) spin current



$J_S = 0$

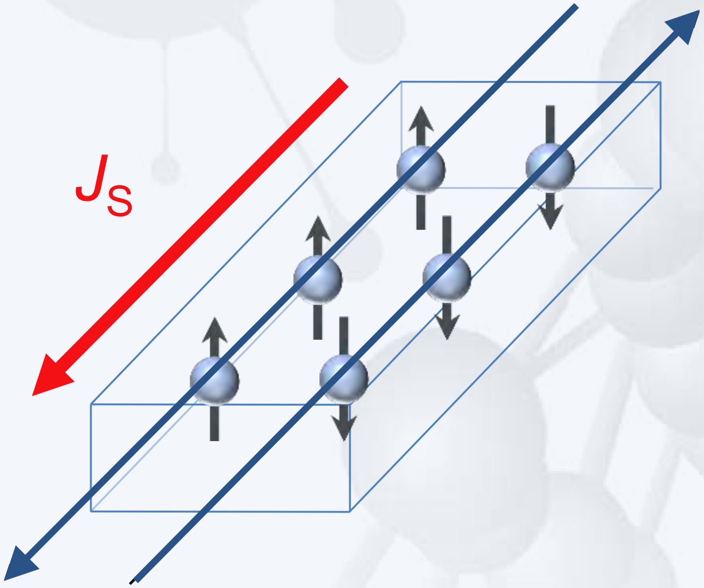
$J_c = 0$

$J_c = 0$

Spin current: no Joule heating!

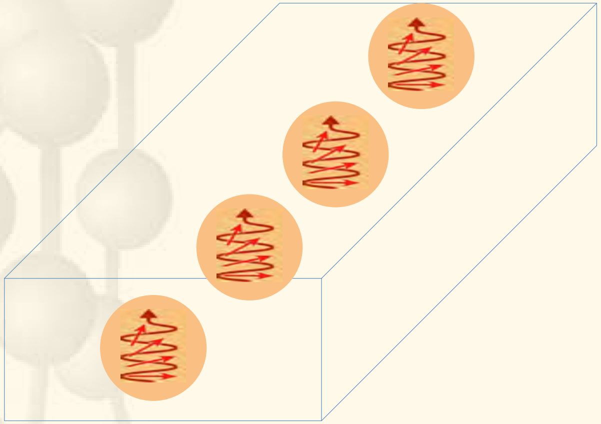
Pure Spin Currents

Magnetic Metal



Net electron spin flow

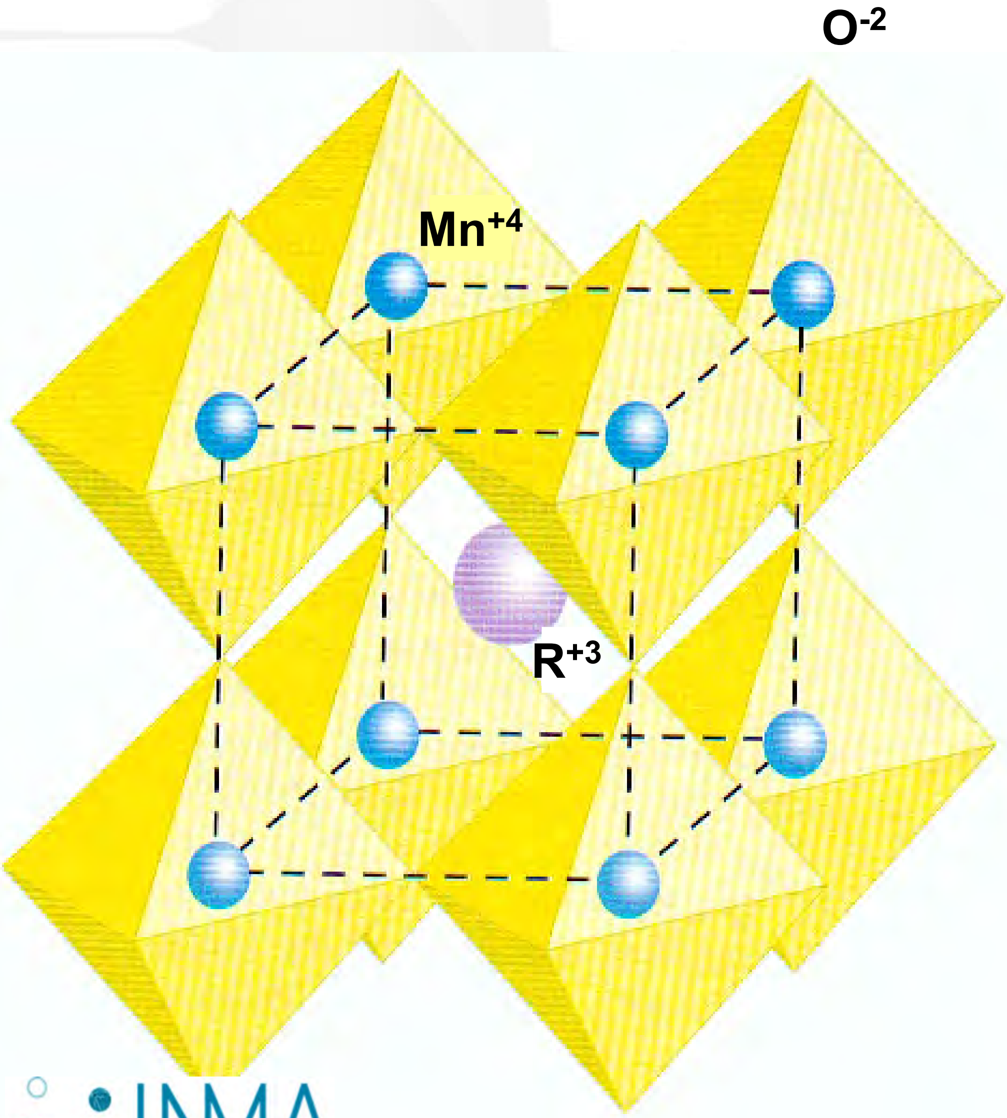
Magnetic Insulator



Magnon flow

Magnetic polarons in manganites

Manganites structure



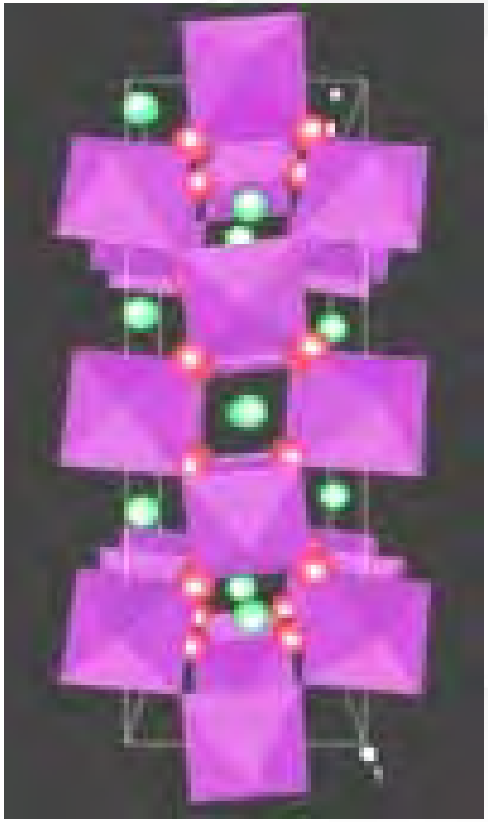
Cubic perovskite structure

$RMnO_3$

-Octahedral coordination of the Mn ions

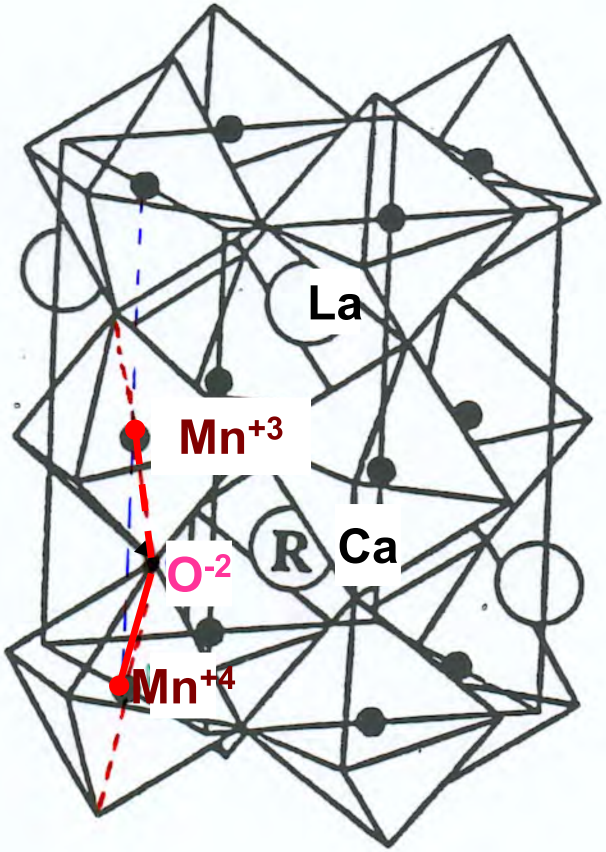
-Mn-O-Mn bound angle 180º

Mixed valence manganites: Distorted perovskite structure



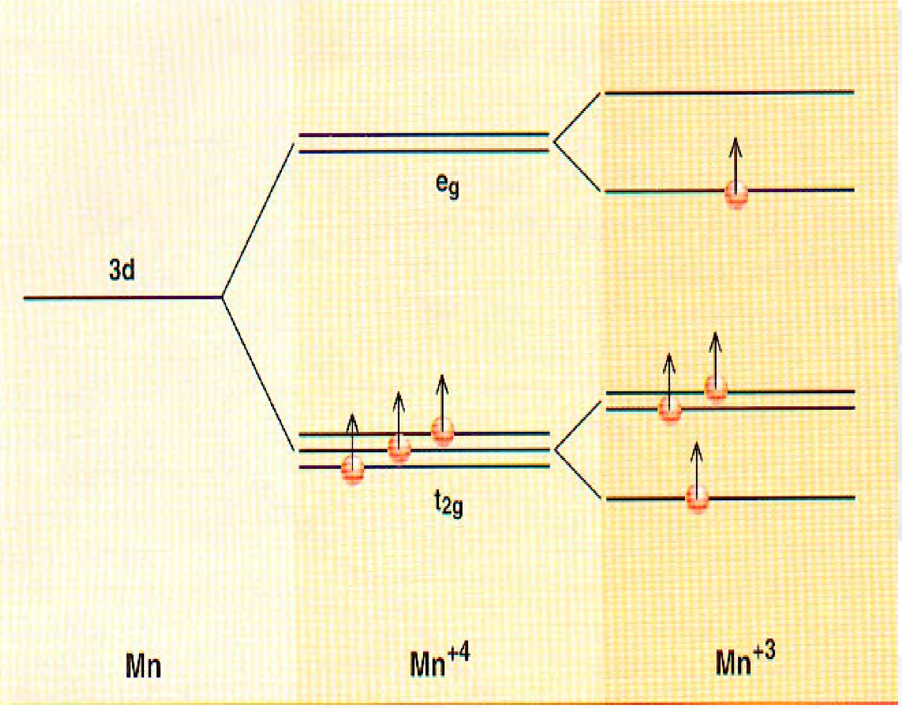
-Change in the bound angle due to different cation size

-Different (La^{+3}) and (Ca^{+2}) valence gives rise to a mixed valent state of the Mn



$La_{1-x}Ca_{x}MnO_3$

Crystal electric field interaction



The t_{2g} electrons are localized on the Mn

The e_g level is partially occupy by an itinerant electron

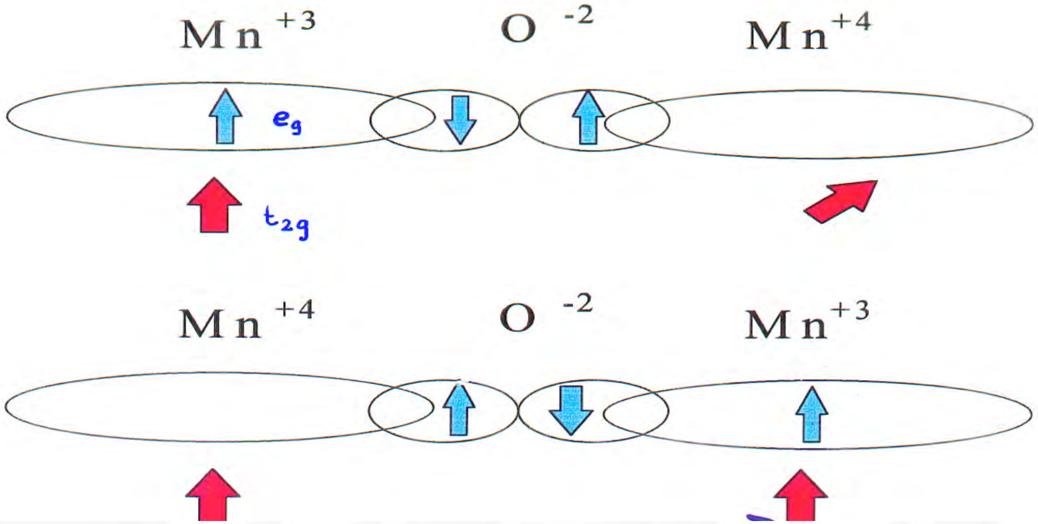
Indirect interactions without overlapping of the magnetic ions charge clouds:

-Antiferro and Ferromagnetic superexchange

-Double exchange is ferromagnetic and strong

→Mixed valence compounds:*ferromagnetic*

Mn^{+4}-O-Mn^{+3} DOUBLE-EXCHANGE



$$t = t_0 \cos[(\Theta)/2]$$

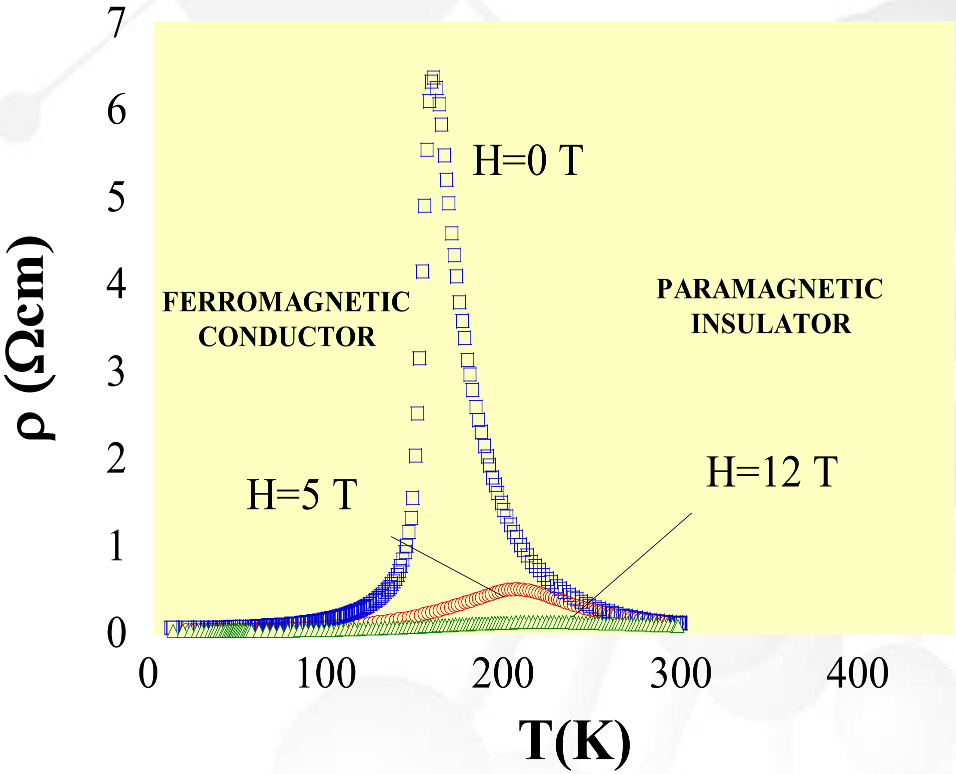
e_g electron travelling in a disorder-order t_g core angular moments background

(Paramagnetic phase)

(Ferromagnetic phase)

(Dr. Francisco Rivadulla courtesy)

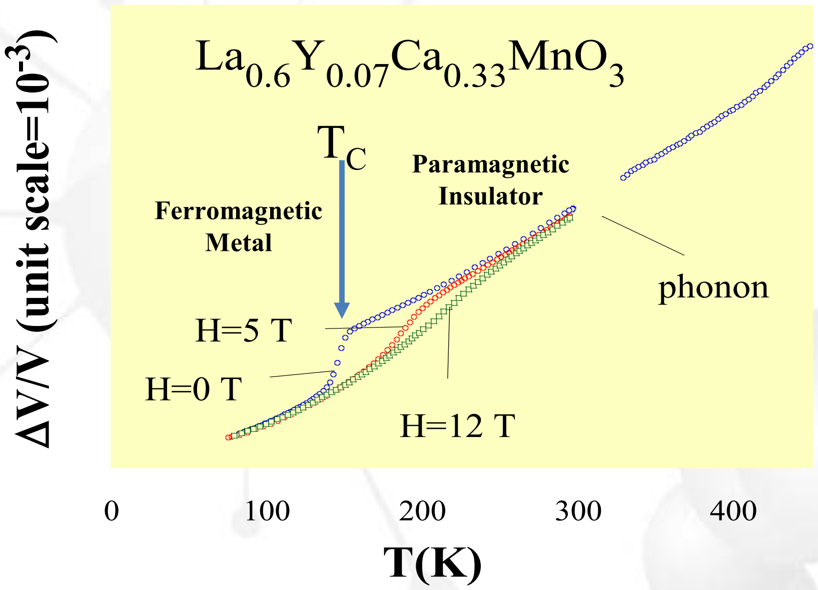
Colosal magnetoresistance



Magnetic and electric phase transition

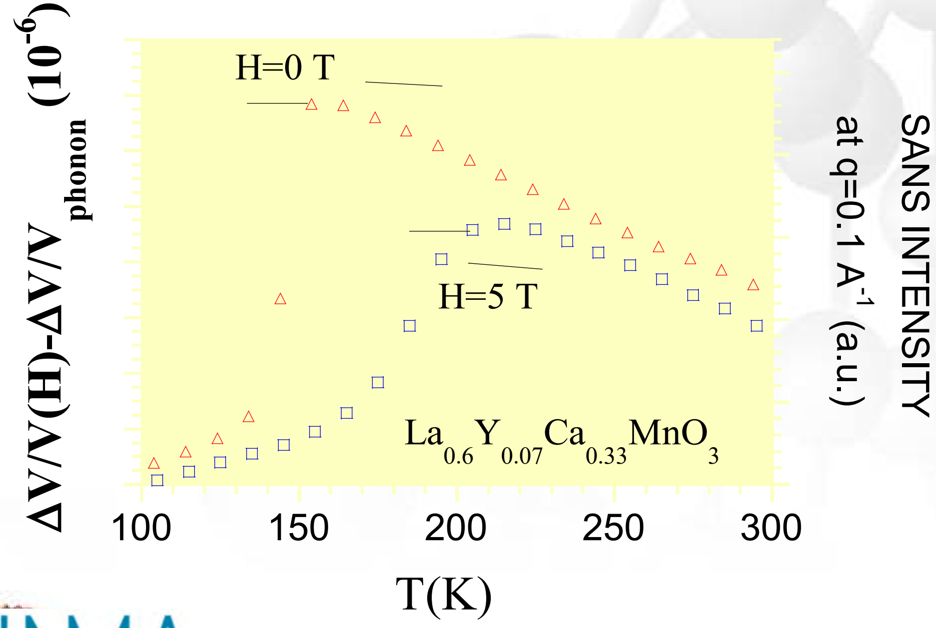
Paramagnetic-Ferromagnetic

Insulator-Metal



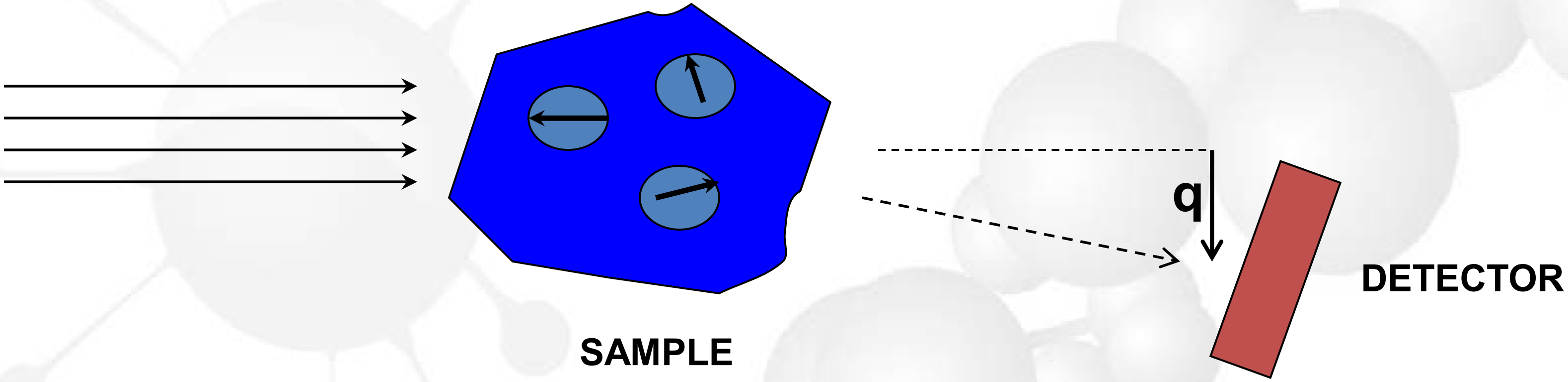
Anomalous thermal expansiion in the paramagnetic phase

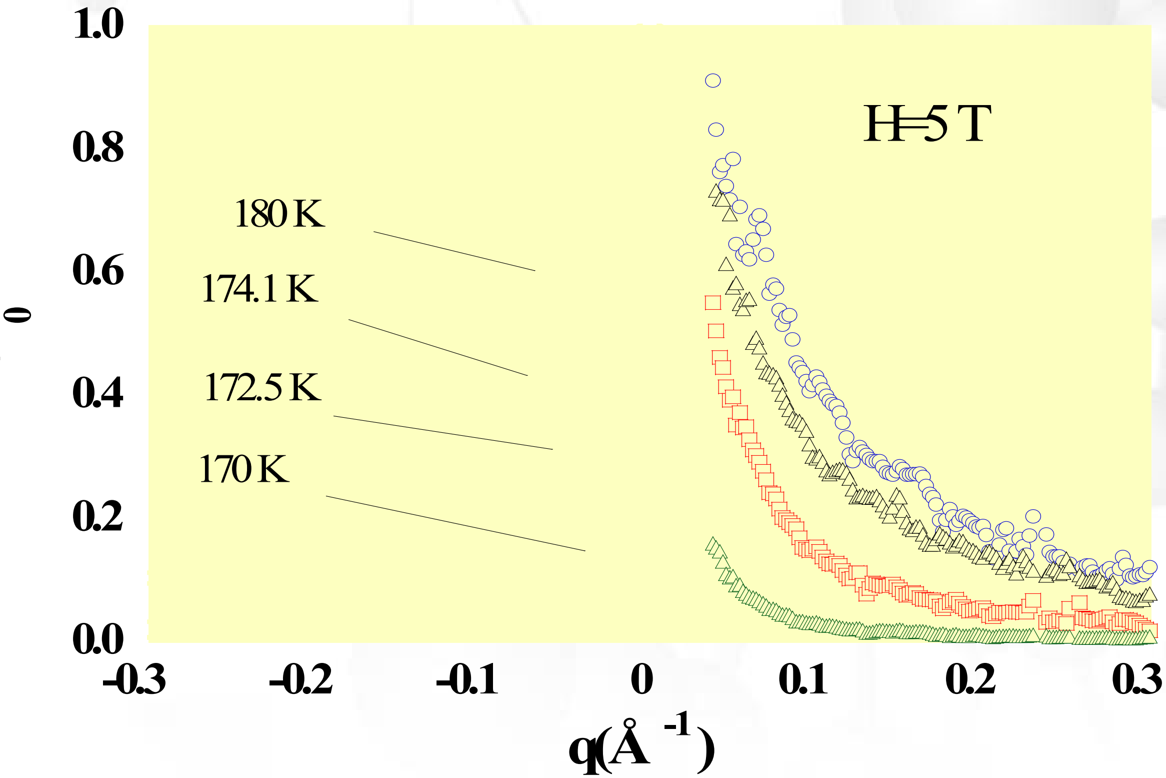
M.R. Ibarra et al. Phys. Rev. Lett. 75 (1995) 3541



Small angle neutron scattering: follows the anomalous thermal expansion

SMALL-ANGLE NEUTRON SCATTERING (SANS)

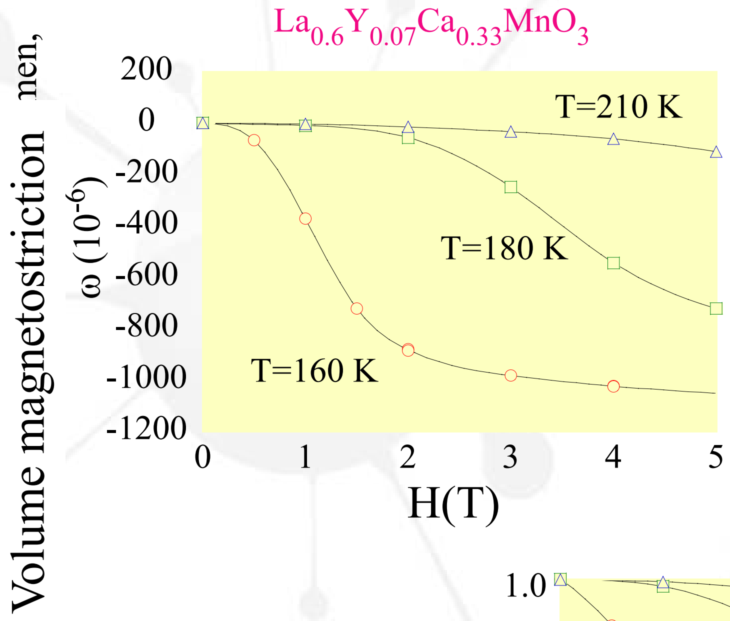




$<M(0).M(r)>\sim[\exp(-r/\xi)]/r$

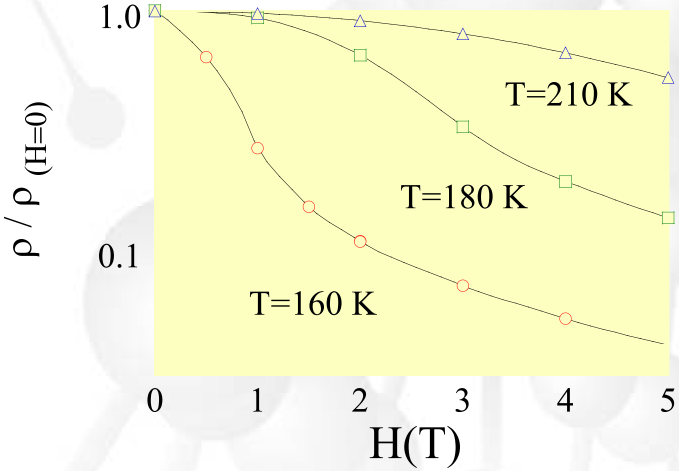
⬇

$$I=I_0/[q^2+(1/\xi^2)]$$

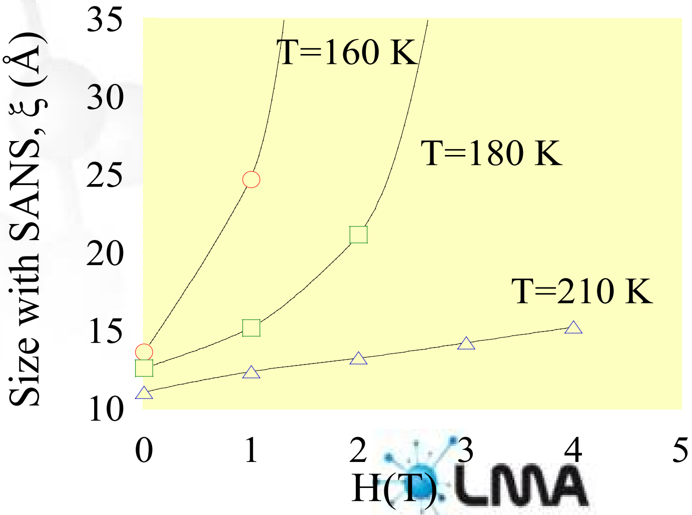


The magnetostriction in paramagnetic phase is quadratic with the field

Magnetoresistance follow the volumen deformation



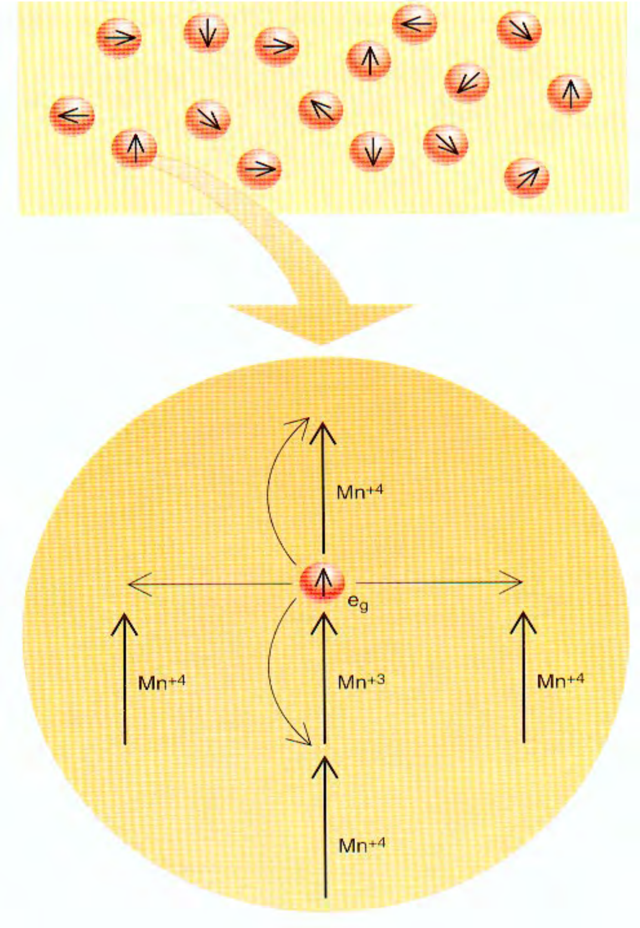
The cluster size increse with the applied field and



Magnetic Polaron

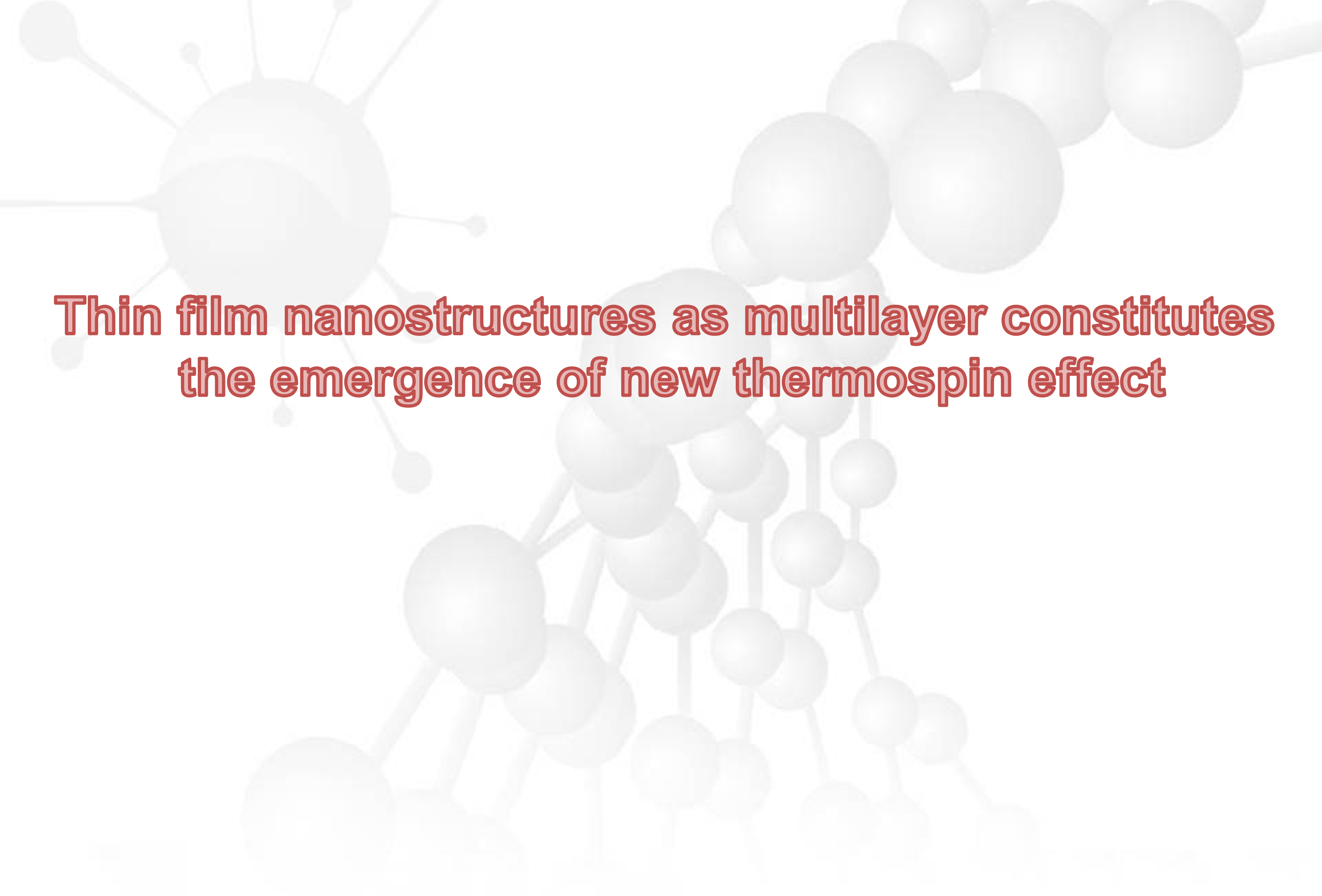
New dynamic phase segregation

De Teresa J.M. , Ibarra M.R.et al. Nature 386 (1997) 256



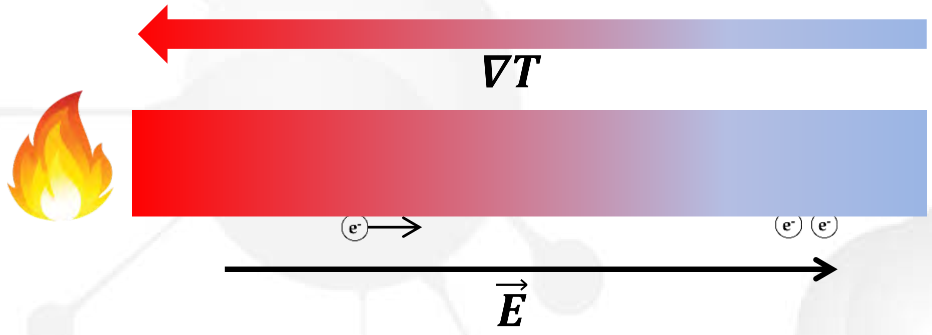
-Hopping intra cluster τ_h<10^{-9} s.

-Polaron average life timeτ_p>10^{-5} s.



Thin film nanostructures as multilayer constitutes the emergence of new thermospin effect

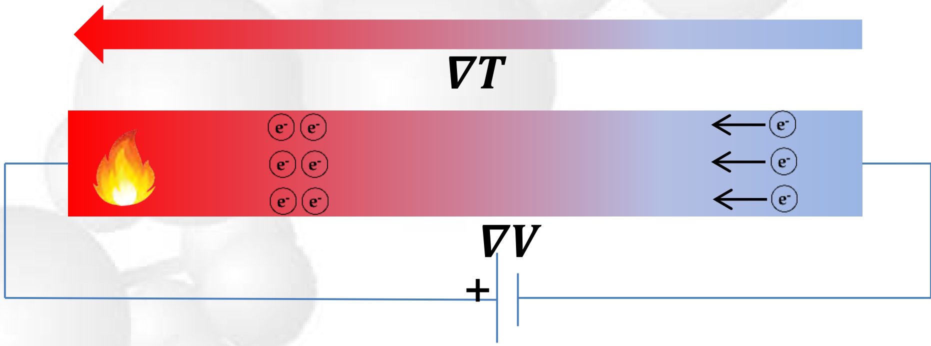
Thermoelectric effects



$$\vec{j} = \sigma(\vec{E} - S\,\nabla T) = 0$$

Seebeck effect: $S = \frac{\vec{E}}{\nabla T}$

Thermoelectric power generation



Peltier effect: $\Pi = S\,T$

Thermoelectric cooling

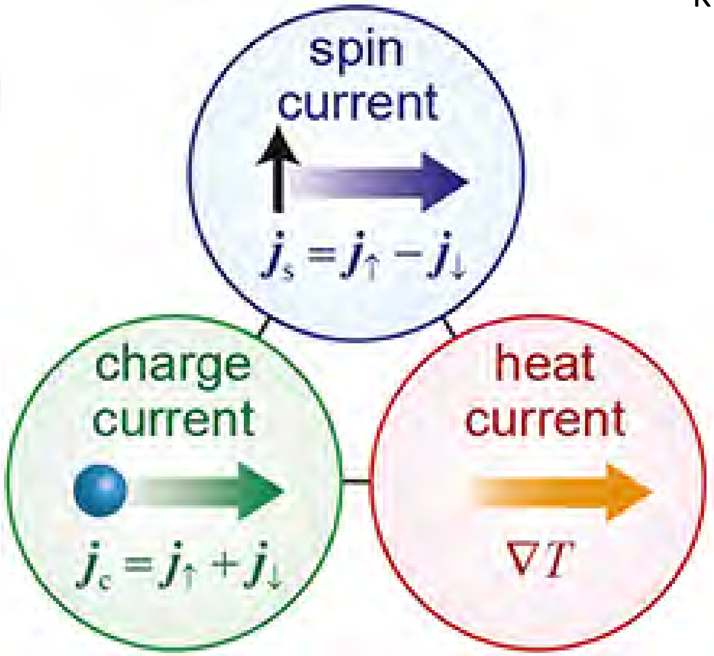
Figure of merit

$$ZT = \frac{S^2\sigma}{\kappa}T$$

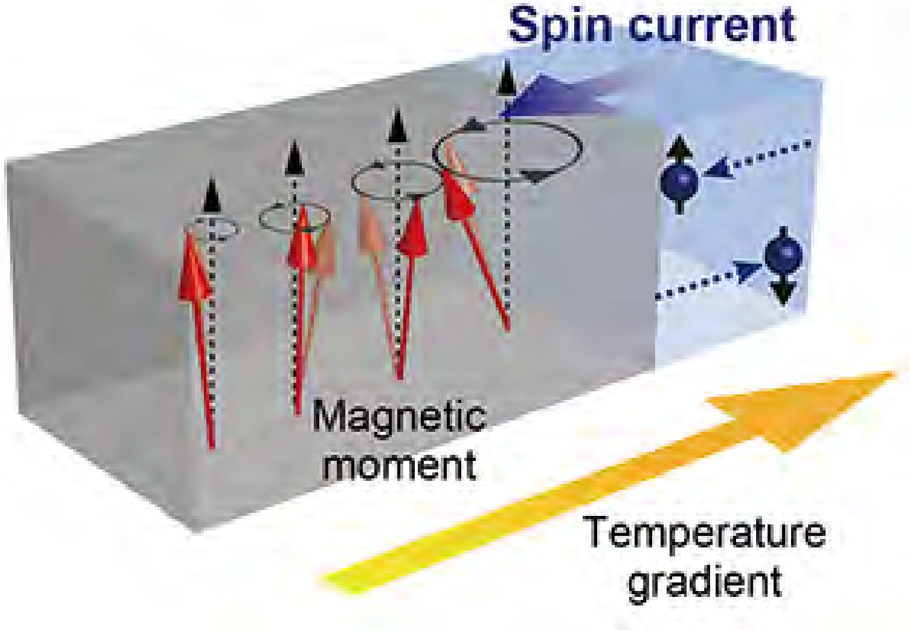
$$\kappa = \kappa_e + \kappa_l \qquad \kappa_e = L\sigma T$$

$$L = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2 = 2.44 \times 10^{-8}\ {}^{W\Omega}/_{K^2}$$

Spin Seebeck effect effect: Spin current generation by heat



K. Uchida et al. Nature 455, 778 (2008)

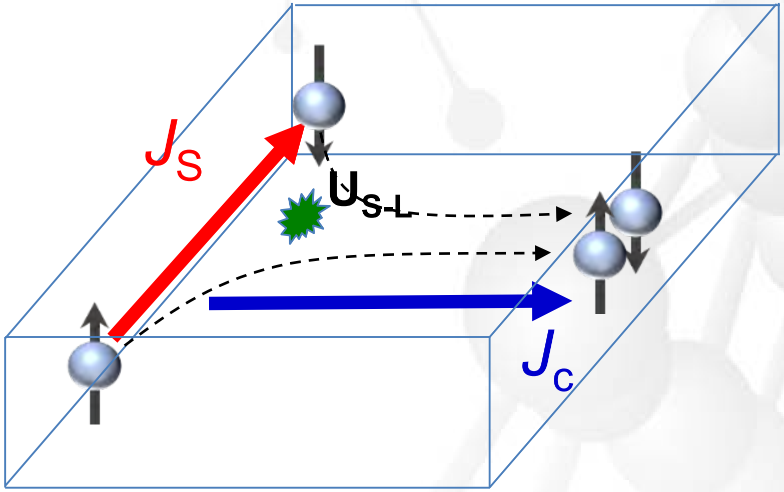


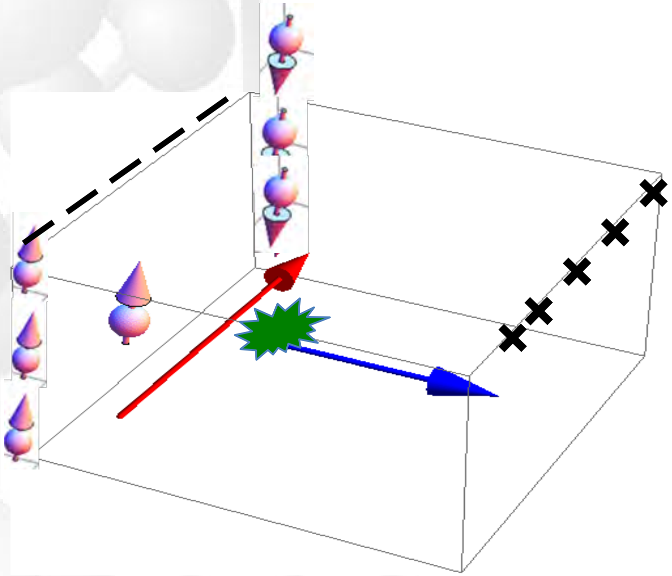
$$I_S = -G_S \frac{k_B}{\hbar}(T_F - T_N)$$

J. Xiao et al. PRB **81,** 214418 (2010)
H. Adachi et al. PRB **83**, 094410 (2011),
Rep. Prog. Phys. **76,** 036501 (2013)

Inverse Spin Hall effect (ISHE)

Interconversion of spin currents – charge currents in non-magnetic metals with high spin orbit coupling (high Z)

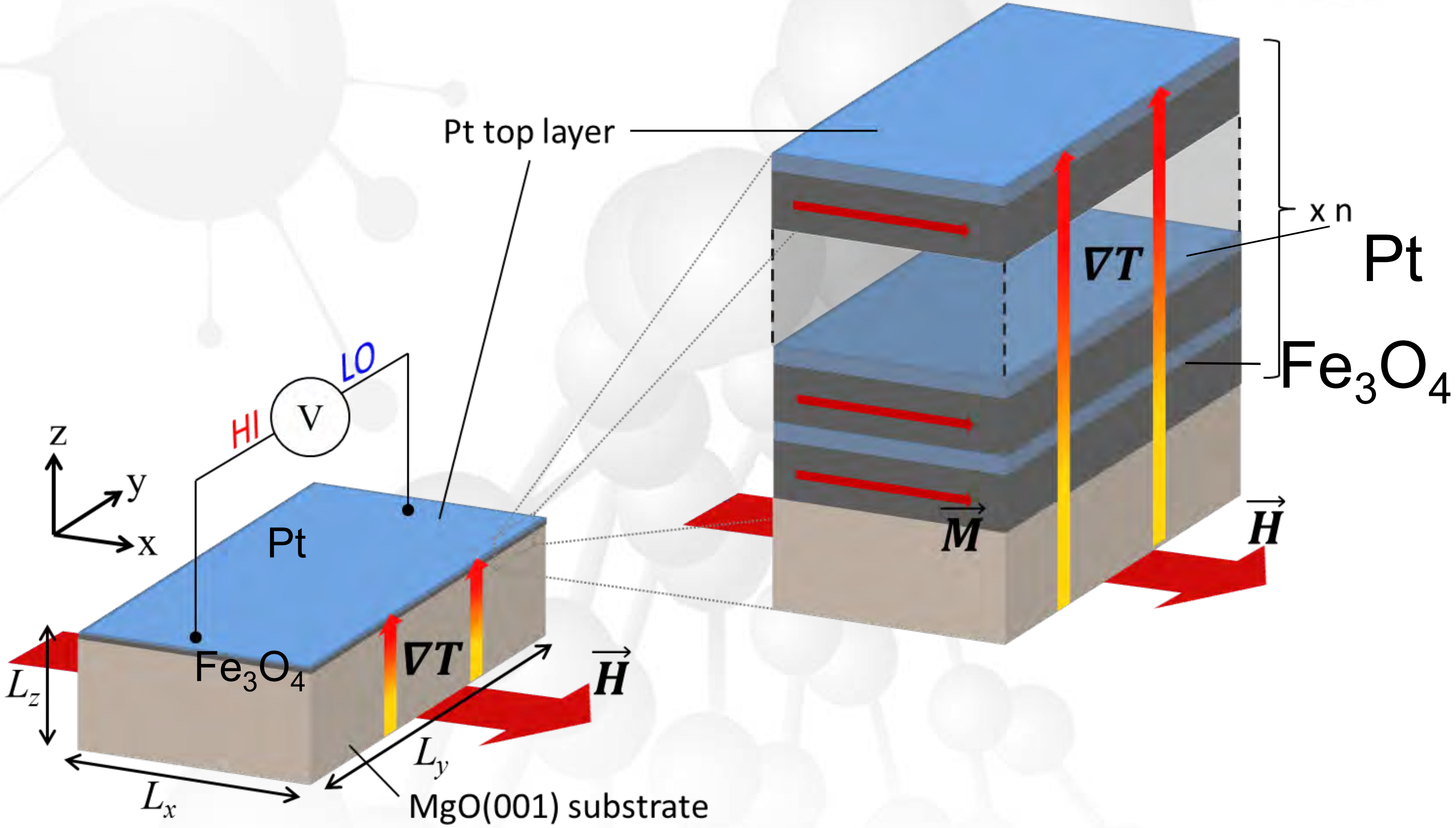




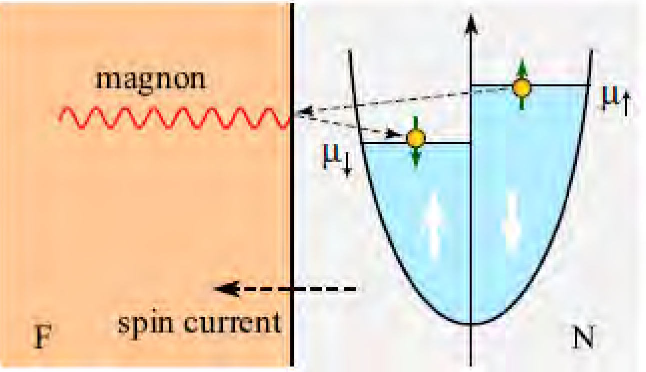
(J_S) Spin ⇒ (J_c) Charge

E. Saitoh et al. Appl. Phys. Lett. 88, 182509 (2006)

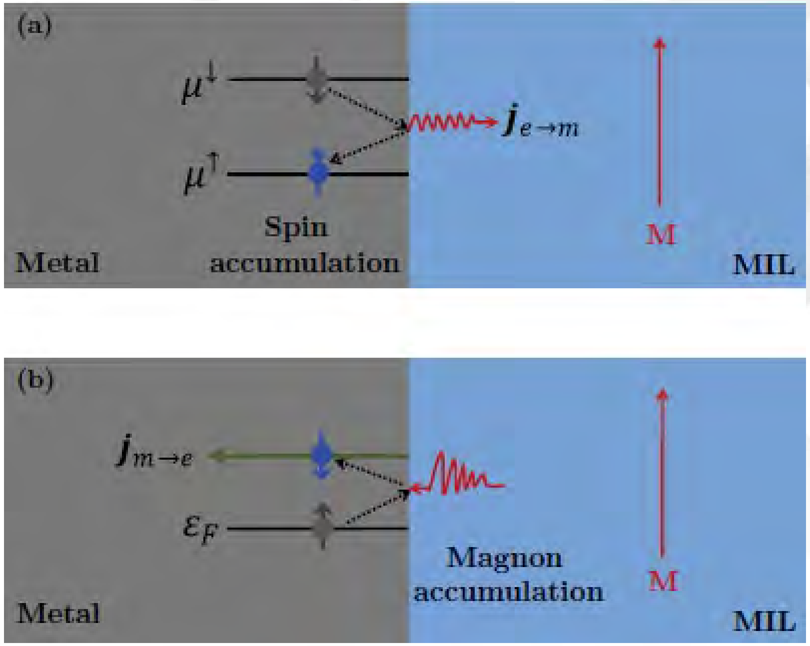
SSE in $[F/N]_n$ multilayers



SPIN CURRENT AT THE INTERFACES

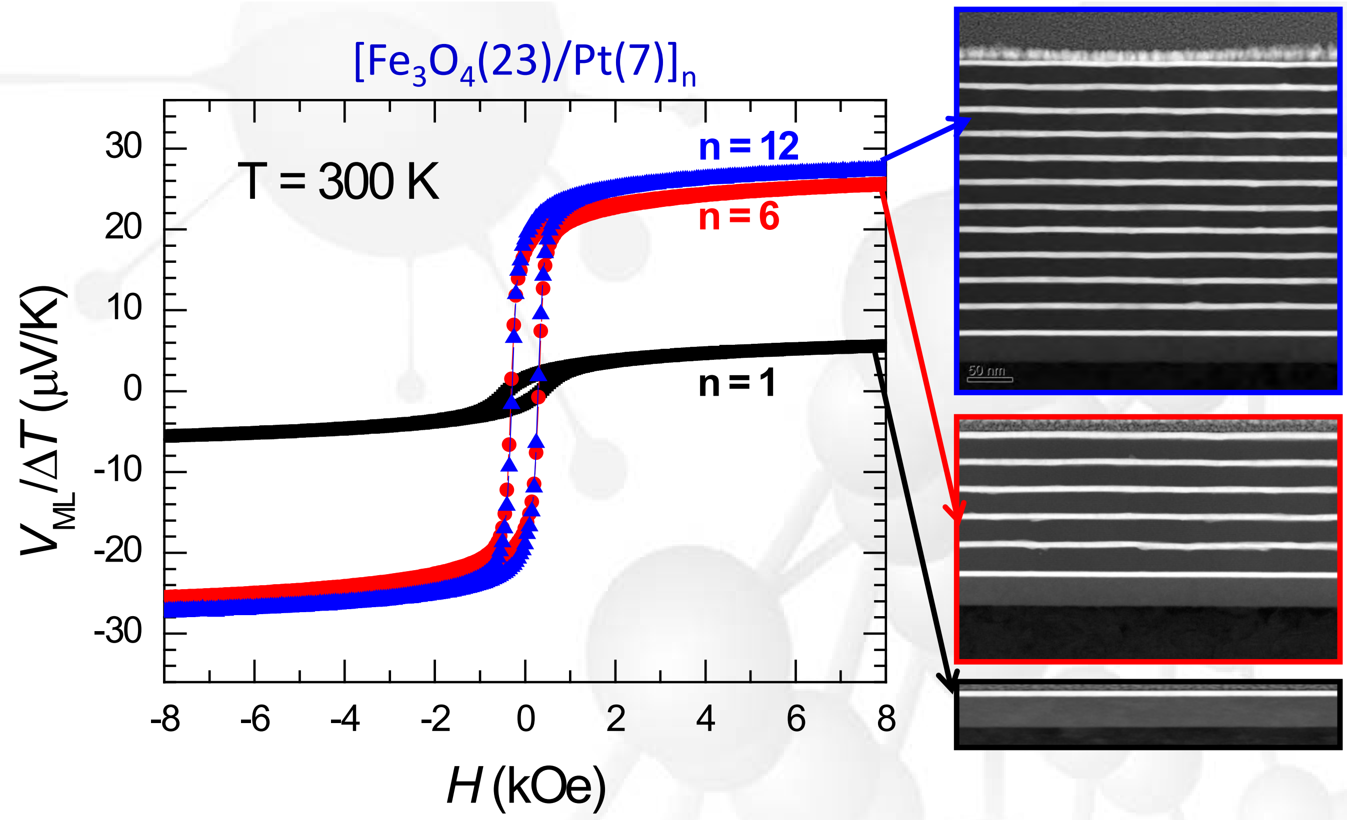


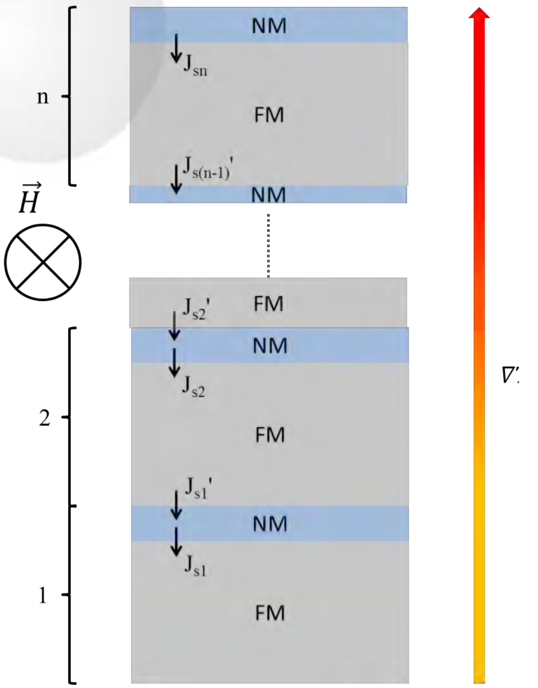
Magnon emission associated with spin accumulation at the metal-ferromagnet interface
(Takahasi et al ICM 2009)



Spin angular momentum transfer at the interface: Magnon and elecron spin current interconversion
(Steven et al. PRB 86 (2012) 214424)

Optimized configuration

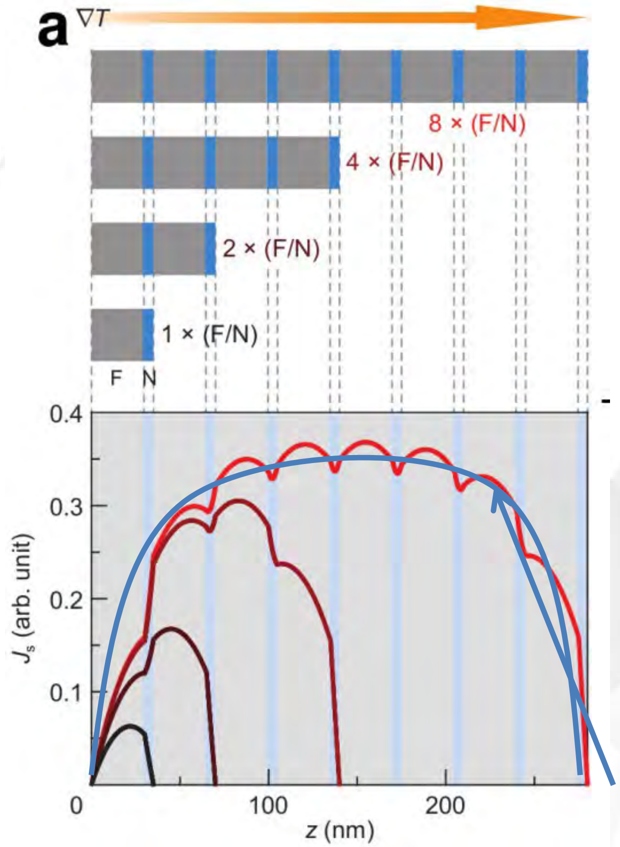




Largest SSE voltage measured in a thin film based structure!!

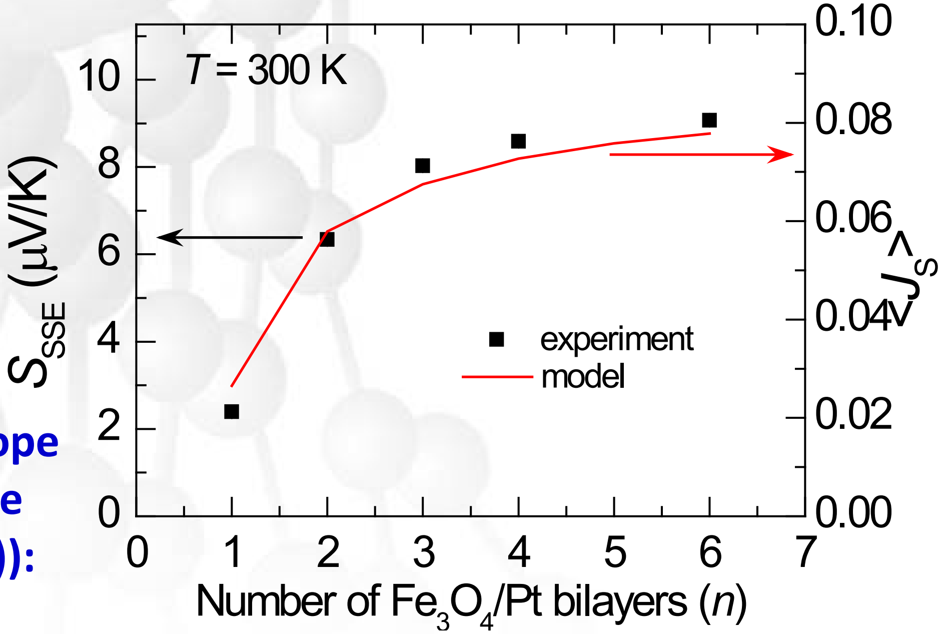
$V_{ML} \approx 28$ μV/ K !!

Qualitative agreement with experimental results



$$\langle J_S\rangle = \frac{1}{t_N n}\sum_{i=1}^{n}\int_{z_i=0}^{t_N} dz\, J_S^{(i)}(z)$$

Average SSE voltage measured:



Envelope curve ($J_S(z)$):

Maximum spin current at central interlayers

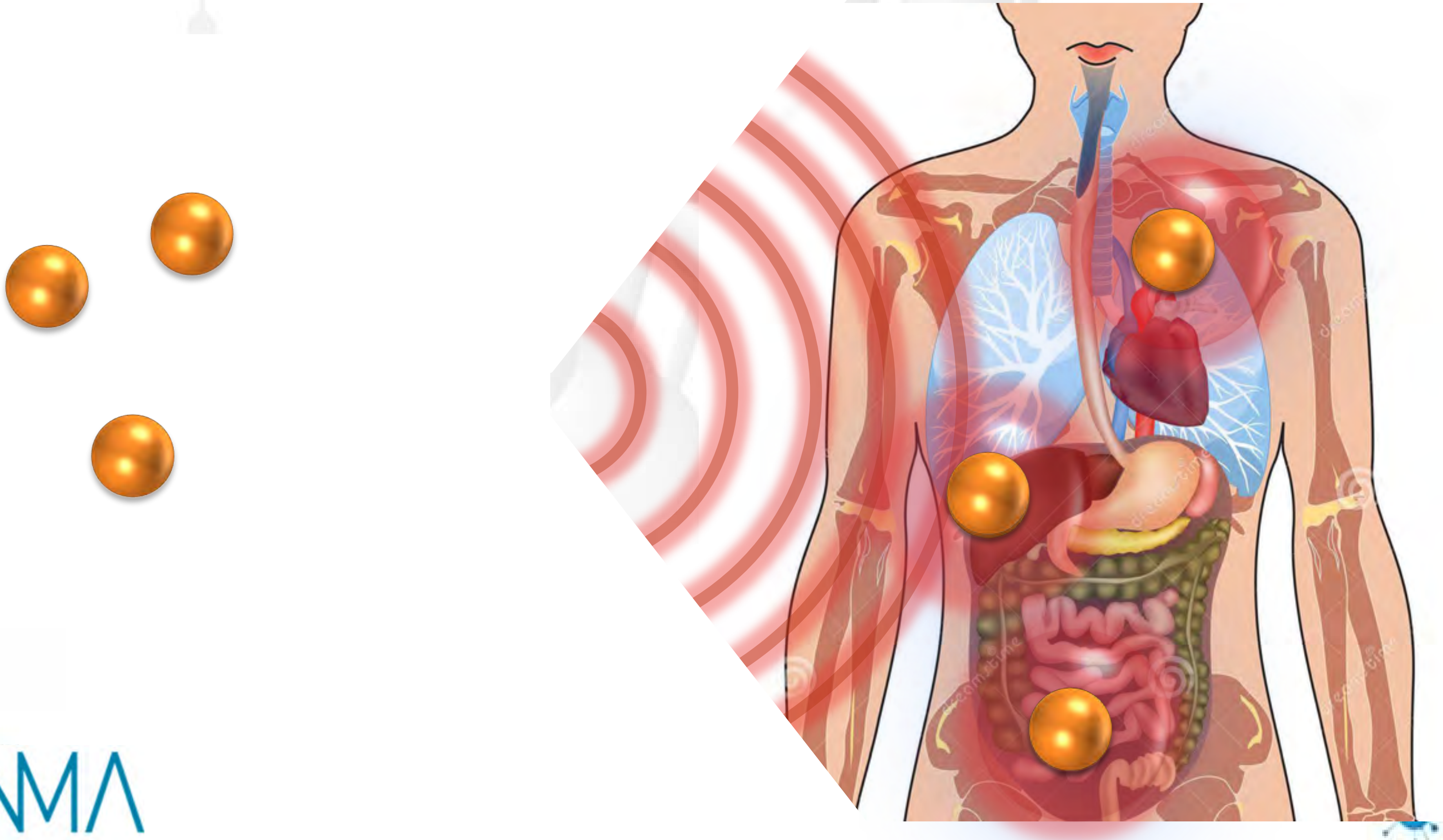
Ramos et al. Phys. Rev. B **92**, 220407(Rap. Comm.) (2015)

Magnetic nanoparticles, due to the electromagnetic radiation adsorption in the radiofrequency range, operate as nanoheaters

ROYAL SOCIETY OF CHEMISTRY

Nanoscale, 2019,**11**, 3164-3172

- **Magnetic hyperthermia** is an experimental treatment for cancer.
- Based on the fact that magnetic nanoparticles can transform electromagnetic energy from an external a.c. field to heat.
- If magnetic nanoparticles are put inside a tumor and the whole patient is placed in an a.c. magnetic field, the tumor temperature will rise.
- The elevation of temperature may enhance radio- and chemo-sensitivity, hopefully shrinking tumors.

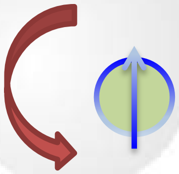


Losses in magnetic colloids

1. In NPs suspensions (@ RT), the Brownian relaxation in viscous media is

$$\tau_B = \frac{3\,\eta\, V_H}{k_B T}$$

Brownian rotation



Physical movement of the MNPs

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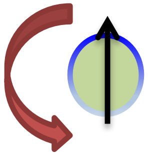
2. Néel relaxation is

$$\tau_N = \tau_0 \exp\left(\frac{K\,V_M}{k_B T}\right)$$

R.E. Ros

Neel relaxation



Rotation of the magnetic moment of the MNPs

The total relaxation is

$$\frac{1}{\tau} = \frac{1}{\tau_B} + \frac{1}{\tau_N}$$

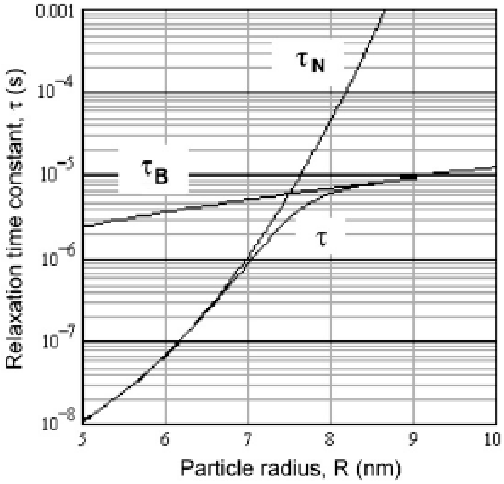
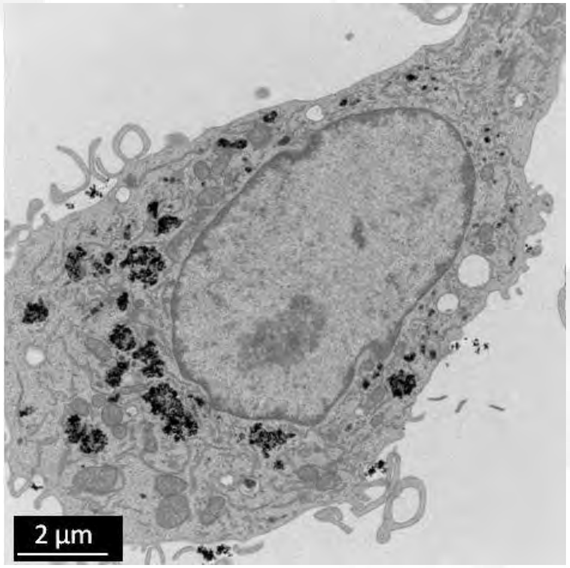
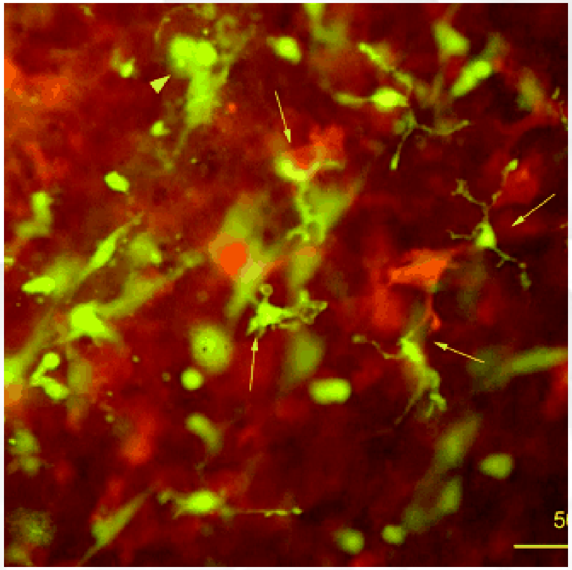


Fig. 2. Time constants vs. particle size for magnetite particles.

Dendritic cells targeting carrying MNPs: magnetic cells



Dendritic cells + NPs

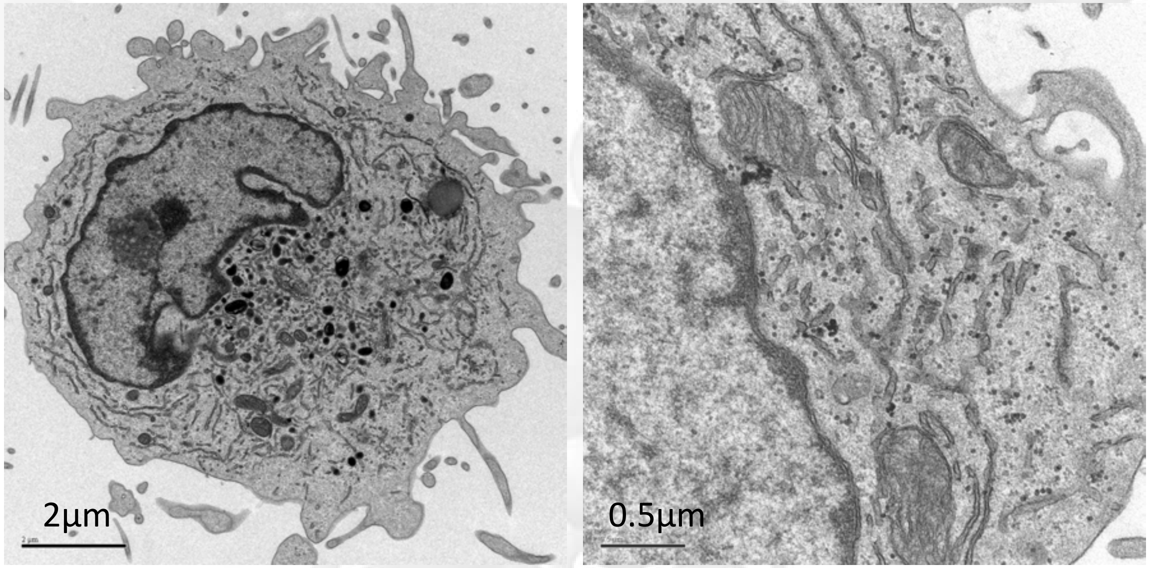


Dendritic cells targeted on tumor

Trojan horse

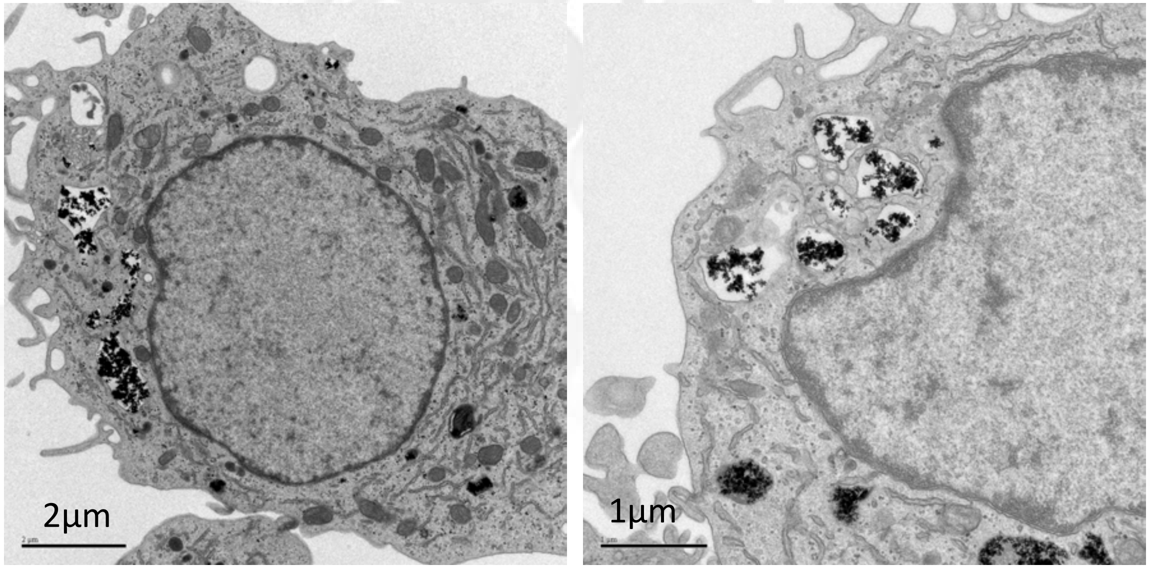
DCs INTERNALIZATION-TEM

DCs

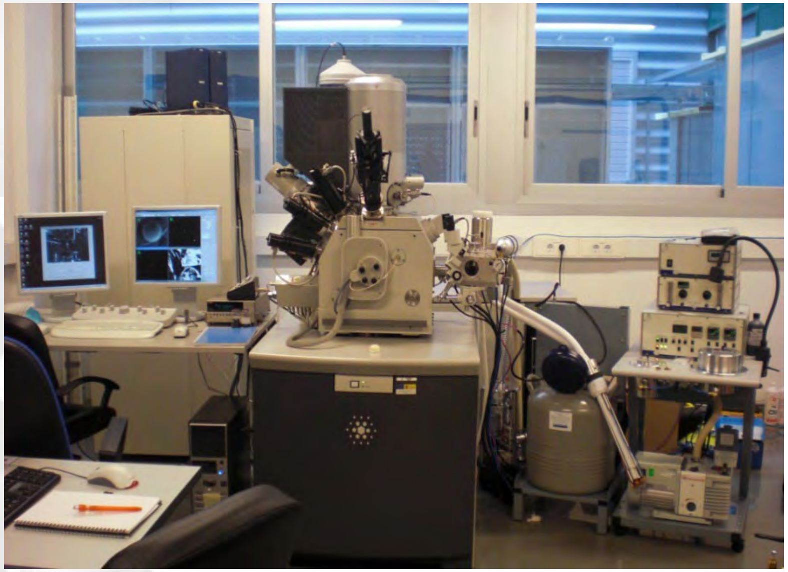


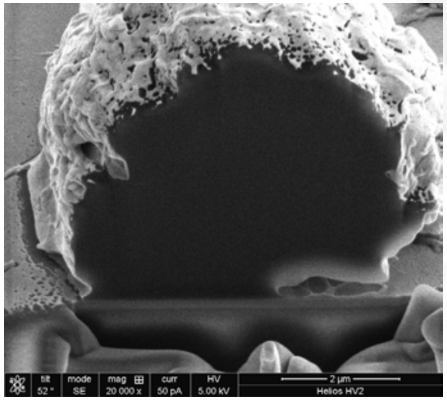
DCs+
MNPs

50 $ugFe_3O_4$/ml

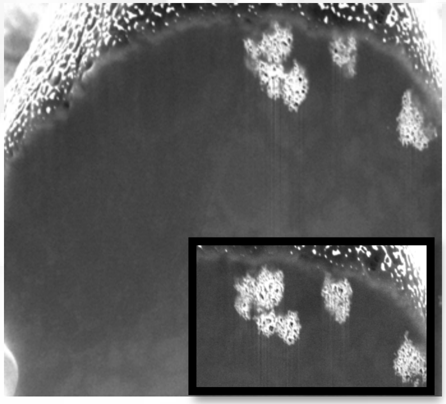


Focused Ion Beam FIB - Dual Beam



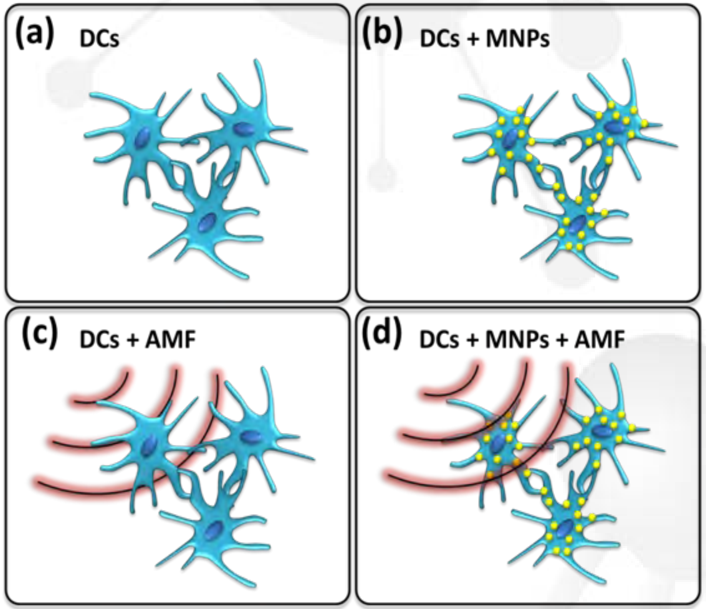


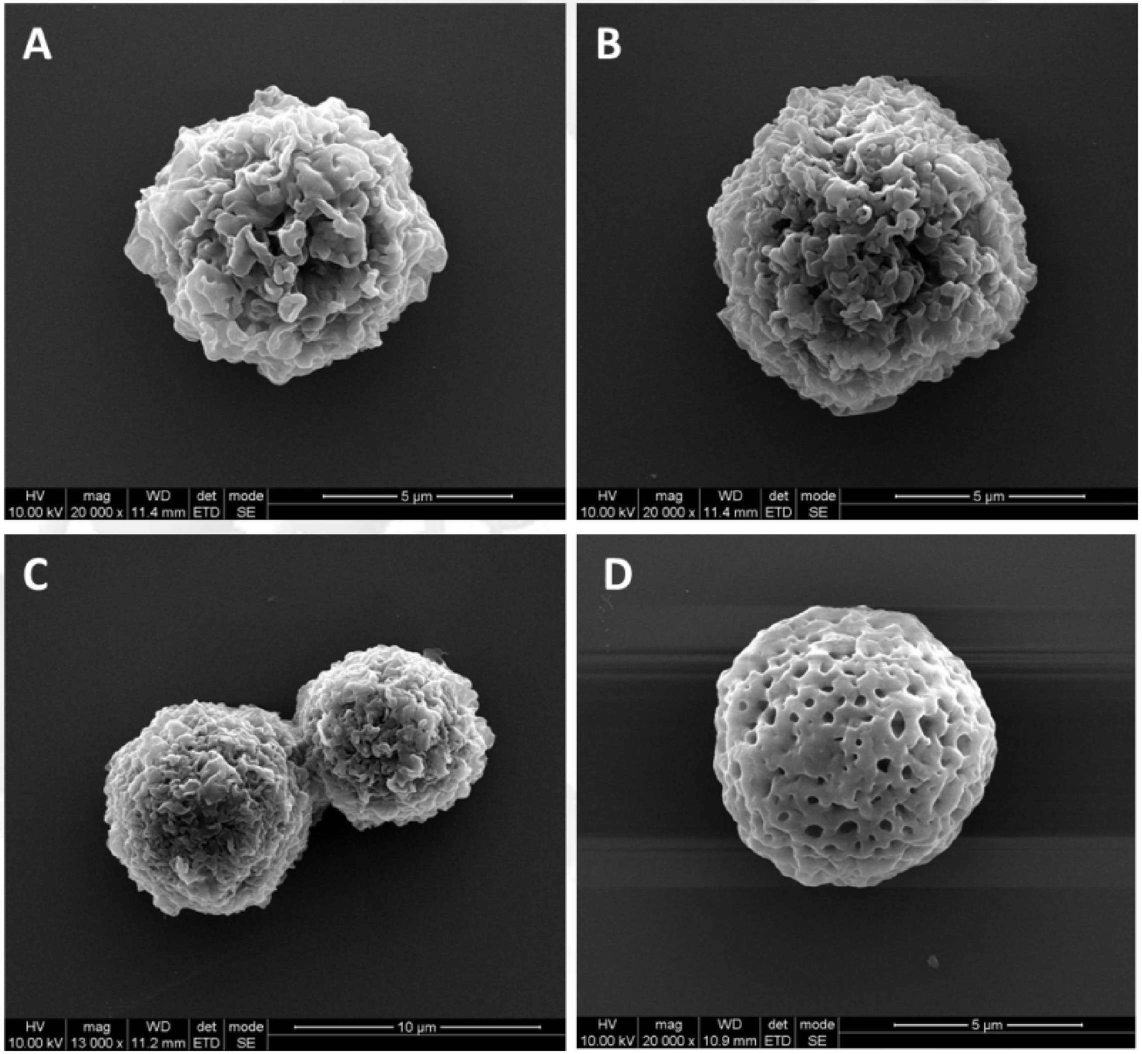
DCs



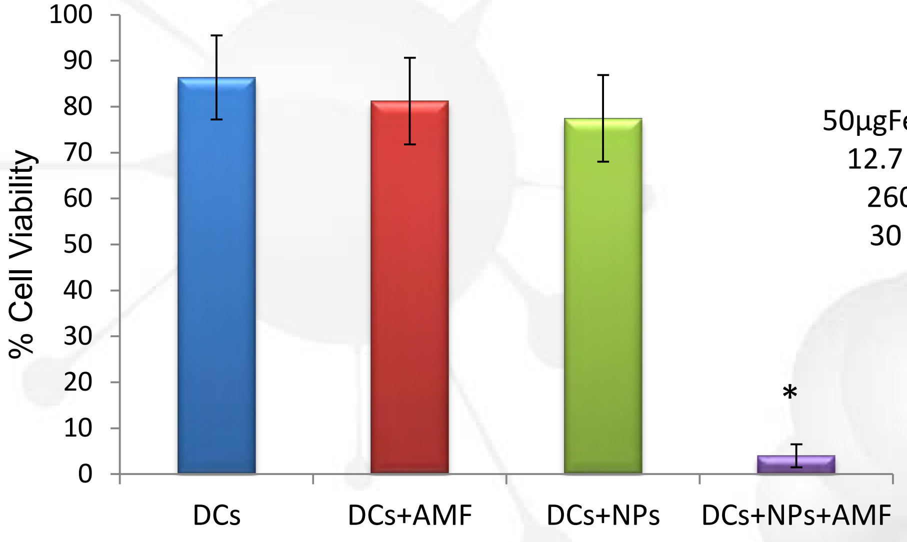
MNPs uploaded DCs

EFFECT OF THE ELECTROMAGNETIC FIELD ON CELL VIABILITY





DENDRITIC CELL VIABILITY

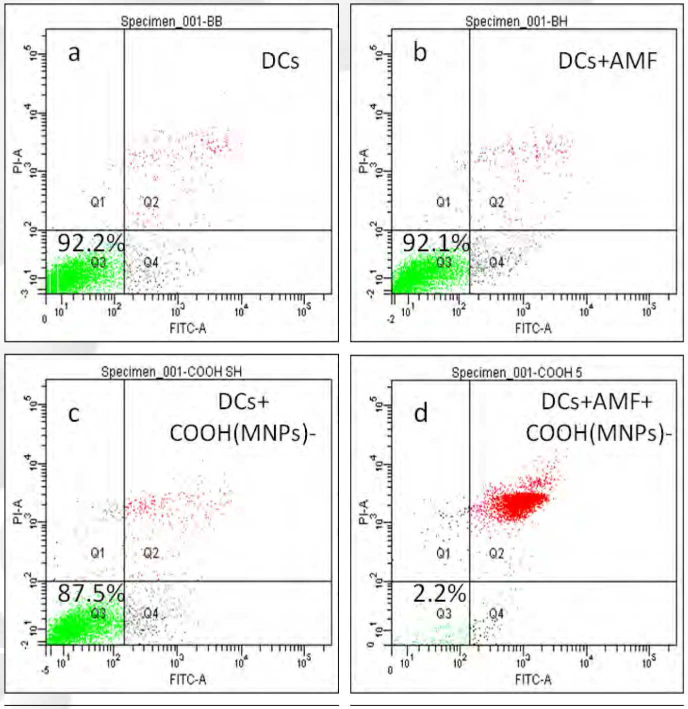


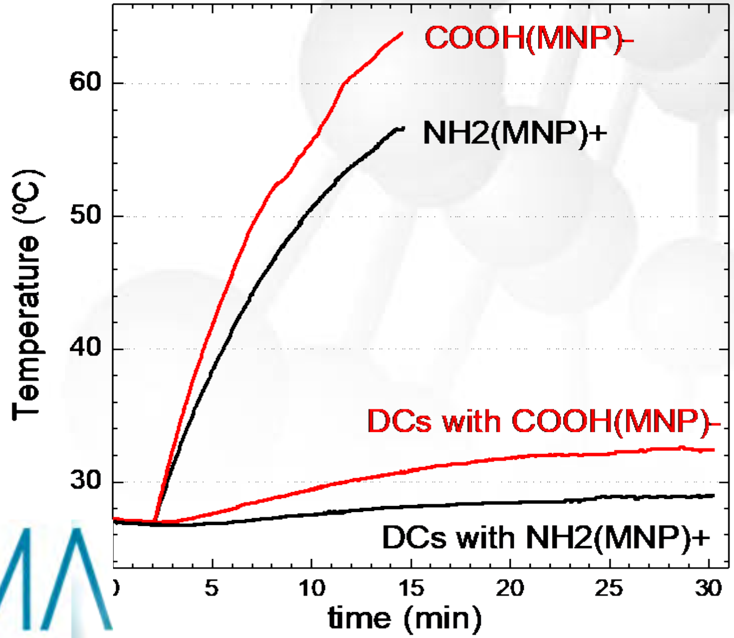
$50 \mu g Fe_3O_4/ml$
12.7 kA/m
260kHz
30 min

N= 6

Trypan Blue

*$p<0.0005$

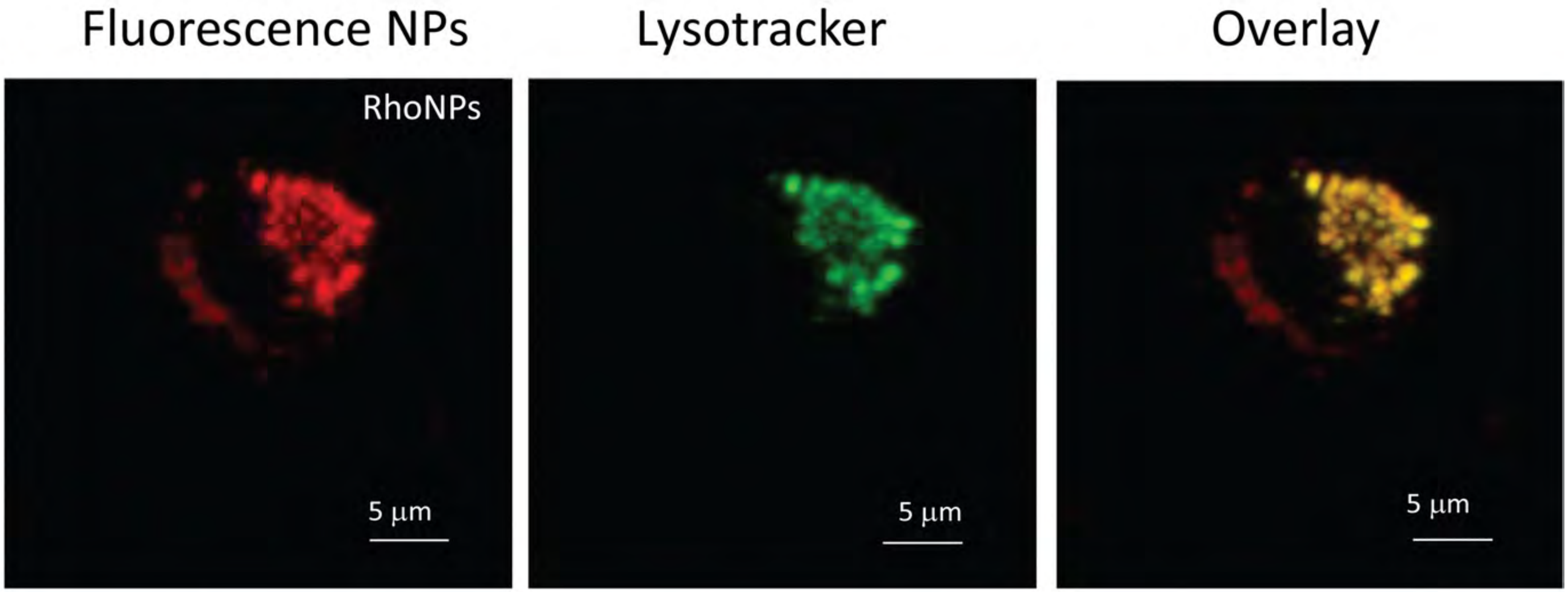




Cell death induced by the application of alternating magnetic fields to nanoparticle-loaded dendritic cells. Marcos-Campos I, Asín L, Torres TE, Marquina C, Tres A, Ibarra MR, Goya GF. Nanotechnology 22 (2011) 205101

No temperature increase!!!

Colocalization of MNP in DCs



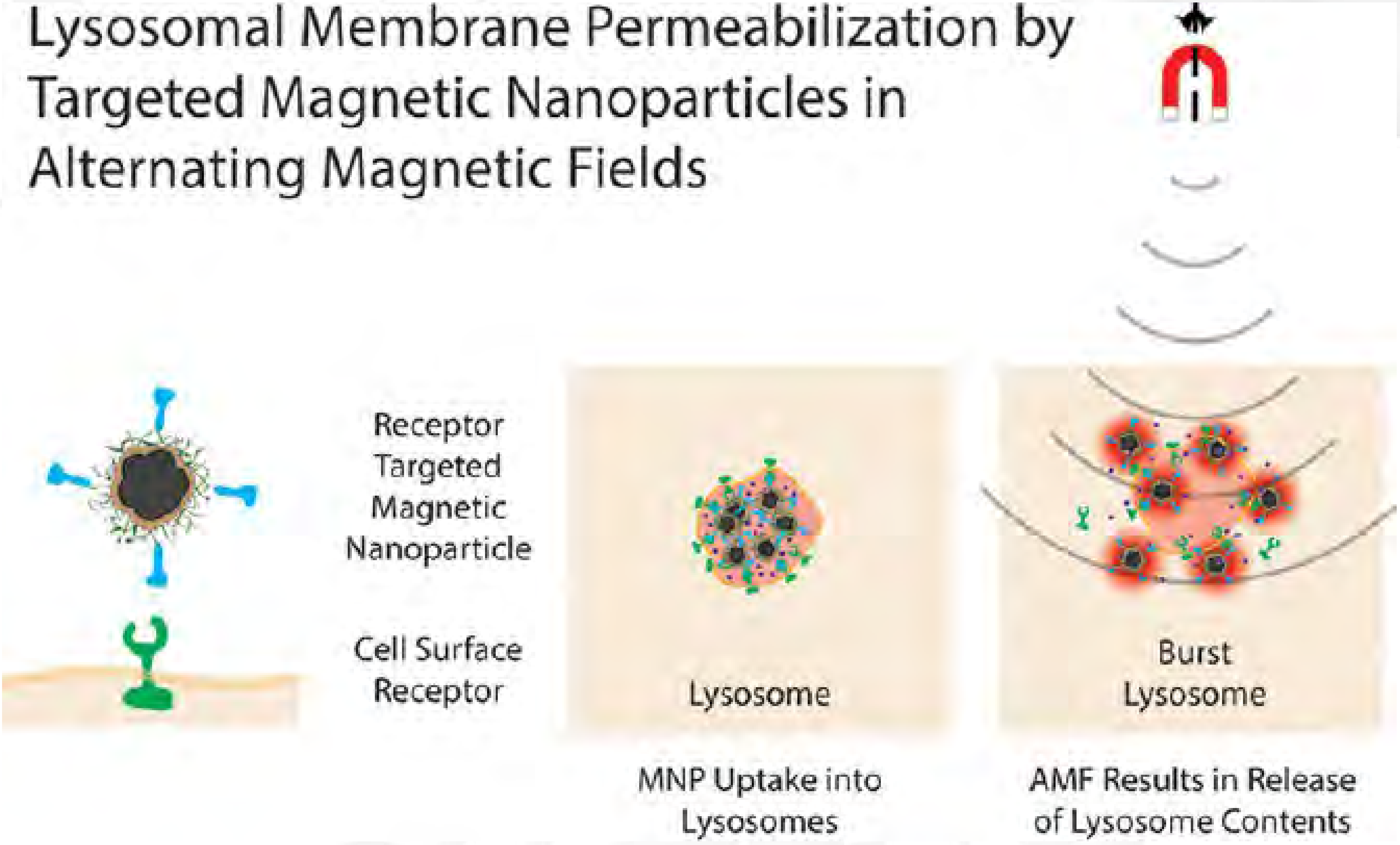
Fluorescence NPs

Lysotracker

Overlay

Goya G.F. et al. Current Nanoscience **12** (2016).

Lysosomal Membrane Permeabilization by Targeted Magnetic Nanoparticles in Alternating Magnetic Fields



MNP Uptake into Lysosomes

AMF Results in Release of Lysosome Contents

Domenech et al. ACS nano (2015)

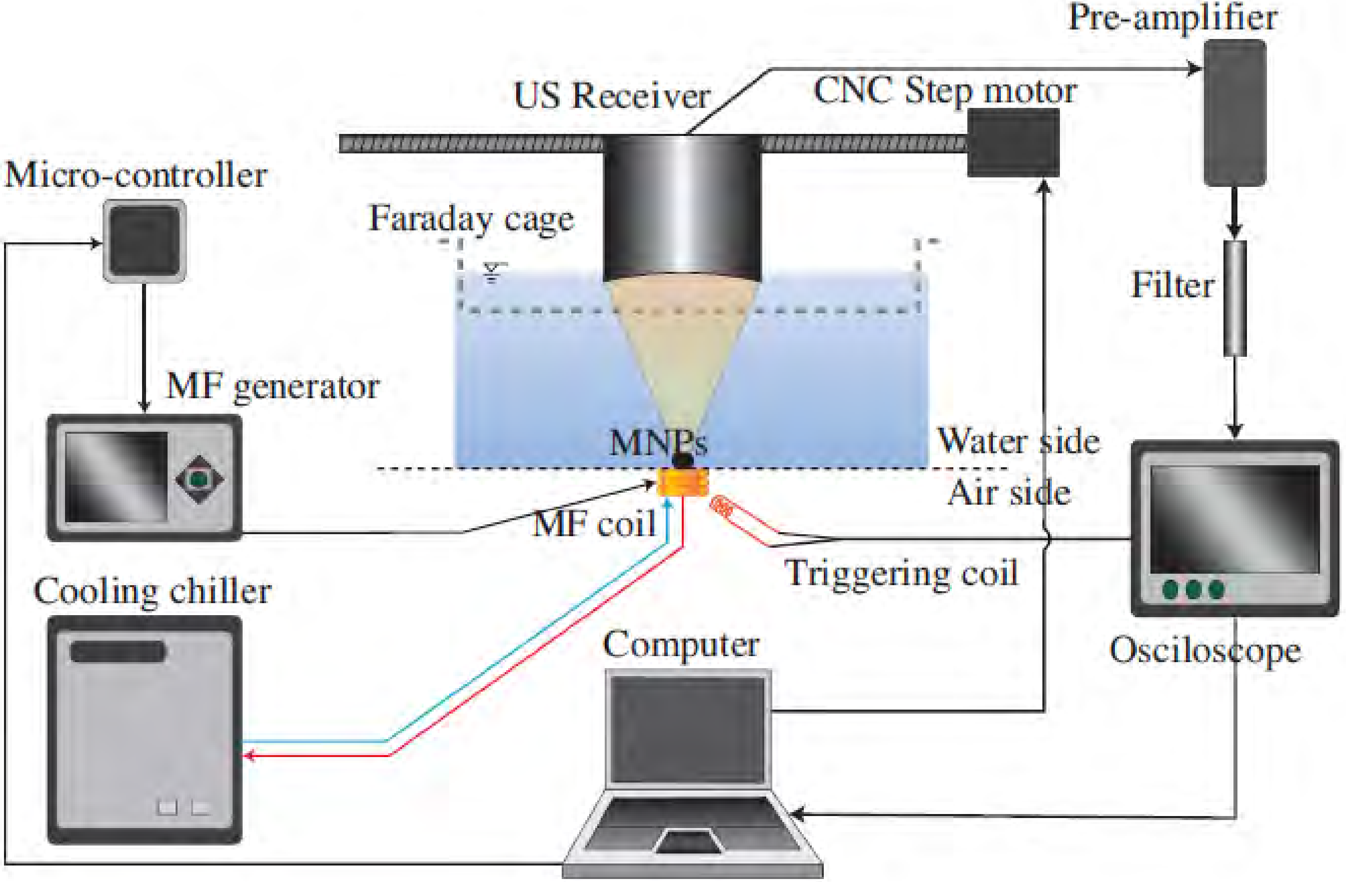
Induced ultrasound generation

Mechanism for membrane disruption?

Mechanical waves, Ultrasound?

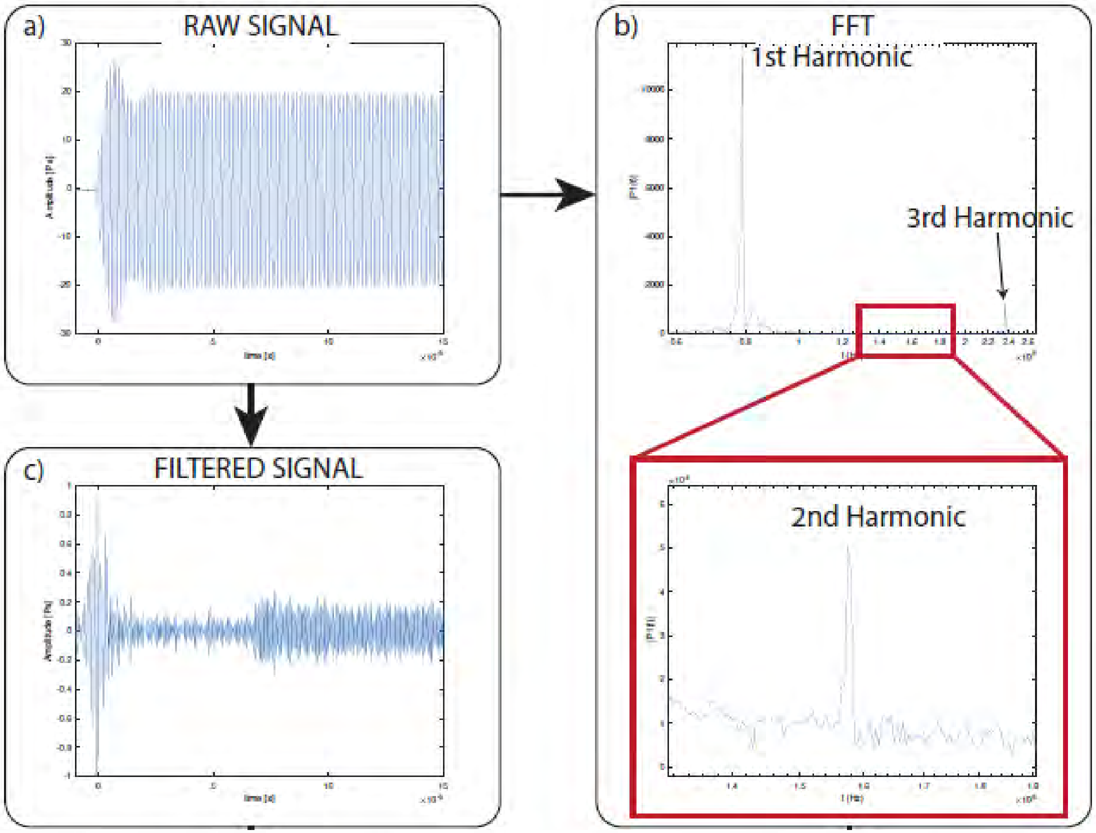
(In collaboratio with Prof. Gullermo Rus, UGR)

Magneto-acustic setup

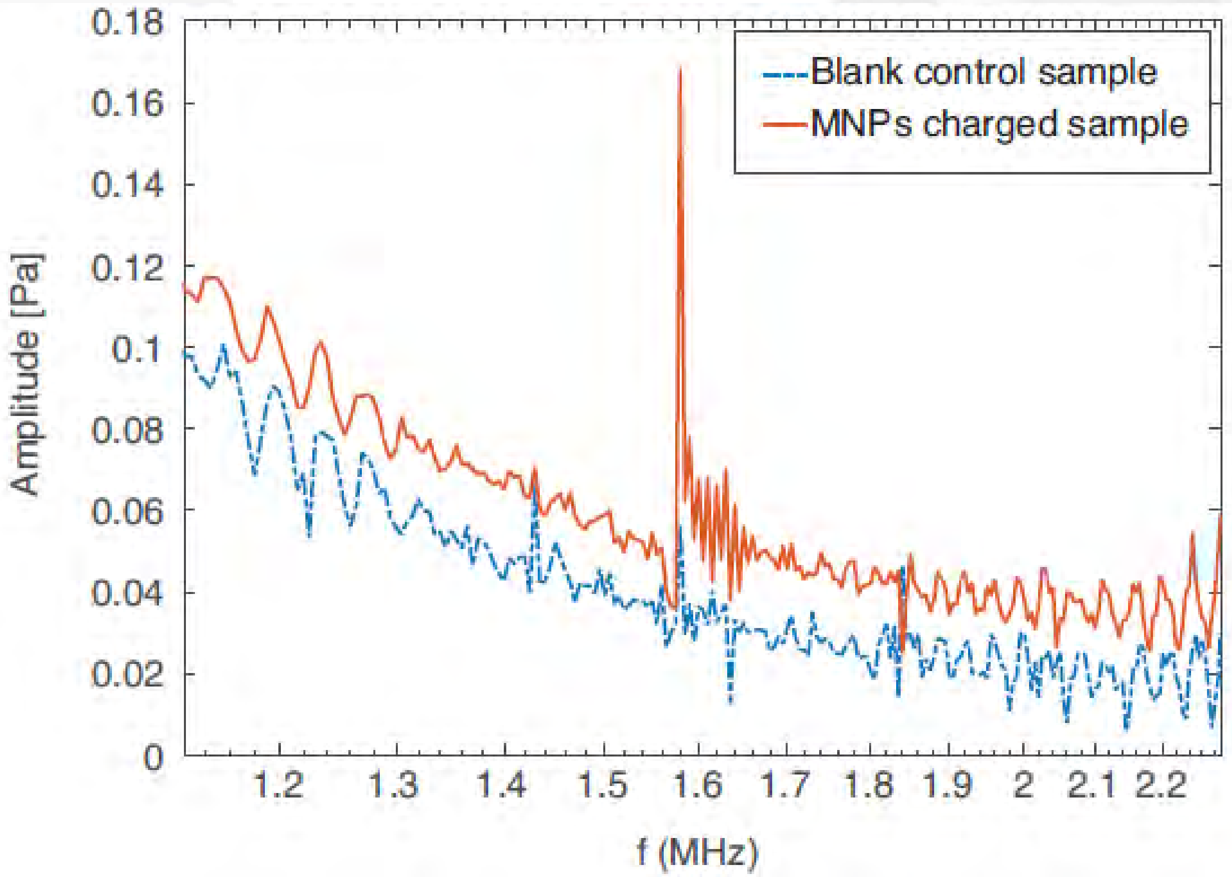


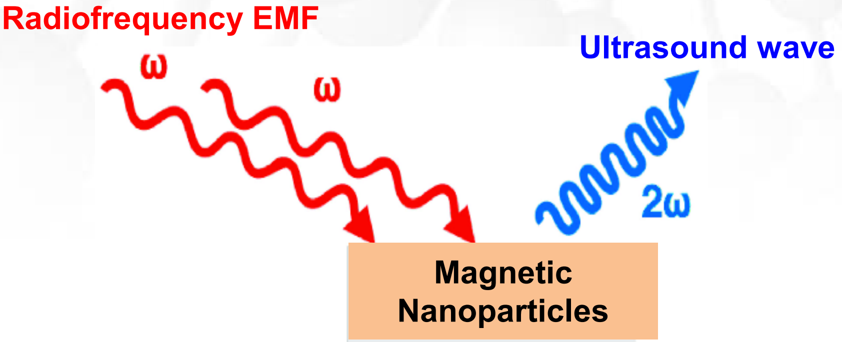
Experimental goals:
-Thermal stability (Short EMF burst)
-Lack of interferences and high sensitivity
-EMF gradients

Ultrasound response to the EMF



US signal due to the MNP



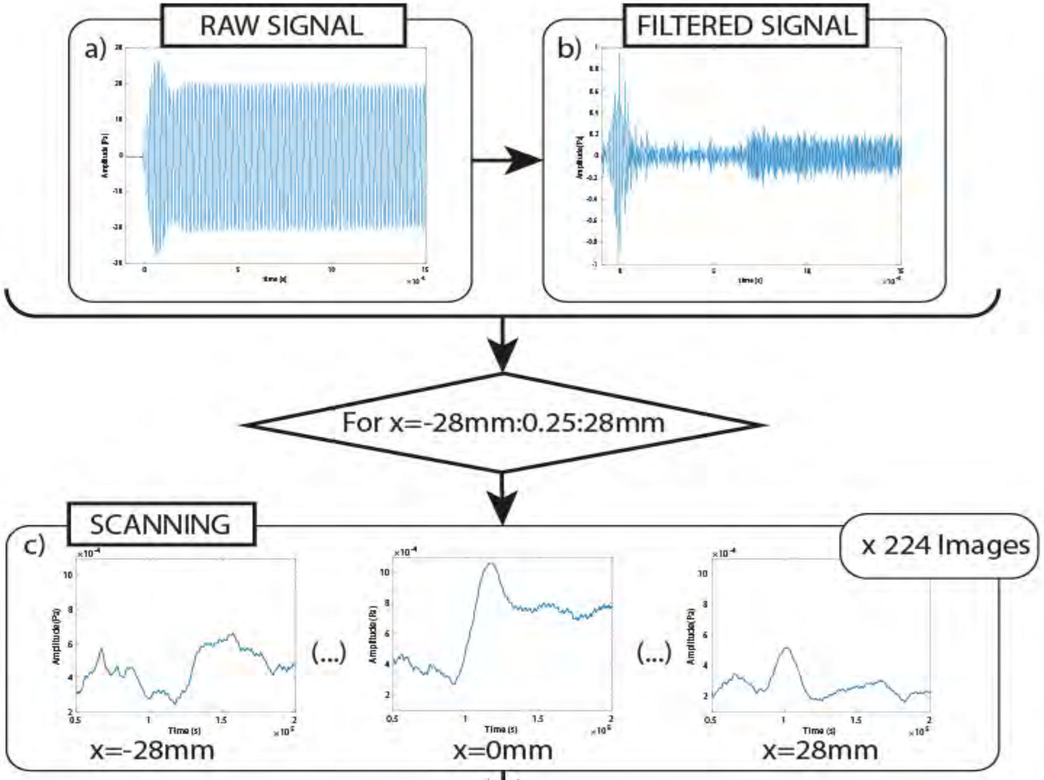


Radiofrequency EMF

Ultrasound wave

Magnetic Nanoparticles

Prototype for scanner



a) RAW SIGNAL

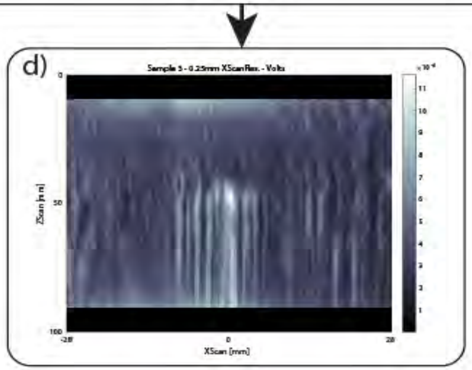
b) FILTERED SIGNAL

For x=-28mm:0.25:28mm

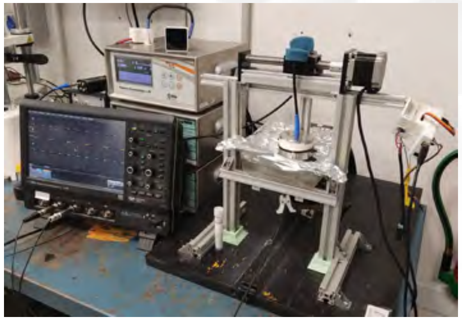
c) SCANNING

x 224 Images

x=-28mm (...) x=0mm (...) x=28mm



d)



Nanomagnetism provides new tools that allows a deep understanding of the phenomena that occurs at the nanoscale even at atomic level

This will allows to design new functional materials.

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THANK YOU FOR YOUR ATENTION

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