Whistler and Alfven Wave Generation Based on Superparamagnetic (SPM)Nanoparticles

THE NEXT STEP

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Outline

- Rotating Magnetic Field (RMF) Antennae – Mechanical Low Frequency Antennae – **What –When – Why – Issues**
- **What can we do with permanent magnets and rotating superconducting coils**
- **The hysteresis cycle as an ELF/VLF antenna – Problems**
- **New Technology – Metamaterials – Magnetic nanonoparticles (MP)**
- **Superparamegnetic (SPM) nanonaparticles**
- **SPM Anenna capabilities**
- **Back to applications**

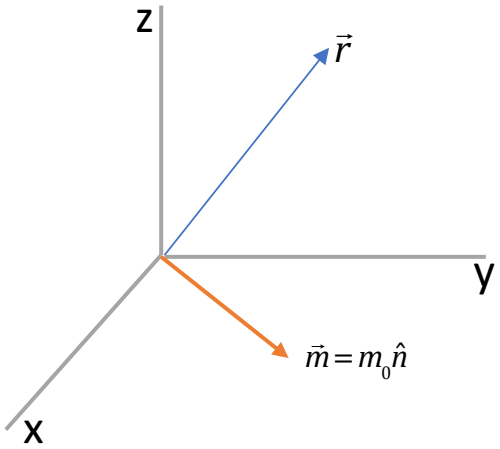
RMF – Basic Concepts - Experiments

RMF Fundamentals

$$\vec{A}=\frac{\vec{m}\times\vec{r}}{r^3}+\frac{\vec{m}'\times\vec{r}}{cr^2}$$

$$\vec{B}=\nabla\times\vec{A}$$

$$\vec{E}=-\frac{\partial\vec{A}}{\partial t}$$



For rotation in the x-y plane

$$\hat{n}=\{\cos\Phi,\sin\Phi,0\},\hat{n}'=\{-\sin\Phi,\cos\Phi,0\},\Phi\equiv[\omega(t-r/c)+\phi_o]$$

$$B_r=2\sin\theta(m_0/r^3)(\cos\Phi-k_o r\sin\Phi)$$

$$B_\theta=\cos\theta(m_0/r^3)[-\cos\Phi+k_o r\sin\Phi+(k_o r)^2\cos\Phi]$$

$$B_\varphi=(m_0/r^3)[-\sin\Phi-k_o r\sin\Phi+(k_o r)^2\sin\Phi]$$

$$\vec{A}(\vec{r},t)=\{0,A_\theta,A_\varphi\}$$

$$A_\theta=(m_o/r^2)(k_o r\cos\Phi+\sin\Phi]$$

$$A_\varphi=(m_o\cos\theta/r^2)(k_o r\sin\Phi-\cos\Phi]$$

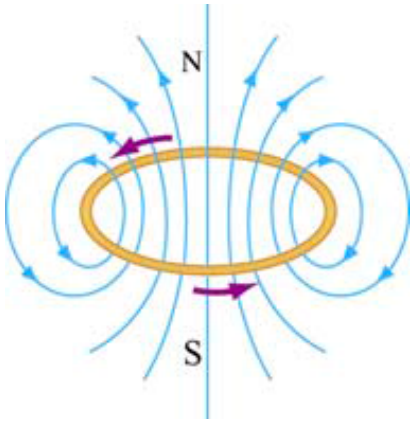
$$\Phi\equiv\omega t-k_o r$$

$$\vec{m}=(\mu_0/4\pi)m\hat{n}\equiv m_0\hat{n}$$

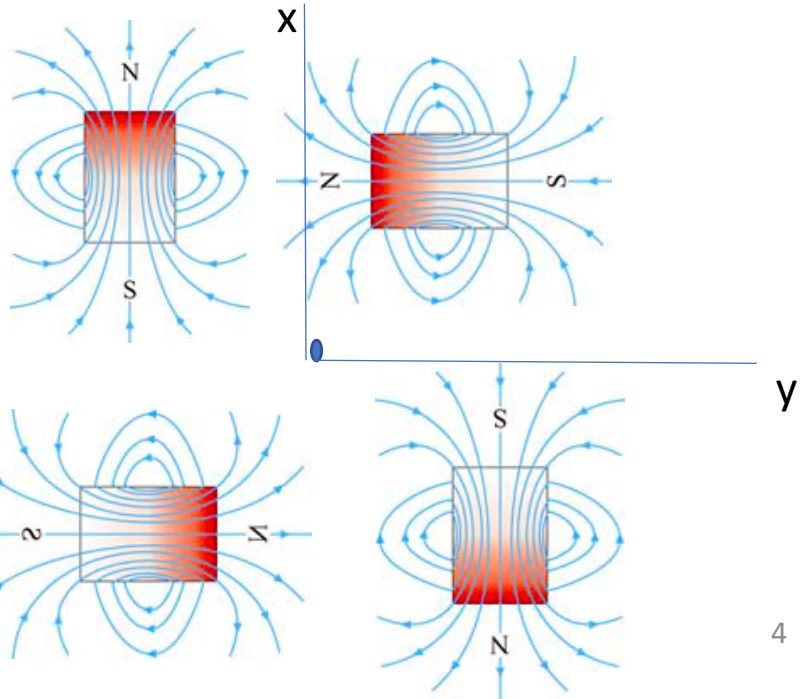
$$E_r=0$$

$$E_\theta=-\frac{\omega m_0}{r^2}(\cos\Phi-k_o r\sin\Phi)$$

$$E_\varphi=-\frac{\omega m_0}{r^2}\cos\theta(\sin\Phi+k_o r\cos\Phi)$$

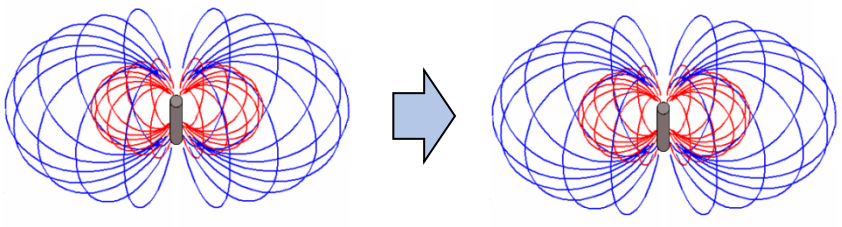


In the near zone
E(r)≈B(r)[ωr+c]



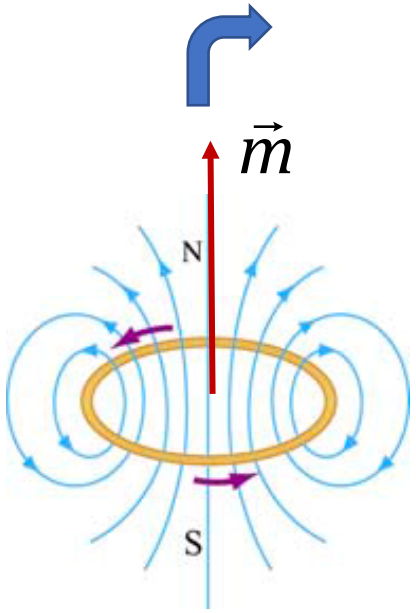
E field drives oscillatory currents in plasmas and conducting regions

RMF – Antenna Options

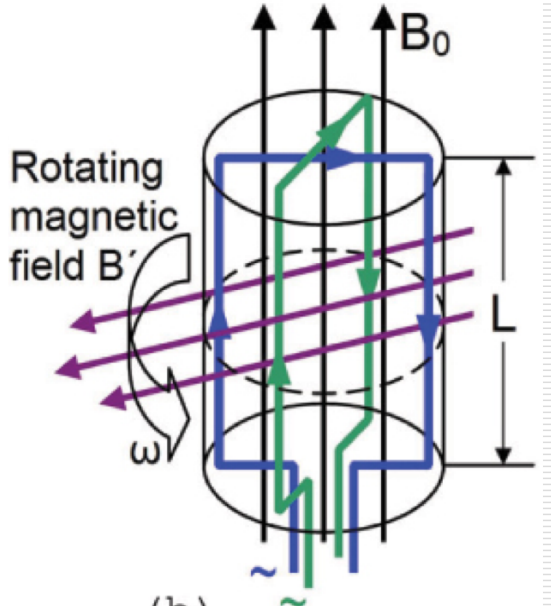


Static DC Field

Rotating AC Field



Rotating Superconducting Coil



Poly-phase Current Loops

RMF – PoP LAPD Experiments

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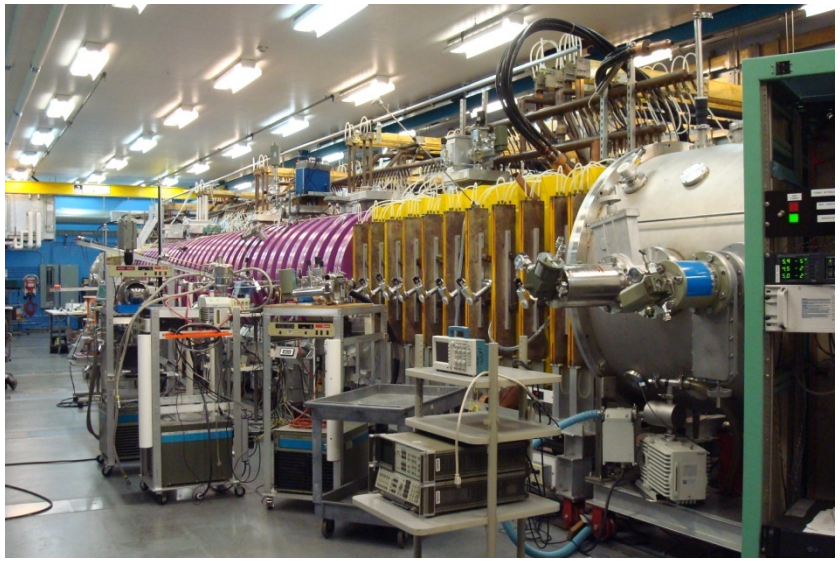
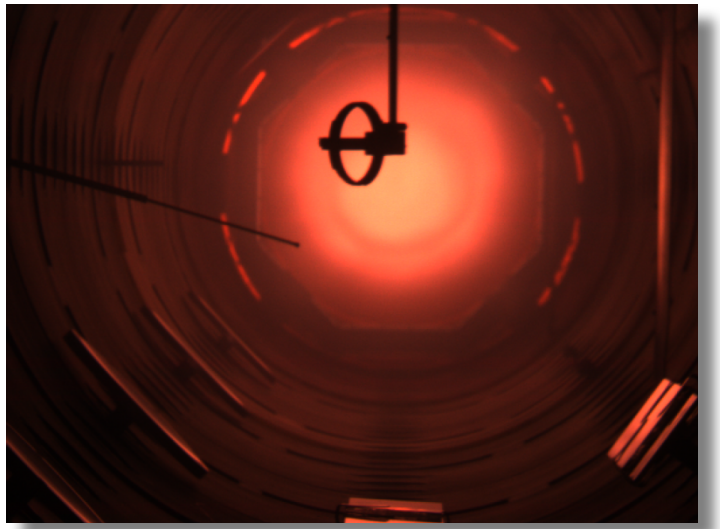
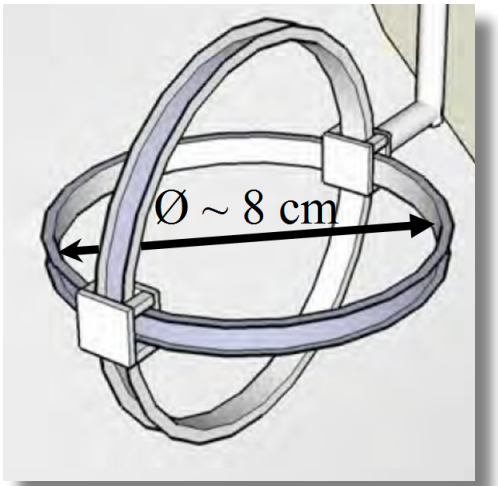
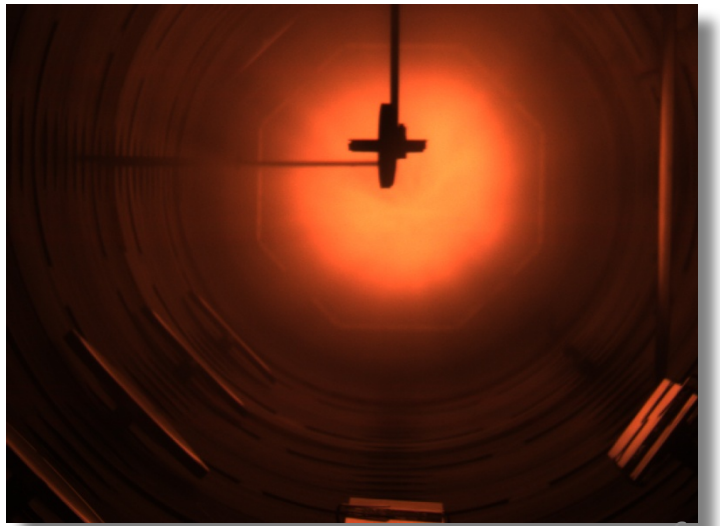


RMF Antenna:

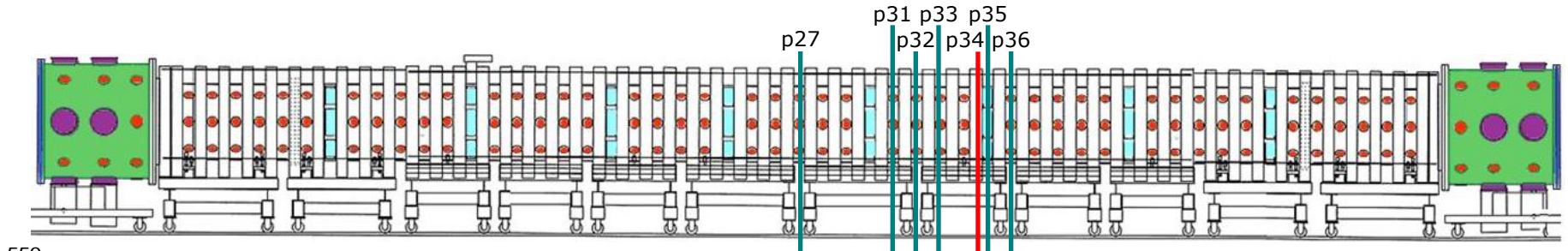
- Two independent coils: 4 turns each
- Operation frequencies 50kHz<f<500 kHz
- Current magnitude 100 – 300 A
- m=4-6 A-m^2

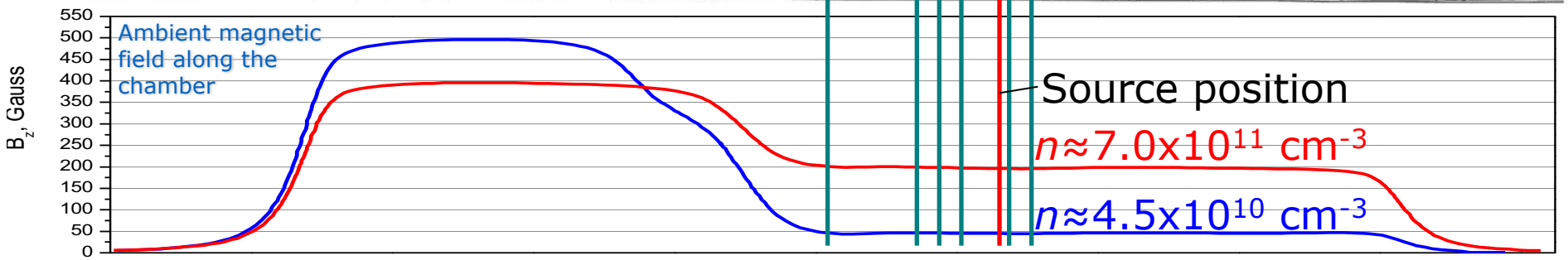


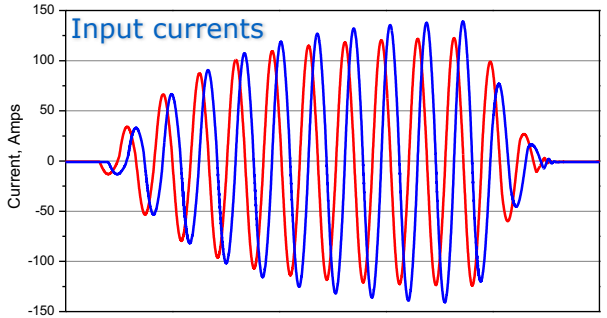




Experimental Set up - Whistler Experiments:







Background magnetic field

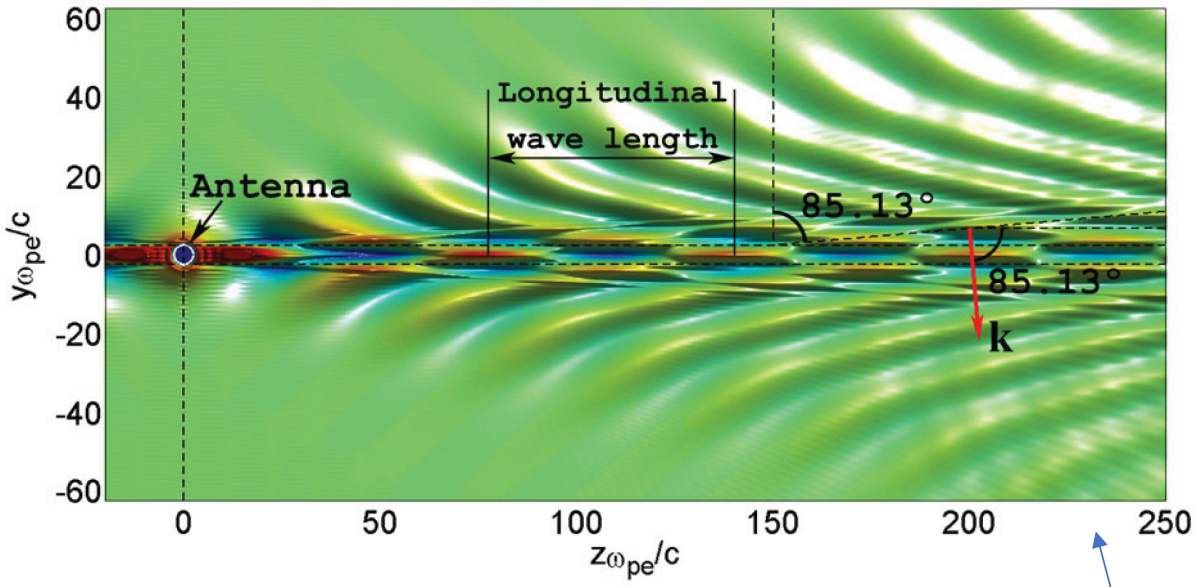
- 50 Gauss
- 200 Gauss

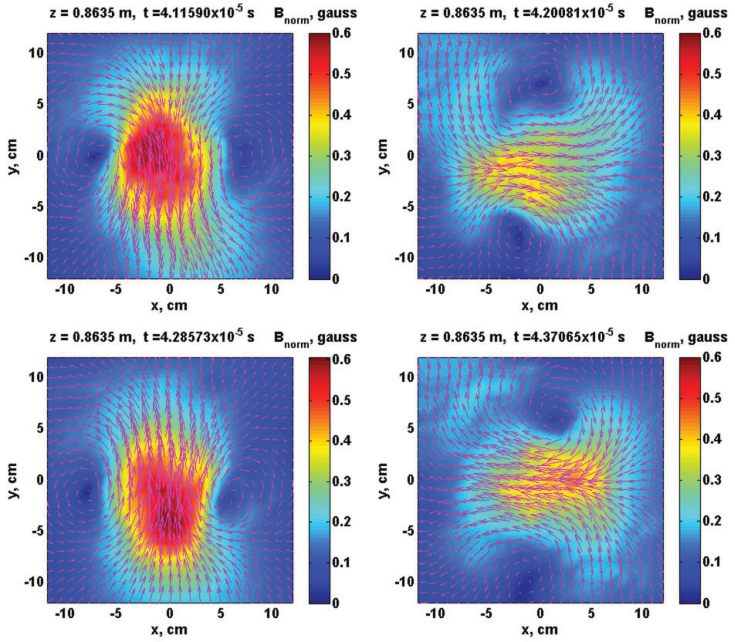
Two nearly identical currents with phase shift $\pi/2$

Frequency f=292 kHz ($\Omega_i << \omega << \Omega_e << \omega_{pe}$)

He gas

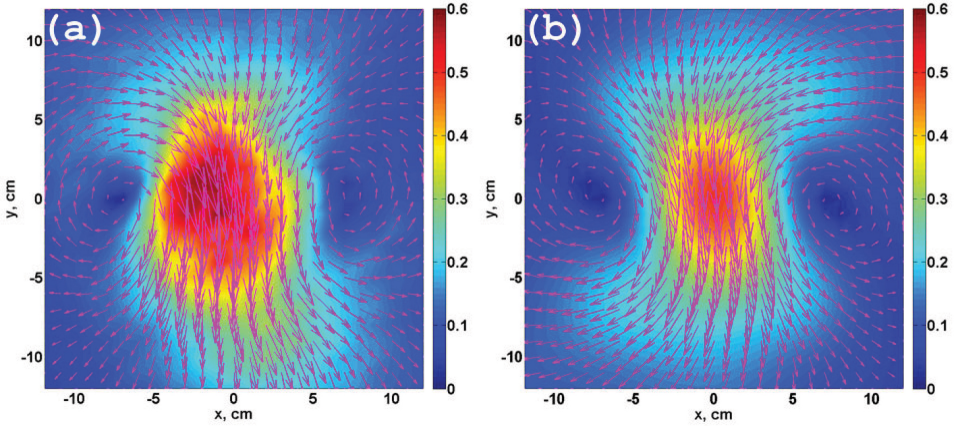
WHISTLER





f=293 kHz
B=50 G
$n=8.3\times10^{10}$ #/cm^3
z=.86 m

Fields separated by t=1/4f



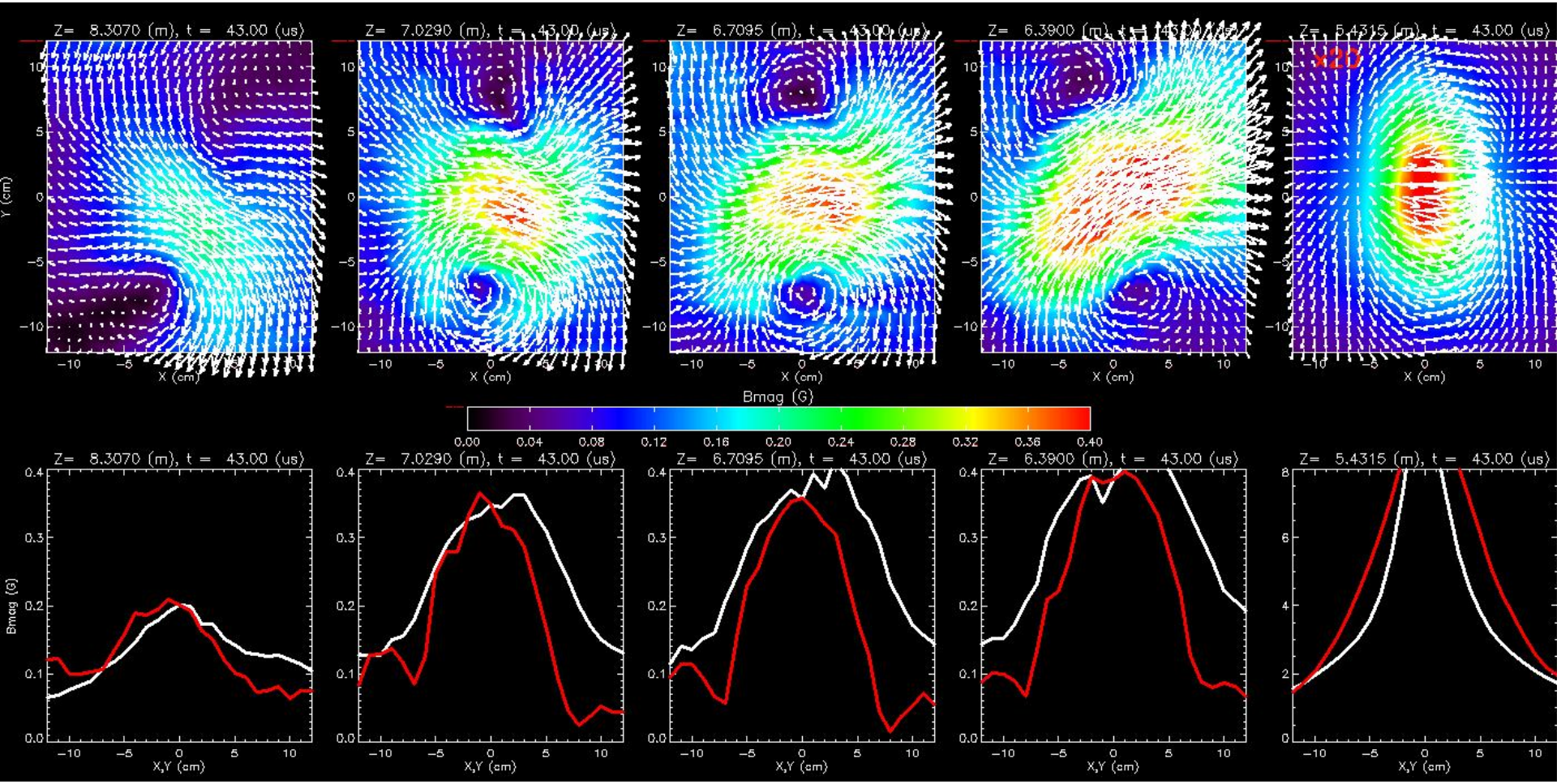
Experiment Simulation

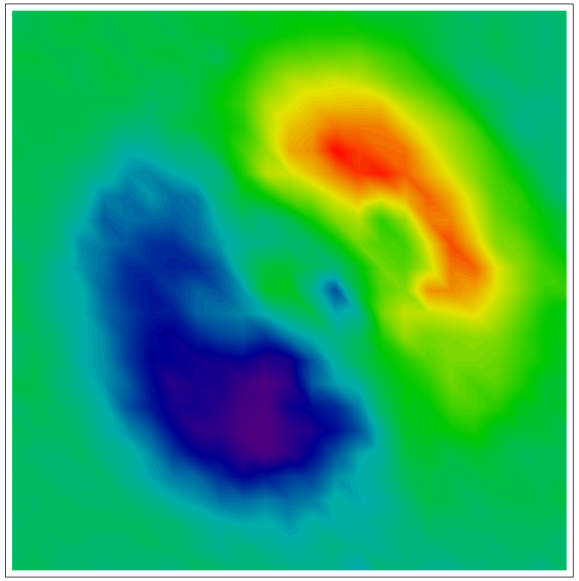
Whistler waves generated by the RMF have cone structure with the magnetic field along the central line much higher than that at the periphery.

At the planes perpendicular to the ambient magnetic field the wave magnetic field has two-vortex structure.

ALFVEN WAVES

p27 p31 p32 p33 p35



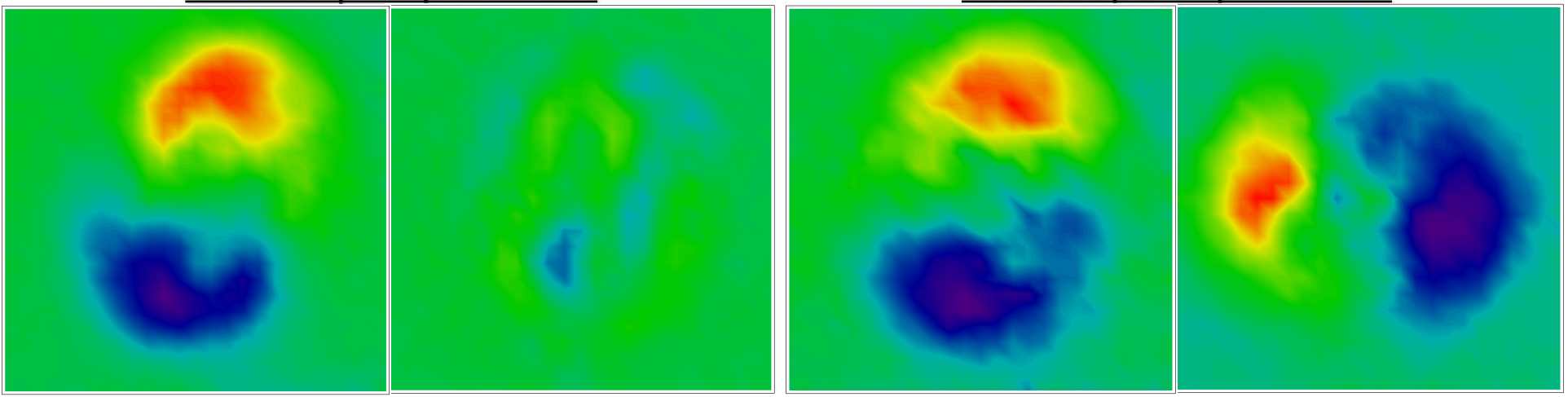


Current along ambient magnetic field line)

Current J_z along ambient magnetic field at t_1 and t_2

One loop experiment

Two loops experiment

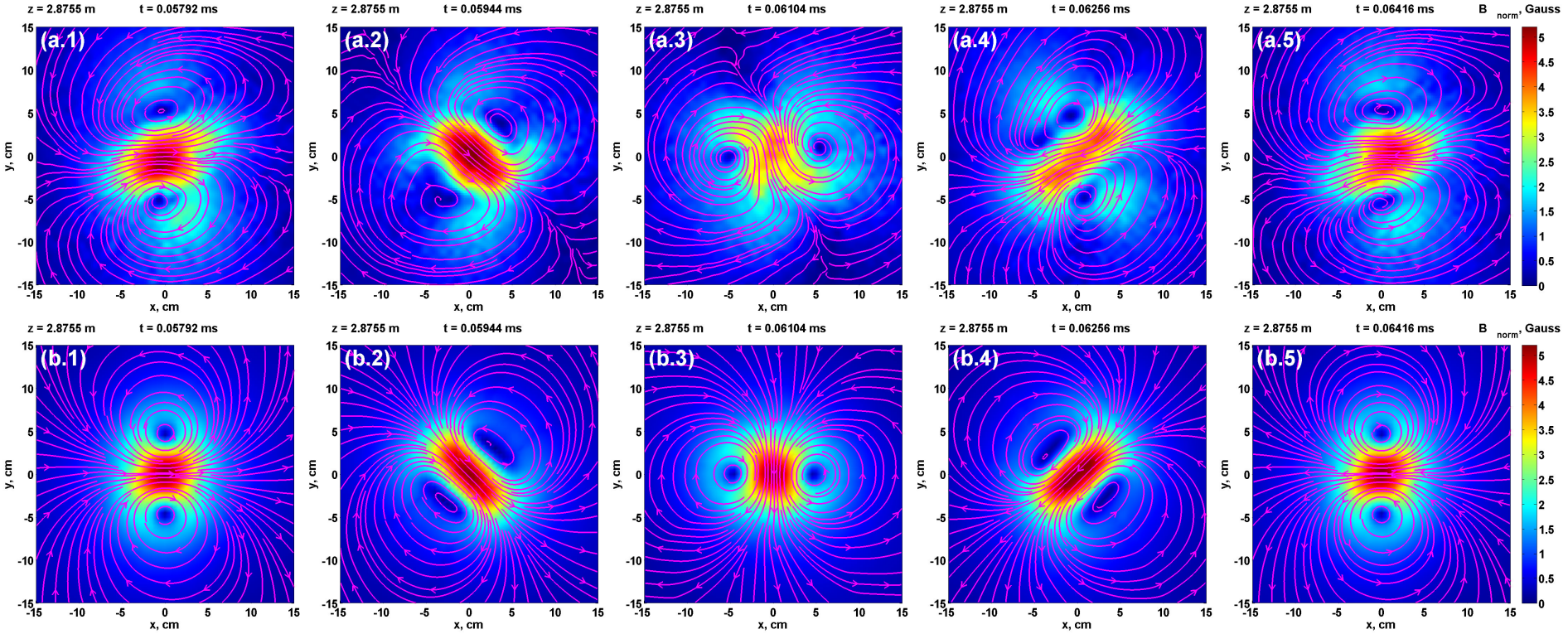


(, where T is the oscillating period)

One-loop: J_z current just oscillates around 0 with frequency ω.

Two-loop: *Jz* always has non-vanishing amplitude and rotates with the magnetic field about z-axis.

RMF Generated Shear Alfven Waves – f=80 kHz



z= 2.9 m
Fields separated by 1/8f

Experiment

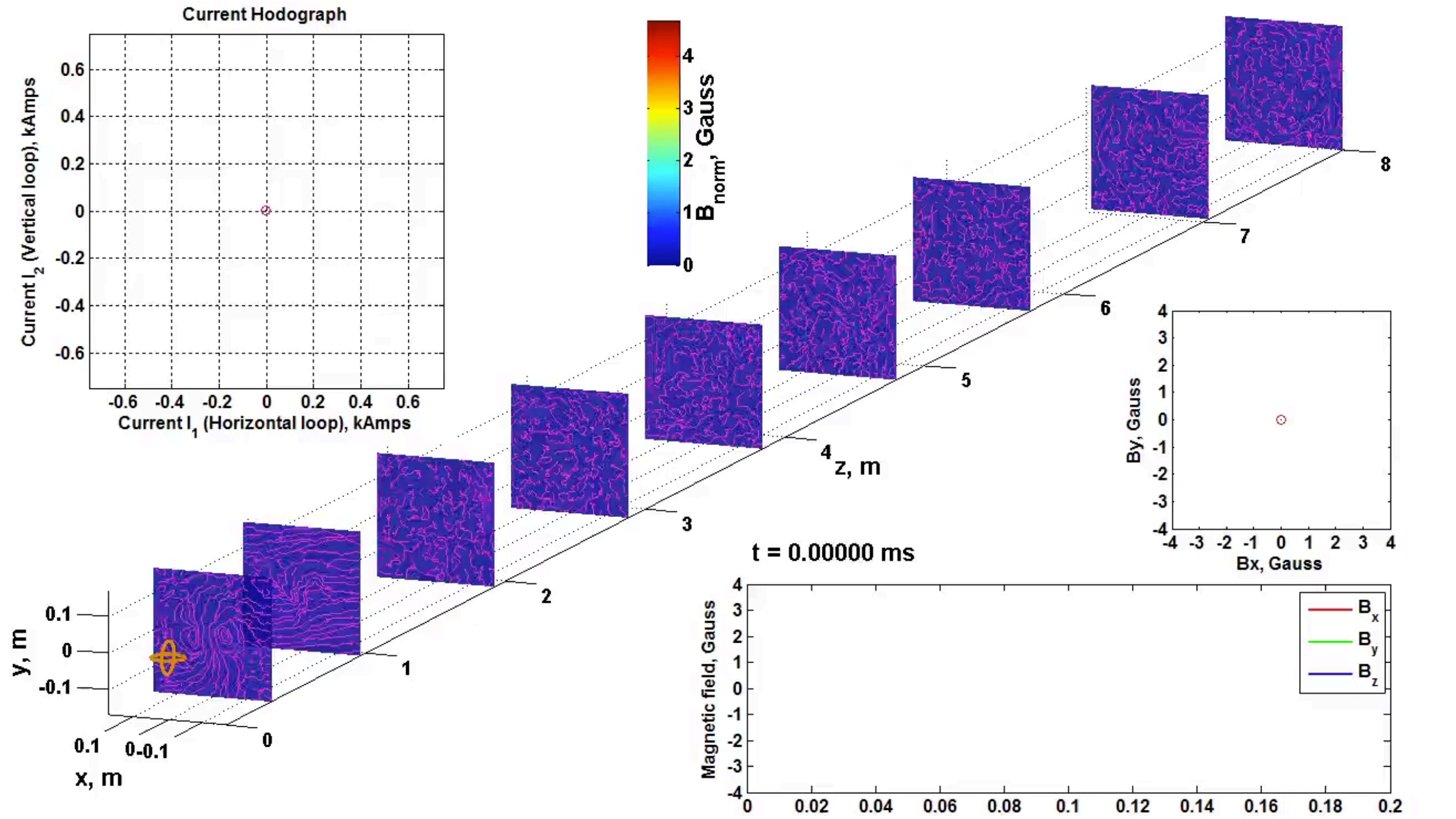
Simulation

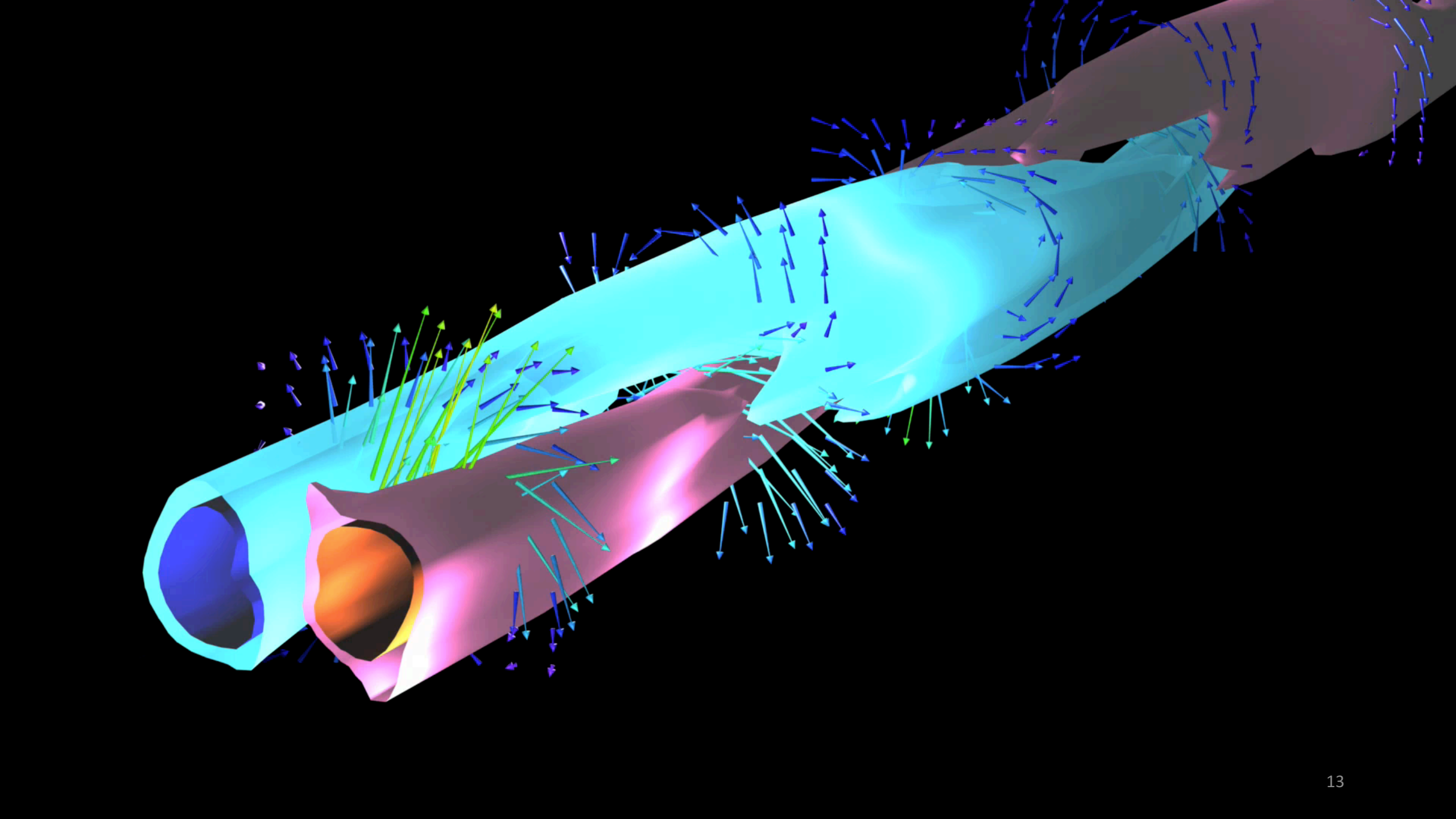
SAW magnetic field structure in the plane perpendicular to the ambient magnetic field generated by the RMF source with left-handed polarization (z ≈ 2.9 m).

In the plane perpendicular to the ambient magnetic field the RMF generated wave has two-vortex structure.

The vortices correspond to field aligned currents.

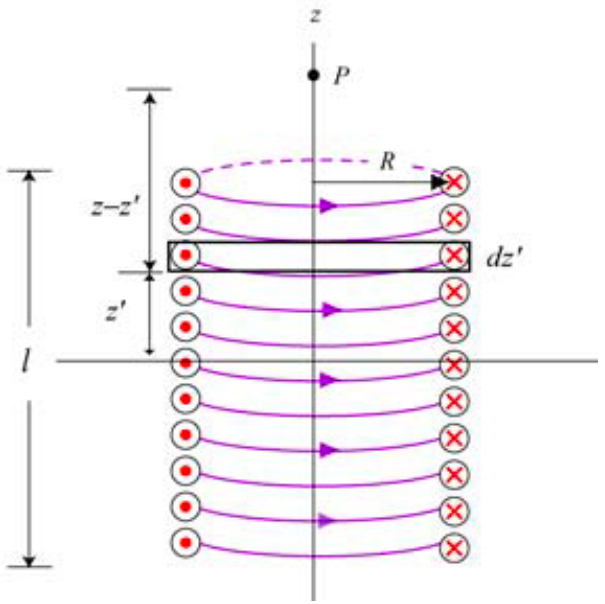
Magnetic field in the center rotates clockwise or counterclockwise depending on the polarization of the RMF source

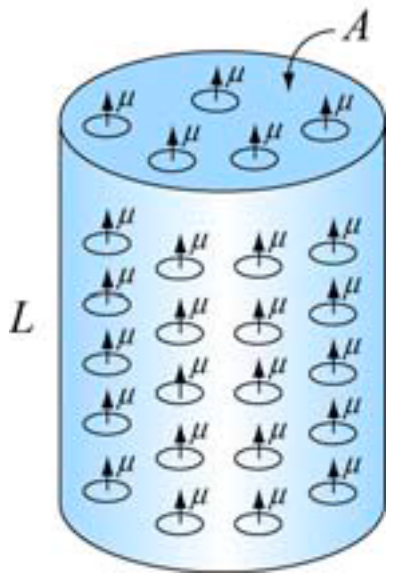

Current Hodograph
Current I2 (Vertical loop), kAmps
Current I1 (Horizontal loop), kAmps
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.6 -0.4 -0.2 0 0.2 0.4 0.6
B norm, Gauss
4
3
2
1
0
z, m
0
1
2
3
4
5
6
7
8
y, m
0.1
0
-0.1
x, m
0.1
0
-0.1
By, Gauss
Bx, Gauss
4 3 2 1 0 -1 -2 -3 -4
t = 0.00000 ms
Magnetic field, Gauss
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2
Bx
By
Bz

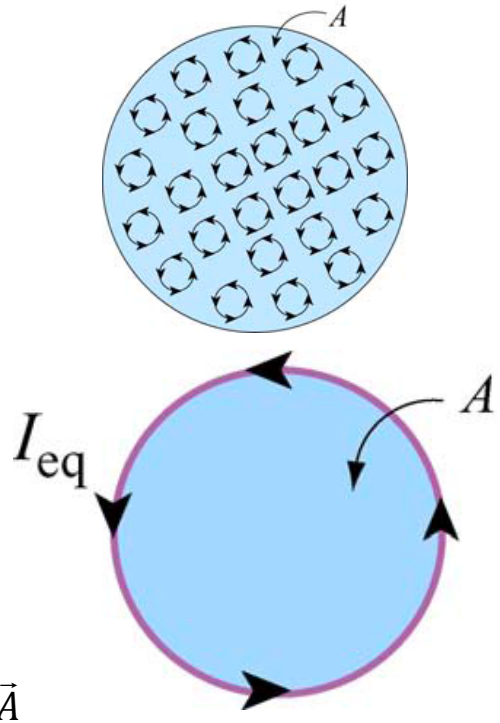


RMF Applications - Limitations

Equivalence of current loops and magnetic cylinders:







$$\vec{m} = NI\vec{A} = \frac{N}{l} Il\vec{A} \equiv Kl\vec{A}$$

$$\vec{m} = ML\vec{A} = n\mu L\vec{A} \equiv K_{eq} L\vec{A}$$

$$K_{eq} = M = n\mu$$ **Equivalent surface current equals magnetization M**

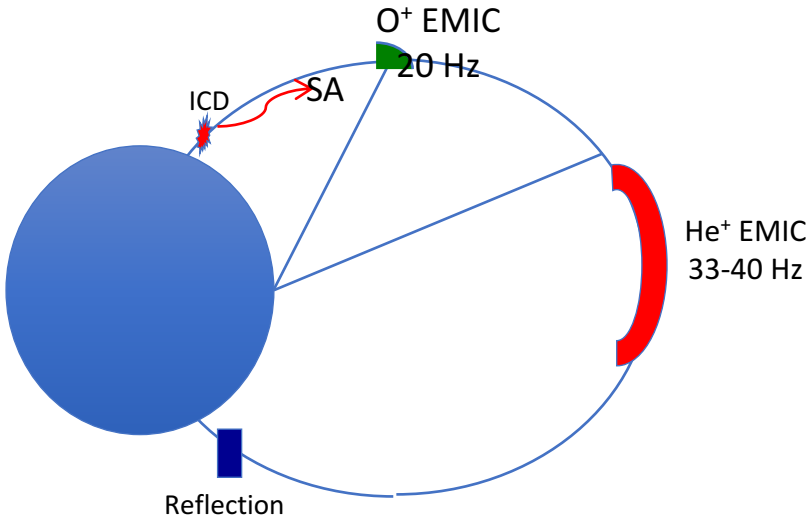
Example – Magnetization of iron

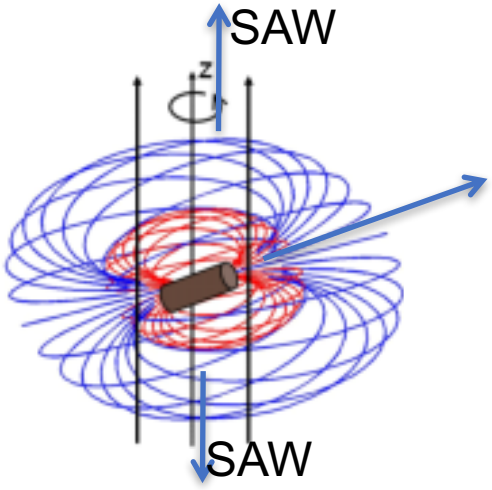
Product of net magnetic moment per atom ($2.22\mu_B$ for iron) and number of atoms present. For iron $n \approx 10^{29}$ #/m^3 $M \approx 2.2 \times 10^{29} \times 10^{-23}$ (A-m^2/m^3) $\approx 2 \times 10^6$ A/m and B ≈1.2 T.

In LAPD m≈4-6 A-m^2 that since for iron M≈2×10^6 A/m can be reproduced by an iron magnet with volume 2-3 cm^3

$$K_{eq} \approx (n/10^{29})(\mu/\mu_B) MA/m$$

EMIC Waves Why ? Dual RBR - PRBR



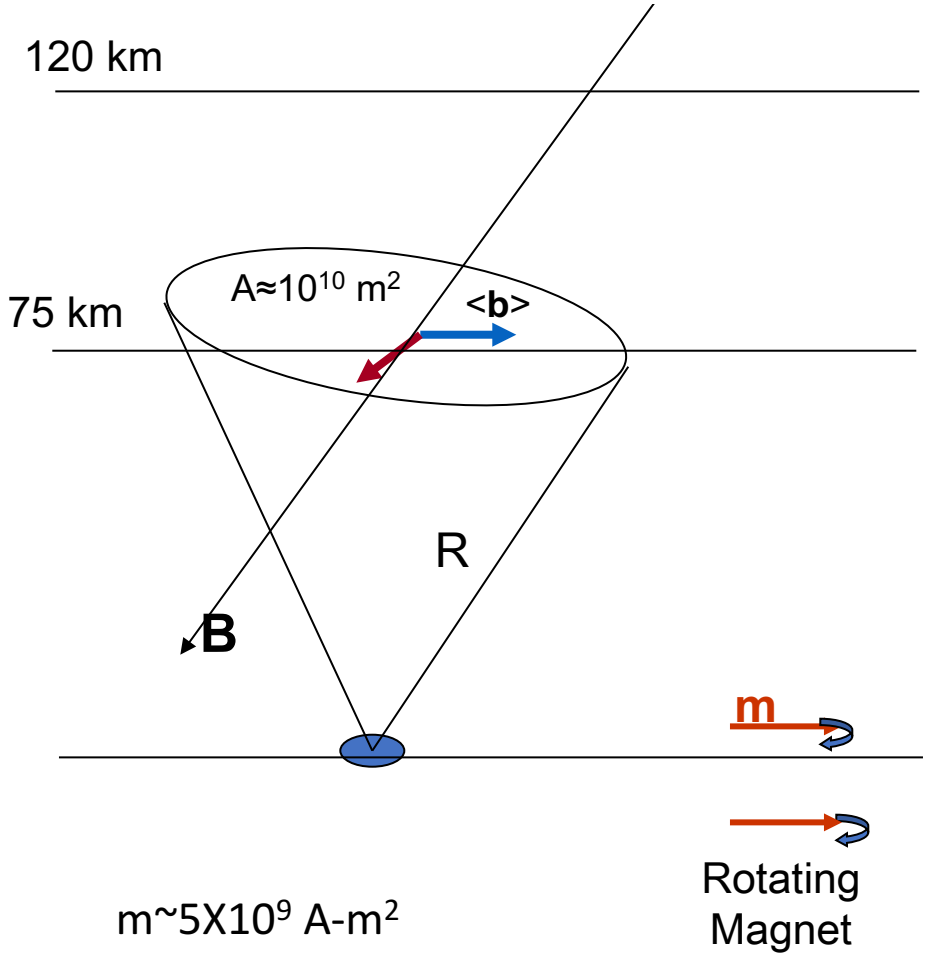


$m \approx MV \approx 2x10^3 (M/2x10^6)(V/10^{-3})$ A-m^2

Major drawback of rotating permanent magnets is limitations on the rotation spin rate and difficulties of modulation.

PRBR – EMIC RBR

To inject 1 kW we require <b>≈30 pT at 75 km, the bottom of the magnetized ionosphere.



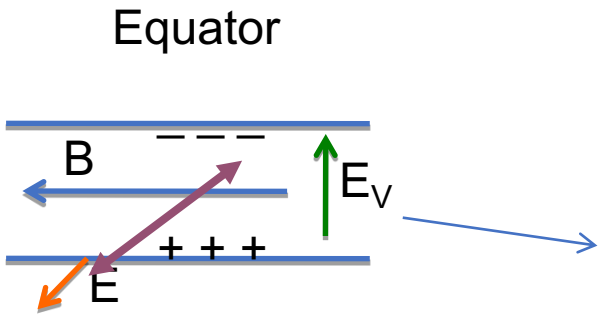
$m \sim 5X10^9$ A-m^2

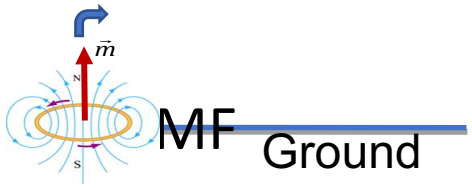
A superconducting magnet rotating at a ULF frequency has a reflected image in phase with primary

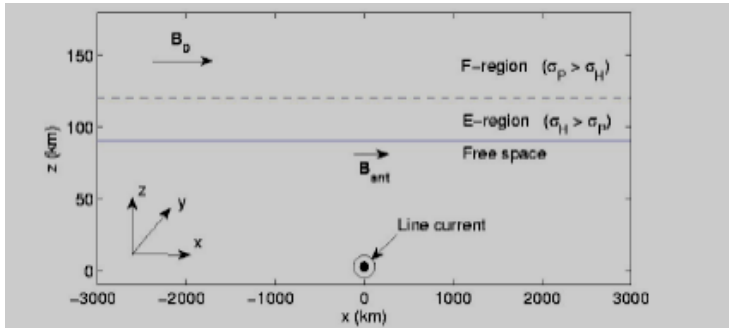
Innovative Sources

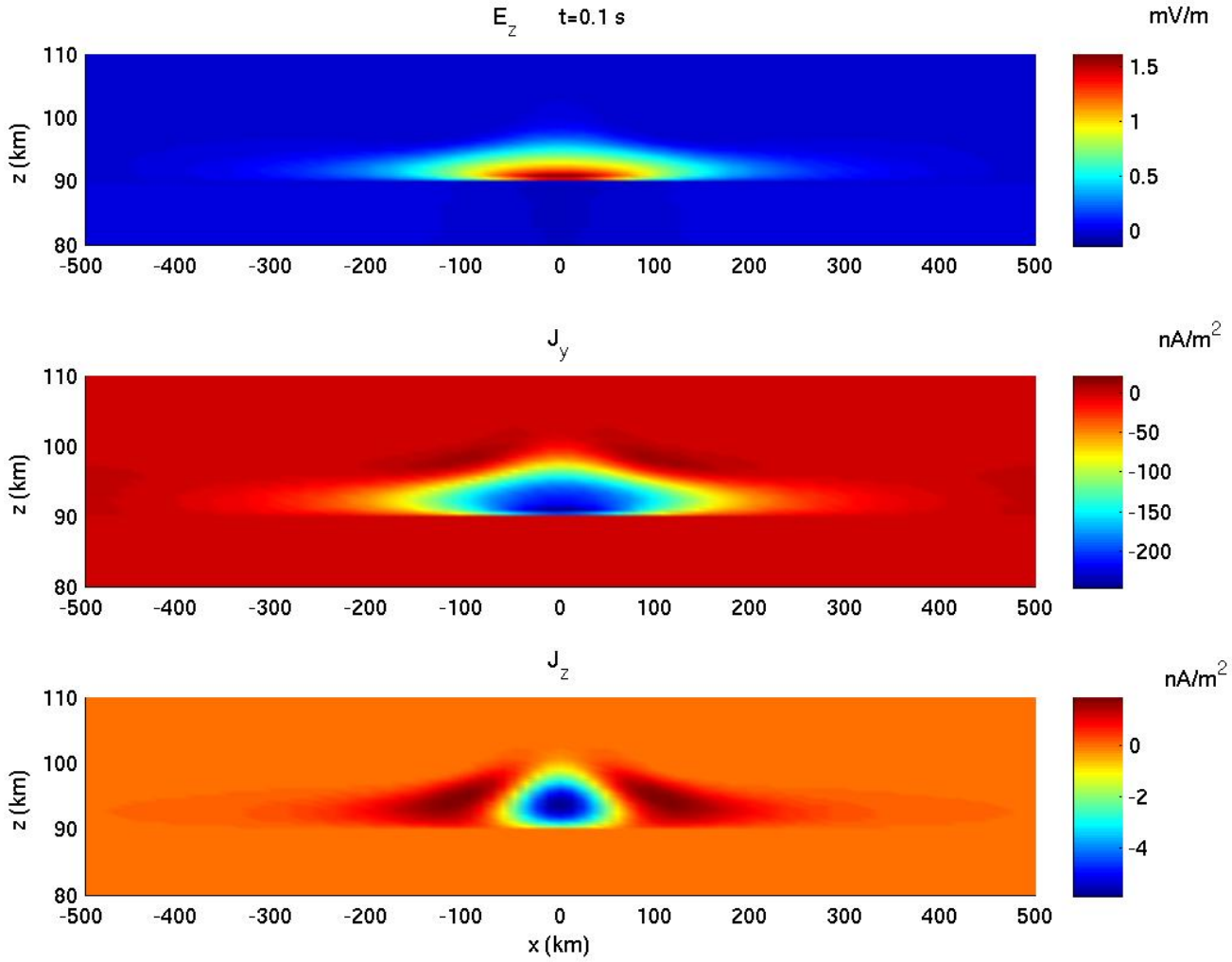
- Rotating superconducting magnets are useful for frequencies of up to 40 Hz
- They are compact sources of large moments and can be used in arrays
- Example design:
  - Superconducting coil 5 m high x 5 m wide x 5 m long
  - 25 m^2 area
  - 100 Amps DC current
  - 4 x 10^4 turns
  - M = 10^8 A-m^2

Magnetic Equator Cowling effect amplifies E by 20

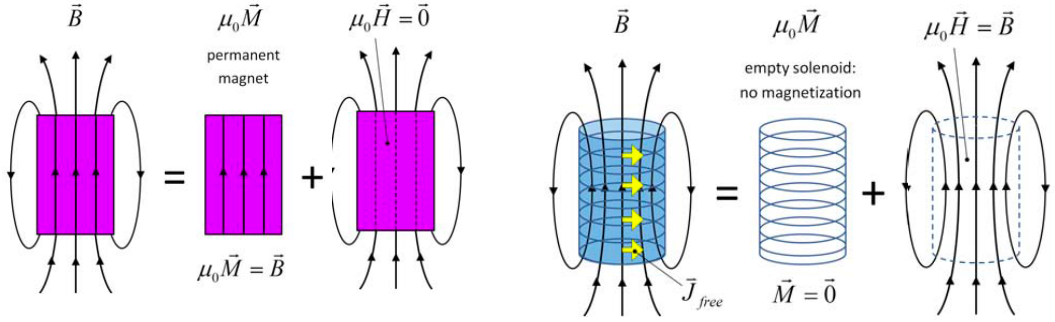




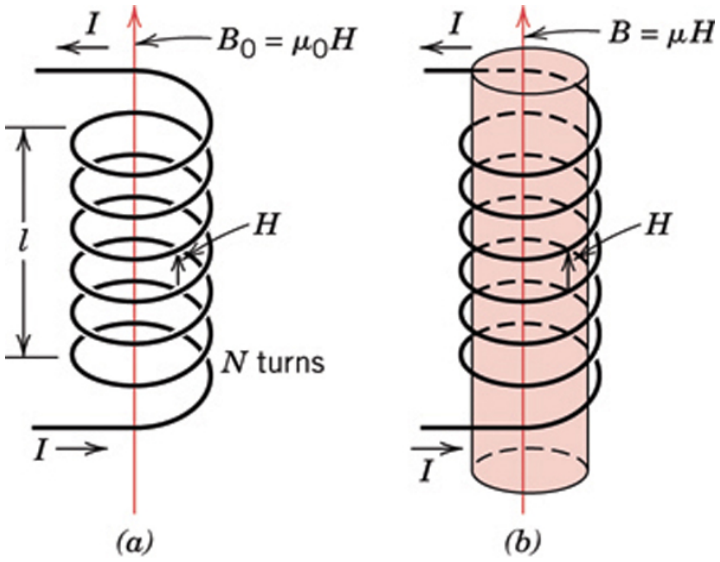




The Hybrid alternative - Combining magnetic cylinders with current loops

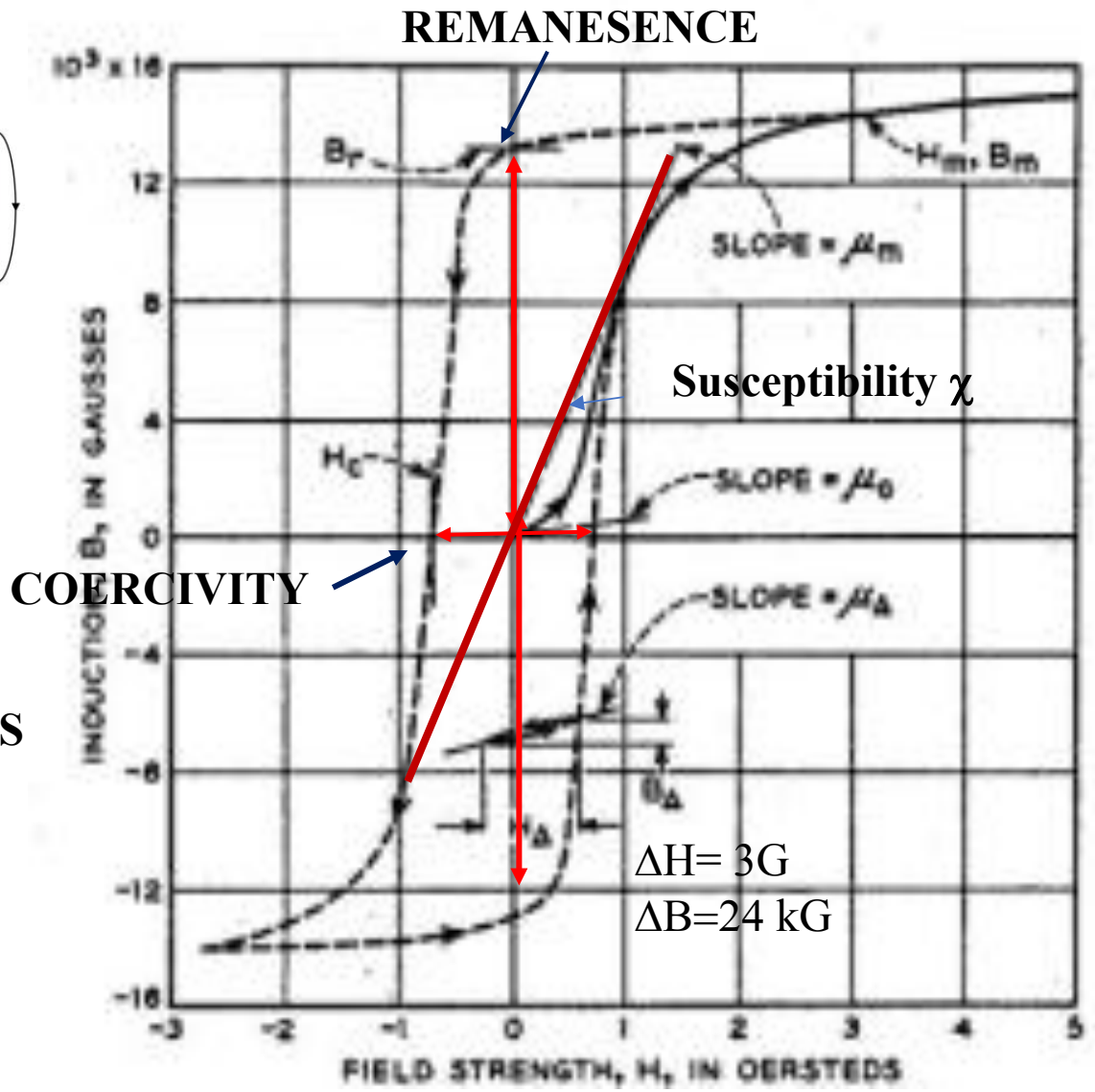


$H = (N/l)I = KI$ $\quad B=\mu_o H+\mu_o M$



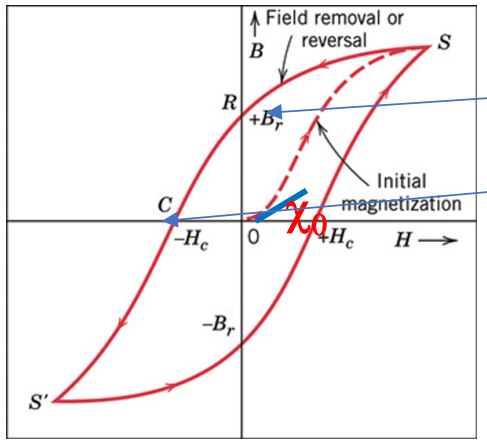
$M=\chi_m H$

CRITICAL ISSUE
HYSTERESIS LOSS
.5 kJ/m^3 per cycle
Eddy Current loss



High χ
Small H_c
Low σ

Optimizing hysteresis loop of magnetic material for RMF transmitters

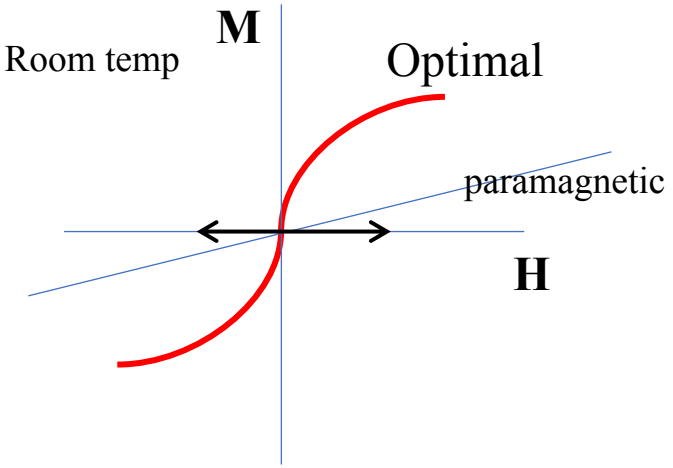


For **FM** materials **M** increases *with* ***H*** until $\mathbf{B_s}$ and $\mathbf{M_s}$ are reached. When H->0 some magnetism, call **remanence**, remains at $\mathbf{B_r}$. ***H*** field must be reversed to $-\boldsymbol{H_c}$ to eliminate residual magnetism (**coercivity**). The slope of the magnetization curve is called **susceptibility**. The area in the hysteresis loop represents work or energy expended in going from (+) to (-) ***H*** and back. The product of **B*H** is measured in **kJ/m^3 or gauss-oersted (MGOe).**

$$\mathbf{B=\mu_o (H+\chi M)}$$

Properties of ideal magnetic material for ELF/VLF transmitter applications:

1. **High value of M_s**
2. **High positive value of susceptibility χ_o**
3. **Zero remanescence (M=0 at H=0) (non-interacting m)**
4. **Open hysteresis loop**
5. **All at room temperature**



Paramagnetic: 3,4,5 Yes; 1,2

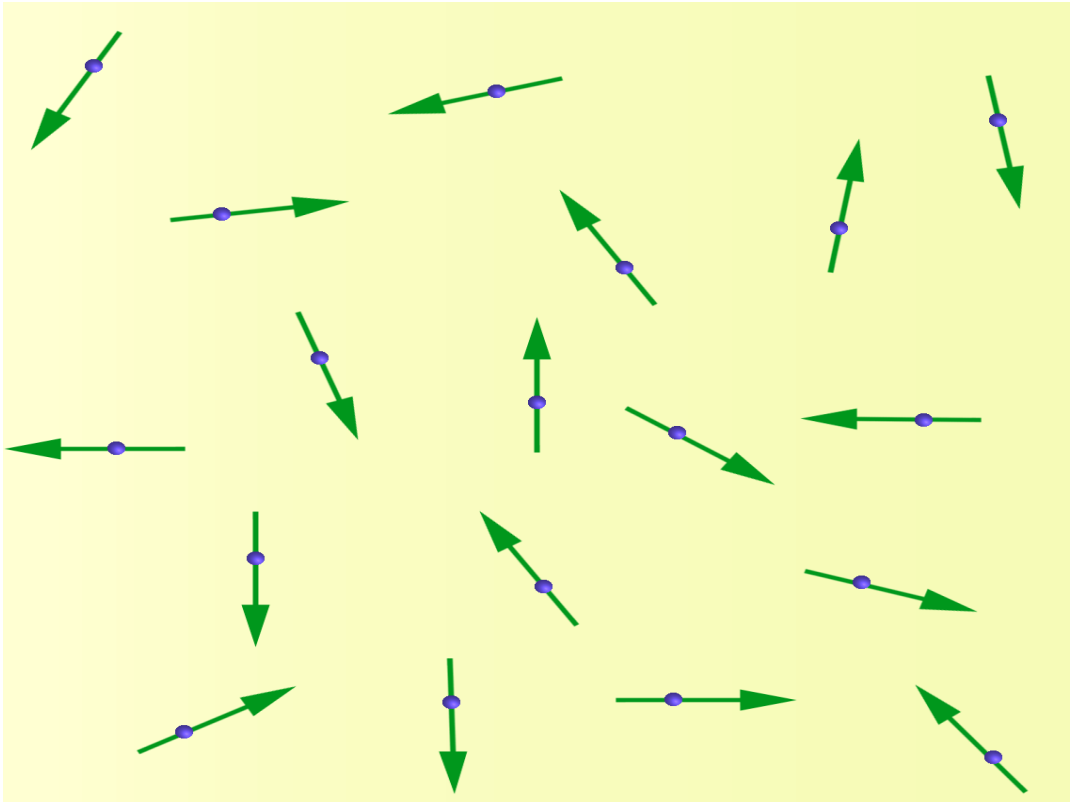
Ferromagnetic: 1, 2 ,5 Yes; 3,4 No

Challenge: Create artificial material with an-hysteresic (open) loop and high χ and short response time τ, τ<<1/f

New technology – Superparamagnetic nanoparticles

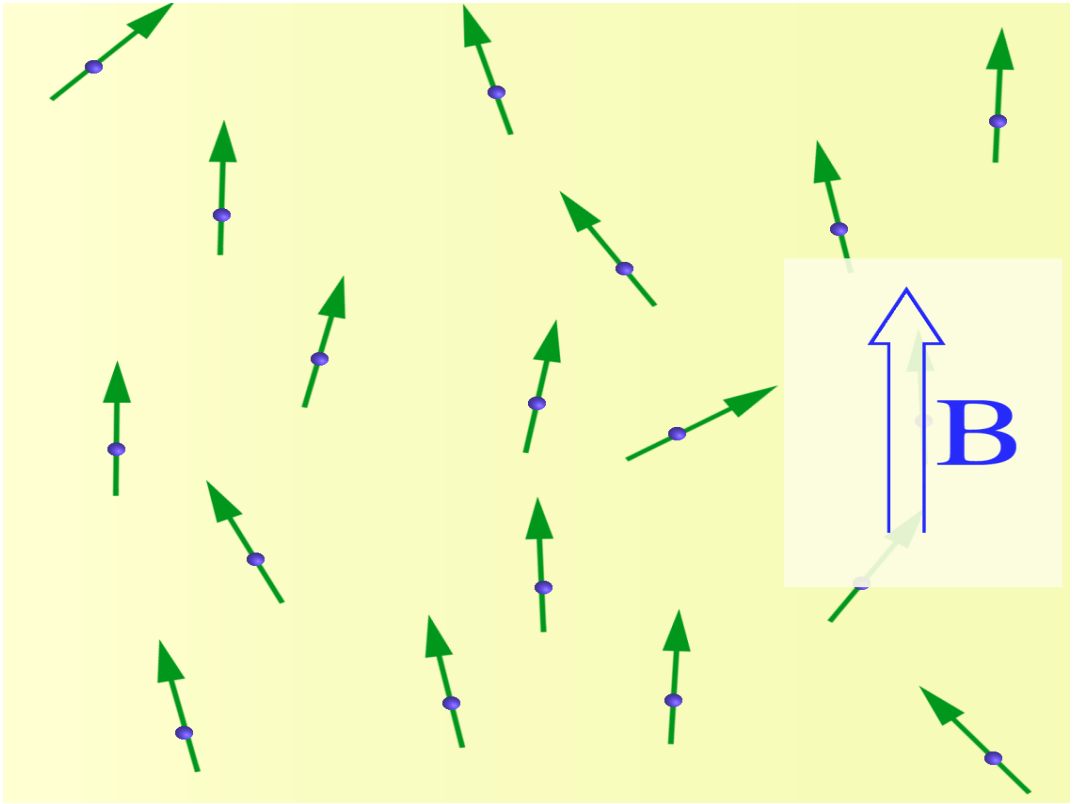
The Importance of Size and Temperature

Paramagnetic gas



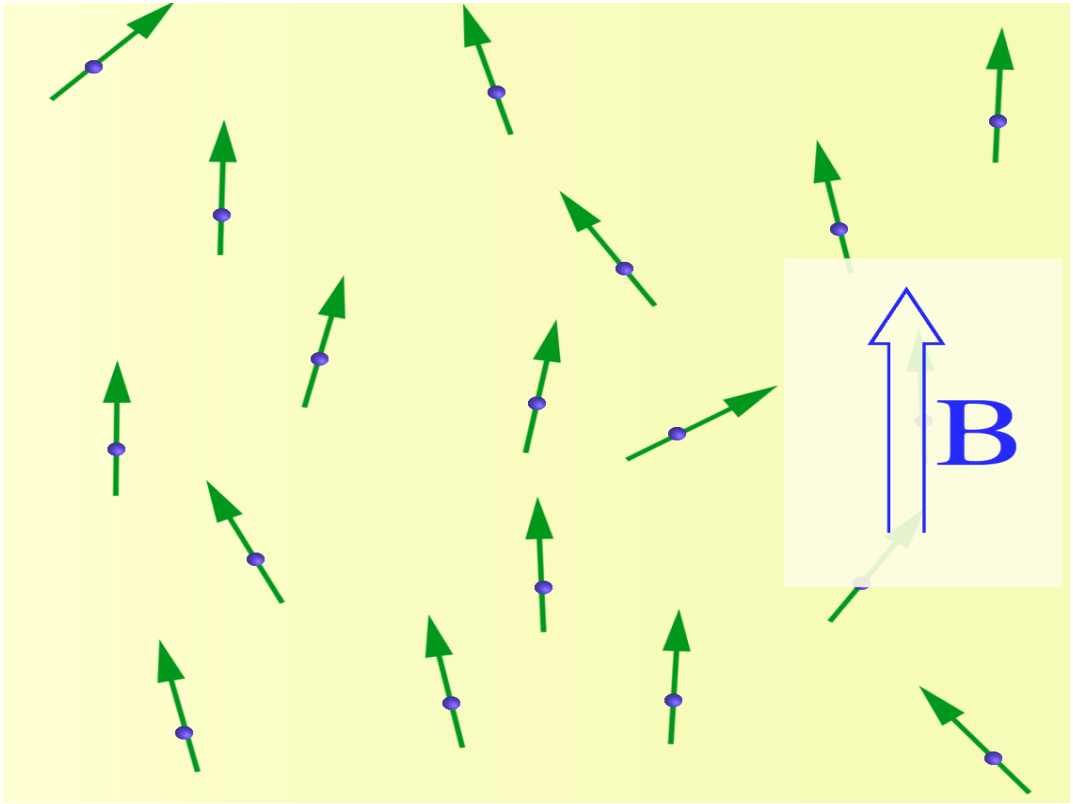
- Imagine a classical gas of molecules each with a magnetic dipole moment
- In zero field the gas would have zero magnetization

Paramagnetic gas



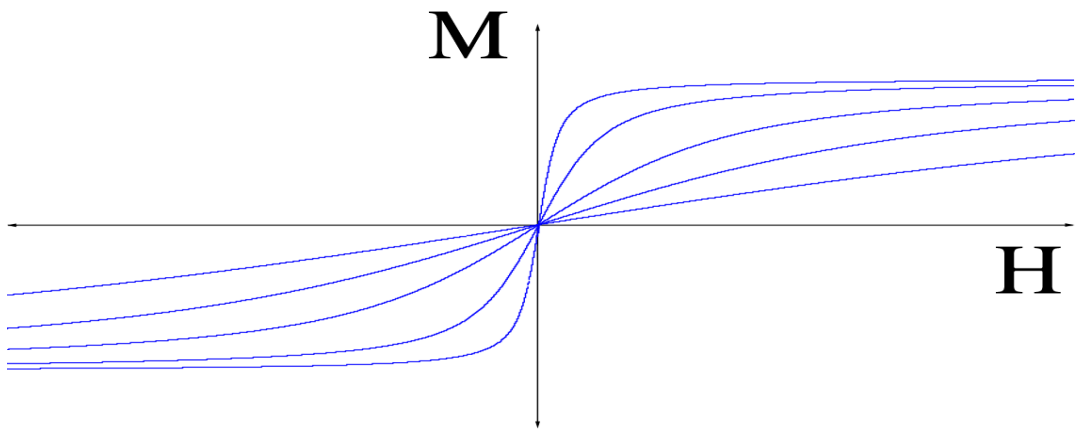
- Applying a magnetic field would tend to orient the dipole moments
- Gas attains a magnetization

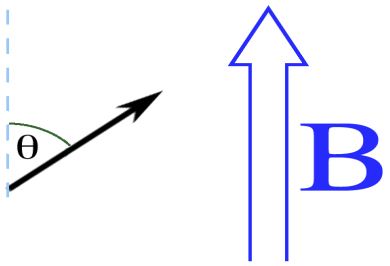
Paramagnetic gas



- Very high fields would saturate magnetization (all moments aligned)
- Heating the gas would tend to disorder the moments and hence decrease magnetization

Paramagnetic gas





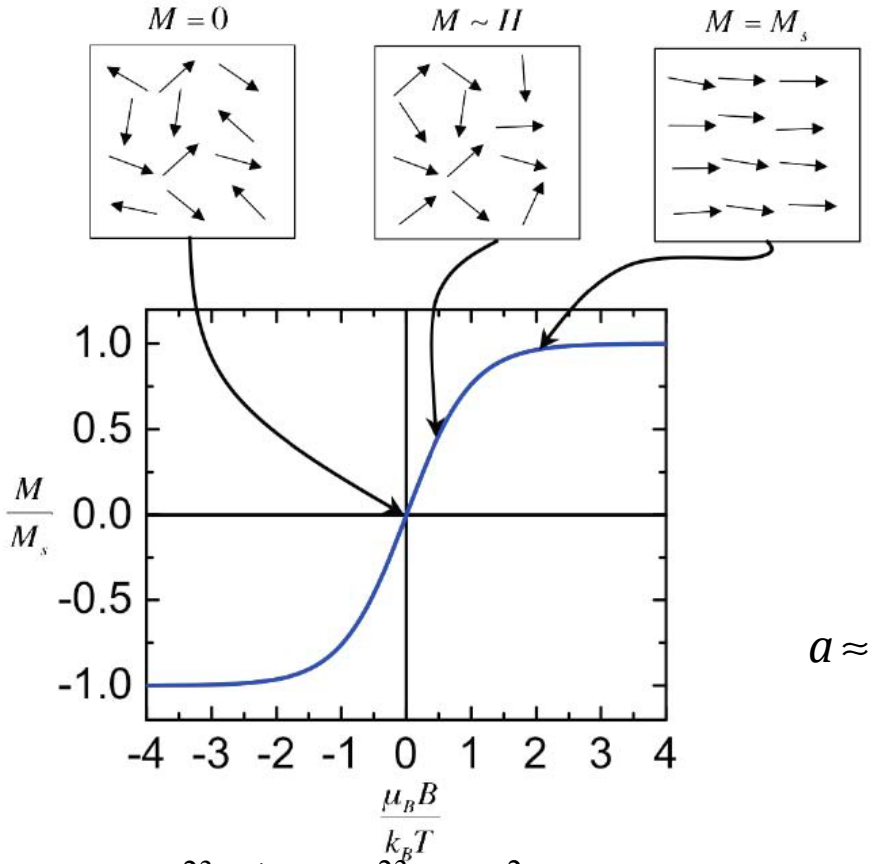
$$E = -m\ B\ \cos[\theta]$$

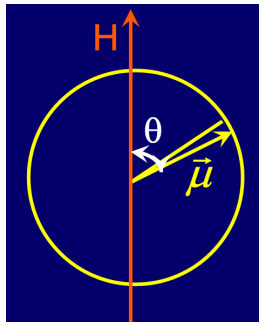
- Theoretical model
- Non-interacting moments
- Boltzmann statistics
- Dipole interaction with B
- Yields good model for many materials
- Examples: ferrous sulfate crystals, ionic solutions of magnetic atoms

The Langevin function

Paramagnetic materials – Caused by spin of unpaired electrons (e.g. manganese, sodium, aluminum…), $\chi \sim 10^{-2} - 10^{-6}$

Can be treated as a gas of non-interacting magnets $m \approx \mu_B$ – Langevin theory predicts their behavior key parameter $a = mB/k_BT$



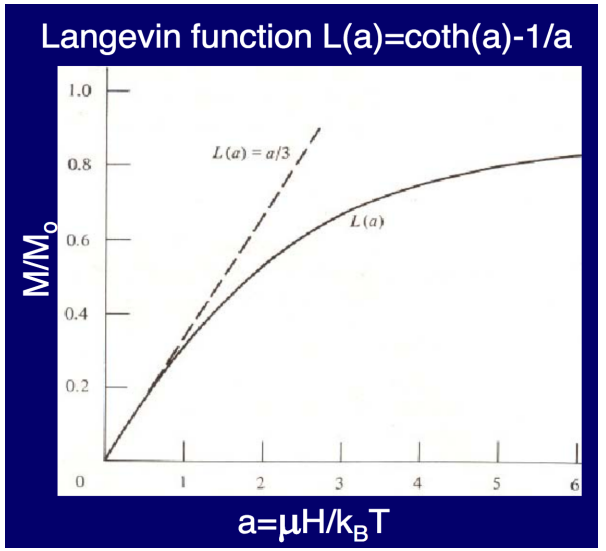


$$E = -mB\cos\theta \qquad M = nm[\coth(a) - \frac{1}{a}]$$

$\chi = n\mu_0 m^2 / k_B T < 10^{-3}$

$$a \approx 3x10^{-3}(T/300K)(B/T)$$

NO HYSTERESIS



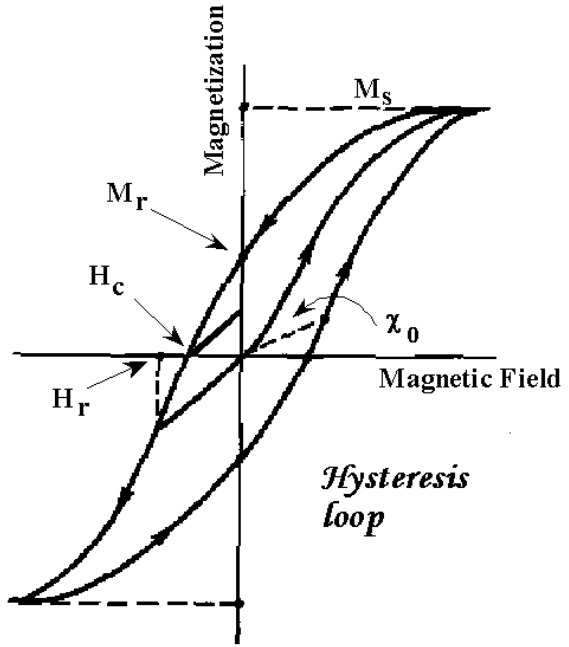
$\mu_B = 10^{-23}$ J/T$=10^{-23}$ A-m^2

$k_B = 10^{-23}$ J/K

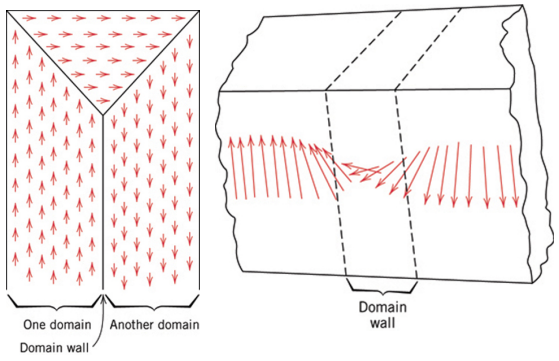
Quantum model Brillouinfunction

What causes hysteresis in FM materials ?

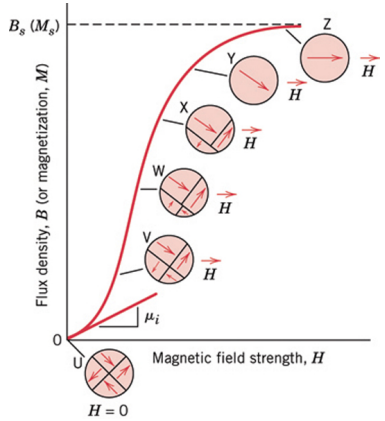
Ferromagnetic materials (F_e, Co, magnetite): Magnetization M≠0 persists upon when H=0 resulting in hysteresis loop and irreversible behavior. Atomic **m** interact strongly by electronic exchange forces →parallel alignment of **m**. Saturation at high H (all moments aligned) , χ is a function of the applied H and at low H has values of 10^3-10^4. Note $H_r > H_c$.



The importance of size – Domains: Experiments indicated that for H=0 the magnitude M_s is uniform but the direction varies from one region to another (on a scale μm to mm). These regions were called domains and are separated by walls.



Dipoles align in each domain



Domains are regions that the spins are collinear.

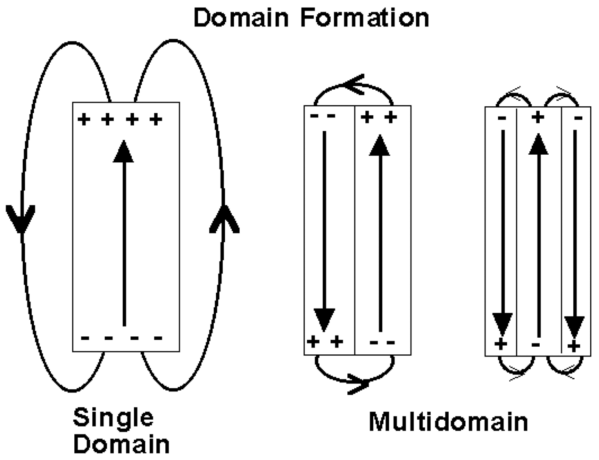
What is the size of a domain?

$$H_{ex} = -2\sum_{i<j} J_{ij}\vec{S}_i \cdot \vec{S}_j - K_{mc}\sum_i (S_{zi})^2$$

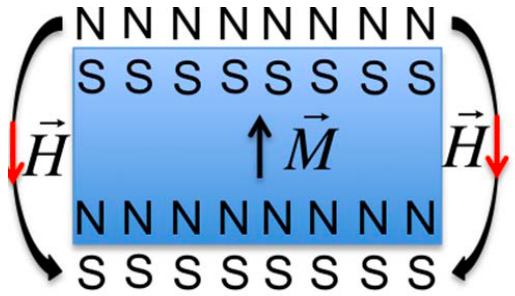
Domain size is equal to the range R of the quantum mechanical spin-exchange forces coupling the neighboring magnetic moments. Analogous to the Debye length in plasmas.

$$E = K_{eff} V \sin^2\theta - \mu_0 H M_s V \cos(\pi - \theta)$$

Magnetic domain walls –Wall thickness > 100 nm

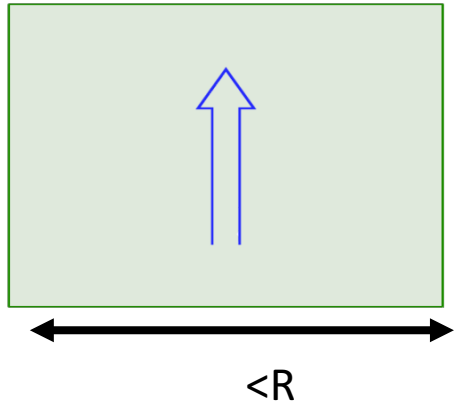


In bulk Multi-Domain (MD) materials single magnetic domains oriented in a way **that minimizes the overall magnetostatic energy of the system due to long range magnetic interactions that compete with short range spin exchange interactions creating macroscopically zero magnetization.** Application of even small **H** induces wall movement and finite **M**.



Edges create demagnetizing fields. To minimize E=HM it breaks to domains

Particles smaller than t have no domains
Single Magnetic Domain (SDM) particles



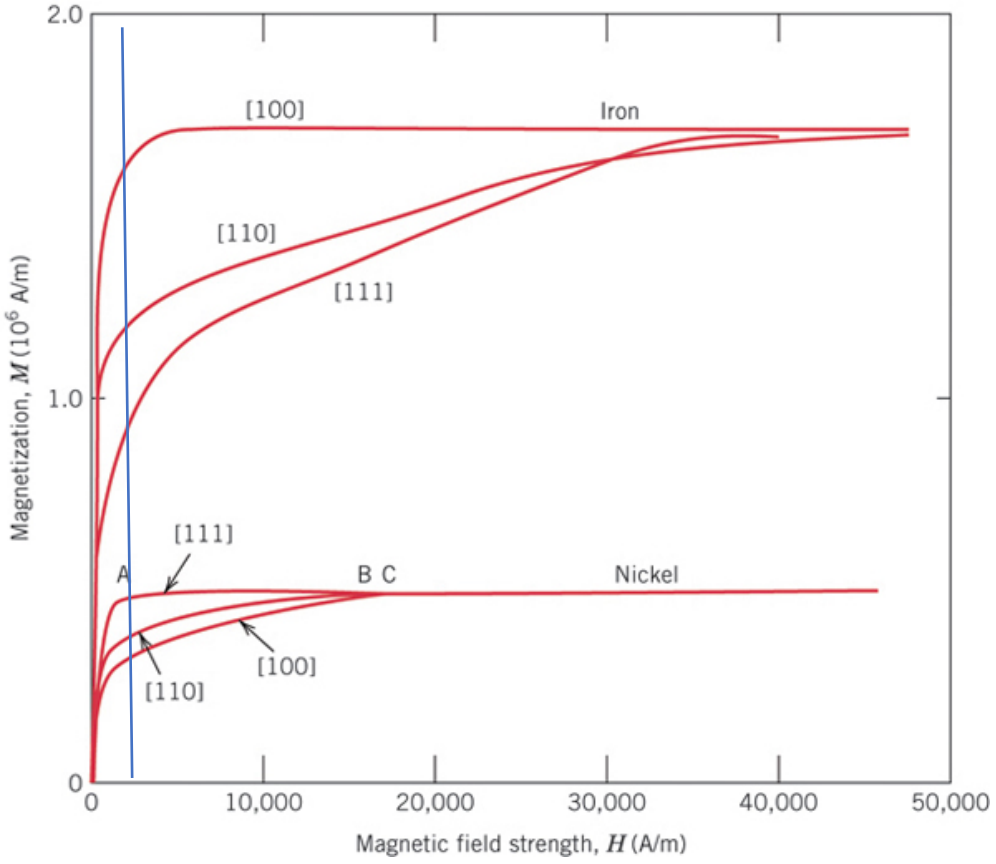
SDM nanoparticles respond to H differently than bulk. They reflect spin rotation rather than wall movement.

$$R_{SMD} = \frac{6\sqrt{AK}}{\mu_0 M_s^2}, A \text{ exchange stiffness, K magnetic anisotopy}$$

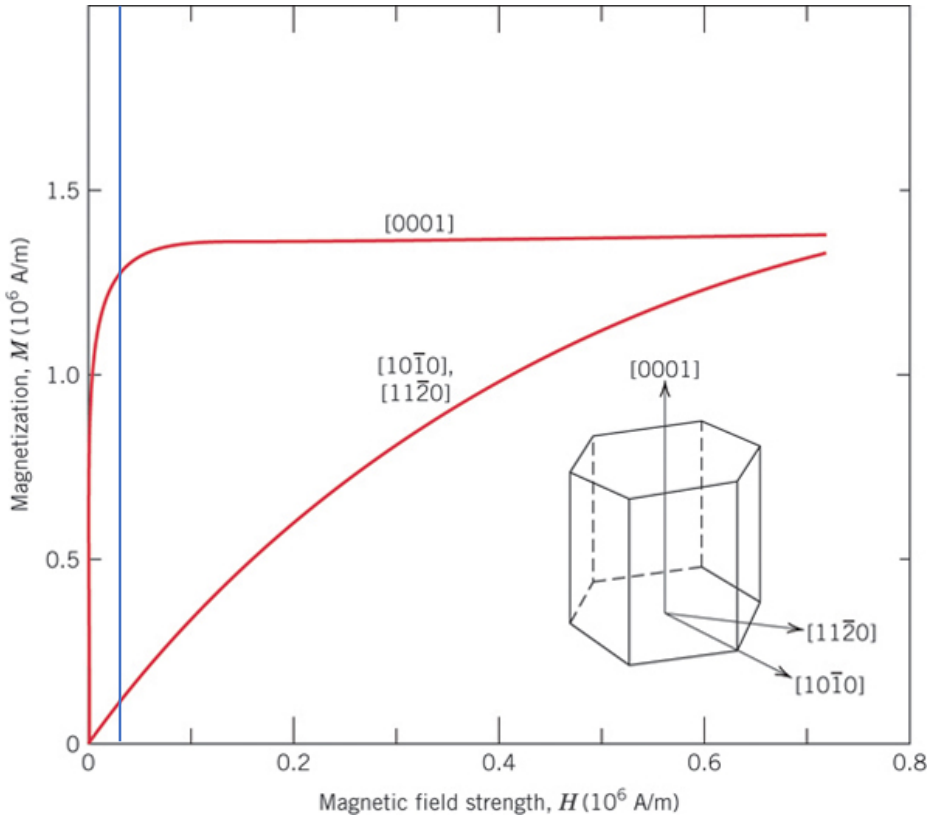
The Importance of anisotropy in SDM particles

Most of the interesting SDM particles show a preference for the magnetization direction including maximum values of saturation and minimum coercivity.

$$H_{ex} = -2\sum_{i<j} J_{ij}\vec{S}_i \bullet \vec{S}_j - K_{mc}\sum_i (S_{zi})^2$$



Magnetization curves for single crystals of iron and nickel. Magnetization varies with crystallographic directions



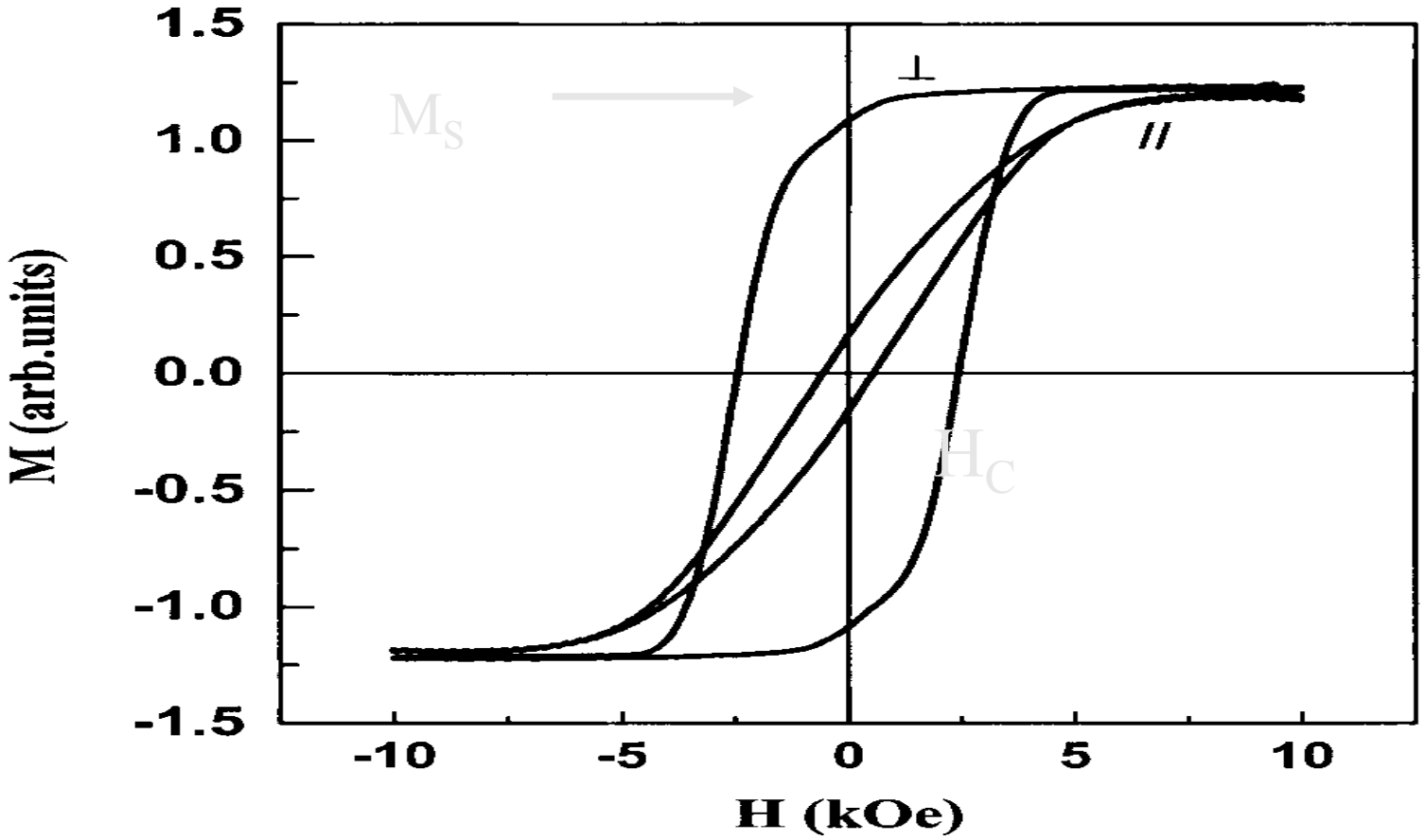
Magnetization curves for single crystals of cobalt.

Typical Measurements

Magnetization vs Field (hysteresis loops)

1 Saturated magnetization M_S

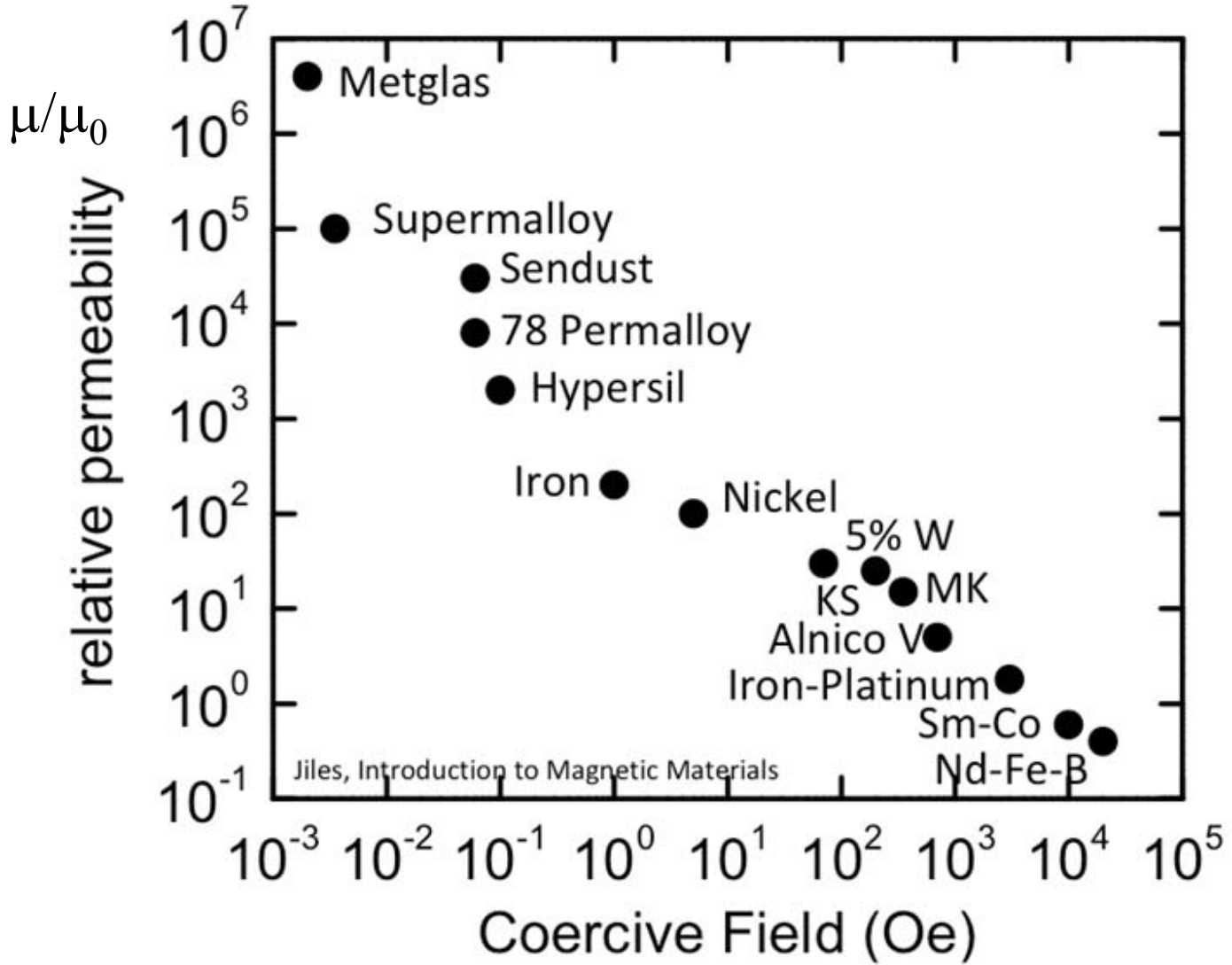
2 Coercivity H_C --Open loop (magnetic order)



REF: J Phys: Condens. Matter 13(2001) R433-R460

Correlation of Susceptibility and Coercivity

$$\chi_m \uparrow \Rightarrow H_c \downarrow$$ **Why? -> Anisotropy**



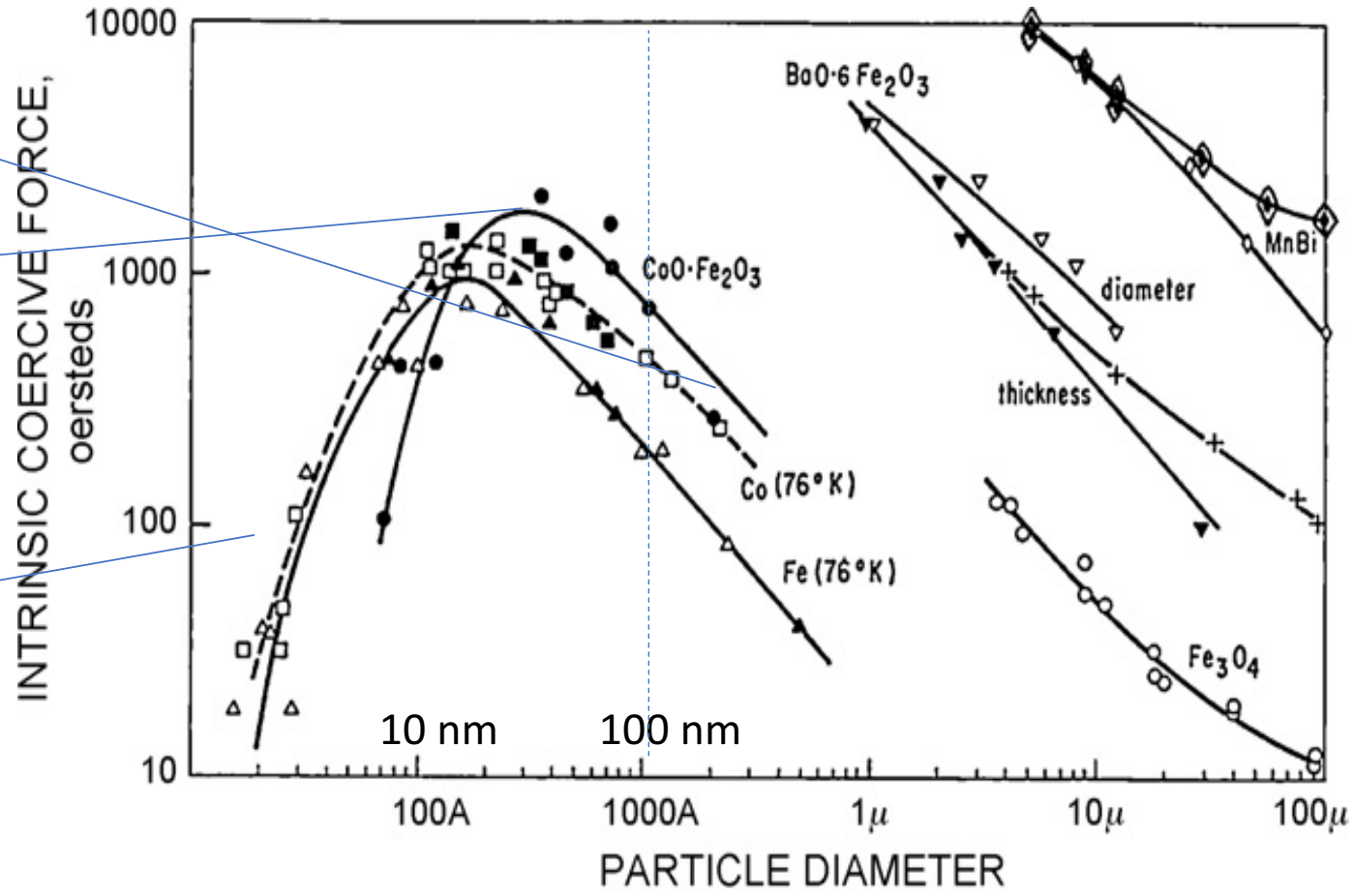
Coercivity increases due to transition from MD to SMD

Maximum H_c when anisotropy energy opposes rotation away from the easy direction of M

Coercivity decreases to zero due to thermal effects that result to fast spin reversals

SUPERPARAMAGNETISM

How fast are the spin reversals. What is the response time of the magntization?

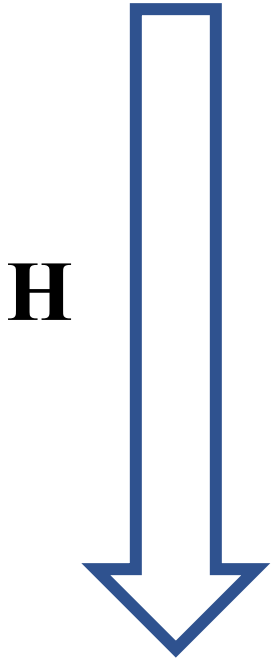


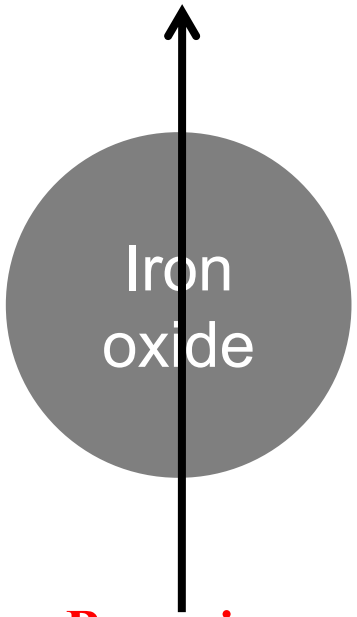
Experimental relation between coercivity and diameter for particles deriving their coercive force principally from crystal anisotropy energy [F.E.Lubrosky, J. Appl. Phys. 32 , S171]

Relaxation Processes

The Landau-Lifshitz –Gilbert equation where is η dimensionless attenuation constant of precession

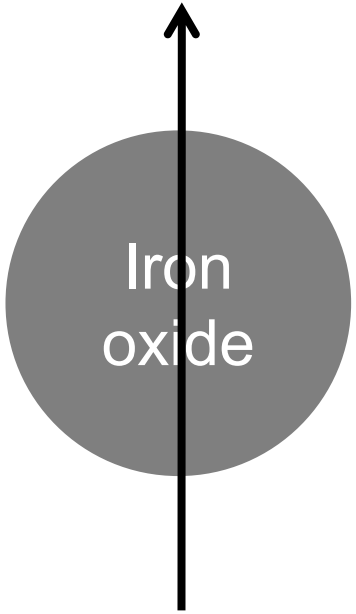
$$\frac{d\vec{m}}{dt} = -\gamma[(\vec{m}\times\vec{H}_{ef}) - \eta\vec{m}\times\frac{d\vec{m}}{dt}]$$





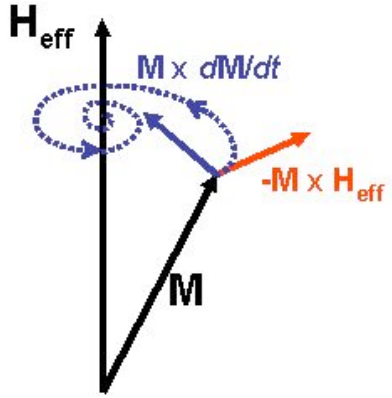
Brownian

Rotation of particle with respect to the matrix



Neel

Rotation with respect to its crystal axis



$$f\tau < 1$$

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

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

Brown vs. Neel relaxation – The eggshell model

What causes the rotation of the nanoparticle?

Shliomis and Stepanov 1994

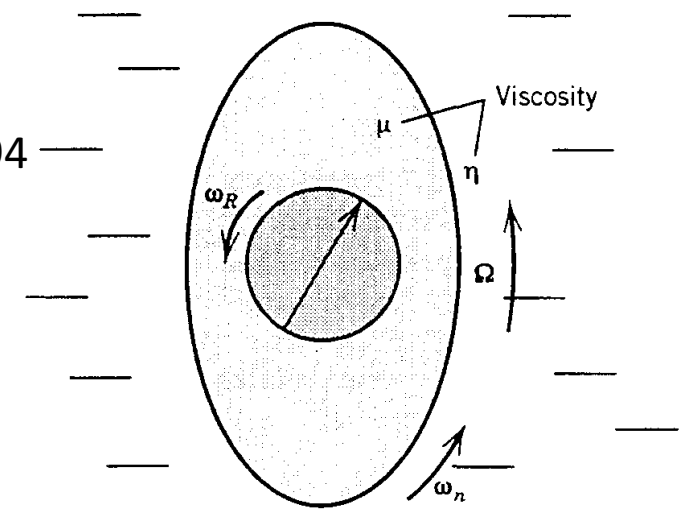


Figure 1. The egg model. The yolk rotates in the white with respect to the eggshell with angular velocity ω_R. The eggshell rotates with respect to the surrounding fluid with angular velocity ω_n; Ω is the local angular velocity of the fluid. The fluid has viscosity η. Viscosity of the white is μ.

$\tau_B = 3\eta V/k_B T$

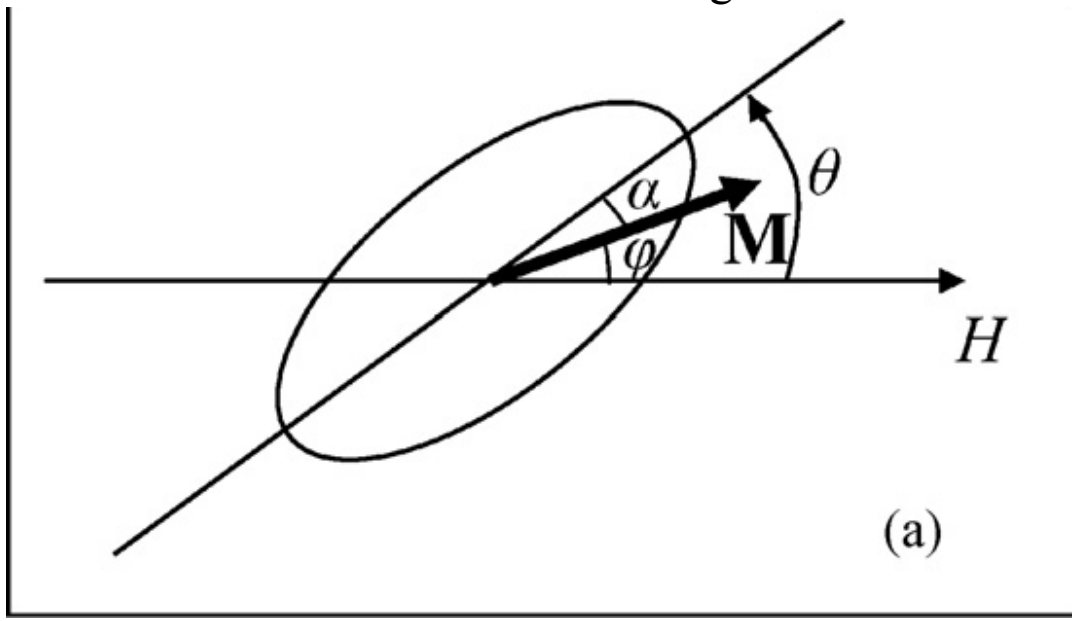
- Notice that $V > V_m$ due to surfactant layer coating to avoid coagulation
- For a solid matrix or at the freezing temperature of a Ferrofluid $\tau_B \rightarrow \infty$ $\tau = \tau_N$

Neel relaxation time

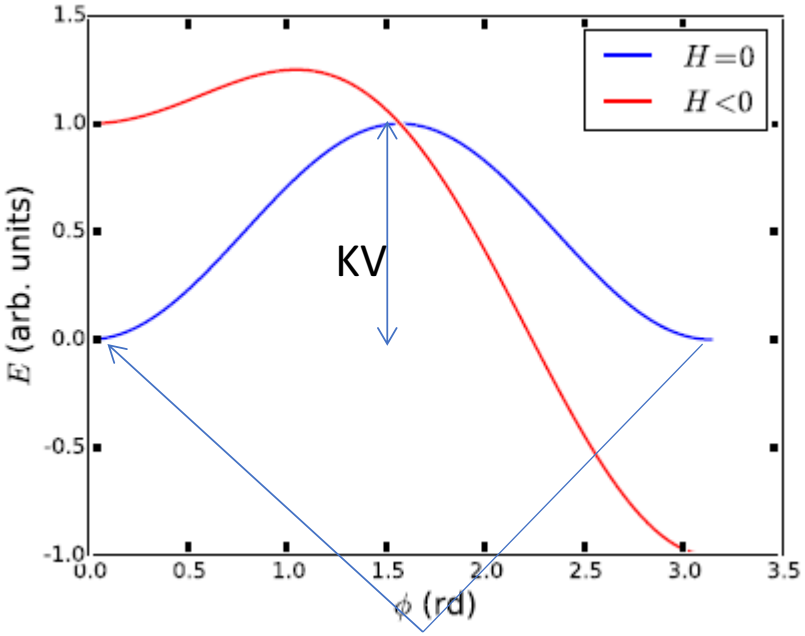
Single grain with uni-axial magnetic anisotropy – Two anti- parallel directions of easy magnetization

Direction of easy magnetization

$$E = KV\sin^2(\varphi-\theta) - \mu_0 M_s V H\cos\varphi - k_B T$$



For θ=



$t_N = t_o \exp(KV_m/k_B T)$; t_o =1-.001 nsec

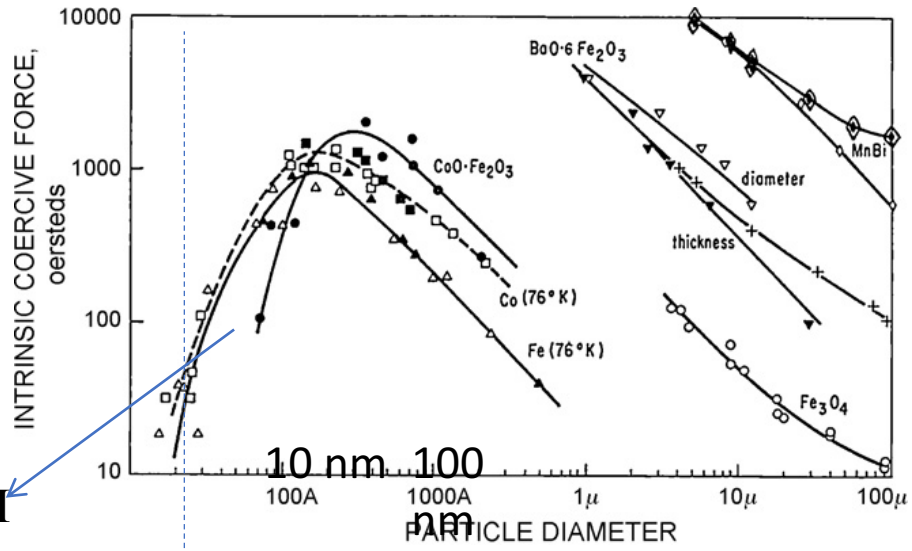
V_m ->0 ideal SPM

For $k_B T > KV$, M=0 at H=0

H≠0 breaks the symmetry favoring one of the easy directions

$$V < \frac{(T/300K)}{(K/3000J/m^3)} \ln(GHz/f)(nm)^3$$

SUPERPARAMAGNETISM



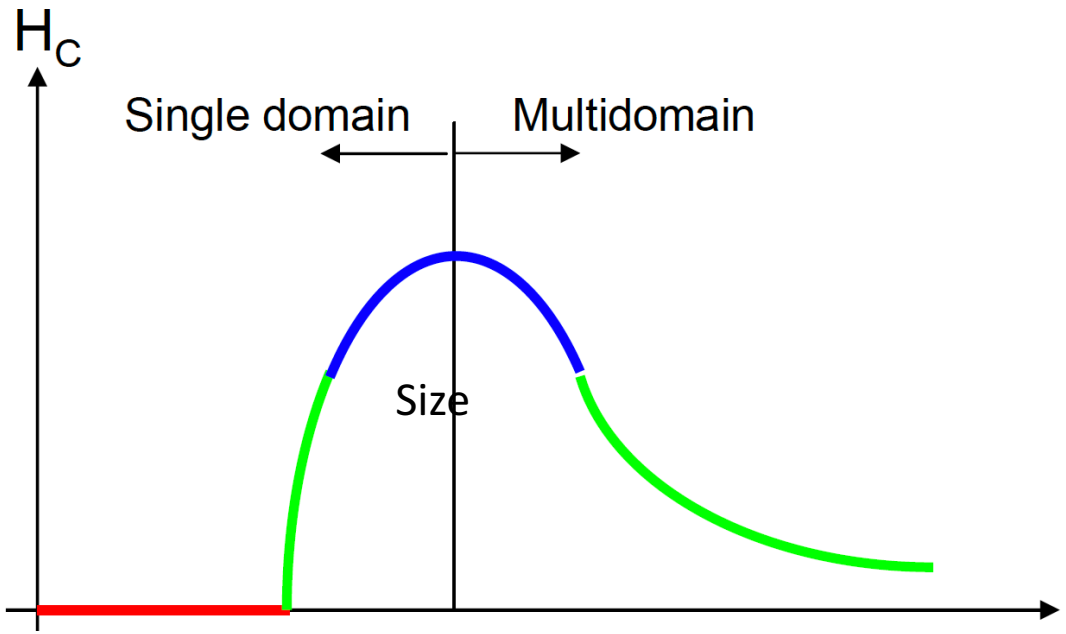
Experimental relation between coercivity and diameter for particles deriving their coercive force principally from crystal anisotropy energy [F.E.Lubrosky, J. Appl. Phys. 32 , S171]

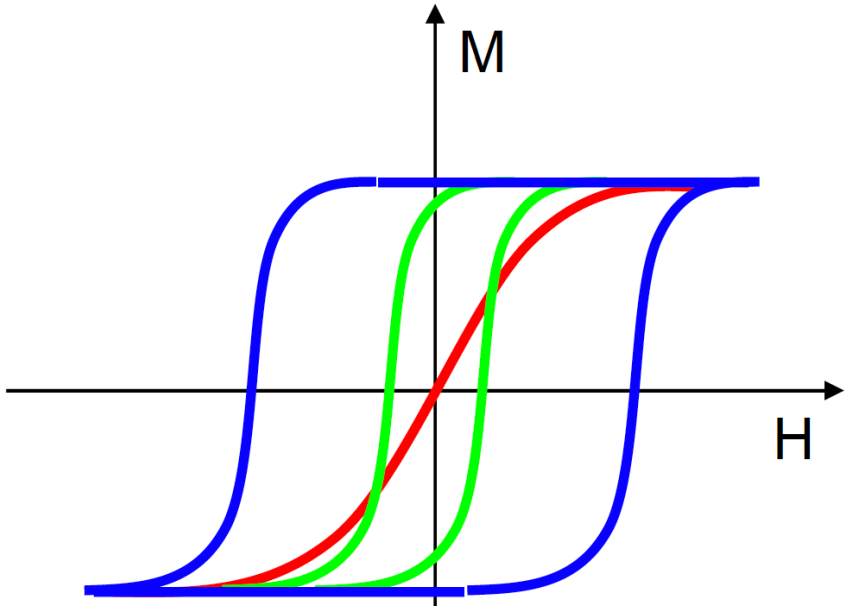
New Properties of SPM

- Small size and larger magnetic moment for each particle like Ferromagnetism --Large M_S and m~ 10^4-10^5 μ_B
- Response to external field like paramagnetic response---No open loop
- Superparamagnetic relaxation when V satisfies the condition $f\tau<1$

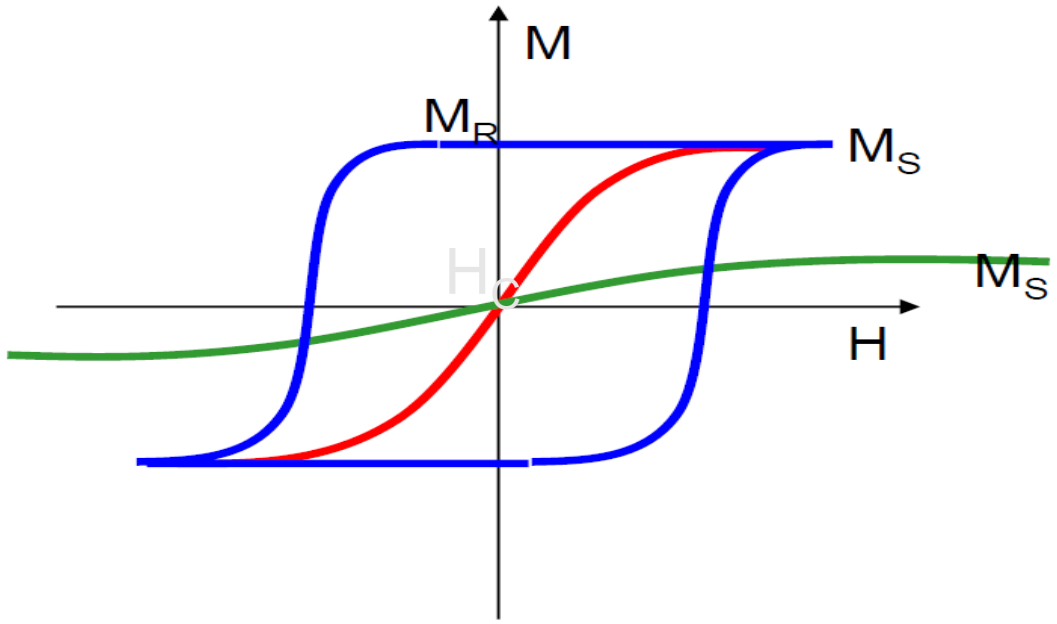
$$\tau=\tau_0 exp(KV / (k_B T))$$ ***Neel-Arrhenius equation***

Magnetic Properties of nanostructured materials - Superparamagnetism





Different Hysteresis Loops



Ferromagnetism

Paramagnetism

Superparamagnetism

Ferromagnetic state

Open loop

Large M_S

Paramagnetic state

No open loop

Small M_S

Superparamagnetic state

No open loop

Large M_S

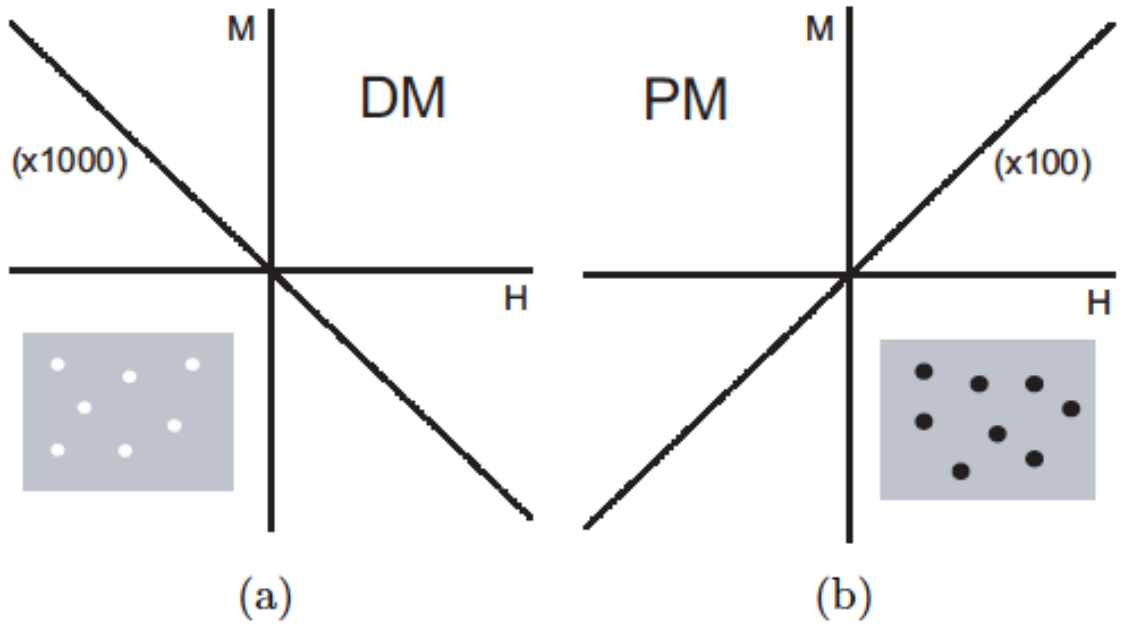
WHAT IS SUPERPARAMAGNETIC MATERIAL

- ***Made of very small (10-60 nm) single-domain non-interacting magnetic grains dispersed in non-magnetic medium***
- ***Magnetization can randomly flip directions with temperature. Timescale of flipping is Neel relaxation time τ_N***
- ***For t> τ_N average magnetization is zero in the absence of a magnetic field***
- ***In SM magnetization of nanoparticle is the sum of the individual moments carried by the atoms composing the nanoparticle (macro-spin approximation)***

WHAT IS SUPERPARAMAGNETIC MATERIAL (CONT)

- ***Blocking temperature T_B is the temperature at which the the relevant frequency 1/f of the application equals τ_N***
- ***For temperatures above T_B superpamagnet can be described by the same equations used for ordinary paramagnet. Namely as an ensemble of non-interacting magnetic moments with energy $E=-\mu B$ when placed in a magnetic field B. The only difference is that the magnetic moment of the individual particles are much larger for SMs since the grains contain 1000s of atoms.***
- ***The magnetization curve of the SM M(H) is similar but much steeper (much higher susceptibility) than paramagnet's.***
- ***Below T_B M(H) has hysteresis and resembles that of ferromagnets.***

Summary of magnetic responses



(a) (b)

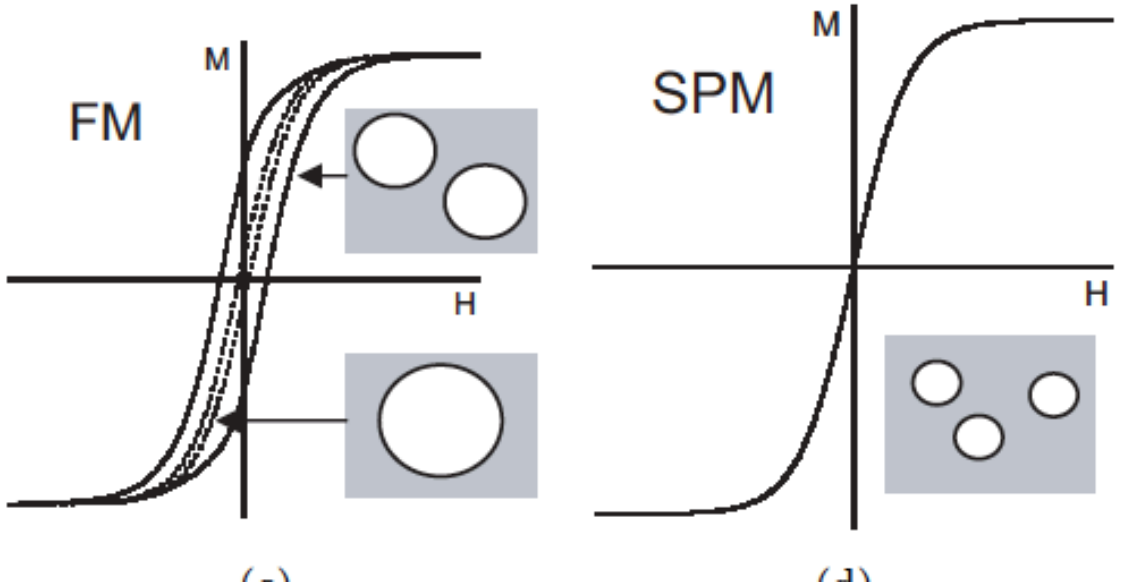
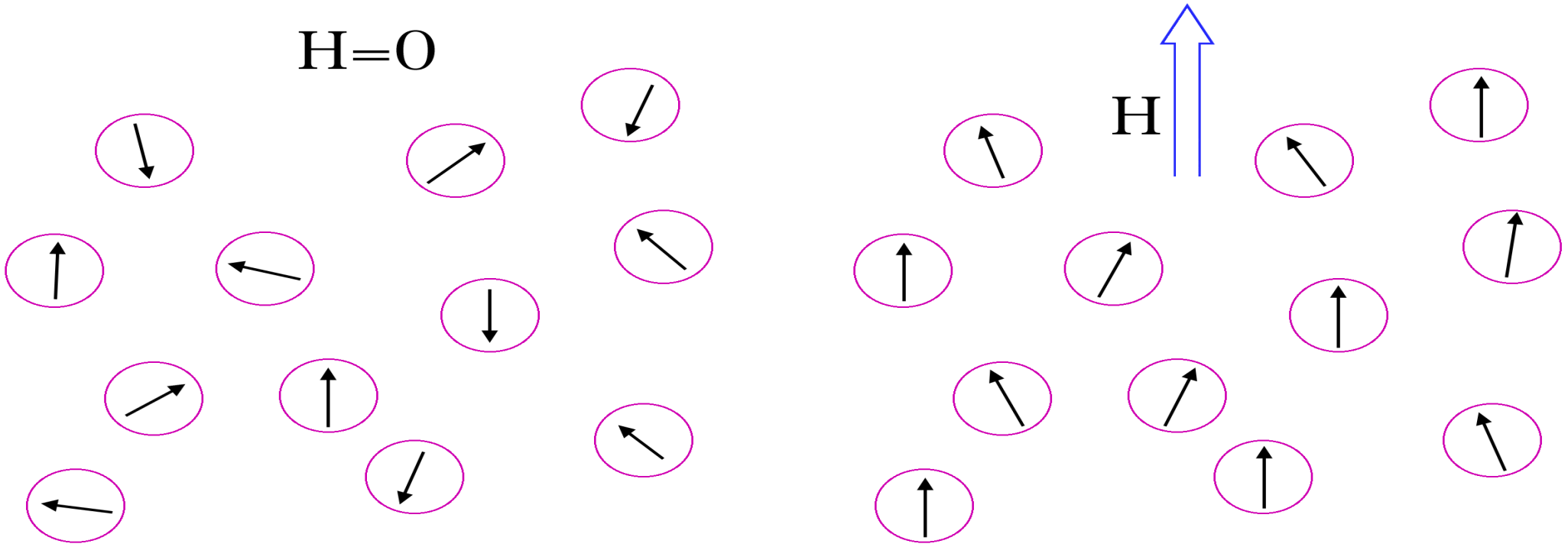


Figure 5: This figure shows the schematic behaviour of diamagnetic, paramagnetic, ferromagnetic or superparamagnetic materials in an external magnetic field. Figure 5(a) (diamagnetic material): The higher the external magnetic field $\vec{H}$, the lower the magnetization $\vec{M}$. Figure 5(b) (paramagnetic material): The higher the external magnetic field $\vec{H}$, the higher the magnetization $\vec{M}$. Figure 5(c) (ferromagnetic material): A hysteresis loop can be seen. For multi-domain particles, the loop is narrower (dashed line), while for a single-domain particle, the loop is quite broad (fully drawn line). Figure 5(d) (superparamagnetic material): Similar to ferromagnetic material is the form of sigmoidal shape, but without any loop. The difference between the ferromagnetic behaviour and the superparamagnetic behaviour is primarily determined by the size of the particle. As soon as it gets small enough, the latter effect takes over. Source: [1].

Superparamagnetism



For our application particles that respond to a field on a time scale shorter than 1/f are considered as superparamagnetic particles

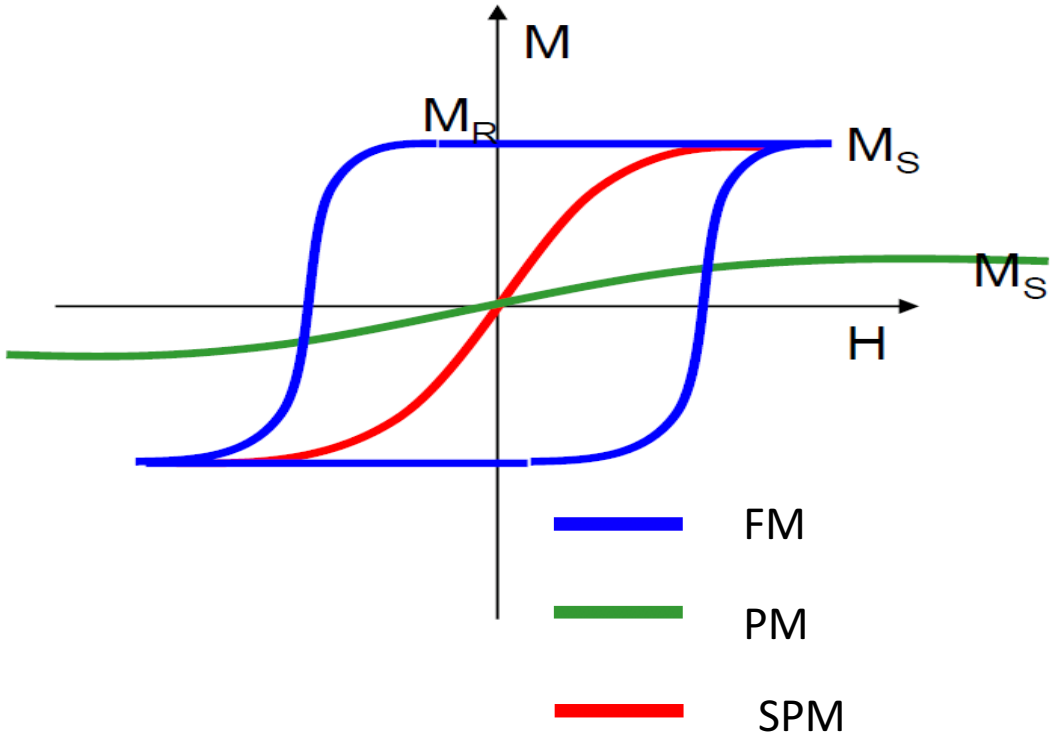
Magnetization Curve M(H)

Focus on k_B T>KV and **mB**>>KV so that E=**-mB** and assume all grains have the same size –**monodisperse.** We use the the same theory as for paramagnetic materials .

$$M = M_s L(x) = M_s[\coth x - \frac{1}{x}], x \equiv \frac{mB}{kT}$$

$$m \approx M_s V$$

Notice that M~x~V and for x->0 M~B/T Curie's law.



Hysteresis Curves SPM particles

$T_B \cong KV/k_B \ln(GHz/f)$ $x=\mu_0 Hm/k_B T$ $m=M_s V$

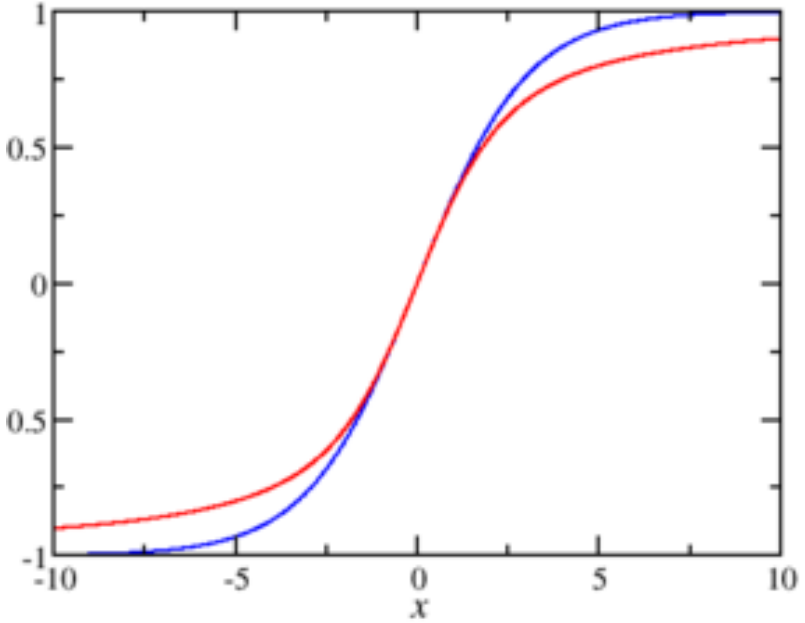
$\chi=n\mu_0 m^2/k_B T$

1. Nanoparticles identical with easy axes oriented parallel to the magnetic field

M(H)=nm *L(x)*

L(x)=coth(x)-1/x

$$M(H) = nm\tanh(x)$$



M(H) for 1 (blue) and 2(red) for $\xi=1/3$

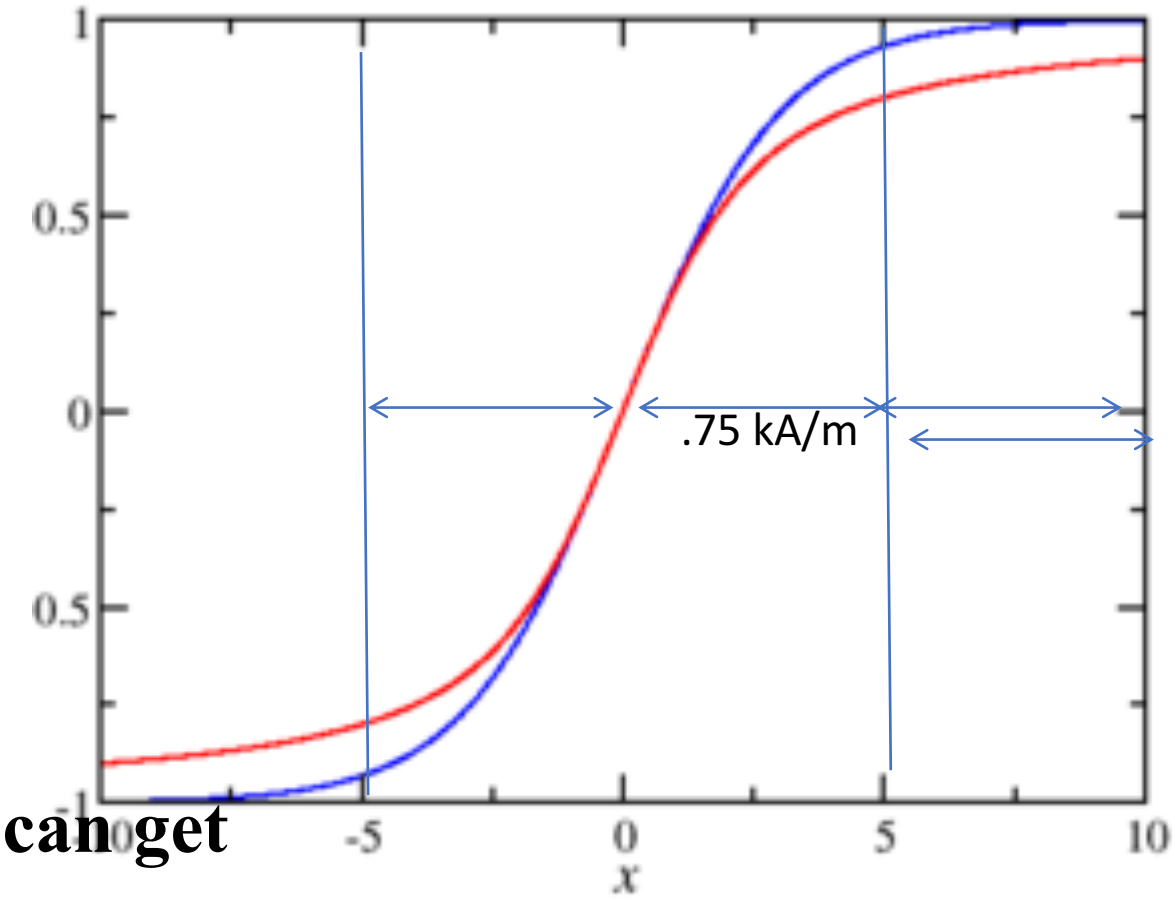
Small x

Material	H_{sat} (A/m)
Iron	1.71×10^{6}
Cobalt	1.44×10^{6}
Magnetite	4.80×10^{5}

R= 10 nm, V= 10^{-23} m^3

$m=M_sV=2x10^{-17}$ A-m^2

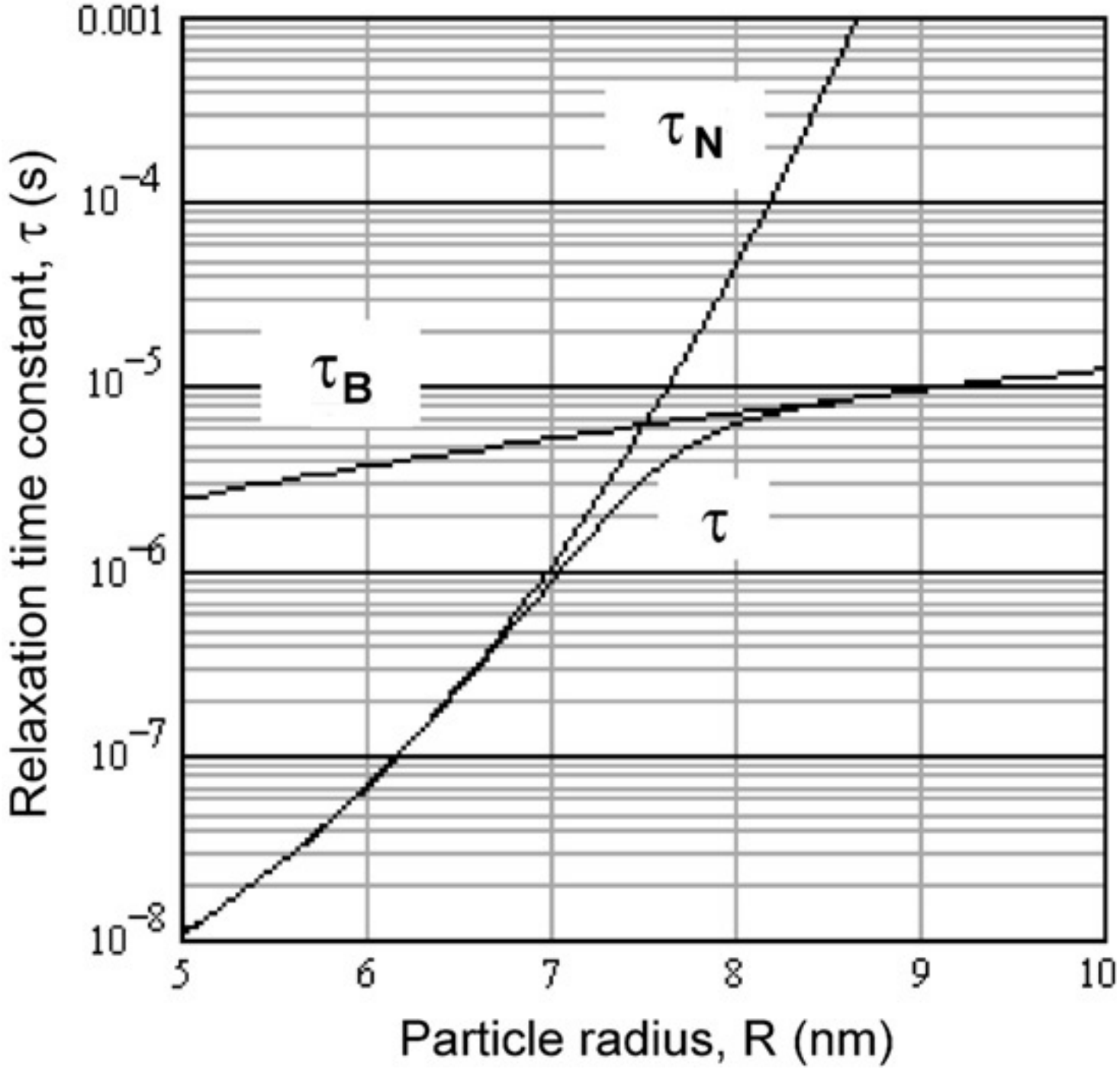
$x=\mu_0 Hm/k_BT\approx$
$\approx H(10^{-6}x2x10^{-17}/10^{-23}\ x300)\approx$
$\approx 5(H/.75kA/m)$

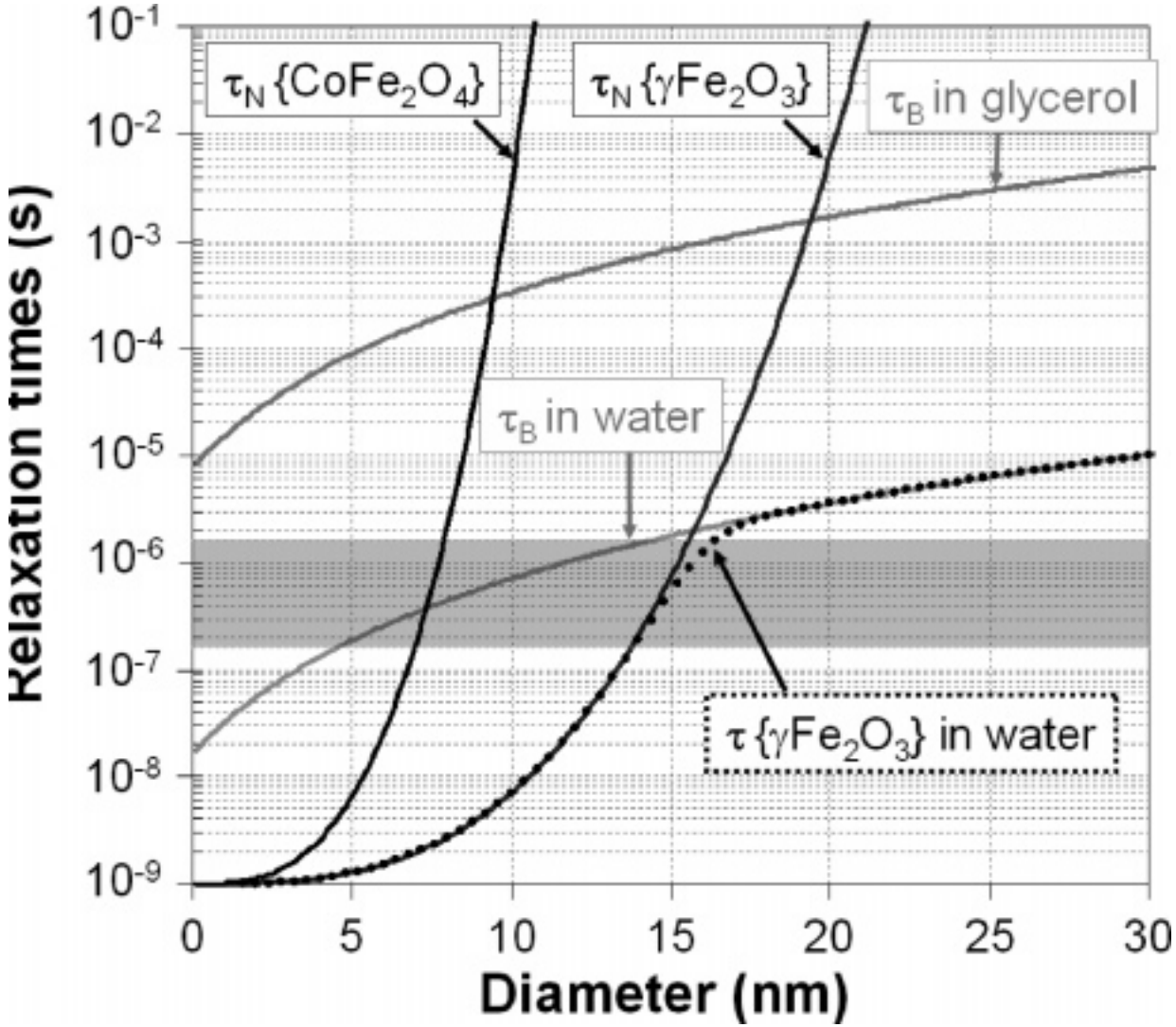


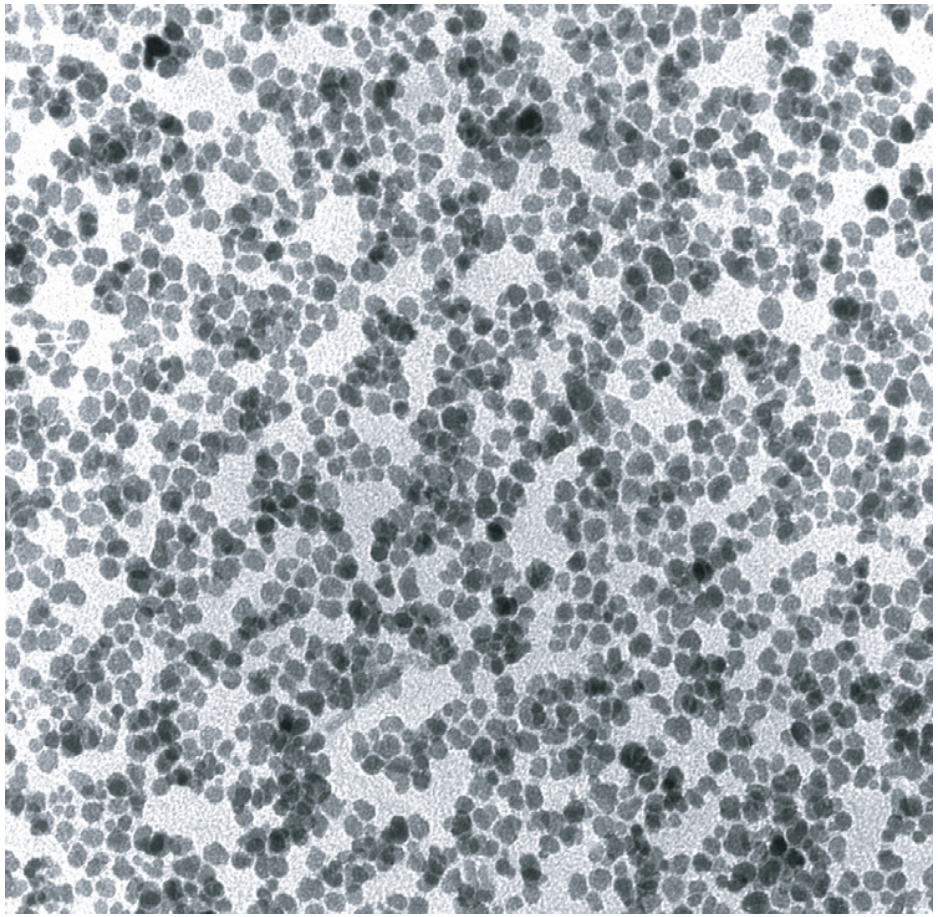
At x=5 with applied field of .75kA/m we can get M~10^6 A-m^2 /m^3

Other issues; matrix, ferrofluid (colloidal support), frozen ferrofluid, solid or just dust (grains)

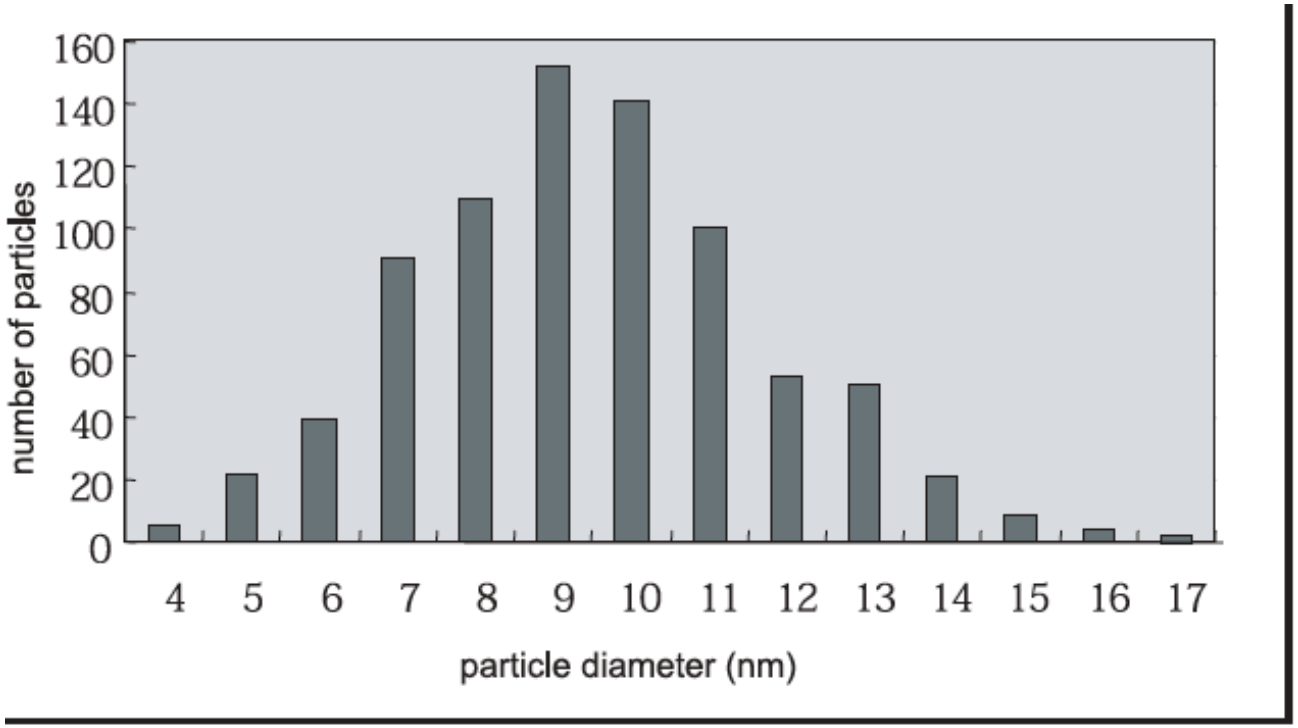
Rosenweig 2002




Relaxation times (s)
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
τN {CoFe2O4}
τN {γFe2O3}
τB in glycerol
τB in water
τ {γFe2O3} in water
0
5
10
15
20
25
30
Diameter (nm)

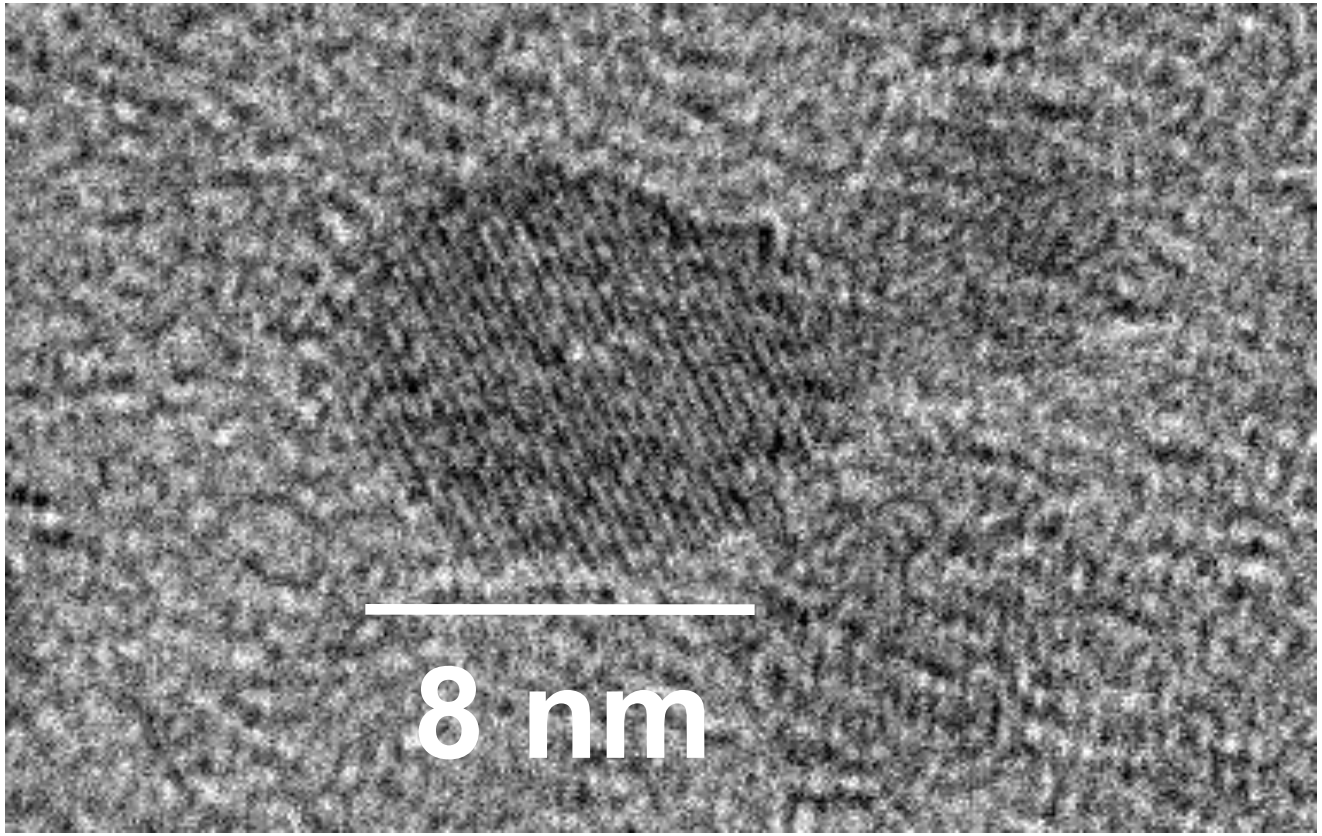


TEM Image of Ferrofluid



Size distribution of magnetic nanoparticles obtained from TEM

TEM image of iron oxide nanoparticle



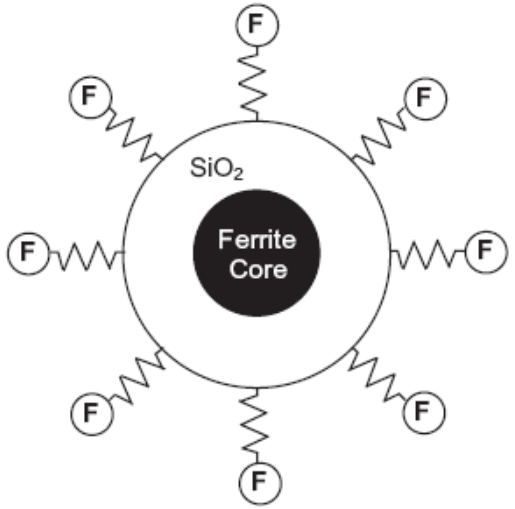
Note the regular crystal structure of the magnetic nanoparticle.

Surfactants

Magnetic nanoparticles can stick together if they collide. This can lead to agglomeration, which is generally detrimental for applications.

In order to prevent agglomeration, nanoparticles are often coated with some material to prevent agglomeration (either because of steric or electrostatic effects).

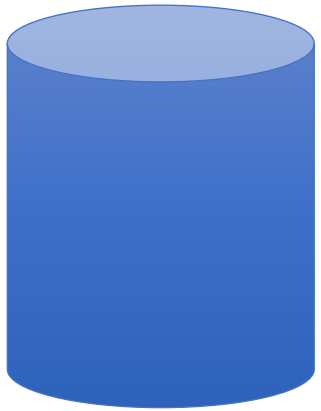
Organic surfactants. Normally long chain molecules, including fatty acids, dextran, alginate, or other polymers.



Inorganic surfactants. Generally non- or weakly-reactive materials, including Si, SiO_2, Au, or others. Core-shell nanoparticle structures can also have other types of functionalities (quantum dots).

Surfactants can also introduce additional binding sites to the magnetic nanoparticles.

Key restriction B/ρ in units Ω-m/mT <1



Eddy current loss for cylinder with diameter d and height h oscillating at frequency f assuming uniform and complete penetration of B field and using Faraday's law with B in the z direction

$$\frac{dW_{eddy}}{dt} = \frac{\pi^2}{12}\frac{B_{\max}^2}{T^2}\frac{d^2}{m^2}\frac{f^2}{Hz^2}\frac{\Omega - m}{\rho}\frac{\pi(d^2/4)h}{m^3}Watts$$

$$\frac{dW_{eddy}}{dt} = 1.6\times10^{-2}(B/mT)^2(d/.28m)^2(f/3kHz)^2(V/3lt)(\Omega - m/\rho)Watts$$

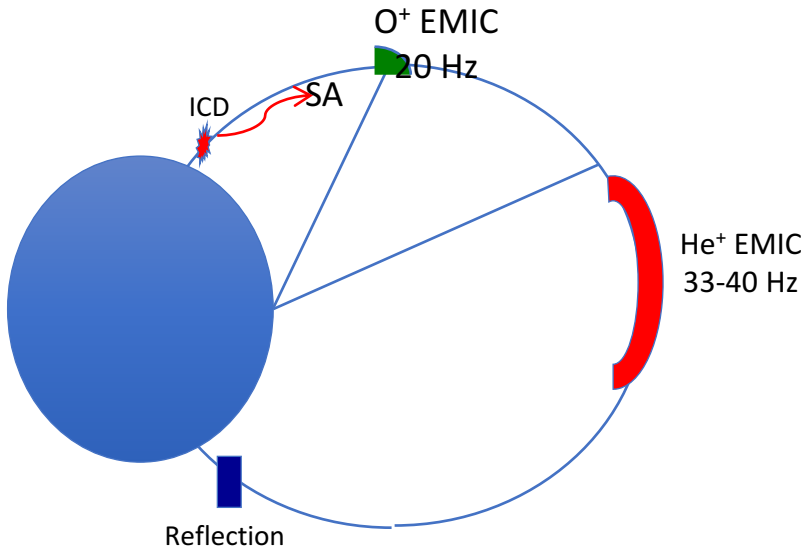
Equivalent formula for magnetization

$$\frac{dW_{eddy}}{dt} = \frac{\mu_o^2 d^2}{24\rho}\left(\frac{dM}{dt}\right)^2\left(\frac{\pi h d^2}{4}\right)Watts$$

Back to Applications

Injection in Space - Whistlers, EMIC, SAW

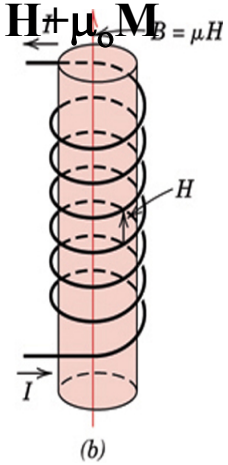
DMX



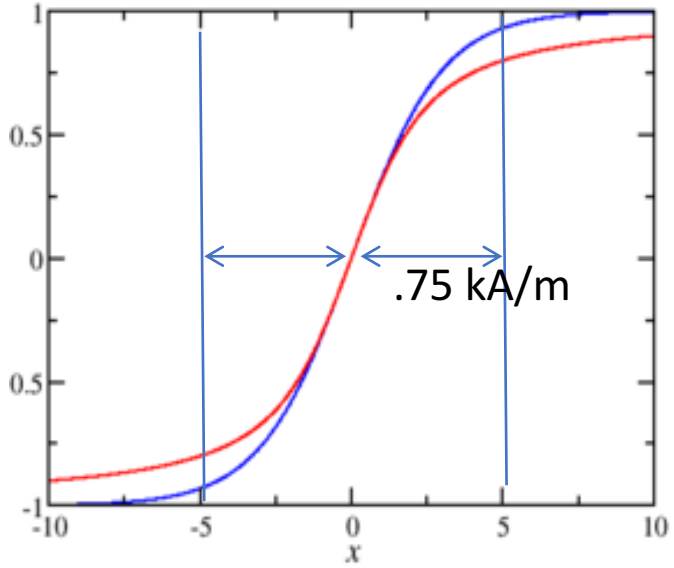
$$m = 10^3 (V / lt) A - m^2$$

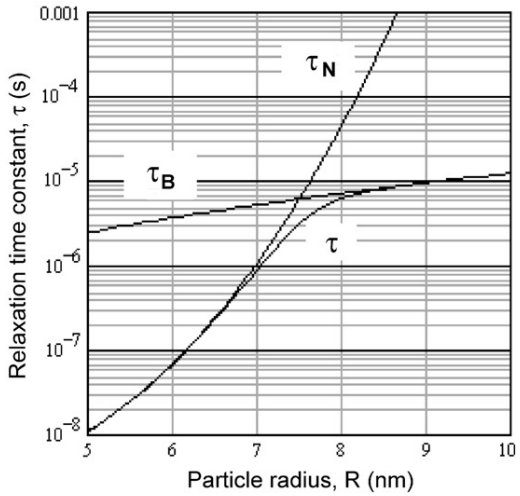
B~ mT at r=1m

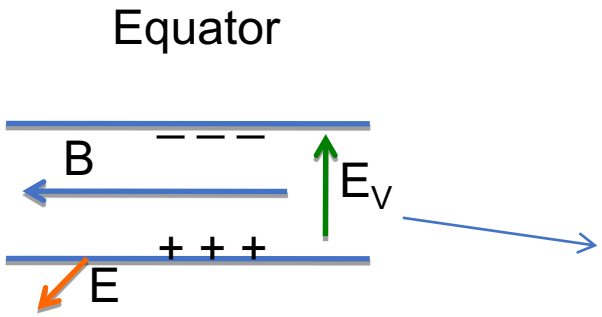
$B = \mu_o H + \mu_o M$



$M = \chi_m H$



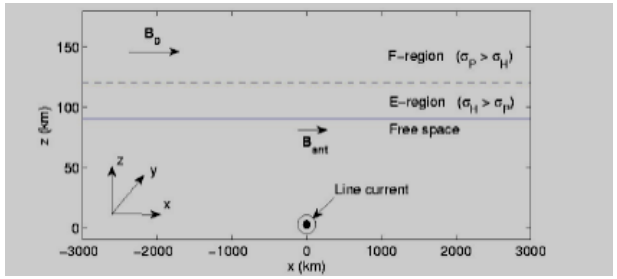


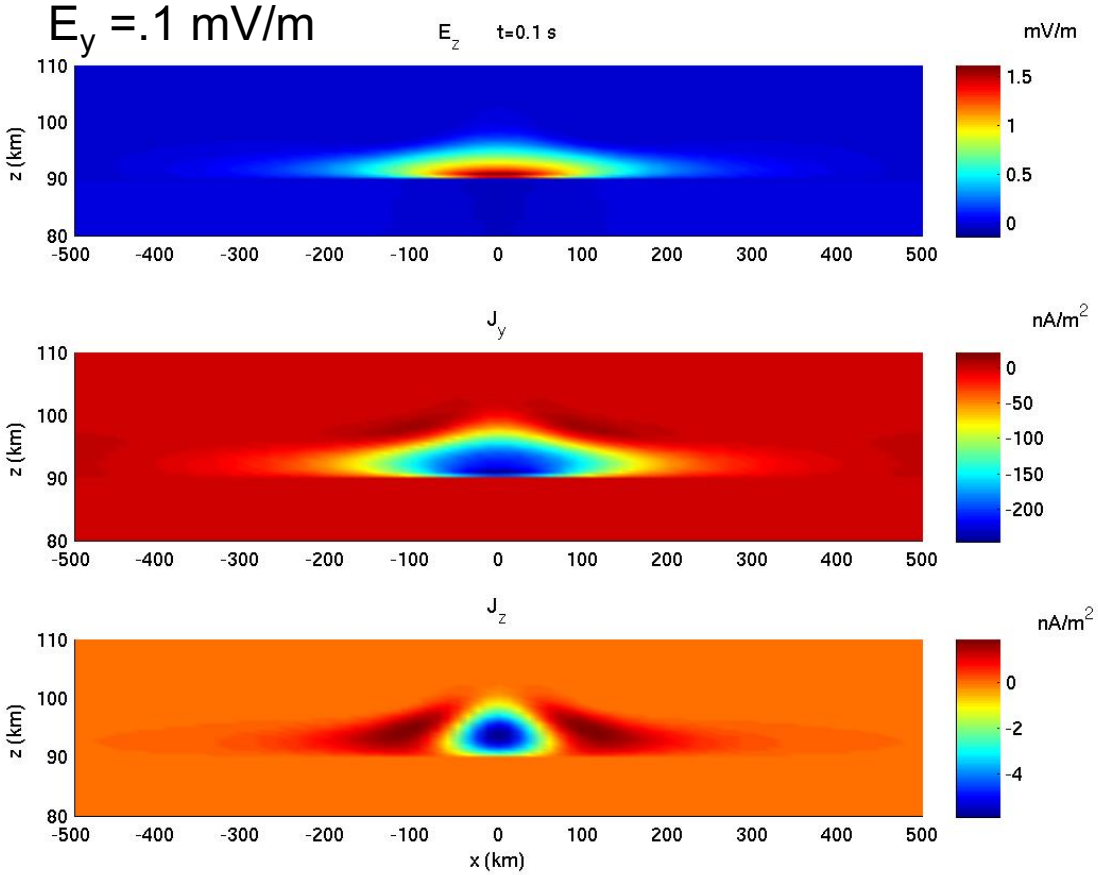


Equator

$$E(80km) \approx (m/10^6\,A - m^2)(f/kHz)\mu\mathrm{V/m}$$

m ~10^6 A-m^2 requires 1m^3



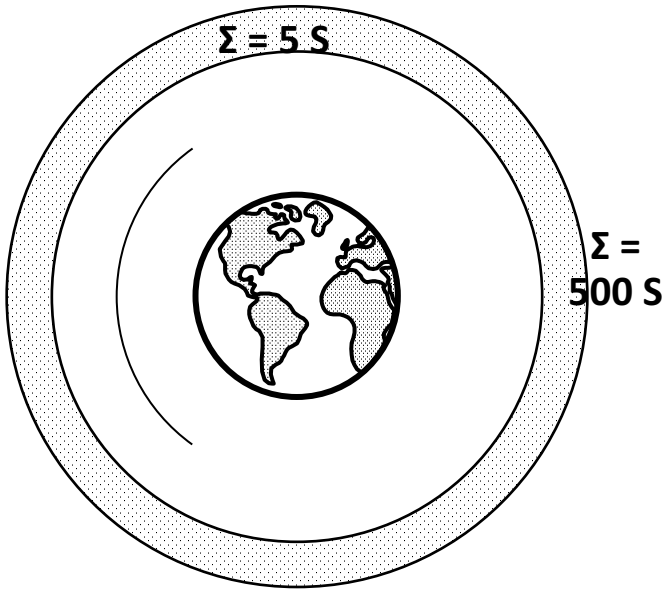


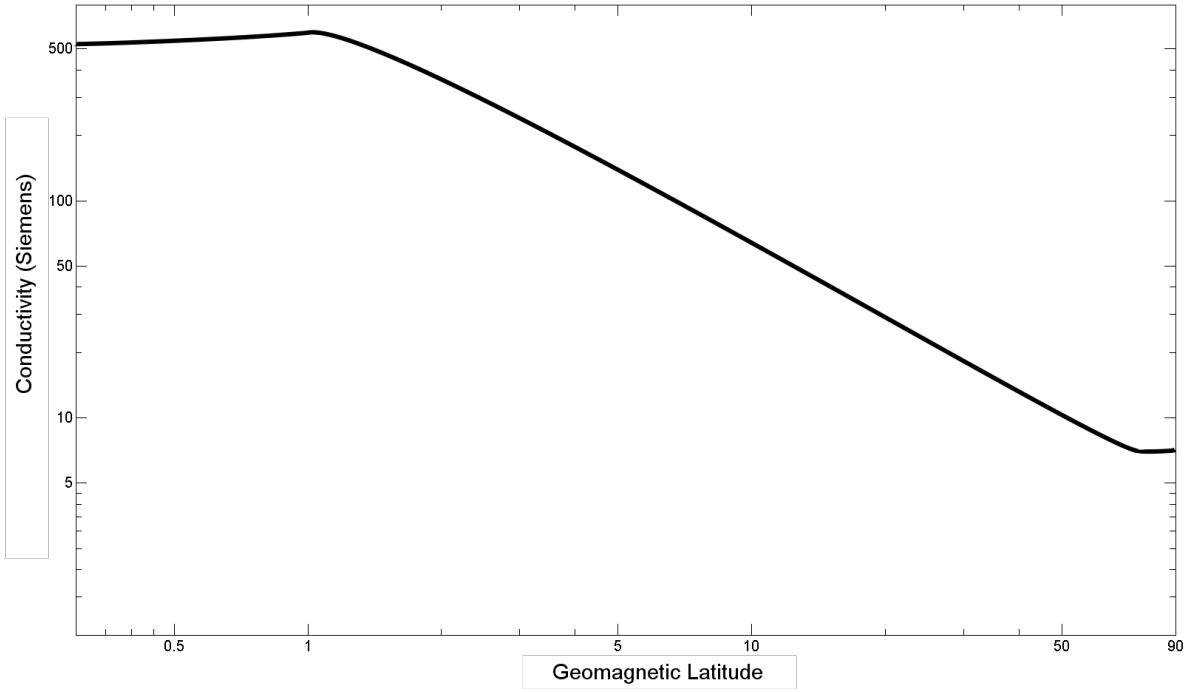
$$I = \Sigma EL \approx 500x10^{-6}(8x10^4)A \approx 40A$$

$$p \approx IL \approx 4x10^5\,A - m$$

56

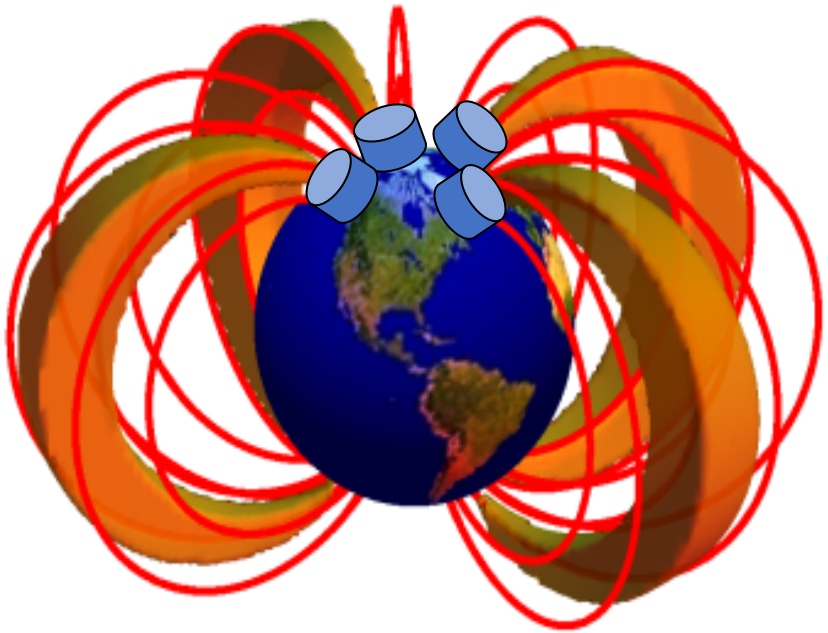
Scaling with geomagnetic latitude

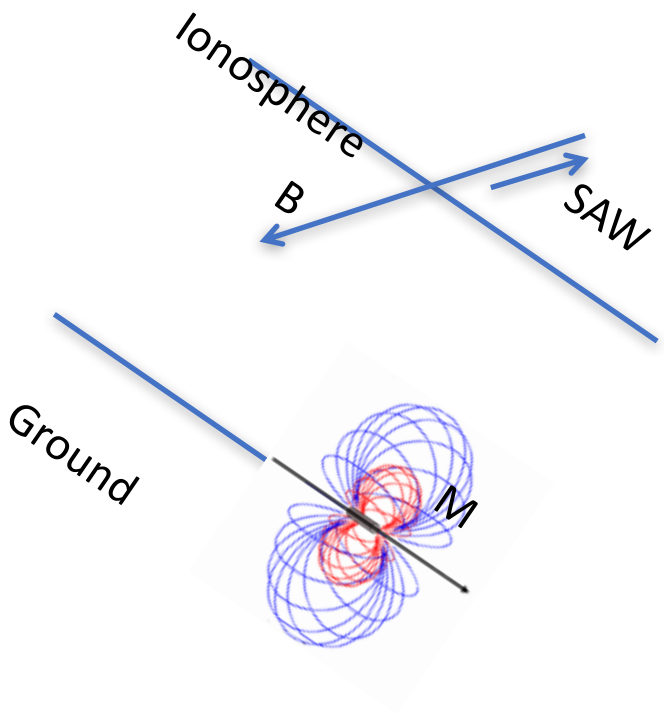




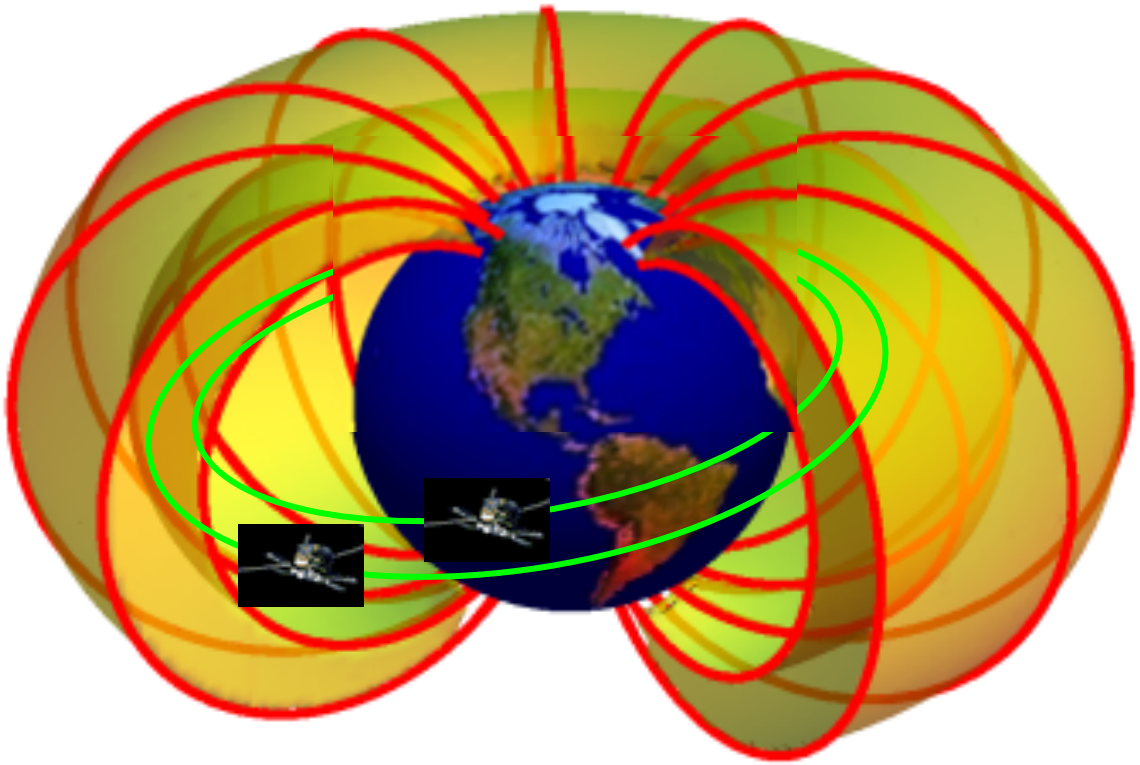
Hall Conductance vs. Geomagnetic Latitude

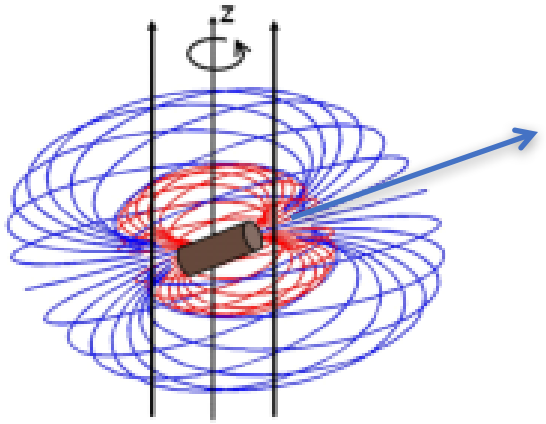
$$E(80km) \approx (m/10^6 A - m^2)(f/kHz)\mu\mathrm{V/m}$$





Magnetic field lines

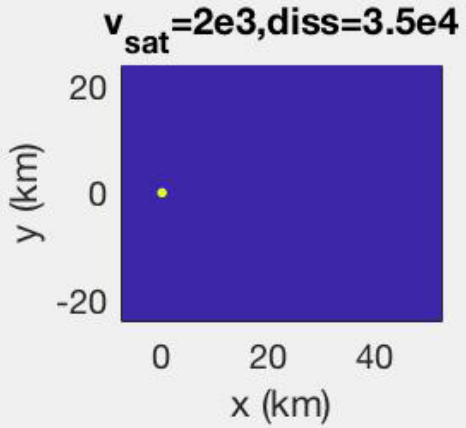


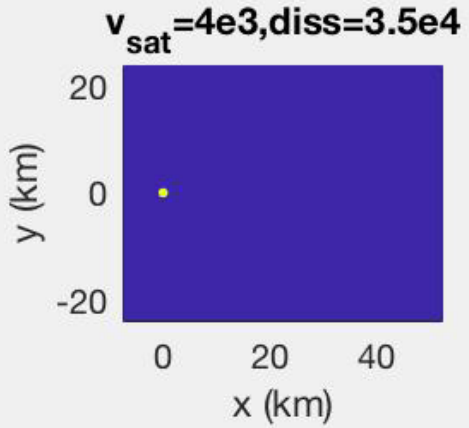

z

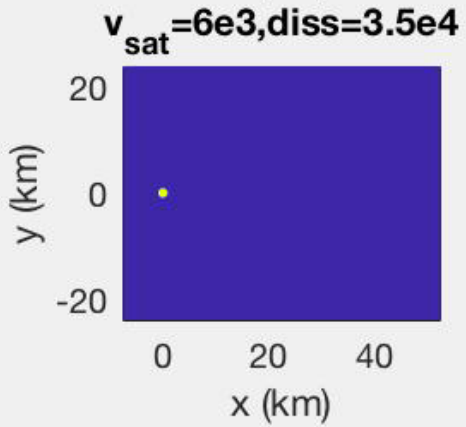
Next Topic (only two slides)
MHD EXPLOSIVE GENERATOR (MAHEM)

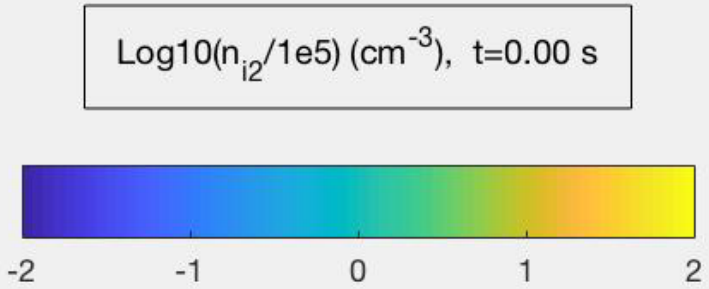
ENIG/UMD/AFRL

- **A Flux Compression Generator (FCG) power source developed by DARPA during ENIG's program can generate ~ 20 MJ (equivalent to Sandia's Z-machine's output per shot) and can melt, vaporize, and ionize 1025 # of e-i pairs to create man-made plasma to control the ionoshpere.**
- **Device can fit in a CubeSat form factor to be deployed by a sounding rocket or orbital launch vehicle**


v_sat=2e3,diss=3.5e4
20
0
-20
y (km)
0
20
40
x (km)


v_sat=4e3,diss=3.5e4
20
0
-20
y (km)
0
20
40
x (km)

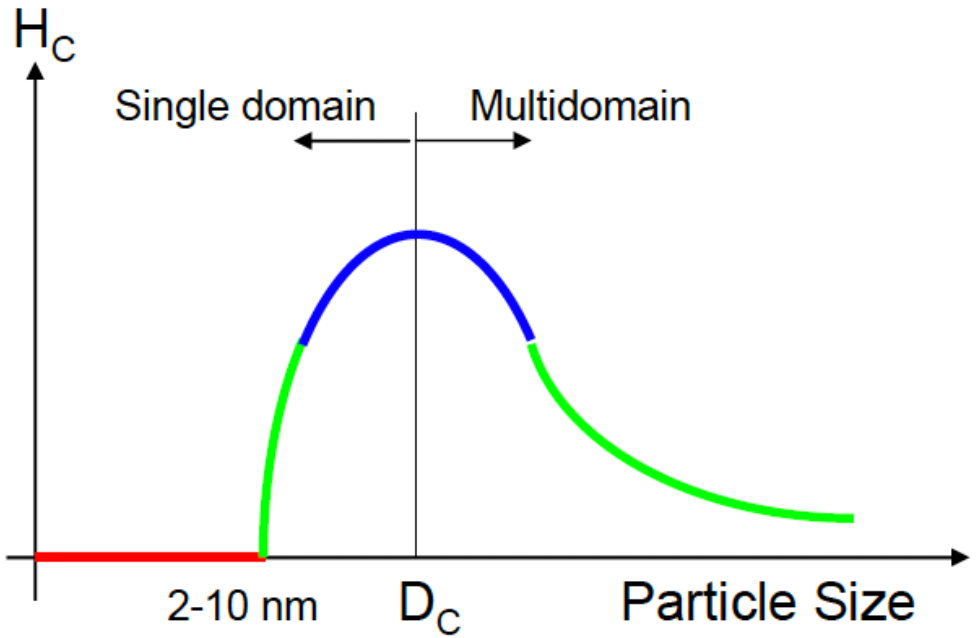

v_sat=6e3,diss=3.5e4
20
0
-20
y (km)
0
20
40
x (km)

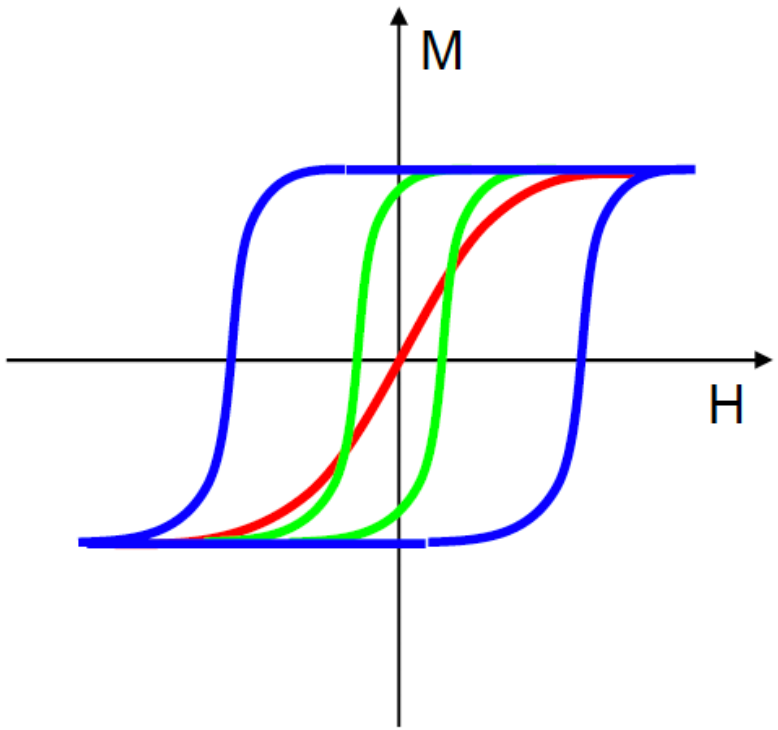

Log10(n_i2/1e5) (cm^-3), t=0.00 s
-2
-1
0
1
2

THANKS

SUPERPARAMAGNETISM - A SIZE EFFECT

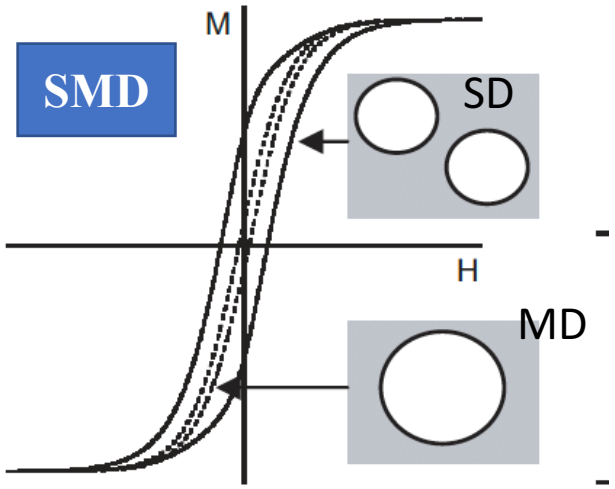
Magnetic Properties of Nanostructured Materials:

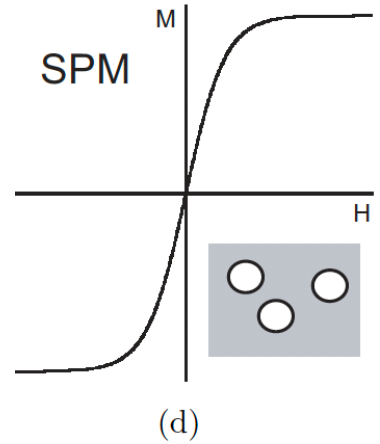




Technology breakthrough – Superparamagnetic nanoparticles

For H=0 the critical radius R_c of a spherical domain corresponds to the radius of a uniformly magnetized sphere with minimum energy. As the size increases the single domain state incurs an energy cost due to demagnetizing forces that tend to rotate the field. The forces are balanced by the energy exchange forces that keep the spins aligned. Single Magnetic Domain (SMD) structures are have all spins collinear and are thus magnetically saturated. The response to SMD particles to external H differs radically from those of bulk particles. Instead of domain wall movement they they respond by spin rotation within a single domain. Typically R_c is about 100 nm.





(d)

$$R_{SMD} = \frac{6\sqrt{AK}}{\mu_0 M_s}$$