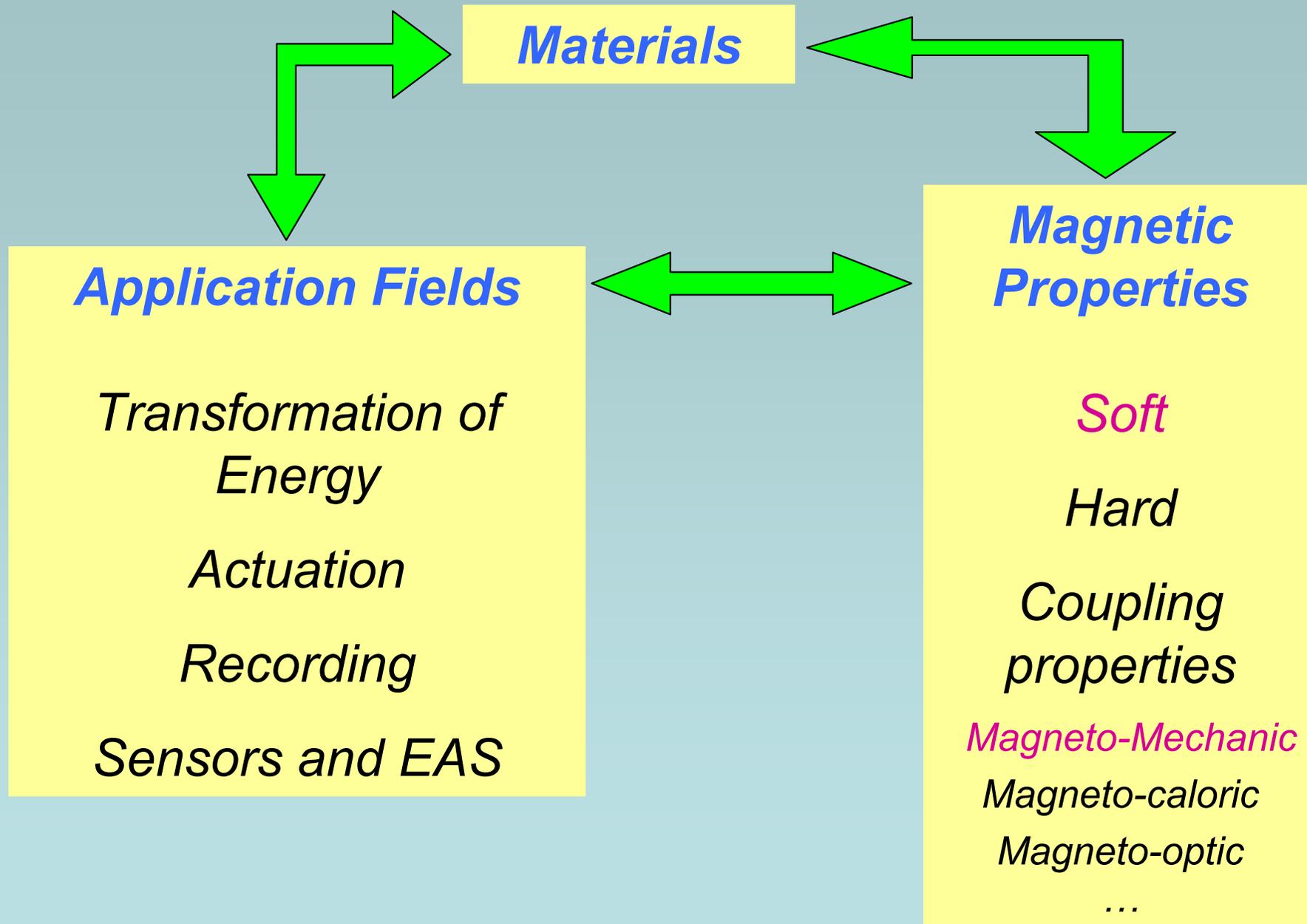


SOFT MATERIALS AND APPLICATIONS

O. Geoffroy

Grenoble Electrical Engineering (G2Elab)

MATERIALS AND APPLICATIONS



Soft Materials : Some General points

- * *The world of soft materials : a Schematic view*
- * *Basic properties and application fields*
- * *How does it work ? (Static)*
- * *The different permeabilities*
- * *How does it work ? (Dynamical)*

Massive, Stacked laminated sheets, wounded ribbons, compacted composites

The different frequency ranges

- * *$f < 1000$ Hz : Classical laminated SiFe, CoFe and futur challenges*
- * *400 Hz $< f < 100$ kHz : Iron based amorphous ribbons*
- * *1000 Hz $< f < 100$ GHz : Soft ferrites*

The Vanishing anisotropies alloys

- * *What does it mean ?*
- * *How do we do ?*
- * *How tailoring the shape of the loop : The induced anisotropies K_u*
- * *Transverse K_u , flat loops and coherent rotation magnetization mechanism*

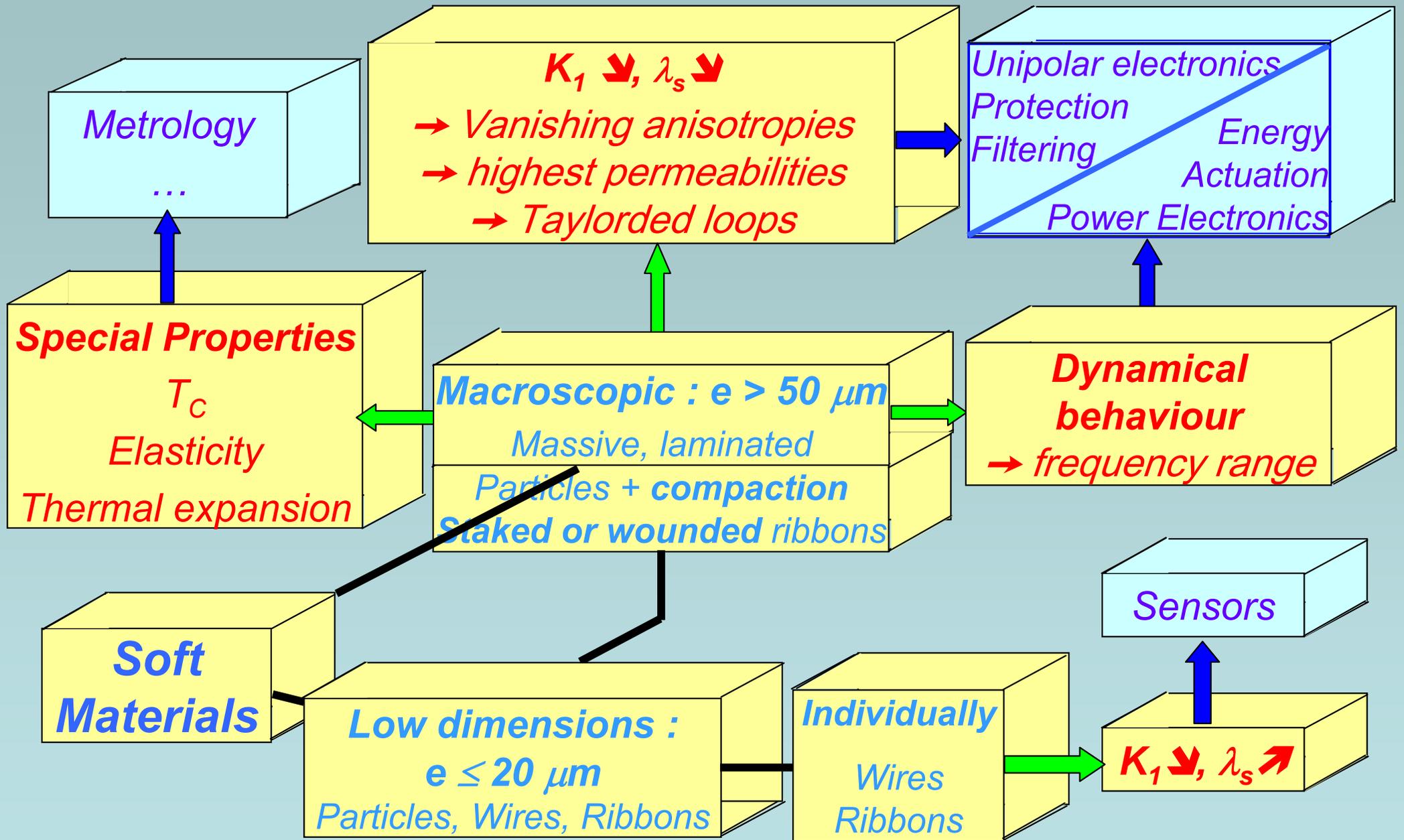
The Very low permeabilities and Energy storage

- * *The classical way : Soft ferrite + Air Gap*
- * *The Soft Composites*

Ribbons, wires and microwires for sensors

- * *The Giant Magneto-Impedance*
- * *Electronic Article Surveillance (harmonic systems, Acousto-magnetic labels)*

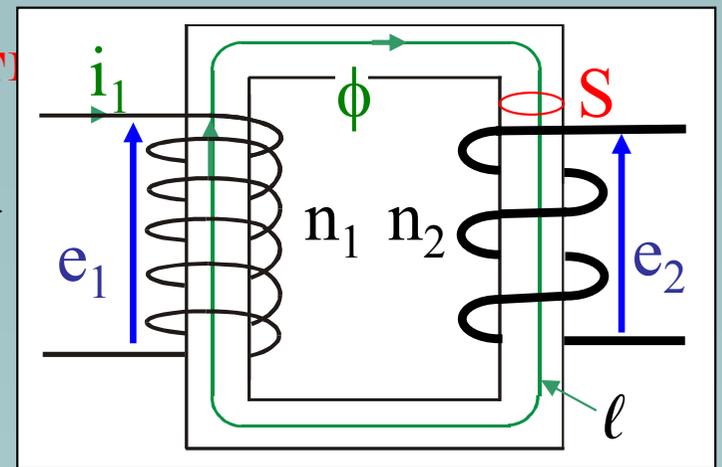
MATERIALS AND APPLICATIONS



Soft Materials

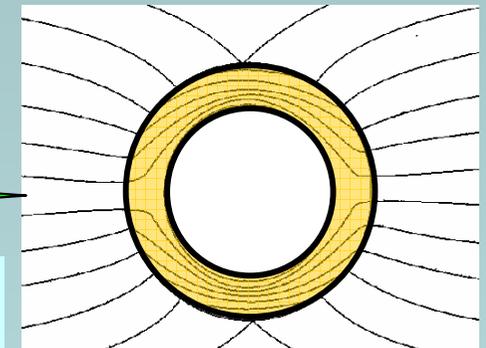
PROPERTIES AND APPLICATIONS

transformers



drive the magnetic flux

Magnetic Shields



Flux detection

Sensors,
fault circuits breakers

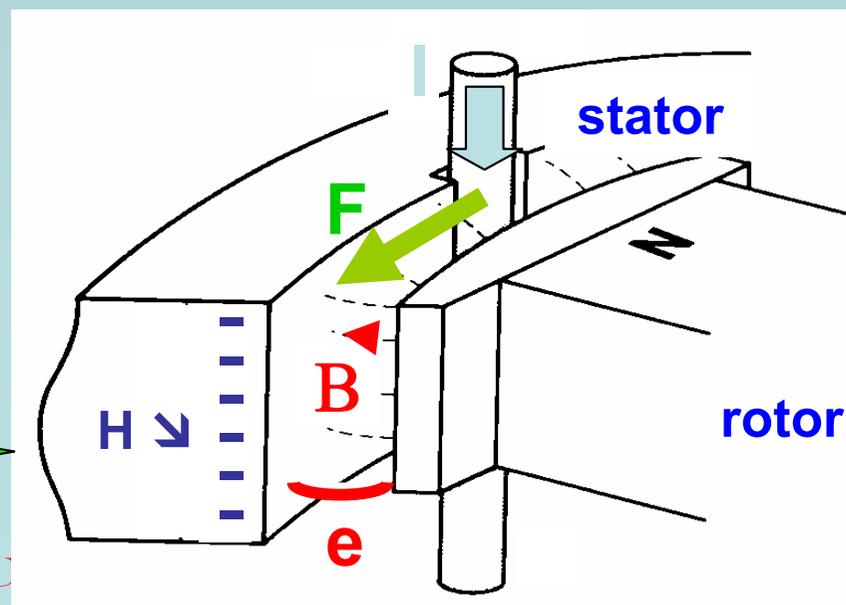
Concentration in air gaps

Electromagnets

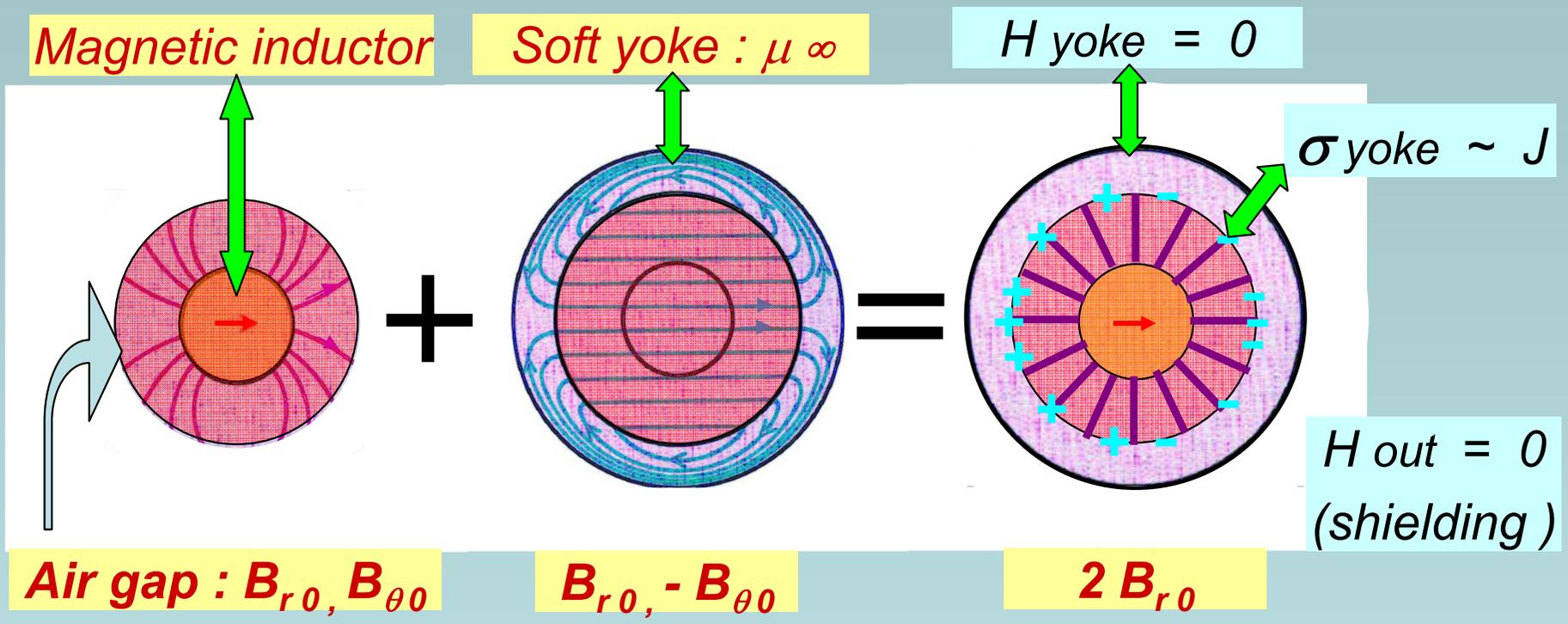
Magnetic forces

Machines

Actuators



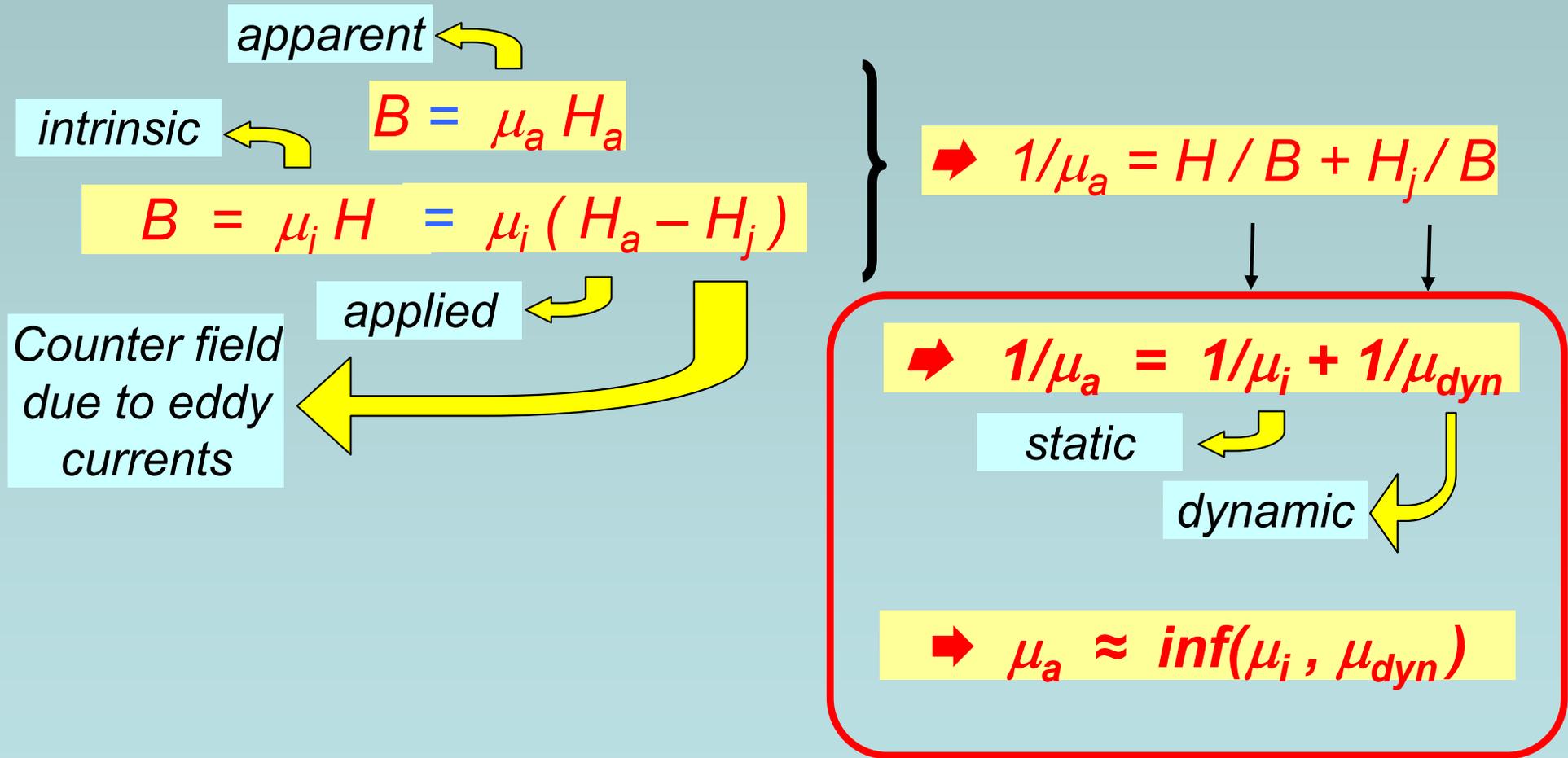
Soft Materials : the mirror effect



➡ **The ideal soft Material : $\mu \nearrow J_s \nearrow$**

➡ **Iron based alloys : $\mu_{r Fe} \approx 8000 \quad J_{s Fe} = 2.2 T$**

Soft Materials : the different permeabilities μ_a , μ_j , μ_{dyn}



Soft Materials under dynamical regime :
Transformation of energy, actuation, power Electronics...

Classical eddy-currents

conductivity

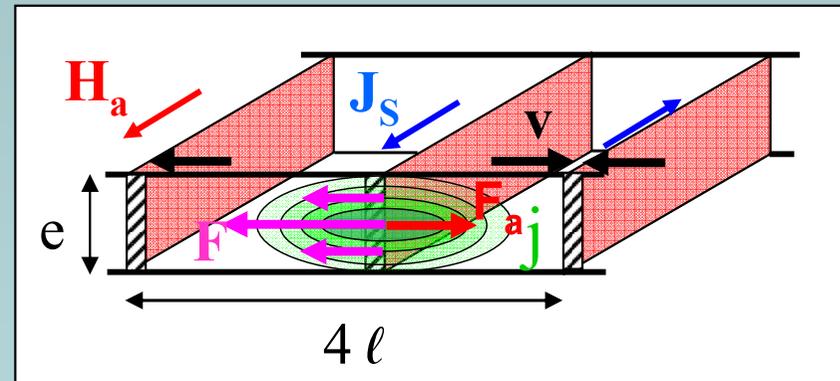
$$e < \delta = (\mu_i \sigma \pi f)^{-1/2}$$

skin depth

thickness

$$P_{vclas} = 0.167 \sigma B_m^2 e^2 \pi^2 f^2$$

Main mechanism : Domain Walls



$$\langle F \rangle = F_a$$

$$\mu_{dyn} = \frac{\pi^2}{16 l e \sigma f}$$

$$P_v = 1,628 P_{vclas} 2l / e$$

⇒ σ ↓
(material)

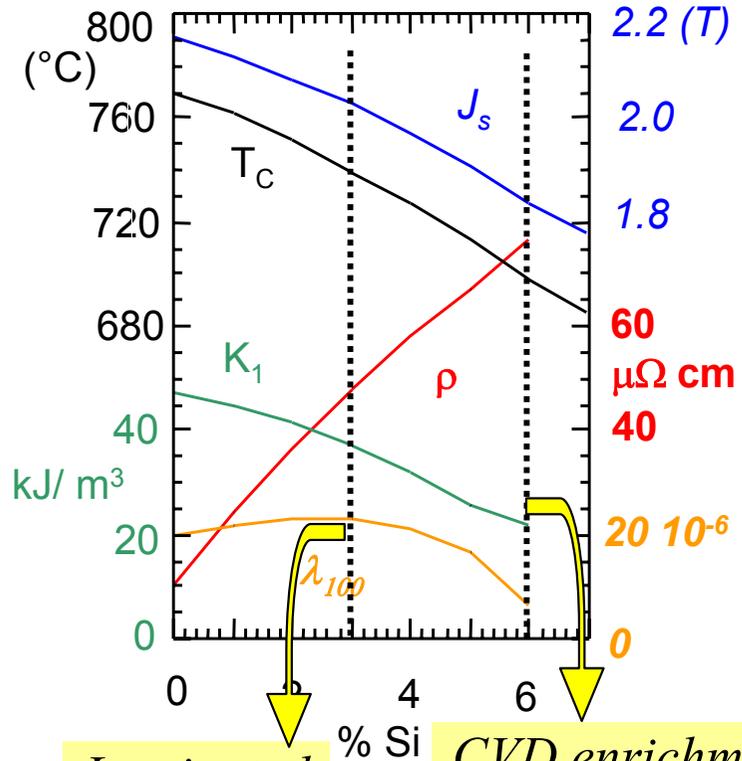
⇒ e ↓
(Process)

⇒ l ↓
(treatments)

Soft Materials under dynamical regime : $f < 1000$ Hz

→ σ ↘

SiFe alloys



Laminated

CVD enrichment after lamination

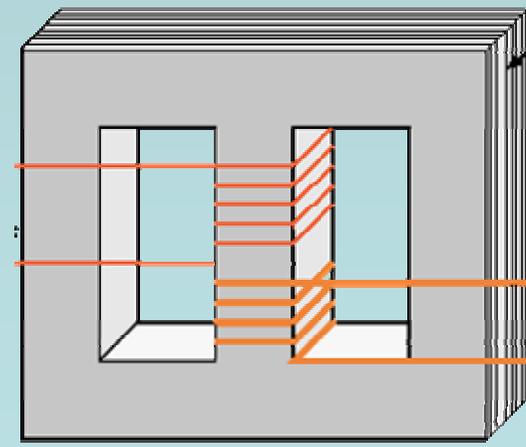
$\rho_{Fe} = 10 \mu\Omega cm$
 $\rho_{FeSi3\%} = 48 \mu\Omega cm$

→ e ↘

Lamination :

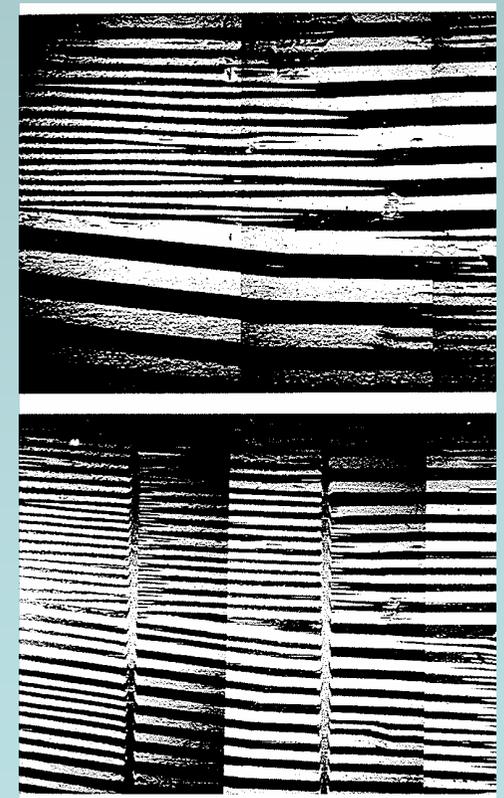
→ $e_{min} \sim 50-100 \mu m$

Stacked or wound magnetic circuits



→ l ↘

Laser irradiation, Plasma etching...



Soft Materials under dynamical regime : $f < 1000$ Hz

Challenges for the next years : the in-board machines

Until now :

*Electromagnetic ;
Hydraulic*

*In the next future :
All Electromagnetic*



Specific power ↗↗

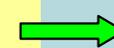
Electrical generation (alternators)

Ω ↗ → Mechanical stress ↗
alternators directly set in the jet engine :
Operating temperature ↗



New CoFe alloys

Tensile Strength : 500 → 700 GPa



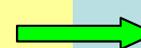
T : 220 → 400 °C



*CoFe alloys ; new
dedicated insulation*

Transformers

J ↗
 f ↗ (400 Hz → 900 Hz) } Acoustic
noise ↗↗



Vanishing λ_{100}



6% SiFe alloys

Soft Materials under dynamical regime : $400 \text{ Hz} < f < 100 \text{ kHz}$

Iron based amorphous ribbons :

magnetism

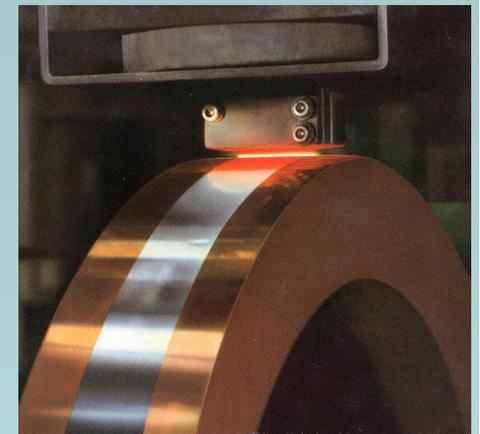
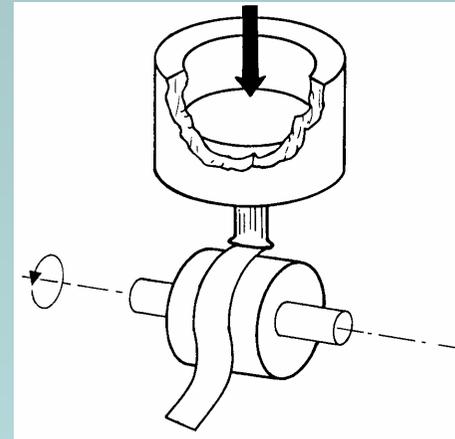
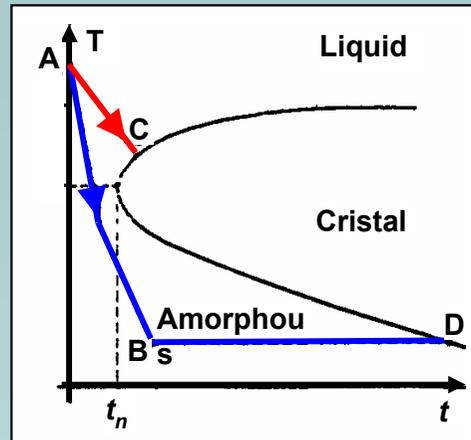
Glass former



resistivity

$\frac{dT}{dt} > 10^6 \text{ K/s}$

Planar flow casting



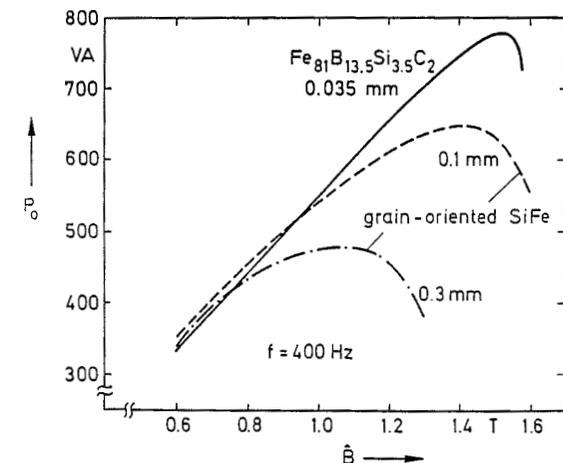
Thickness $e \sim 20\text{-}40 \mu\text{m}$

$\rho \sim 140 \mu\Omega \text{ cm}$
 ($\rho_{\text{FeSi}} \sim 48 \mu\Omega \text{ cm}$)

$J_S \sim 1.6 \text{ T}$

Operating Temperature : $150 \text{ }^\circ\text{C}$

Medium frequency range



Soft Materials under dynamical regime : $f > 100 \text{ kHz}$

Soft Ferrites

Very cheap, $\rho \nearrow \nearrow$ 😊 $J_S \searrow$ ($J_S \text{ MnZn} \sim 0.4 \text{ T}$) ☹️

Powder \rightarrow compaction \rightarrow sintering \rightarrow massive cores

Spinels :

$\rho \text{ MnZn} \sim 1 \Omega \text{ m} \Rightarrow f_{\text{max}} \sim 1 \text{ MHz}$
 $\rho \text{ NiZn} \sim 10^5 \Omega \text{ m} \Rightarrow f_{\text{max}} \sim 100 \text{ MHz}$ } RF

Garnets :

$\rho \text{ YIG} \sim 10^{10} \Omega \text{ m} \Rightarrow f_{\text{max}} \sim 100 \text{ GHz}$ (microwaves)

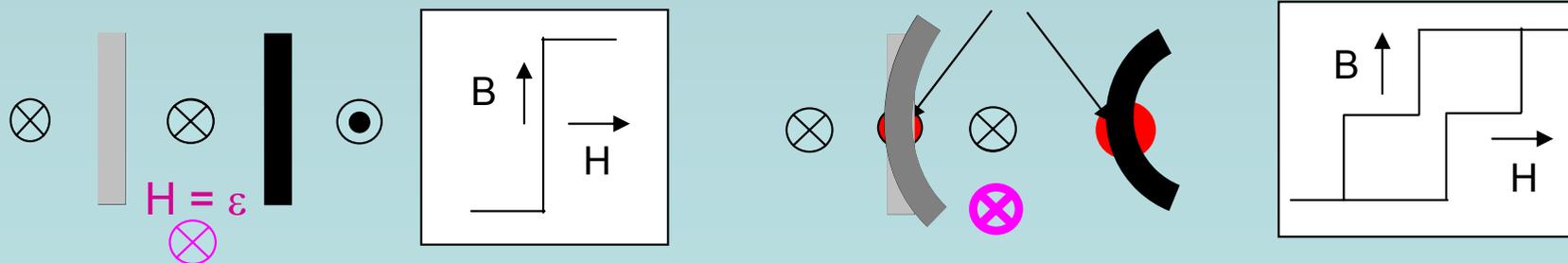
Soft Materials : vanishing anisotropies alloys :
highest permeabilities and taylored loops

$\mu_i \uparrow\uparrow\uparrow$: static magnetic shielding, low voltage circuits breakers, filtering...

inhomogeneities ← $\mu_i = J_s / (b + K_1 + K_u + 3/2 \lambda \sigma)^{1/2}$ → magnetoelastic

magnetocristallne ← → induced

About inhomogeneities :



$b \downarrow\downarrow\downarrow$

Vanishing K_1

Vanishing λ

Soft Materials : vanishing anisotropies alloys :

$b \searrow \swarrow$



process $\nearrow \nwarrow$

Vanishing K_1



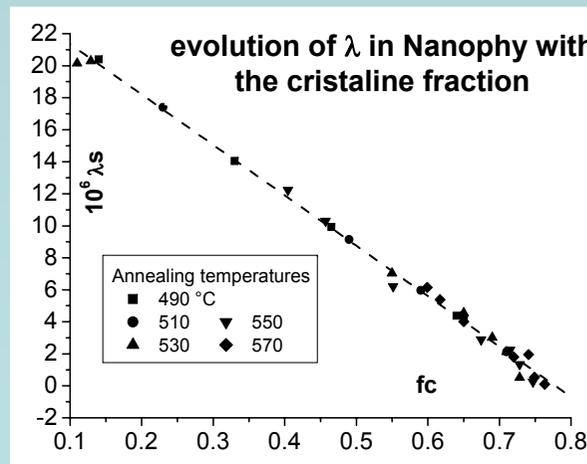
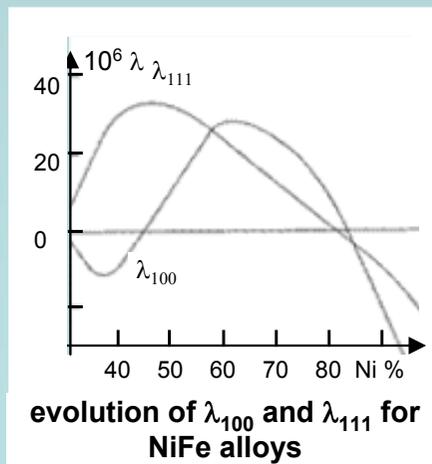
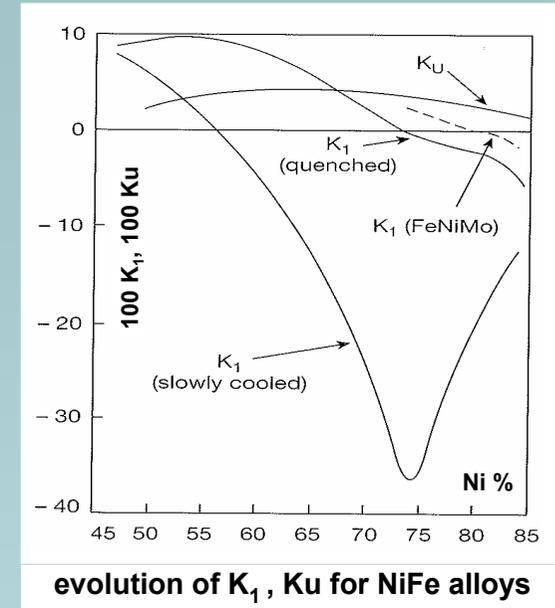
disordered structure :

Amorphous,
Nanocrystalline
solid solution
(NiFe alloys)

Vanishing λ



composition



... The winners :

Co based Amorphous
~~**Fe based Amorphous**~~

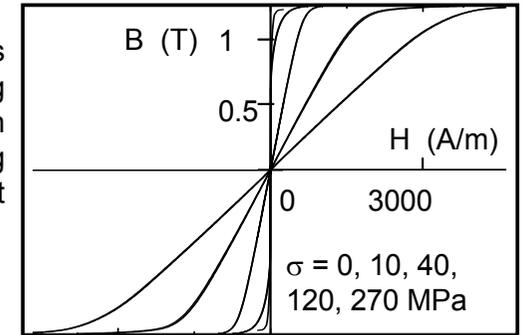
Nanocrystalline (Finemet, Nanoperm, Hitperm...)

$Ni_{80}Fe_{15}Mo_5$ Permalloy

Soft Materials

vanishing anisotropies alloys :
tailored loops and induced K_u

effect of a stress applied during the crystallisation flash annealing on a soft nanocrystalline alloy



$K_u > 200 \text{ J/m}^3$

Heat treatment
→ diffusivity

+

Vanishing λ, K_1
→ isotropy

+

mechanical stress
magnetic field

=

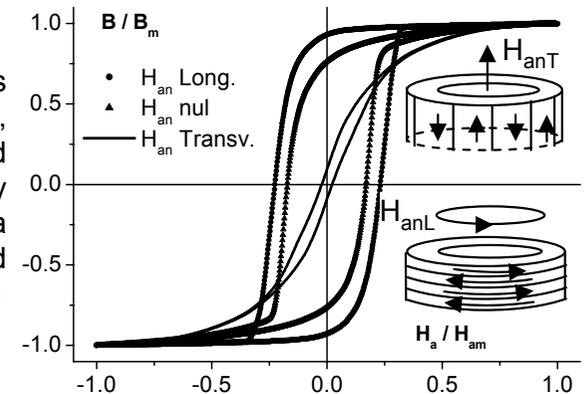
induced K_u

$K_u < 200 \text{ J/m}^3$

Rectangular loops :

magnetic amplifiers, fluxgate sensors...

different shapes (rectangular, flat, round) obtained on Nanophy applying a magnetic field during annealing



Flat loops : $\mu_r = J_s^2 / (2 \mu_0 K_u)$

ground fault circuits breakers,

Unipolar electronics (pulse transformers...)

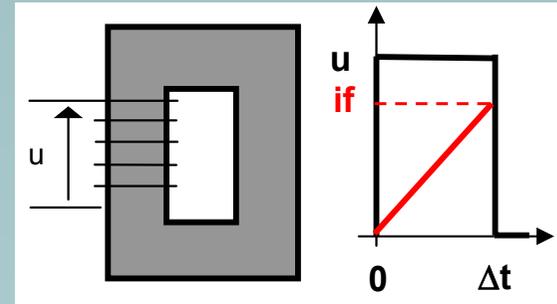
Soft Materials

Flat loops

MATERIALS AND APPLICATIONS

Energy storage

$K_u \rightarrow$ Vanishing K_1, λ , alloys :
Permalloys, Co based amorphous,
soft nanocrystalline



$$E = \frac{1}{2} L I_f^2 = \frac{1}{2} u^2 \Delta t^2 / L$$

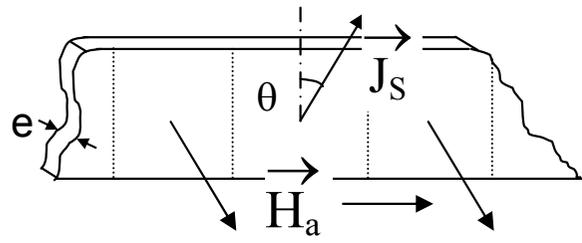
$$L \approx \mu_0 \mu_{ra}$$

$$E \nearrow \rightarrow \mu_{ra} \searrow$$

$2\,000 < \mu_r < 200\,000$
Field annealing

$500 < \mu_r < 2\,000$
Stress annealing

$10 < \mu_r < 500$
Classical : soft Ferrite + Airgap

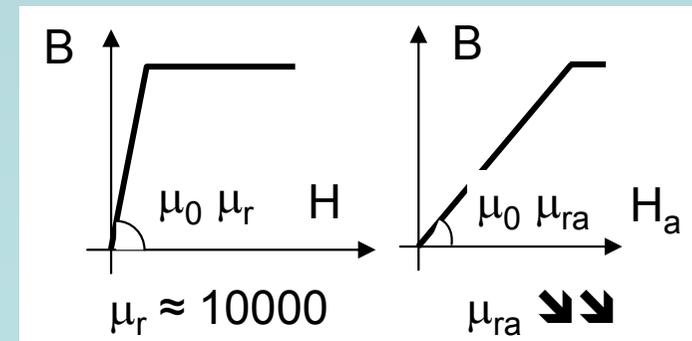
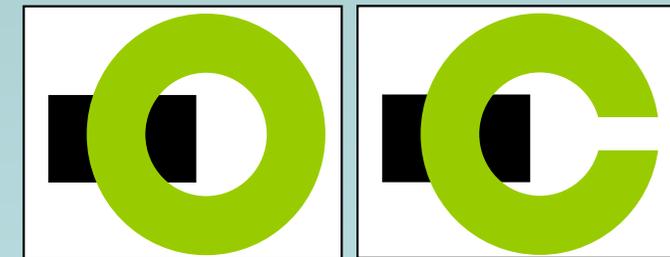


Coherent
rotation
mechanism

CR : $\mu_{dyn} = \frac{1}{e} \sqrt{\frac{2\mu}{\sigma\pi}} \frac{1}{\sqrt{f}}$

DW : $\mu_{dyn} = \frac{1}{e} \frac{\pi^2}{16 \ell \sigma} \frac{1}{f}$

Dynamical
properties $\nearrow \nearrow$



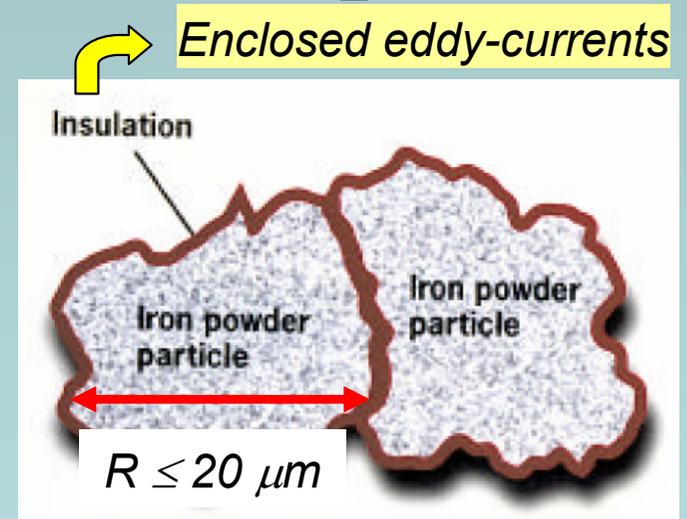
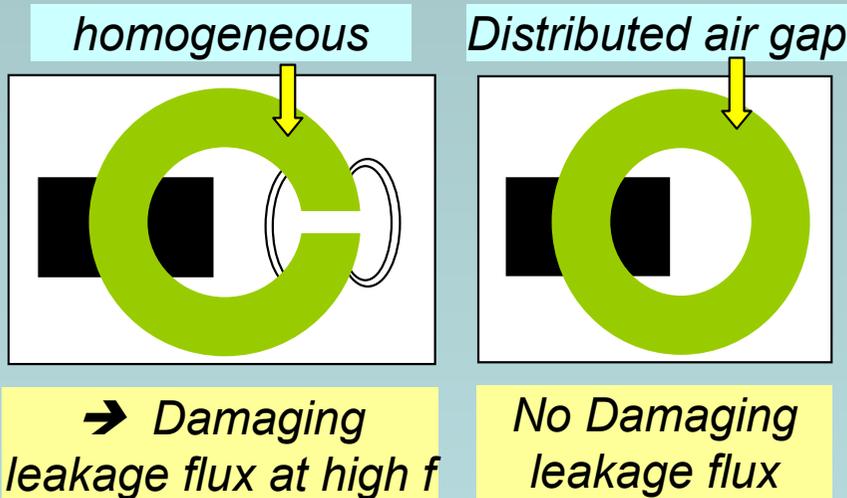
Soft Materials

MATERIALS AND APPLICATIONS

Soft Magnetic Composite materials : $10 < \mu_r < 500$

Energy storage :

High induction Ni Fe Co alloys suitable for high frequency range
($10 \text{ kHz} < f < 100 \text{ MHz}$)



$f < 1000 \text{ Hz}$:

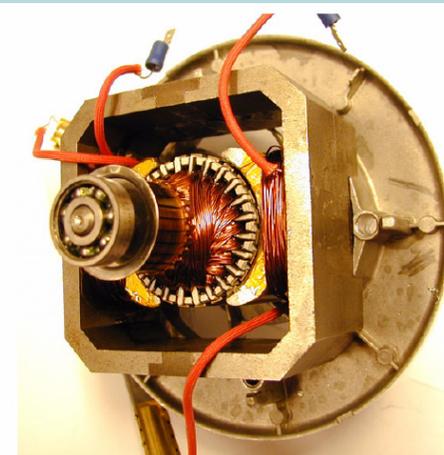
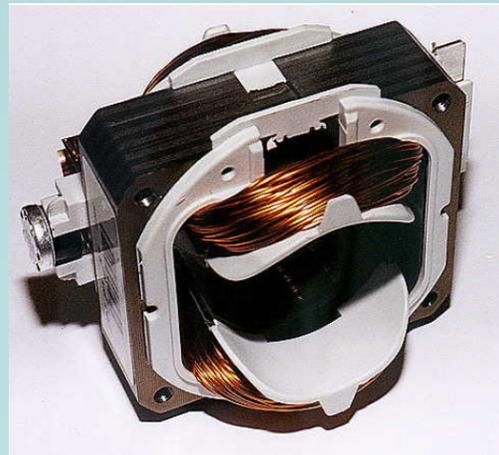
Moulding possibility

→ 3D geometries

$\mu_r \approx 800$

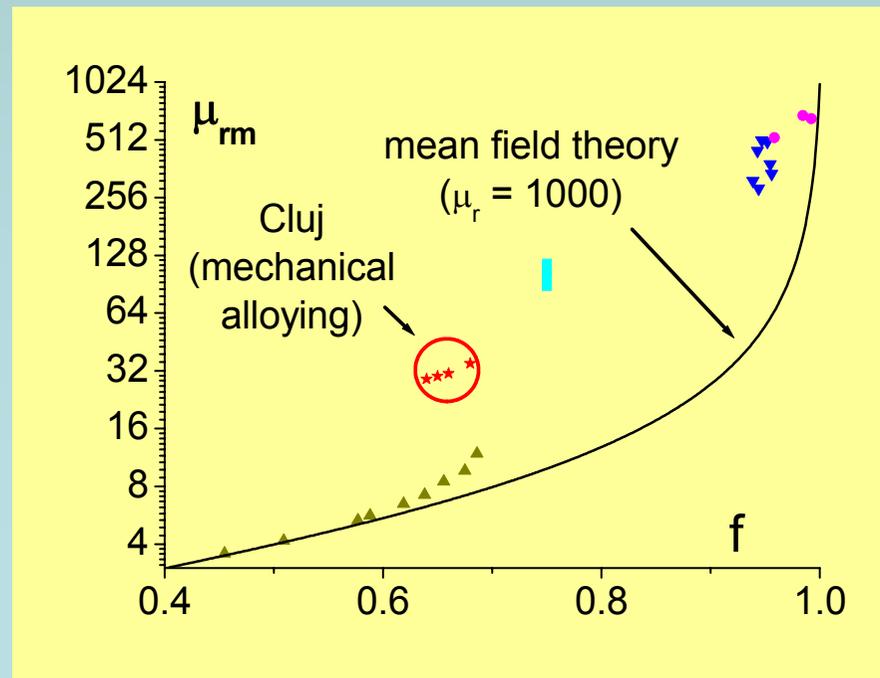
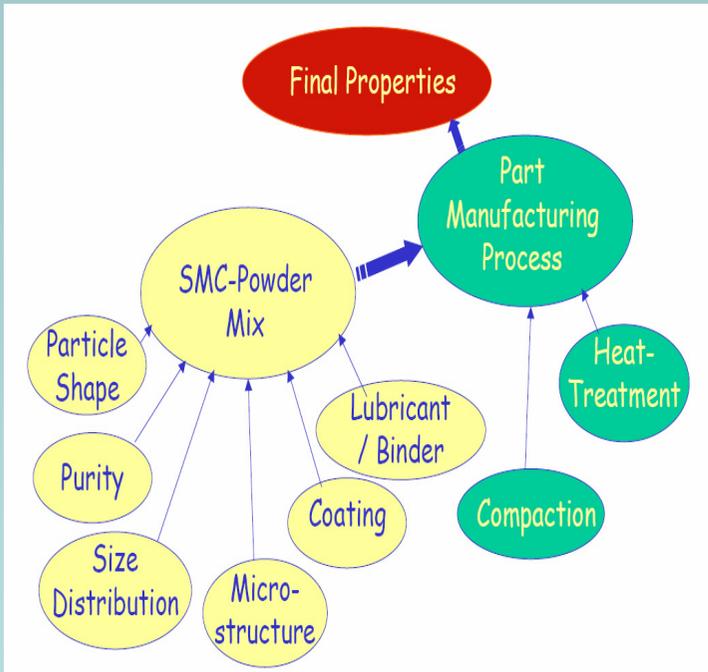
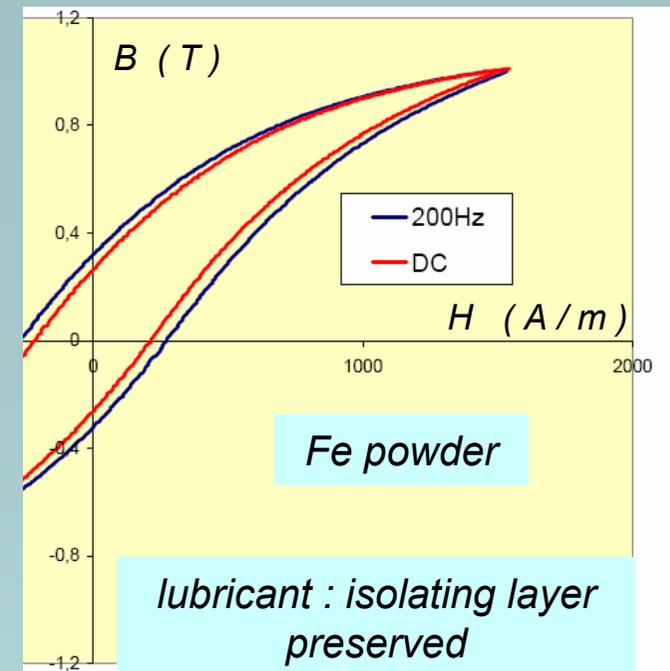
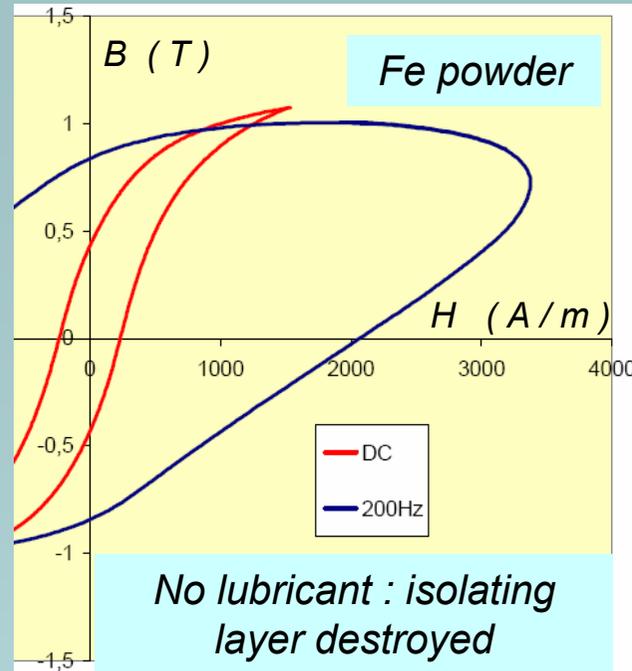
Mechanical

strength ⚡ ☹️

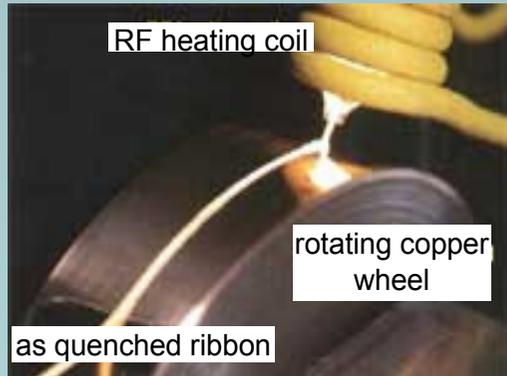


Soft Materials Soft Magnetic Composites: Manufacturing process

MATERIALS AND APPLICATIONS



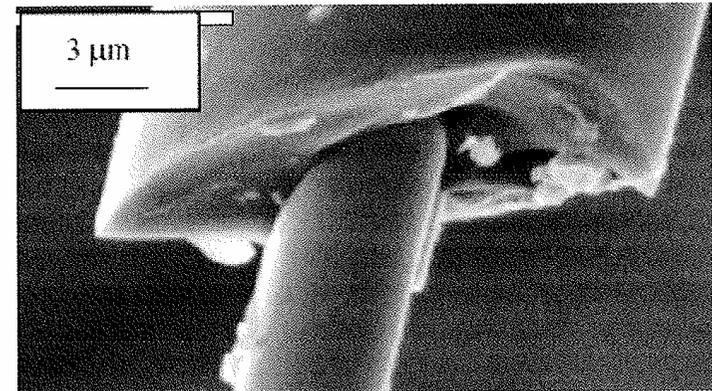
Soft Materials : Ribbons, Wires and Microwires for sensors



*melt spinning Process
≈ 1 mm*



*Amorphous wire 20-
100 μm (Unitika)*



Microwire CoFeNi(SiB) glass coated

Rotating wheel :
Amorphous (Fe or Co based), Nanocrystalline

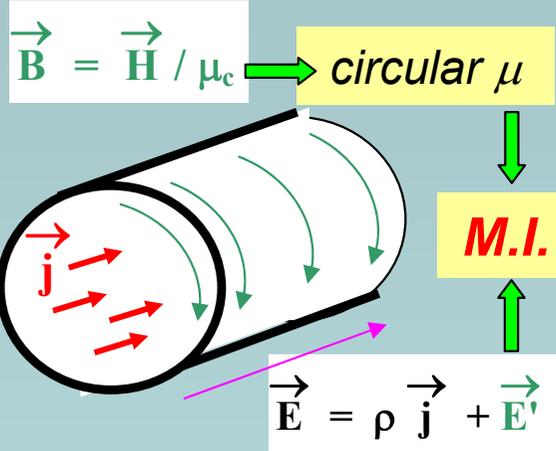
Water Cooled Microwires :
Amorphous (Fe or Co based)

Classical Wire drawing :
Cristalline NiFe mumetal

Soft Materials : MATERIALS AND APPLICATIONS

Ribbons, Wires and Microwires for Giant Magneto-Impedance

Principle :

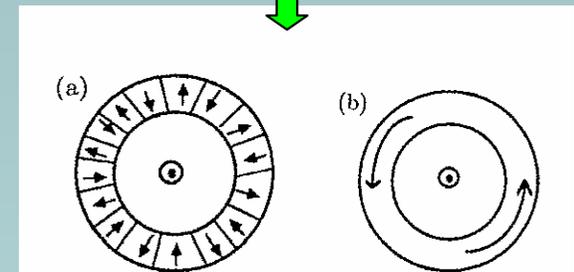


Complex Domain Structure depending on λ_s

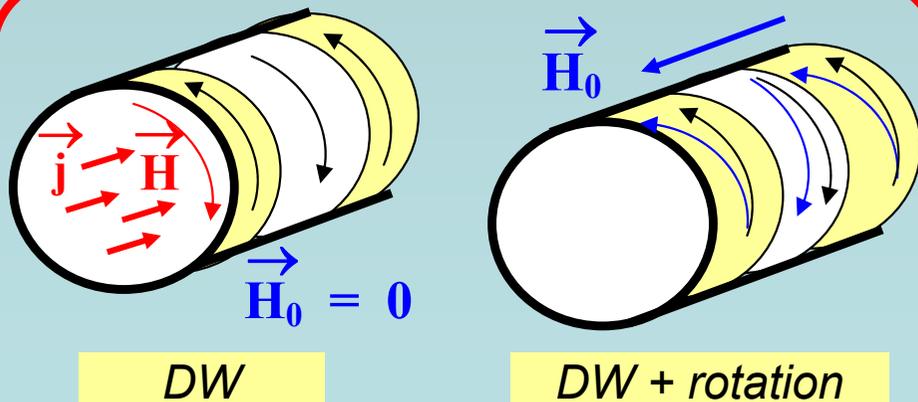
Inhomogeneous stress

Inhomogeneous cooling rate

Quenching process



Domains in a microwire:
 $\lambda_s > 0$ (a), $\lambda_s < 0$ (b)



DW

DW + rotation

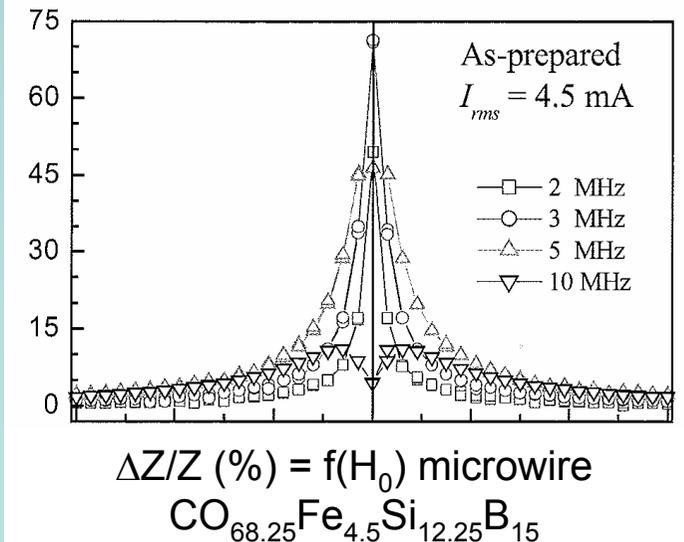
$f \searrow$

$$Z = L\omega \sim \mu_c$$

$f \nearrow$

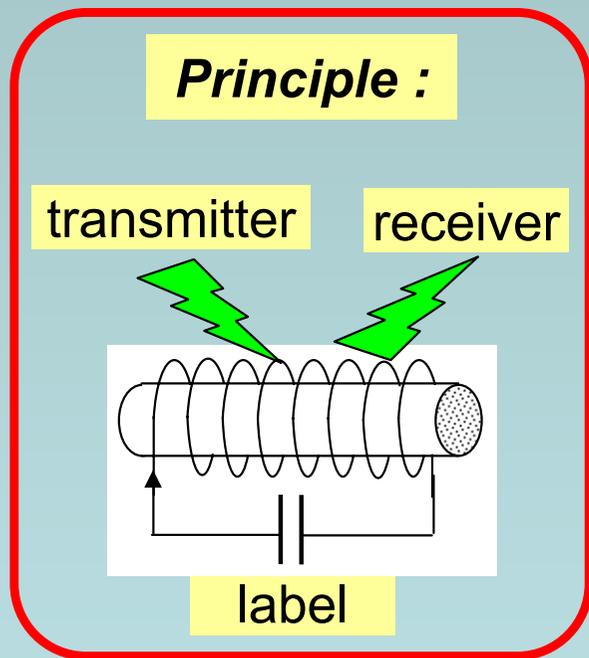
$$Z = R \sim \delta \sim \mu_c^{-1/2}$$

$\mu_c = f(H_0)$ → **Field sensor**



Soft Materials :

Ribbons, Wires and Microwires for *Electronic Article Surveillance*



Basic R.F. labels

Rewritable labels

Harmonic labels

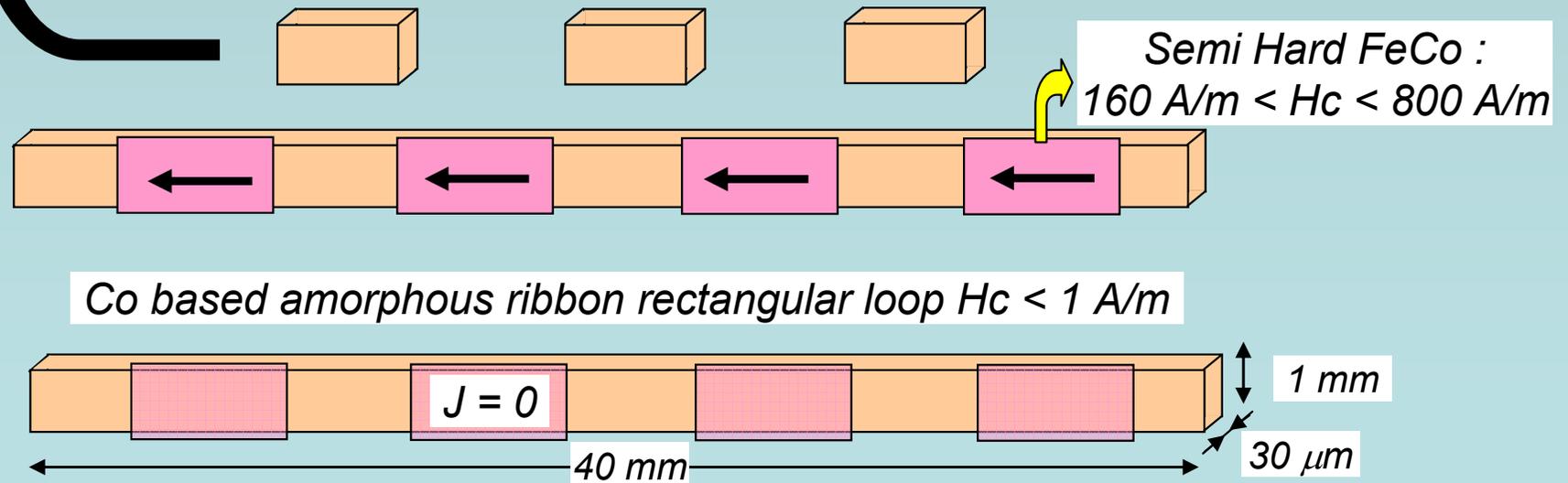
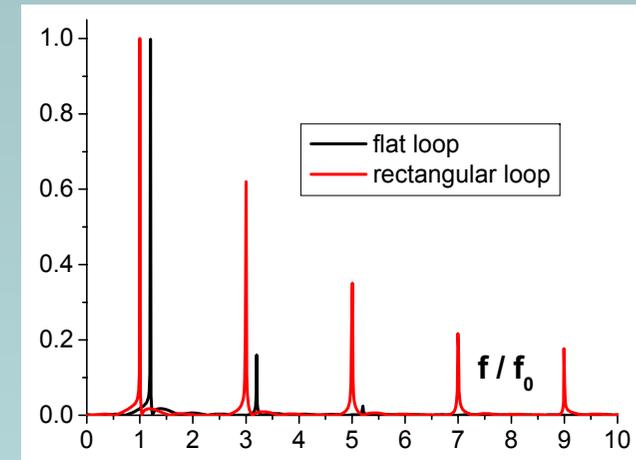
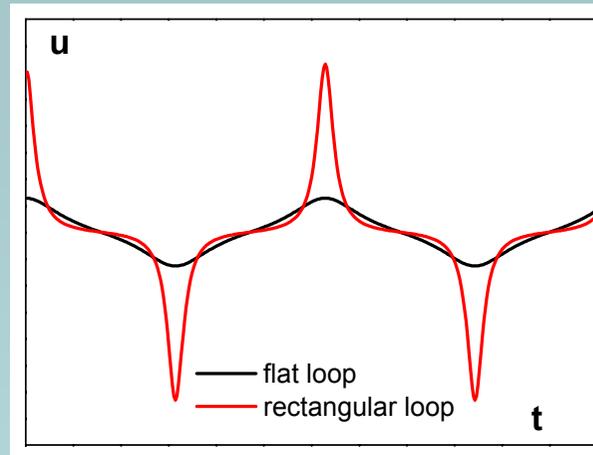
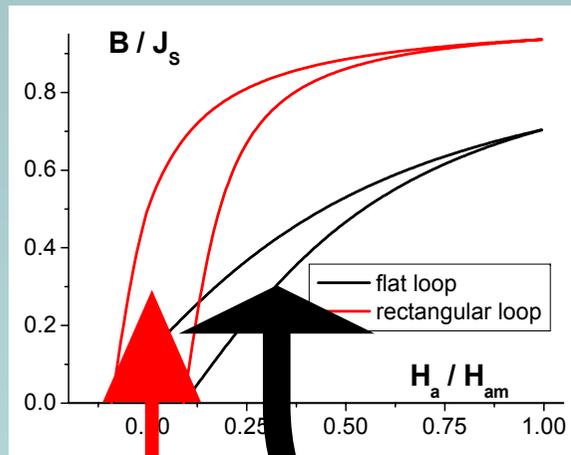
Magneto Acoustic labels

Soft Materials : MATERIALS AND APPLICATIONS

Ribbons, Wires and Microwires for *Electronic Article Surveillance*

Harmonic labels

Harmonic response content = shape dependent



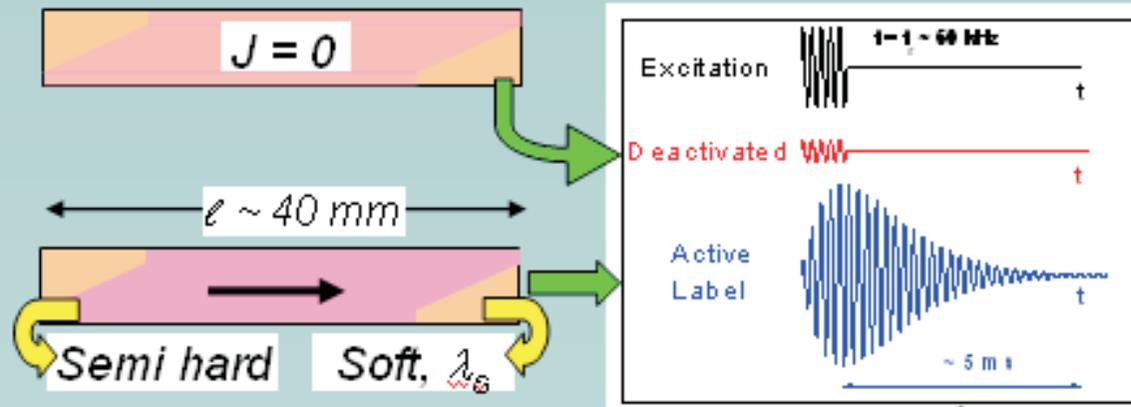
Soft Materials :

MATERIALS AND APPLICATIONS

EAS:

Acousto-Magnetic labels

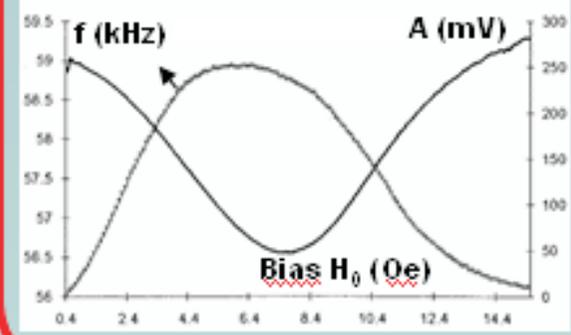
Principle :



ΔE effect:

$$E = f(\lambda_s, H_0)$$

$$\begin{matrix} f_r(H_0) \\ A(H_0) \\ \tau(H_0) \end{matrix}$$



Alternating H

Mechanical inertia

Delayed response

Sensitivity $\uparrow\uparrow$

Alternating J

λ_s

Mechanical vibrations

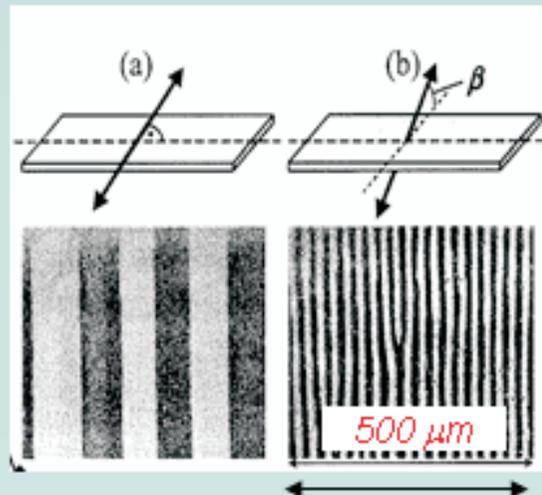
Mechanical resonance

$$f_r = \frac{\sqrt{E/\gamma}}{2\ell}$$

E = Young Modulus
 γ = density

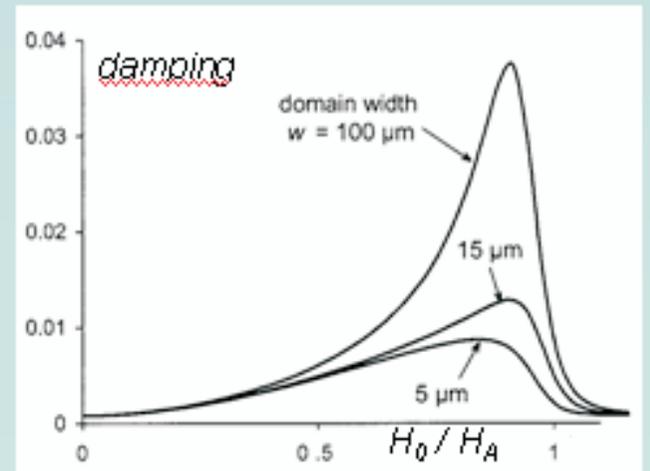
About damping :

Out of plane field annealing
 \Rightarrow Refinement



\Rightarrow Damping $\downarrow\downarrow$

$\Rightarrow (A, \tau) \uparrow\uparrow$



THE END