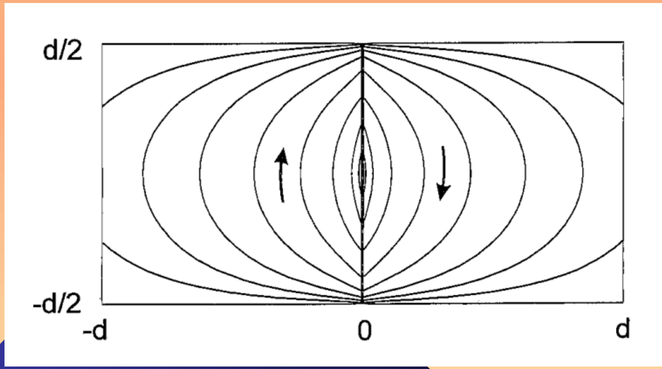
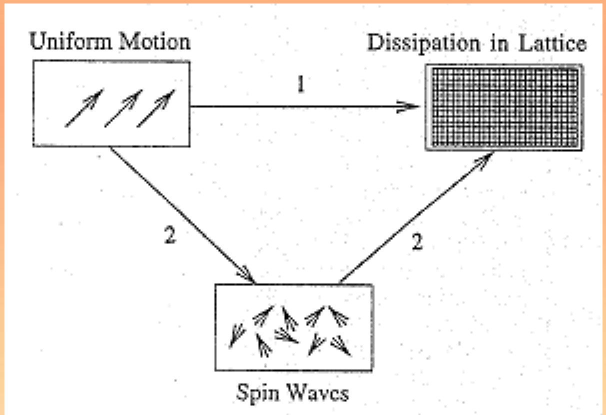
PHENOMENOLOGY OF MAGNETIC LOSSES

Any variation of the flux density in a magnetic material is associated with dissipation of energy. The main physical mechanisms for dissipation are: 1) Eddy currents and the related Joule effect, associated with the scattering of moving charges with phonons and various lattice defects. The Joule effect is dominant in conducting and semiconducting materials. 2) Spin damping, related to the transfer of energy from the precessing spins to the lattice, either directly or via magnon-phonon interaction. This is the favorite mechanism in insulating magnets.





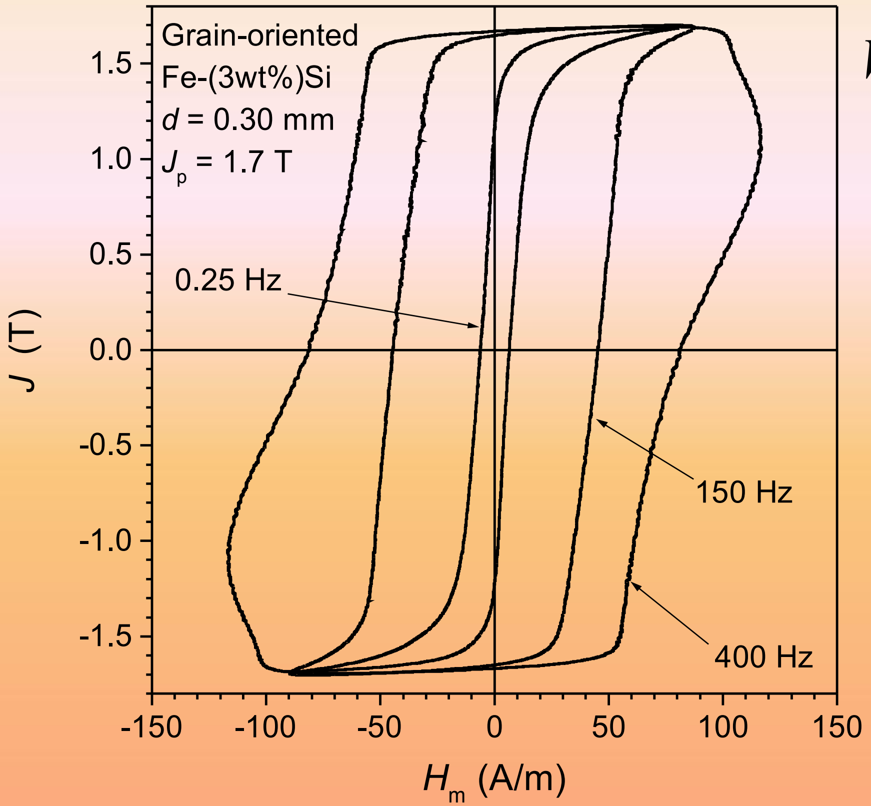
Magnetic losses are conveniently defined under given time periodic law for the rate of change of the magnetization. Typically, one has to deal with either sinusoidal or triangular $B(t)$ waveform. The viscous character of the magnetization process makes attaining a given peak polarization under defined $B(t)$ law increasingly difficult with increasing the magnetizing frequency.

There is an obvious practical appeal to the study of magnetic losses, because there is a stringent need for ther prediction in most electrical/electronic applications. Besides the unnecessary waste of energy, the fast increase of the power loss with the magnetizing frequency (somewhat $\propto f^2$) can make overheating the main obstacle to high-frequency applications ($P = c_v \mathrm{d}T/\mathrm{d}t$).

For sample of volume V subjected to periodic excitation at the frequency $f = 1/T$, we can express the eddy-current energy loss per unit volume on a period as

$$W = \int_V \frac{d^3r}{V} \int_0^T \frac{\left|\mathbf{j}^2(r,t)\right|}{\sigma} dt$$

The space-time behavior of the current density $j(r, t)$ is hopelessly complicated. We need to focus on the general features of the loss behavior, to be treated from a statistical viewpoint.



$$W = \oint H dB = \oint \mu_o H\, dH + \oint H dJ = \oint H dJ$$

H and *X* conjugate work variables

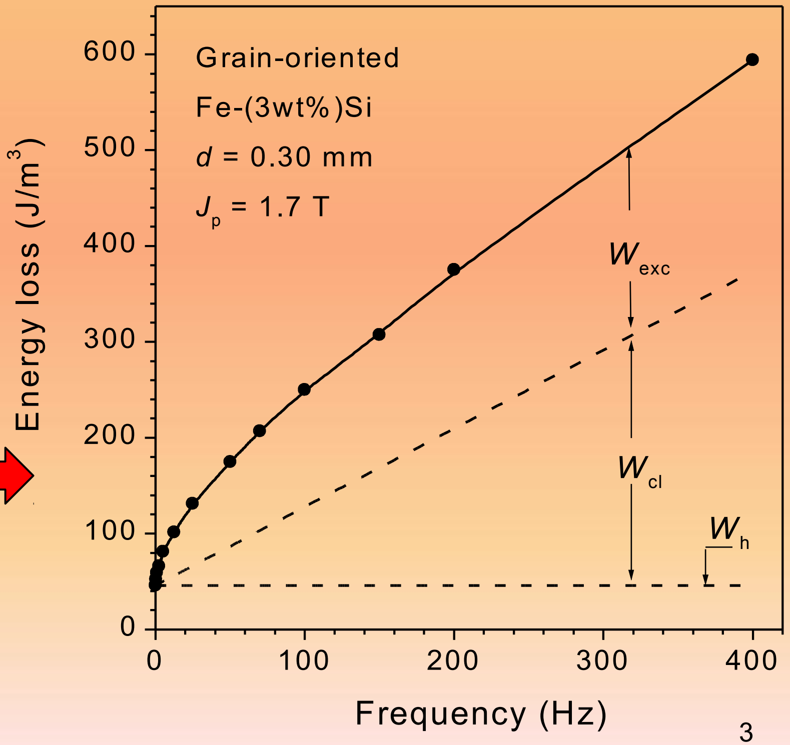
$$dU = H dX + \delta Q$$

Isothermal cycle: $\oint dU = 0$

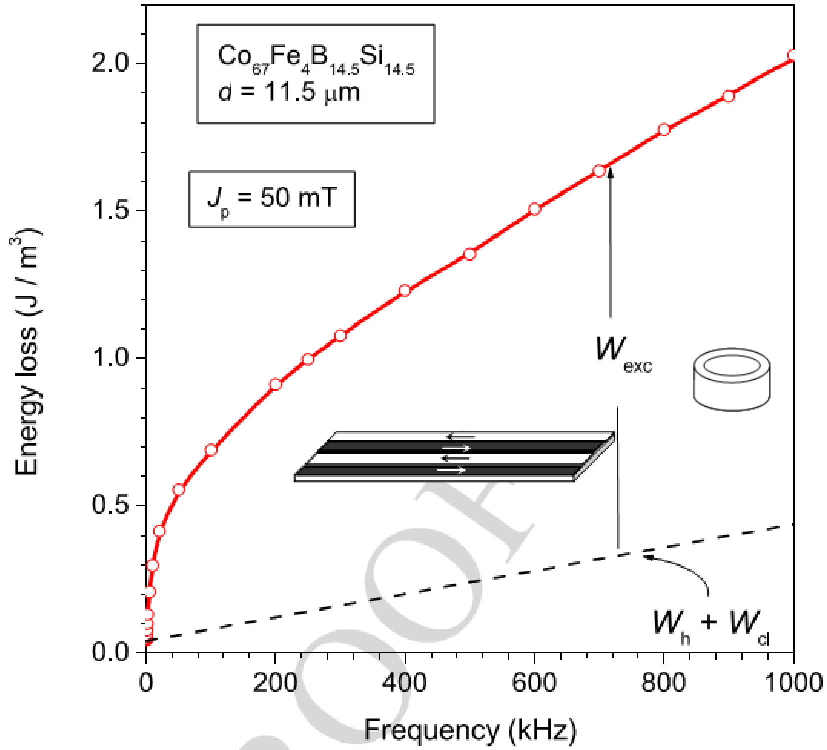
$$\oint H dX = -\oint \delta Q$$

$$\mathbf{W = W_{hyst} + W_{cl} + W_{exc}}$$

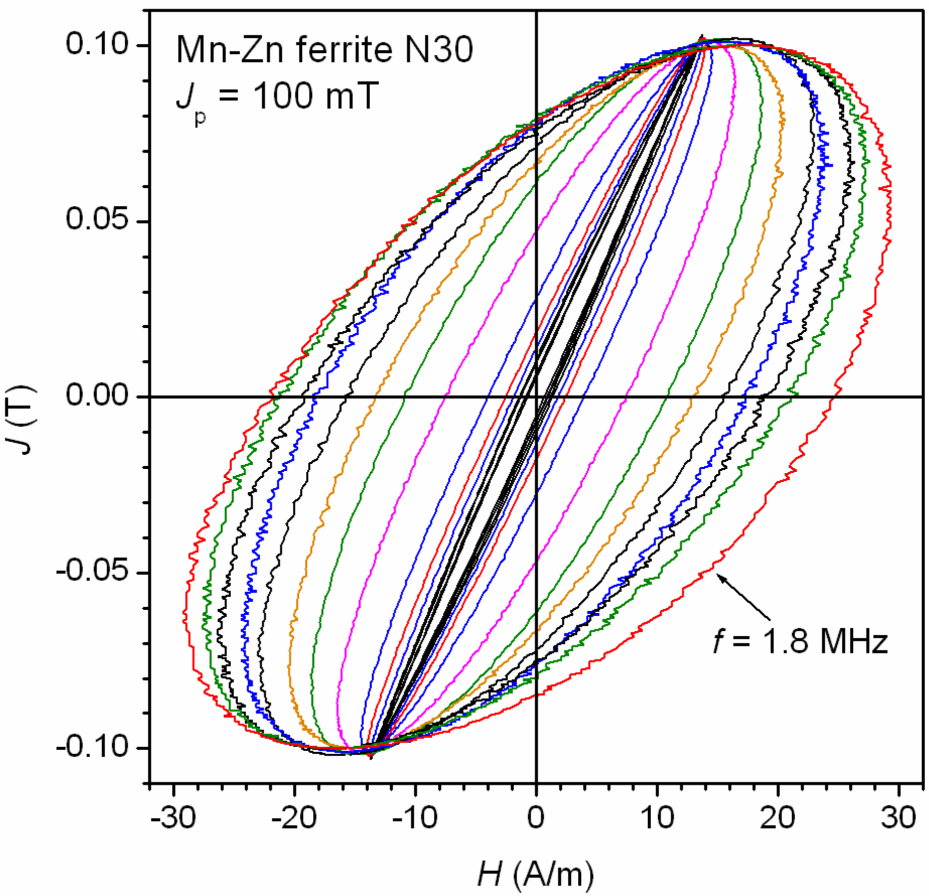
$$W(J_p, f) = W_{hyst}(J_p) + k_{cl} f + k_{exc} f^{1/2}$$



ISTITUTO NAZIONALE DI RICERCA METROLOGICA



Amorphous ribbon



Soft ferrite ring

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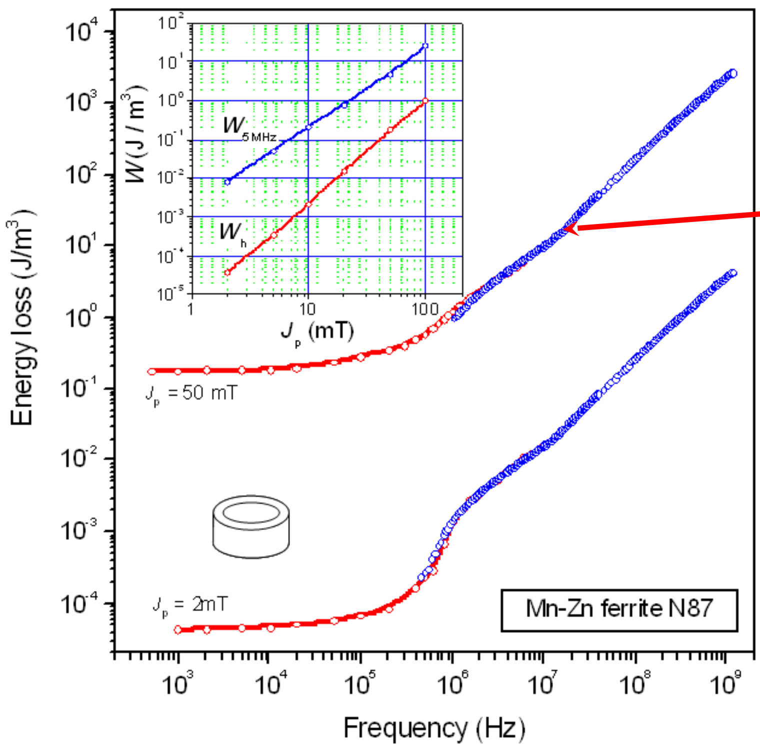
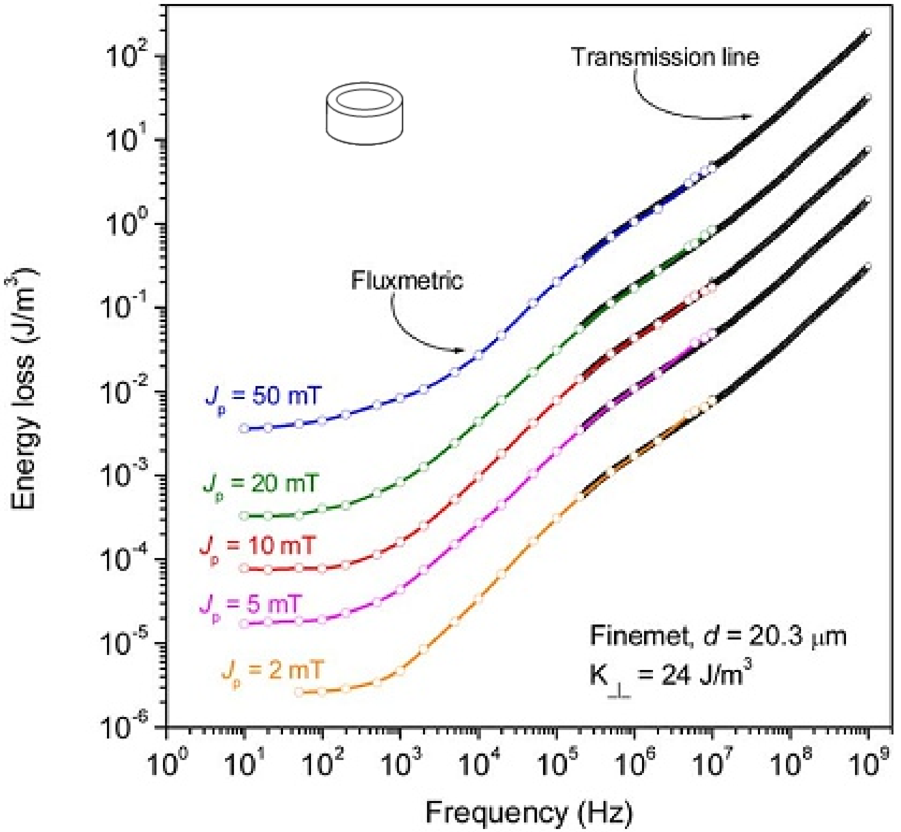
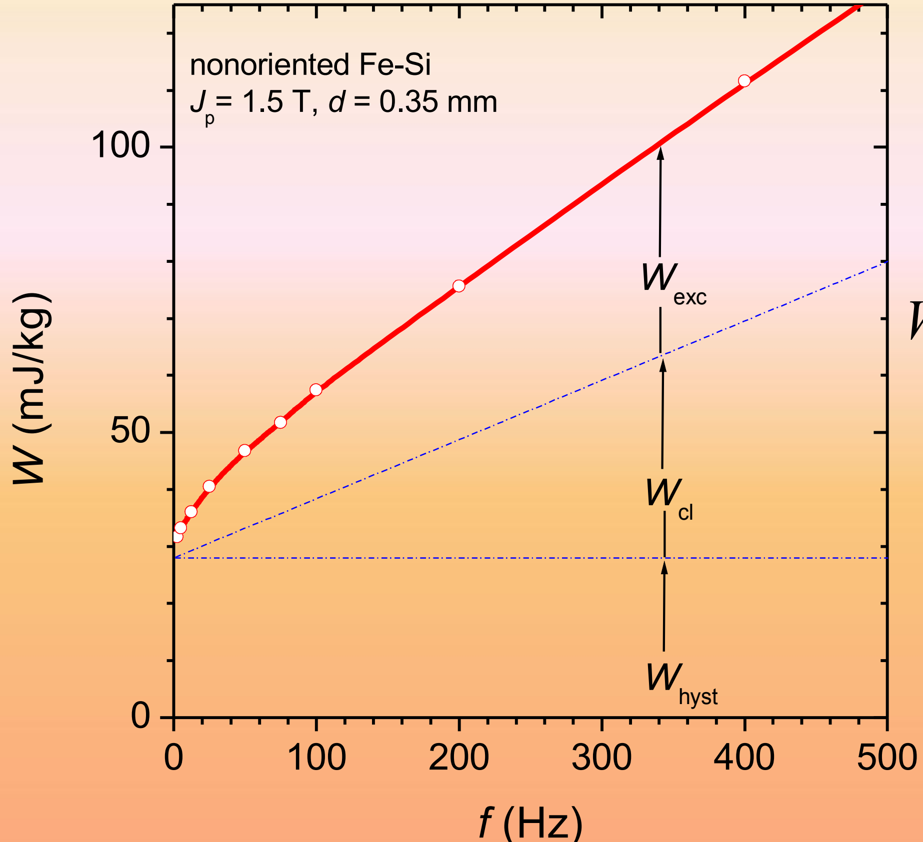


Soft ferrite ring

~ 20 kW/kg

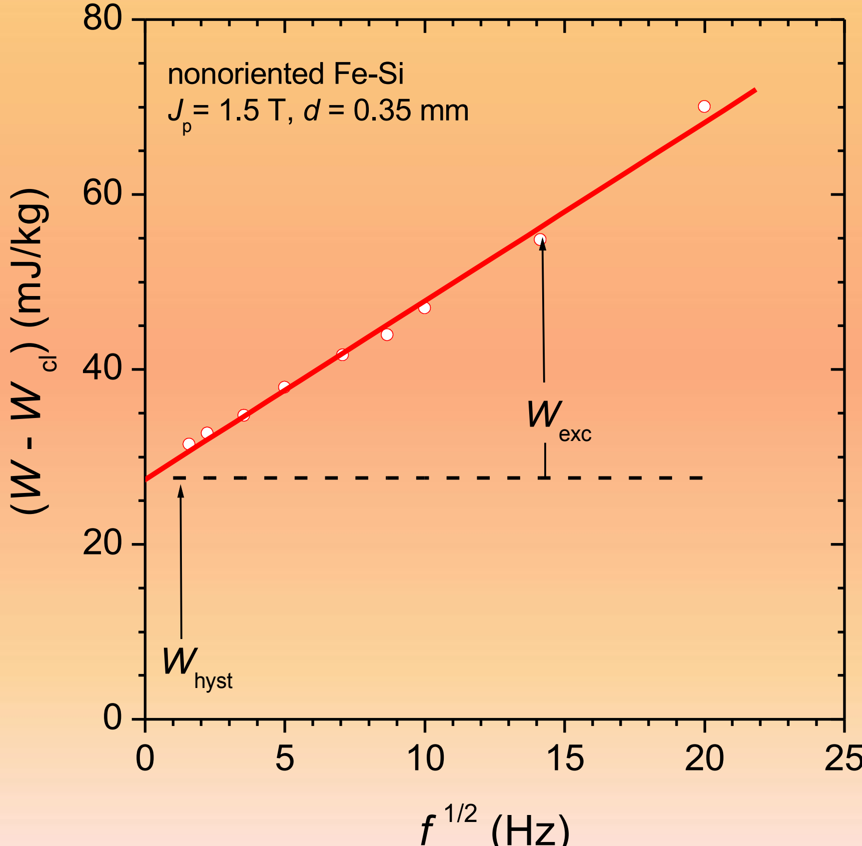


Nanocrystalline ribbon



Excess energy loss under generic polarization rate dJ/dt

$$W_{\mathrm{exc}} = \int_0^T p_{\mathrm{exc}}(t)\,dt = \sqrt{\sigma\; G S V_{\mathrm{o}}} \int_0^T |\,\dot{J}(t)\,|^{\,3/2}\,dt$$

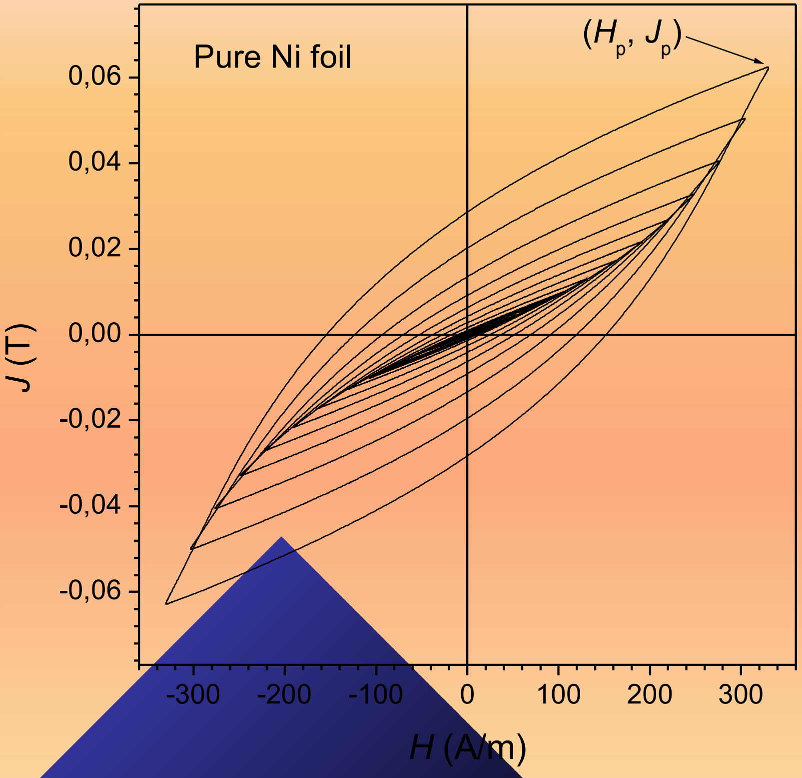


Sinusoidal induction

$$W = W_{\mathrm{h}} + \left(\pi^{2}/6\right)\sigma\, d^{2} J_{\mathrm{p}}^{2}\, f + 8.76\sqrt{\sigma\, G S V_{\mathrm{o}}}\; J_{\mathrm{p}}^{3/2} f^{1/2}$$

ISTITUTO NAZIONALE DI RICERCA METROLOGICA

The hysteresis (quasi-static) energy loss cannot be generally predicted from knowledge of the structural properties and the intrinsic magnetic parameters. At low inductions, however, magnetic hysteresis can usually be described by the analytical Rayleigh law.

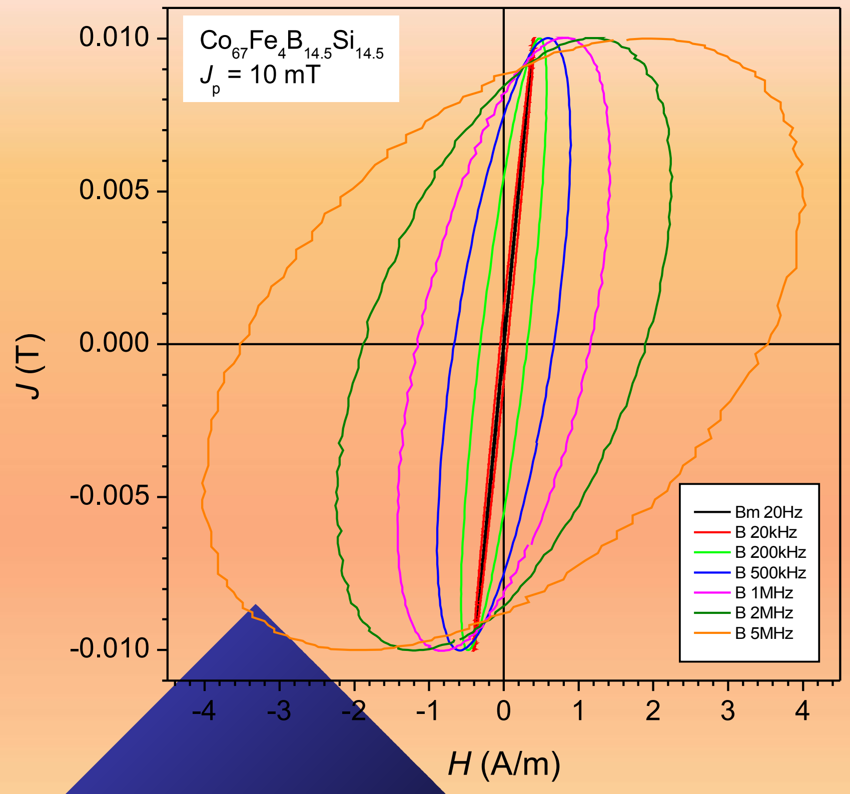


$$J(H) = (a + bH_p)H \mp \frac{b}{2}(H_p^2 - H^2)$$

$$J_p = aH_p + bH_p^2$$

a **≡ initial permeability, resulting from domain wall bending and moment rotations**

The dynamic loss can be formally assessed in a linear (or, in practice, quasi-linear) material, with defined DC permeability. Dissipative phenomena bring about a time delay of the *B*(*t*) waveform with respect to the *H*(*t*) waveform and the resulting hysteresis loop takes an elliptical shape



$$H(t) = H_p \cos\omega t$$

$$B(t) = B_p \cos(\omega t - \delta) =$$

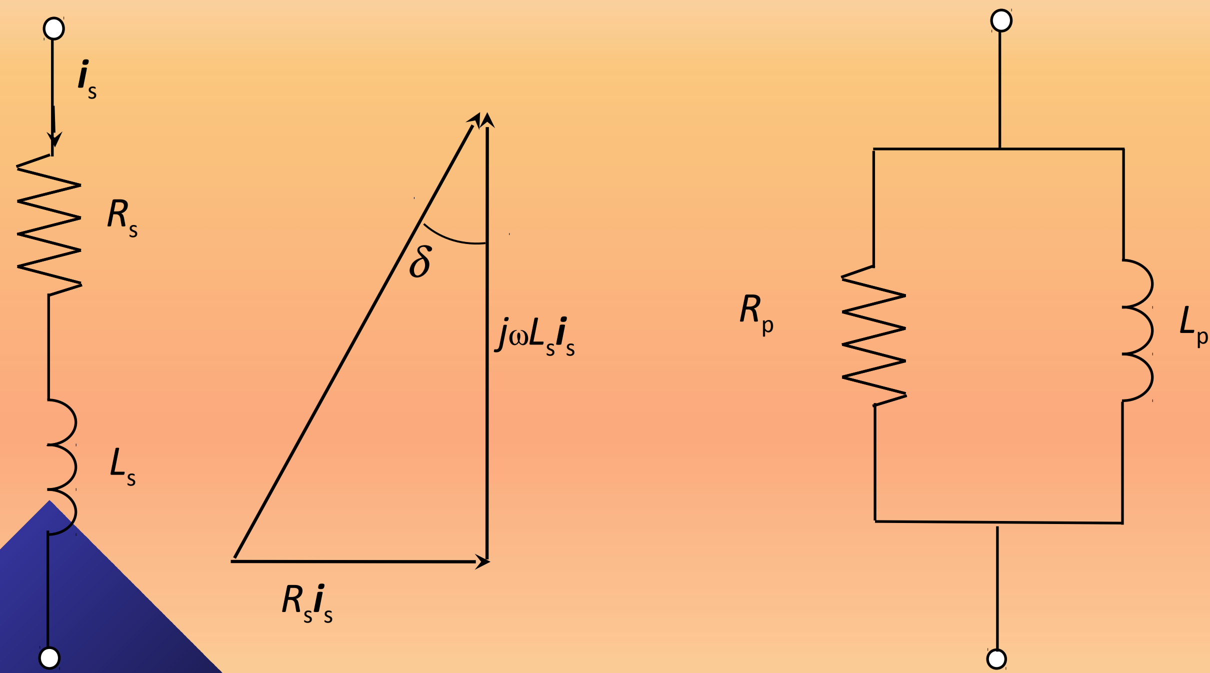
$$= B_p \cos\delta \cos\omega t + B_p \sin\delta \sin\omega t$$

The associated energy loss (area of the elliptical loops) is

$$W = \int_0^T H(t) \cdot \frac{dB(t)}{dt} dt = \pi H_p B_p \sin\delta$$

ISTITUTO NAZIONALE DI RICERCA METROLOGICA

When dealing with a linear system we can attack in a simple way the phenomenology of energy loss and the related concepts of complex permeability, quality factor, and equivalent *L - R* circuit



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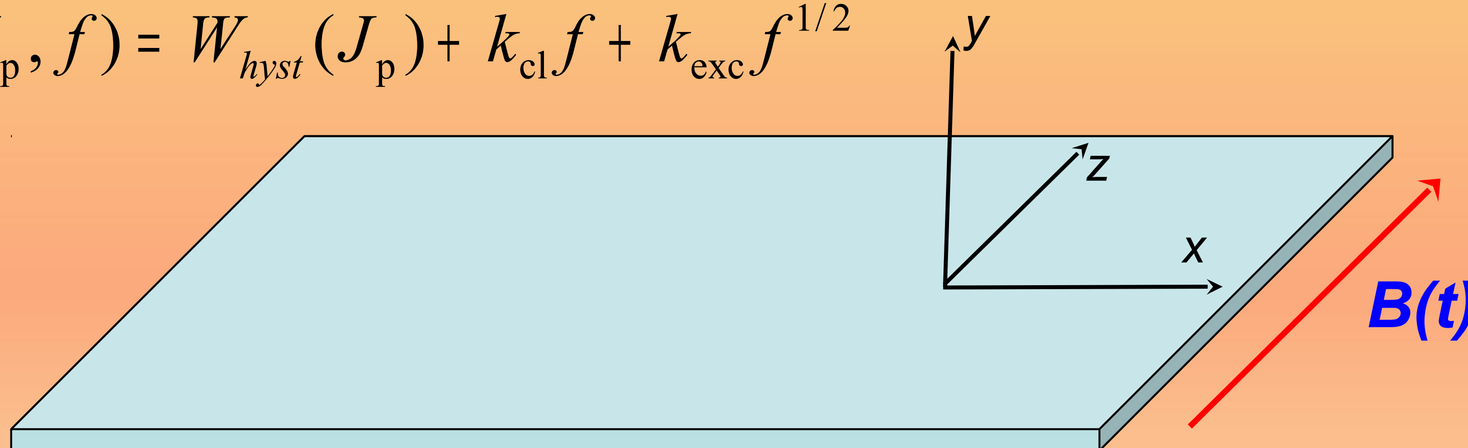
The concept of loss separation can be given a solid physical justification in terms of characteristic space-time scales of the magnetization process (G. Bertotti, *Hysteresis in Magnetism*)**. It is valid in both conducting and non-conducting magnetic materials.**

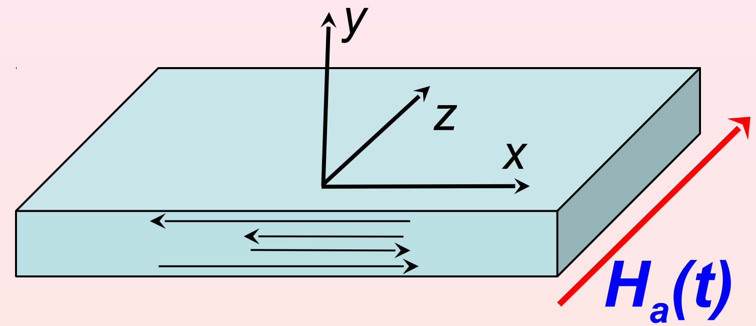
$$\boldsymbol{W = W_{\mathrm{hyst}} + W_{\mathrm{cl}} + W_{\mathrm{exc}}}$$

$$W(J_{\mathrm{p}}, f) = W_{hyst}(J_{\mathrm{p}}) + k_{\mathrm{cl}} f + k_{\mathrm{exc}} f^{1/2}$$



W_{cl} is easily calculated in the simple case of a thin lamination (width >> thickness) under time-varying induction (e. g., $B(t) = B_p \sin \omega t$) uniform across the sheet cross-section.

The full approach to the classical eddy current losses, valid for whatever lamination thickness and material conductivity is based on the diffusion equation for the internal magnetic field.



$$\nabla \times \boldsymbol{E} = -\frac{d\boldsymbol{B}}{dt} \qquad \nabla \times \boldsymbol{H} = -\boldsymbol{j}$$

$$\frac{\partial E}{dy} = -\mu\frac{dH}{dt} \qquad \frac{\partial H}{dy} = -j = -E\sigma$$

$H(t) = H_a(t) - H_{eddy}(t)$

$$\frac{\partial^2 H}{dy^2} = \sigma\mu\frac{dH}{dt}$$

and the boundary conditions

$$H(t) = H_a(t) \quad \text{for} \quad y = \pm d/2$$

$$\partial H/\partial y = 0 \quad \text{at} \quad y = 0$$

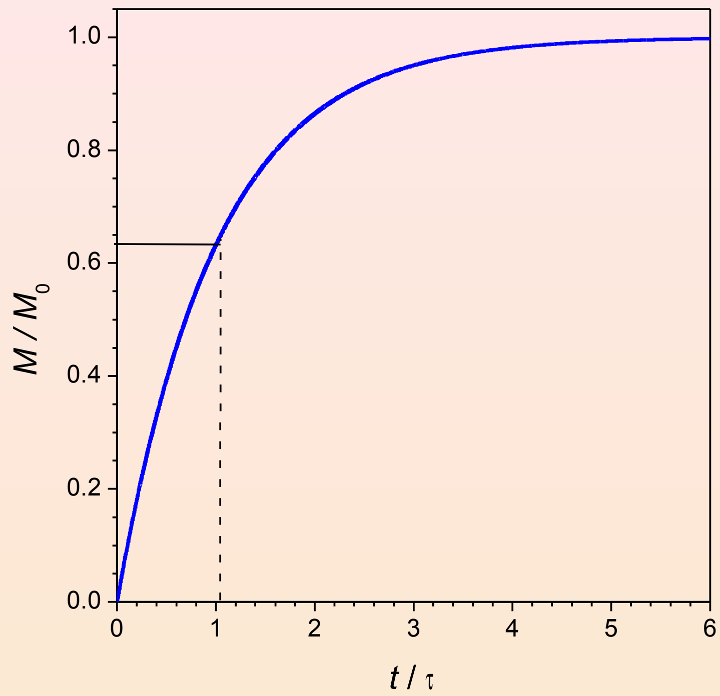
The concept of magnetic losses and hysteresis are associated with that of lag in time of induction with respect to the field. We can therefore talk aboy a time constant (or a distribution of time constants).

The simplest case of relaxation is one where the change of the magnetization with time is proportional to its deviation from the equilibrium value

$$dM/dt = k(M_0 - M(t))$$

$$M(t) = (1 - e^{-t/\tau})M_0$$

with $\tau = 1/k$



If relaxation is due to eddy currents, the time constant will depend on conductivity, permeability, and sample size.

Bibliography

•G. Bertotti, *Hysteresis in Magnetism*, Academic Press, 1988.
•G. Bertotti, *IEEE Trans. Magn*. 24 (1988) 621.
•G. Bertotti, *J. Appl. Phys*. 57 (1985) 2110.
•J.B. Goodenough, *IEEE Trans. Magn*. 38 (2002) 3398.
•F. Fiorillo, C. Appino, M. Pasquale, in *The Science of Hysteresis* (G. Bertotti and I. Mayergoyz, eds., Academic Press, 2006), vol III, p.1.
•R.H. Pry and C.P. Bean, *J. Appl. Phys*. 29 (1958) 532.
• H.J. Williams, W. Shockley, C. Kittel, Phys. Rev. 80 (1950) 1090.
•B.D. Cullity and C.D. Graham, *Introduction to magnetic materials,* Wiley, 2011.
•F. Fiorillo and A. Novikov, *IEEE Trans. Magn*. 26 (1990) 2904.
•G. Bertotti and I. Mayergoyz, eds., *The Science of Hysteresis,* Academic Press, 2006.