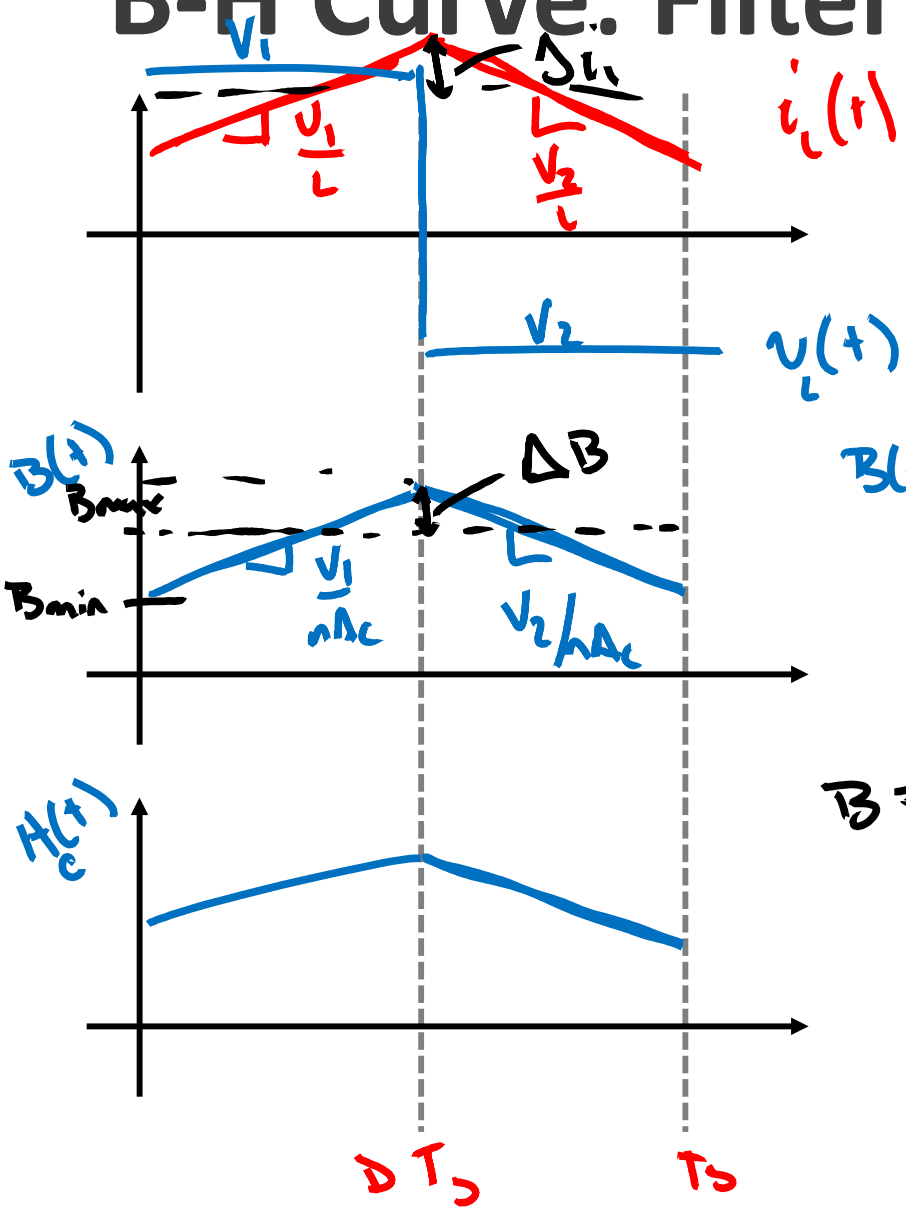
B-H Curve: Filter Inductor



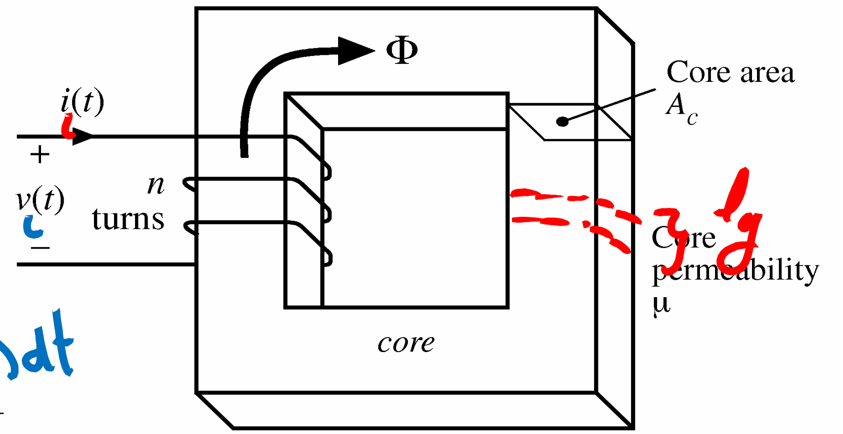
$$v = L\frac{di}{dt}$$

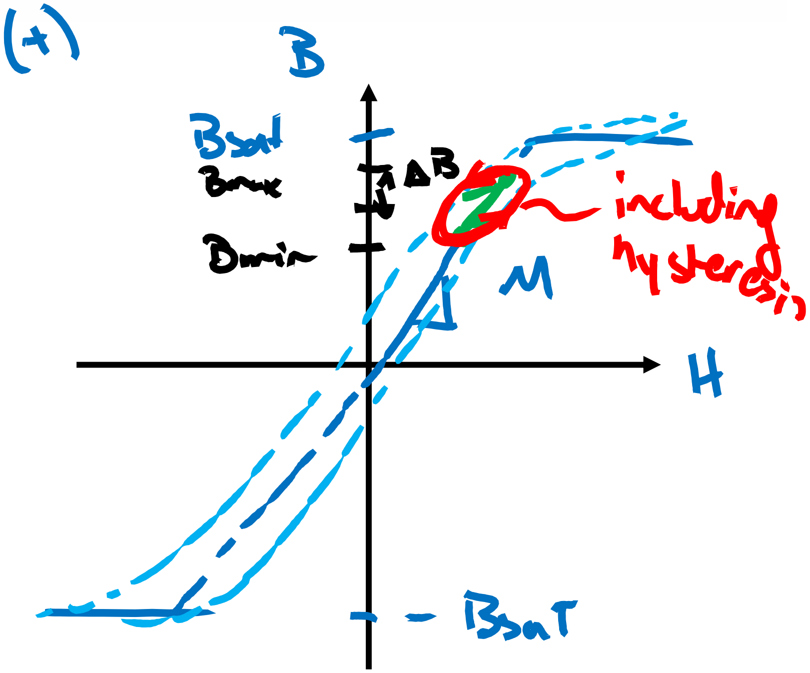
$$i = \frac{1}{L}\int v\,dt$$

$$B(t) = \frac{1}{nA_c}\int v_L(t)\,dt$$

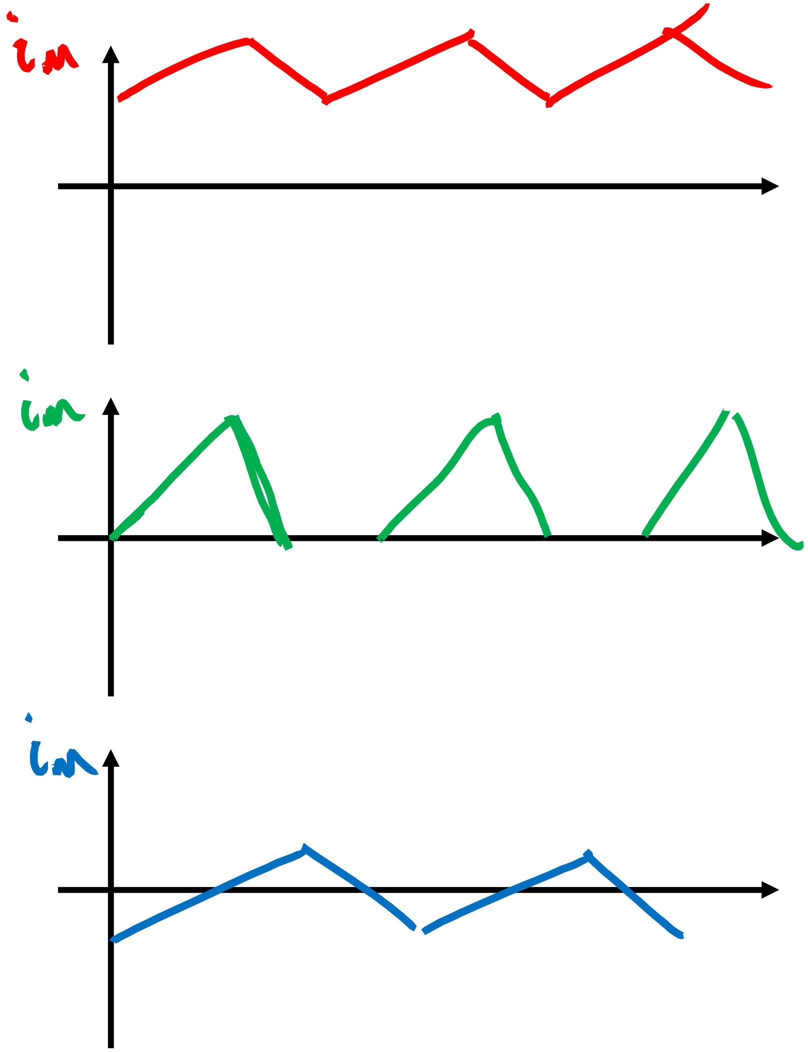
$$B(t) = \frac{L}{nA_c}\, i(t)$$

$$B = \mu H_c$$





B-H Curve: Transformer

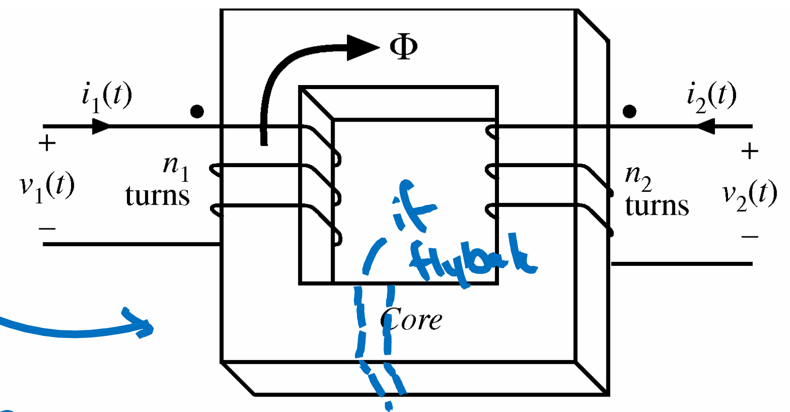


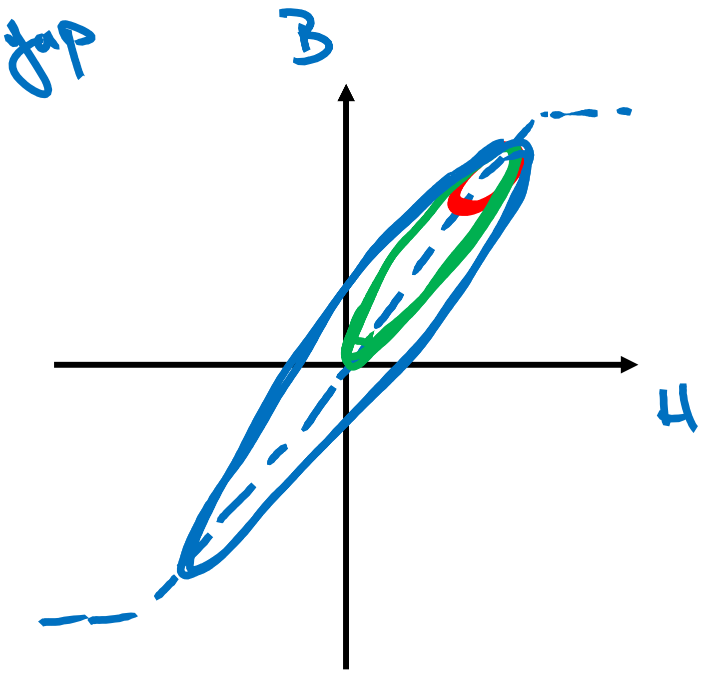
Flyback

Forward

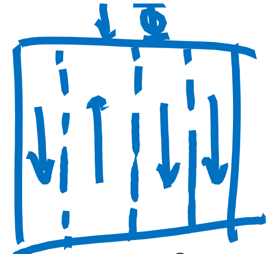
Full Bridge

no gap

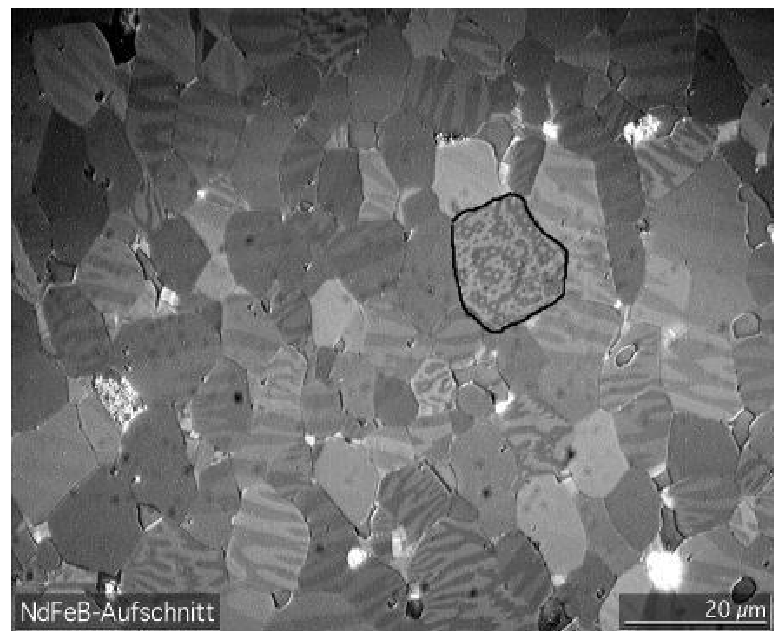




Core Loss

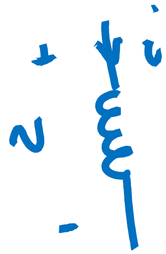


- Physical origin due to magnetic domains
- Modeling Approaches
  - Empirical (curve fit) models of materials
  - Direct measurement-based models
  - Physics-based models

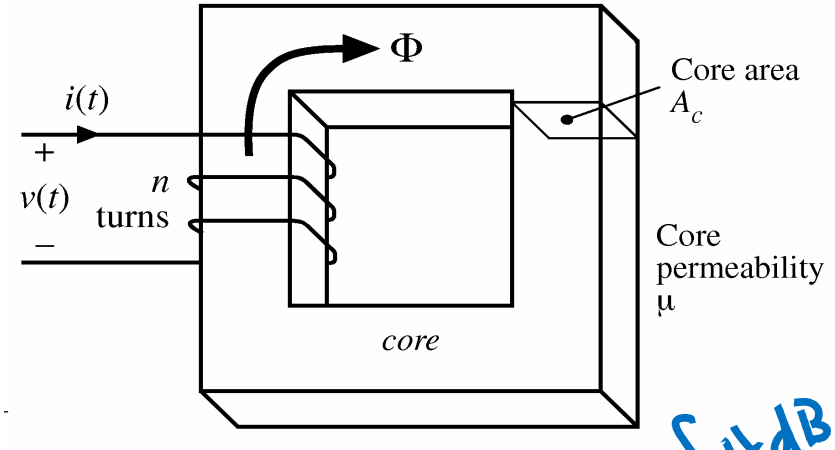


Hysteresis Loss

$P = v \cdot i$



$$\Delta E = \int_{\text{one cycle}} v \cdot i \, dt = \emptyset \text{ for ideal inductor}$$

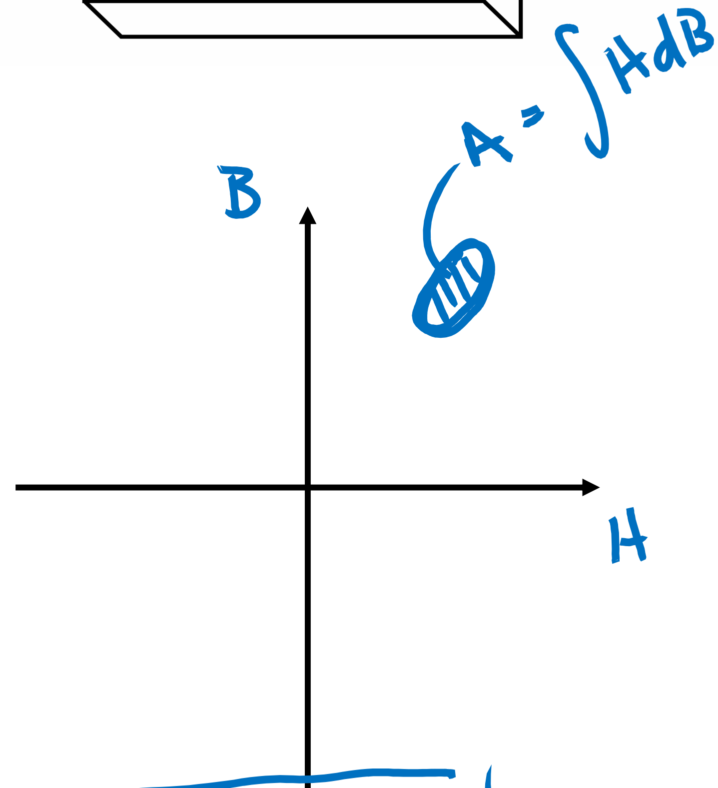


Faraday: $v = n \dfrac{d\Phi}{dt} = n A_c \dfrac{dB}{dt}$

Ampere: $n i = H l_m$

$$\Delta E = \int_{\text{one cycle}} \left(n A_c \frac{dB}{dt}\right)\left(H l_m \frac{1}{n}\right) dt$$

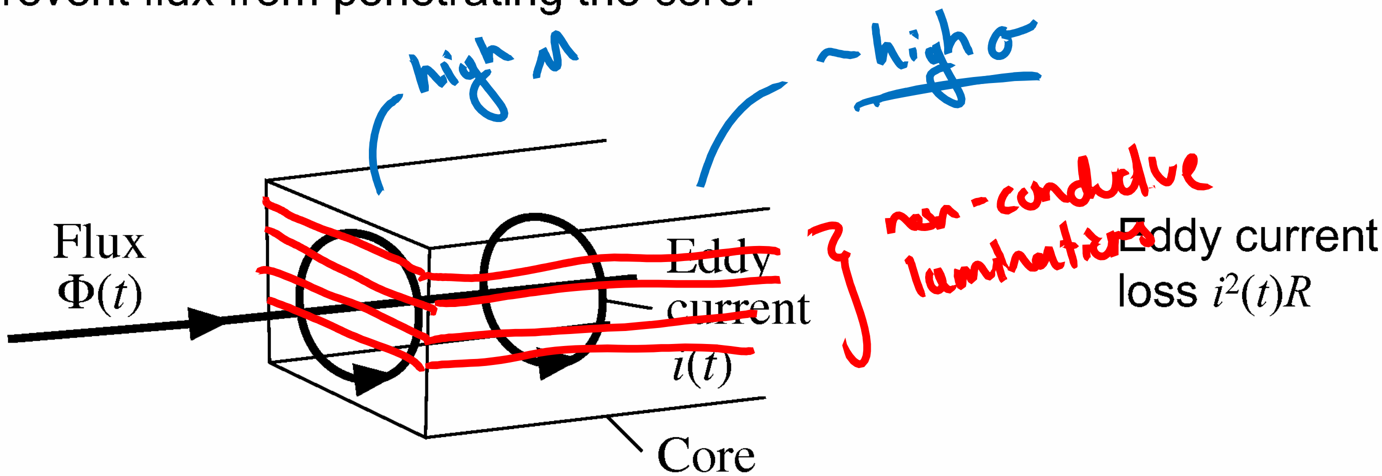
$$\Delta E = A_c l_m \int_{\text{one cycle}} H \frac{dB}{dt} dt = A_c l_m \int_{\text{one cycle}} H \, dB$$



$$\boxed{P = \Delta E f_s = \underbrace{A_c l_m}_{V_e} f_s \int_{\text{one cycle}} H \, dB}$$

Eddy Currents in Magnetic Materials

Magnetic core materials are reasonably good conductors of electric current. Hence, according to Lenz's law, magnetic fields within the core induce currents ("eddy currents") to flow within the core. The eddy currents flow such that they tend to generate a flux which opposes changes in the core flux $\Phi(t)$. The eddy currents tend to prevent flux from penetrating the core.



Eddy Current Losses

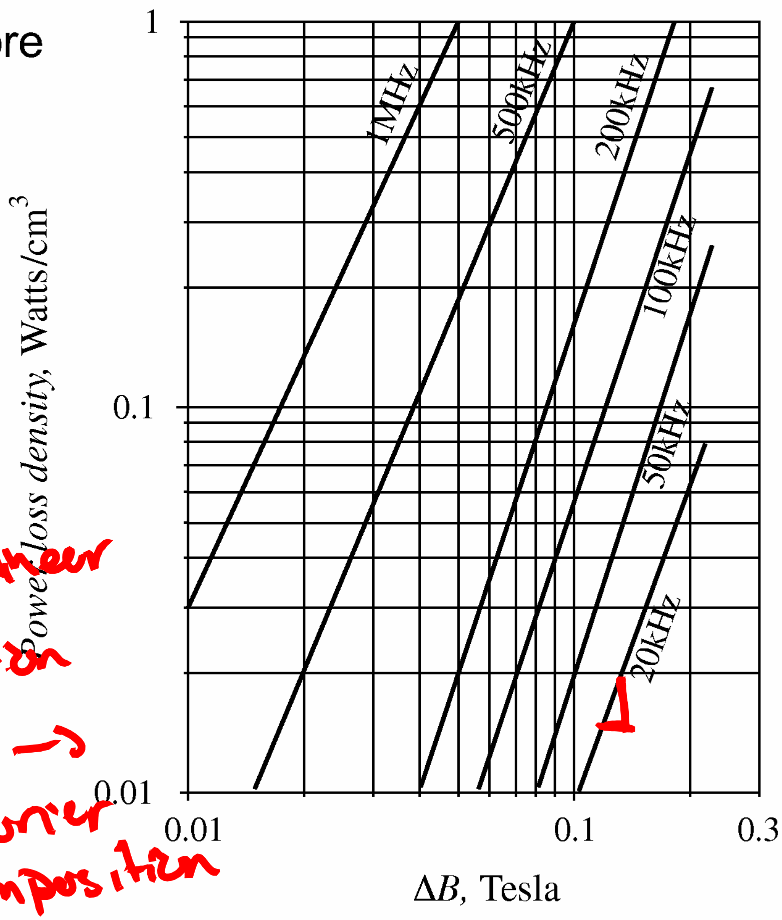
- Ac flux $\Phi(t)$ induces voltage $v(t)$ in core, according to Faraday's law. Induced voltage is proportional to derivative of $\Phi(t)$. In consequence, magnitude of induced voltage is directly proportional to excitation frequency f.
- If core material impedance Z is purely resistive and independent of frequency, $Z = R$, then eddy current magnitude is proportional to voltage: $i(t) = v(t)/R$. Hence magnitude of $i(t)$ is directly proportional to excitation frequency f.
- Eddy current power loss $i^2\cancel{(t)}R$ then varies with square of excitation frequency f.

  $P \propto f^2$
- Ferrite core material impedance is capacitive. This causes eddy current power loss to increase as f^4.

  $P \propto f^4$

The Steinmetz Equation (Empirical)

Ferrite core material



Limits

① only valid for sinusoidal excitation

② Pv is nonlinear so superposition doesn't apply → can't use fourier series decomposition

Empirical equation, at a fixed frequency:

$$P_{fe} = K_{fe} (\Delta B)^{\beta} A_c \ell_m$$

Alternately:

$$P_v = K\cancel{m} f^{\alpha} (\Delta B)^{\beta}$$

Steinmetz Equation: Notes

- Purely empirical; not physics-based
- Parameters α, β, K vary with frequency
- Correct only for sinusoidal excitation
  - Nonlinear; Fourier expansion of waveforms cannot be used
- Modified empirical equations perform better with nonsinusoidal waveforms
  - MSE
  - GSE
  - iGSE
  - i^2GSE

Some Example Core Materials

Core type	B_{sat}	Relative core loss	Applications
Laminations iron, silicon steel	1.5 - 2.0 T	high	50-60 Hz transformers, inductors
Powdered cores powdered iron, molypermalloy	0.6 - 0.8 T	medium	1 kHz transformers, 100 kHz filter inductors
Ferrite Manganese-zinc, Nickel-zinc	0.25 - 0.5 T	low	20 kHz - 1 MHz transformers, ac inductors
Nanocrystalline	1.5 – 2T	low	5kHz – 500kHz
Air	—	ϕ	1+ MHz