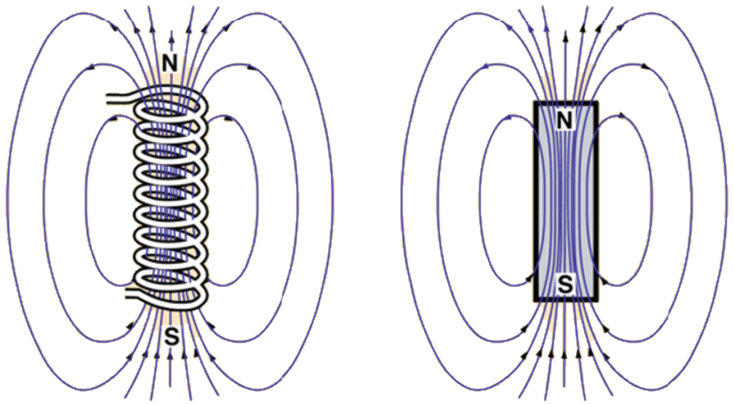
Hard Magnetic Materials
Learning outcome

At the end of this lecture you will be able to:

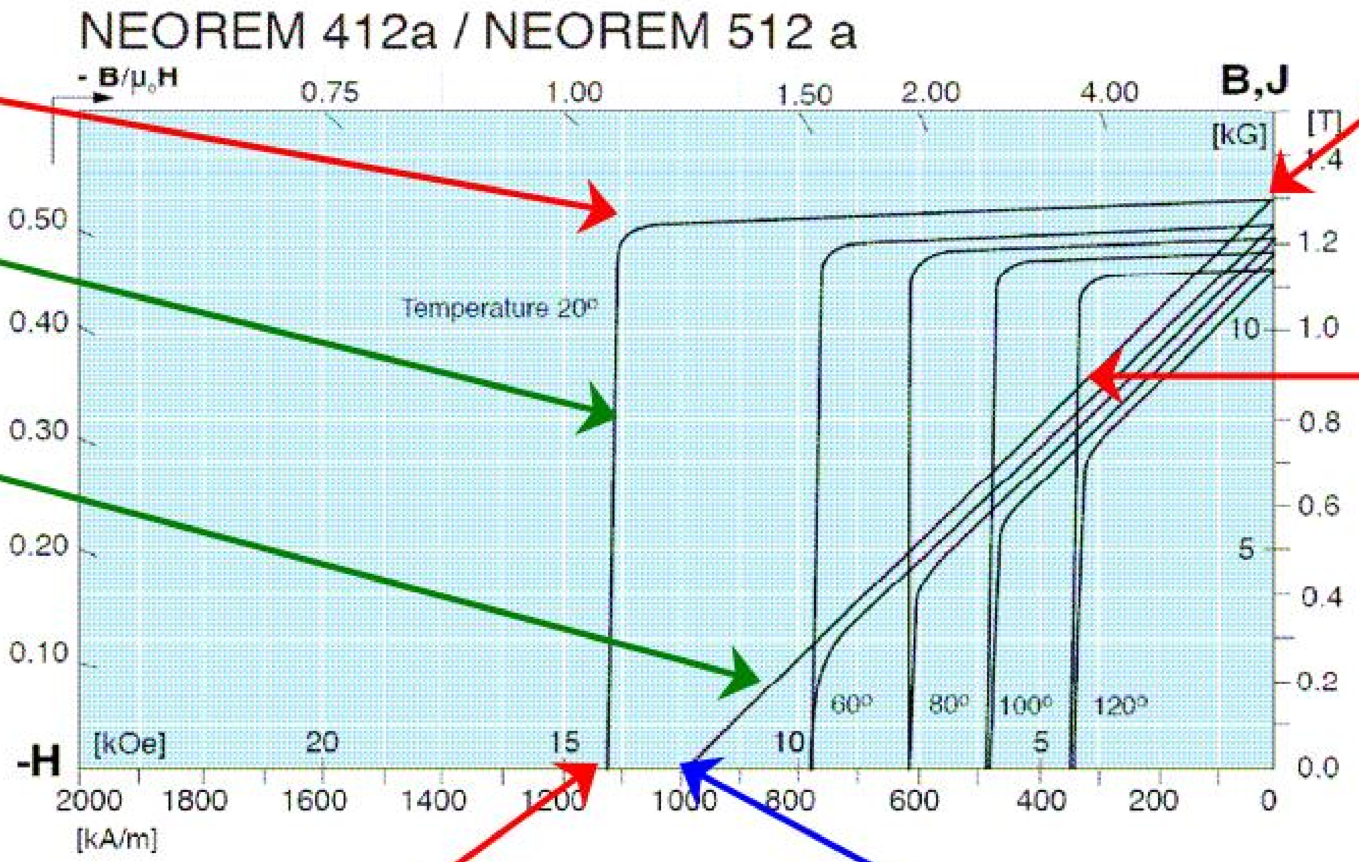
- List different types of permanent magnets and their characteristics
- Explain the manufacturing process of Neodymium Iron Boron magnets
- Calculate the needed magnet volume for given applications

Hard Magnetic Materials

- Hard magnetic materials refer to materials used for making permanent magnets
  - Characterized by a high coercivity 50 – 1600 kA/m
- Permanent magnets (or hard magnets) are useful for their capability to generate a magnetic field without continuous expenditure of energy
- They have the property of retaining firmly their magnetization against external spurious fields and their own demagnetizing field
- From practical point of view a permanent magnet is like a coil with electric current but, be carful with demagnetization.



Hard Magnetic Materials



curve shape (squareness)

HJ-curve

HB-curve

$$B_m = J_m + \mu_0 H_m$$

B_r (T) remanence

Slope of HB-curve: relative permeability: μ_r

${}_J H_c$ (kA/m) intrinsic coercivity

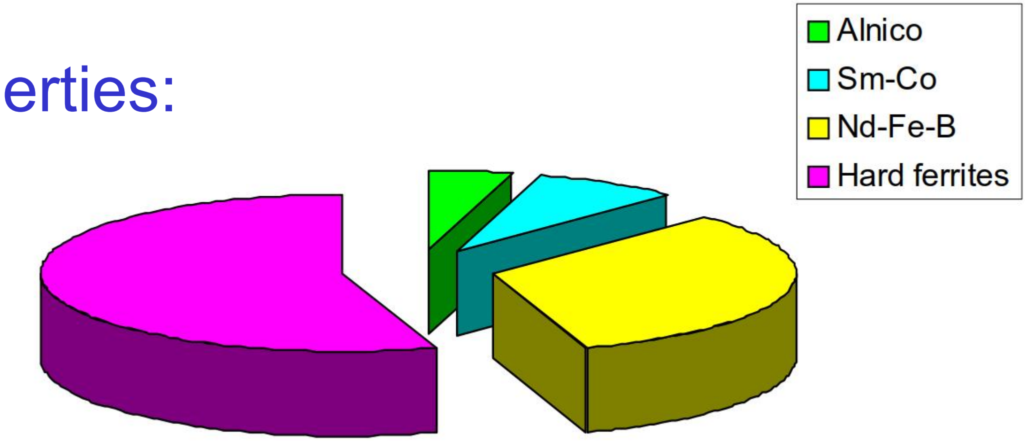
${}_B H_c$ (kA/m) normal coercivity

Brain storming

- Take 10 min and list the permanent magnets you know about

- we will compile the results during the lecture
- List of permanent magnet types or materials

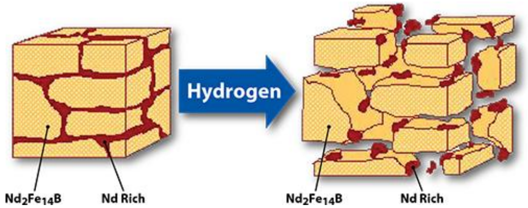
Hard Magnetic Materials

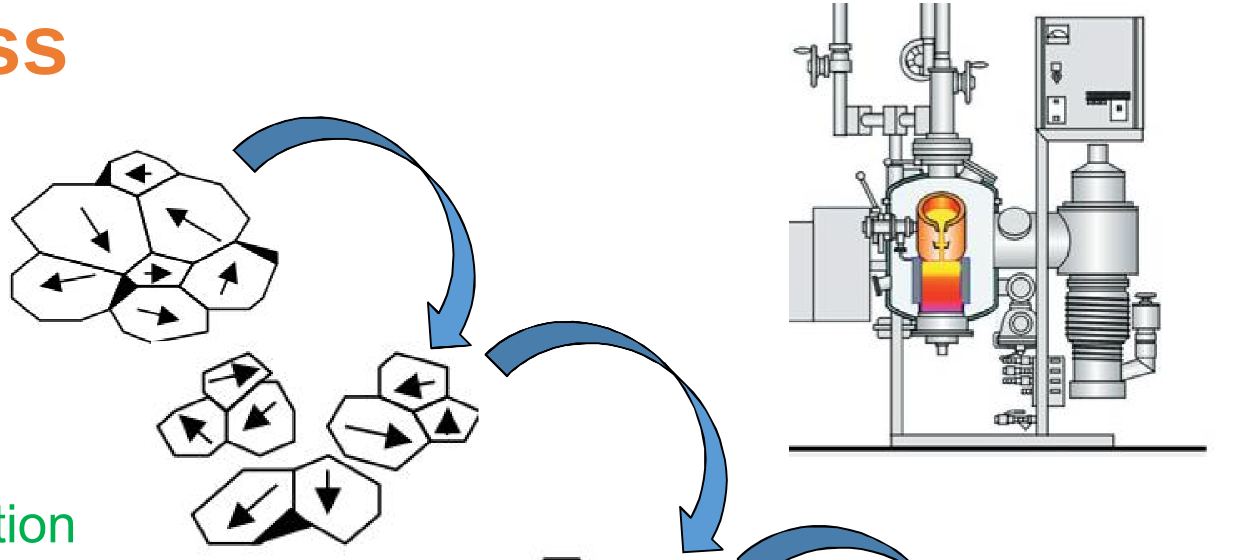


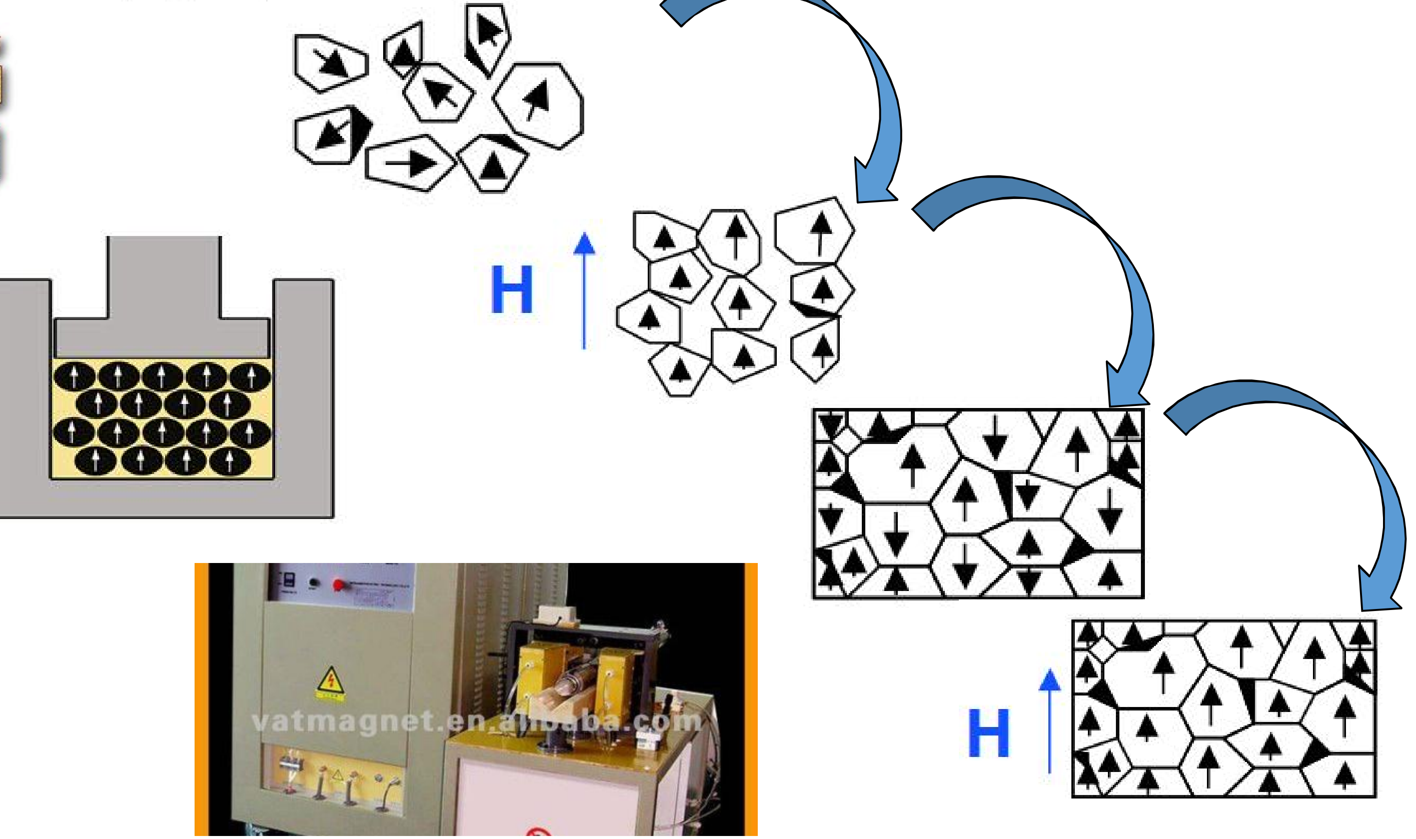
- Some hard magnetic materials and their properties:
- AlNiCo-magnets (1930s)
  - Br > 1T, H_c= 50 kA/m, good corrosion resistance
- Ferrite Magnets (1950s)
  - Br = 0.4 T, non conductive, Hc=300 kA/m, low price
  - MO•(Fe2O3)6 where the metal M can be barium, lead or strontium
- SmCo – magnets (1970s)
  - Br=1 T, Hc=1600 kA/m, high price, low demagnetization with temperature
  - SmCo5 and Sm2Co17
- NdFeB-magnets (1984)
  - Br = 1 .. 1.4 T, Hc= 1000 .. 3200 kA/m, conductive and prone to corrosion
- Bonded magnets
  - Injection molding, compression molding, extruding, Complex shapes, Non-conductive

Manufacturing process

- Vacuum melting and casting
- Crushing and hydrogen decrepitation
- Milling
- Pressing and aligning
- Sintering and heat treatment
- magnetizing



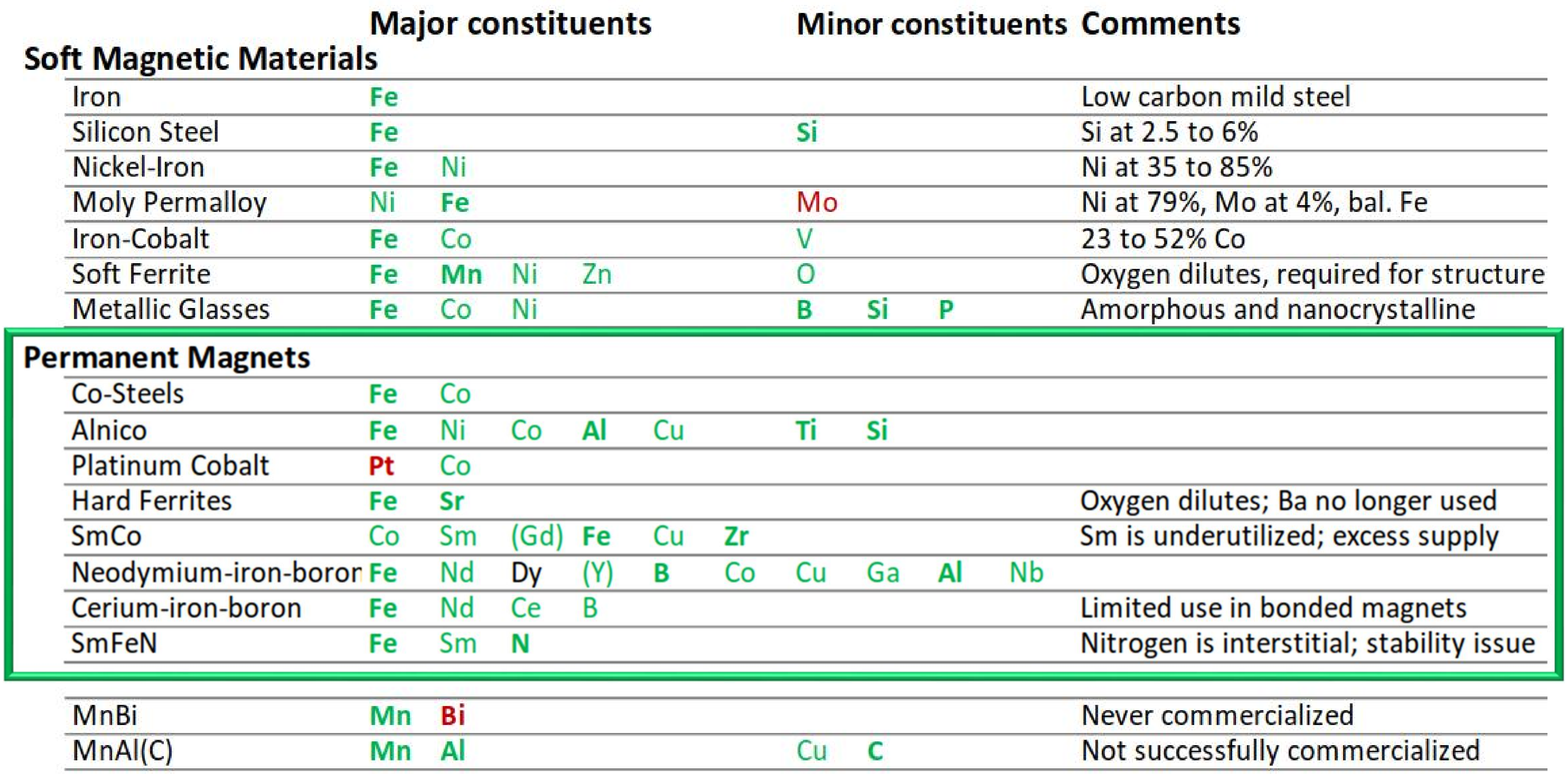




Major manufacturers by countries

	China	Japan & Korea	USA	Europe
ALNICO	Atlas Magtech Chengdu Amoeba China Hope Magnet HPMG Shanghai Dao Ye **Many others**	Pacific Metals	Arnold T&S	SG Magnets Ltd Magnetfabrik Bonn Magneti Ljubljana
FERRITE	Anshang Dekang BGRIMM DMEGC Dongyang Gelin Jiangmen **>50 more**	Hitachi SsangYong TDK Ugimag	Hitachi TDK	Magnetfabrik Bonn Magnetfabrik Schramburg
SmCo	Arnold Chengdu Mag Mat'l TianHe Tiannu Group **>20 more**	Hitachi Shin-Etsu TDK	(Arnold) EEC	Arnold Magnetfabrik Bonn Magnetfabrik Schramburg Vacuumschmelze
NdFeB*	Anhui Earth-Panda AT&M BGMT Ningbo Jinji San Huan Thinova	Daido Hitachi Shin-Etsu TDK	(Hitachi)	Magnetfabrik Bonn (not licensed) Magnetfabrik Schramburg Magneti Ljubljana (not licensed) Vacuumschmelze (Neorem)

Chemical components

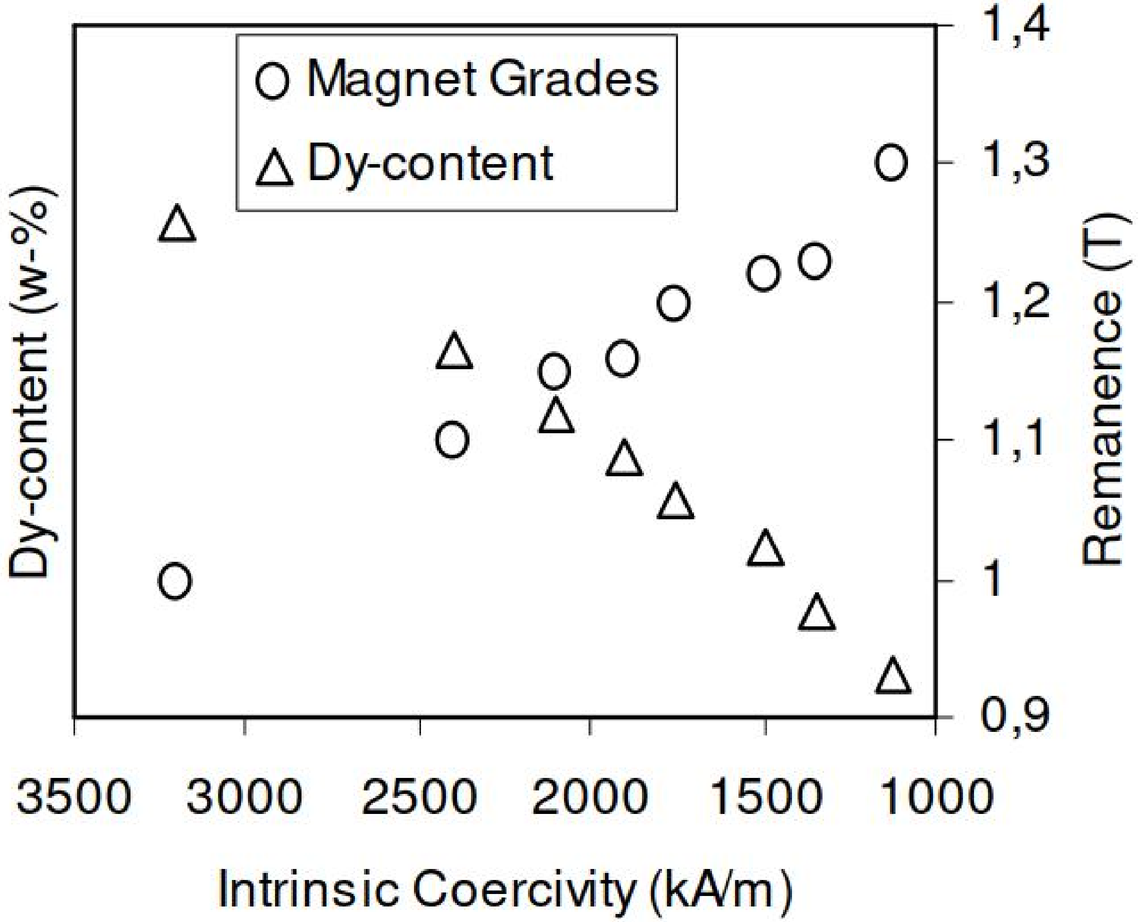


	Major constituents						Minor constituents				Comments
Soft Magnetic Materials											
Iron	**Fe**										Low carbon mild steel
Silicon Steel	**Fe**						**Si**				Si at 2.5 to 6%
Nickel-Iron	**Fe**	Ni									Ni at 35 to 85%
Moly Permalloy	Ni	**Fe**					Mo				Ni at 79%, Mo at 4%, bal. Fe
Iron-Cobalt	**Fe**	Co					V				23 to 52% Co
Soft Ferrite	**Fe**	**Mn**	Ni	Zn			O				Oxygen dilutes, required for structure
Metallic Glasses	**Fe**	Co	Ni				**B**	**Si**	**P**		Amorphous and nanocrystalline
Permanent Magnets											
Co-Steels	**Fe**	Co									
Alnico	**Fe**	Ni	Co	**Al**	Cu		**Ti**	**Si**			
Platinum Cobalt	**Pt**	Co									
Hard Ferrites	**Fe**	**Sr**									Oxygen dilutes; Ba no longer used
SmCo	Co	Sm	(Gd)	**Fe**	Cu	**Zr**					Sm is underutilized; excess supply
Neodymium-iron-boror	**Fe**	Nd	Dy	(Y)	**B**	Co	Cu	Ga	**Al**	Nb	
Cerium-iron-boron	**Fe**	Nd	Ce	B							Limited use in bonded magnets
SmFeN	**Fe**	Sm	**N**								Nitrogen is interstitial; stability issue
MnBi	**Mn**	**Bi**									Never commercialized
MnAl(C)	**Mn**	**Al**					Cu	**C**			Not successfully commercialized

Effect Dy on NdFeB magnets characteristics

Dysprosium is added as substitute of Neodymium to enhance the material coercivity and temperature withstand but it is very expensive

- High Dy content
  - High coercivity
  - High temperature



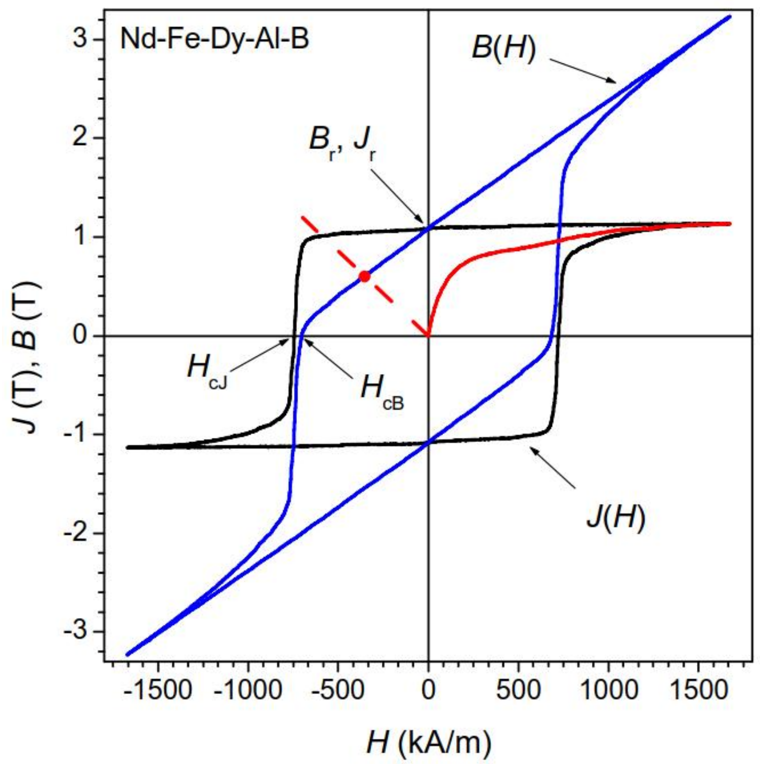
- Low Dy content
  - High remanence
  - Low temperature

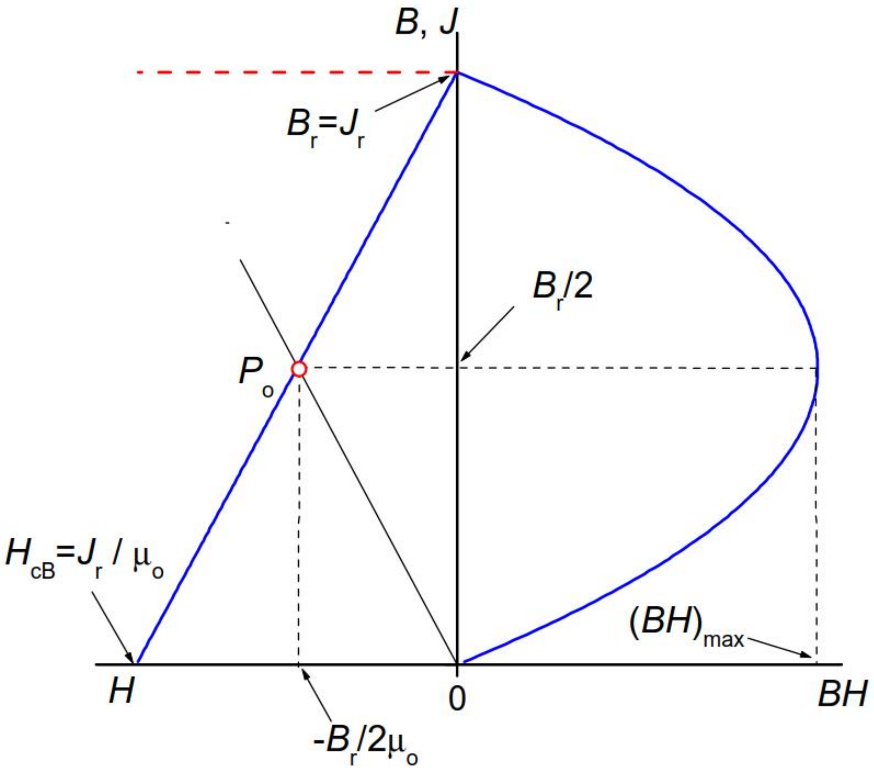
Investigation work 20 min

- Look in internet for what are the other components used as substitute for Neodymium in rare earth magnets (10 min)
  - If possible find their price and compare it with Dysprosium price (451 $/kg in 2017)
- List of materials:
  - https://www.statista.com/statistics/450164/global-reo-dysprosium-oxide-price-forecast/

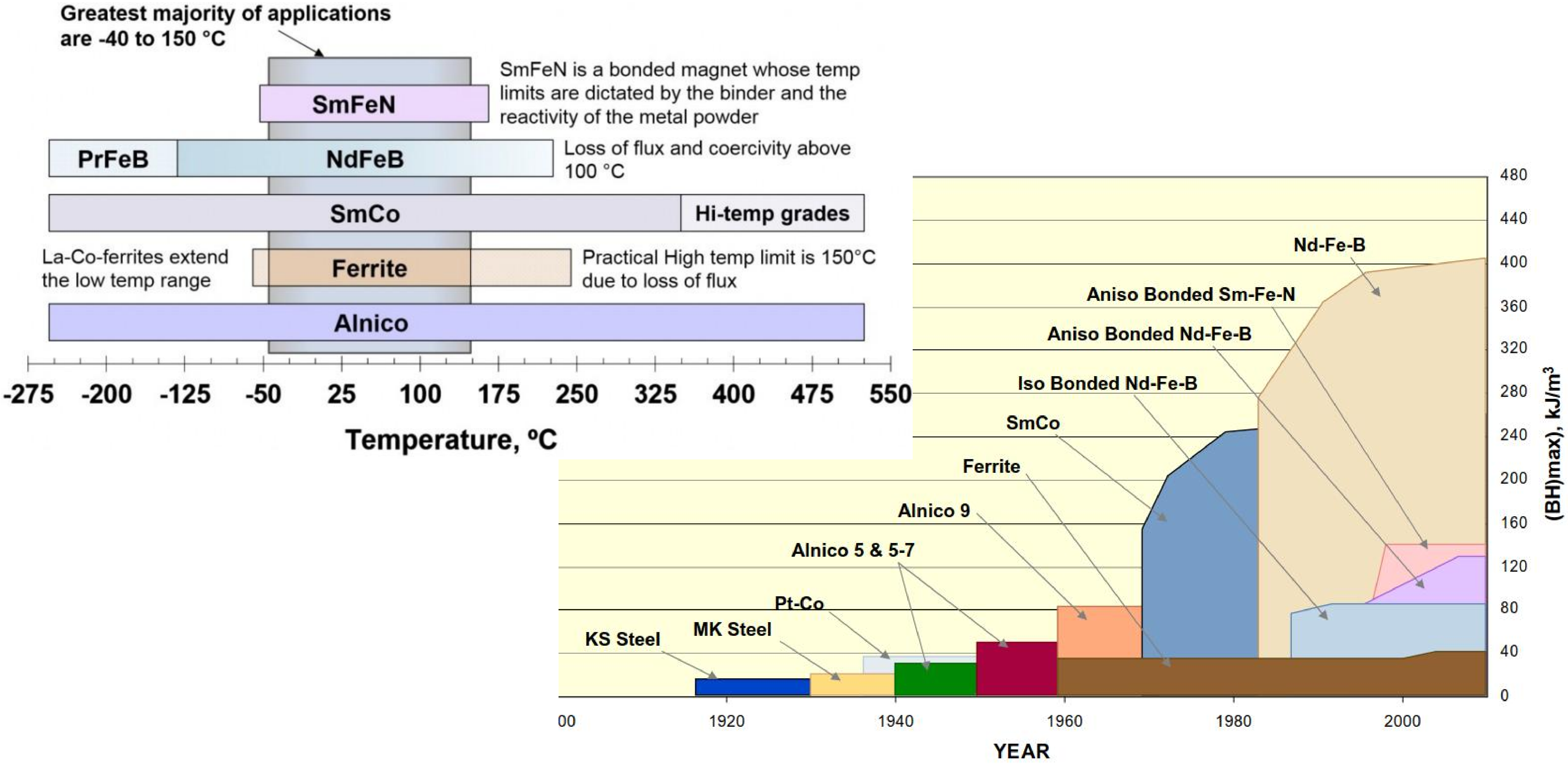
Magnetization process and energy product

- Permanent magnets are magnetized to saturation by means of a strong field transient generated by a Pulsed Field Magnetizer
- The strength of permanent magnets can be measured by the maximum energy product (BH)max, which reflects the capability to store magnetic energy in the unit volume.





Energy product and thermal strength



Greatest majority of applications are -40 to 150 °C

SmFeN is a bonded magnet whose temp limits are dictated by the binder and the reactivity of the metal powder

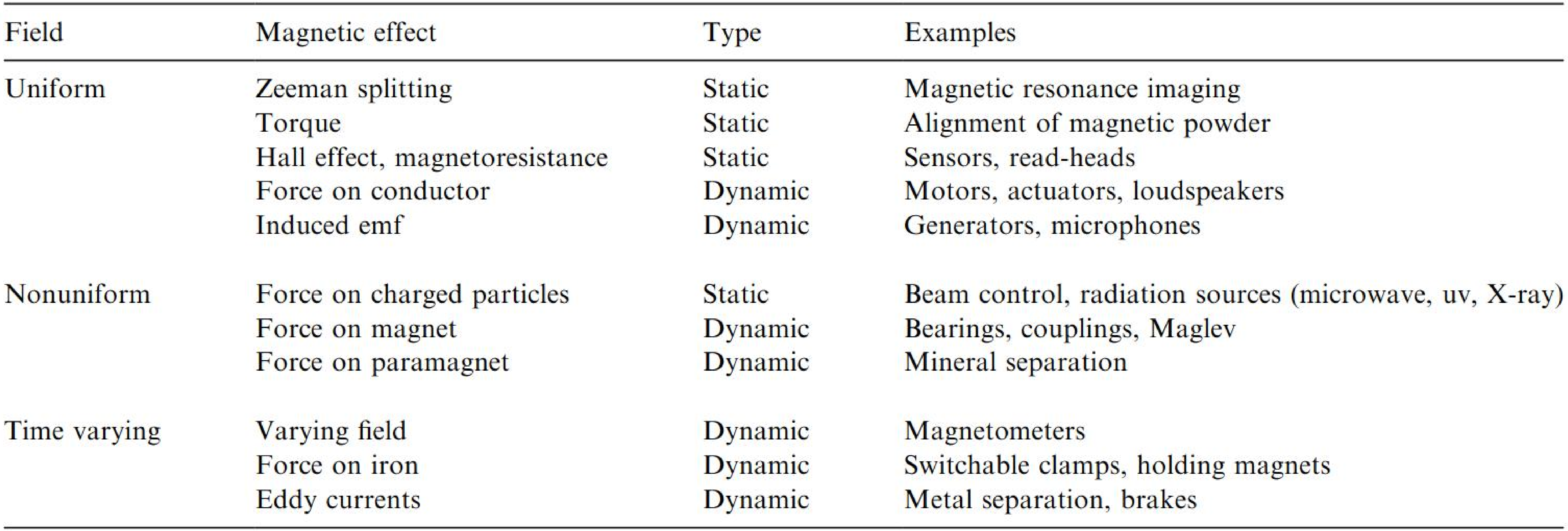
Loss of flux and coercivity above 100 °C

La-Co-ferrites extend the low temp range

Practical High temp limit is 150°C due to loss of flux

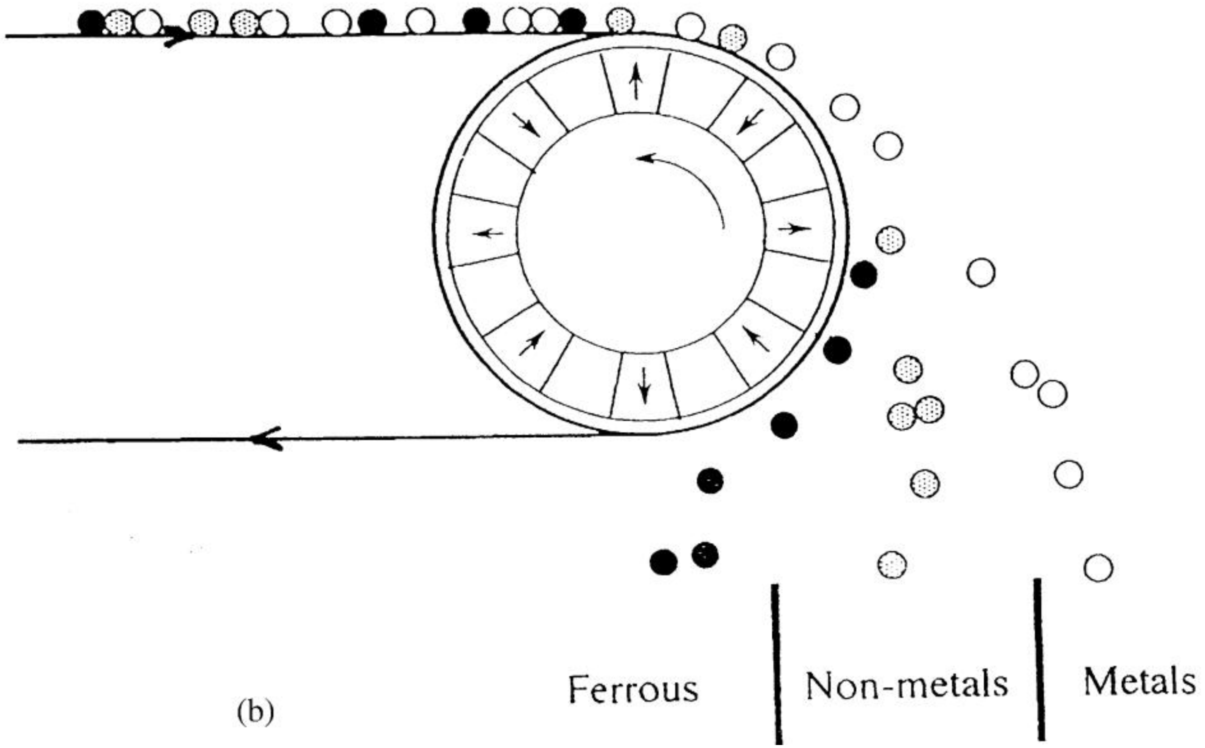
Permanent magnets in use

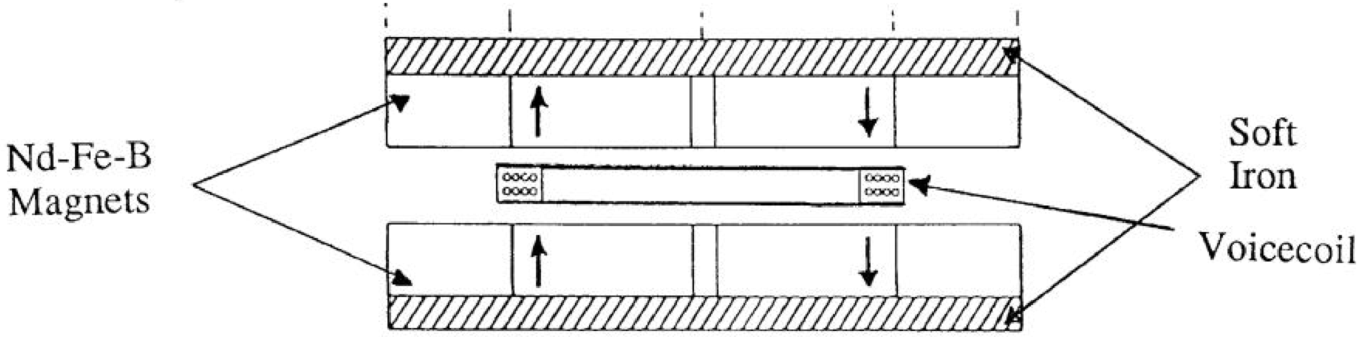
- Permanent magnets are used in many applications
- The applications can be summarized as follows, depending on the spatial and temporal variation of the field



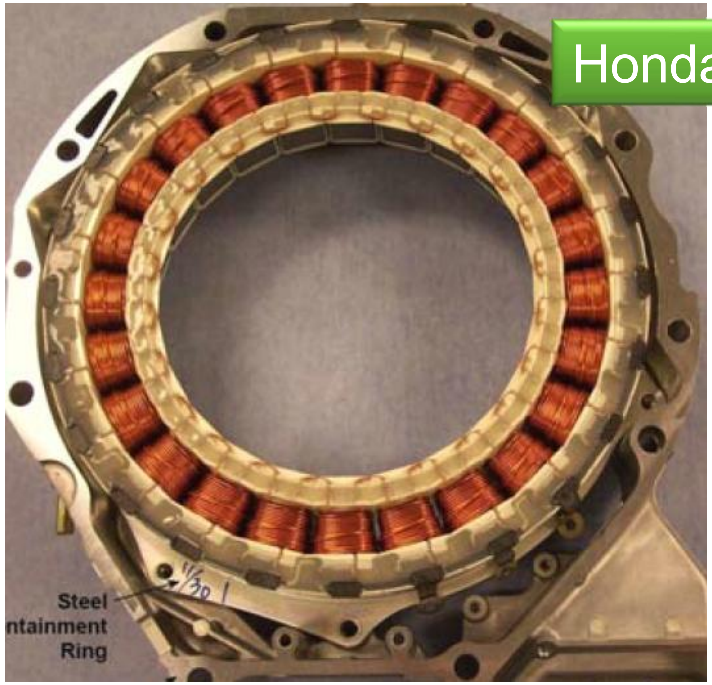
Field	Magnetic effect	Type	Examples
Uniform	Zeeman splitting	Static	Magnetic resonance imaging
	Torque	Static	Alignment of magnetic powder
	Hall effect, magnetoresistance	Static	Sensors, read-heads
	Force on conductor	Dynamic	Motors, actuators, loudspeakers
	Induced emf	Dynamic	Generators, microphones
Nonuniform	Force on charged particles	Static	Beam control, radiation sources (microwave, uv, X-ray)
	Force on magnet	Dynamic	Bearings, couplings, Maglev
	Force on paramagnet	Dynamic	Mineral separation
Time varying	Varying field	Dynamic	Magnetometers
	Force on iron	Dynamic	Switchable clamps, holding magnets
	Eddy currents	Dynamic	Metal separation, brakes

Permanent magnets in use

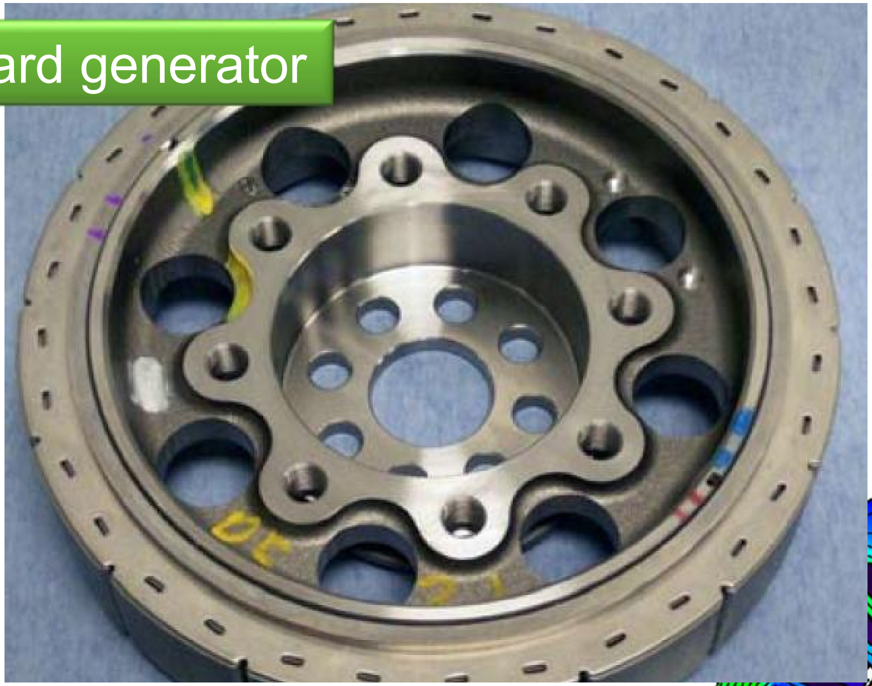


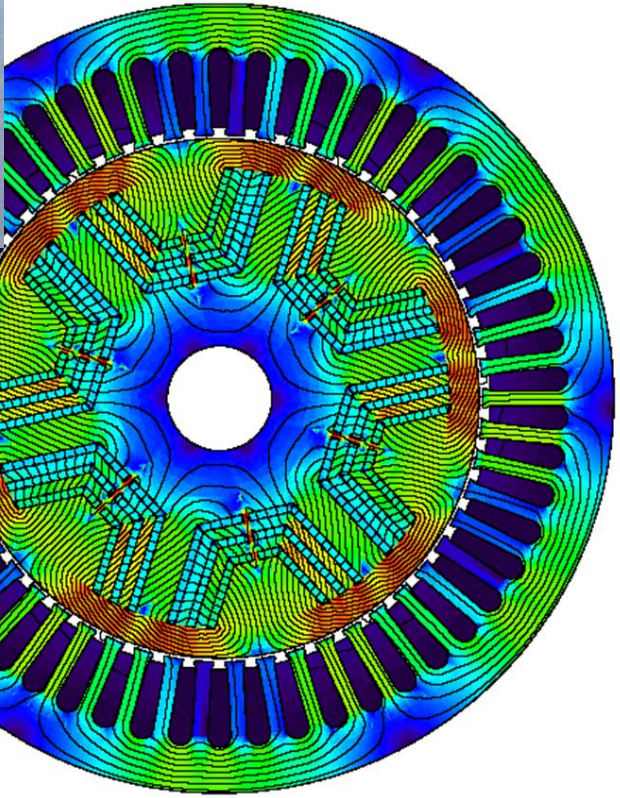


Permanent magnets in use

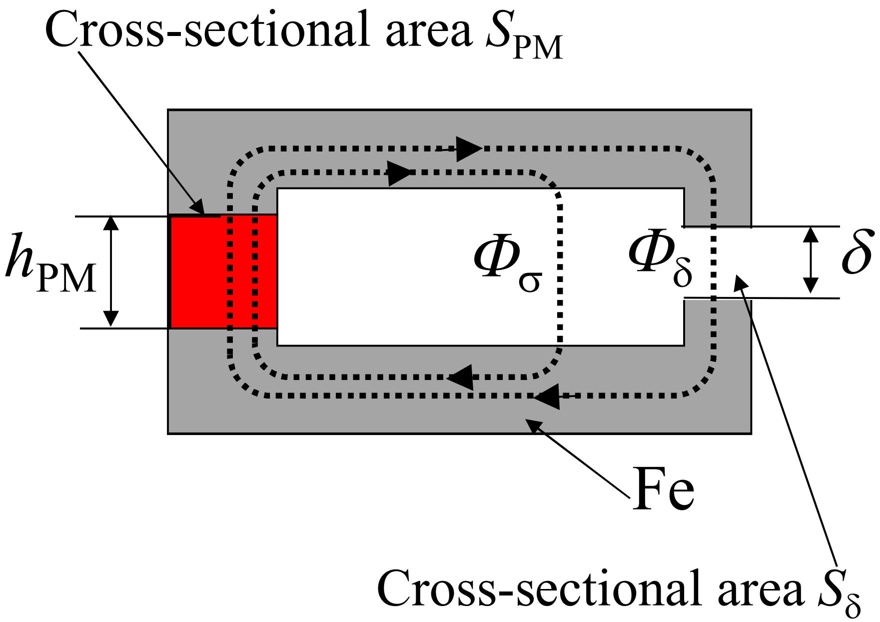


Honda onboard generator





Operation of permanent magnet in unloaded circuits



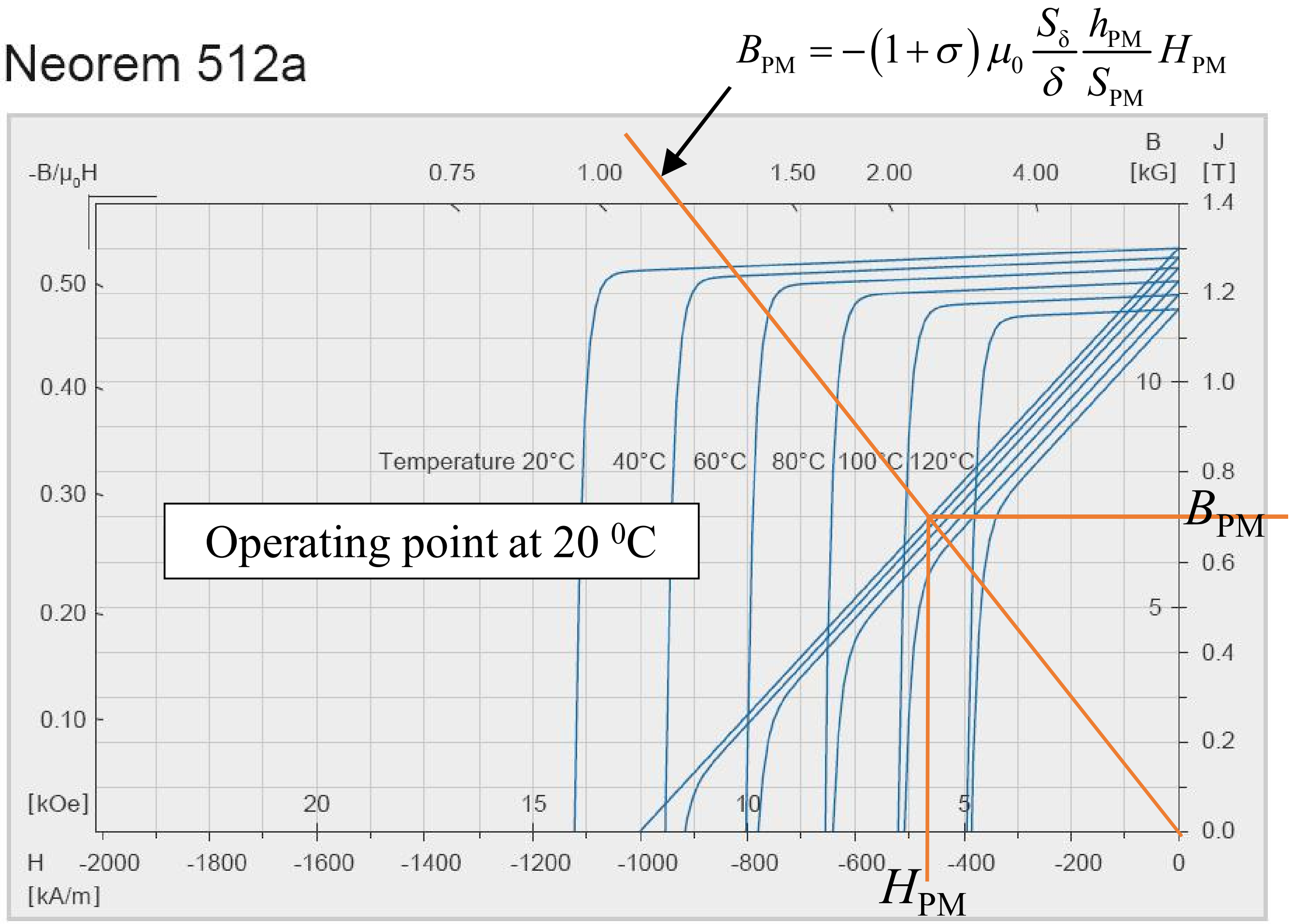
- Ampere's law:

$$\oint H\mathrm{d}l = H_{\mathrm{PM}}h_{\mathrm{PM}} + H_\delta \delta = 0$$

- The flux of the magnet is:

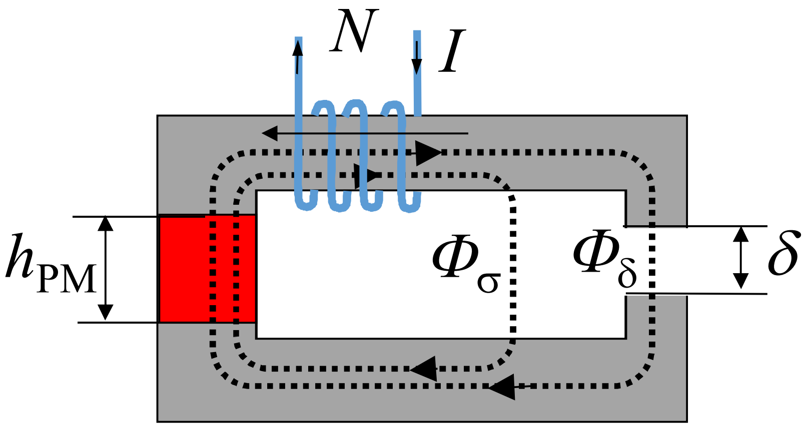
$$\Phi_{\mathrm{PM}} = S_{\mathrm{PM}}B_{\mathrm{PM}} = (1+\sigma)S_\delta B_\delta = (1+\sigma)S_\delta \mu_0 H_\delta$$

$$B_{\mathrm{PM}} = -(1+\sigma)\,\mu_0 \frac{S_\delta}{\delta}\frac{h_{\mathrm{PM}}}{S_{\mathrm{PM}}} H_{\mathrm{PM}}$$



Typical demagnetization curves B(H) and J(H) at different temperatures

Operation under load

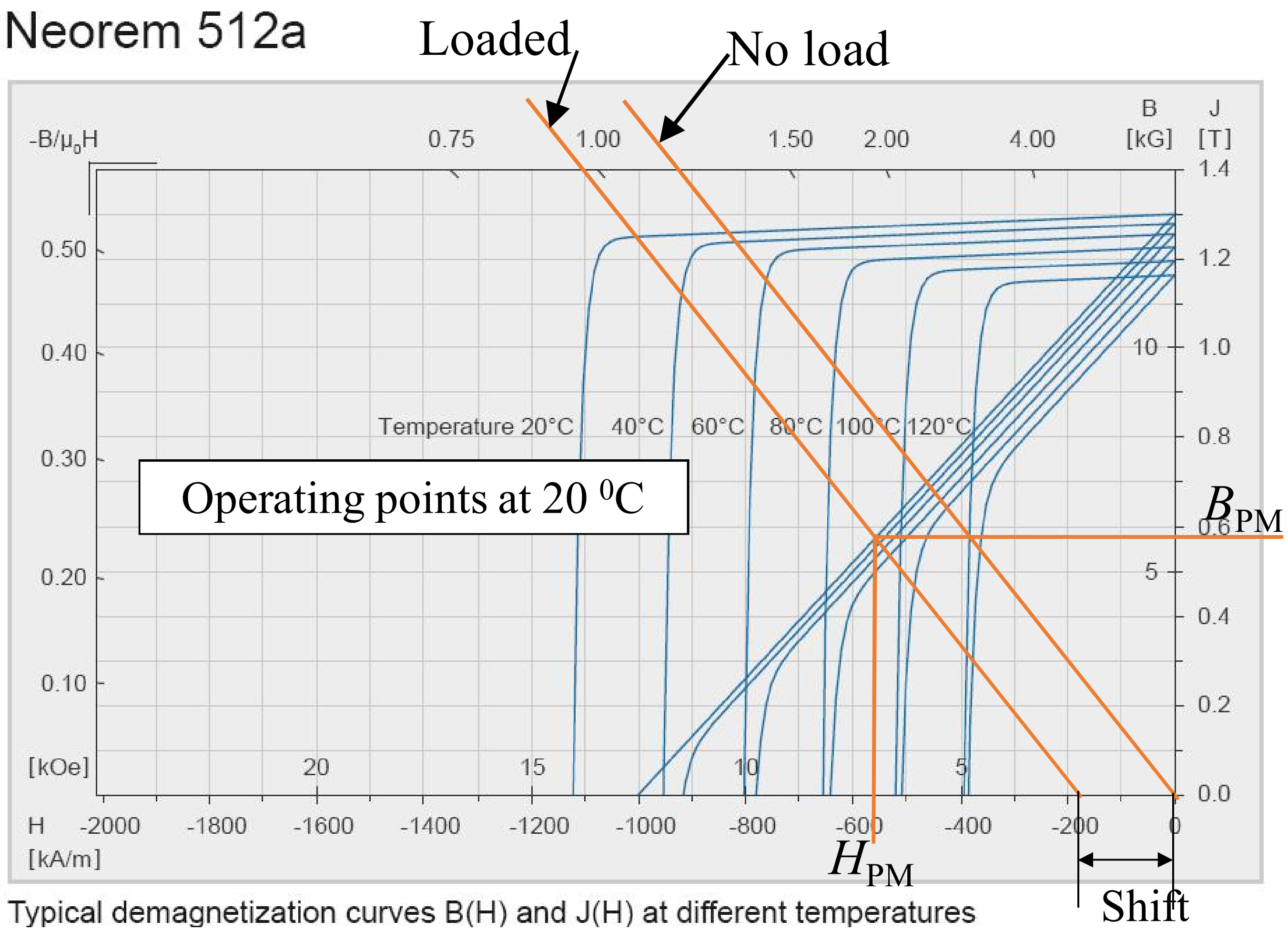


$$\oint H\mathrm{d}l = H_{PM}h_{PM} + H_\delta\delta - NI = 0$$

$$\Phi_{PM} = S_{PM}B_{PM} = (1+\sigma)S_\delta B_\delta = (1+\sigma)S_\delta\mu_0 H_\delta$$

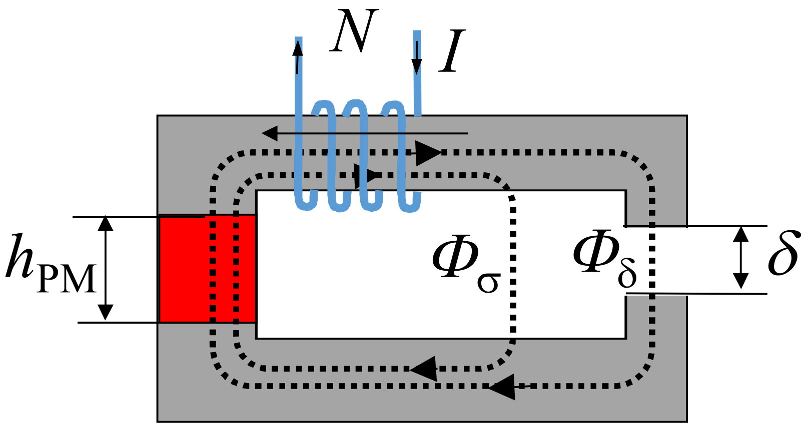
$$H_\delta = -\frac{h_{PM}}{\delta}H_{PM} + \frac{NI}{\delta}$$

$$B_{PM} = -(1+\sigma)\mu_0\frac{S_\delta}{\delta}\frac{h_{PM}}{S_{PM}}H_{PM} + (1+\sigma)\mu_0\frac{S_\delta}{\delta}\frac{NI}{S_{PM}}$$



Typical demagnetization curves B(H) and J(H) at different temperatures

Demagnetization



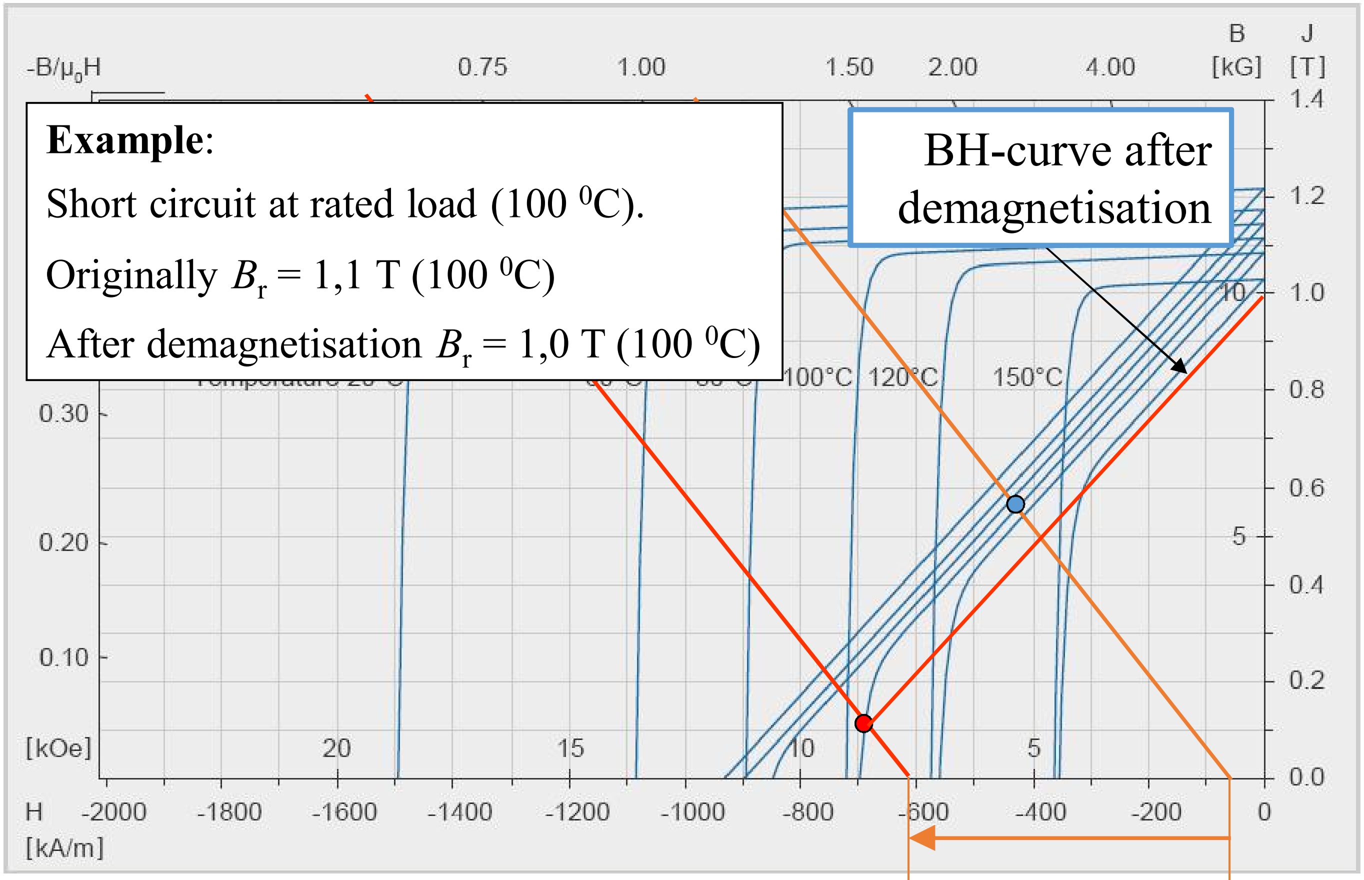
$$\oint H dl = H_{PM} h_{PM} + H_\delta \delta - NI = 0$$

$$\Phi_{PM} = S_{PM} B_{PM} = (1+\sigma) S_\delta B_\delta = (1+\sigma) S_\delta \mu_0 H_\delta$$

$$H_\delta = -\frac{h_{PM}}{\delta} H_{PM} + \frac{NI}{\delta}$$

$$B_{PM} = -(1+\sigma)\mu_0 \frac{S_\delta}{\delta}\frac{h_{PM}}{S_{PM}} H_{PM} + (1+\sigma)\mu_0 \frac{S_\delta}{\delta}\frac{NI}{S_{PM}}$$

Neorem 453a



Example:

Short circuit at rated load (100 ^{0}C).

Originally $B_r = 1{,}1$ T (100 ^{0}C)

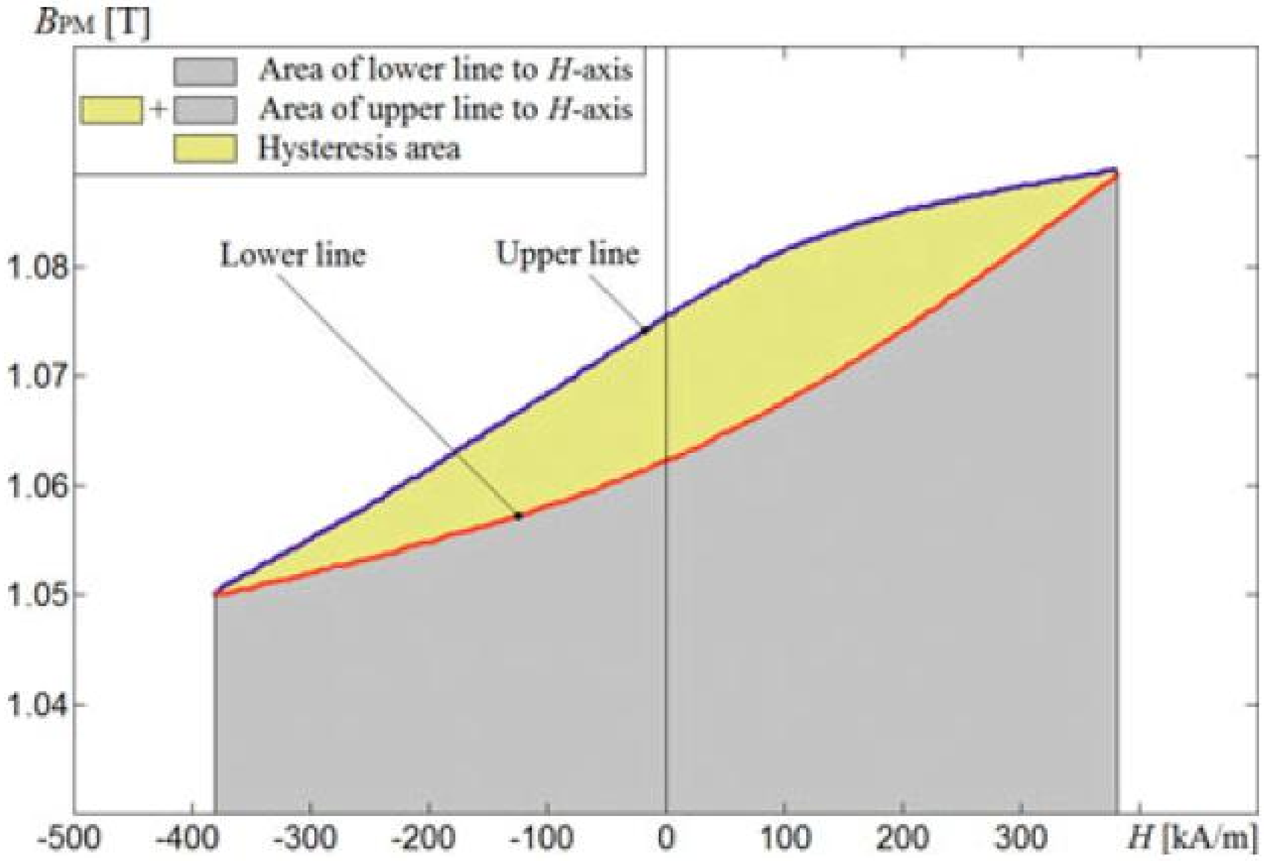
After demagnetisation $B_r = 1{,}0$ T (100 ^{0}C)

BH-curve after demagnetisation

Shift by increased MMF

Magnetic materials and field computation

- Recall line can be approximated by linear single valued curve as far as the flux density does not exceed B_r
- When B_r exceeds, hysteretic behavior takes place and magnet losses increase
-



Magnetic materials and field computation

- Magnetic materials are non linear but useful in energy conversion device
- The solution of electromagnetic field is required for device design
- Electromagnetic field solution is based on numerical analysis (FEM)
- FE computation requires material models
  - Nonlinear magnetic material
    - Spline or analytical equation for either HB-relationship or permeability as function of B
    - Results in iterative solving of the field
    - Newton-Raphson or fixed point method
  - Permanent magnet machine
    - Linear relationship between B and H defined by B_r and H_c
    - Thermal effect modelled as linear change in B_r and/or H_c
    - Does not account for demagnetization risk
    - Demagnetization check in post processing