APPLICATIONS OF HIGH ENERGY DENSITY PERMANENT MAGNETS

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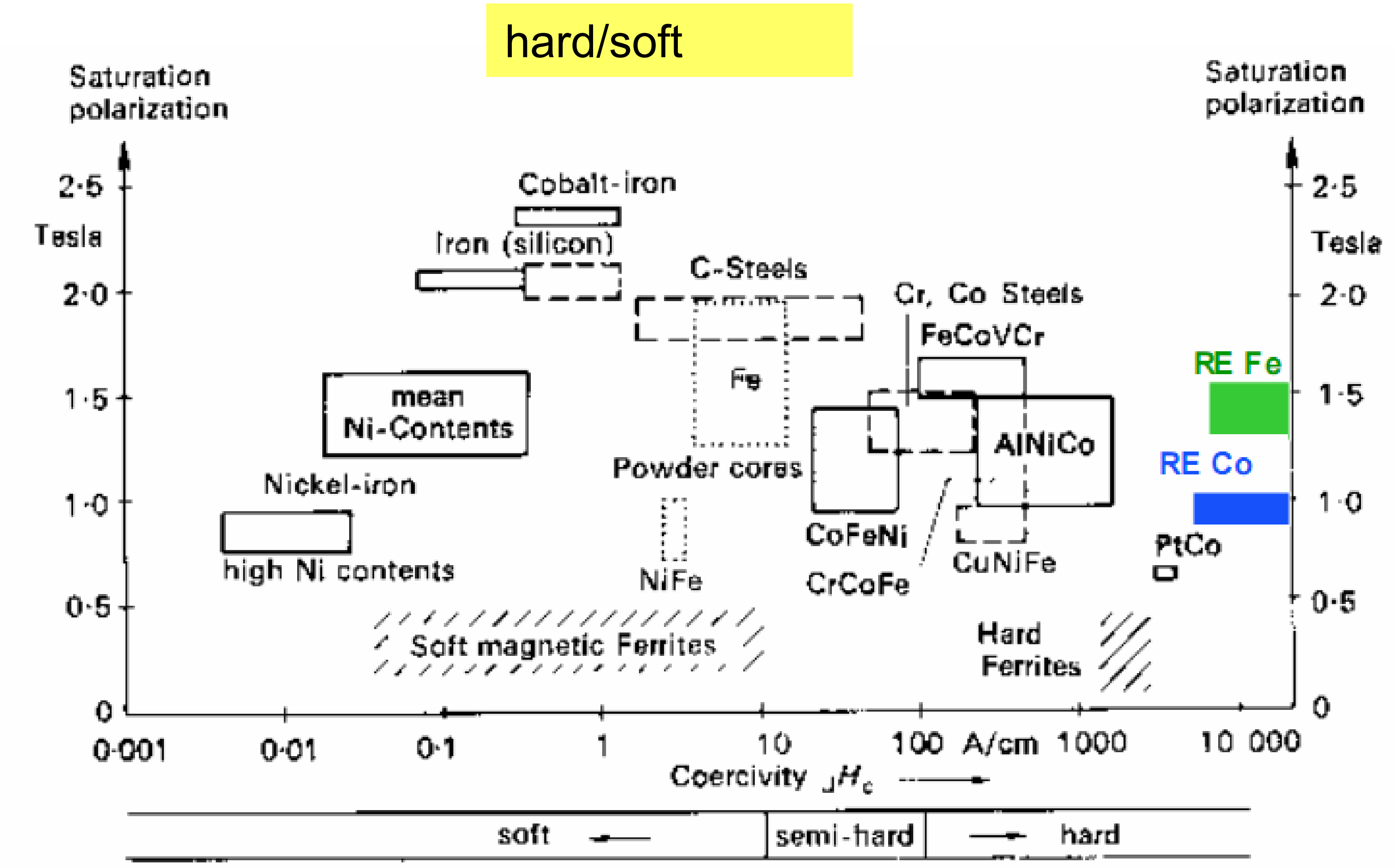
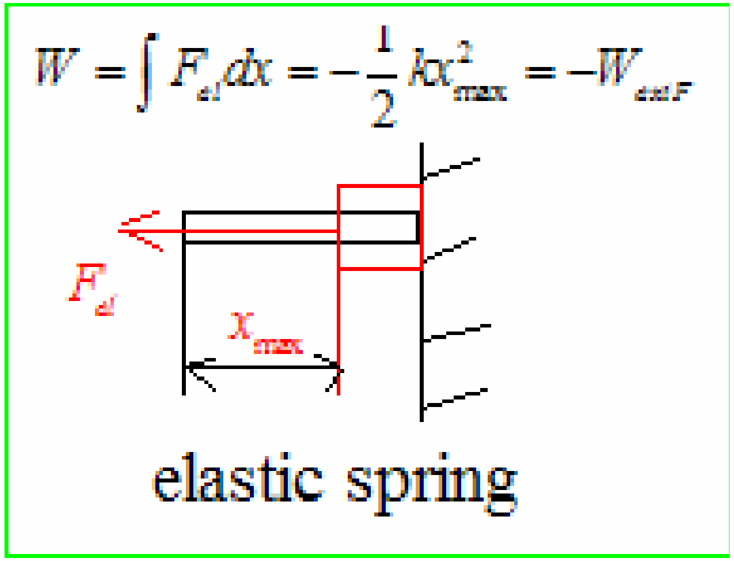
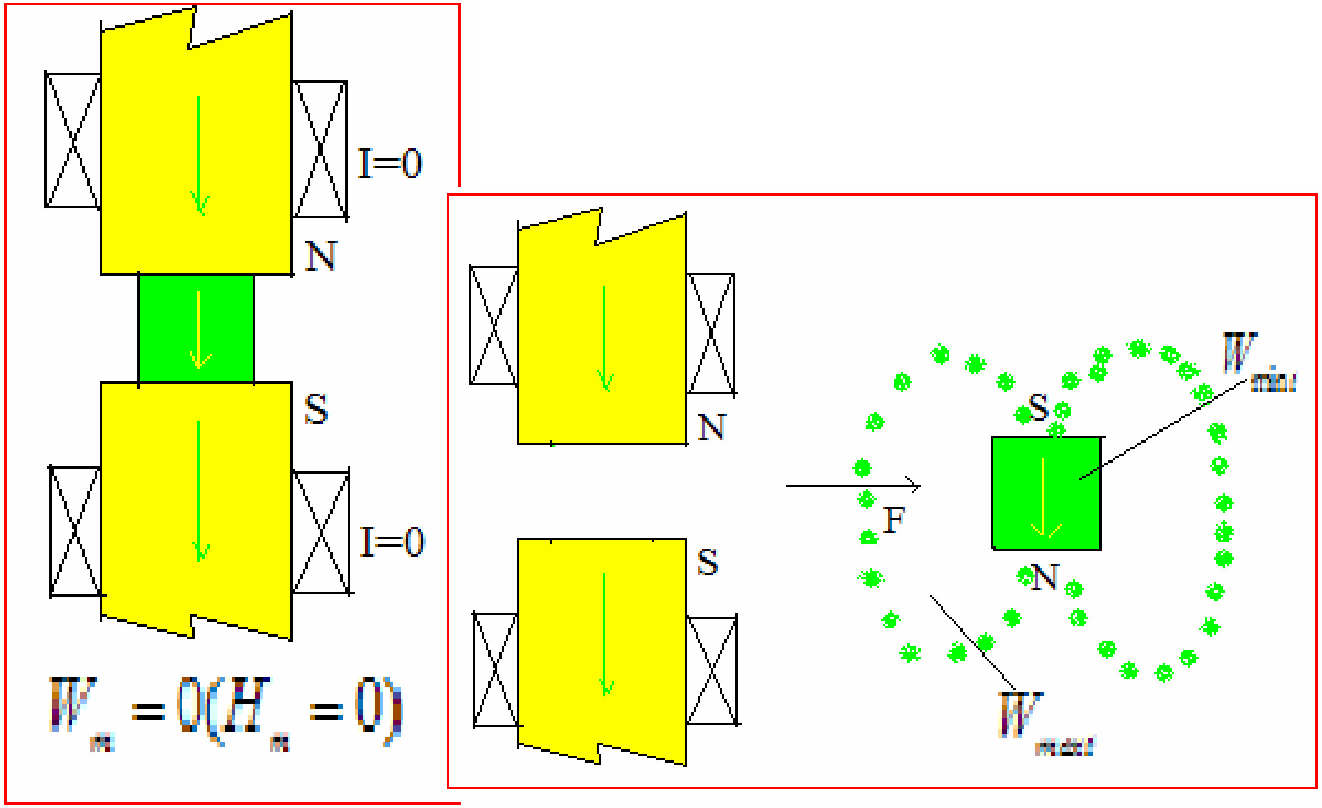
Magnetic Materials



R. Boll, „Soft Magnetic Materials", Siemens AG, Hyden & Son, 1977

How works a PM?





$$W_{mint} = \frac{1}{2} B_m H_m V_m = -\frac{1}{2} B_m |H_m| V_m = -W_{mext}$$

$$W_{mext} = \int_{\infty-m} BHdv = \int_{initial}^{final} Fdl$$

The highest loading energy of a PM

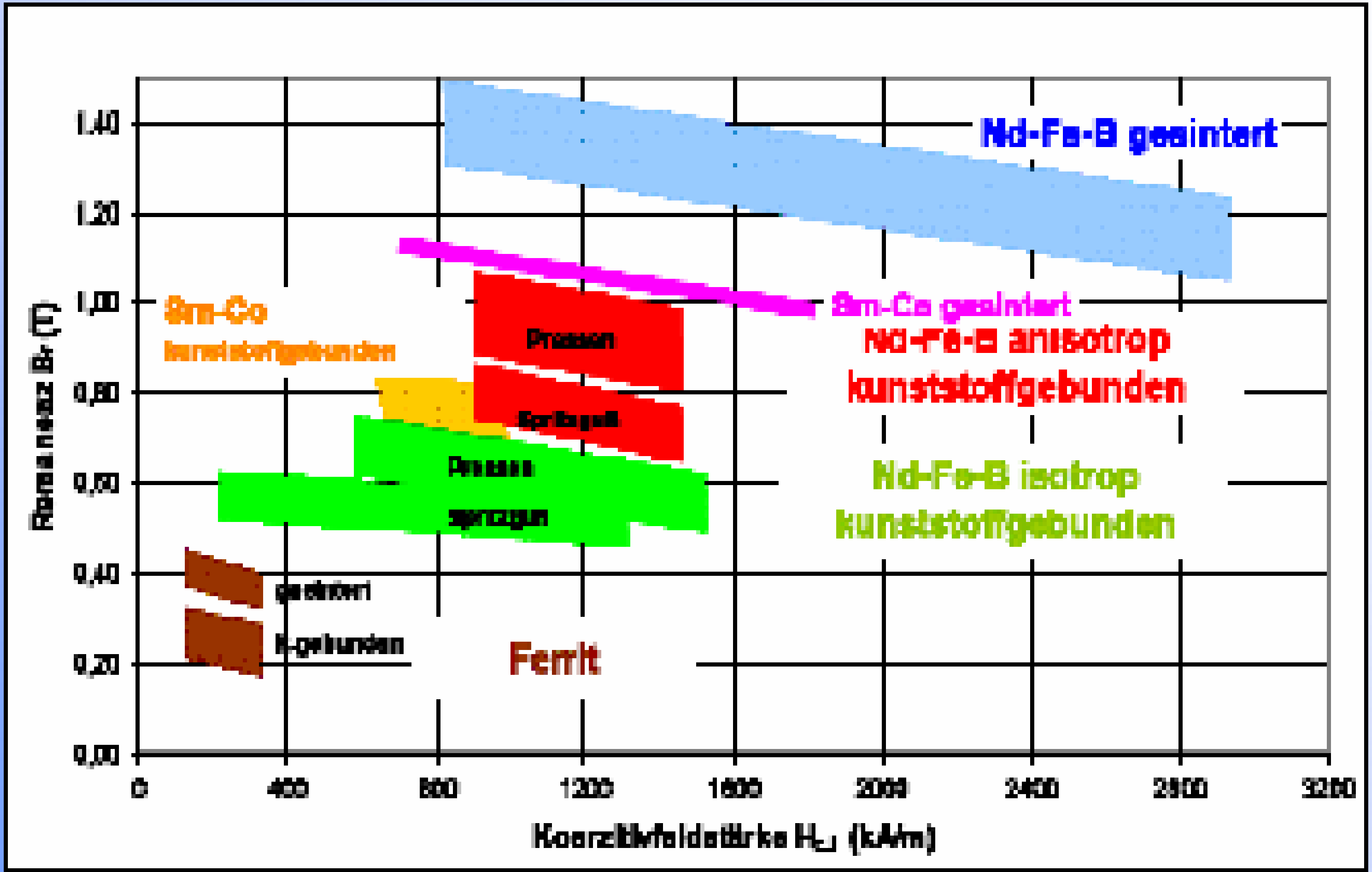
$$\max(W_{\min t}) = \frac{1}{2}(B\,H)_{\max} V_m$$

Example: for NdFeB-PM with

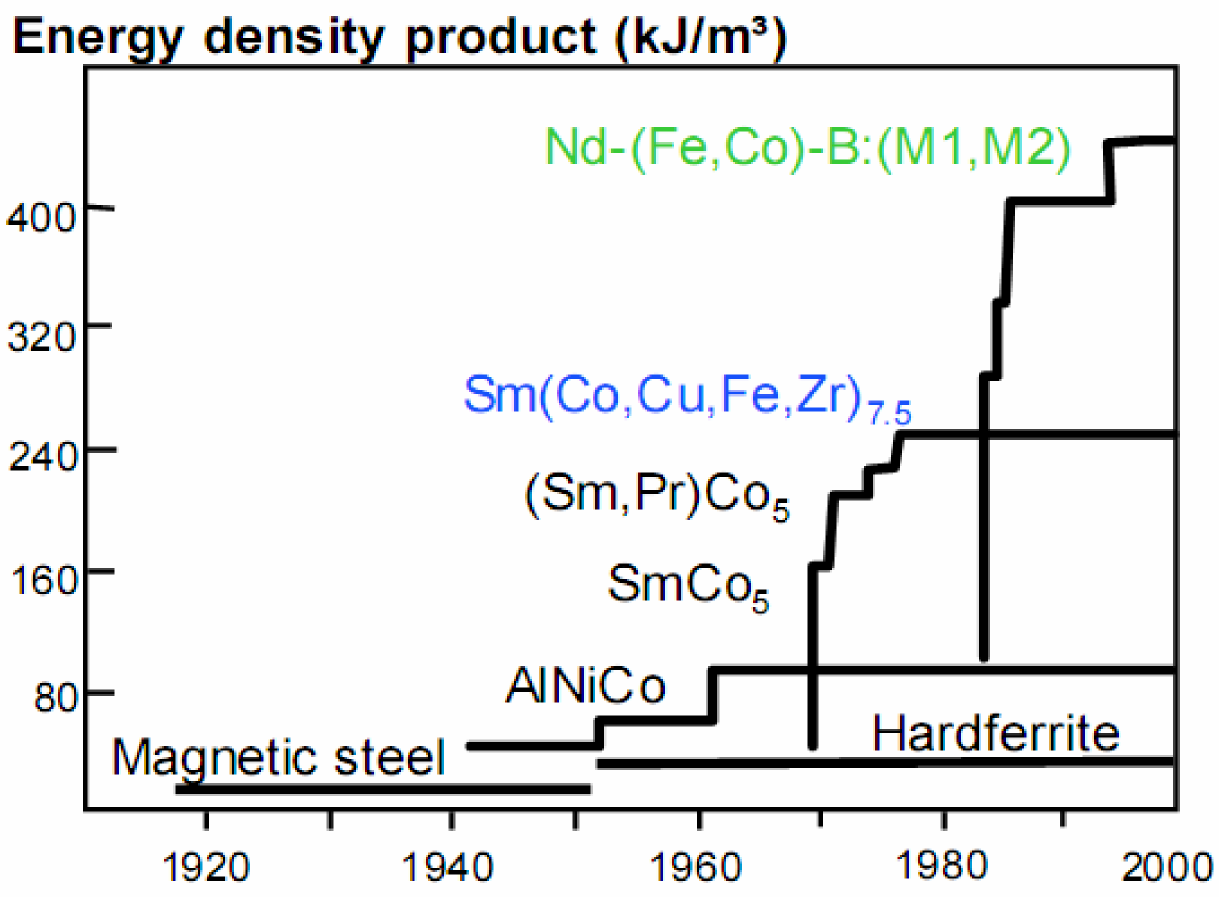
$$\max\ (W_{\min t})/mass = 50J/kg$$

$Comparison:$ $car\ battery\ 12V/60\,Ah\ w_{el} = 10^4\,J/kg$

Manufactured PM



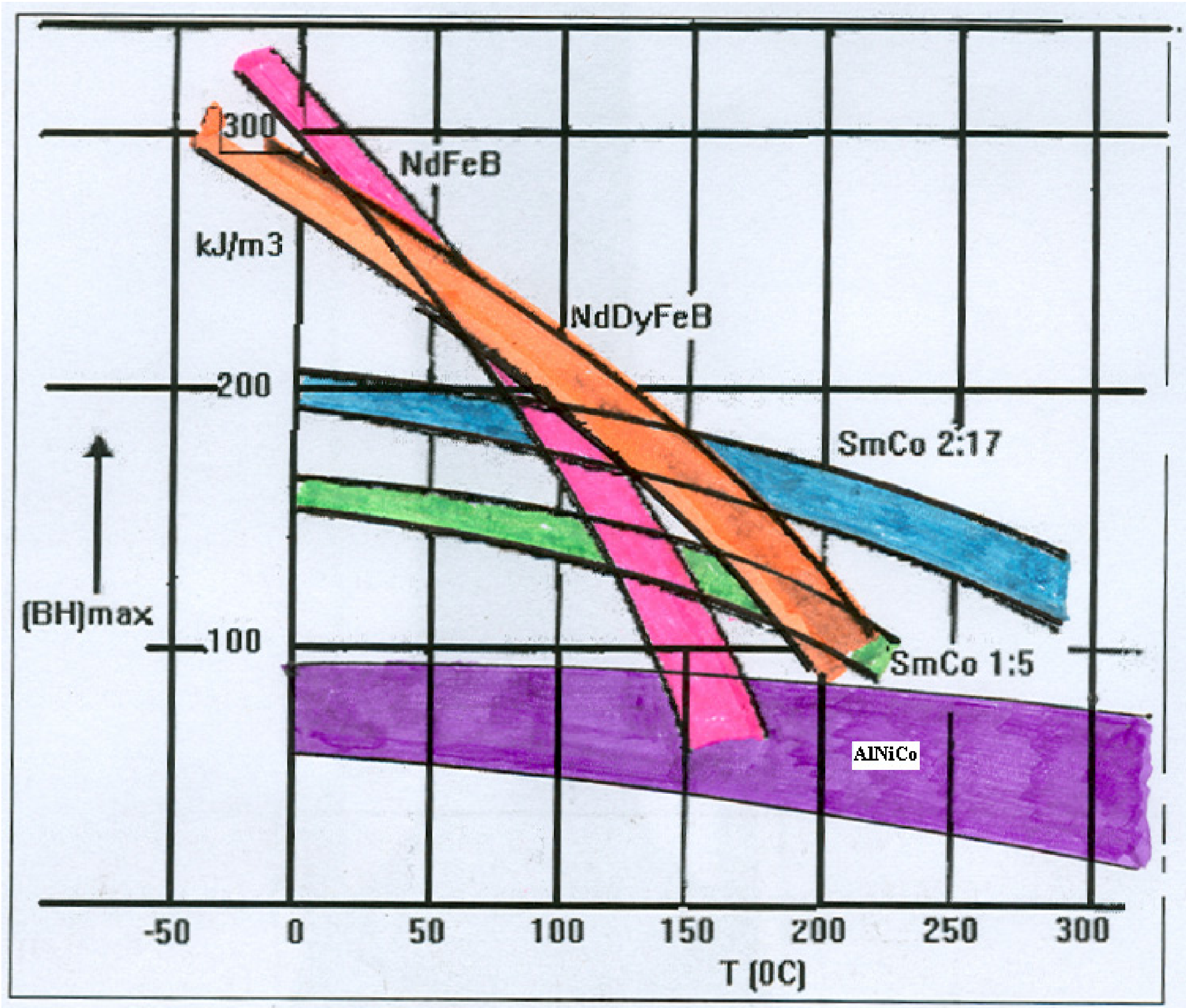
High energy permanent magnets



Magnet	Year	$_JH_c$ (kA/m)	T_c (°C)
Magn. steel	1890	1	
AlNiCo	1955	100	850
Hardferrite	1960	200	450
Sm-Co 1:5	1975	3000	720
Sm-Co 2:17	1982	2000	820
Nd-Fe-B	1990	1500	310

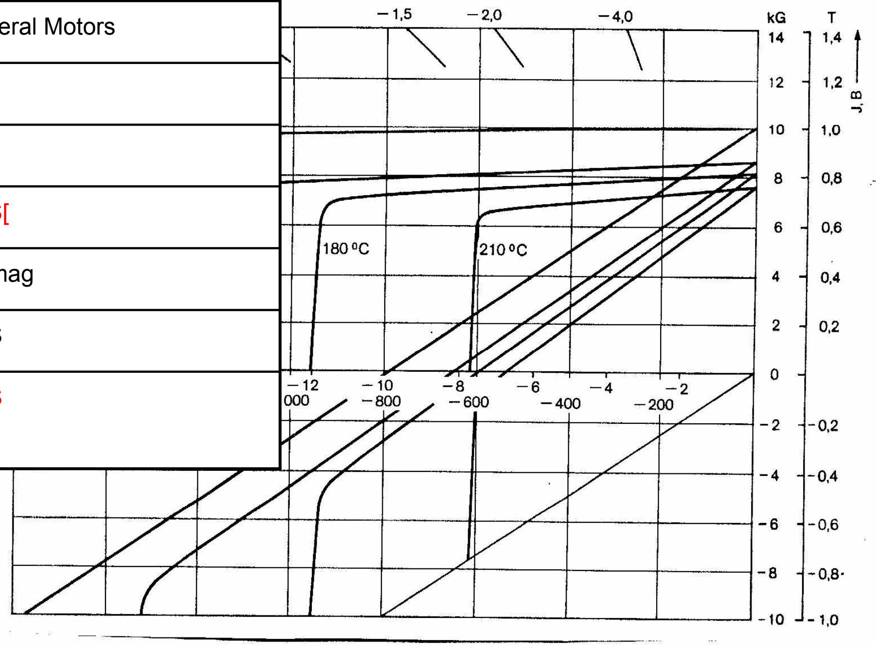
magnet.atp.tuwien.ac.at

Working at high temperature



Working temperature

Properties of some Re-TM permanent magnets						
Permanent magnet	$(BH)_{max}$ (kJ/m³)	B_r (T)	jHc (kA/m)	Manufac-turing method	Highest working Temp. (°C)	Producer
NdFeB	390	1.40	875	sintering	80	Shin Etsu
NdFeB	263	1.17	2387	sintering	180	Shin Etsu
NdFeB	190	1.00	3260	sintering	210	Vacuumschmelze
NdFeB/MQI	64	0.61	1200	bonded	125	General Motors
NdFeB-MQII	112	0,80	1600	densified	200	GM
NdFeB-MQIII	360	1.37	1120	hot worked	150	GM
NdFeB	240	1.11	2800	sintering	220	MFS[
$SmGdCo_5$	80	0.64	2400	sintering	250	Ugimag
SmCos	170	0.93	2000	sintering	250	MFS
Sm_2Co_{17}	215	1.06	2000	sintering	350	MFS



Typical demagnetization curves B(H) and J(H) of VACODYM 411 WZ at different temperatures

Working at high temperatures

Linear approximation: $$(BH)_{\max} = (BH)_{\max o}[1 + \alpha_{BH}(T - T_o)]$$

Where: $\alpha_{BH} = \alpha_I + \alpha_H$ **Two PM at T_e:** $(BH)_{\max 1} = (BH)_{\max 2}$

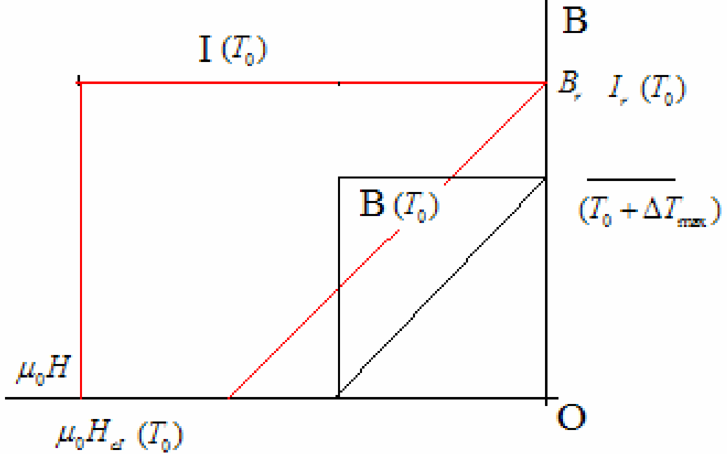
at $$\Delta T_e = \frac{1 - k_{12}}{k_{12}\alpha_{BH1} - \alpha_{BH2}}$$ **, k_{12} = $(BH)_{max1o}$ /$(BH)_{max2o}$**

Exemple Alnico IUNDK8AA, $(BH)_{\max 1} = 100 kJ/m^3$ **,** $\alpha_{BH1} = -0.04\%/K$

NdFeB $(BH)_{\max 2} = 300 kJ/m^3$ **,** $\alpha_{BH2} = -0.70\%/K$

=> $$\Delta T_e = 100^o C$$

Working at high temperatures



$$H_{cI}\mu_o >> I_r$$

We define $T_{max} : H_{cI}\mu_o = I_r$ **from which:** $\Delta T_{max} = \dfrac{1-k}{k\alpha_I - \alpha_H}, k = I_{ro} / \mu_o H_{cIo}$

$$k \to 0 \Rightarrow \Delta T_{max} \to -1/\alpha_H \qquad (1/0.005K^{-1} = 200K$$

$$k \to 1 \Rightarrow \Delta T_{max} \to 0 \qquad \Rightarrow \Delta T_{max} = 200K)$$

If $k_1 > k_2 \Rightarrow \Delta T_{max1} / \Delta T_{max2} < 1$ **That means**

For two PM having the same coercivity, the highest working temperature has the PM with the lower remanence (sintered /bonded)

PM worldwide

$$Energy / mass = (BH)_{max} / \rho$$

$$Energy / cost = (BH)_{max} / \rho : cost / kg$$

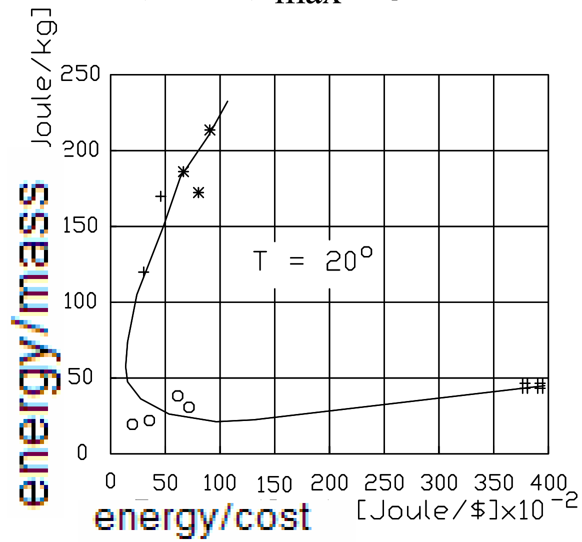
Output of PM in 2004

Country / Area	Alnico (ktons)	Hard ferrite (ktons)	NdFeB (ktons)
China	3.5 (56 %)	S = 350 (51 %) B = 50 (32 %) T = 400 (47 %)	S = 23 (76 %) B = 1.4 (35 %) T = 24 (71 %)
Japan	0.3 (5 %)	S = 196 (28 %) B = 13 (8 %) T = 209 (25 %)	S = 7 (23 %) B = 0.6 (15 %) T = 7.6 (22 %)
USA	0.7 (11 %)	S = 39 (5 %) B = 40 (26 %) T = 79 (9 %)	S = - B = 0.2 (5 %) T = 0.2 (1 %)
Europe	0.8 (12 %)	S = 47 (7 %) B = 42 (27 %) T = 89 (11 %)	S = 0.4 (1 %) B = 0.3 (9 %) T = 0.7 (2 %)
Others	1 (16 %)	S = 60 (9 %) B = 11 (7 %) T = 71 (8 %)	S = - B = 1.4 (36 %) T = 1.4 (4 %)
Total	6.3 (100 %)	S = 692 (100 %) B = 156 (100 %) T = 848 (100 %)	S = 30 (100 %) B = 3.8 (100 %) T = 34 (100 %)

S – sintered

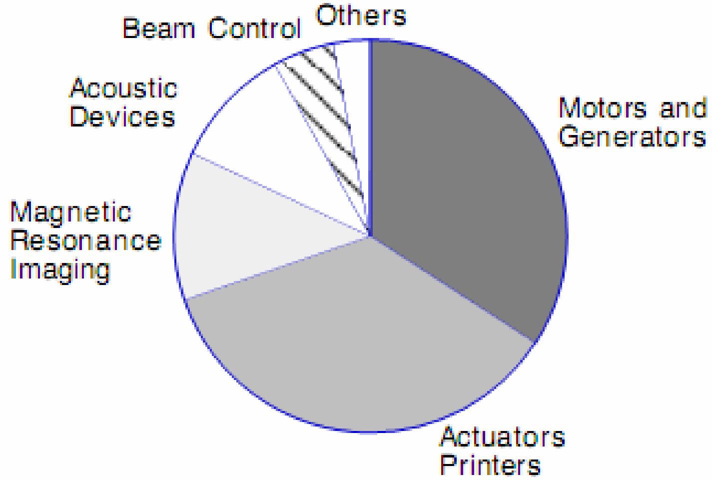
B – bonded

T - total



+ - PRCo; * - NdFeB; # - Ferrite; o - Alnico

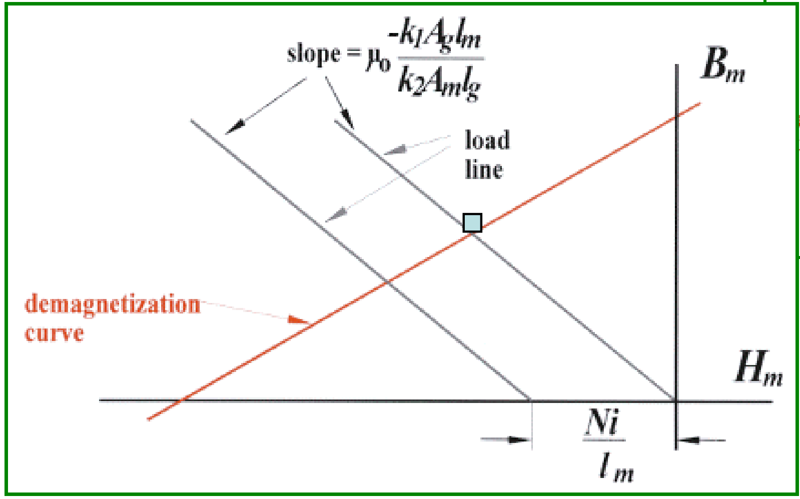
US $ 11.5 Billion in 2000

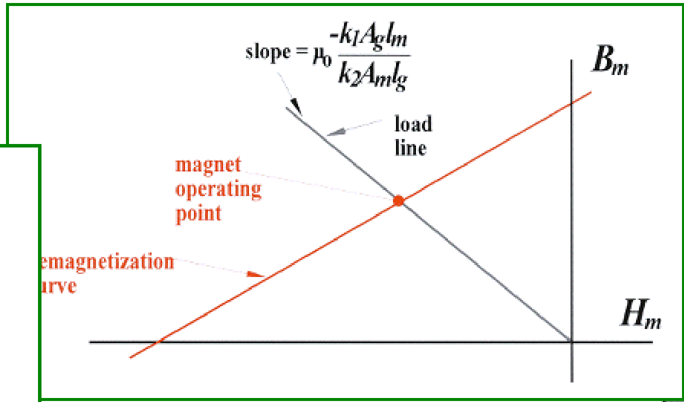


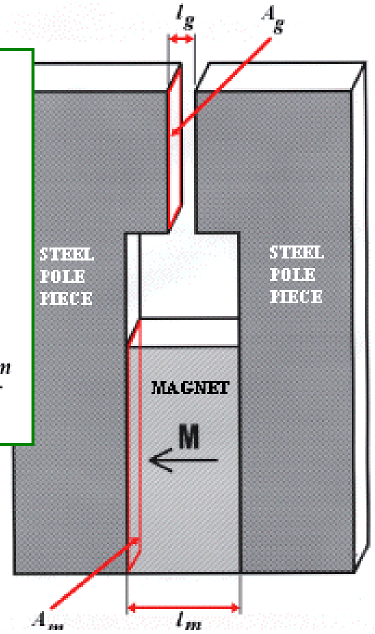
PM worldwide

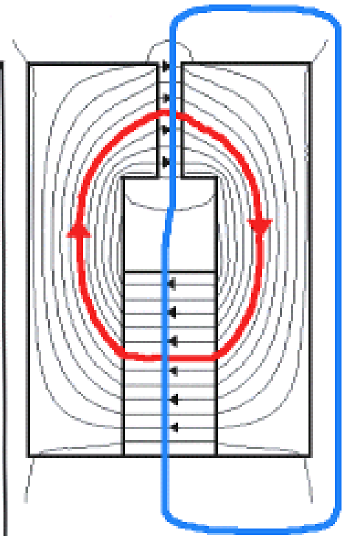
	B_r	H_c	T_c	BH_{max}	Rel. cost	Row material basis
W-steel	10	0.07	1000	0.31	10	critically(W)
Co-Steel	9	0.2	1200	1.0	20	critically(Co)
Alnico 5	12	0.5	850	5.0	15	critically(Co)
Ticonal	11.8	1.3	850	11	30	
Ba-Ferrite	3.9	1.8	450	3.5	5	very good
Sr-Ferrite	3.6	3.6	450	4.2	8	
$SmCo_5$	11.6	26	700	27	100	critically(Co)
Sm_2Co_{17}	11	14	800	32	90	limited(Sm)
$Nd_2Fe_{14}B$	14.1	13.5	300	48	65	good
$Sm_2Fe_{17}N$	6.8	12	550	12	75	limited(Sm)
FePt	12.3	5	750	9	200	critically(Pt)
CoPt	10.3	6	720	10.4	250	critically(Pt, Co)

Load line









$$\oint B \cdot dA = 0$$

$$\int_{circuit} H.dl = 0$$

For a PM

$$\frac{B_m}{\mu_0 H_m} = \frac{H_0 + M(1-N)}{H_0 - NM} \xrightarrow{H_0 \to 0} -\frac{1-N}{N} = -S$$

For the circuit

$$H_m l_m + \int_{circuit-m} Hdl = H_m l_m + \Phi \int \frac{dl}{\mu A} = 0,$$

$$\int_{circuit-m} \frac{dl}{\mu A} = \frac{1}{\Lambda_c} \qquad \Lambda_c \equiv permeance$$

$$S = \frac{k_1 A_g}{l_g} / \frac{k_2 A_m}{l_m} = \Lambda_c / \Lambda_m = \lambda$$ (unit permeance)

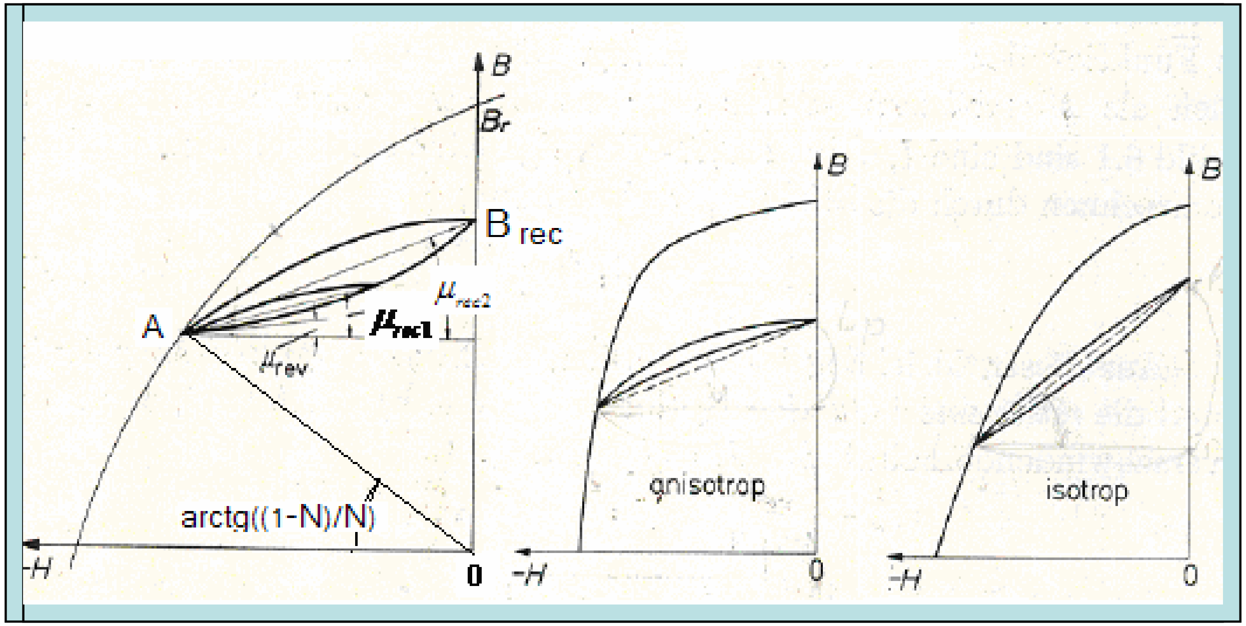
$$B_m A_m - k_1 B_g A_g = 0$$

$$H_m l_m + k_2 H_g l_g = 0$$

$$B_m = \frac{k_1 B_g A_g}{A_m} \; ; \; H_m = \frac{-k_2 H_g l_g}{l_m}$$

$$\frac{B_m}{H_m} = -\mu_o \frac{k_1 A_g l_m}{k_2 A_m l_g} = -\mu_o S$$

Recoil line/minor histerezis loop



Equation of the recoil line: $B_m = \mu_o(\mu_{rec} H_m + M_r)$

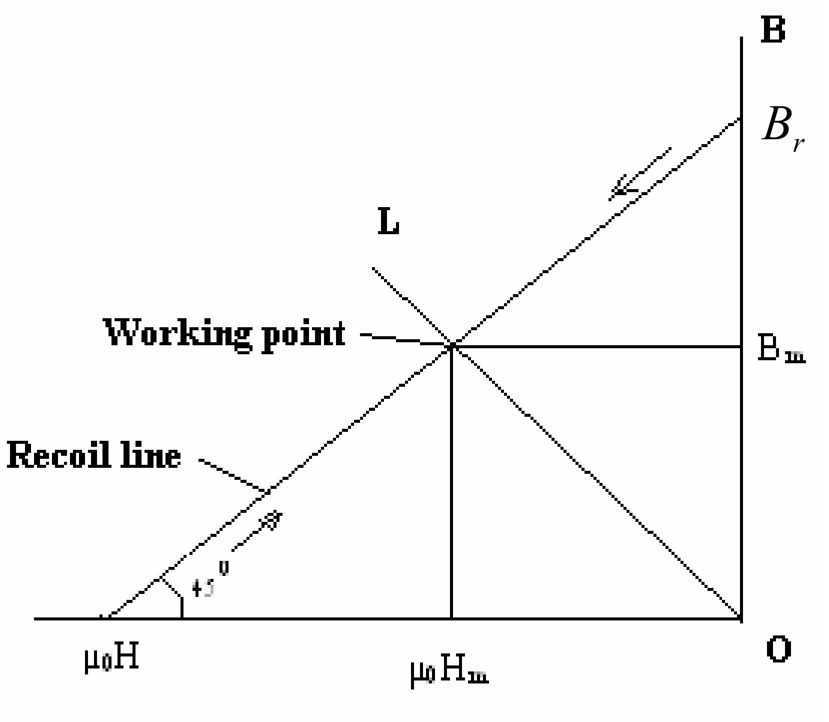
N – demagnetization factor of the PM

Ideal Permanent magnet

$$B_m = \mu_o(\mu_{rec} H_m + M_r)$$

$$\mu_{rec} = 1 \quad \rightarrow \quad B_m = \mu_0(H_m + M_r)$$

(main demagnetisation curve)

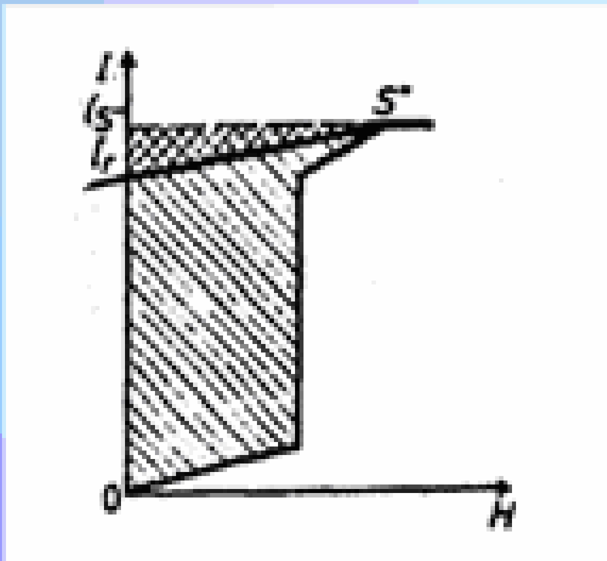


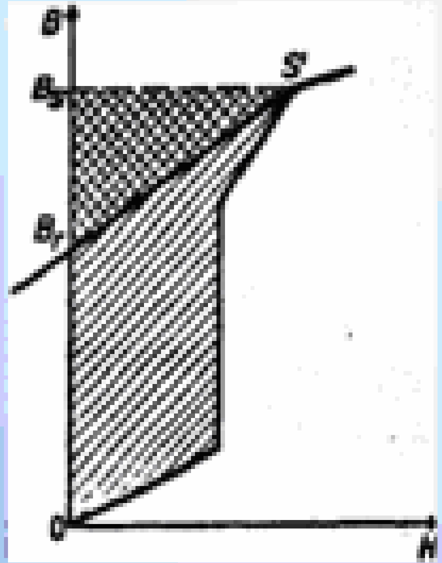
An ideal permanent magnet :

no irreversibil losses until Hd= intrinsec coercivity!

$$(BH)_{max} = (B_r)^2/(4\mu_0)$$

Energy Relations in PM





AM = AH + AI

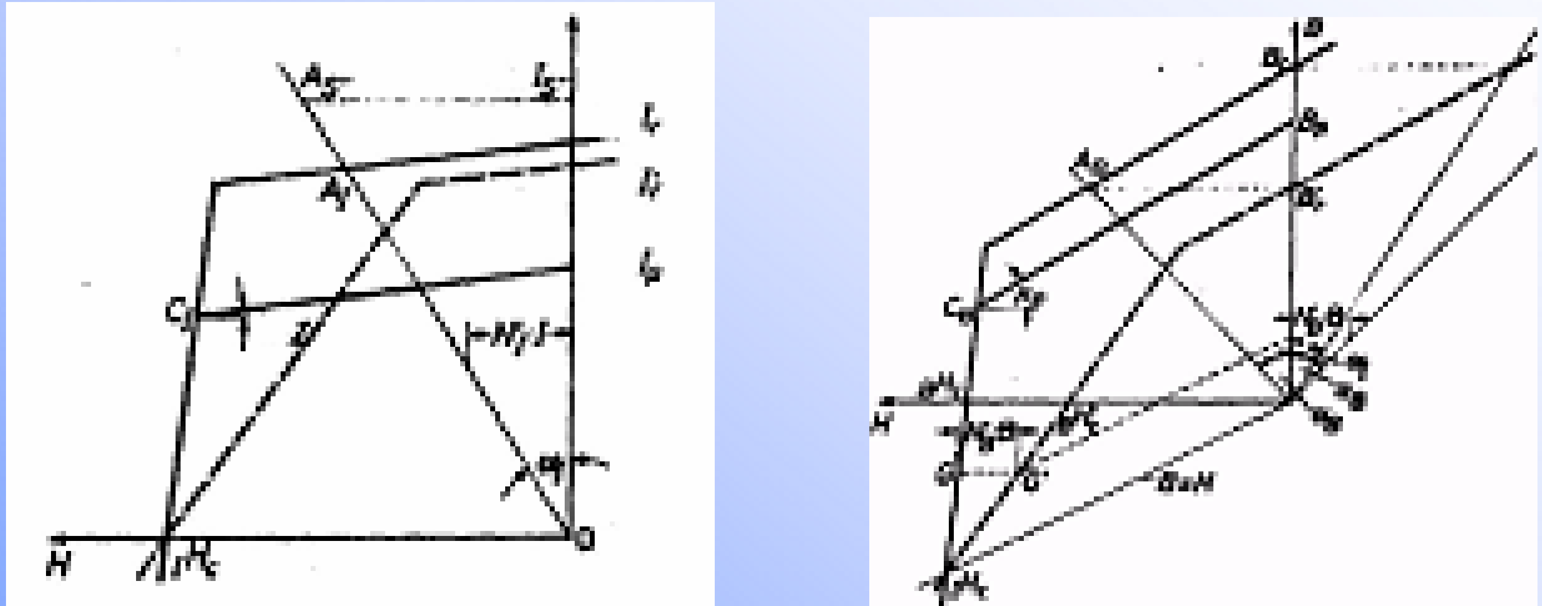
AH = the work done by the field

AI = Surface (OS"IS") = the real work necessary to magnetize at saturation the PM

AM = Surface (OS'BS') = the total work to magnetize the PM

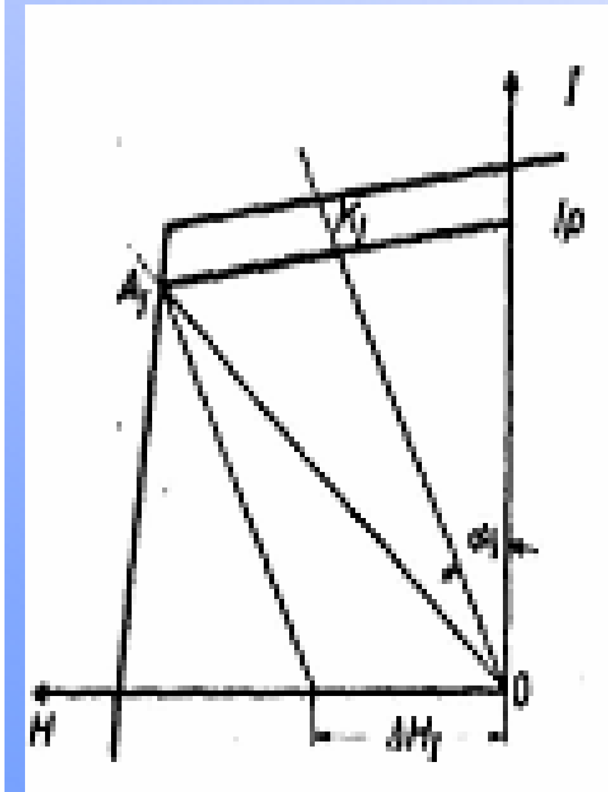
After removing of the magnetizing field, the working point of the permanent magnet moves to Ir resp. *Br*.
The energy density *S"IrS"* and *S'BS'Br* send back to the current supply by the permanent magnet alone resp.
permanent magnet together with the magnetic field.

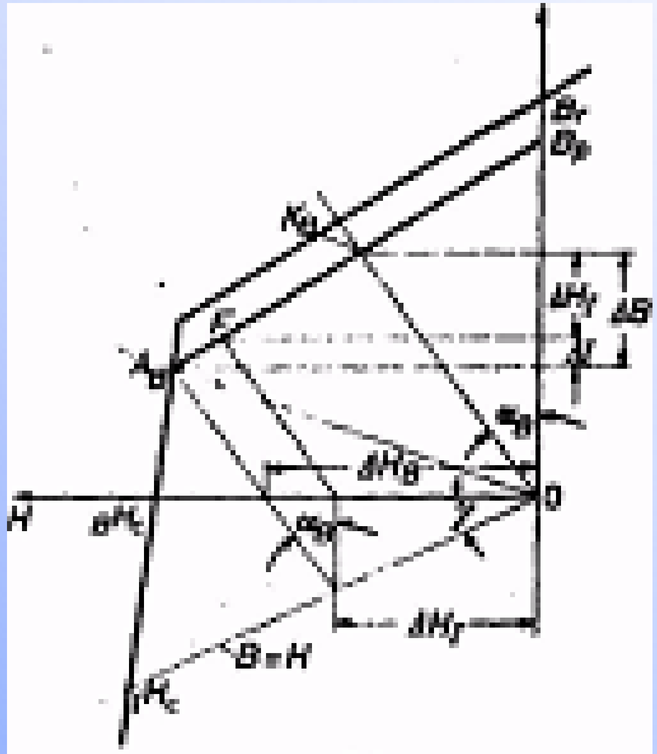
The circuit is Open



When we open the magnetising circuit, the working point of the permanent magnet moves, done by the shearing introduced by the demagnetizing field of the whole circuit to the points Al resp AB in the second quadrant of the hysterezis loop

Action of demagnetising fields



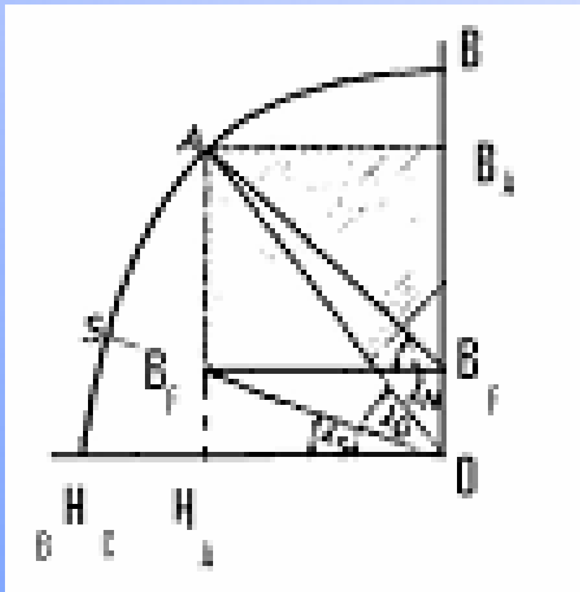


b)

-if the permanent magnet has the working point *KI* resp *KB* , than a demagnetizing field of ? HI brings the working point at AI and if the field is cancelled, then the working point will go back to *KI*.

if the demagnetization field *Hd* >?*HI* then after removing of the demagnetization field, the working point will be, on the load line *OKI*, but below *KI* (irreversible losses).

PM magnetised in the circuit



$B_A H_A V_m = (B_A - B_F) H_A + B_F H_A$

. In the outer space of the PM, the energy $B_A H_A V_m$ (V_m The volume of the PM) is stored

(always equal and with an opposite sign with the energy inside the magnet, because $\oint B dH = 0$) ,

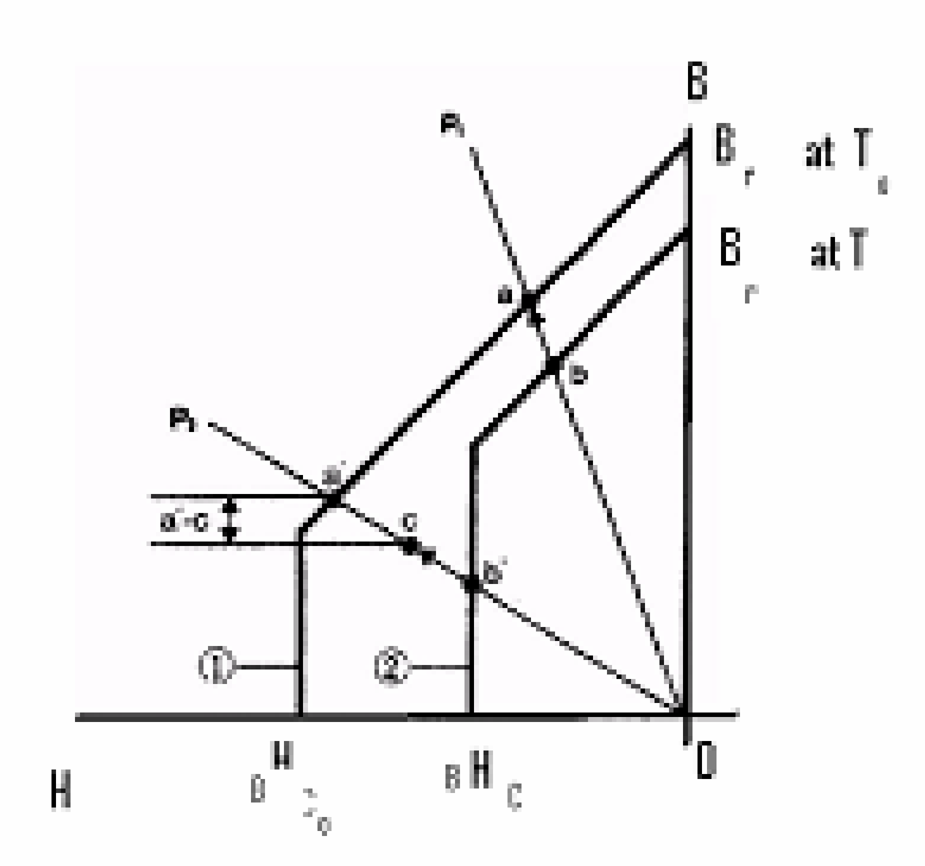
composed from the useful energy in the air gap,

proportional (up to a factor 2) to $(B_A - B_F) H_A$

$$\lambda_G = \lambda_N + \lambda_S$$

and the leakage energy $B_F H_A$

Magnetic temperature losses

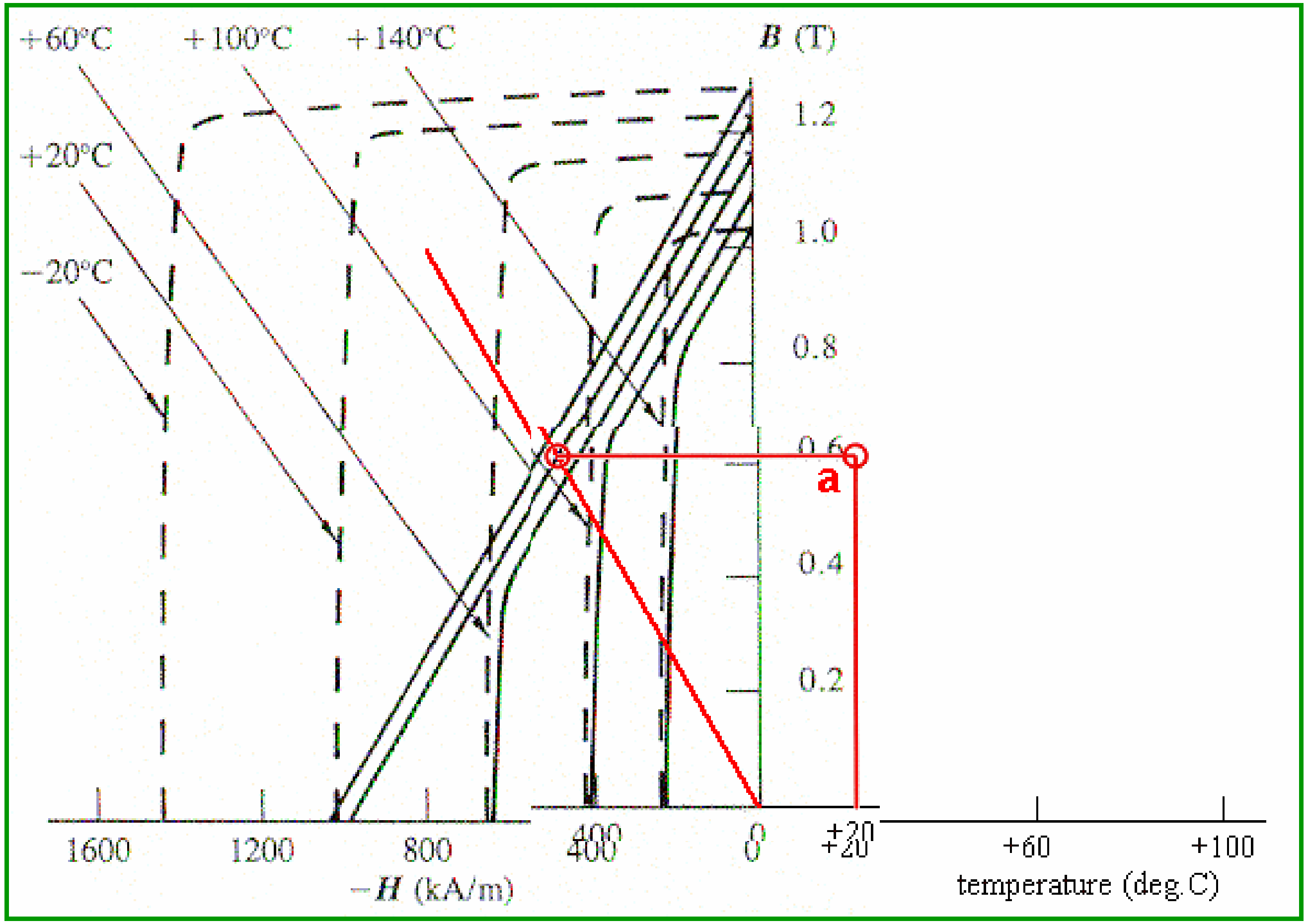


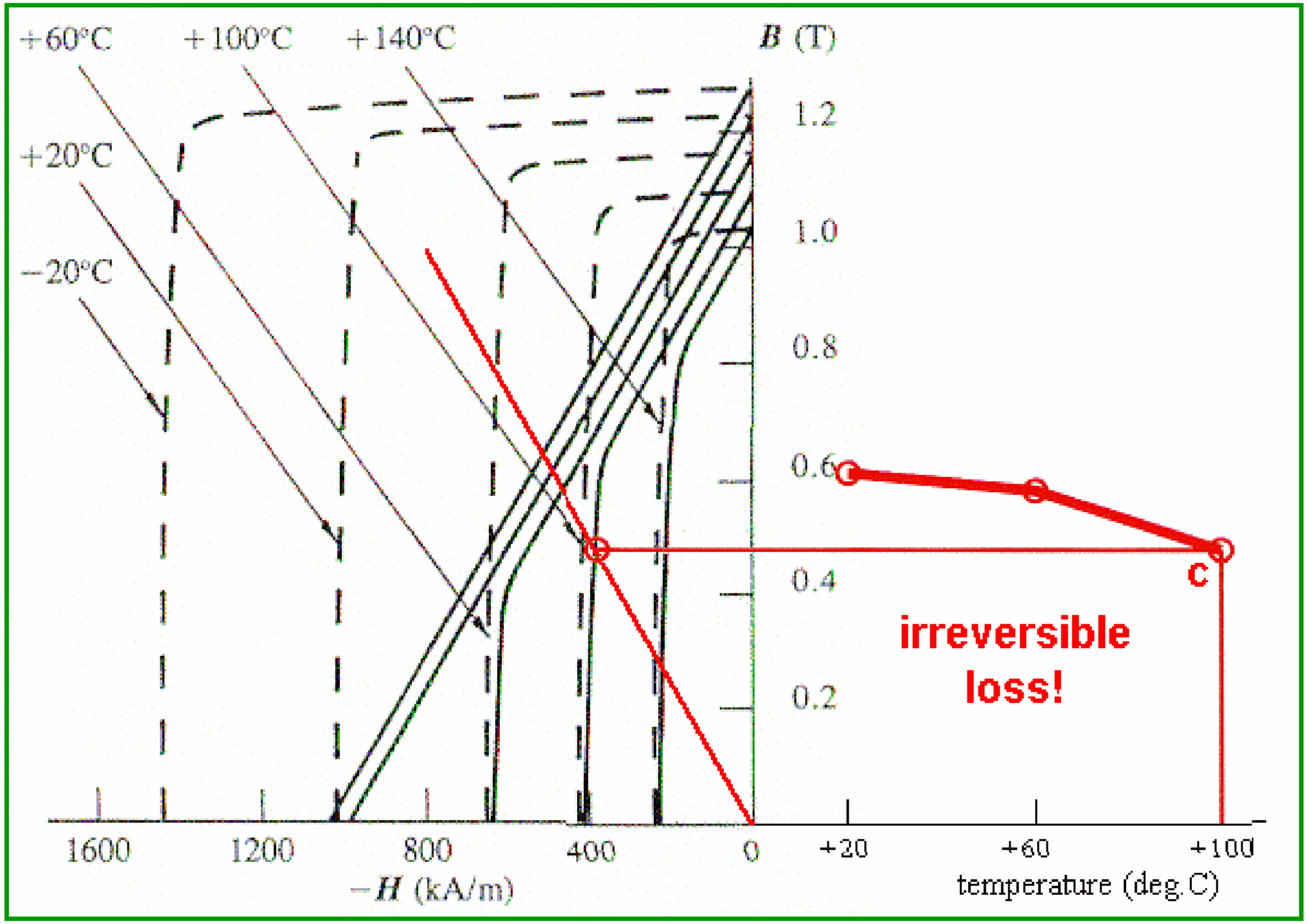
$$H_c = H_{c0}(1+\alpha_H(T - T_0)), \alpha_H \angle 0$$

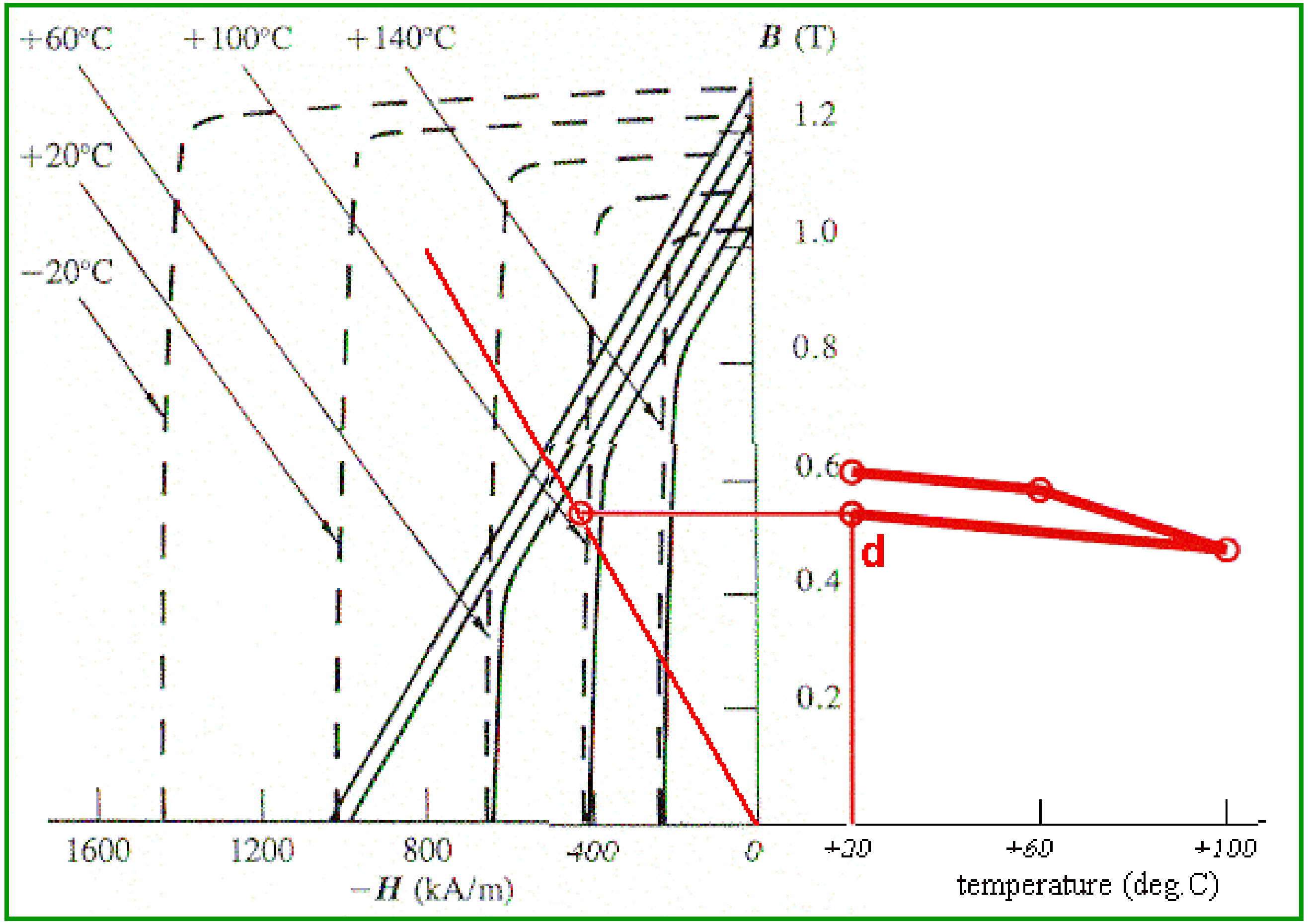
$$I = I_0(1+\alpha_I(T - T_0)), \alpha_I \angle 0$$

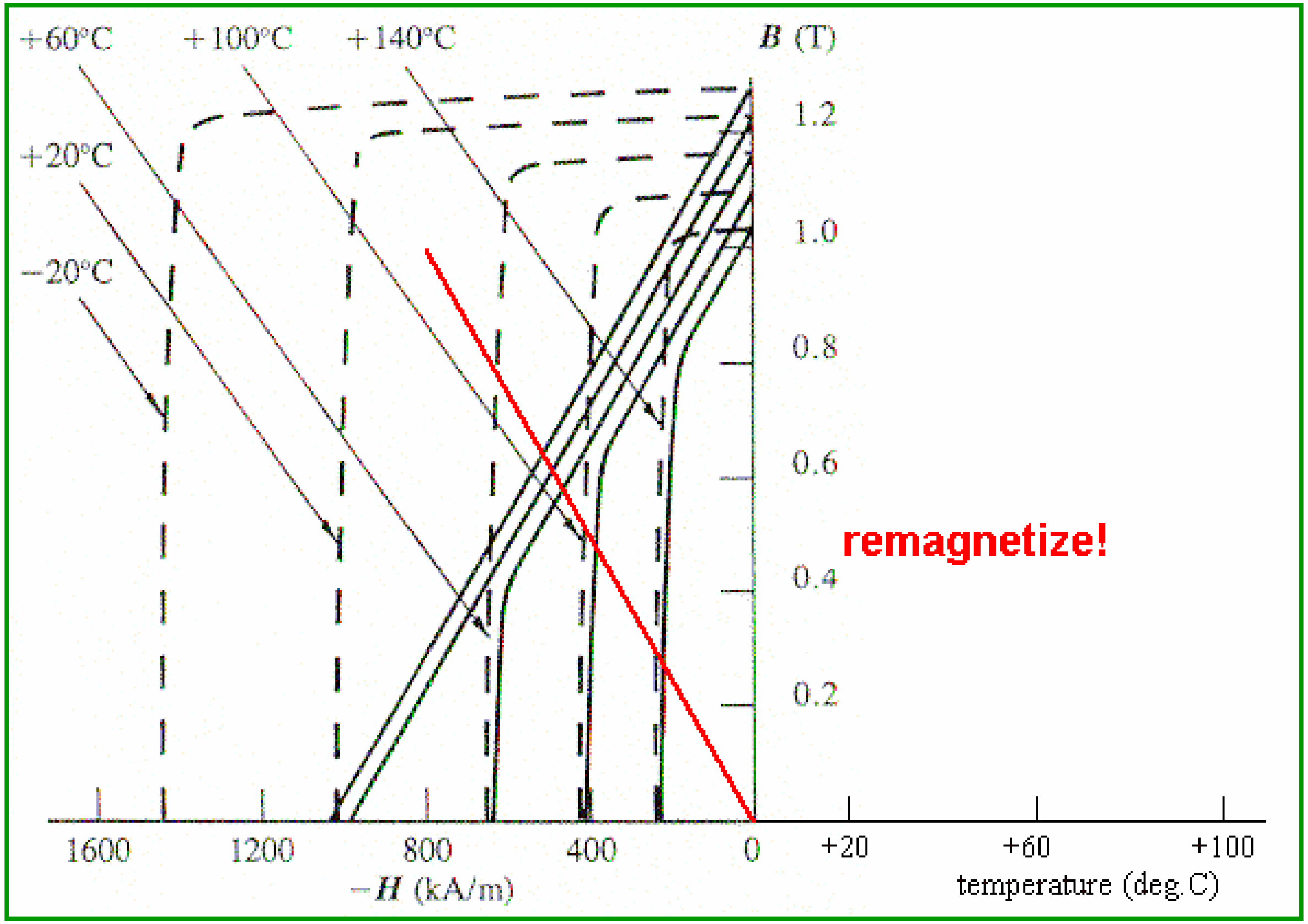
. If the load line of the PM is *P1* — reversible losses:
if the temperature becomes again T0, the working point goes back to „a", because the variation of the induction was identically with that of the magnetization.

If load line is P2 (at T the working point is in "b'", it is under the 'knee', so that returning to T0, B can be restored only to point 'c')—— irreversible losses a'-c

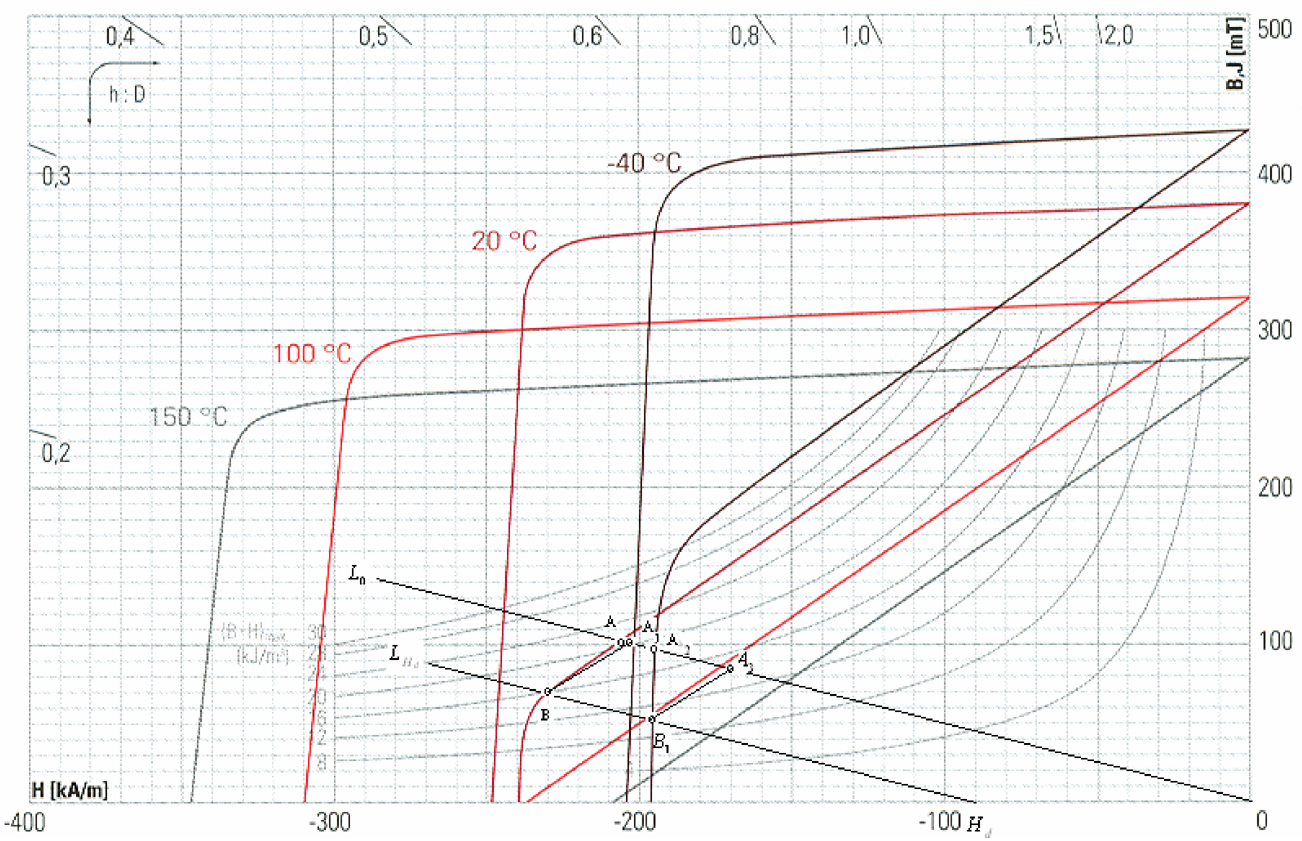

+60°C
+100°C
+140°C
B (T)
+20°C
−20°C
1.2
1.0
0.8
0.6
0.4
0.2
a
1600
1200
800
400
0
+20
+60
+100
−H (kA/m)
temperature (deg.C)


+60°C
+100°C
+140°C
B (T)
+20°C
−20°C
1.2
1.0
0.8
0.6
0.4
0.2
c
irreversible
loss!
1600
1200
800
400
0
+20
+60
+100
−H (kA/m)
temperature (deg.C)


+60°C
+100°C
+140°C
+20°C
−20°C
B (T)
1.2
1.0
0.8
0.6
0.4
0.2
d
1600
1200
800
400
0
−H (kA/m)
+20
+60
+100
temperature (deg.C)


+60°C
+100°C
+140°C
B (T)
+20°C
−20°C
1.2
1.0
0.8
0.6
0.4
0.2
remagnetize!
1600
1200
800
400
0
−H (kA/m)
+20
+60
+100
temperature (deg.C)

Ferrites at low temperatures



$\alpha_H > 0$

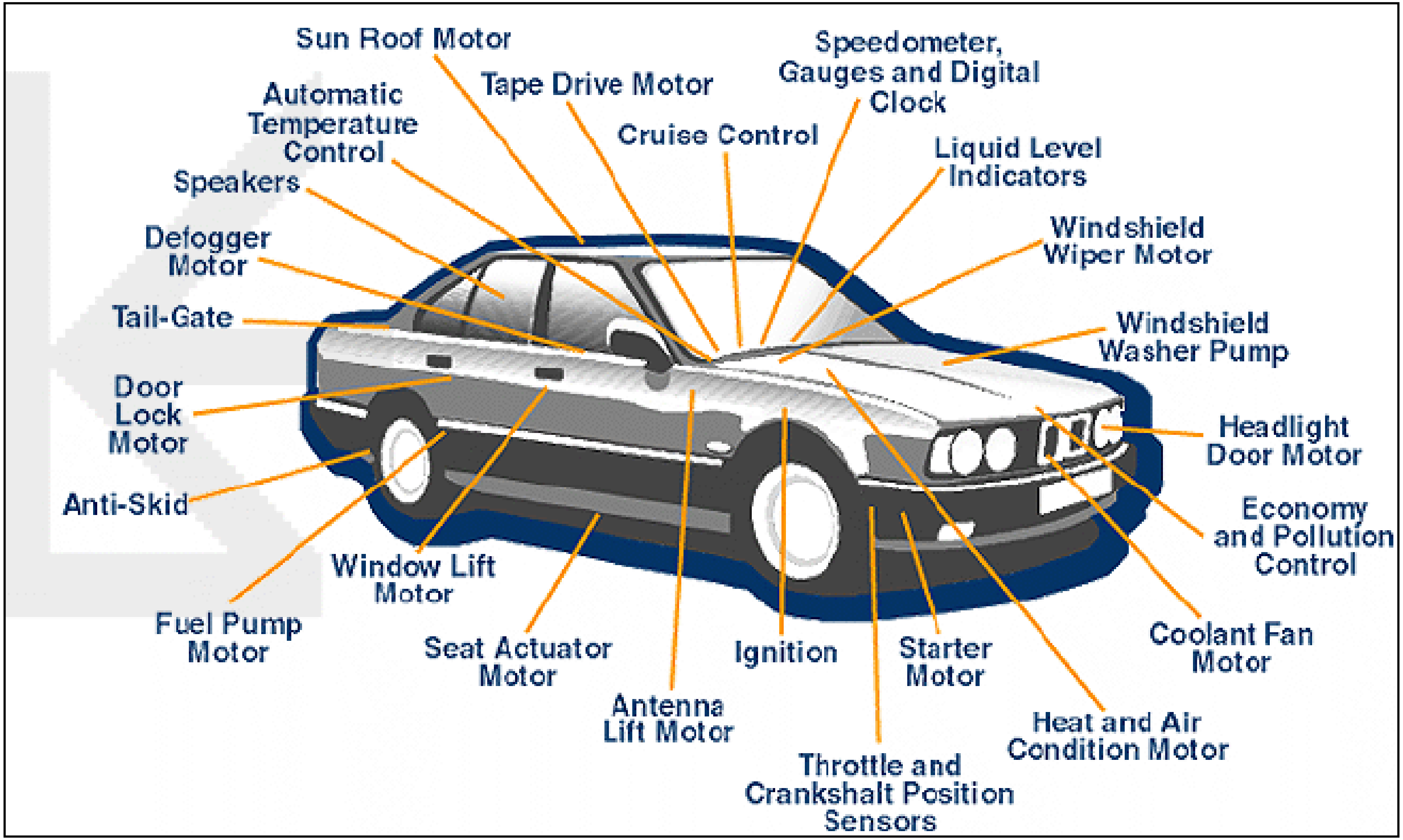
If T→ - 40C, A→A2
on the load line

If Hd is applied,
A→B at 20C
resp. B1 at -40C

If Hd = 0, than B→A1resp B1→A3 along the corresponding recoil lines.

If $T_{-40} \rightarrow T_{20}$, A1 is not restored because the induction (magnetisation) even become smaller at higher temperature

PM Applications



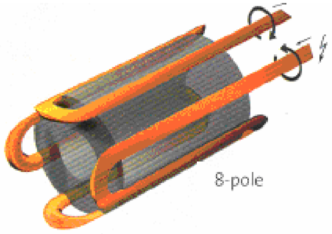
Applications

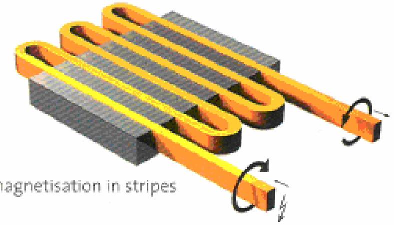
Different types of magnetic materials

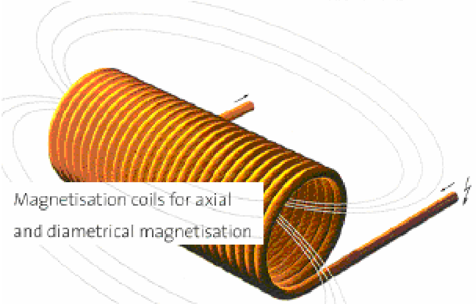
Type of magn.material	SOFT MAGNETIC MATERIALS				HARD MM		Magn. memory	Magnetostriction material		Transport properties
Field of appl.	E-tron.	Sensors	EMC	E-techn.	E-techn.	E-tron.	IT	Actua-tors	Sensors	Sensors
TM-alloys	FeSi, Nano &am FeNi	Nano FeNi	*Composites M+polymers*	FeSi, FeNi, FeCo, Fe	*AlNi-Co*				FeCoZr	Permalloy
RE-TM					*NdFeB SmCo*	*NdFeB SmCo*	TbFeCo	RE-Fe_2		
Ferrit. Manganites	*Soft ferrites*	*Soft ferrites*	*Soft ferrites*	*Magn. liquids*	*Hexa-ferrites*	*Hexa-ferrites*	*Fe_2O_3, CrO_2*			$LaREMnO_3$
Thin films		Alloys, oxids			Metall &oxid systems		CoCrTM-RE/CoCr	RE-TM	Ni	
Multi-layers		M-mu. layers	Mu.-lay.+in sulater		Metall &oxid systems		PtCo	RE-TM,TM-TM’		TM/nonmag/TM,TM/insul./TM
Nano		Am.(Co)	*Fe_2O_3*		*Comp.with exch. interaction*		Magn. wires			

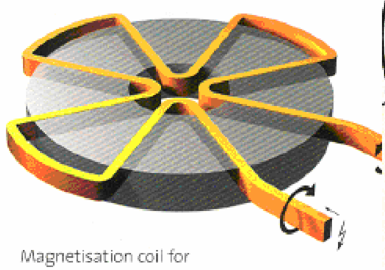
TM=3d-transition metal,RE=rare earth,M=metal

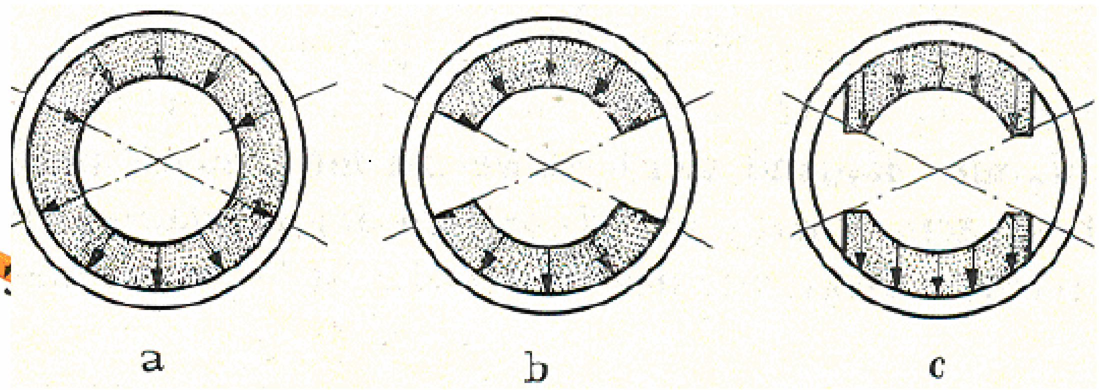
Magnetizing & shapes

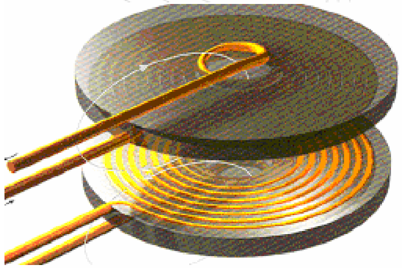


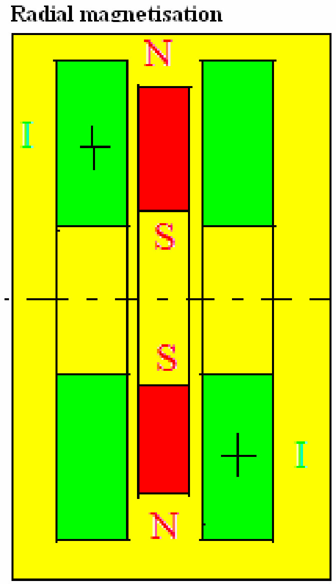


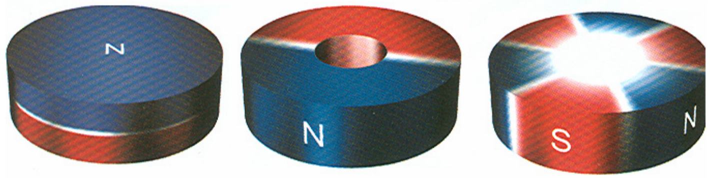


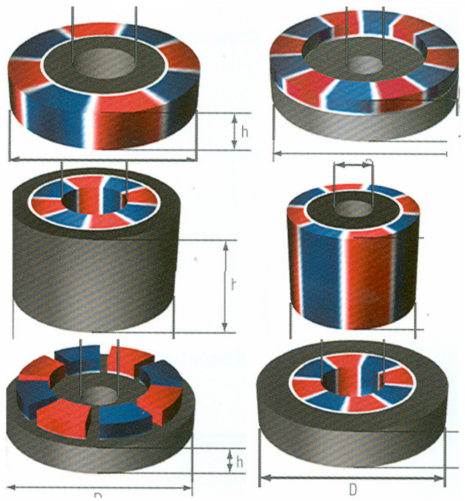


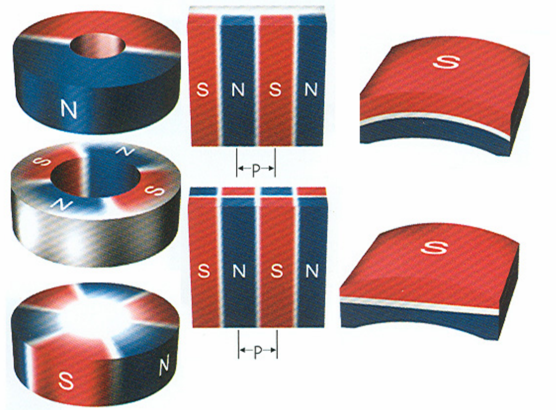








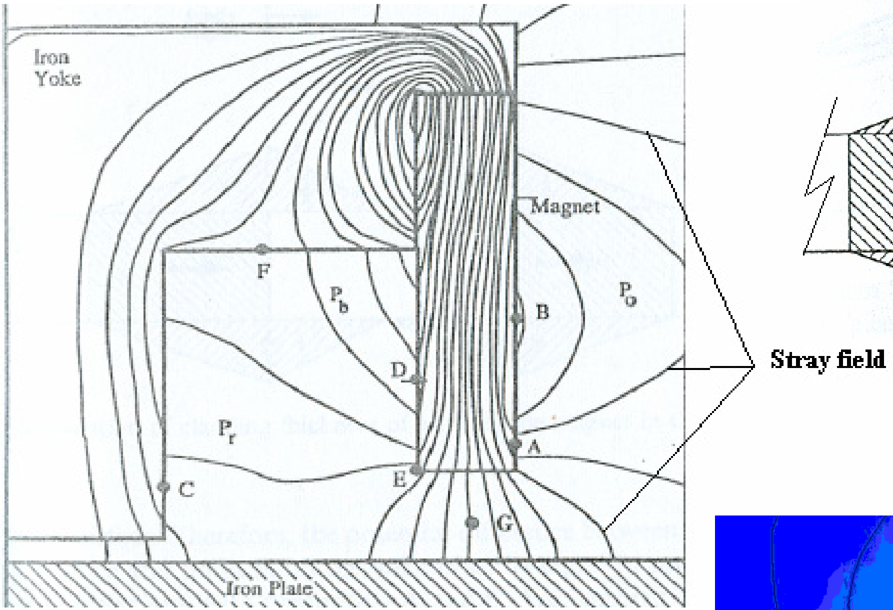


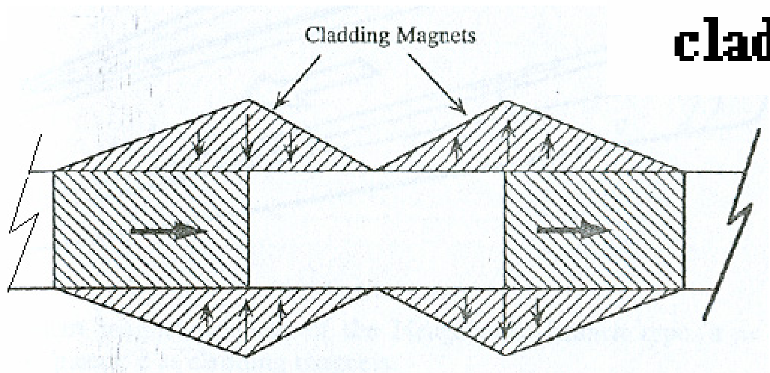


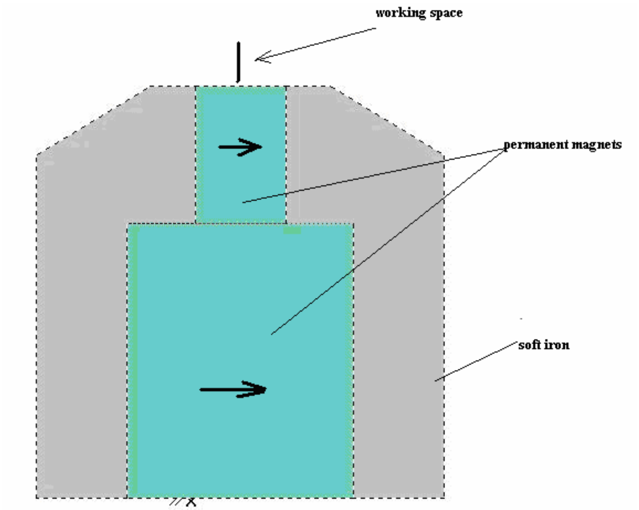
Applications of high energy PM

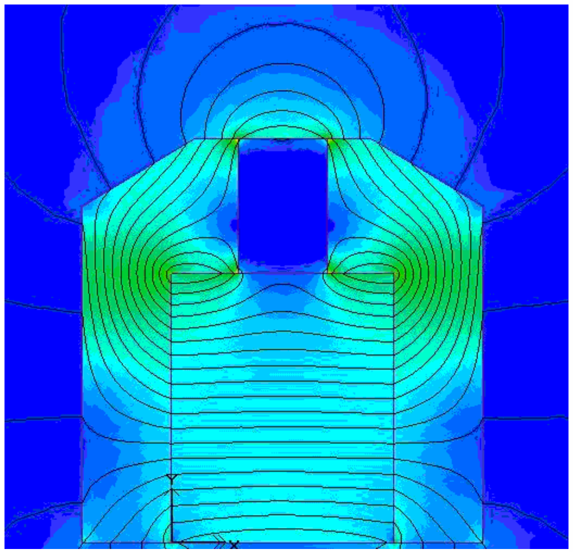
Generating mag. fields

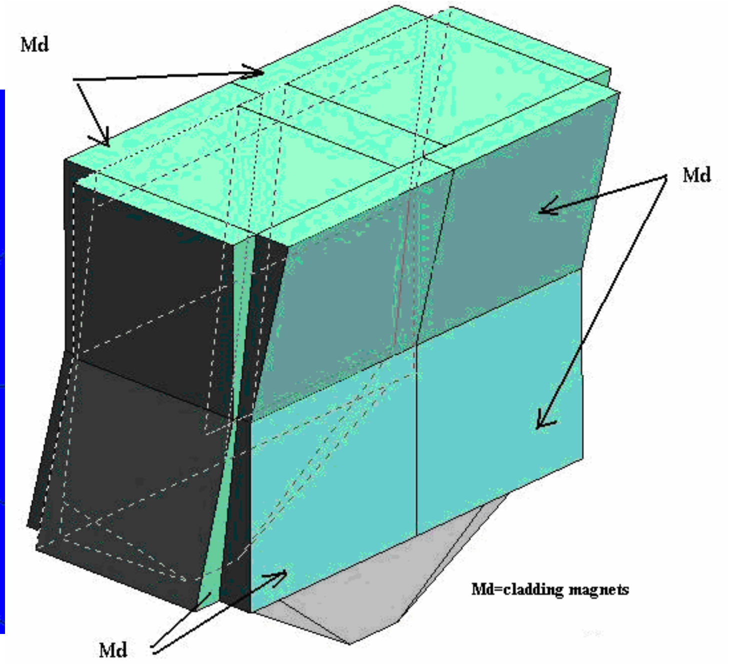
cladding magnets



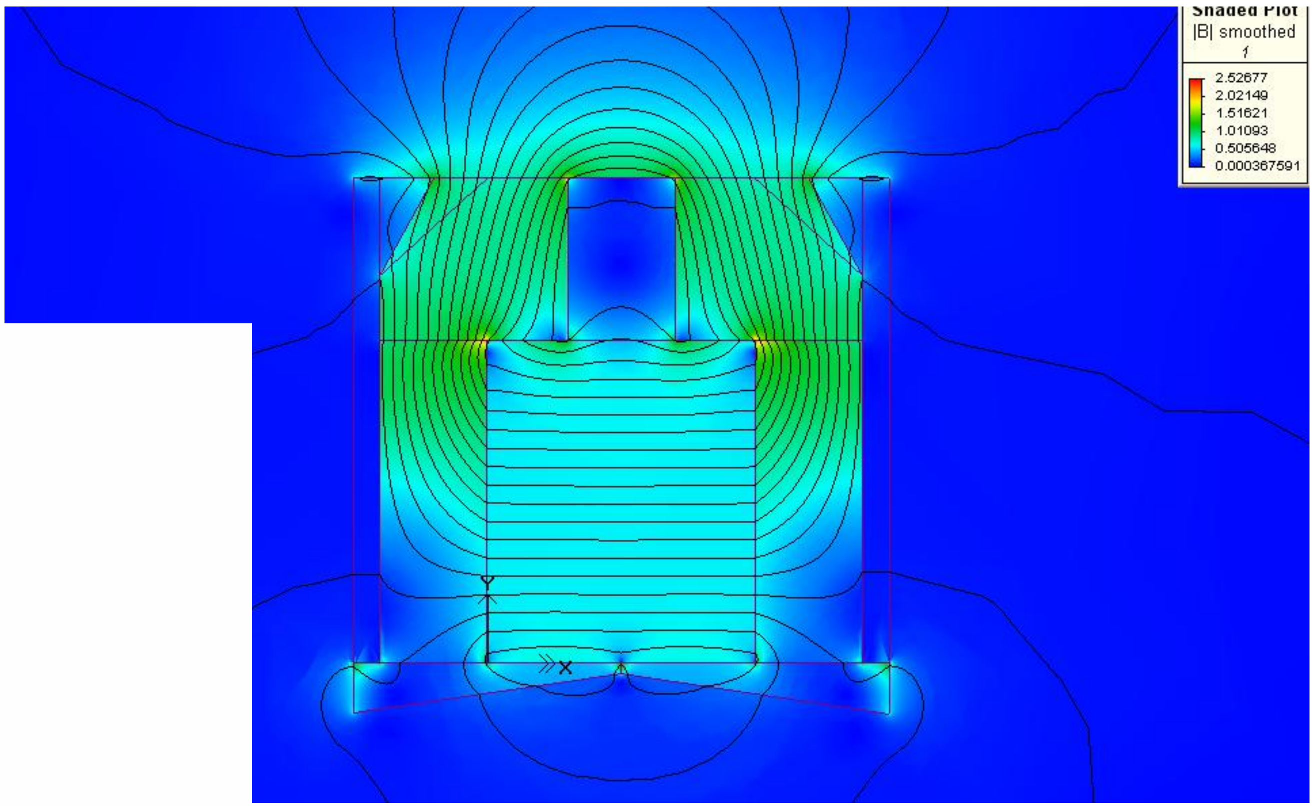


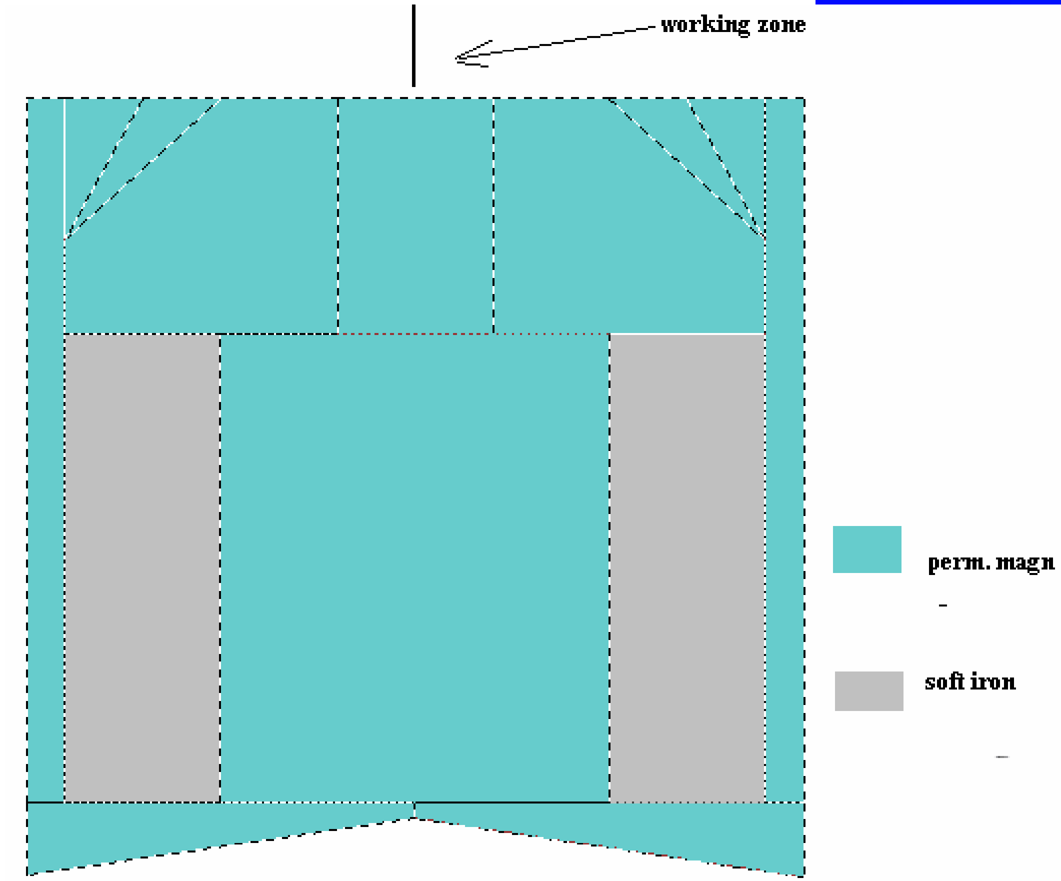






Cladding magnets/effects



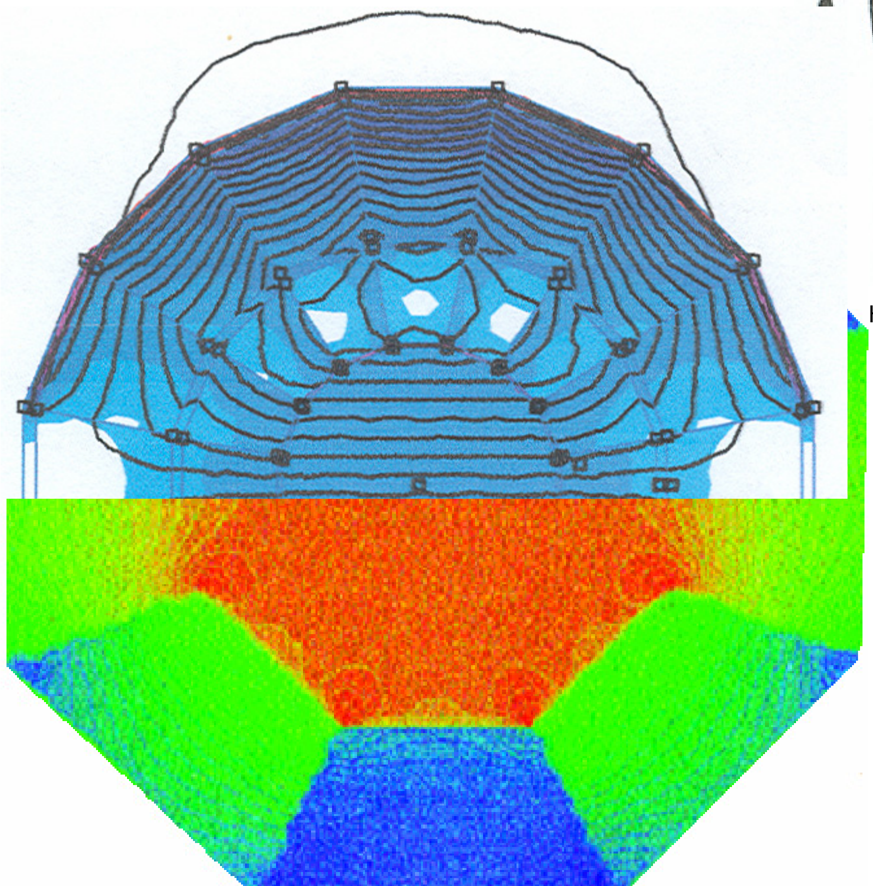


PM Applications

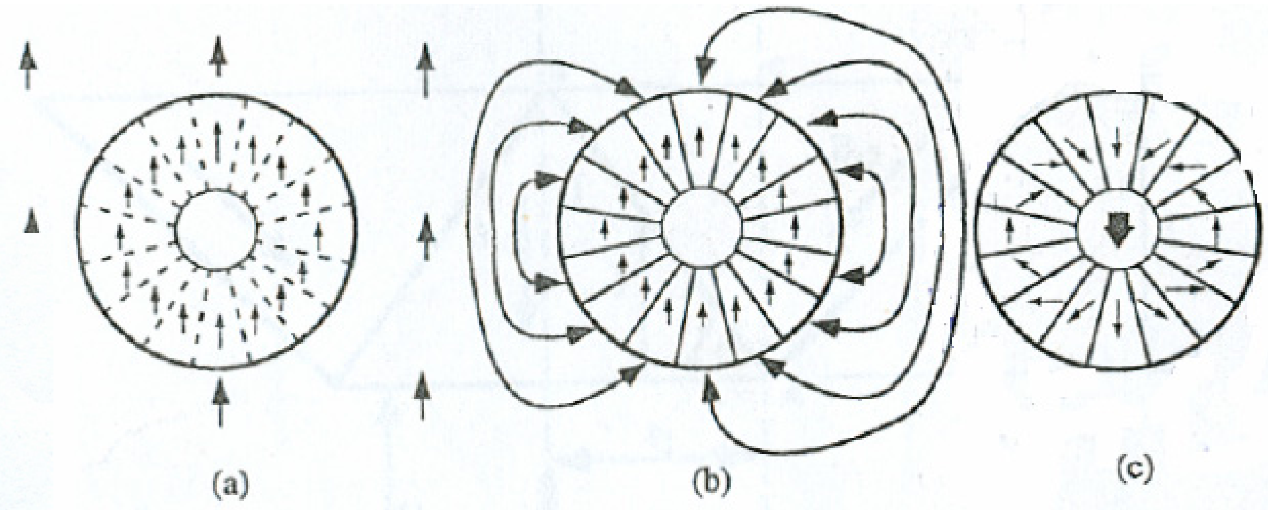
Generating mag. fields

$$B = B_r \frac{\sin(2\pi / N)}{2\pi / N} \ln(R_2 / R_1)$$

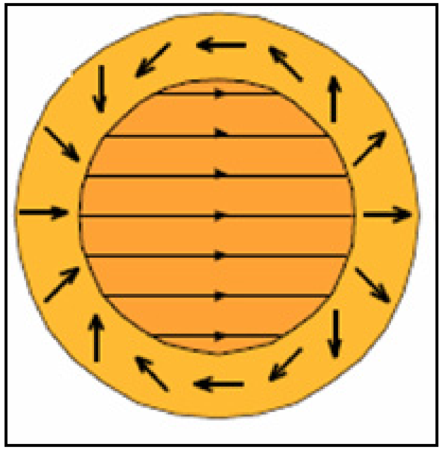
Hallbach (magic) cylinder

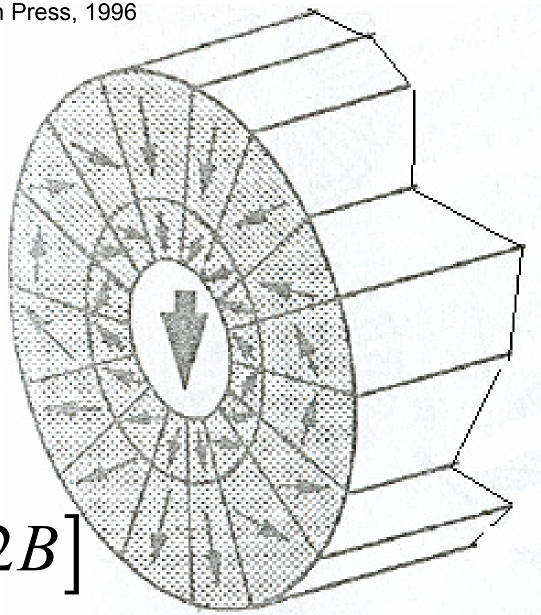


M Coey, D. White, the Ind. Phys. Sept.1998



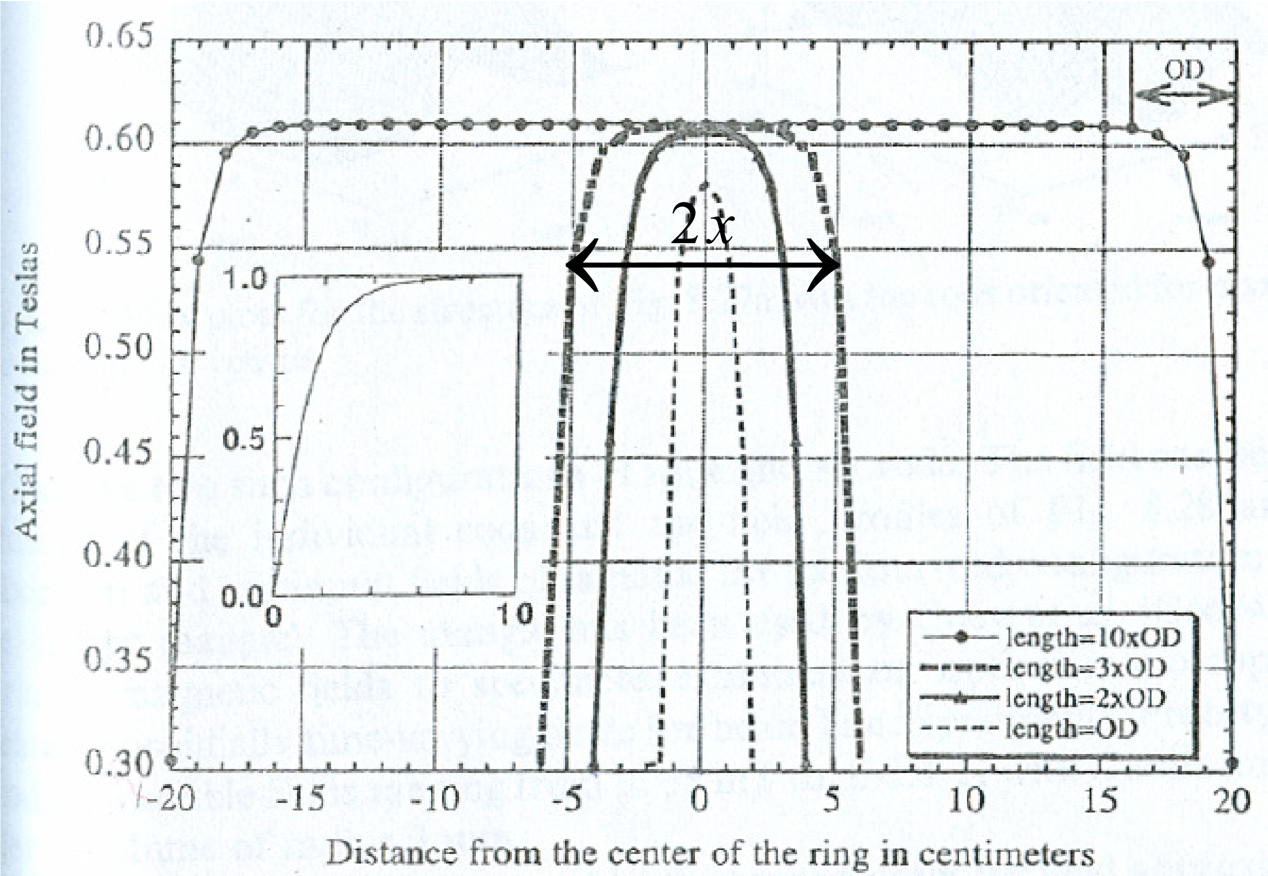
H. A. Leupold,Static Applications, Re-Fe PM, J.M. Coey, Clarondon Press, 1996



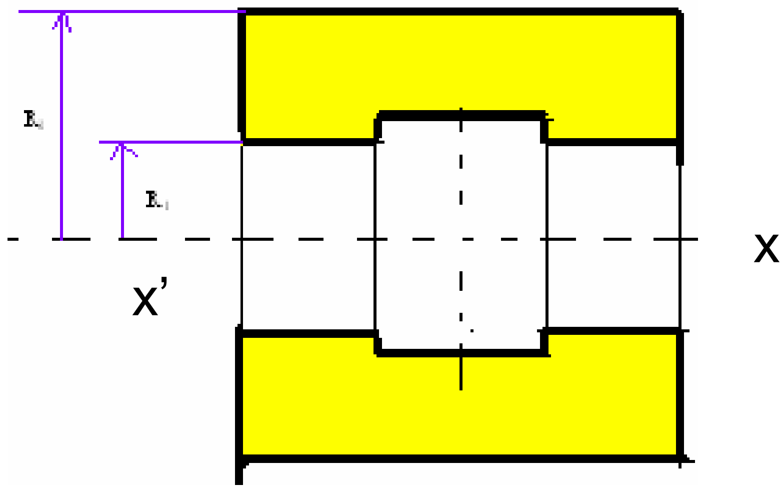


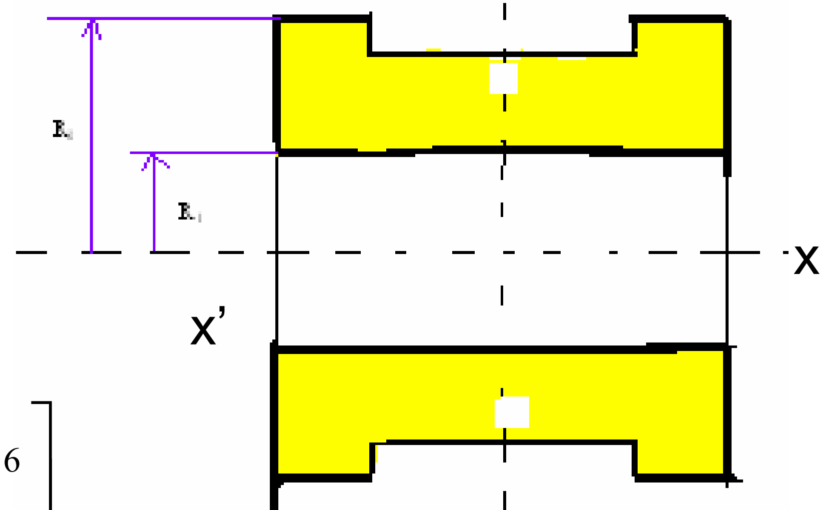
$$B_{\text{int}} \in \left[-2B, 2B\right]$$

Hallbach Cylinder



Inside notch



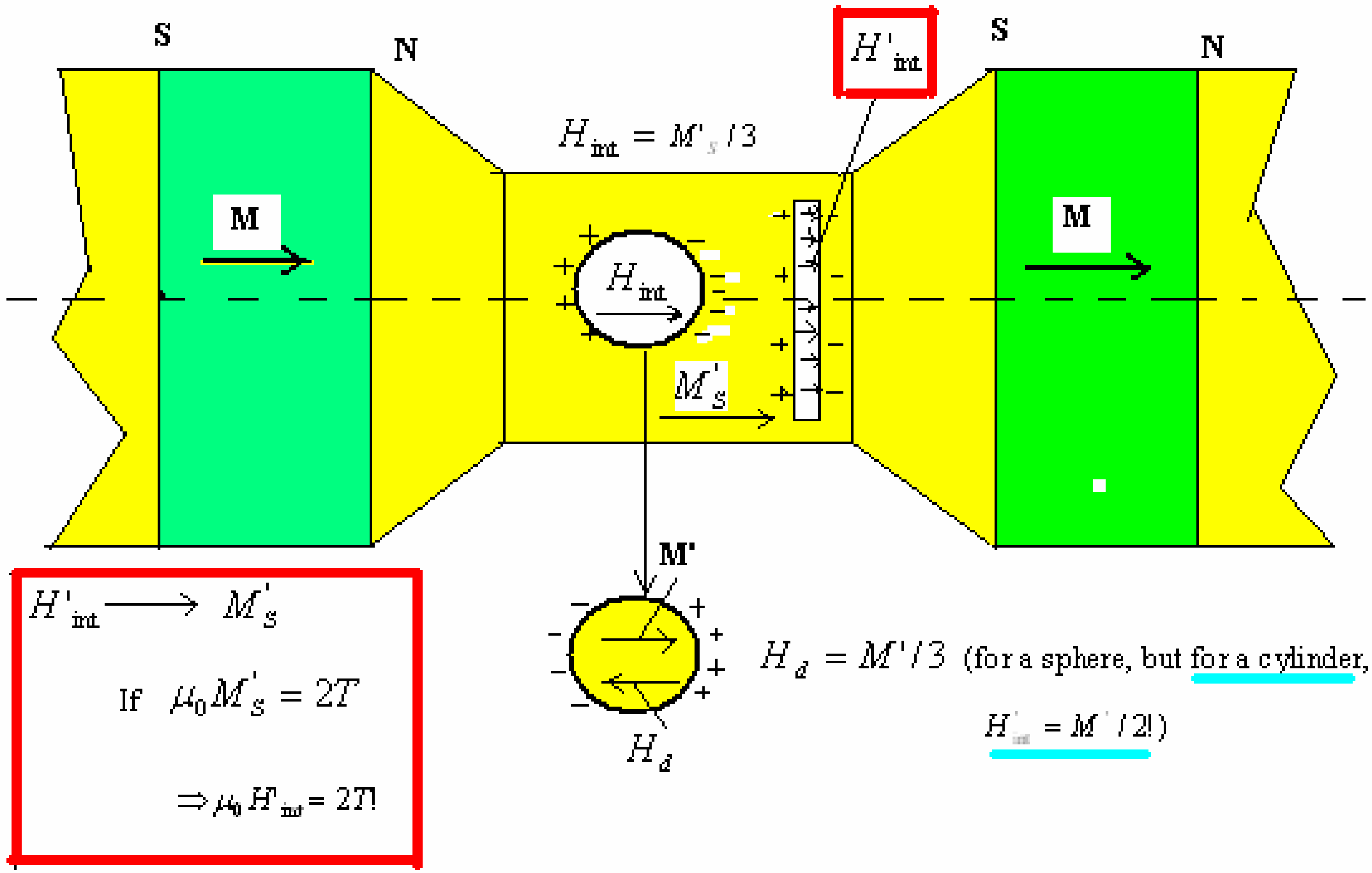


Outside notch

$$B(x) = B_{inside}(0)\left[1 - P_{inside}(geometry)\left(\frac{x}{R_1}\right)^6\right]$$

PM Applications

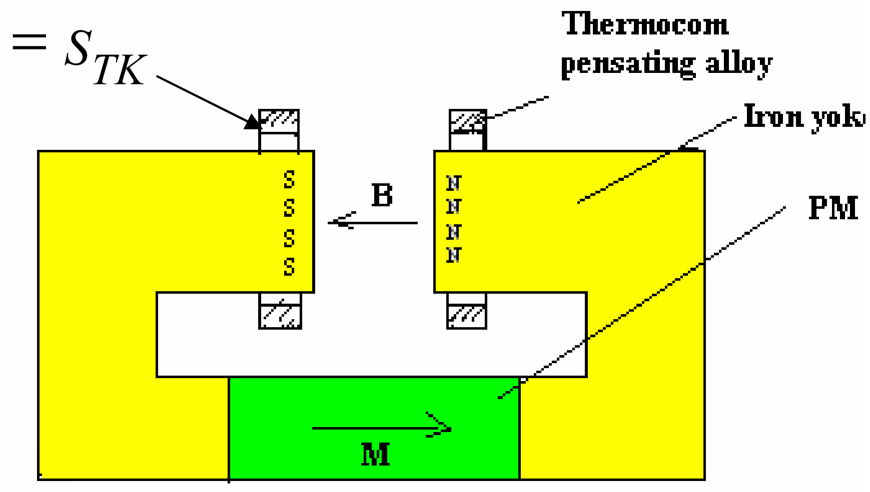
Magnetic Field



Applications: *PM powder pressing tools for anisotropic PM, built from ferromagnetic steels*

dB/dT=0 with thermocompensating alloys

$$\pi(R^2 - r^2) = S_{TK}$$



$$B_m(T) = B_{mo}\left(1 + \alpha_m (T - T_o)\right)$$

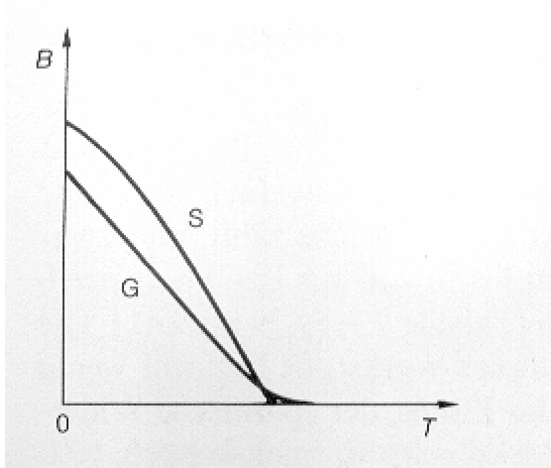
$$B_m S_m = BS + B_{TK} S_{TK}$$

$$S_m \frac{dB_m}{dT} = \frac{dB}{dT} \cdot S + S_{TK} \frac{dB_{TK}}{dT}$$

dB/dT = 0

$$S_{TK} \frac{dB_{TK}}{dT} = S_m B_m (T_o) \alpha_m$$

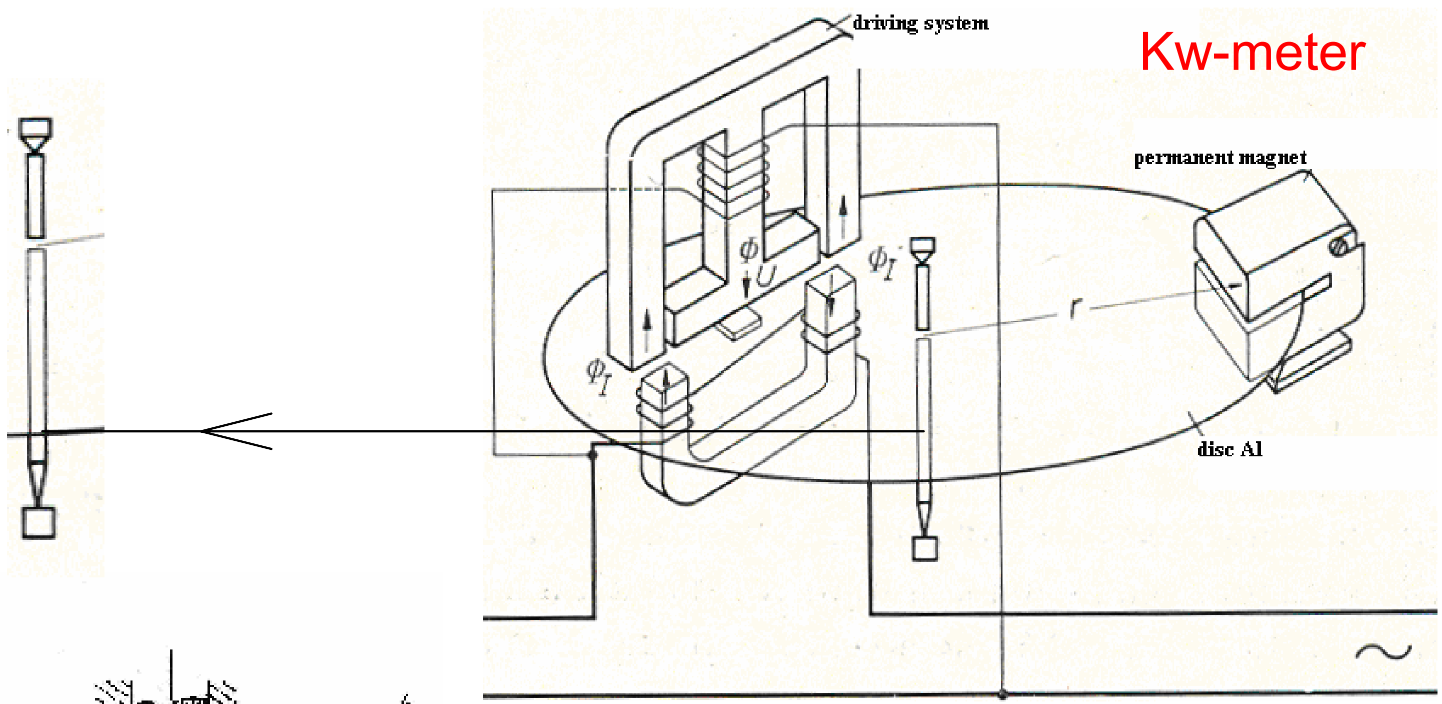
Thermoflux

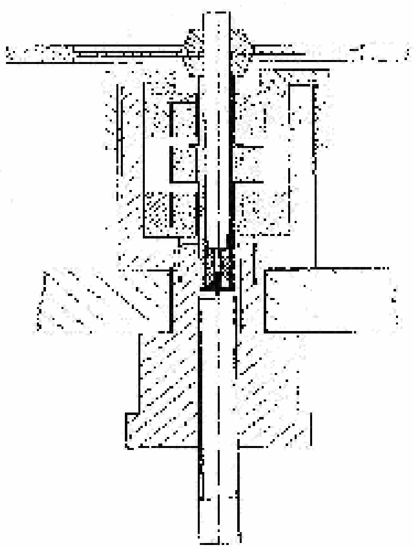


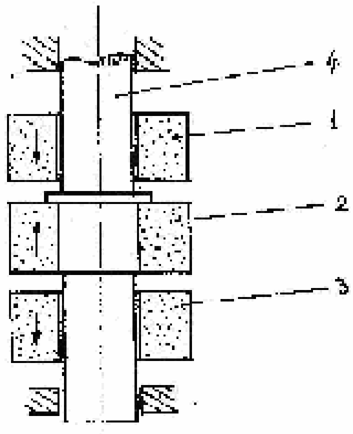
$$S_{TK} = \frac{S_m B_{mo} \alpha_m}{dB_{TK} / dT}$$

dB/dT=0

$$F_x = \frac{1}{2} B_{m1} \frac{dH_2}{dx} V_1$$





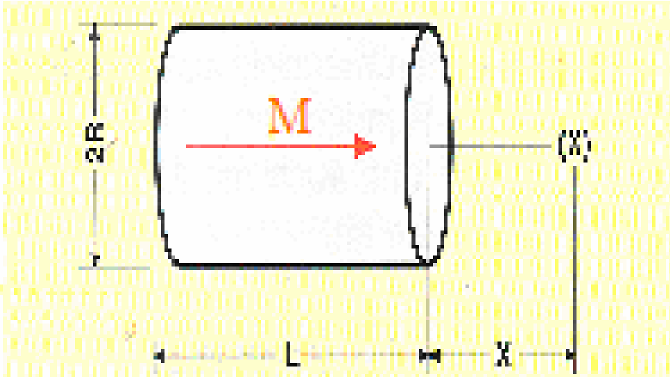


$$M_{break} \propto B^2 / \rho_{Al}$$

$$\rho_{Al}(T0 = \rho_{Al}(T_0)(1 + \alpha_{Al,T}(T - T_0))$$

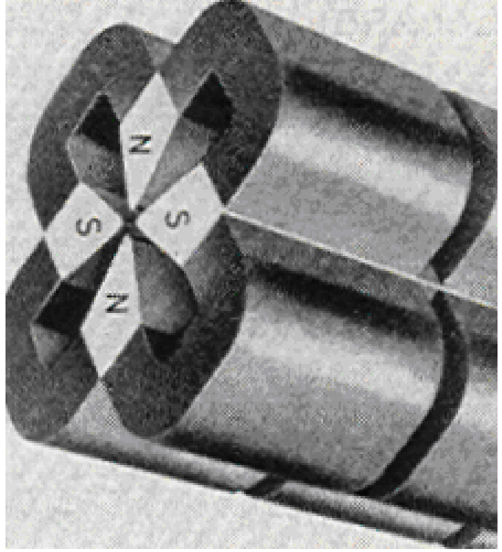
$$\alpha_{Al,T} = -0,4\% /^0 C$$

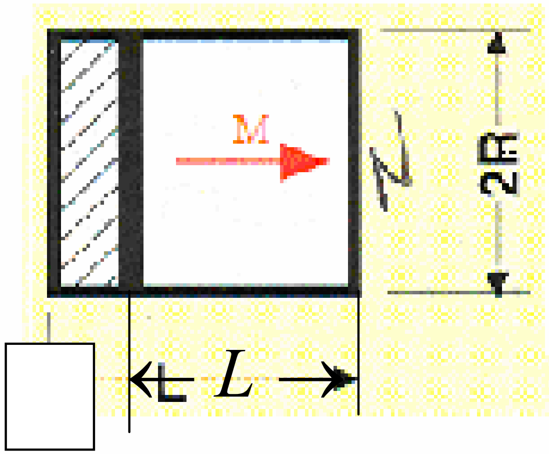
Field Generator



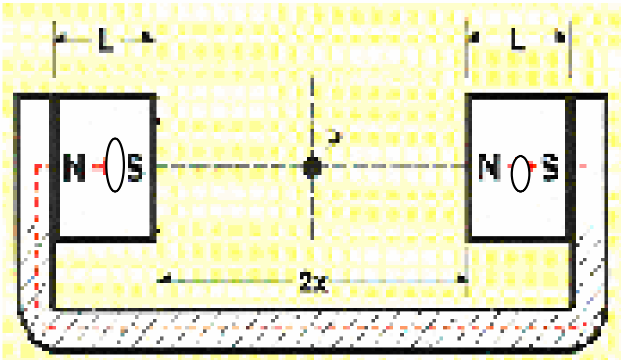
$$B_x(X) = \frac{B_r}{2}\left[\frac{L+X}{\sqrt{R^2+(L+X)^2}} - \frac{X}{\sqrt{R^2+X^2}}\right]$$

$$L \to \infty \ \& \ x = 0 \Rightarrow B_x = M_S/2!$$

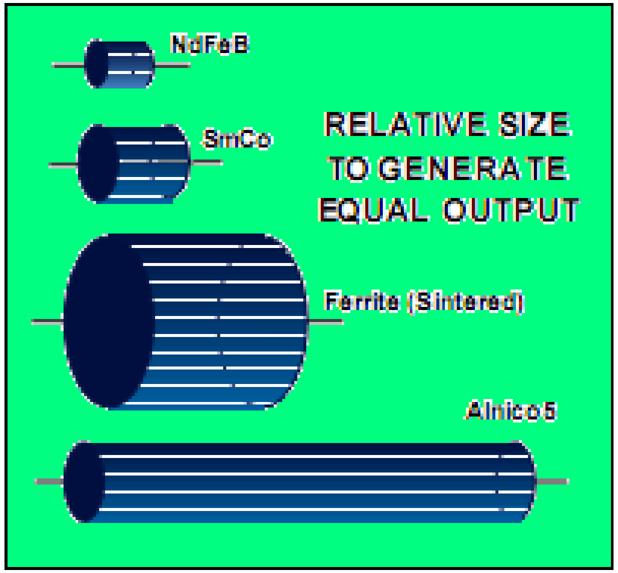




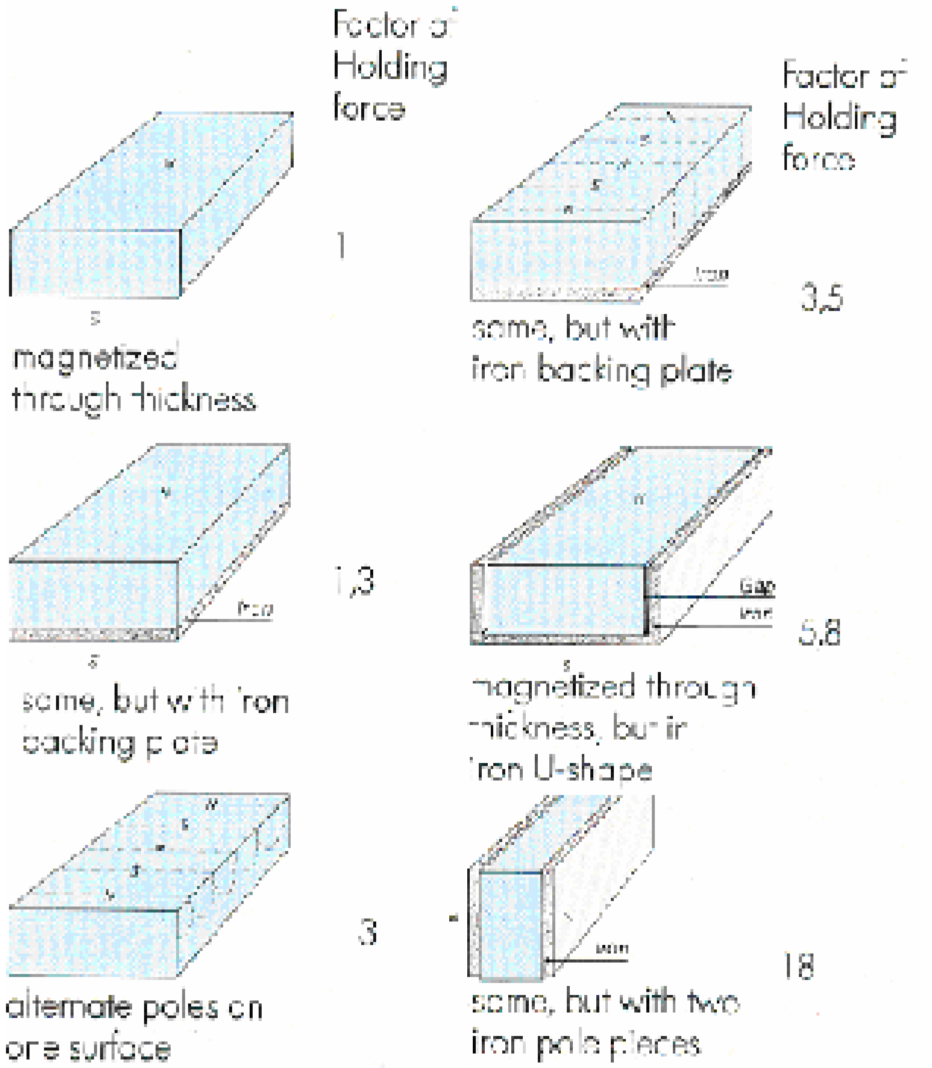
$$L \to 2L$$

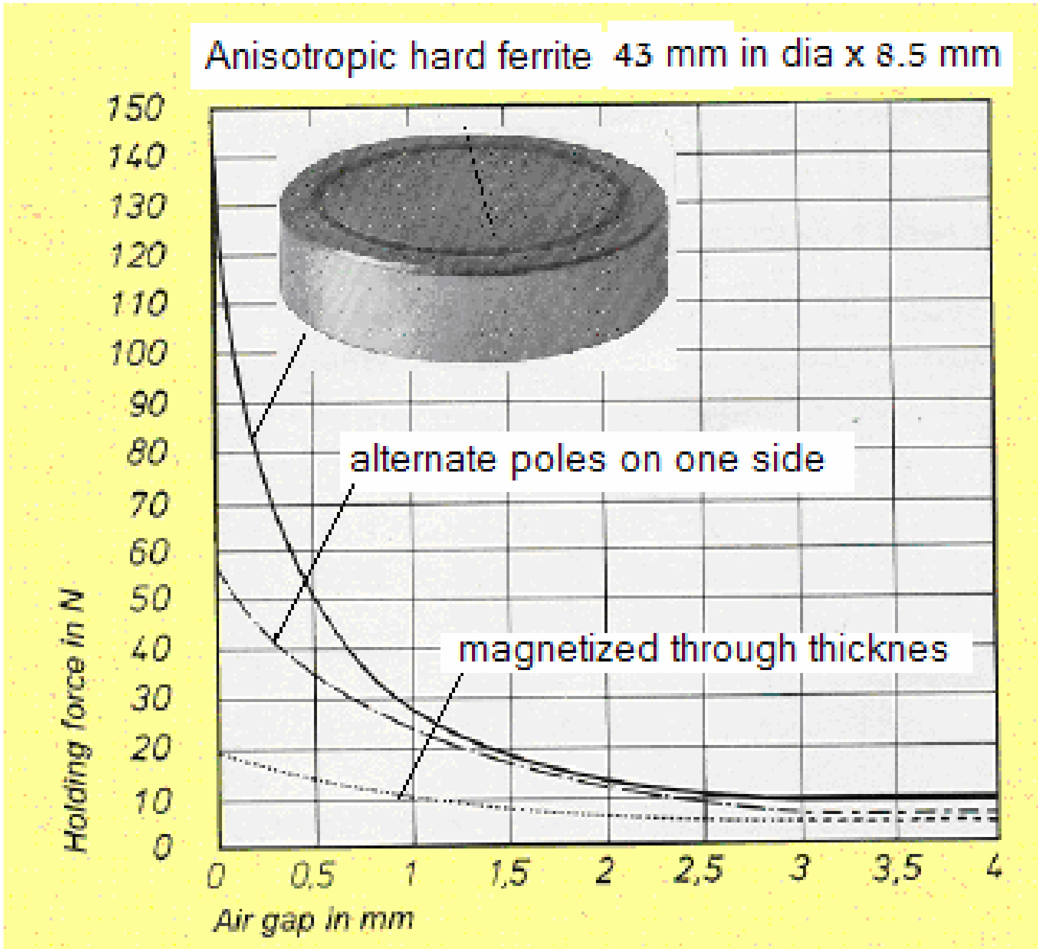


$$B_x \to 2B_x$$



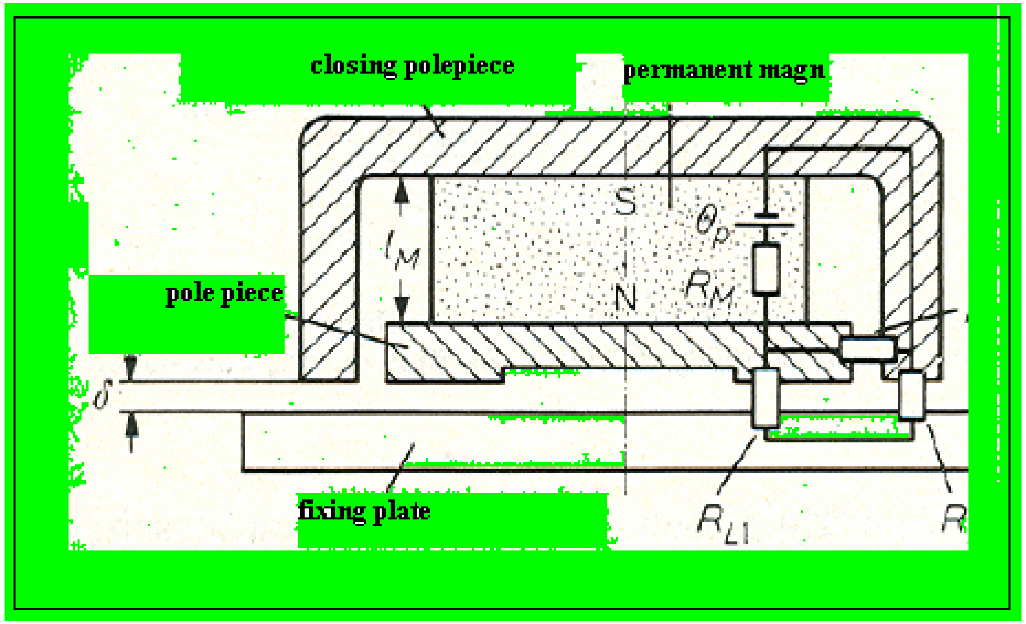
Holding magnets

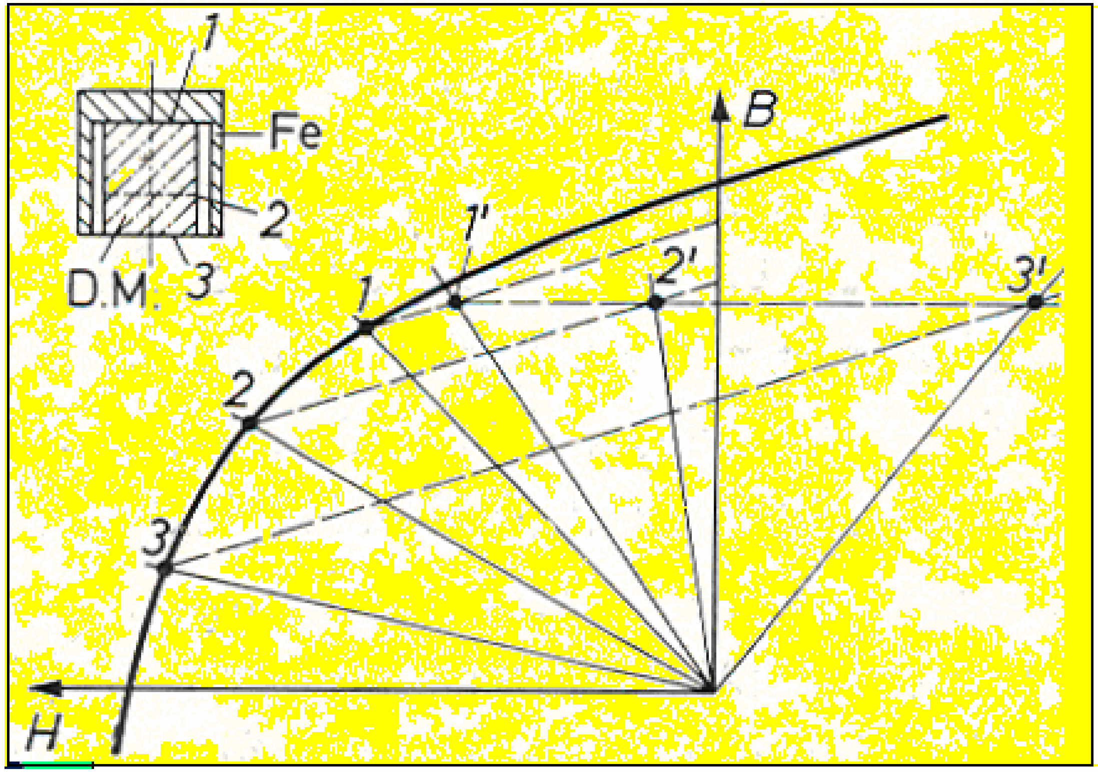




Holding magnets

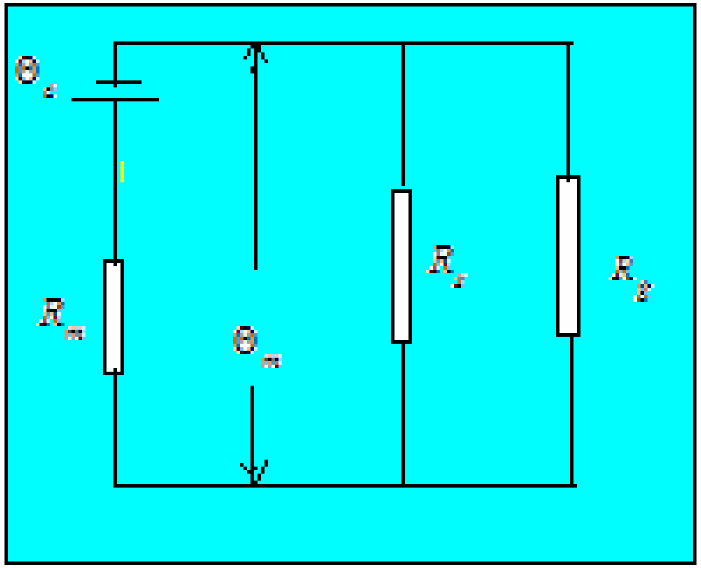
$$R = 1 / \Lambda$$

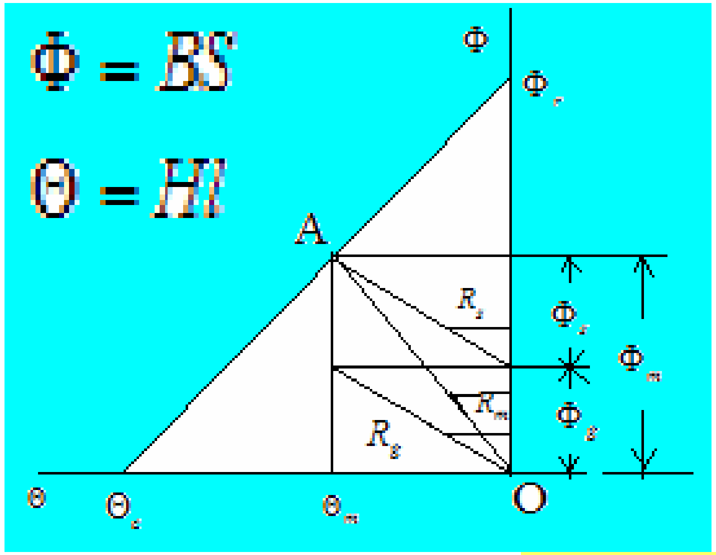




$$F = A \frac{B_L^2}{2\mu_0}$$

$\Phi - \Theta$ -Demagnetisation curve





optimal

$$R_{\text{int}} \equiv R_{ext} = \frac{R_g R_s}{R_g + R_s}$$

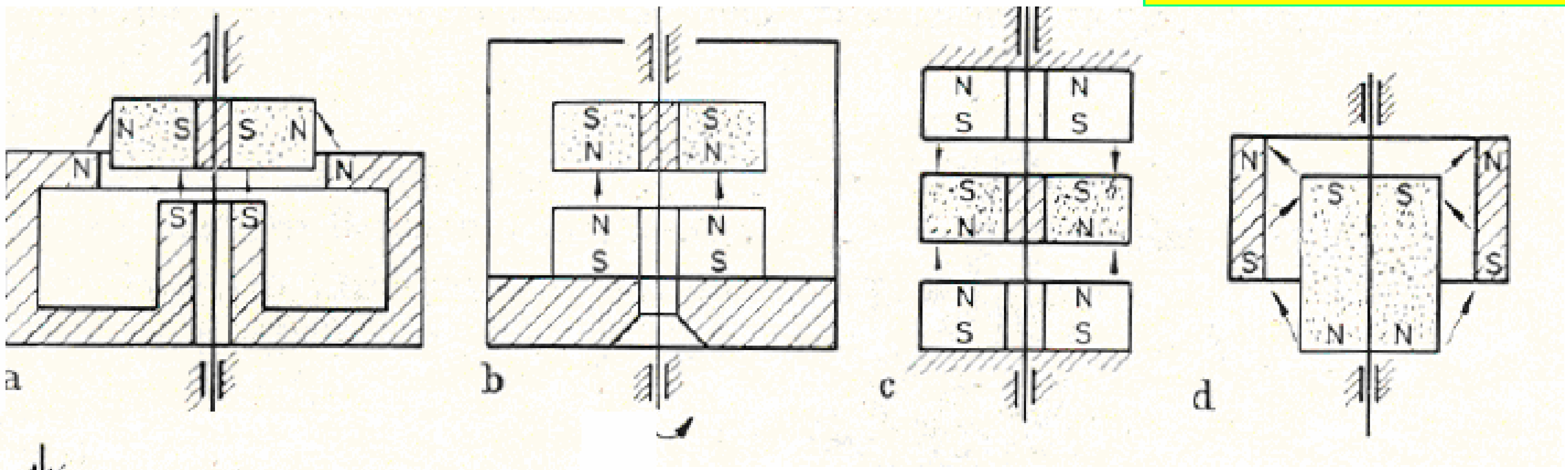
$$\Phi_m = B_m S_m = B_g S_g + B_s S_s = \Phi_g + \Phi_s$$

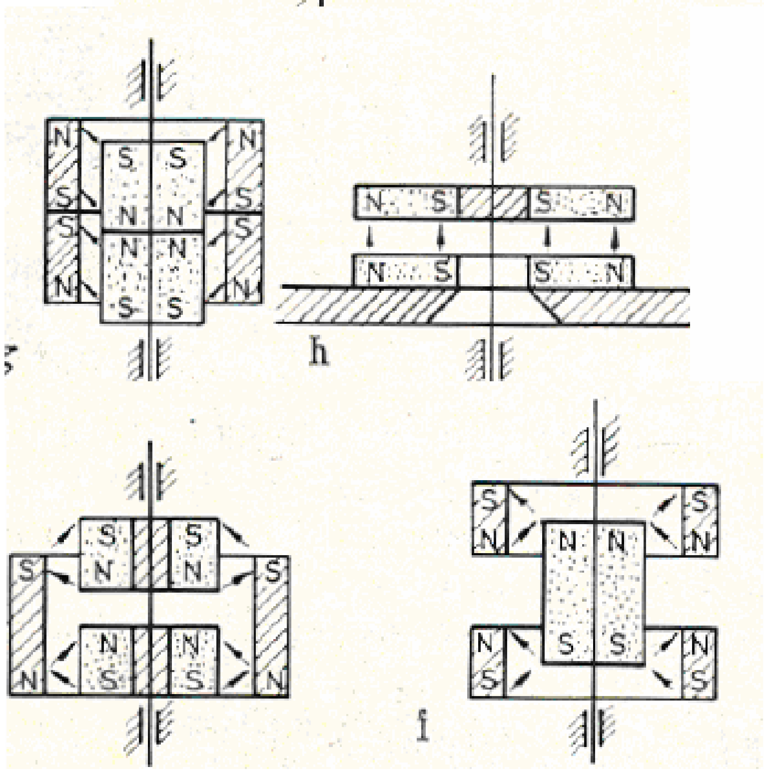
$$\Theta_m = H_m l_m = H_g l_g = \Theta_g = \Theta_s = R_m \Phi_m$$

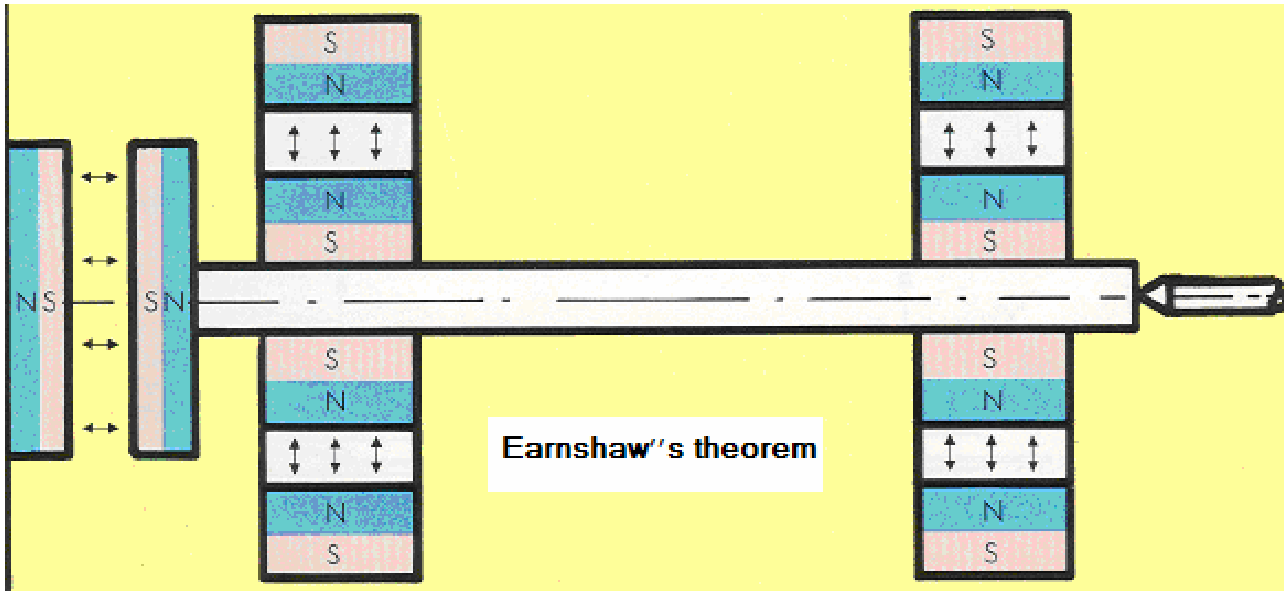
$$tg\alpha = \frac{\Theta_m}{\Phi_m} = R_m = \frac{l_m}{S_m \lambda_m} = \frac{l_m}{S_m B_m / H_m} = \frac{1}{\Lambda_m}$$

Bearings

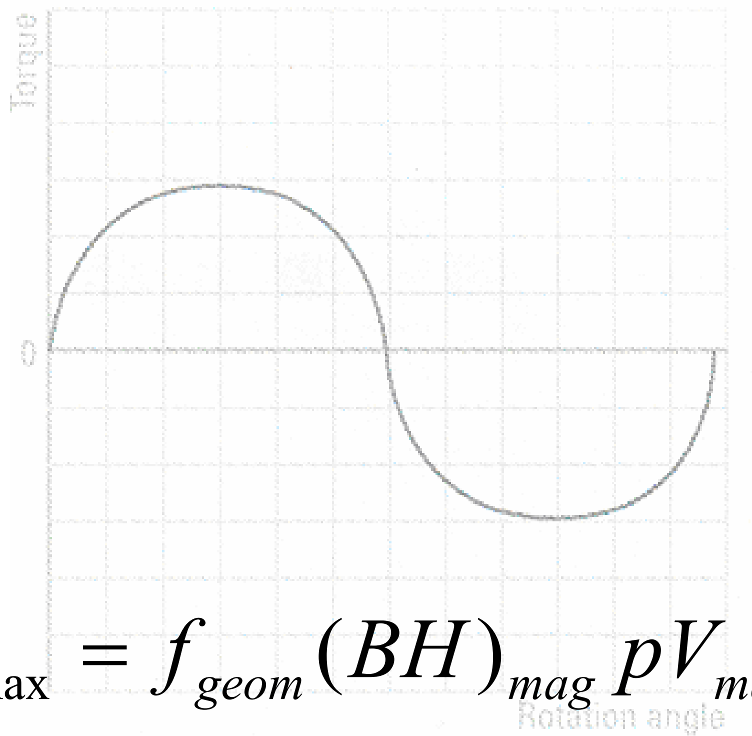
$$F_x = \frac{1}{2} B_{m1} \frac{dH_2}{dx} V_1$$





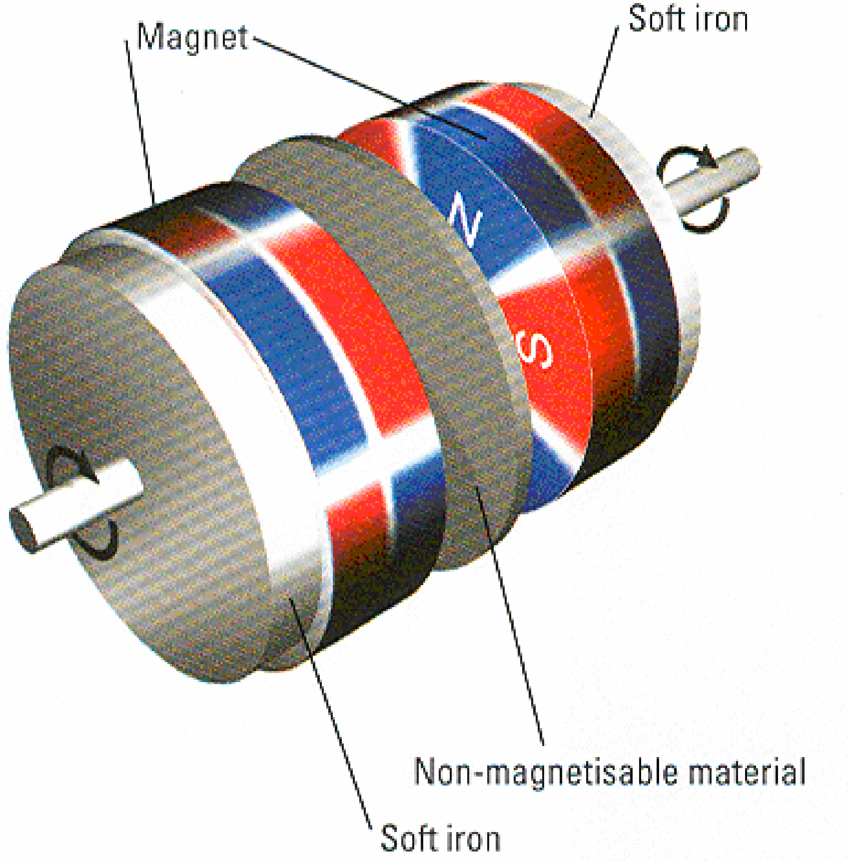


Axial coupling

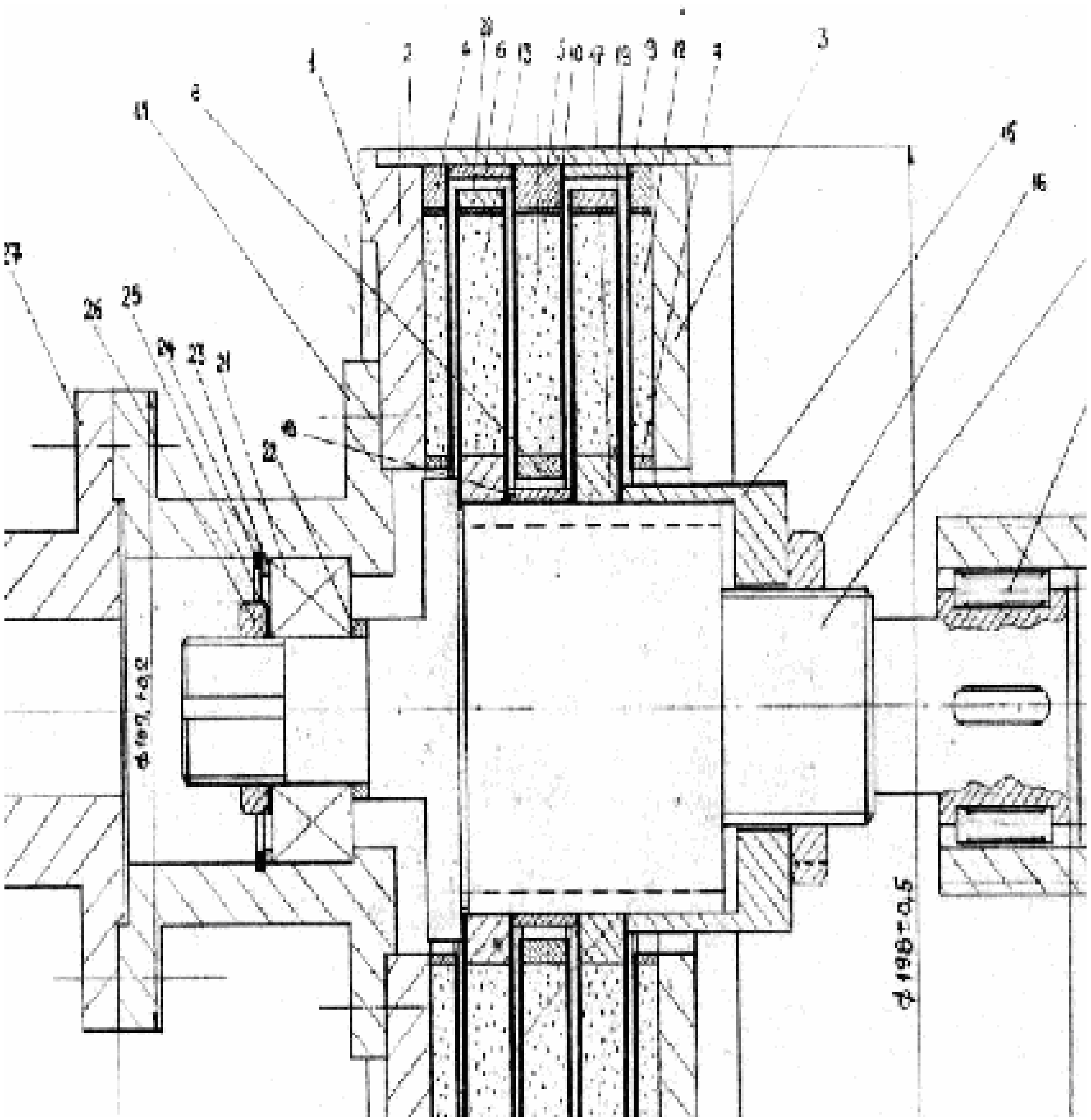


$$M_{\max} = f_{geom}(BH)_{mag}\, pV_{mag}$$

Disc coupling

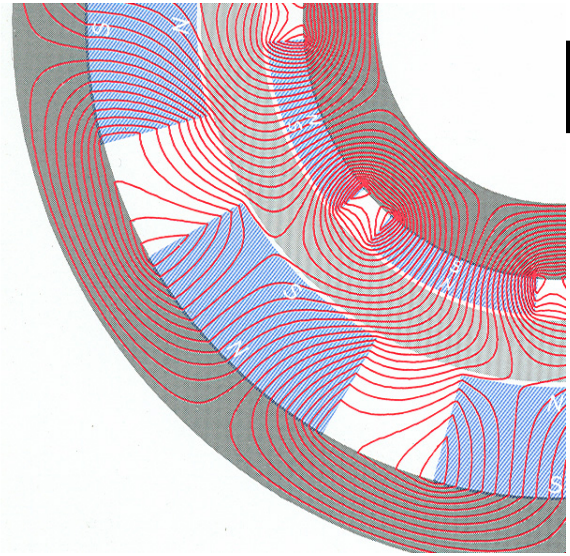


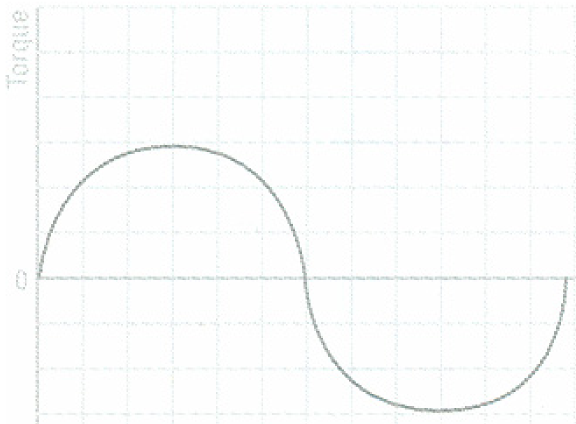
Multiple Radial Coupling

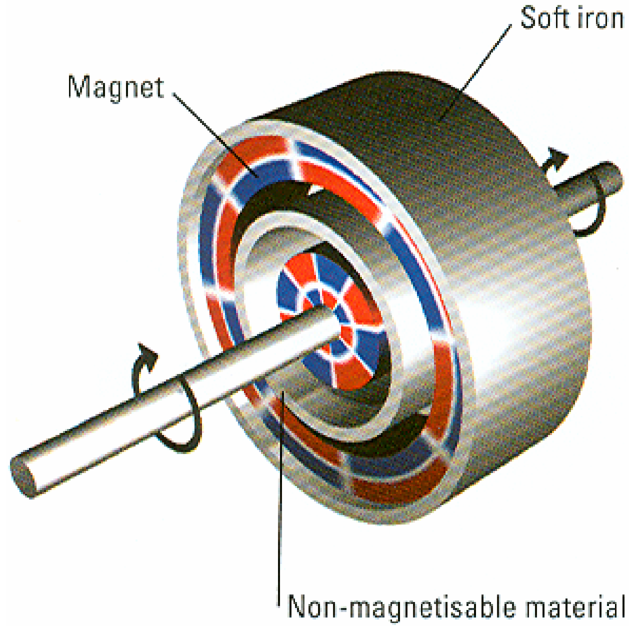


$$T \sim 10^2 - n10^3\, Nm$$

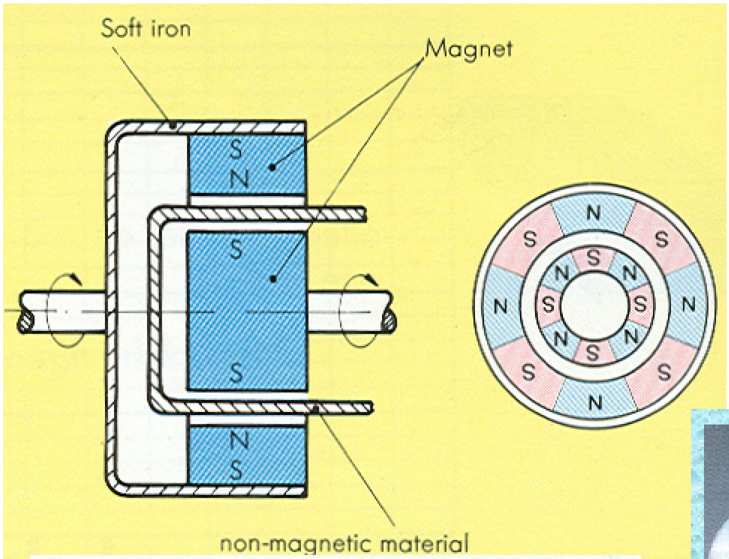
Radial coupling



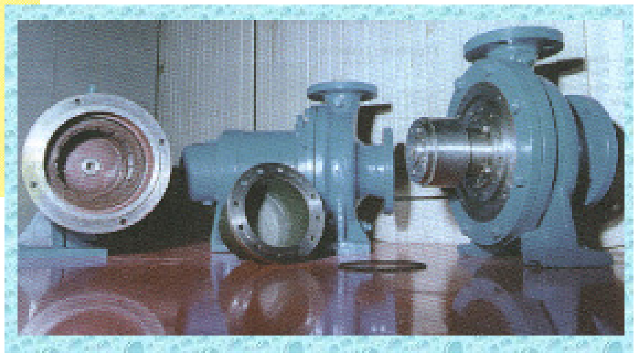


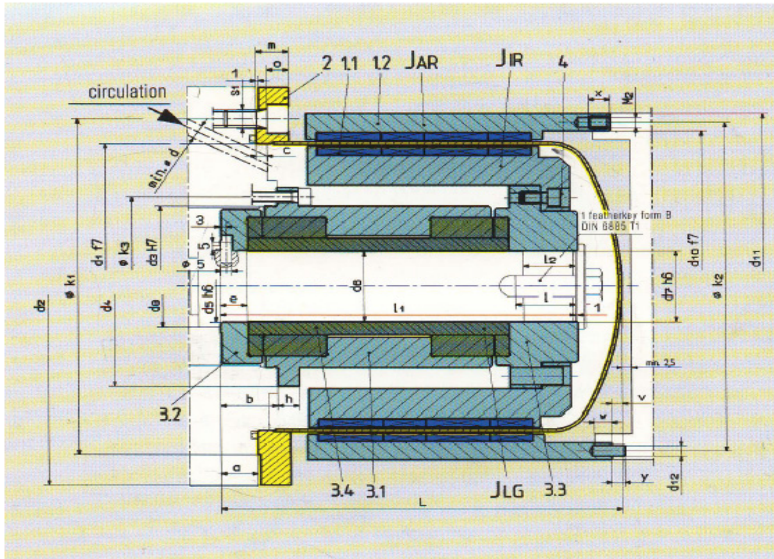


$$M_{max} \propto B_L^2 R^2 L$$

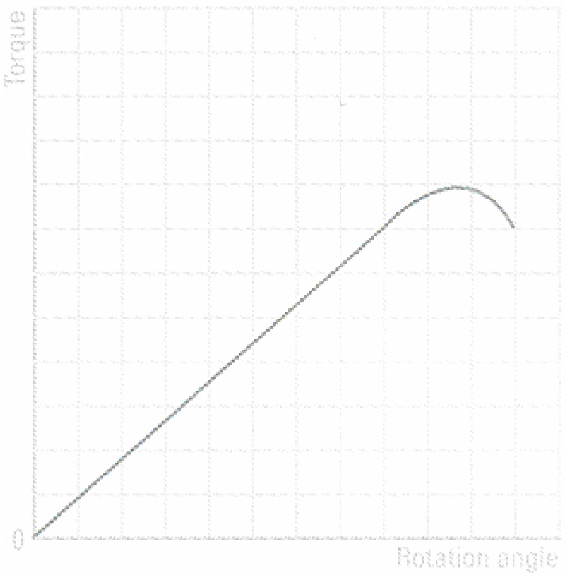


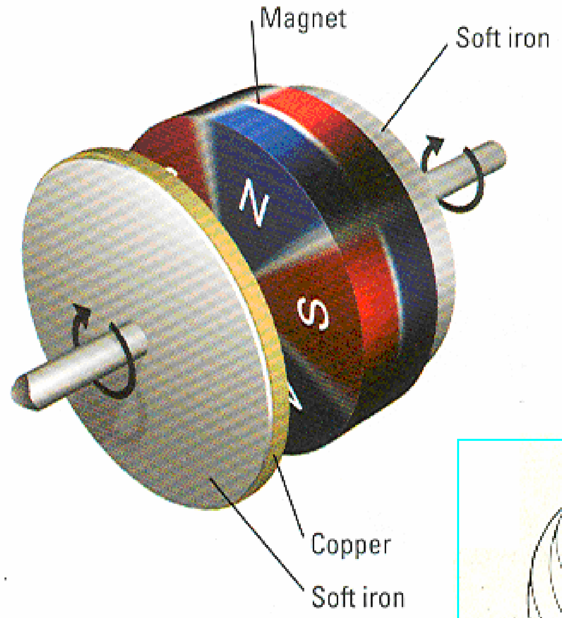
Schematic design for a concentric ring coupling





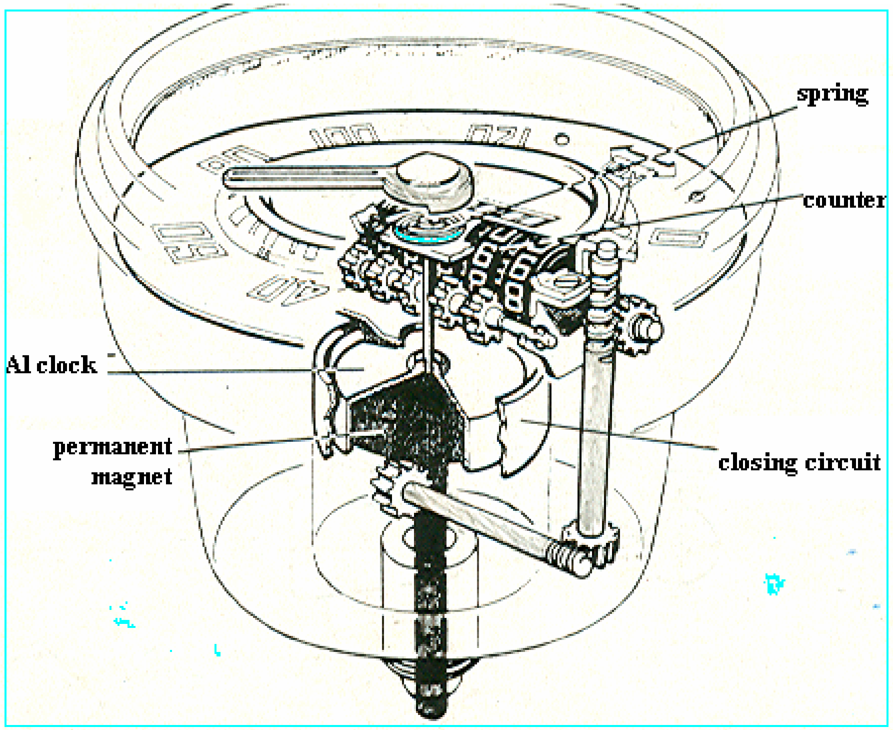
Eddy current coupling





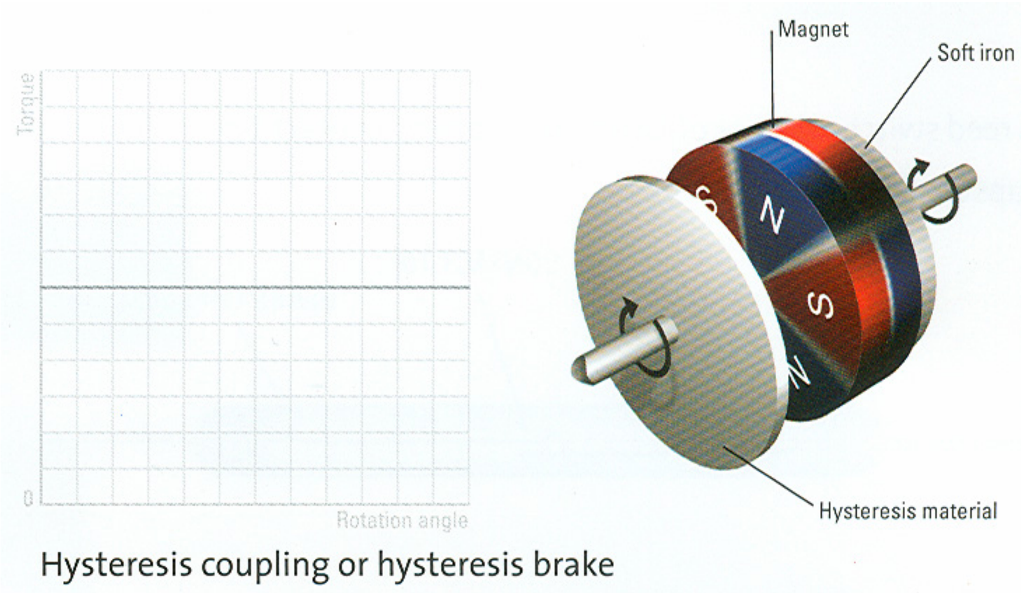
Eddy current coupling and brake

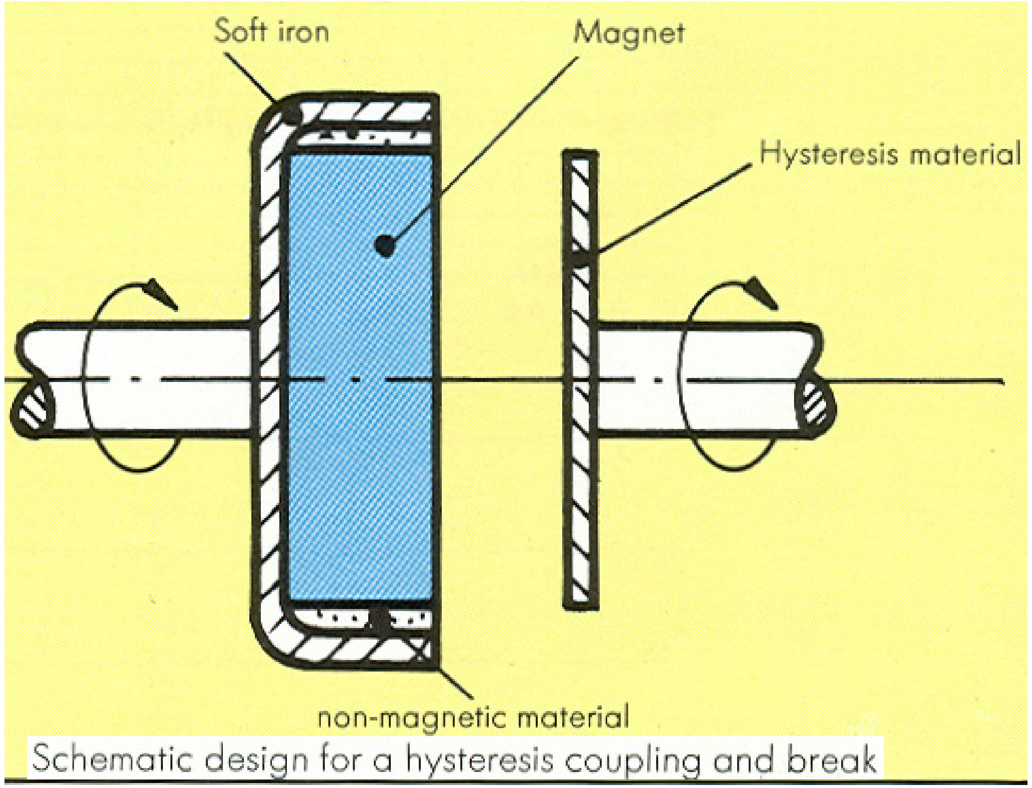
Tahometer



$$M_{max} \propto R^2 B_L^2 / \rho$$

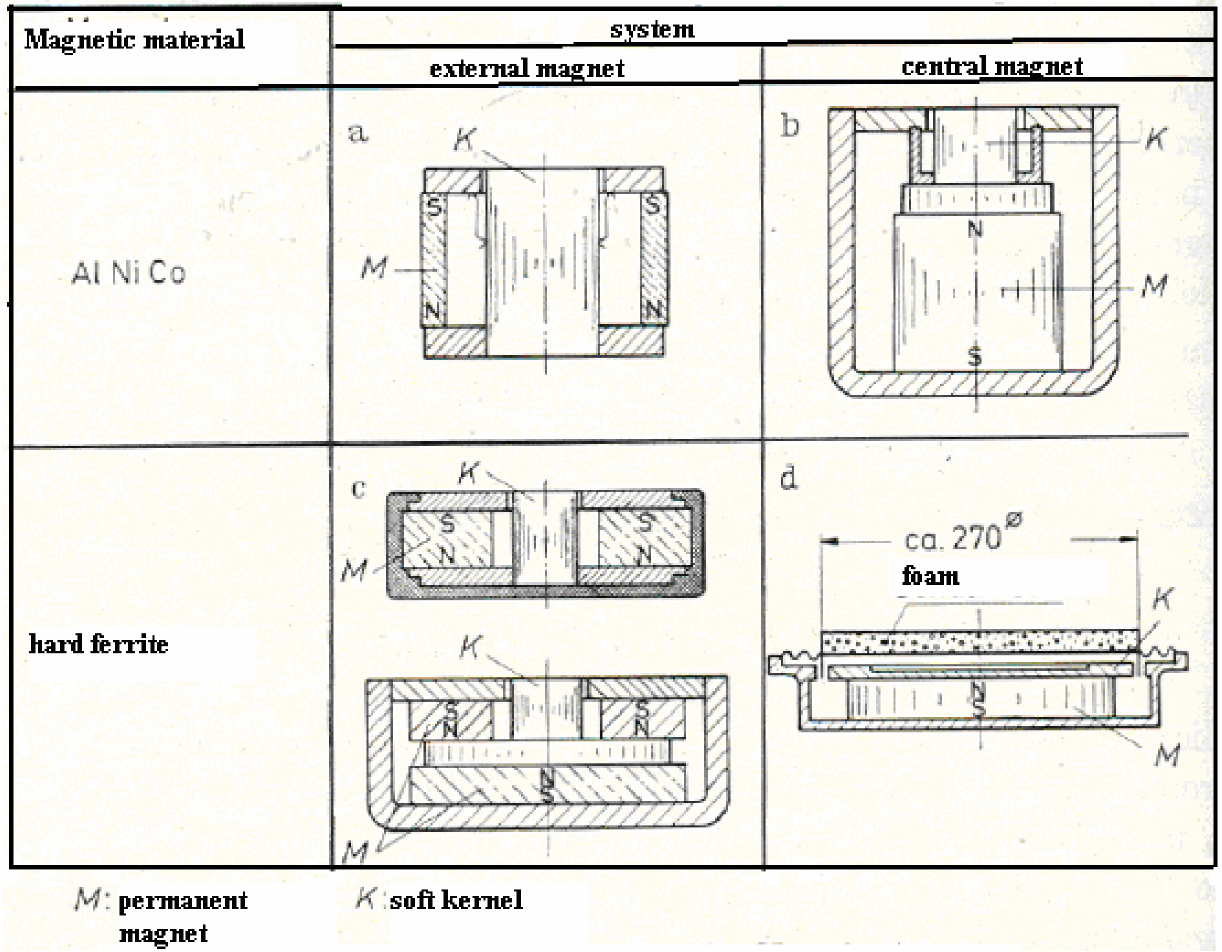
Hysterezis couplings

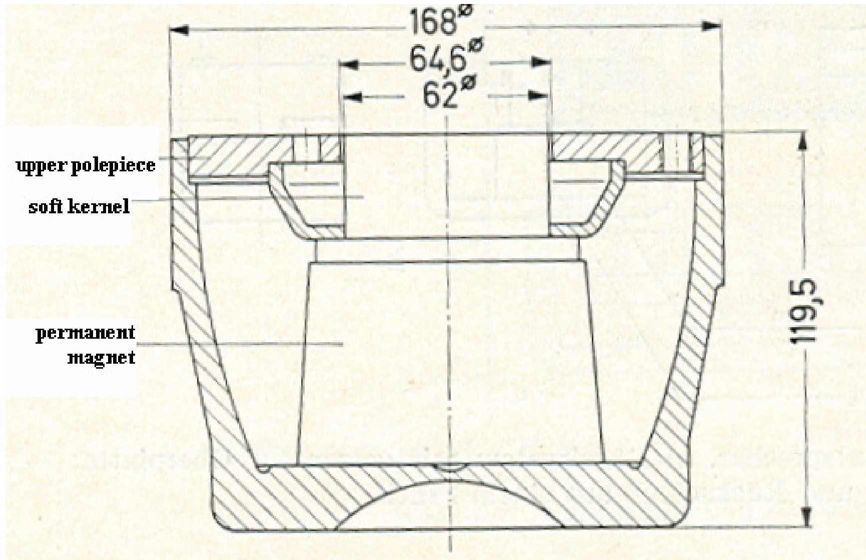




$$M \sim pV_{hyst} \int HdB$$

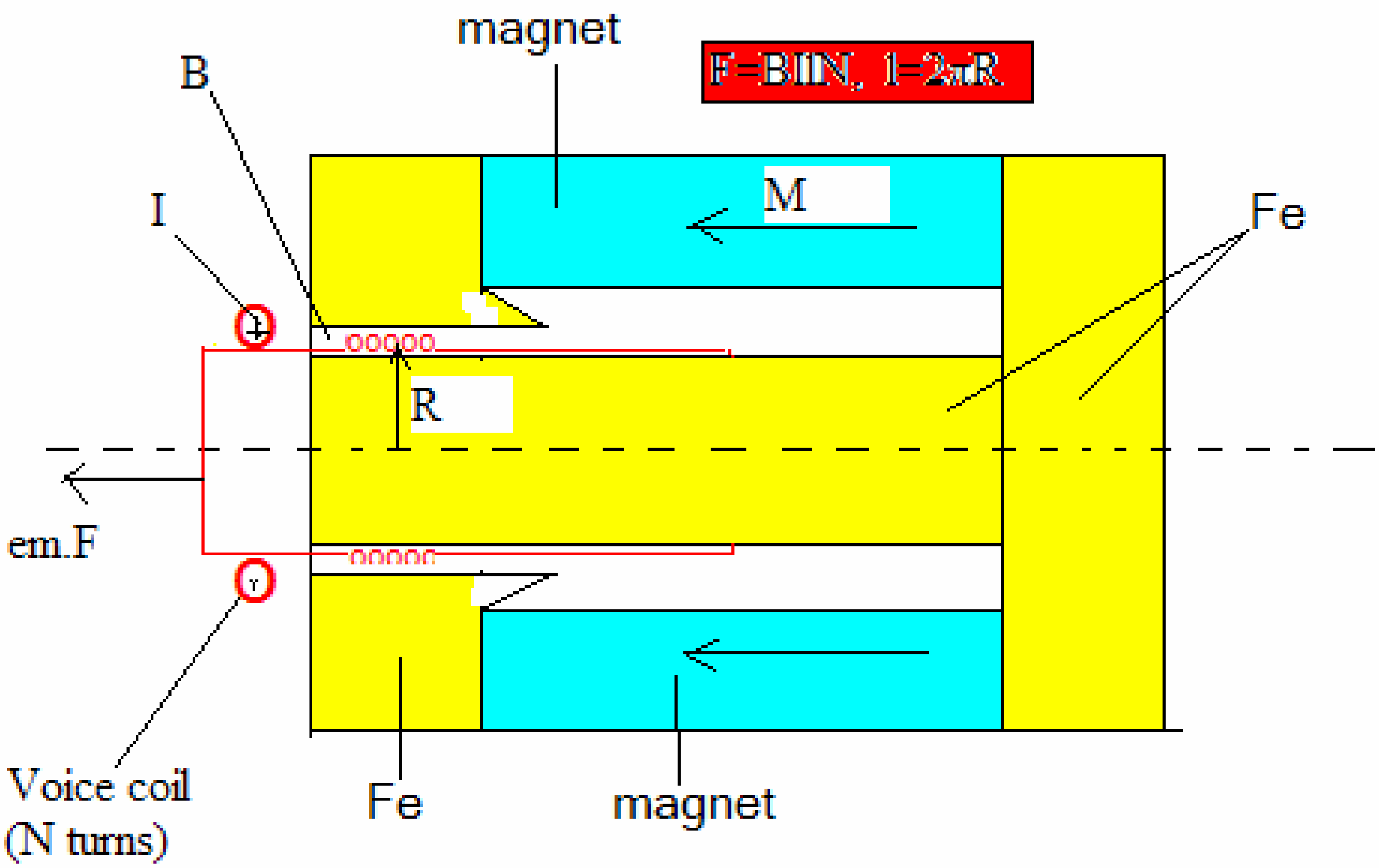
Loudspeaker



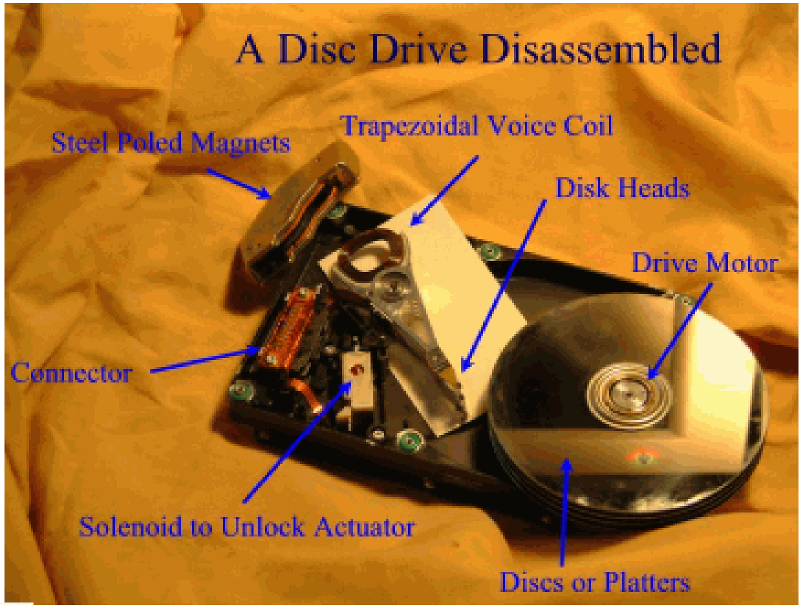


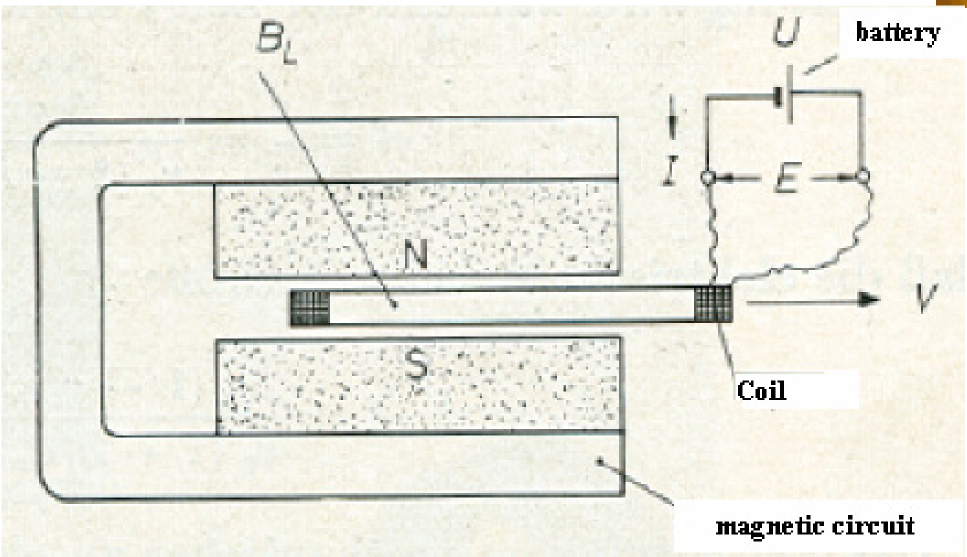
$$W_g = \frac{1}{2}(B_m H_m) V_m \frac{1}{\gamma\sigma}$$

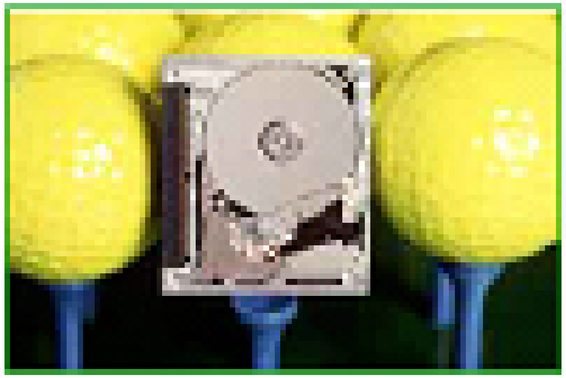
Voice coil motors



Voice coil motors

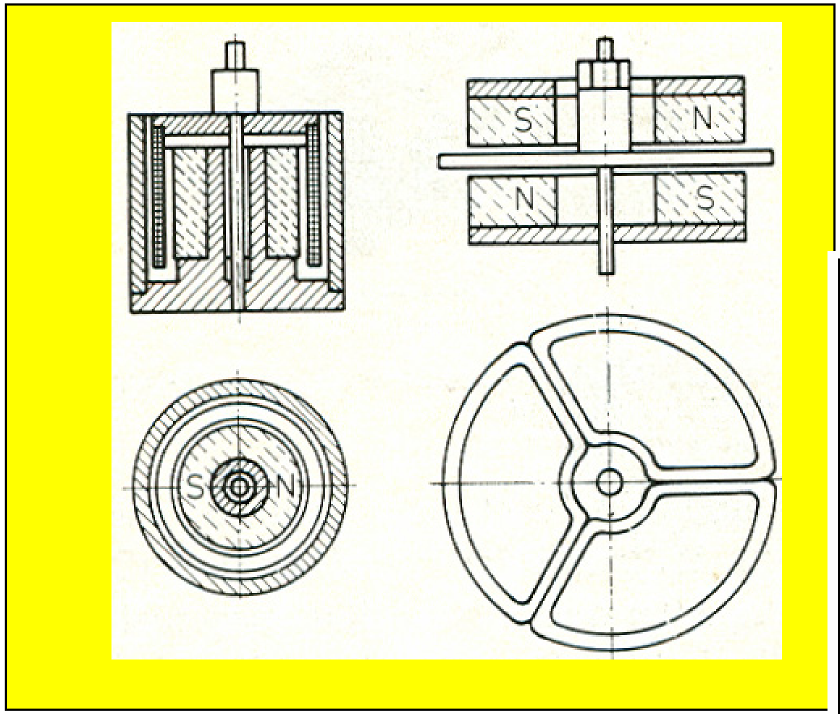


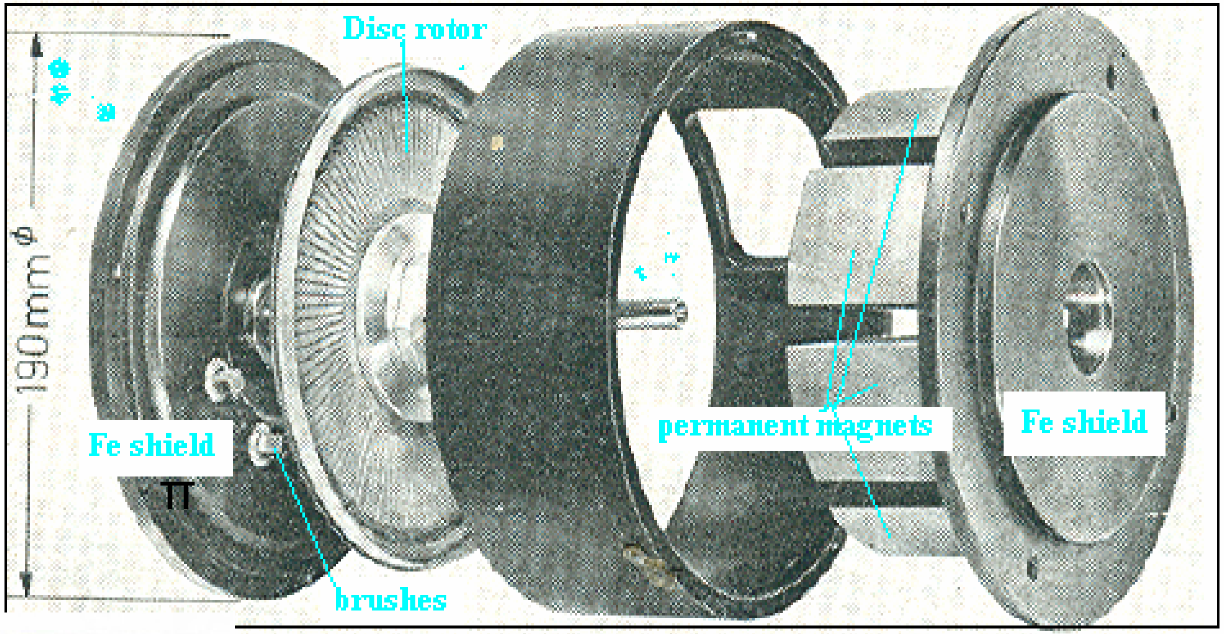




The world's smallest hard disk drive

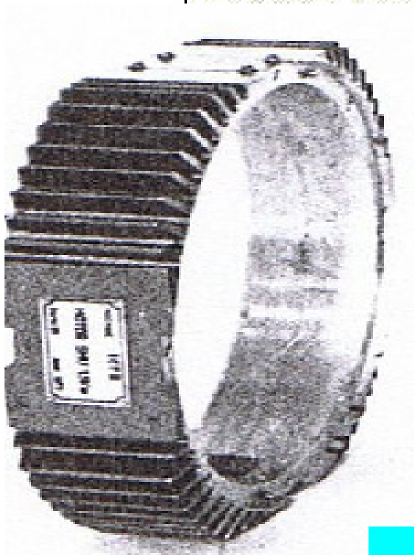
Motors with Nonferrous rotors

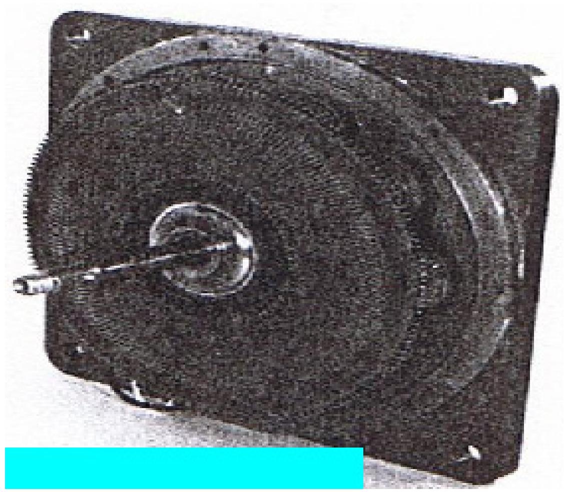




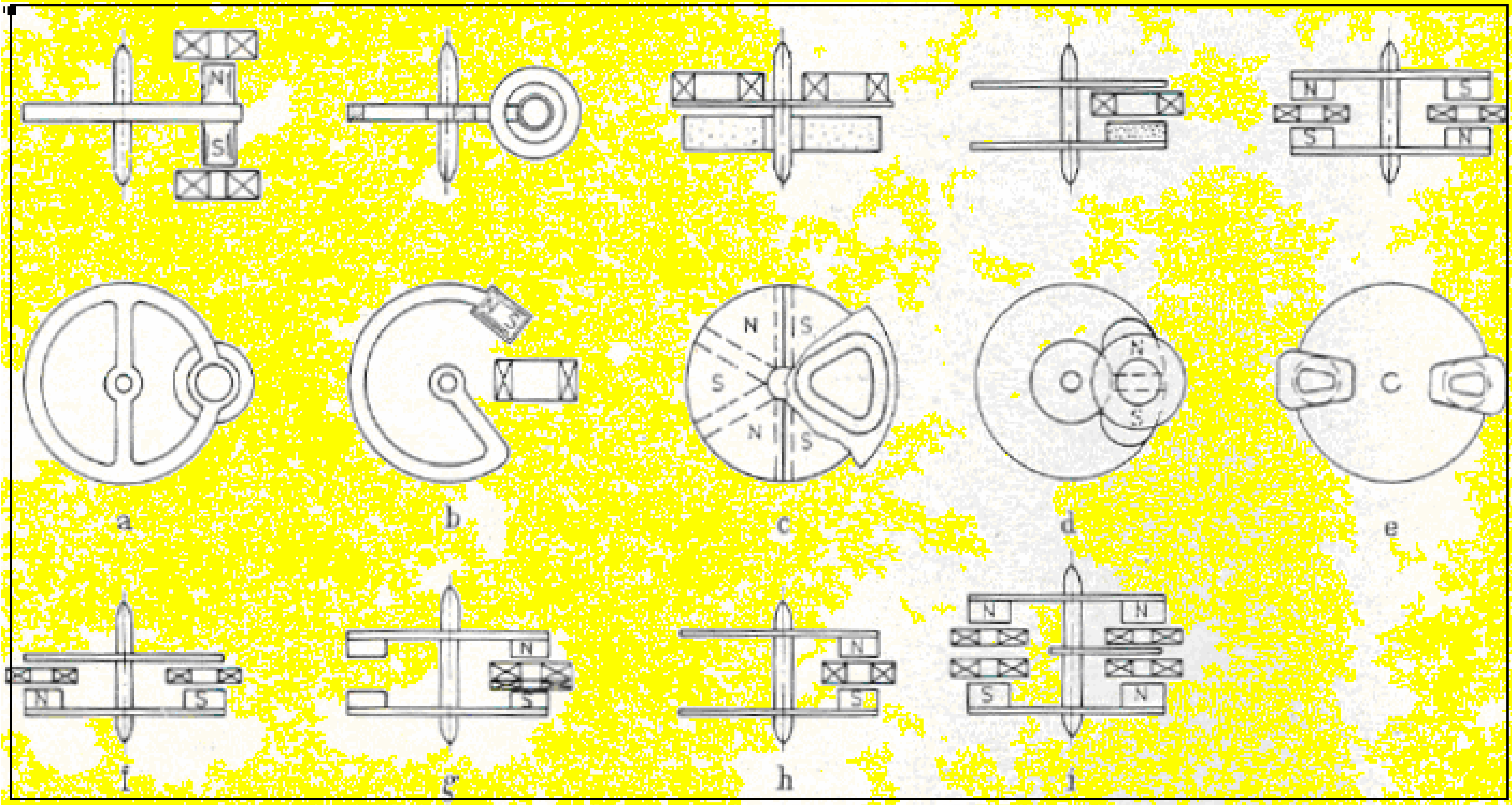
SEA/France

ICPE-1980

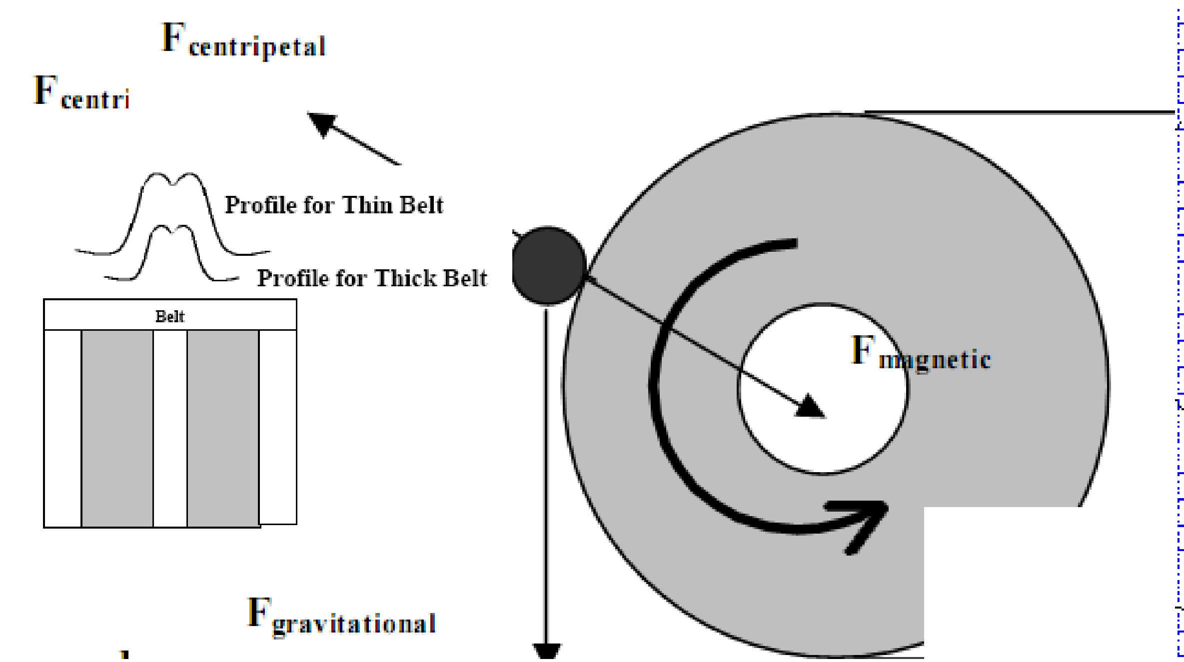


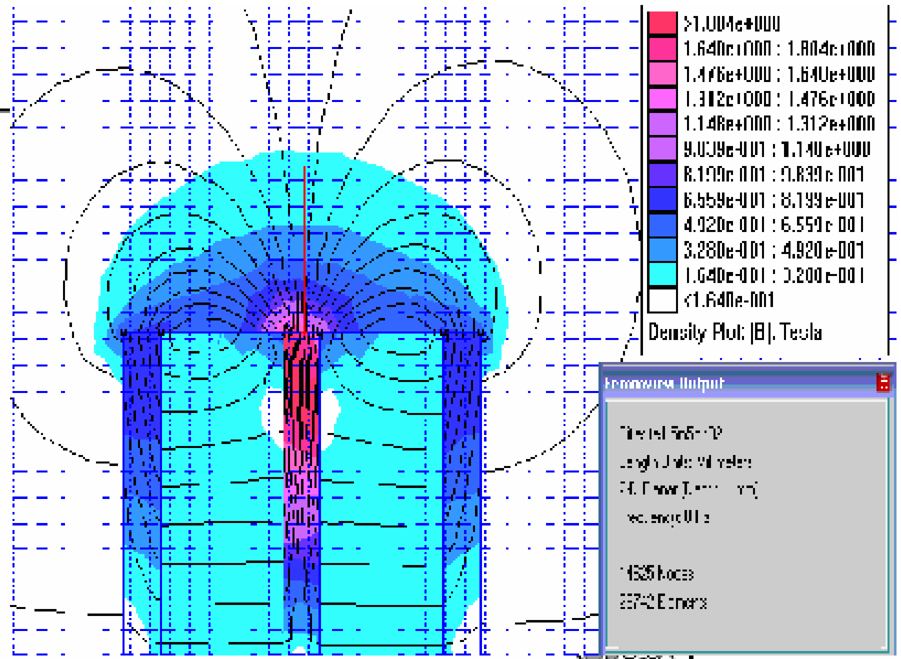


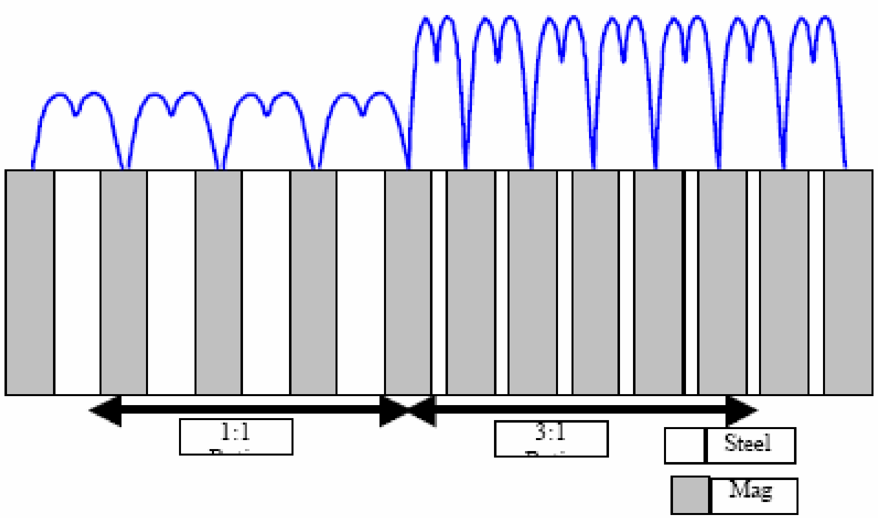
Watches

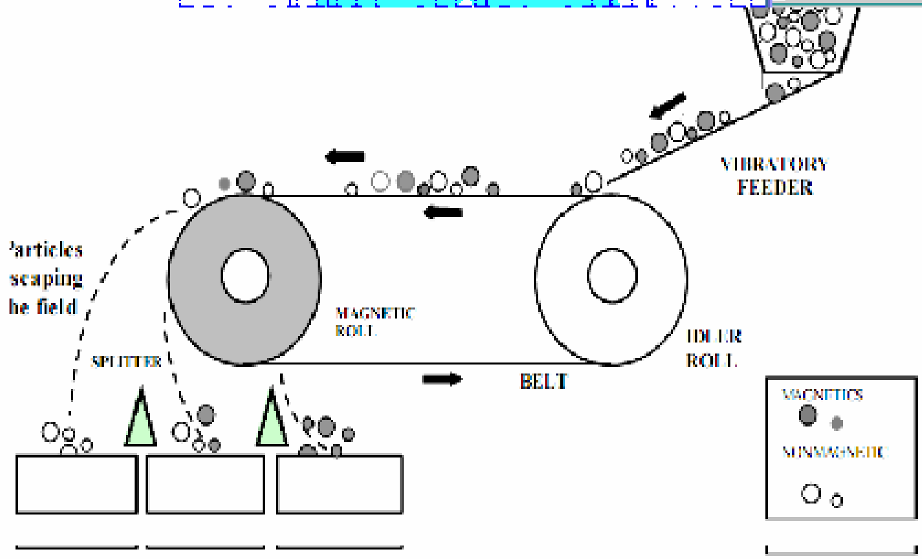


Magnetic separators

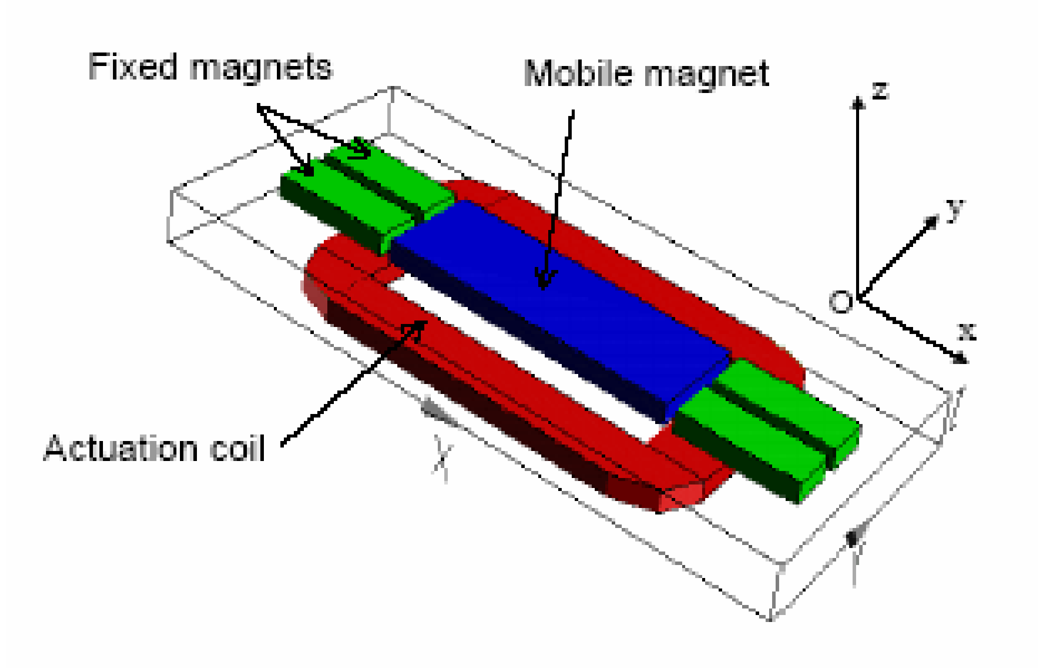


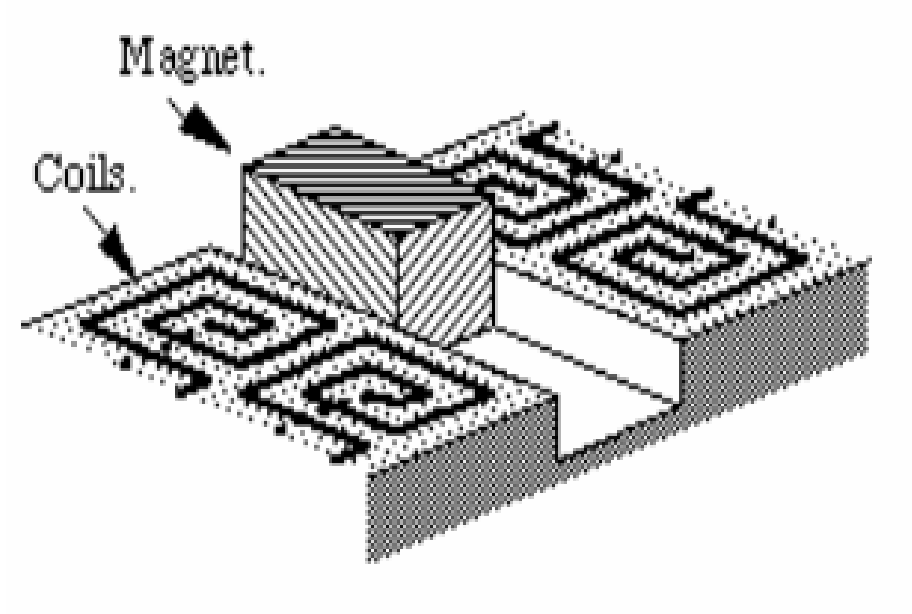






Actuators with PM

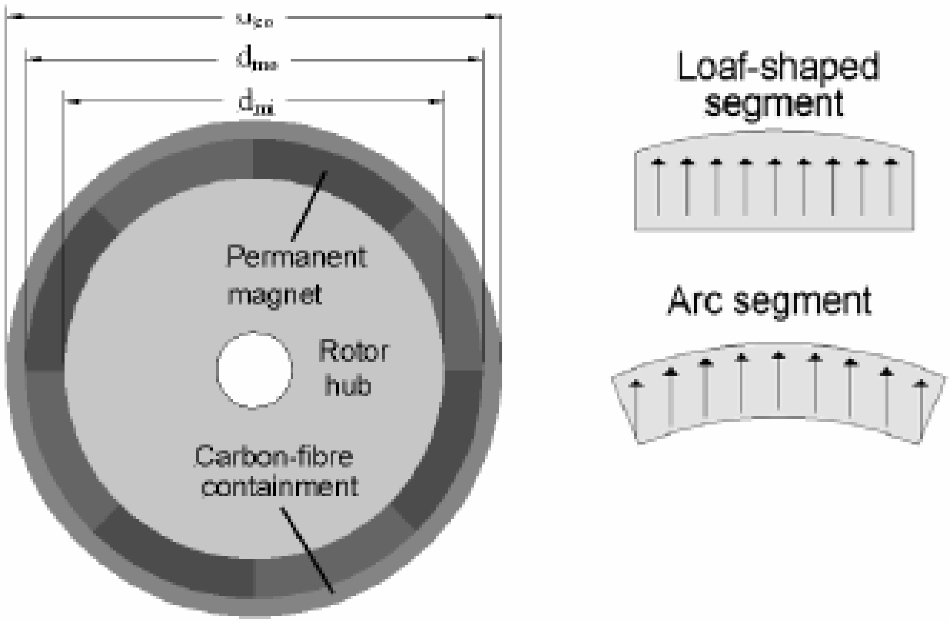


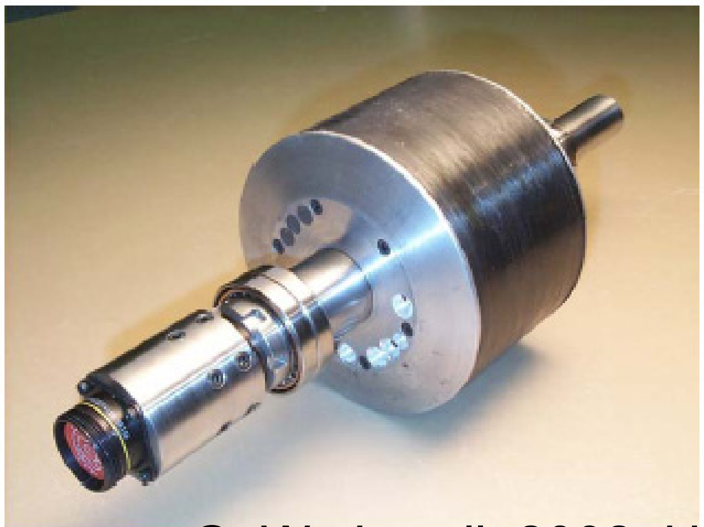


High speed motors

Rotor poles	8
Rotor outer diameter	145mm
Magnet thickness at centre	10mm
Containment thickness	7.8mm
Permanent magnet material (NdFeB)	NdFeB (Neomag 31VC)
Magnet segment axial length	2×45mm

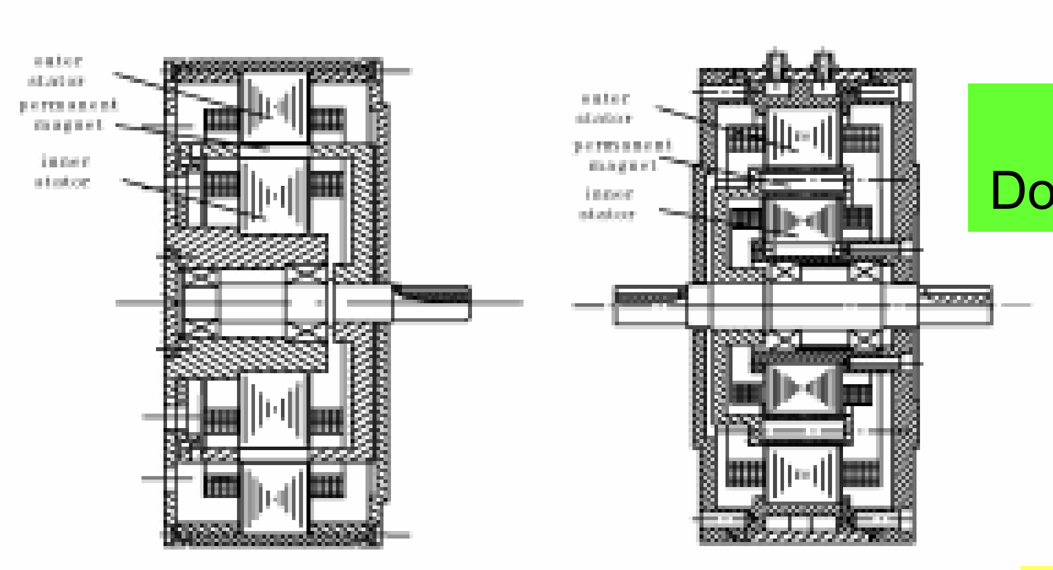
Stator teeth	12
Stator bore diameter	149mm
Slot opening to tooth pitch ratio	0.5
Stator core outer diameter	225mm
Stator slot depth	25mm
Stator core axial length	90mm
Stator core material grade (Silicon Iron)	NO20 (0.2mm)



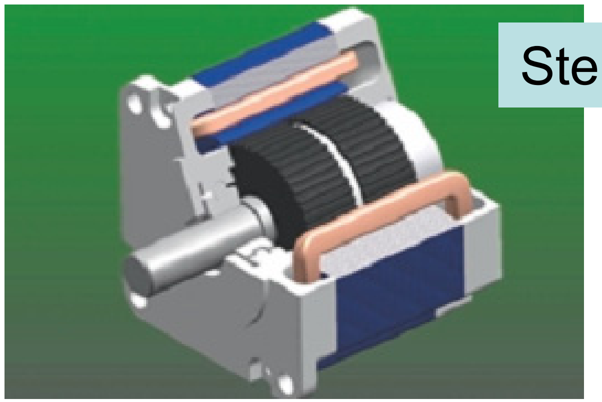


G. W. Jewell, 2002, UK

PM motors



Double Stator Motor

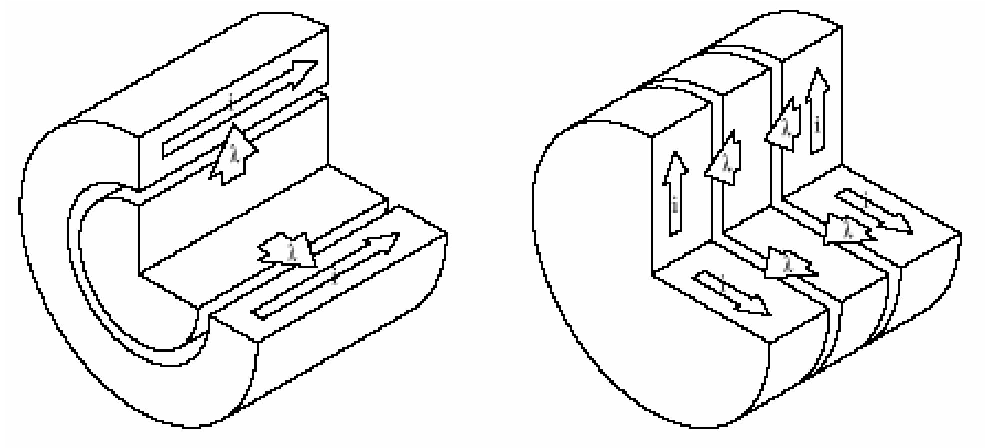


Stepper Motor

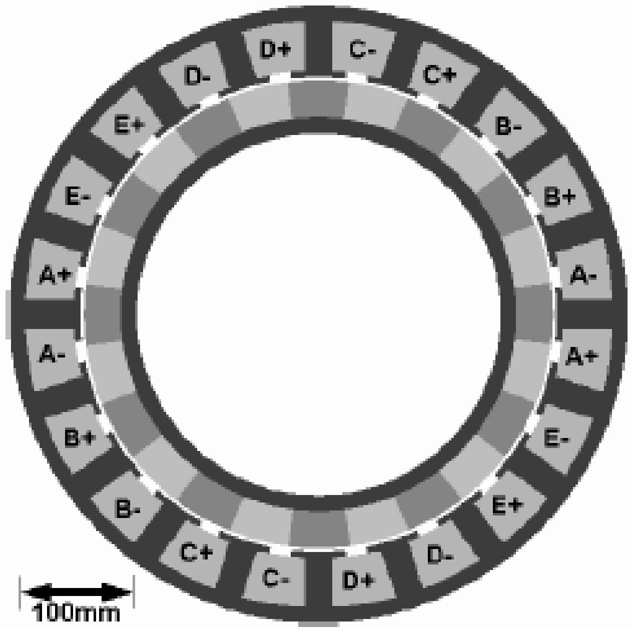
Flux Directions

Radial

Axial



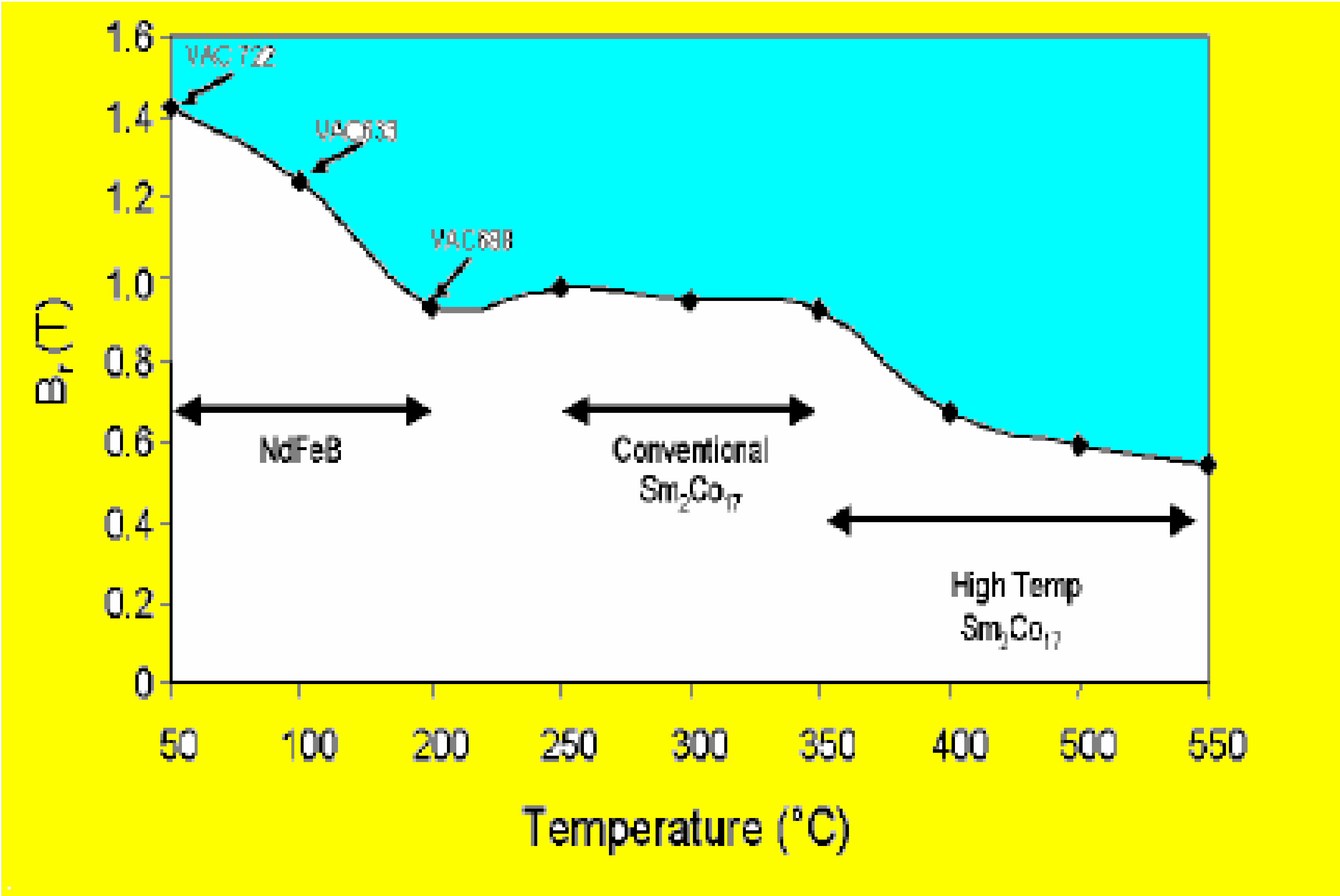
250 kW Generator



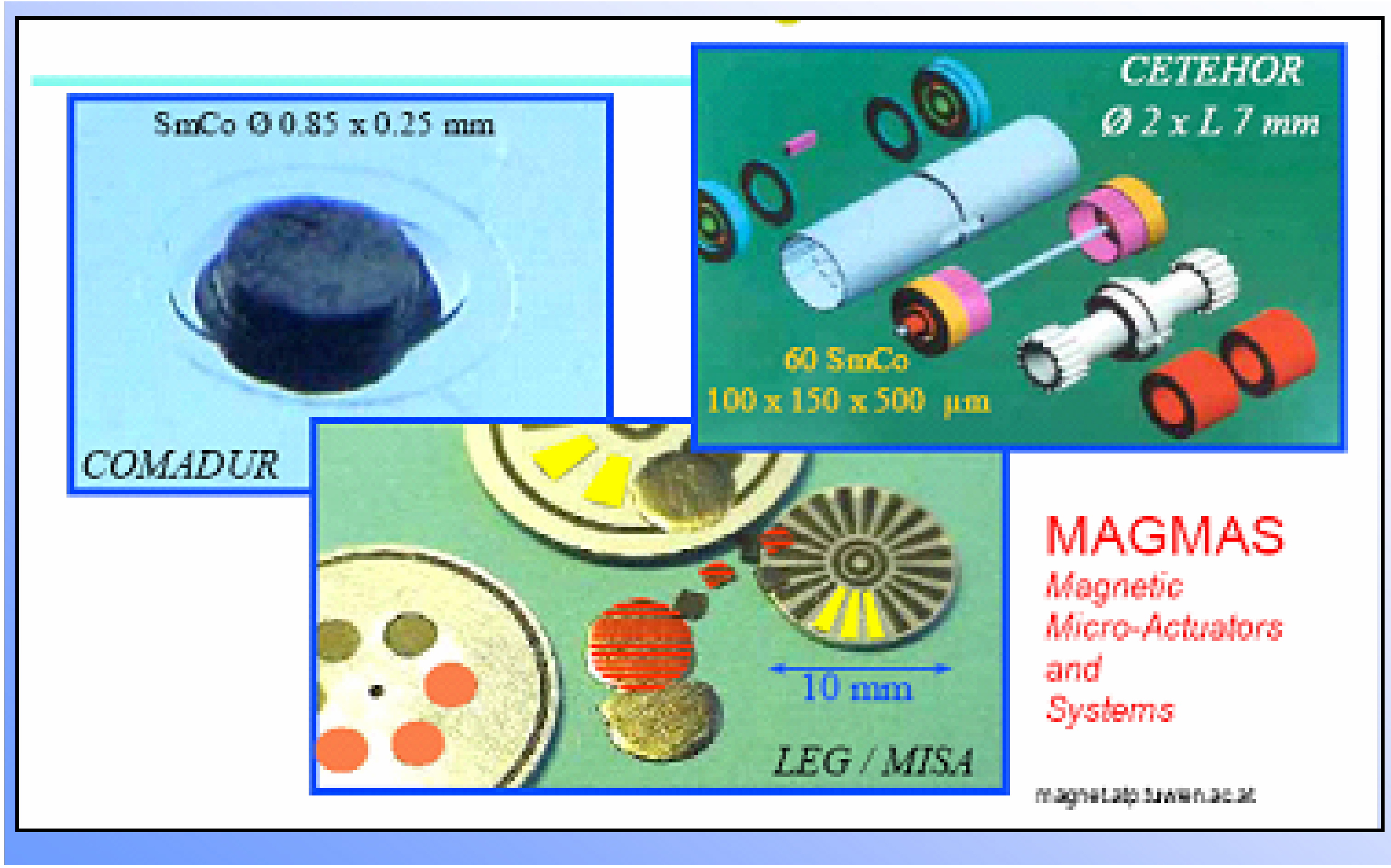
Phases	5
Slots	20
Pole-pairs	12
Stator outer diameter	540 mm
Stator bore diameter	416 mm
Mechanical airgap	3 mm
Magnet radial thickness	32 mm
Rotor inner diameter	317 mm
Active length	190 mm
Stator and rotor core material	49% Cobalt Iron laminations
Magnet	Sm_2Co_{17} (Arnold S3-225)
Magnet mass	60.6 kg
Lamination mass	76.8 kg
Copper mass	43 kg
Overall mass of active components	202.9 kg

G. W. Jewell, 2002, UK

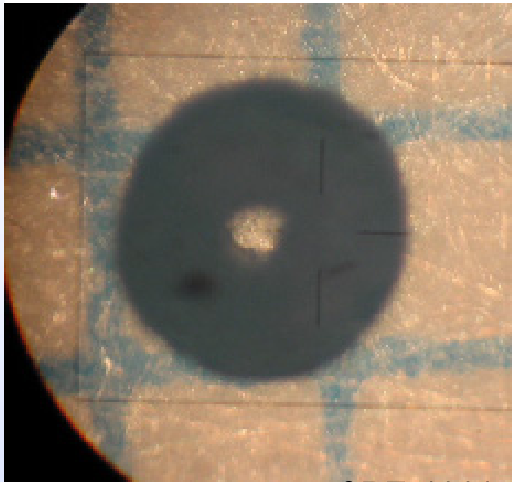
Very high temperature motors



Micromagnets

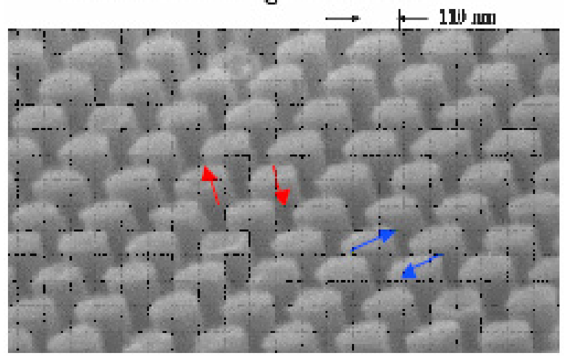


PM for e.m. watch



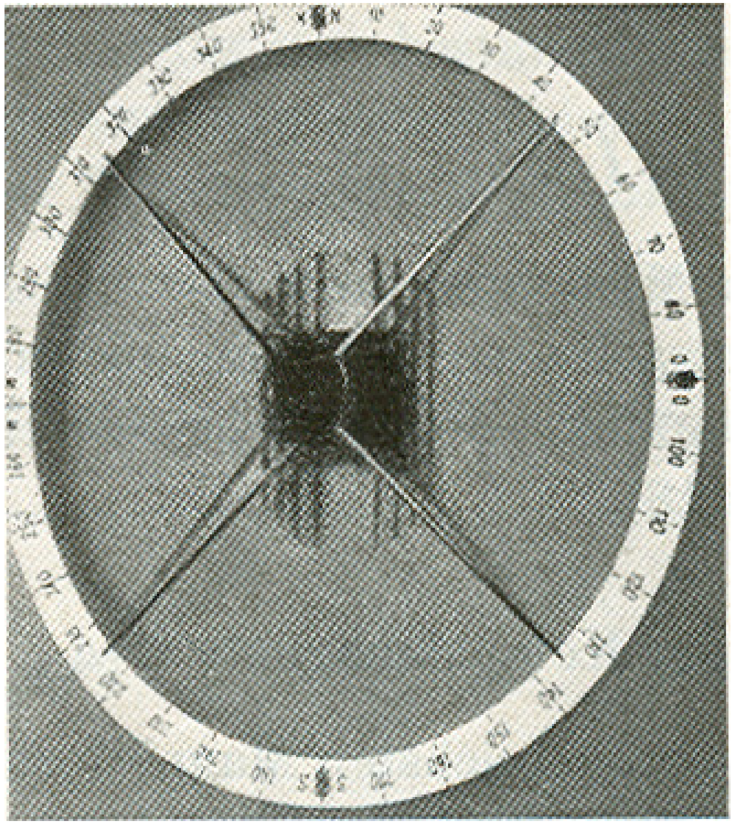
ICPE-1982

Quantized magnetic disk

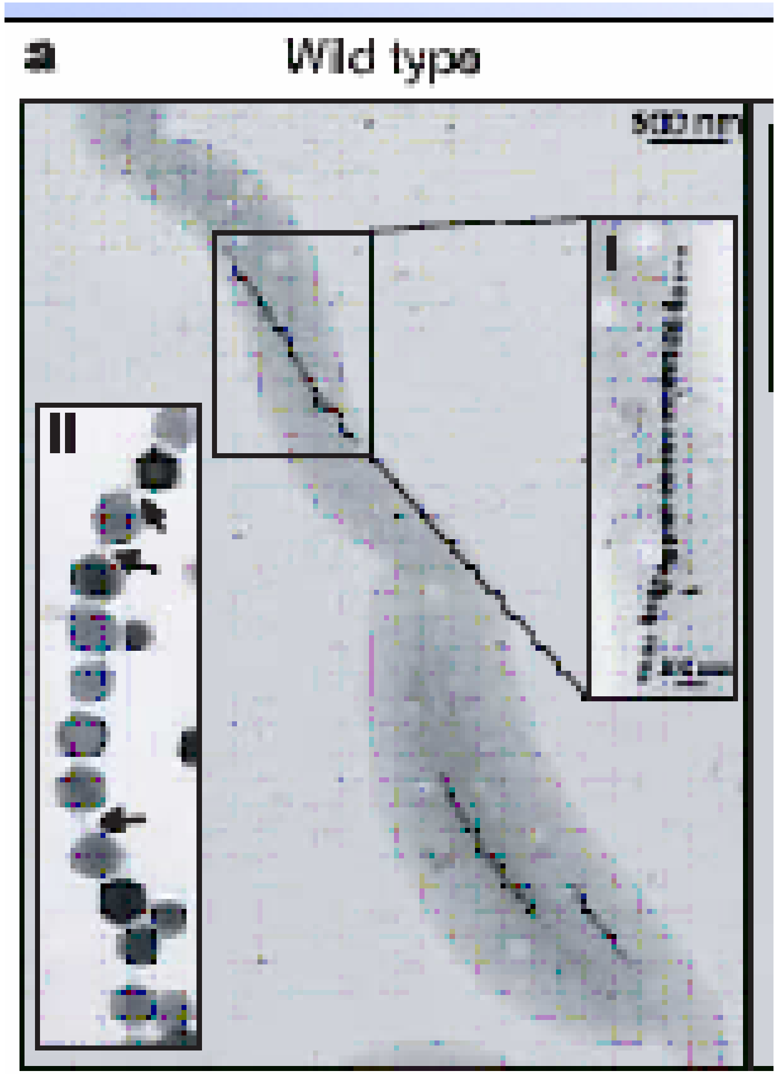


S Chou, J. Vac. Sci. Techn. B16 (1998) 3825.

Magnetic orientation

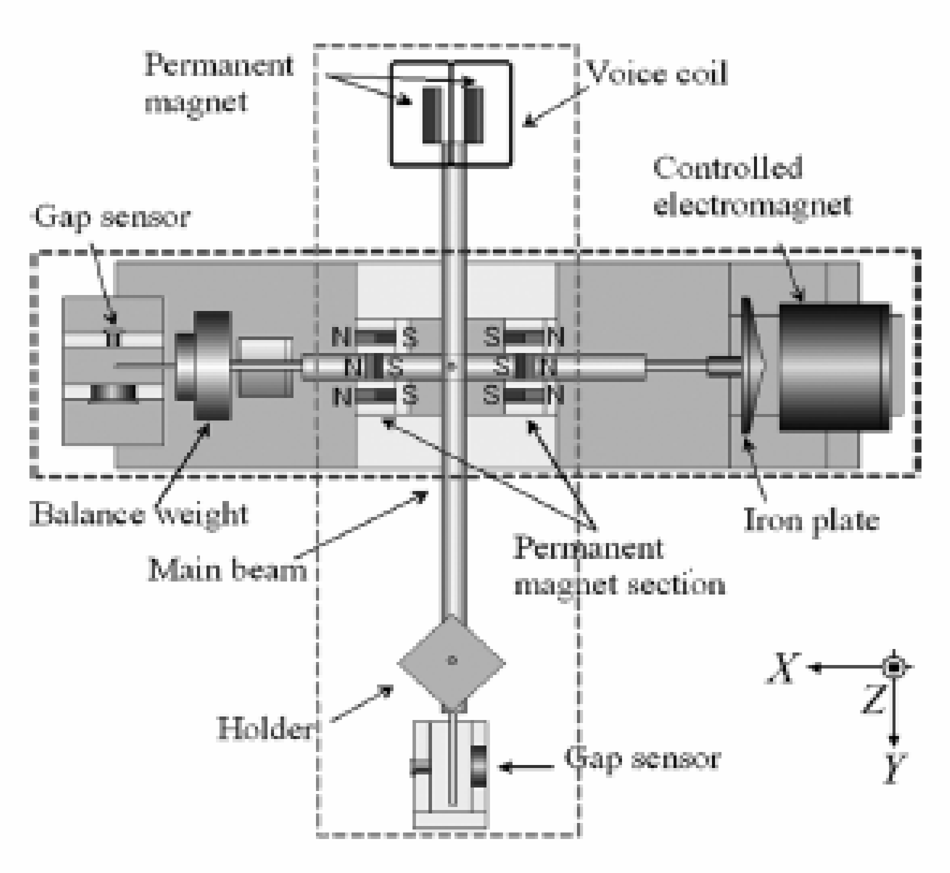


Magnetic navy compass



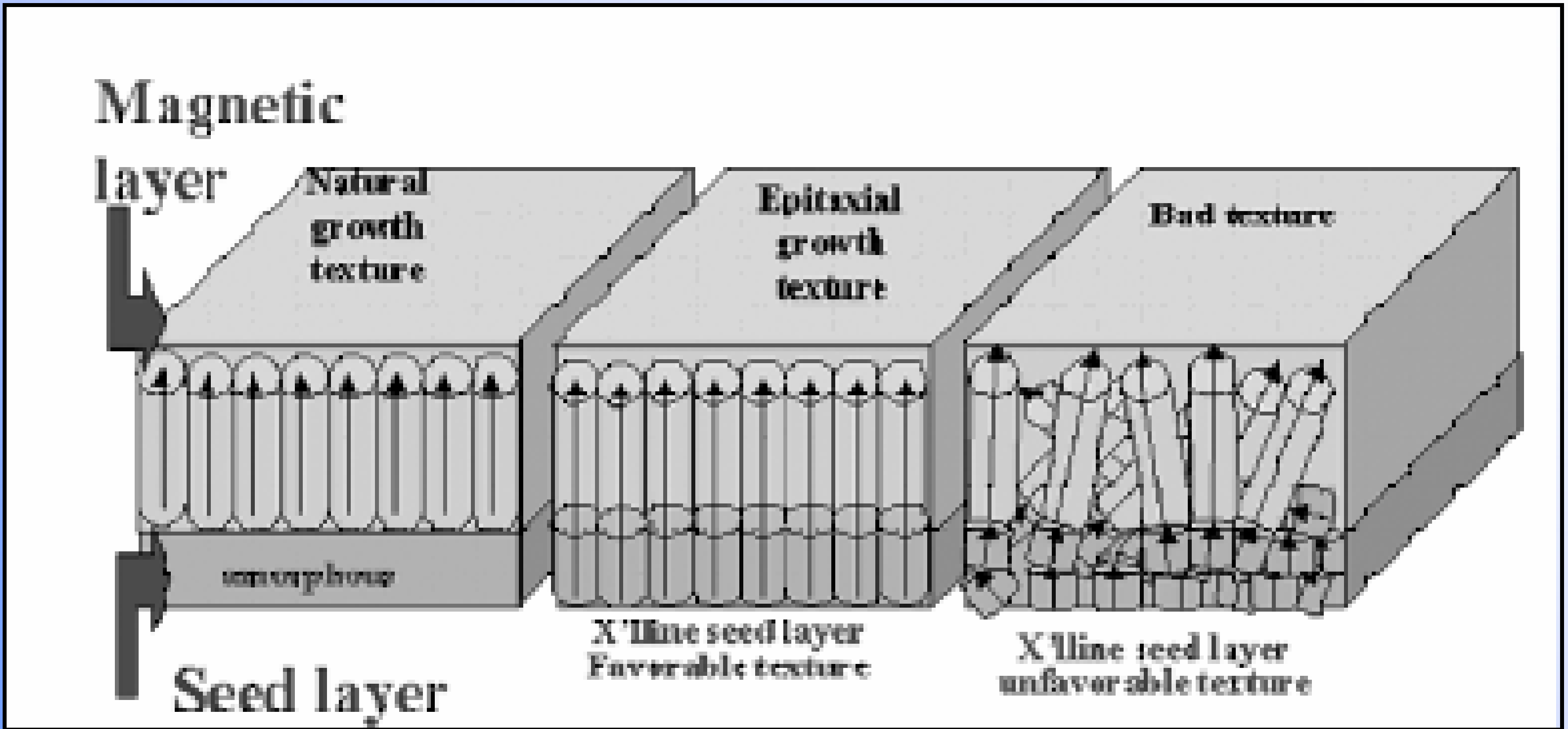
Magnetotactic bacteria

Measuring Equipement

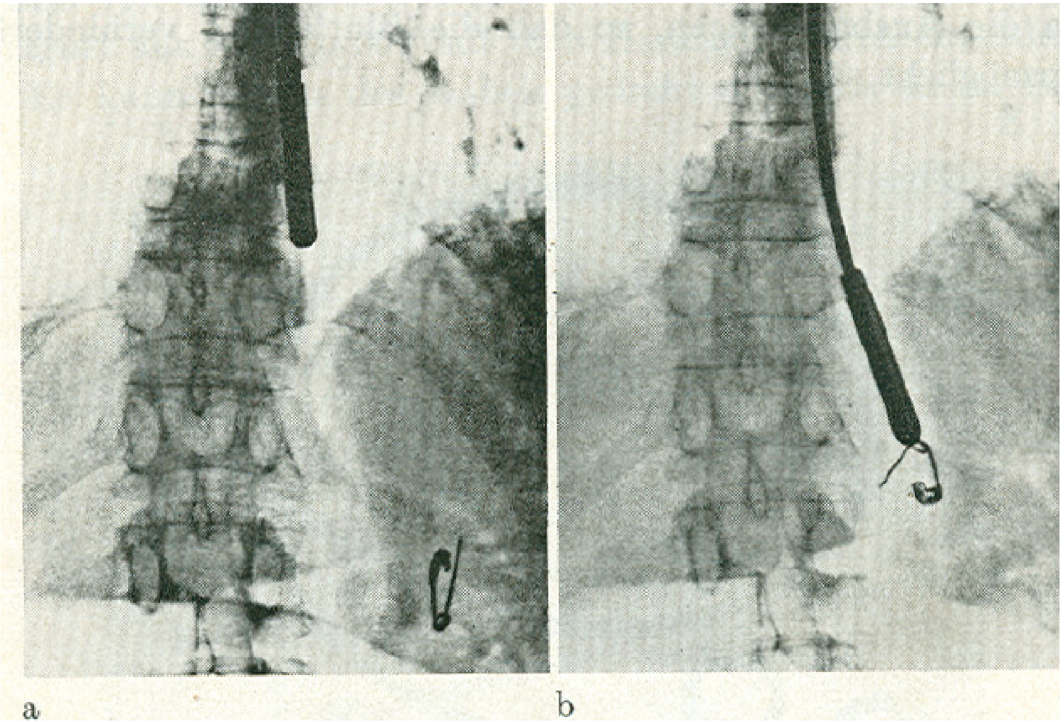


Dipole magnet with a diamater of 1.5 m in the „Alpha Magnetic Spectrometer" particle detector (about 5000 rectangular magnets).

Magnetic recording



Medical Applications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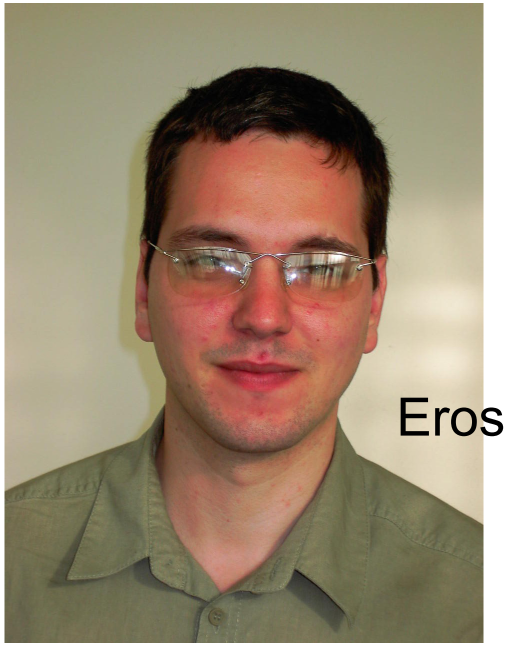
Many thanks to

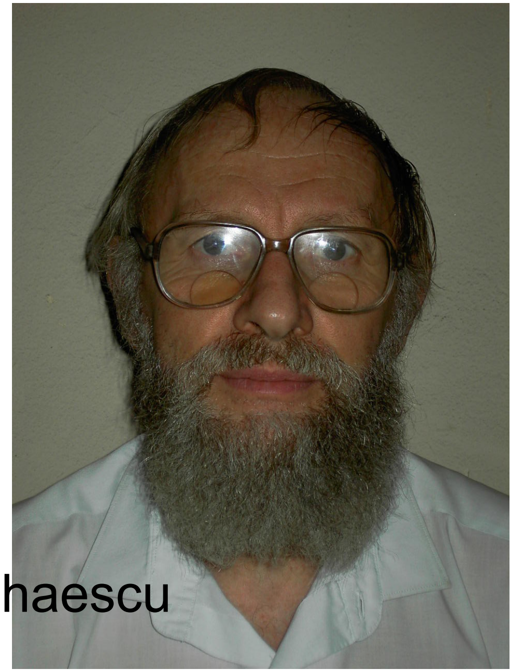


Eros Patroi

Mircea Ignat

Mirela Codescu

Iulian Iordache



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