HELMHOLTZ
ZENTRUM BERLIN
für Materialien und Energie

Permanent Magnets Including Wigglers and Undulators I - III

Johannes Bahrdt

June 20th-22nd, 2009

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Applications
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Fabrication technologies
Measurement of macroscopic properties

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Including Wigglers and Undulators
Part I

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Part I

History

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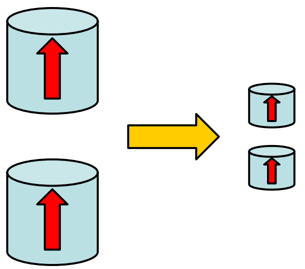
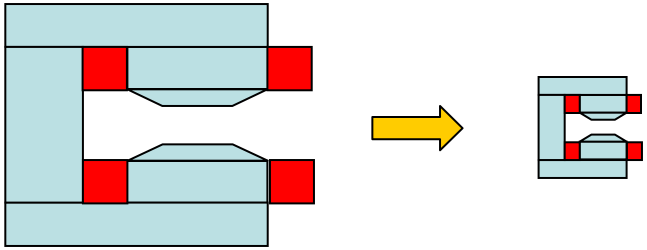
Advantages of permanent magnets versus electromagnets

- different scaling behaviour
- no power consumption
- fail safe (no power supplies)





Scaling of a permanent magnet:
The magnetic field at a given point is constant if a permanent magnet structure is scaled equally in all three directions

Scaling of an electromagnet:
The current density has to be inctreased linearly with the scaling parameter to maintain the magnetic field
⇨ technical limits for small structures appr. 500A / cm^2 (water cooled)

Explanation is the infinite thin surface current layer of an permanent magnet

The development of magnetic materials was / is driven by the demand for:
- high remanence
- stability with respect to reverse fields, temperature
- cost effective fabrication procedure
- availibility of material

Ferromagnetic materials:

- Fe, Co, Ni: Curie temperature several 100°C
- a few Lanthanides: Eu, Gd, Tb, Dy,Ho, Er, Tm
  Curie temperature below room temperature
- many alloys

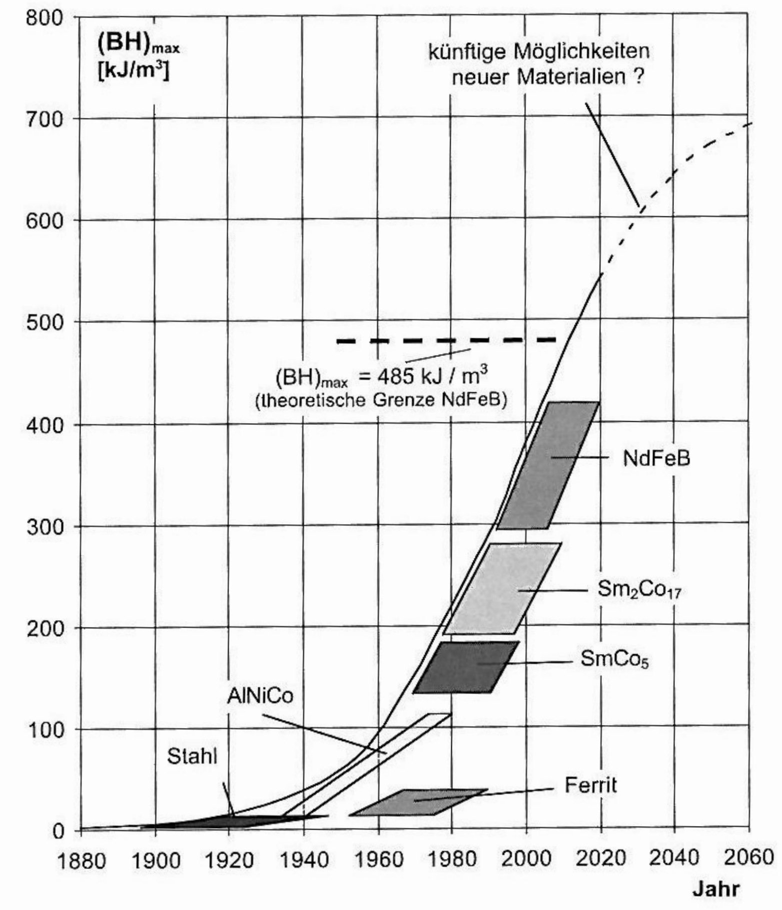
600 b.C.: Thales von Milet believed that magnets have a soul since they attract iron
Stones of magnetite $Fe^{II}(Fe^{III})_2O_4$ were found in the area Magnesia, Greece
200 b.C.: Si Nan (pointing South):

first chinese compass??

1200: Europe: first compass with a Fe-needle magnetized by a lodestone
swimming on a wooden pice in a bowl of water
independent European invention or copy of Chinese compass?
1600: description of Gilbert how to magnetize iron:
- forging or drawing of iron in North - South direction
- cooling down a red hot iron bar in the earth magnetic field
1750: fabrication of ferrites by Knight (first sintering process)
1819: Oersted discovers the magnetic field of a current carrying wire
1825: invention of electromagnet by Sturgeon: easy way to magnetize steel
1867: handbooks recording magnetic alloys made from non magnetic components
and non magnetic alloys made from magnetic components

History II

1916: Cobalt steel
1931: Alnico 3
1938: Alnico 5
1938 improvement of ferrites in Japan
1945: permanent magnets get compatible with electromagnets concerning cost and performance
1956: Alnico 8, 9
until 1970: Alnico is dominant
1970: ferrites take leading role
1970: $SmCo_5$
1971: FeCrCo
1981: $Sm_2(Co,Cu,Fe,Zr)_{17}$
1983: $Nd_2Fe_{14}B$



Vacuumschmelze GmbH & Co. KG, leaflet PD 002 (2007)

Raw Material Implications

Alnico:

Due to Co-crisis in late 70th production declined
companies started to develop products with less Co content

Hard Ferrites:

components are plentiful, cheap, non strategic

Rare earth more abundant than lead or copper,

but not concentrated in big mines and difficult to separate
most material is located in China

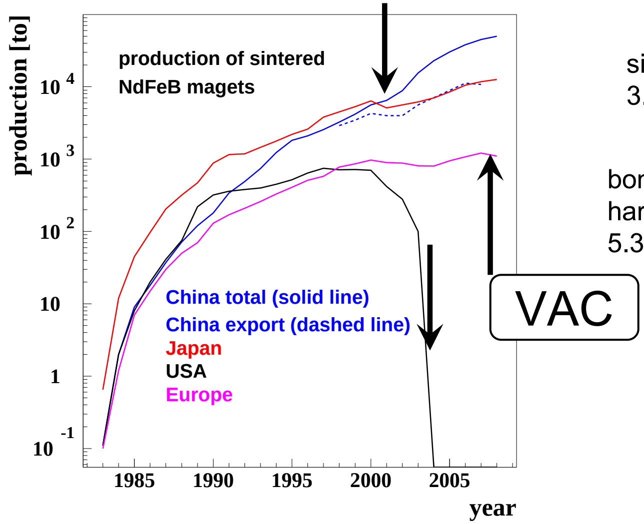
$SmCo_5$ / Sm_2Co_{17}:

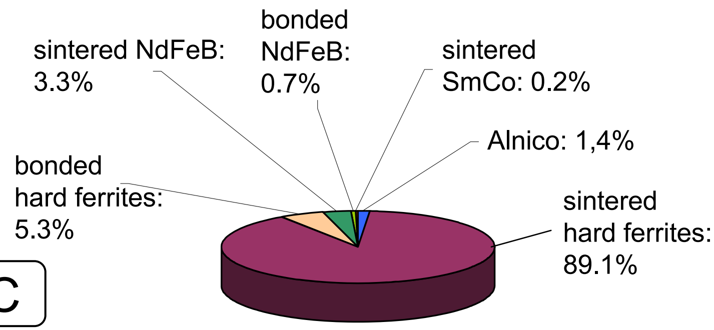
Co and Sm (small percentage of rare earth ore) are expensive
Ca reduction does not require pure Sm anymore but Sm oxide

$Nd_2Fe_{14}B$:

no Co needed, Fe and B is plentyful,
Nd availabilty a factor of ten higher as compared to Sm

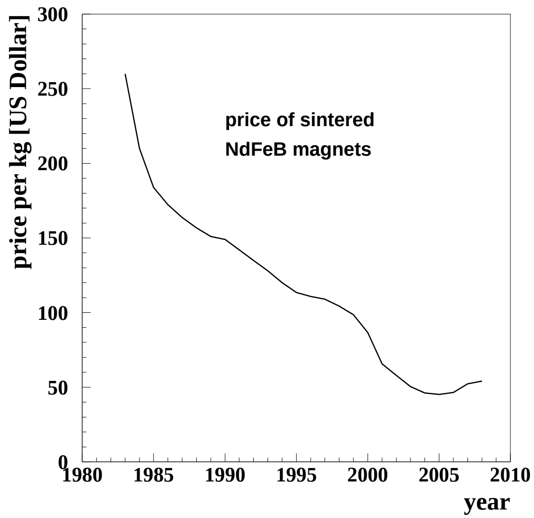
Permanent Magnet Production Worldwide I





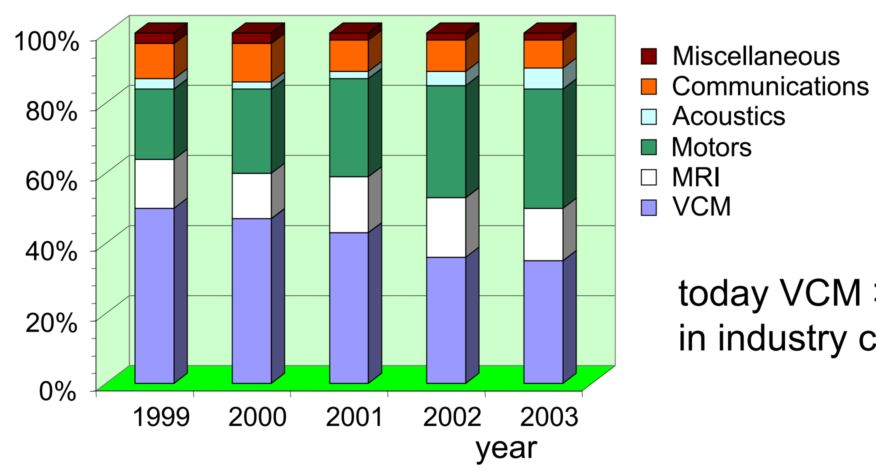
produced magnet types in 2000;
after 2010 NdFeB production will be >50%

Y. Luo: Gorham / Intertech Conference, Hangzhou, 2000.



Y. Luo, REPM, Krete, Greece, 2008

Magnet aplications in 2004



today VCM > 50%
in industry countries

Y. Kaneko: 18th Workshop on HPMA, Annecy, 2004.

Permanent Magnet Production Worldwide II

2009:
- Vacuumschmelze is the only magnet supplier in Europe
- No supplier in the USA anymore
- Hitachi in Japan

industry countries specialize on downstream products (magnet systems) with higher added value

Magnet applications in China in 2007

High tech products (to)		Low tech products (to)	
MRI	1800	Loud speaker	11280
VCM	1300	Separator	3610
CD-pickup	2515	magnetizer	900
DVD / CD-ROM	4060		
Mobile phone	3160		
Coreless tool	3160		
Electric bike etc	5860		

Y. Luo, REPM, Krete, Greece, 2008

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The applications of permanent magnets are based on:

Coulomb force law

compass
magnetic bearings, magnet coupling
fixing tool for mashining
transportation lines, conveyors
hysteresis devices (semi hard magnets)
small MRI systems for medical diagnostics

Faraday's law

dynamo, generators using wind / water energy
microphone
eddy current based speedometer

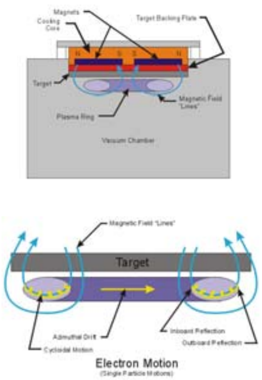
Lorentz force law

loudspeaker
servo motors
voice coil motors (hard disc)

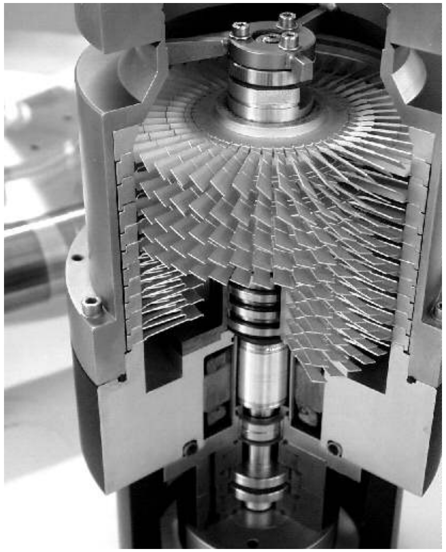
Lorentz force on free electrons

sputter facilities
ion getter pumps
accelerator magnets including undulators
Halbach type dipoles and quadrupoles

Applications for High Quality Permanent Magnets

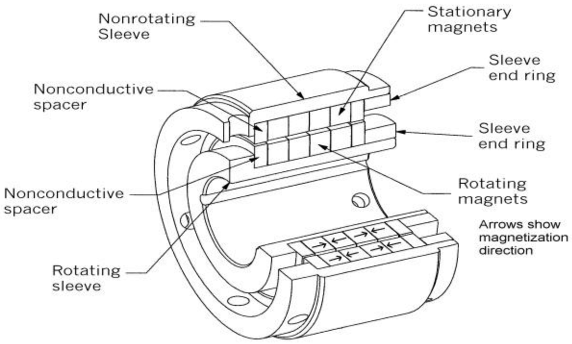


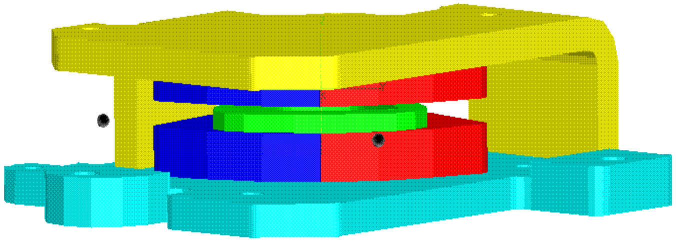
magnetron for
sputter systems



MRI magnets

SECTIONED VIEW OF PERMANENT
MAGNETIC BEARING





voice coil motor of
reading head for hard disk drives

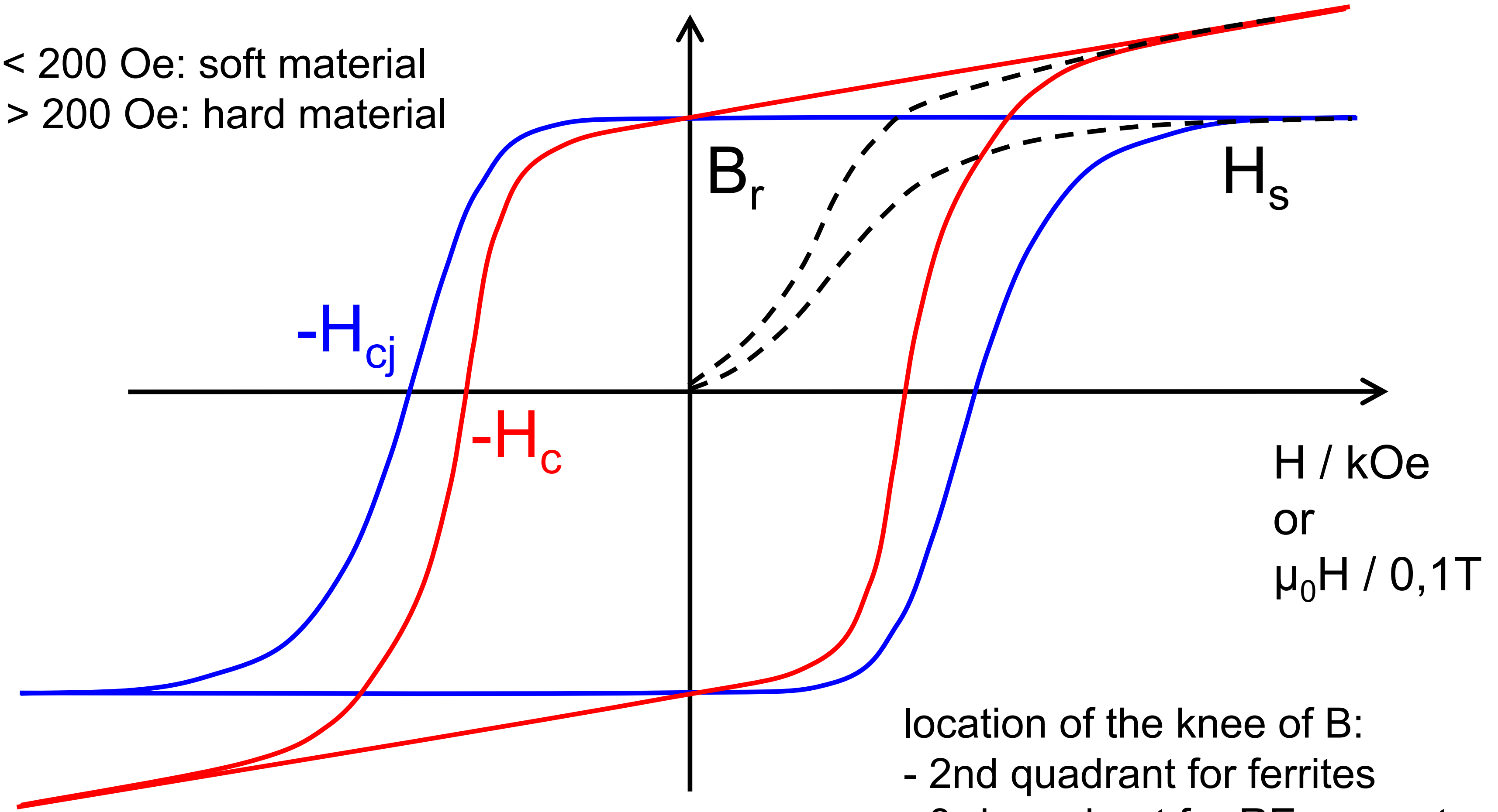
Basic Definitions I, Hysteresis Loop

Induction B / kG or B / 0,1 T

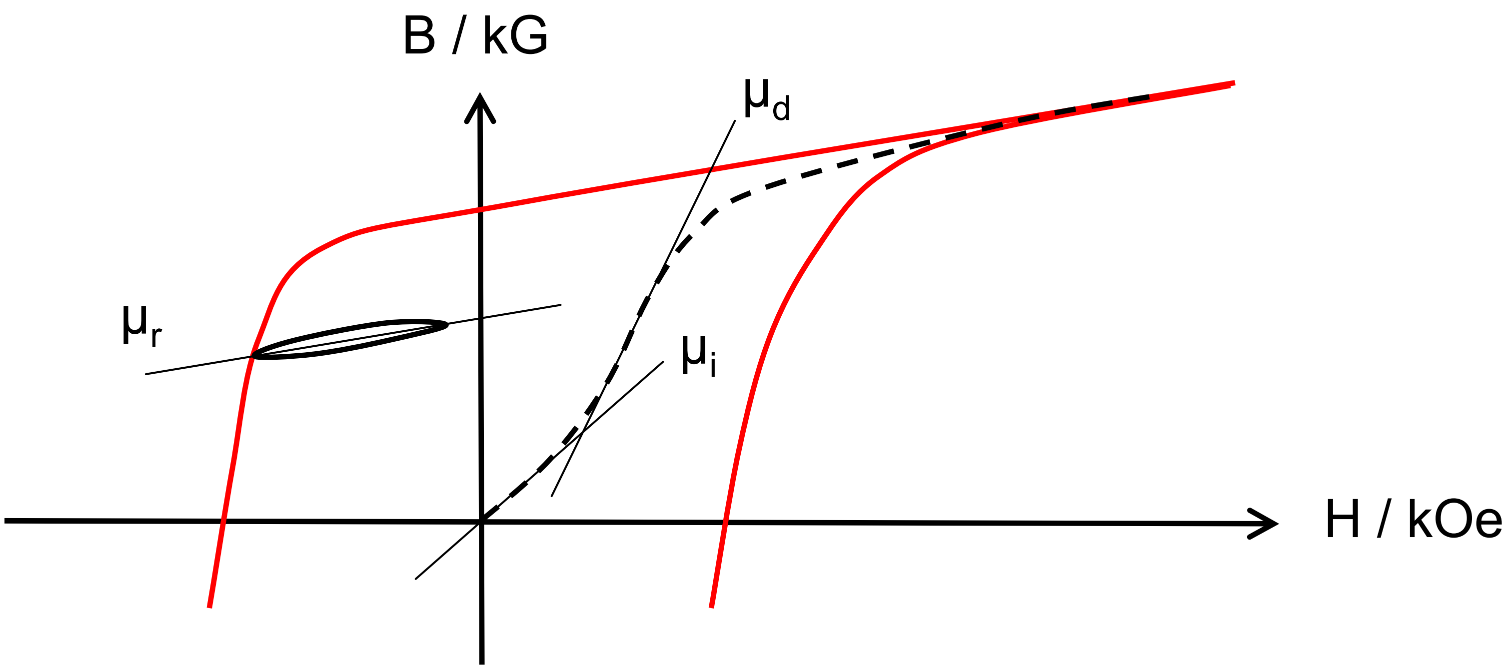
Magnetization 4πM / kG or 4πM / 0,1 T

H_c < 200 Oe: soft material

H_c > 200 Oe: hard material



location of the knee of B:
- 2nd quadrant for ferrites
- 3rd quadrant for RE magnets



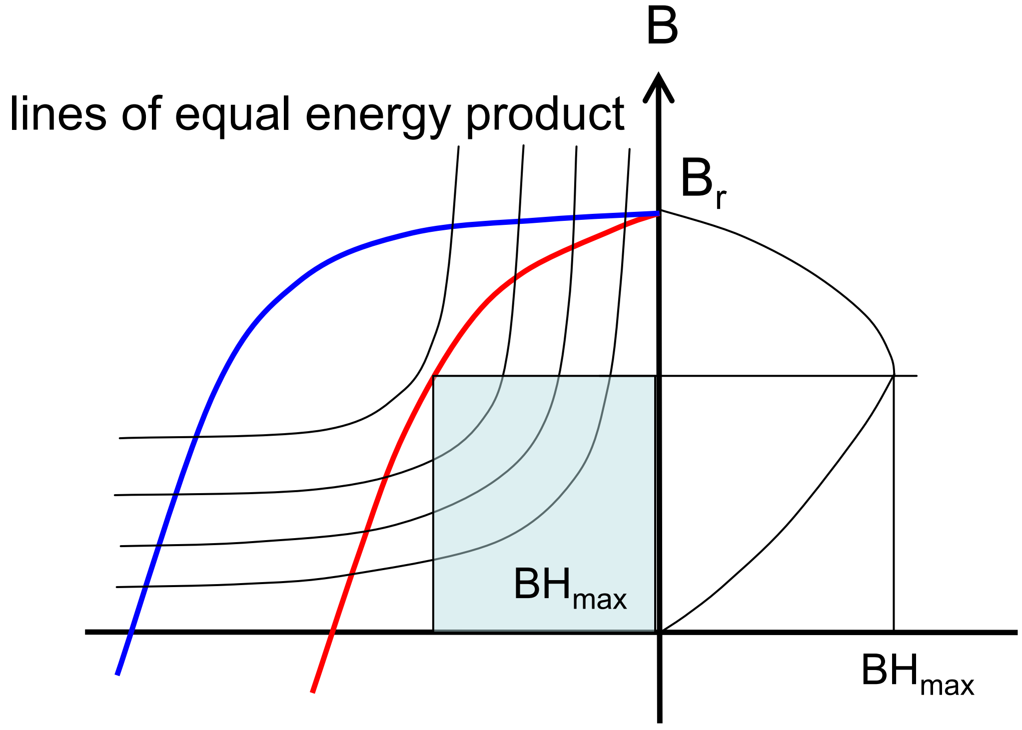
μ_i initial permeability

μ_d differential or maximum permeability

μ_r reversal or recoil permeability

The quality of a magnet is described with maximum possible energy product $(BH)_{max}$

$$(BH)_{max} \leq B_r^2$$



The efficiency of a magnet circuit is described with the permeance

electric circuit

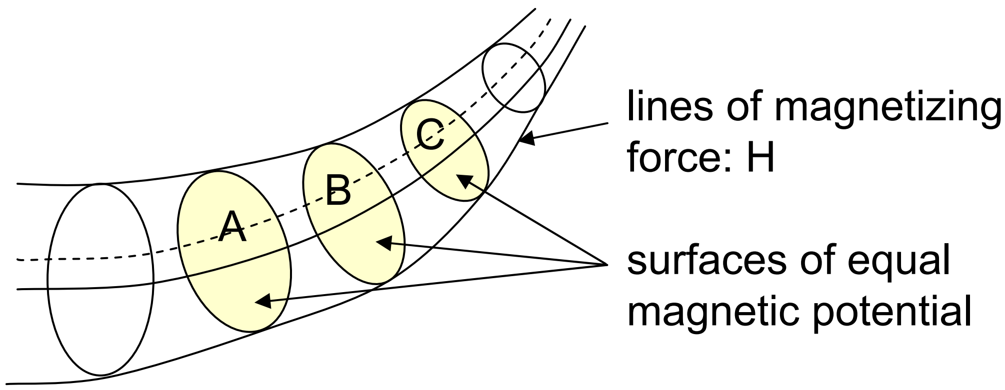
conductivity = 1 / resistance = current / voltage

in analogy: *magnetic circuit*

permeance = 1 / reluctance = flux / magnetomotive force difference

magnetomotive force = potential difference
as produced by currents or magnetized samples

magnetizing force H = derivative of potential



permeance of volume defined by ABC = flux through B / potential difference between A and C

$$P = \frac{\iint \vec{B} \cdot d\vec{s}}{\int \vec{H} \cdot d\vec{l}}$$

Basic Definitions IV, Permeance & Reluctance II

$$\vec{B} = \vec{H} + 4\pi \cdot \vec{M}$$

M = magnetization

$$\vec{H}_d = -D \cdot \vec{M}$$

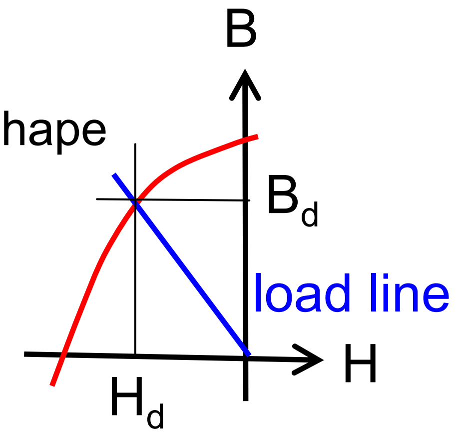
H_d = demagnetization field
D = demagnetization factor

$$\vec{B}_d = \vec{H}_d - \frac{4\pi}{D} \vec{H}_d$$

$$\frac{\vec{B}_d}{\vec{H}_d} = 1 - \frac{4\pi}{D}$$

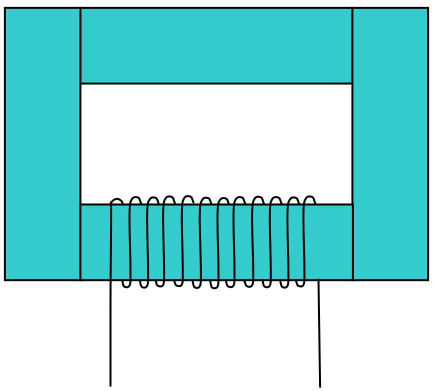
coefficient of self demagnetization or unit permeance

- evaluation of averaged demagnetization factor from magnet shape using tables, approximate formulas, finite element methods
- evaluation of averaged coefficient of self demagnetization this is the slope of the load line
- crossing of load line and B-H curve gives working point



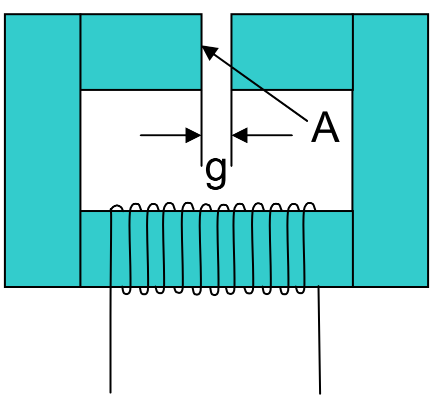
in reality: demagnetization factor and thus permeance varies over the volume closed and open circuit

closed circuit



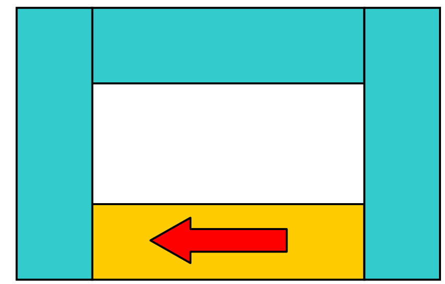
yoke permeance
P = μA/L
A = cross section
area of yoke
L = length of yoke

open circuit with air gap

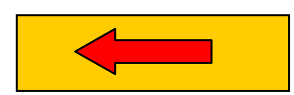


for μ >> 1 in yoke
we have a
gap permeance of
P = AB/Hg = A/g

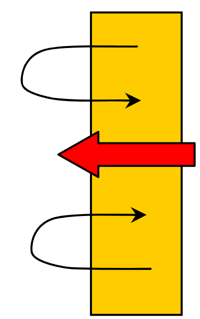
permanent magnet in
closed and open circuit



PL/A >> 1



PL/A ≈ 1



PL/A << 1

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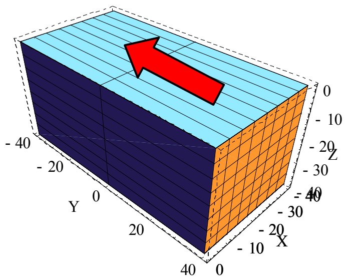
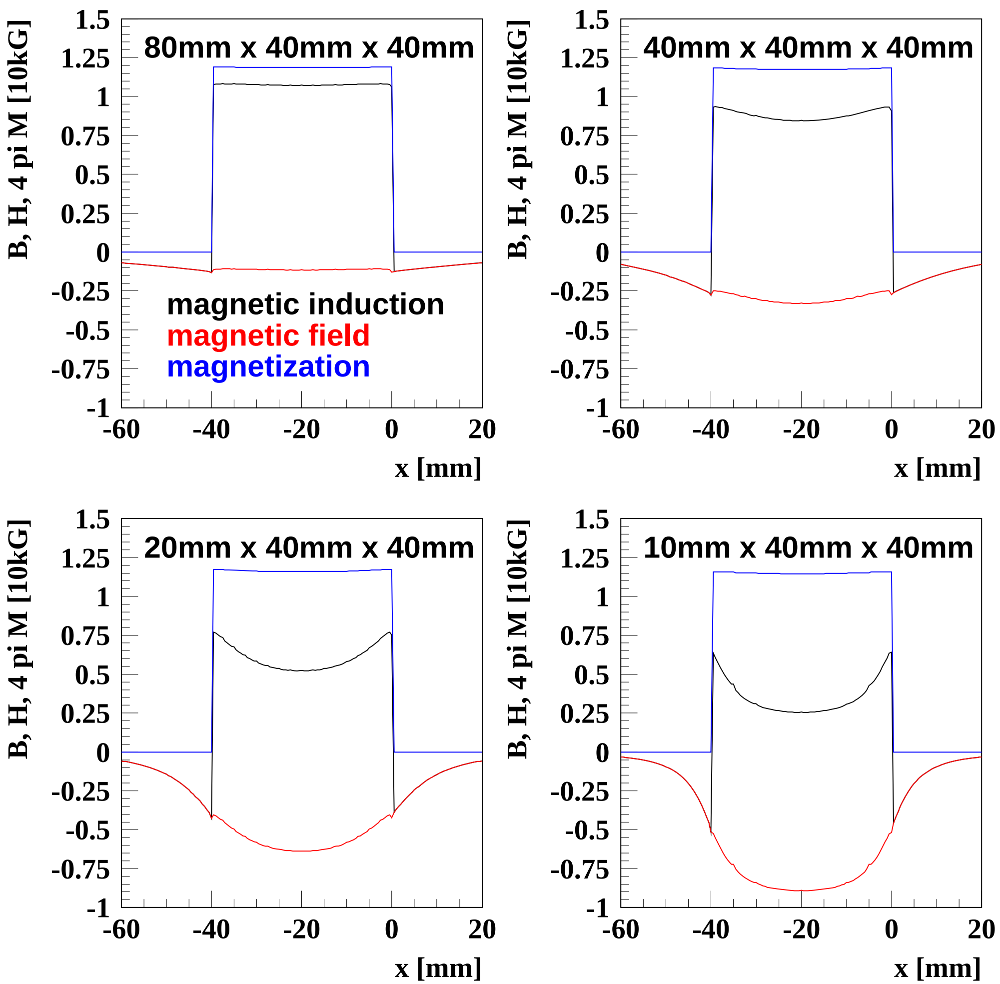
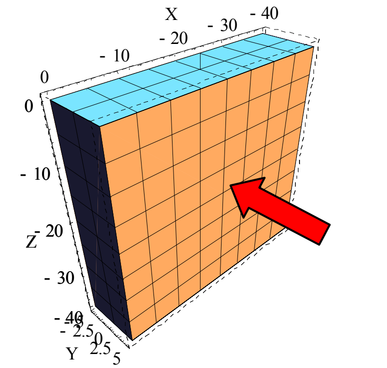
Shape of magnet block defines the working points



small demagnetization



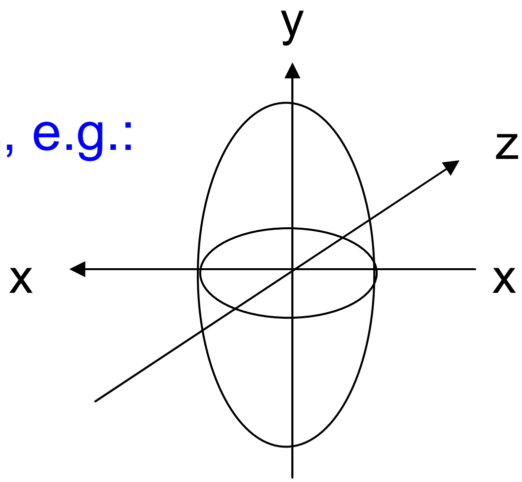
large demagnetization

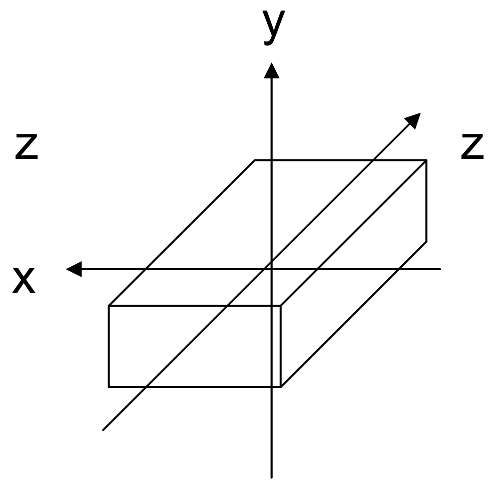


Magnetometric demagnetization: coil along complete sample
yields average demagnetization factor of complete sample
Fluxmetric or ballistic demagnetization: coil around center of sample
averaged demagnetization at center cross sections of magnet
D-fluxmetric < D-magentometric

In a carthesic coordinate system we have always: $D_x + D_y + D_z = 4\pi$

analytic evaluation
is possible only in specific cases, e.g.:
- generalized ellipsoid
- rectangular prism





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Exact D-factor for generalized ellipsoid (overview by Osborn, 1945)

a ≥ b ≥ c (semi axes in directions x, y, z)

$$D_x = \frac{4\pi\cos(\varphi)\cos(\vartheta)}{\sin^3(\vartheta)\sin^2(\alpha)}\left(F(k,\vartheta) - E(k,\vartheta)\right)$$

$$D_y = \frac{4\pi\cos(\varphi)\cos(\vartheta)}{\sin^3(\vartheta)\sin^2(\alpha)\cos^2(\alpha)}\left(E(k,\vartheta) - F(k,\vartheta)\cos^2(\alpha) - \frac{\sin^2(\alpha)\sin(\vartheta)\cos(\vartheta)}{\cos(\varphi)}\right)$$

$$D_z = \frac{4\pi\cos(\varphi)\cos(\vartheta)}{\sin^3(\vartheta)\cos^2(\alpha)}\left(\frac{\sin(\vartheta)\cos(\varphi)}{\cos(\vartheta)} - E(k,\vartheta)\right)$$

$$\cos(\vartheta) = c/a$$

$$\cos(\varphi) = b/a$$

$$\sin(\alpha) = \sin(\varphi)/\sin(\vartheta) = k$$

F and E are elliptical integrals of the 1st and 2nd kind with k=modulus and ϑ= amplitude

Special cases:

sphere: $D_x=D_y=D_z=4\pi/3$

infinite long circular cylinder:

$D_{par}=0$, $D_{perp}=2\pi$

infinite wide plane:

$D_{in\text{-}plane}=0$, $D_{perp\text{-}plane}=4\pi$

prolate / oblate spheroid etc…

J. Osborn, Phys. Rev. Vol. 67, No. 11-12 (1945) 351-357

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Magnetometric D-factor for rectangular prism (Aharoni, 1998)

$$D_z/4 = \frac{b^2-c^2}{2bc}\ln\left(\frac{sabc-a}{sabc+a}\right)+\frac{a^2-c^2}{2ac}\ln\left(\frac{sabc-b}{sabc+b}\right)+\frac{b}{2c}\ln\left(\frac{sab+a}{sab-a}\right)+\frac{a}{2c}\ln\left(\frac{sab+b}{sab-b}\right)$$
$$+\frac{c}{2a}\ln\left(\frac{sbc-b}{sbc+b}\right)+\frac{c}{2b}\ln\left(\frac{sac-a}{sac+a}\right)+2\arctan\left(\frac{ab}{c\cdot sabc}\right)+\frac{a^3+b^3-2c^3}{3abc}$$
$$+\frac{a^2+b^2-2c^2}{3abc}sabc+\frac{c}{ab}(sac+sbc)-\frac{sab^3+sbc^3+sac^3}{3abc}$$

$$sabc=\sqrt{a^2+b^2+c^2}$$
$$sab=\sqrt{a^2+b^2}$$
$$sac=\sqrt{a^2+c^2}$$
$$sbc=\sqrt{b^2+c^2}$$

D_x and D_y can be evaluated in analogy to D_z

A. Aharoni, J. Appl. Phys., Vol. 83, No. 6 (1998) 3432-3434

Special cases:

cube:

$$D_x = D_y = D_z = 4\pi/3$$

infinite long rectangular cylinder:

$$D_{par} = 0$$
$$D_{perp}/4 = \frac{1-p^2}{2p}\ln(1+p^2)+p\cdot\ln(p)+2\cdot\arctan(1/p)$$
$$p = c/a$$

Note:
These expresisons are averaged values over the prism.
Except for an ellipsoid the D-factors vary over the magnet volume.

Magnet Types I and II

Magnet type I

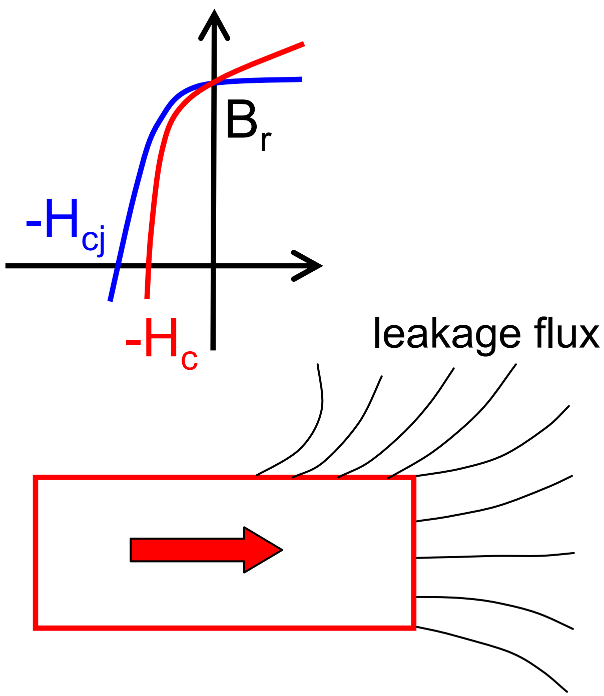
$H_{cj} < B_r$

e.g. 35% Co steel, Alnico

$\mu >> 1$

high leakage flux

much energy is stored in leakage field (not usable)



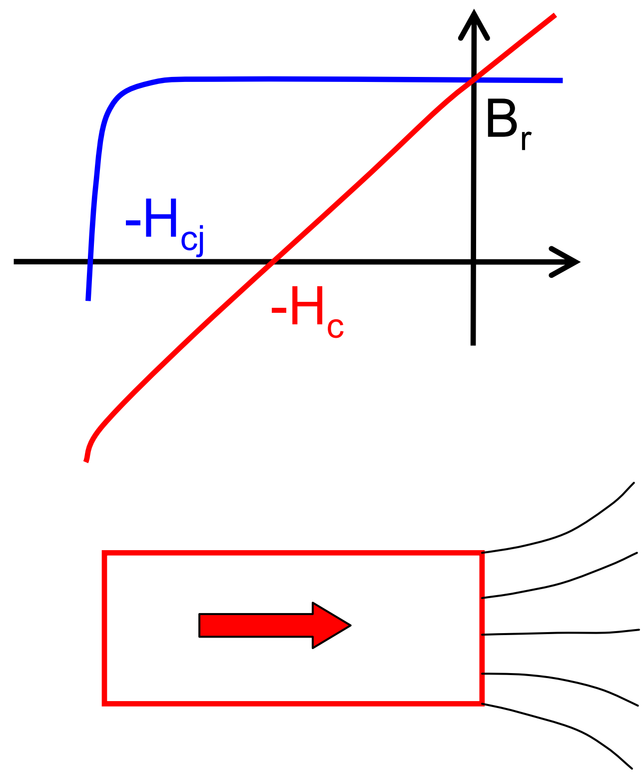
Magnet type II

$H_{cj} > Br$

e.g. hard ferrites, RE-magnet

$\mu \approx 1$

low leakage flux



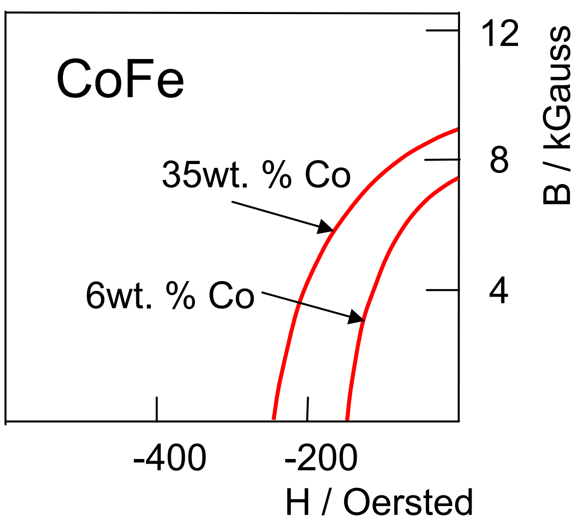
Carbon steel (Martensitic steel):

remanence / coercivity enhanced with up to 36% Co

coercivity further enhanced with

nonmagnetic particles, internal strain, lattice imperfections

grade	remanence	coercivity	energy product
3,5 Cr	9,8 kG	0,05 kOe	0,22 MGOe
36,0 Co	9,6 kG	0,24 kOe	0,94 MGOe



small coercive force

Common Materials II

Alnico: (Fe, Al, Ni, Co, Cu, Ti) alloy

very brittle, extremely hard, therefore difficult to mashine,
problematic to fabricate small magntes

high Br but low Hcj, special geometry is required to avoid demagnetization

several steps of improvement:

- higher energy product: isotropic ⇨ anisotropic magnets (cooling in magnetic field)
- improved mechanical properties: cast ⇨ sintered magnets (starting from powder, using a precise die, taking into account shrinking)

operational up to 550°C, cast: 6,5MGOe, sintered: 4,5MGOe

temperature coefficients: -0.02%(Br) -0.02% to 0.01%(Hcj),

grade	remanence	coercivity (Hc)	energy product
Alnico 5 cast	12,4 kG	0,64 kOe	5,5 MGOe
Alnico 9 cast	11,2 kG	1,5 kOe	11,5 MGOe
Alnico 5 sintered	10,5 kG	0,60 kOe	3,0 MGOe
Alnico 8 sintered	7,6 kG	1,5 kOe	4,5 MGOe

Note: Hc and Hcj differ only by 10% for these materials!

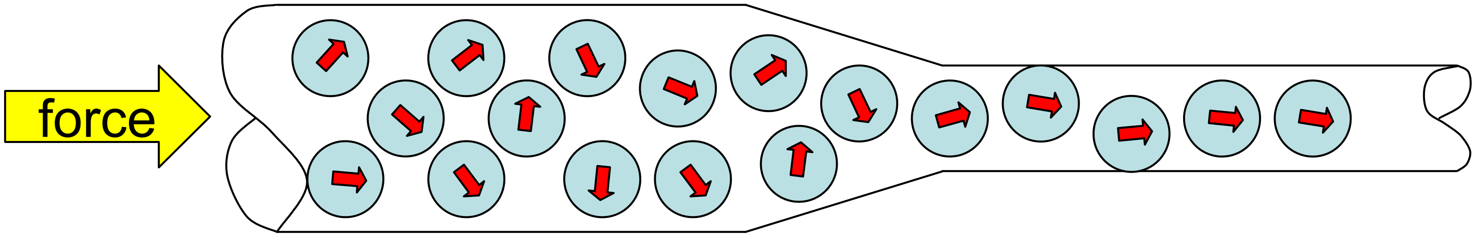
Common Materials III

FeCrCo: cast or sintered
magnetically similar to Alnico 5
but needs less of expensive Co and has higher ductility than AlNiCo
can be oriented by deformation

grade	remanence	coercivity	energy product
	13,0 kG	0,55 kOe	5,0 MGOe

MnCAl: improvement of magnetic performance via orientation by warm extrusion
does not need Co at all, higher ductility than AlNiCo,
however, warm extrusion is expensive

grade	remanence	coercivity	energy product
cast	3,0 kG	0,95	1,0 MGOe
cast & extruded	6,0 kG	2,5 kOe	7,0 MGOe



Common Materials IV

Hard Ferrites: MO 6(F_2O_3) (or $MFe_{12}O_{19}$) with M = Ba, Sr or Pb, sintered

low Br, high Hcj, isotropic and anisotropic

Temperature coefficients: -0.2%(Br) +0.1 to 0.5%(Hc), T_C 450°C

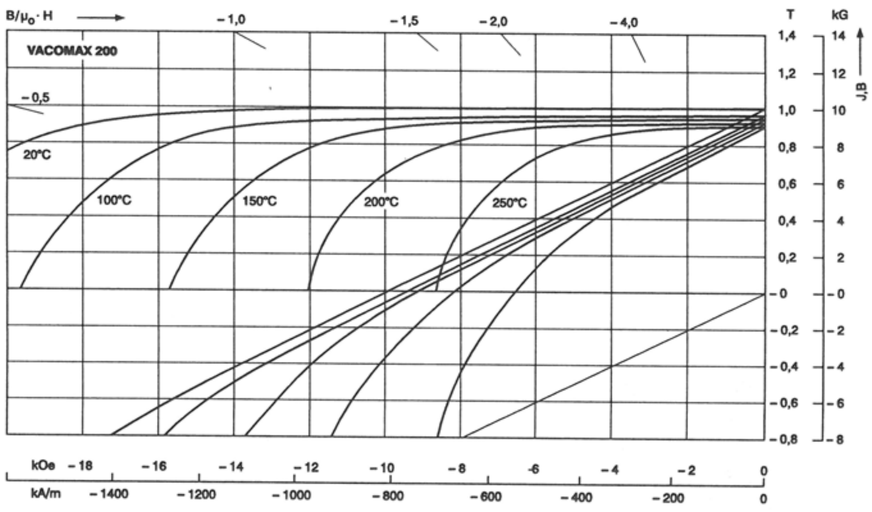
grade	remanence	coercivity (Hc)	energy product
typical:	4,1 kG	2,9 (3,0) kOe	4,2 MGOe

value in bracket refers to Hcj

Hc and Hcj are very similar

knee is in the second quadrant

Sintered SmCo magnets (brittle)



High coercivity

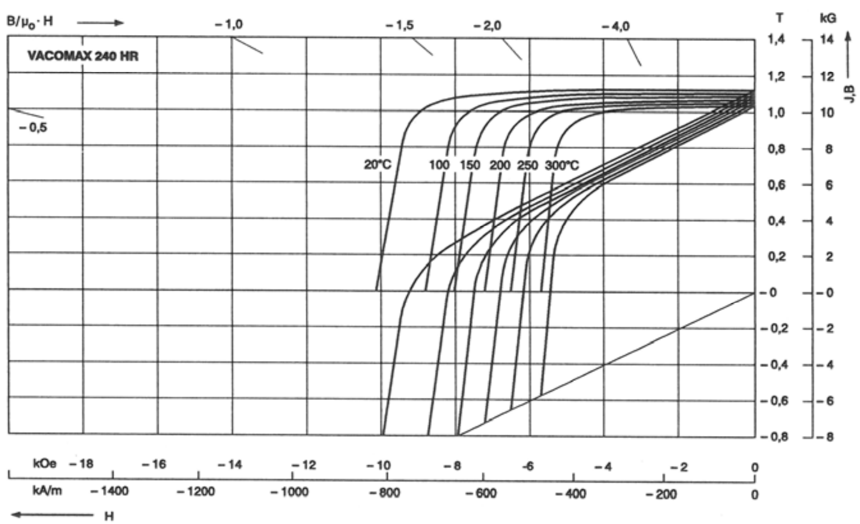
$SmCo_5$

B_r=1.01 T (typical)

H_{cj}=12.5 kOe (minimum)

TK (B_r) =-0,04

TK (H_{cj})=-0,21



High remanence

Sm_2Co_{17}

B_r=1.12 T (typical)

H_{cj}=8.0 kOe (minimum)

TK (B_r) =-0,03

TK (H_{cj})=-0,15

Vacuumschmelze, Data leaflet
DM - VACODYM/VACOMAX , 2007

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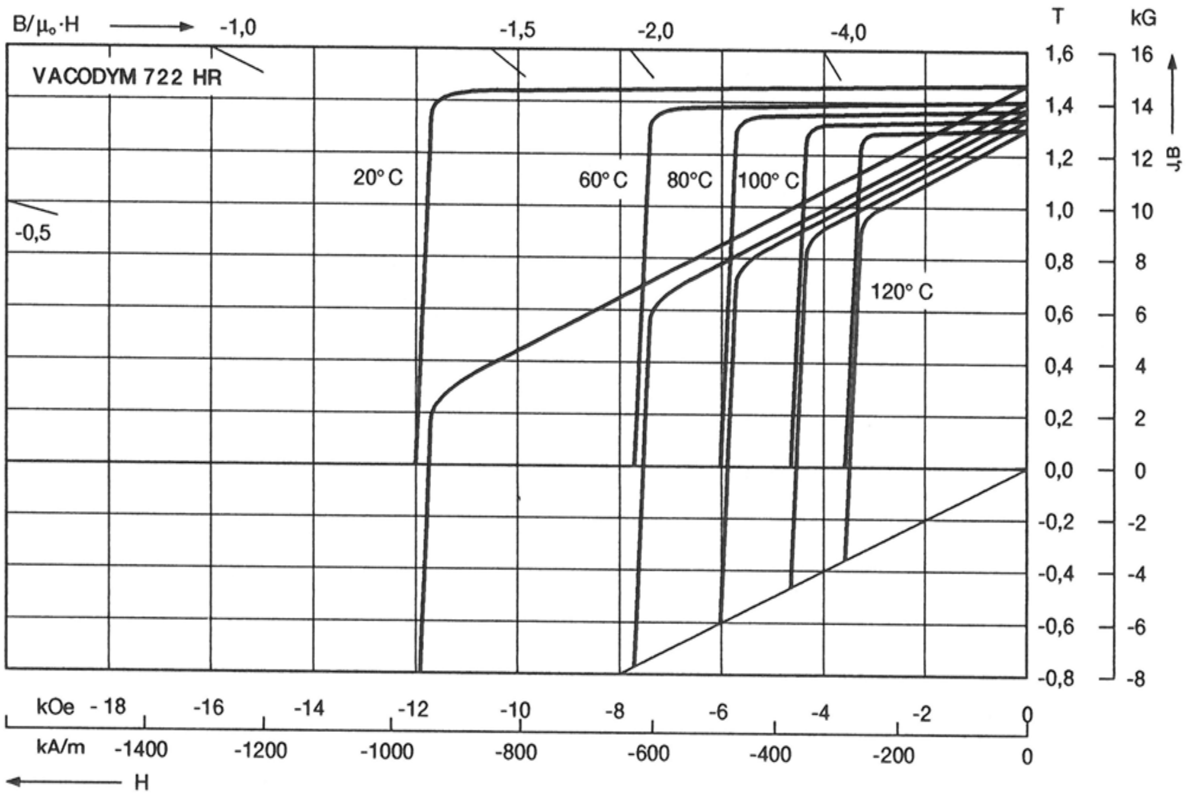
Sintered or melt spun NdFeB magnets



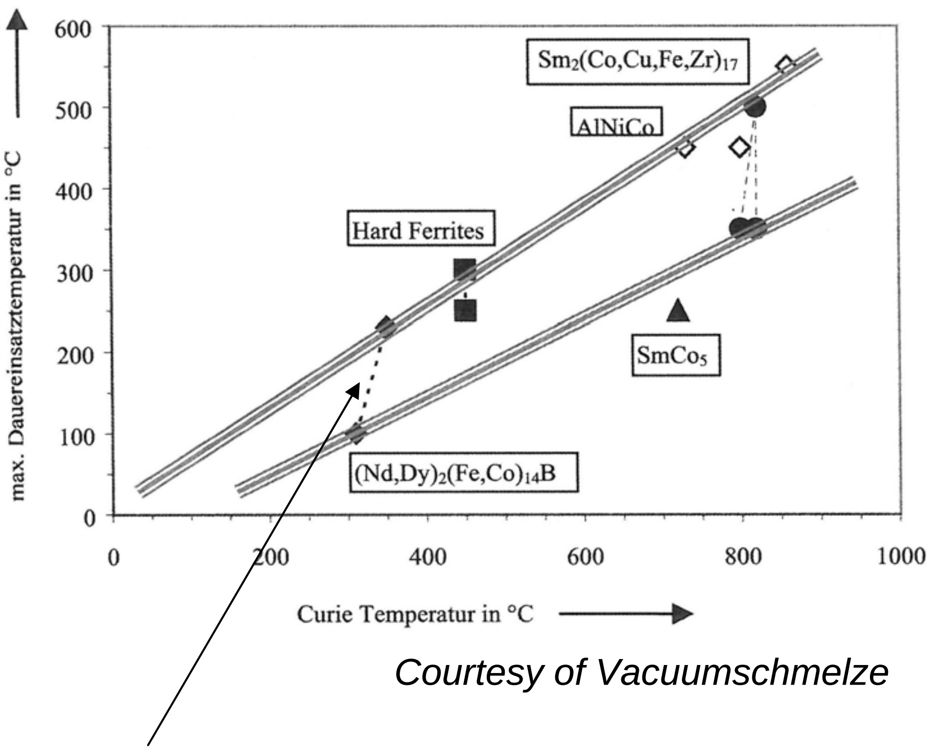
High remanence
$Nd_2Fe_{17}B$

B_r=1.47 T (typical)
H_{cj}=11 kOe (minimum)
TK (B_r) =-0,115
TK (H_{cj})=-0,77

Vacuumschmelze, Data leaflet
DM - VACODYM/VACOMAX , 2007

Curie Temperature

Material	Curie temperature (° C)
Iron	770
Cobalt	1130
Nickel	358
$Nd_2Fe_{14}B$	310
$SmCo_5$, Sm_2Co_{17}	700-800
35% Co Steel	890
CrFeCo	630
Alnico	850
Hard ferrites	400



Courtesy of Vacuumschmelze

max. temperature of pure NdFeB: 80°C
addition of Dy, Pr, Tb raises limit above 200°C

At the Curie temperature
the permanent magnet becomes paramegnetic and the remanence and coercivity get zero.

Permanent magnets are usually used up to 75% of the Curie temperature.

Modification of magnetic properties:

1) Moving the magnet within the linear part of hysteresis loop
   - varying the temperature below Curie temperature
   - applying a reverse field H > Hcj

2) Reversible demagnetization
   - heating above Curie temperature
   - applying high reverse fields H < Hcj
   - exposure to radiation (local demagnetization)

3) Irreversible demagnetization
   - modification of crystal structure
   - modification of specific phases of alloy
   - oxidation

⇒ Aging of magnets for critical applications:
- heating well above final operation temperature for a few hours
- applying reverse fields higher than maximum expected reverse fields

Compensation of Reversible Temperature Changes

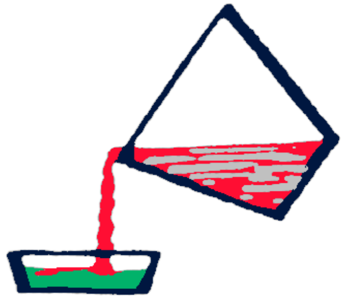
- Temperature dependent flux shunt (NiFe alloys, Curie alloys):
  permeability decreases with temperature
  e.g. calibration of speedometer

- Temperature dependent air gap
  e.g. permanent magnet accelerator components
  LNLS II Dipolmagnet

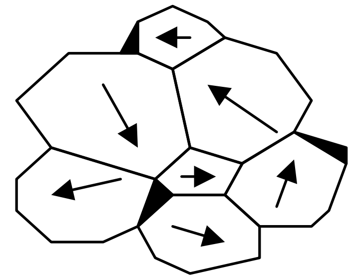
- Mixing of $SmCo_5$ with $ErCo_5$ and / or $GdCo_5$
  which have positive temperature coefficient

Fabrication of Sintered Permanent Magnets I

Production process as developed by SUMITOMO



Vacuum-Melting Casting



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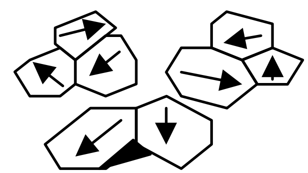
Crushing



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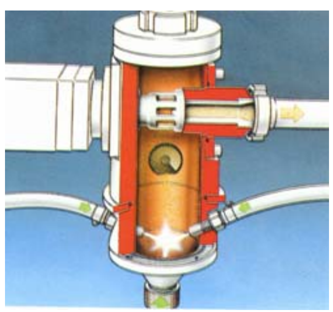
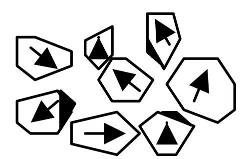


Milling



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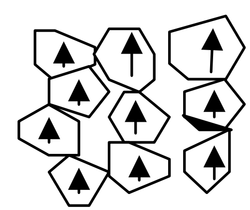
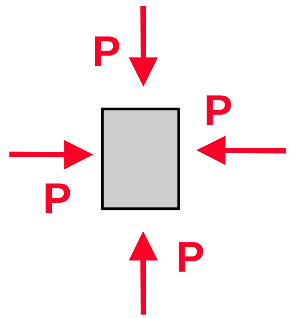
Aligning



Courtesy of Vacuumschmelze

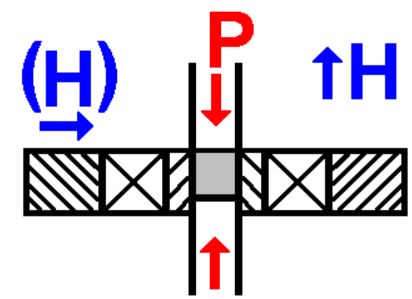
Fabrication of Sintered Permanent Magnets II

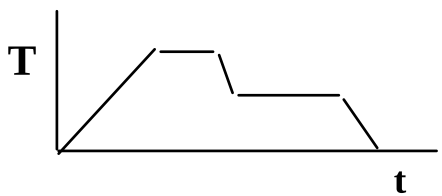


isostatic-pressing

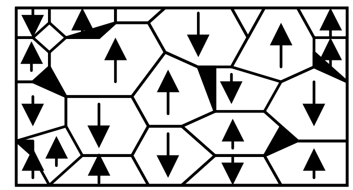
Pressing

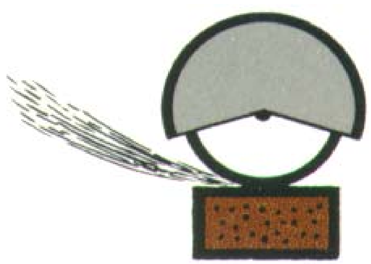
die-pressing



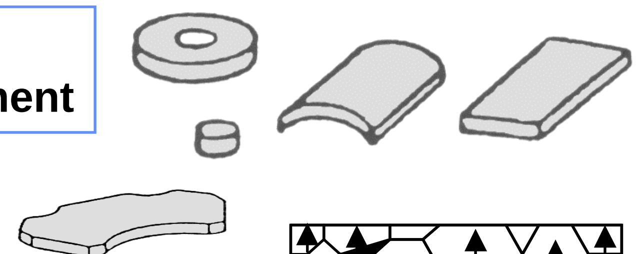


Sintering /Annealing

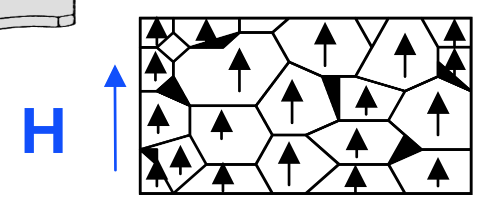




Machining/ Surface-Treatment



Magnetizing



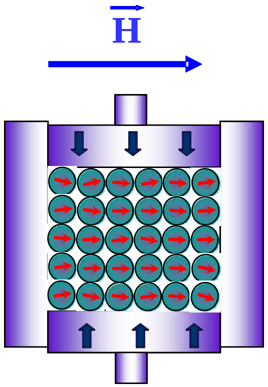
Courtesy of Vacuumschmelze

Pressing Technologies

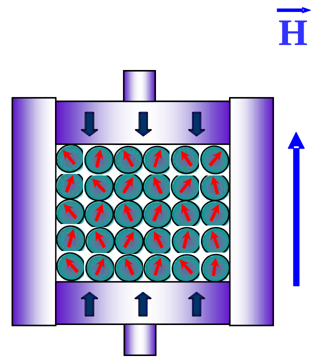
HELMHOLTZ ZENTRUM BERLIN für Materialien und Energie

Die pressed magnets

transverse pressing

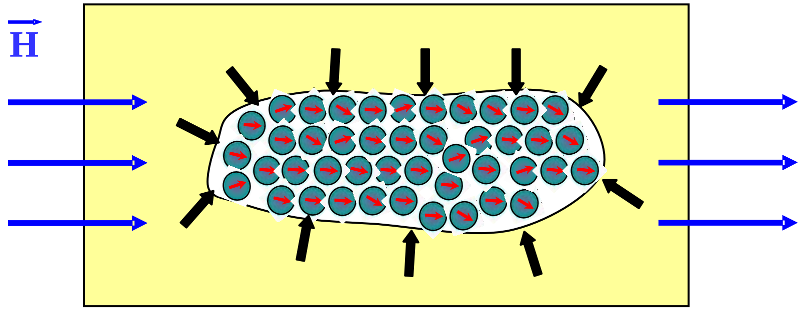


axial pressing



near net-shape production is cost effective

Isostatically pressed magnets



Cold isostatic pressing CIP
Rubber isostatic pressing RIP (*M. Sagawa*)

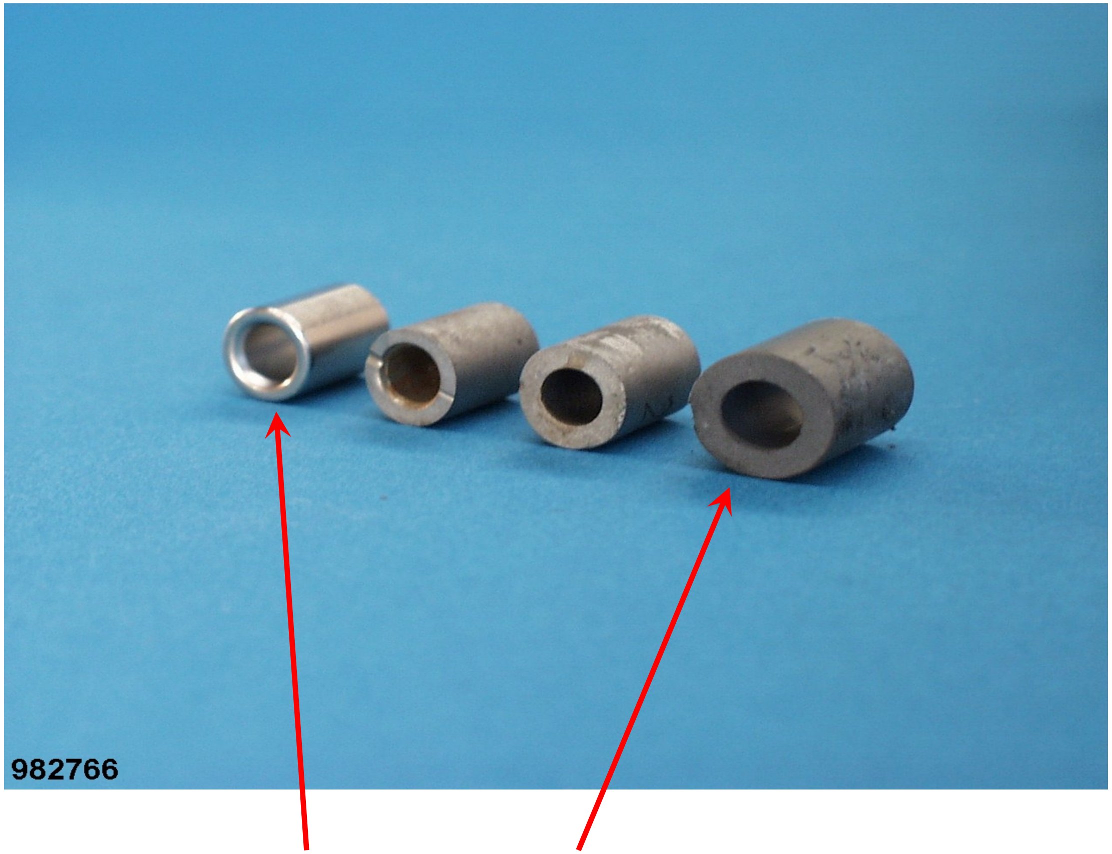
Properties:

Remanence:
isostatic > transverse > axial
2% 4%

Dipole errors:
isostatic > transverse, axial

Higher order multipoles:
transverse, axial > isostatic

Sintering



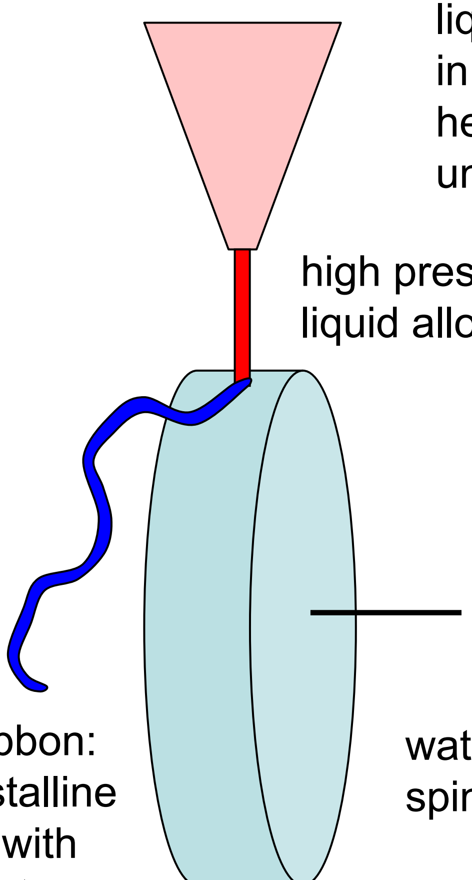
after before sintering

15 - 20% shrinking
has to be regarded when
- designing the pressing die
- aiming for easy axis
  orientatiopns not equal
  0° or 90°

Courtesy of Vacuumschmelze

Melt Spun Process: Magnequench Magnets

Invented and developed by General Motors in 1984



Three types,
based on ribbon material:

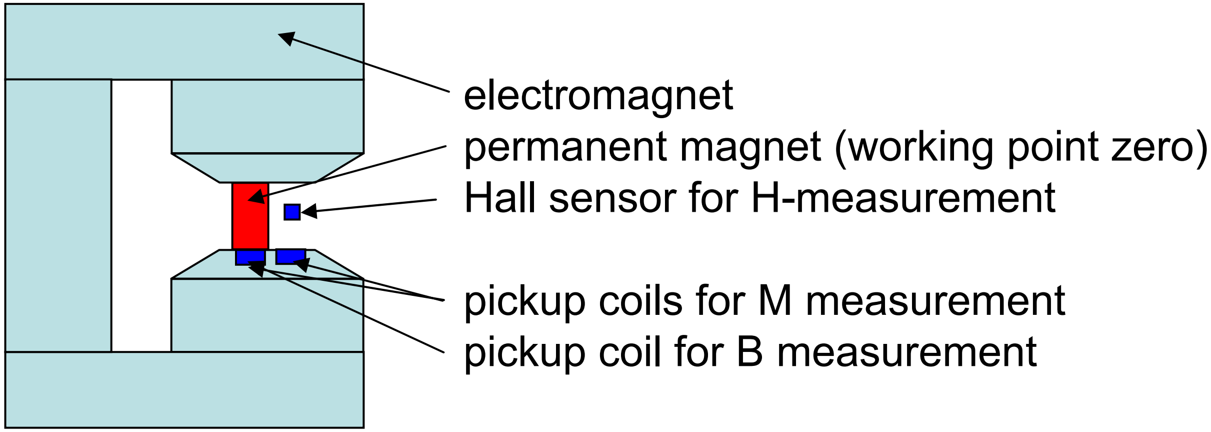
Magnequench I:
matrix or bonded version
isotropic

Magnequench II:
hot pressed dense magnet
isotropic

Magnequench III:
hot deformation of
Magnequench II
anisotropic;
this material has the
highest energy product

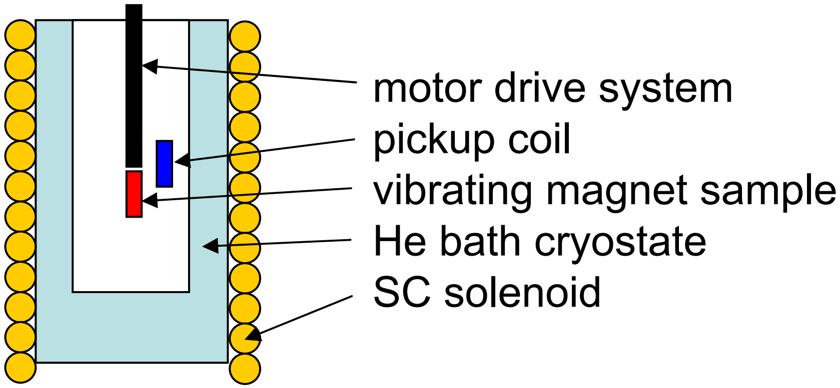
HELMHOLTZ ZENTRUM BERLIN für Materialien und Energie

Closed circuit measurment: Permagraph



Open circuit measurement: Vibrating sample magnetometer

Demagnetization factors have to be regarded!



Magnetizing force H of two parallel coils:

$$H = \frac{2NI}{a}\left[\left(1+\frac{(d/2-x)^2}{a^2}\right)^{-1.5} + \left(1+\frac{(d/2+x^2)}{a^2}\right)^{-1.5}\right]$$

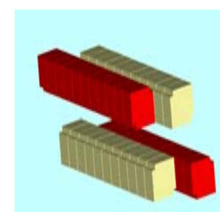
d = distance of coils
a = radius of coils
quadratic terms disapperas if d = a

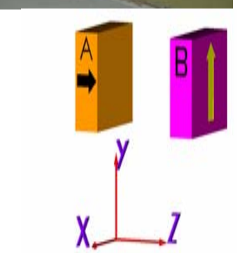
⇨ Helmholtz coil arrangement

measurement of dipole with high accuracy
insensitive on
- displacement of magnet block in the coil
- size of magnet block

Automated Helmholtz Coil at HZB:

APPLE II

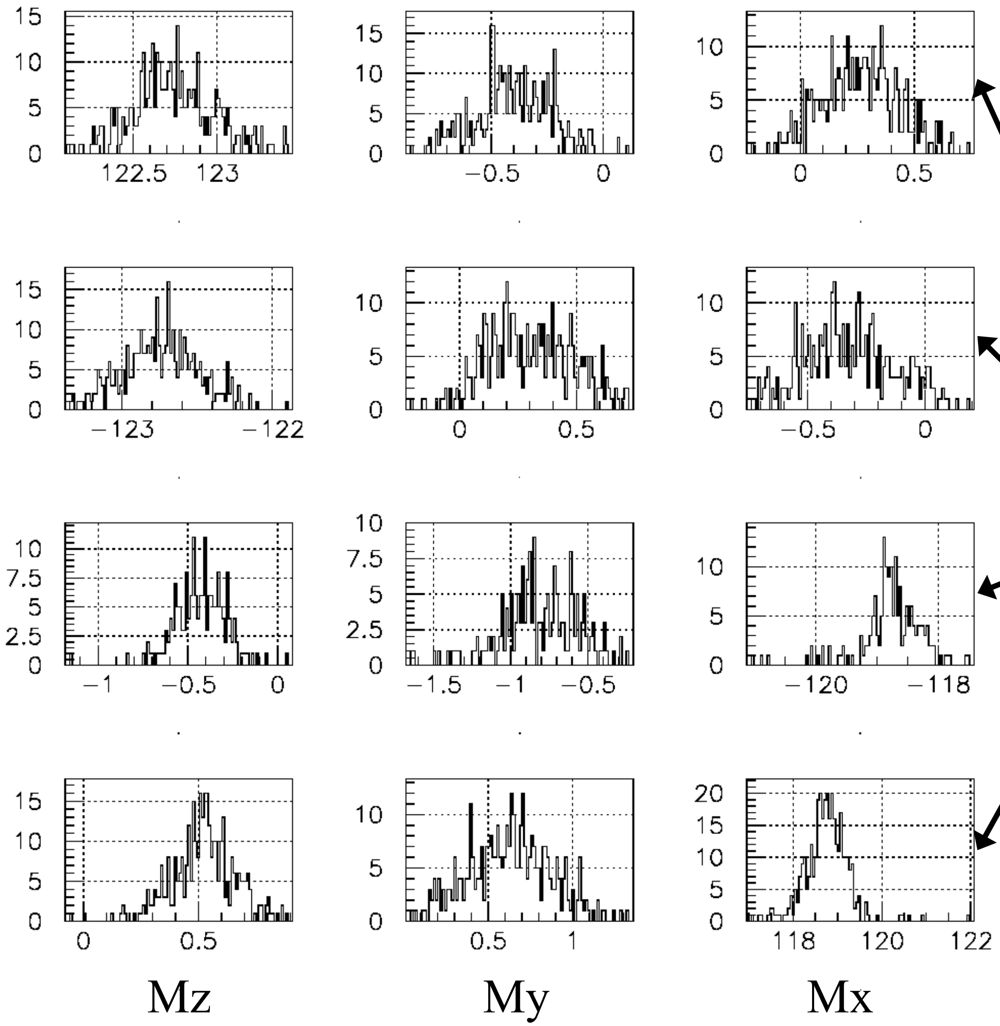




reproducibilities

	Mz	My	Mx
A-magnets	**< 0.07 %**	**< 0.04 deg.**	**< 0.04 deg.**
B-magnets	**< 0.04 deg.**	**< 0.08 deg.**	**< 0.07 %**

⇨ **Data are important but not sufficient for prediction of field integrals**

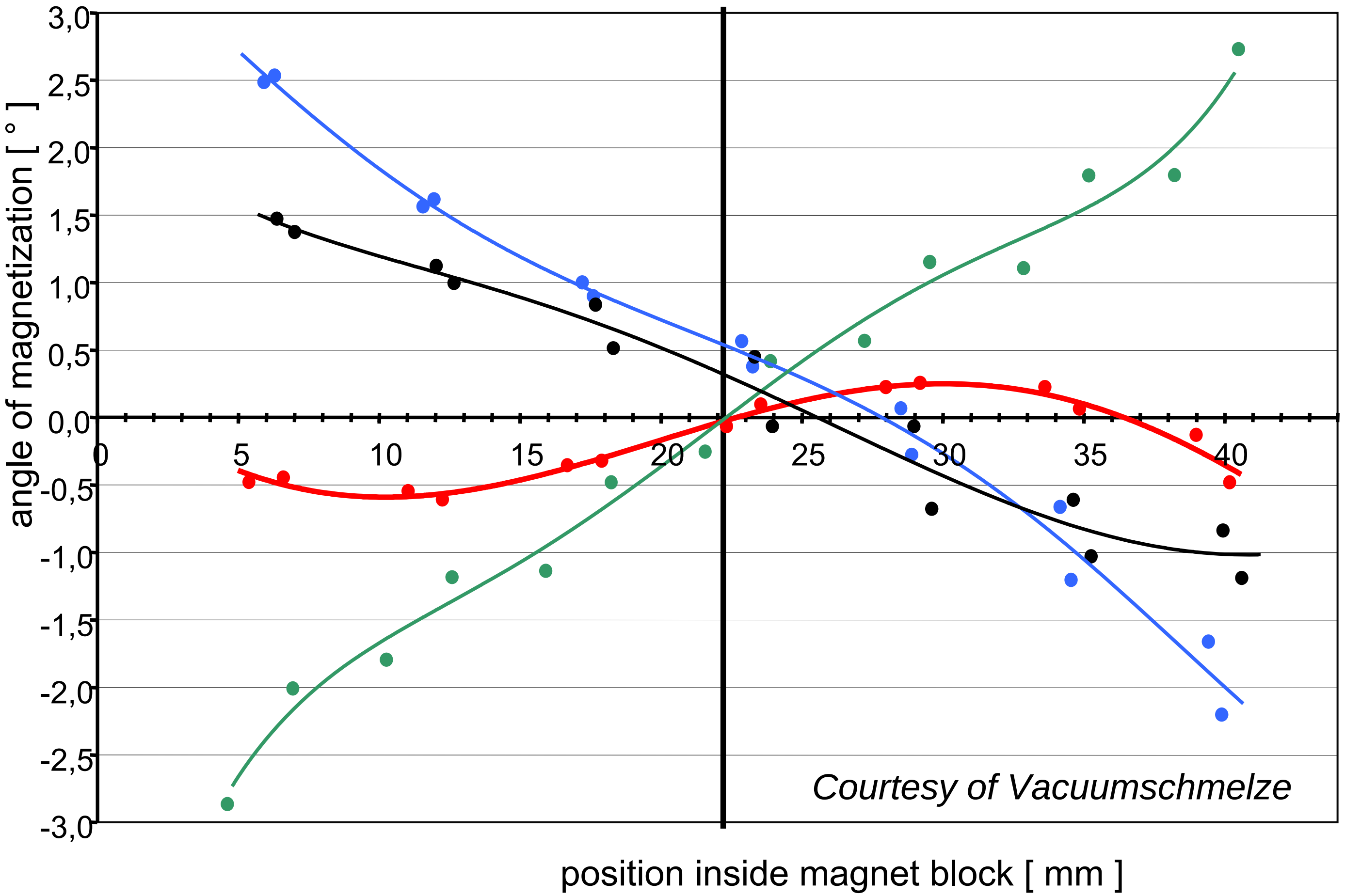


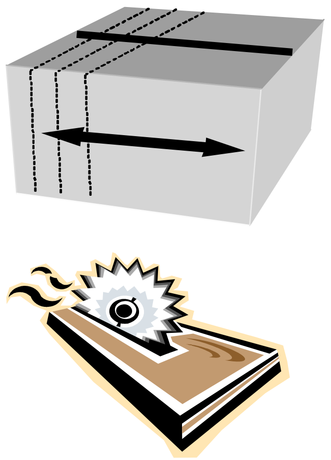
random dipole erors are small:

Type	Mz	My	Mx
AN	122.73	-0.36	0.26
σ	0.25	0.17	0.17
AS	-122.75	0.30	-0.33
σ	0.27	0.22	0.23
BN	-0.44	-0.88	-118.66
σ	0.13	0.36	0.4
BS	0.53	0.63	118.78
σ	0.14	0.26	0.39

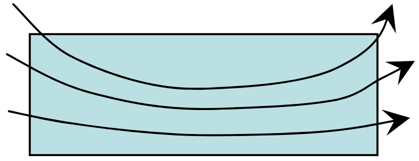
but: systematic dipole errors (offset)

Inhomogeneity Distribution Inside a Magnet I





slices measured in Helmholtz coil

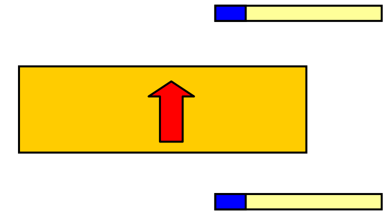


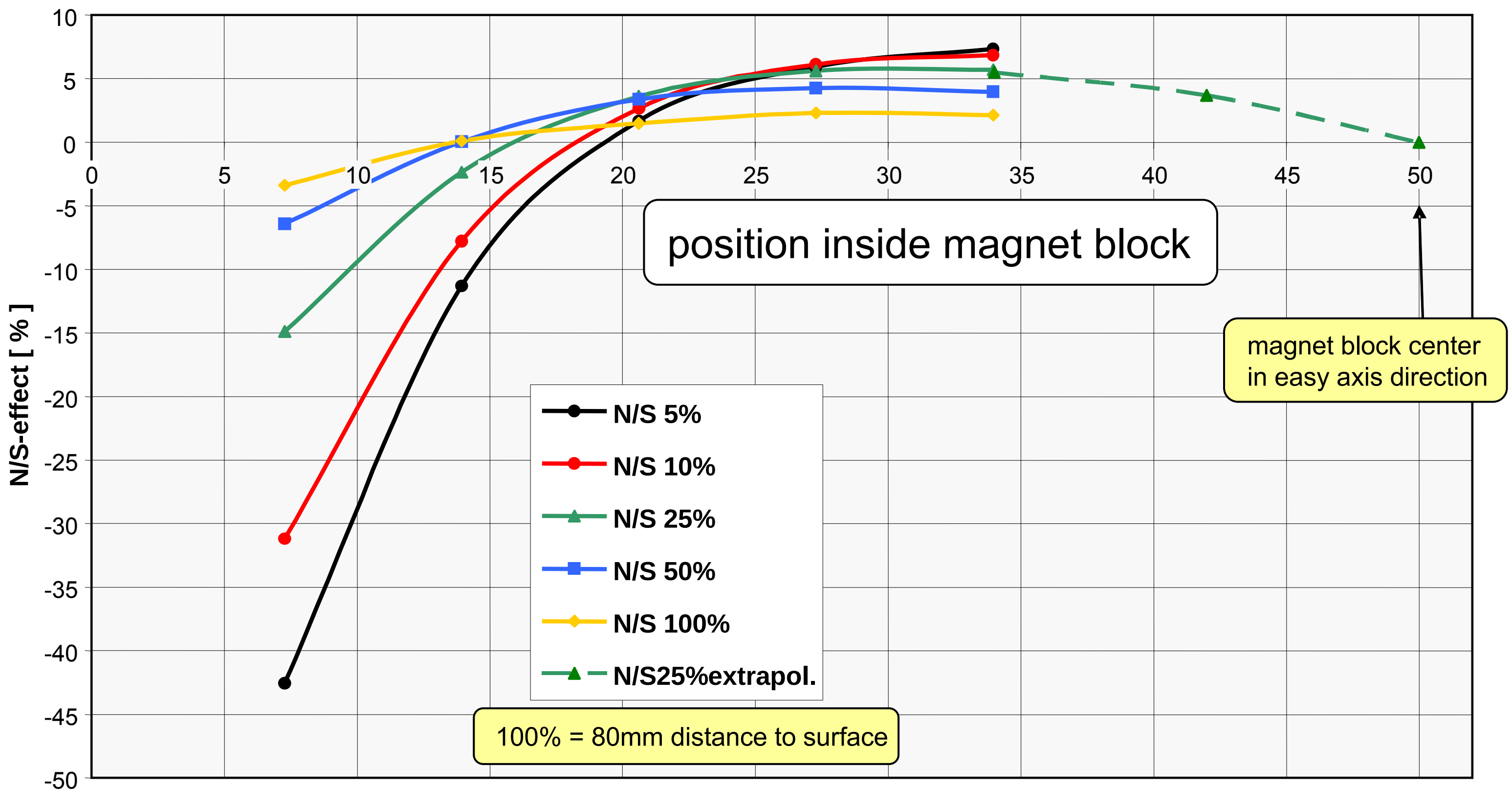
example of an inhomogenious magnet block

The different colours represent different pressing geometries

Rough estimate of magnet inhomogeneity:
North / South pole effect
Measred with a Hall probe

$$N/S - effect = \frac{B_N - B_S}{2(B_N + B_S)}$$





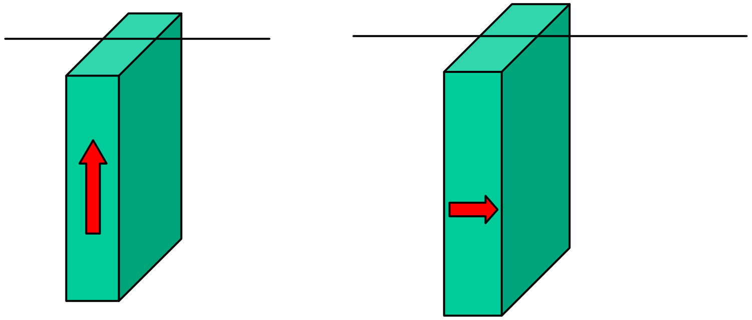
Courtesy of Vacuumschmelze

Detailed knowledge on the block inhomogeneities is essential for an effective sorting

stretched wire system for characterization of inhomogeneities

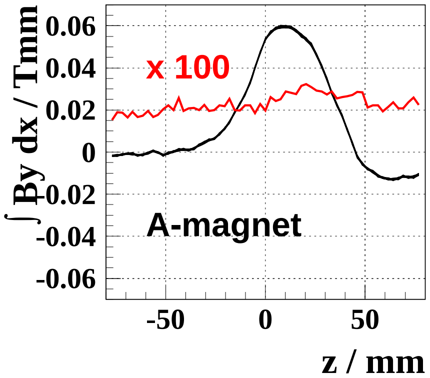
reproducibility:

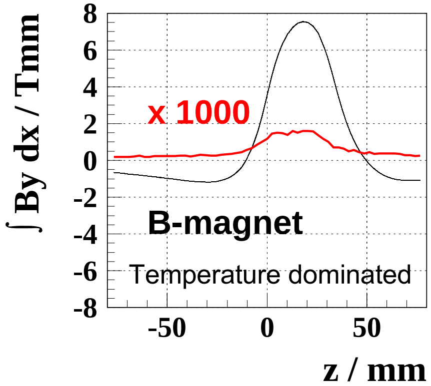
A-magnets:	2.0×10^{-4} Tmm
	3.0×10^{-4} rel.
B-magnets:	1.5×10^{-3} Tmm
	2.1×10^{-4} rel.



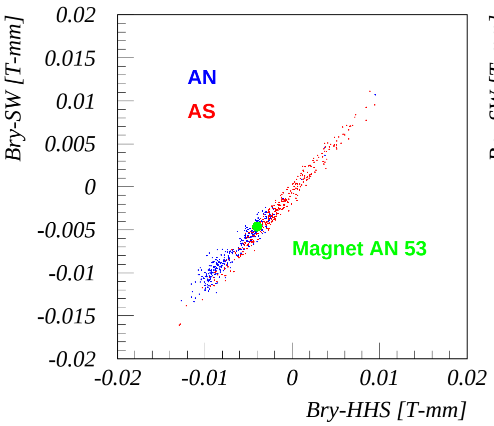
type B magnet

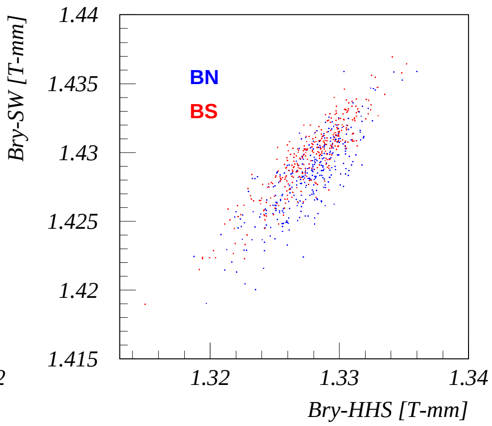
type A magnet

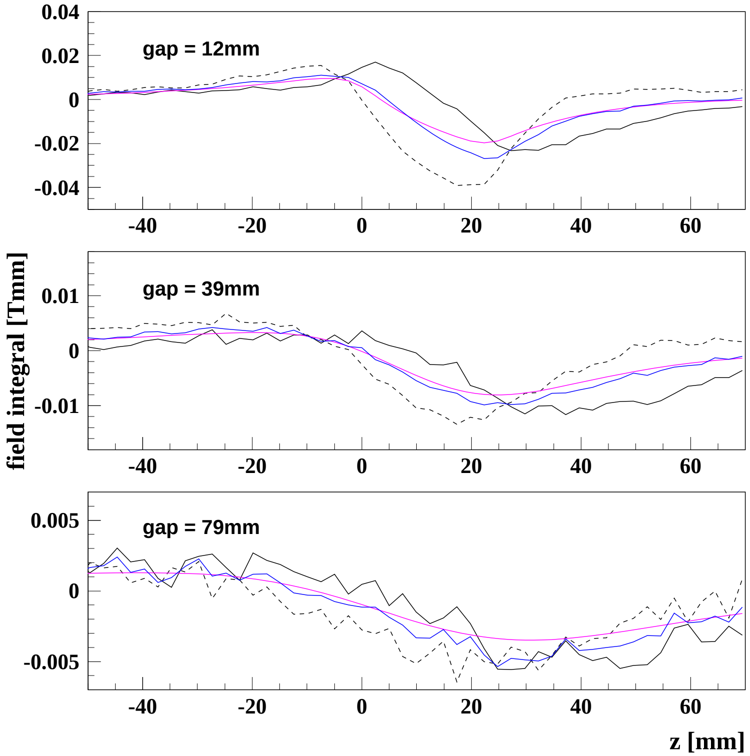




UE-65 Magnet Block Inhomogeneities I





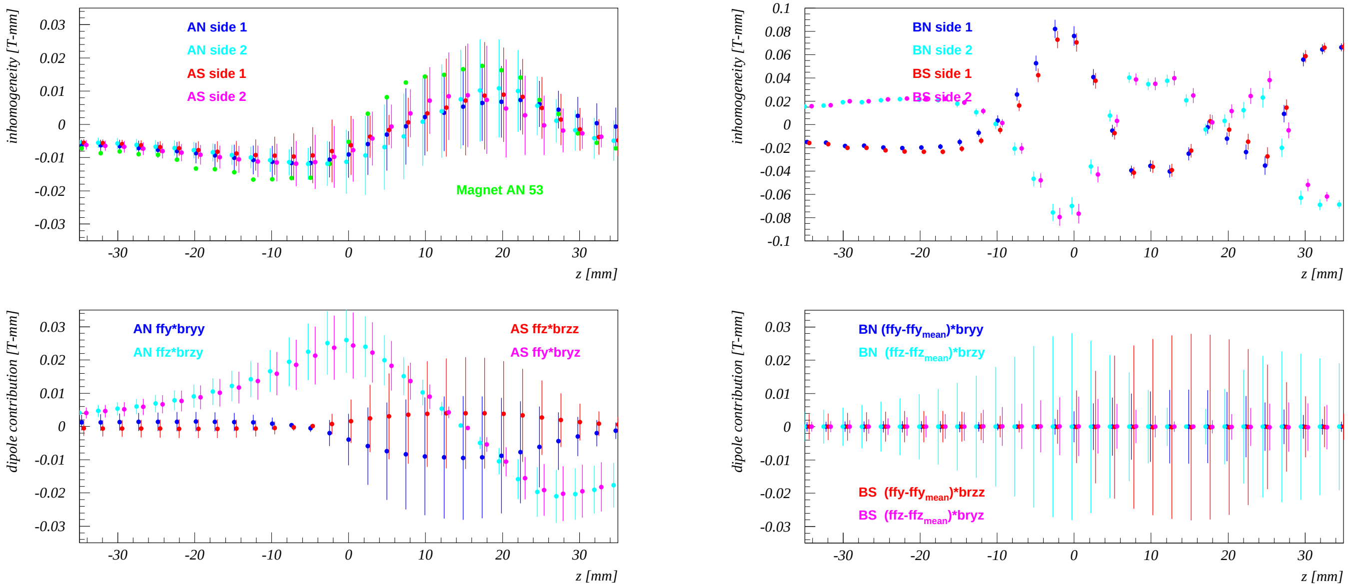


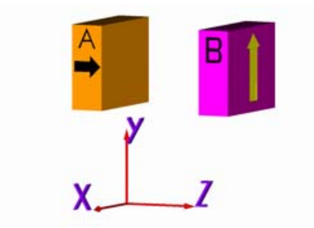
Close correlation between vertical dipole component as measured with the Helmholtz coil (HHS) and the stretched wire system (SW), respectively.

Field integrals measured at two opposite sides of magnet AN 53 (black solid and black dashed (sign reversed)). The average (blue) reproduces the data extrapolated from dipole data (magenta) as measured with the Helmholtz coil.
Inhomogeneities are important even at large gaps.

J. Bahrdt et al., Proc. of EPAC, Genoa, Italy, 2008.

UE-65 Magnet Block Inhomogeneities II





Statistics of 1200 magnets: averaged field integrals and two sigma values

Magnet quality of A-magnets: Dipole and higher order errors of same order

Magnet quality of B-magnets: Higher order multipoles much larger than dipole errors

Systematic effects are due to magnet fabrication process.
These terms can be compensated with appropriate magnet pairing.

Handling of Large Batches of Magnets e.g. for European XFEL

One XFEL undulator requires approximately 20to of magnet material
typical batch size is 1-2 to.
sophisticated mixing strategy is essential for constant magnet properties