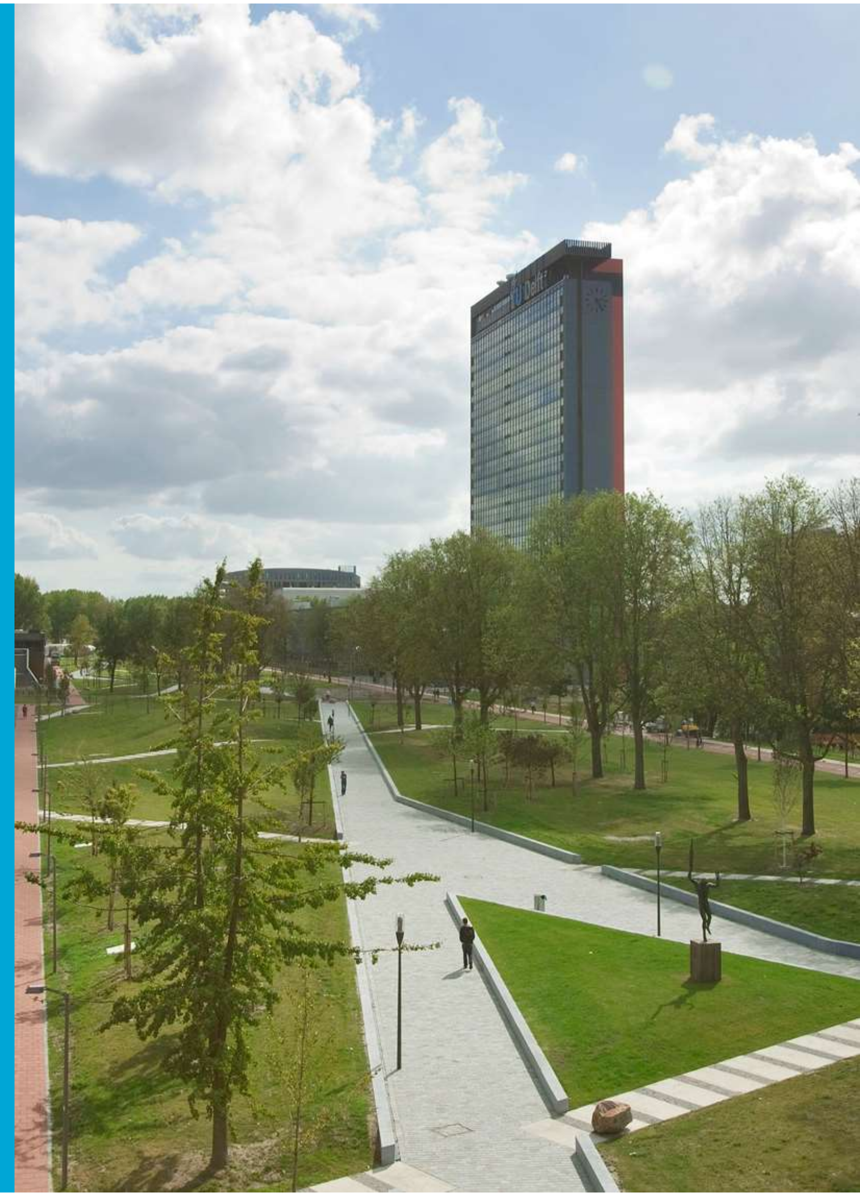
Permanent Magnets

Ekkes Brück



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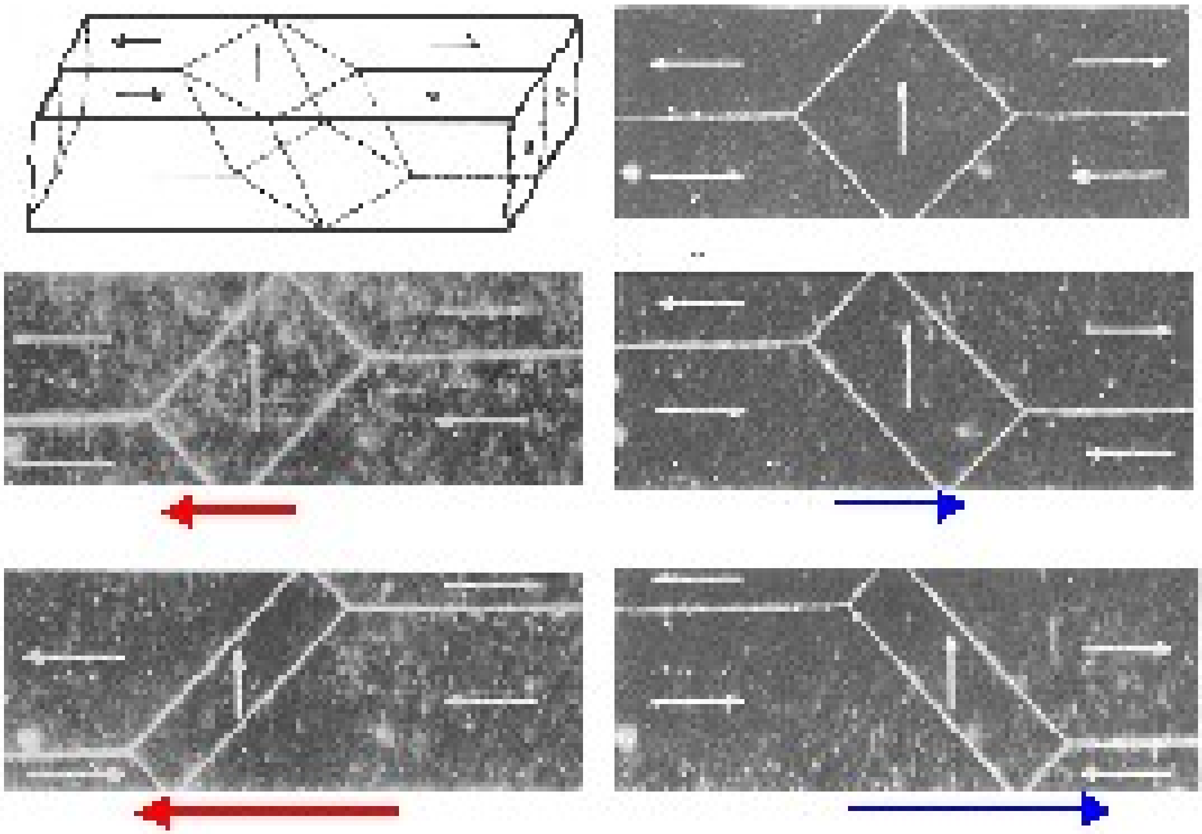
Permanent Magnets Indispensable for:

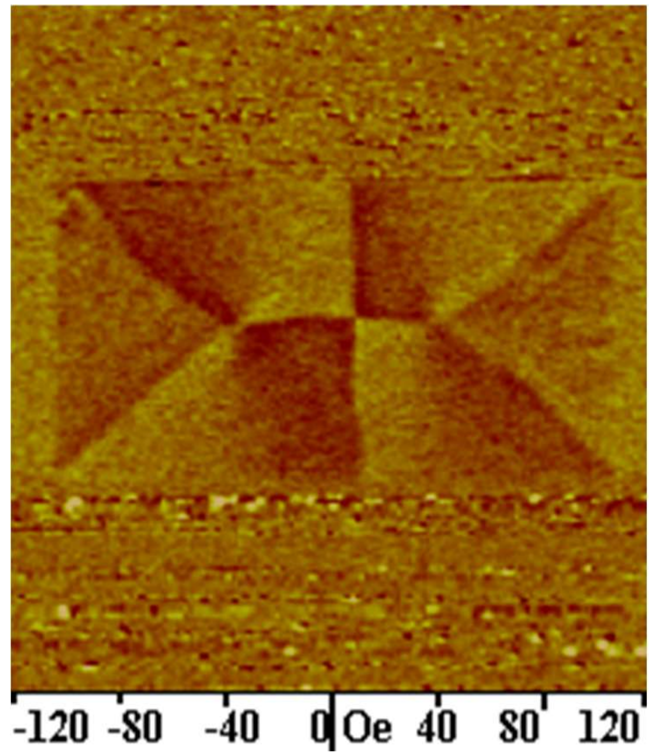
- Conversion of mechanical into electrical energy or vice versa: Windpower, speakers
- Exerting a force on magnetically soft body: Relays, waste separation
- Alignment with respect to a field: Compass, stepping motor
- Exerting a force on moving charge carriers: Magnetron, Hall sensors

Magnetization processes

Ferromagnetic domains

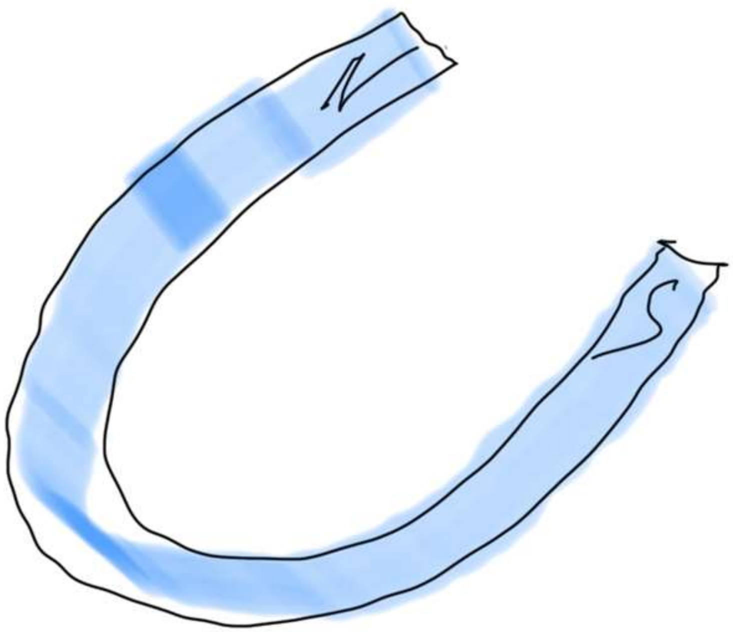
www.ee.umd.edu/~rdgomez/permalloy.htm





9550 A/m

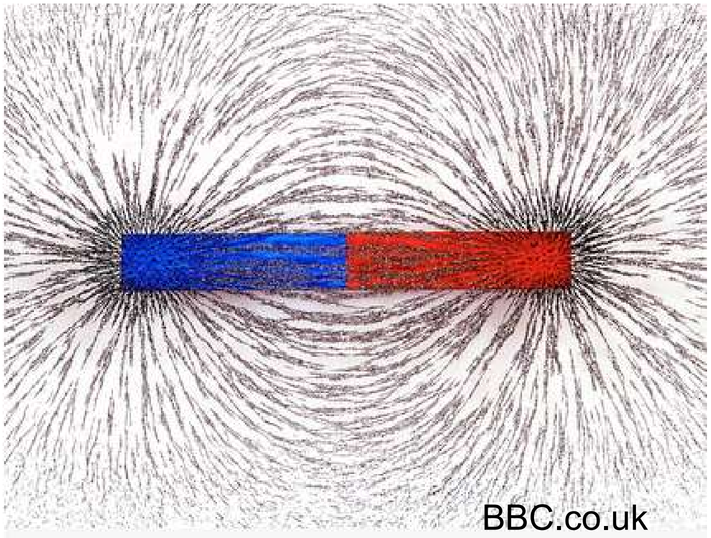
Why do magnets often look like a horseshoe?



Reduce shape dependent demagnetizing field

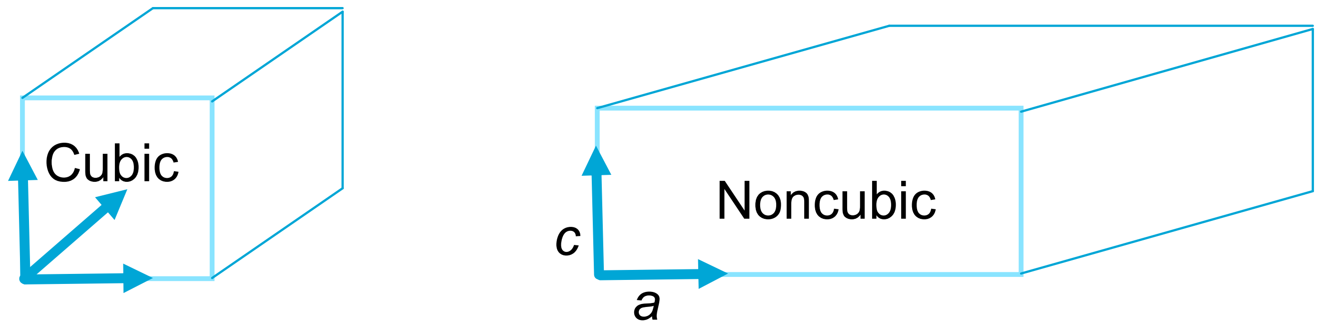
Acting in opposite direction to magnetization.

The longer the magnet the lower it is.



Isotropic (Exchange) Curie temperature

Anisotropic (Spin-orbit coupling)



Anisotropy energy

$$E_A(\theta,\varphi) = K_1 \sin^2\theta + K_2 \sin^4\theta + K_3 \sin^4\theta \cos^4\varphi + \ldots$$

Easy axis for $K_1>0$ and $K_1 \gg |K_2|$

Hard Magnetic materials

Compound	Structure	M_S (T)	Curie T_C (^oC)	K_1 (MJ/m^3)
Co	Hexagonal	1.76	1115	0.53
FePt	Tetragonal	1.43	477	6.6
CoPt	Tetragonal	1.00	567	4.9
Co_3Pt	Hexagonal	1.38	727	2.0
MnAl	Tetragonal	0.62	377	1.7
MnBi	Hexagonal	0.78	357	1.2
$BaFe_{12}O_{19}$	Hexagonal	0.48	450	0.33
Zr_2Co_{11}	orthorhombic	0.52	500	(H_A = 3.4 T)
ε-Fe_2O_3	Orthorhombic	0.10		(H_c = 2.34 T)
$SmCo_5$	Hexagonal	1.14	681	17.0
$Nd_2Fe_{14}B$	Tetragonal	1.60	312	5.0

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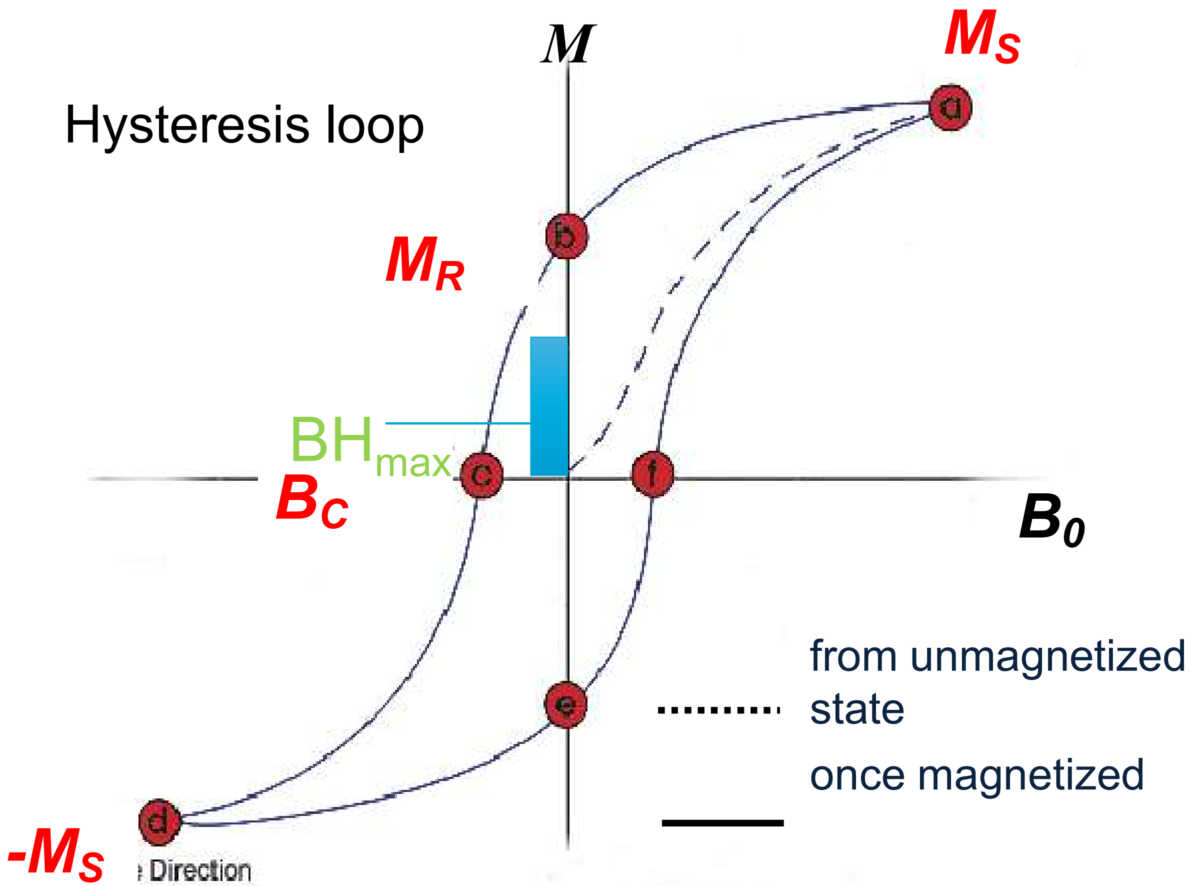
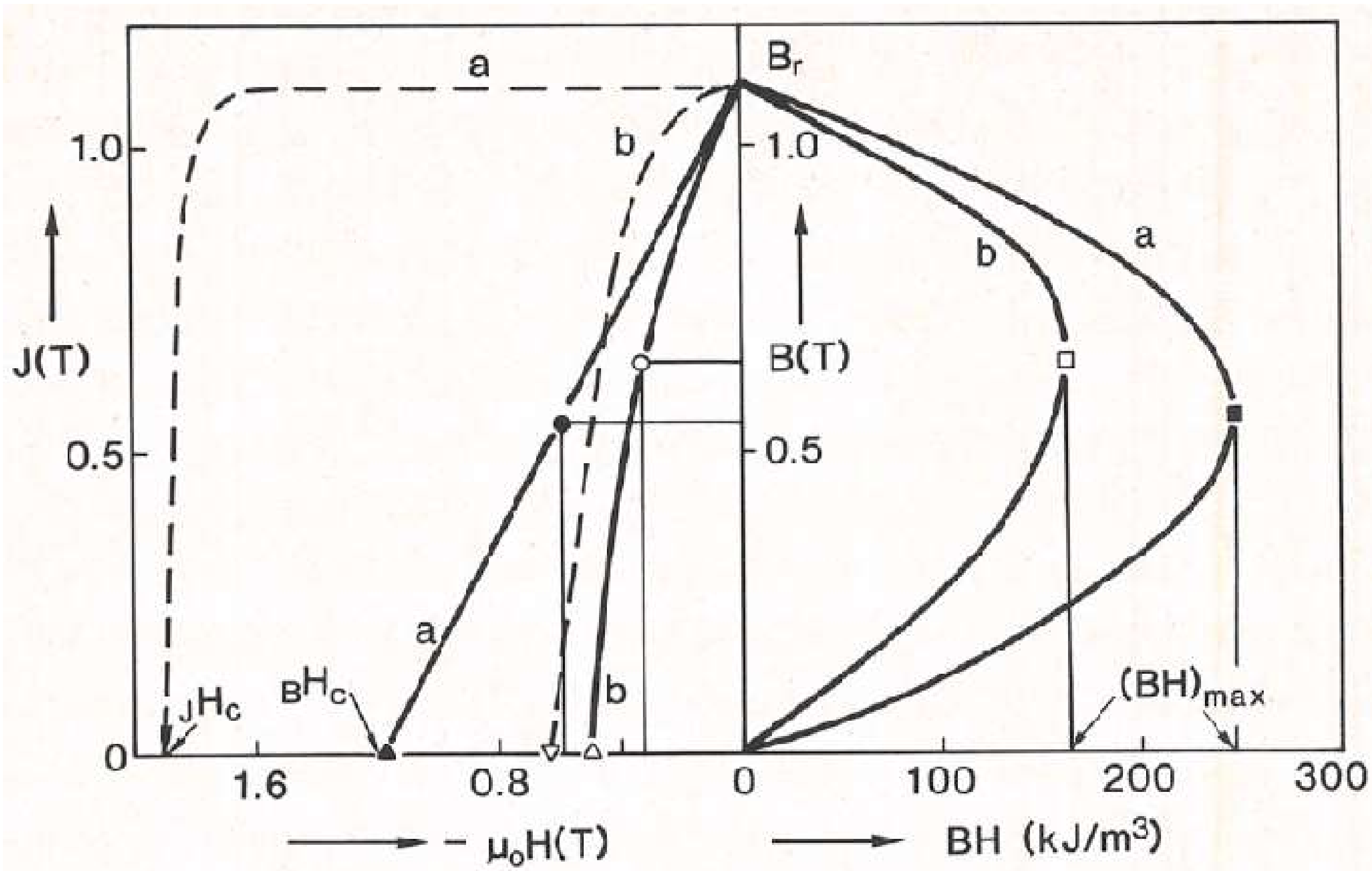
Permanent magnets



BH_{max} determination



K.H.J. Buschow Ferromagnetic Materials Vol. 4

Hard vs soft magnets

	hard	soft
Sat. magnetization	large	large
remanence	large	small
Coercive field	large	small
Hysteresis loop	square	narrow
Crystal symmetry	uniaxial	Cubic, amorphous
elements	Co, Fe, RE, $SrFe_{12}O_{19}$	Ni, Fe, $(Mn,Zn)Fe_2O_4$

Permanent magnets units

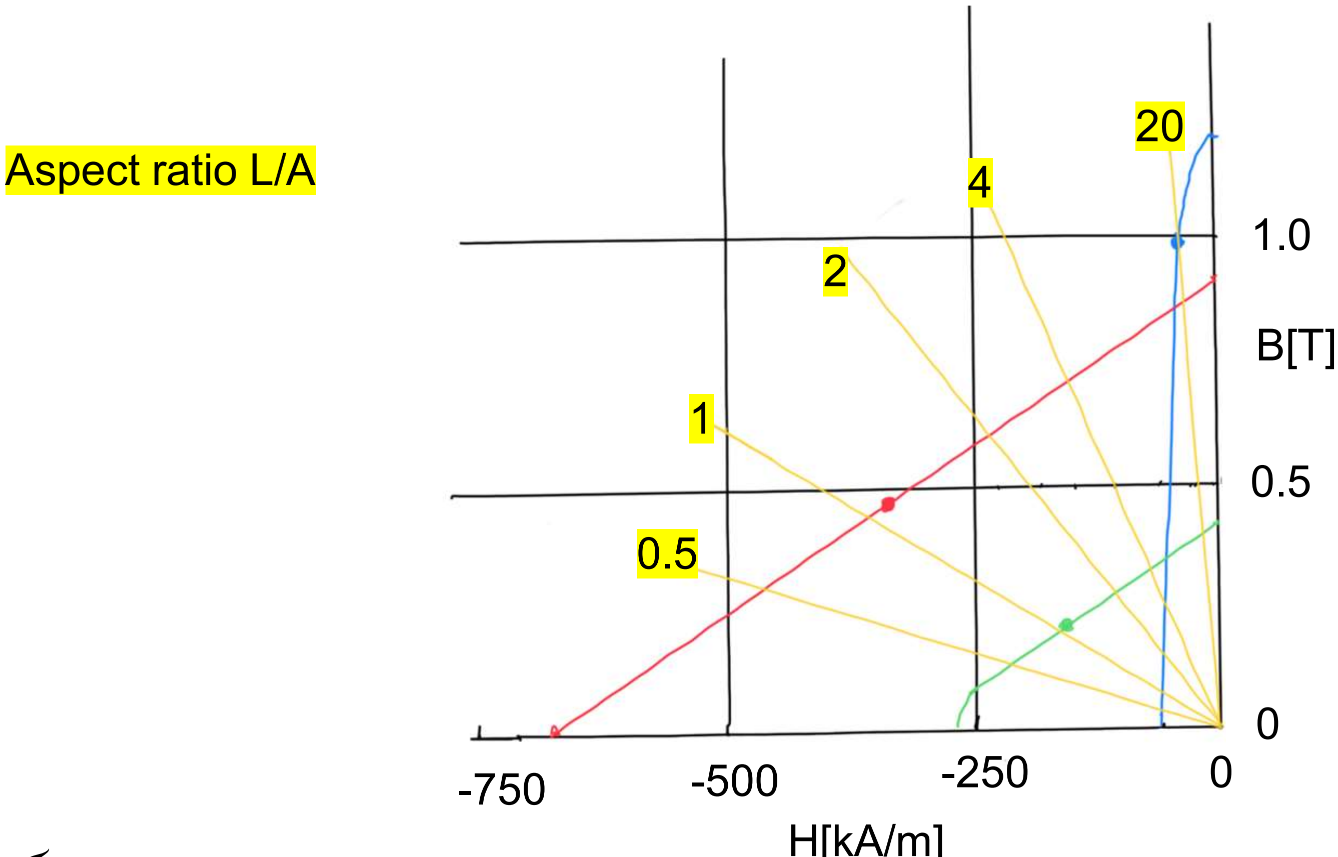
- Magnetic Field or Magnetization

μ_0H or μ_0M (T)	H or M (G)	H or M (A/m)	H (Oe)	M (emu/cc)
1	10 kG	796 kA/m	10 kOe	796
0.00126	12.6	1 kA/m	12.6	1

- Maximum Energy Density $(BH)_{max}$

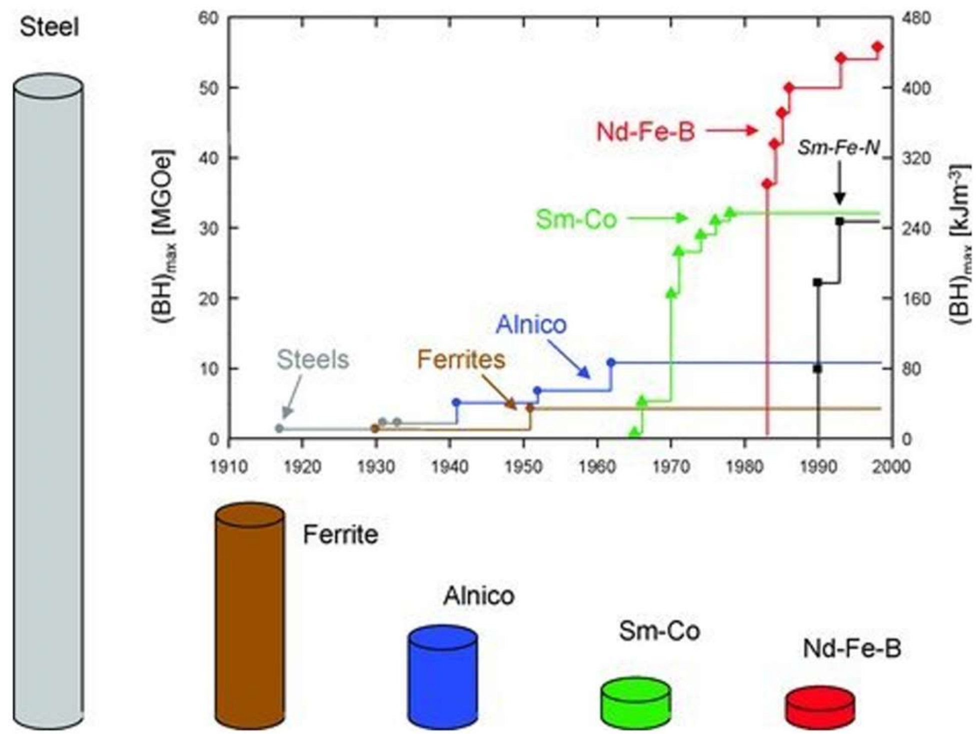
1 MGOe	**7.96 kJ/m³**
1 kJ/m³	0.126 MGOe

Demagnetizing curve of AlNiCo, hard ferrite & $SmCo_5$

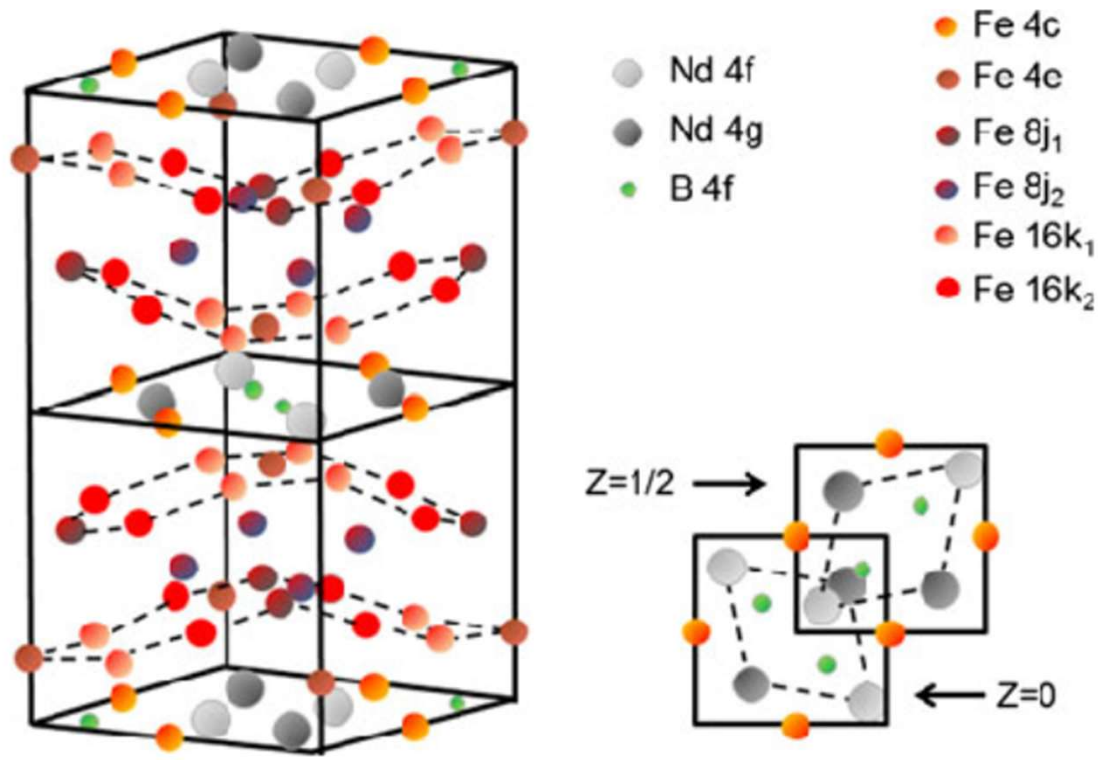


Adopted from H. Stäblein Ferromagnetic Materials Vol. 3

Permanent magnet development



$Nd_2Fe_{14}B$ structure



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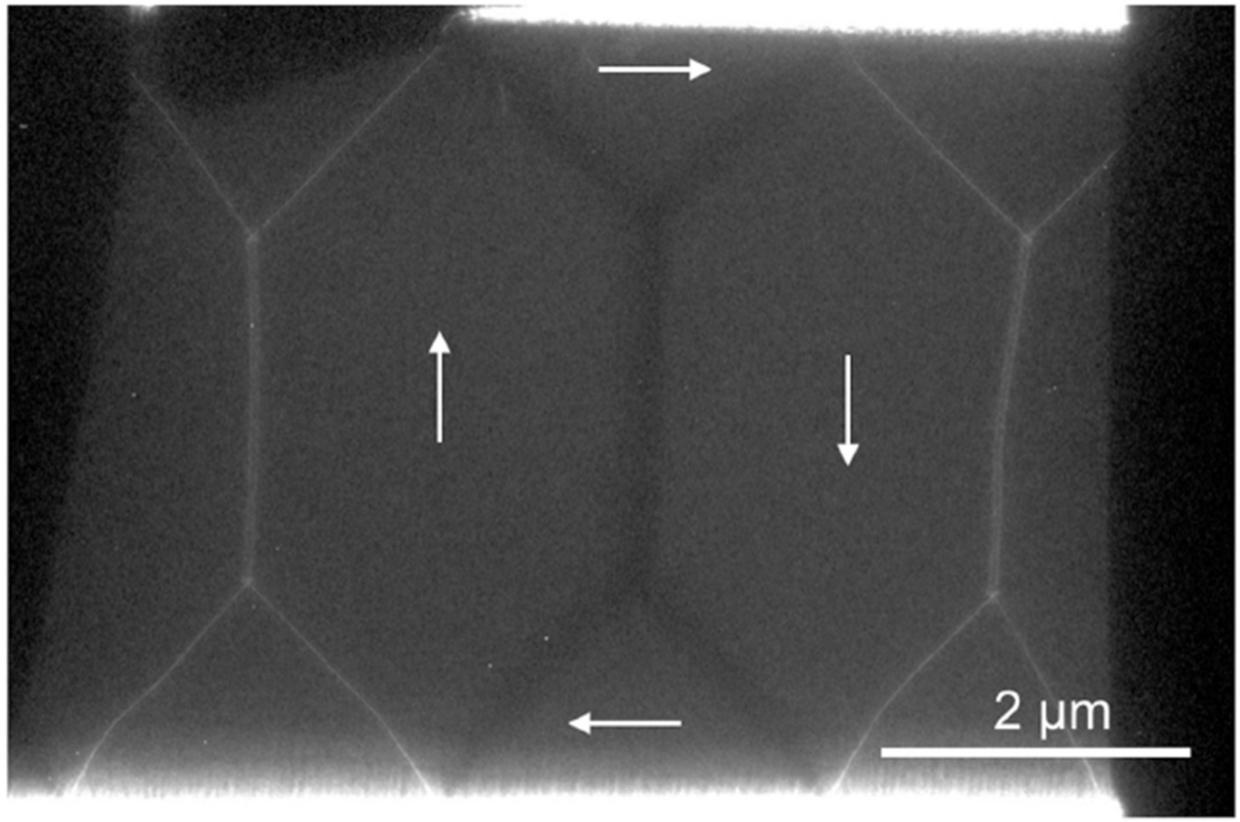
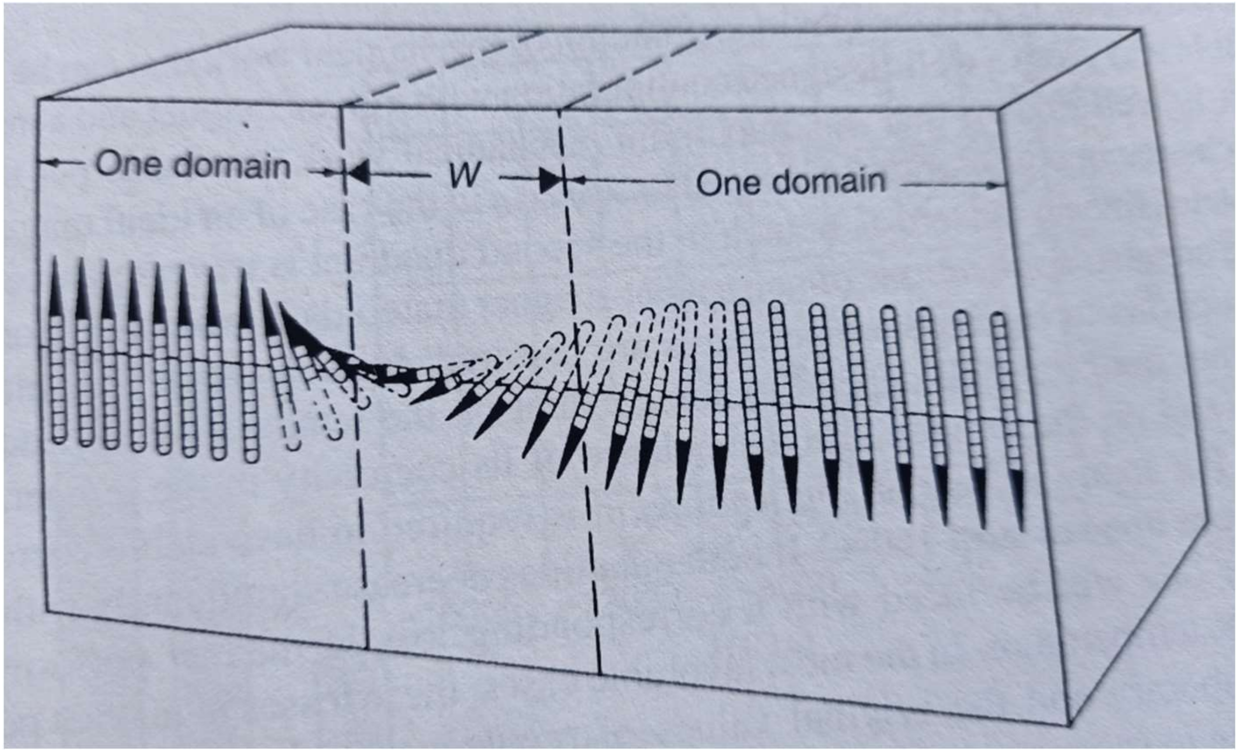
F. Jimenez-Villacorta

Magnetic domains



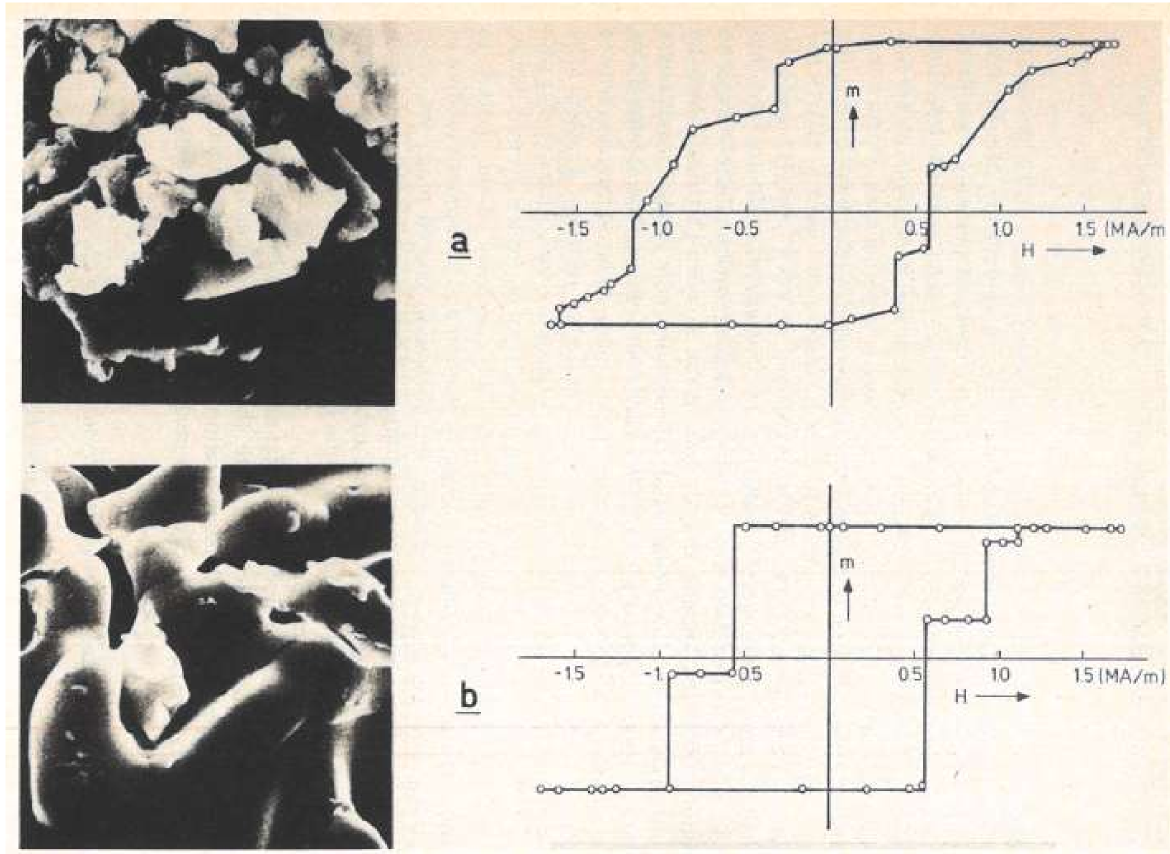
2016 AIP Advances 6: 056501.

180º Bloch wall



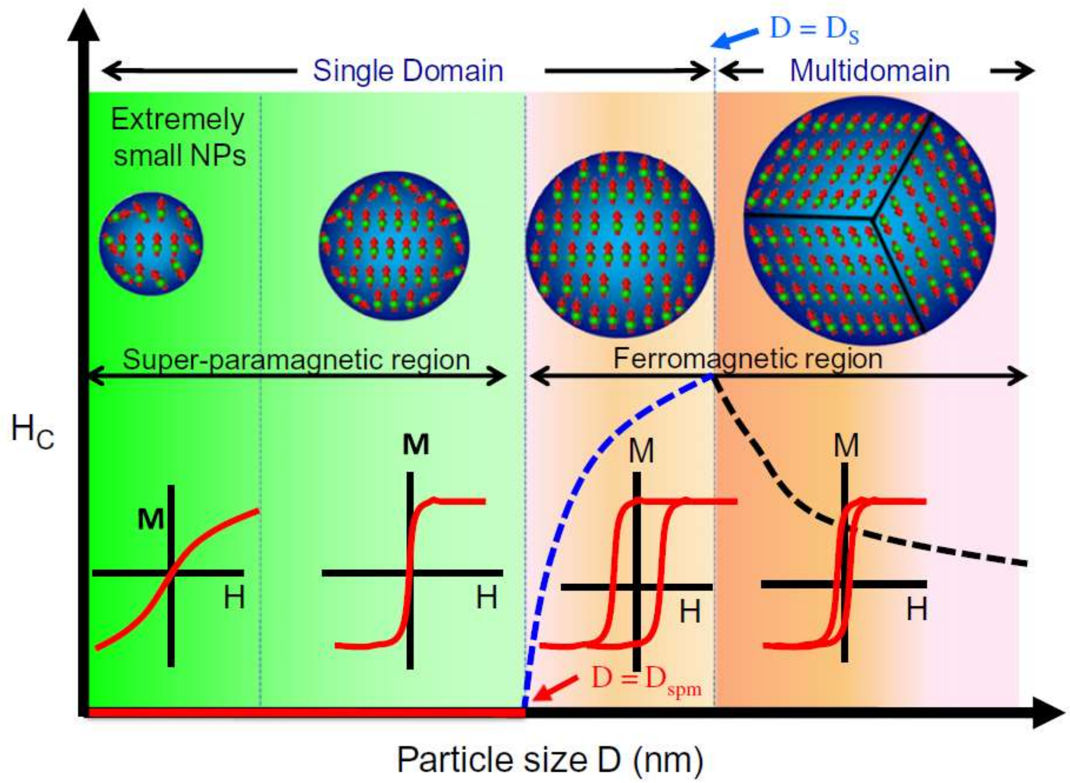
Nucleation of domain walls

- Sharp edges facilitate nucleation



H. Zijlstra Ferromagnetic Materials Vol. 3

Particlesize-dependent magnetic response



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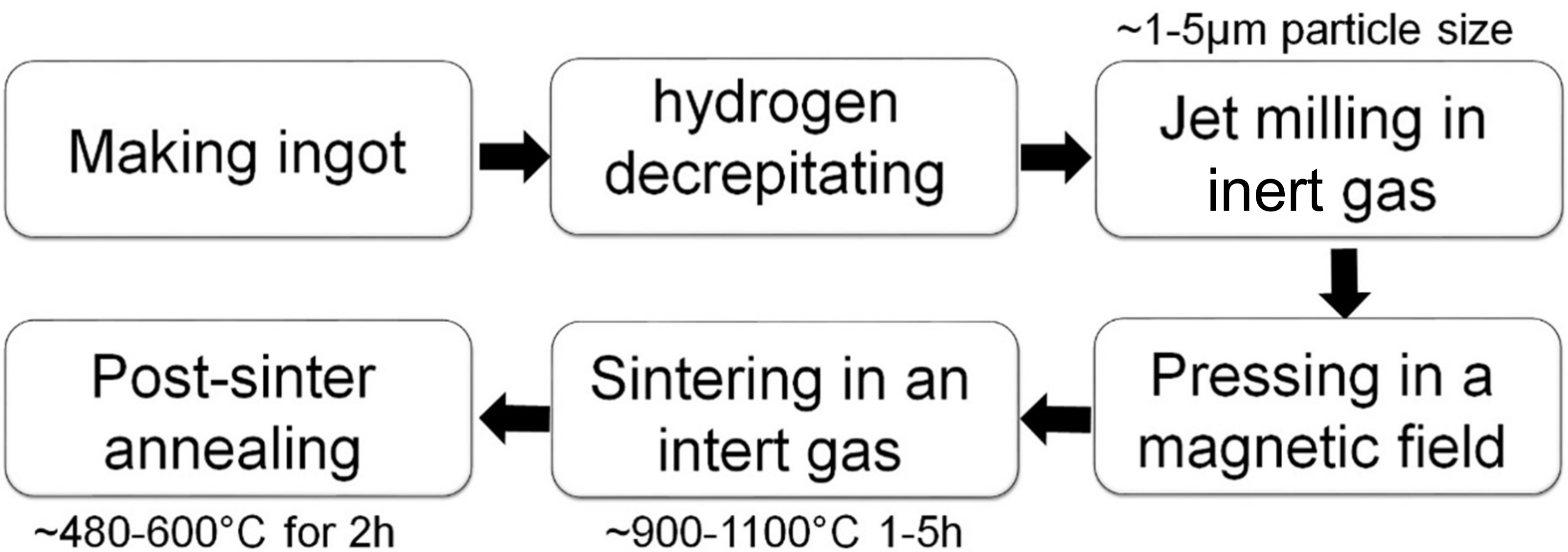
NdFeB sintered magnets



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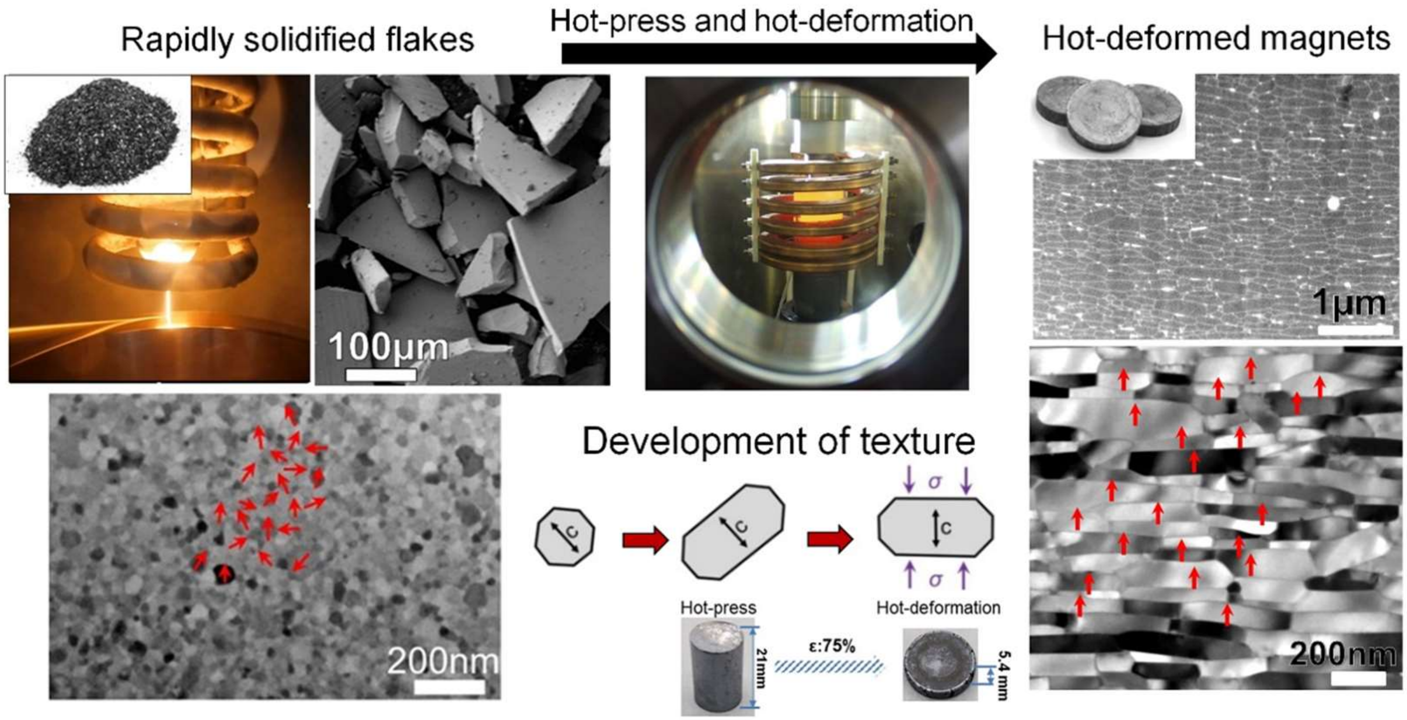
NdFeB hot deformed magnets



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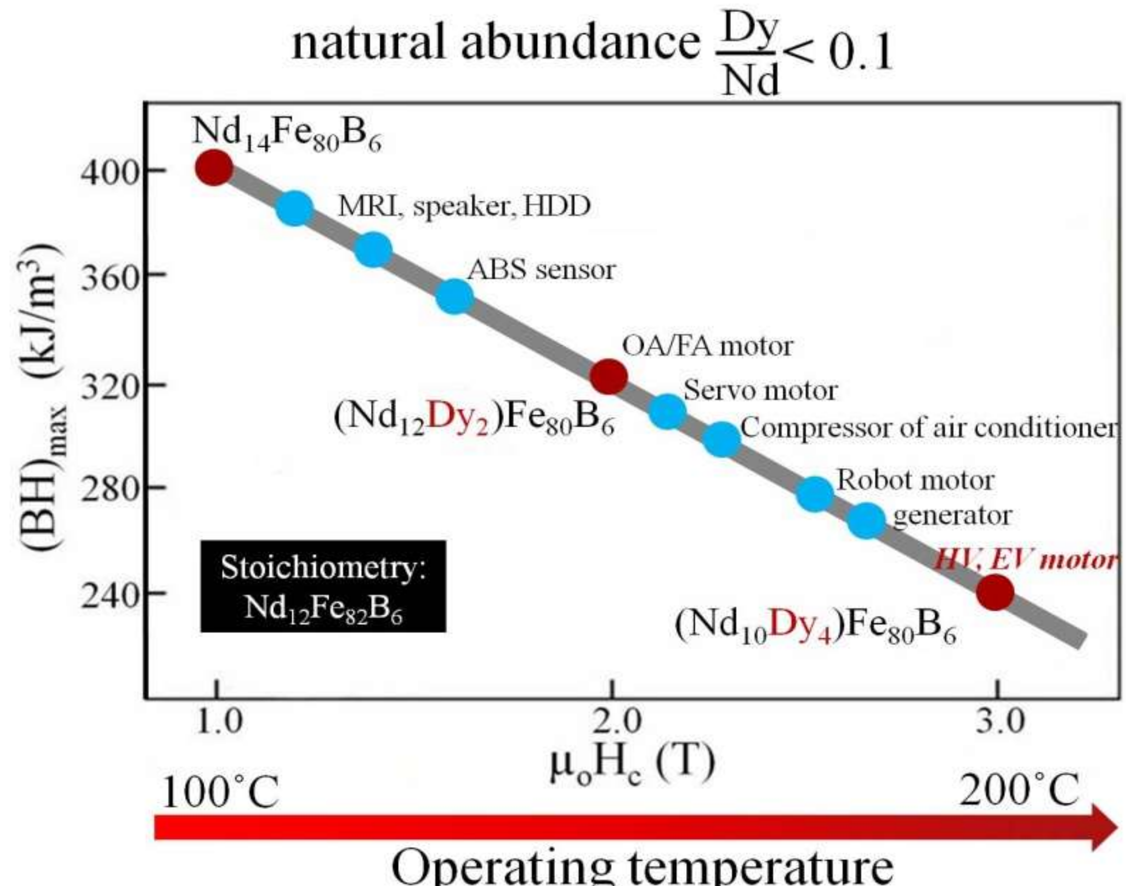
Composition of commercial magnets



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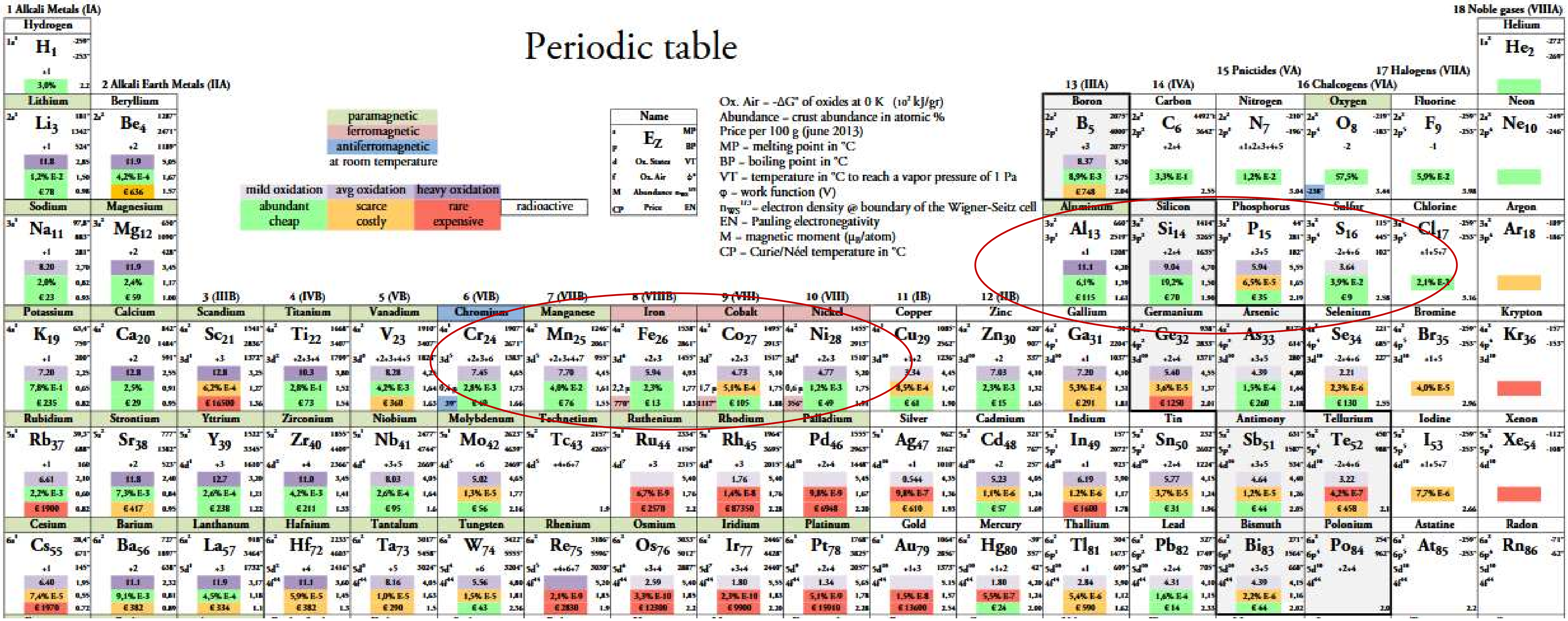
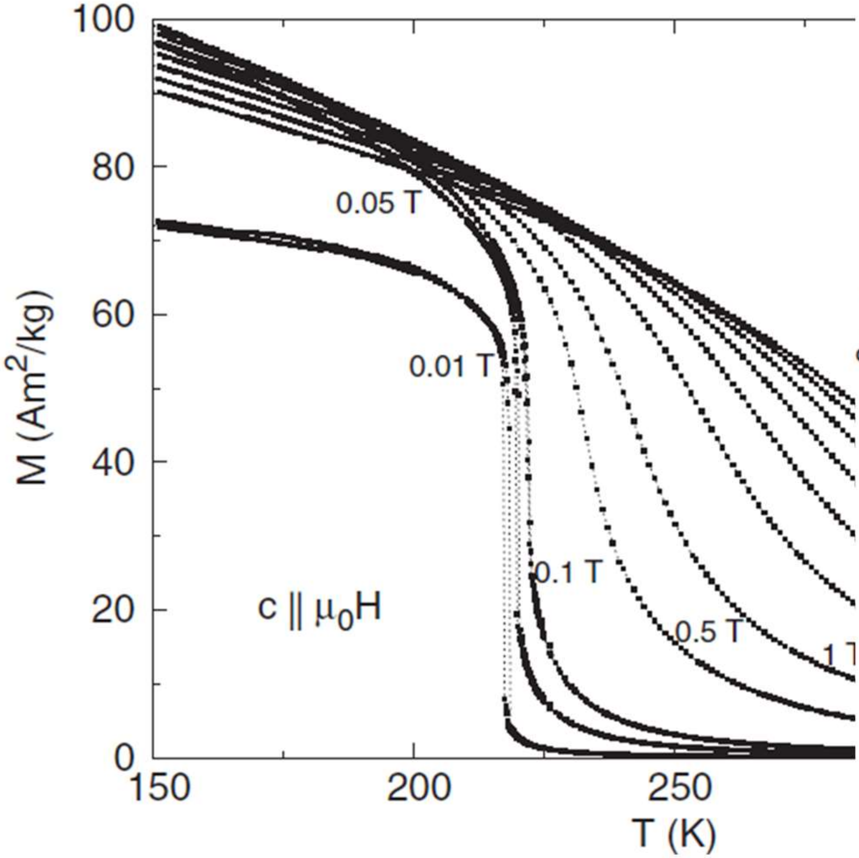
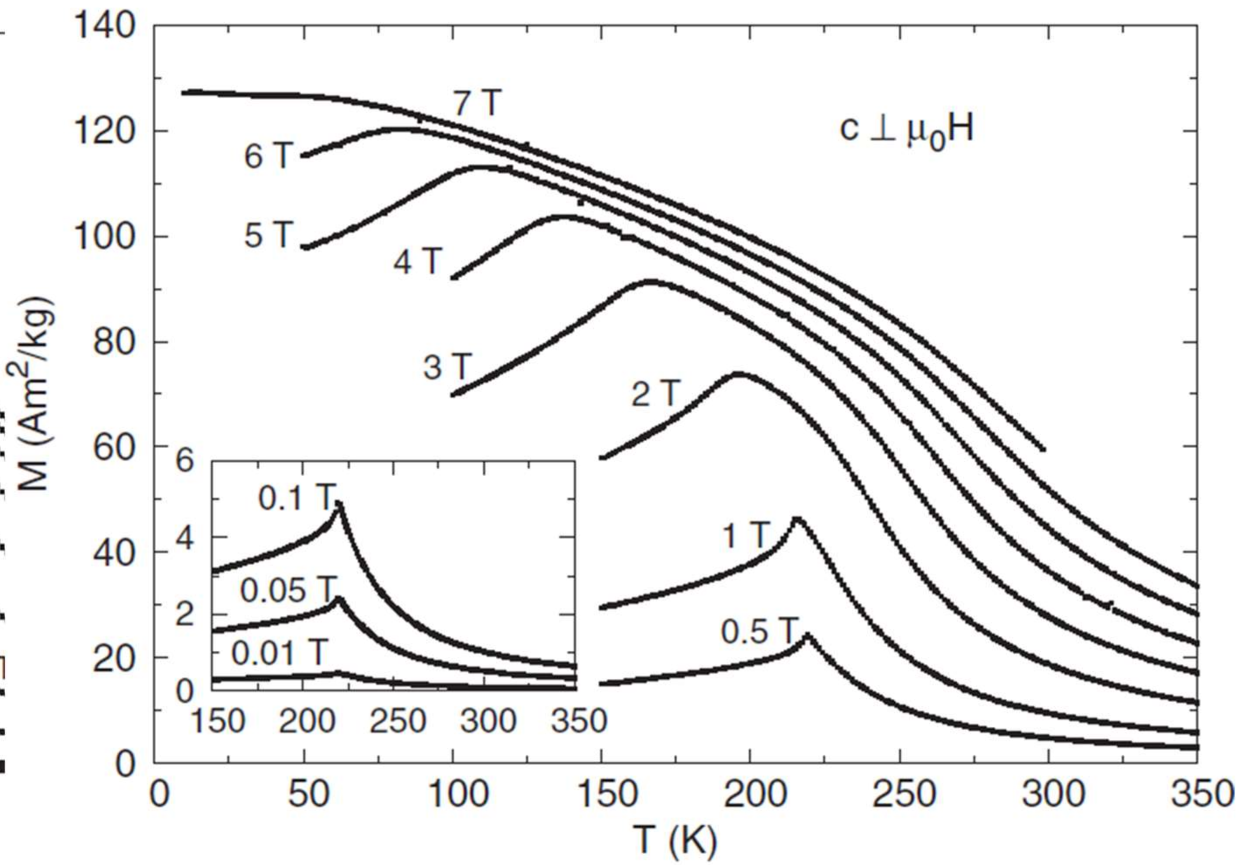
Search for RE free magnets (Gap magnets)



Adopted from PhD thesis Maurits Boeije 2017

Magnetic anisotropy Fe_2P

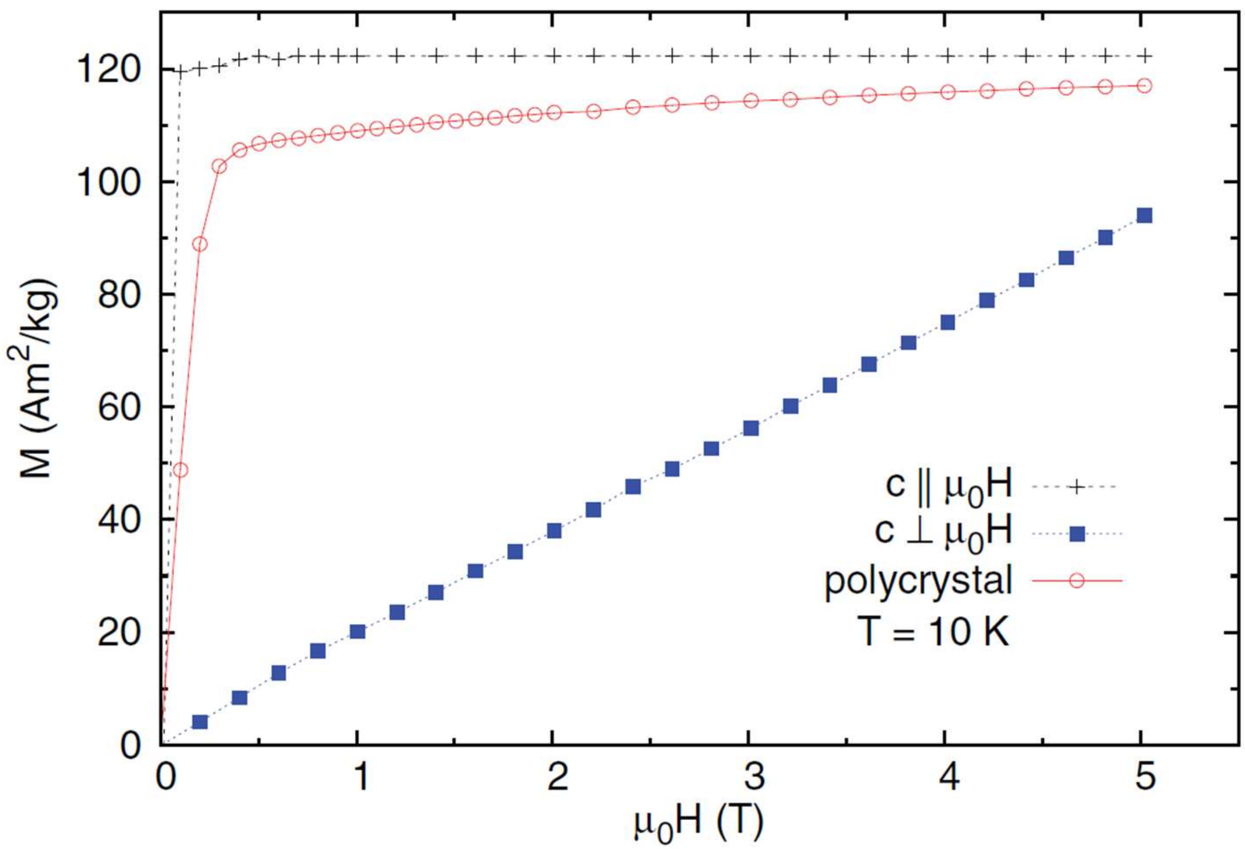




L. CARON *et al.* Phys. Rev. B **88**, 094440 (2013)

Anisotropy field $\mu_0 H_{an} \approx 7T$

Magnetic anisotropy Fe_2P



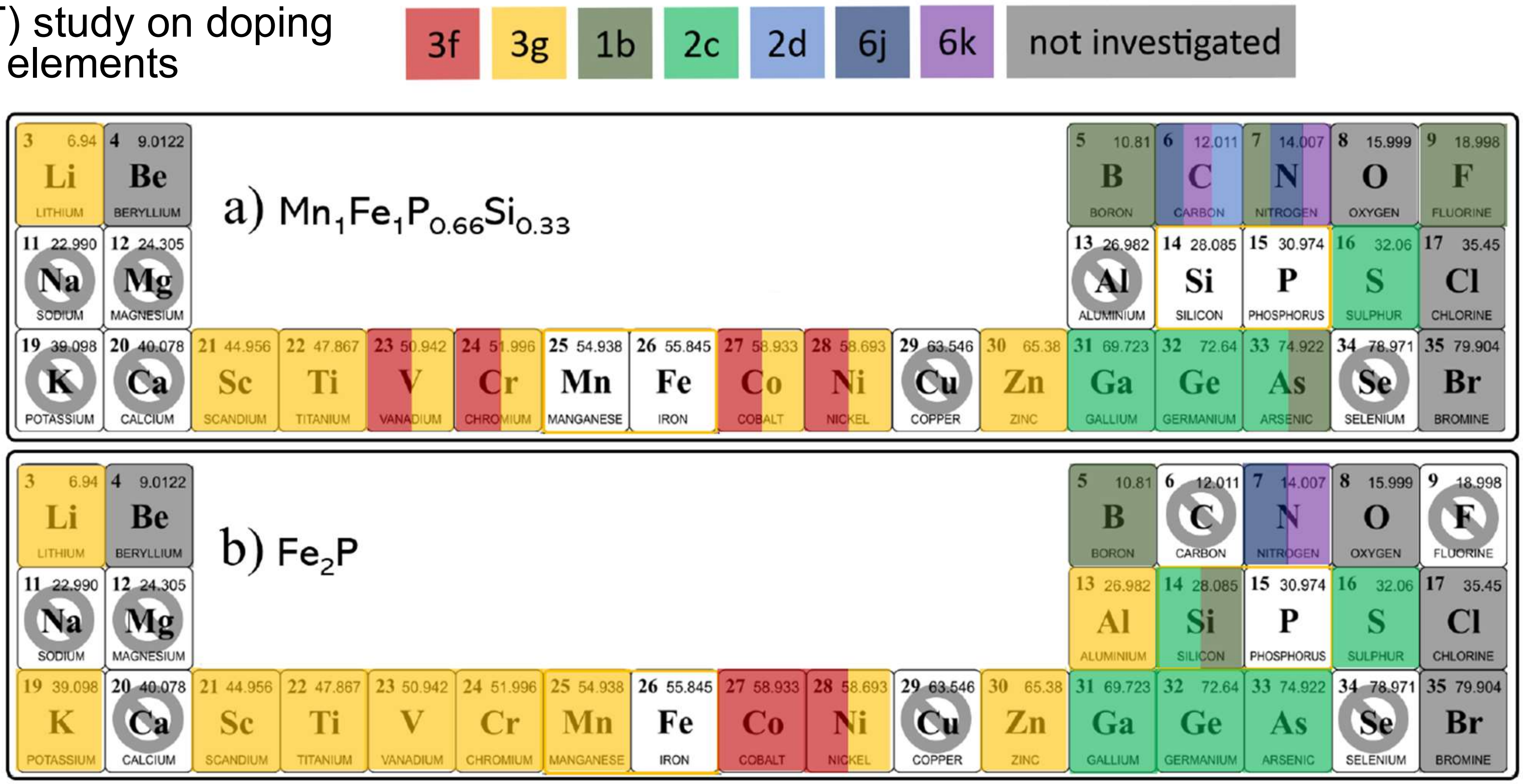
Anisotropy field $\mu_0 H_{an} \approx 7T$

$K_1 \approx 2.3\ MJm^{-3}$

L. CARON *et al.* Phys. Rev. B **88**, 094440 (2013)

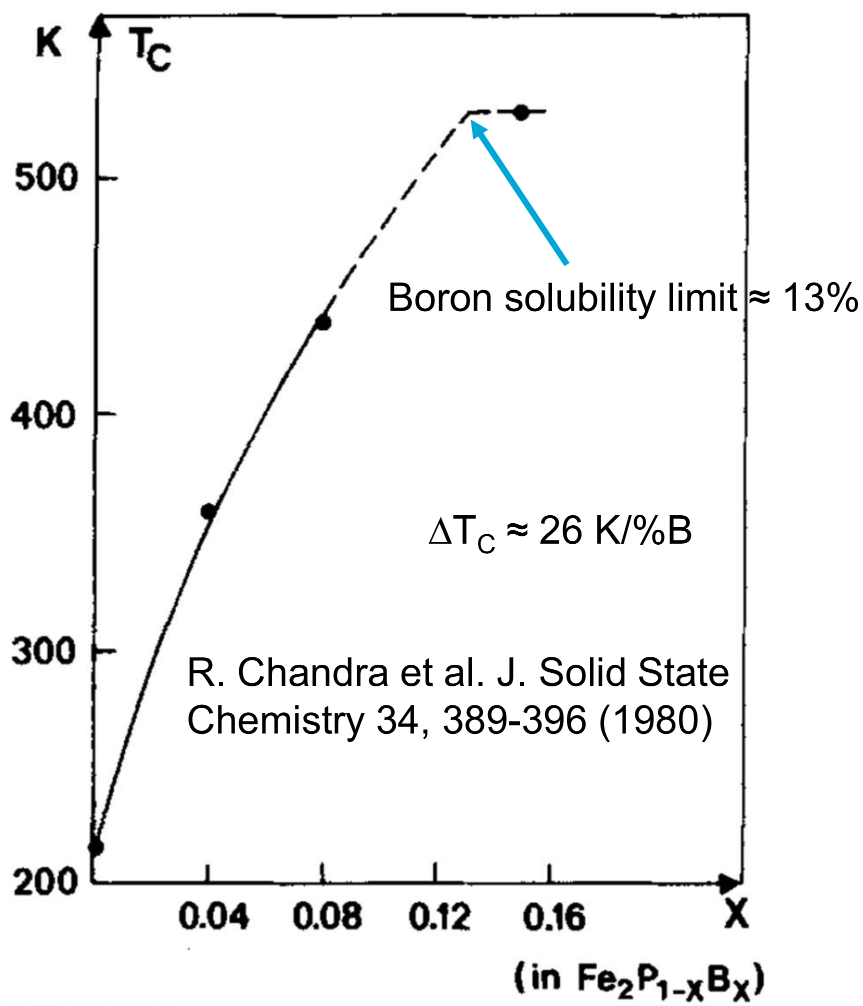
Substitutions:

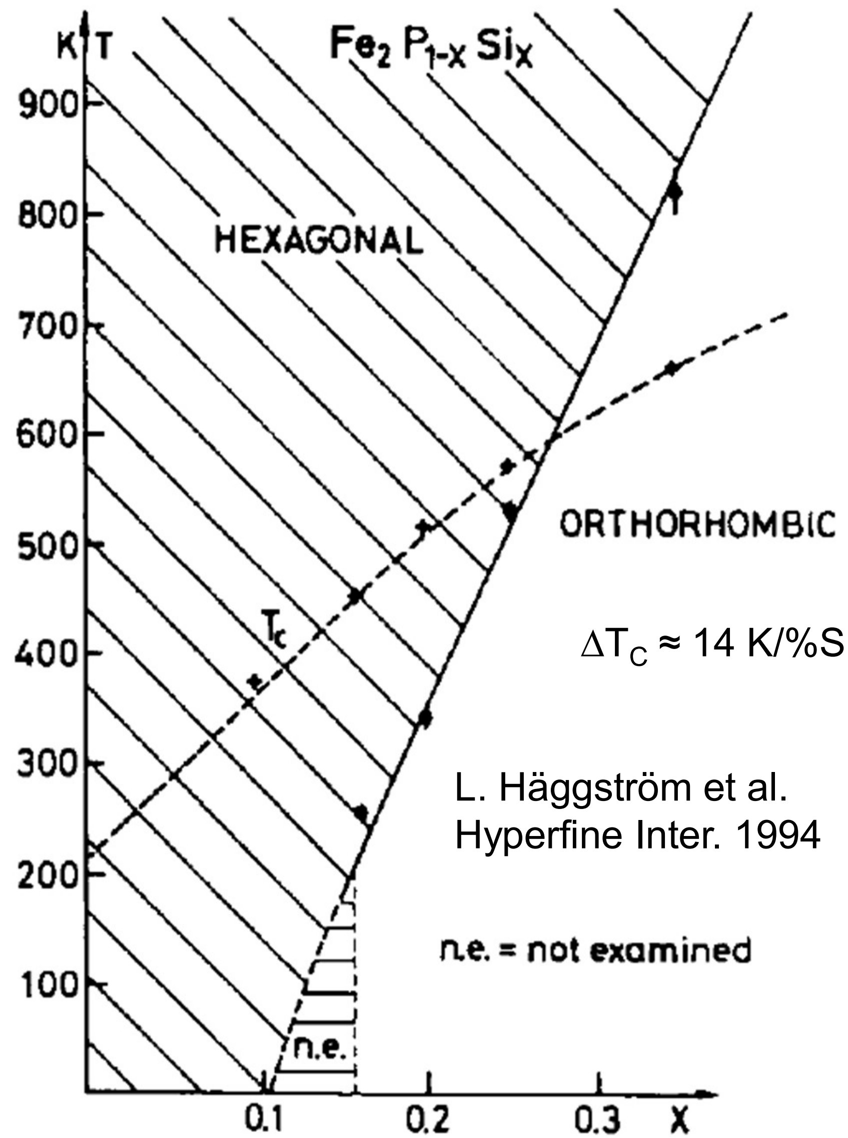
In silico (DFT) study on doping
with 4% light elements



J. Magn. Magn. Mater. 537 (Nov. 2021) 168179 Ekkes Brück ESM 2025

B or Si for high Curie temperature:

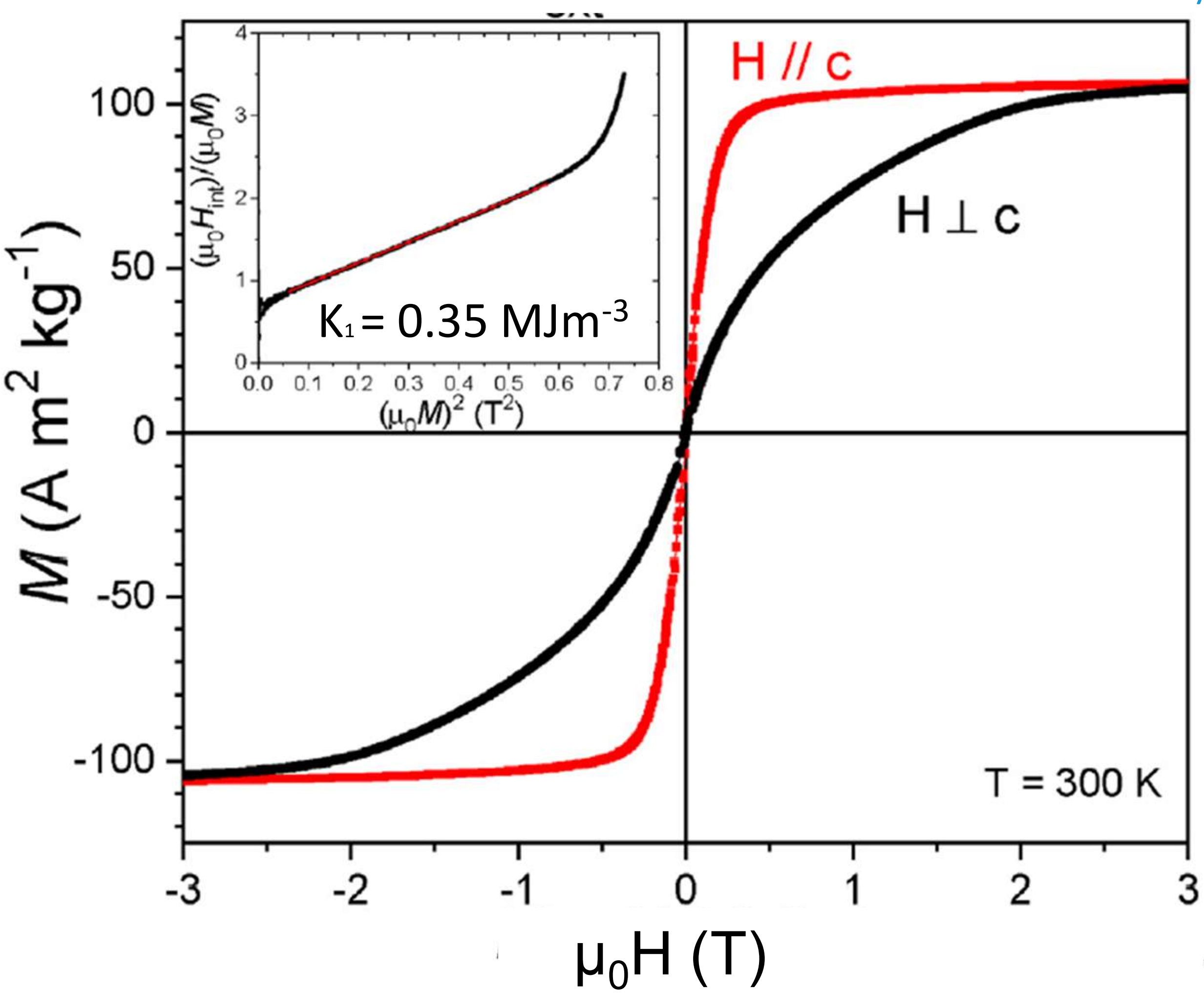




Magnetic anisotropy $Fe_{1.8}Co_{0.2}P_{0.88}B_{0.12}$

F. Guillou et al. J. Alloys and Comp. 800 (2019) 403

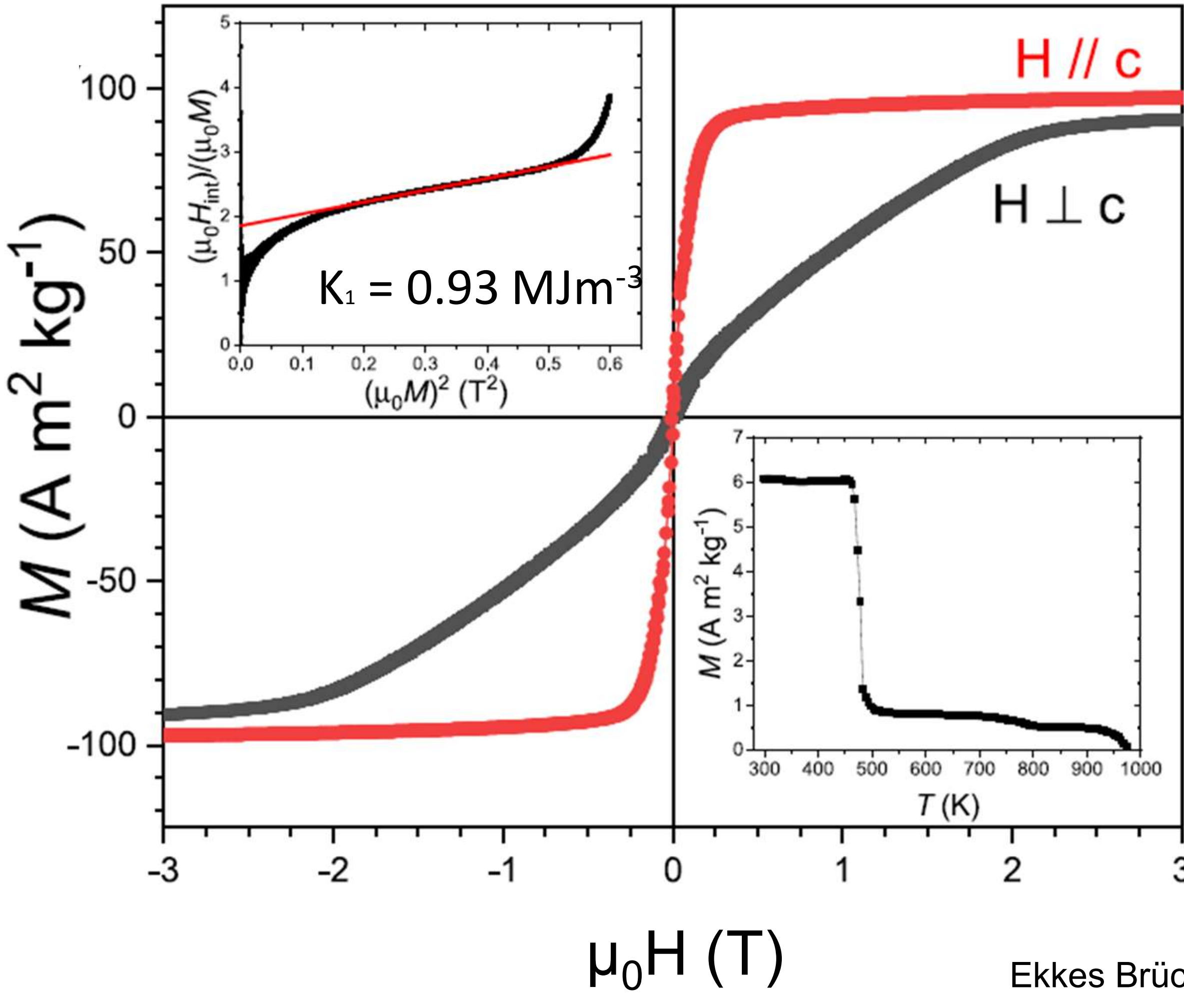
Field aligned powder



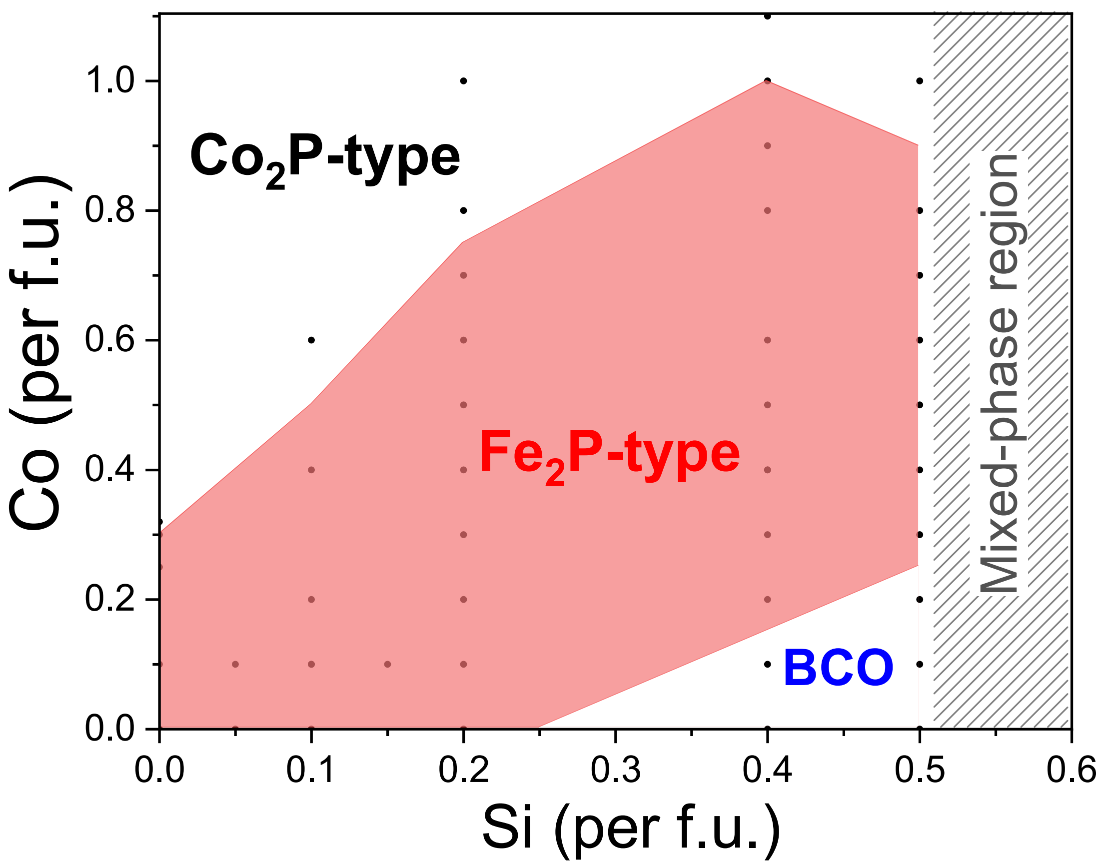
Magnetic anisotropy $Fe_{1.8}Co_{0.2}P_{0.8}Si_{0.21}$

F. Guillou et al. J. Alloys and Comp. 800 (2019) 403

Field aligned powder



Co & Si for high Curie temperature & anisotropy:



L.L. Bao et al. J. Alloys and Comp. 903 (2022) 163770

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Co & Si for high Curie temperature (≤ 640 K) & anisotropy:

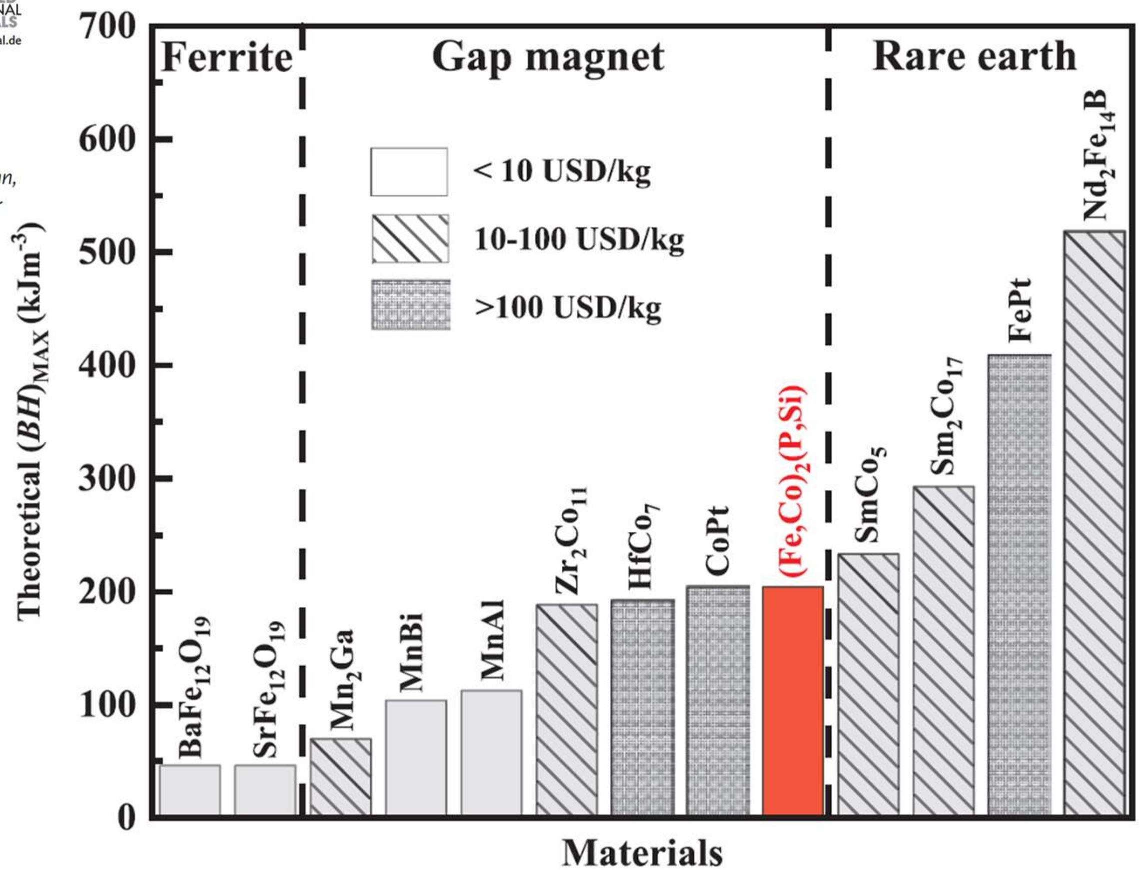
RESEARCH ARTICLE

ADVANCED FUNCTIONAL MATERIALS
www.afm-journal.de

Intrinsic Magnetic Properties of a Highly Anisotropic Rare-Earth-Free Fe_2P-Based Magnet

Yangkun He, Peter Adler, Sebastian Schneider, Ivan Soldatov, Qingge Mu, Horst Borrmann, Walter Schnelle, Rudolf Schaefer, Bernd Rellinghaus, Gerhard H. Fecher, and Claudia Felser*

Adv. Funct. Mater. 2021, 2107513



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Summary permanent magnets

- High magnetization
- High Curie temperature desired
- Large magnetic anisotropy
- Microstructure tuning
- Low cost

Thank you for your attention

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