Slide 1

Agenda

- Welcome & Introduction
- Atomistic Foundations of Magnetism
- Micromagnetic Simulations & Domain Dynamics
- *Short break*
- Microstructural Engineering and Magnet Properties
- Processing Techniques for Permanent Magnets
- *Short break*
- Industrial Applications & Challenges
- Closing remarks

Join at menti.com,
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"Talking Magnets" Webinar Series

An Introduction to BEETHOVEN and GREENE

"From Atoms to Applications: A Multiscale Perspective on Magnetism and Permanent Magnets"

16-10-2025

Presenters: **Adrián Quesada (a) ; Kristina Žužek (b)**
Organisations: (a) **Institute of Ceramics and Glass (CSIC)** ; (b) **Department for Nanostructured Materials ("Jožef Stefan" Institute)**

Consejo Superior de Investigaciones Científicas

Jožef Stefan Institute Ljubljana, Slovenia

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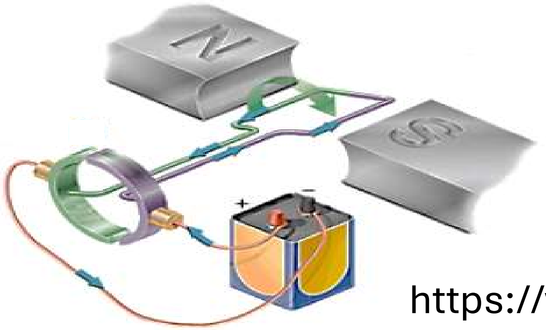
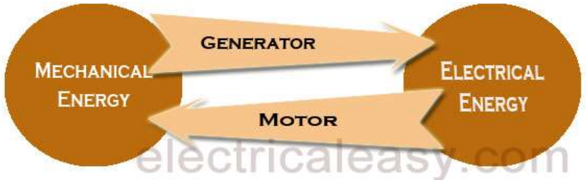
Magnets are crucial for the energy transition





https://www.electricaleasy.com/

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Best magnets contain rare-earth elements

The best magnet in the world, in terms of performance, has the composition Nd2Fe14B

In 2030, total NdFeB demand is set to triple compared to 2020 levels

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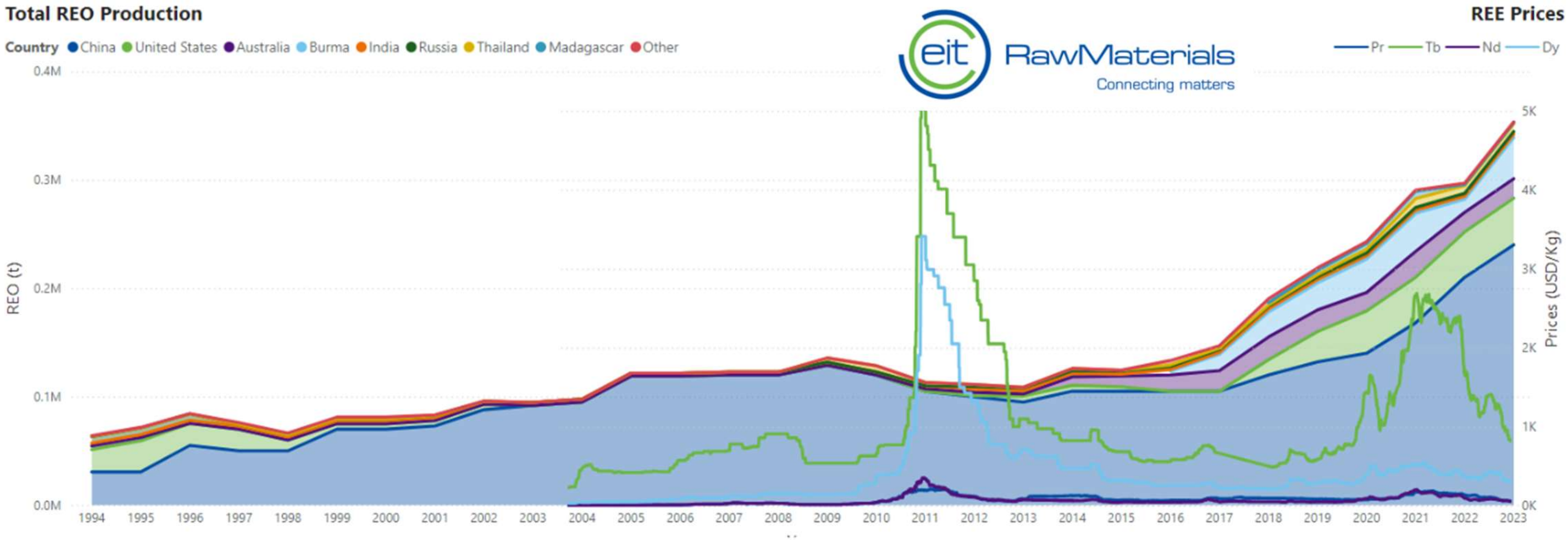
Rare-earths are critical raw materials

Reason 1: Price fluctuations



Reproduced from Nabeel Mancheri (EIT Raw Materials)

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Rare-earths are critical raw materials

Reason 2: Supply risk

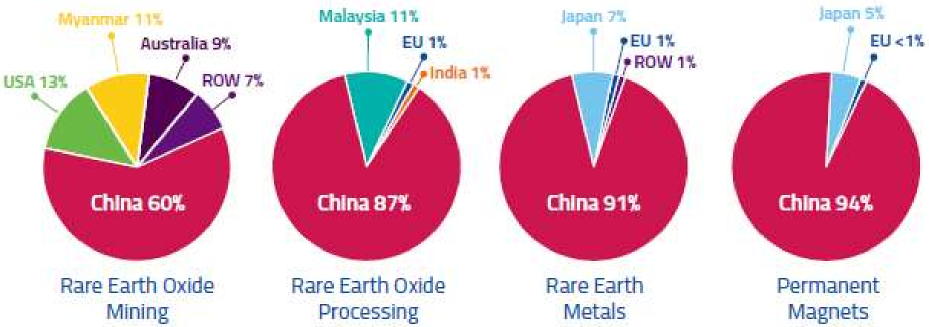

EUROPEAN RAW MATERIALS ALLIANCE | ERMA

RawMaterials Connecting matters

Co-funded by the European Union

Rare Earth Magnets and Motors: A European Call for Action

A report by the Rare Earth Magnets and Motors Cluster of the European Raw Materials Alliance



A single country controls the supply chain


CNBC | MARKETS | BUSINESS | INVESTING | TECH | POLITICS | VIDEO | INVESTING CLUB | JOIN

China expands rare earth export restrictions ahead of possible Trump-Xi meeting

PUBLISHED THU, OCT 9 2025•3:57 AM EDT

Anniek Bao
@IN/ANNIEK-BAO-460A48107/
@ANNIEKBYX

SHARE

KEY POINTS

- China has tightened export controls on rare earths and related technologies, while barring its citizens from participating in unauthorized mining overseas.
- The latest move is a "major upgrade for rare earth export control," expanding restrictions from only raw materials to intellectual properties and technologies, said Dan Wang, China director at Eurasia Group.

Prefer to Listen
NOW
UP NEXT

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Rare-earths are critical raw materials

Reason 3: Social and environmental problem

1 ton of NdFeB = 13 kg of toxic powder, 75 m^3 of residual water, 12,000 m^3 gas, y 1 t de radioactive waste

Illegal mining, human rights violations

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Slide 8

How can we reduce our REE dependence?

- Develop new REE supply chains
- **Develop new magnets that can substitute rare-earths**
- **Reduce REE content**
- Develop rare-earth-free/lean devices
- Increase the recycling rate (currently 1%)

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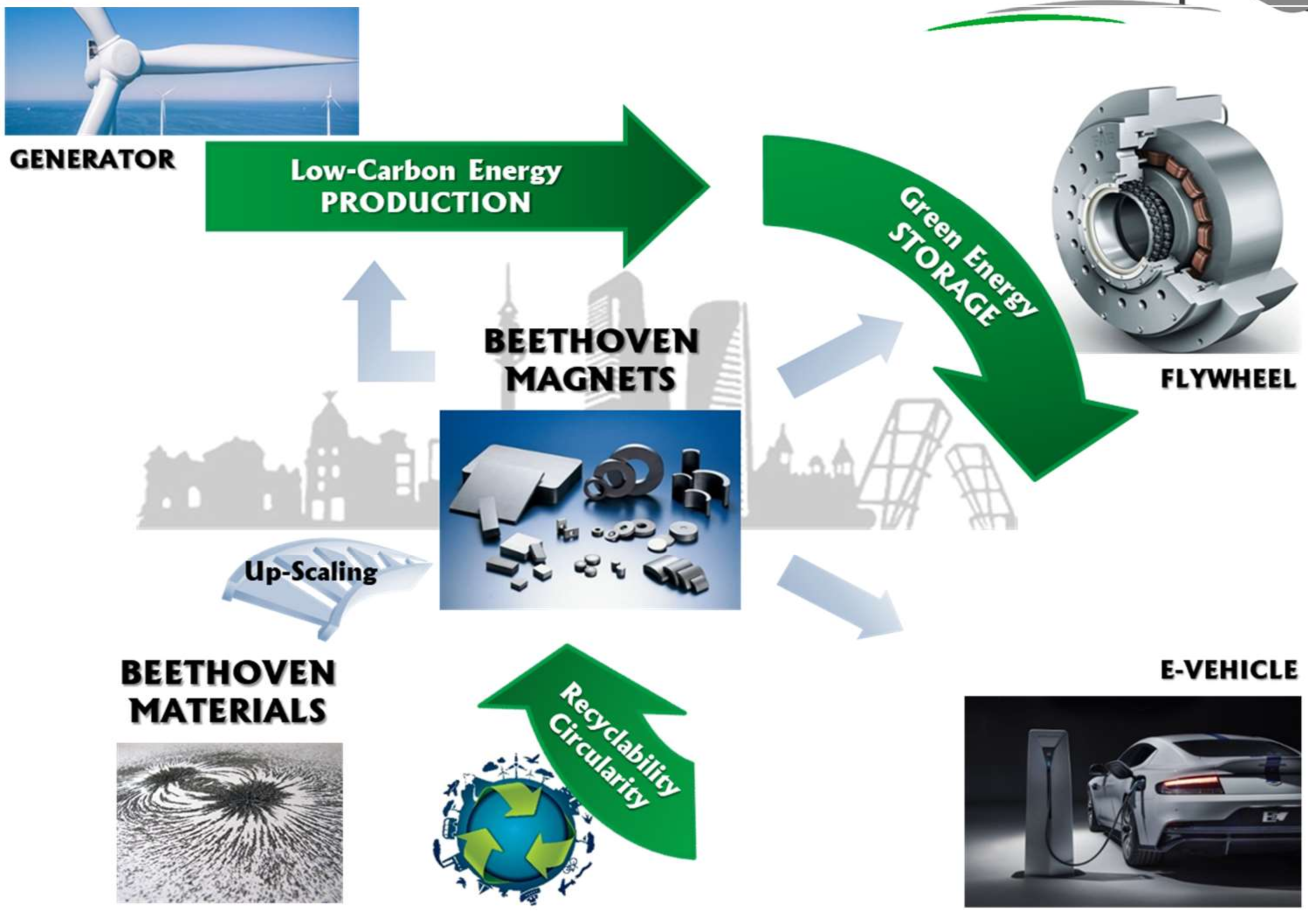
The BEETHOVEN project



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Slide 10

The BEETHOVEN project

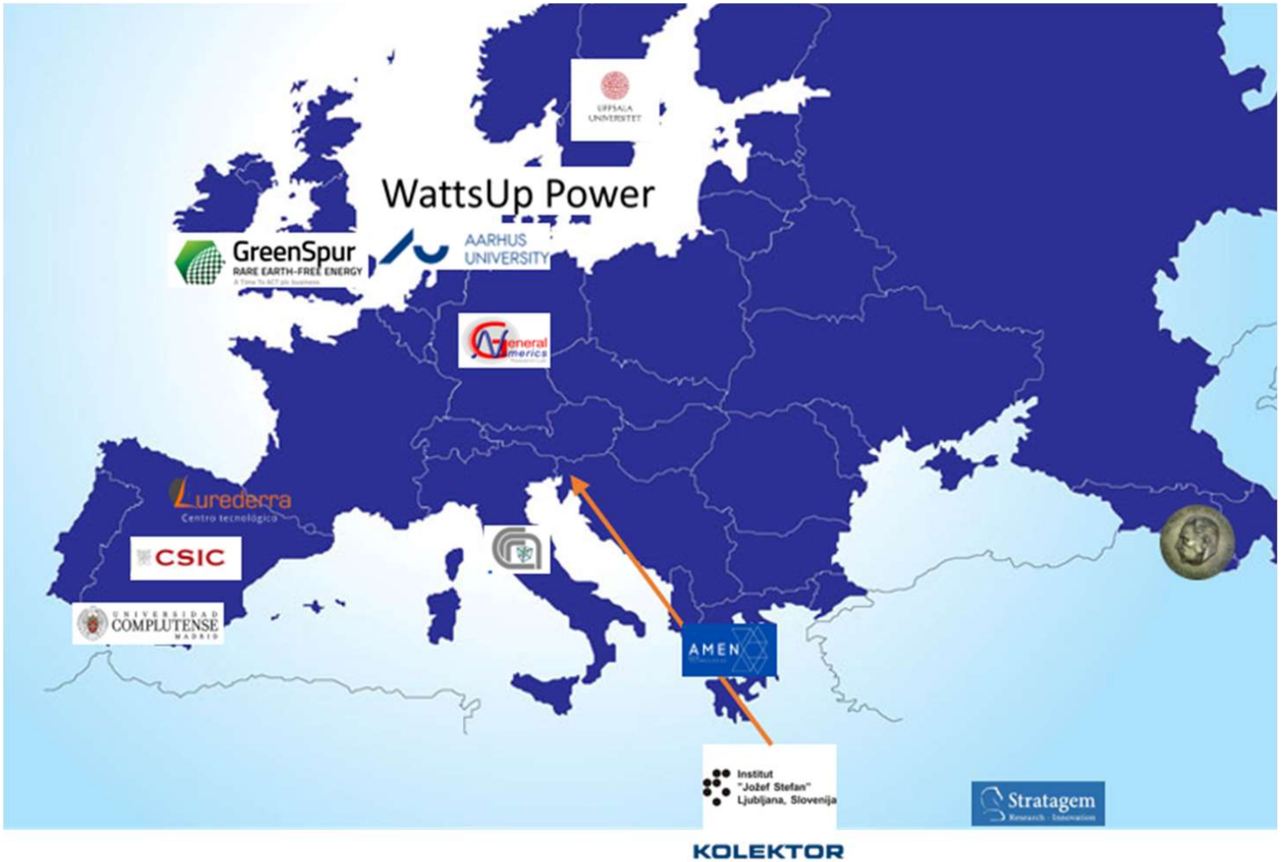
suBstitution of rarE-EarTHs for advanced nOVEl magNets in energy and transport applications

4 years

14 partners

10 countries

7.7 M€



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Slide 11

The BEETHOVEN project

3 types of magnets

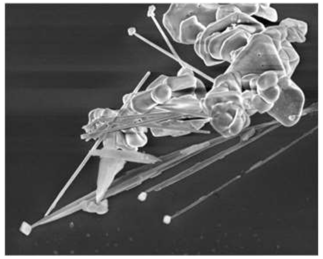
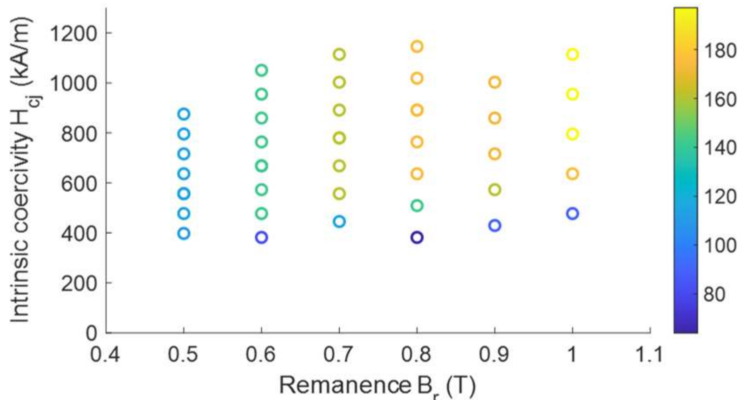
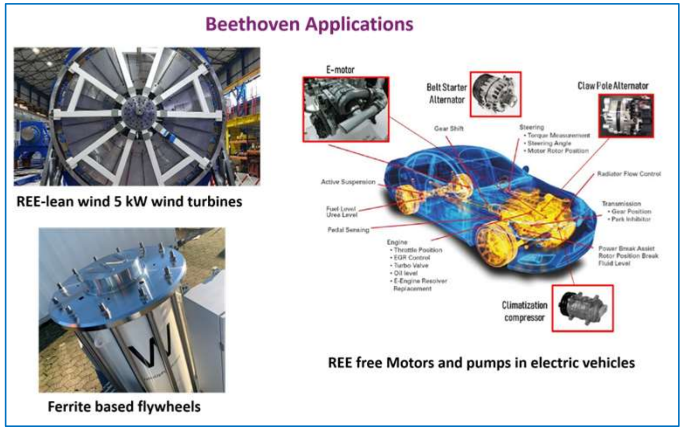


Table 2. BEETHOVEN magnets properties and substitution potential

Sample	Ms(Am²/kg)	Tc (K)	Hc (expected) (T)	$(BH)^{theor}_{max}$ (kJ/m³)	Substitution potential	Estim. cost (€/kg)
$(RE\text{-}HEAs)_2$-$Fe_{14}B$	125-145	550-600	>1	55-220	20-40% of NdPr-Dy	50-60 €/kg
$SrFe_{12}O_{19}$ composites	65-100	723 K	>0.3	55-65	100% of NdPr-Dy	40 €/kg
W-type Ferrites	80-91	700 K	>0.4	55-70	100% of NdPr-Dy	50 €/kg





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BEETHOVEN outputs

Output/Result	SIGNIFICANCE
Novel REE-free/-lean magnetic materials based on ferrites and HEAs (ER1-3)	New gap magnets to be commercialized from Europe
REE-free/-lean devices and magnets & sustainability assessments	2,100 - 4,900 tons substitution by 2033
Recycling Strategies (ER9)	Enhance recycling rate of PMs in production facilities by at least 15%

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Slide 13

Thank you for your attention!

Adrián Quesada

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GREENE Project

greene-project.eu

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CSIC
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Eu_Beethoven

Beethoven Project

projectbeethoven.eu

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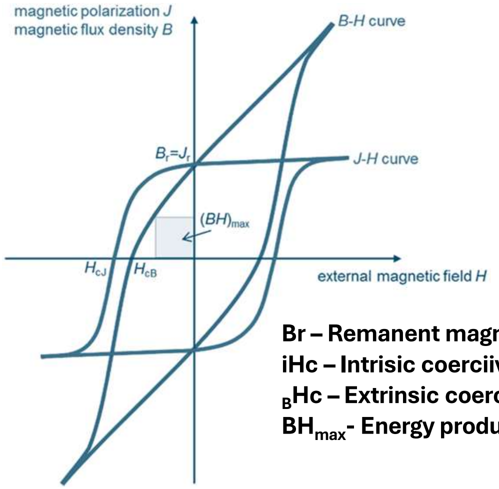
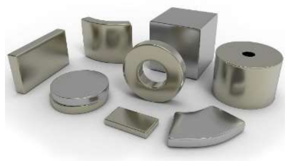
Nd-Fe-B Permanent Magnets' Properties



Br – Remanent magnetization
iHc – Intrisic coerciivty
$_B$Hc – Extrinsic coercivity
BH_{max}- Energy product



$$H_{ci} = \alpha \times H_a - N_{eff} \times M_s$$

Intrinsic properties → Applied properties

	$Nd_2Fe_{14}B$
Tc(°C)	315
M_s(T)	1.61
H_a(kA/m)	5342 kA/m
BH_{max} teor (kJ/m³)	509

N58						
N56	56M					
N54	54M	54H				
N52	52M	52H	52SH			
N50	50M	50H	50SH	50UH		
N48	48M	48H	48SH	48UH		
N45	45M	45H	45SH	45UH	45EH	
N42	42M	42H	42SH	42UH	42EH	
N40	40M	40H	40SH	40UH	40EH	40AH
N38	38M	38H	38SH	38UH	38EH	38AH
N35	35M	35H	35SH	35UH	35EH	35AH

M – 100°C, Hci≥1100 kA/m
H – 120°C, Hci ≥ 1400 kA/m
SH – 150°C , Hci ≥ 1600 kA/m
UH – 180°C, Hci ≥ 2000 kA/m
EH – 200 °C, Hci ≥ 2400 kA/m
AH - 220-230°C, Hci ≥ 2800 kA/m

- N52>: Small consumer electronics (max strength at low temp).
- N42SH–EH: Motors, renewables, EVs.
- N35EH–AH: Aerospace, defense, extreme high-temp stability.

➢ **Improved properties, greater energy efficiency & Recourse efficiency – processing, recycling**

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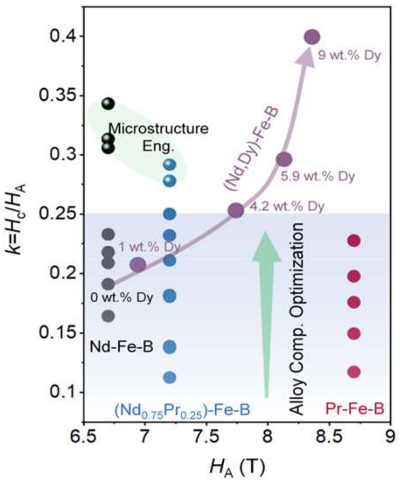
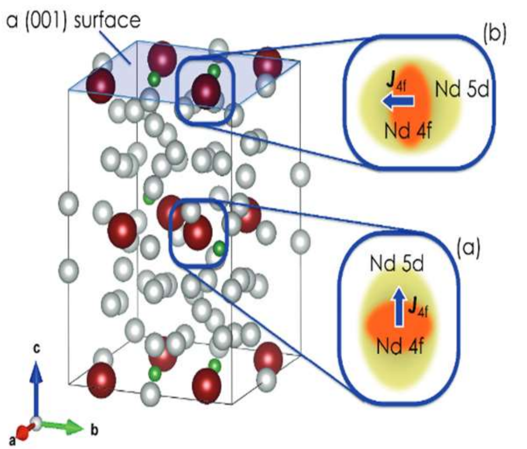
The Scientific Challenge Addressed By GREENE

Single-grain Re-engineered Nd-Fe-B Permanent Magnets

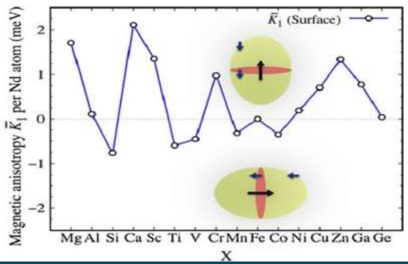
- **Improved magnetic properties: Better utilization of the extensive theoretical potential of magnetocrystalline anisotropy$Nd_2Fe_{14}B$ H_a = 5342 kA/m, while Hcᵢ is only 35% of H_a**

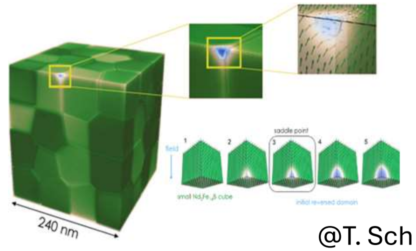
- The anisotropy of the $Nd_2Fe_{14}B$ crystal cell is uniaxial – high H_a
- The local anisotropy on the surface of the $Nd_2Fe_{14}B$ crystal cell is planar – lower H_a and lower Hcᵢ
- Defects/imperfections at the boundaries between the $Nd_2Fe_{14}B$ matrix phase and the intergranular phase result in lower H_a and lower Hcᵢ





Atom substitution in $Nd_2Fe_{14}B$





@T. Schrefl

GREENE – engineering of grain boundaries

- Cu, Ca, Cr
- Locally, where we start from theoretical principles
- Globally, where we aim to create a new microstructure

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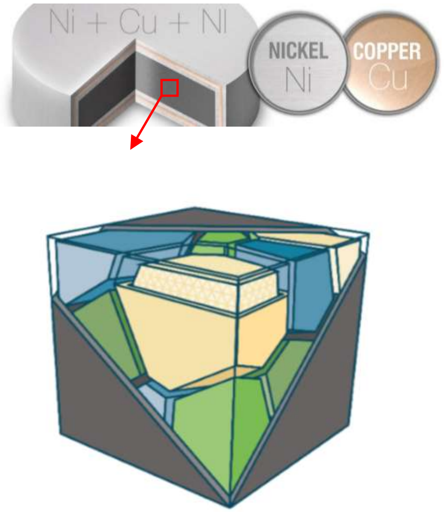
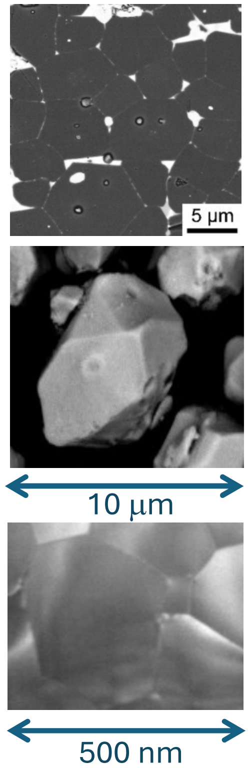
The GREENE Concept

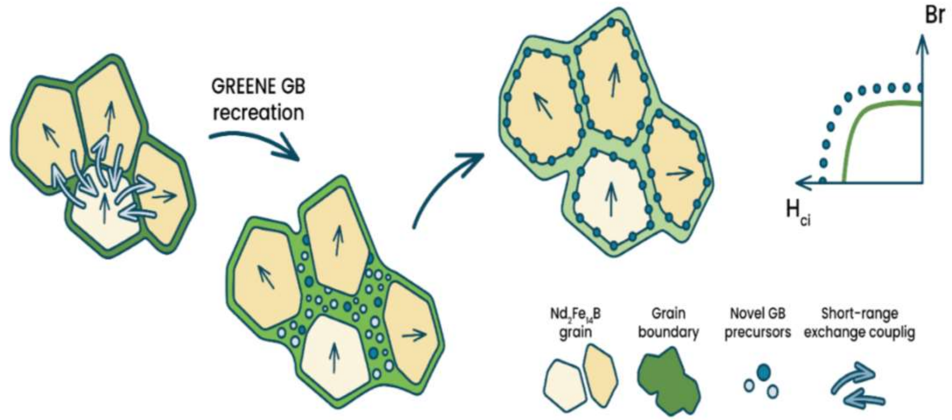
Redesigned/renewed Nd-Fe-B magnets – based on grain boundary engineering, starting from a single grain

Modelling → Single grain concept → Optimization of grain boundaries & Production of magnets with improved properties and fewer critical materials





- Conventional approach: Phase equilibria (PE) governed processes
- „Novel“ GREENE approach: deviation from the PE, SG approach and fast consolidation.



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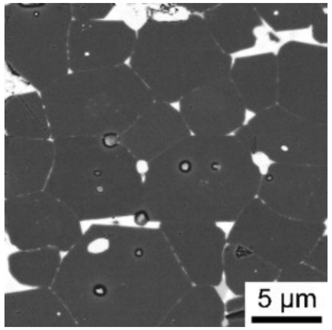
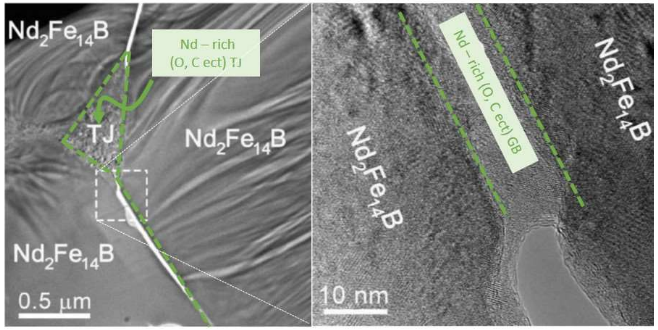
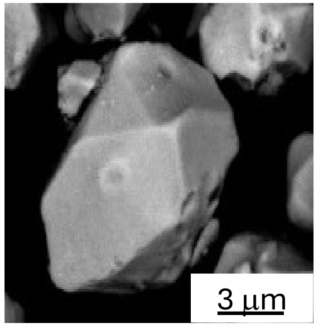
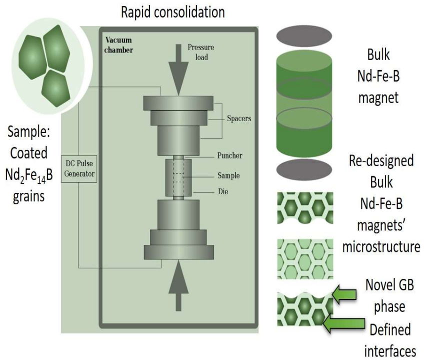
GREENE – Concept Innovation





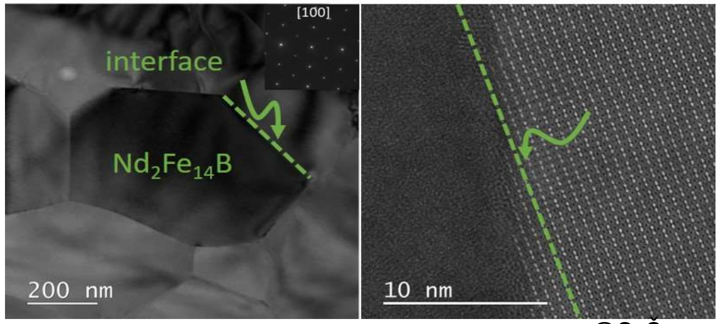
- Conventional approach – conditioned by thermodynamic equilibrium, which determines the phase composition and chemistry





GOAL: Tailor and define the structure and chemistry at the phase boundary with the highest retained Ha

- Higher Hci values and increased utilization of the extensive theoretical Ha potential
- Higher energy efficiency
- Better resource utilization



@S. Šturm

- GREENE approach – moving away from phase equilibrium, direct grain coating and rapid consolidation

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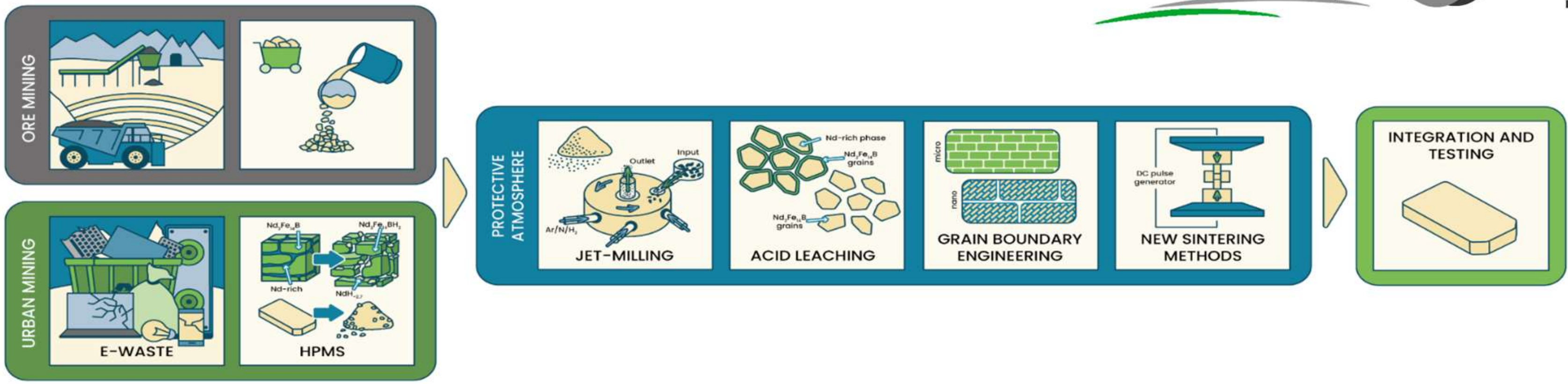
GREENE – Value chain and Goals



GREENE intertwines Efficiency – Environmental sustainability – Economic sustainability – and addresses the Criticality of materials

- **Resource-efficient, high-performance Nd-Fe-B magnets** with -10-20% RE content, +20% coercivity, and maximum energy product +20%
- **Increased sustainability of magnet production** with -5% scrap rates, -15% energy consumed and -30% toxicity
- **Independent, resilient and scalable supply** of key materials, magnets and components within Europe
- **Society and stakeholders better equipped** for a sustainable green transition in Europe

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GREENE – Consortium and Key Figures

8 M€

15 European partners

4 years
06/2024 – 05/2028

Coordination
Jožef Stefan Institute

Permanent magnets, material science
Jožef Stefan Institute
HS PF
Hochschule Aalen
Consiglio Nazionale delle Ricerche

Fundamental magnetism, modelling
Donau Universität Krems
VNTU
cnrs
TU Wien – Technische Universität Wien

Advanced characterizaton
CSIC – Consejo Superior de Investigaciones Científicas
Universidad Zaragoza

LCA/TEA
Universiteit Leiden – The Netherlands

Dissemination, outreach, exploitaion
Steinbeis Europa Zentrum

Industry
Magneti Ljubljana, d.d.
HyProMag – Magnet Recycling
BOSCH

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Slide 20

Thank you for your attention!

Kristina Žužek

tina.zuzek@ijs.si

GREENE Project

greene-project.eu

SCAN ME

Nanostructured materials

Jožef Stefan Institute Ljubljana, Slovenia

Eu_Beethoven

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"Talking Magnets" Webinar Series

Atomistic Foundations of Magnetism

"From Atoms to Applications: A Multiscale Perspective on Magnetism and Permanent Magnets"

16-10-2025

Presenter: **Silvia Gallego**
Organisation: **Instituto de Ciencia de Materiales de Madrid, CSIC**

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Outline

Atomistic Foundations of Magnetism

- Introduction to magnetism: from the hysteresis loop to the quantum concept of spin
- Multiscale simulations in magnetism: ab initio ⟶ atomistic ⟶ micromagnetics
- Ab initio methods: the Density Functional Theory (DFT)
- Extracting magnetic features from DFT simulations
- Connection between DFT and atomistic models

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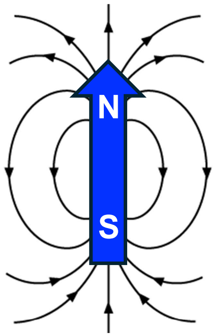
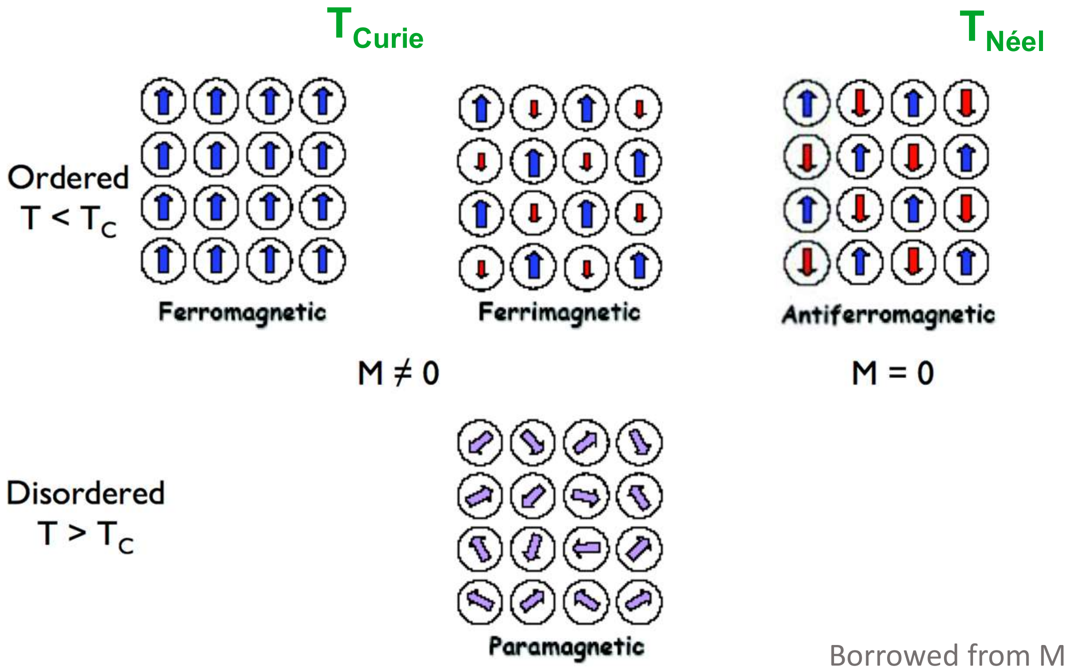
Introduction to magnetism

A magnetic material is one that has a net magnetization per unit volume.

The individual local magnetizations are ordered below a critical temperature, and depending on their relative alignment, different types of materials exist.





Borrowed from M. Coey (lecture 5006-1)

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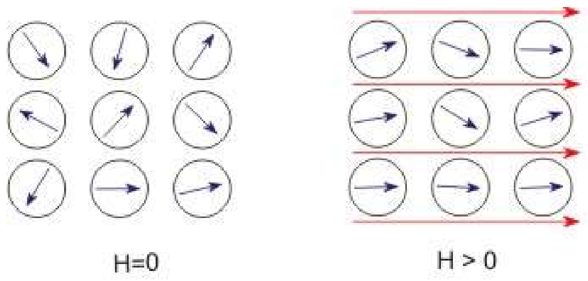
Introduction to magnetism

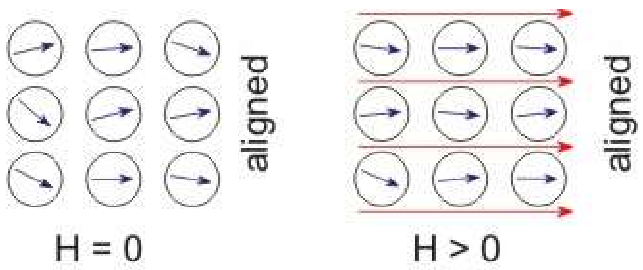
Classification of materials by their response to a magnetic field (H)



Randomly aligned

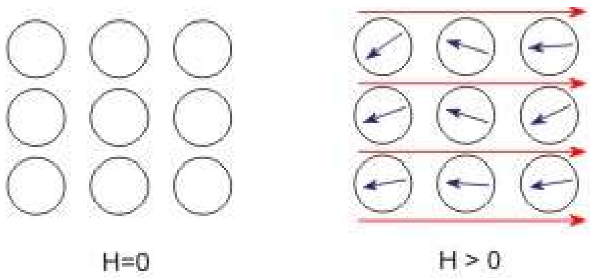
Aligned leading to large magnetization

Paramagnet



Always aligned leading to large magnetization

Ferromagnet



Zero magnetization

Opposing induced magnetization

Diamagnet

Adapted from http://nptel.ac.in/courses/

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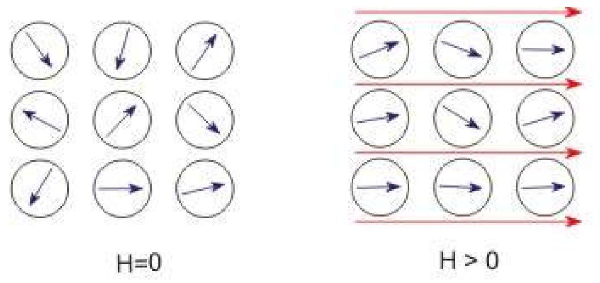
Introduction to magnetism

Classification of materials by their response to a magnetic field (H)



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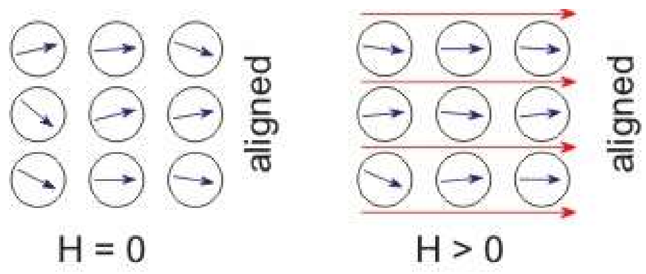
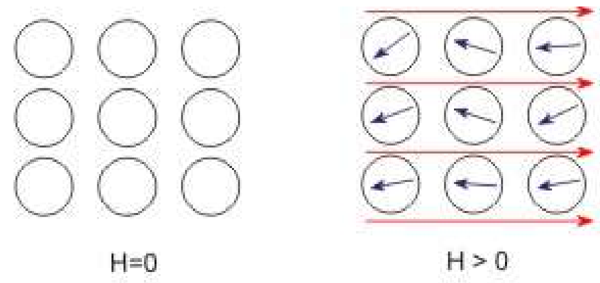
Aligned leading to large magnetization

Paramagnet



Always aligned leading to large magnetization

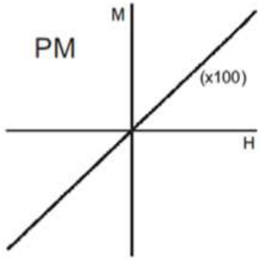
Ferromagnet

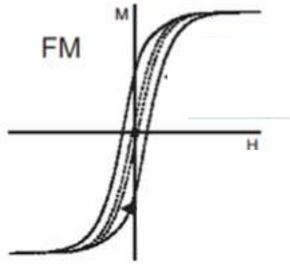


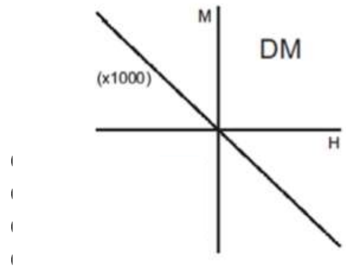
Zero magnetization

Opposing induced magnetization

Diamagnet







BD Plouffe et al., Rep. Prog. Phys. 78, 016601 (2015).

Adapted from http://nptel.ac.in/courses/

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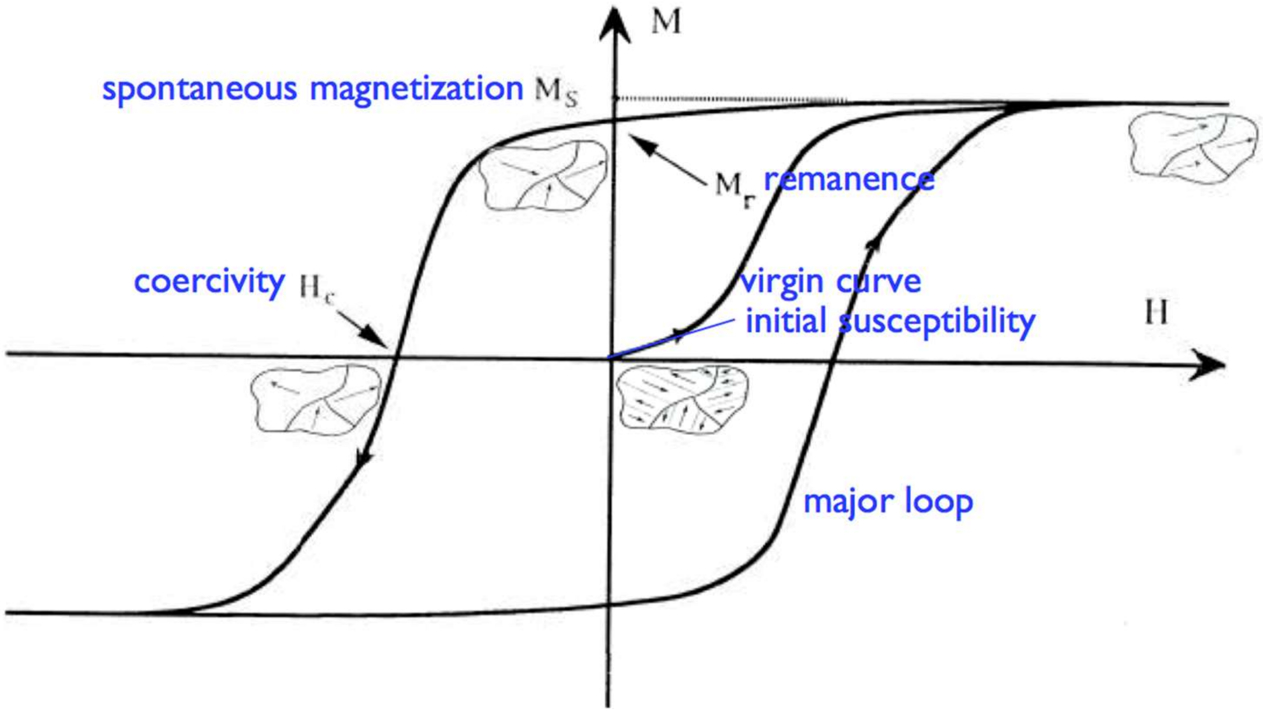
Introduction to magnetism

The hysteresis loop of a ferromagnet



The hysteresis loop shows the irreversible, nonlinear response of a ferromagnet to a magnetic field.
It also reflects the arrangement of the magnetization in ferro*magnetic domains*.

Borrowed from M. Coey (lecture 5006-1)

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Introduction to magnetism

But where do those magnetic moments come from? … the mysterious Weiss field

Phenomenological Weiss theory

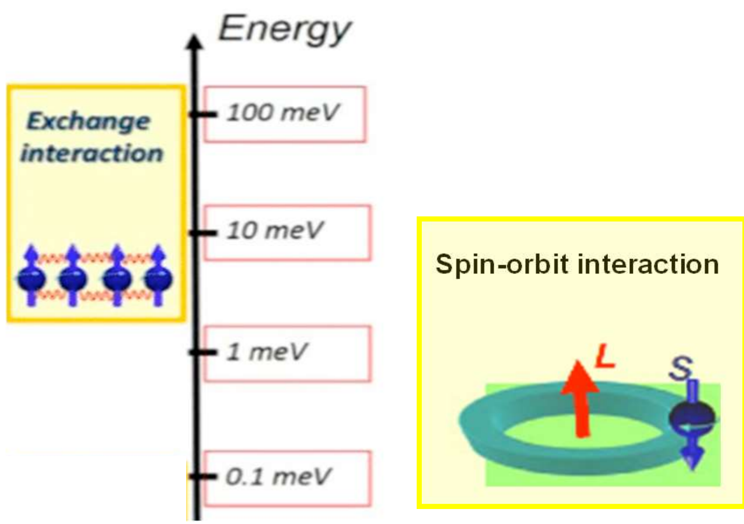
$$W = \frac{A}{M_s^2}\sum_i (\partial_i \mathbf{M})^2 + K(\boldsymbol{M}\cdot\boldsymbol{u})^2 - \frac{1}{2}\mu_0 \mathbf{M}\cdot\mathbf{H}_\mathrm{d}$$

Magnetic exchange — Anisotropy — Demagnetization

Fundamental magnetic interactions

In a static situation, the magnetic energy of a material is the sum of the contributions from magnetic exchange, magnetic anisotropy and stray fields.

Scale of the interactions



Adapted from F. Hellmann et al., Rev. Mod. Phys. 89, 025006 (2017)

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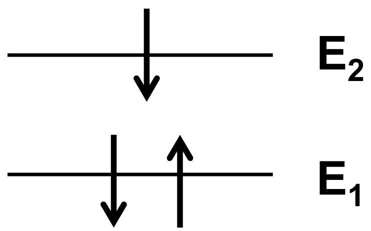
Introduction to magnetism

Origin of magnetism: the Quantum Theory of Physics

Pauli exclusion principle: two identical fermions cannot occupy the same quantum state simultaneously.

To understand the electronic levels leading to the Periodic Table of the Elements, we need to introduce a fourth quantum number: **$|n\ \ell\ m_\ell\ m_s>$ = E, orbital, orbital moment, spin**



$E_{max} = E_2$ **Magnetic** — Atoms with electronic levels not completely filled

$E_{max} = E_1$ **Diamagnetic** — Atoms where all electrons are paired

General form of a spinor (wavefunction in spin space) for a spin ½ particle:

$$|\Psi\rangle = \cos\frac{\vartheta}{2}|+\rangle_z + \sin\frac{\vartheta}{2}e^{i\phi}|-\rangle_z$$

The local magnetic moment of an atom arises from its spin moment. In the case of solid state systems with broad electronic levels (bands), it takes values different from ± ½.

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Introduction to magnetism

Origin of magnetism: the Quantum Theory of Physics

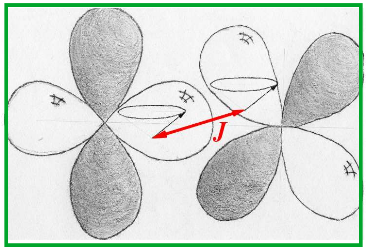
Interaction between spins: the **magnetic exchange (J).**

When two atoms with a net magnetic moment come close, the overlap of their wavefunctions gives rise to an interaction (magnetic exchange) that depends on the distance between atoms. Governed by the Pauli exclusion principle and the balance with kinetic energy, this leads to the parallel (ferromagnetism) or antiparallel (antiferromagnetism) alignment of spin moments.

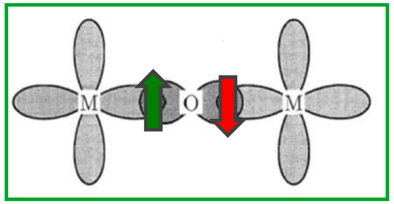
This interaction is usually represented by a Heisenberg model:

$$H = \mathbf{J}_{ij} \cdot \mathbf{S}_i \cdot \mathbf{S}_j$$

An indirect exchange interaction may also exist mediated by neighboring non-magnetic atoms

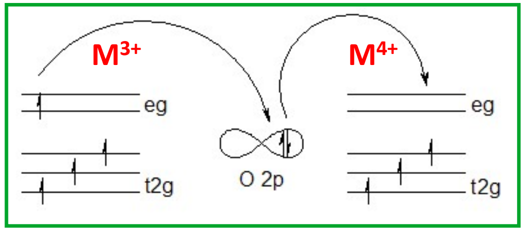


Direct exchange



Superexchange

(hybridization)



Double exchange

(hopping)

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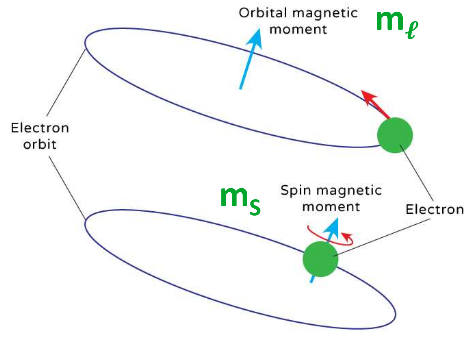
Introduction to magnetism

Origin of magnetism: the Quantum Theory of Physics

Electronic levels: **|n ℓ m_ℓ m_S > = E, orbital, orbital moment, spin**



https://www.sciencefacts.net

ℓ m_ℓ describe the orbital motion of the electron around the nucleus (orbital moment)

The spin admits a classical interpretation as the angular momentum of an electron rotating around its own axis.

As two angular momenta interact, there is a **spin-orbit coupling (SOC)** due to the electron orbit around the nucleus.

$$H_{SOC} = -\frac{e\hbar}{4m^2c^2\sqrt{1-v^2/c^2}}(\vec{\nabla}V \times \vec{p})\vec{\sigma} = \xi \vec{L}\cdot\vec{S}$$

The SOC can be interpreted classically: the electron is a charged particle in movement that feels a magnetic field (**H**) originated by the electric field **E** created by the positive nucleus. Thus, the SOC is higher for the heaviest elements of the Periodic Table of the Elements (5*d* metals, rare earths, etc.)

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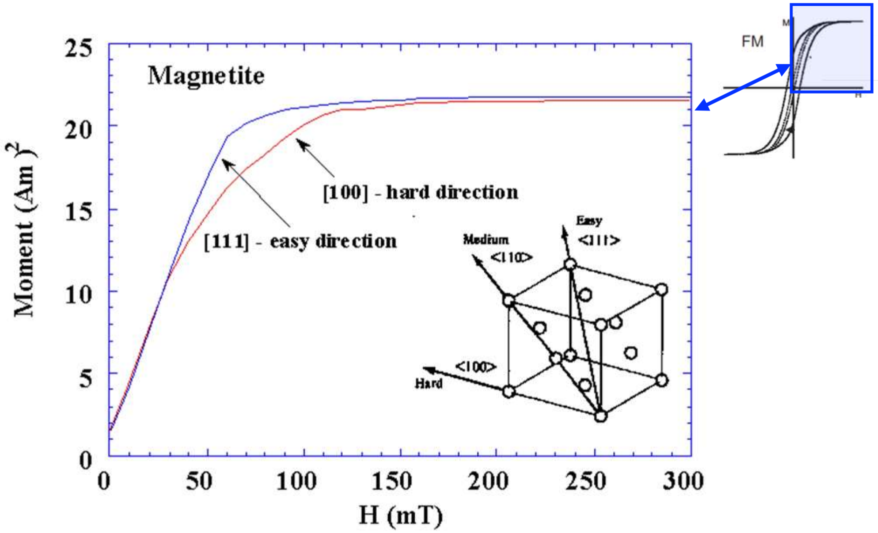
Introduction to magnetism

Origin of magnetism: the Quantum Theory of Physics

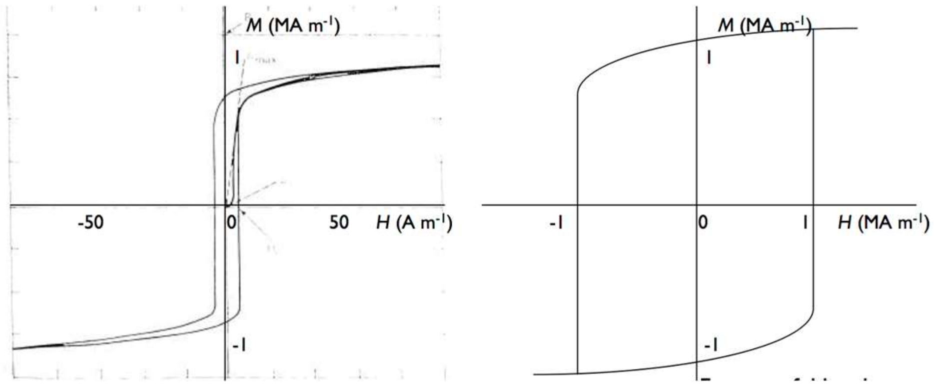
One of the consequences of the SOC is that it connects the spin space to the real space. This brings the concept of **magnetic anisotropy (MA)**: the existence of preferred real space directions (*easy axis*) for the orientation of the magnetization.



Hitchiker's Guide to Magnetism

Soft magnet – low MA

Hard magnet – high MA



Borrowed from M. Coey (lecture 5006-1)

When a magnetic field H is applied along the direction of an easy axis, the reorientation of the magnetization upon reversal of H has an energy cost.

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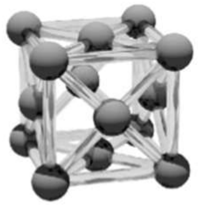
Multiscale simulations in magnetism

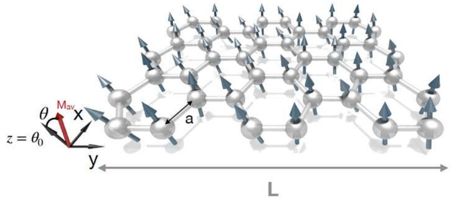
BEETHOVEN greene

Ab initio



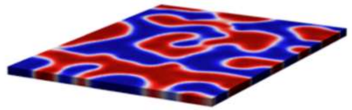
- Electronic level (quantum)
- ~100 atoms
- Ground state properties (isolated system, T=0)

Atomistic



- Atomic level (quantum or classical)
- 10^3 to 10^6 atoms
- Mesoscopic dynamical properties (effect of fields & T)

Micromagnetics



- Continuum theory
- Scale of microns (shape, domains)
- Macroscopic dynamical properties (effect of fields & T)

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Multiscale simulations in magnetism

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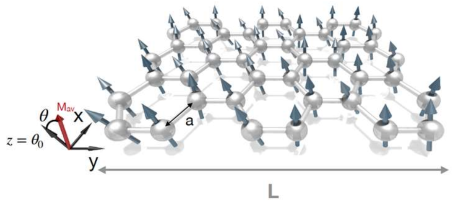

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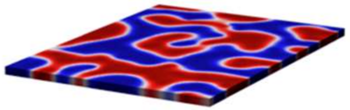
Micromagnetics



- Continuum theory
- Scale of microns (shape, domains)
- Macroscopic dynamical properties
  (effect of fields & T)

No parametrization

Materials properties & design

Import material parameters

Dynamical response

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Multiscale simulations in magnetism

BEETHOVEN greene

Ab initio

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- ~100 atoms
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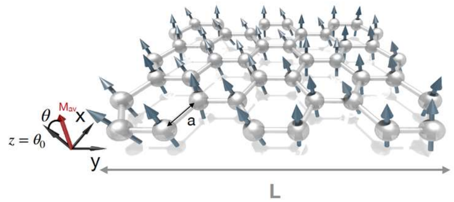
Atomistic



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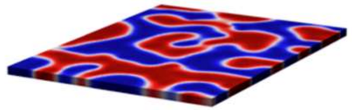

- Continuum theory
- Scale of microns (shape, domains)
- Macroscopic dynamical properties (effect of fields & T)

Transferability →

← **Computational cost**

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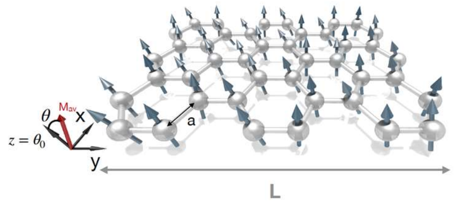
Multiscale simulations in magnetism

BEETHOVEN greene

Ab initio

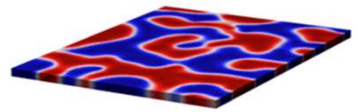
μ, J, d

Atomistic



M, A, K

Micromagnetics



Refine model

T_C, M_S, H_R, H_C

$(BH)_{max}$

Experiments

μ = atomic moments
J = exchange constants
d = atomic anisotropies

M = saturation magnetization
A = exchange stiffness
K = effective anisotropy

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Ab initio methods: DFT

Born-Oppenheimer approximation

We describe a many-body system formed by N_e electrons and N nuclei, solving the Schrödinger equation:

$$[T_N + T_e + V_{ee} + V_{NN} + V_{Ne}]\, \Phi(\mathbf{r},\mathbf{R}) = E\Phi(\mathbf{r},\mathbf{R})$$

The differences in the time-scales of nuclear and electronic motions enable to separate the variables describing the electron (**r**) and nuclei (**R**) positions:

$$\Phi(\mathbf{r},\mathbf{R}) = \Psi(\mathbf{r},\mathbf{R})\chi(\mathbf{R})$$

This way we decouple the adiabatic Schrödinger equations of electrons and nuclei:

$$[T_e + V_{ee} + V_{Ne}(\mathbf{r},\mathbf{R})]\, \psi(\mathbf{r},\mathbf{R}) = \varepsilon(\mathbf{R})\Psi(\mathbf{r},\mathbf{R}) \qquad \textit{electrons}$$

$$[T_N + V_{NN}(\mathbf{R}) + \varepsilon(\mathbf{R})]\, \chi(\mathbf{R}) = E\chi(\mathbf{R}) \qquad \textit{nuclei}$$

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Ab initio methods: DFT

Born-Oppenheimer approximation

The B-O is based on two assumptions:

1) Adiabatic approximation: the ions move on the potential-energy surface of the electronic ground state.

2) Neglect quantum effects in ionic dynamics: replace time-dependent ionic Schrödinger equation by a classical Newtonian equation of motion.

$[T_N + V_{NN}(\mathbf{R}) + \varepsilon(\mathbf{R})]\ \chi(\mathbf{R}) = E\chi(\mathbf{R})$ ⇨ Solved by molecular mechanics: consider atoms as classical objects.

$[T_e + V_{ee} + V_{Ne}(\mathbf{r},\mathbf{R})]\ \psi(\mathbf{r},\mathbf{R}) = \varepsilon(\mathbf{R})\Psi(\mathbf{r},\mathbf{R})$ ⇨ Quantum mechanics to determine the electronic ground state.

Hellman-Feynmann theorem. Couple the electronic Schrödinger equation and the ionic Newtonian equations: *The forces acting on the ions are given by the expectation value of the gradient of the electronic Hamiltonian in the ground state.*

$$\vec{F}_N = -\vec{\nabla}_N E_0\left(\vec{R}\right) = -\vec{\nabla}_N\left[\varepsilon_0(\vec{R}) + V_{NN}(\vec{R})\right]$$

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Ab initio methods: DFT

Solving the Schrödinger equation (DFT)

The ***Hohenberg-Kohn-Sham theorem****:*

1) The ground state energy, *E*, of a many-body system is a unique functional of the particle density, *n*.

2) The functional has its minimum relative to variations of the particle density at the equilibrium density, n_0.

$$E[n_0] = \min\{E[n]\}$$

The total energy functional:

$$E[n] = T[n] + E_H[n] + E_{xc}[n] + V[n]$$

Size scale: $O(N^3)$

T = kinetic energy

E_H = Hartree energy (electron-electron repulsion)

E_{xc} = exchange correlation energy

V = external potential term

Unknown functional forms

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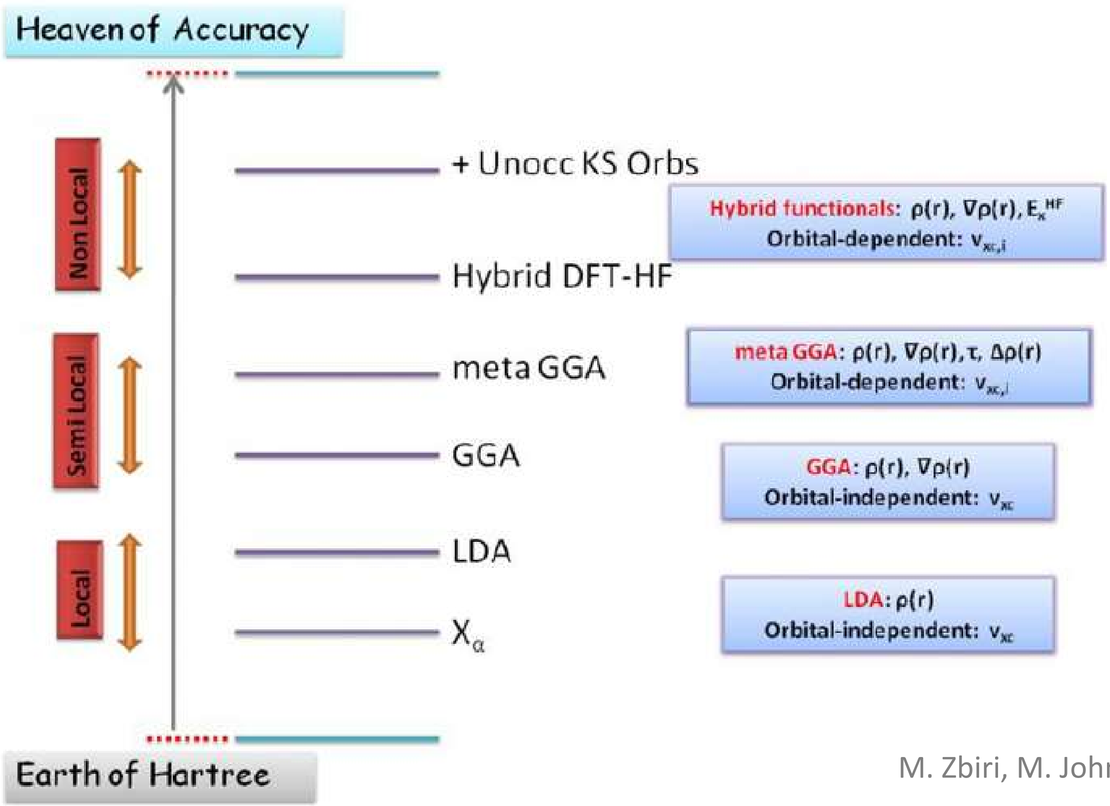
Ab initio methods: DFT

Solving the Schrödinger equation (DFT) – choice of functional forms



The exact form of T[n] & E_{xc}[n] is unknown. The different choices lead to the different flavors of DFT: LDA (free electron gas), GGA (general gradient approximation), hybrid functionals (mixtures with Hartree-Fock model), DFT+U (addition of a local Hubbard term), etc.

M. Zbiri, M. Johnson, H. Schober, S. Rois, *Collection SFN* 12, 77 (2011)

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Ab initio methods: DFT

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DFT computational flow diagram

END

Observables

Ground state, n

YES

Hellman-Feymann forces =0?

NO

nuclei

Molec. Dyn. Newtonian eq.

New structure

Scf resolution Schrödinger eq.

electrons

Structure
Magnetic order

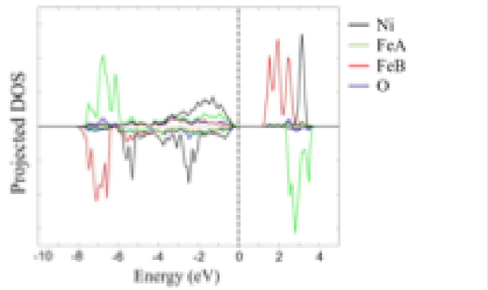
Initial state, n_0

START

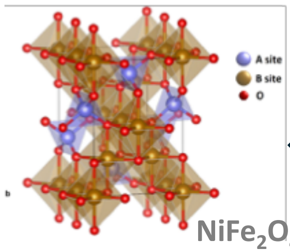
Theoretical conditions

Basis set
Treatment of core
Accuracy
xc functional

Electronic gap, magnetization (M_S), energy



C. Tejera-Centeno, R. Rico, S. Gallego, *J Mater Sci* 58, 5658 (2023)



$NiFe_2O_4$

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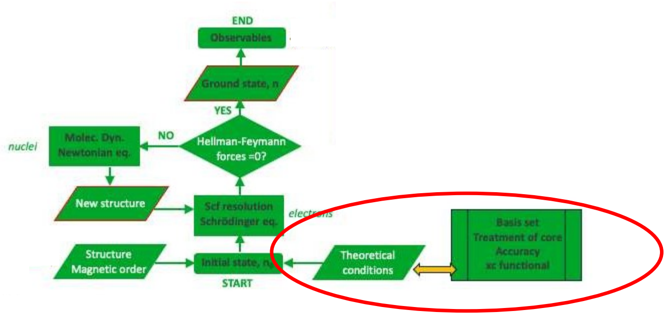
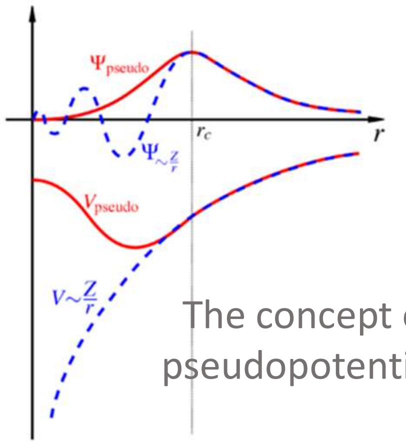
Ab initio methods: DFT

BEETHOVEN greene

Solving the Schrödinger equation (DFT)





The concept of pseudopotentials

- Choose the complete basis set to express that of your system.
- Choose if core and valence electrons are considered on equal footing.

Choose your code !

VASP: Vienna Ab-initio Simulation Package

Plane wave basis set

Pseudopotentials

www.flapw.de Fleur

JuKKR

Green function methods

All electron

AkaiKKR machikaneyama

siesta

Localized atomic orbitals basis set

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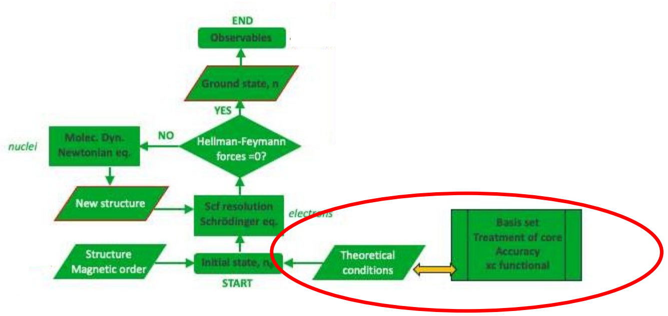
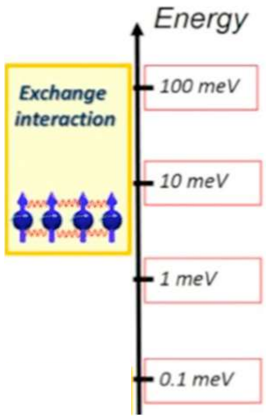
Ab initio methods: DFT

Solving the Schrödinger equation (DFT)

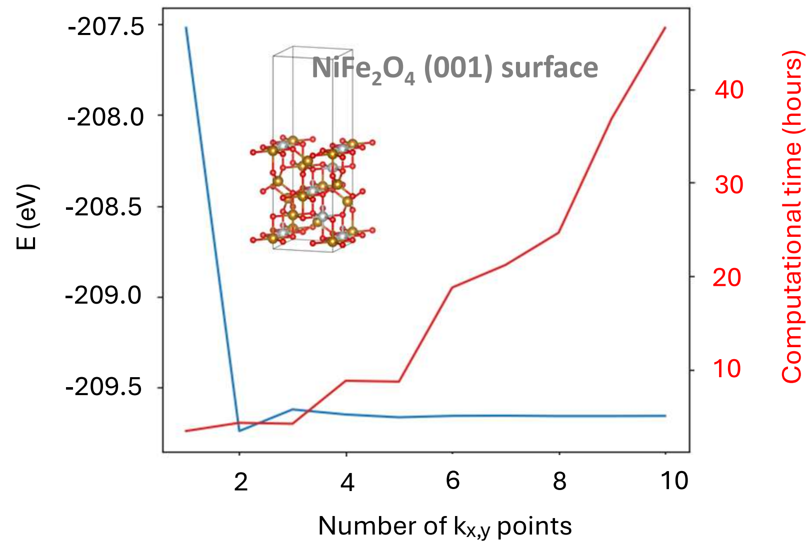




Scale of the interactions

Accuracy: determine the dependence of the theoretical conditions (truncation of complete basis set, Brillouin Zone sampling, etc.) on the required precision.

No. $k_{x,y}$	Energy (eV)
6	-209.6557
7	-209.6548
8	-209.65693
9	-209.65686
10	-209.65614



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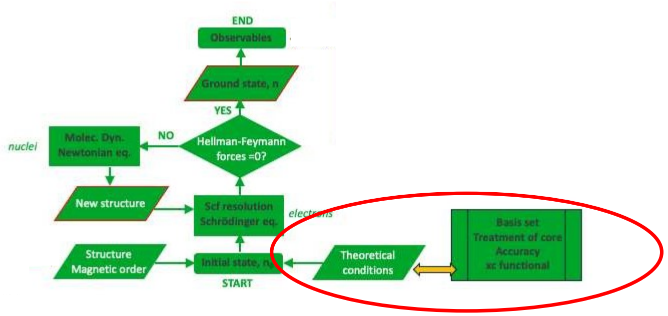
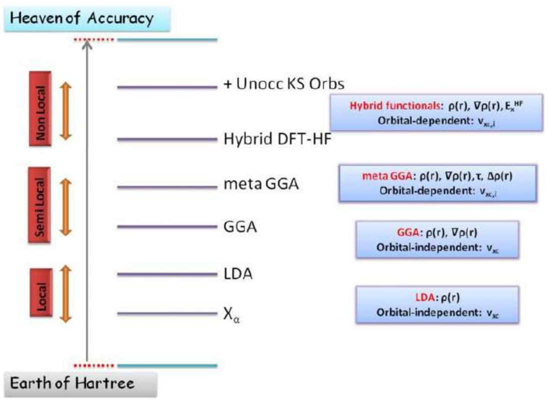
Ab initio methods: DFT

BEETHOVEN greene

Solving the Schrödinger equation (DFT)



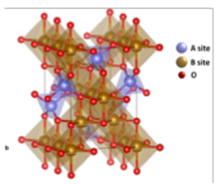


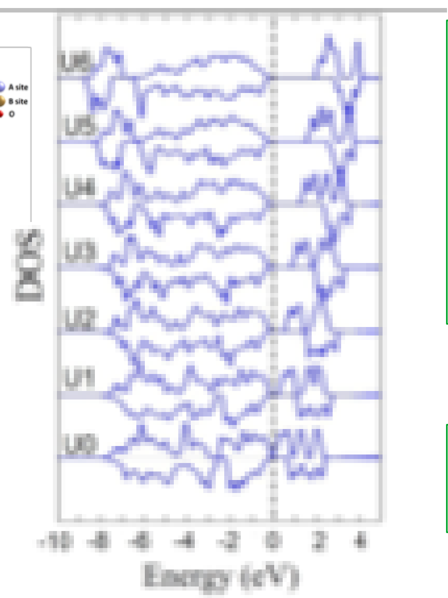
Collection SFN 12, 77 (2011)

Choice of the xc functional: the example of DFT+U

$$E_{\mathrm{DFT+U}} = E_{\mathrm{LSDA}} + \frac{(U-J)}{2}\sum_{\sigma}\left[\left(\sum_{m_1} n^{\sigma}_{m_1,m_1}\right) - \left(\sum_{m_1,m_2} \hat{n}^{\sigma}_{m_1,m_2}\hat{n}^{\sigma}_{m_2,m_1}\right)\right].$$

$NiFe_2O_4$





J Mater Sci 58, 5658 (2023)

$NiFe_2O_4$ is known to have an insulating gap around 1.5 eV. To reproduce this with DFT, a E_{xc} beyond LSDA or GGA is needed.

Adding a local Hubbard-like repulsion potential (U) to the *d* electrons enables to recover the experimental gap for U ≈ 4 eV.

Introducing U as a parameter, the ab initio feature is partially lost.

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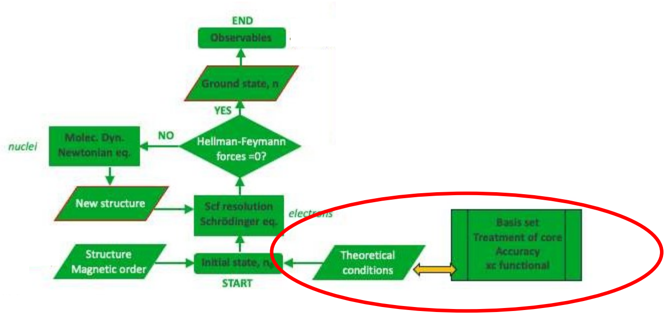
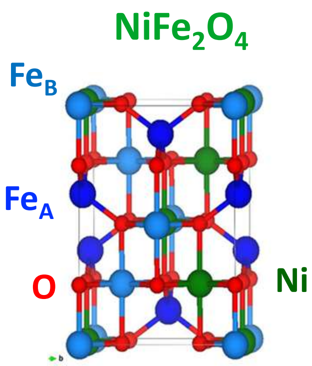
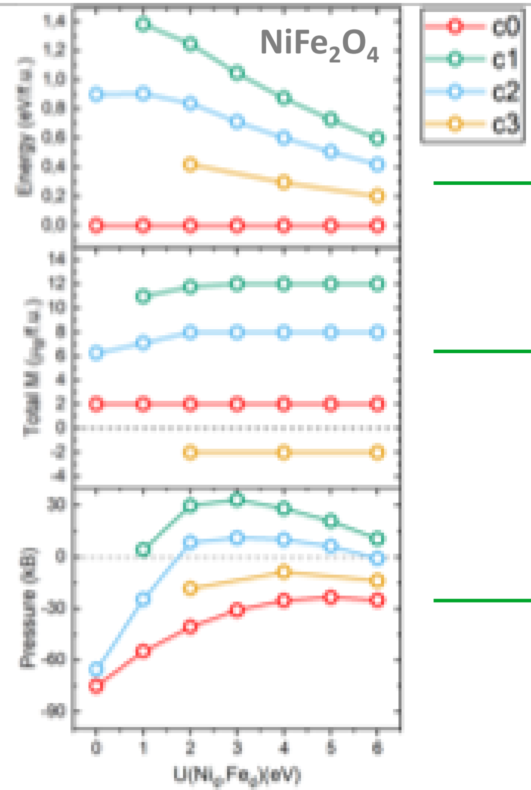




Mag. Config.	Fe_A	Fe_B	Ni
c0	+	-	-
c1	+	+	+
c2	+	+	-
c3	+	-	+

C. Tejera-Centeno, R. Rico, S. Gallego, *J Mater Sci* 58, 5658 (2023)

Variation vs. U of the ground state energy, the net magnetization & the internal pressure at the experimental lattice parameter for different magnetic orders.



The ground state magnetic configuration (c0) is well identified for all U. The energy barrier between configurations decreases with U.

The net magnetization is independent of U for all configurations.

The ground state volume depends on U, but differences between configurations are similar for all U values.

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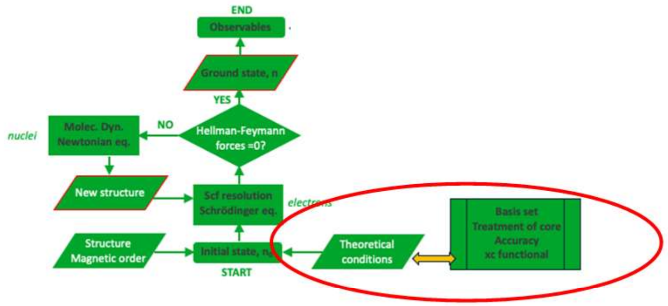
Ab initio methods: DFT

Solving the Schrödinger equation (DFT)

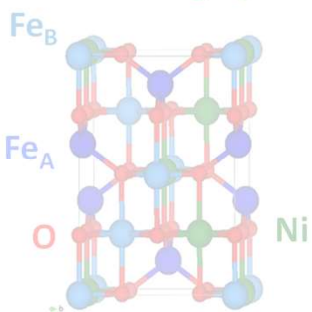


Choice of the xc functional: the example of DFT+U

$$E_{\mathrm{DFT+U}} = E_{\mathrm{LSDA}} + \frac{(U-J)}{2}\sum_{\sigma}\left[\left(\sum_{m_1} n^{\sigma}_{m_1,m_1}\right) - \left(\sum_{m_1,m_2} \hat{n}^{\sigma}_{m_1,m_2}\hat{n}^{\sigma}_{m_2,m_1}\right)\right].$$

...guration U. The energy barrier between configurations decreases with U.

$NiFe_2O_4$



Mag. Config.	Fe_A	Fe_B	Ni
c0	+	-	+
c1	+	+	+
c2	+	+	-
c3	+	-	-

The specific value of the materials features depends on U, and this can be used to optimize it comparing to the experimental data.

But usually trends between different systems/configurations are robust vs. variations of U.

...are similar for all U values.

C. Tejera-Centeno, R. Rico, S. Gallego, *J Mater Sci* 58, 5658 (2023)

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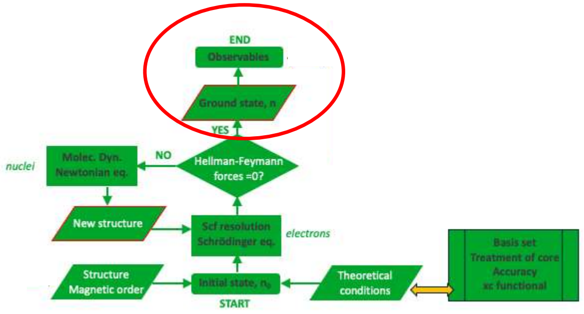
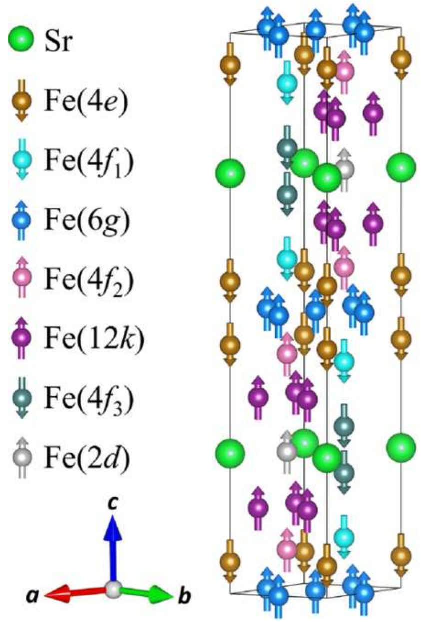
Extracting magnetic features from DFT



Magnetization

Solution of the Schrödinger equation directly provides the total magnetization at the ground state (equivalent to M_S) and the local atomic contributions.

$SrFe_{18}O_{27}$



Site	Moment (μ_B)
4e	-3.52
4f1	-3.52
6g	3.65
4f2	3.70
12k	3.75
4f3	-3.24
2d	3.65
Total (f.u.)	56

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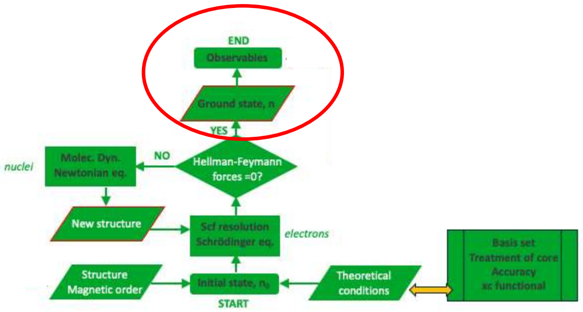
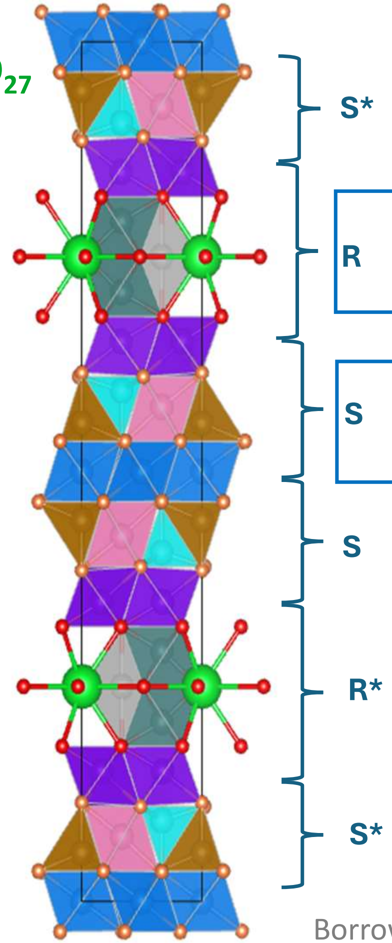
Extracting magnetic features from DFT



Magnetic Anisotropy (MA)

The MA is determined from the differences between the total energies of configurations with the magnetization aligned at different directions.

$SrFe_{18}O_{27}$

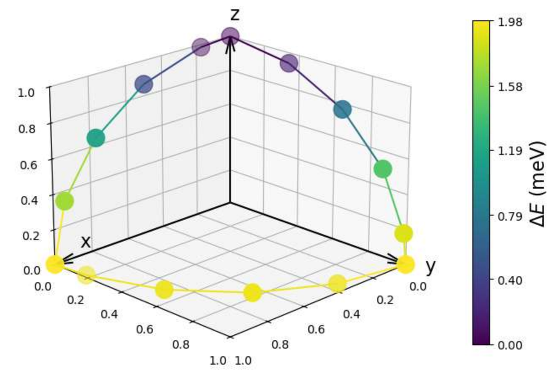


$SrFe_6O_{11}$
$M = 8.28\ \mu_B$
$K_u = 0.96$ meV

Fe_6O_8
$M = 7.80\ \mu_B$
$K_u = -0.06$ meV

$K_u = E_{001} - E_{100}$

MAE = $E(M_0) - E(M_i)$



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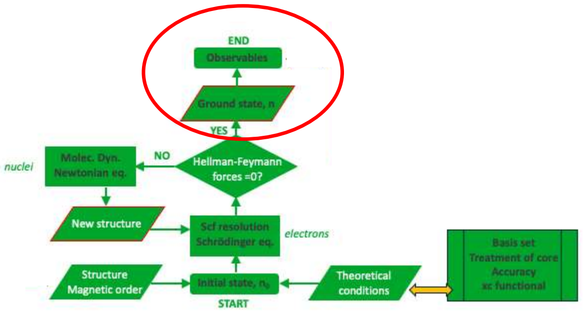
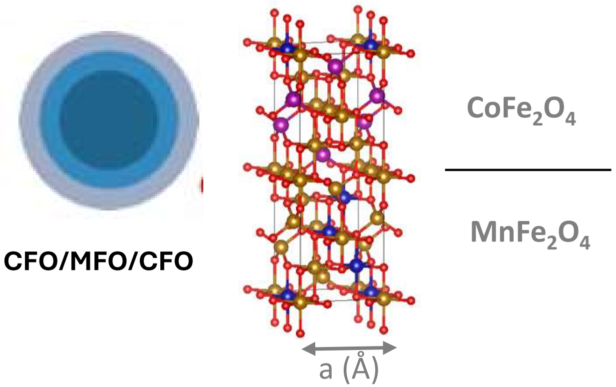
Extracting magnetic features from DFT





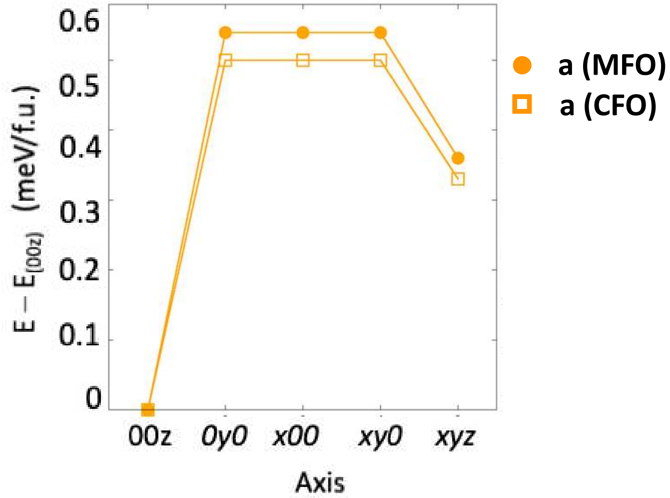
Magnetoelastic properties

Magnetoelasticity is the change of the magnetic properties of a material under mechanical deformation. DFT determines it from the correlation between the system energy, the magnetic anisotropy and the structural deformation.

Ferrite	$CoFe_2O_4$	$MnFe_2O_4$
a (Å)	8.35	8.46

Deformation when $CoFe_2O_4$ adopts the lattice parameter of $MnFe_2O_4$	
Orientation	(001)
Δx	+1.6 %
Δz	-2.7 %

Variation of the MAE of $CoFe_2O_4$ for different directions under the deformation imposed by growth on $MnFe_2O_4$



César Tejera-Centeno, *PhD tesis* (2022)

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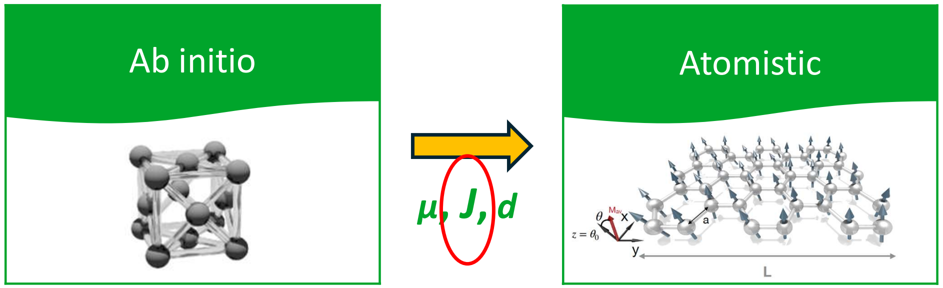
From DFT to atomistic models

Exchange interactions
Critical T



How to extract the Magnetic Exchange interactions (J)

The method is based on the mapping of the DFT energies to a Heisenberg-like Hamiltonian, assuming all changes between different magnetic orders can be assigned to the magnetic exchange interaction.

Energy from Heisenberg model:

$$E_{ex} = \frac{1}{2} \sum_{i=1}^{N} \sum_{\substack{j=1 \\ j\neq i}}^{N} n_i z_{ij} J_{ij} S_i S_j \sigma_i^{(\alpha)} \sigma_j^{(\alpha)}$$

- n_i number of inequivalent sites at sublattice *i*
- z_{ij} number of *i,j* neighbors
- $S_i\ \sigma^{(\alpha)}_i$ spin at *i* site in sublattice α

Assuming invariance of the local moments S_i across the different configurations α, the magnetic exchange interactions between magnetic sublattices (J_{ij}) can be obtained:

$$J_{ij} = \frac{\Delta(\alpha_{ij} - \alpha_0) - \Delta(\alpha_i - \alpha_0) - \Delta(\alpha_j - \alpha_0)}{4 n_i z_{ij} S_i S_j \sigma_i{}^{(0)} \sigma_j{}^{(0)}}$$

- α_0 magnetic configuration at ground state
- α_i configuration reversing sublattice *i*
- $\Delta(\alpha_i - \alpha_0)$ energy difference between configurations

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From DFT to atomistic models

Exchange interactions
Critical T

BEETHOVEN greene

Extracting the magnetic exchange interactions (J_{ij})

An already visited example, the case of **$NiFe_2O_4$**:

$$J_{ij} = \frac{\Delta(\alpha_{ij} - \alpha_0) - \Delta(\alpha_i - \alpha_0) - \Delta(\alpha_j - \alpha_0)}{4 n_i z_{ij} S_i S_j \sigma_i^{(0)} \sigma_j^{(0)}}$$

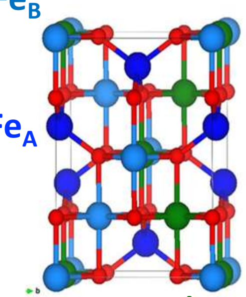
Configurations α

Mag. Config.	Fe_A	Fe_B	Ni
c0	+	-	-
c1	+	+	+
c2	+	+	-
c3	+	-	+

Magnetic sublattices S_i

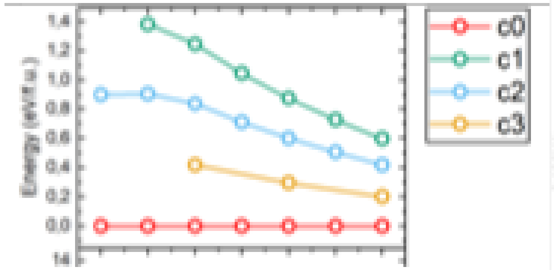
F = Fe_B

A=Fe_A

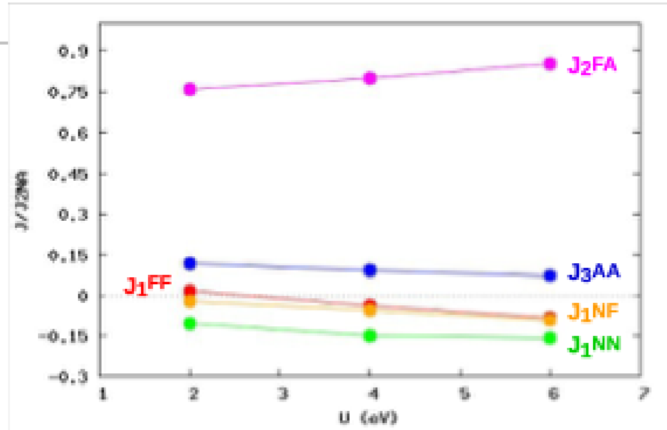


N= Ni

Energy differences Δ (vs. U)



Relative J_{ij} value vs. U (J_{ij}/J_{NA})



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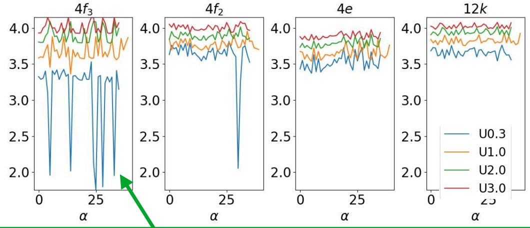
From DFT to atomistic models

Exchange interactions
Critical T

Extracting the magnetic exchange interactions (J_{ij})

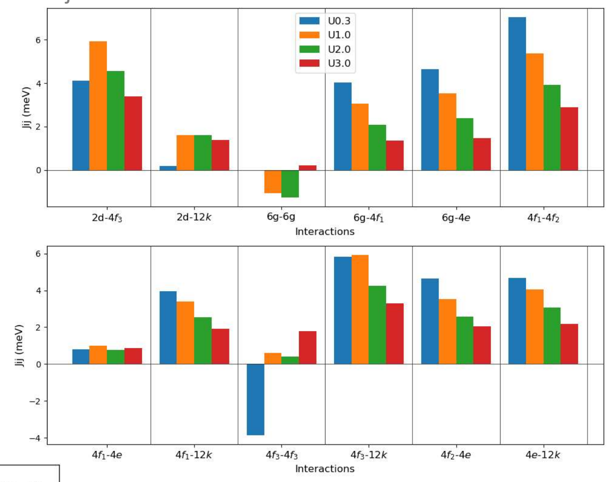
A BEETHOVEN example, the W-hexaferrite **$SrFe_{18}O_{27}$**:



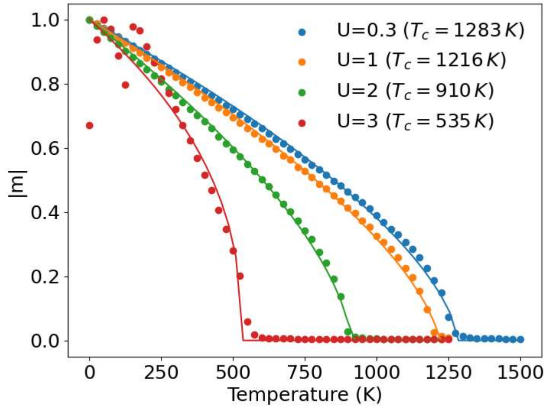
Variation of S_i, S_j vs. U for different sublattices.

The method is based on the mapping of the DFT energies to a Heisenberg-like Hamiltonian, *assuming all changes between different magnetic orders can be assigned to the magnetic exchange interaction*.

J_{ij} vs. U between pairs of sublattices



Determination of the **magnetic ordering temperature** based on atomistic simulations (*VAMPIRE code*)



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Thank you for your attention!

Silvia Gallego

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"Talking Magnets" Webinar Series

Micromagnetic simulation and domain dynamics

"From Atoms to Applications: A Multiscale Perspective on Magnetism and Permanent Magnets"

16-10-2025

Presenter: **Thomas Schrefl**
Organisation: **University for Continuing Education Krems**

University for Continuing Education Krems

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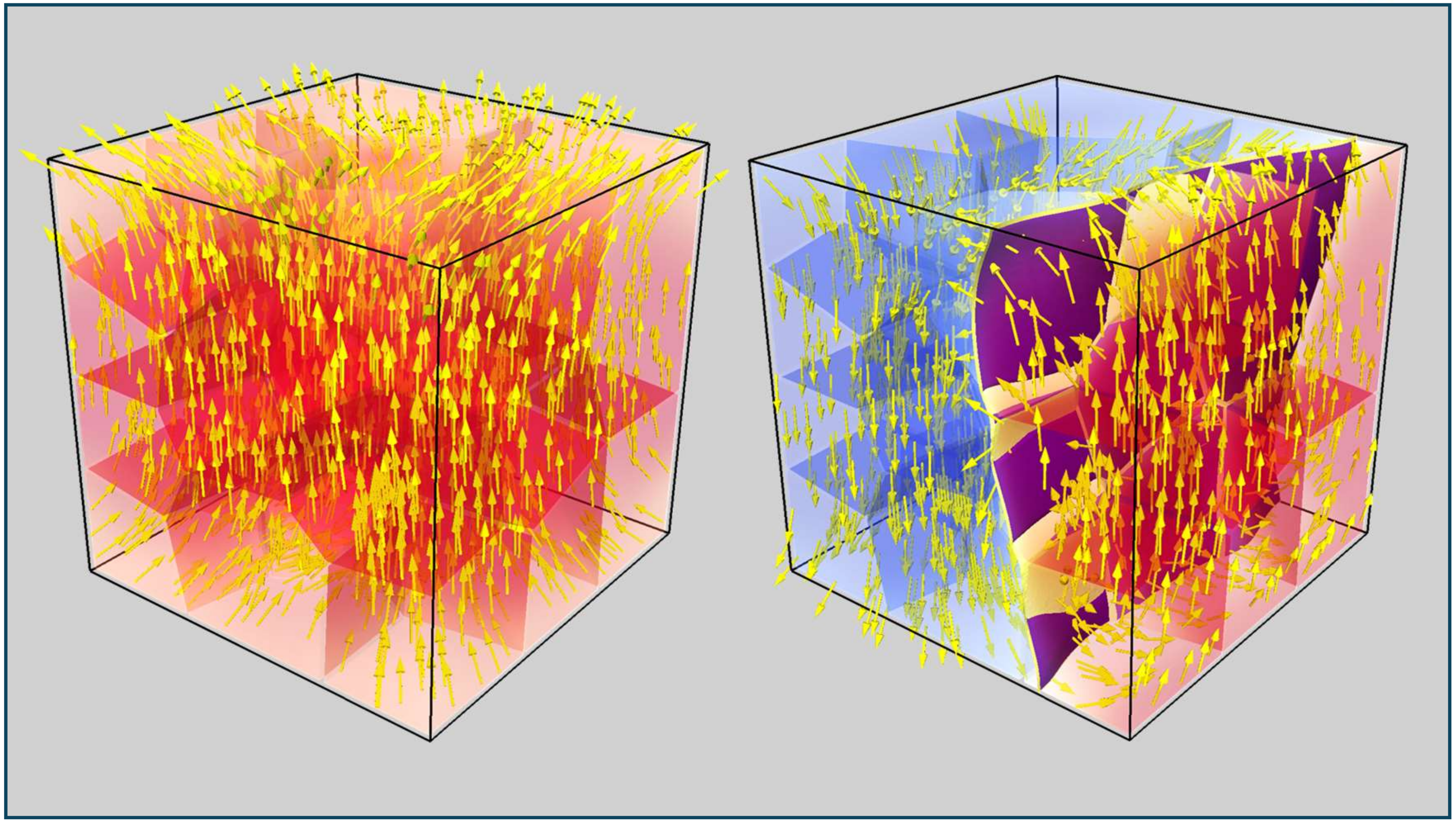
Computing magnetization reversal



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Outline

- Unboxing micromagnetic solvers
- Small particles
- Domain walls and domain patterns
- Micromagnetic software

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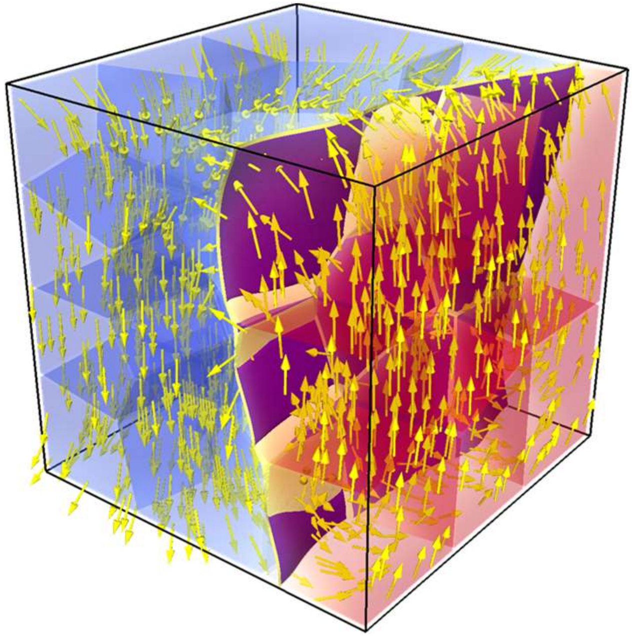
Micromagnetism



- Continuum theory
- Magnetization is a continuous vector function in space

$$\mathbf{M} = \mathbf{M}(\mathbf{x})$$

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anisotropy energy

+

Zeeman energy (external field)

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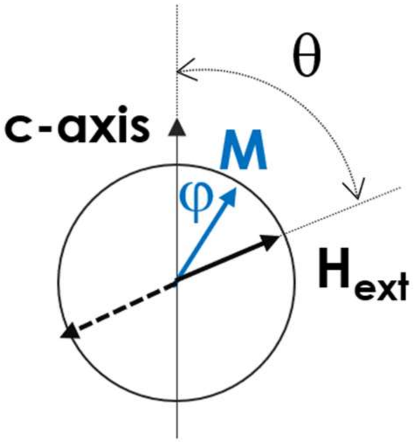
Stoner Wohlfarth particle



$$E = KV \sin^2\varphi - \mu_0 H_{ext} M_s V \cos(\theta - \varphi)$$

anisotropy energy (for $KV \sin^2\varphi$)

Zeeman energy (for $- \mu_0 H_{ext} M_s V \cos(\theta - \varphi)$)

K anisotropy constant in units of J/m^3
V volume of the particle in units of m^3
M_s spontaneous magnetization in units of A/m

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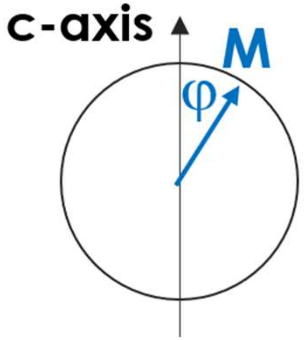
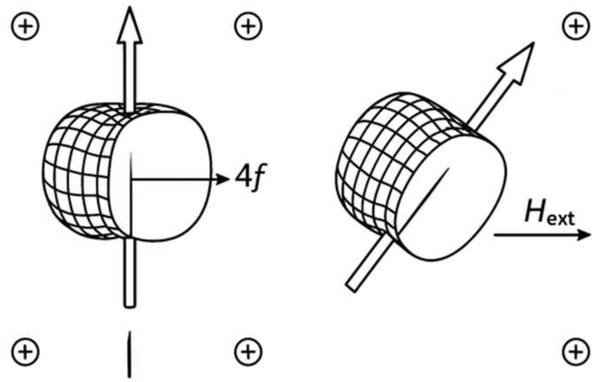
Anisotropy energy



$$E_{ani} = KV \sin^2\varphi$$



electrostatic interaction energy between the charge cloud of the 4f electrons and the electrostatic crystal field

Kronmüller, Fähnle, Micromagnetics and the microstructure of magnetic solids, Cambridge University Press, 2009

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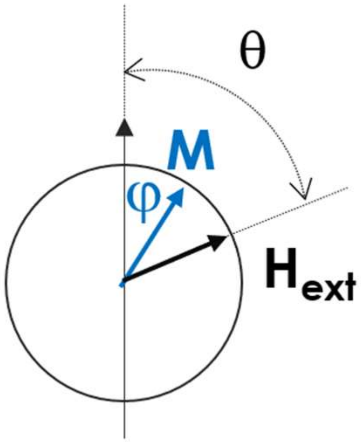
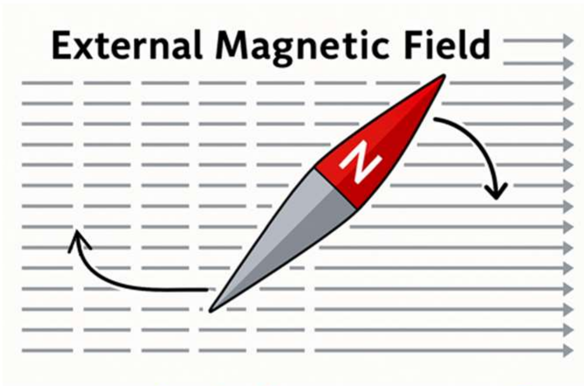
Zeeman energy



$$E_{ext} = -\mu_0 H_{ext} M_s V \cos(\theta - \varphi)$$

magnetic moment



magnetostatic energy of a dipole in an external magnetic field

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Try yourself

launch binder

https://mybinder.org/v2/gh/thomasschrefl/micromagnetic_basics/HEAD

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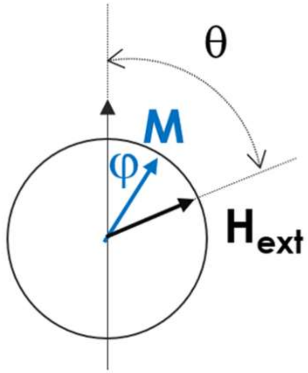
hysteresis curve of a small particle



anisotropy energy density and Zeeman energy

$$E_{\mathrm{ani}} = K \sin^2(\varphi) V$$

$$E_{\mathrm{zee}} = -H J_{\mathrm{s}} \cos(\theta - \varphi) V \,, J_{\mathrm{s}} = \mu_0 M_{\mathrm{s}}$$

normalize energies: divide by $2KV$

$$e_{\mathrm{ani}} = \frac{1}{2} \sin^2(\varphi)$$

$$e_{\mathrm{zee}} = -h \cos(\theta - \varphi), \text{ with } h = H \frac{J_{\mathrm{s}}}{2K}$$

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$$e_{\text{ani}} = \frac{1}{2}\sin^2(\varphi)$$

$$e_{\text{zee}} = -h\cos(\theta - \varphi), \text{ with } h = H\frac{J_s}{2K}$$

energy density

In [2]:

```
def energy_density(phi, h, theta):
  e_ani = 0.5*(np.sin(phi))**2
  e_zee = - h*np.cos(theta-phi)
  return (e_ani + e_zee).squeeze()
```

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In [1]:
```
import matplotlib
import matplotlib.pyplot as plt
matplotlib.rcParams.update({'font.size': 12})

import numpy as np
from scipy.optimize import minimize
```

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hysteresis loop

In [3]:

```
h_values = np.concatenate( (np.linspace( 1.2,-1.2,100),   # down
                            np.linspace(-1.2, 1.2,100)) ) # up

theta = np.radians(15.0) # field angle
phi = theta              # initial magnetization angle

mh = []
for h in h_values:
  res = minimize(energy_density,phi,args=(h,theta))
  phi = res.x[0]
  mh.append(np.cos(phi-theta).squeeze())
```

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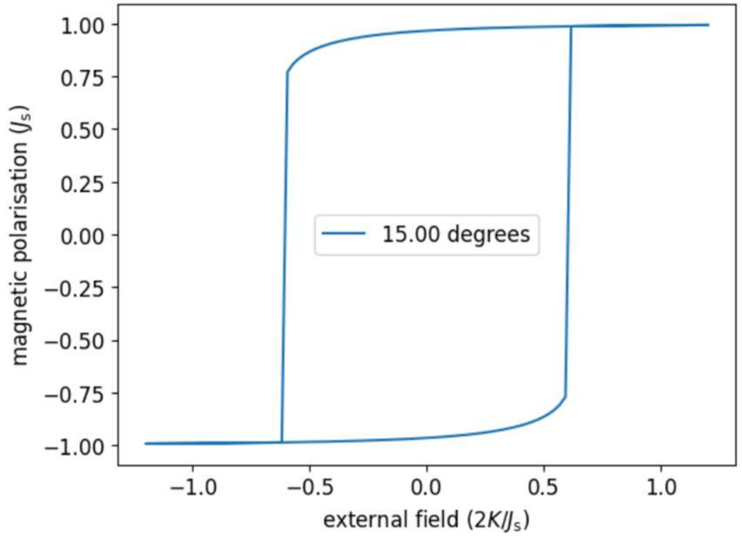
Slide 66

plot

```
[5]: plt.plot(h_values,mh,label=f'{np.degrees(theta):.2f} degrees')
     plt.xlabel(r'external field $(2K/J_\mathrm{s})$')
     plt.ylabel(r'magnetic polarisation $(J_\mathrm{s})$')
     plt.legend()
```



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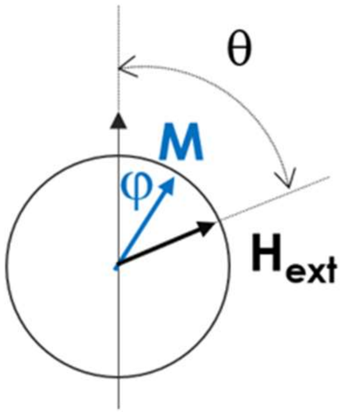
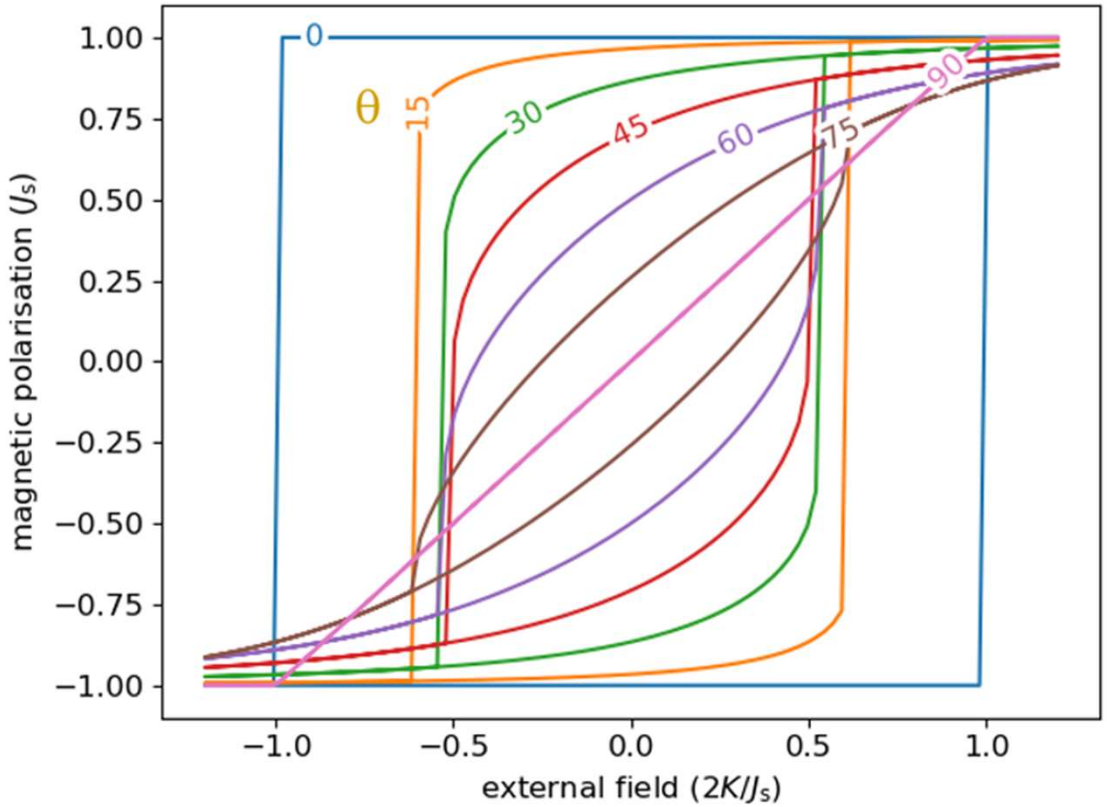
Angle dependence of coercivity





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anisotropy energy

+

exchange energy

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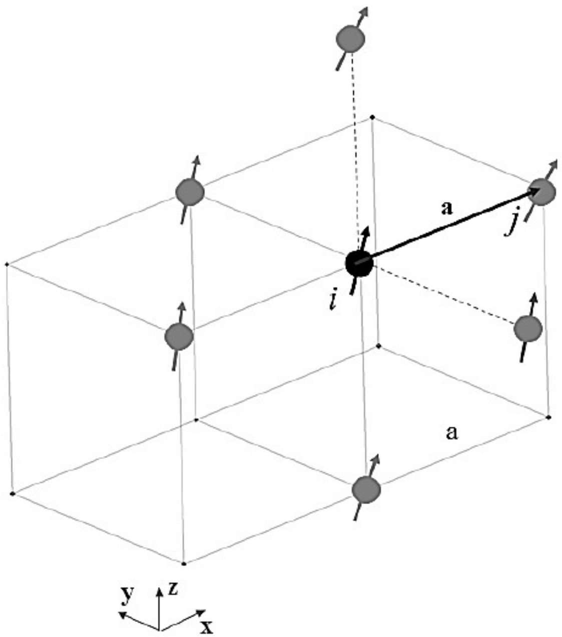
Exchange energy



- Exchange interactions between neighboring spins $\sim \mathbf{S}_i \cdot \mathbf{S}_j$
- Replace spin with continuous function of $\mathbf{x}$
- Taylor expansion of $\varphi(x)$

$$E_{\mathrm{ex}} = \int A \left(\frac{d\phi}{dx} \right)^2 dx$$

A exchange constant in units of J/m

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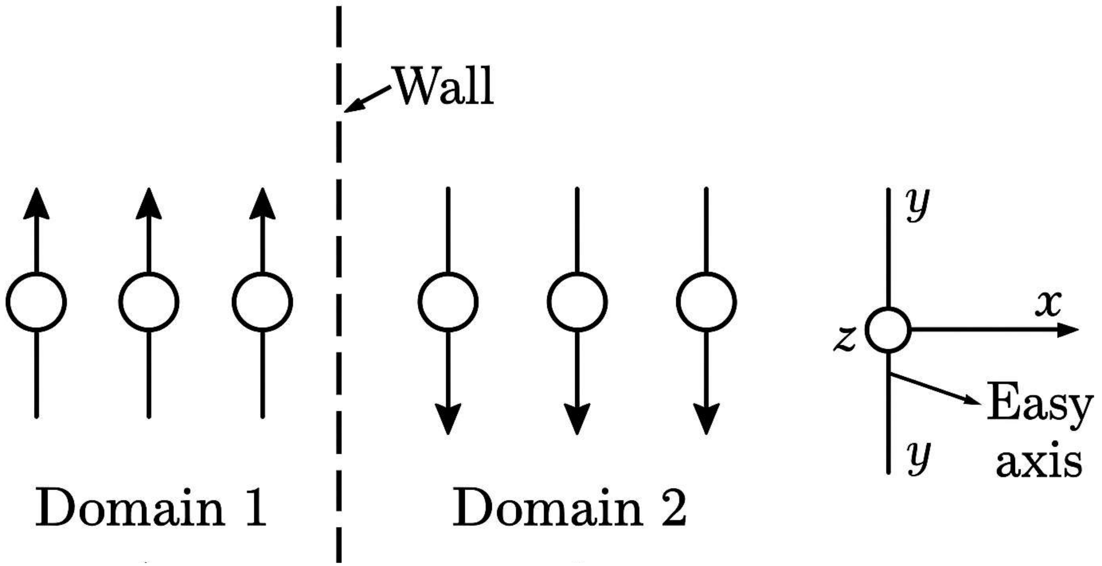
Magnetization distribution in domain walls



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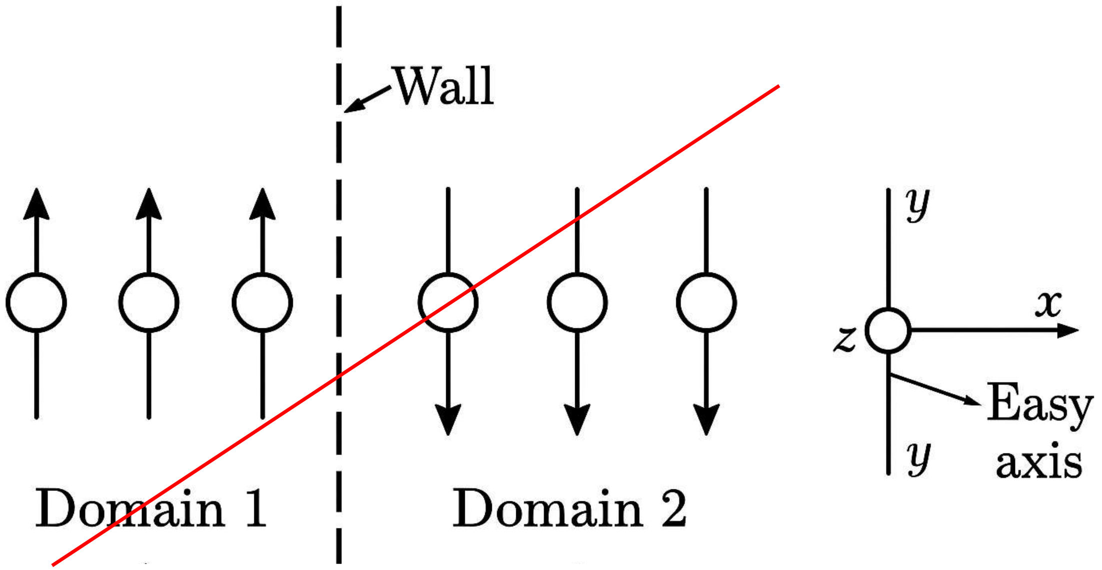
Magnetization distribution in domain walls



sharp transition has higher energy than smooth domain wall

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How to calculate $\mathrm{M}(x)$

Material properties

In [2]:

```
K   = 410e3              # J/m3 anisotropy constant
A   = 31e-12             # J/m  exchange constant

delta0 = np.sqrt(A/K)  # Bloch parameter
```

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Computational grid

In [3]:

```
a = -40.0e-9    # start of region in nm
b =  40.0e-9    # end   of region in nm
N =  80         # number of cells
L = b-a         # length of region
d = L/N         # cell size
```

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Energy

In [4]:

```
def energy(phi,d,L,K,A):
  phic  = 0.5*(phi[:-1]+phi[1:]) # phi in center of each element
  dphi  = (phi[1:]-phi[:-1])/d   # first derivative
  e_ani = K*(np.sin(phic)**2)    # anisotropy energy density
  e_ex  = A*(dphi*dphi)          # exchange energy density
  e = np.sum( d*(e_ex + e_ani) ) # sum up energy of each cell
  return e
```

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minimize energy

```
In [5]:
phi0 = (N//2)*[np.pi] + (N//2)*[0]          # initial magnetization
phi0 = np.array(phi0)

res  = minimize(energy,phi0,args=(d,L,K,A))
phi  = res.x
```

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plot

In [6]:

```
x = np.linspace(a,b,N)              # coordinates of nodes for plotting
plt.figure(figsize=(12, 6))

plt.plot(x*1e9, np.cos(phi0),     '--',label='initial')
plt.plot(x*1e9, np.cos(phi),           label='final')
plt.plot(x*1e9, np.tanh(x/delta0),':',label='analytic', color='r')

plt.quiver(x*1e9, np.zeros_like(x),
           np.zeros_like(x), np.cos(phi),
           scale=40, linewidth=0.05, minshaft=2, width=0.002, pivot='mid')
```

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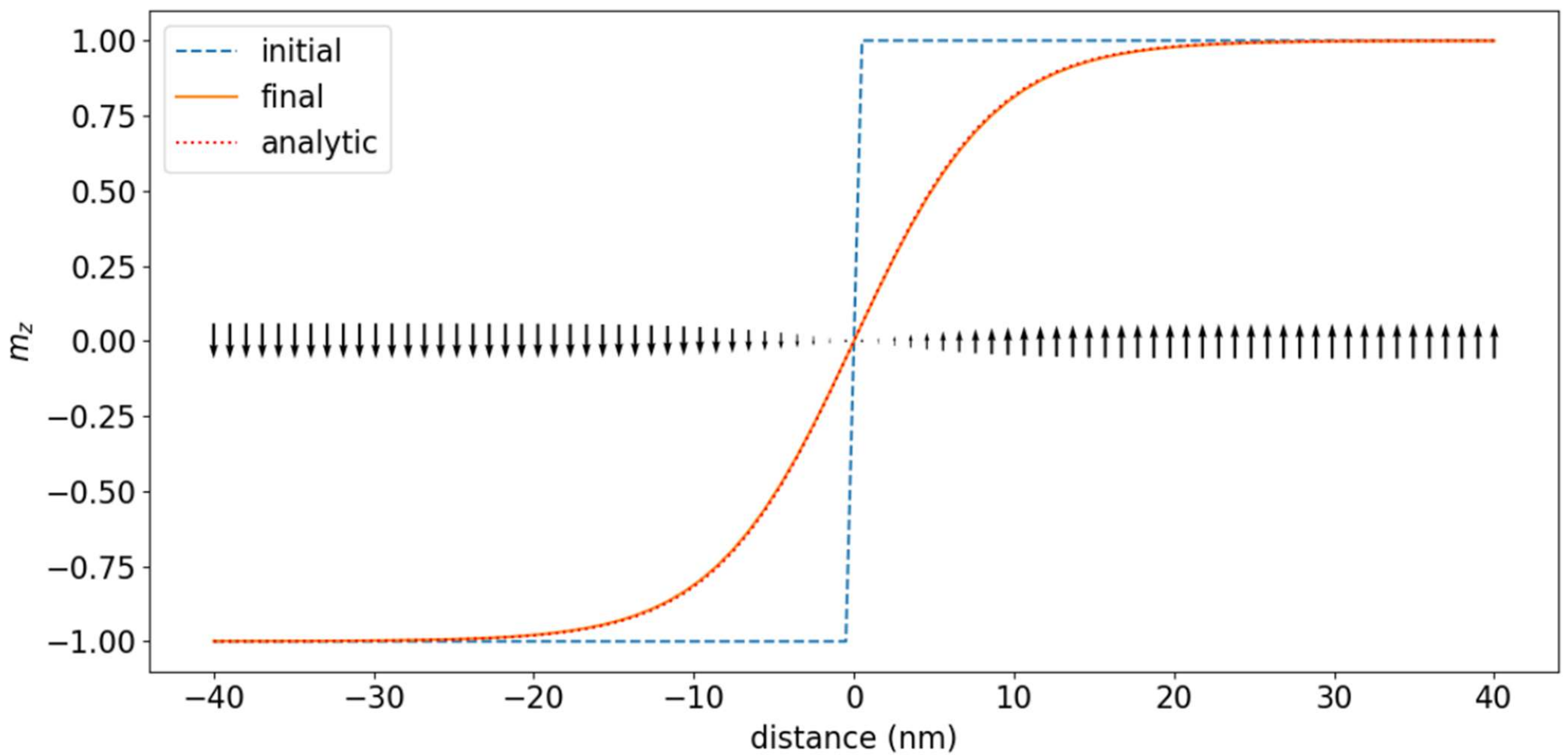
Out [6]:



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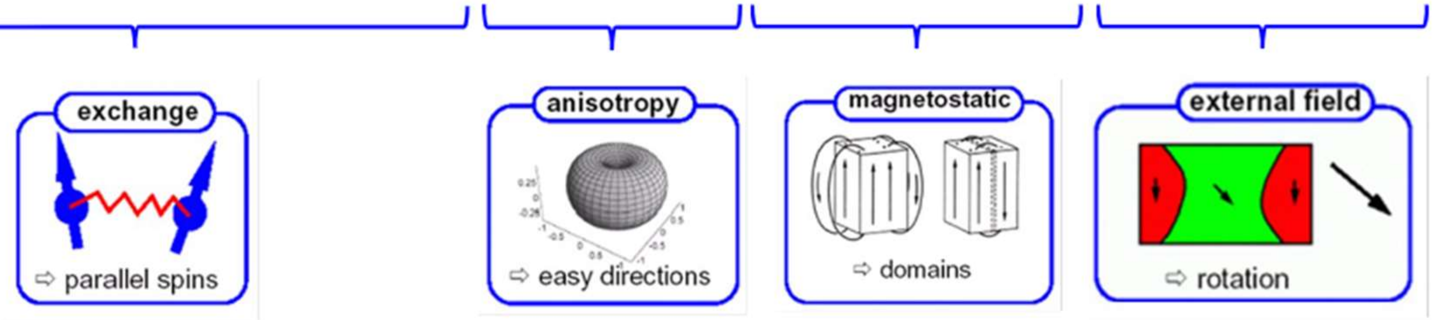
Minimizing the energy gives domain pattern

$$E(\mathbf{m}) = \int dV \left\{ A\left(\left(\frac{\partial m_x}{\partial x}\right)^2 + \left(\frac{\partial m_y}{\partial y}\right)^2 + \left(\frac{\partial m_z}{\partial z}\right)^2 \right) - K(\mathbf{m}\cdot\mathbf{k})^2 - \frac{\mu_0 M_s}{2}(\mathbf{H}_\mathrm{d}\cdot\mathbf{m}) - \mu_0 M_s(\mathbf{H}_\mathrm{ext}\cdot\mathbf{m}) \right\}$$



$$\mathbf{m} = \mathbf{M}/|\mathbf{M}|$$

$|\mathbf{m}| = 1$ ⇨ Diffusion on the surface of a sphere

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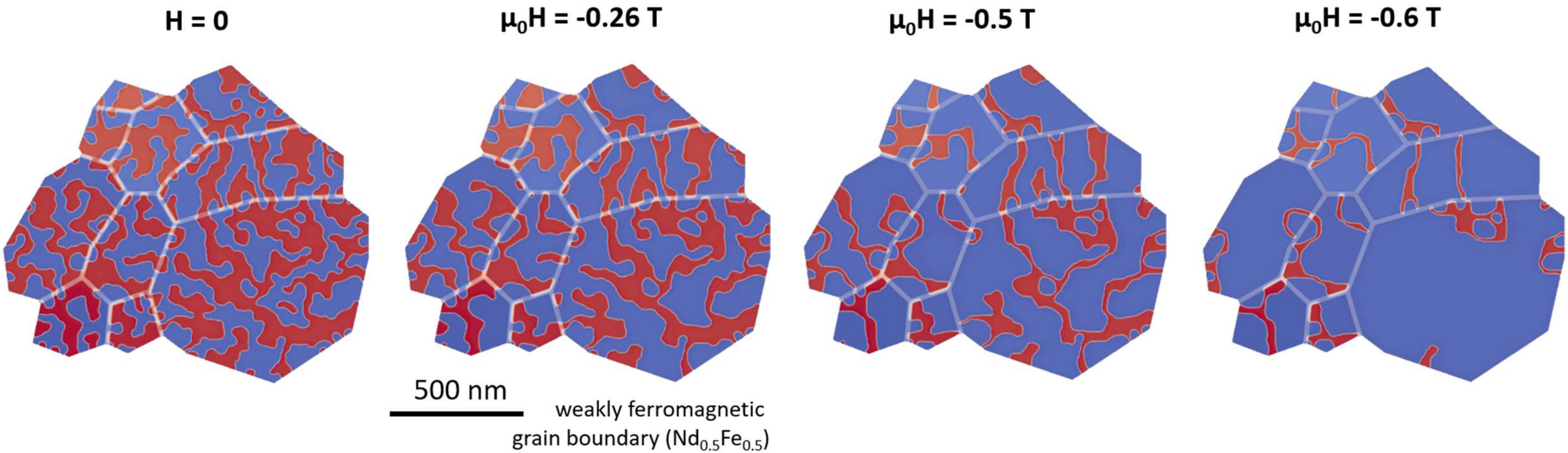
Domain patterns in $Nd_2Fe_{14}B$ foils



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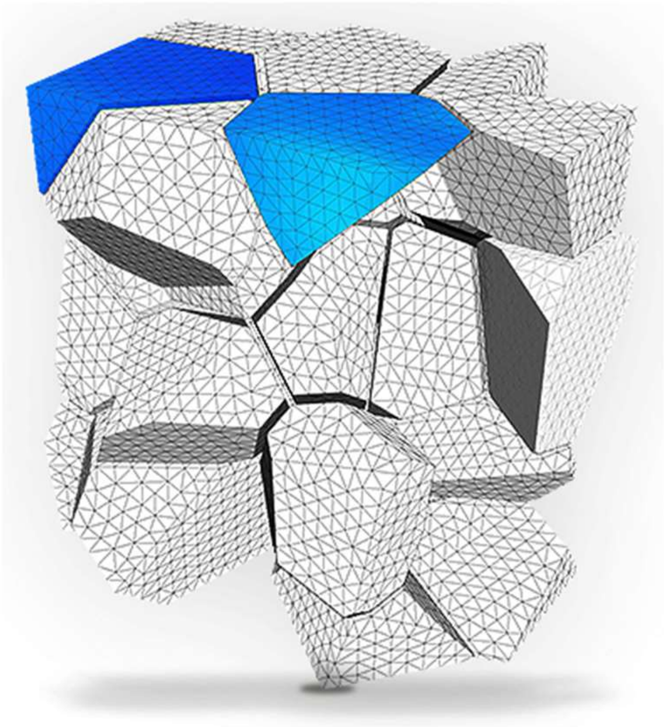
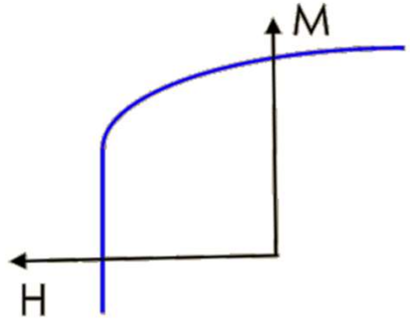
Finite element micromagnetics



subdivide grains into finite elements

interpolate magnetization and magnetic scalar potential

minimize the energy for varying applied fields



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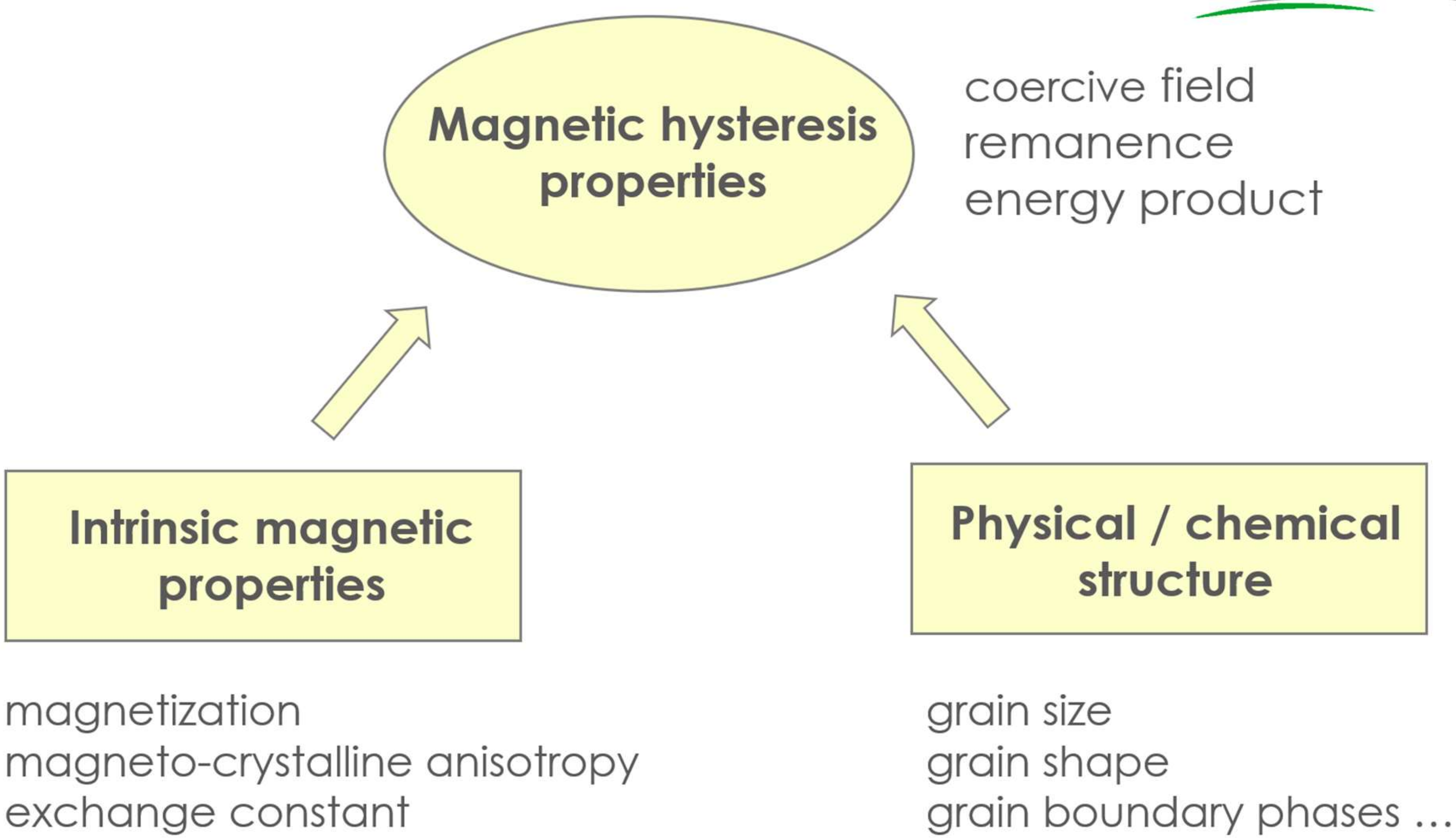
Finite element micromagnetics



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Summary

- Micromagnetism is a continuum theory
- Fine computational grid to resolve the transition of the magnetization in domain walls
- The competitive effects of the energy terms upon minimization determine the magnetic state
- You can run micromagnetic simulations in the browser https://ubermag.github.io/
- Check your results carefully change mesh sizes and tolerances
- Micromagnetics helps to design magnetic materials and devices

Try it in your browser

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Thank you for your attention!

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"Talking Magnets" Webinar Series

Microstructural Engineering and Magnet Properties

Presenter 1: **Dr. César de Julián Fernández**
Organisation: **Italian National Research Council**

Presenter 2: **Dr. Tomaž Tomše**
Organisation: **Jožef Stefan Institute**

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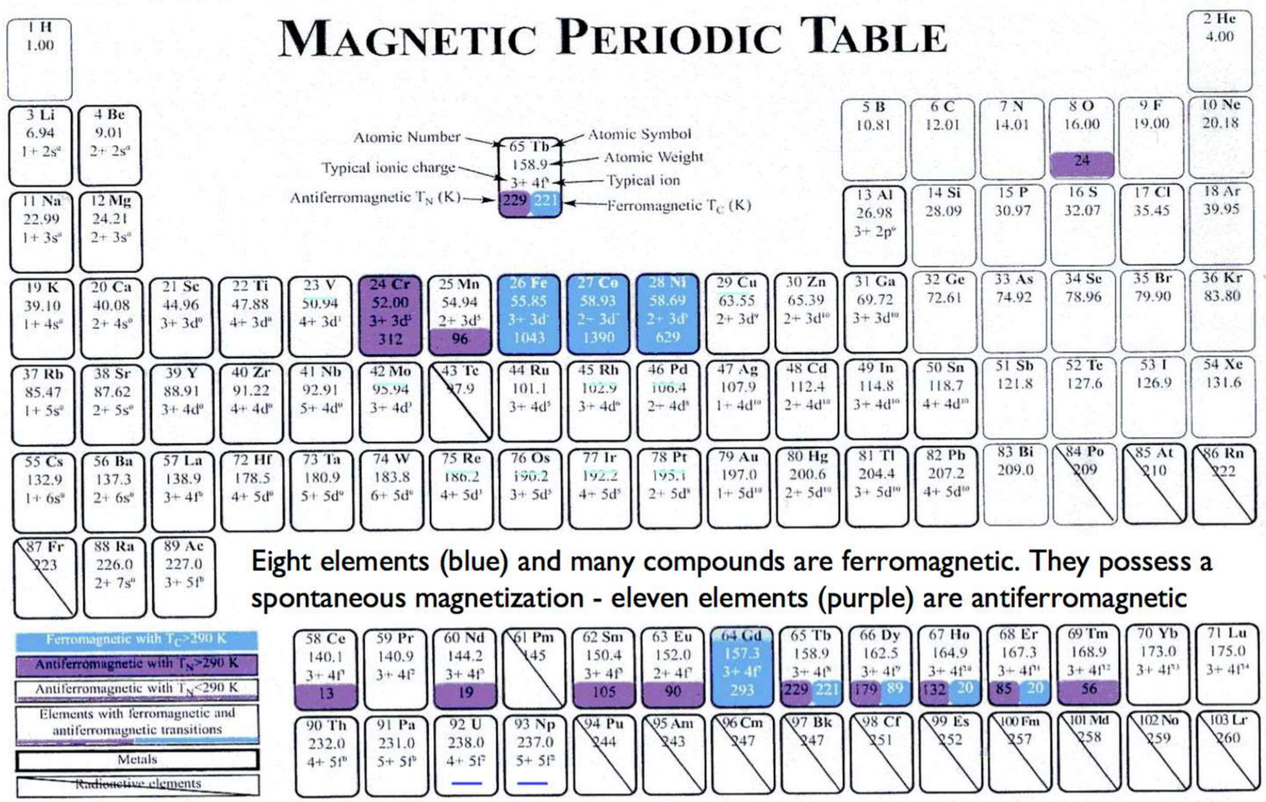
Introduction to magnetism

Magnetism is an exotic property



From M. Coey, Trinity College, Dublin.

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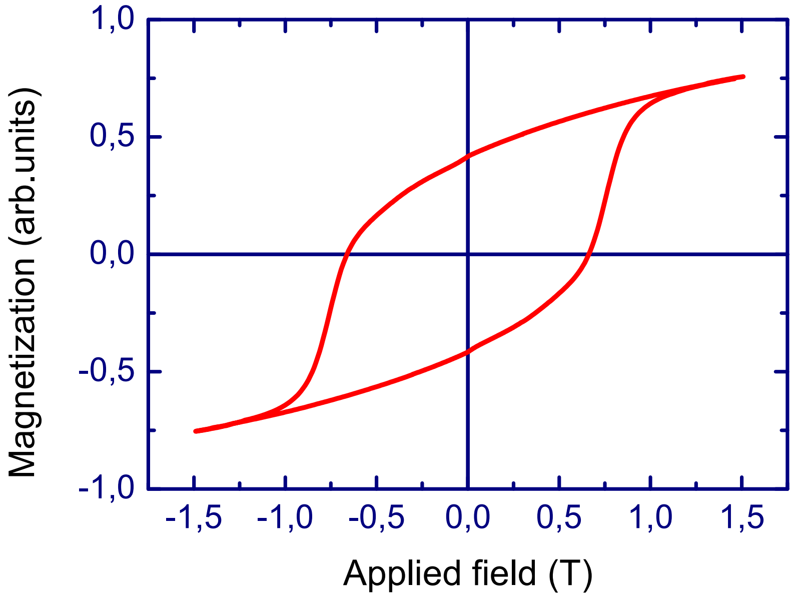
Microstructural Engineering and Magnet Properties

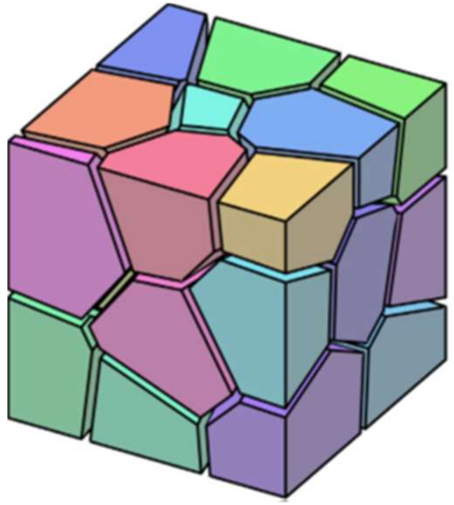
Magnets

Magnetite Nd-Fe-B

Hexaferrite

The hysteresis loop represents the reversal process of the magnetization





Microstructure and magnetic properties

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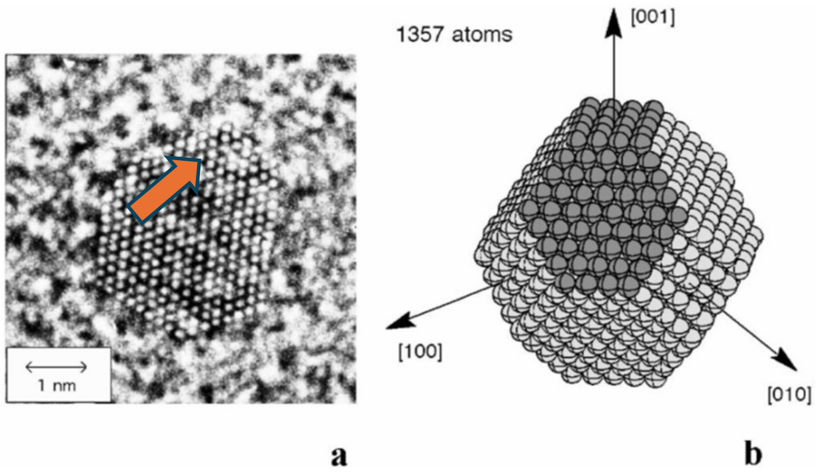
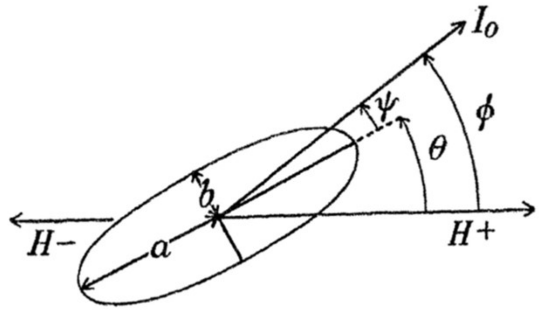
Reversal process in single domain particles

Single domain Co nanoparticles particles



Adapted from Janet PRL 86 (2001) 4676

Stoner – Wolfarth model



$$E(\psi,\theta) = -M_S\, H \cos(\psi - \theta) + K_1 \sin^2(\theta) + K_2 \sin^4(\theta)$$

Magnetostatic term Magnetic anisotropy terms

Dream conditions

- Coherent magnetization
- Non interacting particles
- No thermal effects

Stoner E C and WohlfarthE P (1948), Phil. Trans. Roy. Soc. **A240**:599–642

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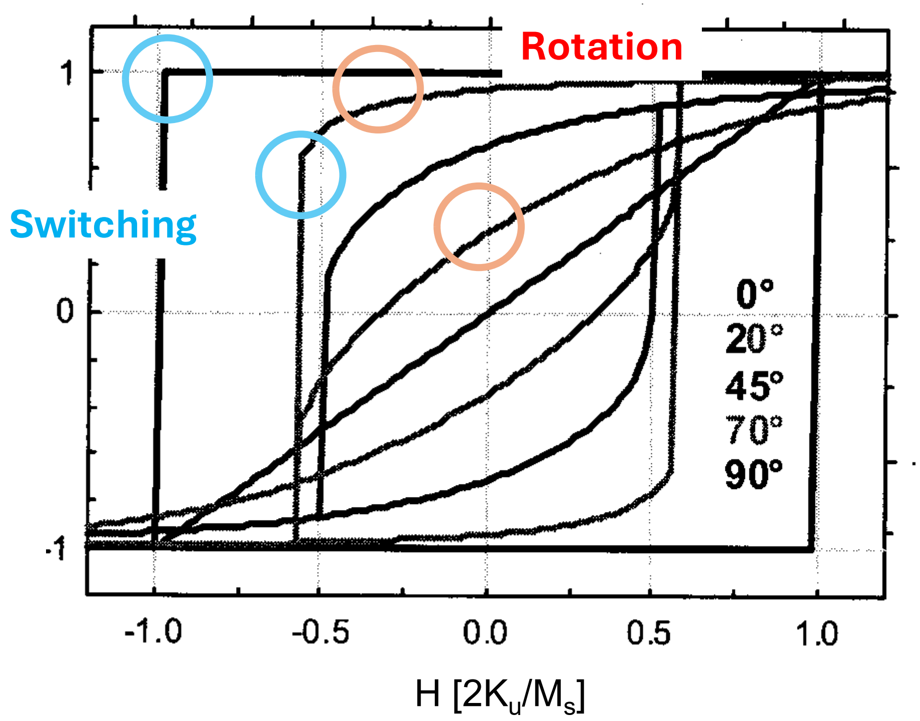
Reversal process in single domain particles

Stoner – Wolfarth model

Angular dependence of the histeresis loops



Stoner E C and WohlfarthE P (1948), Phil. Trans. Roy. Soc. **A240**:599–642

The reversal process combines the rotation and switching processes of the magnetization

Full oriented magnet

Easy axis parallel to the magnetic field direction

$$H_C = H_A = 2K_1/\mu_0 M_S$$

$$M_r = M_S$$

Best properties of a Magnet

K1 is the magnetocrystalline anisotropy term depending on material

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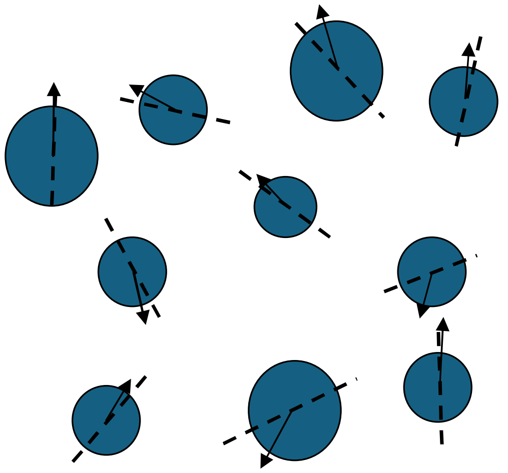
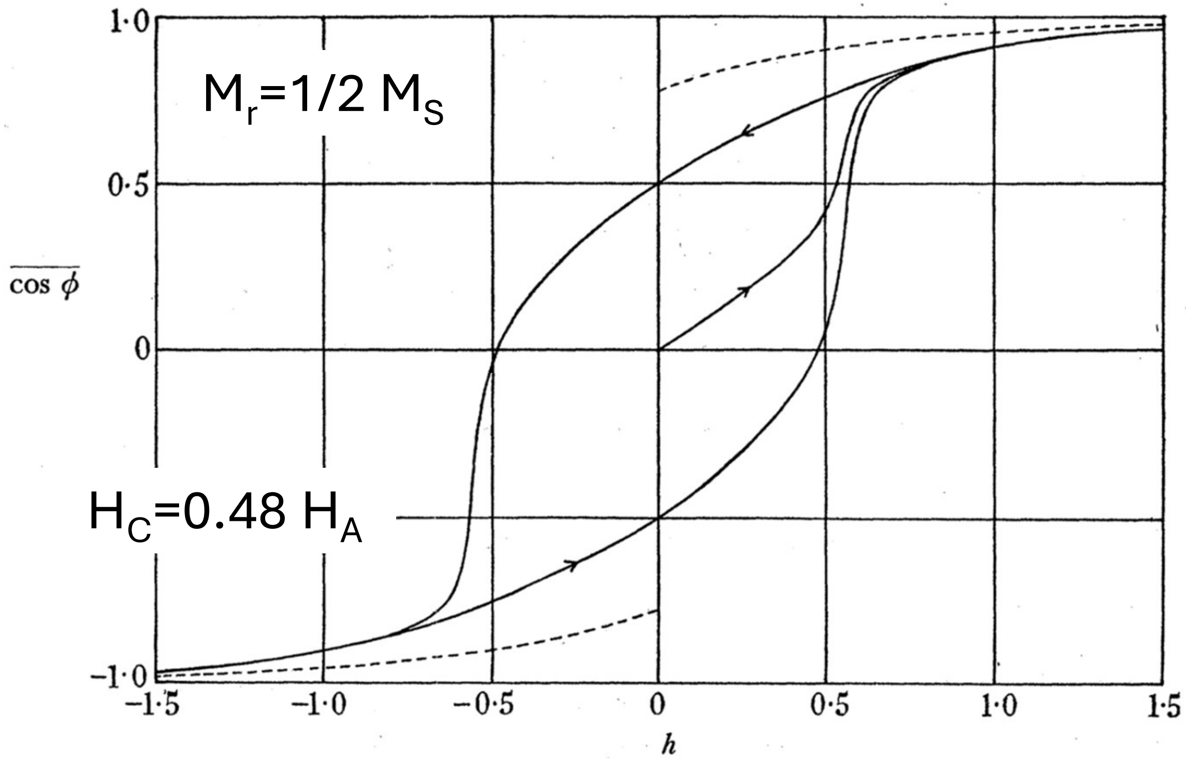
Magnet market & energy product

Random oriented particles
(isotropic magnets)





Stoner E C and WohlfarthE P (1948), Phil. Trans. Roy. Soc. **A240**:599–642

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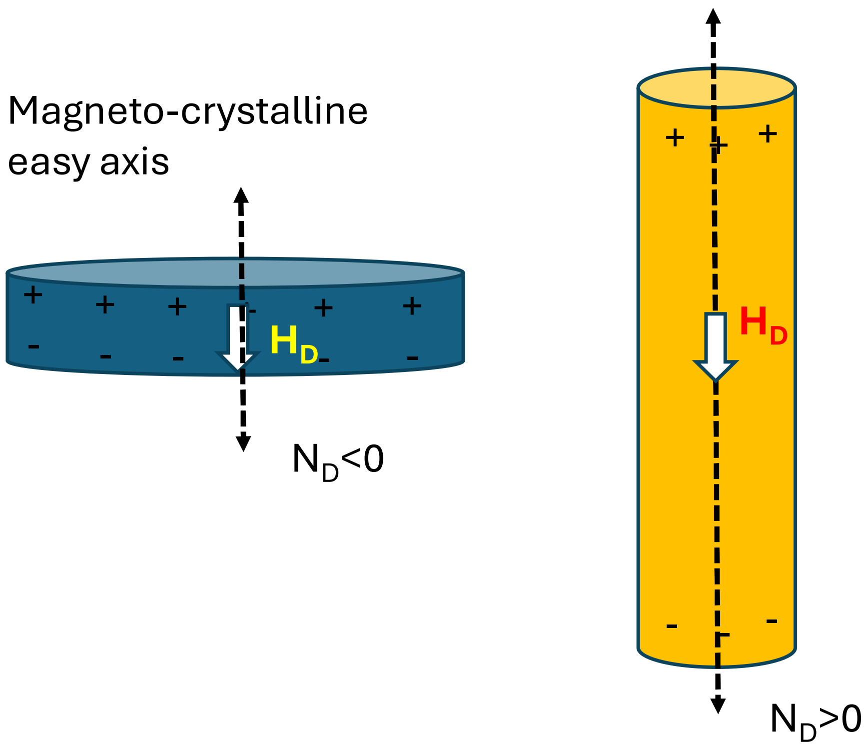
Reversal process in single domain particles

Shape anisotropy



The **morphology** determines the internal field distribution that act as a determagnetizing effect. This give rise to the shape anisotropy

$H_S = N_D\ Ms$ N_D is shape depending

Stoner – Wolfarth model.

$$H_A = 2K_1/\mu_0 M_S + N_D\ Ms$$

Other contributions can be present due to the pressure (magnetostriction), surface and interface (surface anisotropy)

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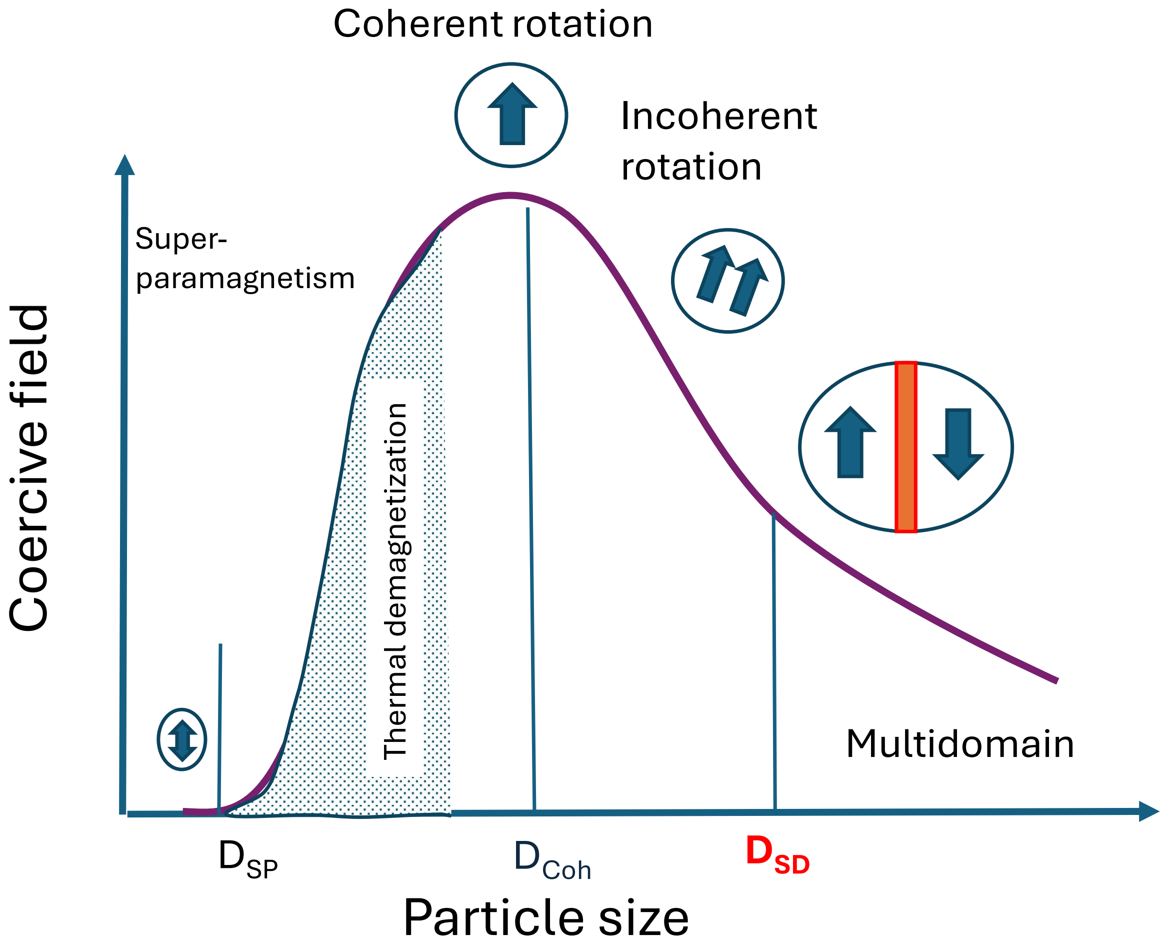
Effect of size



$D_{SD} = 72\sqrt{AK_1/\mu_0 M_S^2}$ **Single domain size**

$D_{coh} = 4\sqrt{3A/\mu_0 M_S^2}$ **Coherent size**

$D_{SP} = 2\sqrt[3]{6k_B T/K_1}$ **Superparamagnetic size**

$l_{ex} = \sqrt{A/\mu_0 M_S^2}$ **Exchange length**

$\delta_W = \pi\sqrt{A/K_1}$ **Domain wall length**

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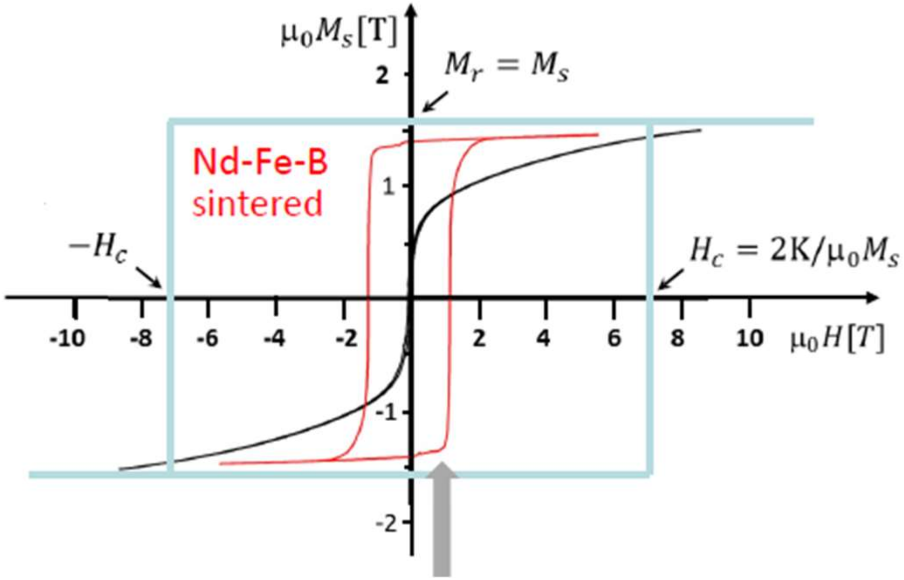
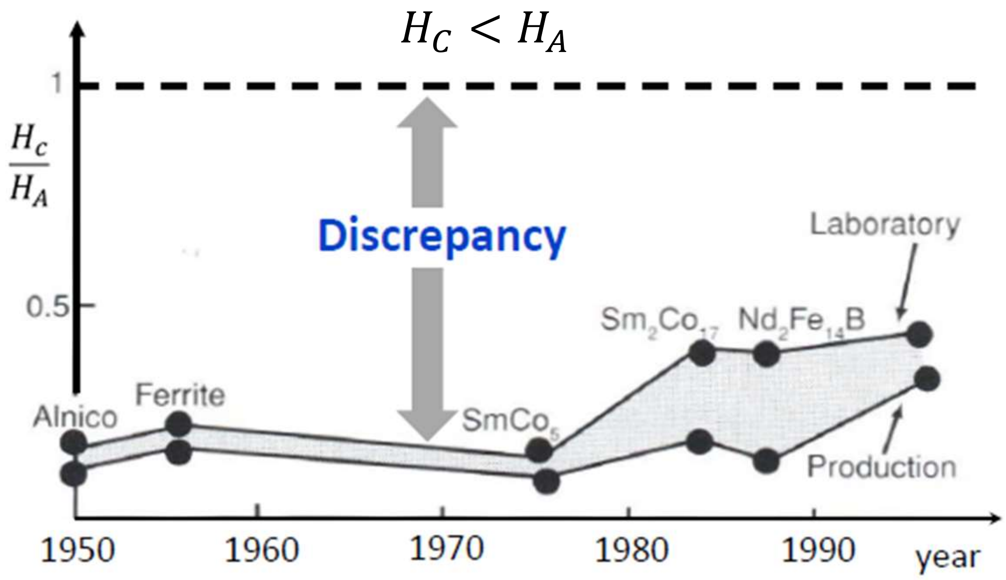
Brown's paradox

Comparison between real and model magnet





Key role of the nanostructure

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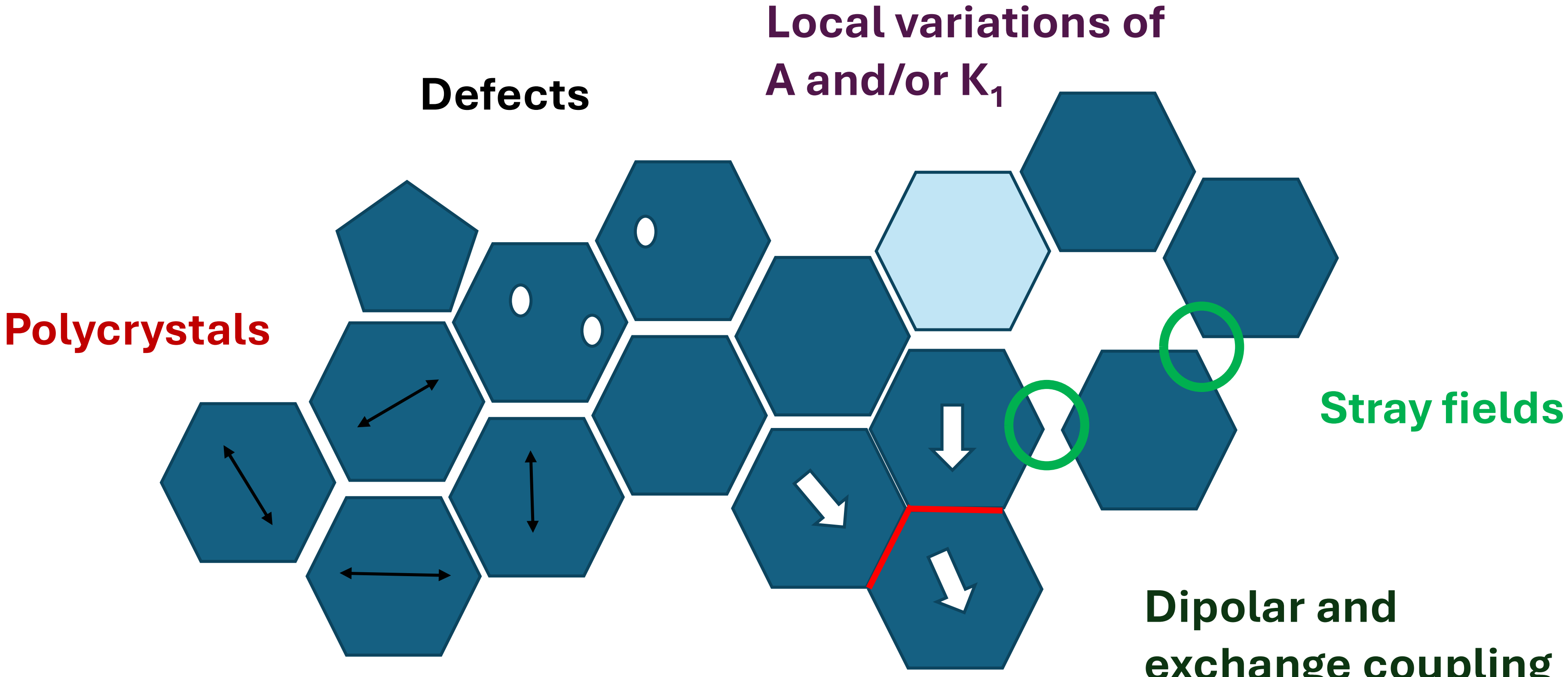
Reversal process and nanostructure



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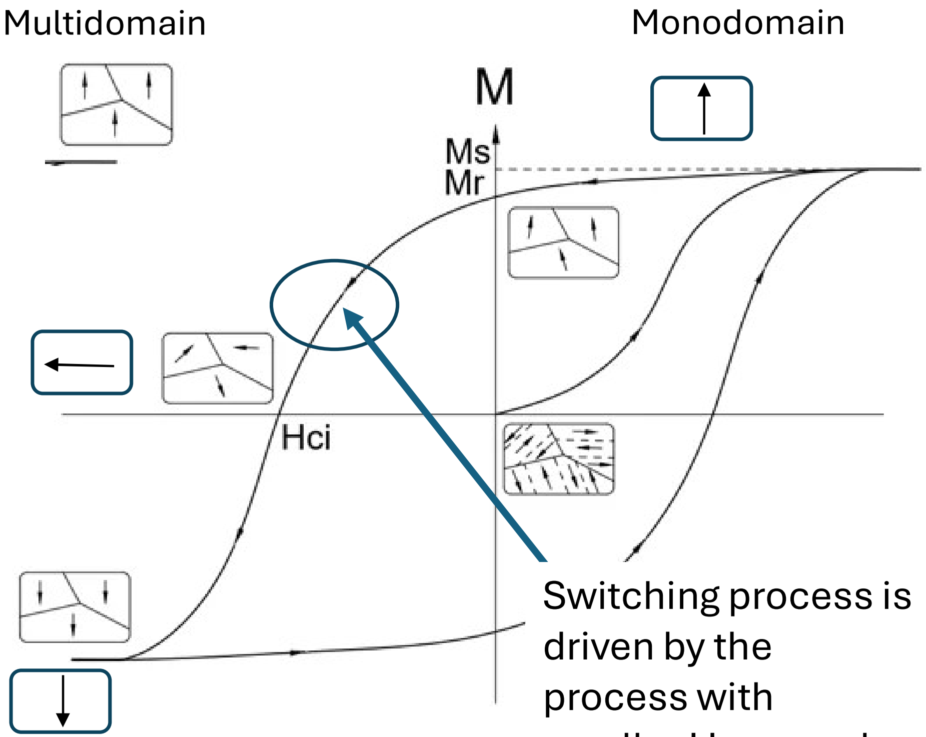
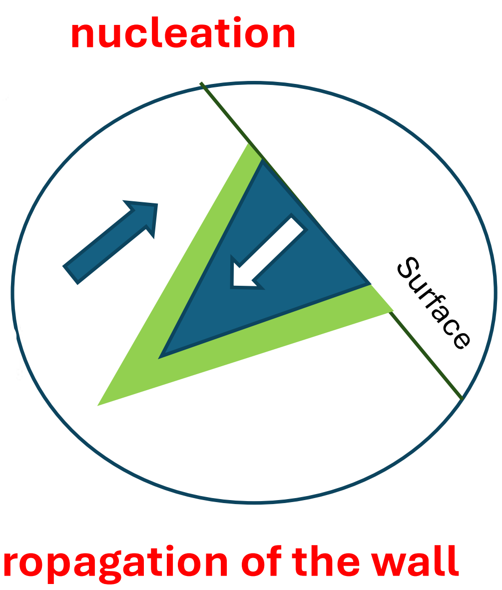
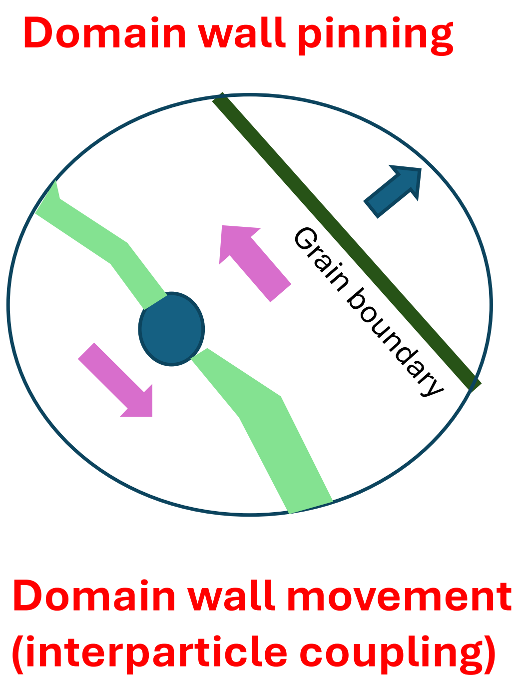
Microstructural Engineering and Magnet Properties

Reversal process exhibits different steps of nucleation, domain wall movement and pinning, driven by exchange or dipolar interparticle grain



Switching process is driven by the process with smaller H reversal





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Performance of hard magnets

	Nd-Fe-B	Sm-Co	Sm-Fe-N	Hard ferrites	Alnico
Coercivity – H_{ci} (kA/m)	**≈ 3000** (Dy, Tb doped)	≈ 2000	≈ 2000	≈ 340	≈ 150
Remanence – M_r or B_r (T)	**> 1.4**	≈ 1.2	≈ 0.9	≈ 0.44	≈ 1.25
Maximum energy product – $(BH)_{max}$ (kJ/m^3)	**≈ 450**	≈ 240	≈ 110	≈ 44	≈ 80
Operating temperature (°C)	≈ 230 (Dy, Tb doped)	≈ 500	≈ 180	≈ 300	**≈ 525**
Rare-earth content (at.%)	≈ 13 (Nd – highly critical RM)	≈ 16.7 ($SmCo_5$) or ≈ 10.5 (Sm_2Co_{17})	≈ 9 ($Sm_2Fe_{17}N_3$)	/	/

Prof. Michael Coey

(1945 – 2025)

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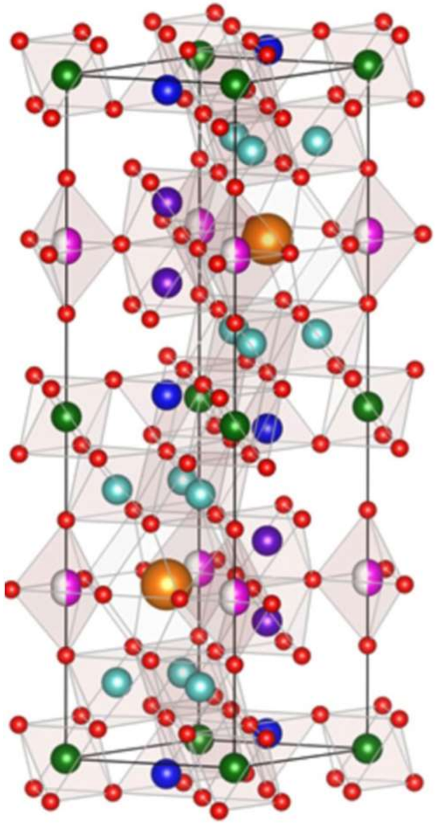
M-type hexaferrites (Sr, Ba)$Fe_{19}O_{12}$



Tetrahedral structure
With 5 magnetic sites

12f ⇧⇧⇧⇧⇧⇧
2a ⇧
2b ⇧
4f1 ⇩⇩
4f2 ⇩⇩

Ferrimagnetic behaviour determines M_S

Anisotropy is associated to 2b bipyramidal site
→ Easy axis ‖ C direction
→ $E_K = K_1 \sin^2\theta$

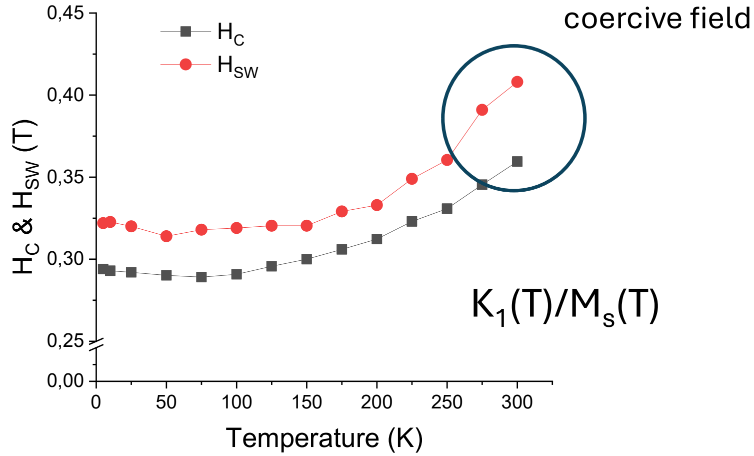
R.C. Pullar Progress in Materials Science 57 (2012) 1191–1334

Magnetic properties and lengths

	T_C (K)	M_S (MAm^{-1}/ T)	K_1 (kJm^{-3})	$\mu_0 H_A$ (T)		D_{SD} (nm)	D_{coh} (nm)	D_{SP} (nm)	δ_w (nm)
BaM	740	0,38 (0,45)	330	1,7		~600	~60	~8	14
SrM	746	0,38 (0,45)	350	1,8					

Doping with La-Co allows to obtain best properties

Temperature dependence of the coercive field



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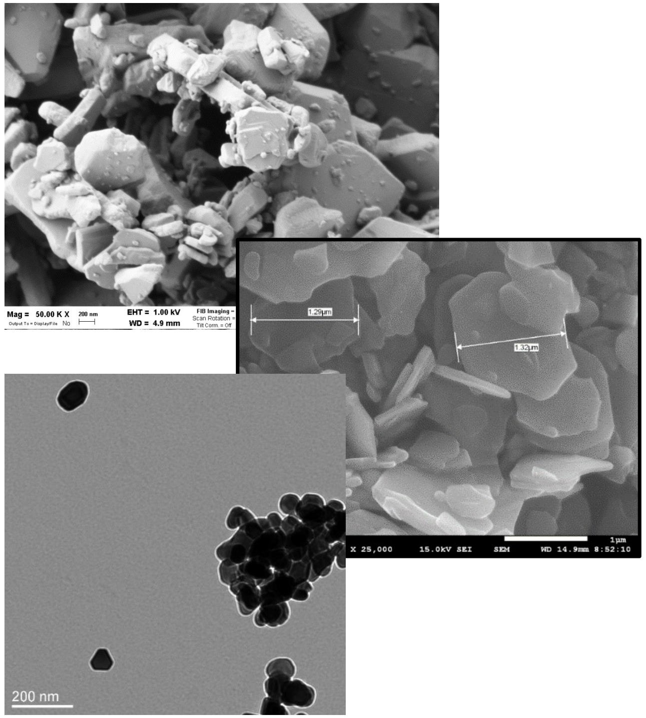
M-type hexaferrites (Sr, Ba)$Fe_{19}O_{12}$

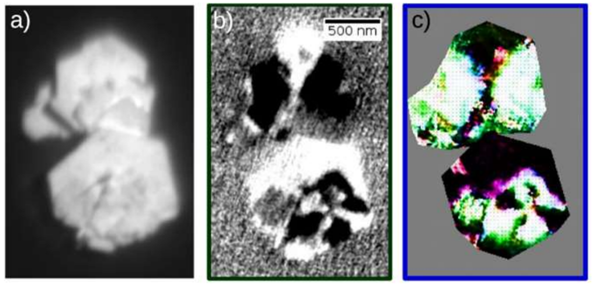
Platelet morphology



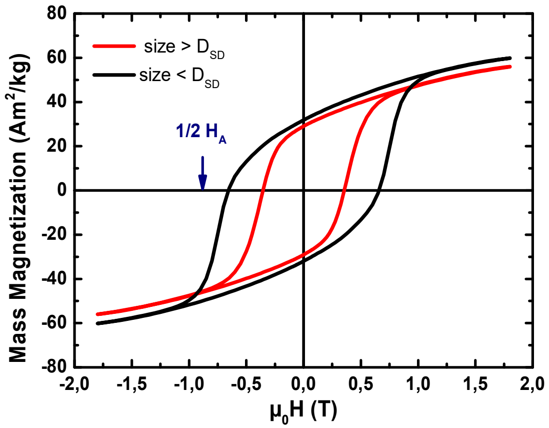
$H_A = 2K_1/\mu_0 M_S - N_D M_s$

Particle size

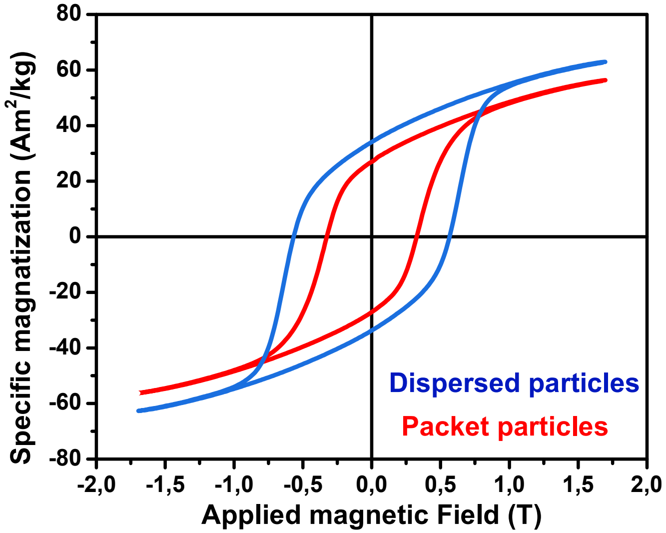
D_{SD} ~0,6 μm, D_{Coh} ~60 nm



G. D. Soria *et al.* Scientific Reports 9 (2019) 11777



Interactions



Mainly dipolar driven demagnetization processes

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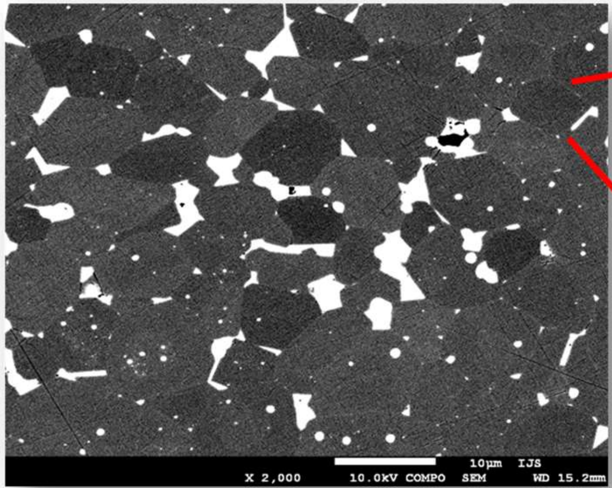
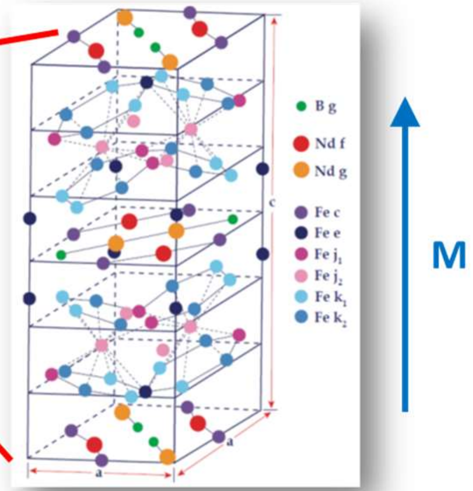
Slide 98

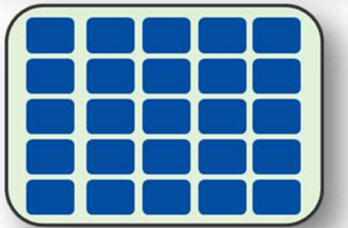
$Nd_2Fe_{14}B$ PHASE: ORIGIN OF MAGNETISM

SEM image of a sintered Nd-Fe-B magnet:





$E_K = K_1 \sin^2\theta + K_2 \sin^4\theta$



(simplified presentation...)

Intrinsic properties: *

- Anisotropy field - H_A: 5350 kA/m
  (demagnetization resistance – VERY GOOD)
- Saturation magnetization - M_S: 1.61 T
  (strength - EXCELLENT)
- Curie temperature - T_C : 312 °C
  (thermal stability – MODERATE)

**Governed by exchange interaction involving the unpaired spins in the 3d-4f system*

- Body-centered tetragonal crystal structure (space group P42/mnm)
- Unit cell: 4 formula units, 68 atoms
- Uniaxial magnetocrystalline anisotropy favoring c-axis (= ''easy'' axis of magnetization)

→ Nd and Fe moments are ferromagnetically coupled & aligned along this direction.

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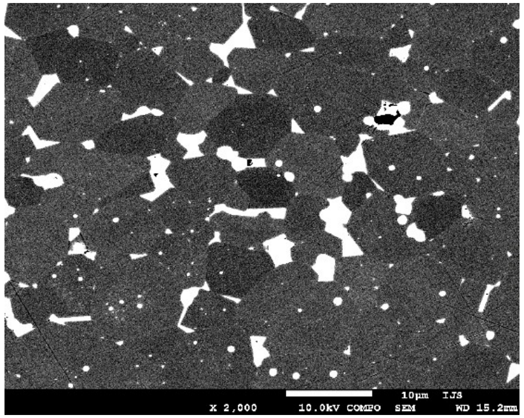
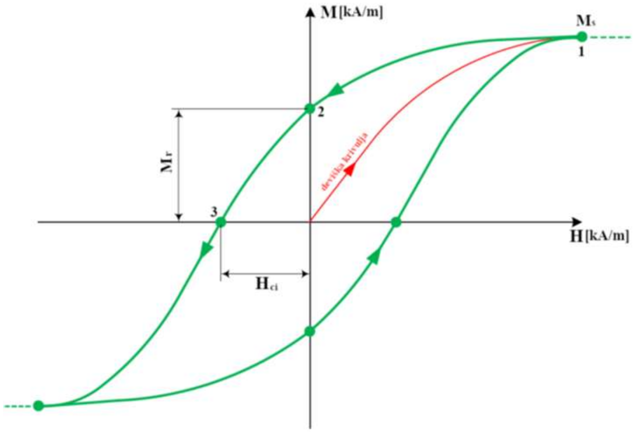
Nd-Fe-B: EXTRINSIC PROPERTIES & MICROSTRUCTURE



BUT, real magnets are multiphase, polycrystalline materials…

→ INTRINSIC PROPERTIES *VS* EXTRINSIC PROPERTIES

INTRINSIC PROPERTIES ($Nd_2Fe_{14}B$)	EXTRINSIC PROPERTIES (real bulk magnets)
H_A: 5350 kA/m	H_{ci}: 20 – 30 % of H_A
M_s: 1.61 T	M_r (or J_r or B_r): ≈ 0.6 – 1.5 T
	$(BH)_{max}$: $J_r^2/4\mu_0$ *(maximum energy product)*



- ''Intrinsic'' coercivity – H_{ci}: The magnitude of the external field required to completely demagnetize the magnet
- Remanent magnetization – M_r: The magnetization that remains ''indefinitely'' after the magnet is magnetized

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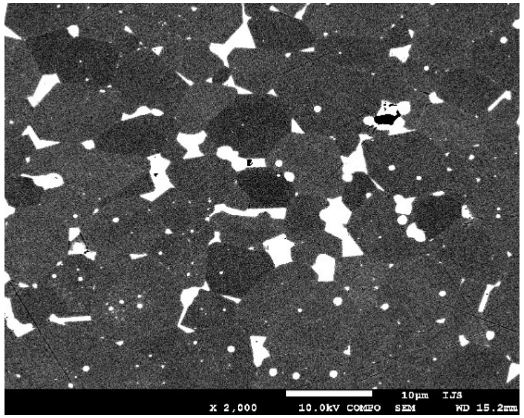
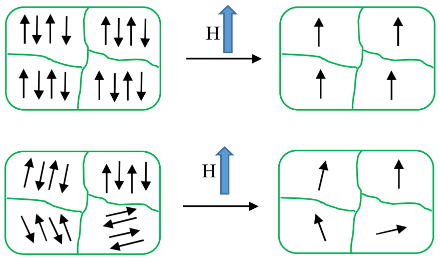
Nd-Fe-B: MICROSTRUCTURE & REMANENCE



(each arrow presents one magnetic domain in a $Nd_2Fe_{14}B$, i.e., matrix *grain*)*



** In a magnetized state, each grain contains one domain*

Remanent magnetization – M_r:

- Volume fraction of the $Nd_2Fe_{14}B$ phase
- Density
  (best: fully-dense, metallic magnets)
- Crystallographic texture
  (alignment of c-axes of individual hard magnetic grains)
- Chemical composition
  (due to changes in intrinsic properties)

Anisotropic magnets: textured
→ M_r close to 1.6 T
(typically ≈ 1.4 T)

Isotropic magnets: randomly oriented grains
→ $M_r \approx 0.5 \times 1.6$ T = 0.8 T

Chemical composition of a sintered Nd-Fe-B magnet: COMPLEX.

Rare-earths (REs): $Nd_{24.3}Pr_{0.6}$**$Dy_{7.1}$**
$Fe_{63.7}$**$Co_{3.0}$**
$B_{0.9}$
$Ga_{0.2}Al_{0.1}Cu_{0.1}$

Dy, Tb:
- increase H_A and consequently H_{ci}
- Reduce M_s due to antiferromagnetic coupling with Fe

Co: improves Tc

Ga, Al, Cu: grain boundary structure refinement…

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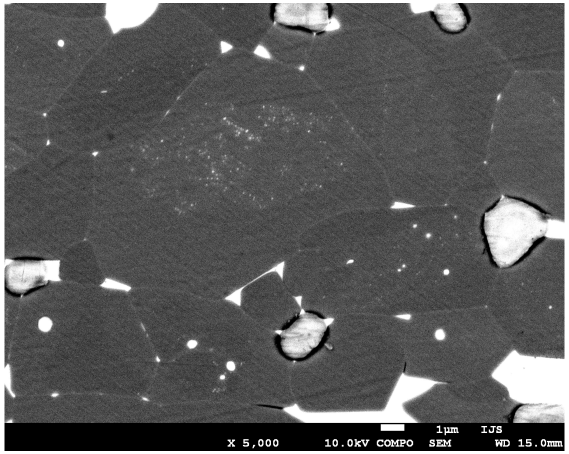
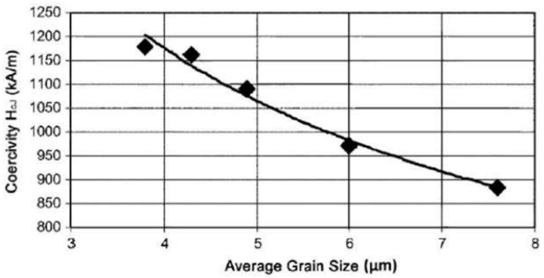
Nd-Fe-B: MICROSTRUCTURE AND COERCIVITY



Uestuener et al., IEEE trans. on mag. 42 (2006) 2897–2899



Intrinsic coercivity – H_{ci} (≈ 20 – 30 % of H_A):

Kronmüller equation: $H_{ci} = -N_{eff} \times M_s + \alpha_K \alpha_\psi \times H_a$

Dipolar interactions: source of a demagnetization field of the order of material's magnetization!

N_{eff}….. **Effective demag. factor**; depends on the magnet's shape, grain size & shape, amount of non-magnetic impurities

(consider each grain as a separate tiny magnet whose magnetization is trying to demagnetize its neighbors…)

Coercivity depends on the grain size, because: Dipolar interactions are larger in bigger grains.

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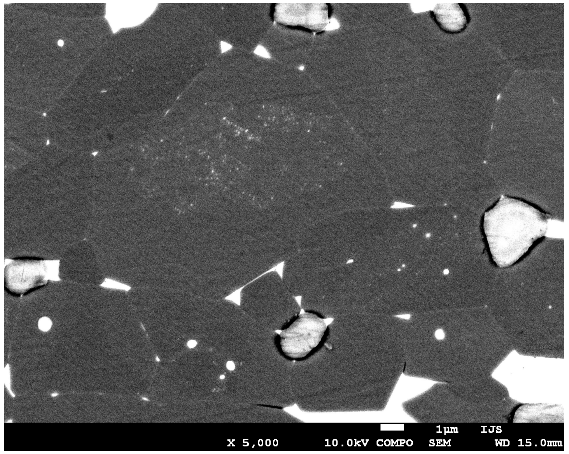
Nd-Fe-B: MICROSTRUCTURE AND COERCIVITY



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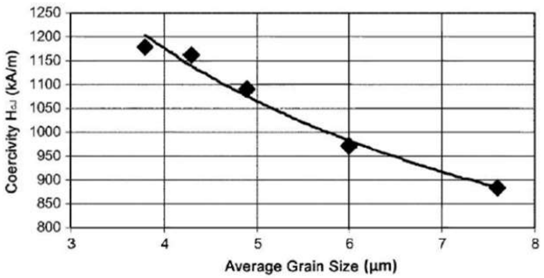
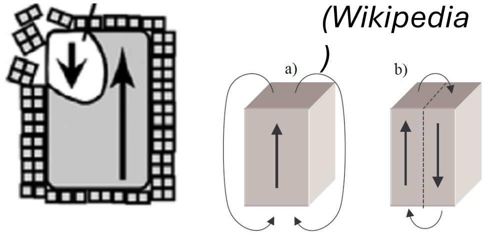


<u>**Intrinsic coercivity**</u> **– H_{ci}** (≈ 20 – 30 % of H_A):



Kronmüller equation: $H_{ci} = -N_{eff} \times M_s + \alpha_K \alpha_\psi \times H_a$

<u>Defects on the surface of the matrix grains</u>: in terms of structure, surface is always different than the bulk

→ Lower magnetocrystalline anisotropy, meaning lower resistance against demagnetization → <u>nucleation of reverse domains</u>

α_K …….. Decrease in the magnetocrystalline anisotropy of the grain surface
α_ψ ……..Effect of misalignment of the $Nd_2Fe_{14}B$ grains

<u>Coercivity depends on the grain size, because:</u>

- In small (single-domain grains, < 200 nm), the defects are less likely to cause magnetization reversal due to nucleation of reverse domains
- Bigger grains: magnetostatic energy is lowered by splitting large domain into smaller ones *(net magnetization of the magnet is lost…)*

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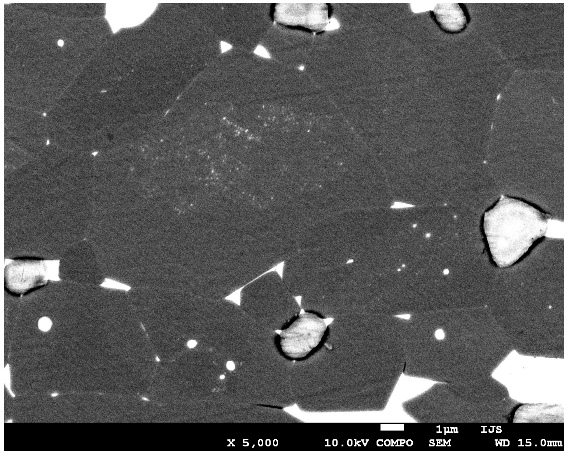
Slide 103

Nd-Fe-B: MICROSTRUCTURE AND COERCIVITY



Intrinsic coercivity – H_{ci} (≈ 20 – 30 % of H_A):

Kronmüller equation: $H_{ci} = -N_{eff} \times M_s + \alpha_K \alpha_\psi \times H_a$

A "million €" question: How to improve the coercivity?

- Reduce the grain size
- Ensure good grain boundary wetting to magnetically decouple the matrix grains (in terms of exchange interaction)

  (GOAL: reversal of one grain does not effect the magnetization of its neighbors)
- Improve grain-boundary structure

  (another million € question: what is the perfect GB structure???)
- Increase H_A by substituting a fraction of Nd with heavy-rare-earth (HRE) elements (Dy or Tb)

→ !!! We lose magnetization (reduced M_S)

SUMMARY:

- ✓ Small grains
- ✓ Magnetically decoupled grains
- ✓ Good grain-boundary (GB) structure
- ✓ Optimized (local) chemical composition

PROCESSING.

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Thank you for your attention!

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“Talking Magnets” Webinar Series

Processing Techniques for Permanent Magnets

"From Atoms to Applications: A Multiscale Perspective on Magnetism and Permanent Magnets"

16-10-2025

Presenter: **Prof. Kristina Žužek**
Organisation: **Jožef Stefan Institute, Ljubljana, Slovenia**

Nanostructured materials

Jožef Stefan Institute Ljubljana, Slovenia

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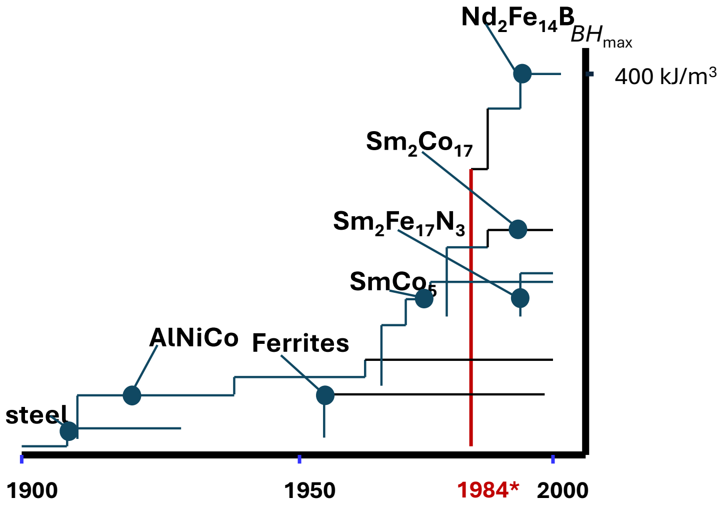
Permanent magnets: perspectives and challeng

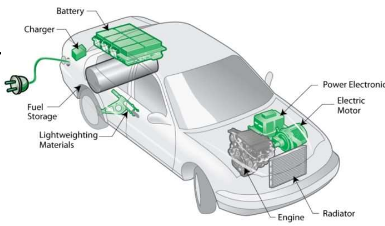


*Masato Sagawa, Japan, metallurgical process, John J. Croat, General Motors, U.S., melt-spinning

- A permanent magnet is an energy storage device. The maximum energy product (BH_{max}) determines how much energy it can store.
- Nd-Fe-B permanent magnets exhibit the highest BH_{max}.
- They are indispensable in e-motors in e-mobility and green energy applications
- The EU considers them to be key in th European Green Deal, the Zero Industry Ac the New Circular Economy Act, and th Critical Raw Materials Act.

500 kg Nd-Fe-B PMs / 1MW

https://renewcosolar.com.au/windmills/



https://blog.upsbatterycenter.com/electric-car-battery-differenc

2.5 kg Nd-Fe-B PMs/e-vehicle

Ferite SmCo NdFeB

Magnet power↑ magnet size↓ motor size ↓ battery size ↓ milage ↑

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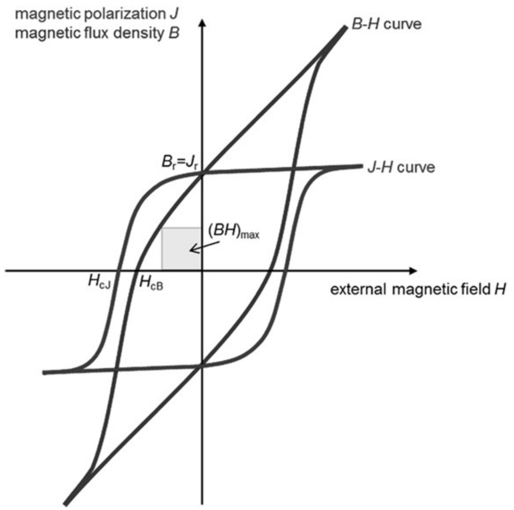
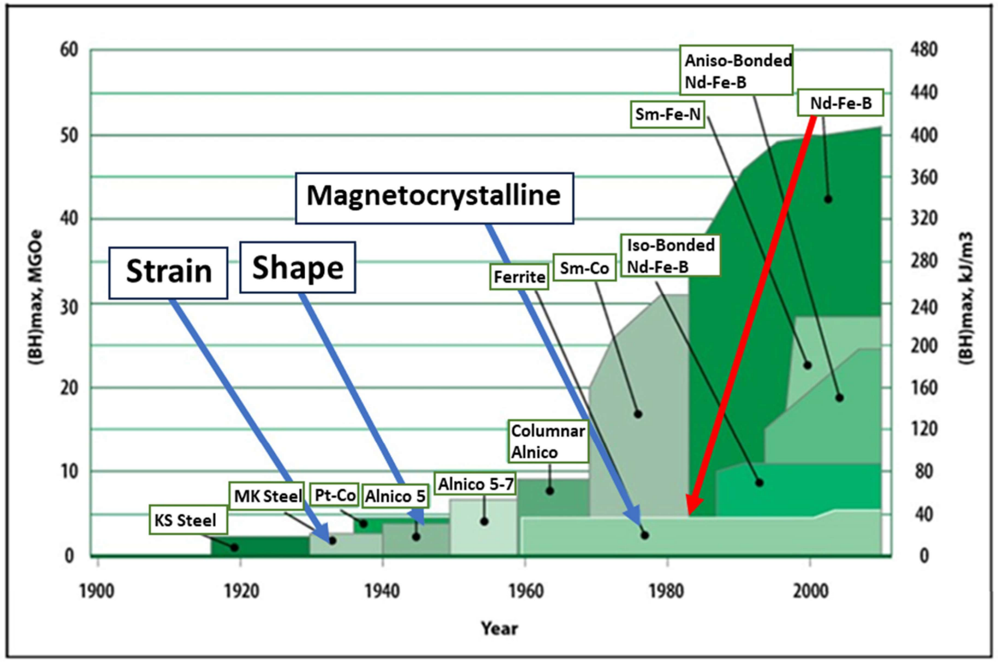
Nd-Fe-B permanent magnets' properties



Br – Remanent magnetization
iHc – Intrisic coerciivty
$_B$Hc – Extrinsic coercivity
BH_{max}- Energy product

$(BH)_{max}=Br^2/\mu_0$	1MGOe ~ 8 kJ/m^3	
Hci	10 KOe ~ 800 kA/m	
Br	1 G ~ 10^{-4} T	
Magnetic units	CGS	SI



https://www.slideshare.net/slideshow/2019-01-17-magnetics-2019/129998652

➢ **Improved properties, greater energy efficiency & Recourse efficiency – processing, re**

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Nd-Fe-B permanent magnets' properties

„N48 UH“

- **Number indicates BH(max) in MGOe 48 x 8 =384 kJ/m³**
- **Suffix indicates the Hci**

Br tesla	1.05	1.10	1.15	1.20	1.25	1.29	1.32	1.35	1.38	1.40	1.42	1.45	1.49	Max Temp
Label	GRADES													deg C
AH	28AH	30AH	33AH	35AH	38AH	40AH								230
EH	28EH	30EH	33EH	35EH	38EH	40EH	42EH	45EH						200
UH		30UH	33UH	35UH	38UH	40UH	42UH	45UH	48UH	50UH	52UH	54UH		180
SH		30SH	33SH	35SH	38SH	40SH	42SH	45SH	48SH	50SH	52SH			150
H		30H	33H	35H	38H	40H	42H	45H	48H	50H	52H			120
M		30M	33M	35M	38M	40M	42M	45M	48M	50M	52M			100
		N30	N33	N35	N38	N40	N42	N45	N48	N50	N52	N54	N55	80
BHmax	28	30	33	35	38	40	42	45	48	50	52	54	55	MGOe

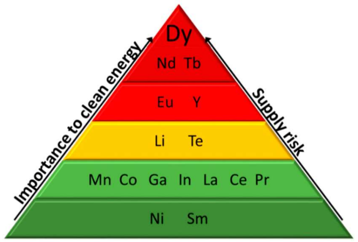
M – 100°C, Hci≥1100 kA/m
H – 120°C, Hci ≥ 1400 kA/m
SH – 150°C , Hci ≥ 1600 kA/m
UH – 180°C, Hci ≥ 2000 kA/m
EH – 200 °C, Hci ≥ 2400 kA/m
AH - 220-230°C, Hci ≥ 2800 kA/m

$Nd_2Fe_{14}B$

Tb, $Dy_2Fe_{14}B$

Rao D et al., Machines MDPI 2021, 9, 124

- N52>: Small consumer electronics (max strength at low temp)
- N42SH–EH: Motors, renewables, EVs
- N35EH–AH: Aerospace, defence, extreme high-temp stability



Cardoso CED et al., Nanomaterials 2019 9(6):814

➢ **Improved properties, greater energy efficiency & Recourse efficiency – processing, re**

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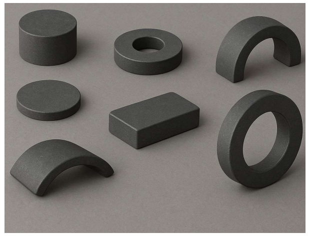
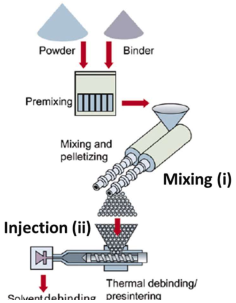
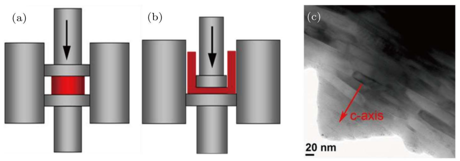
Nd-Fe-B PMs production routes

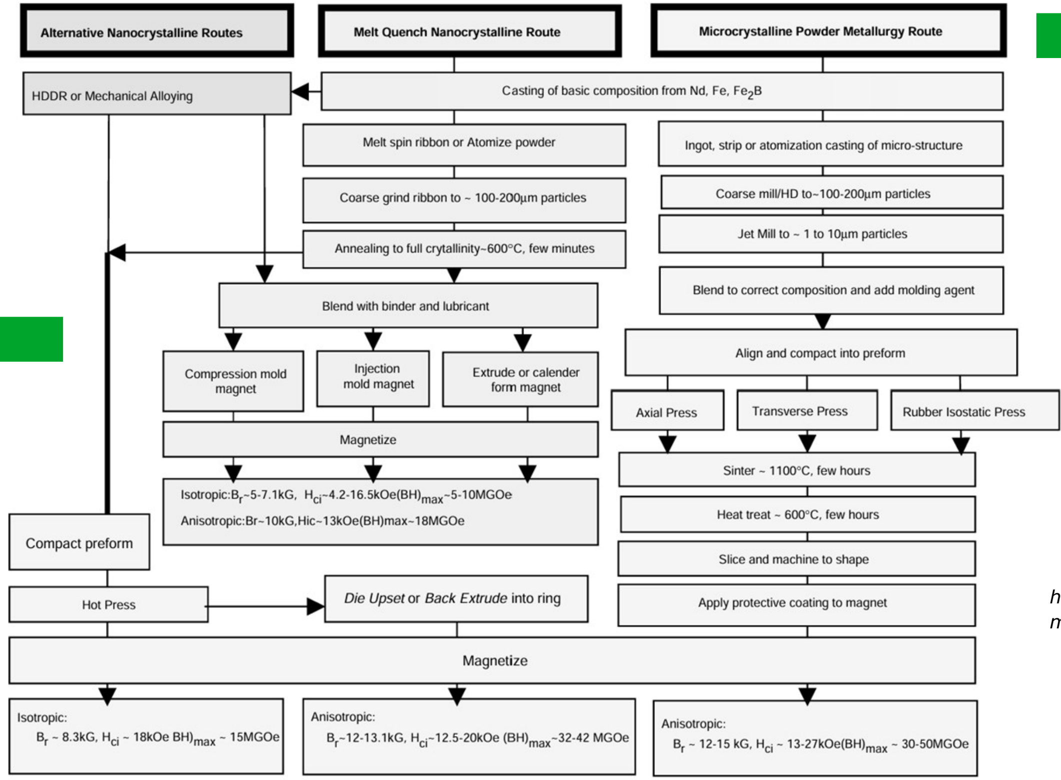




T. Crozier-Bioud et al., Mater. Today Phys. 34, 2023, 101082

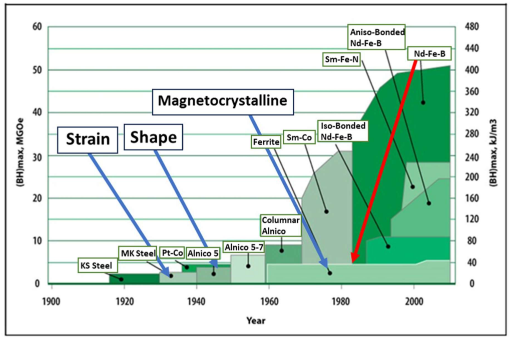


R. Chaunbing et al., Chn. Phys. B, 2028, 27(11):117502



D. Brown et al., JMMM, 248 (2002)

Microcrystalline Nd-Fe-B SINTERED



https://www.slideshare.net/slideshow/2019-01-17-magnetics-2019/129998652

Source: AI

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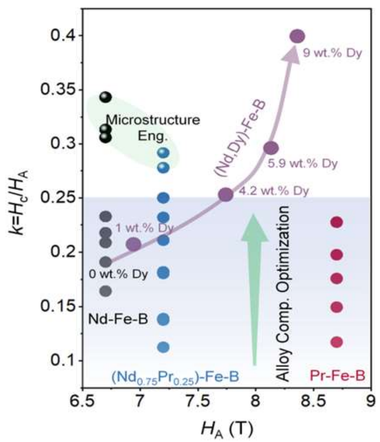
Sintered: Nd-Fe-B – Coercivity Hci



X. Tang, K. Hono, NPG Asia Materials 15 50 (2023)

Reduced coercivity of the magnet

Hci ~25 %~ 35 %Ha

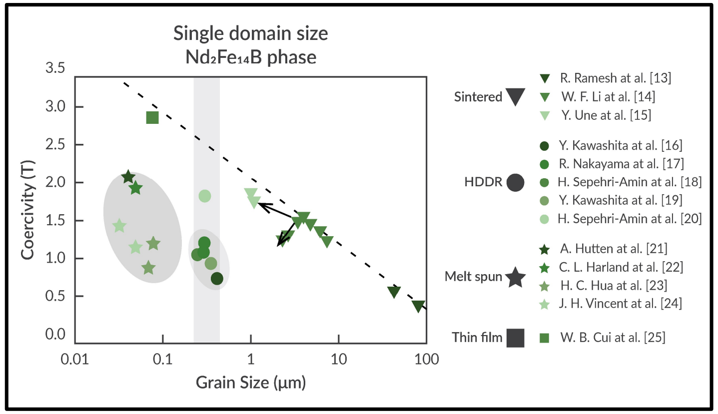
Kronmüller equation:

$$H_{ci} = \alpha_K \alpha_\psi \times H_a - N_{eff} \times M_s$$

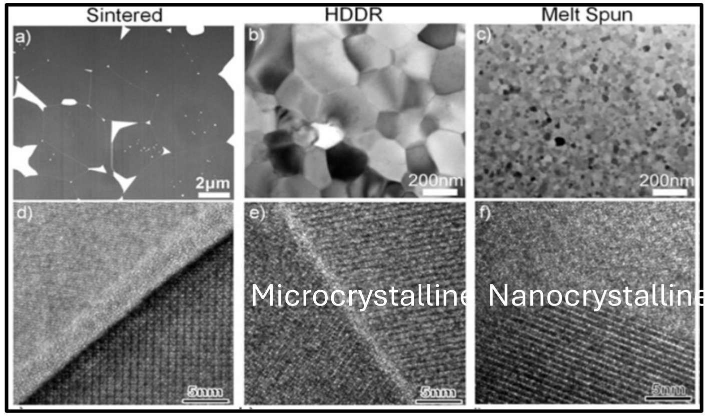
How to improve coercivity?

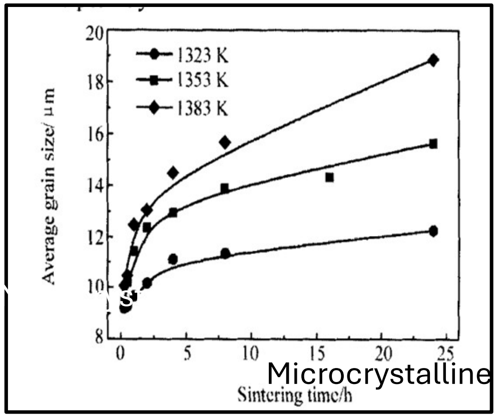
- Reduce grain size - **Neff**
- Ensure good grain boundary wetting → magnetic decoupling of grains
- Optimize grain-boundary structure (What is the perfect GB structure?) **$\alpha_K \alpha_\psi$**
- Increase anisotropy field (HA) by partial substitution of Nd with Dy or Tb →, **high Ha**, but this lowers magnetization (**M_S**) and increases cost

- **Neff & Grain size ↓**



- **Grain size ↓, manufacturing method & procesing method, thermal t.**





K. Hono et al., Scripta Mater. 2012

L. Xianglian et al., J. Rare. Eart. 25 (2007)

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Sintered: Nd-Fe-B – Coercivity Hci

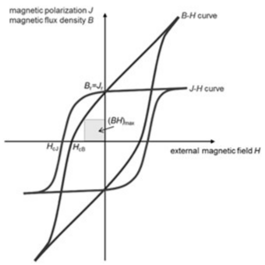
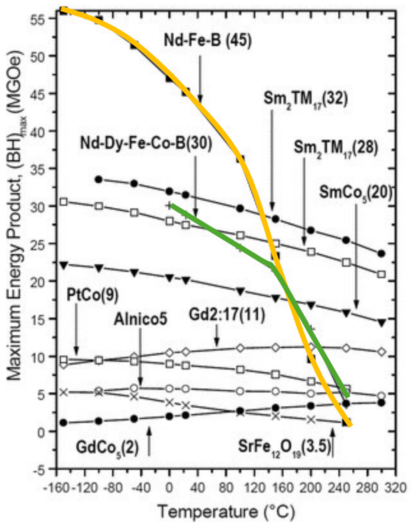
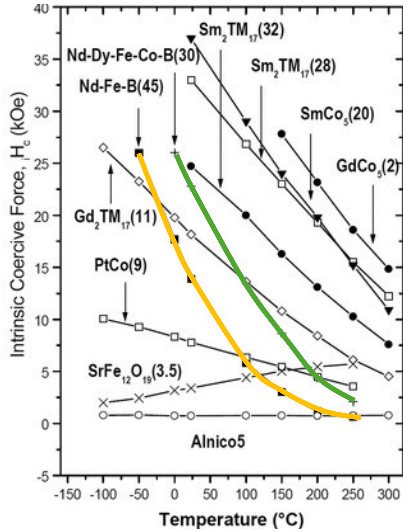


Table 1. Some properties of permanent magnets (PMs) relevant to electrical machines.

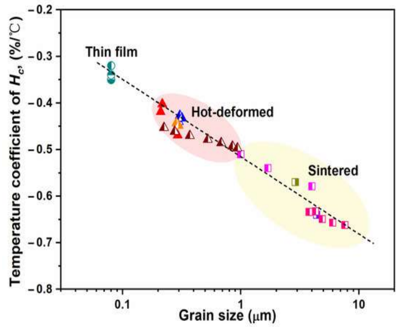
Quantity	Symbol [unit]	NdFeB	SmCo	Ferrite	Alnico
Remanence	B_r [T]	1.08–1.49	0.87–1.19	0.20–0.46	0.55–1.37
Intrinsic coercivity	H_{ci} [kA/m]	876–2710	1350–2400	140–405	38–151
Relative permeability	μ_r [-]	1.0–1.1	1.0–1.1	1.05–1.2	1.3–6.2
Energy product	$(BH)_{max}$ [kJ/m^3]	220–430	143–251	6.4–41.8	10.7–83.6
Density	D [kg/dm^3]	7.4–7.5	8.2–8.5	4.9–5.1	6.8–7.3
Electrical resistivity	ρ [nΩm]	12–16	50–60 or 530–900	10^7–10^{11}	470–750
Curie temperature	T_c [°C]	310	720–820	450	800
Maximal operation temperature	T_{max} [°C]	150	250–350	300	500

S. Kontos et al., Energies 2020, 13, 554





O. Gutfleisch et. Al., Advanced Materials, Volume: 23, Issue: 7, Pages: 821-842



R. Chen et al., MDPI materials, 16, 13, 2023

- Relatively low Tc for Nd-Fe-B 310°C
- $BH_{(max)}$ and H_{ci} decrease with T
- High T applications desired

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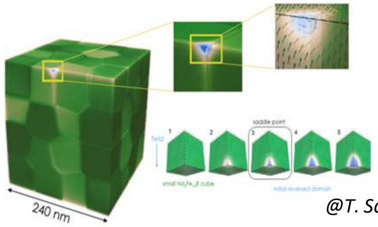
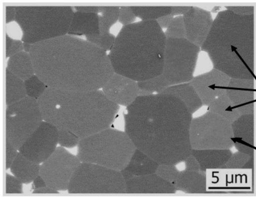
Sintered: Nd-Fe-B – Coercivity Hci

- **Interfacial control, H_a control**

Additive element	Location in the microstructure	Effect on microstructure	Effect on magnet's properties
Co	Matrix phase and grain boundaries	▪ Partly substitutes Fe atoms of the matrix phase ▪ Forms Nd_3Co at grain boundary phase	▪ Increases T_c of $Nd_2Fe_{14}B$ phase ▪ Improves the corrosion resistance ▪ Increases B_r ▪ Decreases H_{ci}
Cu	Grain boundaries	▪ Modifies grain boundary phase ▪ Improves wettability → smoother grain boundary phase	▪ Improves H_{ci} by small additions ▪ Unaffected B_r by small additions
Al	Matrix phase and grain boundaries	▪ Partly substitutes Fe atoms of the matrix phase ▪ Forms low-melting phases in the grain boundary phase ▪ Improves wettability → smoother grain boundary phase	▪ Improves H_{ci} due to higher anisotropy field of $Nd_2(Fe,Al)_{14}B$ phase ▪ Decreases B_r due to the formation of non-magnetic phases ▪ Decreases T_c
Ga, Sn	Grain boundaries	▪ Improves wettability → smoother grain boundary phase Forms non-magnetic phases that magnetically isolate grains	▪ Improves H_{ci} ▪ Decreases B_r and $(BH)_{max}$ due to the formation of non-magnetic phases
Nb, V, Mo, W, Cr, Zr, Ti ext.	Grain boundaries	▪ Suppresses the formation of α-Fe to some extend ▪ Inhibits the grain growth ▪ Forms borides in grain boundary phase or/and matrix phase	▪ Improves H_{ci} ▪ Decreases B_r and $(BH)_{max}$ due to the formation of non-magnetic phases
HRE (Dy, Tb)	Matrix phase	▪ Partly substitutes Nd atoms of the matrix phase	▪ Improves H_{ci} due to increasing magnetocrystalline anisotropy ▪ Decreases B_r due to anti-ferromagnetic coupling



@T. Schrefl



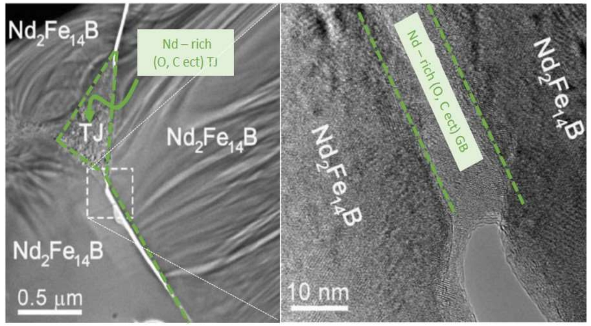
1) K. Löwe, D. Benke, C. Kübel, T. Lienig, K. Skokov und O. Gutfleisch, Acta Materialia, Bd. 124, p. 421, 2017.

$Nd_2Fe_{14}B$
Nd – 26.7 wt % + surplus ~ 30 wt. %
Fe – 73.2 wt %
B – 0.09 wt %
+ Dy, Tb

1 wt % Dy, Tb
↑ Hc ~ 120kA/m, ↓Br 3%

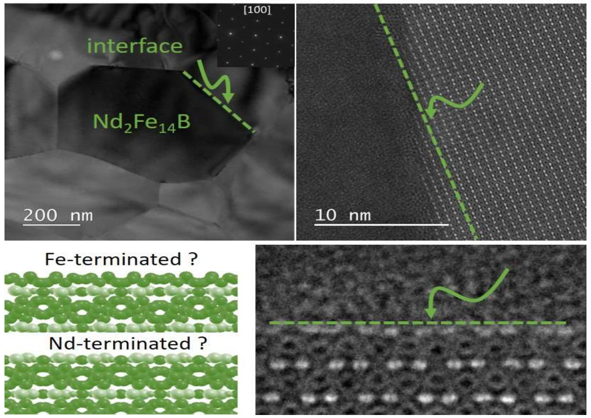
Al, Nb, Gd, Ga, Co, Pr ect…

- Microcrystalline



A. Mazilkin et al., Mater. Desig. 199 (2021)

- Nanocrystalline



@S. Šturm, M. Komelj

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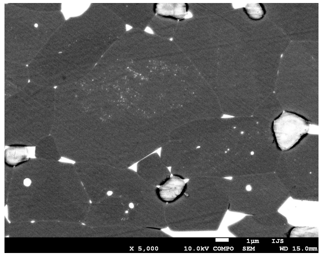
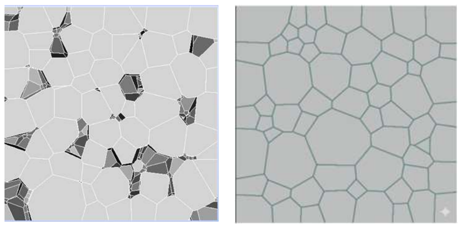
Sintered: Nd-Fe-B – Coercivity Hci – Remanence Br

BEETHOVEN greene



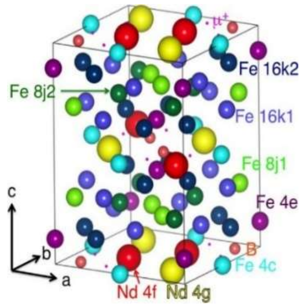


Real → Ideal

@J. Fischbacher, T. Scherfl

▪ Grain boundaries

Reduction of coercivity owing to surface anisotropy, surface defects, and local strains. Impact of grain boundary geometry on coercivity



J.Sugiyama et al., Phys. Rev. Mater 3(6):064402-1-9

$$K1, K2, B_{11}, B_{12}, B_{13}\ldots \xrightarrow[\text{micromagnetism input}]{\text{DFT output}} \text{coercivity}\ldots$$

@M. Komelj

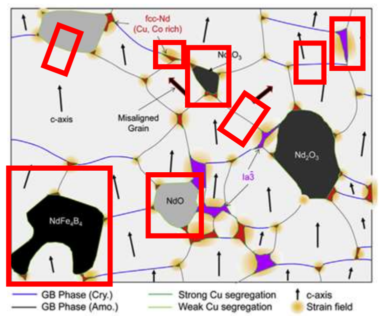
▪ Tripple pockets

Reduced coercivity forms at triple junctions minimize it via grain refinement and rounded, concave junctions, reducing the Br

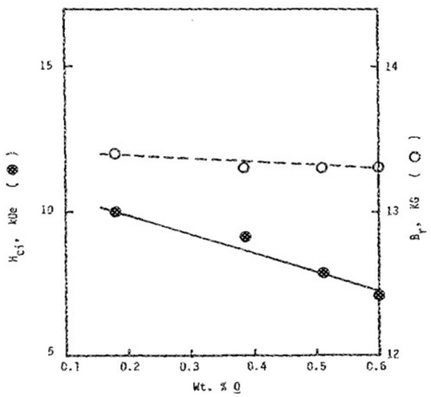
▪ Oxide phases

Removing the oxides from direct contact with the main phase improves coercivity and the remanence

T.T. Sasaki et al. / Acta Materialia 115 (2016) 269–277



▪ Effect of oxygen and oxides



A. S.Kim J. Appl. Phys. 64, 5571–5573 (1988)

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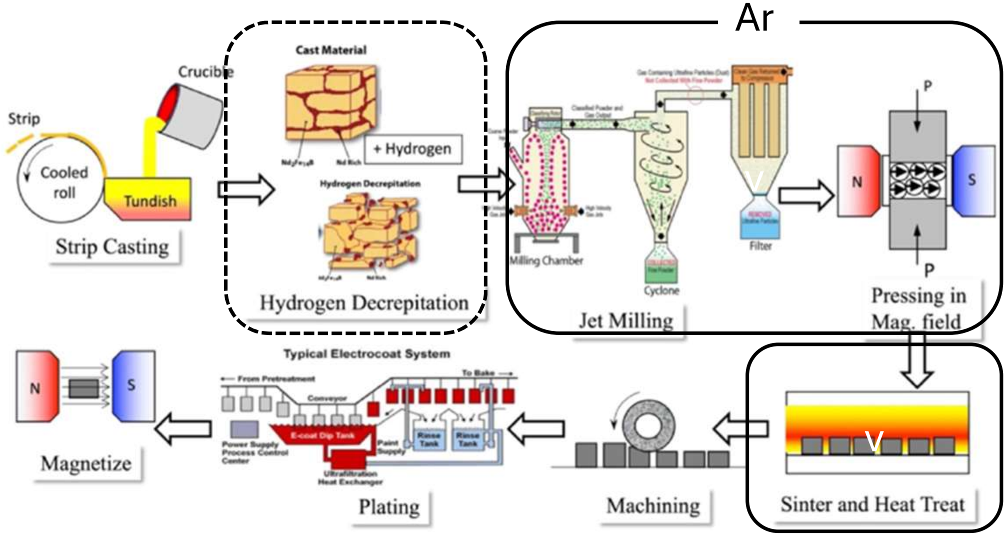
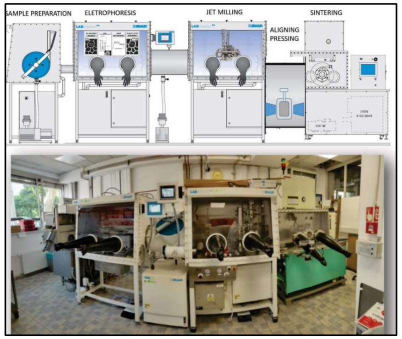
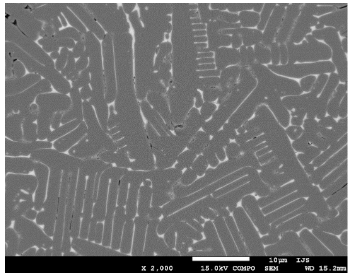
Sintered: Nd-Fe-B – production



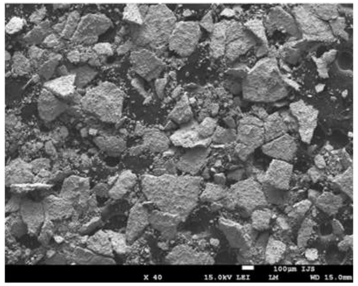
J. Cui, J. Ormerod J. Min. Met. Mater. Soc, 74(4) 1-17, 2022



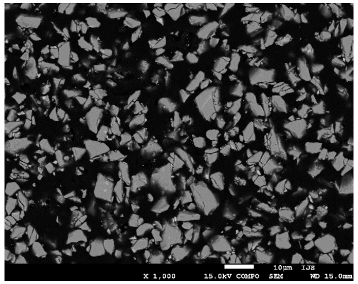
- Strip-cast alloy: lamellar-like structure, α-Fe free
- Hydrogen decrepitation (HD) → coarse, friable powder
- Jet-milling → <u>micron-sized, near-monocrystalline powder</u>
  - Aligning in magnetic field, pressing → high anisotropy
  - Sintering, annealing, machining, coating



Strip-cast alloy:
(microstructure)



HD powder:
(morphology)



Jet-milled powder: *

@T. Tomše

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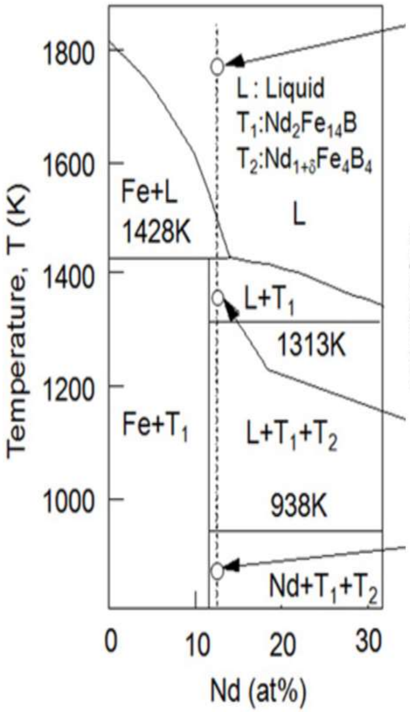
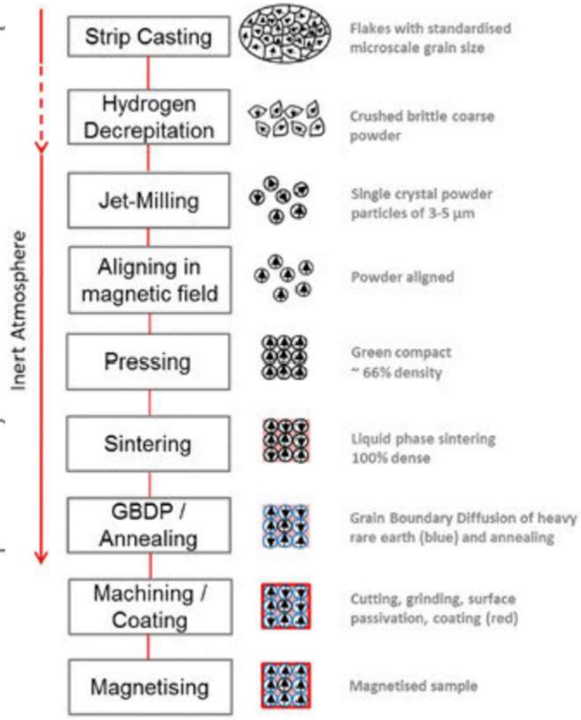
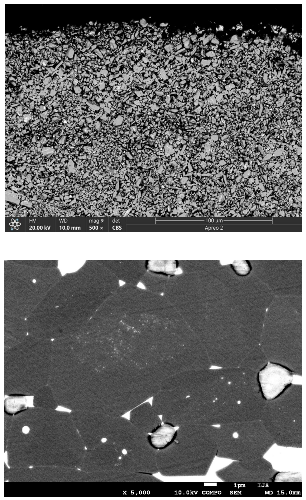
Sintered: Nd-Fe-B – production

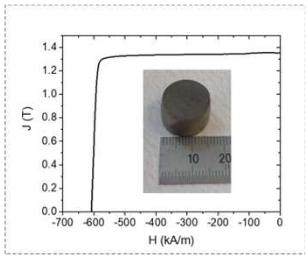


S. Sugimoto, Journal of Physics D: Applied Physics, vol. 44, p. 064001, 2011.



X. Yang et al., J. Sust. Metal. 2017



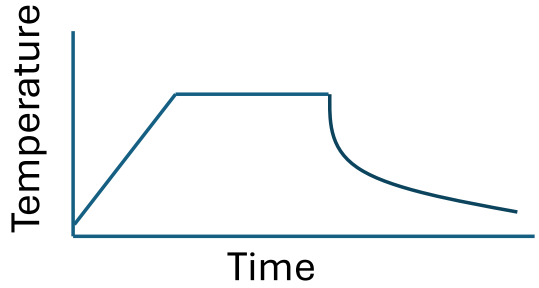


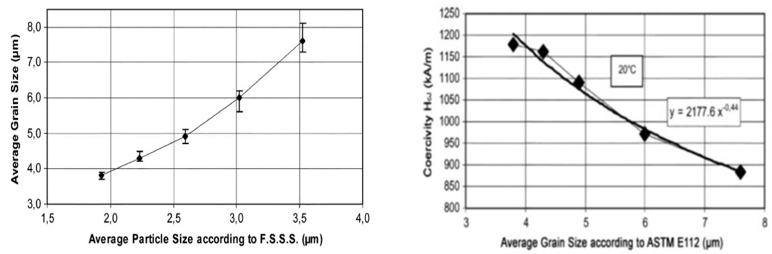
@T. Tomše

Nd-Fe-B no HRE

Sintering profile multiple steps: 0-1000-1100°C, time: h –Hci~ 1200 kA/m, Br ~ 1.3-1.46T

Grain size control vs. Hci





(Uestuener et al., IEEE Trans. on Magn., 2006)

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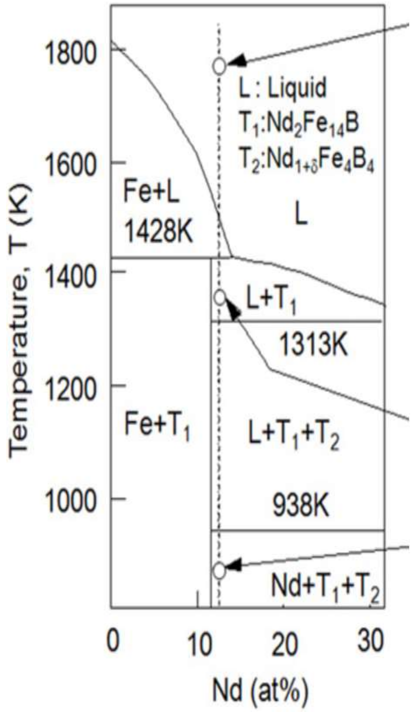
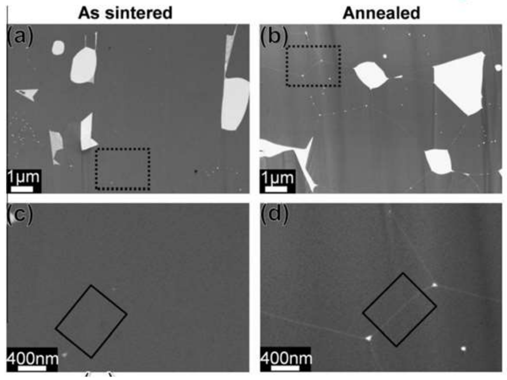
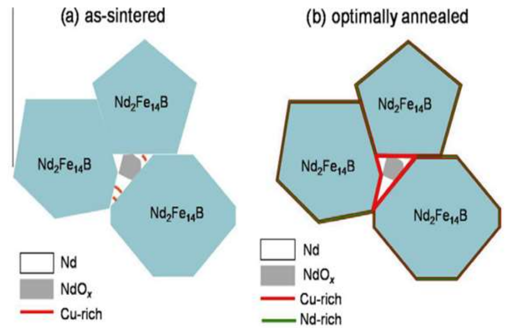
Sintered: Nd-Fe-B – production



S. Sugimoto, Journal of Physics D: Applied Physics, vol. 44, p. 064001, 2011.

Post-sintering annealing

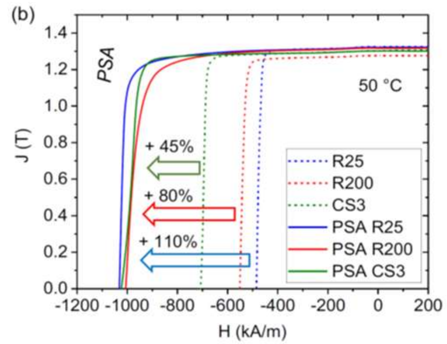




H. Sepheri – Amin et al., Act. Mater, 2012

Post sintering annealing

- Builds continuous Nd-rich grain-boundary phase/non-magnetic layers around $Nd_2Fe_{14}B$ grains
- Exchange-decouples grains & removes easy nucleation sites
- Improves micromagnetic factors: Stress relief + cleaner boundaries improving coercivity without changing Br.



T. Tomše et al., Adv. Eng. Mater. 2024

Nd-Fe-B no HREs

Sintering profile- multiple steps: 0-1000-1100°C, time: h –Hci~ 1200 kA/m, Br ~ 1.3-1.46T

Post sintering annealing: 2 step – 500-620 °C, time: h – Hci ~ 1600 kA/m, Br ~ 1.3-1.46T

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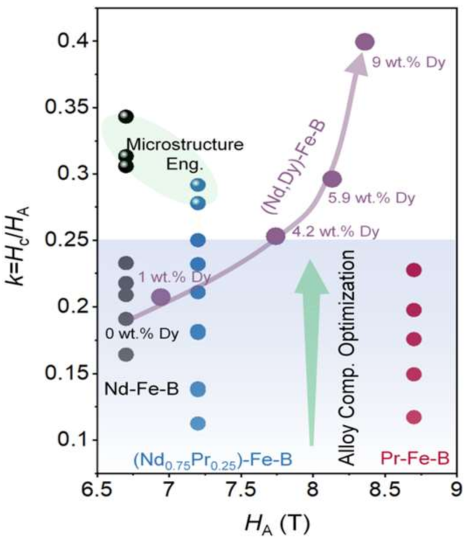
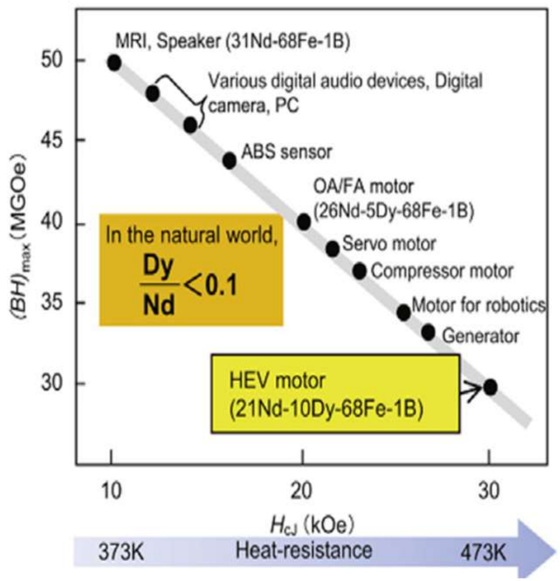
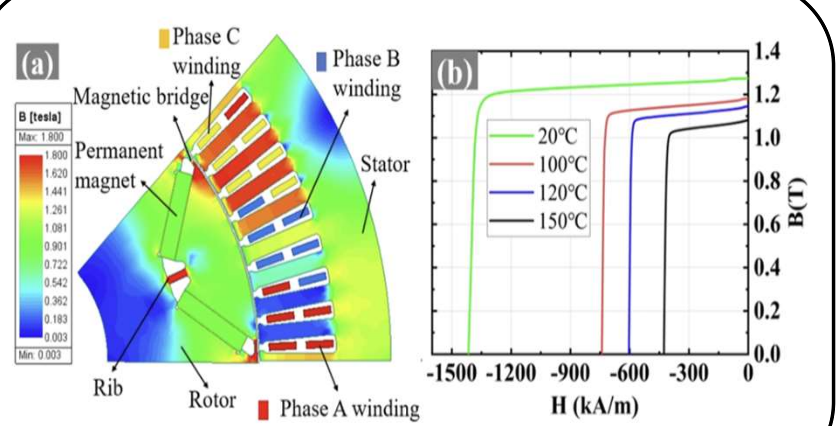
Sintered: Nd-Fe-B – CRM – Hci - GBDP



X. Tang, K. Hono, NPG Asia Materials 15 50 (2023)



Z. Liu, J. He and R.V. Ramanujan, Materials & Design 2024



W. Li et al., AIP Advances 2024

- ➢ HRE content up to 9 wt %, for Hci in e-mobility
- ➢ How to achieve high coercivity for e-motors without scarifying too much of precious Dy, Tb (HREs)?
- ➢ We only have to do it locally!

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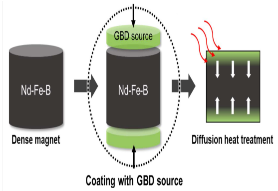
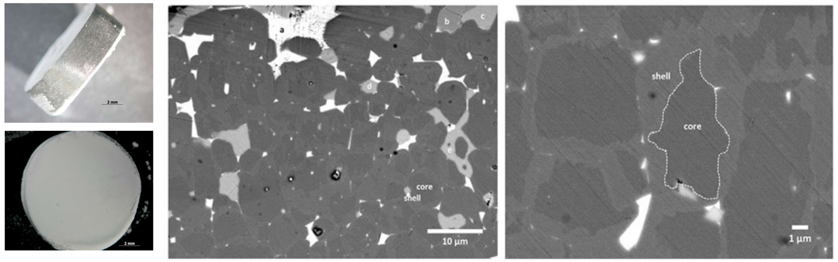
Sintered: Nd-Fe-B – CRM – Hci - GBDP

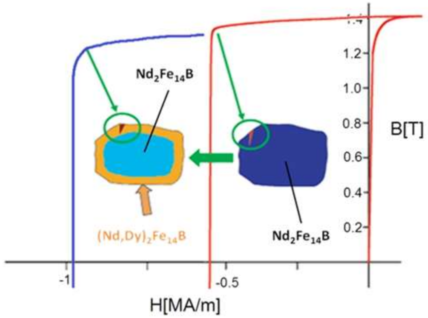
GBDP concept, TDK Patent
H.Nakamura *IEEE Transactions son Magnetics*, 2005

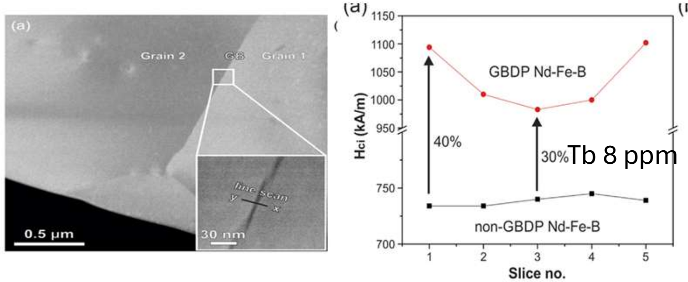
M. Soderžnik et al,, *Intermetallics* **23** (2012), pp. 158–162.



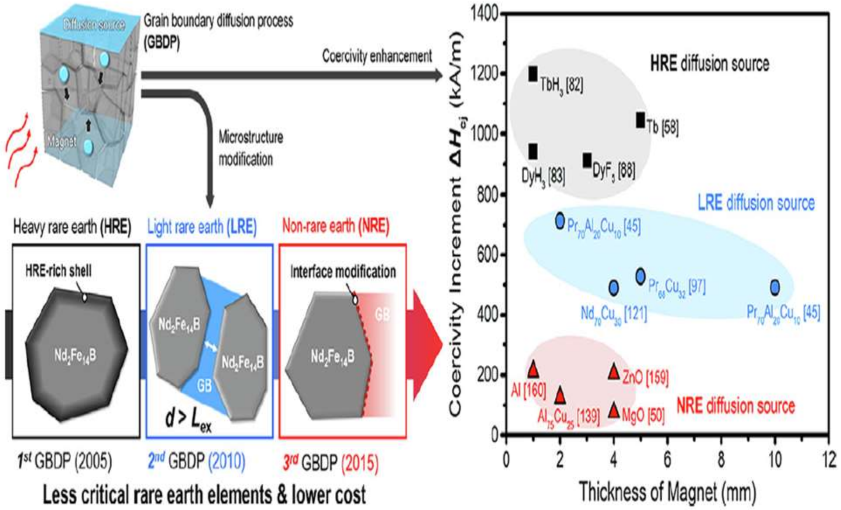
@S. Šturm





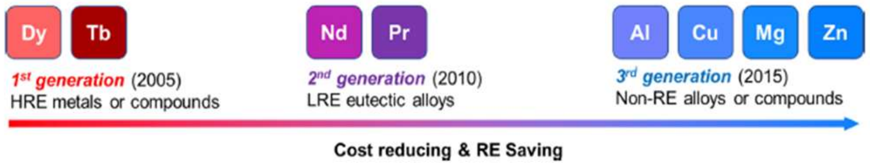


K . Žagar Soderžnik, et al., JALCOM 2021



Z. Liu, J. He and R.V. Ramanujan, Materials & Design 2024

- ➢ Small HREE (Dy, Tb) addition: from 9 wt.% → <1 wt.% at grain boundaries
- ➢ Higher anisotropy at grain edges
- ➢ Increased coercivity with minimal remanence loss
- ➢ **GBDP generations (1–3): addressing both H_a and interface control**



Z. Liu, J. He and R.V. Ramanujan, Materials & Design 2024

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Remanence Br: Isotropic vs. Anisotropic magnets

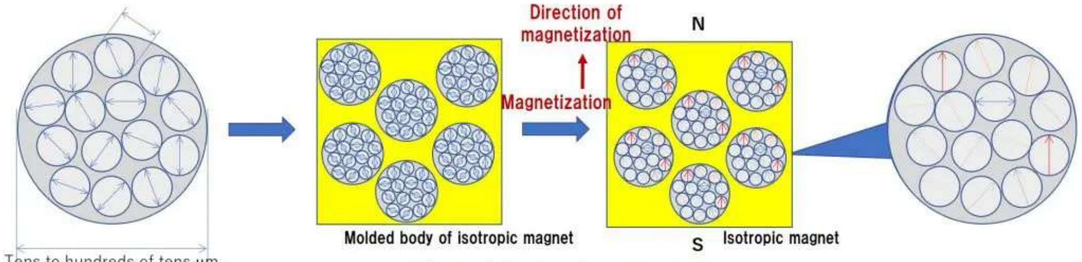
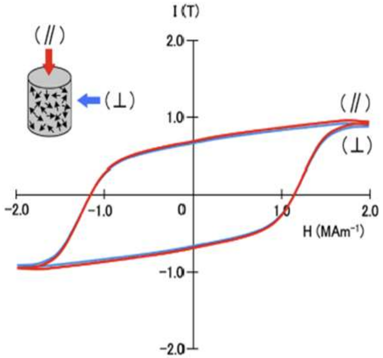


Figure 1 Isotropic magnet



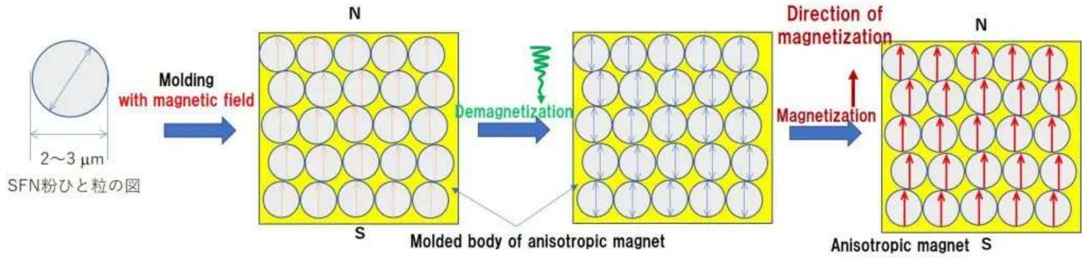
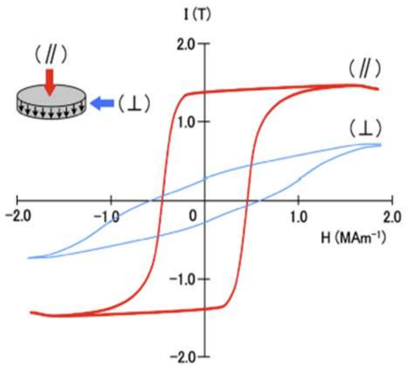
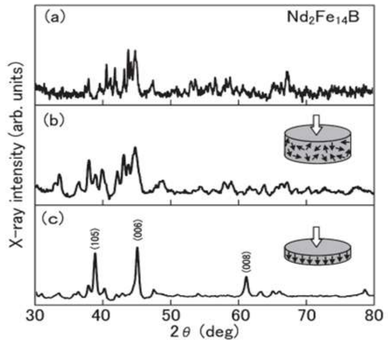


Figure 2 Anisotropic magnet





https://crossmining.smm-g.com/glossary/isotropic-magnet-and-anisotropic-magnet/

T. Saito et al., J. Jpn. Soc. Pow. Met. 63,7, 2016

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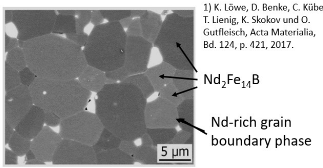
Sintered: Nd-Fe-B – Remanence Br

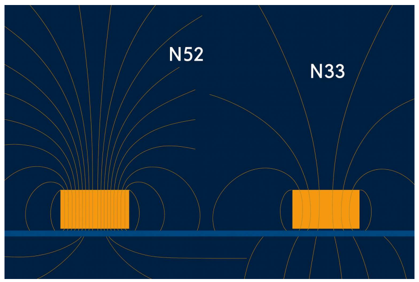
- The composition/amount of the $Nd_2Fe_{14}B$ phase



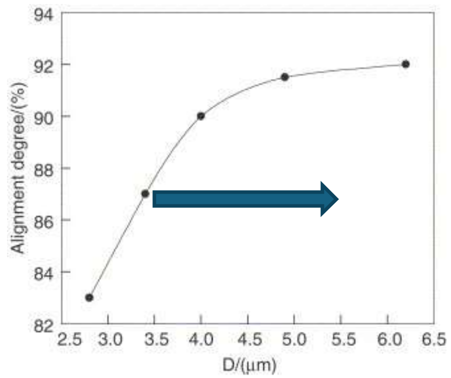
1) K. Löwe, D. Benke, C. Kübel, T. Lienig, K. Skokov und O. Gutfleisch, Acta Materialia, Bd. 124, p. 421, 2017.

$Nd_2Fe_{14}B$
Nd – 26.7 wt % + surplus ~ TRE - 30 wt. %
Fe – 73.2 wt %
B – 0.09 wt %
+ Dy, Tb **1 wt % Dy, Tb**
↑ **Hc ~ 120kA/m, ↓Br 3%**

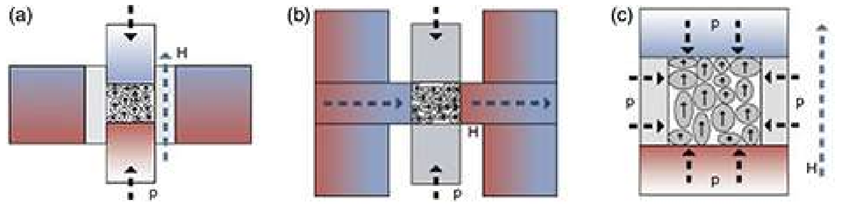
Source: AI



N52 – Br (20°C) = 1.4 T



- The degree of alignment



Axial Transverse Isostatic

Vacuumschmeltze (2012), Magnetic field pressing technology

Lubricant doses (wt%)	B_r (KG)	$_jH_c$ (KOe)	$(BH)_{max}$ (MGOe)	ρ (g/cm^3)	Content of C (ppm)
0.02%	14.06	14.36	49.73	7.55	146
0.05%	14.47	14.43	51.30	7.52	233
0.10%	14.37	14.53	47.60	7.36	587

Isostatic

Y. Sun et al., JMMM 299 (2006)

Small particle size, difficulty in flowability, pressing, lubricants addition

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Nd-Fe-B permanent magnets' properties outlook

B_r tesla	1.05	1.10	1.15	1.20	1.25	1.29	1.32	1.35	1.38	1.40	1.42	1.45	1.49	Max Temp
Label	GRADES													deg C
AH	28AH	30AH	33AH	35AH	38AH	40AH								230
EH	28EH	30EH	33EH	35EH	38EH	40EH	42EH	45EH						200
UH		30UH	33UH	35UH	38UH	40UH	42UH	45UH	48UH	50UH	52UH	54UH		180
SH		30SH	33SH	35SH	38SH	40SH	42SH	45SH	48SH	50SH	52SH			150
H		30H	33H	35H	38H	40H	42H	45H	48H	50H	52H			120
M		30M	33M	35M	38M	40M	42M	45M	48M	50M	52M			100
		N30	N33	N35	N38	N40	N42	N45	N48	N50	N52	N54	N55	80
BHmax	28	30	33	35	38	40	42	45	48	50	52	54	55	MGOe

Rao D et al., Machines MDPI 2021, 9, 124

Hci

- **Interfacial control, H_a control**
- **Grain size control**

Br

- **Alignment, pressing, density**

- Improved properties, greater energy efficiency
- No or low HREs
- Cost efficiency, price driven
- In situ GBDP
- Recourse efficiency – processing, recycling

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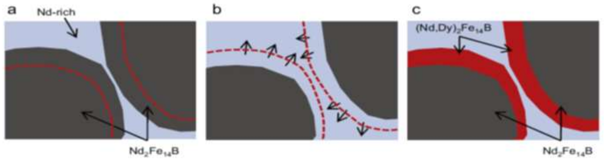
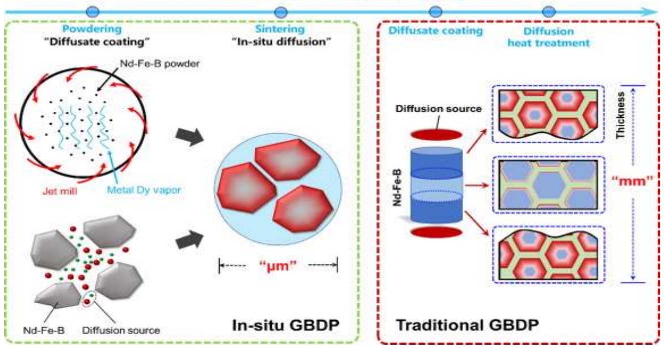
Consolidated Nd-Fe-B PMs - opportunities

Conventional sintering:

- Grain growth (limits H_{ci})
- Material waste and basic shapes *(for electric motors, magnet's shape is a factor!)*
- Properties trade-off due to alloying *(GBDP - grain-boundary diffusion process – FOR THIN MAGNETS)*



Oono et al., JMMM 323 (2011) 297 – 300

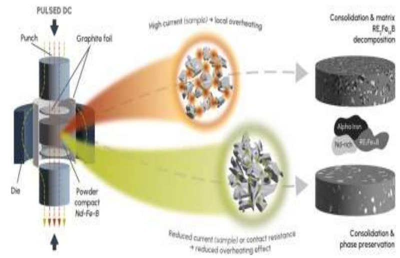


Liu et al., Materials & Design, 2021, 2029, 110004

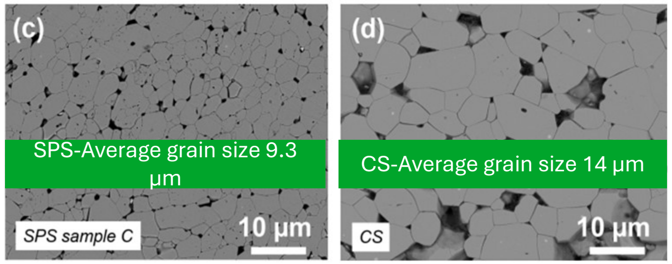
Fast consolidation via Spark Plasma Sintering -SPS

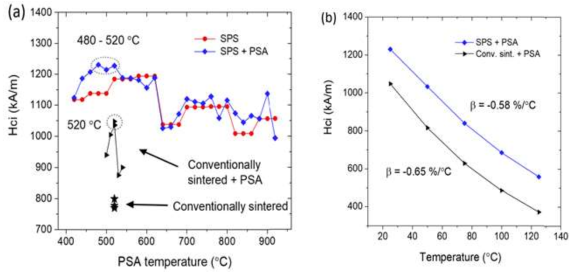
To address/overcome the limitations of the conventional powder metallurgy approach concerning

- Materials composition (REEs, Cu, HREE)
- Microstructure (grain growth, core-shell, GB chemistry, and structure)
- Size and shape (limitation of GBDP, vast number of shapes and geometries)
- Higher densities and Br and BH_{max}



Tomše et al, J. Mater. Proc. Tech. 2024, vol. 328, art. 118405





Tomše T., IEEE Trans. Magn.. 2024, 60, 8, 2100406

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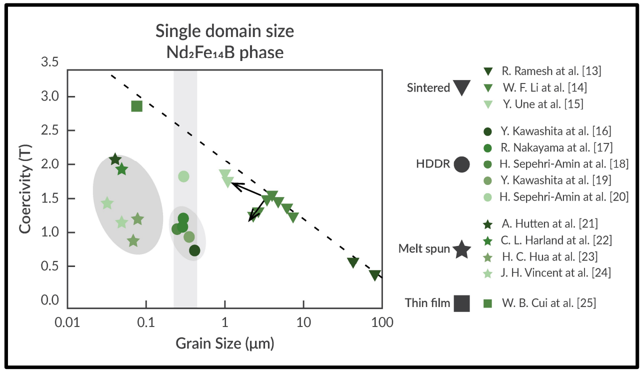
Nanocrystalline - Nd-Fe-B – HDDR



K. Hono et al., Scripta Mater. 2012

Disproportionation →

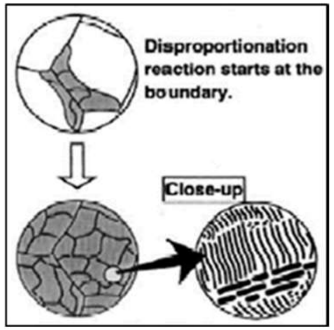
$$Nd_2Fe_{14}B + 2H_2 \leftrightarrow 2NdH_2 + 12\alpha\text{-}Fe + Fe_2B$$

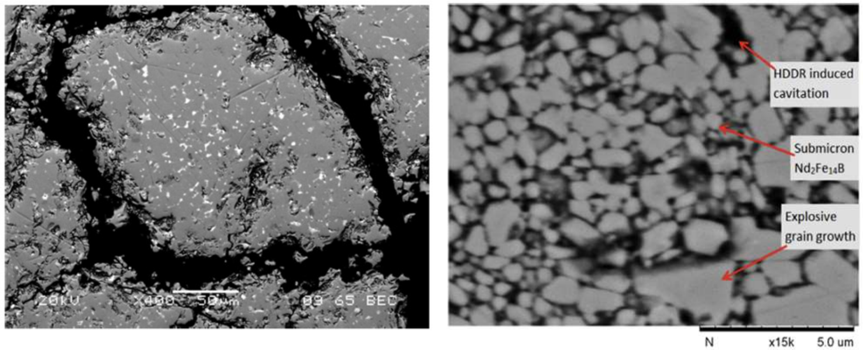
recombination ←

<u>Hydrogenation – disproportionation – desorption – recombination process:</u>

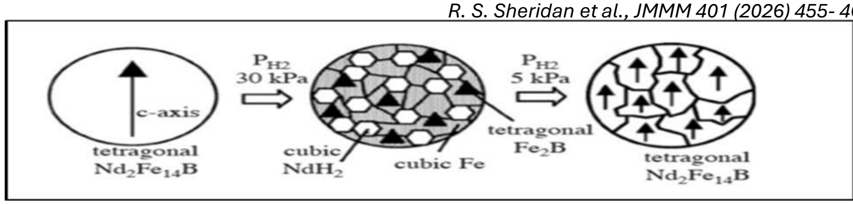
- ➢ HDDR carried out in H_2 at elevated temperature
- ➢ Proper parameters → anisotropic, polycrystalline powder (~300 nm grains)
- ➢ Fe_2B (tetragonal) phase retains texture memory of the original 2–14 phase
- ➢ Key factors: temperature and pressure
- ➢ Kinetics tunable with alloying (e.g., Co, Ga)

- ➢ **POWDER: Nanocystalline Hci ~ 1T (800 kA/m), Br > 1T – BONDED MAGNETS**
- ➢ **Not appropriate for „conventional“ sintering – grain growth**
- ➢ **BULK MAGNETS: Fast consolidation Hci ~ 1T (800 kA/m), Br > 1T**





R. S. Sheridan et al., JMMM 401 (2026) 455- 462



Honkura no et al., JMMM 290-291 (2005) 1282 – 1285

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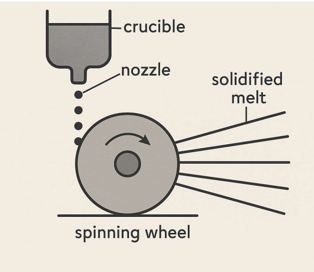
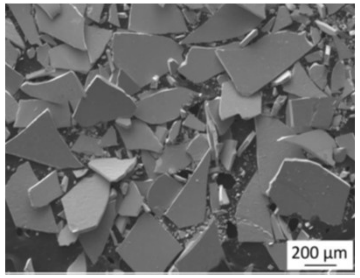
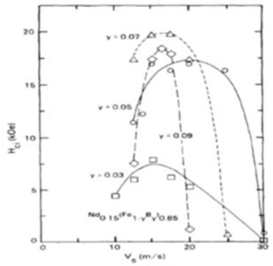
Nanocrystalline - Nd-Fe-B – melt spinning

- Flakes, powder ISOTROPIC, ANISOTROPIC (?) + resin

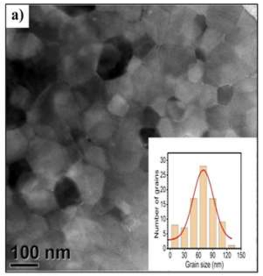
Source: AI

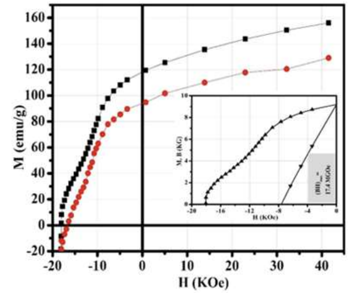






Croat et al., Appl Phys Letter 144 (1984) 2083-2087



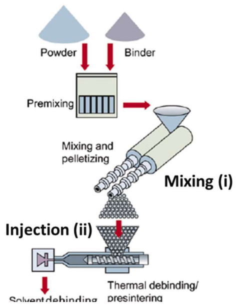


T. H. Nguyen et al., JALCOM, 1005 (2024) 176122

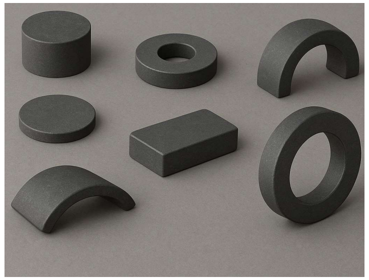
- Rapid solidification of the melt, Cooling rates: ≈ 10^{-6} K/min

- **Bonded magnets magnetic**

- powder + binder
- \+ Large flexibility in shapes and magnetization patterns
- \- Reduced Br and BH_{max}, due to dilution of the magnetic phase



T. Crozier-Bioud et al., Mater. Today Phys. 34, 2023, 101082



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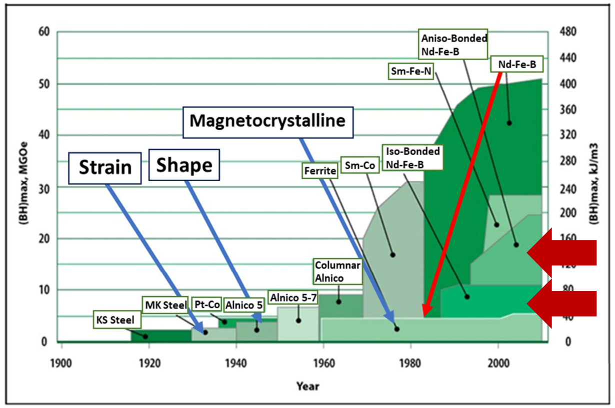

https://www.slideshare.net/slideshow/2019-01-17-magnetics-2019/129998652

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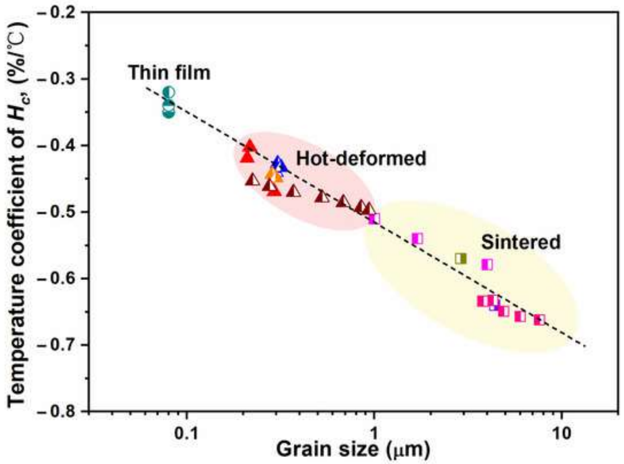
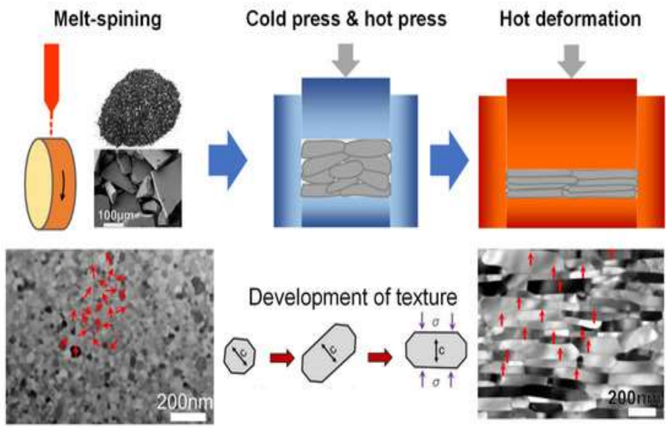
Nanocrystalline - Nd-Fe-B – hot deformation

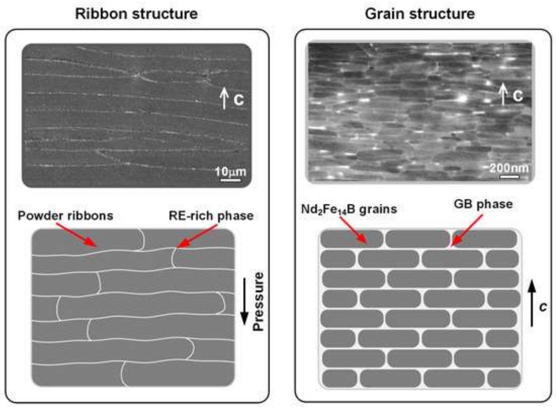
Hot deformation (HD)

- Plastic deformation of isotropic precursor results in rotation of grains & grain growth perpendicular to press direction
- Grains are below single-domain size → high H_{ci}
- Good thermal stability due to small grain size
  (temperature coefficient of coercivity depends on the grain size)
- Not for net-shaping



R. Chen et al., MDPI materials, 16, 13, 2023





R. Chen et al., MDPI materials, 16, 13, 2023

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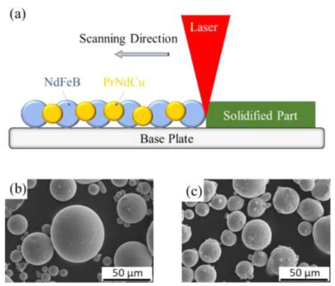
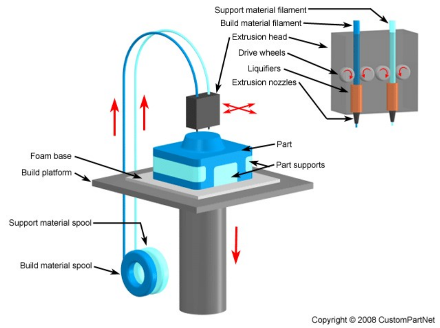
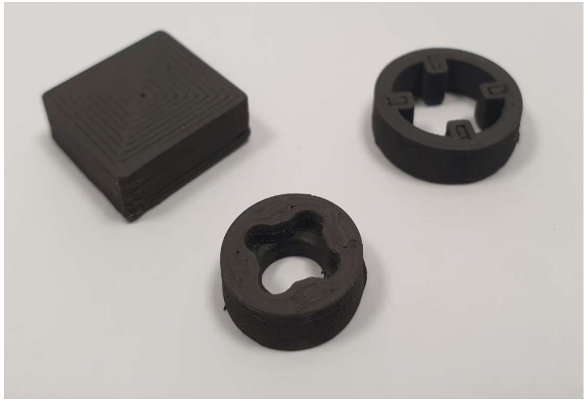
Nd-Fe-B – 3D printing

- Powder Bed Fusion
- Fused filament



BHmax= up to 58 kJ/m3
Hci= up to 950kA/m

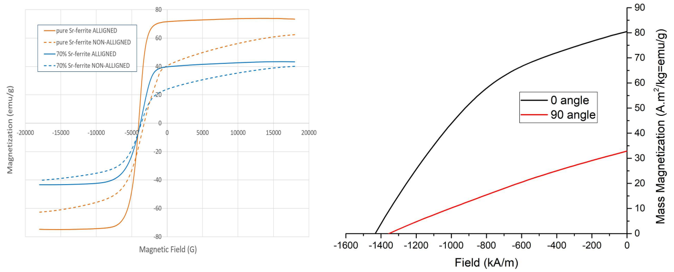




Jhang Jian W-Y et al., Materialia 21, 2022, 101351 *K.Dhal, MSc Thesis, 10.13140/RG.2.2.27244.31364*

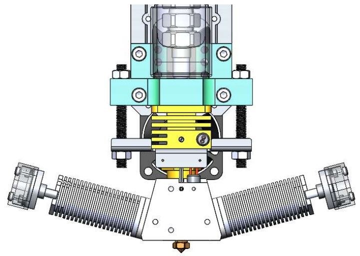
- Complex designs – new magnetic fields
- Fast prototyping – cheaper compared to molds for injection molding
- Net free production – less Waste material

Field-assisted 3D printing of magnets



B. Podmiljšak et al., JMMM 2023

3D printer for Magnets- Anisotropic



@S. Arshad

Slovenian Patent application approved (PCT/SI2025/000004)
EU patent pending

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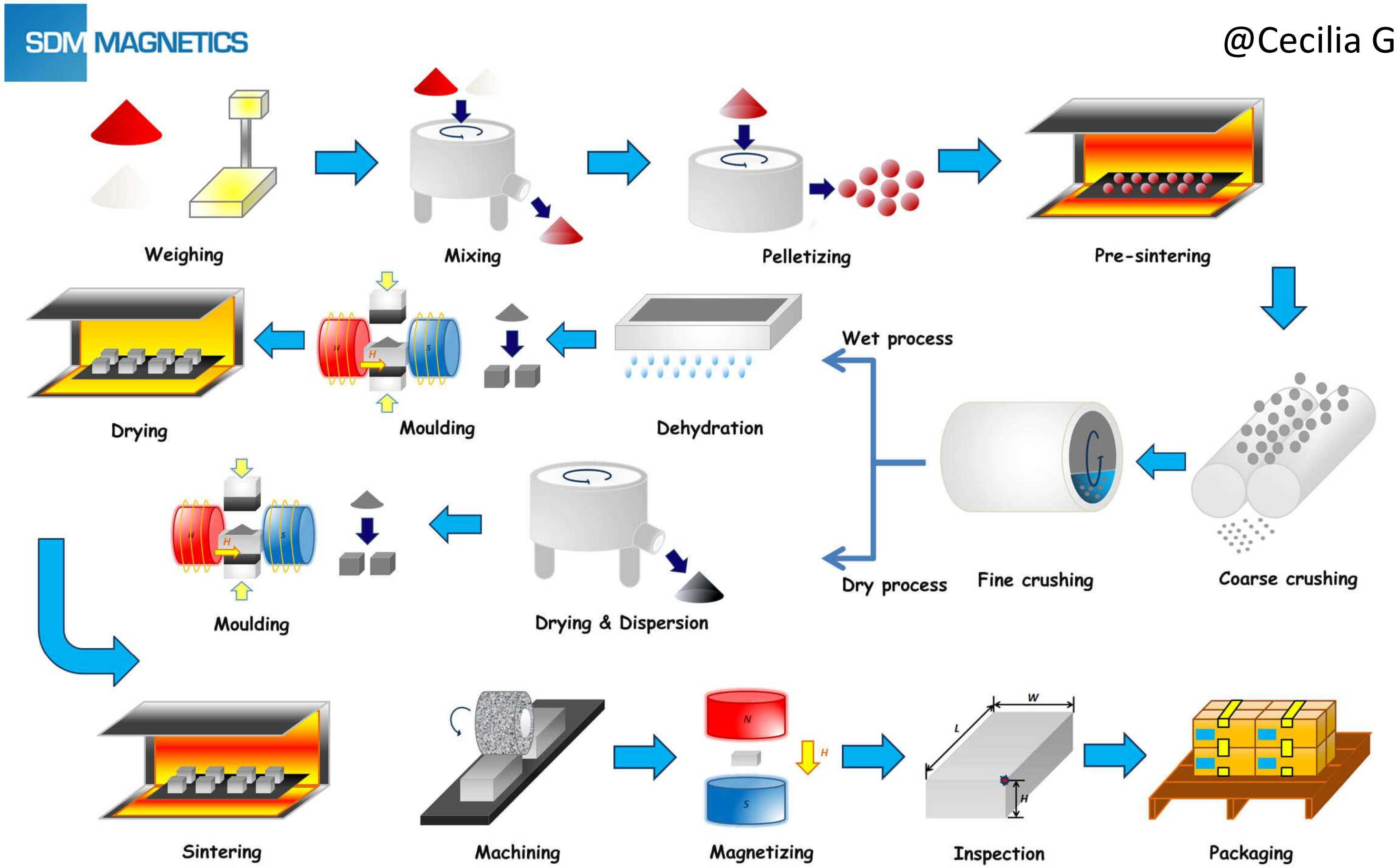
ndustrial manufacturing of ferrite magnets

@Cecilia Granados, CSIC



https://www.magnet-sdm.com/1186/

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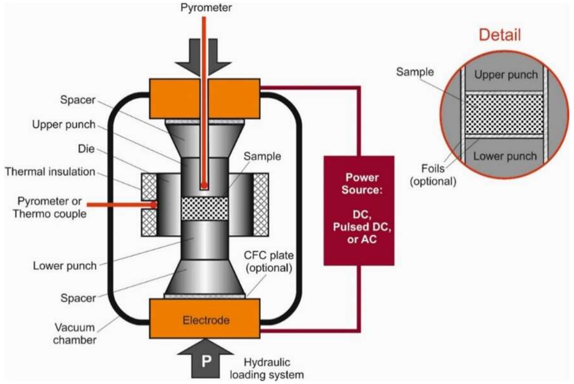
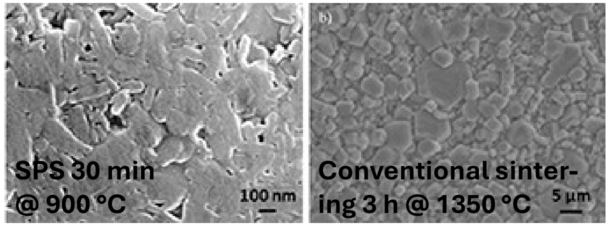
on-conventional sintering methods for ferrite PM

Spark Plasma Sintering (SPS)

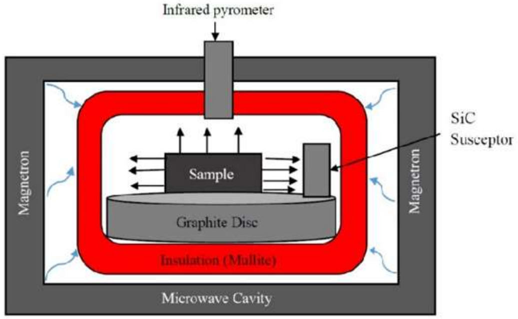


https://doi.org/10.1002/adem.202301391

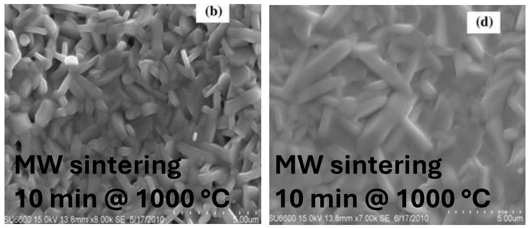


https://doi.org/10.1016/j.jeurceramsoc.2013.07.027

Microwave Sintering (MW)

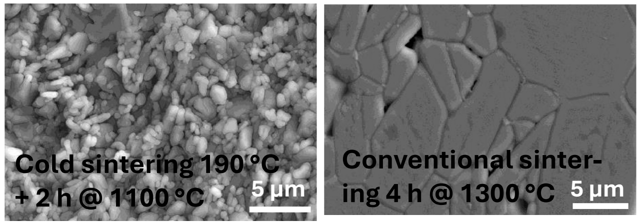


https://doi.org/10.53063/synsint.2023.33129



https://doi.org/10.1007/s10854-013-1333-9

Cold sintering process (CSP)



https://doi.org/10.1016/j.actamat.2021.117262

Granados-Miralles et al. 2023 "Permanent Magnets Based on Hard Ferrite Ceramics", InTech Open - https://doi.org/10.5772/intechopen.1002234

Granados-Miralles et al. 2021 J. Phys. D: Appl. Phys. 54, 303001 - https://doi.org/10.1088/1361-6463/abfad4

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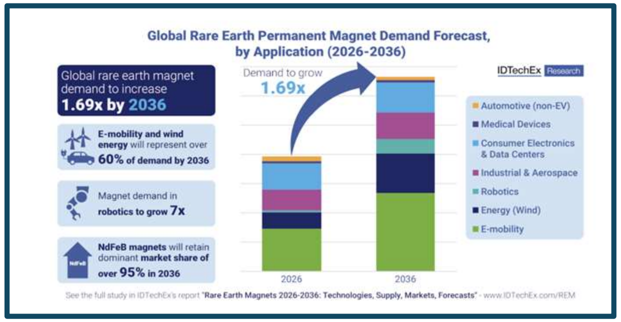
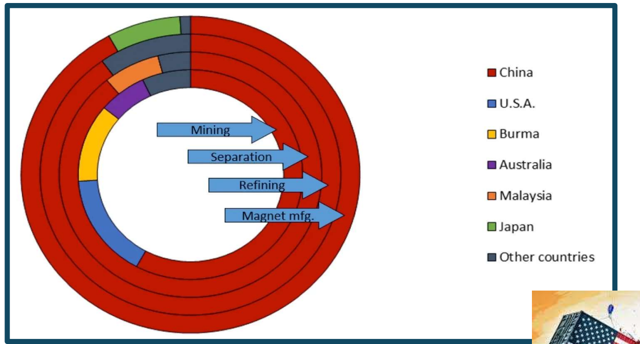
Conclusion





- ➢ Global PM Demand forecast to 2026-2036 1.69x
- ➢ Increase the capacity by several times ~3x only to meet the demand in e-mobilty and several folds more in the PMs segment.

PRIORITY:

- ➢ Excellent Know-how
- ➢ Improved magnetic properties
- ➢ Greater energy efficiency
- ➢ Recourse efficiency – processing, recycling
- ➢ Optimization of materials flows
- ➢ Knowledge transfer to full-scale operation of innovative pilot/production lines

https://www.idtechex.com/en/research-article/2025-to-be-a-defining-year-for-the-rare-earth-magnet-market/33601
https://robertbryce.substack.com/p/swedish-rare-earths-wont-dent-chinas

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Thank you for your attention!

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GREENE Project

greene-project.eu

SCAN ME

Nanostructured materials

Jožef Stefan Institute Ljubljana, Slovenia

Eu_Beethoven

Beethoven Project

projectbeethoven.eu

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"Talking Magnets" Webinar Series

Industrial Applications & Challenges

"From Atoms to Applications: A Multiscale Perspective on Magnetism and Permanent Magnets"

16-10-2025

Presenter: **Matej Zaplotnik**
Organisation: **Magneti Ljubljana d.d.**

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Magneti Ljubljana milestones





1951 established

Until 1970 production for domestic market

1988 – new program – REMAG

1989 – no more in ISKRA Group

1992 – privatized

09.11.1993 – ISO 9001 (DQS)

1995 – named Magneti Ljubljana, d.d.

17.2.2000 – VDA 6.1. (BVQi)

15.12.2000 – ISO 14001 (BVQi)

8.5.2002 - ISO/TS 16949 (BVQi)

2003 - OHSAS 18001

2012 – IRIS

2016- SAP

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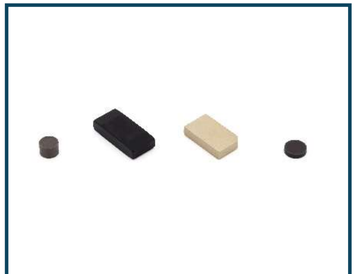
Magneti Ljubljana portfolio


Cast AlNiCo magnets


Sintered AlNiCo magnets


PPS bonded NdFeB magnets


Sintered SmCo magnets


Sintered NdFeB magnets


Magnetic systems

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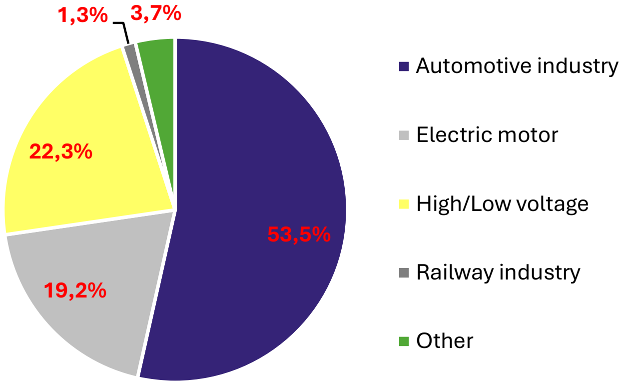
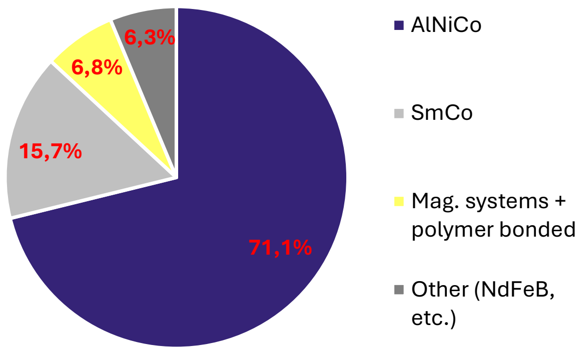
Slide 134

Magneti Ljubljana portfolio





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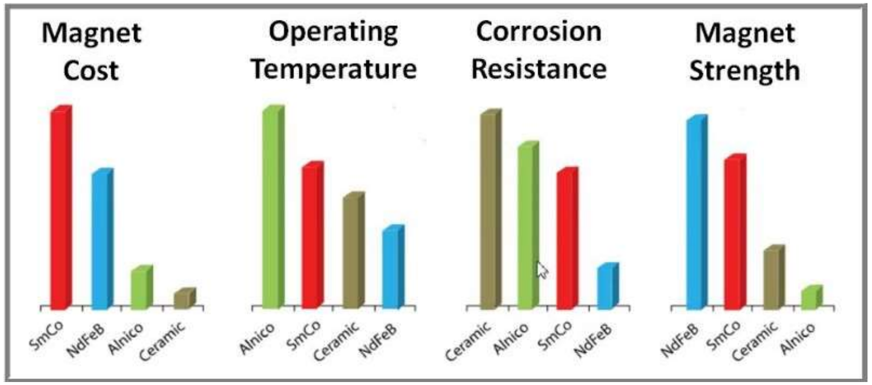
Types of magnets

Magnets are divided between:

- **Sintered magnets**
- **Plastic bonded magnets**

or

- **Rare earth magnets (SmCo, NdFeB, SmFeN),**
- **Non rare earth magnets (Ferrite, AlNiCo, Fe_2N)**



Borrowed from Dura Magnetics

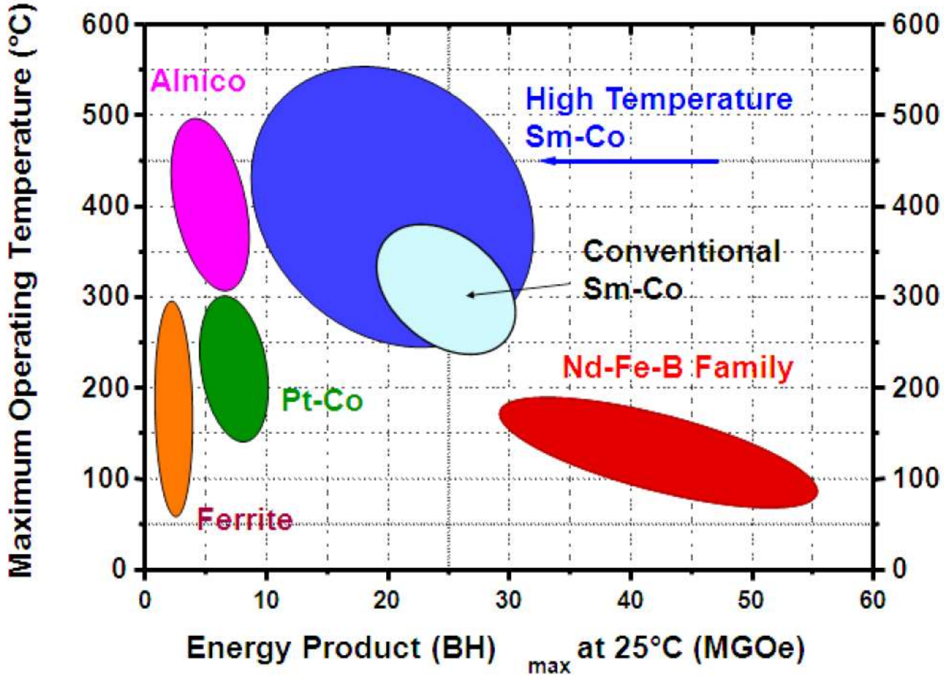


Figure 3-2: Families of Permanent Magnet Materials Plotted by Typical Energy Products and Maximum Operating Temperatures. The NdFeB permanent magnets have the highest energy products but are limited in maximum operating temperature [source: GE Global Research].

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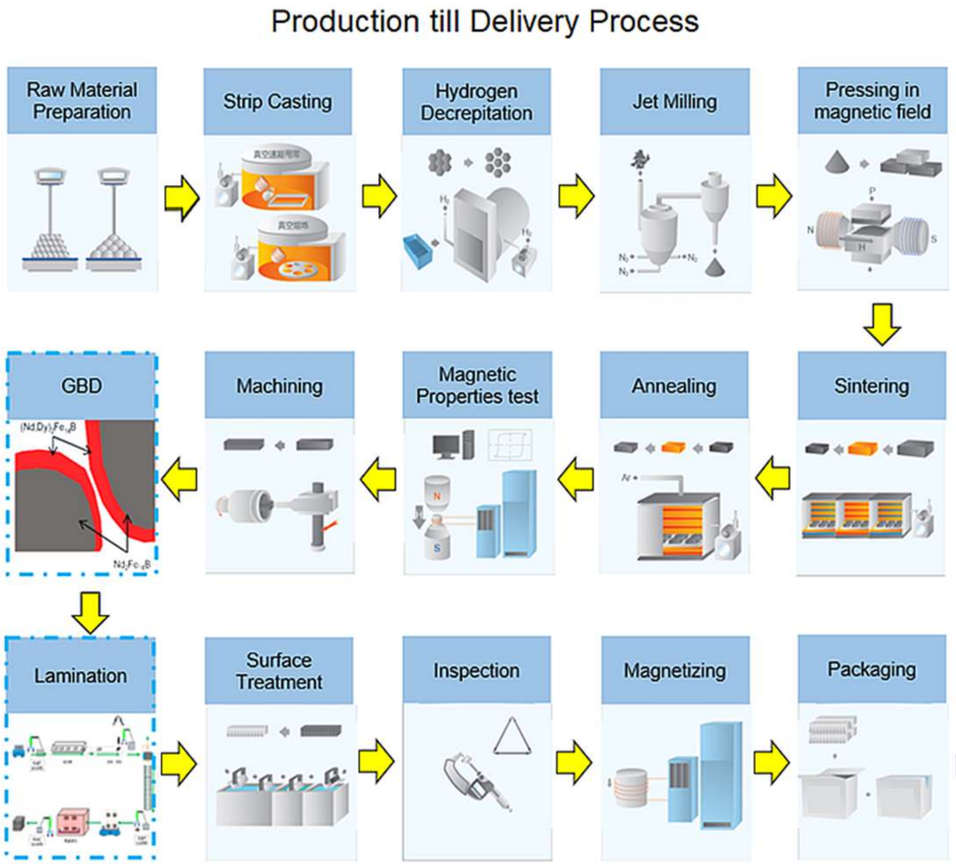
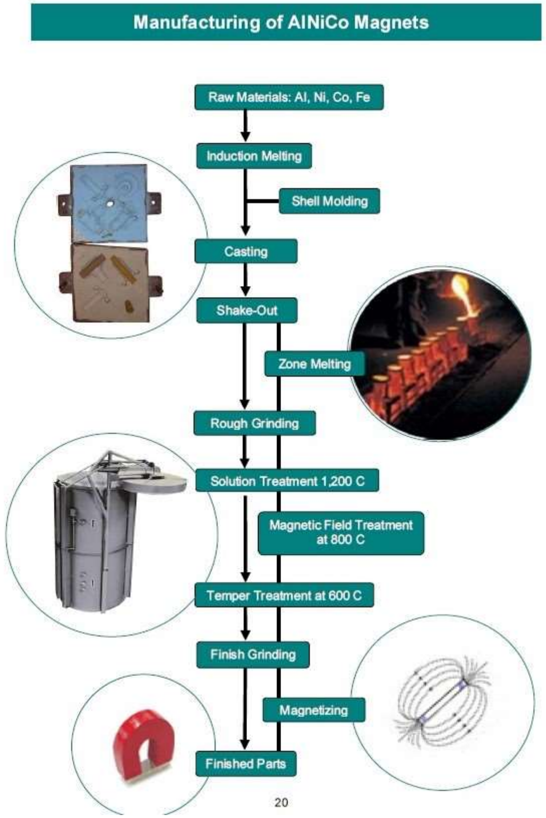
NdFeB/SmCo and AlNiCo production production process



Borrowed from Magnet Tec GmbH



Borrowed from KST Magnet Co.,Ltd

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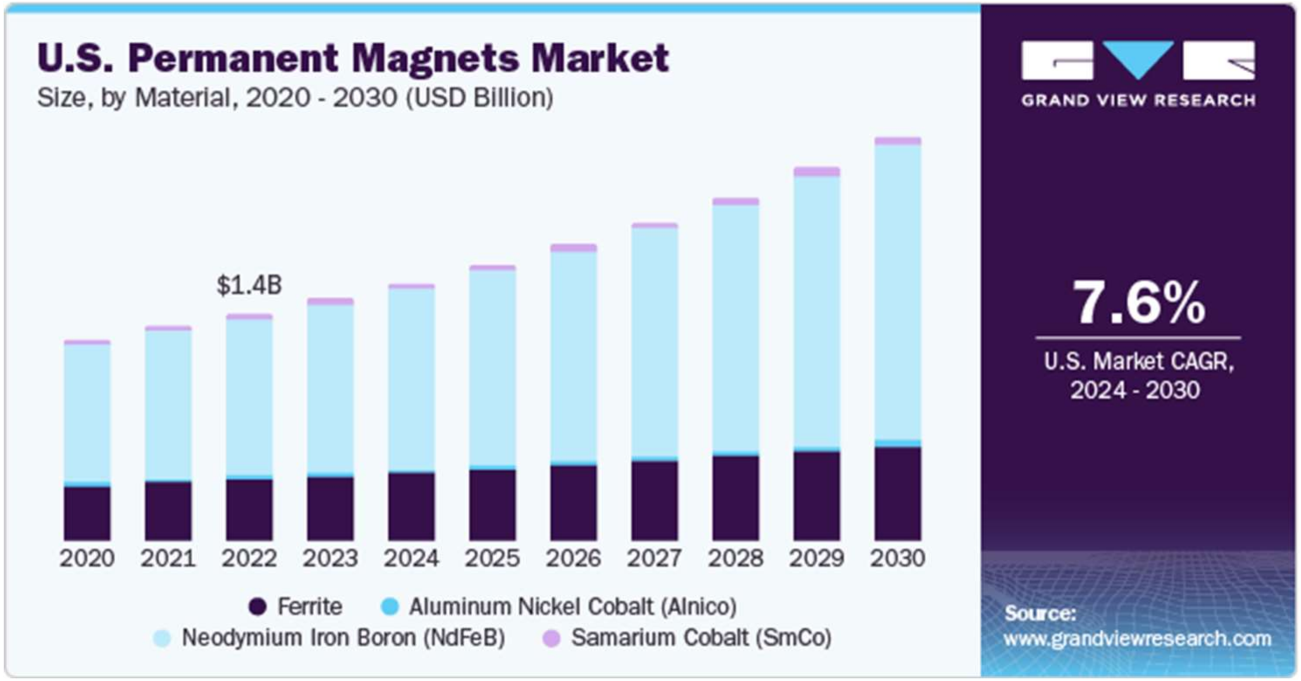
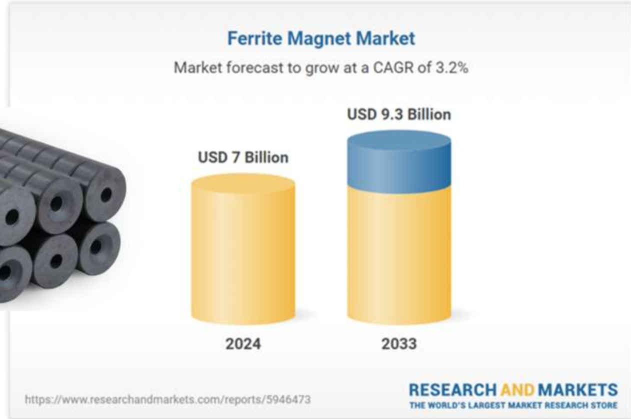
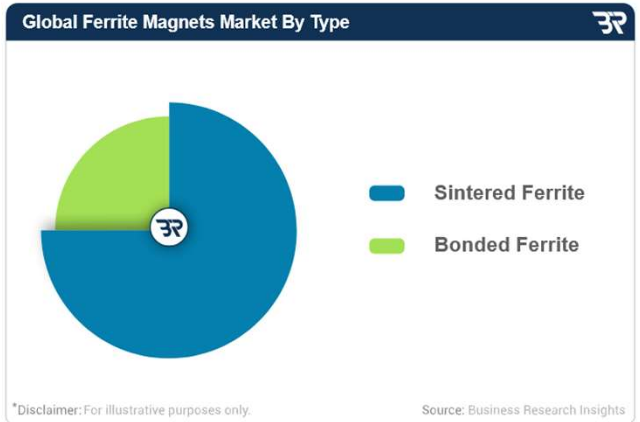
Market share by magnet type

Ferrite magnets are valued for their stability, cost-effectiveness, and corrosion resistance. They represent **~85% of the market in weight**.



Borrowed from Grand View Research





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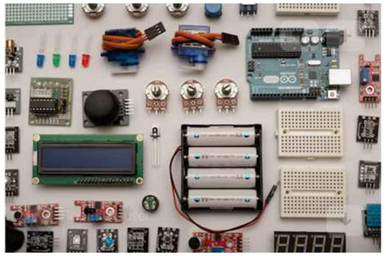
Ferrite magnets applications

Electro-Acoustic Products: Their use in the magnetic circuits of speakers, microphones, and headphones is a significant application.

Electronics: They are employed in various electronic components like ferrite cores for transformers, inductors, smartphones and antennas.



Power Tools: Ferrite magnets provide the rotational force needed in power tools such as drills and grinders.

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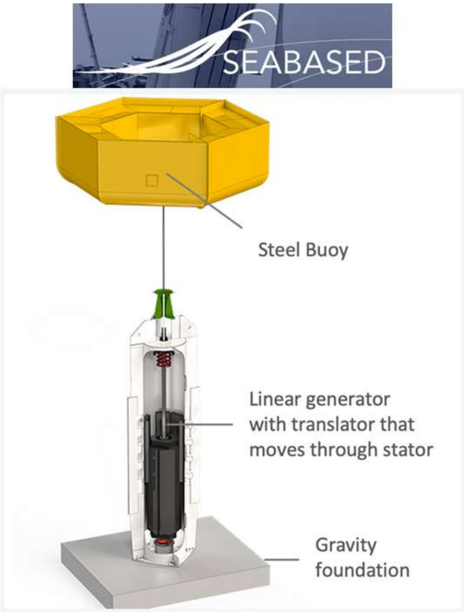
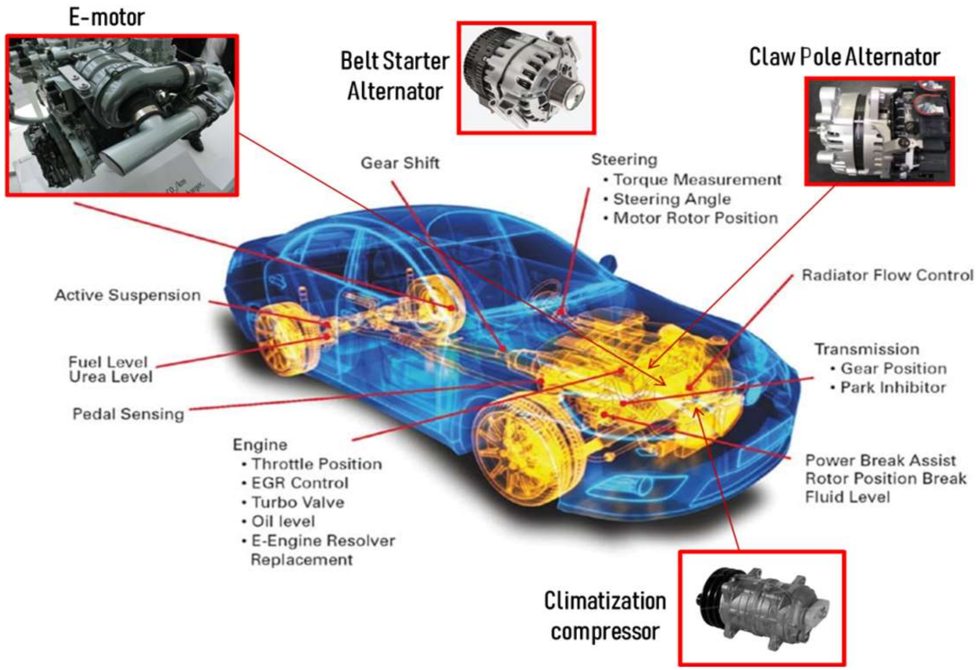
Ferrite magnets applications

The growing demand for magnets in general is driving an increased use of ferrites in renewable energy applications

Wave-park generators



Increased substitution of REE in vehicles



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Policies, regulation and export ban on rare earths

License Requirement:
Exporters must apply for a license for each shipment containing restricted rare earth elements.

End-Use Verification: Detailed documentation about the product's composition, end-use, and end-user is mandatory.

Exemptions: Certain applications, especially those involving low concentrations of Dy and Tb (< 0.1 w.t. %) for consumer electronics, may qualify for exemptions.

Rare earth elements on the export ban list: holmium, erbium, thulium, europium, ytterbium, dysprosium, terbium, samarium, gadolinium, lutetium, scandium, ytrium

Borrowed from Mainrich Magnets

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Policies, regulation and export ban on rare earths

Announcements made on 9.10.2025

Announcement No. 56

- Export licenses from MOFCOM are required for equipment related to rare earth metal and magnet processing, including machining.

Announcement No. 57

- Imposes export controls on holmium-containing permanent magnet materials, effective from November 8, 2025.

Announcement No. 61

- Related to oversea companies/ individuals distributing/selling products to the countries/regions except Ch ina products contains controlled elements need to apply the license from MOFCOM.

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Further policies, regulation and export ban

2B902.o – Rare earth permanent magnet vacuum induction strip casting furnaces:

- Periodic vacuum induction strip casting furnace (Customs Code Ref: 85142000)
- Induction melting furnace under vacuum

2B902.p – Components for equipment under 2B902.o:

- Water-cooled cables
- Copper rollers
- Crucibles
- Tilt controllers
- Cooling systems

2B902.q – Hydrogen decrepitation furnaces for rare earth permanent magnets:

- Continuous atmosphere heat treatment furnace
- Rotary hydrogen decrepitation furnace
- Explosion-proof continuous hydrogen decrepitation furnace

2B902.r – Components for equipment under 2B902.q:

- Valves
- Hydrogen manifold

Borrowed from Ministry of Commerce, PRC

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Further policies, regulation and export ban

2B902.s – Air jet mills for rare earth permanent magnets with all the following:

- Particle size ≤ 5 μm
- Total powder yield ≥ 99%
- Internal oxygen content ≤ 80 ppm

2B902.t – Rare earth permanent magnet forming presses with magnetic induction ≥ 1.5T

2B902.u – Automatic hot pressing equipment for rare earth permanent magnets

2B902.v – Cold isostatic presses for rare earth permanent magnets not listed under 2B104 (Customs Code Ref: 84798310)

2B902.w – Vacuum sintering furnaces for rare earth permanent magnets meeting all of the following:

- Cooling time ≤ 20 min
- Heating temperature 500–1200 ℃
- Temperature uniformity within ±3 ℃ at 1000 ℃
- Types:
- Single horizontal sintering furnace
- Continuous vacuum sintering furnace
- Vertical sintering furnace

Borrowed from Ministry of Commerce, PRC

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Further policies, regulation and export ban

2B902.x – Equipment for machining rare earth magnets:

- Multi-wire cutting machines
- Laser cutting machines
- Automatic adhesive application machines
- Vertical grinders
- Double-sided grinders
- End grinders
- Through-feed grinders

2B902.y – Grain boundary diffusion equipment:

- Physical vapor deposition magnetron sputtering coaters (Customs Code Ref: 84798999)
- Rare earth permanent magnet vacuum diffusion furnaces
- Rare earth permanent magnet screen printing devices

Borrowed from Ministry of Commerce, PRC

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Challenges

Technological

- very limited/non existent equipment producers,
- technology upscaling,
- metallization and magnet production are biggest bottle necks

Economical

- EU magnets 50-100 % more expensive than China,
- high production cost (labour, electricity, raw materials),
- underdeveloped supply chain (100 % of rare earths comes from China)

Political

- export restrictions on raw materials (Nd, Dy, Sm,Tb),
- export restriction on equipment (strip casting, grain boundary diffusion equipment),
- Eol magnets are not being collected (lack of policy)
- dual use might harm/stop magnet supply chain

Social/Environmental

- strict regulation, general public rejects (e.g. mining),
- conflict with climate goals (magnet production energy intensive)

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Possible solutions

BEETHOVEN greene

Technological

- key equipment should be produced in EU
- investment in magnet factories, processing facilities for raw and recycled materials,
- **Magneti Ljubljana** could in current location produce 500 t/year of NdFeB, 500 t/year of AlNiCo and 200 t/year of SmCo – **with investment**

Economical

- Subsidies in EU produced magnets (30 %)
- EoI magnets collected in Europe and reused as secondary material,
- Electricity prices should be controlled (electricity cap)
- New companies for raw material production are emerging **Lynas Rare Earth → 2025/2026**

Political

- help from governments, embassy to get export license (equipment, raw materials),
- EoI magnets/materials needs to be collected, stop sending them on trains/ships back to China
- policy for scrap collection, recycling, magnet passport

Social/Environmental

- change the perspective, industry in EU is becoming undesired due to CO_2 emissions, waste waters etc.

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