Magnetic materials for energy



Franca Albertini

Magnetic and Multiferroic Materials Group

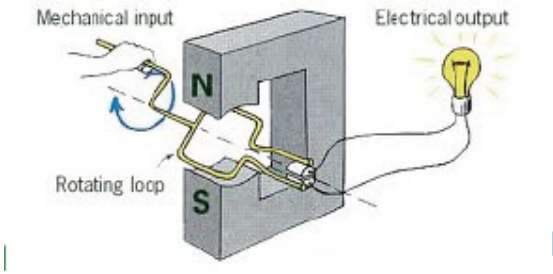
Institute of Materials for Electronics and Magnetism (IMEM) - CNR

Parma, Italy

contact: franca.albertini@imem.cnr.it

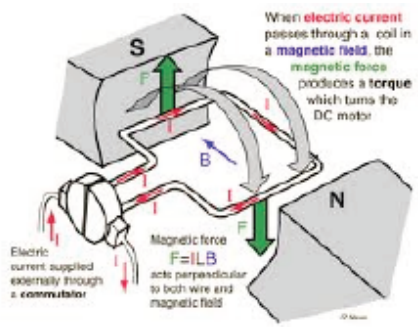
Magnetic materials for energy

Electric generator



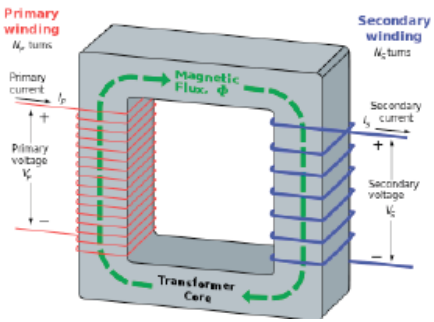
Mechanical to electrical E

Electric motor



Electrical to mechanical E

Transformer



Energy transfer

N. Dempsey, ESM 2013

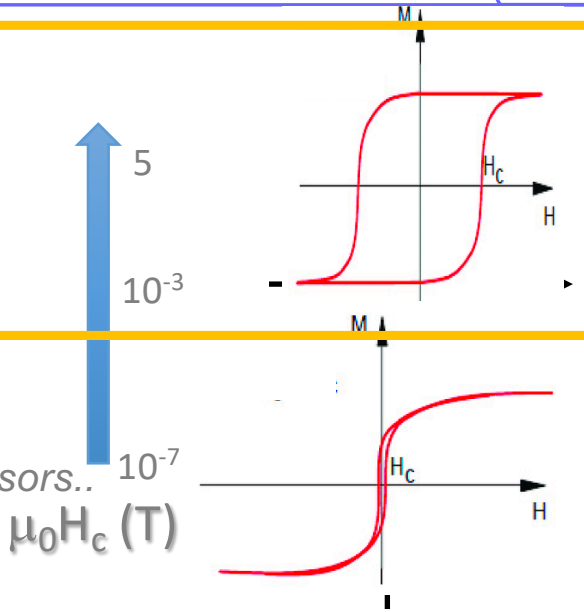
Magnetic materials play a major role in:

Energy production
Energy conversion
Energy transmission and distribution

Energy efficient and smart technologies

Functional magnetic materials

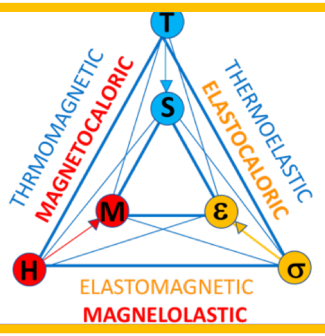
➡ **Hard magnetic materials:**
Permanent magnets
Memories



➡ **Soft magnetic materials:**
Electrical motors, inductors, transformers, sensors..

Tiberto's lecture: Soft magnetic materials and their applications

➡ **Multifunctional magnetic materials**
Magnetic field driven functional properties: e.g. magnetocaloric effect, magnetic shape memory, magnetostriction ⟺ external-field driven magnetic properties

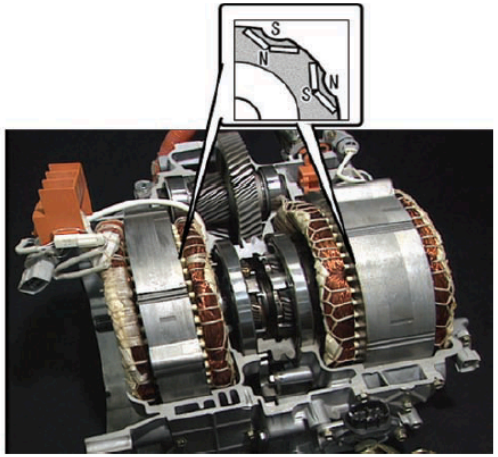


Permanent magnets in green technologies





600 kg Nd(Dy)-Fe-B per 1 MW wind turbine i.e. 24 Kg of Dy, 168 Kg of Nd

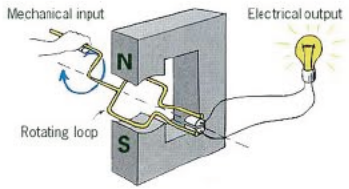


1-2 Kg of Nd-Fe-B in a e- vehicle

From: O. Gutfleisch at al. Adv. Materials 2011

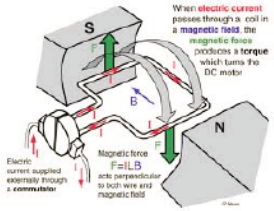
Permanent magnets: applications

Electric generator



Mechanical to electrical E

Electric motor

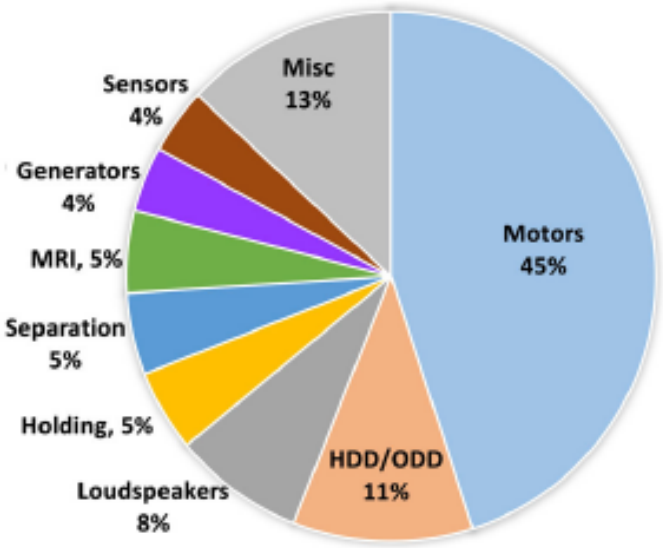


Electrical to mechanical E

- Conversion of mechanical energy into electrical energy
- Conversion of electrical energy into mechanical energy

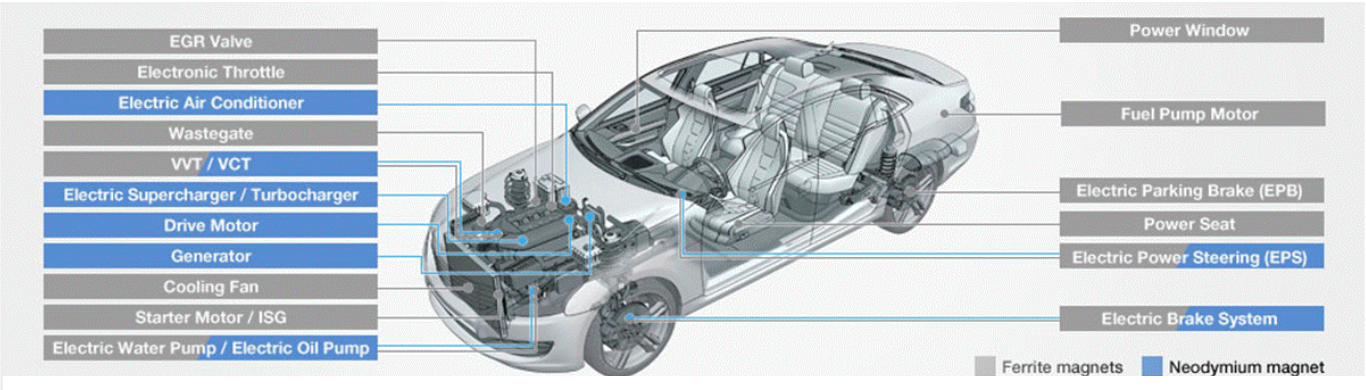
- Production of fields (field gradients), exploitation of attraction-repulsion
- Control of electron beams
- Memories
- Control of multifunctional properties with magnetic field
- Diagnostics, measurement systems

Thin films: Application in magnetic microsystems (MagMEMS), lab-on-chip, energy harvesting devices



Cui et al. JOM, vol. 74, 2022
Total market 19 B$

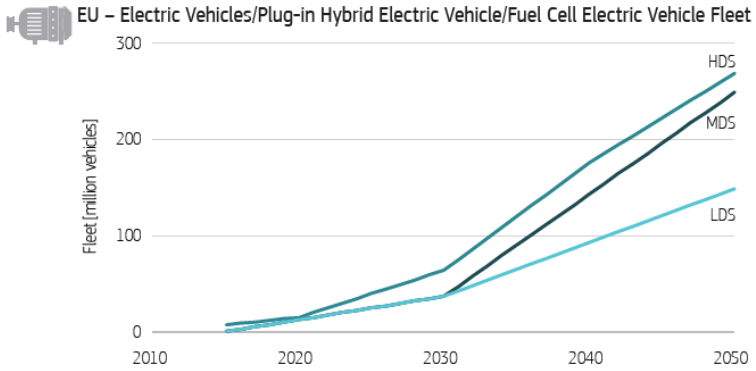
Permanent magnets in automotive applications



Source: TDK: https://product.tdk.com/info/en/products/magnet/technote/ap_automotive.html

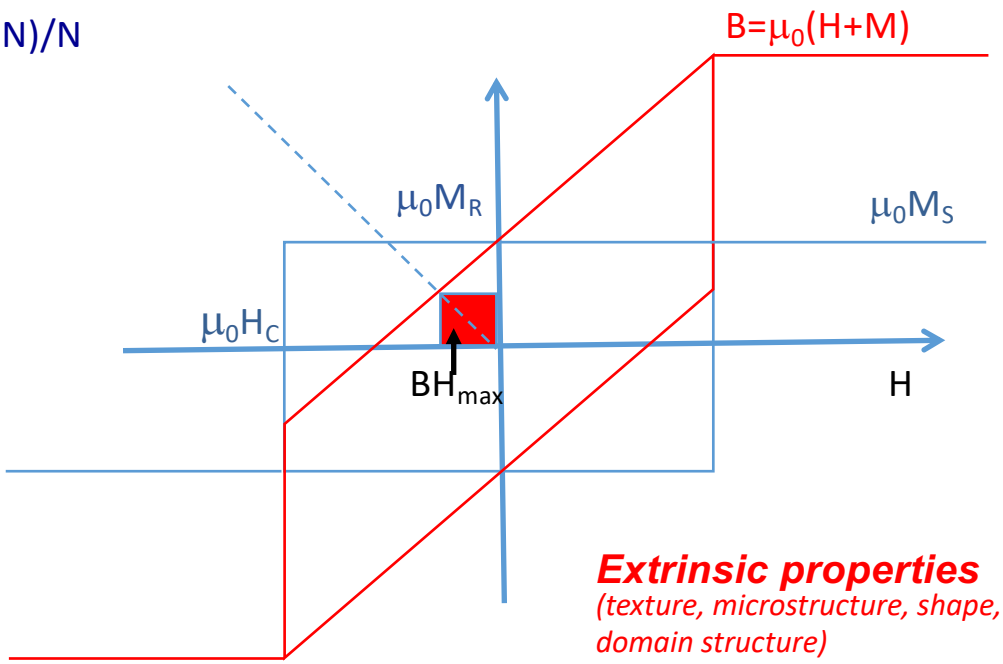
Electric vehicle growth projections
In 2021, sales of electric vehicles nearly doubled 2020 sales to 6.6 million (a sales share of nearly 9%) bringing the number of electronic cars on the road to 16.5 million (International Energy Agency)

- By 2025, electric vehicle sales could reach 20% of new car sales
- By 2030, electric vehicle sales could reach 40% of new car sales
- By 2040, electric vehicle sales could account for nearly all new car sales



Permanent magnets: requirements and properties

Working point:
slope: -1(1-N)/N



Intrinsic properties

High Saturation Magnetization, M_S
High Magnetic Anisotropy, Easy-axis
High Curie Temperature

Extrinsic properties
(texture, microstructure, shape, domain structure)

High Remanence
High Coercive field
High Maximum Energy Product, BH_{max}

Squared Loop

Brown's paradox

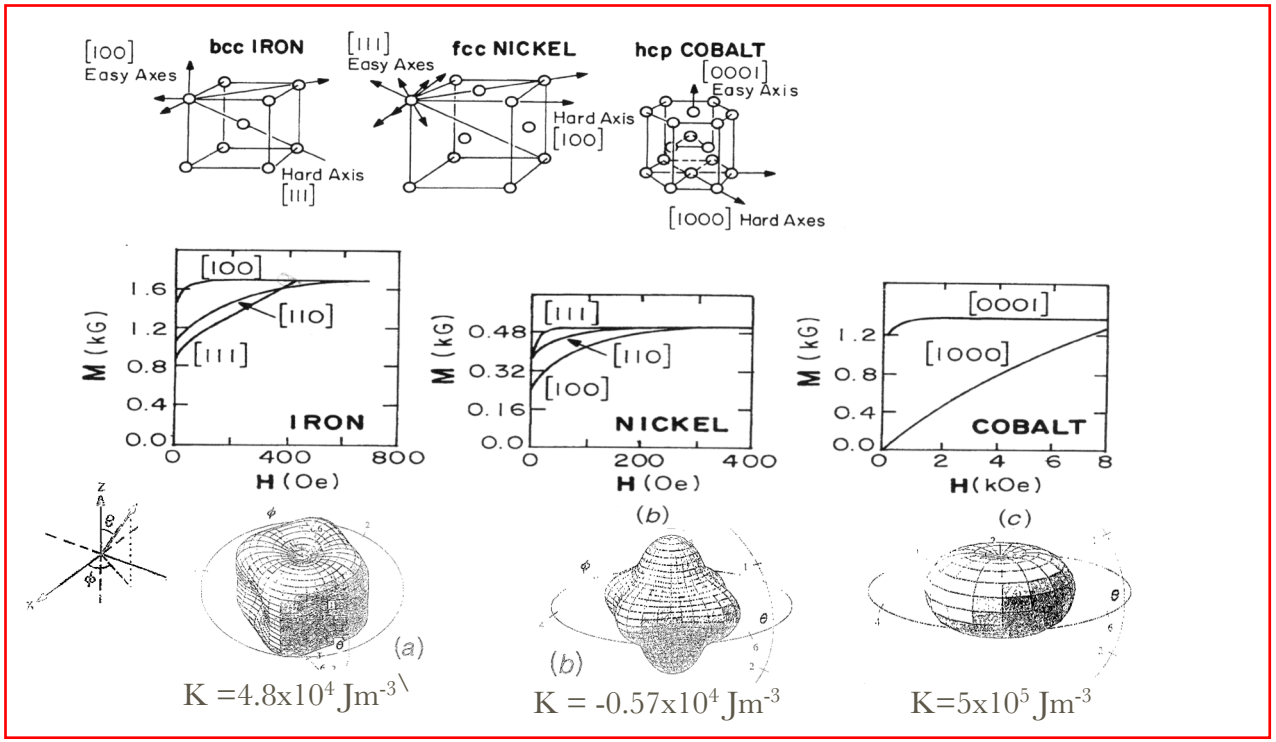
Coercive field reaches 20-30% of the theoretical value (i.e. the anisotropy field)

Microstructure plays a major role:

- Texture
- Polycrystalline character
- Local reduction of exchange and anisotropy
- Defects and secondary phases at grain boundaries

Magnetocrystalline anisotropy

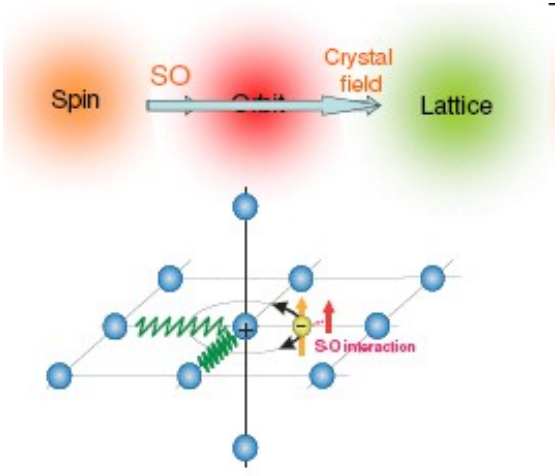
from textbooks

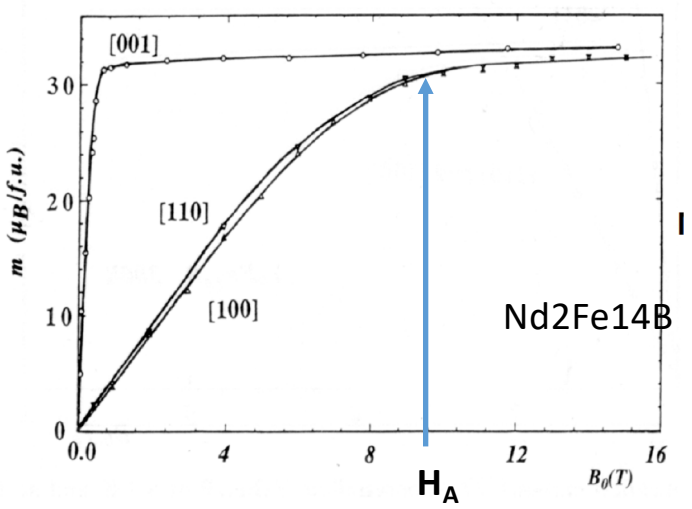


Energy density necessary to saturation depends on the orientation of the magnetic field with respect to the crystallographic axis

Magnetocrystalline anisotropy

Requirements for PM: High magnetocrystalline anisotropy , **easy-axis**





- Anisotropic crystal field

- Low symmetry crystal structure
- Orbital moment different from zero
- Spin-orbit interaction

- Magnetic anisotropy determines the easy magnetization direction
- It strogly influences the magnetization process
- It sets the upper limit of the coercive field

Magnetocrystalline anisotropy

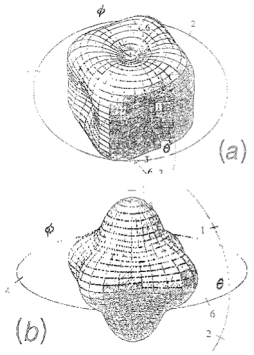
Energy density needed to saturate the sample along different crystallographic directions

Phenomenological description

Cubic Symmetry

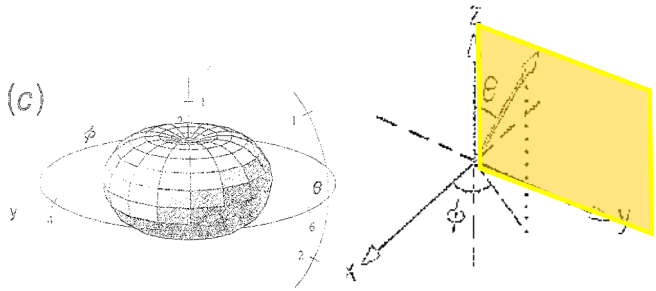
$$E_{MCA} = K_0 + K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + K_2(\alpha_1^2\alpha_2^2\alpha_3^2) + \ldots$$

$$E_{MCA} = K_1 + K_2 \sin^2\theta(\cos^4\theta \sin^2\phi \cos^2\phi + K_1 \sin^2\theta \cos^2\theta)$$



Hexagonal symmetry

$$E_{MCA} = K_1 \sin^2\theta + K_2 \sin^4\theta + K_3 \sin^6\theta + K_3' \sin^6\theta \cos 6\phi$$



Uniaxial cylindrical symmetry: bidimensional problem

Minimization of anisotropy energy density: determination of easy and hard magnetization directions

Versus temperature: possible Spin Reorientation Transition

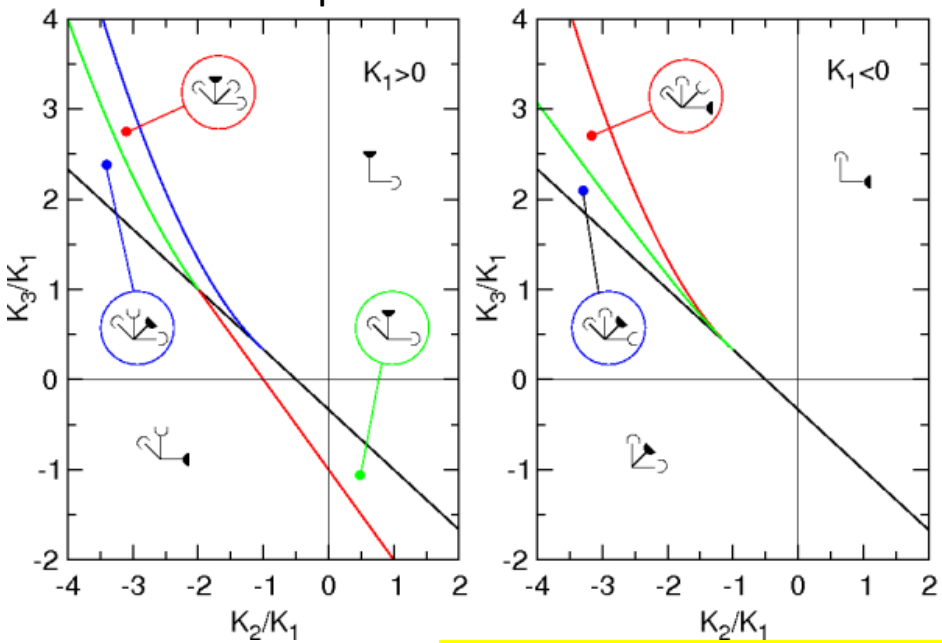
Magnetic anisotropy - easy magnetization direction & SRT

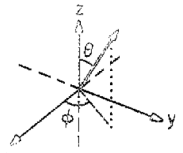
Uniaxial system

$$E_{MCA} = K_1 \sin^2\theta + K_2 \sin^4\theta + K_3 \sin^6\theta$$

➡ Easy magnetization directions

➡ Spin reorientation transitions





$\theta = 0$ $\theta = 90$ $\sin\theta_c = [-K_2 \pm (K_2^2 - 3K1K_3)^{1/2}]/3K_3^{1/2}$

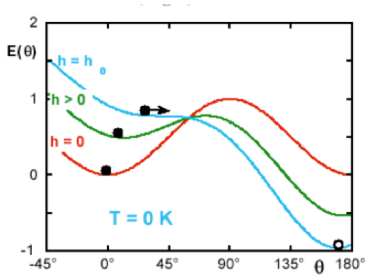
G. Asti, F. Bolzoni, JMMM 20 (1980) 29

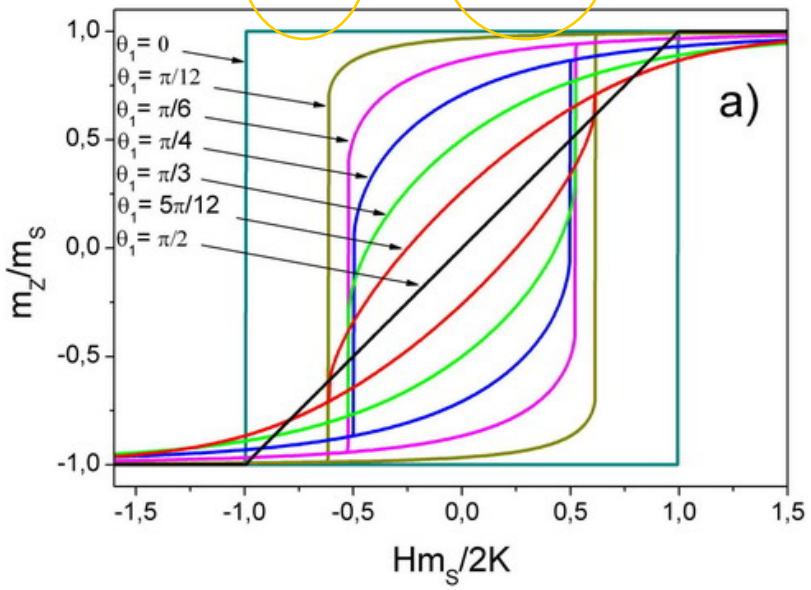
Magnetization process (S-W)

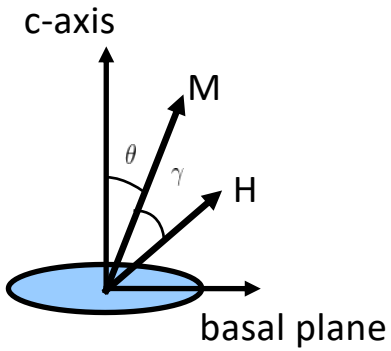
Single domain non interacting magnetic nanoparticles. - magnetization rotation

$$E_{TOT} = E_{MCA} + E_Z$$

$$E_{MCA} = K_1 \sin^2\theta + K_2 \sin^4\theta + K_3 \sin^6\theta \qquad E_Z = -HM_S \cos\gamma$$





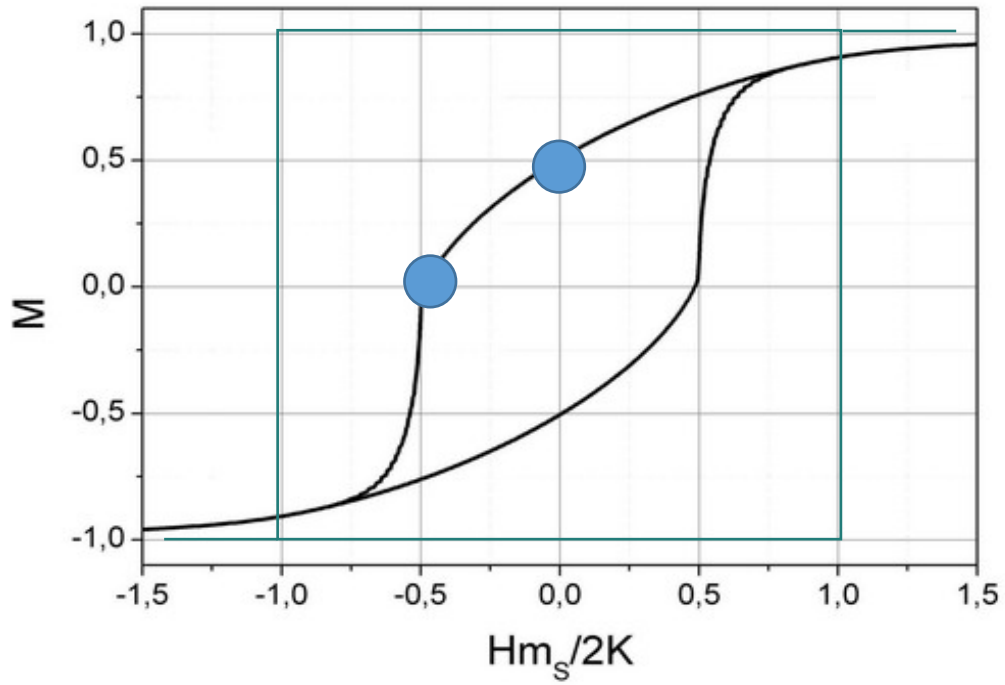


$\theta_1 = \gamma + \theta$

- Magnetic anisotropy sets the upper limit of the coercive field

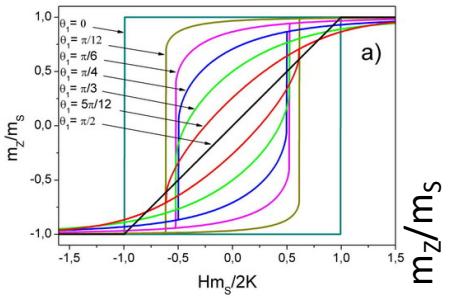
Magnetization process (S-W)

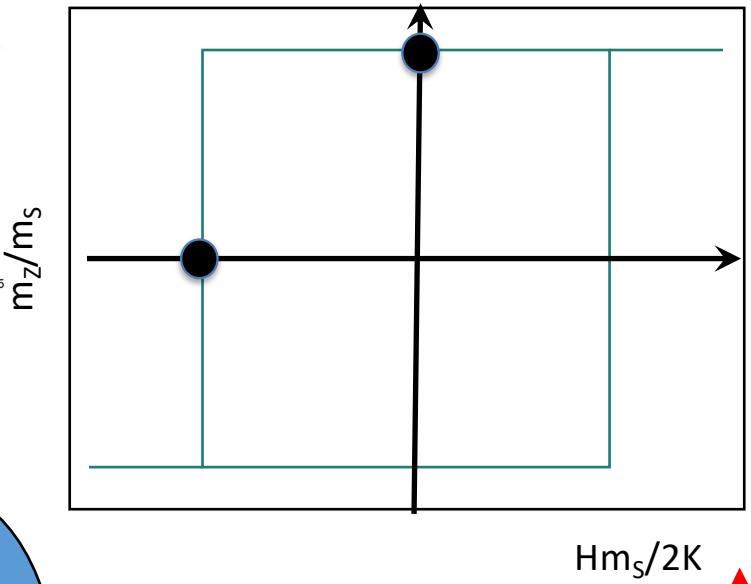
Randomly-oriented single domains non interacting particles (S-W model)

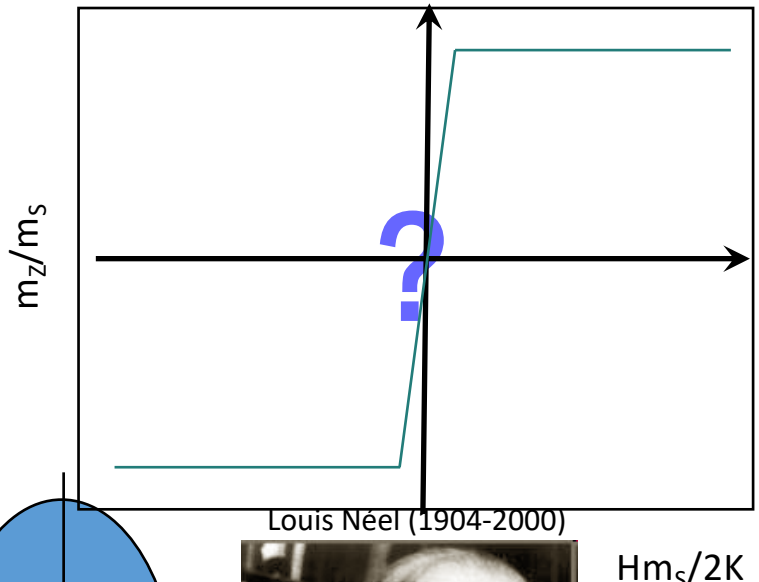


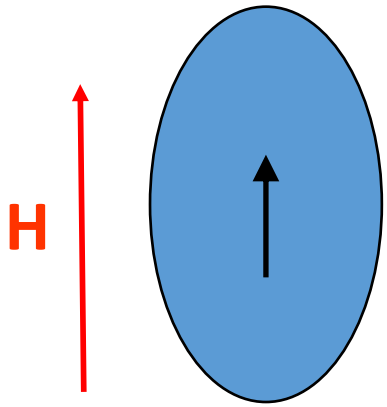
Orientation !

Magnetization process along the easy direction

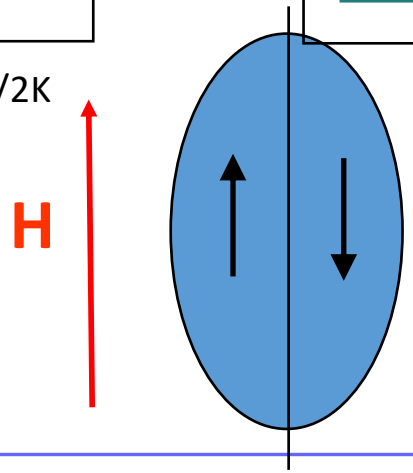




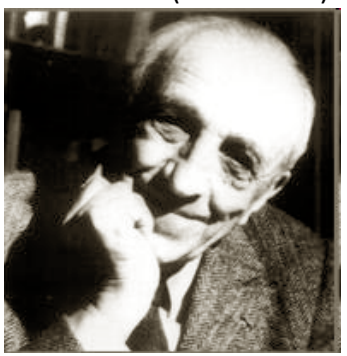




Single domain



Louis Néel (1904-2000)

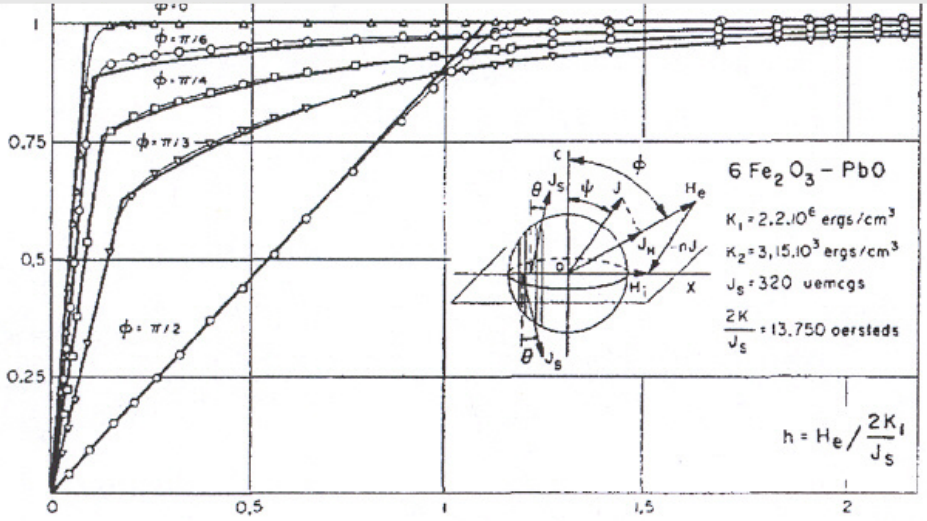


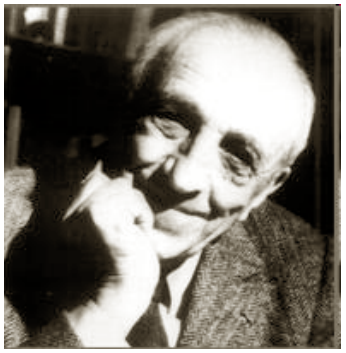
Magnetization process

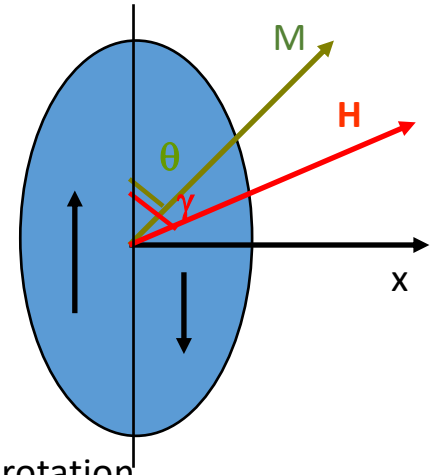
JOURNAL OF APPLIED PHYSICS SUPPLEMENT TO VOL. 31, NO. 5 MAY, 1960

On the Laws of Magnetization of Ferromagnetic Single Crystals and Polycrystals. Application to Uniaxial Compounds

L. NÉEL, R. PAUTHENET, G. RIMET, AND V. S. GIRON*
University of Grenoble, France







Projection of the field

Hcosγ

Hsinγ

Along EASY-direction: domain wall movement

Hard direction: magnetization rotation

internal field=0 $H\cos\gamma - NM_z = 0$; $M_x^2 + M_z^2 = M_s^2$

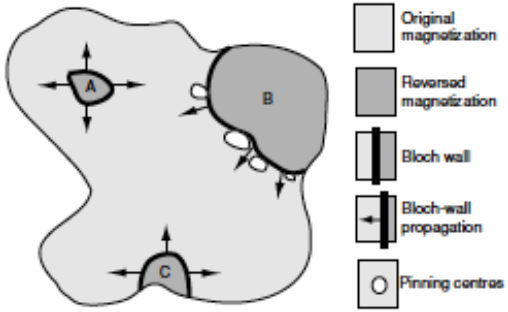
$$E = K_1 \sin^2\theta - H\sin\gamma M_s \sin\theta + \frac{1}{2} N M_s \sin^2\theta$$

H_C in real materials: well below the intrinsic limit

Coercivity (H_C) in bulk **magnets is a fraction (20-30%**)
of the intrinsic upper limit (**anisotropy field, H_A**)

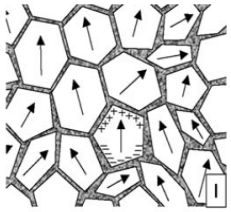
Microstructure plays a major role:

- Polycrystalline character (misallignement) – TEXTURE
- Magnetic domains
- Grain boundaries
- Defects and secondary phases
- Local variation of exchange and anisotropy
- Stray fields



Nucleation and pinning control the starting and propagation of magnetization reversal

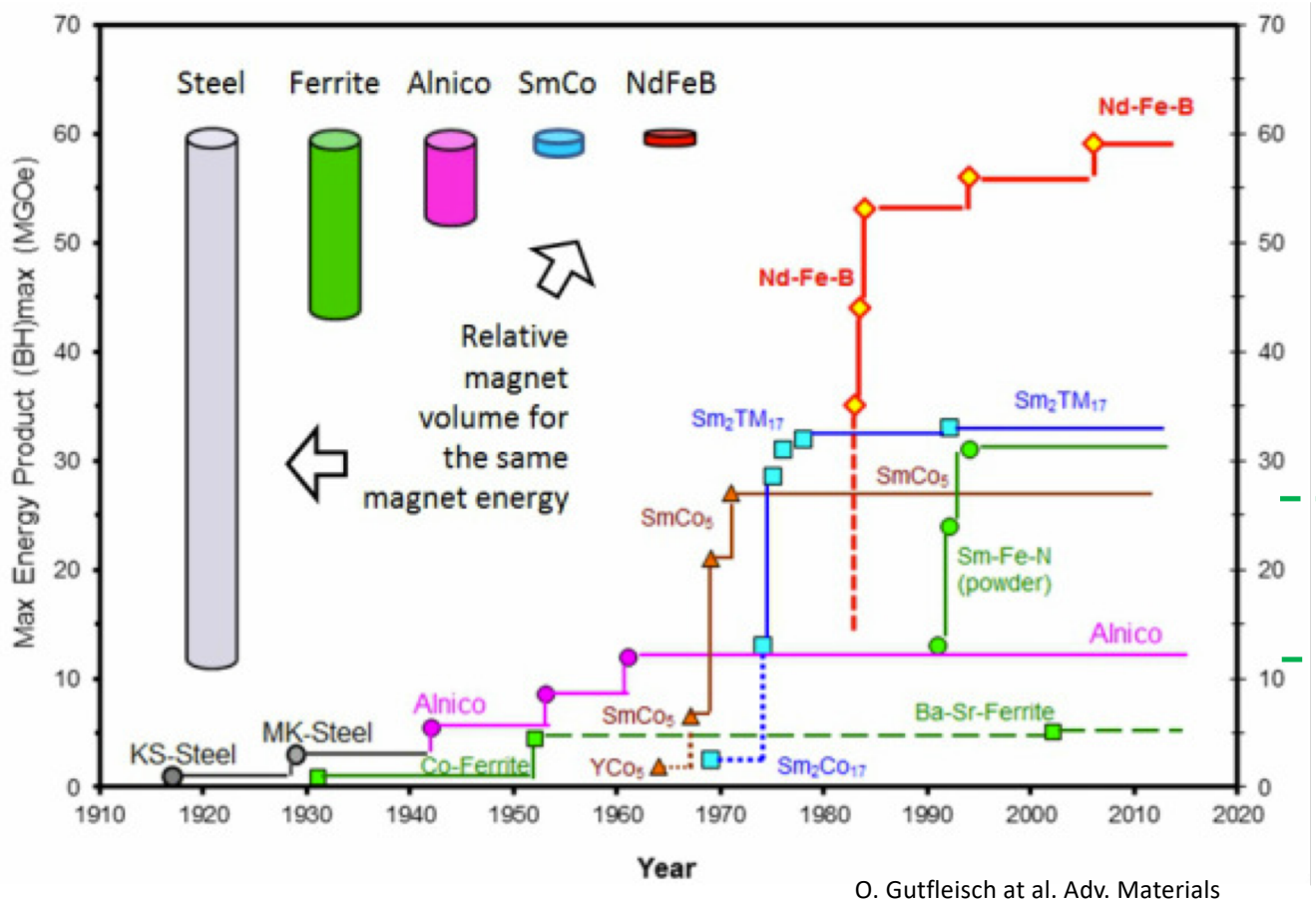
Kronmüller equation: $H_c(T)=\alpha H_A(T)-N_{eff}Ms(T)$

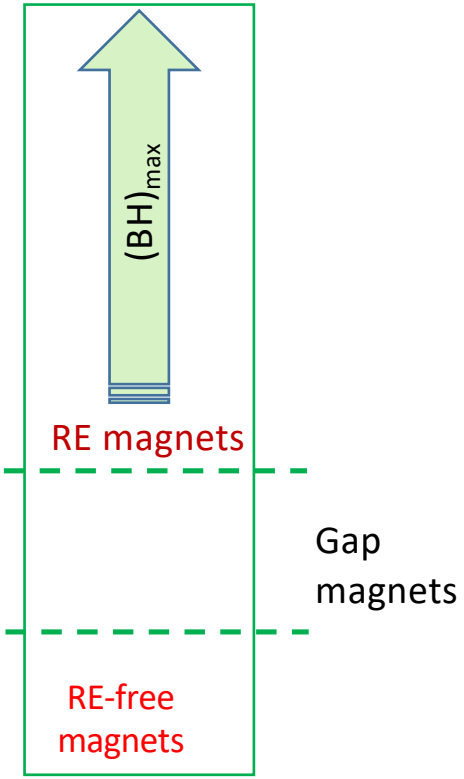


Decupled grains

Domain elimination or pinning by
-grain size reduction
-pinning centers

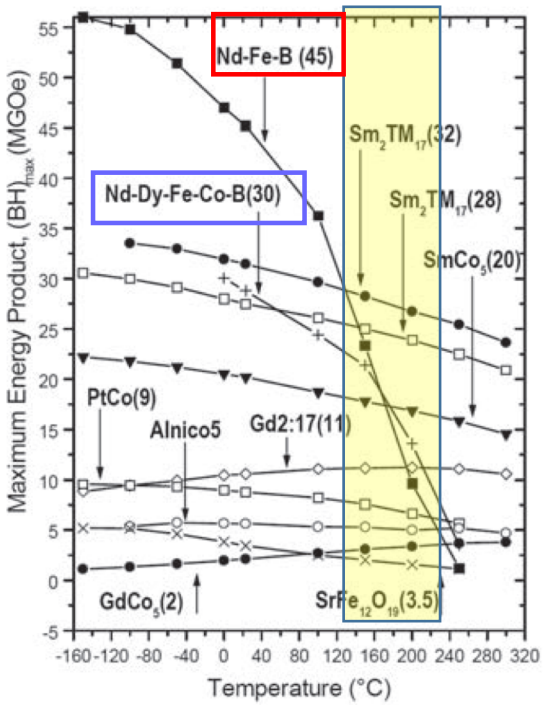
Materials for permanent magnets

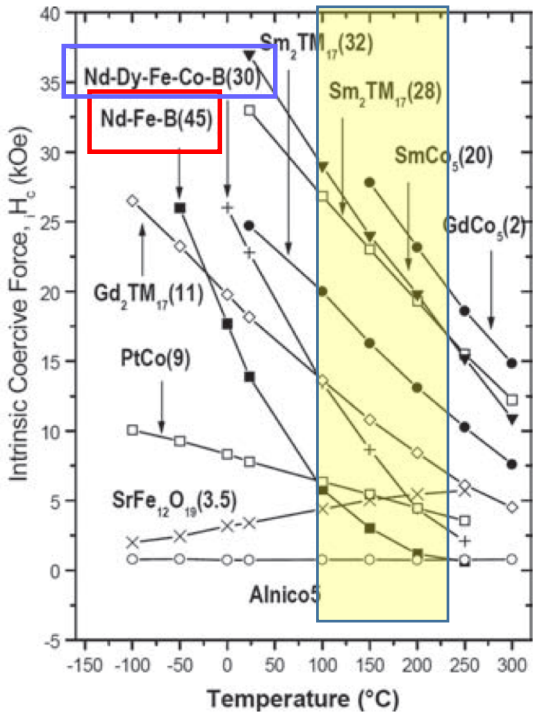




O. Gutfleisch at al. Adv. Materials

High T performances





T dependence of maximun energy product and coercivity of NdFeB prevents its full exploitation at high operating T

Heavy rare earth (Tb , Dy) addition:

1. In the alloy

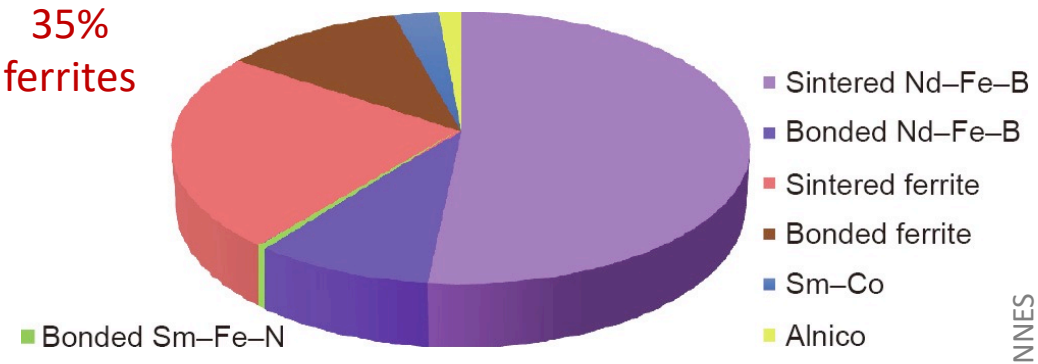
2. Grain boundary diffusion (binary hydrides/fluorides (e.g., DyH3, TbH3,binary low-melting alloys (e.g., Tb70Cu30, Dy70Cu30), quaternary and quinary HRE-containing alloys (e.g. Tb–Pr–Cu–Al–Ga)

A. Durgun et al. Adv. Eng. Mater. (2025) 2501145

Two main materials

Market share

35% ferrites

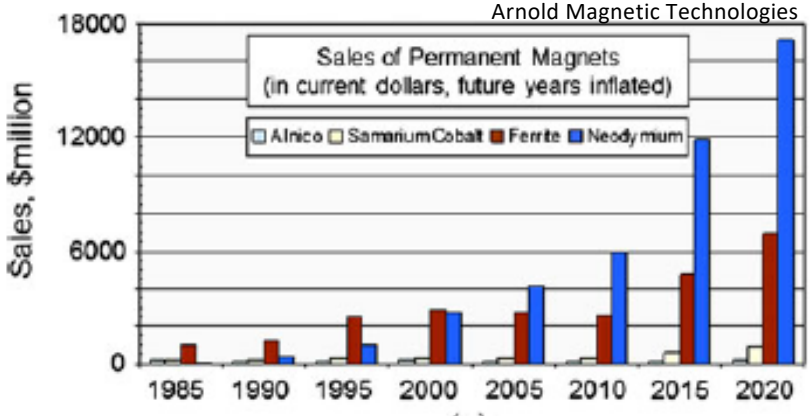


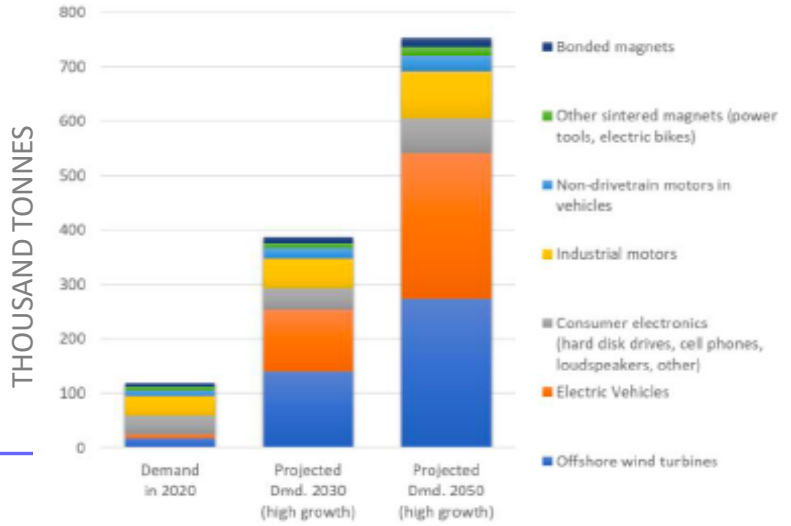
> 60% RE-based

M. Coey Engineering 6 (2020) 119–131

Market evolution

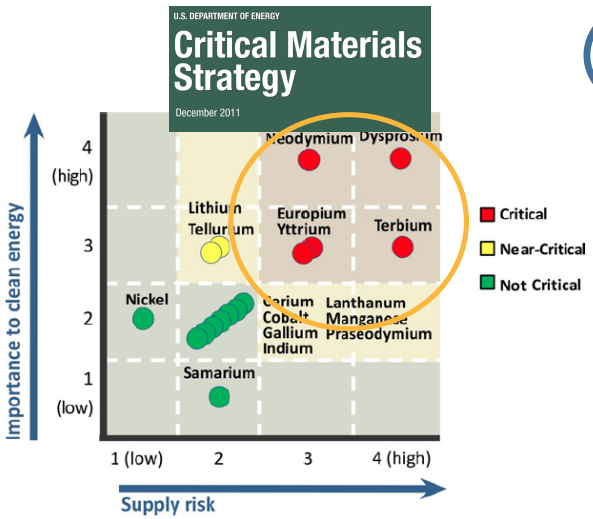
Arnold Magnetic Technologies

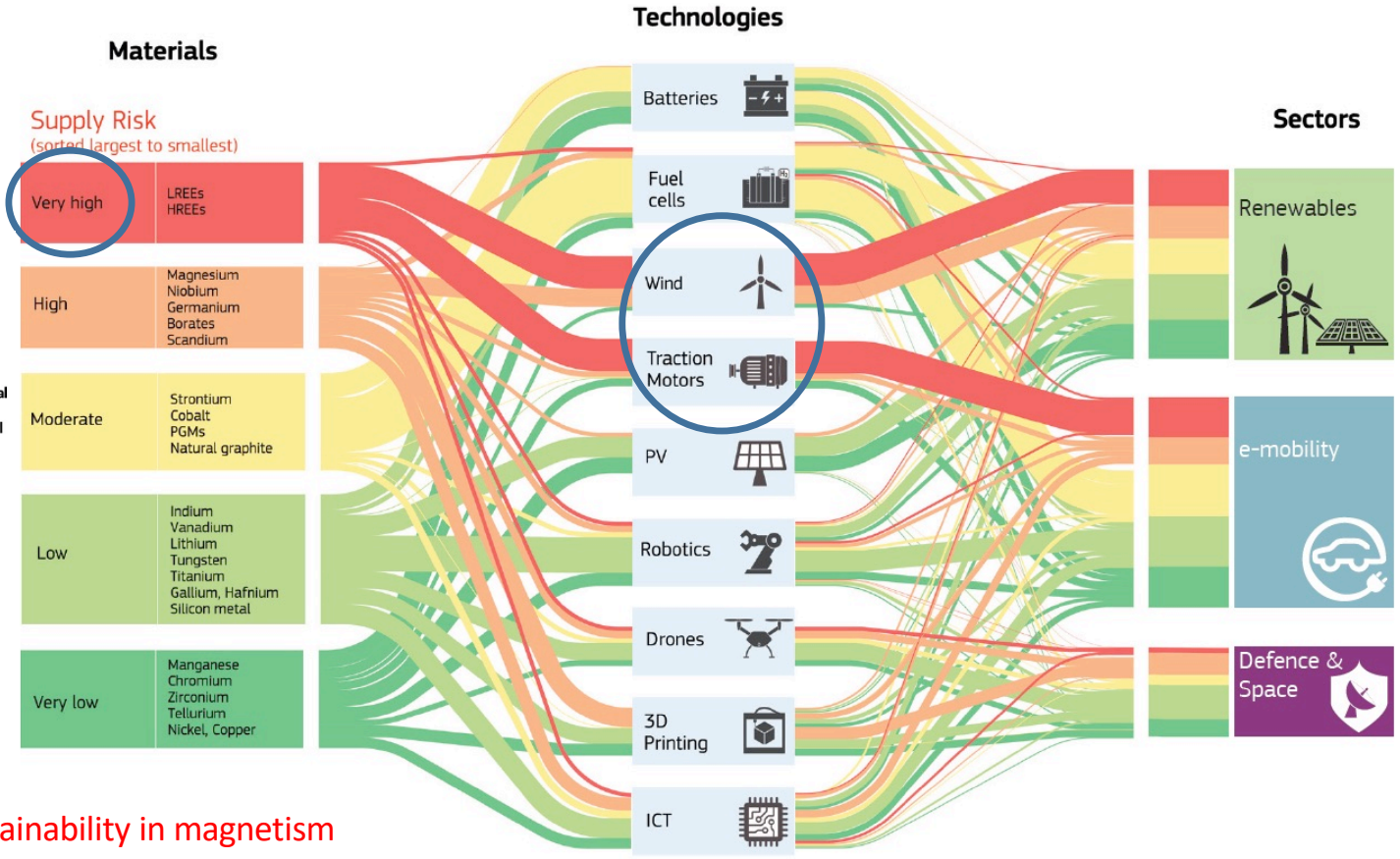




Esitmated NdFeB demand growth

CRMs and magnets for energy technologies





See also Varvaro's lecture: towards sustainability in magnetism

"European Commission, Critical materials for strategic technologies and sectors in the EU - a foresight study, 2020"

EU Recommendations

- Diversification of materials supply
- Improving mining, including non conventional sources
- Improving refining and manufacturing opportunities in the EU
- **Enhancing the circularity of the value chain: set higher levels of reuse, remanufacturing and recycling**
- **Substitution and alternative solutions**

  - Increase REE materials efficiency: reducing the amount of REE and mainly of HREE necessary to produce NdFeB magnets

  -Alternative materials Some magnets have been developed, such as plastic **ferrites**, other (ceramic) ferrites, and alloys (AlNiCo or Ce-Co doped alloys), with performances inferior to REE-based permanent magnets. Further R&D is needed.

  -Component substitution: new design, new technologies

European Commission, Critical materials for strategic technologies and sectors in the EU - a foresight study, 2023

Research strategies on permanent magnets

Multidisciplinary research effort from basic science to applications

- Increase of REE efficiency and reduction of HREE. Microstructure control, grain boundary engineering of RE-based compounds
- Development of new RE-free compositions
- Improve ferrite performances by hybrid micro-nanocomposites
- Collaborate to the improvement of motor design to reduce and possibly eliminate the content of RE-based magnets
- Recycling of RE-based magnets obtained by end of life devices

GREENE
SINGLE-GRAIN RE-ENGINEERED ND-FE-B PERMANENT MAGNETS

MOST
CENTRO NAZIONALE PER LA MOBILITÀ SOSTENIBILE

BEETHOVEN
MiCROSTRUCTURE SUBSTITUTION OF RARE-EARTHS FOR ADVANCED NOVEL MAGNETS IN ENERGY AND TRANSPORT APPLICATIONS

HYPERMAG
HYbrid ferrite nanocomposites for novel Rare-earth free PERmanent MAGnets

POR-FESR (2021-2027)
Magmove

FISA
Madleine
MATERIALS AND DESIGN FOR ELECTRICAL VEICHLES

eit RawMaterials
INSPIRES

Research strategies on permanent magnets

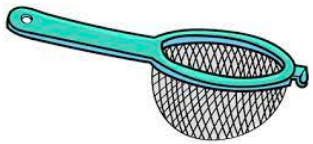
Multidisciplinary research effort from basic science to applications

- Increase of REE efficiency and reduction of HREE. Microstructure control, grain boundary engineering of RE-based compounds

Grain-boundary engineering



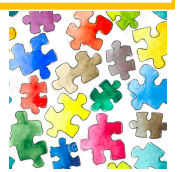
- Development of new RE-free compositions



Intrinsic properties

Curie Temperature
Saturation magnetization
Magnetocrystalline anisotropy

Grain-boundary engineering

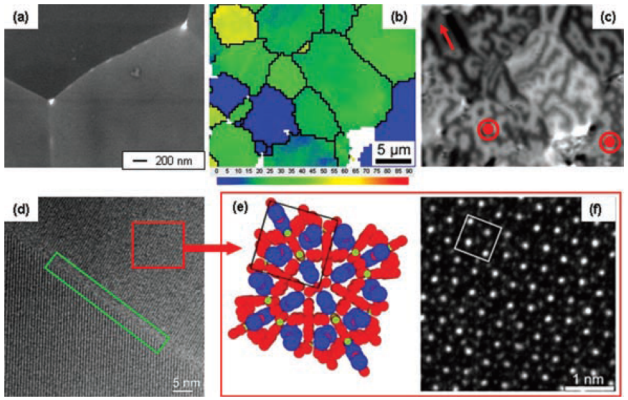


- Improve ferrite performances by hybrid micro-nanocomposites

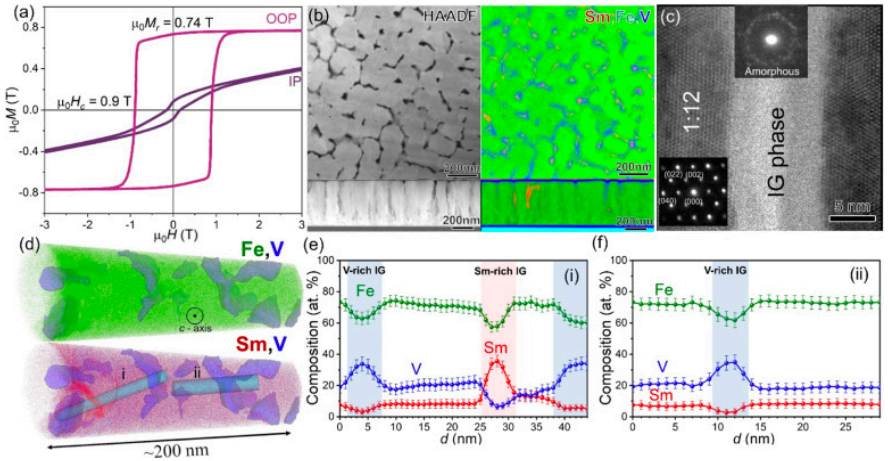
- Collaborate to the improvement of motor design to reduce and possibly eliminate the content of RE-based magnets

- Recycling of RE-based magnets obtained by end of life devices

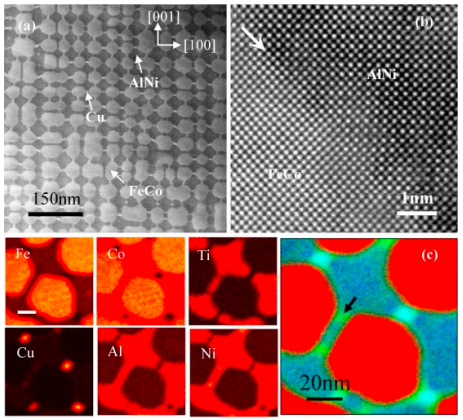
Grain boundary engineering



NdFeB- O. Gufleisch et al, Adv. Materials 23 (2011) 821



SmFeV –Acta Materialia 258 (2023) 119197



Alnico -L.. Zhu et al., J. Magn.Magn.,Mater 471 (2019) 142

Grain boundary engineering

- Advanced multiscale characterization
- Calculations: from the atomic to the micro/macro scale
- Thin films as model systems

Microstructure control: elimination of heavy RE

Scripta Materialia 154 (2018) 277–283

Contents lists available at ScienceDirect

Scripta Materialia

journal homepage: www.elsevier.com/locate/scriptamat

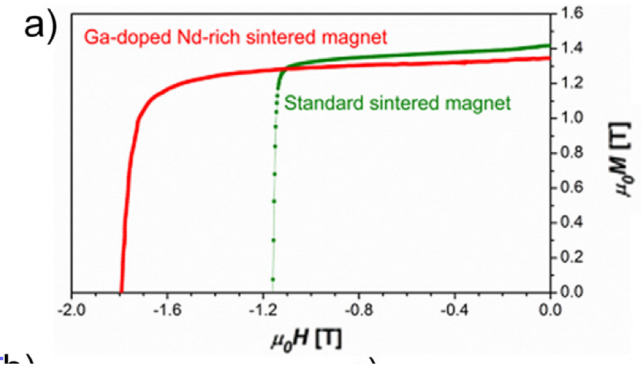
Viewpoint set

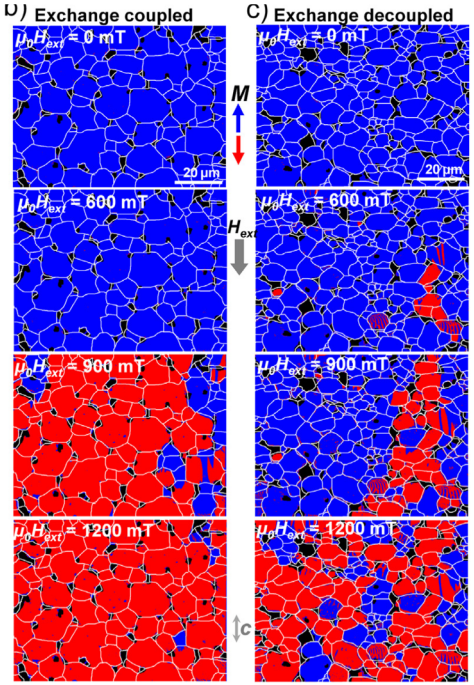
Reprint of Prospect for HRE-free high coercivity Nd-Fe-B permanent magnets☆

K. Hono *,1, H. Sepehri-Amin

Elements Strategy Initiative Center for Magnetic Materials, National Institute for Materials Science, Tsukuba 305-0047, Japan

New findings on the microstructural features and mechanism of coercivity





The coercivity of exchange coupled sintered magnets is governed by the pinning mechanism at ferromagnetic grain boundaries, while the exchange decoupled sintered magnets are governed by the nucleation mechanism.

The poor squareness of exchange decoupled magnets can be overcome by reducing the size and orientation distribution of $Nd_2Fe_{14}B$ grains.

Further improvement of microstructure will lead to HRE-free permanent magnets with $\mu_0 Hc$ ~ 2.5 T, $\mu_0 Mr$ >1.35 T and $\mu_0 Hc$ @180 °C ~ 0.8 T, which will fulfil the requirements for the traction motors of (H)EV.

Single Grain Re-engineered Nd-Fe-B permanent magnets

COORDINATOR: JOŽEF STEFAN INSTITUTE
+ 14 EU PARTNERS
COORD: PROF. KRISTINA ŽUŽEK

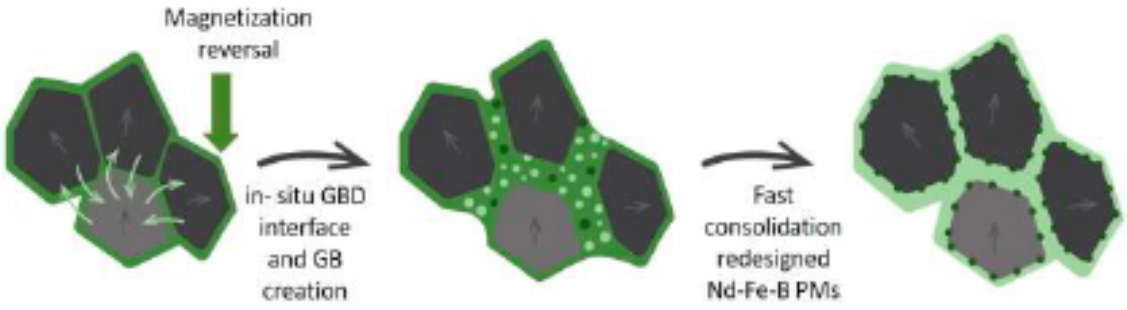


Figure 3 GREENEs principle of redesigned Nd-Fe-B PMs

Beyond the state of the art

- The conventional Nd-rich phase, which is a consequence of the phase diagram and necessary for regular sintering, will be replaced by a new structure that is tuned to give us interface-controlled magnetization reversal.
- By using 300-nm grains extracted from HDDR material we will have 100× smaller grains as the starting point for the grain-boundary re-engineering and subsequently higher coercivities. Recycled feedstock will also be used.
- Conventionally sintered magnets contain about 85% $Nd_2Fe_{14}B$ phase. The GREENE magnets with their new form of grain boundaries and the absence of impurities will reach 95%,

INTERFACES

GRAIN SIZE

RECYCLED FEEDSTOCK

MORE NdFeB PHASE

Research strategies on permanent magnets

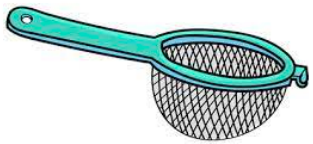
Multidisciplinary research effort from basic science to applications

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Grain-boundary engineering



- Development of new RE-free compositions



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New materials: gap magnets

RE- free/RE-lean/RE-cheap materials of new composition for intermediate performances “gap magnets”

Ferrites

$SrFe_{12}O_{19}$
$BaFe_{12}O_{19}$

Low cost
Abundant materials

Low performance

$(BH)_{MAX} \approx 50\ kJm^{-3}$

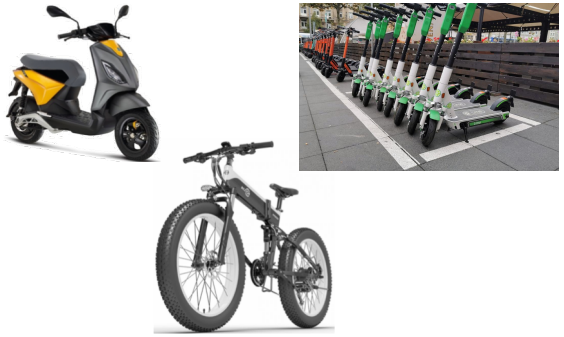
Gap Magnets

?

Low cost
Abundant materials

Intermediate Performance

$(BH)_{MAX} \approx 200\ kJm^{-3}$



RE Magnets

$Nd_2Fe_{14}B$
SmCo

More expensive
Environmental risk
Supply risk

High performance

$(BH)_{MAX} \approx 500\ kJm^{-3}$

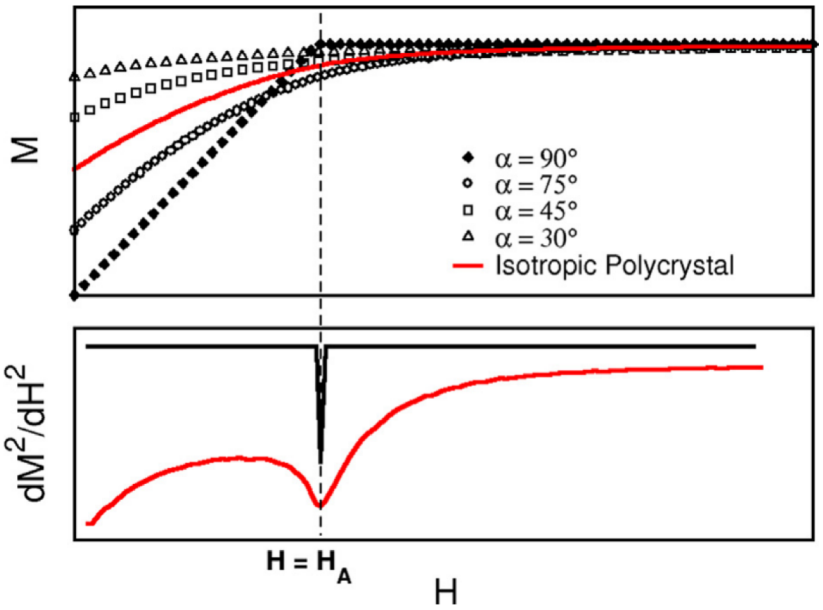


MOST
CENTRO NAZIONALE PER LA MOBILITÀ SOSTENIBILE

Permanent magnets: new materials

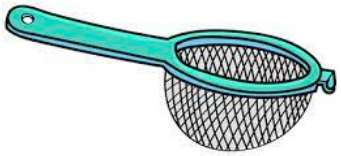
Study of new RE-free compositions
based on FeSiB ; $(FeCo)_2P$

@IMEM:Singular point detection technique (SPD)
for the study of magnetic anisotropy in polycrystalline materials



Intrinsic properties

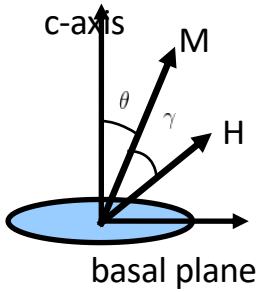
Curie Temperature
Saturation magnetization
Magnetocrystalline anisotropy





Grain-boundary engineering

The singular point detection technique (SPD)

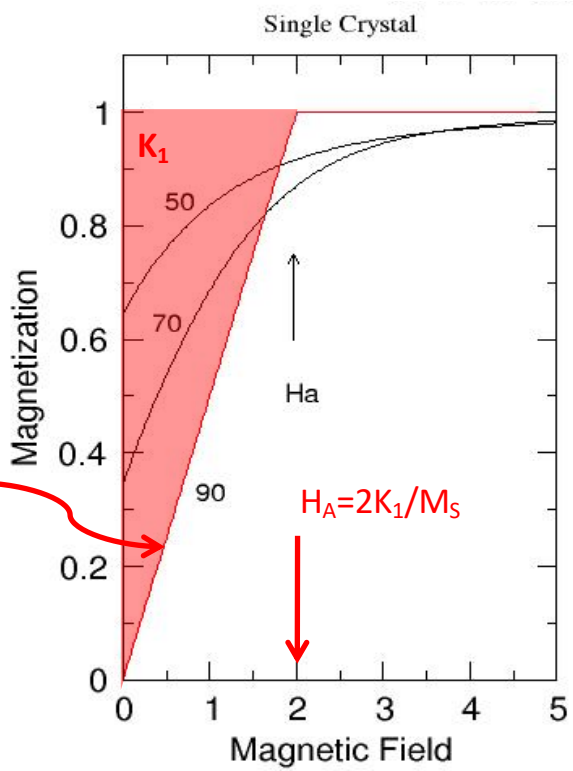


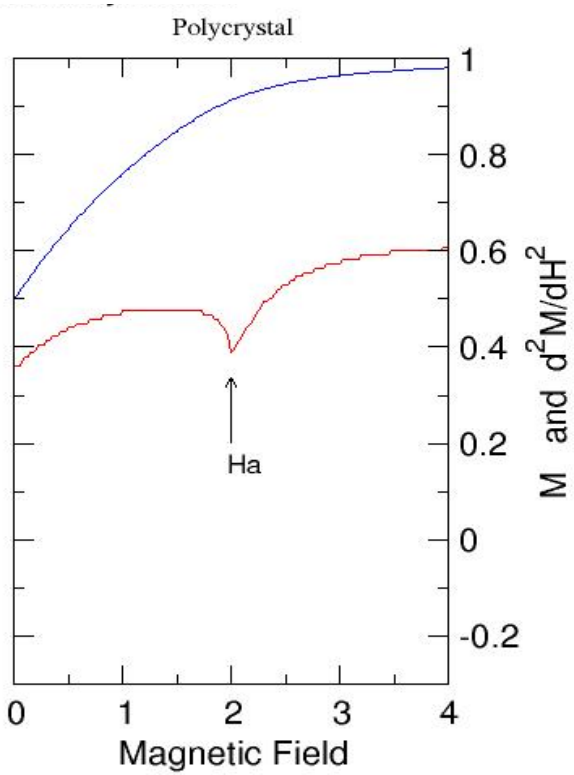
$q_1=g+q$

$K_1>0$, $K_2=K_3=0$

$slope=M_S^2/2K_1$

Study of the successive derivatives of the magnetization curve





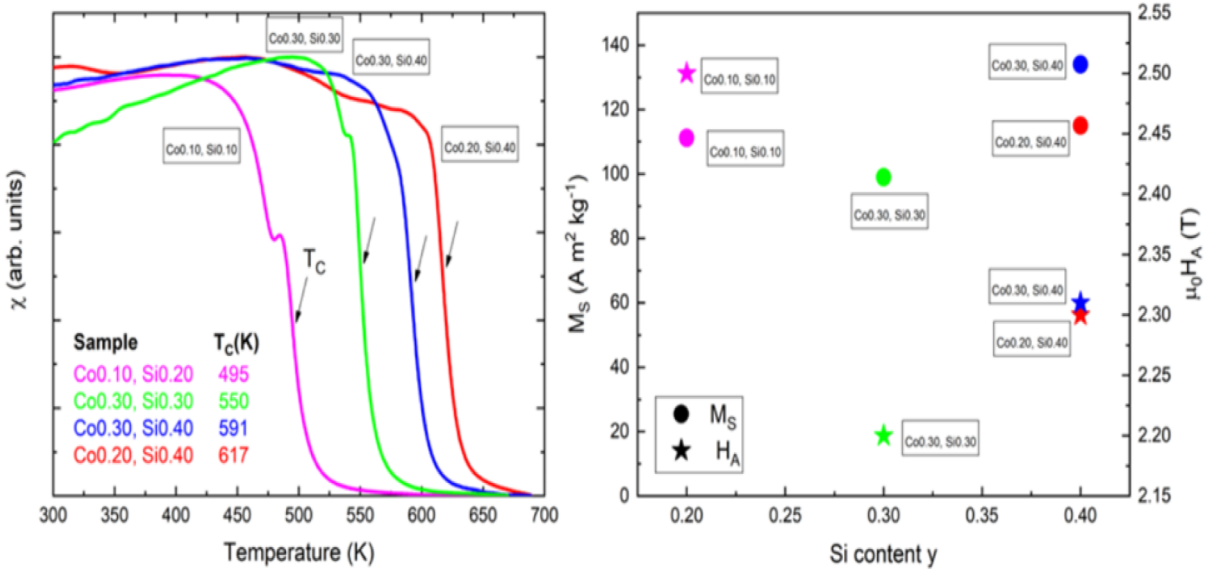
Peak amplitude: dH/dt, n° of grains with hard direction parallel to the applied field

Order of derivation: cylindrical simmetry Hard plane: 2 Hard –axis: 3

See R. Cabassi Measurement 160 (2020) 107830 and references therein

RE-free hard magnetic materials

$Fe_{2-x}Co_xP_{1-y}Si_y$



Good intrinsic properties

Next steps:

-up-scaling of the material by powder metallurgy methods

-preparation of bonded and sintered porotype magnets

Italian companies involved

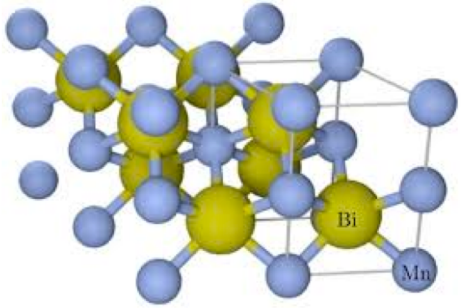
M. Casadei et al., submitted 2025

MOST CENTRO NAZIONALE PER LA MOBILITÀ SOSTENIBILE

MATERIALI MAGNETICI E MULTIFERROICI imem

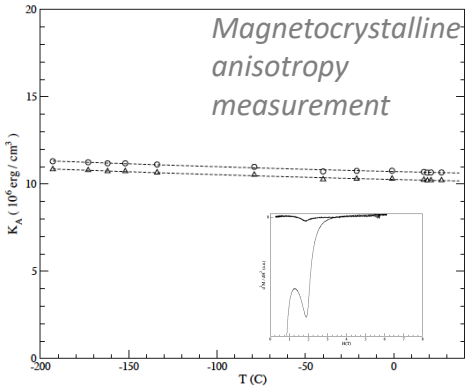
Altenative materials: obtaining structural distorsion

MnBi, NiAs type hexagonal, thin films and bulk
Difficult to obtain as single phase



Maogang Gong and Shenqiang Ren
Chem. Mater., 2015, 27 (22), pp 7795.

Fe-Ni, Tetragonal $L1_0$
slow kinetics of formation
L10 FeNi—the mineral
*"**tetrataenite**"—has been characterized using specimens found in nickel-iron meteorites.*
(NWA 6259 recovered from Northwest Africa is 95 vol. % tetrataenite with a composition of 43 at. % Ni)



Metastable metal-metalloid Heuslers

α"-Fe16N2 : poor thermal and chemical stability, k=0.5 semi-hard
Possible future competition with hexagonal ferrites and AlNiCo

Sample from L. Lewis
NE-University, Boston

Research on permanent magnets

Processing
Bulk
Reduction of grain size
Grain boundary engineering
Fabrication and handling of nano powders
Low temperature compaction
Films
Model systems for H_c analysis
High throughput material screening
μ-system applications

Surface science

New model systems

Improved Magnets
New Magnets

Characterisation
Structural
TEM, STEM+EELS
3D-atom probe tomography
Magnetic
STXM, XMCD
Lorentz TEM
SANS

Modelling
Magnetistion reversal
Ab-initio
Molecular Dynamics
Micro-magnetics
Search for new materials
electronic structure calculations

N. Demspey in "The magnetism roadmap 2014, J. Phys D Appl. Phys 47 (20014) 333001

Ecological transition



Materials criticality



New design

Machine learning

3D printing

Data mining

Recycling

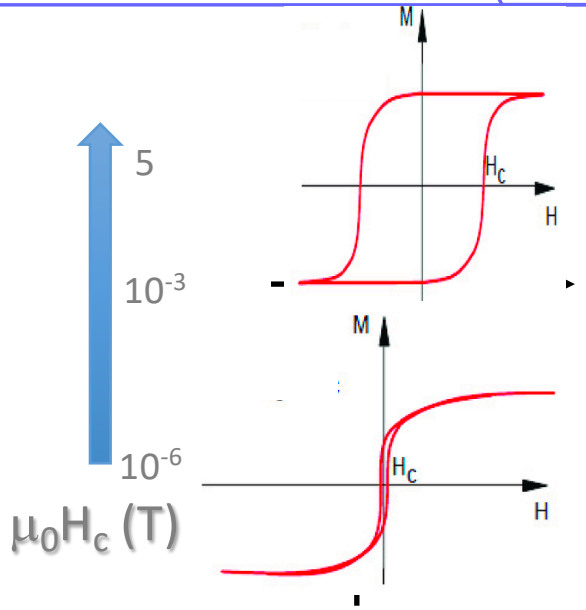
Waste reduction

Functional magnetic materials

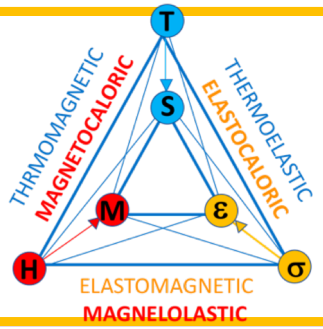
➡ **Hard magnetic materials:**
Permanent magnets
Memories

➡ **Soft magnetic materials:**
Inductors, transformers, sensors

Tiberto's lecture: Soft magnetic materials and their applications



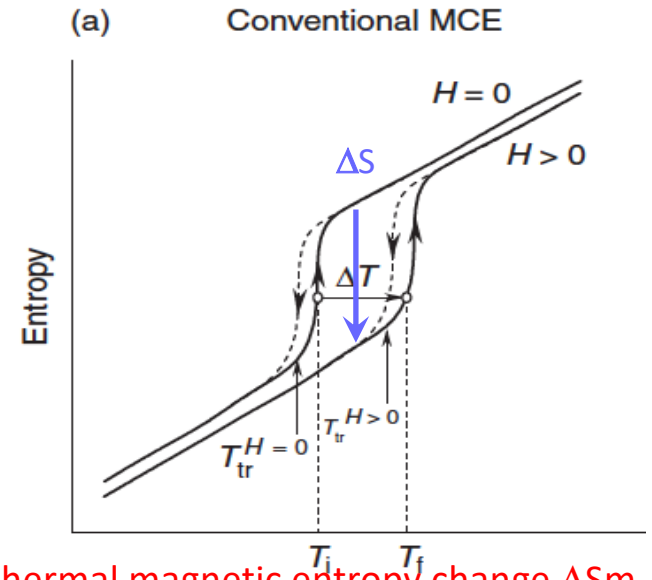
➡ **Multifunctional magnetic materials**
Magnetic field driven functional properties: e.g.
magnetocaloric effect, magnetic shape memory,
magnetostriction ⟺ external-field driven magnetic properties



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imem

Magnetocaloric effect

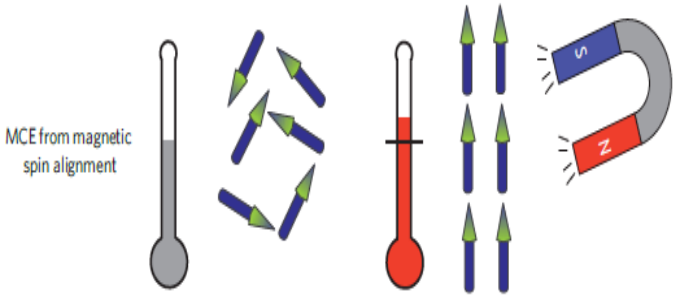
Magneto-thermodynamic effect of magnetic materials induced by the application/removal of a magnetic field



Isothermal magnetic entropy change ΔSm

$$\left(\frac{\partial S}{\partial H}\right)_T = \left(\frac{\partial M}{\partial T}\right)_H \rightarrow \Delta S(T) = \int_{H=0}^{H=H_{max}} \left(\frac{\partial M}{\partial T}\right)_H dH$$

magnetization change



Adiabatic temperature change ΔT_{ad}

$$\Delta T_{ad}(T,\Delta H) = -\int_{H_1}^{H_2} \left(\frac{T}{C(T,H)}\right)_H \left(\frac{\partial M(T,H)}{\partial T}\right)_H dH$$

MCE is maximum across magnetic transitions

History: magnetocaloric effect and magnetic refrigeration

1843 *Joule discovered that heat is generated in Fe sample under repeated magnetization/demagnetizations*

1843 *Thomson studied the T dependence of magnetization and predict a cooling effect when drawn away from a magnet*

1881 *Warburg Hysteresis. Some T experiments, not conclusive*

1917-1918 Weiss and Piccard discover the magnetocaloric effect ("novel magnetocaloric phenomenon") in Ni

1926-1927 P. Debye and W.F. Giauque suggest to use MCE to refrigerate

1933 Giauque and MacDougall reach 0.25K through adiabatic demagnetizaton of paramagnetic salts.

1935 Urbain finds ferromagnetism in Gd

1949 Giauque's Nobel Prize

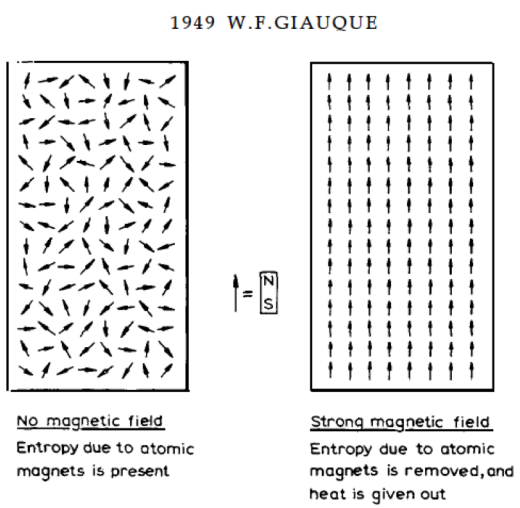
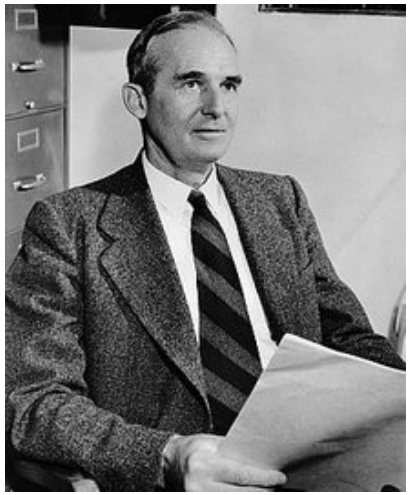


Fig. 12. Atomic magnets in crystal lattice.



1976 Brown: pioneeristic work on magnetocaloric effect at room temperature (Gd) linear device

1978 Steyert rotary device

http://www.nobelprize.org/nobel_prizes/chemistry/laureates/1949/giauque-lecture.pdf

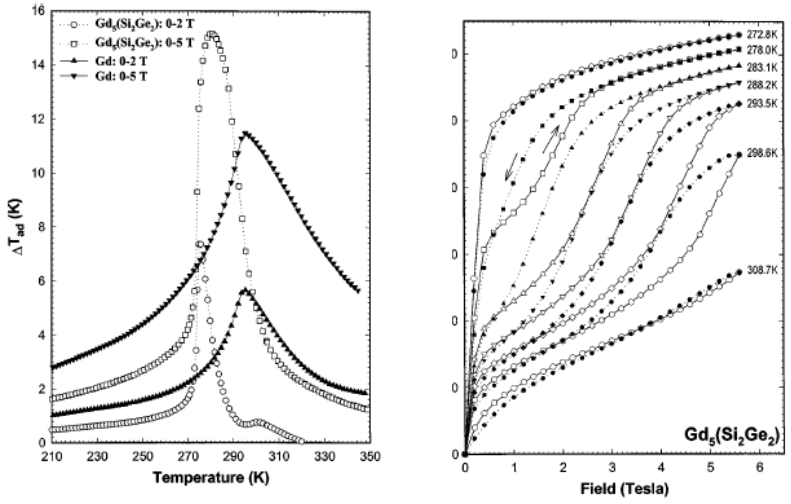
Smith, A. Who discovered the magnetocaloric effect?. *EPJ H* **38**, 507–517 (2013).

History: magnetocaloric effect and magnetic refrigeration

1995-1998 K.A. Gschneidner Jr. @ Ames Lab and C.B. Zimm @ Astronautic Corporation announce the results of their three-year project

Proof-of-priciple unit: it ran for over 5000 hours in 18 months
applied fied = **5T** superconducting magnet
Wcool=600 W
Temperature span =10 K
Material: Gd spheres (5 Kg)

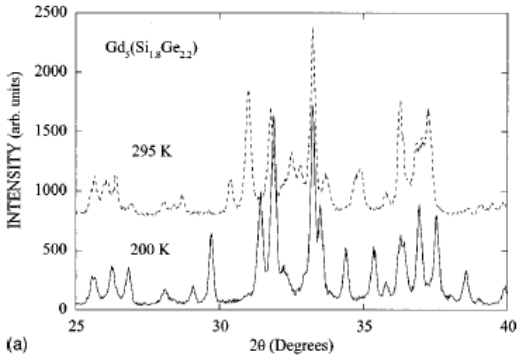
1997 K.A. Gschneidner's group **materials with** "*GIANT MAGNETOCALORIC*" effect: $Gd_5(SiGe)_4$



V. K. Pecharsky et al. Journal of Alloys and Compounds 344 (2002) 362–368

Magnetostructural transition

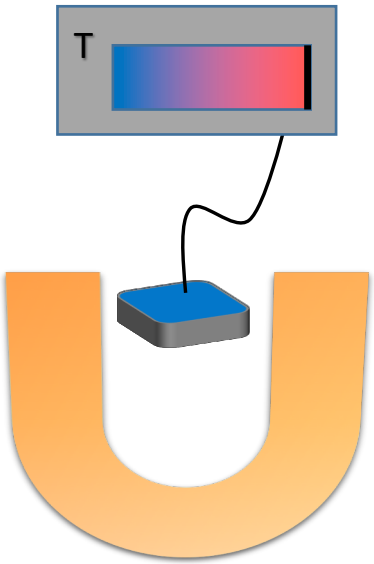
Magnetic field induces a structural phase transition (from para M to Ferro O)

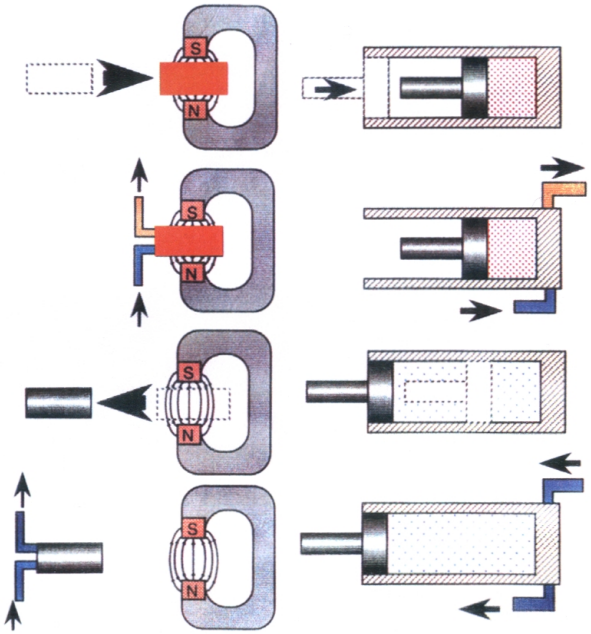


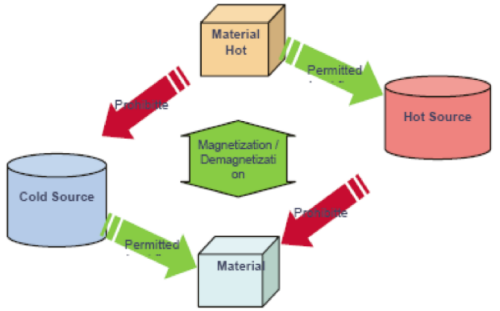
Morellon et al, Phys Rev B 58, (1998) R14 721

Magnetic Refrigeration

- New refrigeration technology based on the magnetocaloric effect







Environmentally friendly technology

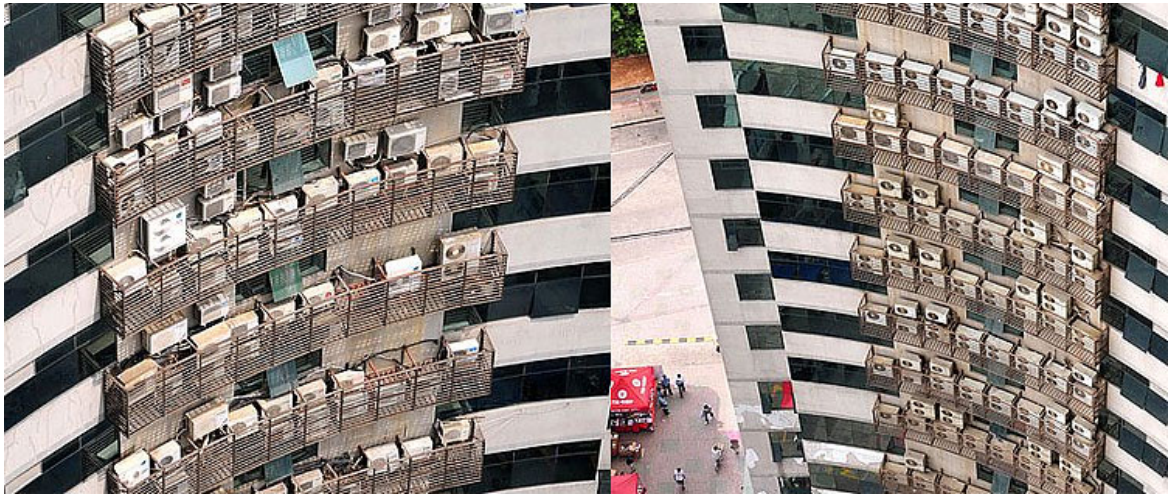
High efficiency: >30% higher than vapor compression

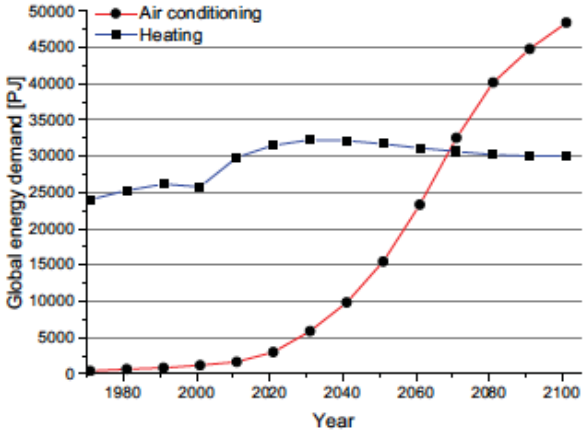
Elimination of harmful gases

Solid state: more compact, scalable

Low noise, no vibrations

Room temperature refrigeration





R. Gauß et al, J. of Industrial Ecology 21 (2016) 1291

About 20% of total worldwide energy consumption involves the use of refrigeration and air conditioning: from <5% (temperate zones) up to 80% (tropical islands); > **8% of total greenhouse emission**

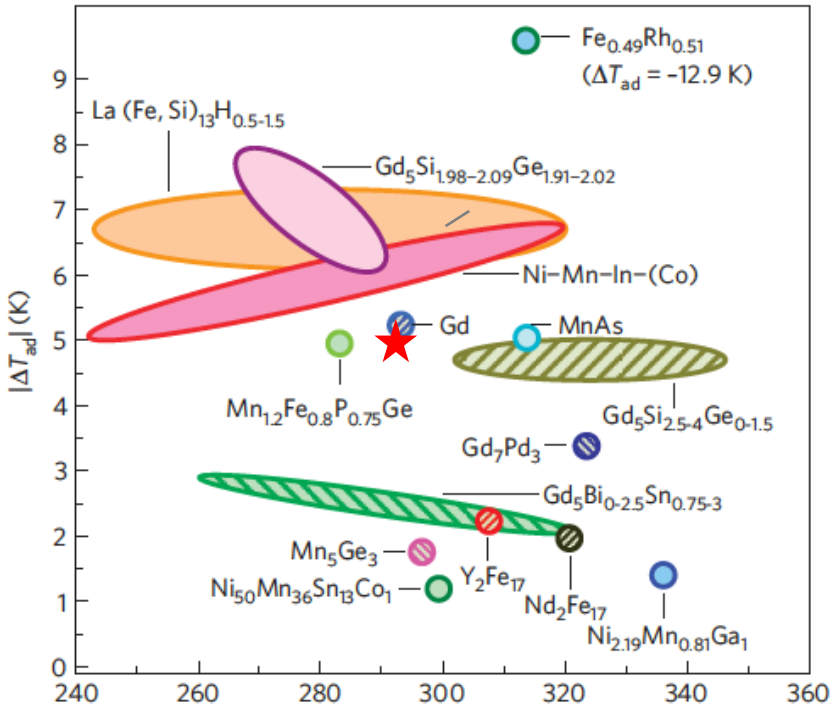
Air conditioning demand is increasing: by 2025, ~1 billion of new citiziens will become "consumers": their first purchase will be an air conditioner (McKinsey Global Initiative)



Montreal (1989) and Kyoto (1997) protocols.EU-F-Gas regulation (2024)

Urgent demand of novel solutions for drastically reducing the carbon footprint of cooling technology

Materials overview



$MnFe_{0.95}P_{0.595}B_{0.075}Si_{0.33}$
Guillou et al. Adv. Materials 2014

★ ΔT_{ad} values in a 2T field.

MnFePSi: highly reversible ΔT_{ad}, low raw material cost.

MnAs, MnPGe: high ΔS_{mag}, As replaced by P and Ge. Low raw material cost, Mechanical properties?

La(FeSi): to increase Tc → LaFeSiH
Low cost of raw materials, hydrogenated phase

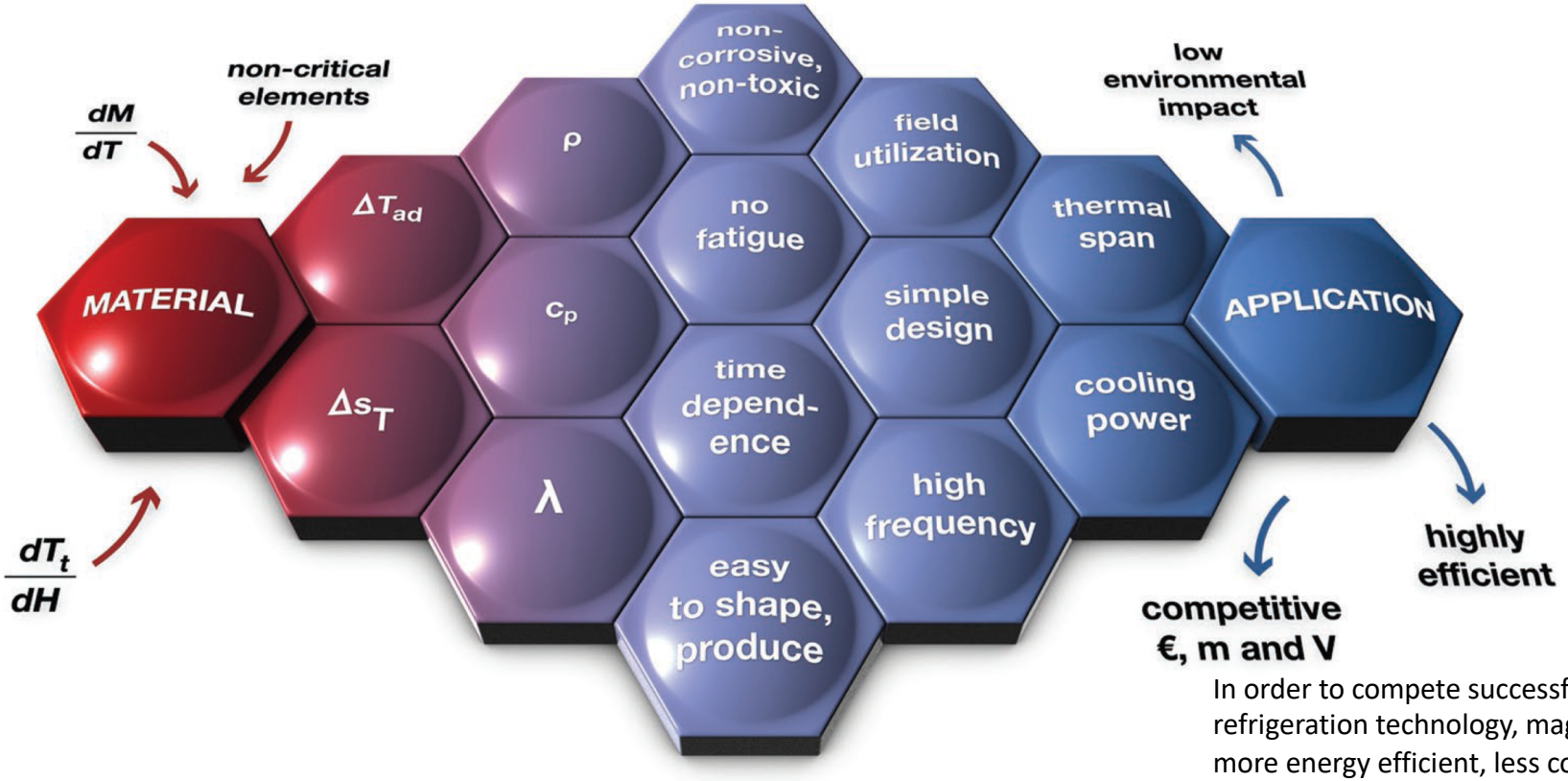
$Gd_5(SiGe)_4$ high ΔS_{mag}, ΔT_{ad} high raw material cost, difficult preparation route

Ni-Mn-X Heusler compounds: high Δs_{mag}, high ΔT_{ad}

Wide possibility of tailoring order and kind of transition, and type of magnetocaloric effect: DIRECT-INVERSE
Hysteresis losses and mechanical stability issues

From Liu et al. Nature Materials vol.11, p620 (2012)

Magnetic refrigeration: requirements and challenges



In order to compete successfully with conventional refrigeration technology, magnetic refrigeration must be more energy efficient, less costly, environmentally friendly, comparable in weight and volume, and less noisy.

Magnetic refrigeration is a concerted scientific and technological problem

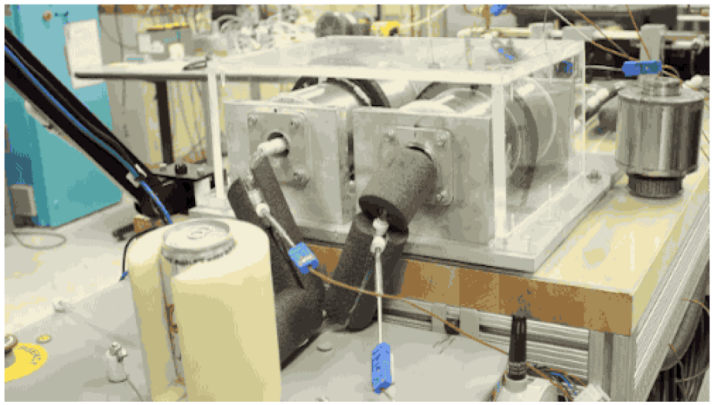
T. Gottschall et al. Adv. Energy Mater. 2019, 9, 1901322

Prototypes -refrigerators



Haier,
Astronautics &
BASF.
Low cooling
power
Refrigerator(ΔT
max = 20K).
Released in
2015





General electrics &
Oak Ridge National Labs
Demonstrator,
60W, 4-times more
expensive than
conventonal
refrigerator
20% energy saving



Magnotherm
ECLIPSE 2D
40W, capacity 1.110L,
Temperature 1-5 °C
Released in November 2024

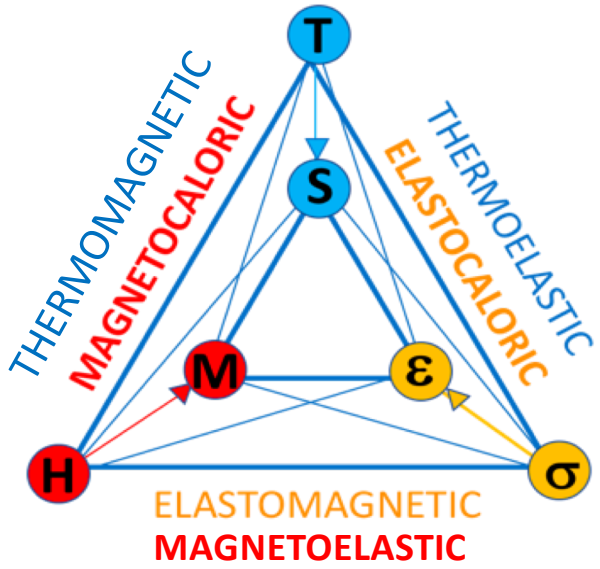
Solid state caloric cooling

Magnetocaloric effect is one in a family of caloric effects

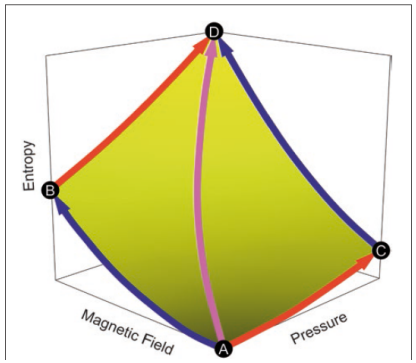
$$dG(T,H,p,\sigma,E) = -SdT - MdH + Vdp + \varepsilon d\sigma + PdE = -SdT + \sum X_i dx_i$$

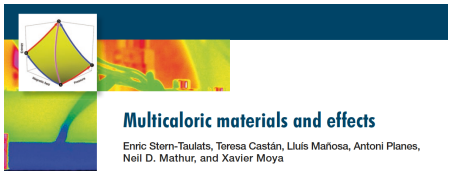
Barocaloric — Electrocaloric — Magnetocaloric — Elastocaloric

- X_i is the generalized displacement (M, V, ε, P); x_i is the generalized force (H, p, σ, E)



MultiCaloric Exploitation



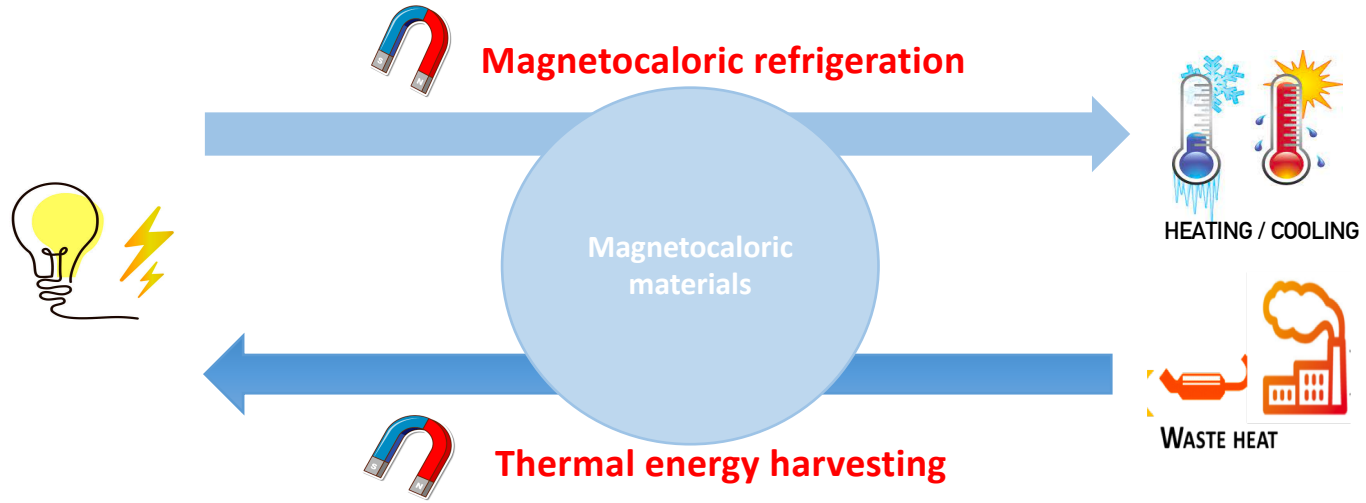


X. Moya et al. Science (2020)

See also : Agata Czernuszewicz et al., Adv Materials Technologies, 25 June 2025
DOI: (10.1002/admt.202500545)

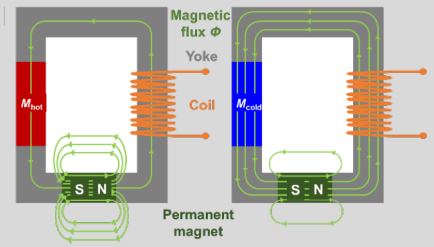
"From the Discovery of the Giant Magnetocaloric Effect to the Development of High-Power-Density Systems"

Magnetocaloric refrigeration– Thermal energy harvesting

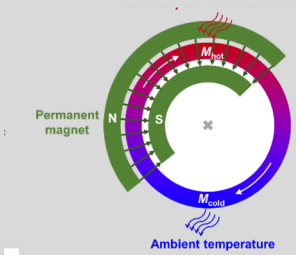


Huge and reversible magnetization change at a tunable T

A. Waske, Nature Energy 2019

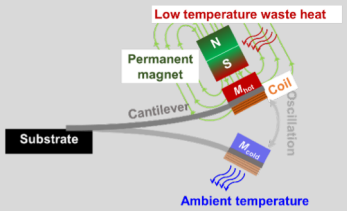


Thermomagnetic generator



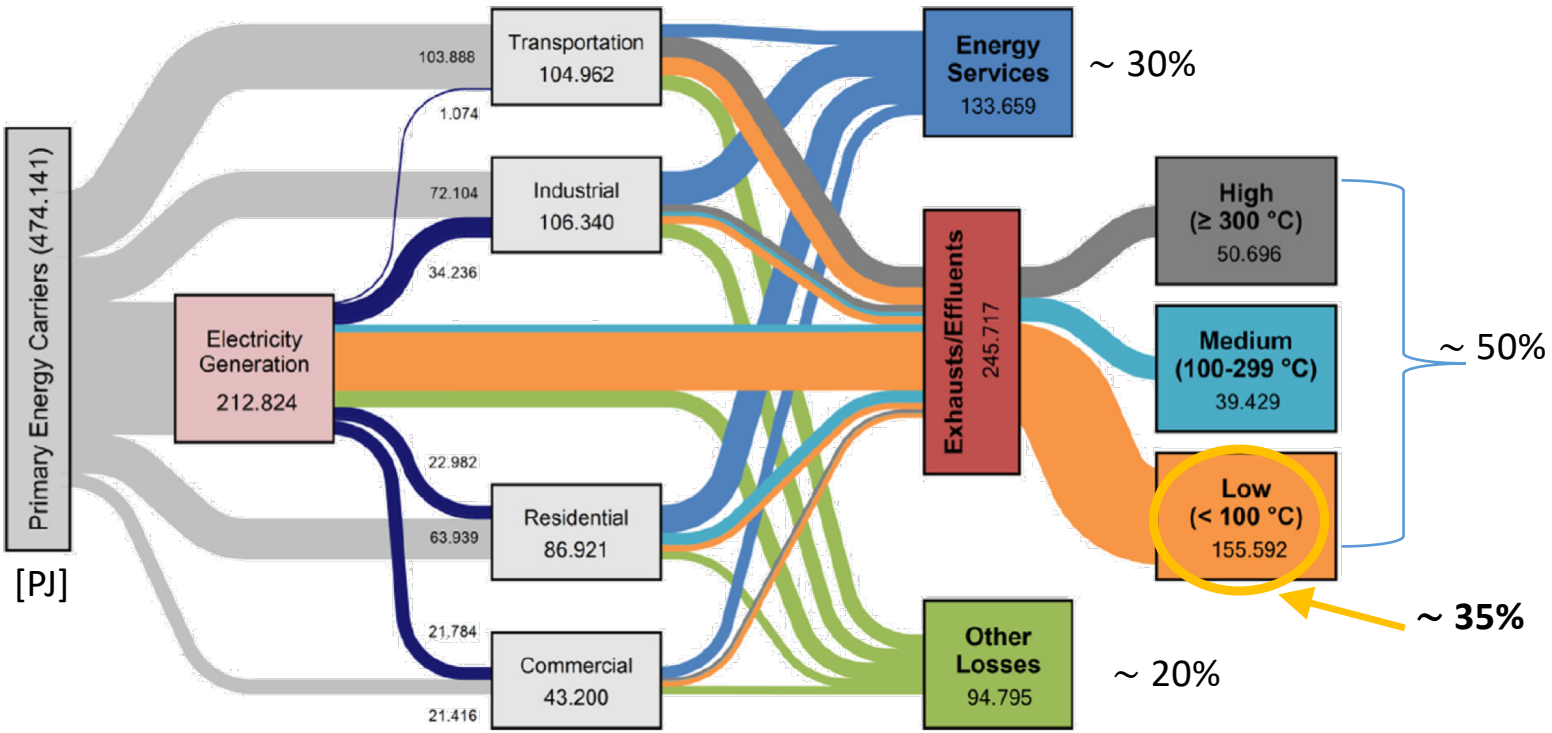
«Curie Wheel»

Thermomagnetic motor



Thermomagnetic oscillator

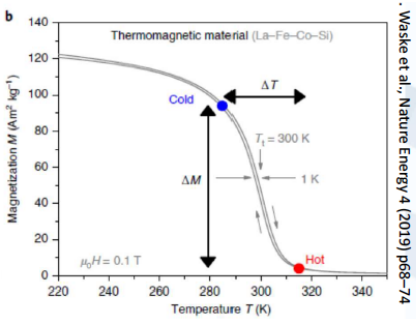
Energy efficency - waste heat



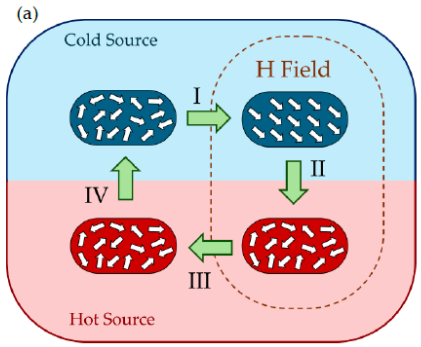
C. Formann et al. , Renewable and Sustainable Energy Reviews **57** 1568–1579 (2016)

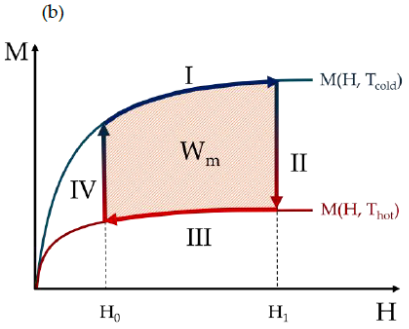
Goal: to harvest and convert waste heat for low T sources (below water boiling point)

Exploitation of magnetization variations induced by T in a small T range cycling around the transition. The magnetic flux change induces an electric voltage (Faraday Law)



Thermomagnetic generation: materials' requirements

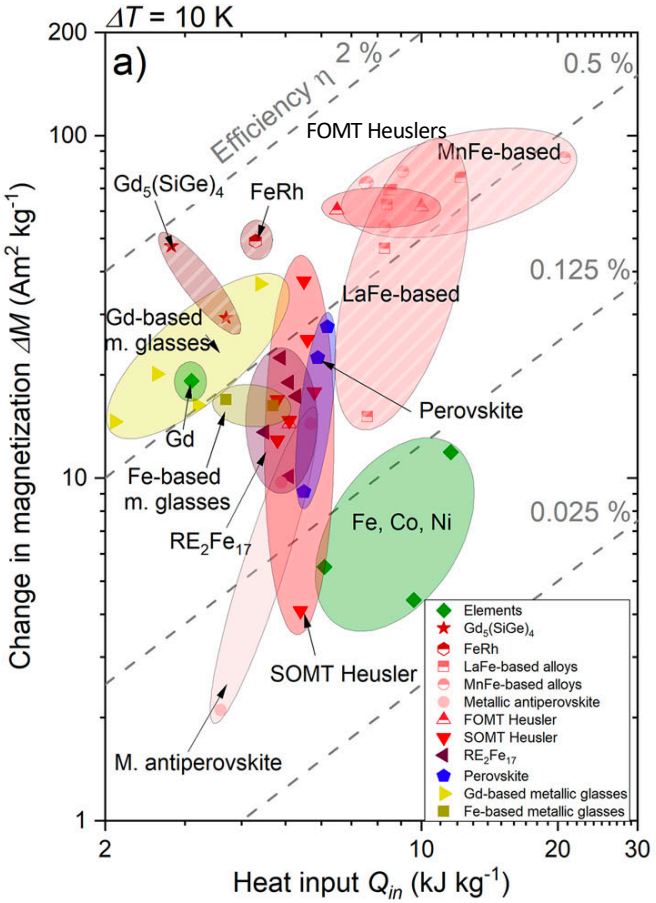




Thermomagnetic work $$W = \oint_{M(H,T_{hot})}^{M(H,T_{cold})} H\, dM$$

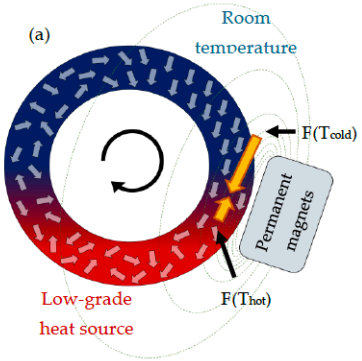
- Phase transition at the right temperature
- High magnetization variation
- Low thermal hysteresis
- High thermal diffusivity: $$\alpha = \frac{k}{\rho\, c_p}$$

- Materials free of critical elements and cost-effective

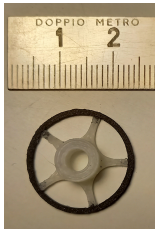


D. Dzekan et al. APL Mater. 9, 011105 (2021)

Thermomagnetic generation – Thermal energy harvesting

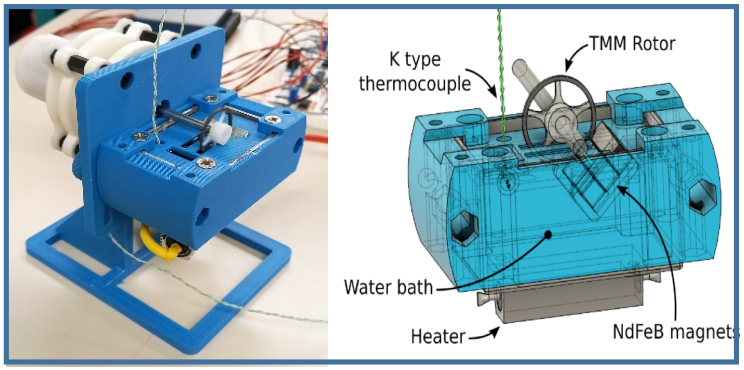


Scalable towards big devices



Thermomagnetic rotor: very small mass of the material (m=0.5 g)

ThermoMagnetic motor «Curie Wheel»



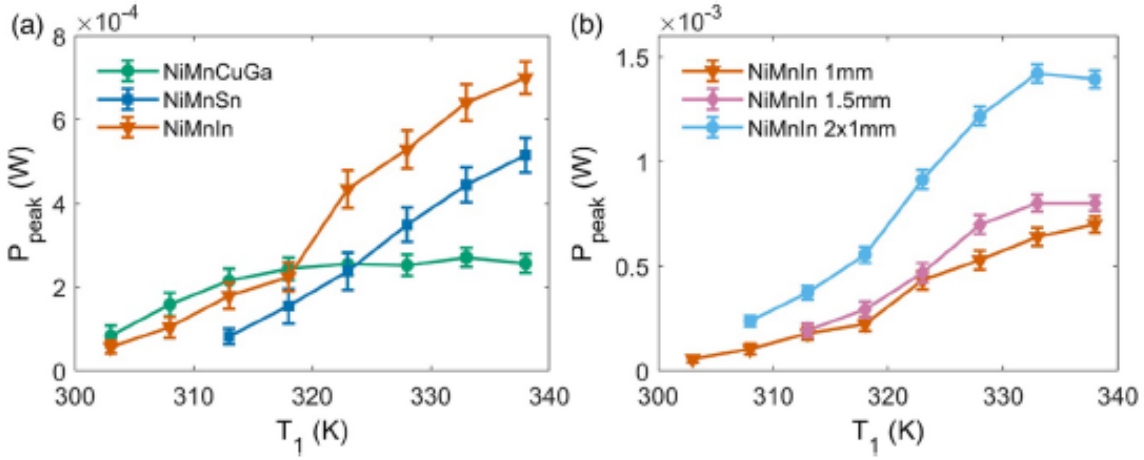
F. Cugini et al. Acta Materialia, 288, (2025,)120847

- Magnetic field gradient: 0-1 T
- Cold source: RT
- Hot source up to 60°C

➡ Production of thermomagnetic composites to be tested *in-operando.*

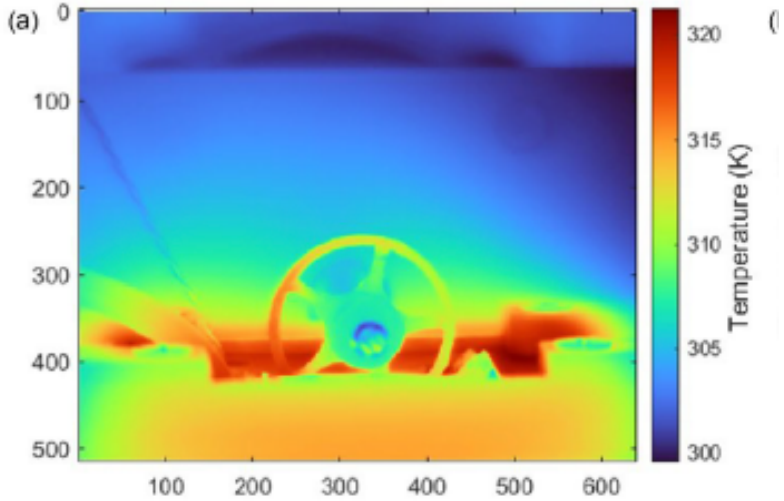
➡ Comparison between first and second order materials

Thermomagnetic measurements



Maximum measured power output as a function of the T of the hot source

Thermal exchange is a limiting factor



ΔT=5K Thot=5K lower than water T
Tcold=14K higehr that RT

Additive manufactured rotors

F. Cugini et al. Acta Materialia, 288, (2025) 120847

Magnetic materials for energy

Ecological transition



Materials criticality

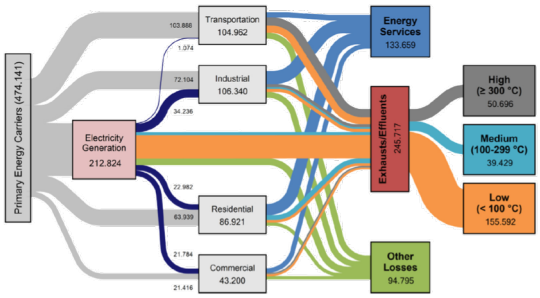


Magnetic materials for energy is an exciting field of multidisciplinary research spanning from basic science to applications and to atom to macro

Climate change - gas regulations



Waste of energy



CIMTEC 2026

16th International Ceramics Congress & 10th Forum on New Materials

FORUM ON NEW MATERIALS

Perugia / Italy June 21-25 2026

Symposium FL

Caloric and Multicaloric Materials and Effects: from Fundamentals to Applications

Chairs:
Franca ALBERTINI, IMEM-CNR, Parma, Italy *(Convener)*
Luana CARON, Bielefeld University, Germany
Lluis MANOSA, University of Barcelona, Spain



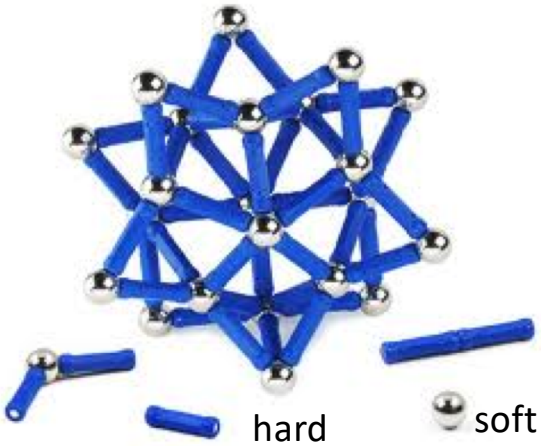
Submission deadline: October 25, 2025

Magnetism...

"…it is a divine power that moves you, just as in that stone which Euripides calls a 'Magnet" but which most people call Herakleian. For this stone not only moves iron rings but it also imbues the rings with the same power so that they can do the same thing as the stone in turn—they move other rings and as a result there is a great chain of iron and rings connected to each other. But the power from that stone runs through them all. In this way, the Muse herself makes people inspired, and a linked chain of inspired people extend from her"

(about Homer and epic poets)

"Ion", Plato (428/427-348/347 a.C.)



Thank you for your attention!