IEEE Magnetics Society

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FIELD OF INTEREST

"Treatment of all matters in which the dominant factors are the fundamental developments, design, and certain applications of magnetic devices. This includes consideration of materials and components as used therein, standardization of definitions, nomenclature, symbols, and operating characteristics; and exchange of information as by technical papers, conference sessions, and demonstrations."

MEMBERSHIP STATISTICS

Approx. 3000 members in 33 chapters

USA, Canada, South America

Alabama, Brazil, Boston, Chicago, Denver Rocky Mountain, Houston, Milwaukee, Oakland-East Bay, Pikes Peak, Philadelphia, San Diego, Santa Clara Valley, Twin Cities, Washington/North Virginia, Toronto

Europe, Middle East and Africa

Italy, France, Germany, Poland, Romania, Spain, Sweden, UK and Rep. of Ireland

Asia and Asia-Pacific

Japan Council, Nagoya, Sendai, Seoul, Singapore, Taipei, Hong Kong, Nanjing, Beijing

PUBLICATIONS

Society Newsletter
IEEE Transactions on Magnetics
IEEE Magnetics Letters

For more information and to join visit
www.ieeemagnetics.org

ACTIVITIES/OUTREACH

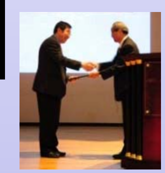
Conferences:

- INTERMAG
- MMM/Intermag (joint w/ AIP)
- TMRC

Education:

Graduate Student Summer Schools

Awards



- Student Travel Grants to attend conferences
- Best Student Presentation at Intermag
- Achievement Award

Distinguished Lecturers 2012


Shinji Yuasa, "Magnetoresistance and spin torque in magnetic tunnel junctions"
George C. Hadjipanayis, "Science and Technology of Modern Permanent Magnet Materials"
Gerrit Bauer, "Spin Caloritronics"
Masahiro Yamaguchi, "Soft Magnetic Thin Film Applications at Radio Frequencies"


Science and Technology Of Modern Permanent Magnet Materials

George C. Hadjipanayis

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Work supported by DOE, ARPA-E and NSF

Outline

- Brief Introduction to Magnetism
- Impact on Applications
    - Wind Mill / Electric Car/ Energy Storage
- $(BH)_m$ – Figure of Merit of Permanent Magnets
- Historical Magnet Development: Dramatic progress in last 100 yrs

  Interplay Between Theory and Experiment
- Challenges/Problems: Current Problems with Rare Earths
- Drive Towards RE-lean and Higher $(BH)_m$: Anisotropic Nanocomposites
- ✓ Bottom-up Approach: Nanoparticles/Nanoflakes
- Dy Challenge: Used in PM Motors for EV/HEV
- Non-Rare Earth Magnets
- ✓ Fe-Co-X Change Cubic Symmetry
- ✓ New Compounds
- ✓ New Government-funded Programs

The Magic of Magnets

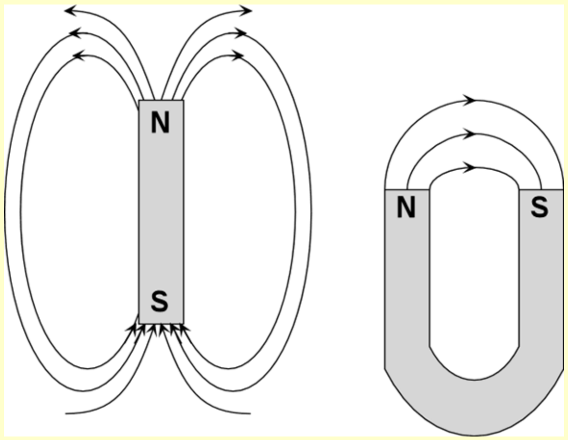
- Magnets are currently being used in many industrial applications including electric, electronic and automobile industries, communications, information technologies and automatic control engineering.

- Magnets have played a key role in the development of our modern technology.

- Today, magnets are an integral part of our life.

Magnets are Everywhere

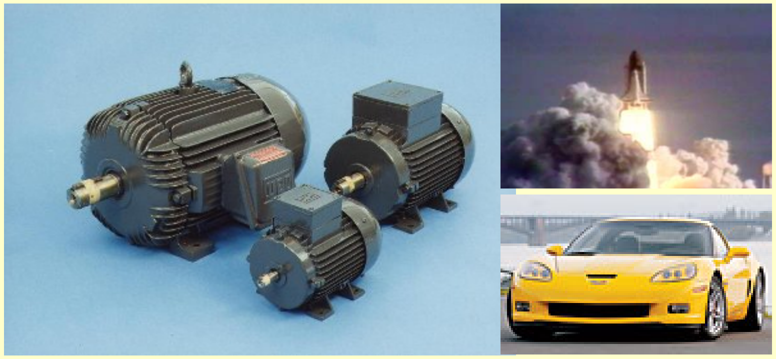
- Not only in the family notes and signs or decorations you stick on your refrigerator.



Magnets are Everywhere

- **First of all, most of electricity is generated using magnets**

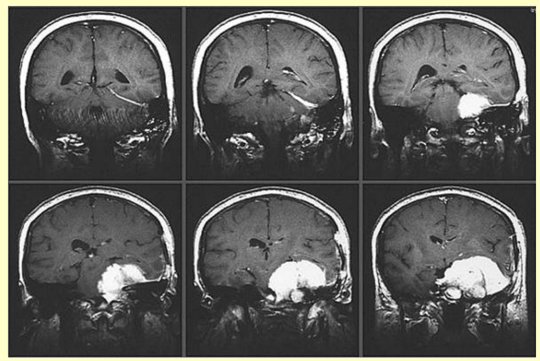
The Unsung Hero of Modern Technology



Motors used in cars, airplanes and everywhere!!

Magnetic Cranes

Magnetic Levitation Train (v>250mph)



MRI

Computer Hard Drive

Roller Coaster in Six Flags in Southern CA(v>100mph)

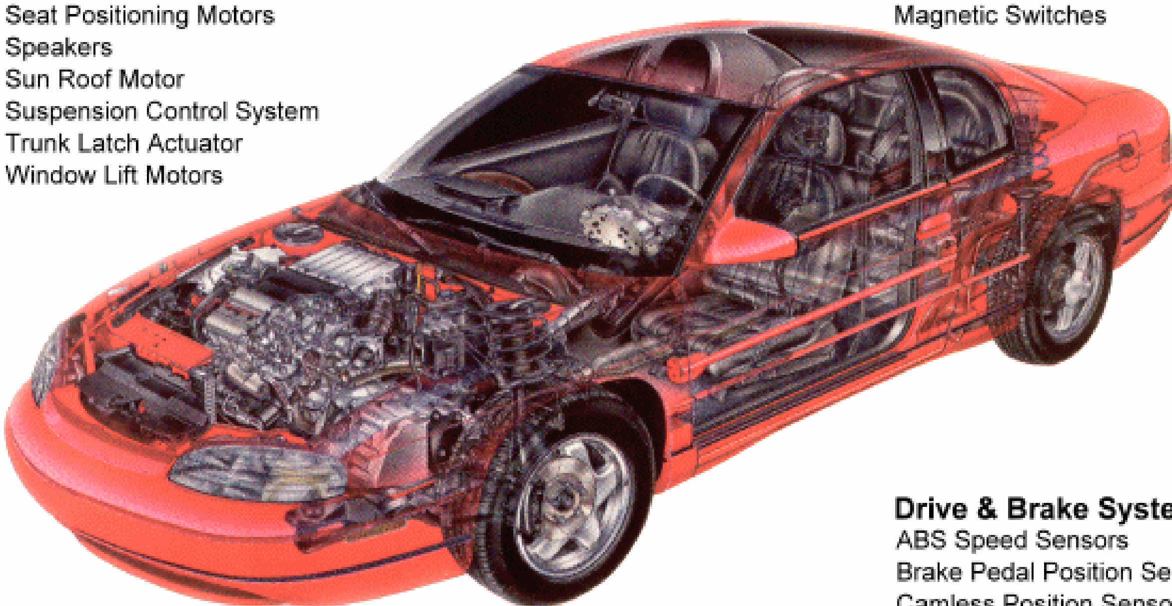
And many, many more……

Automotive Devices Using Magnets and Magnetic Materials

Comfort and Convenience
Compass
Door Lock Actuators
Entertainment System Drives & Controls
HVAC Fan Motor
Seat Position Sensors
Seat Positioning Motors
Speakers
Sun Roof Motor
Suspension Control System
Trunk Latch Actuator
Window Lift Motors

Passenger Safety
Air Bag Sensor
Seat Belt Sensors

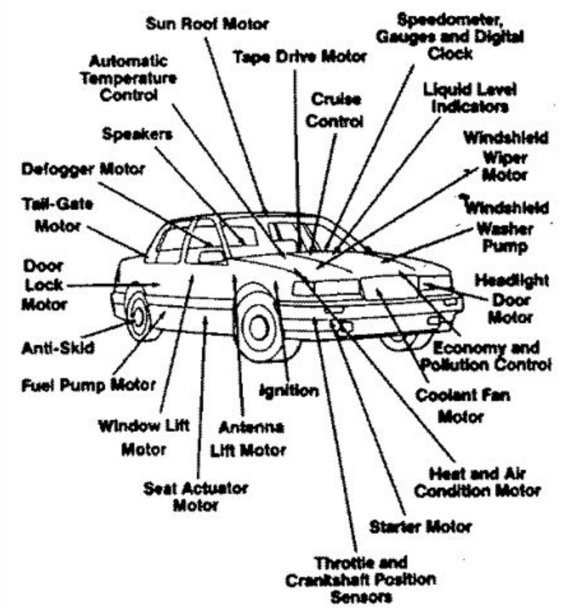
Cockpit Controls
Cruise Control
Electric Power Steering
Electronic Key Sensor
Instrumentation Gauges
Liquid Level Sensors
Magnetic Switches



Engine System
Alternator
Cooling Fan Motor
Crankshaft Position Sensor
Emission Control Vent Motors
Fuel Pump Motor
Idle Speed Control
Starter Motor
Throttle Position Sensor

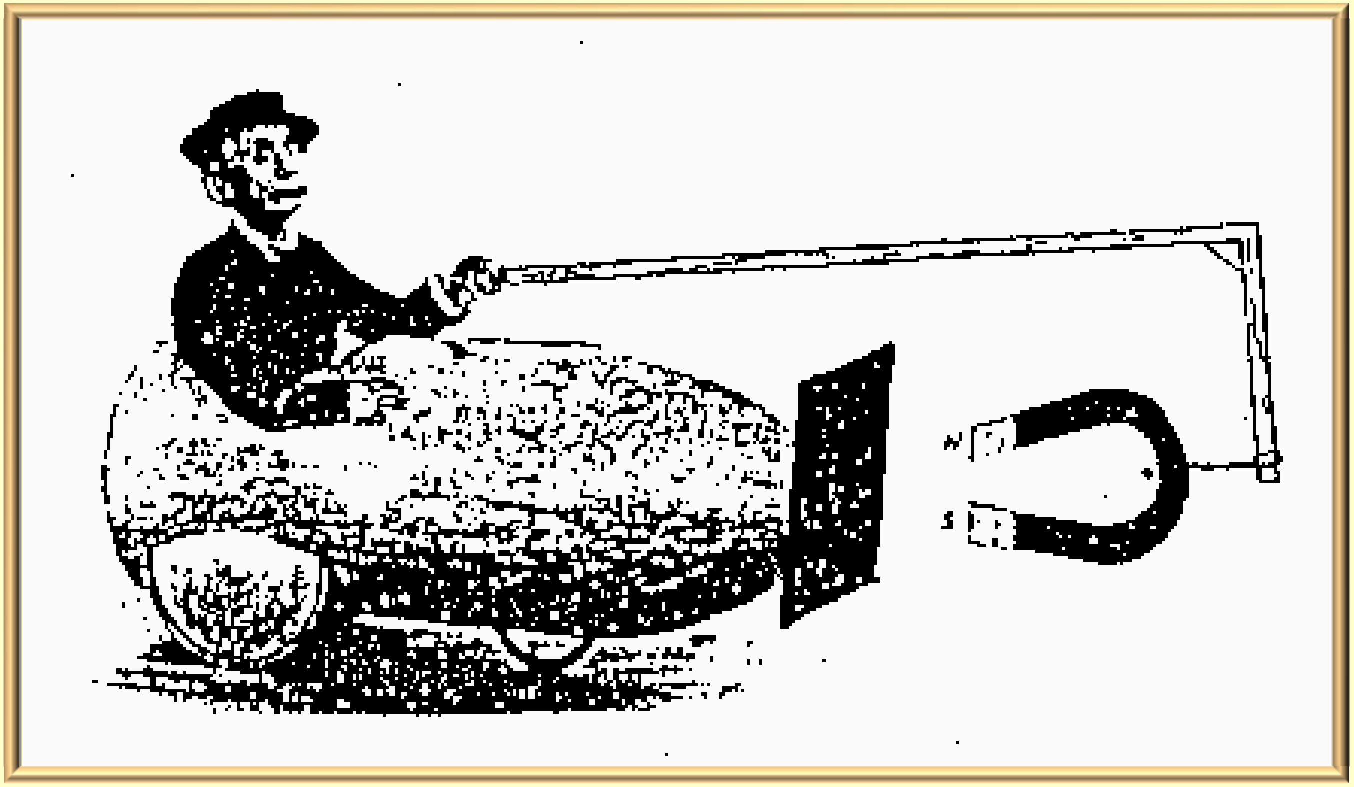
External Systems
Antenna Lift Motor
Headlight Door Motors
Headlight Aiming Motors
Mirror Positioning Motos
Windshield Wash Pump Motor
Windshield Wiper Motor

Drive & Brake Systems
ABS Speed Sensors
Brake Pedal Position Sensor
Camless Position Sensor
Electric Brake Actuators
Transmission Chip Collector
Transmission Shift Sensor



✧ **In a modern car, magnets are used in more than 30 places.**

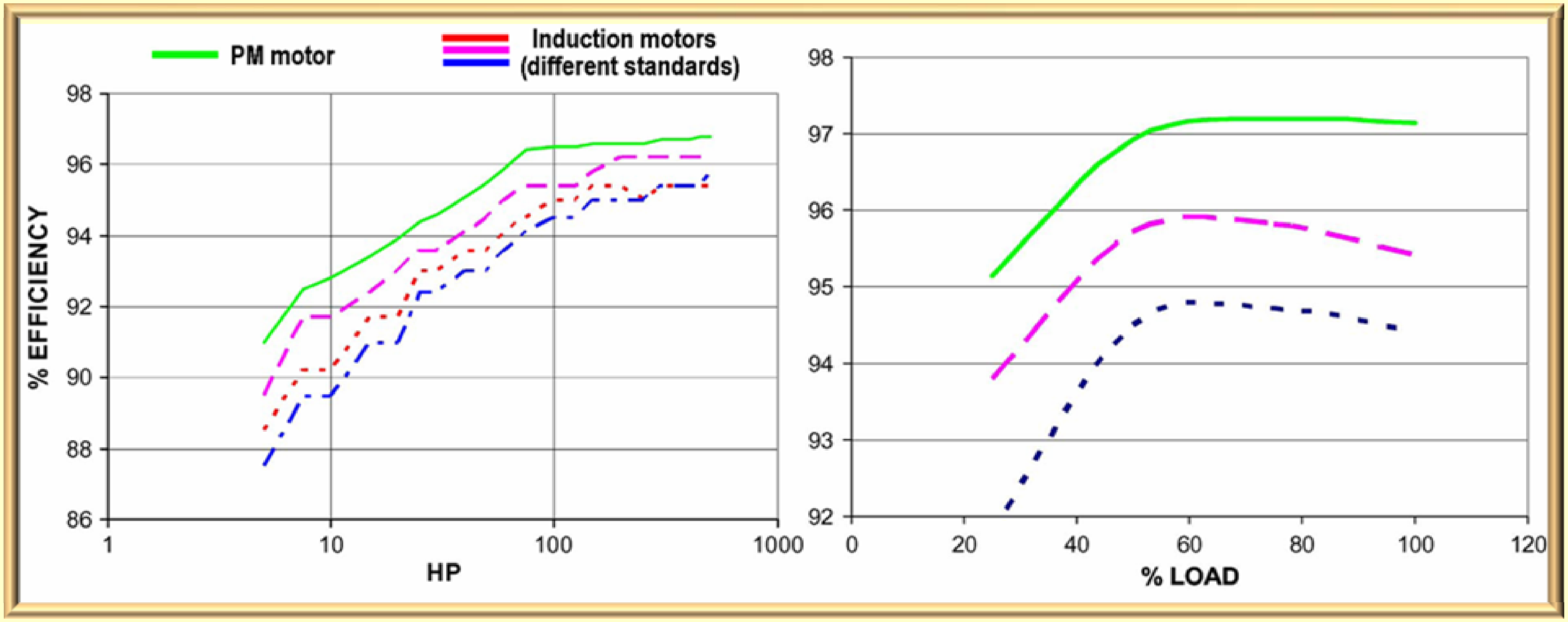
A Magnetic Perpetual Motion Machine



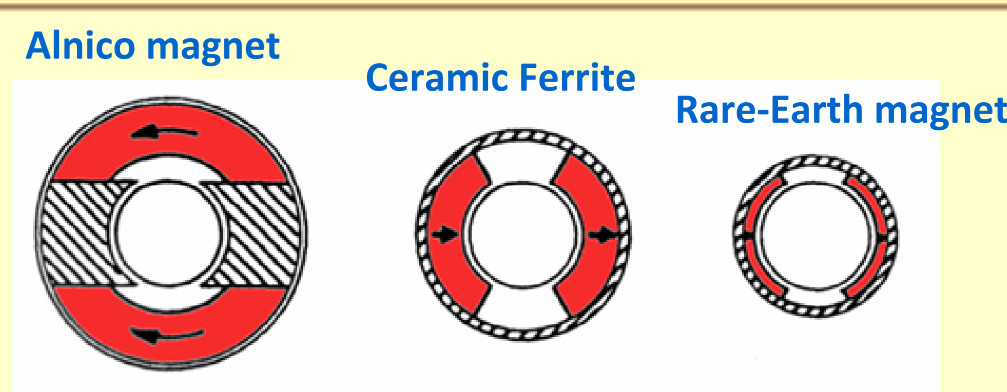
The US patent office was issuing patents for magnetic perpetual motion machines as late as the 1970's!

Permanent Magnets in Electric Motors & Generators

✧ **The single most important application for permanent magnet materials is in electric motors and power generators.**

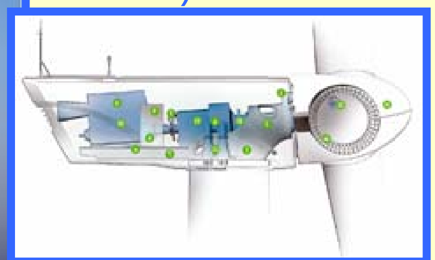


Permanent magnet stator for a dc motor:
Size and weight decrease substantially.



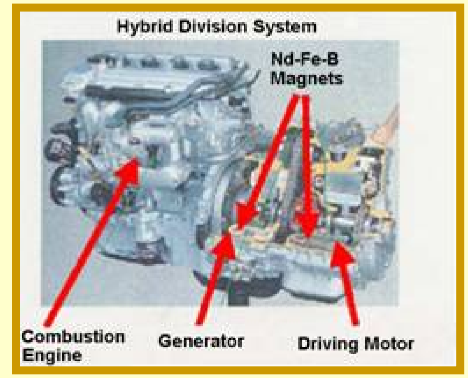
Applications of Permanent Magnets

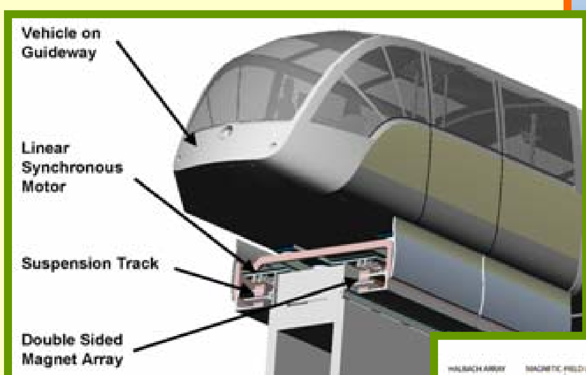
✧The **strength of permanent magnets** (PMs) is the most important parameter that affects the **power density and energy efficiency** of countless devices.

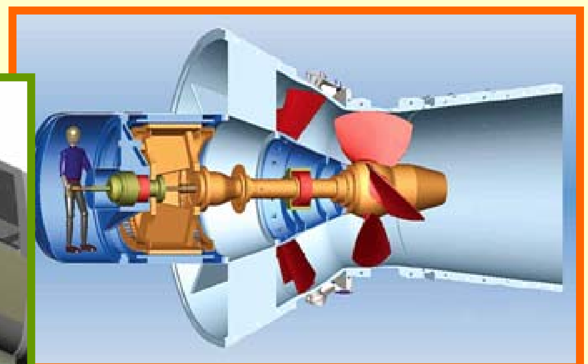


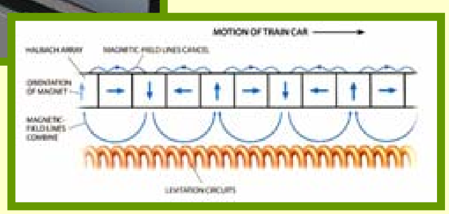
Wind turbines with PM generators are very efficient at low wind speeds (amount in tons).

Hybrid electric vehicles are particularly demanding for power density of their PM motors (amount in Kgs)



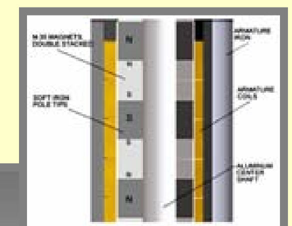


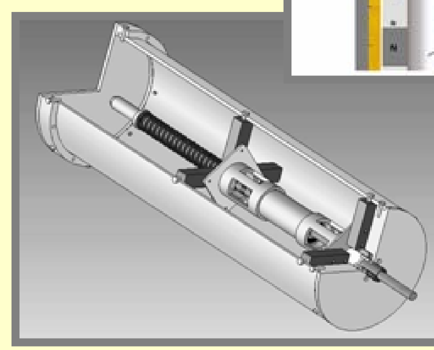




Efficient and fail-safe *Inductrack* maglev train

PM hydroelectric turbine generators eliminate need for gearboxes

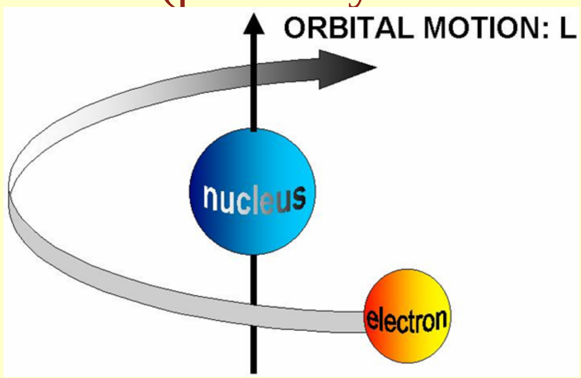




In this generator buoy, the floater moves coils relative to the PM to induce voltages

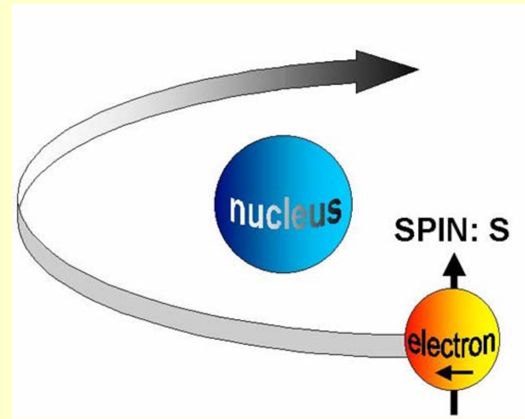
Origin of Magnetism

- Magnetism is originated from the motion of electrons around the nucleus (planetary like motion)



The magnetic moment due to orbital motion:

$$\mu_L = -\frac{\mu_B}{\hbar}\mathbf{L}$$

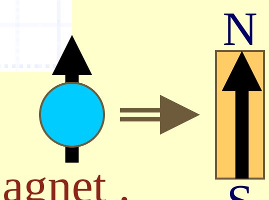


The magnetic moment due to spin motion:

$$\mu_S = -g\mu_B \mathbf{S}$$

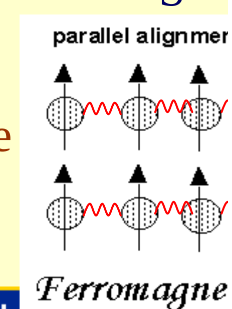
$$\mu_T = \mu_L + \mu_S$$

- Atoms with incomplete shells have permanent magnetic moment (Fe,Co,Ni 3d shells, rare earths Nd,Pr,Sm 4f shells). Each atom can be viewed as a tiny bar magnet .



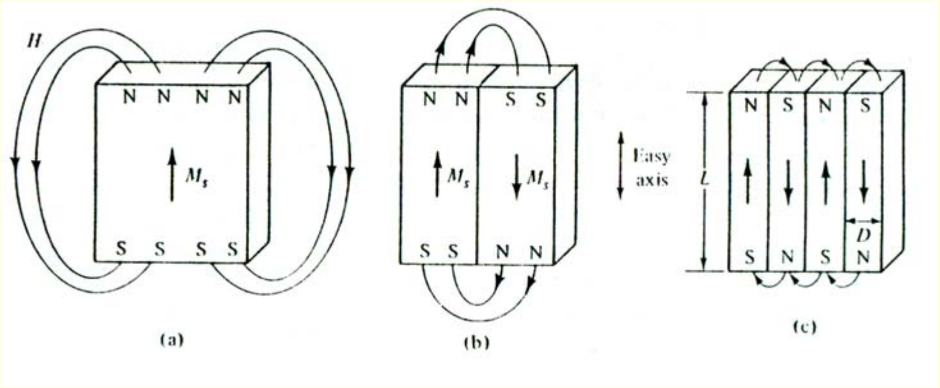
- Moments interact with each other through exchange interaction; in ferromagnetic materials J is positive and the magnetic moments align parallel to each other.
- At a high temperature (Curie Temperature) thermal energy overcomes the exchange interaction and the material becomes paramagnetic.

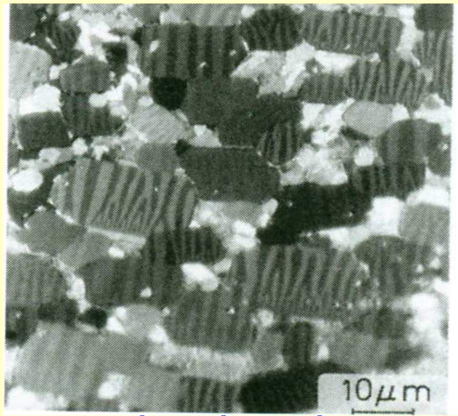
$$E_{ex} \sim -J\vec{S}_i \cdot \vec{S}_j$$



Magnetic Domains-Domain Walls

- The magnetic moments of ferromagnetic materials are arranged in magnetic domains to reduce the large demagnetization energy due to the large stray fields.



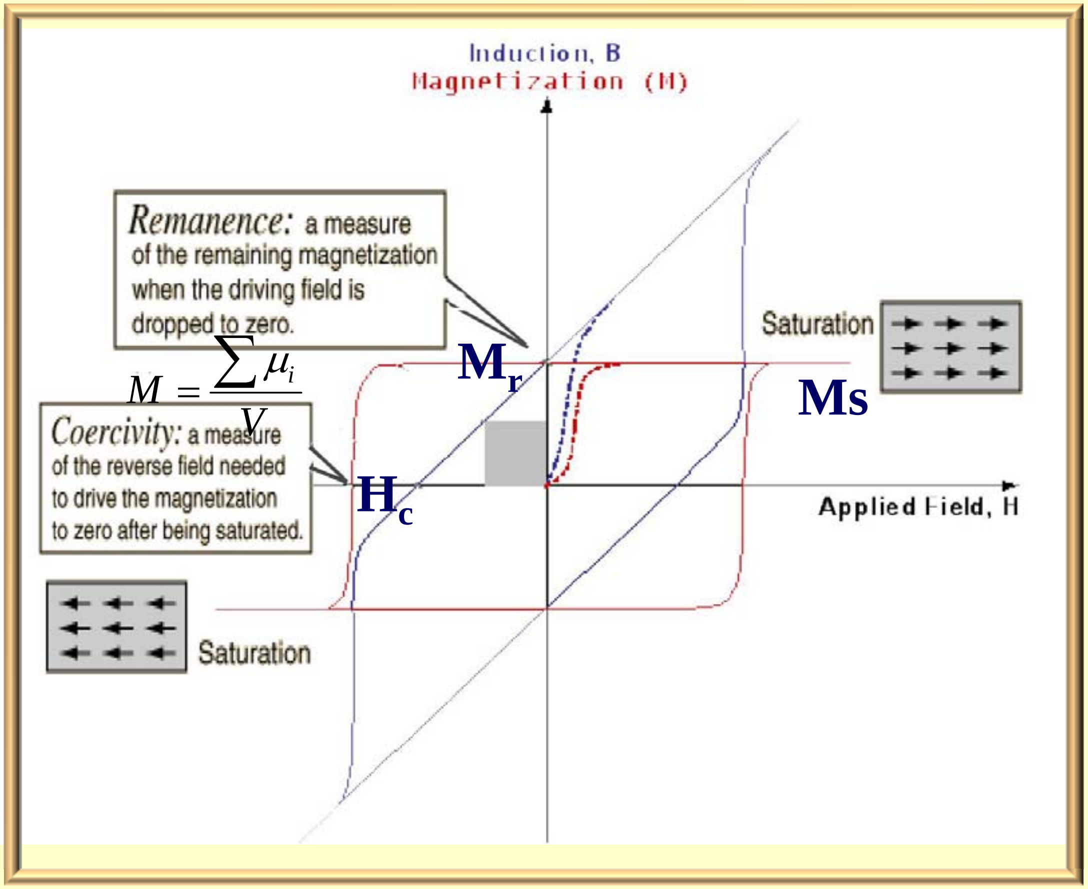


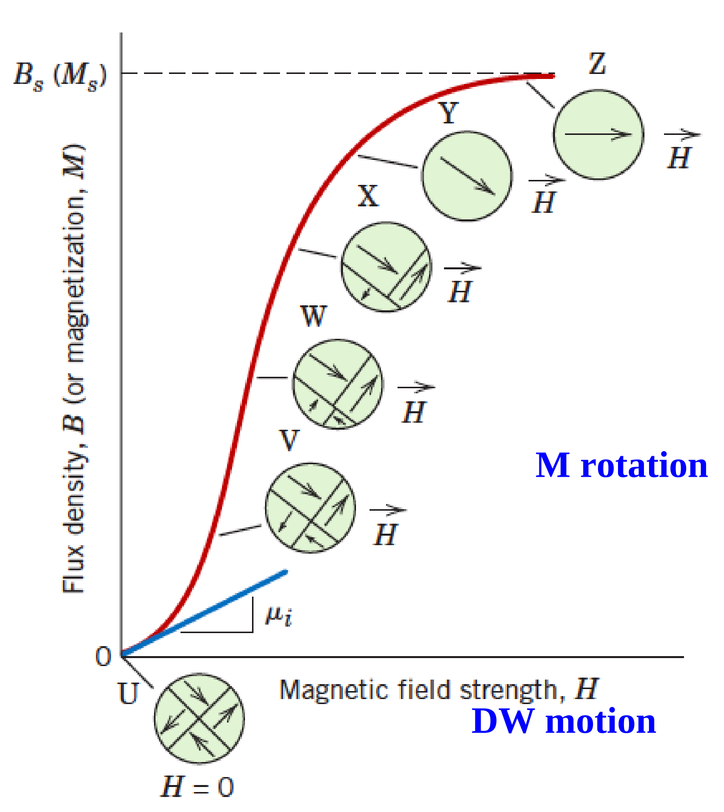
- Inside each domain the moments are parallel to each other; however, the direction of different domains is random, so in the absence of a magnetic field the net moment is zero.

- The boundaries between the different domains are known as domain walls.

- The magnetic moments can be aligned by the application of a magnetic field.

Hysteresis Loops M(H) & B(H)



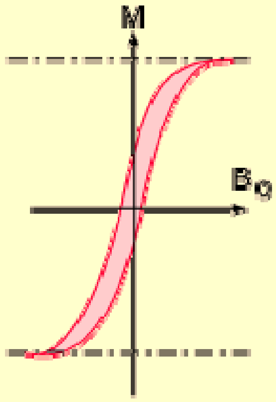


$B = \mu_o (H + M)$ (SI)

$B = H + 4\pi M$ (CGS)

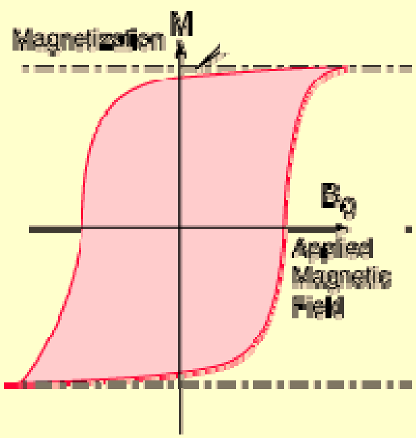
- Area under hysteresis loop represents the energy losses which are converted to heat.
- **Hindrances to DW motion and M rotation cause the high coercivity.**

Soft and Hard Magnetic Materials



Soft Materials: Co, Ni, Fe, NiFe (permalloy)

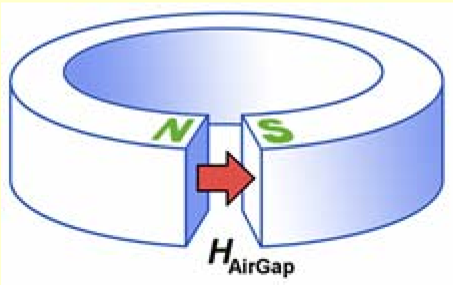
- **large Ms ($4\pi M_s^{Fe}$ ~ 22 kG), low Hc, (narrow loop and therefore, low losses)**
- **Used where a high magnetic induction and low losses are required such as transformers and biomedical applications.**



Hard Materials: Sm-Co, Nd-Fe-B, CoPt, FePt, etc.

- **large Ms ($4\pi M_s^{Nd\text{-}Fe\text{-}B}$ ~ 16 kG),**
- **High Hc (> 6 kOe), (wide loop)**
- **Used where a high remanence is required such as permanent magnets and magnetic recording**

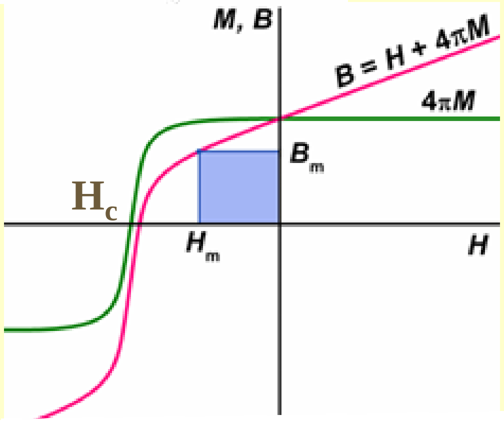
Strength of a Permanent Magnet: Energy Product $(BH)_m$



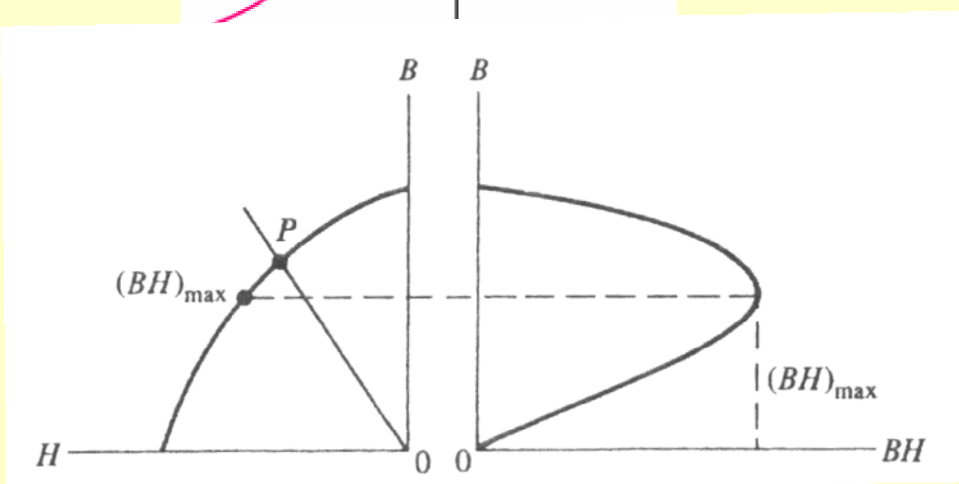
L.C. Cullity, "Introduction to Magnetic Materials"

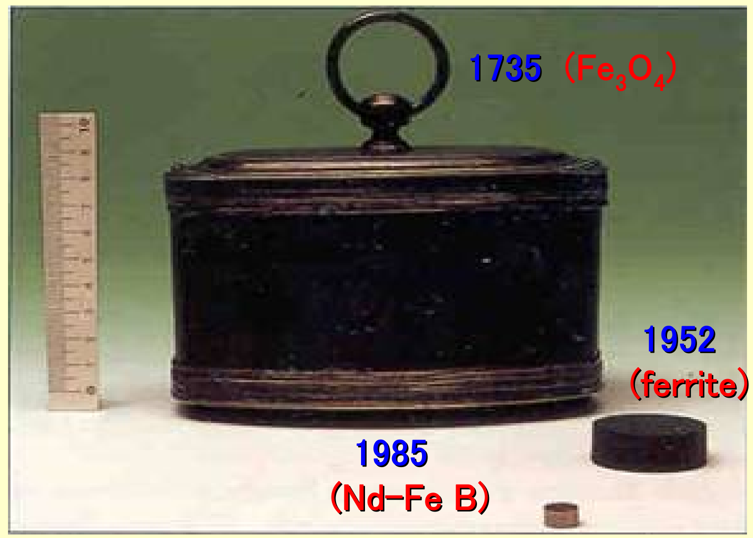
$$H_{ag} \sim \sqrt{\frac{V_m (B_m | H_m|)}{V_{ag}}}$$

$$(BH)_m \sim H^2_{ag} V_{ag} / V_m$$



The higher the $(BH)_m$ the smaller the V_m!





Permanent Magnet Characteristics

✧ **Permanent magnets are characterized by:**

- **A high remanence to produce a large magnetic induction(need texture/alignment obtained by powder metallurgy).**
- **A high H_c ($H_c \geq M_r/2$) to avoid easy demagnetization (need high K and proper microstructure).**
- **A high T_c to resist thermal demagnetization.**

$$(BH)_m = (4\pi M_s/2)^2$$

144 MGOe for Fe-Co

✧ **Current high performance permanent magnets are based on Fe(Co)-rich rare-earth alloys:**

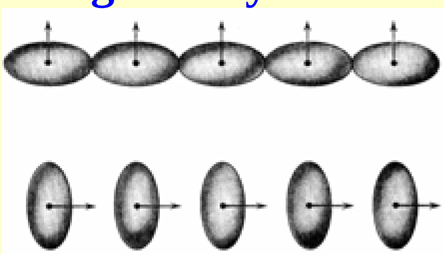
- **Fe(Co) provides the high magnetization and high Curie temperature.**
- **Rare earth metals, such as Sm, Nd, Pr, provide the high anisotropy.**

Magnetic Anisotropy and Coercivity

- Materials for permanent magnets must have **a large magnetic anisotropy and the proper microstructure** that causes the high coercivity.

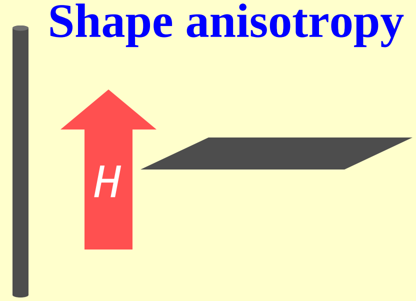
- Magnetic anisotropy is usually caused either by large **crystal electric fields (spin orbit coupling), known as magnetocrystalline anisotropy** (RE-TM, CoPt) or by the sample shape, **shape anisotropy, $H_d = -NM$**.

Magnetocrystalline



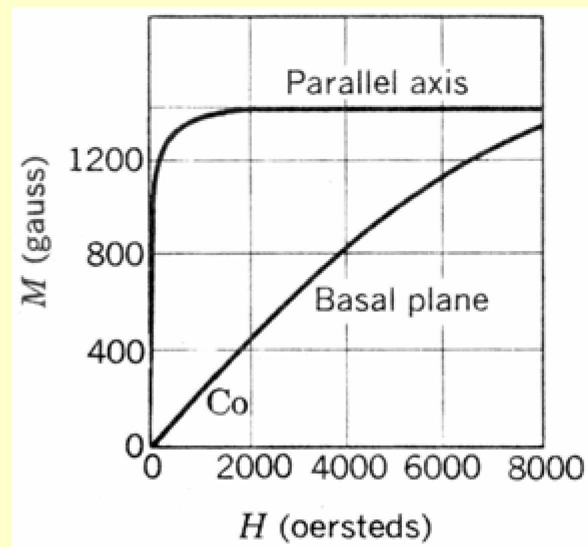
Spin-orbit coupling

Shape anisotropy



$N = 0$ $N = 1$

Easy axis of magnetization
C-axis for hcp Co.



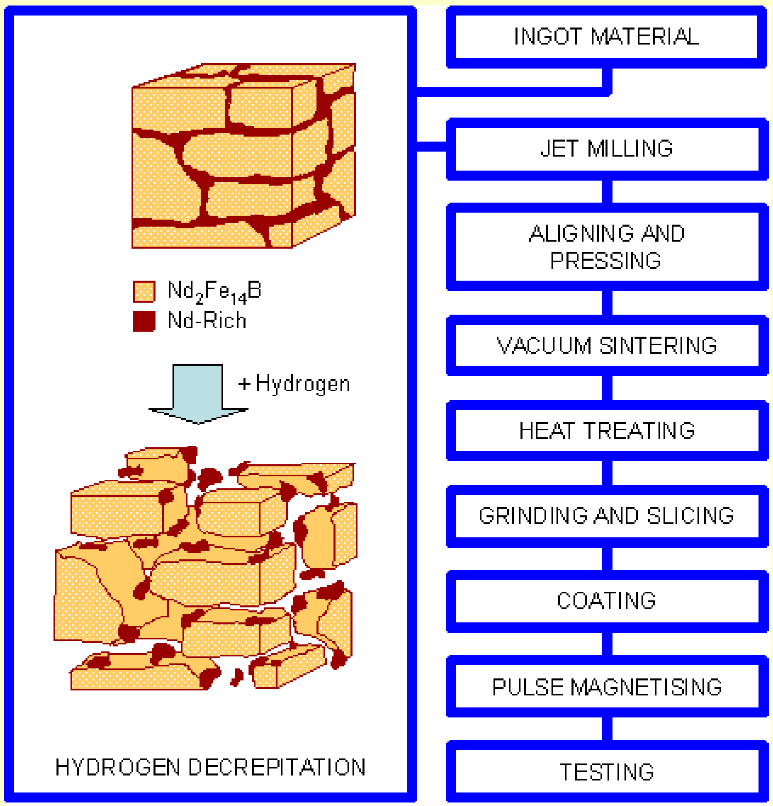
- **To "convert" the magnetic anisotropy into H_c** the material must have the **proper microstructure**, which **either inhibits the nucleation of reversed domains (nucleation magnets, Nd-Fe-B) or propagation of domain walls (domain wall pinning magnets, $Sm(Co,Fe,Cu,Zr)_z$).**

L.C. Cullity, "Introduction to Magnetic Materials"

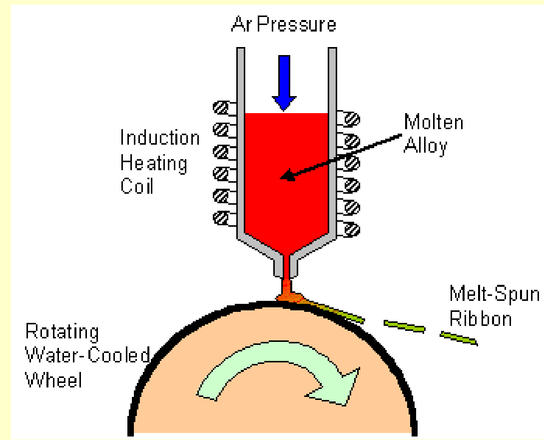
Modern Fabrication of Permanent Magnets

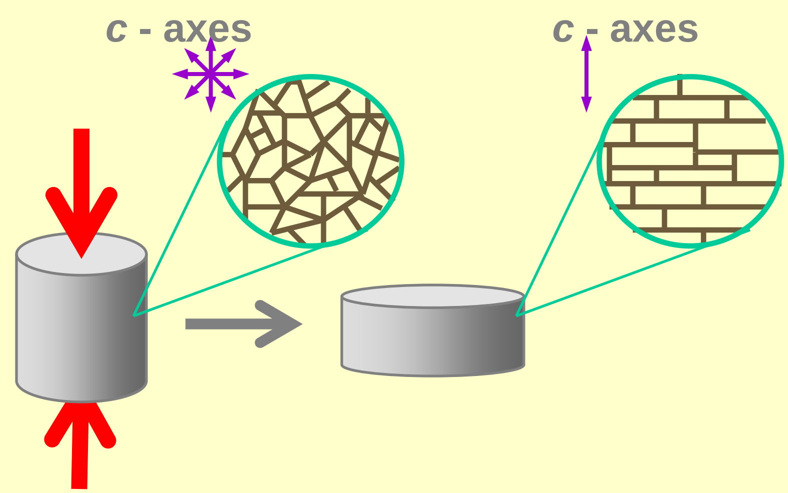
Anisotropic Sintered Magnet: m_r=1 (m_r=.5)

Powder Metallurgy



Isotropic Magnets: Melt-spun





Thick Film Magnets (MEMS)

Anisotropic Die-upset Magnets (m_r=1)

Nd-rich phase plays a key role.

Fabrication of Permanent Magnets

Magnets fabrication
according to Gilbert (1540 - 1603)
as described in "De Magnete"

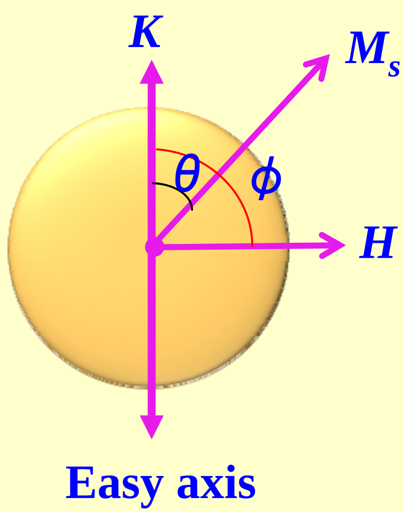
Bar of iron oriented parallel to the track of a meridian circle

Early fabrication of magnets

- Need a large remanence M_r (high degree of texture/alignment)
- Need a high H_c (large K, proper microstructure which is induced by ANNEALING).

Coercivity of Small Particles

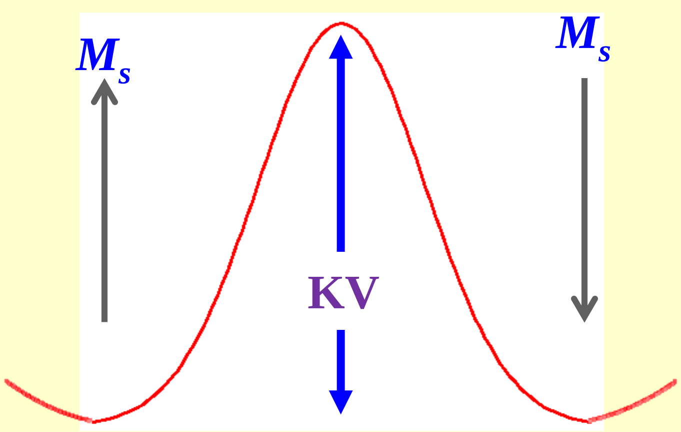
✧ **Stoner & Wohlfarth :** ***Coherent Magnetization Rotation***



$$E_t = E_K + E_H$$

$$= KV\sin^2\theta - HMV\cos(\varphi-\theta)$$

$$\frac{dE_t}{d\theta} = 0 = K\sin 2\theta - HM_S\sin(\varphi-\theta)$$



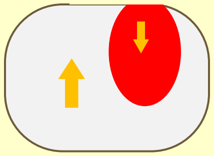
$$H_A = H_c = \frac{2K}{M_s}$$

$$H_c = (N_a - N_c)M_s$$ (Shape anisotropy)

$$H_c = 0.96\frac{K}{M_s}$$ (Random anisotropy)

How to Induce Coercivity in Real Materials

In bulk materials, defects control coercivity.



✧ **Nucleation of Reversed Domains:** ***Brown`s Paradox***, $H_c << H_A = 2K/M_s$
nucleation occurs at weak links with lower K and large N_{ef}

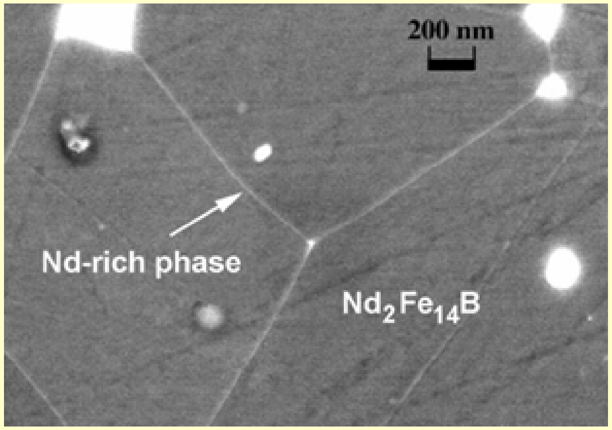
$$H_c = \alpha_K \frac{2K}{M_s} - N_{eff} M_s$$

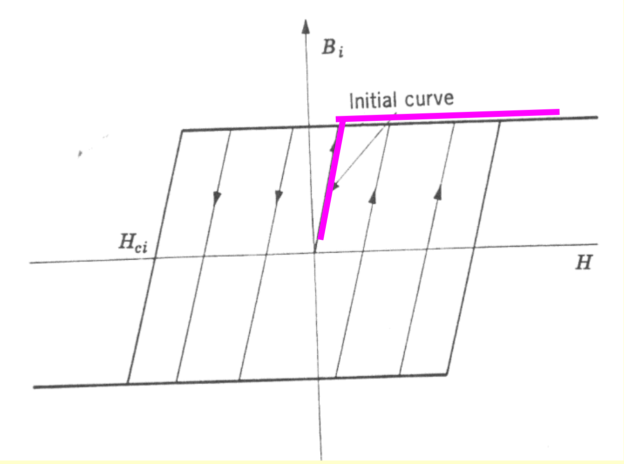
(α_K depends on deficiencies in K and N_{eff} on stray fields at edges) **Kronmüller,1991**

Typical nucleation-type magnets: Nd-Fe-B, $SmCo_5$

✧ **In these magnets the domain walls move easily inside the grains. Nucleation usually occurs at the low anisotropy intergranular phases. MUST DEVELOP THE PROPER MICROSTRUCTURE.**

✧ **The initial curve is steep and H_c increases with H until saturation.**

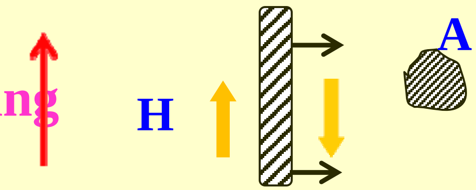




Origin of Coercivity in Real Matrerials

Defects (A) pin the domain walls.

✧ **Domain Wall Pinning**



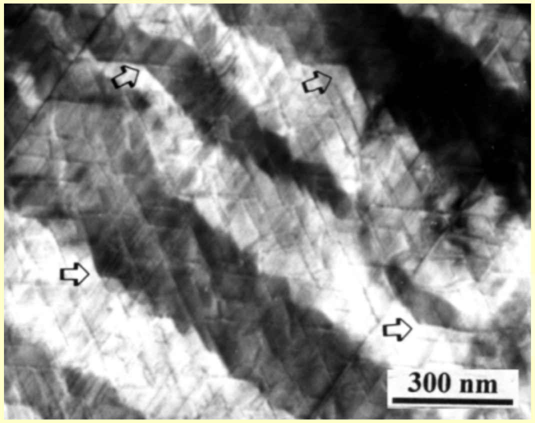
$$H_c = \frac{1}{2MA}\left(\frac{du}{dx}\right)_{max}$$

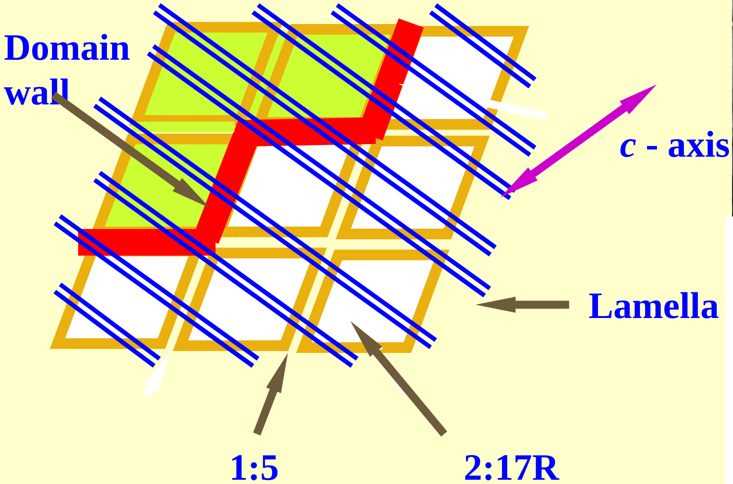
$$H_c \sim \frac{2\,H_a}{\pi}\,\frac{\delta}{D}\left[\frac{\Delta A}{A} + \frac{\Delta K}{K}\right]$$

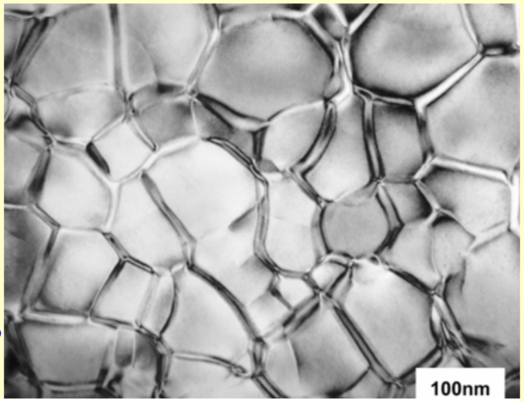
(domain walls are pinned by planar defects of thickness D with different exchange A and anisotropy K)

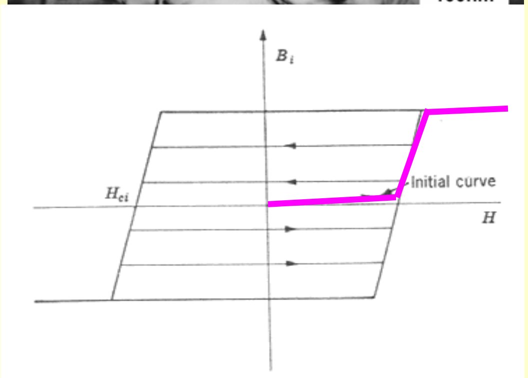
✧ **Typical example is the $Sm_2(Fe,Co,Cu,Zr)_{17}$ Precipitation Hardened Magnets which develop the cellular microstructure.**

Domain walls are pinned by the 1:5 cell boundaries.



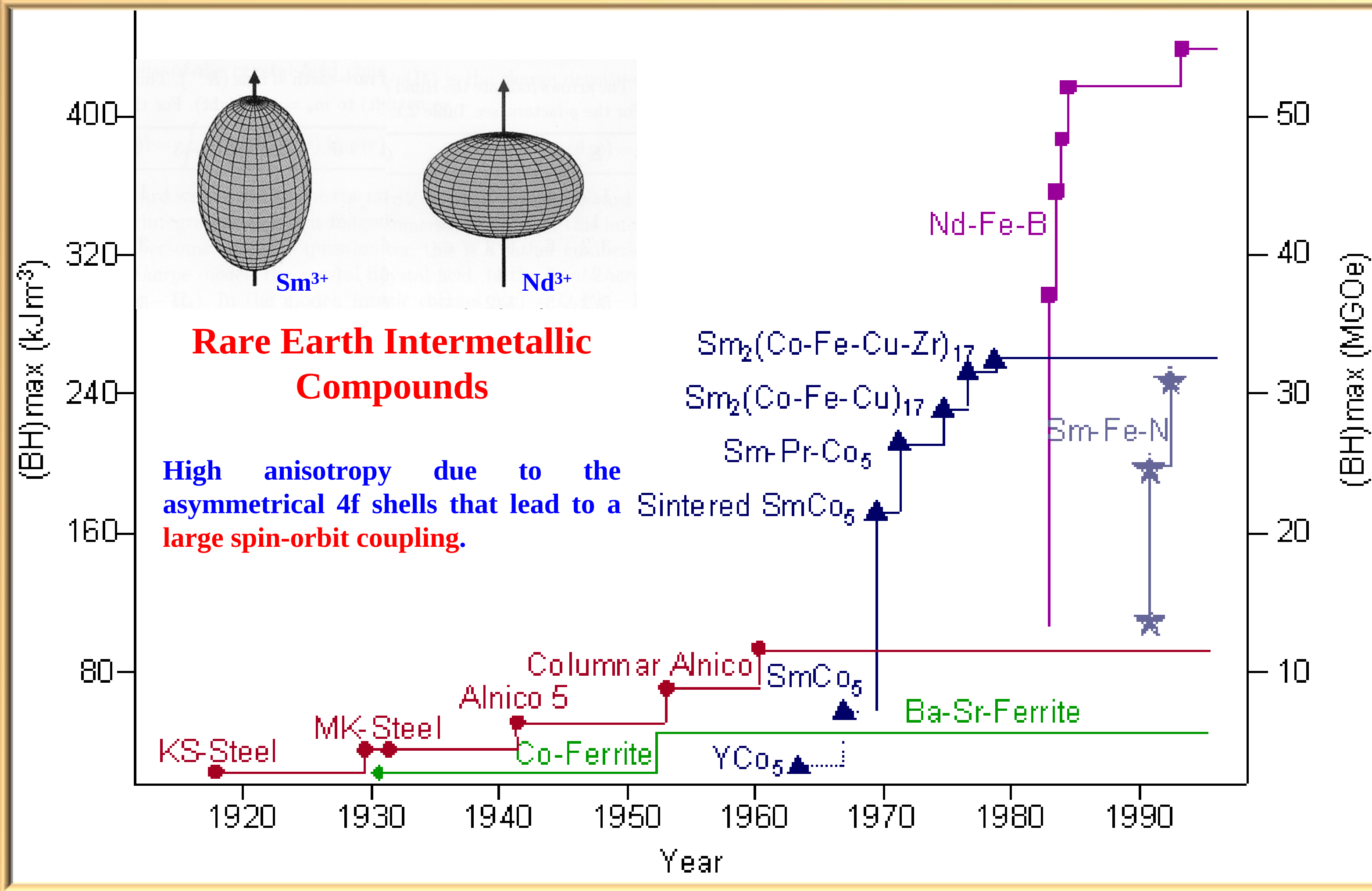






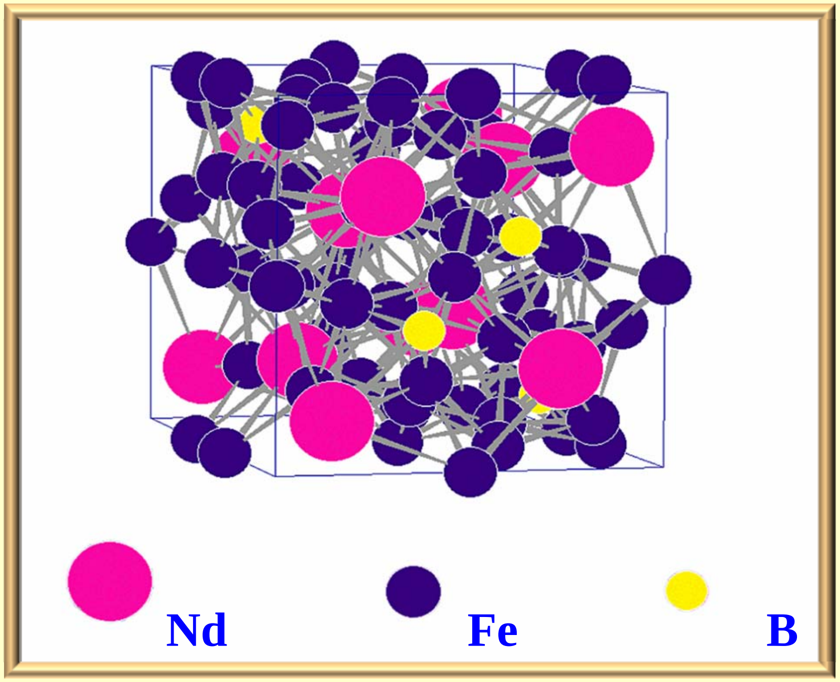
✧ **The initial curve shows a small increase up to a critical field and then increases rapidly to saturation.**

Development of Permanent Magnets



- ✧ In the last 100 years, the strength of the magnets [$(BH)_{max}$ and H_c] increased dramatically (by a factor of 100).
- ✧ This is the result of an interplay between theory and experiment.

High Performance Magnets: Nd-Fe-B Magnets

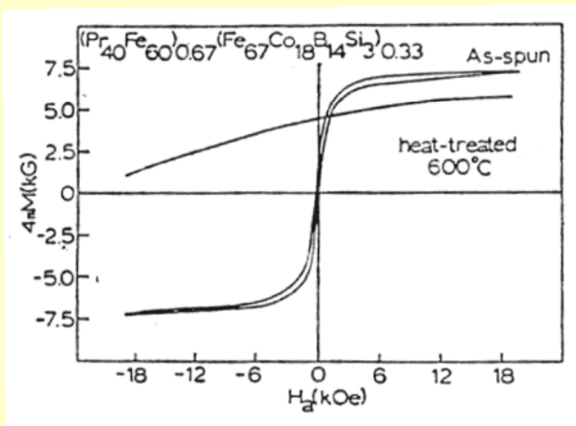


- ✧ $Nd_2Fe_{14}B$ has a tetragonal structure with 68 atoms per unit cell is with *a*=0.88 nm and *c*=1.22 nm.
- ✧ $K=5x10^7$ ergs/cc, $4\pi M_s$ ~ 16 kG, $(BH)_m$=57 MGOe
- ✧ Three groups were involved in the initial discovery of 2:14:1 phase; GM (J. Croat), Kollmorgen (G.Hadjipanayis) Sumitomo Metals (M. Sagawa).

<u>**Our Discovery (Kollmorgen) of R-Fe-B Phase**</u>

Hadjipanayis et.al. APL, 43, 797 (1983)

- ✧ ONR proposal (Grant N00014-81-C-0752): **Investigation of as-cast Fe-light rare earth alloys for permanent magnets**
- ✧ <u>Objective</u>: **Search for metastable phases in Pr(Nd)-Fe based alloys prepared by melt-spinning.**



High Performance Permanent Magnet Materials

- ✧ **All of these materials have one thing in common: their hard magnetic properties arise from the fundamental properties of their major constituent compound.**
- ✧ **The $(BH)_{max}$ limits set by the intrinsic properties of these compounds have been reached** $(BH)_{max} = (4\pi M_s/2)^2$

Fundamental magnetic properties of hard magnetic compounds

Compound	Saturation magnetization	Anisotropy field	Curie temperature	Theoretical $(BH)_{max}$
$Nd_2Fe_{14}B$	16.0 kG	67 kOe	312 ºC	64.0 MGOe (57 MGOe)
$Sm_2Fe_{17}N_{2.3}$	15.4 kG	140 kOe	476 ºC	59.3 MGOe (47 MGOe)
Sm_2Co_{17}	12.5 kG	65 kOe	920 ºC	39.1 MGOe (33 MGOe)
$SmCo_5$	11 kG	≤ 440 kOe	681 ºC	30.2 MGOe (25 MGOe)
$PrCo_5$	12.3 kG	≥ 145 kOe	620 ºC	37.8 MGOe

Prospects for the Development of New Advanced Magnets

✧ **Probability exists for discovery of new anisotropic compounds, possibly with less RE content ; but search is extremely difficult.**

✧**A new concept of high performance RE-lean exchange-coupled nanocomposite magnets was proposed in the early 90s but has not yet materialized.**

✧**Non-RE magnets remain a possibility but a focused and concerted effort is needed (97% of rare earths produced in China!).**

China Dominates Magnet Materials

WW Total Market Size: $9.1B in 2007

Projected: $11.8B in 2011, $21B by 2020

NdFeB magnets: 75%

Rare Earth Oxide Ore reserves: 50%

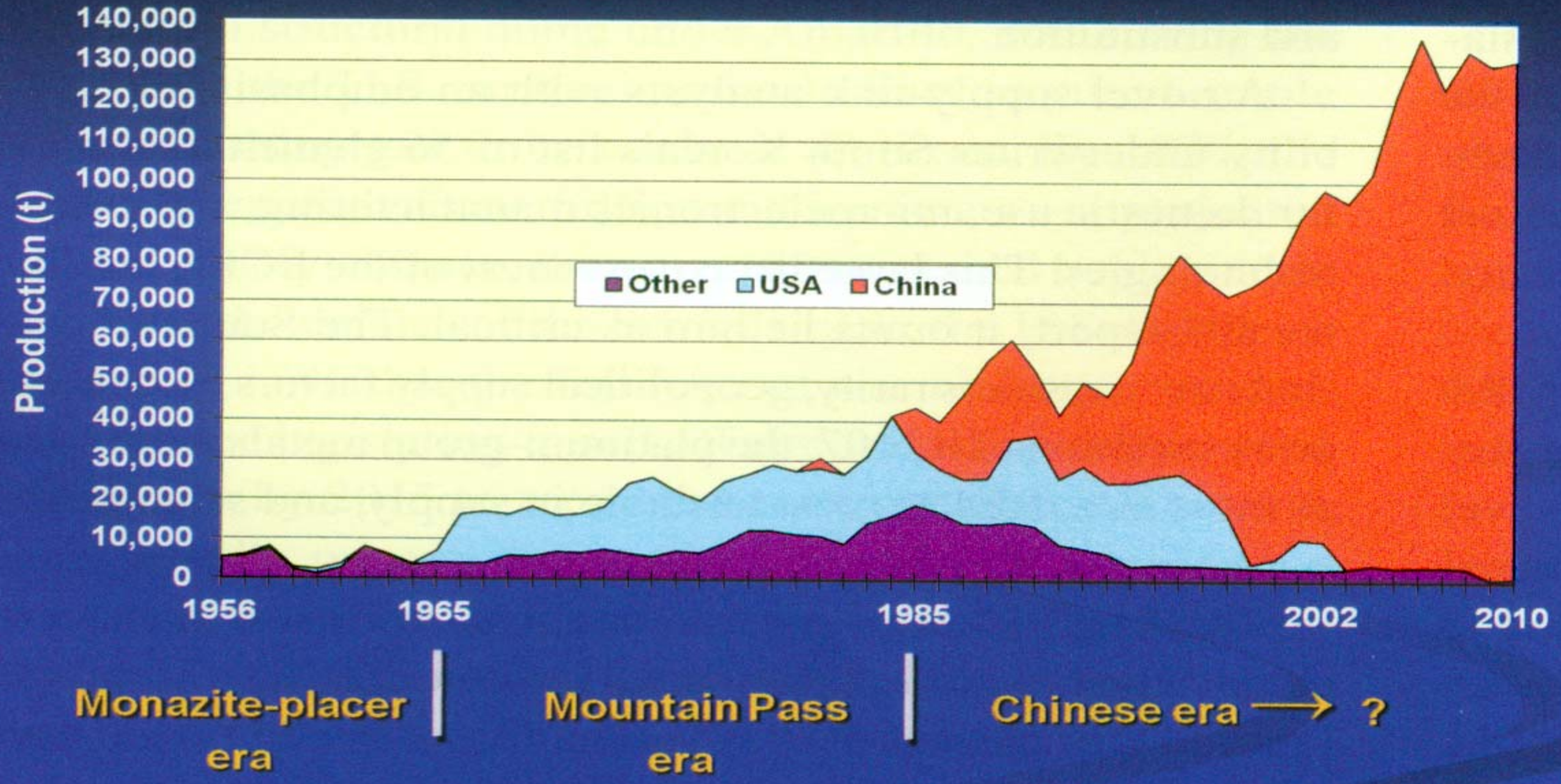
Alnico & SmCo: 50+%

Rare Earth Oxide Ore production: 97%

Hard Ferrites: 85+%

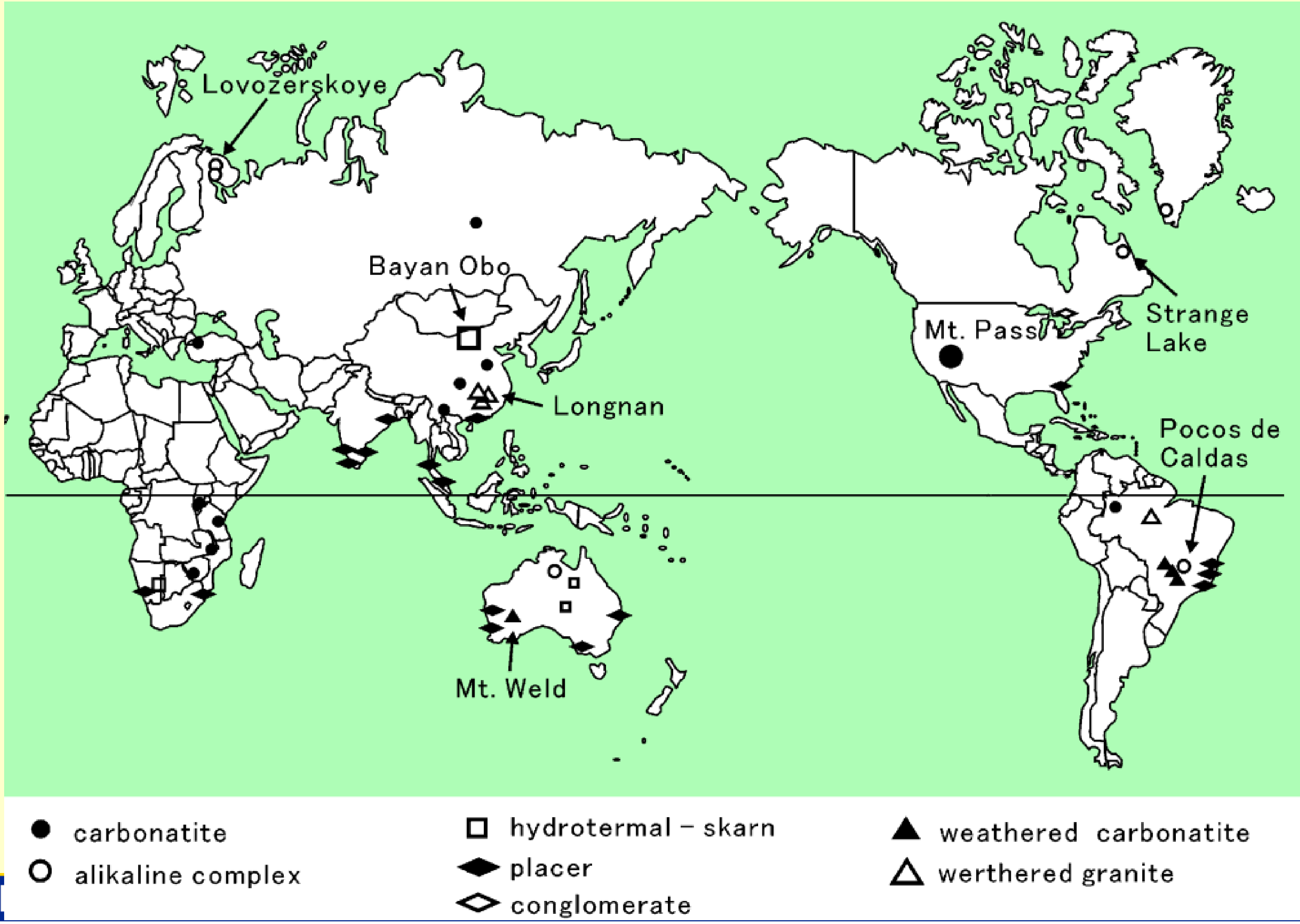
Rare Earth pure metals: about 97%

China Dominates Magnet Materials

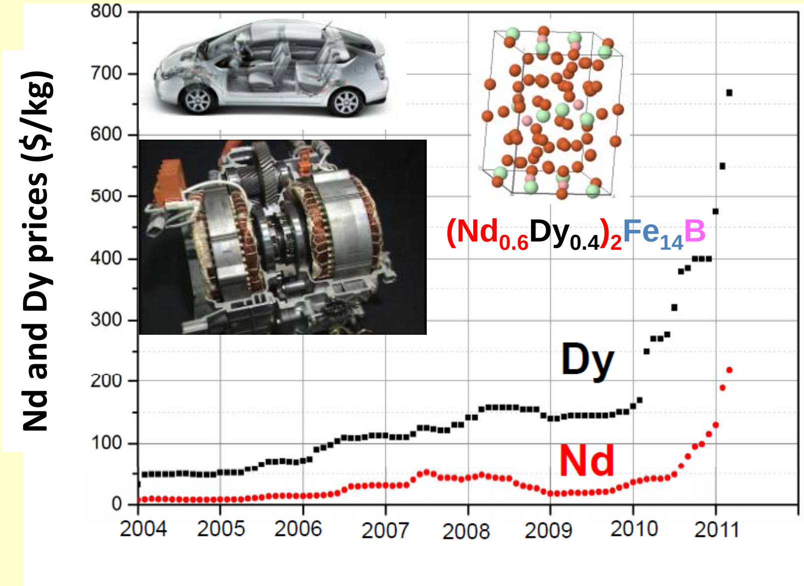


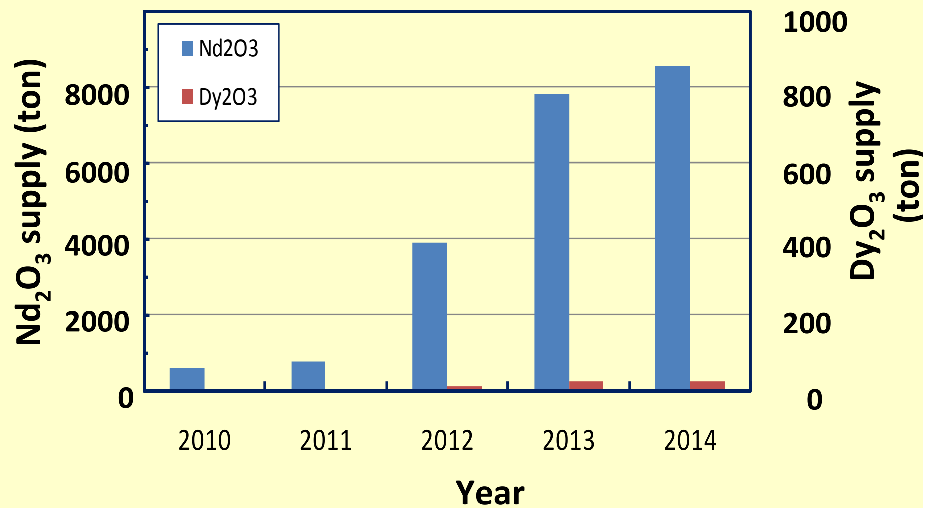
In the 60s, US was the number one in R&D of Permanent Magnets. Today we are the last!

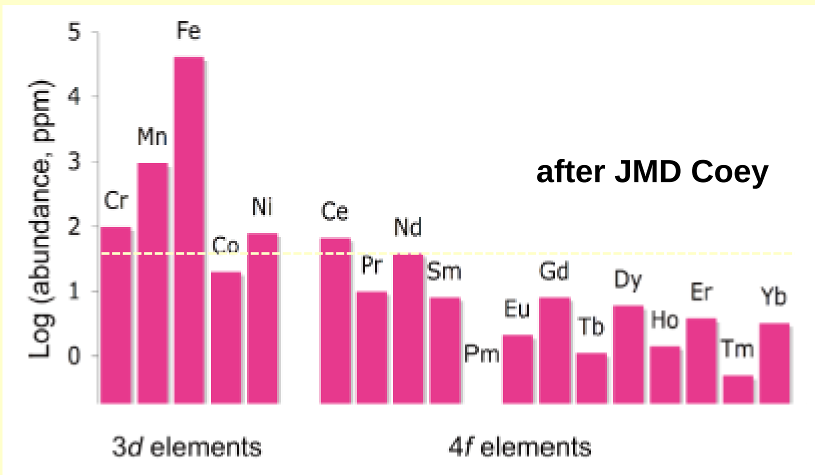
Rare Earth Deposits

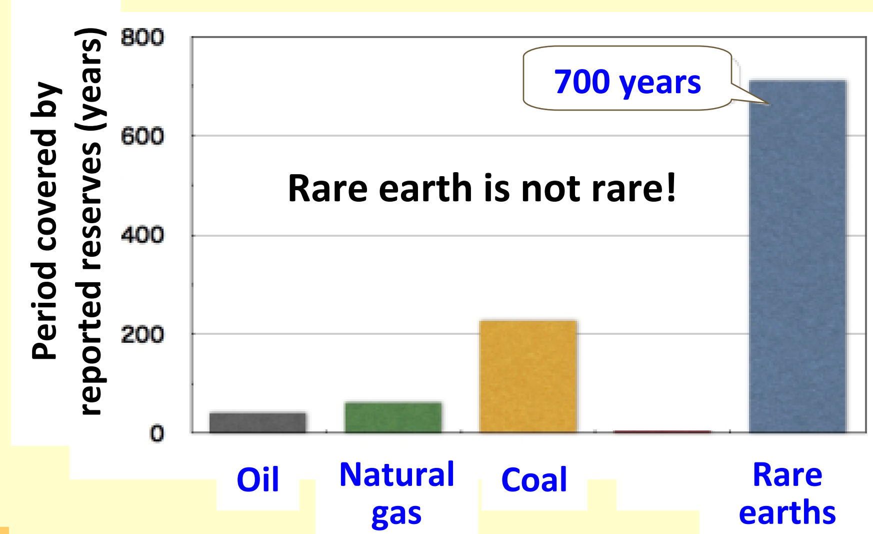


Supply and Availability of Nd and Dy



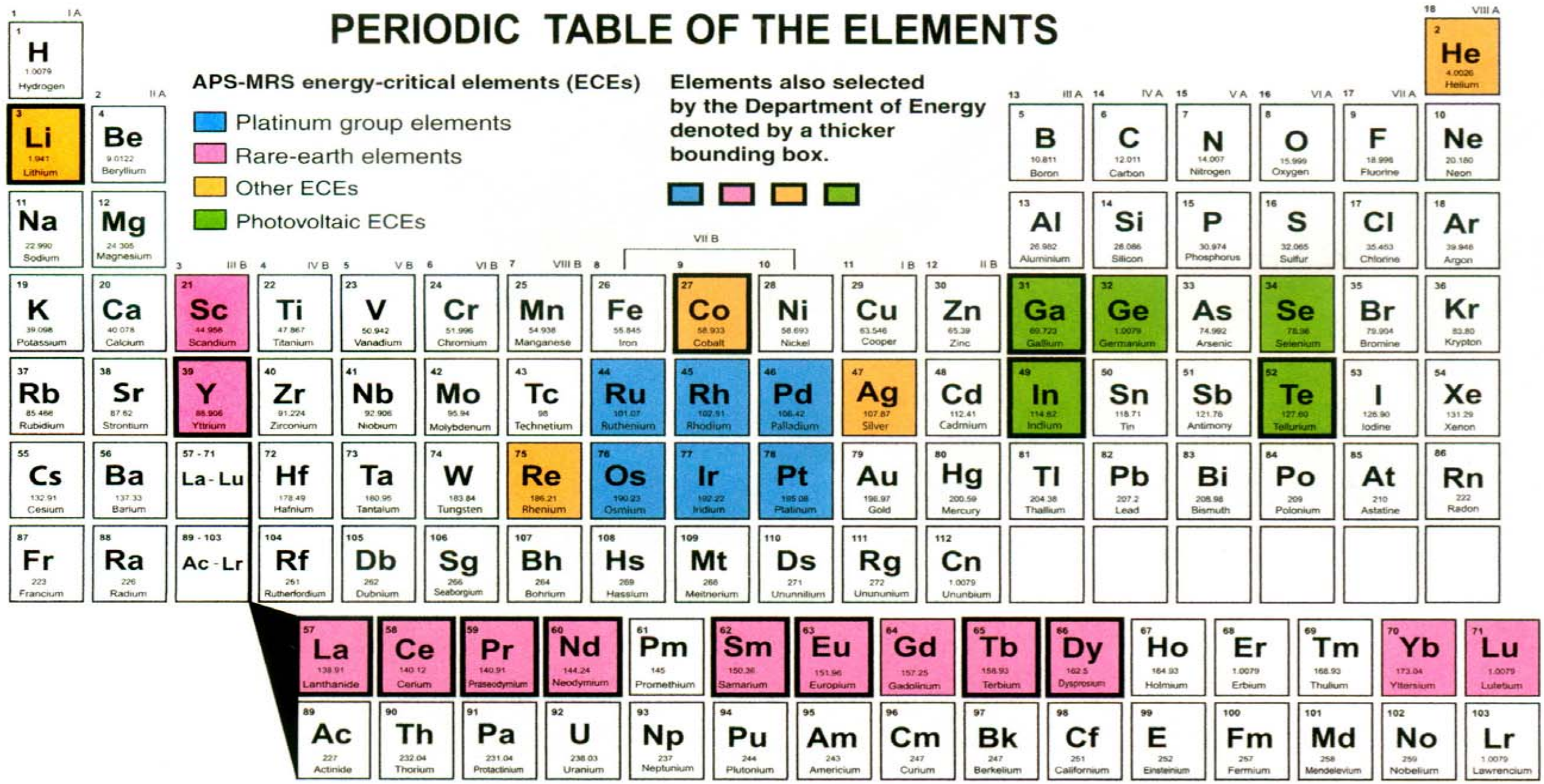






http://homepage3.nifty.com/bs3/Magnet/

Critical Elements

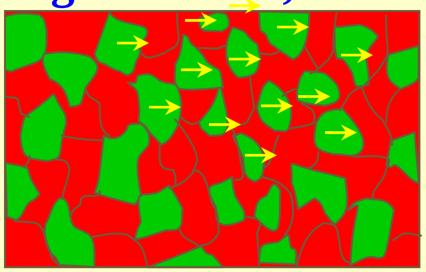


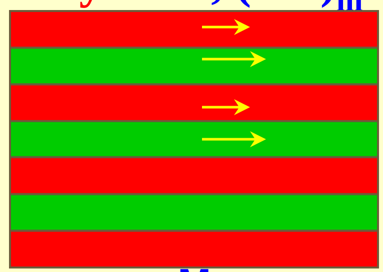
Critical elements chosen by the American Physical Society (APS)–Materials Research Society (MRS) energy-critical element study panel[1] and by the U.S. Department of Energy Office of Energy Policy.[3,4] Selection criteria differed in the two studies, leading to 29 elements for the APS–MRS and 14 elements for the U.S. Department of Energy.

Nanocomposite Magnets: Next Generation of Magnets?

- Consist of a fine mixture of exchange-coupled soft and hard phases. The soft phase provides the high magnetization and the hard phase the high coercivity. RE Lean!
- For optimum exchange coupling, the size of soft is $D_s=2\,\delta_w^{\,h}$ (10 nm for Nd-Fe-B).
  Kneller et.al., IEEE Trans. Magn., 1991)
- Exchange coupling leads to an enhanced remanence and therefore higher $(BH)_m$. According to models, Skomski&Coey 1993, $(BH)_m$ can reach values over 100 MGOe!

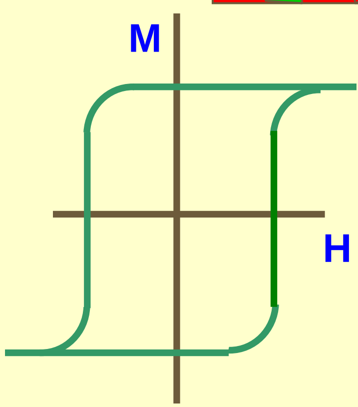
Bulk



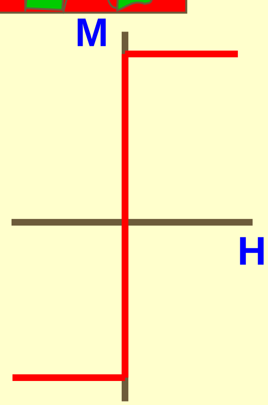


Multilayers

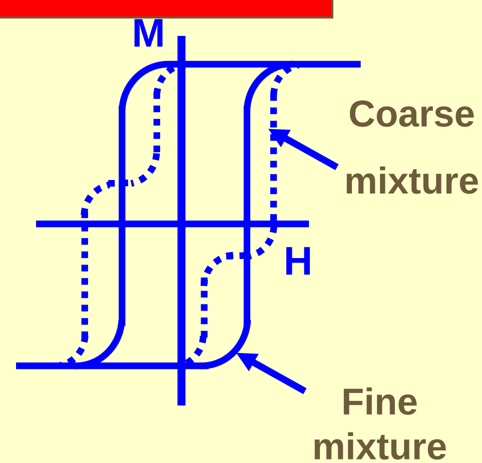
Fullerton et.al., JMMM,1999



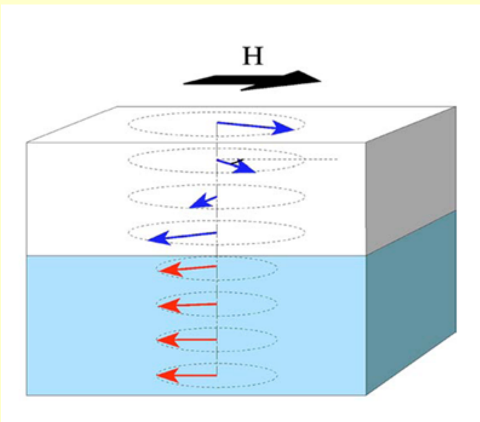
Hard Phase
High H_c



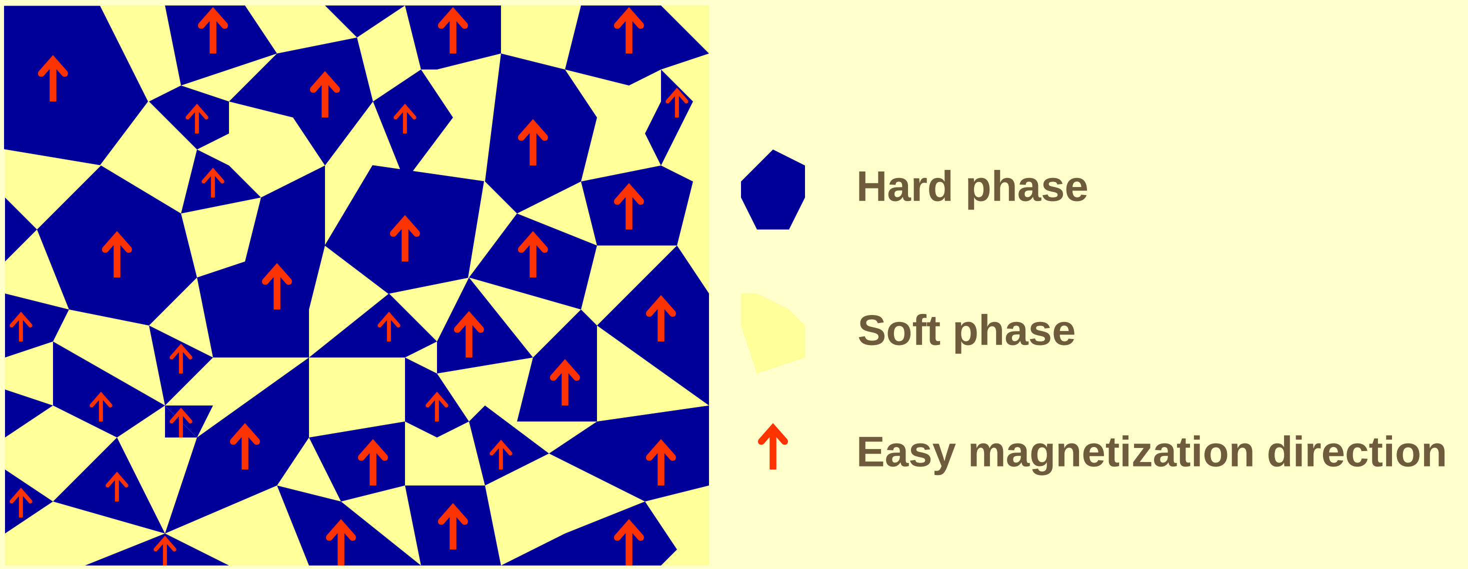
Soft Phase
High M_s



Hard + Soft

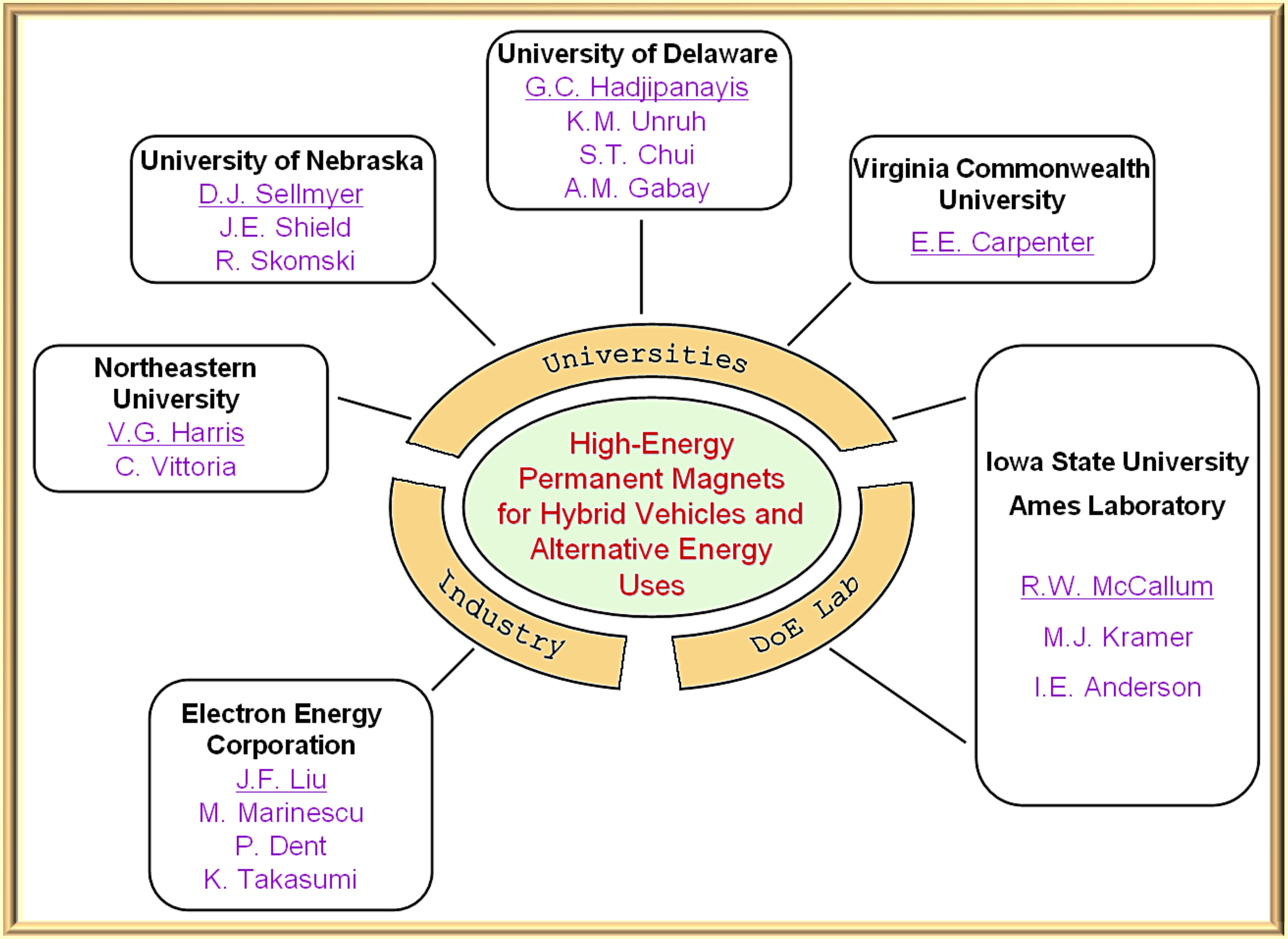


Anisotropic Nanocomposite Magnets: Challenges



- All top-down approaches so far failed to fabricate a nanocomposite magnet with the predicted properties.
- It is difficult to obtain fully aligned nanocomposites consisting of nano soft and hard phases with optimum properties.

Our DOE ARPA-E Project

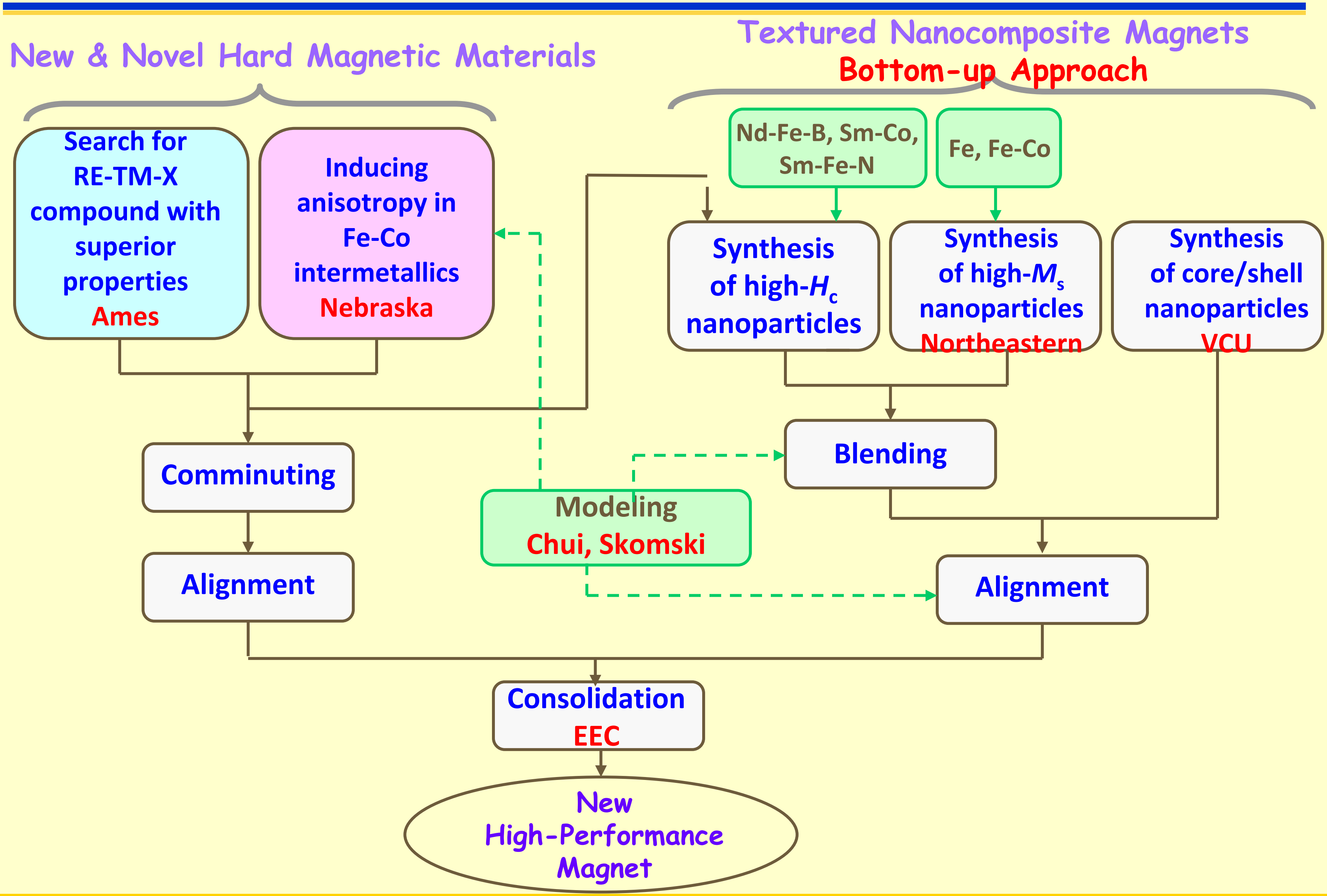


Project Objectives and Expected Impact

- ✧ The main objective is to develop/discover materials with **magnetic properties significantly better than those of Nd-Fe-B.**
- ✧ This must allow us to synthesize *the next generation high energy permanent magnets* with **potential energy products exceeding 100 MGOe**, about two times greater than those of the best available Nd-Fe-B magnets.

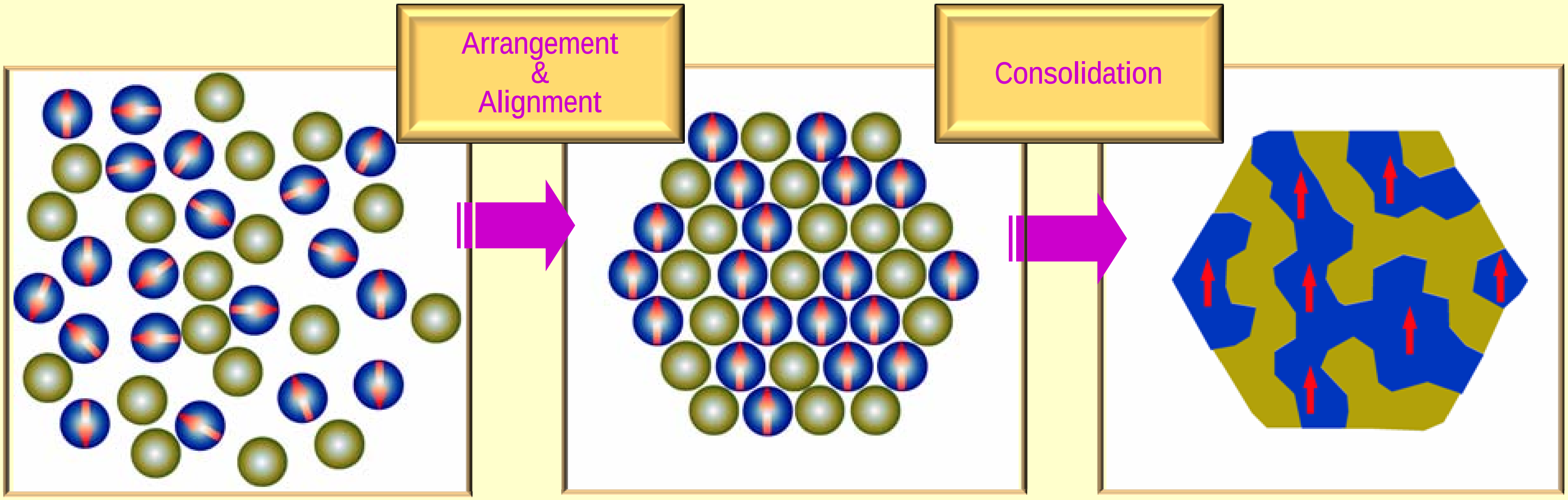
- ✧ The new nanocomposite magnets not only will contain a significantly lower amount of RE **(RE-Lean Magnets)** but will also allow the **development of smaller, lighter and much more energy efficient devices**.
- ✧ The project will also allow us to **educate the next generation of scientists and engineers** in this important and critical and revive the R&D efforts on PM in USA.

Our Current ARPA-E Projects



Fabrication of Nanocomposites from Nanoparticles

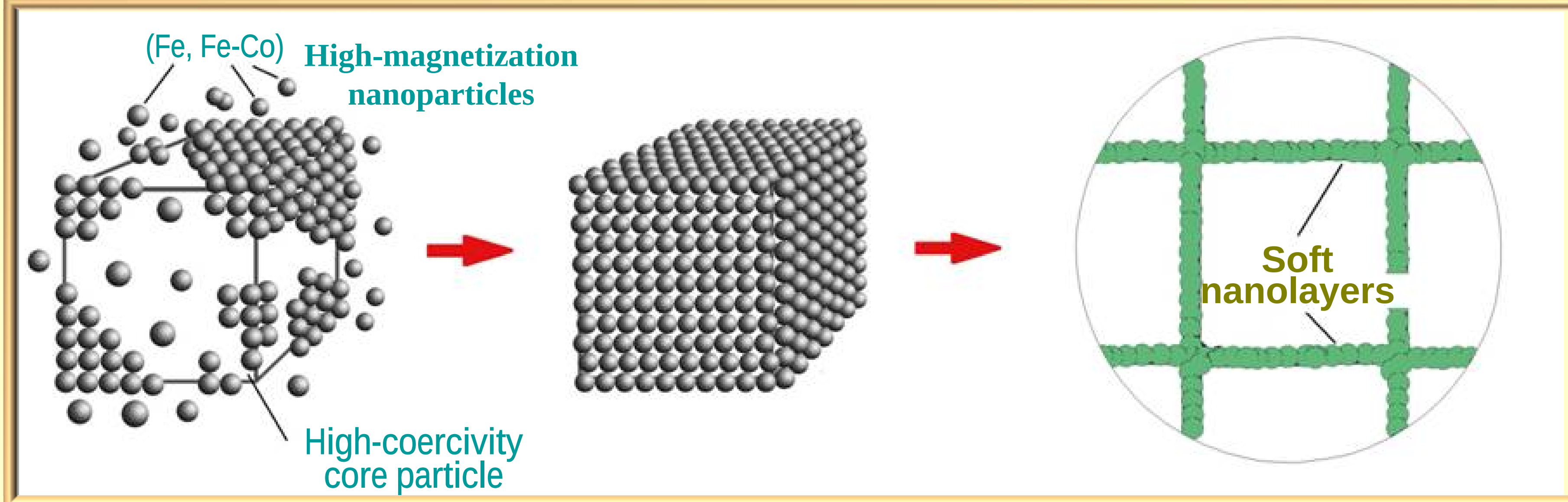
Concept of a "Bottom-Up" Approach



✧ **Particles must be single crystals with coercivity > 10 kOe for the hard and J_s>20 kG for the soft phase.**

Fabrication of Nanocomposite Magnets from Core/Shell Elements

- ✧ **Exchange-coupled composite magnets can be also built by coating the high-coercivity particles with the high-magnetization particles.**
- ✧ **This approach will assure a uniform distribution of the high-magnetization soft magnetic phase in the consolidated magnets.**



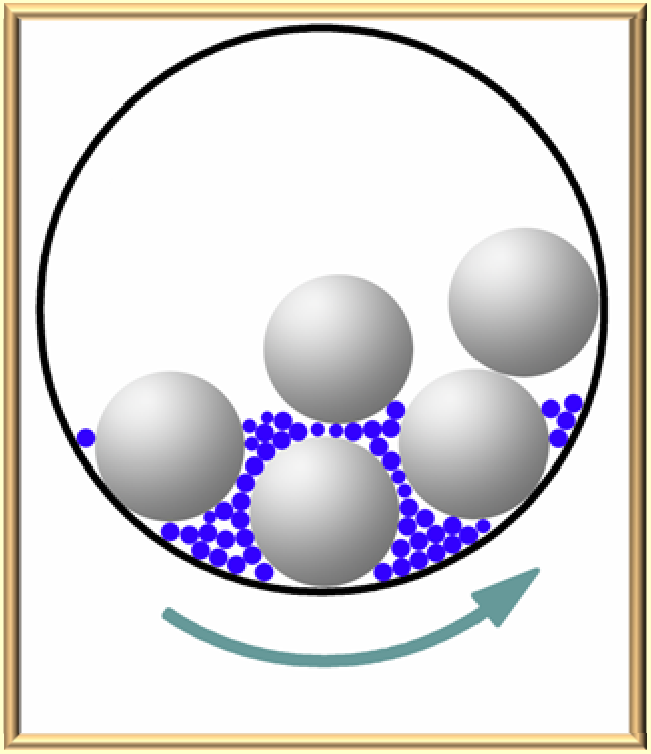
- ✧ **Both RE-Co nanoparticles and nanoflakes (with their large specific surface) may serve as the core hard magnetic particles.**

Fabrication of Nanocomposites from Nanoparticles

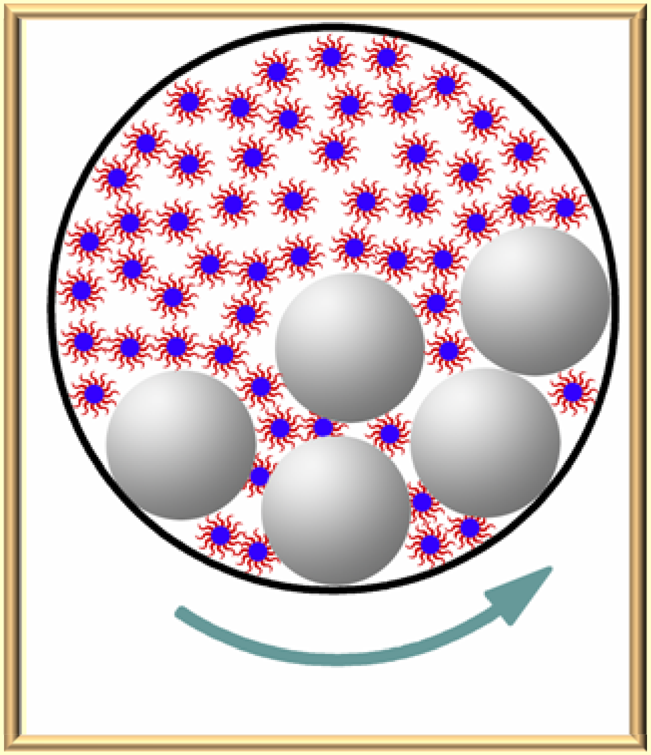
Synthesis of RE-TM Nanoparticles by Surfactant-Assisted Ball Milling

✧ **Surfactants allow milling proceed without simultaneous cold welding.**

Low-energy milling in heptane



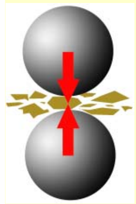
Low-energy milling in heptane with small amount oleic acid added



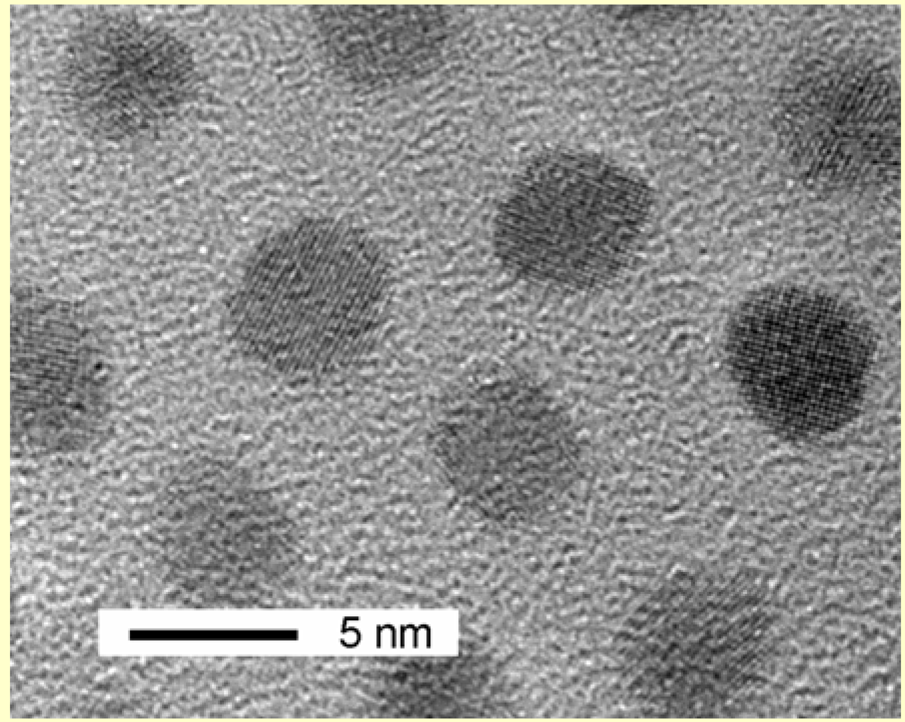
✧ **Technique can be easily scaled up and it can yield anisotropic powder.**

Fabrication of Nanocomposites from Nanoparticles

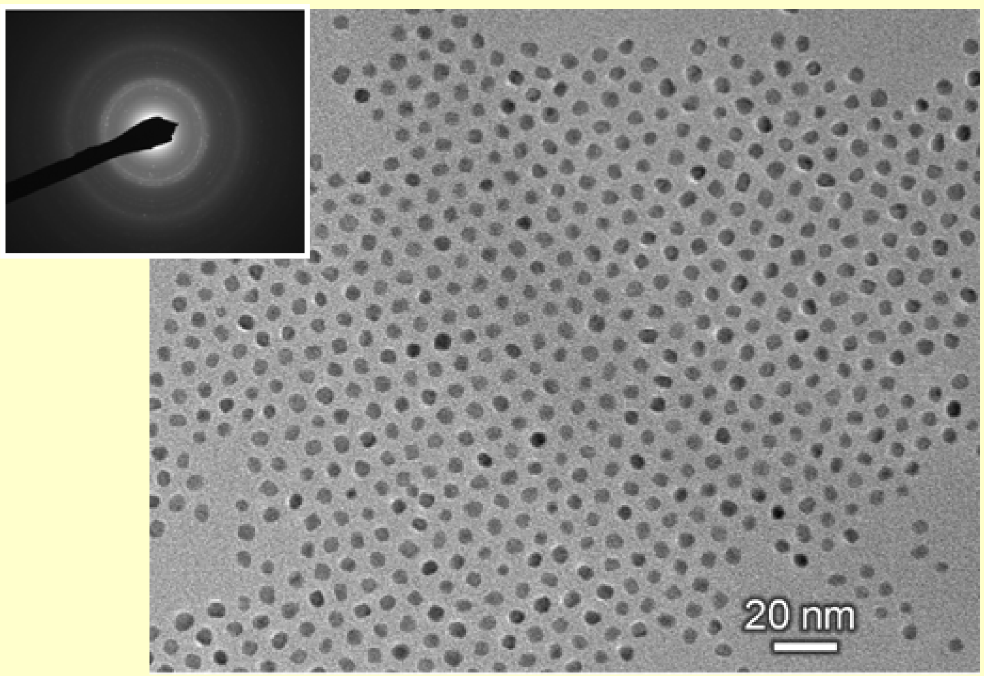
Synthesis of RE-TM Nanoparticles by Surfactant-Assisted Ball Milling



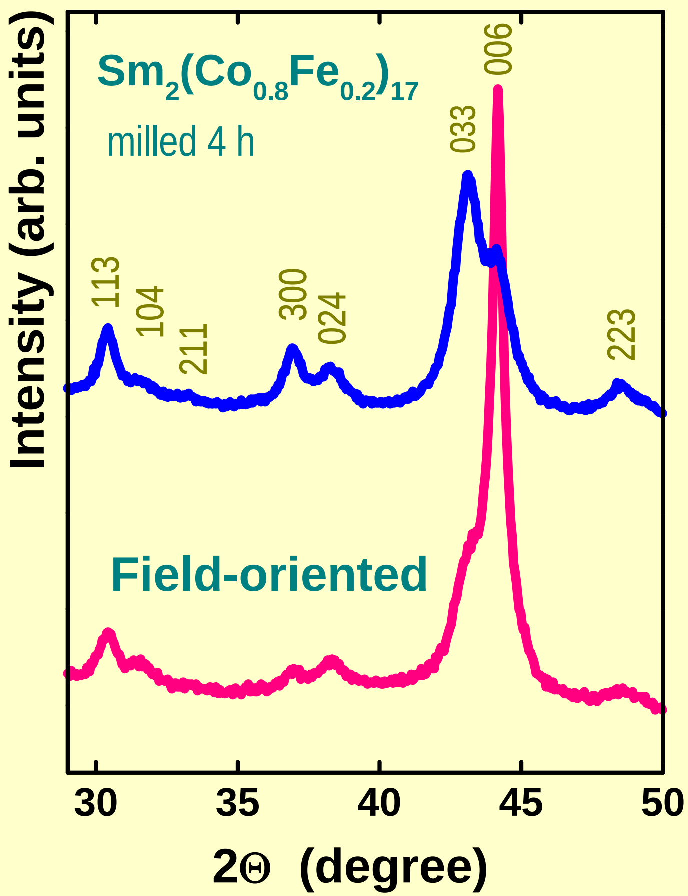
- **High-energy milling with surfactants produced highly uniform $Sm_2(Co,Fe)_{17}$ nanoparticles.**

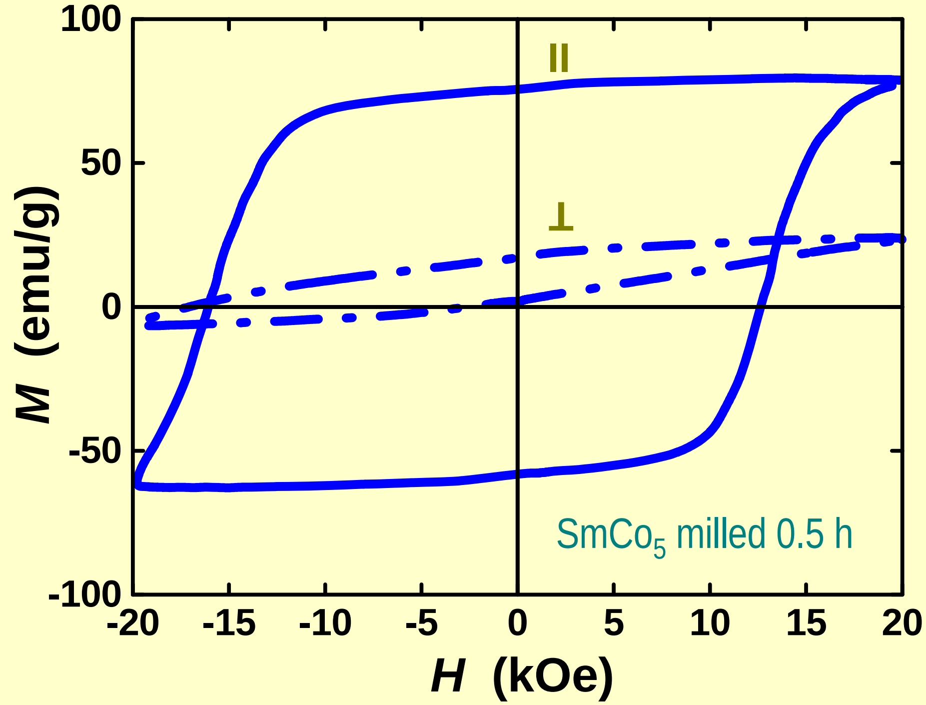


High-energy milling for 4 hours, no washing



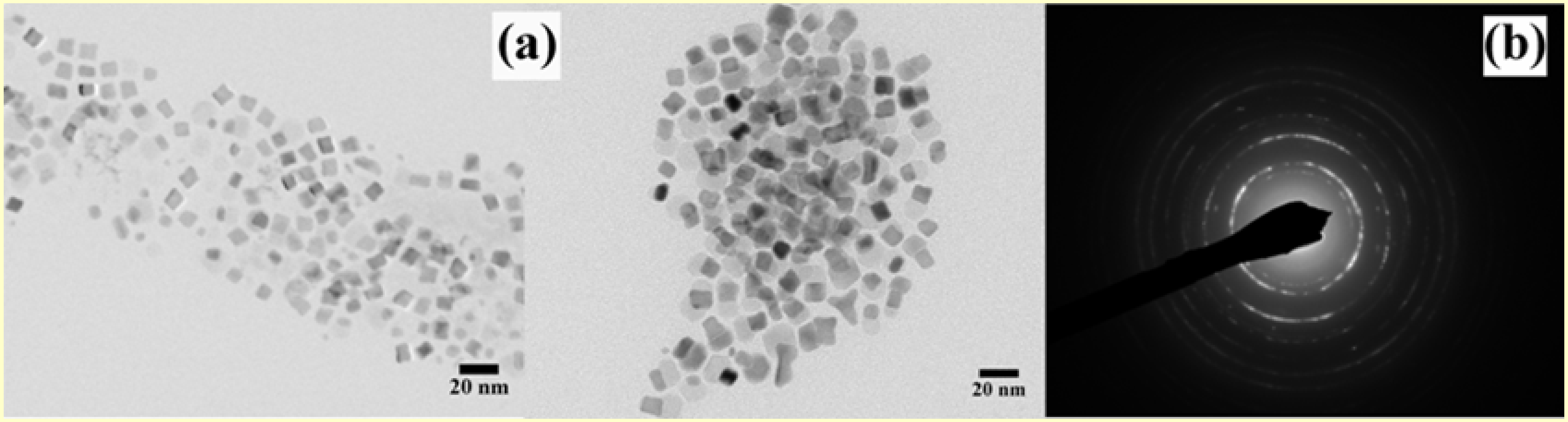
Synthesis of Hard Magnetic Sm-Co Nanoparticles

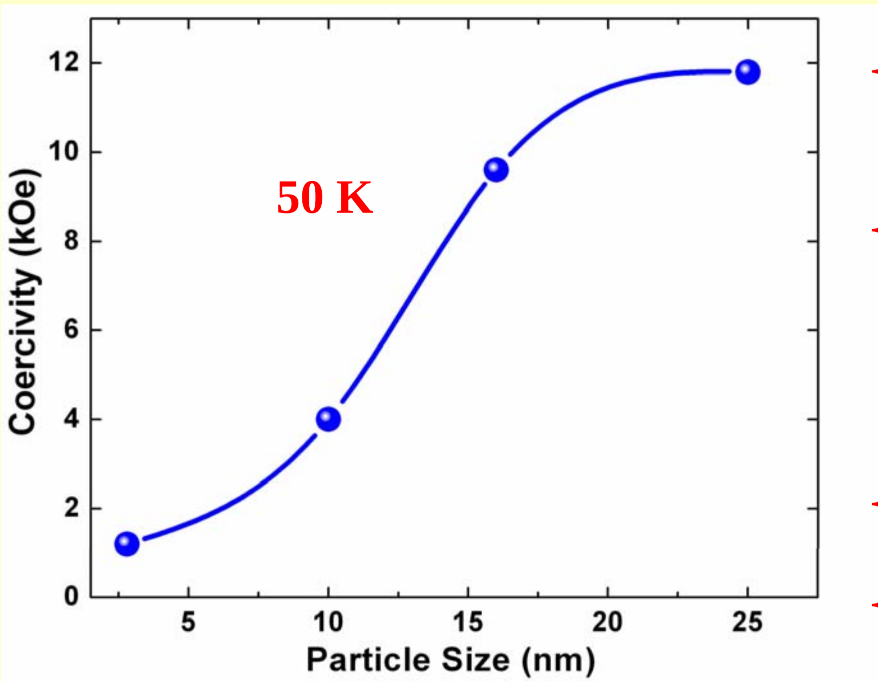




- Single crystal $Sm_2(Co,Fe)_{17}$ and $SmCo_5$ nanoparticles can be produced by HEBM with high coercivity.

Square Nd-Fe-B Particles

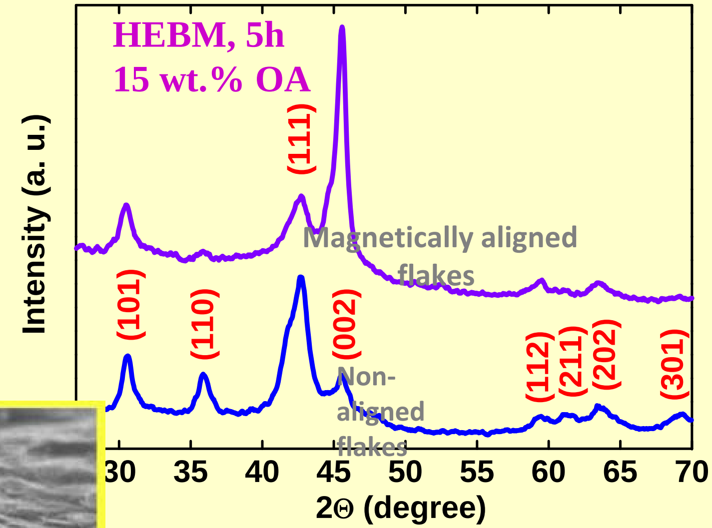


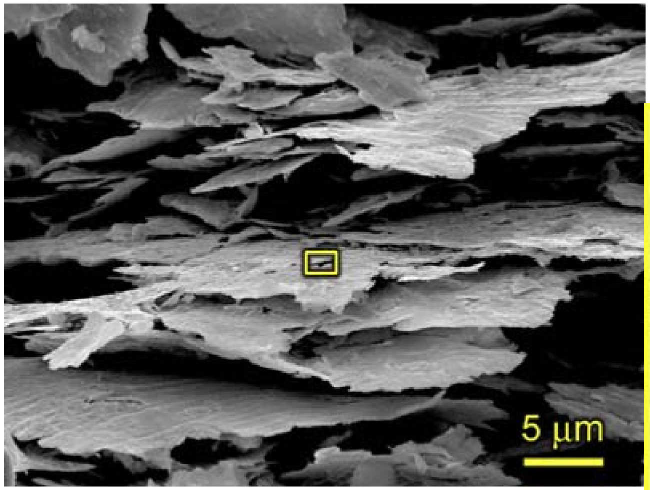


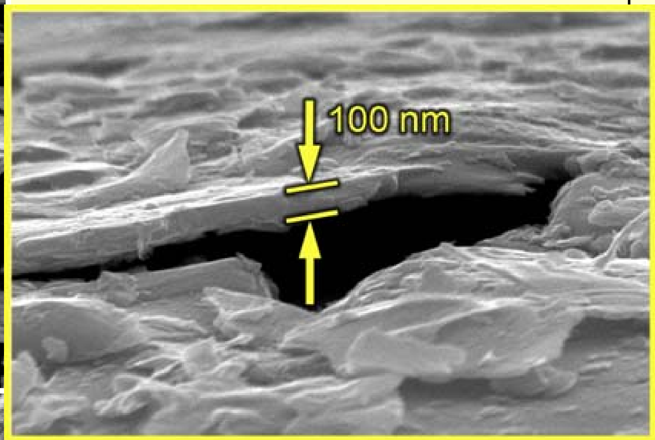
- A strong dependence of coercivity on particle size is observed.
- The reason for this behaviour could be attributed to thermal effects and to a reduced magnetocrystalline anisotropy because of surface effects.
- Highest coercivity obtained at RT is 4 kOe.
- Ongoing research is focused on the fabrication of larger particles.

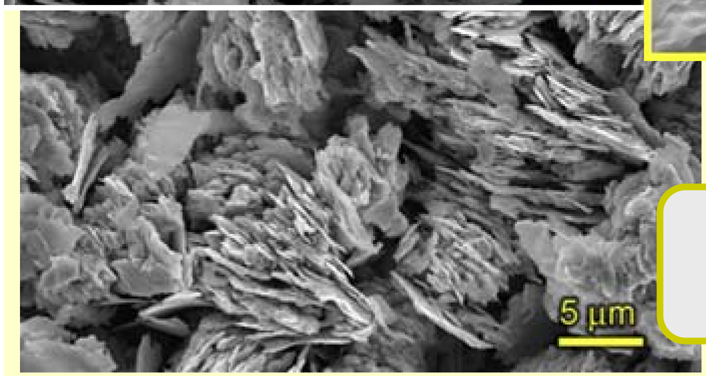
Anisotropic $SmCo_5$ Nanoflakes via Single Surfactant-Assisted HEBM

- $SmCo_5$ coarse powders subjected to surfactant-assisted HEBM can evolve into (001) textured and magnetically anisotropic flakes tens of nm thick.
- The flakes are ideal for coating with soft Fe.

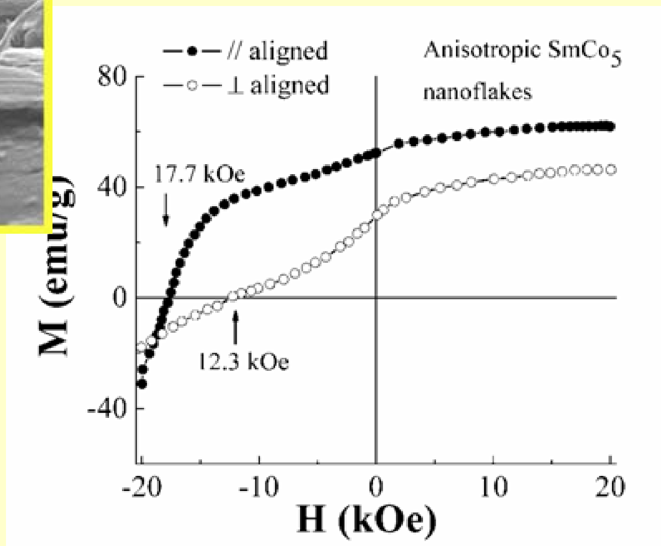








"Kebab-like" morphology

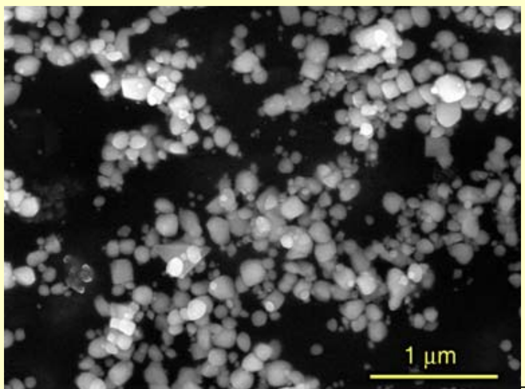


Sm-Co and Nd-Fe-B Nanoparticles by Mechanochemical Synthesis

✧**Chemical reactions activated by the high levels of mechanical energy occur at the surfaces/interfaces of the nanometer-sized grains** **which are continuously regenerated during milling. This allows reduction/diffusion to** **proceed** **<u>at low temperatures</u>.**

✧ **For the first time we produced high H_c Nd-Fe-B nanopaticles with this technique!**

Sm-Co

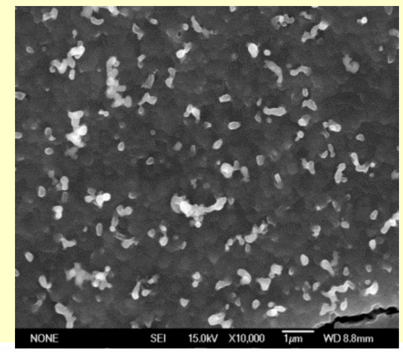


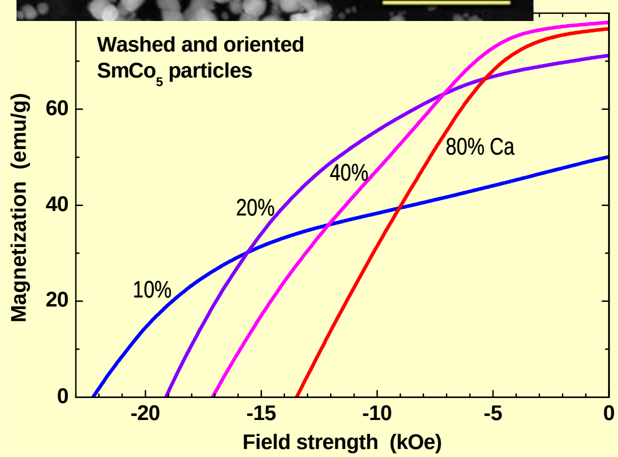
$$Nd_2O_3 + 14Fe + B + 3Ca \rightarrow Nd_2Fe_{14}B + 3CaO$$

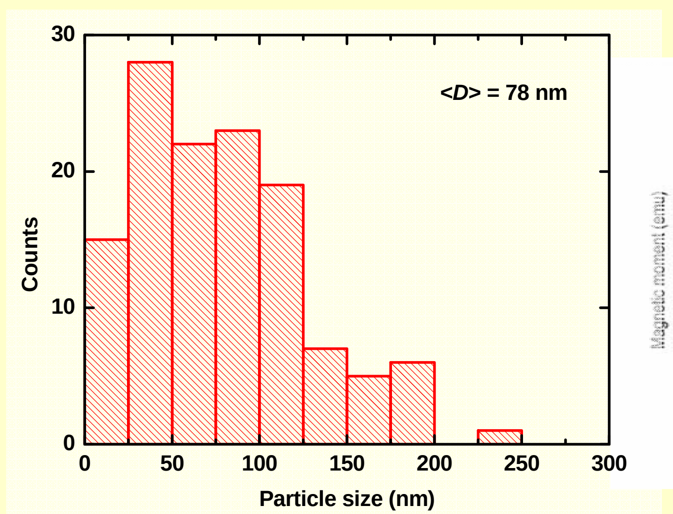
$$Sm_2O_3 + 10CoO + 13Ca \rightarrow 2SmCo_5 + 13CaO$$

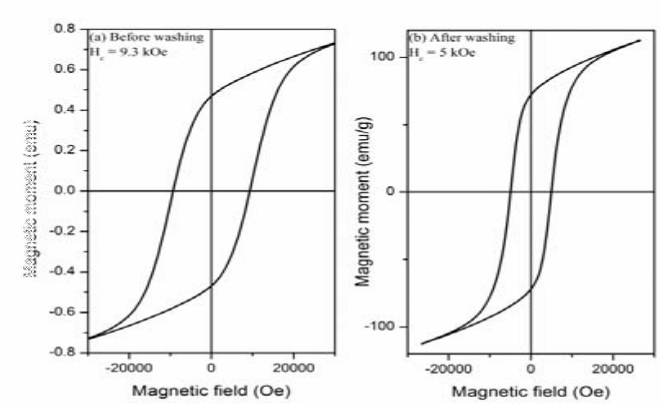
$$Sm_2O_3 + 17CoO + 20Ca \rightarrow Sm_2Co_{17} + 20CaO$$

Nd-Fe-B





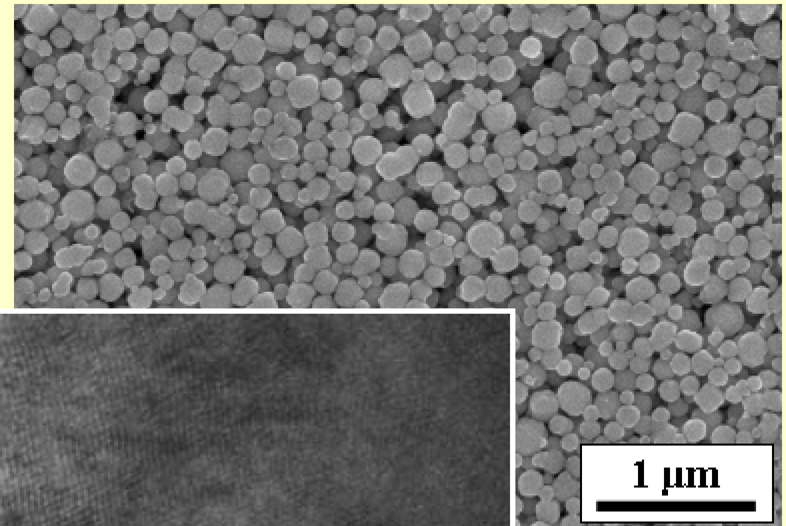


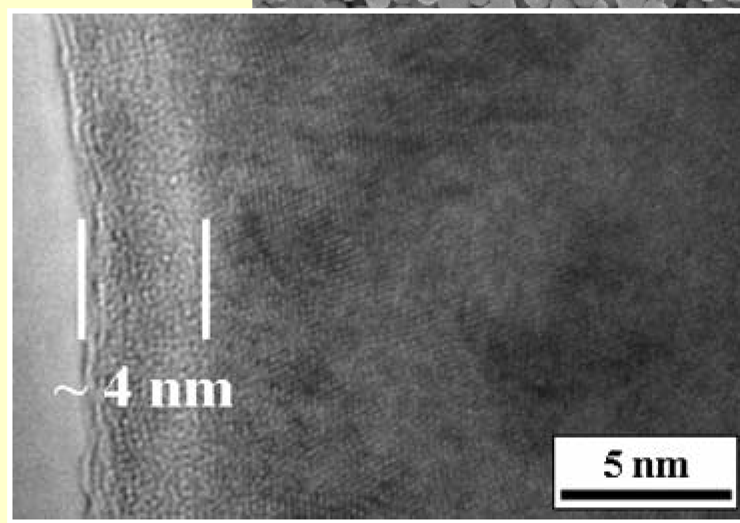


Fe(Co) Nanoparticles with High Magnetization

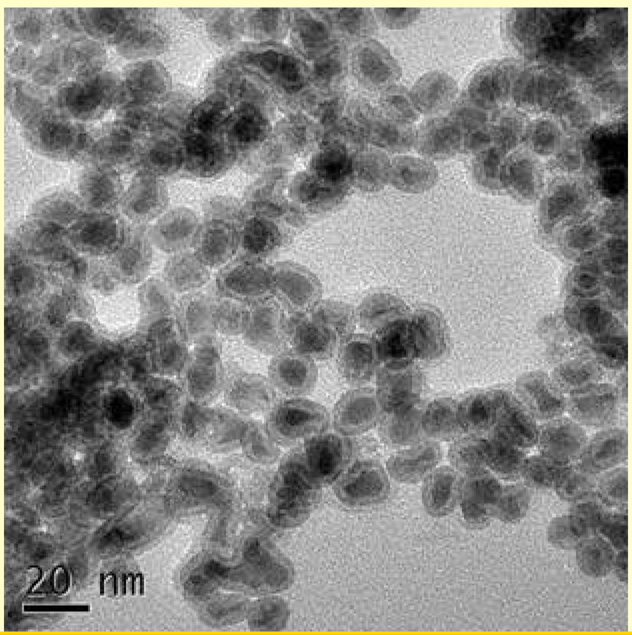
- ✧ **The University of Delaware group (Prof. K.M. Unruh) used reduction in the presence of citrate ions to produce Fe particles smaller than 30 nm with M_s > 175 emu/g which are assembled into in ≈100 nm aggregates.**
- ✧ **A 4 nm passivation layer surrounding the aggregates makes them air-stable without diluting the M_s.**

Spherical aggregates of Fe nanoparticles and surface passivation layer





$Fe_{50}Co_{50}$ nanoparticles with a surfactant shell



- ✧ **The Northeastern University group (Prof. V.G. Harris) used a modified polyol reaction method to produce Fe-Co (≈ $Fe_{50}Co_{50}$) particles 20 - 25 nm with M_s ≈ 200 emu/g.**

Hard Cubes in Soft Matrix

Micromagnetics: Monte Carlo (Chui)

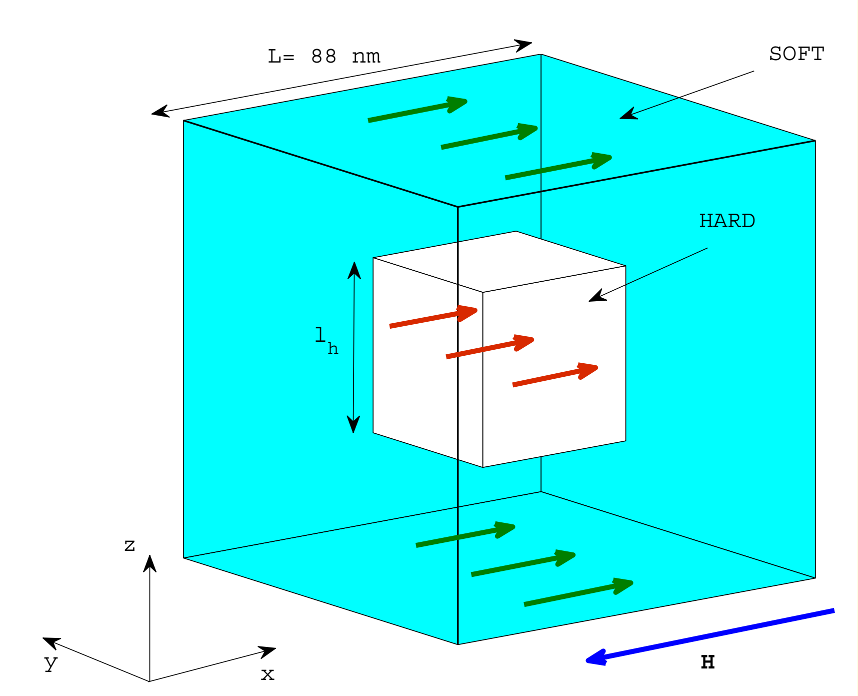
$$U = U_d + U_{ex} + U_{an} + U_m, \quad (5)$$

$$U_{an} = -\sum_{\mathbf{R}_a} K_a (S_a^z)^2, \quad U_m = -\sum_{\mathbf{R}_a} M_a S_a^z H^z \quad (6)$$

$$U_d = \frac{1}{2} \sum_{\mathbf{R}_a, \mathbf{R}_b}' V_d(\mathbf{R}_{ab}), \quad (1)$$

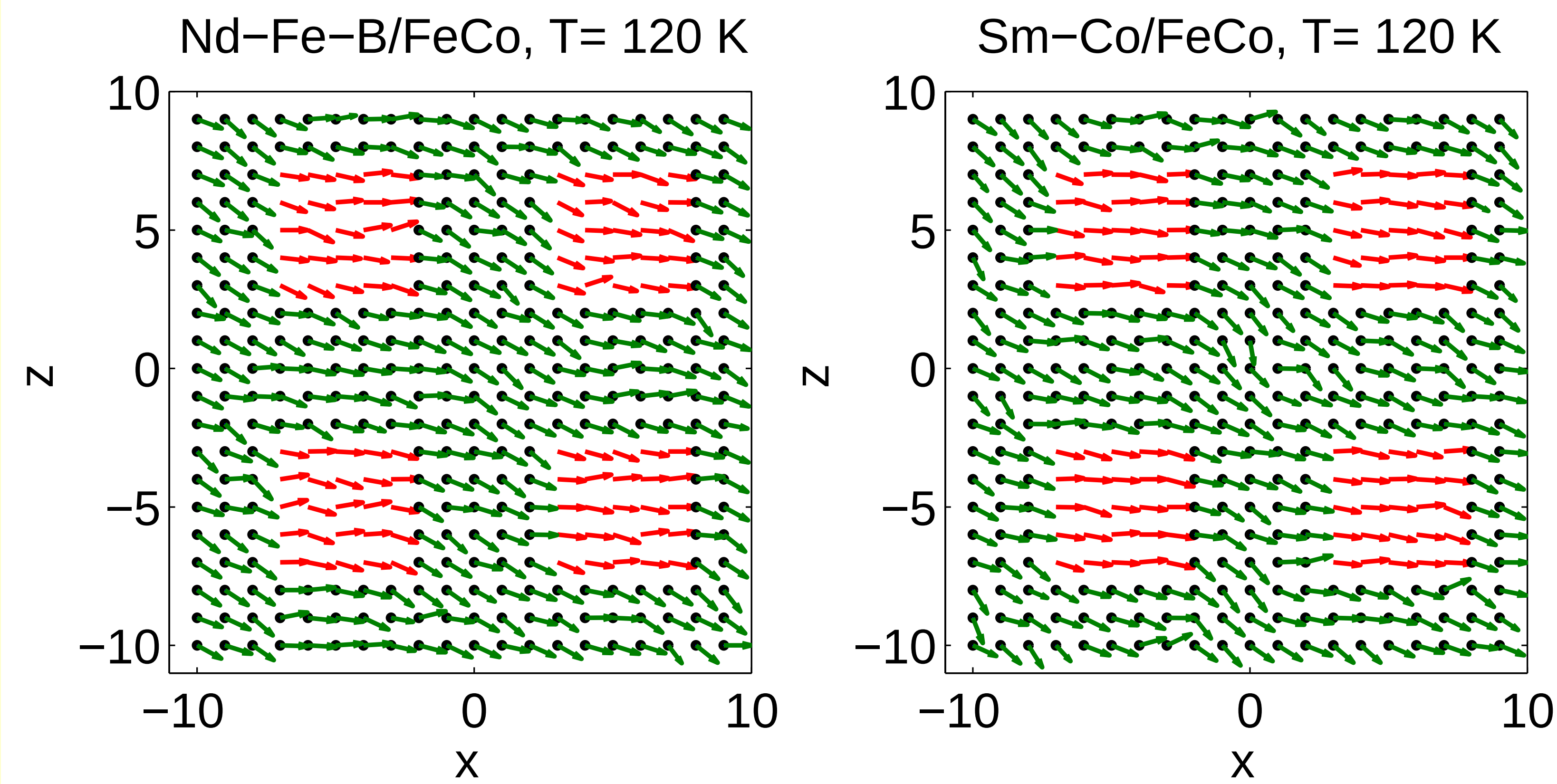
$$V_{ex}(\mathbf{R}_{ab}) = -J_{ab} (\mathbf{S}_a \cdot \mathbf{S}_b)\, \delta_{\mathbf{R_b}, \mathbf{R_a} + \mathbf{d}} \quad (4)$$

$$V_d(\mathbf{R}_{ab}) = g_{ab} \left(\frac{(\mathbf{S}_a \cdot \mathbf{S}_b)}{R_{ab}^3} - \frac{3 (\mathbf{S}_a \cdot \mathbf{R}_{ab})(\mathbf{S}_b \cdot \mathbf{R}_{ab})}{R_{ab}^5} \right) \quad (2)$$



Theoretical Modeling-Monte Carlo (Chui, UD)

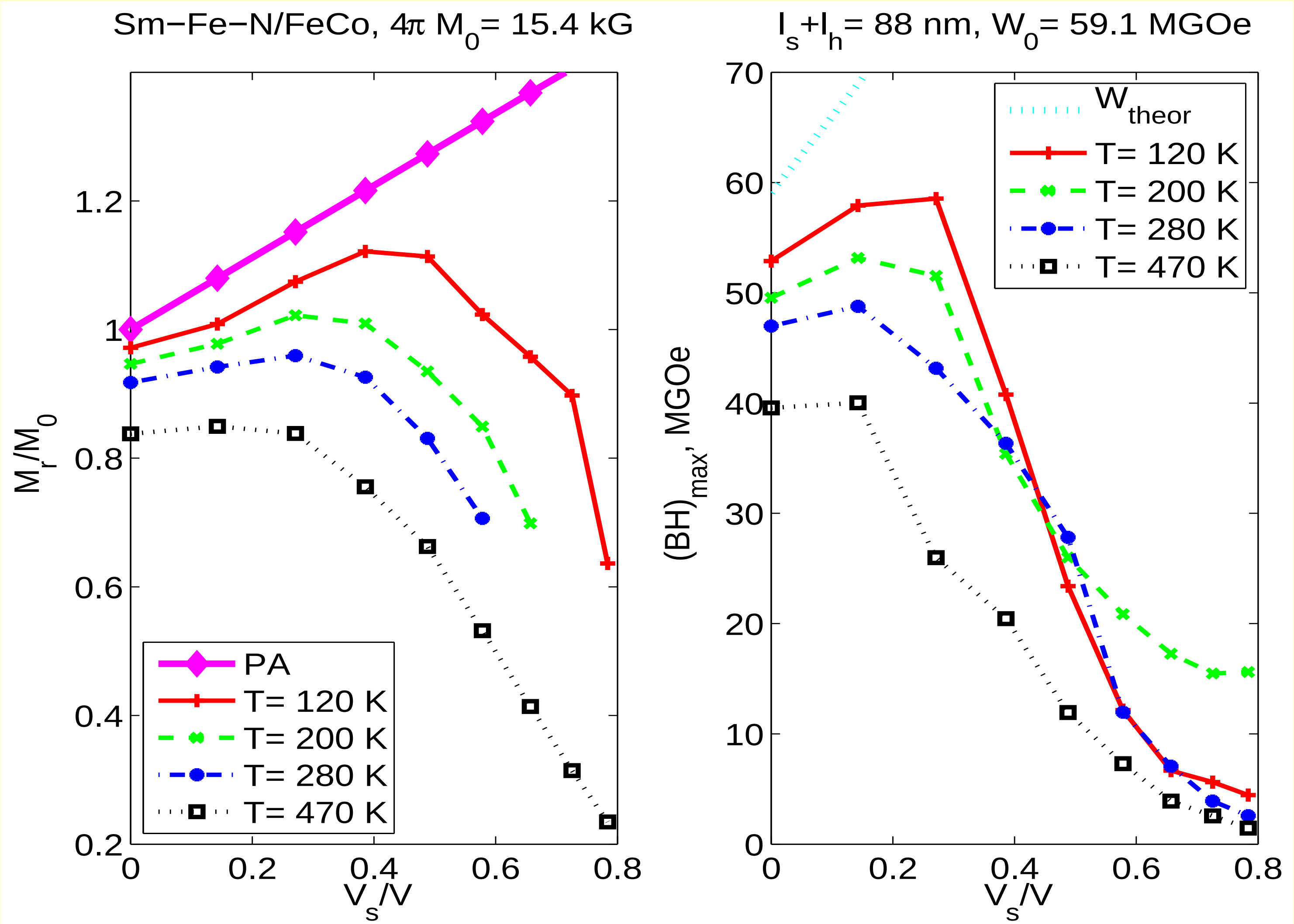
Hard cubes in a soft matrix



✧At the soft/hard interface div **M** is not zero (M_s^{Fe-Co},=24kG, M_s^{Sm-Co} =11 kG) and this leads to free poles at the interfaces.

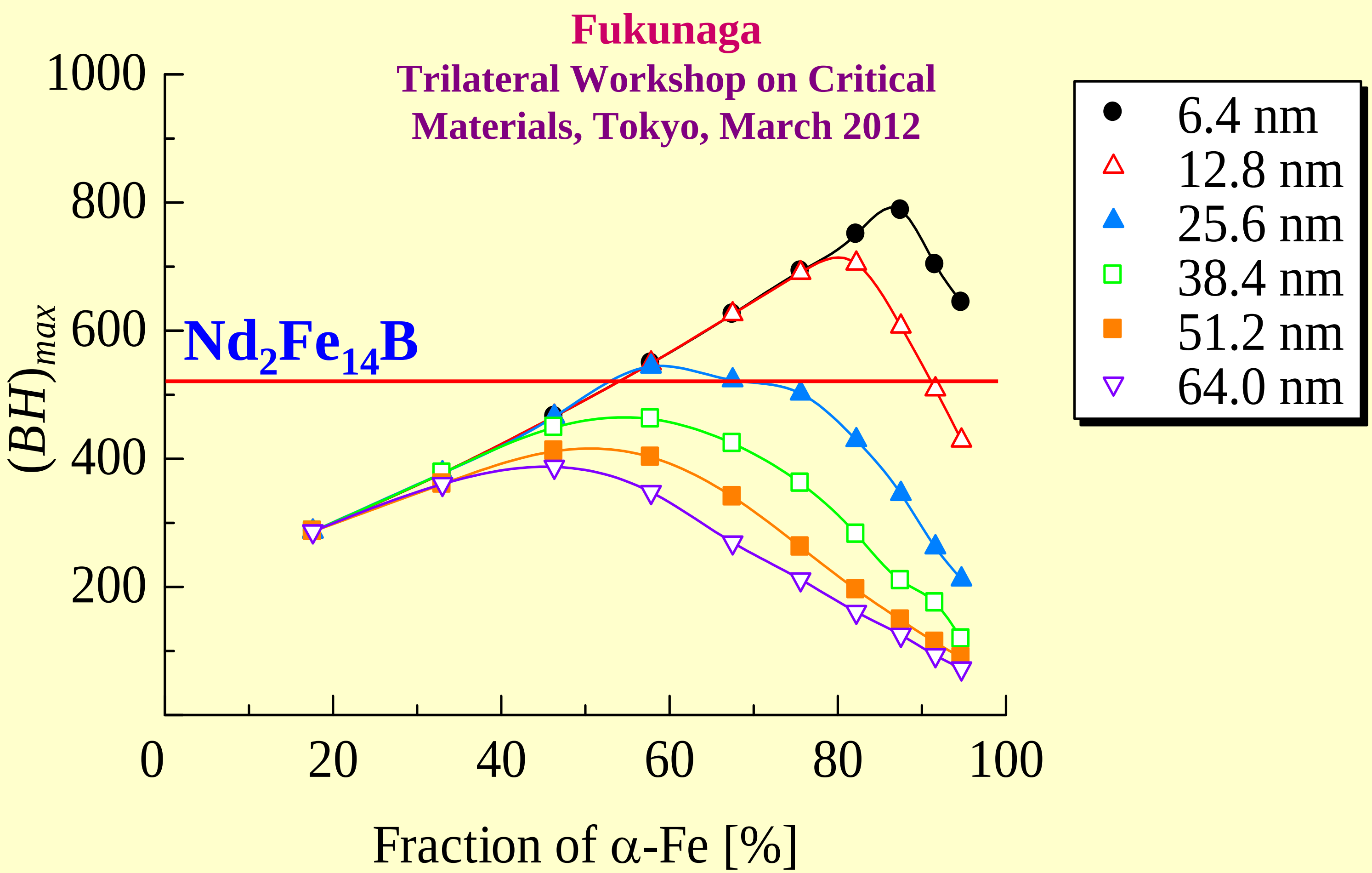
✧Preliminary data indicate that magnetostatic coupling leads to enhancement of thermal fluctuations that lead to a decrease of remanence at high T.

M_r and $(BH)_m$ Versus the Amount of Soft Phase (Chui, UD)



- M_r and therefore $(BH)_m$ do not increase drastically with the addition of soft phase.
- We are currently examining the case of a graded interface.

4. $SmCo_5/\alpha$-Fe Core-Shell Nanocomposite Magnets

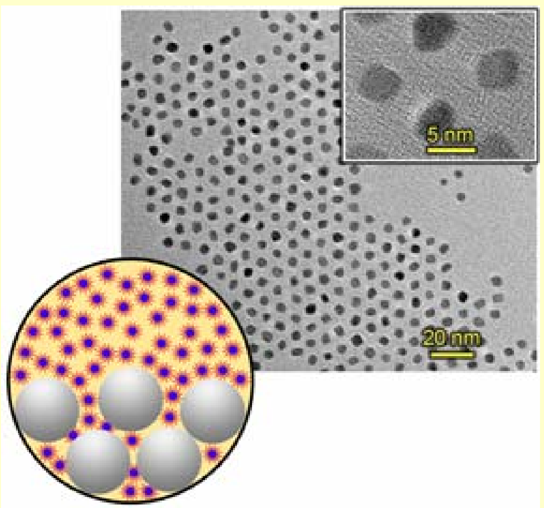


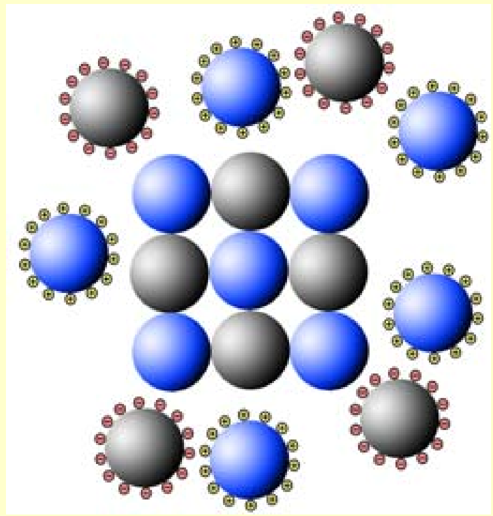
✧ **Fukunaga predicted a drastic increase in *(BH)*$_{max}$ of $SmCo_5/\alpha$-Fe as a function of α-Fe fraction.**

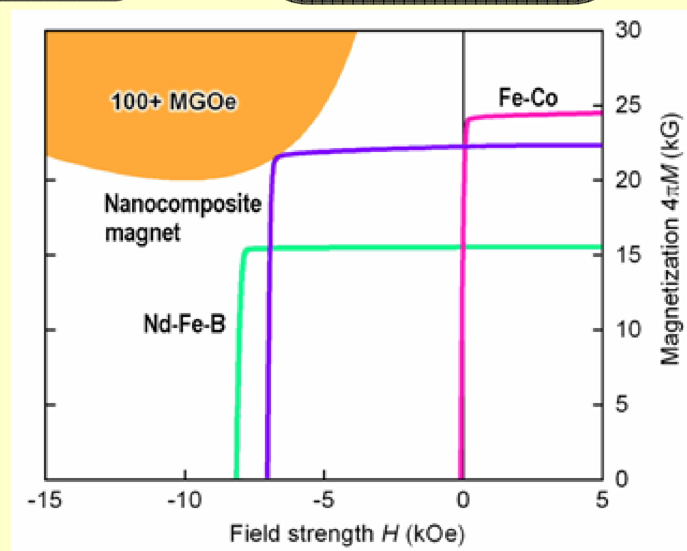
Ongoing Projects at the University of Delaware

New Material Discovery / Synthesis → Nanoparticle Synthesis → Arrangement, Alignment and Consolidation → Up to 100 MGOe Permanent Magnet

New Material Discovery / Synthesis → Up to 100 MGOe Permanent Magnet





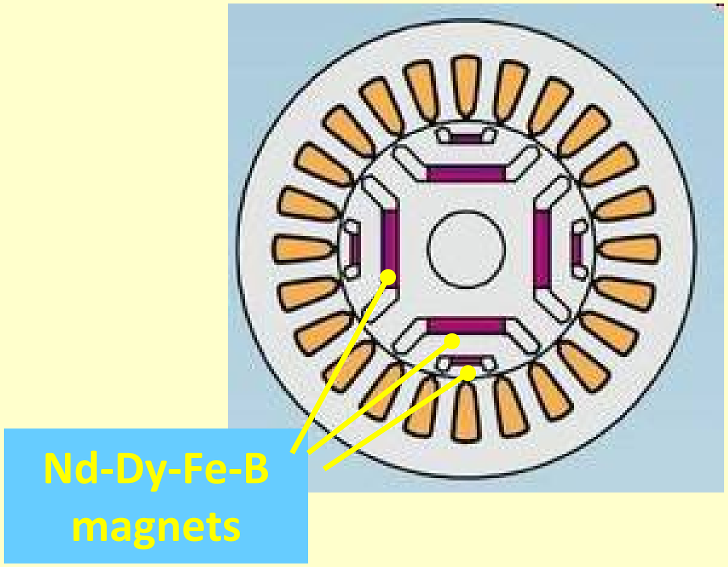


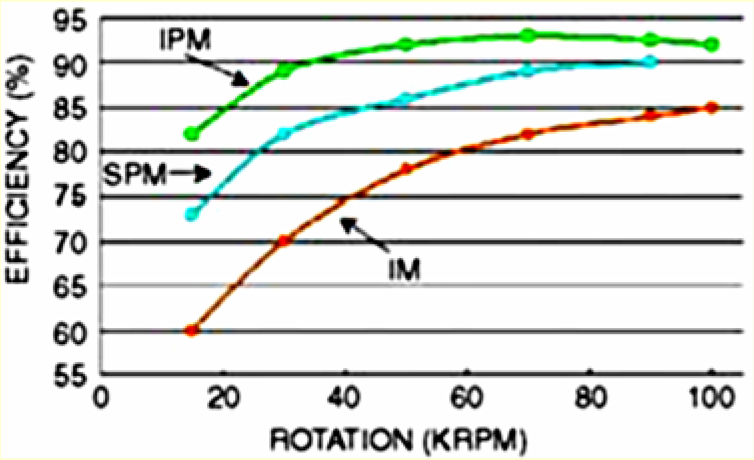
- ✧ **Synthesis of hard magnetic nanoparticles via surfactant-assisted HEBM.**
- ✧ **Synthesis of soft magnetic nanoparticles via chemical routes.**
- ✧ **Arrangement of the hard and soft magnetic nanoparticles assisted by surface functionalization.**
- ✧ **Nanocomposite magnets combining the high coercivity of the hard magnetic phase and the high magnetization of the soft magnetic phase.**

Dy Problem: Motors for HEV Contain Nd-Dy-Fe-B Magnets

✧Electrical motors for the drive-train of HEVs and EVs are required to have a high starting torque and a constant-power over a wide range of speeds.

✧At the present, there requirements are best met by the Interior Permanent Magnet Synchronous Motors (IPMSMs) in which powerful permanent magnets (almost exclusively Nd-Dy-Fe-B) are embedded deep into the rotor.





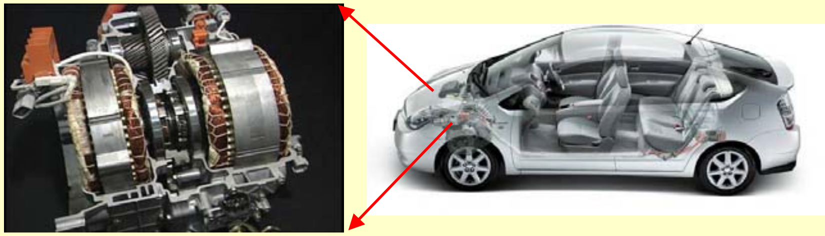
Y. Matsuura. *J. Magn. Magn. Mater.* 303 (2006).

✧ In the IPMSM design, the permanent magnets are subjected to strong demagnetizing fields and moderately high temperatures.

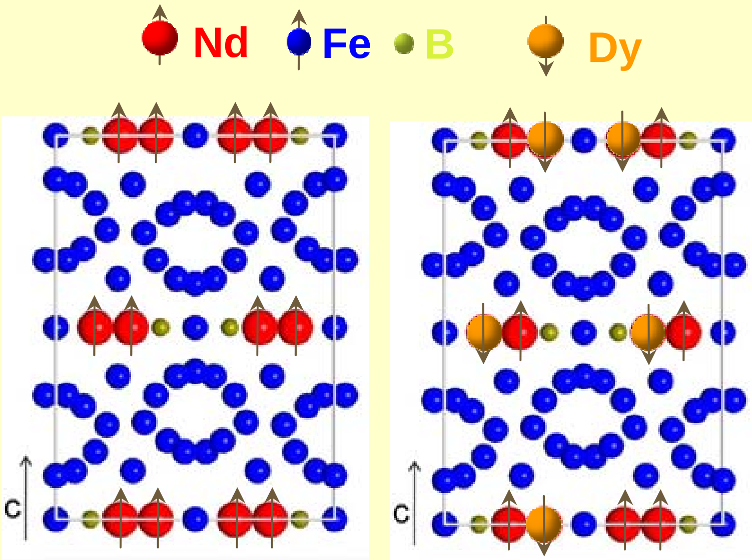
✧ Thus, the magnets must have a high coercivity and an operating temperature of at least 200 ºC. This is presently done with Dy-containing Nd-Dy-Fe-B magnets.

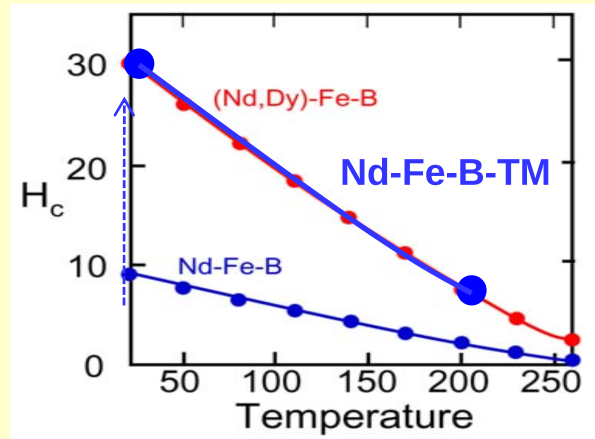
✧ Dy is among the most scarce REs!

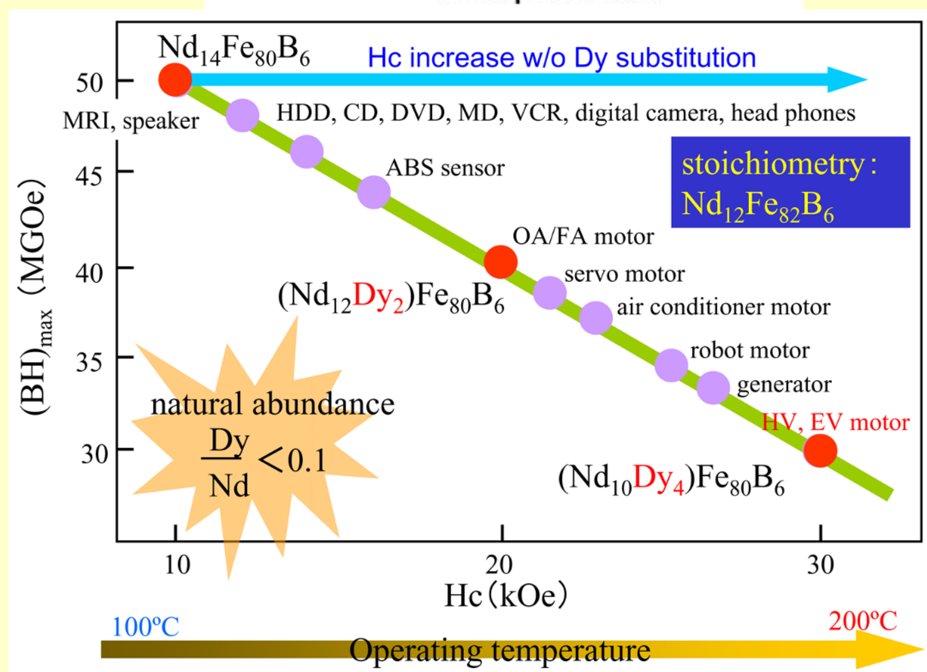
Permanent Magnets for HV and EV



200°C



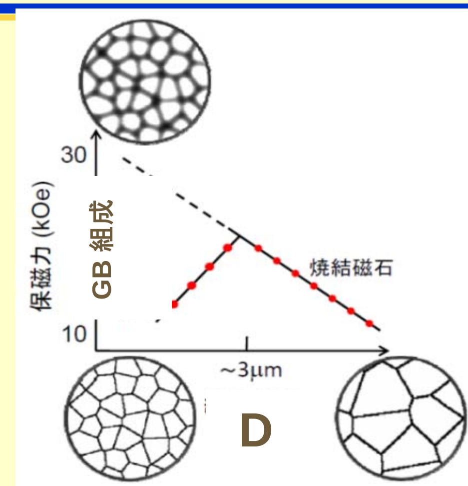




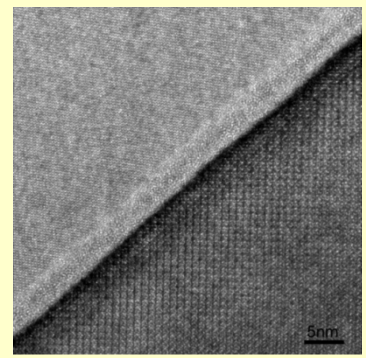
$K_u(Nd_2Fe_{14}B) < K_u(Dy_2Fe_{14}B)$
$J_s(Nd_2Fe_{14}B) > J_s(Dy_2Fe_{14}B)$

Hono, Euromat 2011

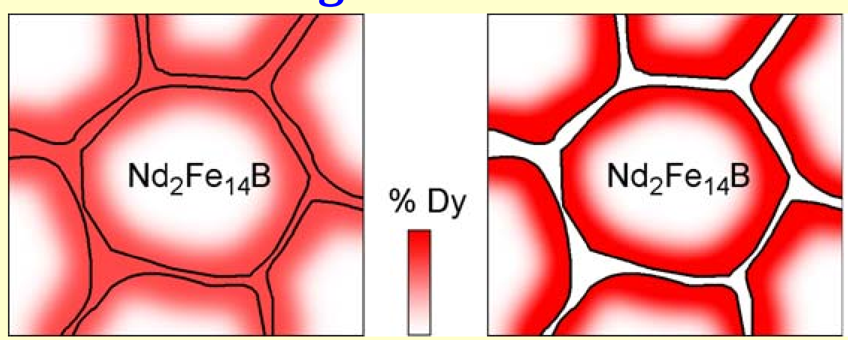
Ways to Increase H_c of Nd-Fe-B Magnets with Less or no Dy



- **Reduce grain size of sintered magnets**
  - **use finer powders**
  - **modify sintering parameters**
- **Control intergranular structure**
  - **by proper annealing**
  - **by proper composition adjustments**



- **Concentrate Dy on surface of Nd-Fe-B grains**
  - **internally**
  - **externally**



Superior Rare Earth-Free Magnets ?

- Since late 1960s nearly all the R&D efforts were focused on perfecting the RE magnets.
- RE-free hard magnetic compounds exist: FePt, CoPt, MnBi, MnAl, Zr_2Co_{11}, ε-Fe_2O_3
- Even the Alnico-type magnets still have a room for improvement; their theoretical $(BH)_{max}$ is 36-49 MGOe and they have excellent temperature stability!

Compound	Structure	Saturation magnetization	Curie temperature (°C)	Anisotropy constant K_1 (MJ/m^3)	$(BH)_m$ (MGOe)
Co	hexagonal	17.6 kG	1115	0.53	
FePt	tetragonal	14.3 kG	477	6.6	
CoPt	tetragonal	10.0 kG	567	4.9	
Co_3Pt	hexagonal	13.8 kG	727	2.0	
MnAl	tetragonal	6.2 kG	377	1.7	9.6
MnBi	hexagonal	7.8 kG	357	1.2	15.2
$BaFe_{12}O_{19}$	hexagonal	4.8 kG	450	0.33	2.2
Zr_2Co_{11}	orthorhombic(?)	≈70 emu/g	500	? (H_A = 34 kOe)	14
ε-Fe_2O_3	orthorhombic	≈16 emu/g	?	? (H_c = 23.4 kOe)	
Alnico	Cubic (shape)	12-14			36-49
$SmCo_5$	hexagonal	11.4 kG	681	17.0	
$Nd_2Fe_{14}B$	tetragonal	16.0 kG	312	5.0	

New Projects on Non-Rare Earth Magnets

- DOE REACT Program
  - **Ce-Based Magnets (Ames Lab)**
  - **Exchange-Spring Magnets (Argonne)**
  - **Iron-Nitride (Case-western, Univ. Minessota)**
  - **Mn-Al Magnets (Dartmouth)**
  - **Mn-Based Magnets (Pacific Northwest National Lab)**
  - **$L1_0$ Fe-Ni (Northeastern Univ.)**
  - **C-Based Magnets (Virginia Commonwealth Univ.)**
  - **Rare Earth Nanostructured Magnets (Univ. Alabama)**
- EU REFREEPERMAG
  - **Greece (Niarchos), Austria , France, Germany, Spain, Sweden, USA**

Superior Rare Earth-Free Magnets ?

- Since the late 1960s nearly all the R&D efforts were focused on perfecting the RE magnets.
- A comprehensive and concerted effort is needed to search for rare earth free magnets.
- Such program needs to include scientists and engineers with a wide expertise from materials design (theory), phase diagrams, design of microstructures, applied magnetics and fabrication techniques (combinatorial approach).

Possible Approaches

Shape Anisotropy Materials
- Fe(Co)
- Fe(Ni)

Nanorods (Nanowires)

Change cubic symmetry of high-M_s materials to uniaxial
- Fe-Co-X
- Fe-Ni-X

Non-equilibrium techniques

New uniaxial compounds
- Fe-V(Cr)
- Tetragonal Heusler alloys

T_C > 400 °C
$4\pi M_s$ > 10 kG
K_1 > 10^7 erg/cm^3

Nanocomposite magnets
- X/Y (hard/soft)

Chemical deposition
Core-shell structures

Conclusions

✧ In the Age of Exploration

Magnets in compasses guided Columbus to the "New" world.

✧ In the Age of Electricity

Magnets in telephones and telegraphs, and in motors, generators, and transformers guided us into our modern, high-tech world.

✧ Today

Hidden magnets far more powerful than those available to Columbus or Alexander Graham Bell guide the latest devices of our Information and Green Energy Age.

-- James Livingston
Driving Force, Harvard U. Press,1996

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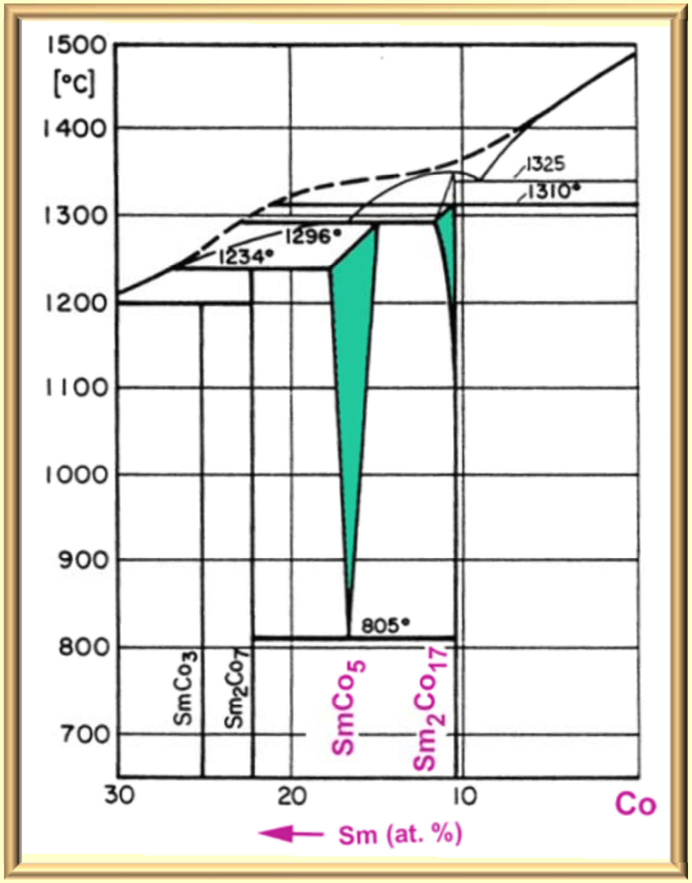
Demokritos, Greece (Niarchos, Tzitzios)

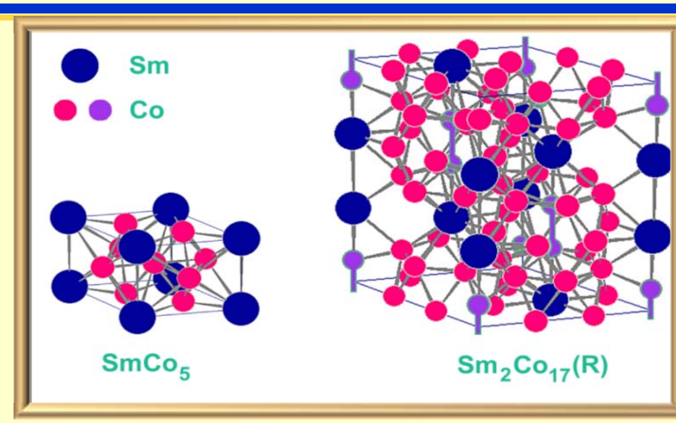
University of Nebraska (Dave Sellmyer)

High Performance Magnets: Sm-Co Magnets

Phase Diagrams: Binary Alloys



$SmCo_5$, K= 1x10^{8}erg/cc, 4πM$_s$ ~ 10 kG, (BH)=25MGOe
Sm_2Co_{17}, K=4x10^7 erg/cc, 4πM$_s$ ~ 12 kG,(BH)=30MGOe
NUCLEATION-TYPE Magnet



- **The parent $SmCo_5$ (1:5) structure is hexagonal.**
- **If extra Co atoms are added, pairs of them replace the larger Sm atoms as the so-called "dumbbells". Random replacement does not change the lattice symmetry leading to the off-stoichiometric 1:5 structure, sometimes called the "1:7" structure.**
- **The 2:17 structure can be obtained if 1/3 of Sm is replaced by ordered Co dumbbells (if stacking is ABAB..Hexagonal 2:17, ABCABC…Rhombohedral 2:17) .**

JOURNAL OF APPLIED PHYSICS VOLUME 38, NUMBER 3 1 MARCH 1967

A Family of New Cobalt-Base Permanent Magnet Materials

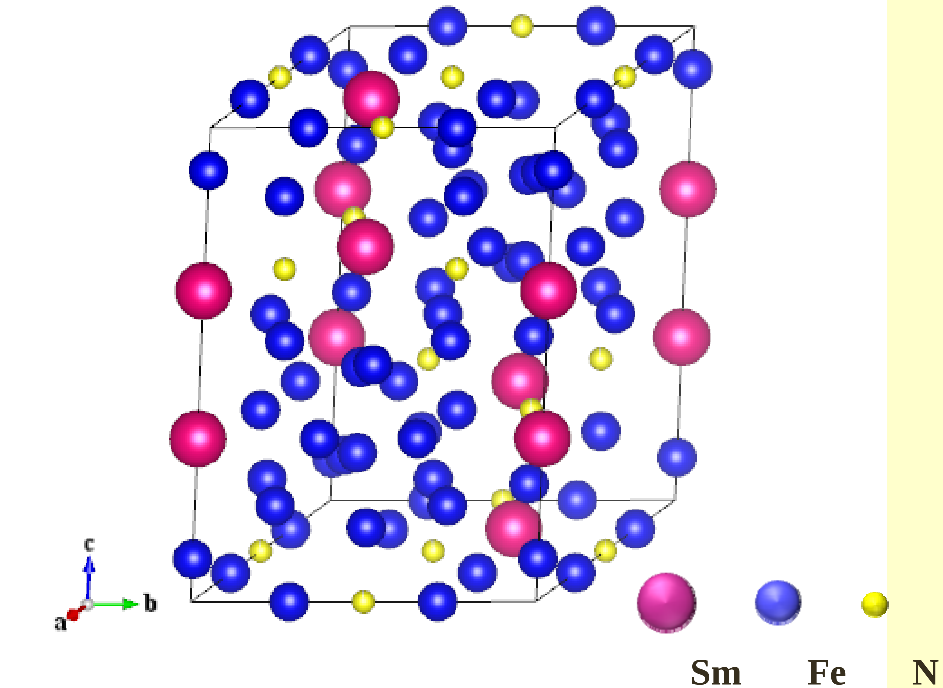
K. Strnat, G. Hoffer, J. Olson, and W. Ostertag
Air Force Materials Laboratory, Dayton, Ohio
and
J. J. Becker
General Electric Research and Development Center, Schenectady, New York

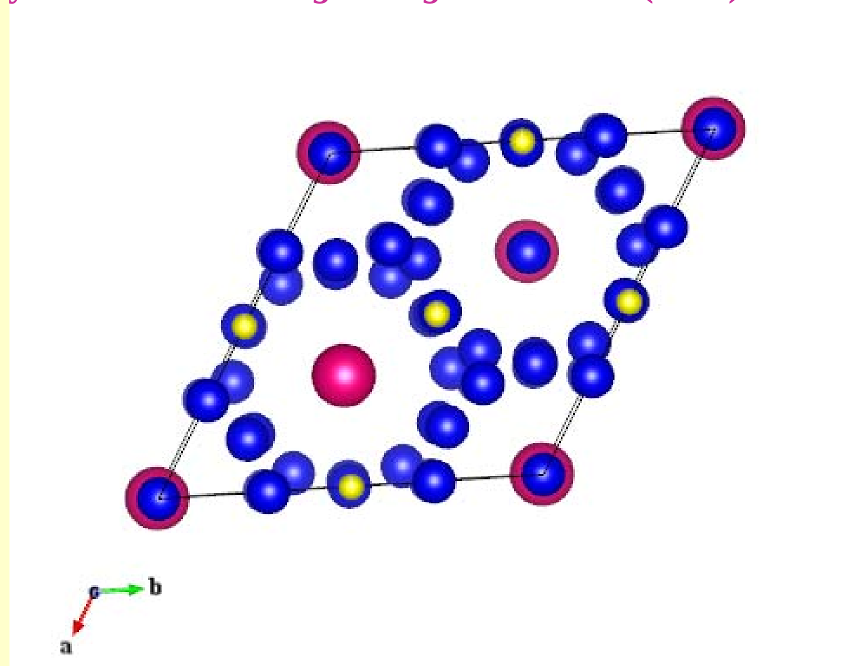
The magnetocrystalline anisotropy of several intermetallic phases of the type RCo_5 (R = Y, Ce, Pr, Sm, Y-rich and Ce-rich mischmetals) has been investigated, and it is concluded that these alloys are promising candidates for fine-particle permanent magnets. They have extremely high uniaxial anisotropy ($K = 5.4$ to 7.7×10^7 erg/cm³), single easy axis, high saturation ($B_s = 8500$ to 11 200 G) and Curie point ($t_c = 464°$ to 747°C). Approximate upper limits for the possible energy product lie between 18 and 31.3 MGOe. Experimentally, coercive forces of over 8000 Oe and $(BH)_{max} = 5.1$ MGOe have been observed in $SmCo_5$ merely ground at room temperature. Grinding of YCo_5 and (Ce–MM)Co_5 produces an increase of $_MH_c$ to 2200 and 2700 Oe, respectively, followed by a decrease as particle size continues to decrease.

High Performance Magnets: $Sm_2Fe_{17}N_x$

- Nitrogen enters the 2:17 structure interstitially, expanding the unit cell by 6%; a=8.54 Å, c=12.43 Å for Sm_2Fe_{17} and a=8.73 Å and c=12.64 Å for $Sm_2Fe_{17}N_3$.

J.MD. Coey and H. Sun *J. Magn. Magn. Mater.* 87 (1990) L251.





- The expansion in the lattice leads to an increase in Curie temperature (from 389 K to 749 K) and changes the anisotropy from planar to uniaxial with $K=8.6 \times 10^7$ erg/cc and $J_s=1.54$ T.
- Material is unstable above 500 C.
- Material was discovered by Coey in 1990.

Magnetization Reversal in Real Materials

- **Micromagnetics**

$$E_t = E_{ex} + E_H + E_D + E_K$$

$$E_t = \int A\left(\nabla \frac{M}{M_s}\right)^2 dv - \mu_o \int \left(\vec{M}\cdot\vec{H} + \frac{1}{2}\vec{M}\cdot\vec{H_d}(M)\right) dr + \int \left[(K_1 + 2K_2)\frac{(\vec{n}\cdot\vec{H})^2}{{M_s}^2} - K_2\frac{(\vec{n}\cdot\vec{H})^4}{{M_s}^4}\right] dr$$

↓

Minimize Total Energy

↓

Set of Differential Equations

↓

Boundary Conditions

↓

M (H)

Permanent Magnet Materials Sales by Type