Arbeitskreis Energie der DPG

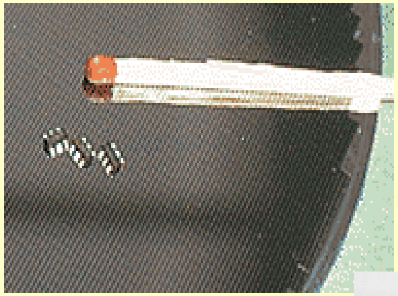
UNIVERSITÄT
DUISBURG
ESSEN
Offen im Denken

Magnetische Materialien für energieeffizientere Anwendungen vom Atom zur Turbine

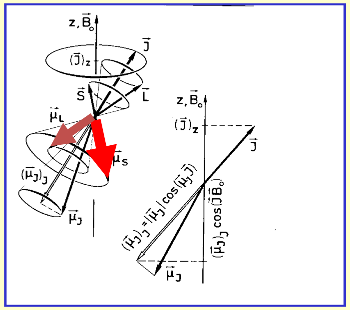
Prof. Dr. Michael Farle

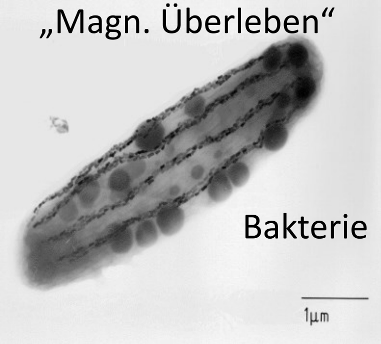
Fakultät für Physik , U. Duisburg-Essen

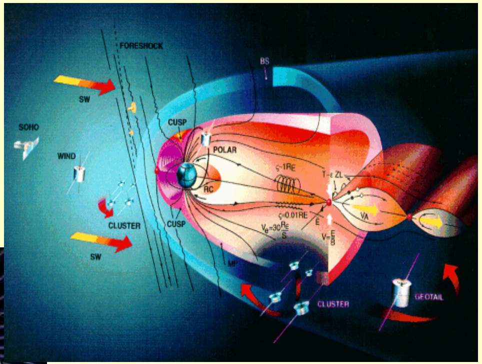
Struktur und Magnetismus nanoskaliger Systeme

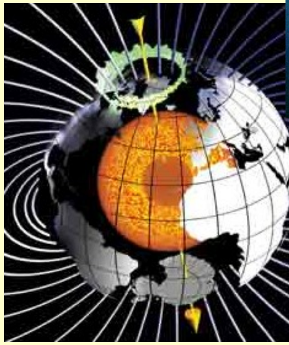


Magnetowiderstands-
sensoren

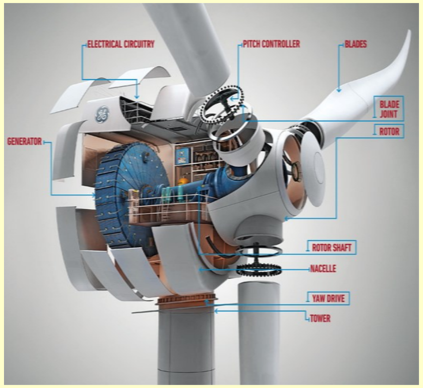






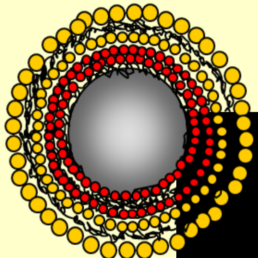


Magnete
als Klimaretter

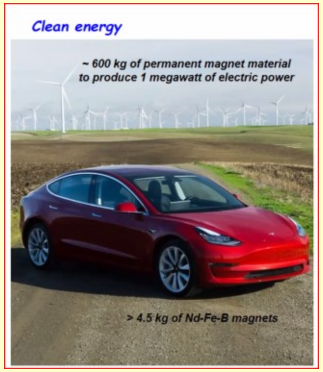


Die weite Welt magnetischer Technologien

- **Nicht invasive Medizin**
- Magnetische Mikroschwimmer
- Diagnose & Therapie („Theranostics“)
  Hyperthermie / Magnetomechanics



- **<u>Energieeinsparung</u>**
- **Datenspeicherung und -prozessierung**
  (Festplatte,Spinwellenlogik)
- **E-Mobilität (Kfz, Fahrrad, Roboter…..)**
  Generatoren, Transformatoren, Sensoren
- **Magnetische Kühlung**
  (Magnetokalorik für Klimaanlagen, Kühlschränke,..)



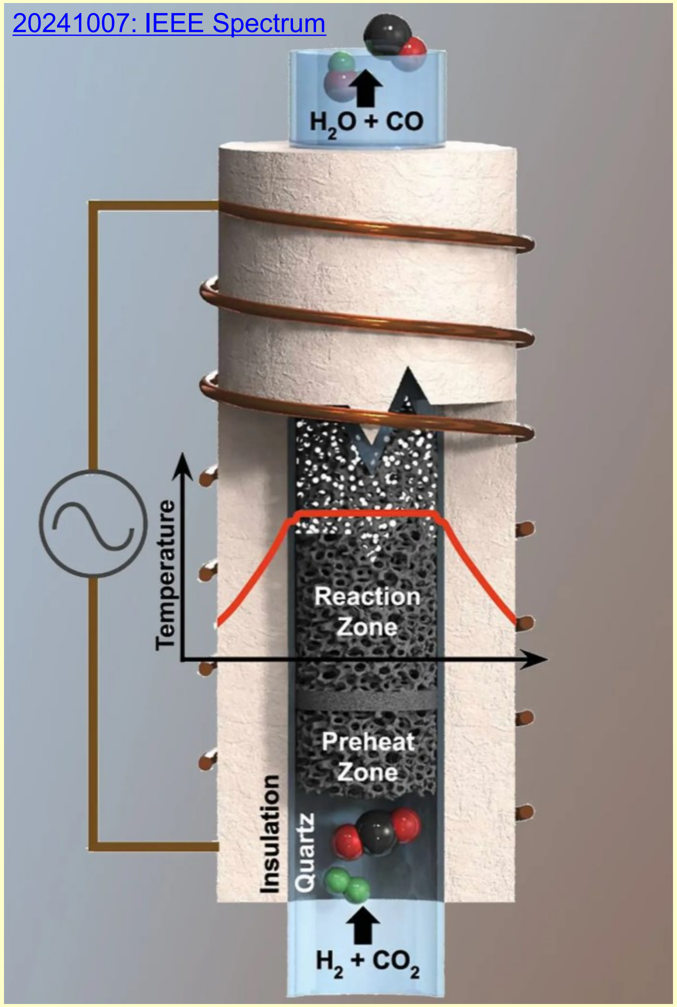
Chemische Industrie

Energie sparen mit magnetischer Induktion

UNIVERSITÄT DUISBURG ESSEN

Open-Minded

20241007: IEEE Spectrum



Electromagnetic induction heats a porous ceramic metamaterial to make industrial reactions greener.

Dolly Mantle/Stanford University/Joule

Challenge:

decarbonize ! BUT the required high-grade heat is typically supplied by **combusting fossil fuels**.

Innovation:

metamaterial reactors → , volumetric heating is achieved with near-unity conversion of electricity to internal heat.

Reactor scaling to industrially relevant sizes can be achieved.

Highlights

- A metamaterial reactor powered using high-frequency magnetic induction
- Volumetric heating is realized by metamaterial baffle and power electronics co-design
- The conversion efficiency of electricity to internal reactor heat is **over 85%**
- Near-equilibrium conversion of the reverse water-gas shift reaction is demonstrated

Datenverarbeitung mit Spins

Drei Ansätze für die Datenverarbeitung

Bild der Wissenschaft (2022)

For more concrete data

5.8 Terawatt hours

San Francisco

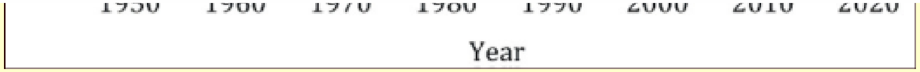
5.7 Terawatt hours

2015, Increase of 30%/year

Google

At our level: 30 Google searches cost as much energy as to bring a liter of water to boil

Nat. Com. 10, 4345 (2019)



Datenverarbeitung mit Spins

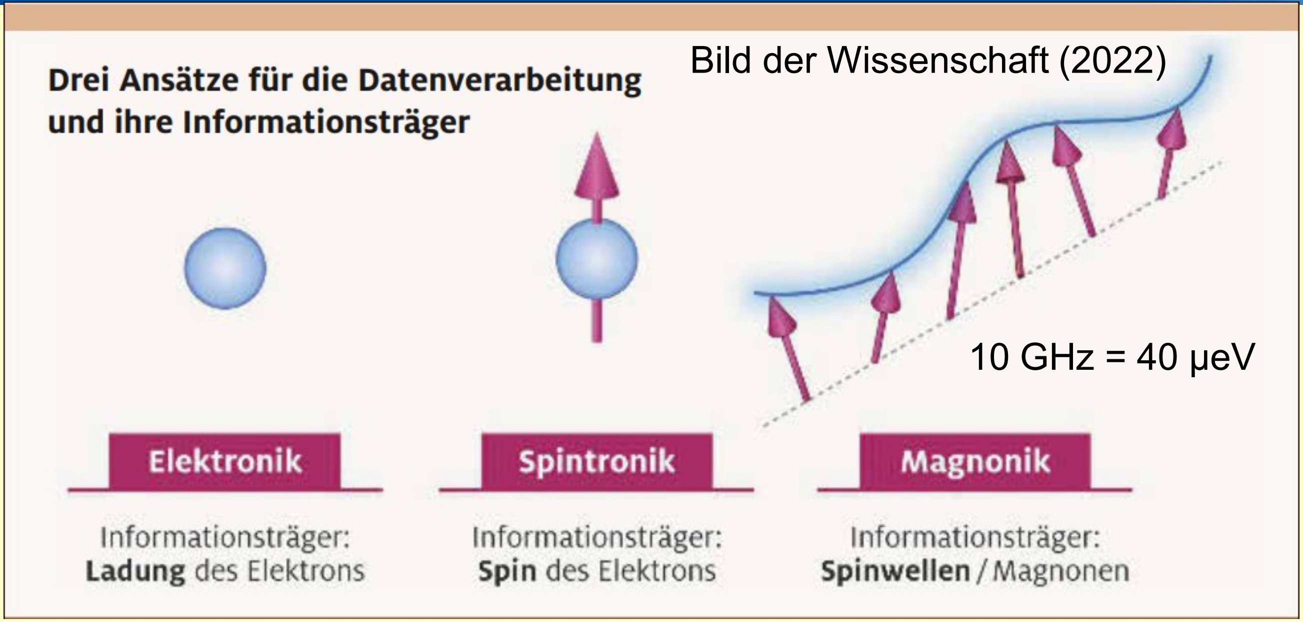
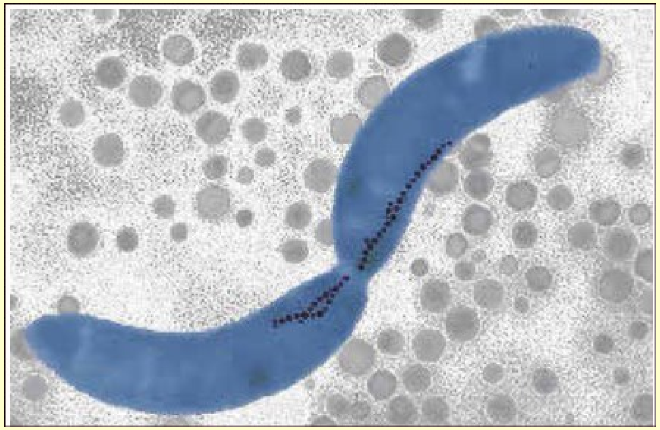


Bild der Wissenschaft (2022)

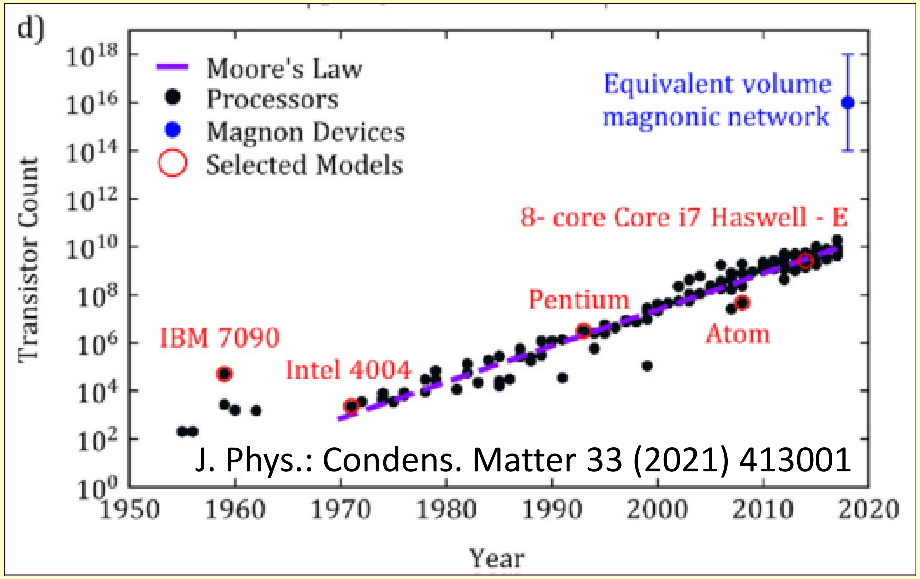
10 GHz = 40 µeV

Magnonik:
Magnon (Spinwelle)
nur ca 1/100 der Energie pro Prozess im Vergleich zur Ladung (Elektronik)

Rechnen mit Bakterien

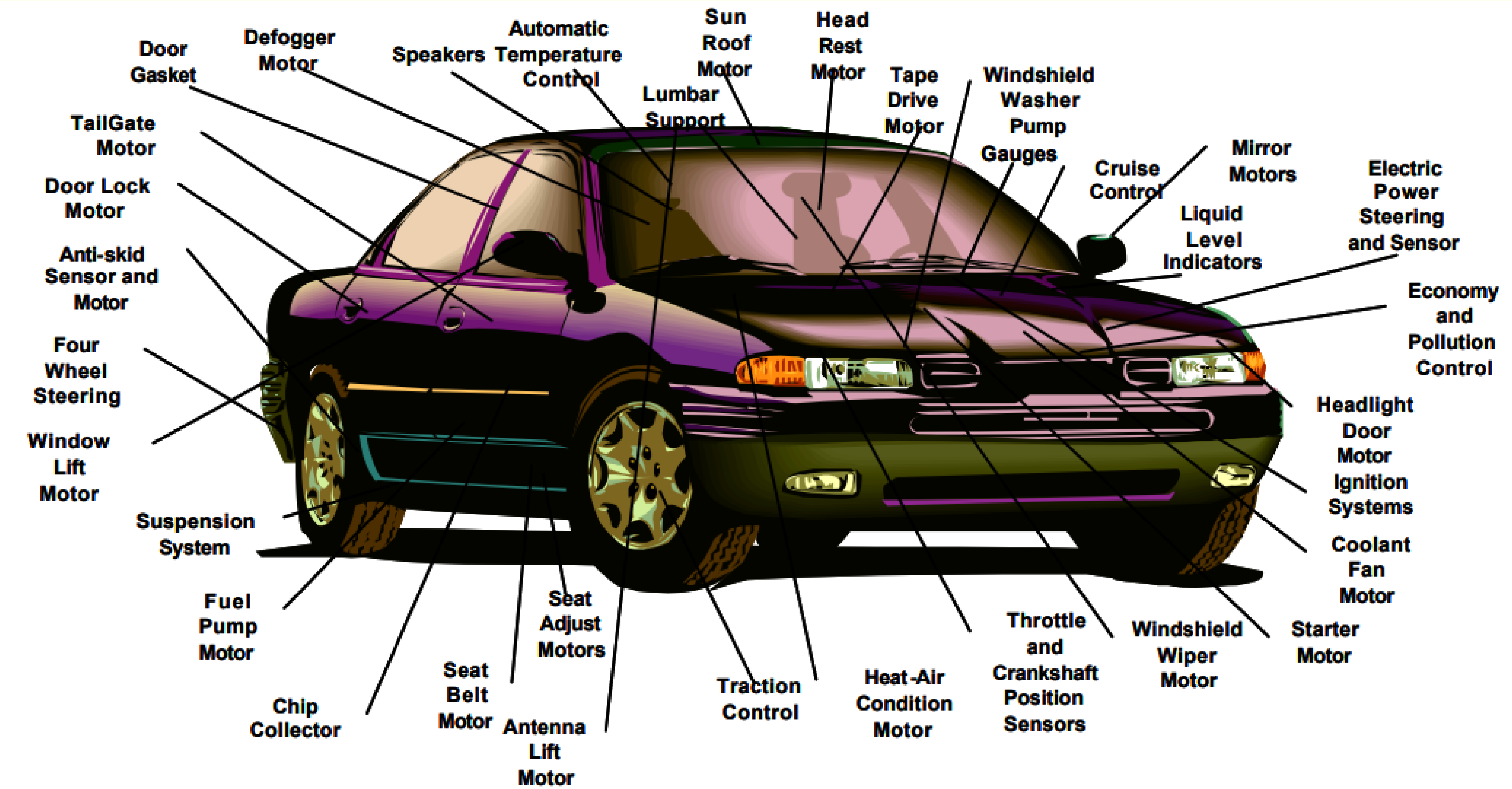


Nat. Com. 10, 4345 (2019)



J. Phys.: Condens. Matter 33 (2021) 413001

Permanent Magnets:
Applications in a typical automobile



M. Garrell, North Carolina State University, MSc thesis (2002)

Transport und Logistik

Energie sparen mit Hartmagneten

Hartmagnet/Supraleiter Achterbahn: Reibungsloser Transport

Demonstrator SFB/TRR270 , Jahr 2024, N. Josten, P. Kükenbrink, P. Steinkraus

Gebäudemanagement

Ein Fahrstuhl ohne Seile („ropeless elevator“)

Conventional elevator

Traditional elevators in tall buildings require a large footprint and waste leasable space.

Double-decker elevator

Move more people by stacking cars. But inevitably, extra power will hav

TWIN, two cabins in one shaft

TWIN is more efficient because of independent operation of the cars, so that you can park cars if not in use. The flexibl work

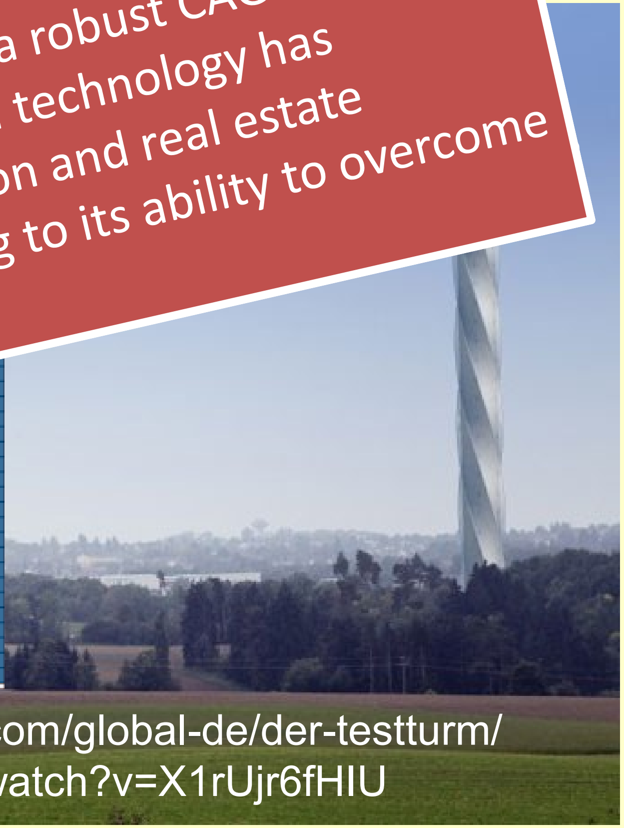
MULTI

Mehrere, unabh

vo

ht !

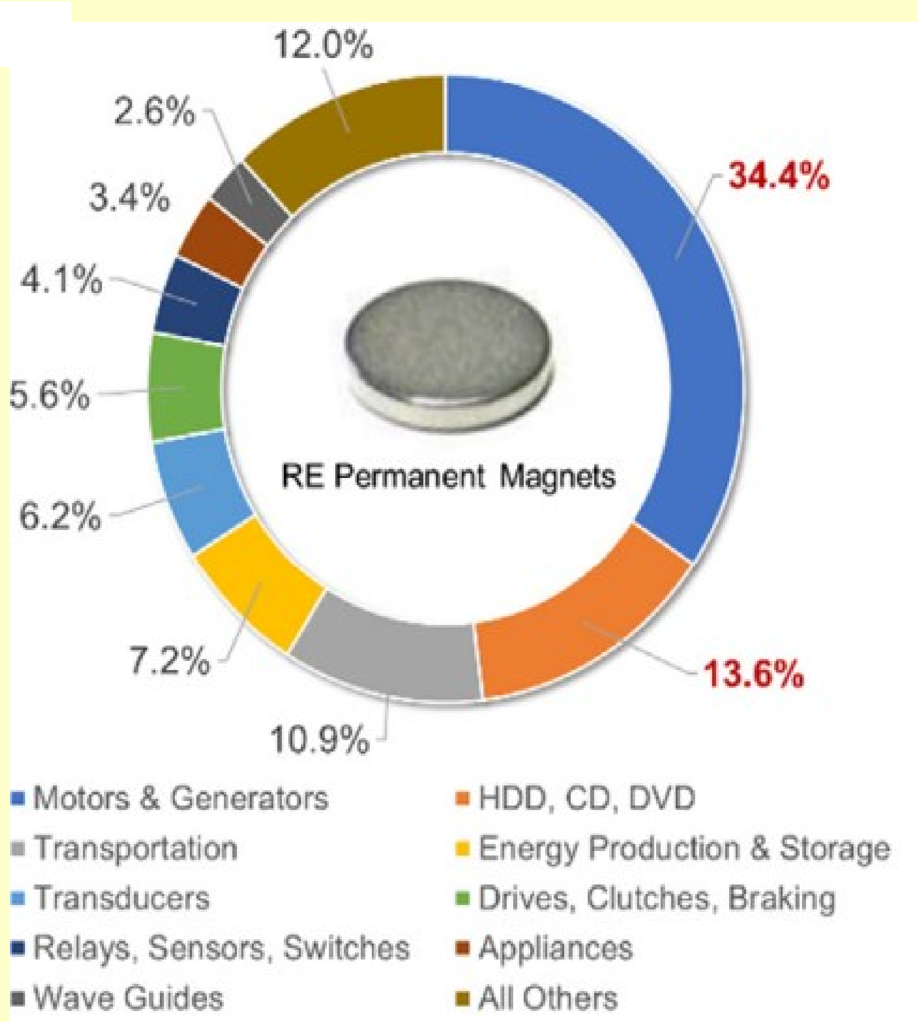
NEWARK, Del, Oct. 14, 2024 (GLOBE NEWSWIRE) – The global Ropeless Elevator Market is poised for substantial growth over the next decade, with its value projected to grow from **USD 155.6 million** in 2024 to a staggering **USD 483.3 million** by 2034, at a robust CAGR of **12.8%**. This breakthrough in vertical transportation technology has garnered increasing attention from the construction and real estate sectors, as well as architects and engineers, owing to its ability to overcome the limitations of conventional elevators.

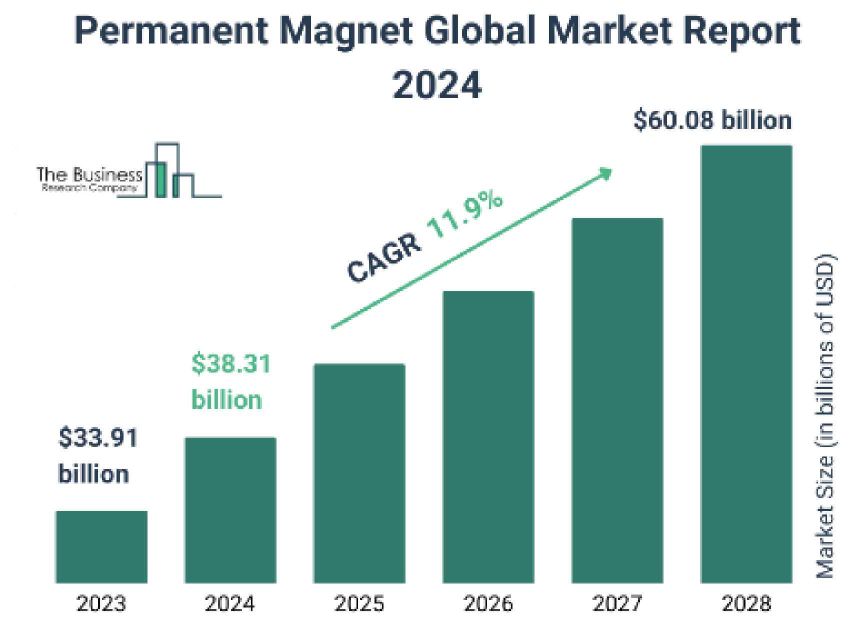


https://testturm.tkelevator.com/global-de/der-testturm/
https://www.youtube.com/watch?v=X1rUjr6fHIU

Permanent Magnets:
Applications & Market Report

Liu et al., Significant progress of grain boundary diffusion process for cost-effective rare earth permanent magnets: A review (2021)



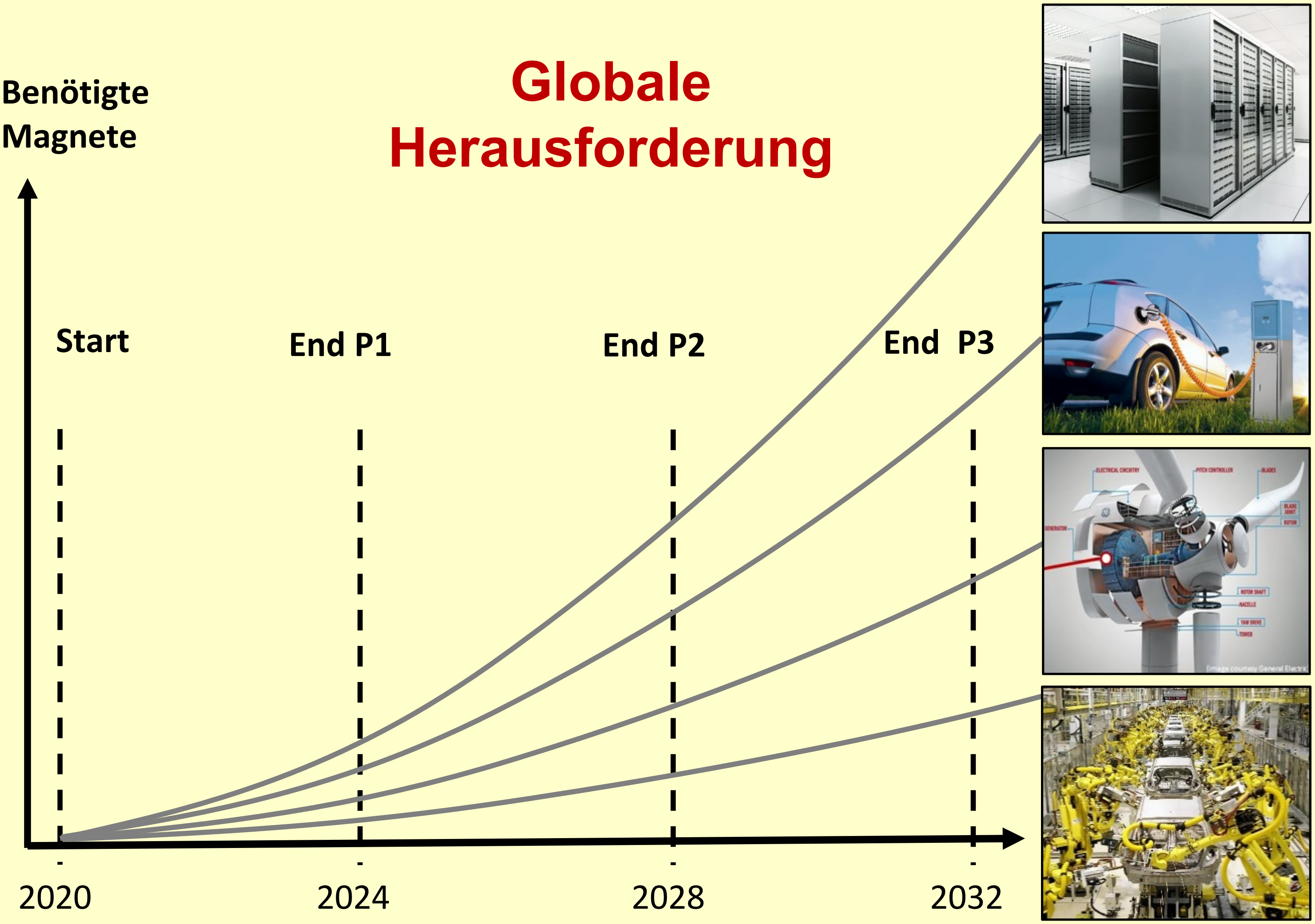


CAGR: Compound annual growth rate

https://www.thebusinessresearchcompany.com/report/permanent-magnet-global-market-report

Magnete als Klimaretter?

Globale Herausforderung



(magnetic) cooling

electro-mobility

wind energy

robotics

Wir brauchen bessere Magnete !

Magnetische Kühlung:

„To cool our homes we heat the planet“

➔ **Wir brauchen**

Magnetische Kühlung

Festkörperkühlung

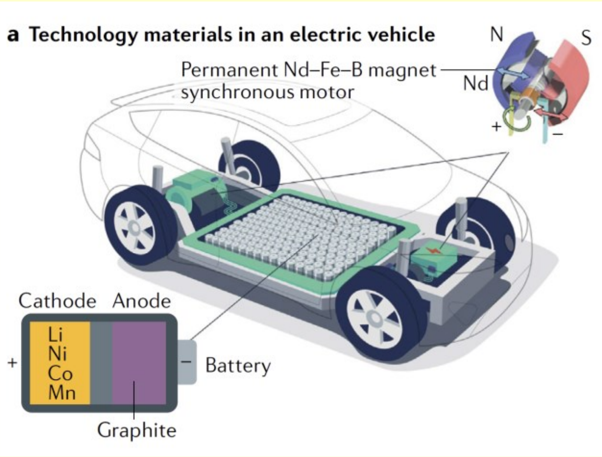
ohne Gaskompression

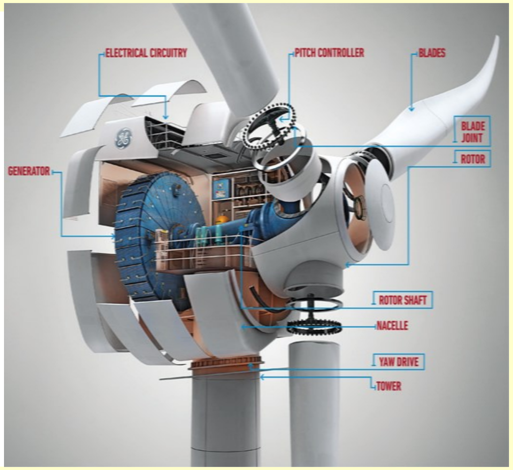
Leichtere/transparente(?)/effizientere Magnete

Wind-/Wasserkraft, Motoren, Generatoren

© Magnotherm

Klimaanlage

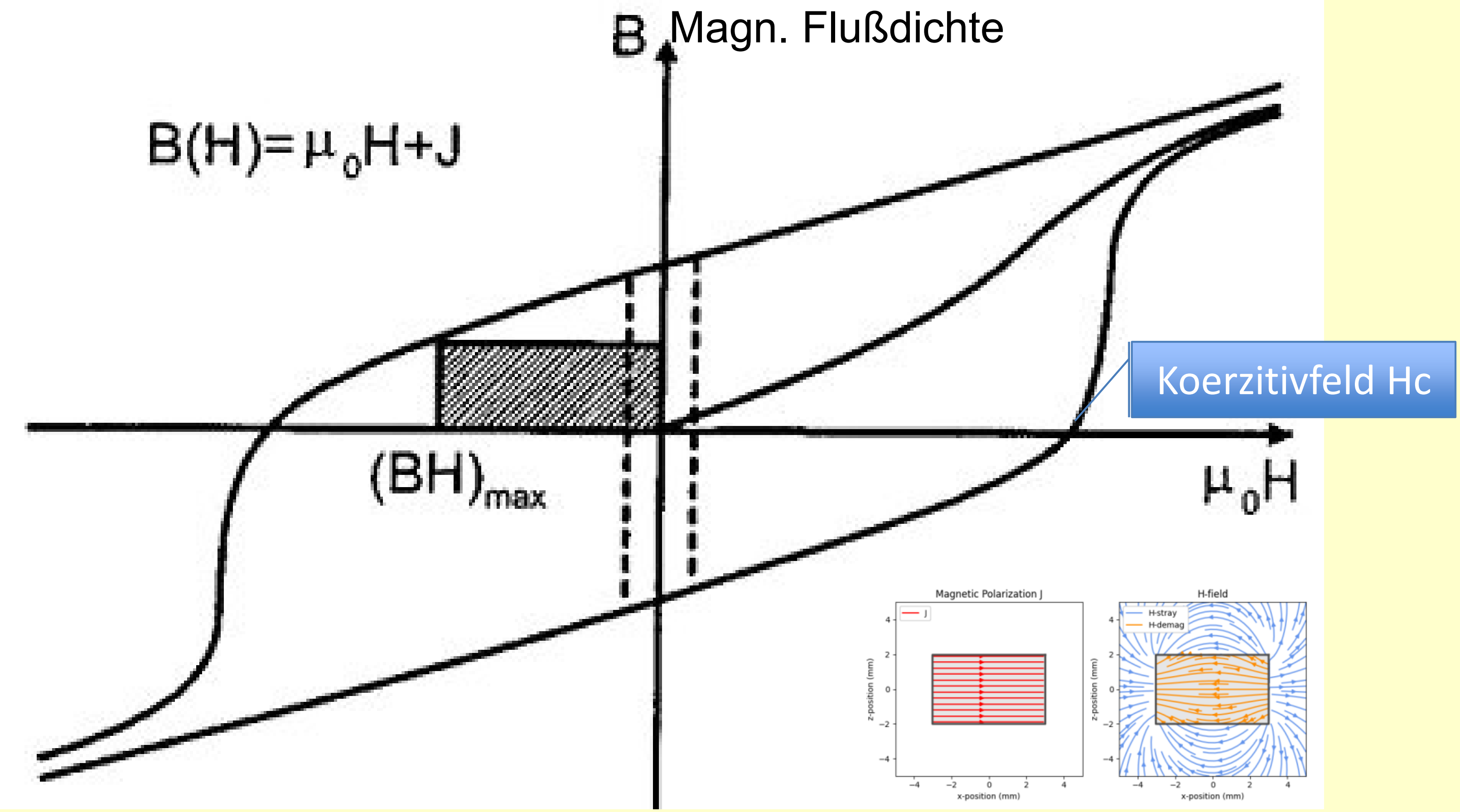




- **Silent, No pollution**
- **Re-charging over night**
- *large battery packs needed*
- **US $300,000**

Magnetisches Energieprodukt

Magnetische Hysterese



Das Energieprodukt ist definiert als der Maximalwert des Produktes aus B und H (|−BH|)

Permanent magnets: Magnetic Energy Product

Magnetisches Energieprodukt = gespeicherte Energiedichte im Magnet

Beispiel:

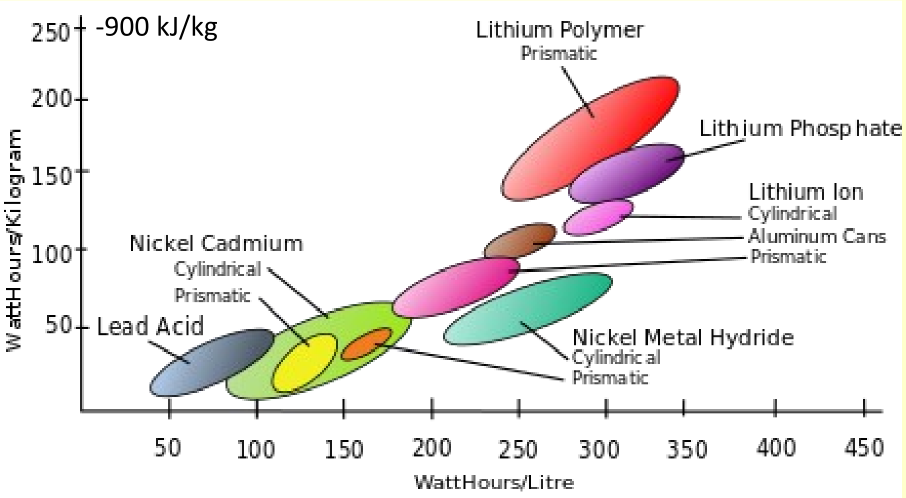
$Nd_2Fe_{14}B$, „N45“, hat Energieprodukt von 45 MGOe (358 kJ/m^3 = **47 kJ/kg**), FeNdB: 7.5 g/cm^3
→

*Ein solcher Magnet hätte bei einer Dicke von einigen cm und einer Polfläche des Nordpols bzw. Südpols von etwa 20 cm ^{2} eine **Haftkraft an Weicheisen von über 1000 N**. Man könnte mit so einem Magneten also einen 100 kg schweren Eisenblock anheben.*

Die bezeichnete Haftkraft hängt jedoch stark von der Form des Magneten, der Beschaffenheit der Oberflächen und von der Reinheit des angezogenen Eisens ab. Es handelt sich um idealisierte, errechnete Werte.

Energiedichte von:

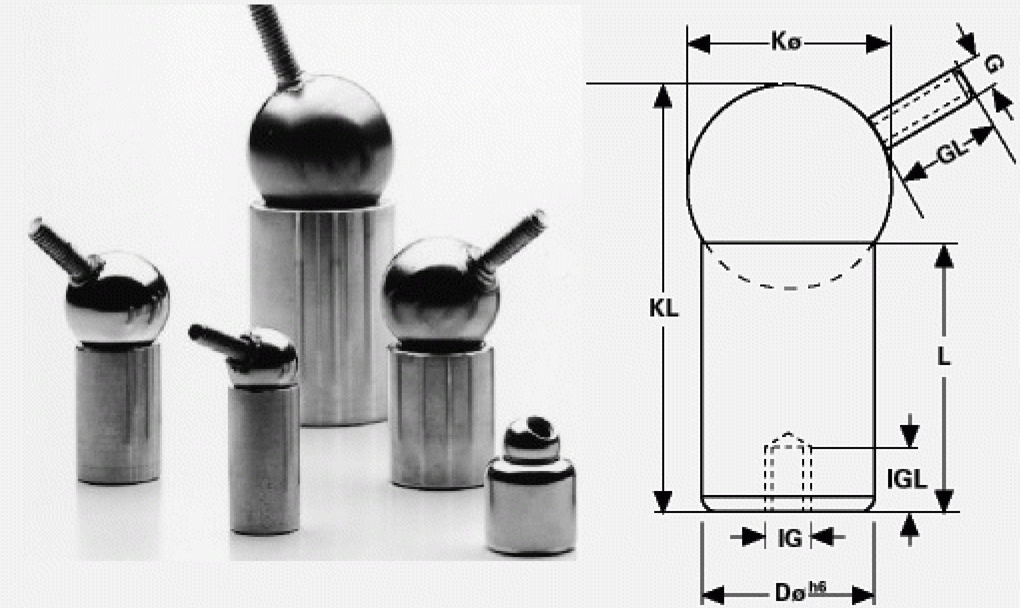
Braunkohle:	≅ 9100 kJ/kg
Steinkohle:	≅ 31000 kJ/kg



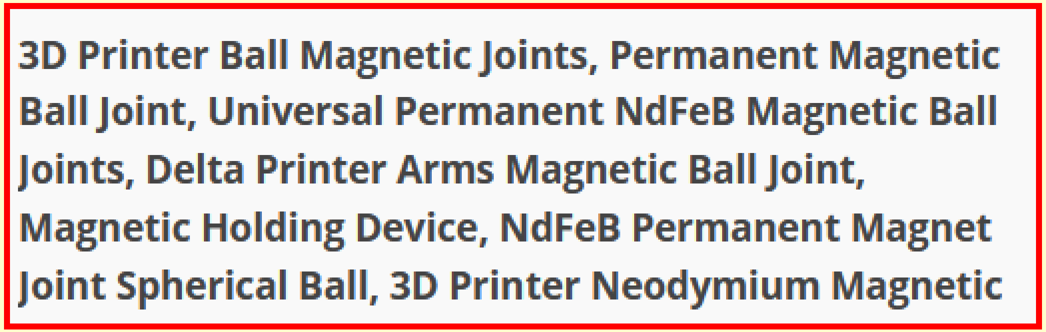
https://de.wikipedia.org/wiki/Energiedichte_von_Energiespeichern

The strongest magnet

Holding Force up to 200 N



Magnetic-Ball-Joints



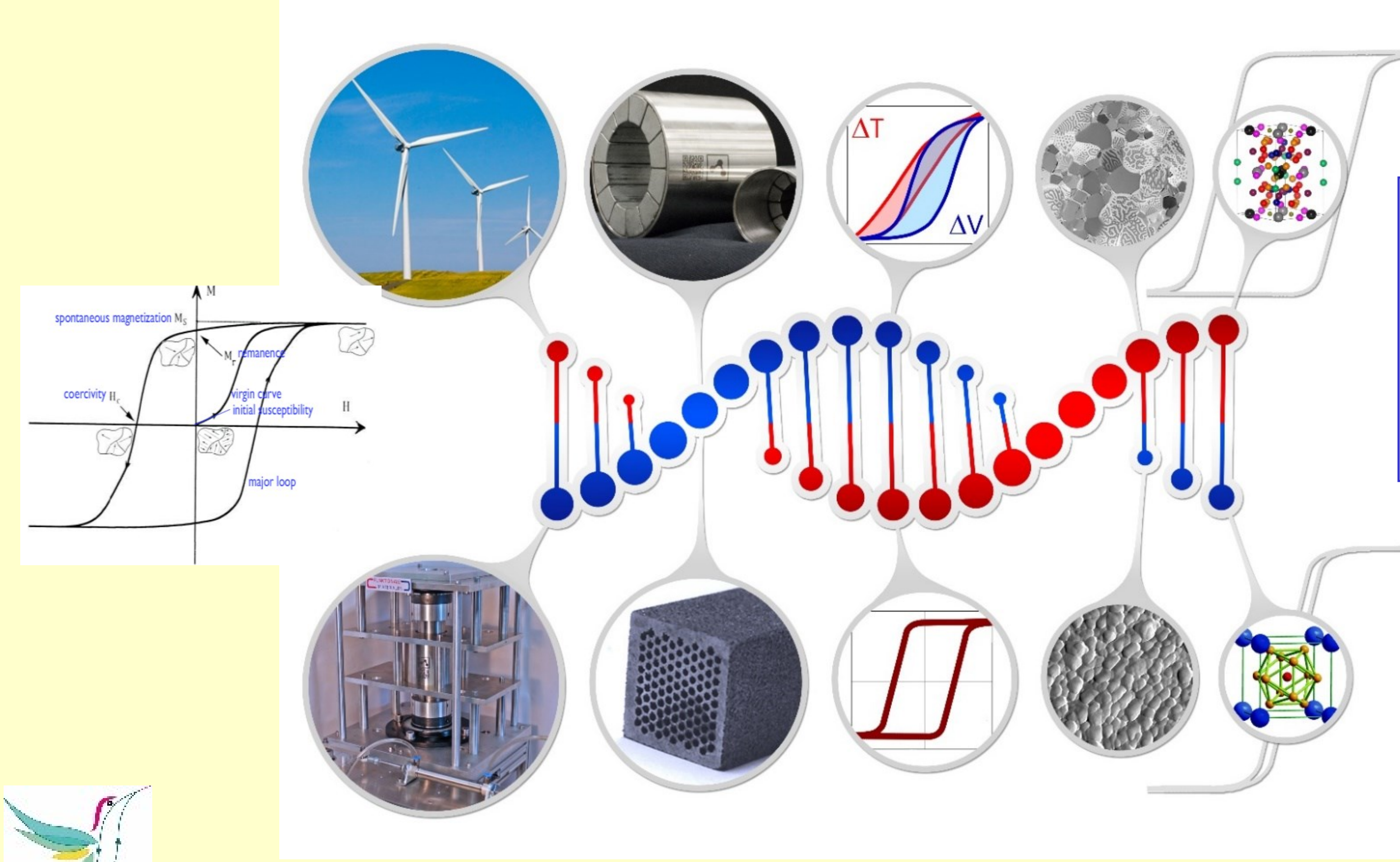
3D Printer Ball Magnetic Joints, Permanent Magnetic Ball Joint, Universal Permanent NdFeB Magnetic Ball Joints, Delta Printer Arms Magnetic Ball Joint, Magnetic Holding Device, NdFeB Permanent Magnet Joint Spherical Ball, 3D Printer Neodymium Magnetic

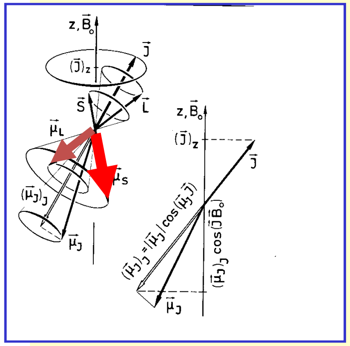
Masato Sagawa
$NdFe_{14}B$ Magnet (1983)

Der Ansatz im SFB/TRR270 …

HoMMage: Hysteresis Design of Magnetic Materials for Efficient Energy Conversion

Identifiziere die **“DNA”** der magnetischen Hysterese in permanenten Magneten und magnetokalorischen Materialien





CRC/TRR 270 *HoMMage*: Hysteresis Design of Magnetic Materials for Efficient Energy Conversion (*© O. Gutfleisch)*

Konzept für neue Magnete (Grundlagen)

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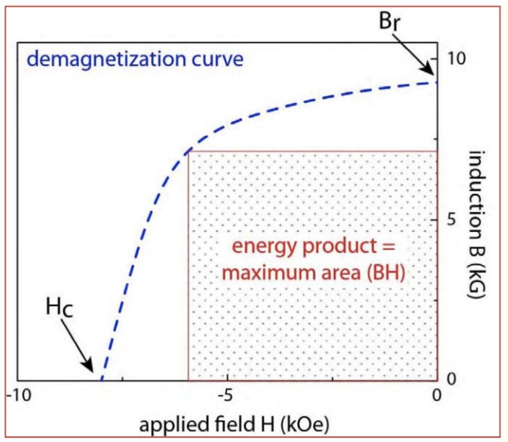
Open-Minded

Ziel: entwickle eine neue Generation von
high performance permanent magnets
ohne Seltene Erden oder teure Elemente wie Platin



The figure of merit for a Ferromagnet: Energy Product **(BH)max**

Large H_c

Atomare magnetische Momente groß für großes B_r

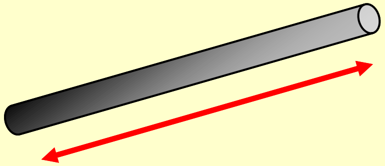
Magnetisches Anisotropiefeld bestimmt Koerzivität:

$$H_{an} = H_{mc} + H_{shape} + H_{strain} + H_{sur/interf} + H_{exch}$$

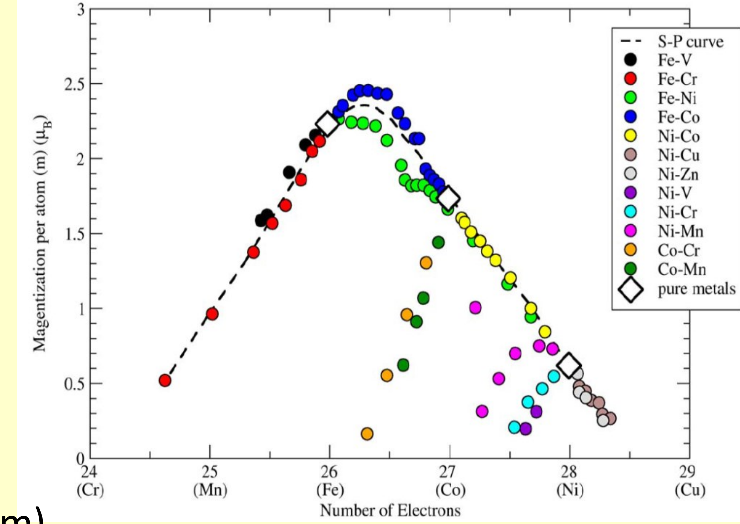
$$H_{MCA} = \frac{2K_1}{M_s}$$

$$H_{shape} = \Delta N \cdot M_s^2$$

$$H_{exchange} = -J_{12} s_1 s_2$$



- Großes Aspekt Verhältnis
- Magnetisierung entlang Achse
- Q.m. Austauscheffekte (afm – fm)



Slater-Pauling Curve

Magnete (zeitliche Entwicklung)

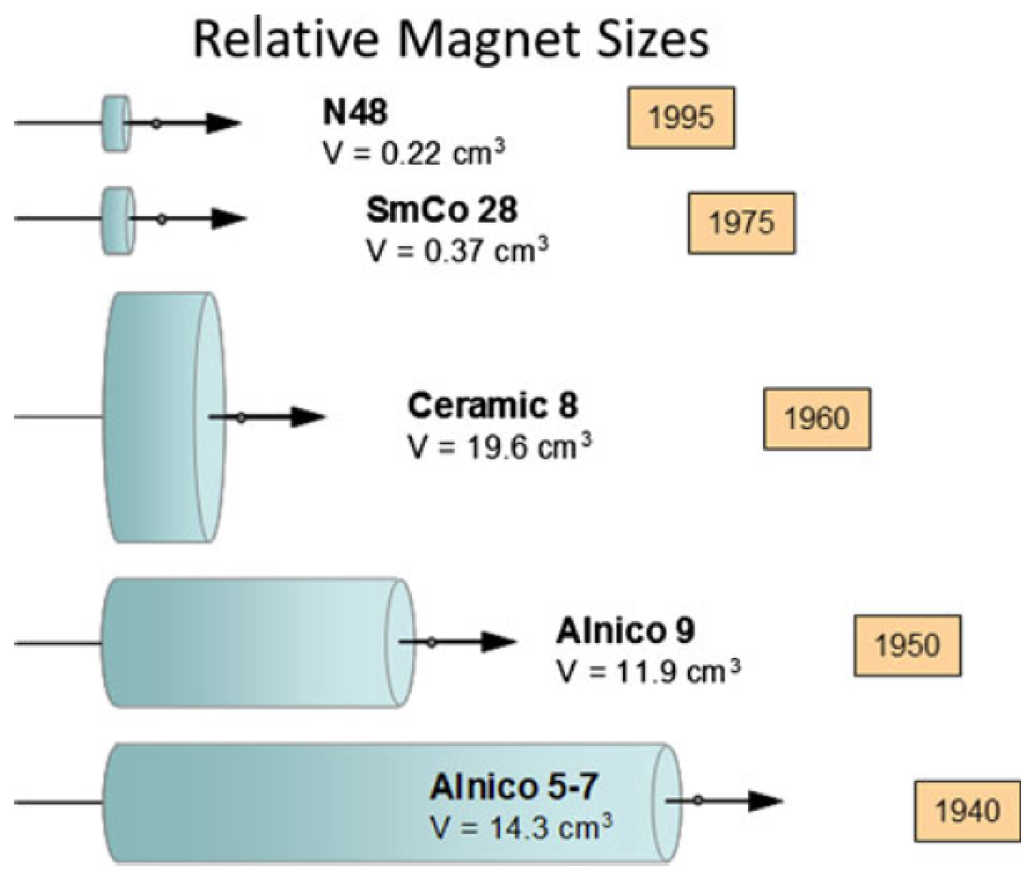


Fig. 2—Relative magnet size and shape of various permanent magnet materials to generate 1000 G at 5 mm from the pole face of the magnet. (Figure courtesy of Arnold Magnetic Technologies.).

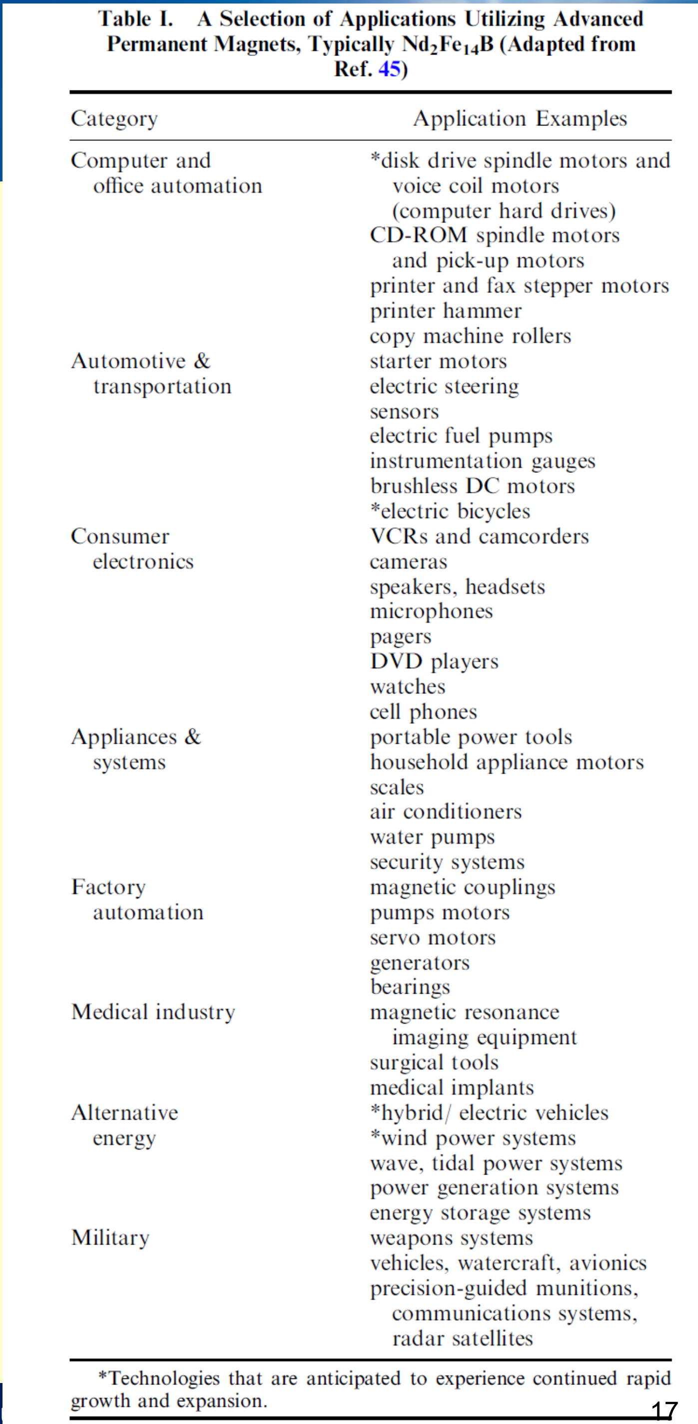
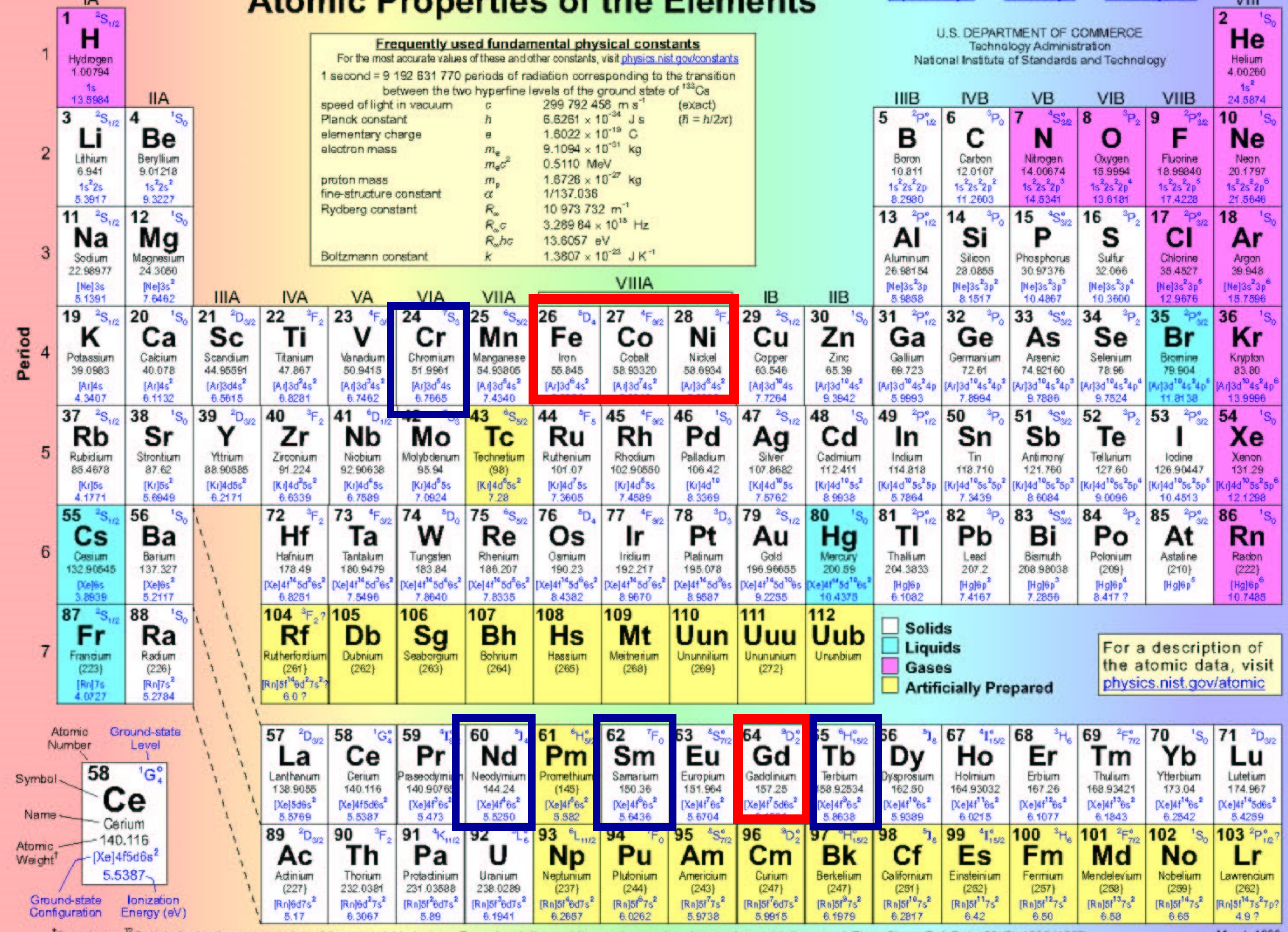


Table I. A Selection of Applications Utilizing Advanced Permanent Magnets, Typically $Nd_2Fe_{14}B$ (Adapted from Ref. 45)

Category	Application Examples
Computer and office automation	*disk drive spindle motors and voice coil motors (computer hard drives) CD-ROM spindle motors and pick-up motors printer and fax stepper motors printer hammer copy machine rollers
Automotive & transportation	starter motors electric steering sensors electric fuel pumps instrumentation gauges brushless DC motors *electric bicycles
Consumer electronics	VCRs and camcorders cameras speakers, headsets microphones pagers DVD players watches cell phones
Appliances & systems	portable power tools household appliance motors scales air conditioners water pumps security systems
Factory automation	magnetic couplings pumps motors servo motors generators bearings
Medical industry	magnetic resonance imaging equipment surgical tools medical implants
Alternative energy	*hybrid/ electric vehicles *wind power systems wave, tidal power systems power generation systems energy storage systems
Military	weapons systems vehicles, watercraft, avionics precision-guided munitions, communications systems, radar satellites

*Technologies that are anticipated to experience continued rapid growth and expansion.



PERIODIC TABLE

Atomic Properties of the Elements

Physics Laboratory physics.nist.gov

NIST www.nist.gov

Standard Reference Data Program www.nist.gov/srd

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum	c	$299\,792\,458\ \mathrm{m\,s^{-1}}$	(exact)
Planck constant	h	$6.6261 \times 10^{-34}\ \mathrm{J\,s}$	($\hbar = h/2\pi$)
elementary charge	e	$1.6022 \times 10^{-19}\ \mathrm{C}$	
electron mass	m_e	$9.1094 \times 10^{-31}\ \mathrm{kg}$	
	m_ec^2	$0.5110\ \mathrm{MeV}$	
proton mass	m_p	$1.6726 \times 10^{-27}\ \mathrm{kg}$	
fine-structure constant	α	$1/137.036$	
Rydberg constant	R_∞	$10\,973\,732\ \mathrm{m^{-1}}$	
	$R_\infty c$	$3.289\,84 \times 10^{15}\ \mathrm{Hz}$	
	$R_\infty hc$	$13.6057\ \mathrm{eV}$	
Boltzmann constant	k	$1.3807 \times 10^{-23}\ \mathrm{J\,K^{-1}}$	

Period	Group IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA			IB	IIB	IIIB	IVB	VB	VIB	VIIB	VIII
1	1 ${}^2S_{1/2}$ **H** Hydrogen 1.00794 1s 13.5984																	2 ${}^1S_0$ **He** Helium 4.00260 $1s^2$ 24.5874
2	3 ${}^2S_{1/2}$ **Li** Lithium 6.941 $1s^22s$ 5.3917	4 ${}^1S_0$ **Be** Beryllium 9.01218 $1s^22s^2$ 9.3227											5 ${}^2P^{\circ}_{1/2}$ **B** Boron 10.811 $1s^22s^22p$ 8.2980	6 ${}^3P_0$ **C** Carbon 12.0107 $1s^22s^22p^2$ 11.2603	7 ${}^4S^{\circ}_{3/2}$ **N** Nitrogen 14.00674 $1s^22s^22p^3$ 14.5341	8 ${}^3P_2$ **O** Oxygen 15.9994 $1s^22s^22p^4$ 13.6181	9 ${}^2P^{\circ}_{3/2}$ **F** Fluorine 18.99840 $1s^22s^22p^5$ 17.4228	10 ${}^1S_0$ **Ne** Neon 20.1797 $1s^22s^22p^6$ 21.5646
3	11 ${}^2S_{1/2}$ **Na** Sodium 22.98977 [Ne]$3s$ 5.1391	12 ${}^1S_0$ **Mg** Magnesium 24.3050 [Ne]$3s^2$ 7.6462											13 ${}^2P^{\circ}_{1/2}$ **Al** Aluminum 26.98154 [Ne]$3s^23p$ 5.9858	14 ${}^3P_0$ **Si** Silicon 28.0855 [Ne]$3s^23p^2$ 8.1517	15 ${}^4S^{\circ}_{3/2}$ **P** Phosphorus 30.97376 [Ne]$3s^23p^3$ 10.4867	16 ${}^3P_2$ **S** Sulfur 32.066 [Ne]$3s^23p^4$ 10.3600	17 ${}^2P^{\circ}_{3/2}$ **Cl** Chlorine 35.4527 [Ne]$3s^23p^5$ 12.9676	18 ${}^1S_0$ **Ar** Argon 39.948 [Ne]$3s^23p^6$ 15.7596
4	19 ${}^2S_{1/2}$ **K** Potassium 39.0983 [Ar]$4s$ 4.3407	20 ${}^1S_0$ **Ca** Calcium 40.078 [Ar]$4s^2$ 6.1132	21 ${}^2D_{3/2}$ **Sc** Scandium 44.95591 [Ar]$3d4s^2$ 6.5615	22 ${}^3F_2$ **Ti** Titanium 47.867 [Ar]$3d^24s^2$ 6.8281	23 ${}^4F_{3/2}$ **V** Vanadium 50.9415 [Ar]$3d^34s^2$ 6.7462	24 ${}^7S_3$ **Cr** Chromium 51.9961 [Ar]$3d^54s$ 6.7665	25 ${}^6S_{5/2}$ **Mn** Manganese 54.93805 [Ar]$3d^54s^2$ 7.4340	26 ${}^5D_4$ **Fe** Iron 55.845 [Ar]$3d^64s^2$	27 ${}^4F_{9/2}$ **Co** Cobalt 58.93320 [Ar]$3d^74s^2$	28 ${}^3F_4$ **Ni** Nickel 58.6934 [Ar]$3d^84s^2$	29 ${}^2S_{1/2}$ **Cu** Copper 63.546 [Ar]$3d^{10}4s$ 7.7264	30 ${}^1S_0$ **Zn** Zinc 65.39 [Ar]$3d^{10}4s^2$ 9.3942	31 ${}^2P^{\circ}_{1/2}$ **Ga** Gallium 69.723 [Ar]$3d^{10}4s^24p$ 5.9993	32 ${}^3P_0$ **Ge** Germanium 72.61 [Ar]$3d^{10}4s^24p^2$ 7.8994	33 ${}^4S^{\circ}_{3/2}$ **As** Arsenic 74.92160 [Ar]$3d^{10}4s^24p^3$ 9.7886	34 ${}^3P_2$ **Se** Selenium 78.96 [Ar]$3d^{10}4s^24p^4$ 9.7524	35 ${}^2P^{\circ}_{3/2}$ **Br** Bromine 79.904 [Ar]$3d^{10}4s^24p^5$ 11.8138	36 ${}^1S_0$ **Kr** Krypton 83.80 [Ar]$3d^{10}4s^24p^6$ 13.9996
5	37 ${}^2S_{1/2}$ **Rb** Rubidium 85.4678 [Kr]$5s$ 4.1771	38 ${}^1S_0$ **Sr** Strontium 87.62 [Kr]$5s^2$ 5.6949	39 ${}^2D_{3/2}$ **Y** Yttrium 88.90585 [Kr]$4d5s^2$ 6.2171	40 ${}^3F_2$ **Zr** Zirconium 91.224 [Kr]$4d^25s^2$ 6.6339	41 ${}^6D_{1/2}$ **Nb** Niobium 92.90638 [Kr]$4d^45s$ 6.7589	42 ${}^7S_3$ **Mo** Molybdenum 95.94 [Kr]$4d^55s$ 7.0924	43 ${}^6S_{5/2}$ **Tc** Technetium (98) [Kr]$4d^55s^2$ 7.28	44 ${}^5F_5$ **Ru** Ruthenium 101.07 [Kr]$4d^75s$ 7.3605	45 ${}^4F_{9/2}$ **Rh** Rhodium 102.90550 [Kr]$4d^85s$ 7.4589	46 ${}^1S_0$ **Pd** Palladium 106.42 [Kr]$4d^{10}$ 8.3369	47 ${}^2S_{1/2}$ **Ag** Silver 107.8682 [Kr]$4d^{10}5s$ 7.5762	48 ${}^1S_0$ **Cd** Cadmium 112.411 [Kr]$4d^{10}5s^2$ 8.9938	49 ${}^2P^{\circ}_{1/2}$ **In** Indium 114.818 [Kr]$4d^{10}5s^25p$ 5.7864	50 ${}^3P_0$ **Sn** Tin 118.710 [Kr]$4d^{10}5s^25p^2$ 7.3439	51 ${}^4S^{\circ}_{3/2}$ **Sb** Antimony 121.760 [Kr]$4d^{10}5s^25p^3$ 8.6084	52 ${}^3P_2$ **Te** Tellurium 127.60 [Kr]$4d^{10}5s^25p^4$ 9.0096	53 ${}^2P^{\circ}_{3/2}$ **I** Iodine 126.90447 [Kr]$4d^{10}5s^25p^5$ 10.4513	54 ${}^1S_0$ **Xe** Xenon 131.29 [Kr]$4d^{10}5s^25p^6$ 12.1298
6	55 ${}^2S_{1/2}$ **Cs** Cesium 132.90545 [Xe]$6s$ 3.8939	56 ${}^1S_0$ **Ba** Barium 137.327 [Xe]$6s^2$ 5.2117		72 ${}^3F_2$ **Hf** Hafnium 178.49 [Xe]$4f^{14}5d^26s^2$ 6.8251	73 ${}^4F_{3/2}$ **Ta** Tantalum 180.9479 [Xe]$4f^{14}5d^36s^2$ 7.5496	74 ${}^5D_0$ **W** Tungsten 183.84 [Xe]$4f^{14}5d^46s^2$ 7.8640	75 ${}^6S_{5/2}$ **Re** Rhenium 186.207 [Xe]$4f^{14}5d^56s^2$ 7.8335	76 ${}^5D_4$ **Os** Osmium 190.23 [Xe]$4f^{14}5d^66s^2$ 8.4382	77 ${}^4F_{9/2}$ **Ir** Iridium 192.217 [Xe]$4f^{14}5d^76s^2$ 8.9670	78 ${}^3D_3$ **Pt** Platinum 195.078 [Xe]$4f^{14}5d^96s$ 8.9587	79 ${}^2S_{1/2}$ **Au** Gold 196.96655 [Xe]$4f^{14}5d^{10}6s$ 9.2255	80 ${}^1S_0$ **Hg** Mercury 200.59 [Xe]$4f^{14}5d^{10}6s^2$ 10.4375	81 ${}^2P^{\circ}_{1/2}$ **Tl** Thallium 204.3833 [Hg]$6p$ 6.1082	82 ${}^3P_0$ **Pb** Lead 207.2 [Hg]$6p^2$ 7.4167	83 ${}^4S^{\circ}_{3/2}$ **Bi** Bismuth 208.98038 [Hg]$6p^3$ 7.2856	84 ${}^3P_2$ **Po** Polonium (209) [Hg]$6p^4$ 8.417 ?	85 ${}^2P^{\circ}_{3/2}$ **At** Astatine (210) [Hg]$6p^5$	86 ${}^1S_0$ **Rn** Radon (222) [Hg]$6p^6$ 10.7485
7	87 ${}^2S_{1/2}$ **Fr** Francium (223) [Rn]$7s$ 4.0727	88 ${}^1S_0$ **Ra** Radium (226) [Rn]$7s^2$ 5.2784		104 ${}^3F_2$? **Rf** Rutherfordium (261) [Rn]$5f^{14}6d^27s^2$? 6.0 ?	105 **Db** Dubnium (262)	106 **Sg** Seaborgium (263)	107 **Bh** Bohrium (264)	108 **Hs** Hassium (265)	109 **Mt** Meitnerium (268)	110 **Uun** Ununnilium (269)	111 **Uuu** Unununium (272)	112 **Uub** Ununbium						

57 ${}^2D_{3/2}$ **La** Lanthanum 138.9055 [Xe]$5d6s^2$ 5.5769	58 ${}^1G^{\circ}_4$ **Ce** Cerium 140.116 [Xe]$4f5d6s^2$ 5.5387	59 ${}^4I^{\circ}_{9/2}$ **Pr** Praseodymium 140.90765 [Xe]$4f^36s^2$ 5.473	60 ${}^5I_4$ **Nd** Neodymium 144.24 [Xe]$4f^46s^2$ 5.5250	61 ${}^6H^{\circ}_{5/2}$ **Pm** Promethium (145) [Xe]$4f^56s^2$ 5.582	62 ${}^7F_0$ **Sm** Samarium 150.36 [Xe]$4f^66s^2$ 5.6436	63 ${}^8S^{\circ}_{7/2}$ **Eu** Europium 151.964 [Xe]$4f^76s^2$ 5.6704	64 ${}^9D^{\circ}_2$ **Gd** Gadolinium 157.25 [Xe]$4f^75d6s^2$	65 ${}^6H^{\circ}_{15/2}$ **Tb** Terbium 158.92534 [Xe]$4f^96s^2$ 5.8638	66 ${}^5I_8$ **Dy** Dysprosium 162.50 [Xe]$4f^{10}6s^2$ 5.9389	67 ${}^4I^{\circ}_{15/2}$ **Ho** Holmium 164.93032 [Xe]$4f^{11}6s^2$ 6.0215	68 ${}^3H_6$ **Er** Erbium 167.26 [Xe]$4f^{12}6s^2$ 6.1077	69 ${}^2F^{\circ}_{7/2}$ **Tm** Thulium 168.93421 [Xe]$4f^{13}6s^2$ 6.1843	70 ${}^1S_0$ **Yb** Ytterbium 173.04 [Xe]$4f^{14}6s^2$ 6.2542	71 ${}^2D_{3/2}$ **Lu** Lutetium 174.967 [Xe]$4f^{14}5d6s^2$ 5.4259
89 ${}^2D_{3/2}$ **Ac** Actinium (227) [Rn]$6d7s^2$ 5.17	90 ${}^3F_2$ **Th** Thorium 232.0381 [Rn]$6d^27s^2$ 6.3067	91 ${}^4K_{11/2}$ **Pa** Protactinium 231.03588 [Rn]$5f^26d7s^2$ 5.89	92 ${}^5L^{\circ}_6$ **U** Uranium 238.0289 [Rn]$5f^36d7s^2$ 6.1941	93 ${}^6L_{11/2}$ **Np** Neptunium (237) [Rn]$5f^46d7s^2$ 6.2657	94 ${}^7F_0$ **Pu** Plutonium (244) [Rn]$5f^67s^2$ 6.0262	95 ${}^8S^{\circ}_{7/2}$ **Am** Americium (243) [Rn]$5f^77s^2$ 5.9738	96 ${}^9D^{\circ}_2$ **Cm** Curium (247) [Rn]$5f^76d7s^2$ 5.9915	97 ${}^6H^{\circ}_{15/2}$ **Bk** Berkelium (247) [Rn]$5f^97s^2$ 6.1979	98 ${}^5I_8$ **Cf** Californium (251) [Rn]$5f^{10}7s^2$ 6.2817	99 ${}^4I^{\circ}_{15/2}$ **Es** Einsteinium (252) [Rn]$5f^{11}7s^2$ 6.42	100 ${}^3H_6$ **Fm** Fermium (257) [Rn]$5f^{12}7s^2$ 6.50	101 ${}^2F^{\circ}_{7/2}$ **Md** Mendelevium (258) [Rn]$5f^{13}7s^2$ 6.58	102 ${}^1S_0$ **No** Nobelium (259) [Rn]$5f^{14}7s^2$ 6.65	103 ${}^2P^{\circ}_{1/2}$? **Lr** Lawrencium (262) [Rn]$5f^{14}7s^27p$? 4.9 ?

□ **Solids**

🟦 **Liquids**

🟪 **Gases**

🟨 **Artificially Prepared**

For a description of the atomic data, visit physics.nist.gov/atomic

†Based upon ^{12}C. ( ) indicates the mass number of the most stable isotope. For a description and the most accurate values and uncertainties, see J. Phys. Chem. Ref. Data, **26** (5), 1239 (1997).

March 1999

Design neuer magnetischer Magnete

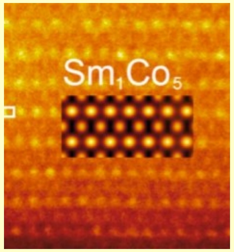
neue *high performance* Magnete
aus nachhaltigen, wiederverwertbaren Werkstoffen

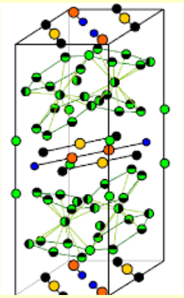
CRC/TRR 270 *HoMMage*: Hysteresis Design of Magnetic Materials for Efficient Energy Conversion

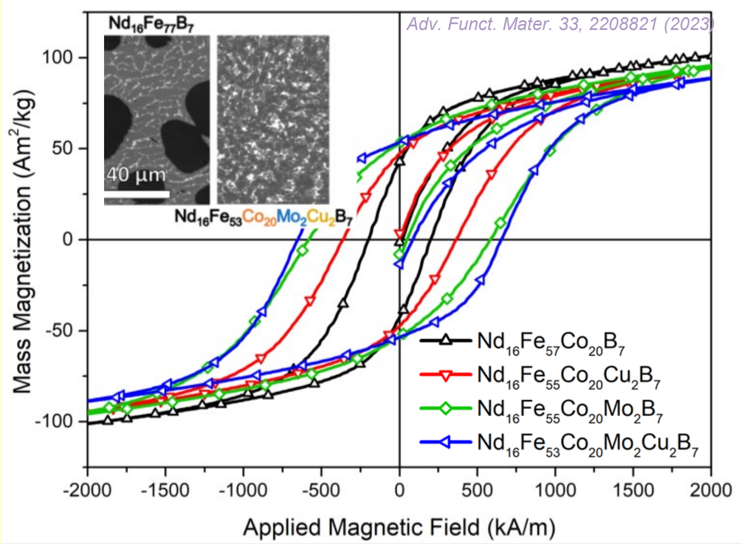
Binäre und ternäre Legierungen als Start

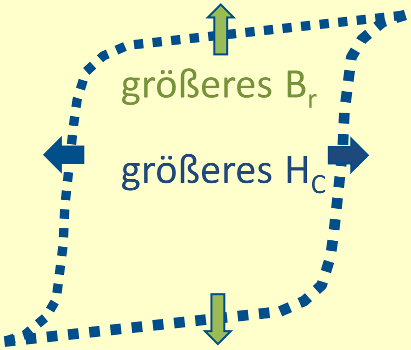
Dotierung/Mischung von Legierungen

komplexe multi-element Materialien









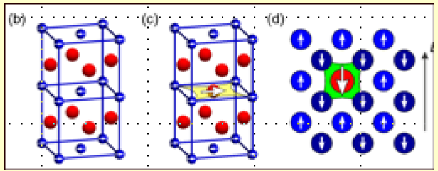
Zukunft

Vom Einkristall

Wachsende strukturelle/chemische Komplexität

Zur komplexen Nano/ Mikrostruktur

Neue Mechanismen der Ummagnetisierung ?

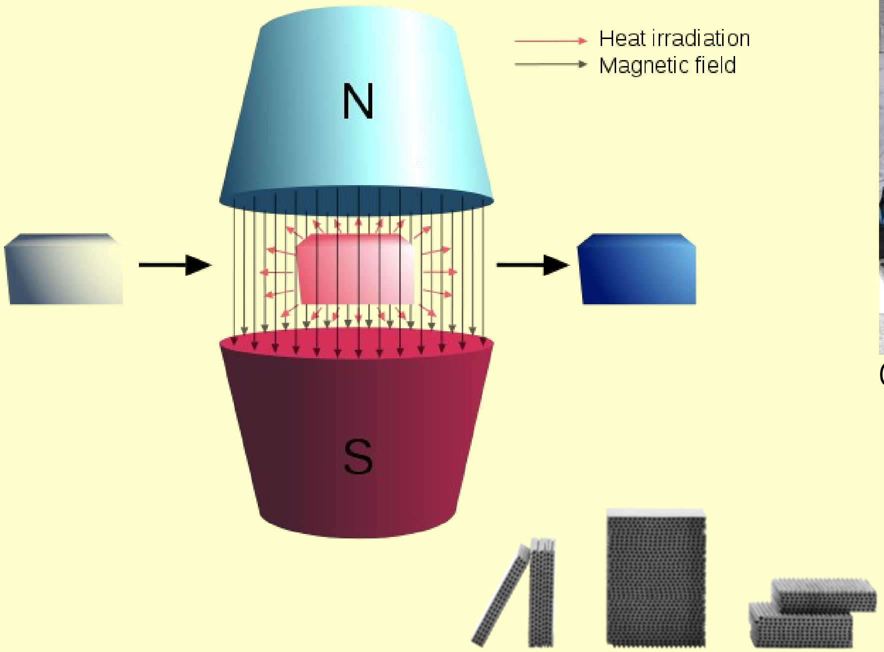


Beispiel: $Ni_{51}Mn_{49}$
Verständnis auf atomarer Skala!

Magnetische Kühlung

Magnetokalorischer Werkstoff:

Erwärmt sich im Magnetfeld, gibt die Wärme an die Umgebung ab und wird ohne Magnetfeld kälter als vorher.



https://vacuumschmelze.de/produkte/einzigartige-technologien/magnetokalorischer-werkstoff-calorivac

Kühlschrank ohne Kompressor

magnetische Kühlung ohne klimaschädliche Kühlmittel

© Magnotherm

Klimaanlage

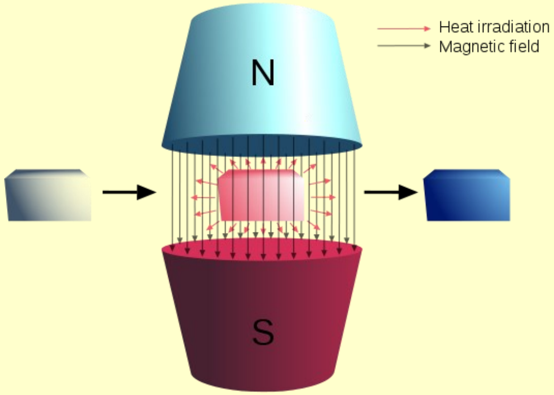
Wasser, kein Kühlmittel

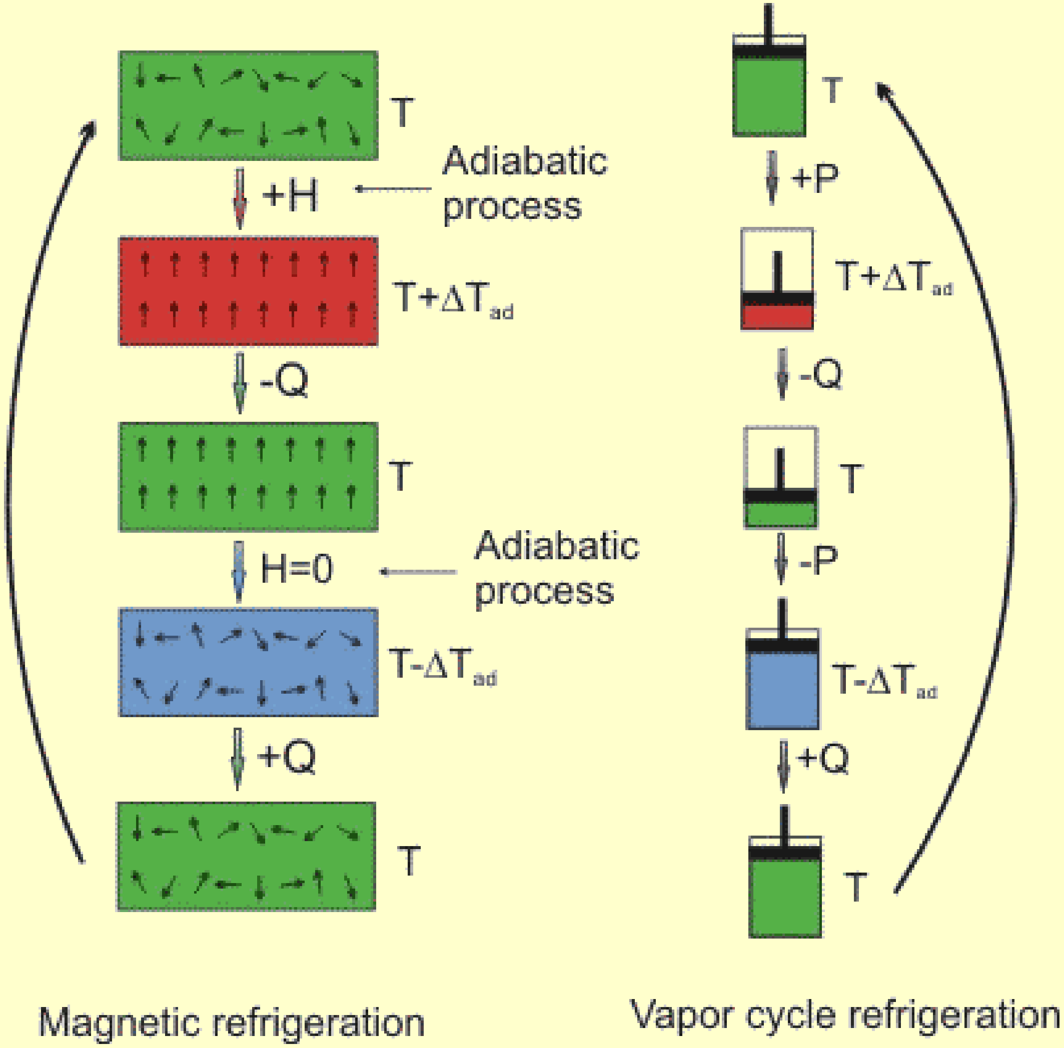
© BASF SE

The Haier Winecooler

Magnetisches Kühlung (Wie geht das?)

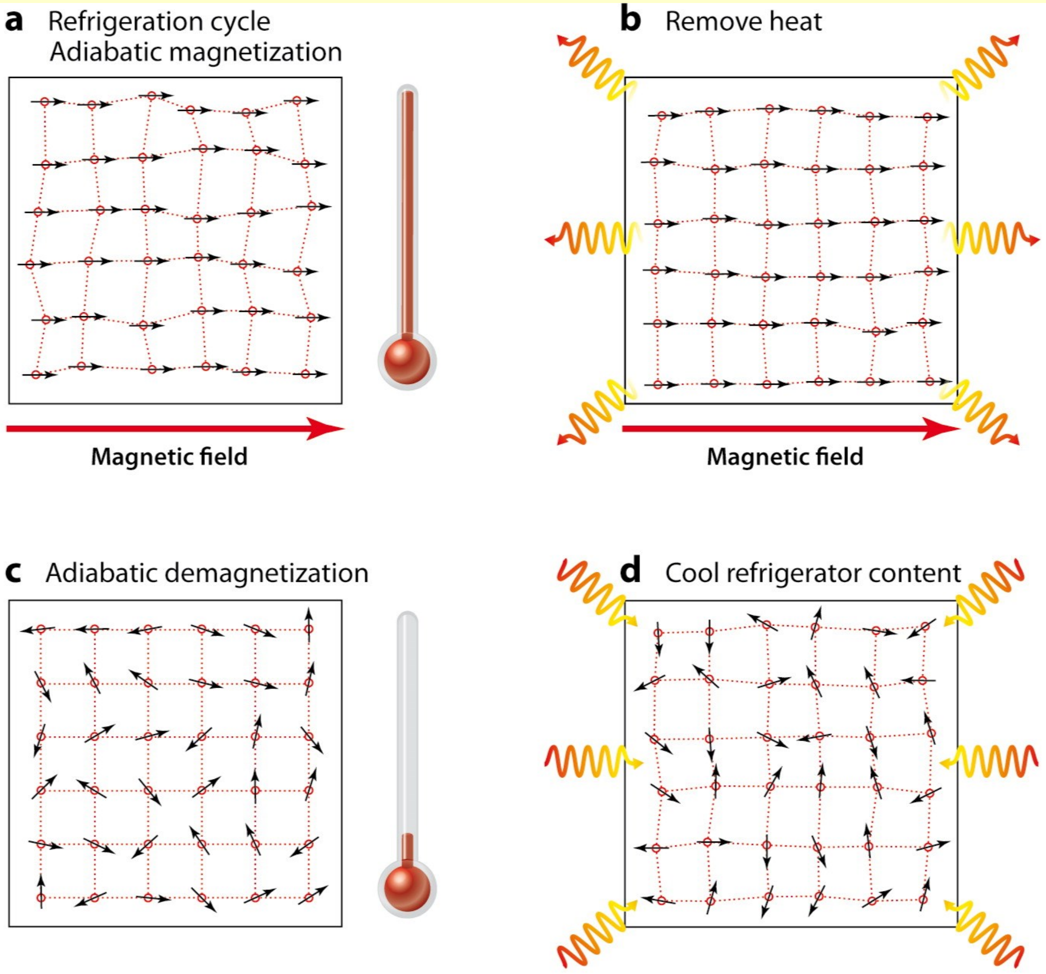
Gadolinium alloy heats up inside the magnetic field and loses thermal energy to the environment, so it exits the field cooler than when it entered.





- The Magnetocaloric Effect (how it works)
- Magnetic Fields: Magnetic Cooling
- Magnetic Refrigeration (11/2014)
- BASF: Principle of Magnetocaloric Cooling
- **GE Magnetic Refrigeration: How it Works**

Magnetische Kühlung (Spins und Vibrationen)



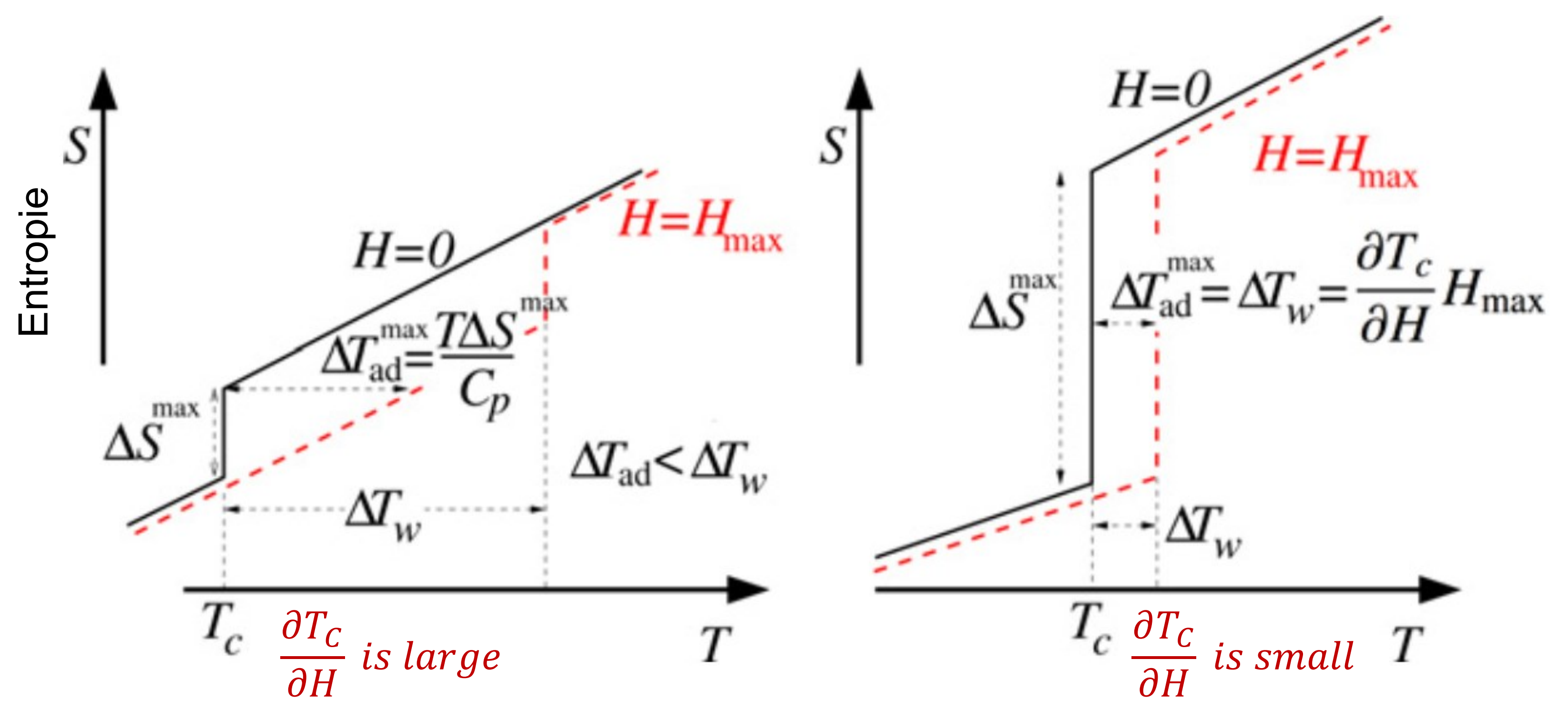
Franco V, et al. 2012.
Annu. Rev. Mater. Res. 42:305–42

https://www.annualreviews.org/doi/full/10.1146/annurev-matsci-062910-100356#_i11

Theoretischer Grenzwert ΔT_{ad} (adiabatische Temperaturänderung)

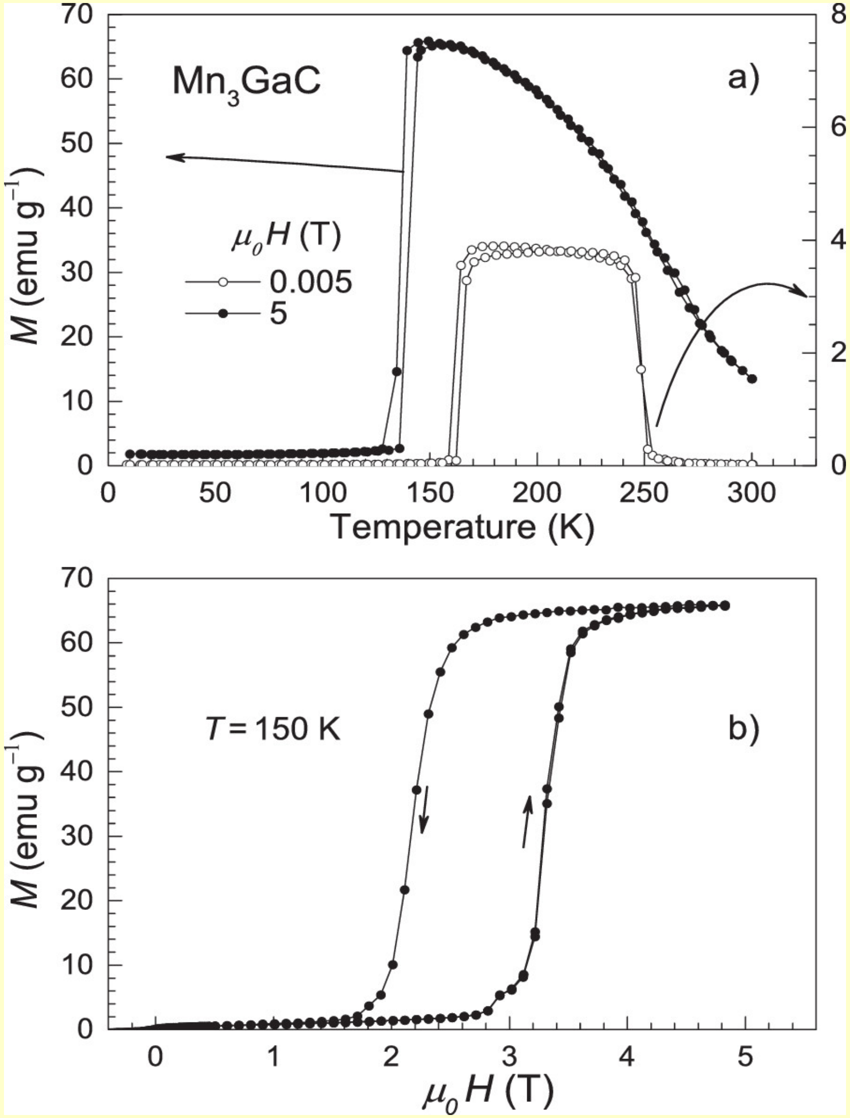
$$\Delta T_{ad}(T, H_{max}) = \int_0^{H_{max}} \frac{T}{C_p(T,H)} \left(\frac{\partial M}{\partial T}\right)_H dH$$

Phasenübergangstemperatur hängt von Stärke des Magnetfeldes ab!
Konzept: zwei unterschiedliche Materialien. Welches erzielt größere ΔT_{ad} ?



Welches Material ?
Magnetostruktureller Phasenübergang (Mn$_3$GaC)

Journal of Applied Physics **115**, 043913 (2014)



Mn$_3$GaC :

large <u>inverse magnetocaloric</u> effects at

a) the first-order antiferromagnetic to ferromagnetic magnetostructural transition at T_t = 165 K

b) the second-order ferro- to paramagnetic transition at T_C = 250 K.[5,12,16]

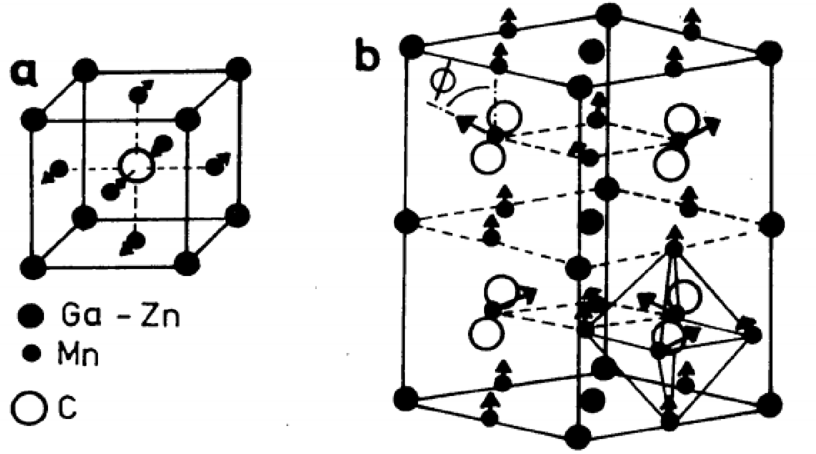
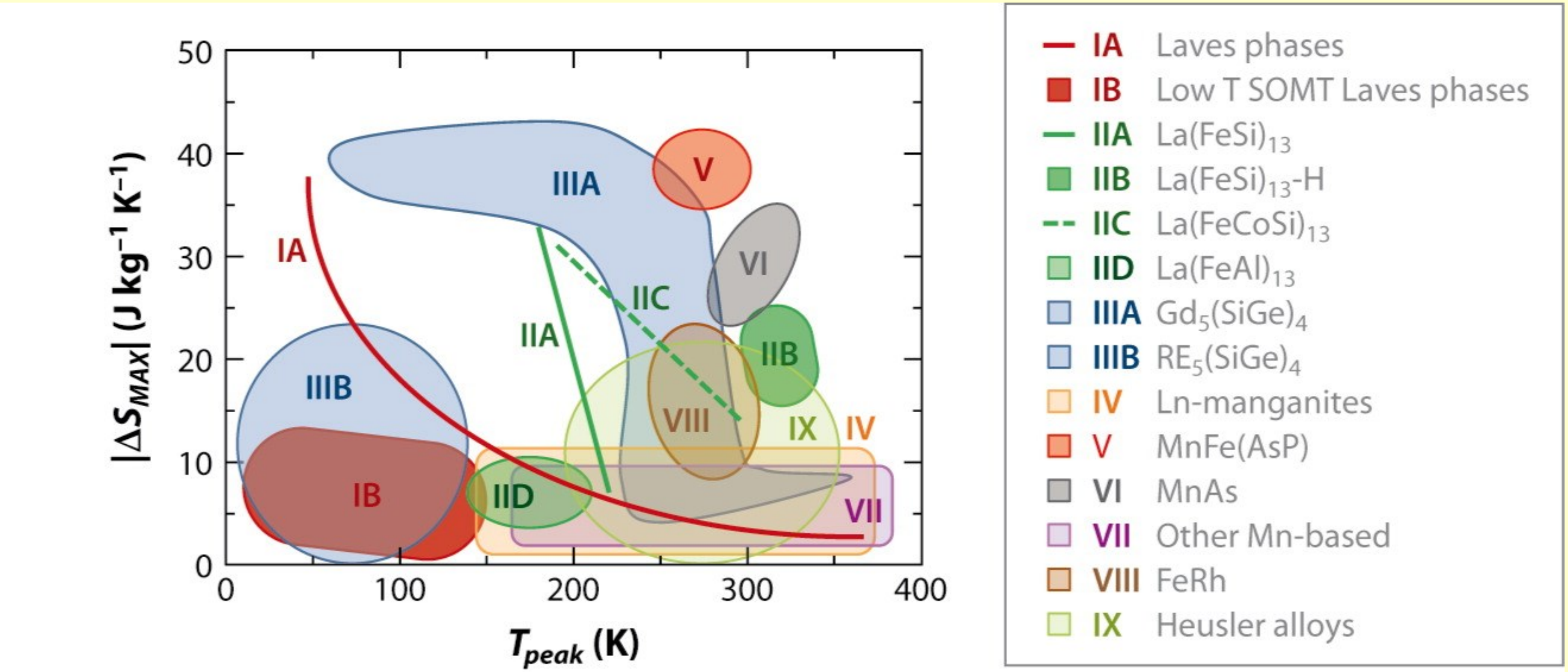


Fig. 5. (a) Antiferromagnetic structure of Mn$_3$GaC (one unit-cell drawn). (b) Low temperature magnetic structure (a$\sqrt{2}$, a$\sqrt{2}$, 2c) of Mn$_3$ZnC ($\phi \simeq 65$ degrees) and of Mn$_3$GaC$_{0.935}$ ($\phi \simeq 20$ degrees).

The magnetic characterization of the sample. (a) Temperature dependence of the magnetization under 5 mT (right scale) and 5 T (left scale). The shift in T_t is about −4 K T^{-1}.

(b) The field dependence of the magnetization at 150 K showing the field-induced transition.

Magnetokalorische Materialien



Franco V, et al. 2012.
Annu. Rev. Mater. Res. 42:305–42

https://www.annualreviews.org/doi/full/10.1146/annurev-matsci-062910-100356#_i11

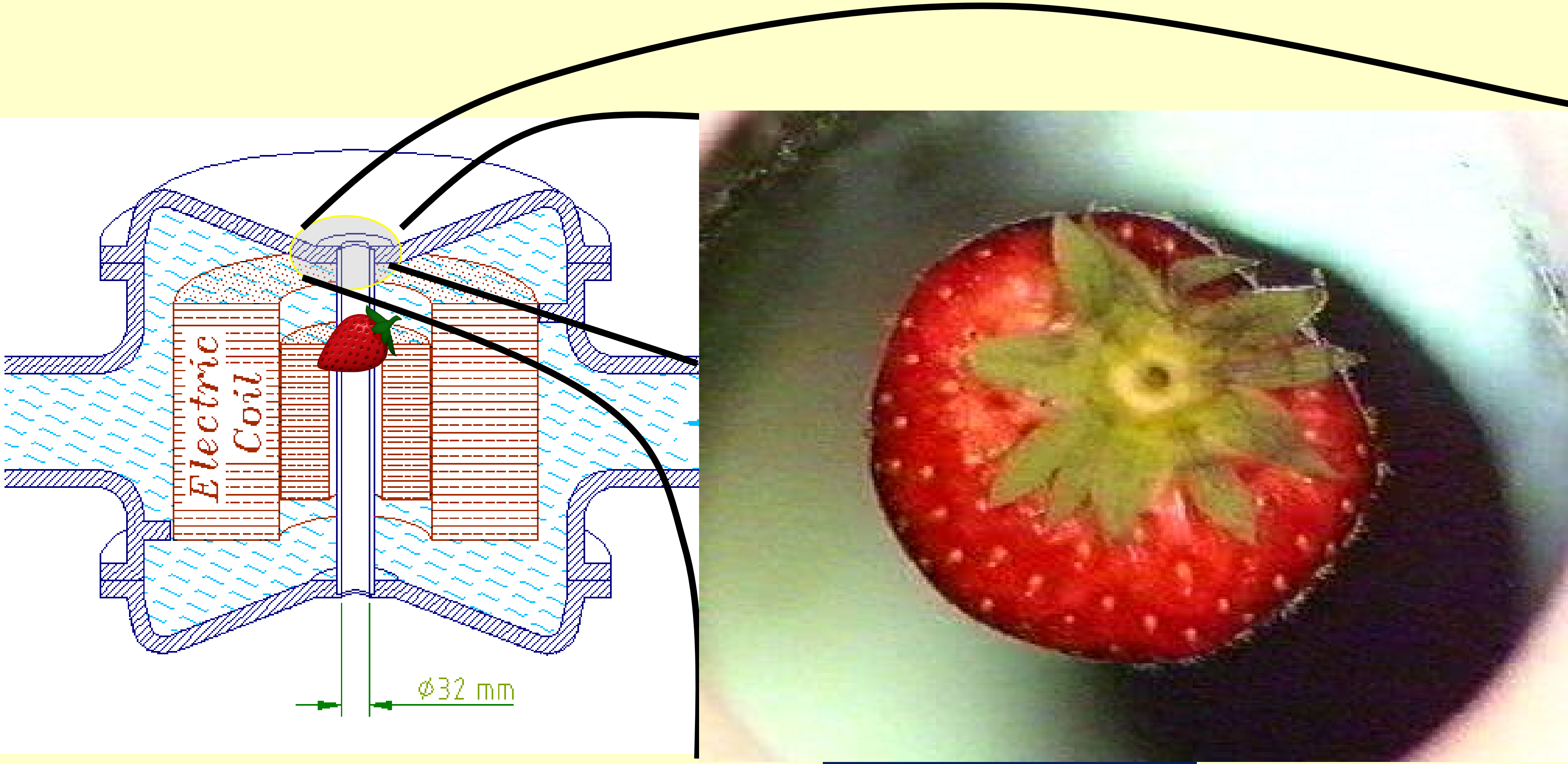
Magnetism is magic …

- Diamagnetism (always!)
- Paramagnetism (often, unpaired spin)
- Ferro-, ferri-, antiferro magnetism (sometimes)

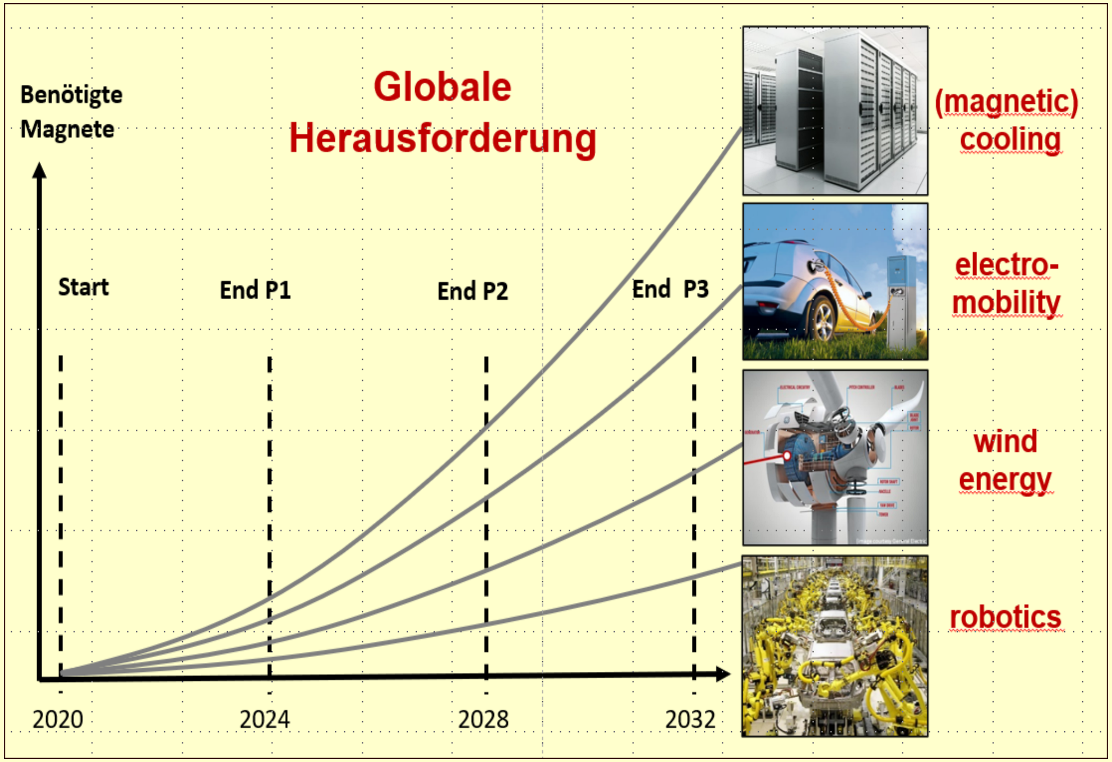
All materials are magnetic !!

Ist eine Erdbeere magnetisch ??

Experiment : Magnetfeld ungefähr 16 Tesla
Ø 32mm Bohrung in einem Bitter –Magnet
(320.000 größer als Erd-Magnetfeld)
Nijmegen High **Field Magnet Laboratory**



Zusammenfassung:

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2024 | Berichte aus Forschung und Lehre

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Offen im Denken

60

Magnete als Klimaretter
Materialien für eine emissionsfreie Zukunft

Oliver Gutfleisch „Die Energiewende ist eine Materialwende!" 8

Michael Farle Ein mysteriöses Material mit magischer Wirkung? 12

Magnete: Forschung für mehr Klimaneutralität !

CRC/TRR 270 *HoMMage*: Hysteresis Design of Magnetic Materials for Efficient Energy Conversion

UNIKATE 60:

Magnete als Klimaretter

Our HoMMage team

October 2022

Mai 2019

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WUPPERTAL

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Forschungszentrum

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für Mikroskopie
und Spektroskopie
mit Elektronen
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Ernst Ruska-Centre for Microscopy
and Spectroscopy with Electrons

MAX-PLANCK-INSTITUT
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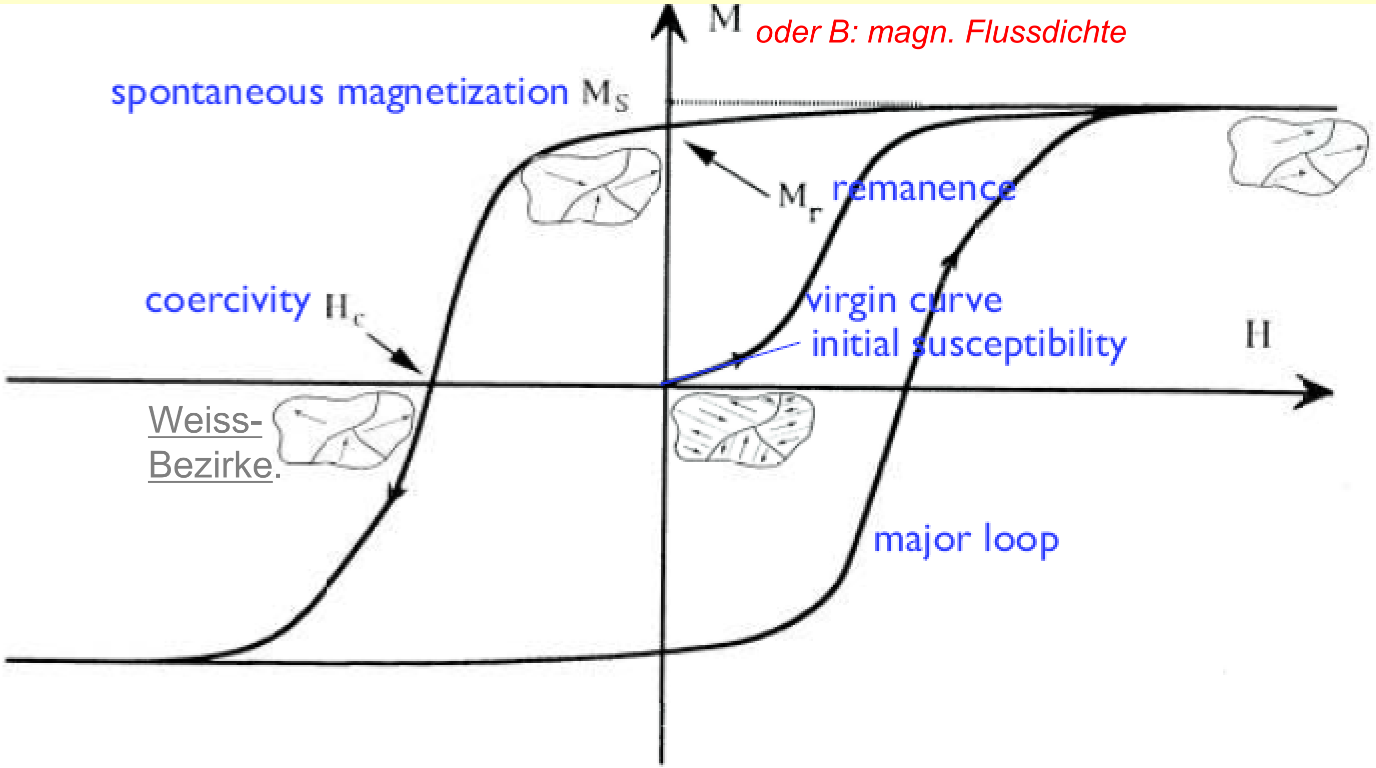
Thank YOU for your attention !

Magnetic Hysteresis: Definitions

Hysteresis



The hysteresis loop shows the irreversible, nonlinear response of a ferromagnet to a magnetic field . It reflects the arrangement of the magnetization in ferromagnetic *domains*. The magnet cannot be in thermodynamic equilibrium anywhere around the open part of the curve! ***M*** and ***H*** have the same units (A m^{-1}).

Je mehr wir kühlen, desto wärmer wird es …….

Magnetische Kühlung als Alternative

~ 10% aller Treibhausgase
~ 20% aller Elektrizität (2018)

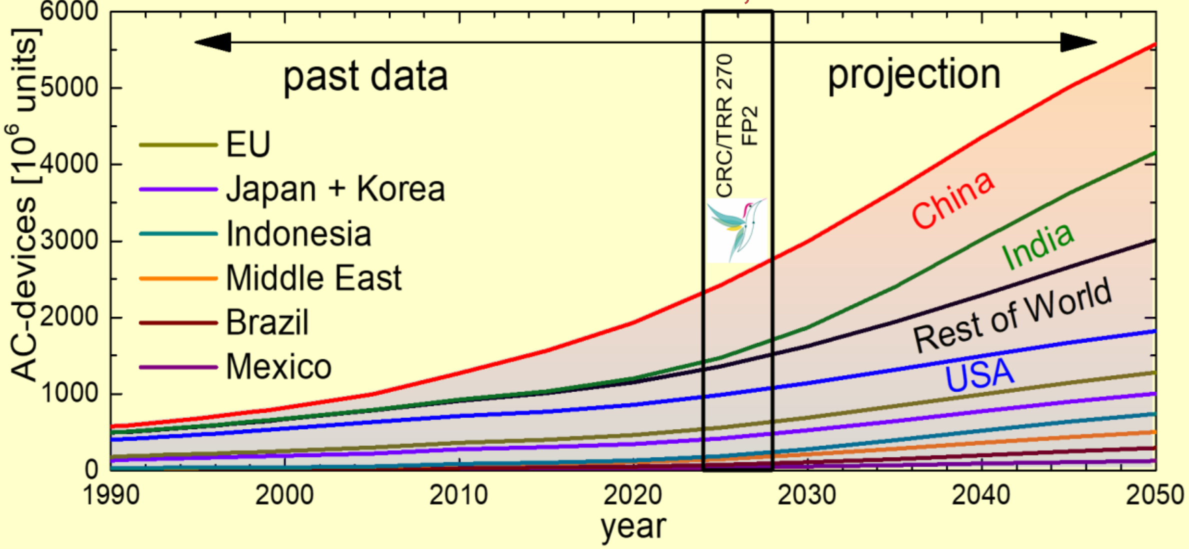
Zukunft: Wasserstoff Veflüssigung

App. Materials Today 29 (2022) 101624
J. Phys. Energy 5 (2023) 034001

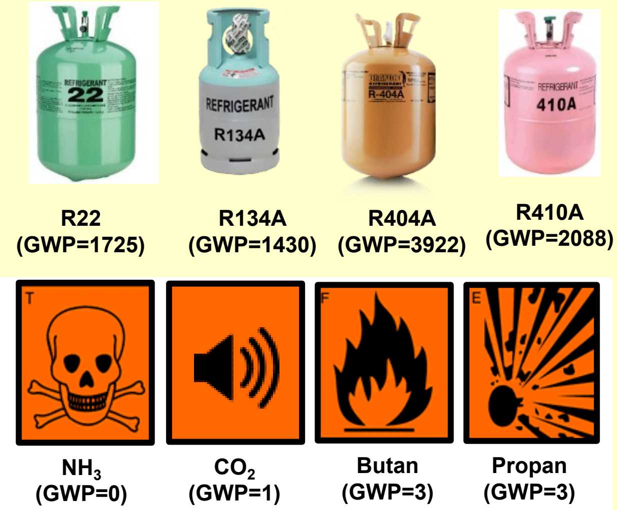
Am wenigsten beachtete Herausforderung :
Der wachsende Bedarf an Klimatisierung. IEA 2018

EU regulates usage of Hydroflurocarbons (HFCs)

Global air conditioner stock, 1990-2050



IEA: The Future of Cooling (2018) Percentage of households equipped with air conditioner in selected countries



CRC/TRR 270 *HoMMage*: Hysteresis Design of Magnetic Materials for Efficient Energy Conversion
© O. Gutfleisch

Neuronen Aktivierung mittels Magnetfeldern

20241007: IEEE Spectrum

Tiny Implantable "Microcoils" in the Brain Activate Neurons Via Magnetic Fields :Precise stimulation could be useful for visual prosthetics or brain-computer interfaces