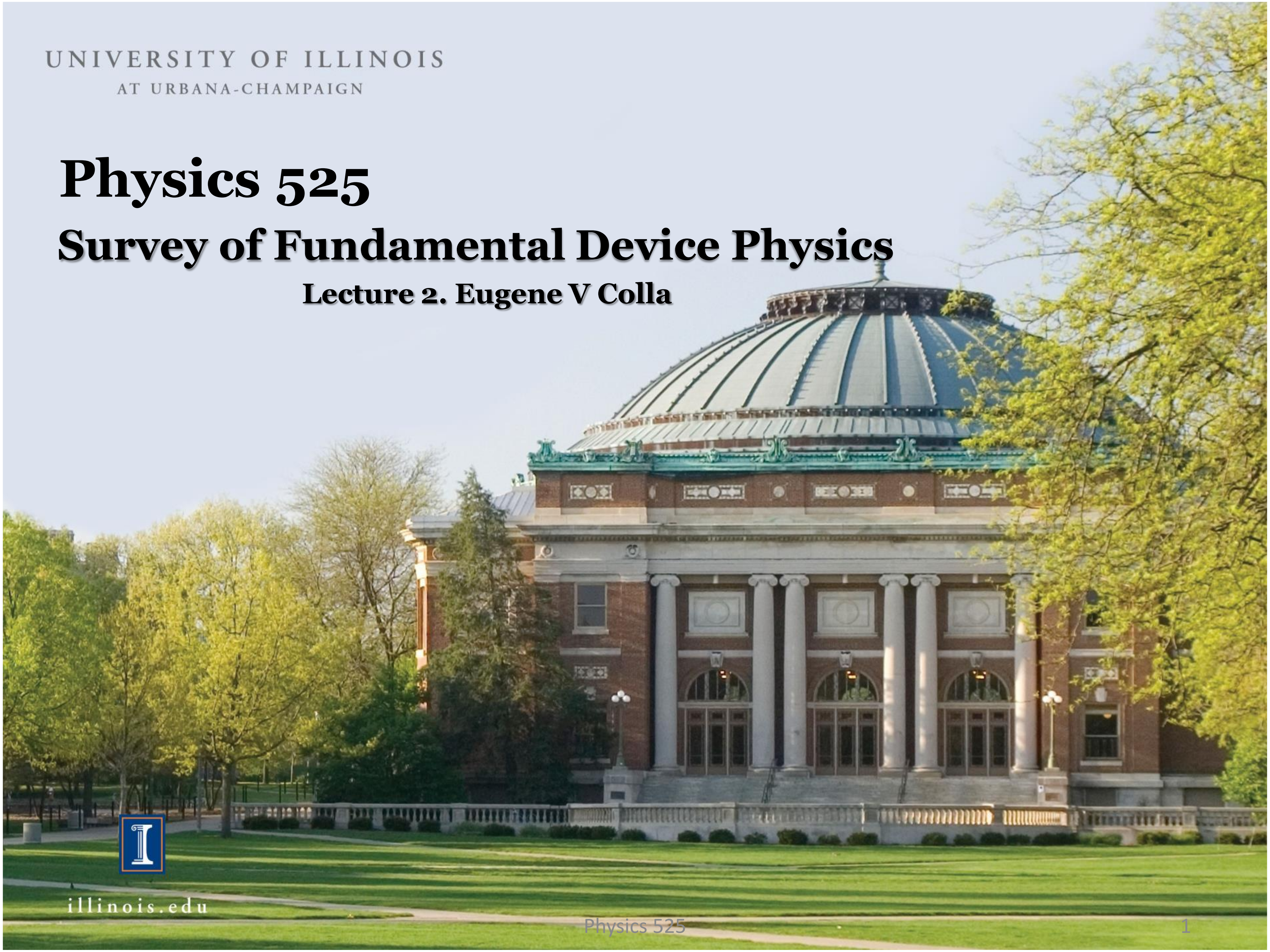
UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN

Physics 525

Survey of Fundamental Device Physics

Lecture 2. Eugene V Colla



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Unit 6. lecture 2. Magnetic properties of materials. Ferromagnetic. Applications.

Agenda

1. **Maxwell equation in magnetic materials.**
2. **Paramagnetics. Diamagnetics. Ferromagnetics.**
3. **Domains. Domains in Magnetic Field**
4. **Barkhausen Noise**
5. **Domains. Visualization of the domains.**
6. **Applications of ferromagnetic materials.**

Magnetic materials.

Magnetic Inductance. Susceptibility. Definitions.

In case if we looking for magnetic inductance in media but not in vacuum, we need to include in consideration the magnetization of material *M*

$$B = \mu_0 \left(H + M \right) ;$$

B – magnetic induction, H - magnetic field and M - magnetization and μ_0 – permeability of free space. $\mu_0 = 4\pi 10^{-7}$ H/m

$$M = \chi H$$

χ - is magnetic susceptibility of the medium $\chi = \frac{dM}{dH}$

$$B = \mu_0 \left(H + \chi H \right) = \mu_0 (1 + \chi) H = \mu_0 \mu_r H = \mu H$$

$\mu_r = (1 + \chi)$ **relative magnetic permeability (unitless)**

Magnetic materials.

Magnetic Inductance. Susceptibility. Definitions.

$$B = \mu_0 \left(H + \chi H \right) = \mu_0 (1 + \chi) H = \mu_0 \mu_r H = \mu H$$

$$\mu_r = (1 + \chi)$$

In real materials χ is a function of magnetic field H and temperature T $\chi(H, T)$

Dependable on the value and sign of c we can consider three gropes of materials:

$\chi < 0$ - diamagnetics, $\mu_r < 1$

$\chi > 0$ - paramagnetics $\mu_r > 1$

$\chi >> 0$ - ferromagnetics $\mu_r >> 1$

Magnetic materials.

Magnetic Inductance. Diamagnetic materials.

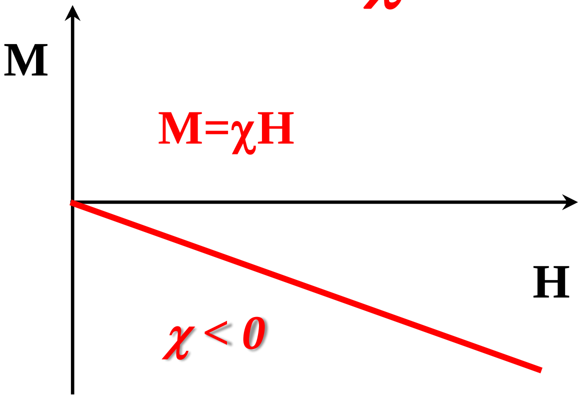
P. Langevin
1872-1946

$$\boxed{\chi < 0 \quad - \quad \mu_r < 1}$$

In diamagnetic materials the induced by the magnetic field ***H*** magnetization will align in the opposite direction than ***H*** . The explanation of diamagnetism was done in 1905 by Paul Langevin[1]. His simple model was based on contribution to magnetization provided by the orbital electrons exposed to external magnetic field.

$$\chi = -\frac{\mu_0 n Z e^2}{6m}\left\langle r^2 \right\rangle$$

Z number of electrons belonging to atom, ***n*** – number of electrons per unit volume, $\langle r^2 \rangle$ – mean square distance of electron from nucleus, ***m*** – mass of the electron



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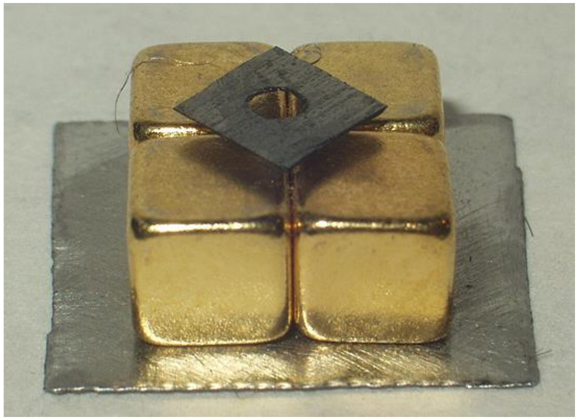
[1] P. Langevin, J. Phys. Theor. Appl. **4** 678-693 (1905)

Magnetic materials.

Magnetic Inductance. Diamagnetic materials.

$\chi < 0 \quad - \quad \mu_r < 1$

Typical value of susceptibility for majority of diamagnetic materials is small ~10^{-5}. Excluding the case of superconductor, the largest c has pyro graphite ~ -4 $\times 10^{-4}$.



Levitation of layer of pyrolytic graphite over the permanent neodymium magnet

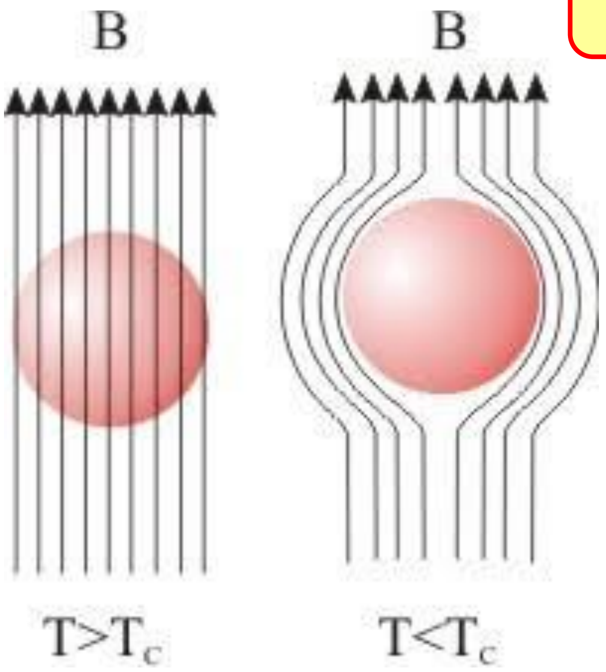
Courtesy Wikipedia

Material	$\chi[\times 10^{-5}]$
Superconductor	-10^5
Pyrolytic carbon	−40.9
Bismuth	−16.6
Neon	−6.74
Mercury	−2.9
Silver	−2.6
Carbon (diamond)	−2.1
Lead	−1.8
Carbon (graphite)	−1.6
Copper	−1.0
Water	−0.91

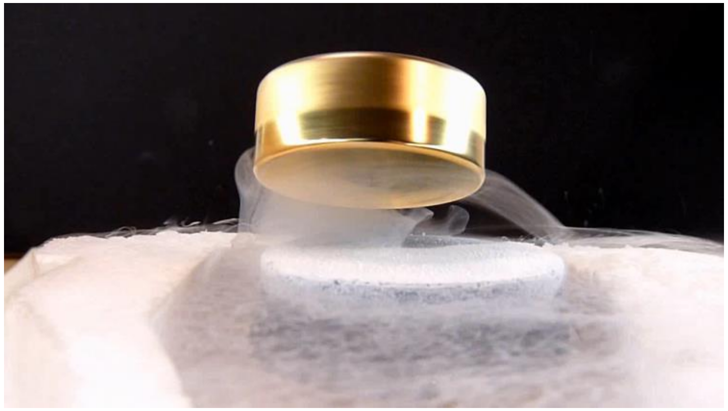
Magnetic materials.

Magnetic Inductance. Diamagnetic materials. Perfect Diamagnetism

$\chi < 0$ - $\mu_r < 1$



Material	χ
Superconductor	−1



Courtesy Wikipedia

Courtesy of YouTube

Magnetic materials.

Magnetic Inductance. Paramagnetic materials.

$\chi > 0 \quad - \quad \mu_r > 1$

Paramagnetic materials are characterized by existence of nonzero magnetic moment in atoms and without magnetic field they randomly oriented resulting in net magnetic moment close to zero. Applying of the magnetic field forces to change the orientation of these domains in the direction of the magnetic field. Typical susceptibility of paramagnetic materials is positive but very small ~ 10^{-5}

Material	$\chi[\times 10^{-5}]$
Tungsten	6.8
Caesium	5.1
Aluminium	2.2
Lithium	1.4
Magnesium	1.2
Sodium	0.72

Magnetic materials.

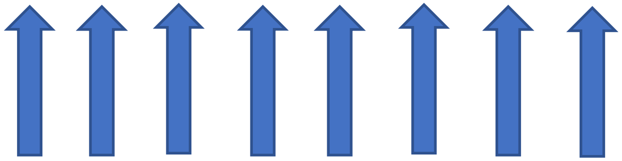
Magnetic Inductance. Ferromagnetism.

$\chi > 0 \quad - \quad \mu_r >> 1$

Ferromagnetism is the phenomenon related to appearance in materials spontaneous magnetization: a net magnetic moment in the absence of an external magnetic field.

Terminology "*ferromagnetism*" came from Latin name of iron Fe "*Ferrum*"

Magnetic moment provided by electron spins arranged in regular order.

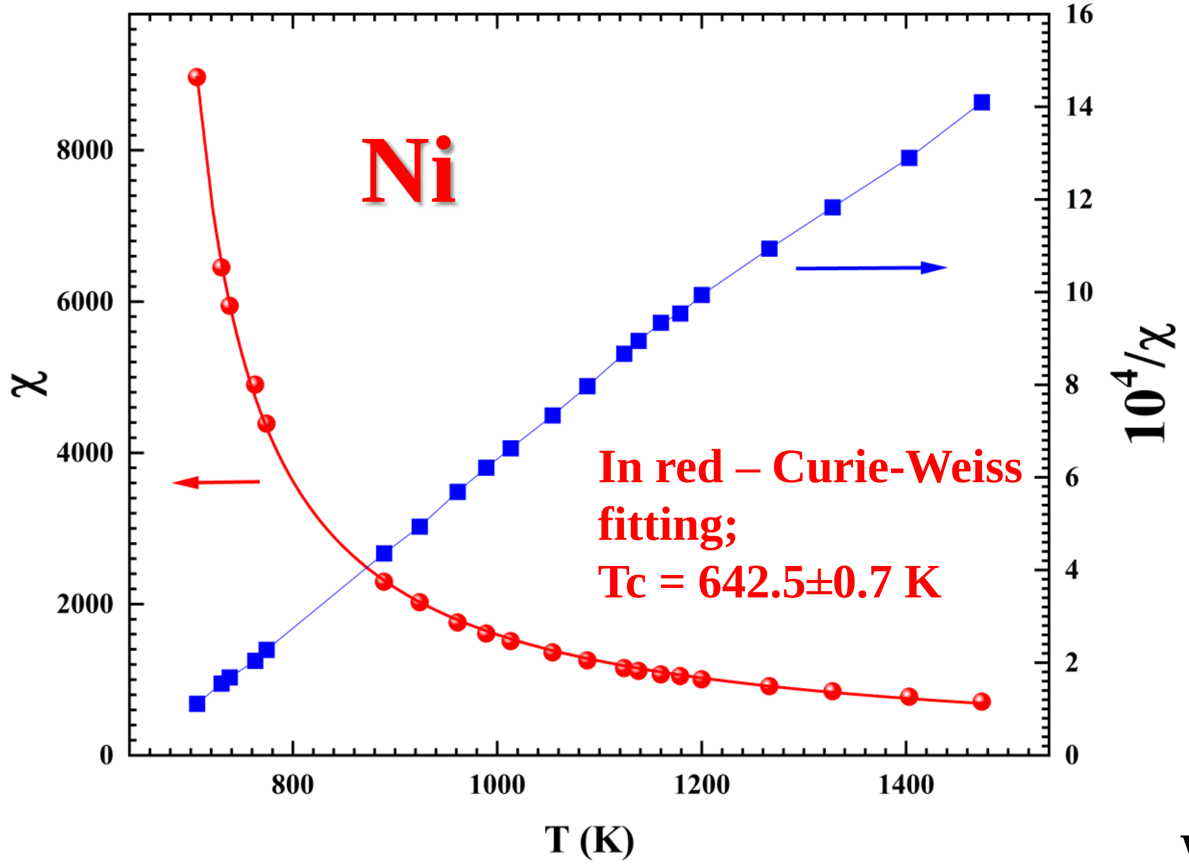


Ferromagnetic ordering

Ferromagnetic properties exist below some critical temperature T_c (Curie temperature). Above T_c the spontaneous magnetization disappears and usually material shows the paramagnetic properties.

Magnetic materials.

Ferromagnetism.



Data from James W. Sucksmith and R. R. Pearce Proceedings of the Royal Soc. Of London Math. And Phys. Sci. 167, issue 929, (1938)

Pierre Curie (1850-1906)

Pierre-Ernest Weiss (1865–1940)

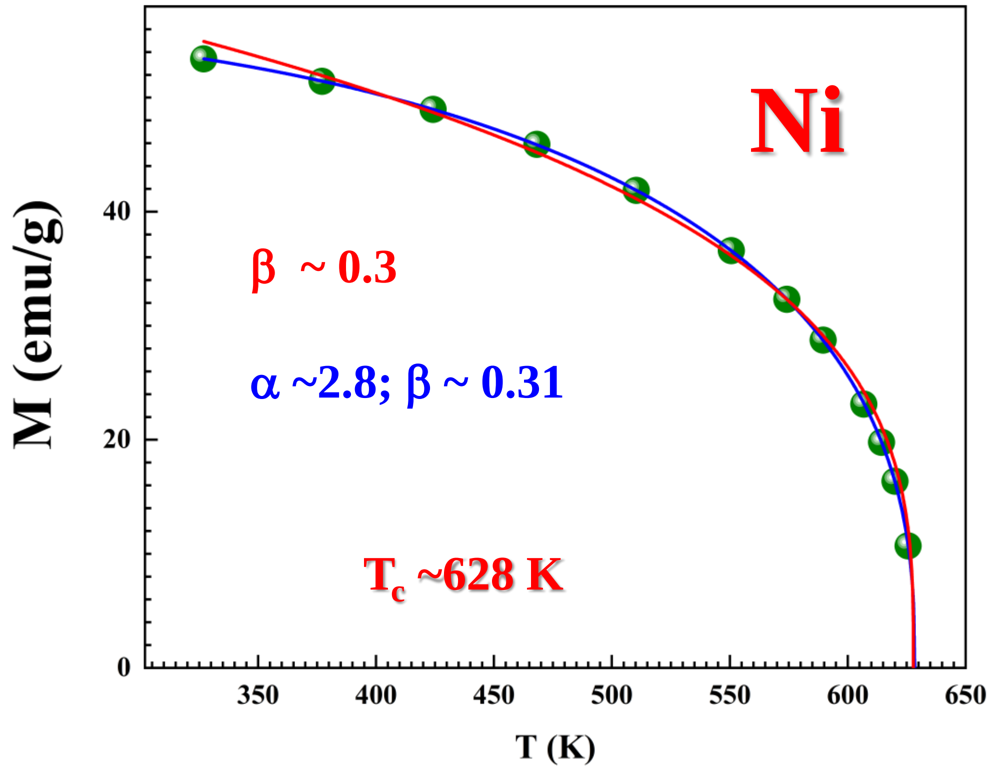
Above Tc susceptibility follows Curie-Weiss law:

$$\chi = \frac{C}{T - T_c} \quad ,$$

Where C – Curie constant, Tc Curie temperature (critical temperature)

Magnetic materials.

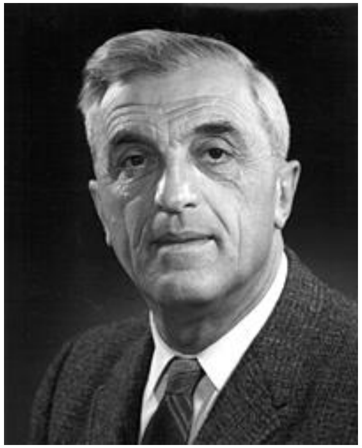
Spontaneous magnetization.



Data from Weiss, M. P., and Forrer, R., 1926. Aimantation et Phenome Magnetocalorique du Nickel, Ann. Phys. Paris, Vol. 5, pp. 153-213.

$$M(T) = M(0)\left(1-\left(\frac{T}{T_c}\right)^{3/2}\right)$$

Bloch equation. Works well at low T for isotropic materials



Felix Bloch (1905-1983)

Near Curie temperature: $M(T) \propto \left(1-\frac{T}{T_c}\right)^{\beta}$

Empirical combination of both regimes (T<<Tc and T~Tc):

$$M(T) = M(0)\left(1-\left(\frac{T}{T_c}\right)^{\alpha}\right)^{\beta}$$

Magnetic materials.

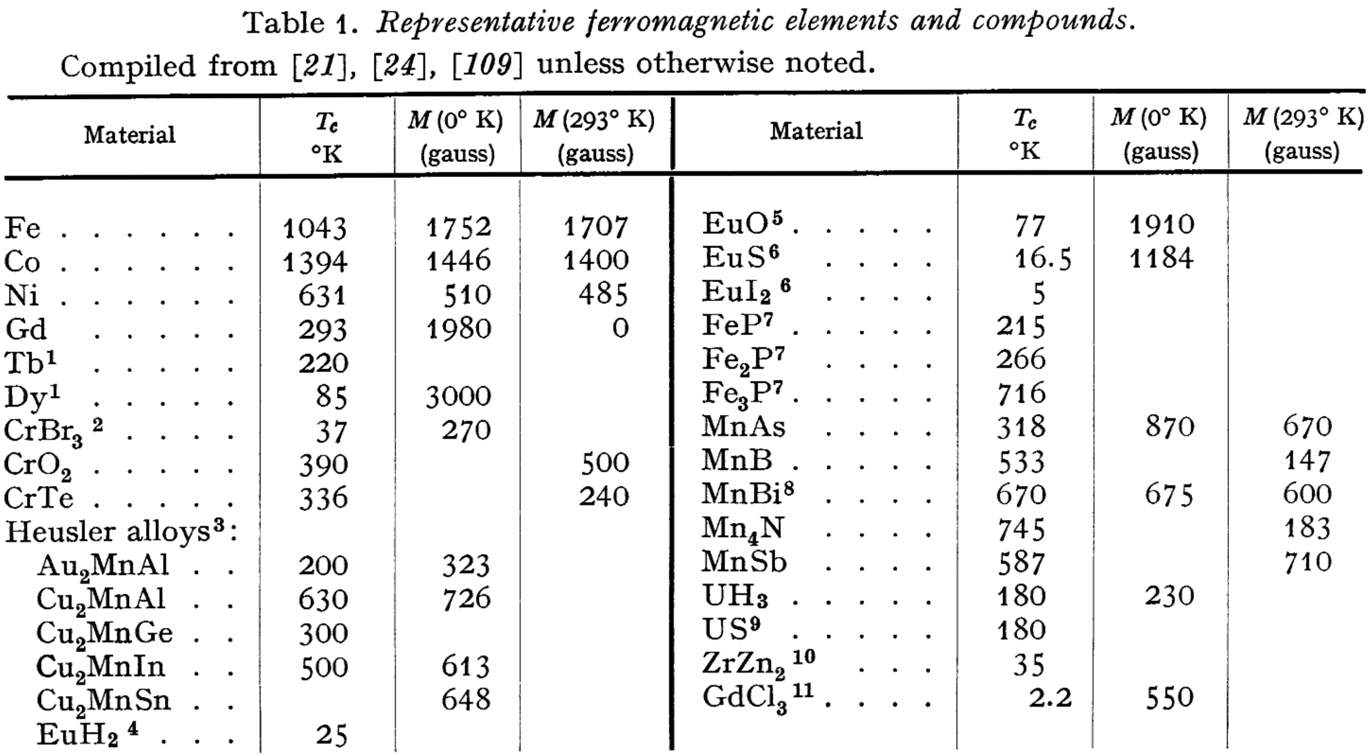


Table 1. *Representative ferromagnetic elements and compounds.*
Compiled from [*21*], [*24*], [*109*] unless otherwise noted.

Material	T_c °K	M (0° K) (gauss)	M (293° K) (gauss)	Material	T_c °K	M (0° K) (gauss)	M (293° K) (gauss)
Fe	1043	1752	1707	EuO[5]	77	1910	
Co	1394	1446	1400	EuS[6]	16.5	1184	
Ni	631	510	485	EuI_2[6]	5		
Gd	293	1980	0	FeP[7]	215		
Tb[1]	220			Fe_2P[7]	266		
Dy[1]	85	3000		Fe_3P[7]	716		
$CrBr_3$[2]	37	270		$MnAs$	318	870	670
CrO_2	390		500	MnB	533		147
$CrTe$	336		240	$MnBi$[8]	670	675	600
Heusler alloys[3]:				Mn_4N	745		183
Au_2MnAl	200	323		$MnSb$	587		710
Cu_2MnAl	630	726		UH_3	180	230	
Cu_2MnGe	300			US[9]	180		
Cu_2MnIn	500	613		$ZrZn_2$[10]	35		
Cu_2MnSn		648		$GdCl_3$[11]	2.2	550	
EuH_2[4]	25						

HANDBUCH DER PHYSIK; HERAUSGEGEBEN VON S. FLOGGE BAND XVIII/2, FERROMAGNETISMUS, SPRINGER-VERLAG, BERLIN· HEIDELBERG· NEW YORK, 1966

Magnetic materials. Domains.

Horseshoe Magnet

Iron based alloys (ferromagnetic)

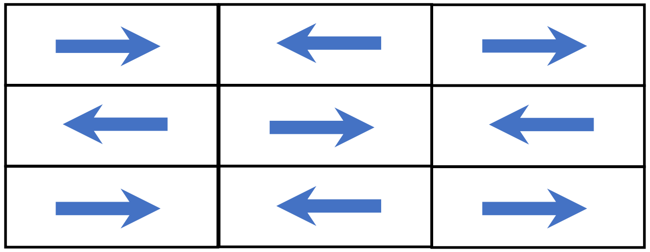
No attraction

Bolt attracted by screwdriver

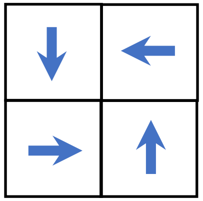
At room temperature screwdrivers and bolts are ferromagnetic. Why in firs case (1) there are no attraction and in second (2) bolt sticks to screwdriver ?

Magnetic materials. Domains.

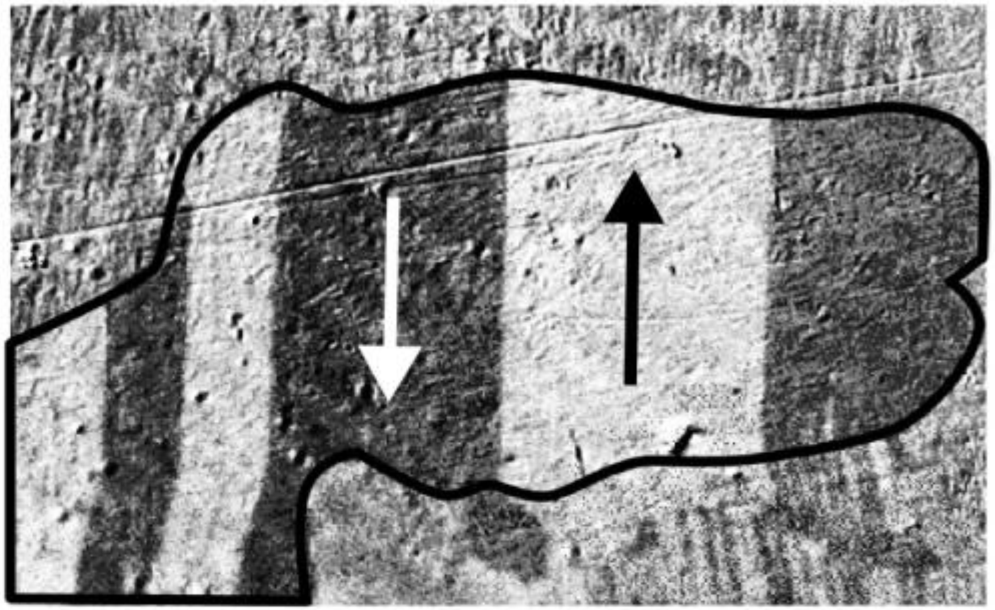
Cooling down below the critical temperature the ferromagnetic material exabits the spontaneous magnetization. If this process goes in zero external magnetic field the ferromagnetics in majorities of cases will form domains. Domains are *macroscopic* units of the material with uniform magnetization. The domains in the bulk piece of material have different orientation minimizing the net magnetization.



180^o domains



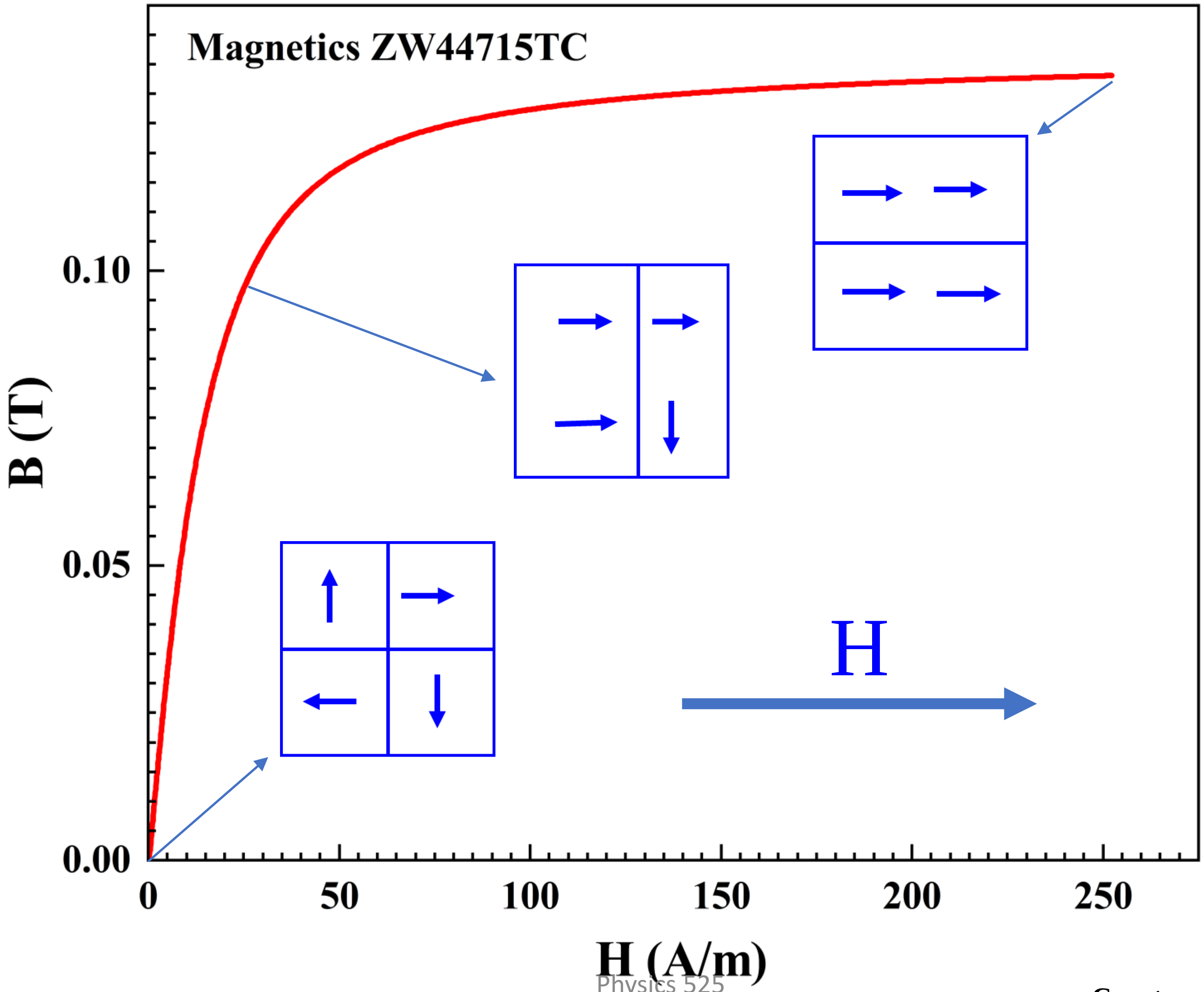
90^o domains



Magnetic domains in a single grain of non-oriented electrical steel. The photo shows an area 0.1 mm wide.

Credit to: S. Zurek, Encyclopedia Magnetica, CC-BY-4.0

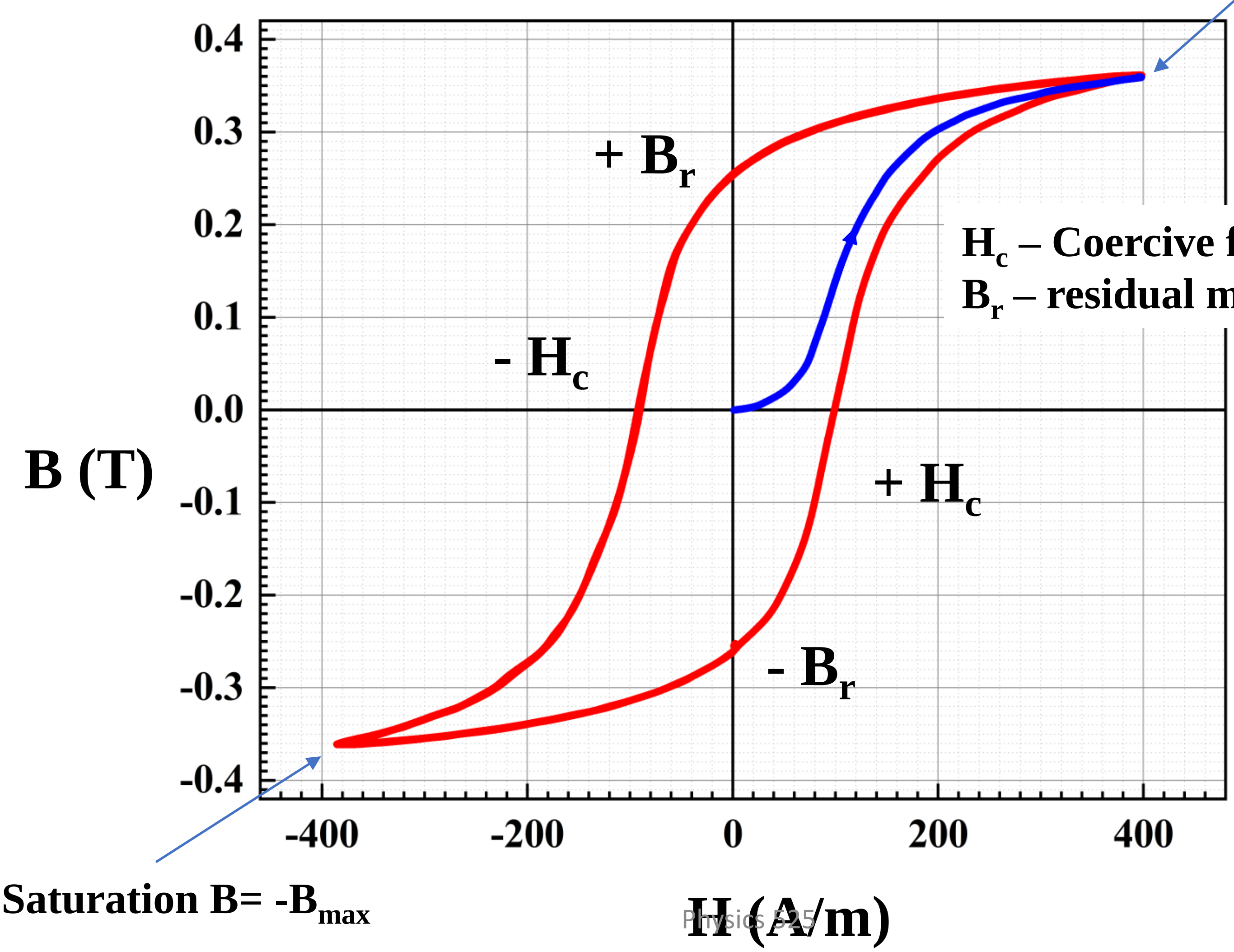
Domains in Magnetic field.



Courtesy P401 course

Domains. Hysteresis Loop

Blue line – magnetization of the demagnetized sample

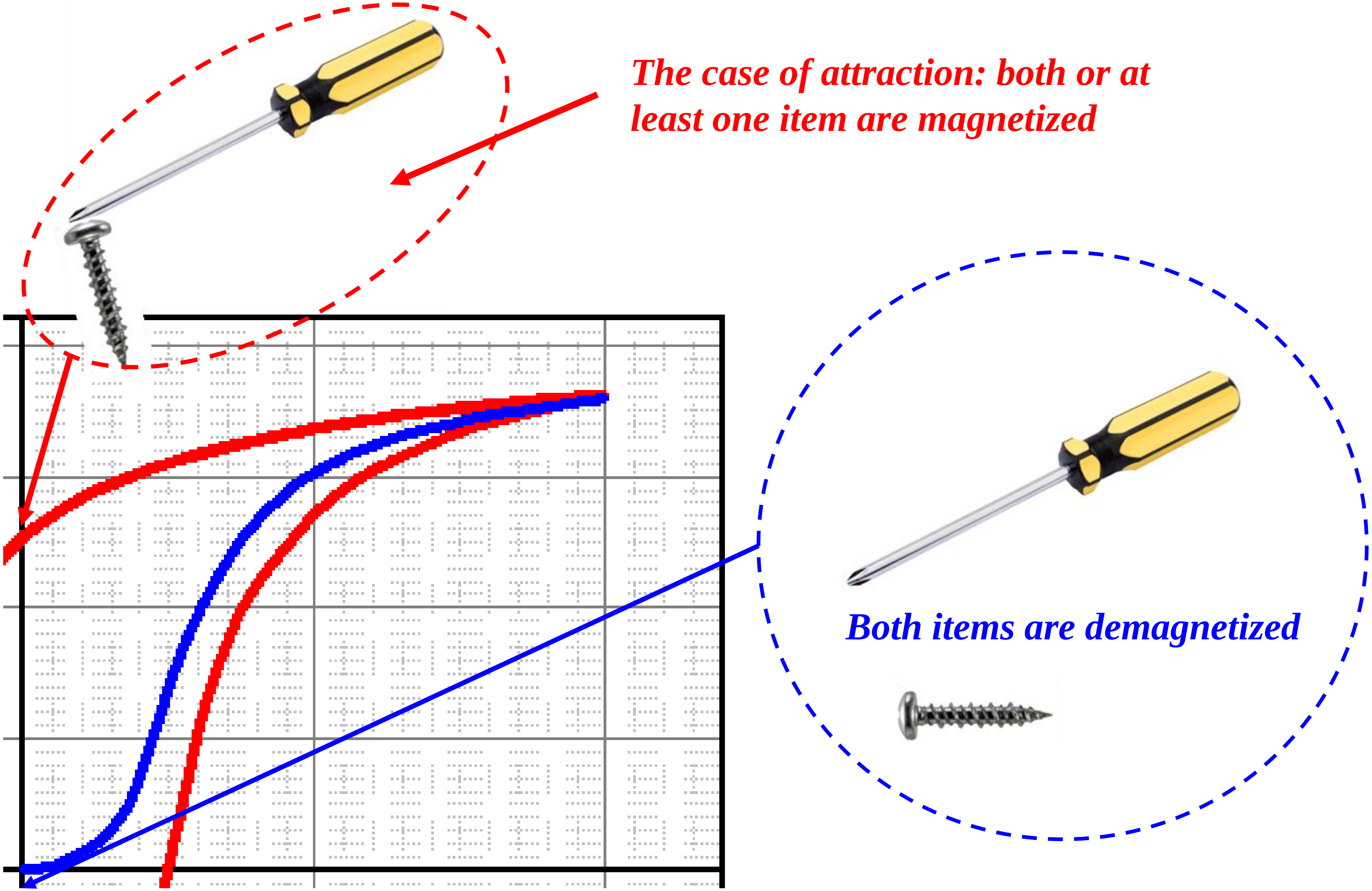


Saturation B= $+B_{max}$

H_c – Coercive field
B_r – residual magnetization

Saturation B= $-B_{max}$

Domains. Hysteresis Loop

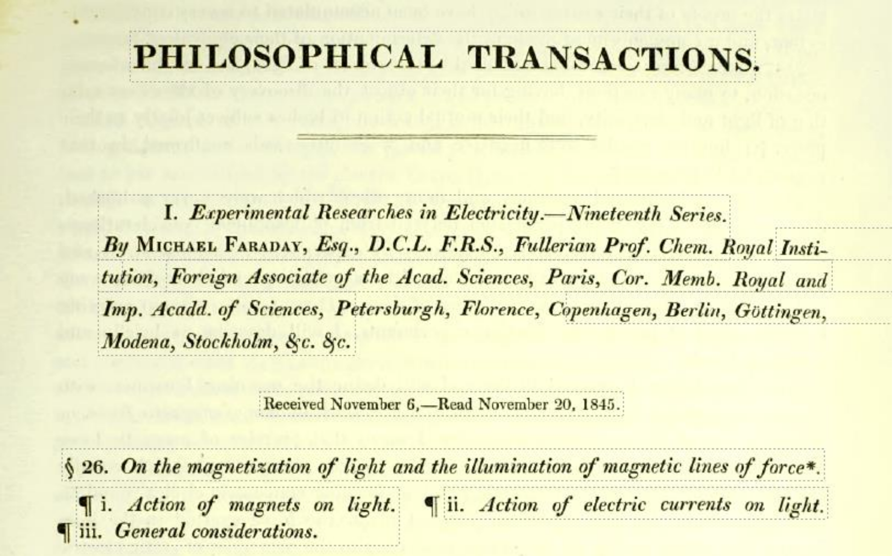


The case of attraction: both or at least one item are magnetized

Both items are demagnetized

Faraday Effect.

Michael Faraday
1791-1867



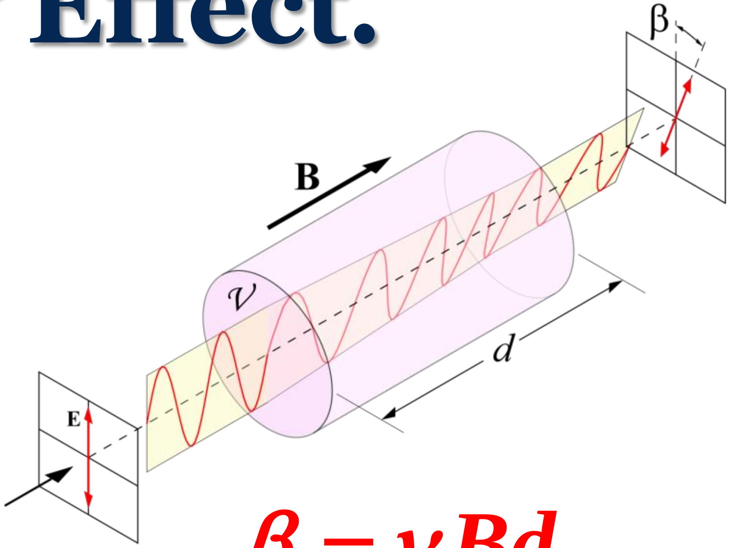
PHILOSOPHICAL TRANSACTIONS.

I. *Experimental Researches in Electricity.—Nineteenth Series.*
By Michael Faraday, *Esq., D.C.L. F.R.S., Fullerian Prof. Chem. Royal Institution, Foreign Associate of the Acad. Sciences, Paris, Cor. Memb. Royal and Imp. Acadd. of Sciences, Petersburgh, Florence, Copenhagen, Berlin, Göttingen, Modena, Stockholm, &c. &c.*

Received November 6,—Read November 20, 1845.

§ 26. *On the magnetization of light and the illumination of magnetic lines of force*.*

¶ i. *Action of magnets on light.* ¶ ii. *Action of electric currents on light.*
¶ iii. *General considerations.*



$$\beta = \nu B d$$

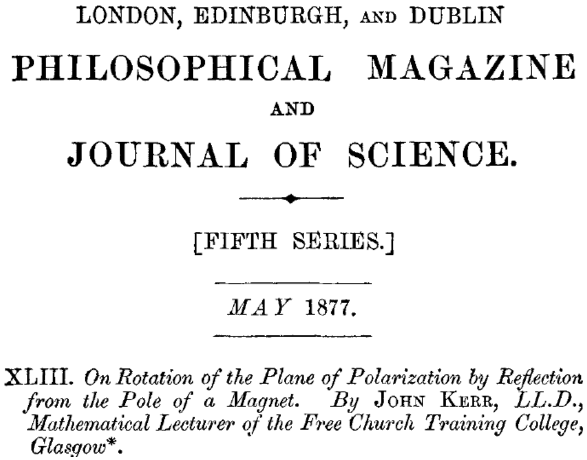
β – angle of rotation (rad)
B – magnetic inductance (T)
ν – Verdet constant (rad/T*m)

$$\nu = \frac{e}{2mc}\lambda\frac{dn}{d\lambda}$$

Courtesy of Wikipedia

Kerr Effect.

John Kerr
1824-1907



LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

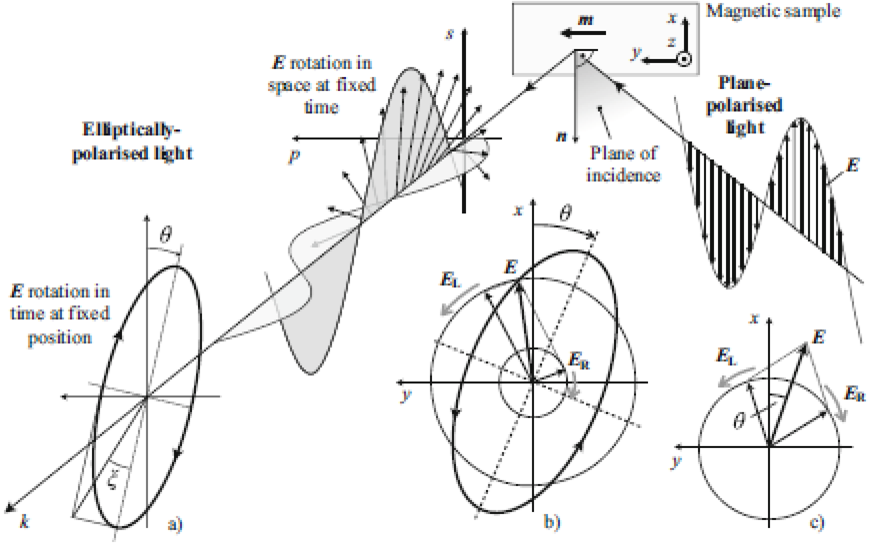
AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

MAY 1877.

XLIII. *On Rotation of the Plane of Polarization by Reflection from the Pole of a Magnet. By* John Kerr, *LL.D., Mathematical Lecturer of the Free Church Training College, Glasgow**.

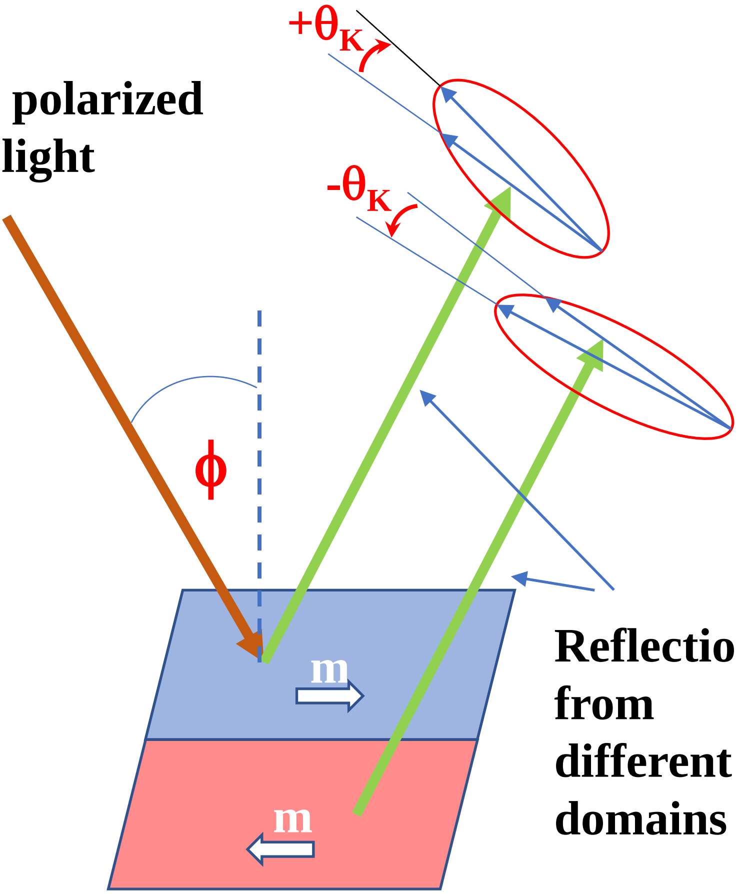


Incident light is linear polarized; reflected – elliptically polarized; polarization ellipse has An angular shift of azimuth θ. Sign of θ depends on the direction of direction of the magnetic moment m

Rudolf Schäfer and Jeffrey McCord, “Magneto-Optical Microscopy” in “Magnetic Measurement Techniques for Materials Characterization”, Springer 2021

Kerr Microscopy. Main Idea.

Linearly polarized incident light



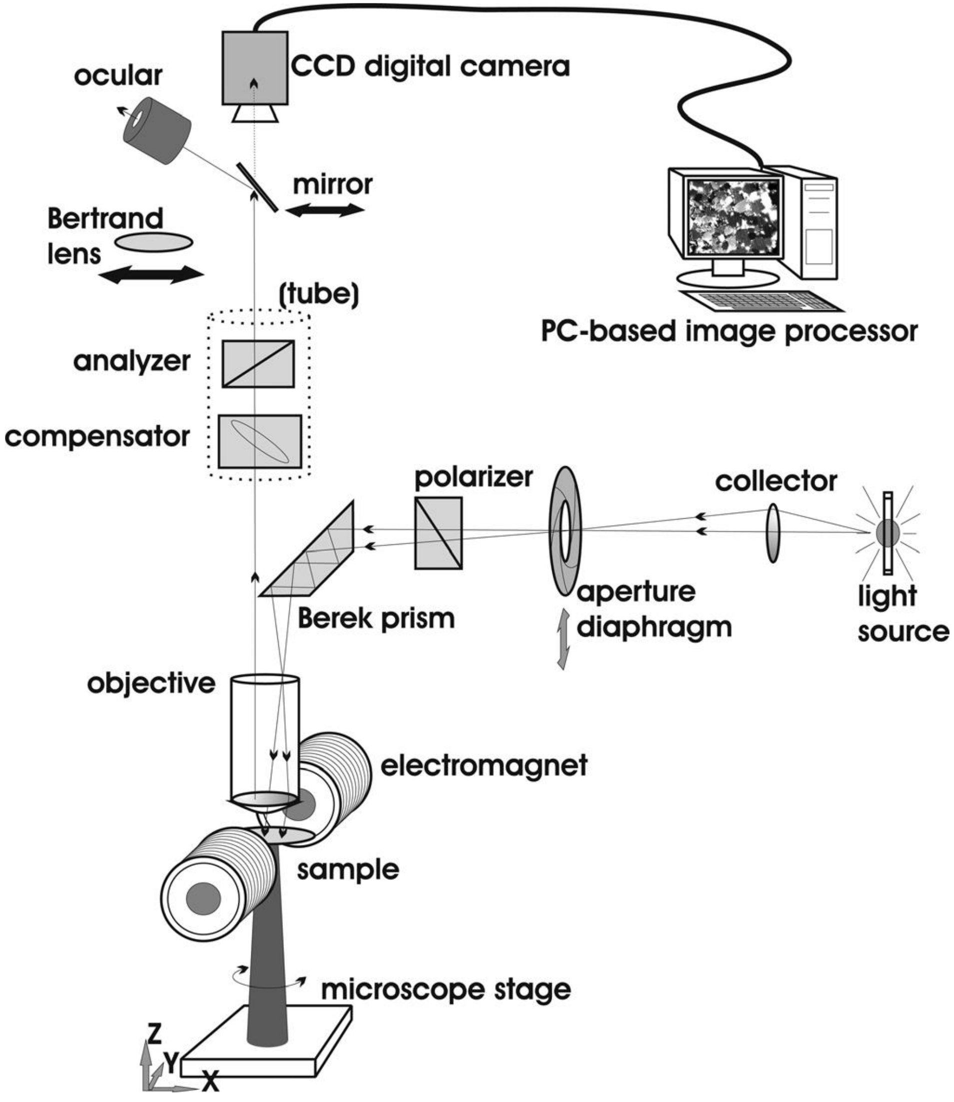
Reflections from different domains

180^o domains;
m - magnetization

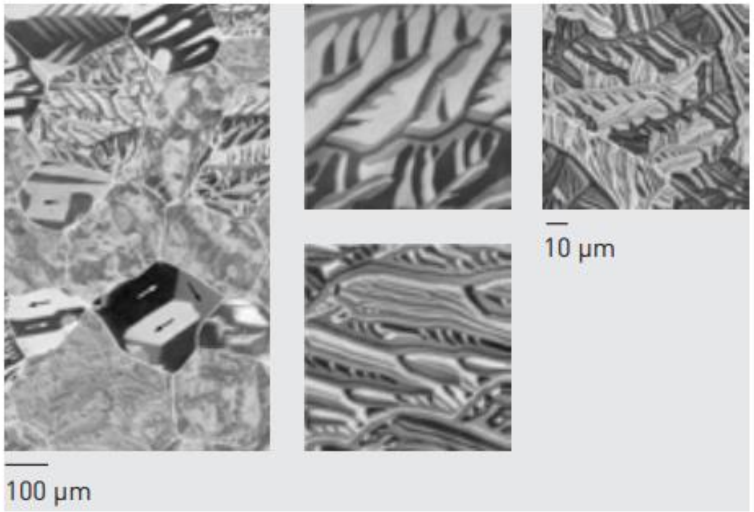
Longitudinal Kerr effect

Direction of the rotation of the main ellipse axis depend on the direction of the magnetization in the domain. The amplitude of the rotation depends on the material parameters and angle of the incident light ϕ

Kerr Microscope.



David Neff et all, *American Journal of Physics* 82, 574–582 (2014)

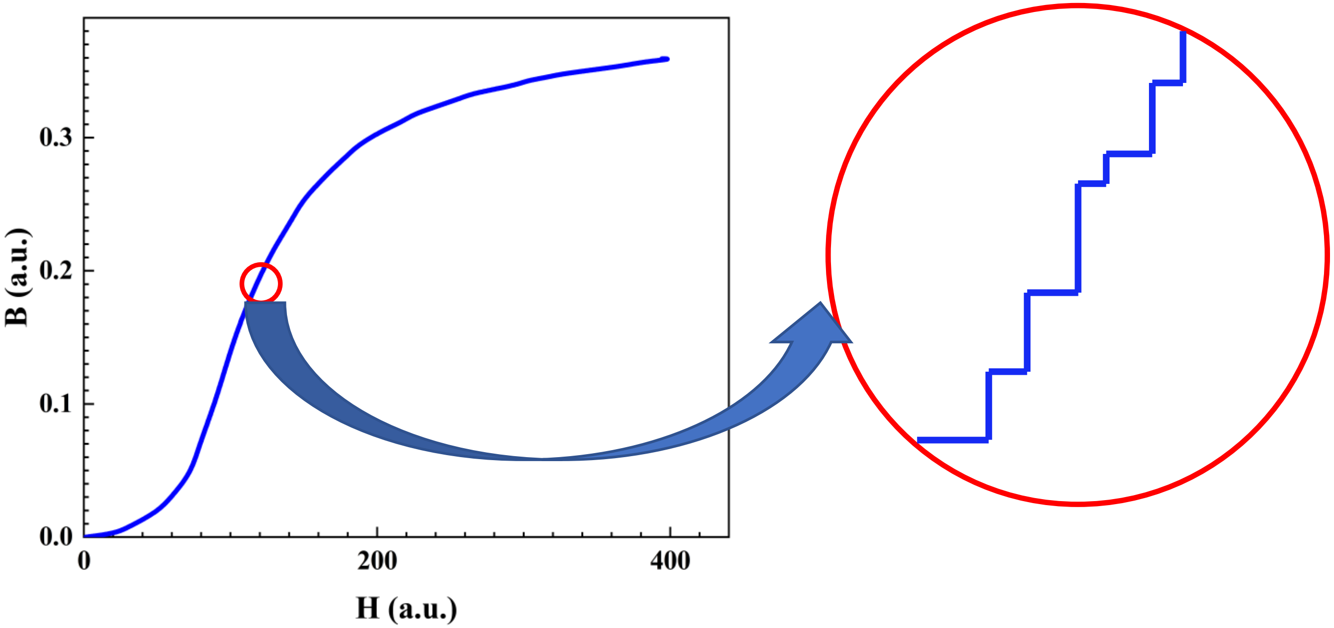


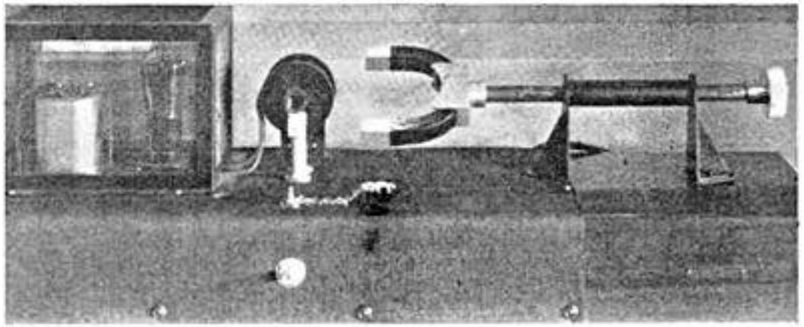
FeSi: Combination of high and low resolution images on non-oriented FeSi electrical steel sheet

Courtesy of evicomagnetic

Barkhausen effect.

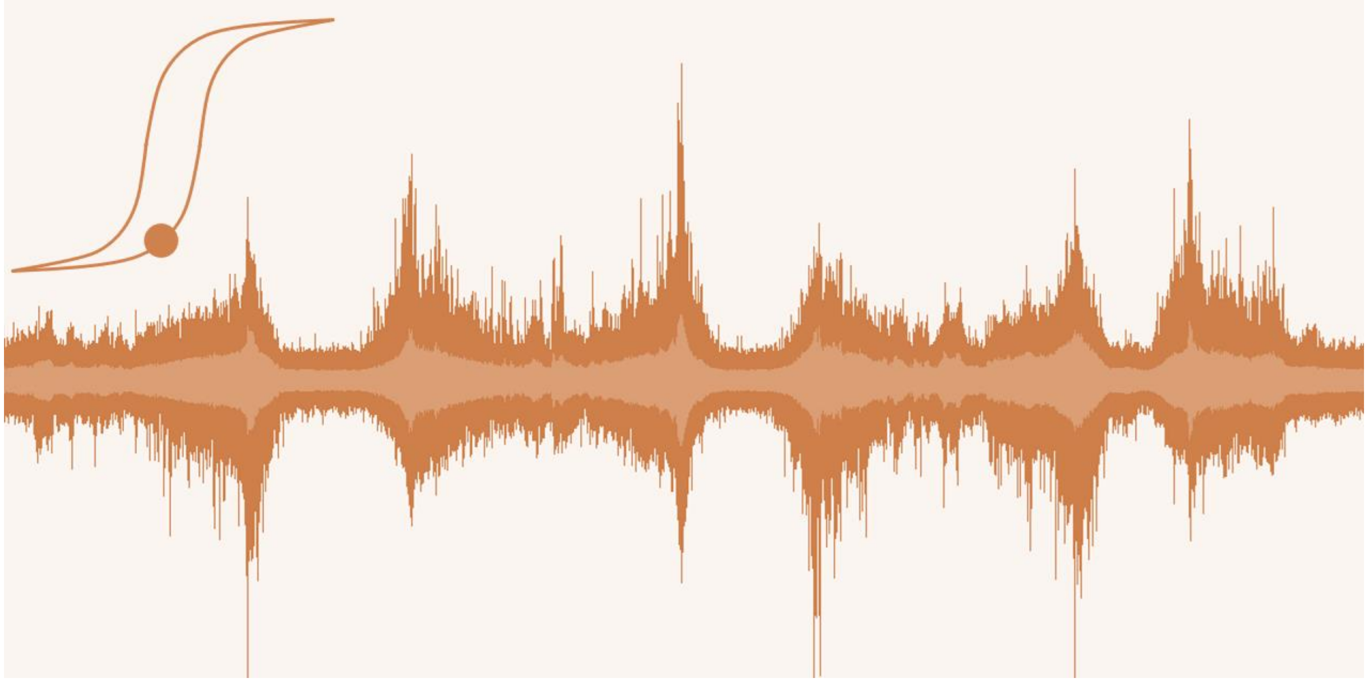
Heinrich Georg Barkhausen
1881-1956





Replica of Barkhausen's original apparatus, consisting of an iron bar with a coil of wire around it (center) with the coil connected through a vacuum tube amplifier (left) to an earphone (not shown). When the horseshoe magnet (right) is rotated, the magnetic field through the iron changes from one direction to the other, and the crackling Barkhausen noise is heard in the earphone. (courtesy of Wikipedia)

Barkhausen effect.



Courtesy of Encyclopedia Magnetica™

Applications of Barkhausen effect.

Pergamon

Acta mater. Vol. 46, No. 14, pp. 4873–4882, 1998
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Printed in Great Britain
PII: S1359-6454(98)00205-5 1359-6454/98 $19.00 + 0.00

CHARACTERIZATION OF PURE IRON AND (130 P.P.M.) CARBON–IRON BINARY ALLOY BY BARKHAUSEN NOISE MEASUREMENTS: STUDY OF THE INFLUENCE OF STRESS AND MICROSTRUCTURE

C. GATELIER-ROTHEA, J. CHICOIS, R. FOUGERES and P. FLEISCHMAN
Groupe d'Etudes de Métallurgie Physique et de Physique des Matériaux–UMR CNRS 5510, Inst
National des Sciences Appliquées, 69621 Villeurbanne Cedex, France

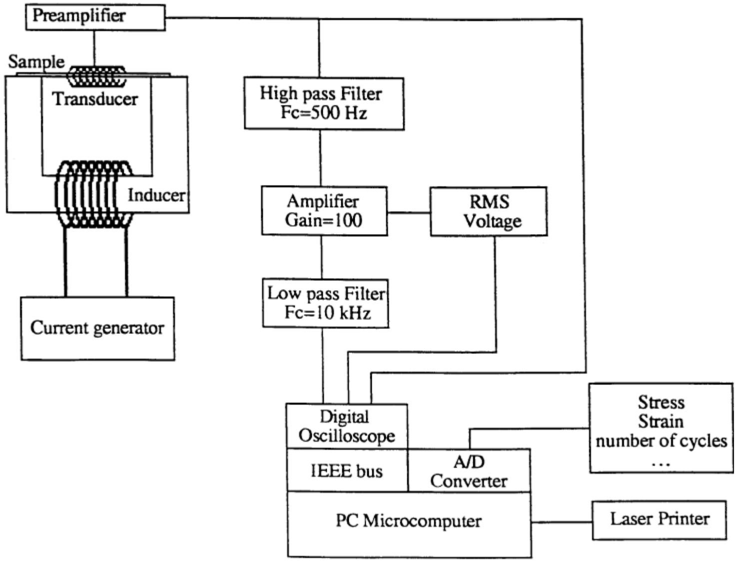


Fig. 1. Experimental device for magnetic measurements.

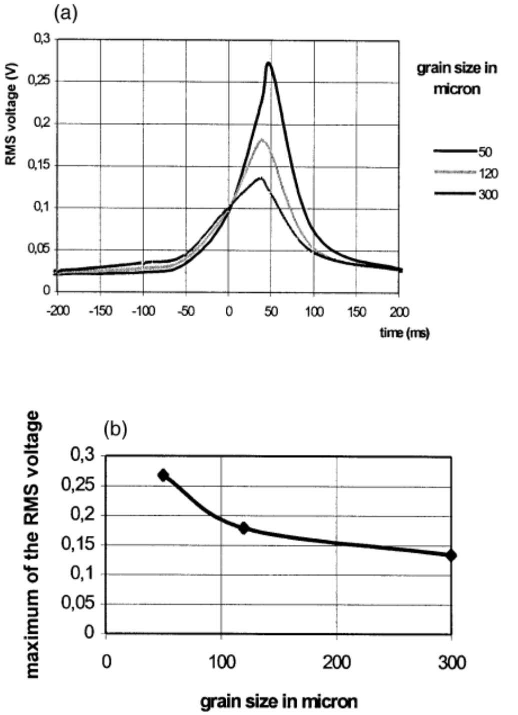
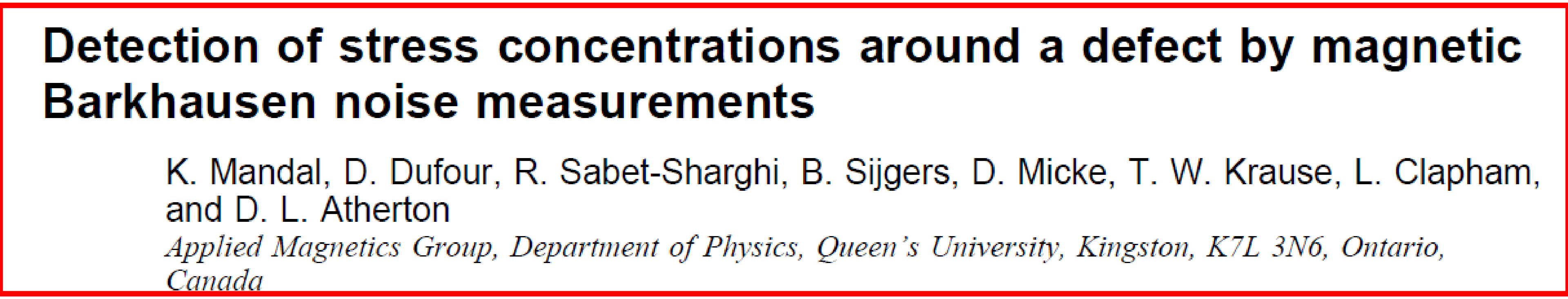


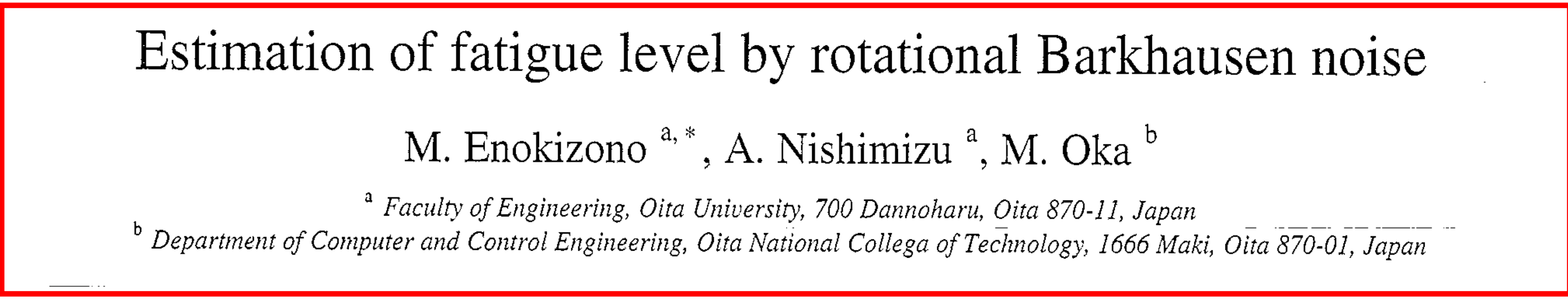
Fig. 2. Pure iron magnetic characterization: (a) r.m.s. voltage for three different grain sizes; (b) evolution of maximum amplitude of the Barkhausen r.m.s. signal.

Applications of Barkhausen effect.



Detection of stress concentrations around a defect by magnetic Barkhausen noise measurements

K. Mandal, D. Dufour, R. Sabet-Sharghi, B. Sijgers, D. Micke, T. W. Krause, L. Clapham, and D. L. Atherton
Applied Magnetics Group, Department of Physics, Queen's University, Kingston, K7L 3N6, Ontario, Canada



Estimation of fatigue level by rotational Barkhausen noise

M. Enokizono [a,*], A. Nishimizu [a], M. Oka [b]

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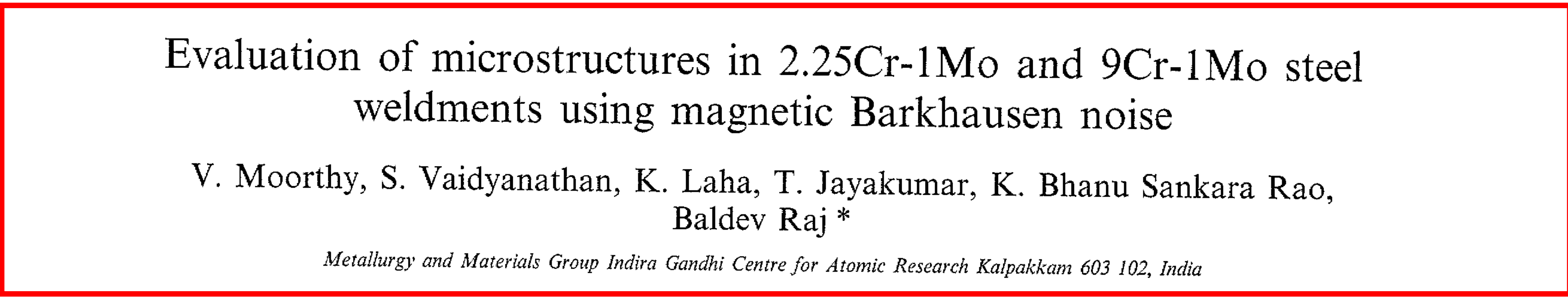
[b] *Department of Computer and Control Engineering, Oita National Collega of Technology, 1666 Maki, Oita 870-01, Japan*

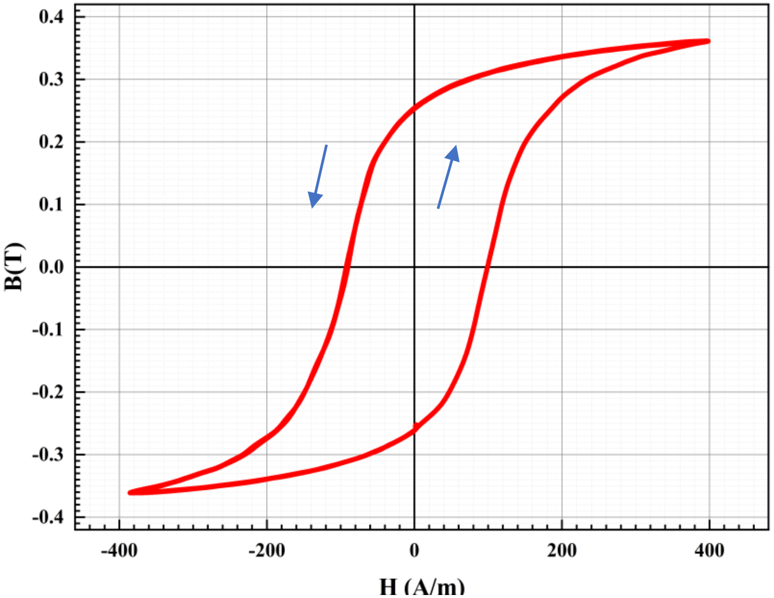


Evaluation of microstructures in 2.25Cr-1Mo and 9Cr-1Mo steel weldments using magnetic Barkhausen noise

V. Moorthy, S. Vaidyanathan, K. Laha, T. Jayakumar, K. Bhanu Sankara Rao, Baldev Raj *

Metallurgy and Materials Group Indira Gandhi Centre for Atomic Research Kalpakkam 603 102, India

Magnetic hysteresis. Energy.

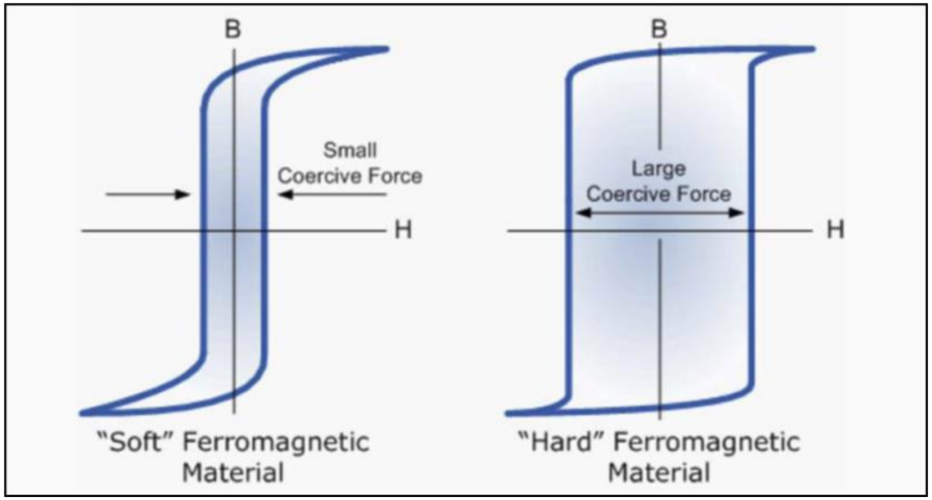


By cycling over the hysteresis loop the energy loss can be calculated as:

$$W = V\int BdH$$

B is magnetic flux density [T]=kg·s^{-2} ·A^{-1}
H – magnetic field [A/m]
V – volume of the magnetic material [m^3]
W – energy [J]=kg·m^2·s^{-2}

It follows that the energy lose while cycling along the loop is proportional to area of the hysteresis loop. Dependable on this the magnetic materials could be divided in two groups: soft magnetics and hard magnetics



Soft Magnetic Materials.

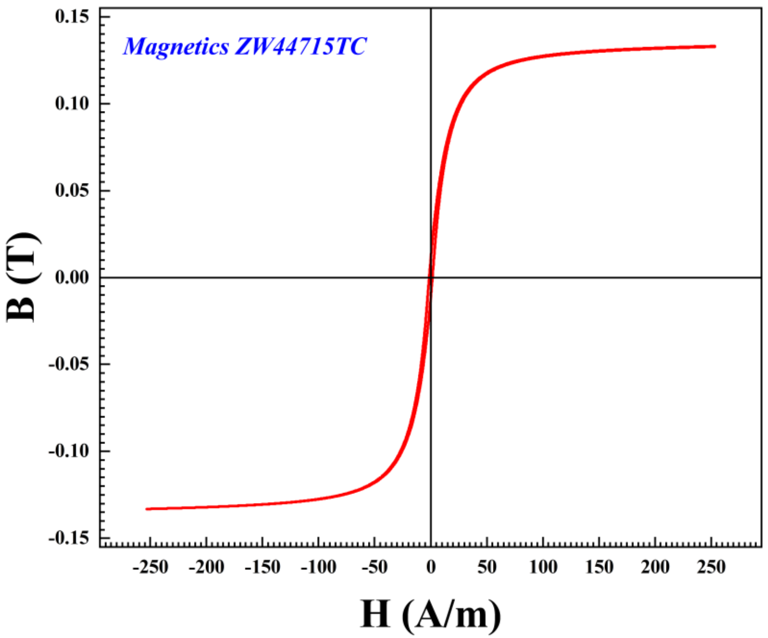


Fig. 1. An example of "slim" hysteresis loop (Courtesy of P401 course)

Main feature of the soft ferromagnetic is small coercive field. For shown in the Fig. 1 H_c ~1.5 A/m

Some soft Ferromagnetics

Material	Composition	Hc (A/m)	Bs (T)
Iron	99.9 Fe	0.08	2.16
Fe-Si	96Fe-4Si	40	1.95
50 Permalloy	50Ni-50Fe	4	1.6
μ metal	75Ni-18Fe-5Cu-2Cr	4	0.75
Supermalloy	79Ni-15.5Fe-5Mo-0.5Mn	0.32	0.8
Perminvar	50Fe-50Co	2.4	1.5

Courtesy of SM Magnetics

Self Inductance.

$\Phi(\vec{B}) = \int_A \vec{B}\bullet d\vec{A}$ Equation for magnetic flux created by the field $\vec{B}$ over the surface $\vec{A}$

In the case of uniform $\vec{B}$ $\Phi(\vec{B}) = \vec{B}\bullet\vec{A}$

In linear system $B \propto I$ (here B is generated by the current – no magnetic material)

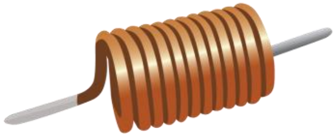
and $\Phi \propto I$ or $\Phi = L \bullet I$ L – self Inductance

In case of magnetic environment $B = \mu_0 \mu_r H$ L becomes a function of μ_r

and could be nonlinear in respect of applied magnetic field H if $\mu_r(H)$

Soft Magnetic Materials. Inductors, Chokes.

$$\Phi = L \bullet I$$



Magnetic flux is proportional the coil current I and constant of proportionality L is called the self inductance.

Using the Faraday law and Lenz law we can calculate the self inductance of the long solenoid as:

$$L = \frac{\mu_0 N^2 A}{l} = \frac{\mu_0 N^2 2\pi r^2}{l}$$

N number of turns, r – radius of the solenoid, and l – its length

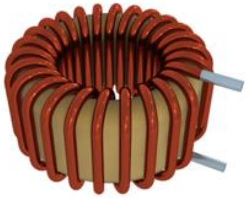
In case of ferromagnetic core this equation will be modified as:

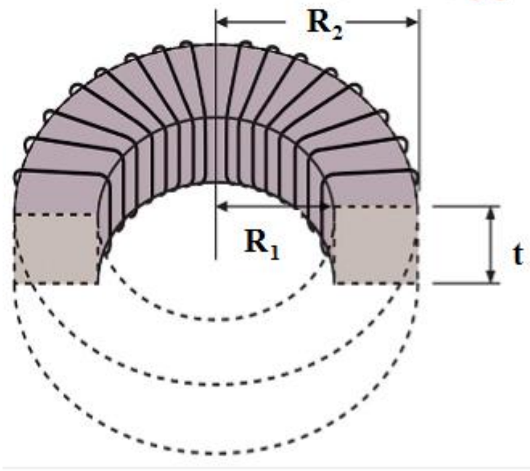
$$L = \frac{\mu_r \mu_0 N^2 A}{l} = \frac{\mu_r \mu_0 N^2 2\pi r^2}{l}$$

μ_r is the permeability of the core material

Soft Magnetic Materials. Inductors, Chokes.

Toroid





The Inductance of the toroidal coil can be calculated as:

$$L = \frac{\mu\mu_0 N^2 t}{2\pi} \ln\frac{R_2}{R_1} \cong \frac{\mu\mu_0 N^2 A}{2\pi r}$$

N number of turns

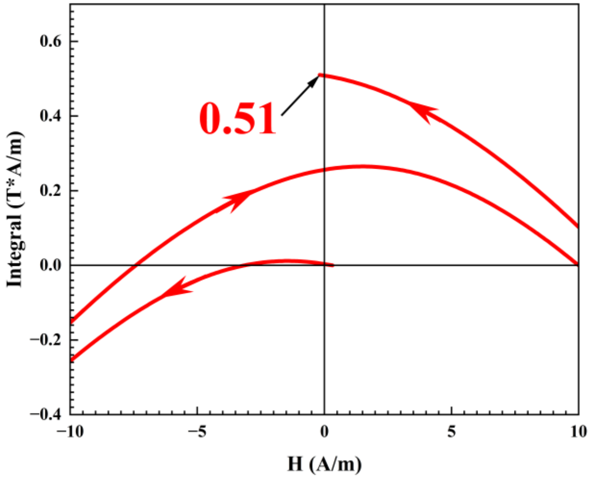
$A = (R_2-R_1)\cdot t$ – cross-sectional area of magnetic

$R = (R_2+R_1)/2$ – mean radius of the toroid

μ – magnetic permeability of the material

$\mu_0 = 4\pi\cdot10\text{-}7$ H/m

Calculations of the losses in the toroid. The integration One cycle of the hysteresis loop gives 0.51 T·A/m. The parameters of ZWTC44715TC are: R_1=27mm, R_2=46.9mm t=15mm. This comes with ~$19\cdot10^{-6}$ m^3 as the volume of magnetic. The energy loos per cycle will be ~$9.7\cdot10^{-6}$ J. If we will use this inductor on the frequency 1 MHz with amplitude of the field 250 A/m the dissipation power will be 9.7 W.



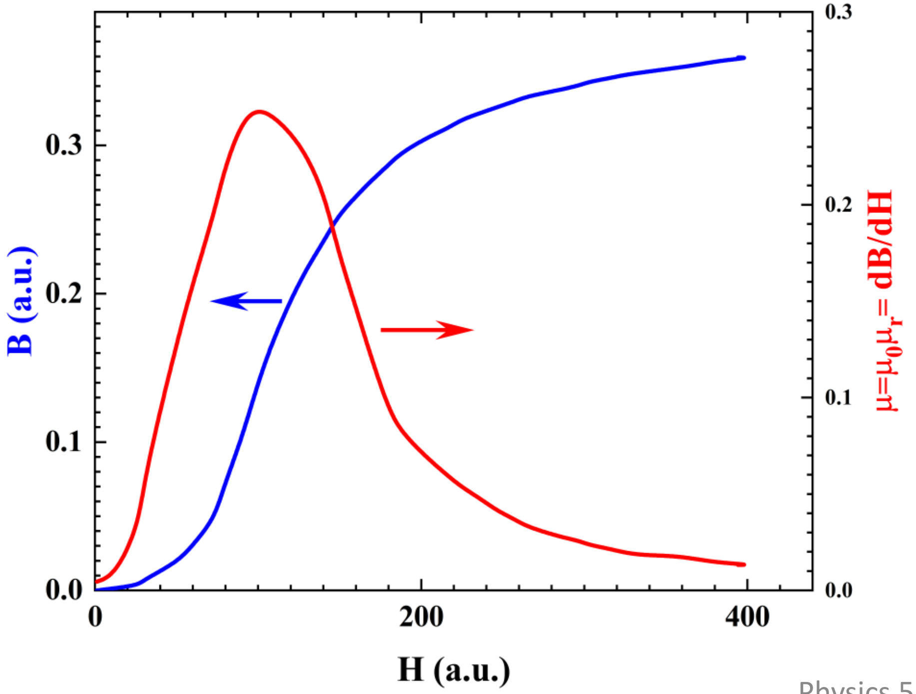
Soft Magnetic Materials. Inductors, Chokes.

$$L = \frac{\mu_r \mu_0 N^2 A}{l} = \mu_r L_0$$

$$L_0 = \frac{\mu_0 N^2 A}{l}$$

In the case of core Mutual Inductance L depends on the magnetic permeability of the core material μ_r. From magnetization curve (B vs H) it is clear that μ_r is a function of the magnetic field. μ_r is also function of the temperature and frequency.

$$\mu_r(H, T, f)$$



At high field, the ferromagnetic material can reach the saturation and μ_r becomes close to 1

Soft Magnetic Materials. Applications.

Low power applications: different inductors with different ferromagnetic materials as a core

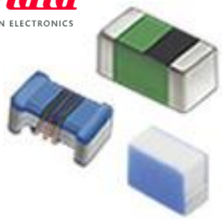
Toroidal core inductor

Rod core inductor

Pot core inductor

muRata

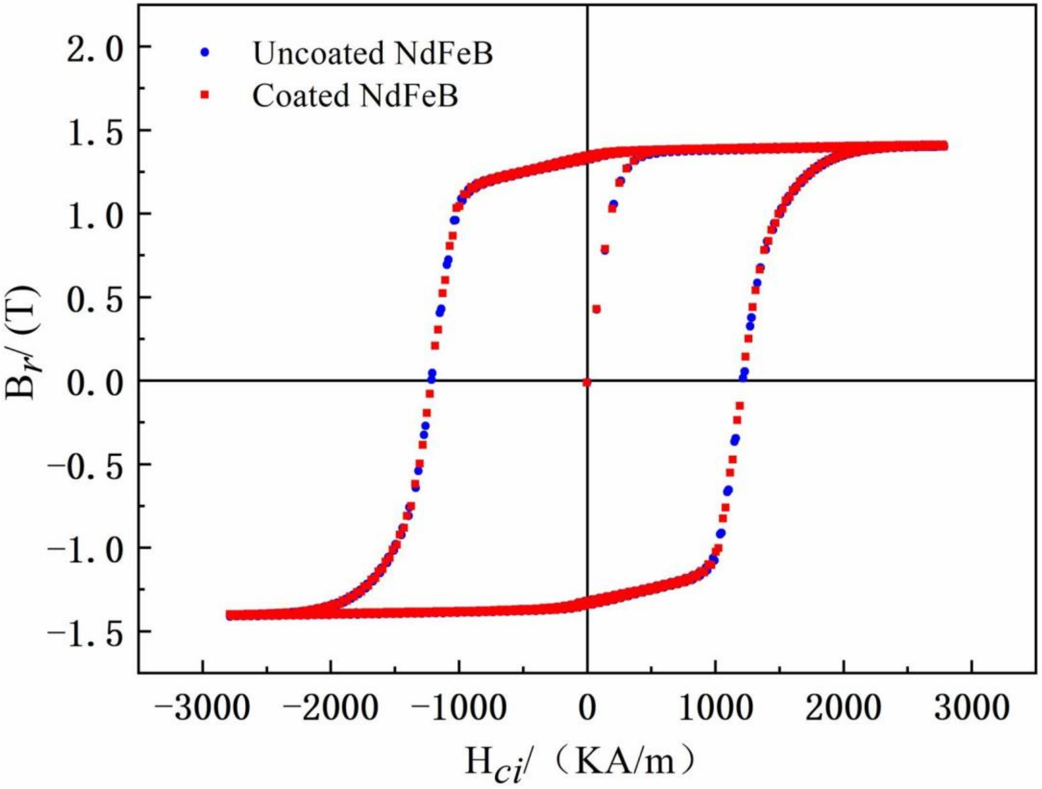
INNOVATOR IN ELECTRONICS



Inductors for high f applications designed to be placed on PCB

High power applications: transformers, chokes, solenoids etc.

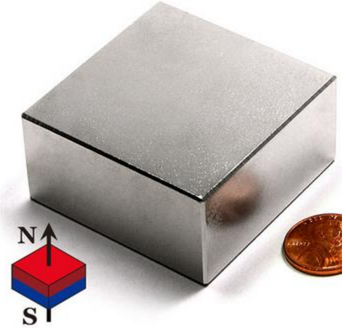
Hard Magnetic Materials.



Hysteresis loops of the uncoated NdFeB and AlCoCrFeNi coated samples.

L.W. Zhang et all, Journal of Magnetism and Magnetic Materials 551 (2022) 169136

NdFeB **is excellent material for permanent magnets and an example of hard magnetic material**

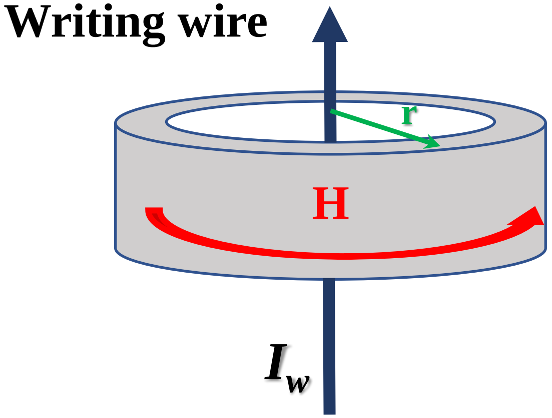


Remnant magnetization ~1.44 T , huge coercive field ~ 10^6 A/m

CMS MAGNETICS
Quality Service and Fast delivery

Energy necessary for changing the direction of magnetization is ~ 1.5 10^6 J/m^3 (for magnet from CMS magnets shown on this slide W~100J)

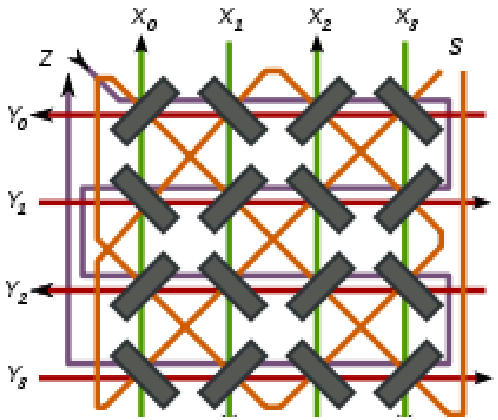
Hard Magnetic Materials. Applications. Magnetic RAM.



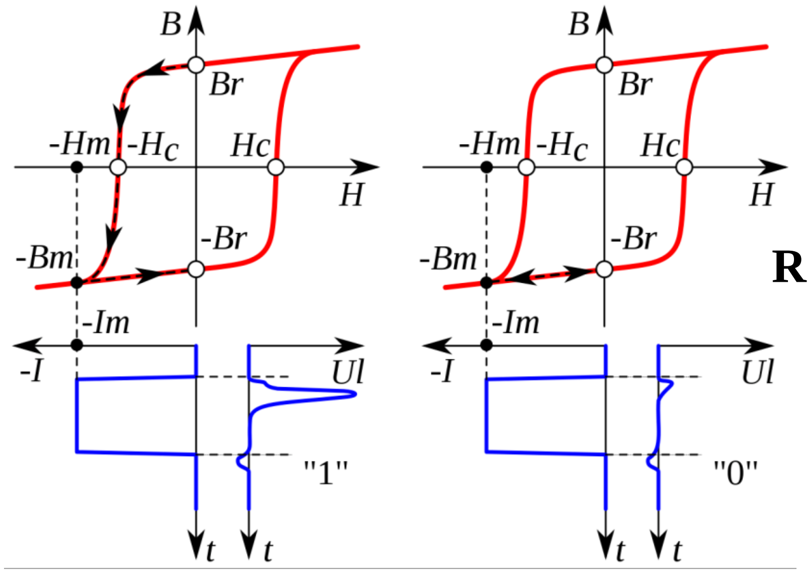
$$H = \frac{I_w}{2\pi r}$$

I_w up – H ccw “0”

I_w down H cw “1”

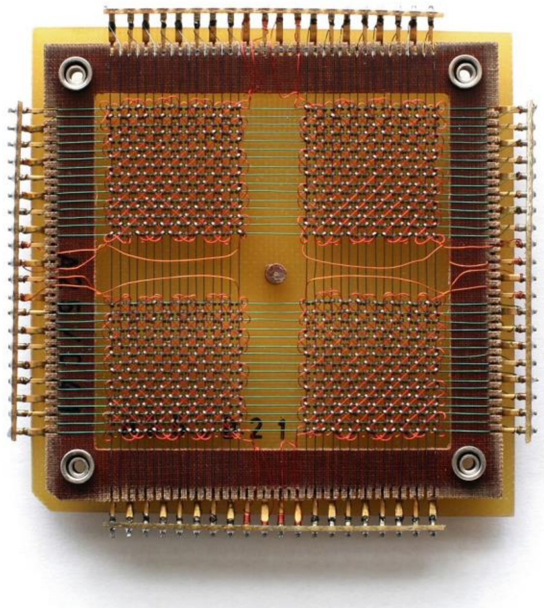


One ferromagnetic ring – 1 bit of information



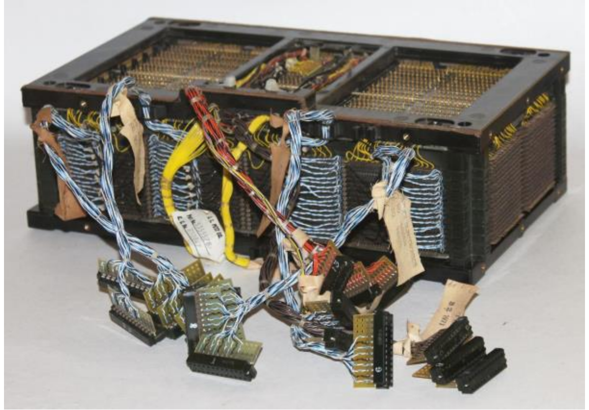
Courtesy of Wikipedia

Read operatio

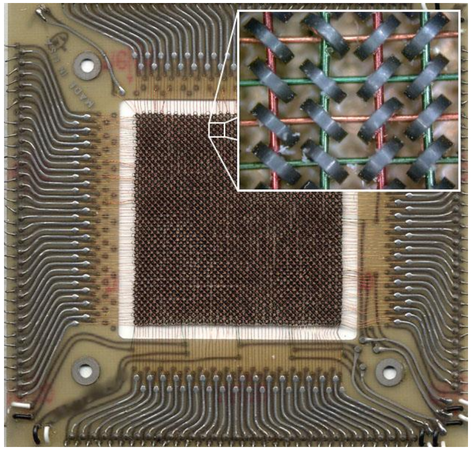


32x32 core memory 1024 bits

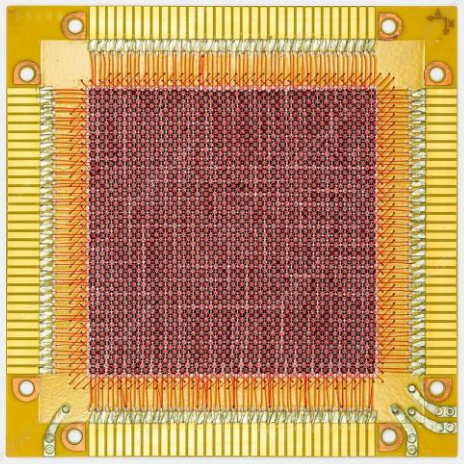
Hard Magnetic Materials. Applications. Magnetic RAM.



IBM S/360 core memory: In the 1960s, 128 kilobytes weighed 610 pounds



A 10.8×10.8 cm plane of magnetic core memory with 64 x 64 bits (4 Kb), as used in a CDC 6600



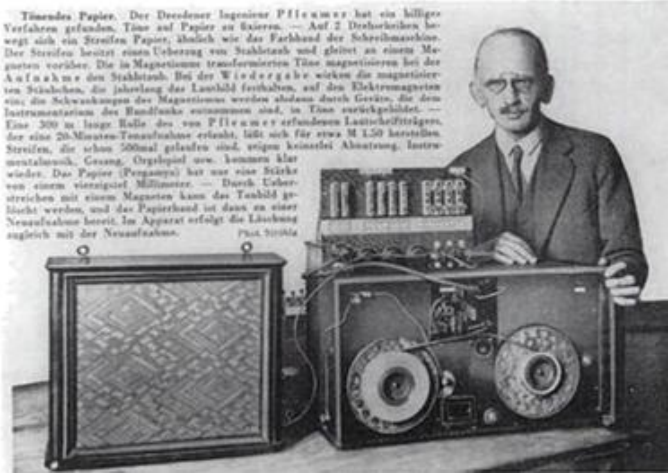
Magnetic-core memory of Univac Computer

IBM360 models

model	announced	Memory bandwidth (MB/s)	Memory size (kB)
30	Apr 1964	0.7	8-64
44	Aug 1965	4.0	32-256
195	Aug 1969	169	1,024-4,096

Hard Magnetic Materials. Applications. Tape Recording Technique.

Fritz Pfleumer
1881 – 1945



Fritz Pfleumer, with his magnetic tape machine (1931)

BASF audio magnetic tape

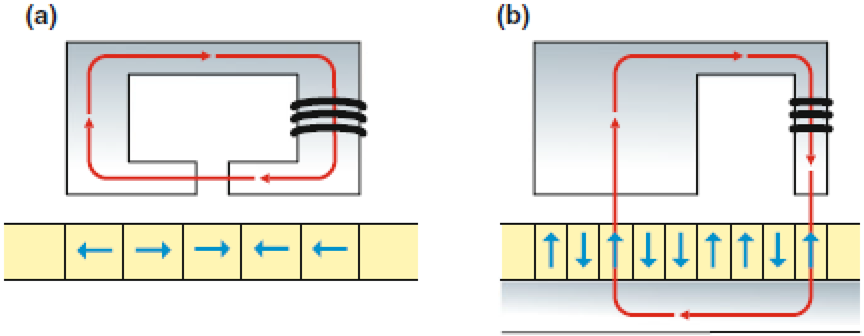


Fig. 7.1 Longitudinal (a) and perpendicular (b) write heads showing schematically the two types of magnetic recording technologies.

Telefunken stereo tape recorder "magnetophon 203", 1967

© Springer International Publishing AG 2017
A.P. Guimarães, Principles of Nanomagnetism, NanoScience and Technology

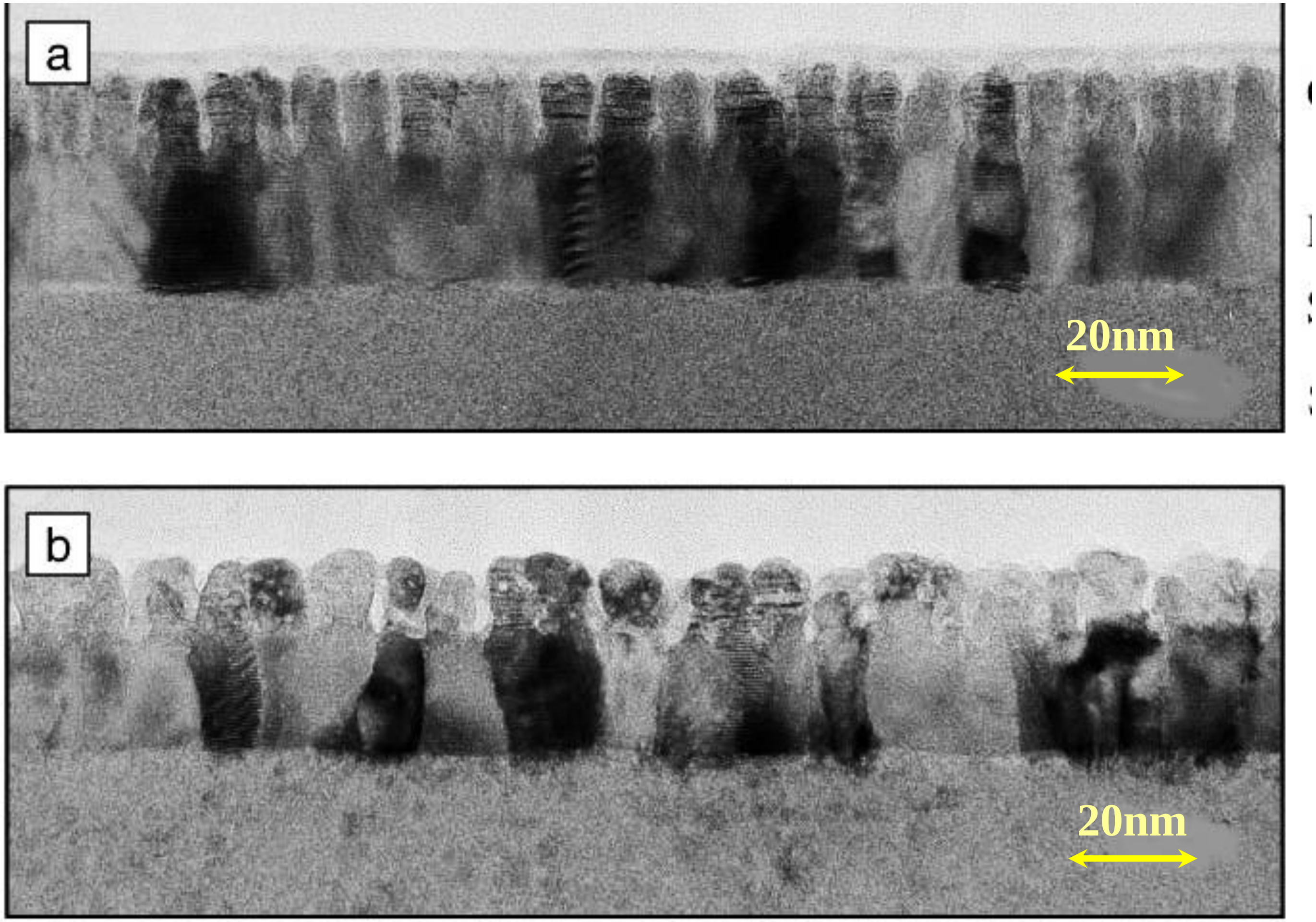
Hard Magnetic Materials. Applications. Materials.

Material	Saturation Magnetization	Curie Temperature	Domain walls width	Dimensions of a cube representing magnetic energy ~40k_BT
	kA/m	K	nm	nm
Co	1440	1404	19	6.7
Co3Pt	1100	1200	9.9	4.4
CoCrPt	200–700	500	14–30	8–14
CoX/Pt	360	500	9.9	5.5
CoX/Pd	360	500	13	6.5
FePt	1140	750	3.8	2.9
CoPt	800	840	6.3	3.2
SmCo5	910	1000	3.8	2.3

Magnetic Properties of Various Materials Considered for High-Density Magnetic Recording

H.J. Richter and S.D. Harkness IV, MRS BULLETIN, 31, 384, (2006)

Hard Magnetic Materials. Applications. Materials.



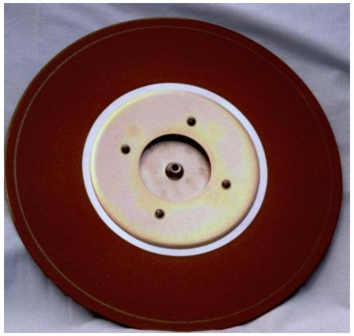
(a) Cross-sectional transmission electron micrograph of a typical perpendicular recording medium design.
(b) Cross-sectional image of a medium design lacking an appropriate seed layer.

H.J. Richter and S.D. Harkness IV, MRS BULLETIN, 31, 384, (2006)

Hard Magnetic Materials. Applications. Floppy Disks, Hard Drives.

1972

digital



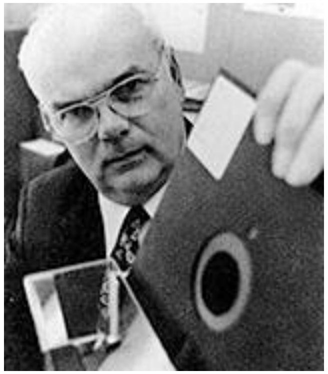
Average Access Time 70 millisecond
Data Transfer Rate (150 kB/s)
Iron oxide disk, 14 inches in diameter
total capacity ~2.5MB

https://www.pdp-11.nl/peripherals/disk/rk05-info.html

2023

Capacity: 22Tb
Transfer Rate : 1200 Mbps
Z-height : 26.1 Mm
Dimensions (W X D) : 101.6 X 147 Mm
Weight : 670 G

Hard Magnetic Materials. Applications. Floppy Disks, Hard Drives.



David L. Noble
1918-2004

8-inch Floppy Disk

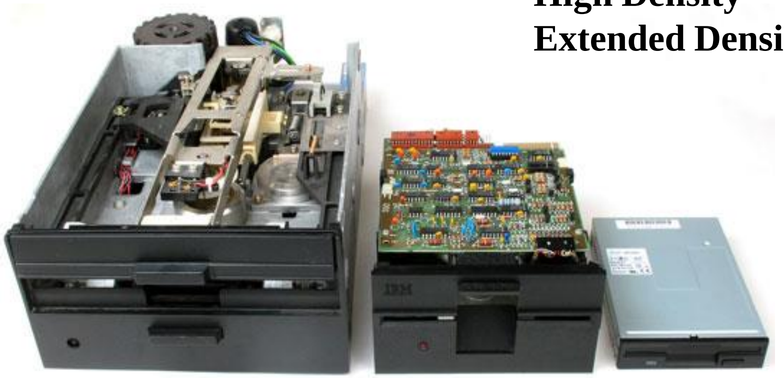
Single Sided – 110 ÷ 160 KB
Double Sided – 360 KB
Quad Density – 720 KB
Double Sided High Density – 1.2 MB

5.25-inch Floppy Disk

Single Sided – 110 KB ÷ 160 KB
Double Sided – 360 KB
Quad Density – 720 KB
Double Sided High Density – 1.2 MB

3.5-inch Floppy Disk

Single Sided – 280 KB
Double Density – 720 KB
High Density – 1.44 MB
Extended Density – 2.88 MB



Homework

On fig is shown the hysteresis loop of “some” ferromagnetic material

Based on information provided by this graph

Calculate:

1. Unsaturated magnetic permeability of the material
2. Energy dissipation by one cycle of H variation ($0 \rightarrow 400 \rightarrow -400 \rightarrow 0$)
3. Power dissipation while driving the material be $H=H_0\sin(\omega t)$ with $\omega=2\pi f$ and $f=60\text{Hz}$ and $H_0=400$ A/m