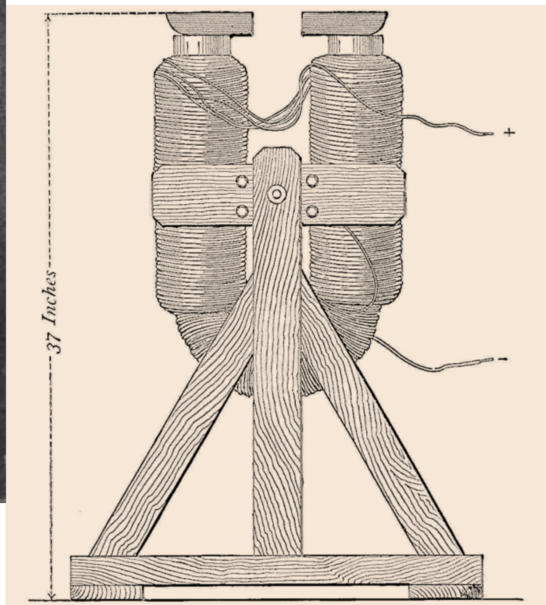
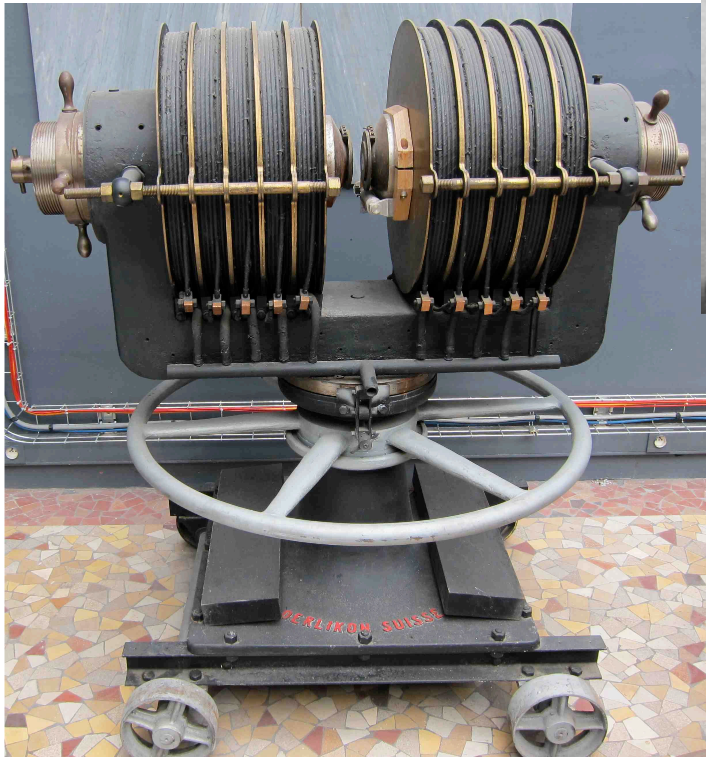
SPG/ÖPG Joint Annual Meeting
Linz, September 5, 2013

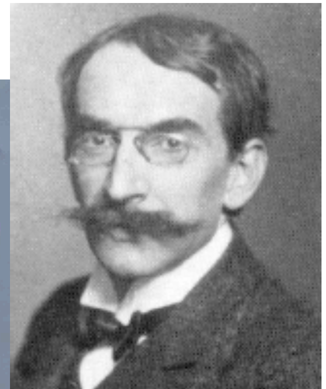
Physics in magnetic fields from Michael Faraday to Pierre Weiss & his contemporaries

Faraday c. 1845



FARADAY'S ELECTROMAGNET AT THE ROYAL INSTITUTION.





Weiss c. 1913

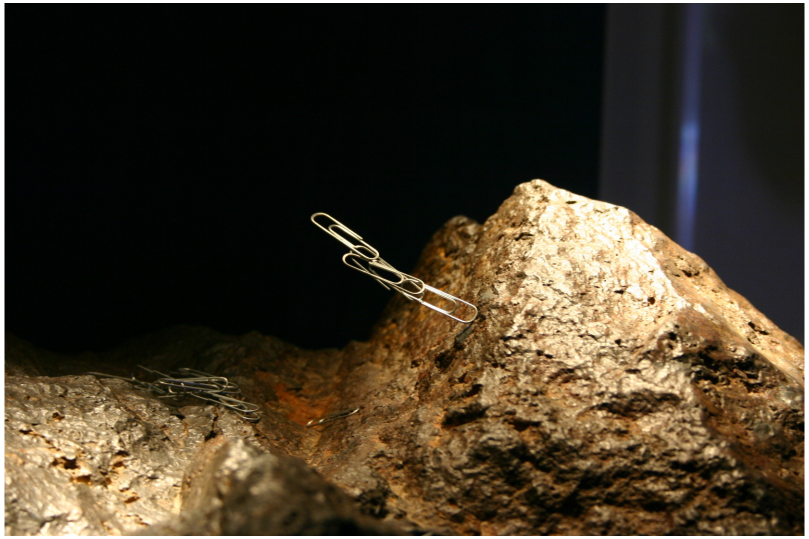
Jean-François LOUDE – École Polytechnique Fédérale de Lausanne (Suisse)
Dominique BERNARD – Université de Rennes 1 (France)

Abstract

Physics in magnetic fields from Faraday to Pierre Weiss and his contemporaries

The mechanical action on iron of the first horseshoe electro-magnets (1824) was obvious. They quickly found important applications (telegraphy). Their use to investigate more subtle magnetic, magneto-optical, atomic or nuclear properties of matter began in 1845 with Faraday. Until the 1970s, when superconducting magnets became common, iron-cored electromagnets were normally used to produce steady magnetic fields of high intensity. We will follow the history of a series of fundamental physics discoveries, often made using rather primitive electromagnets, as well as the evolution of laboratory electromagnets from Faraday to Ruhmkorff to Pierre Weiss. The electromagnet published by Weiss in 1907 became the archetype of many later ones.

Magnetism before Oersted



Certain stones ("lodestones") attract iron
Naturally (by a lightning bolt?) magnetised piece of magnetite, an iron ore

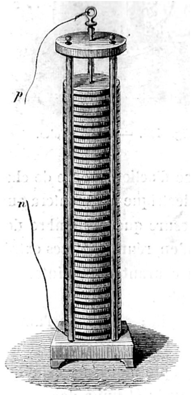
First application: compass, first for geomancy in China, then for navigation

William Gilbert (1600):
De Magnete, Magneticisque Corporibus, et ***de Magno Magnete Tellure***
First mention of the Earth as a giant magnet

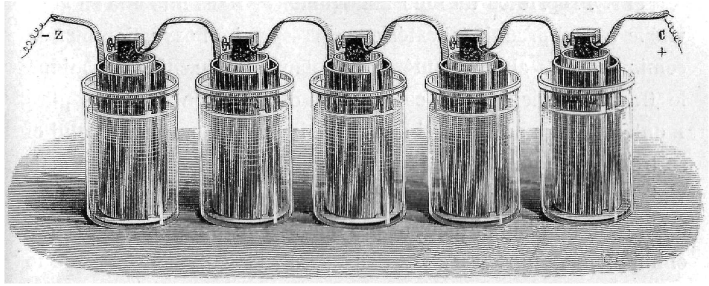
Concerted international studies of geomagnetism begin in the 1880s

S. J. Brugmans in 1778: Bi and Sb are repelled by a magnet!

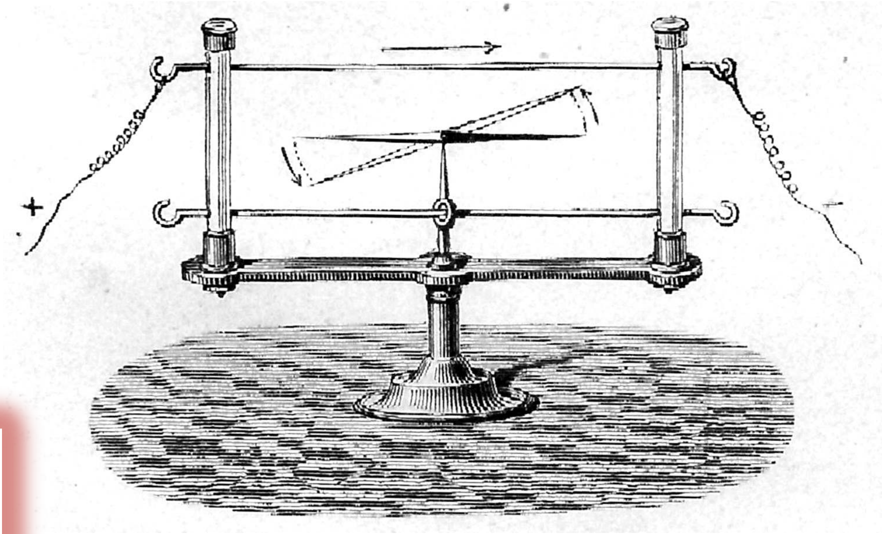
First electromagnets (E–M)



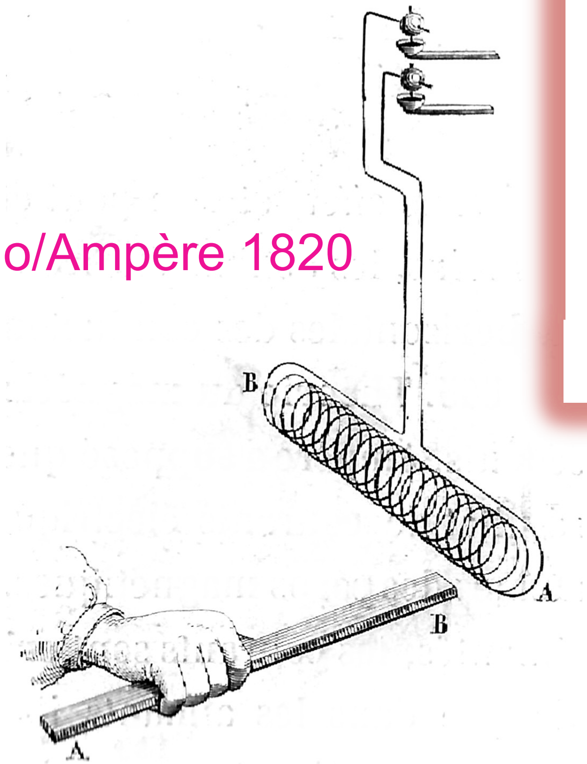
Volta 1800



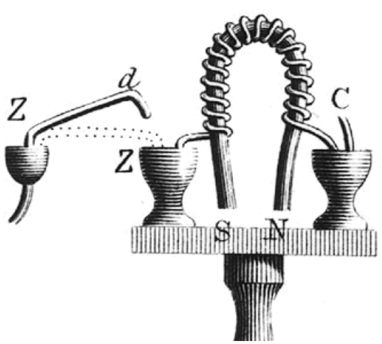
Bunsen electrochemical cells



Oersted 1820

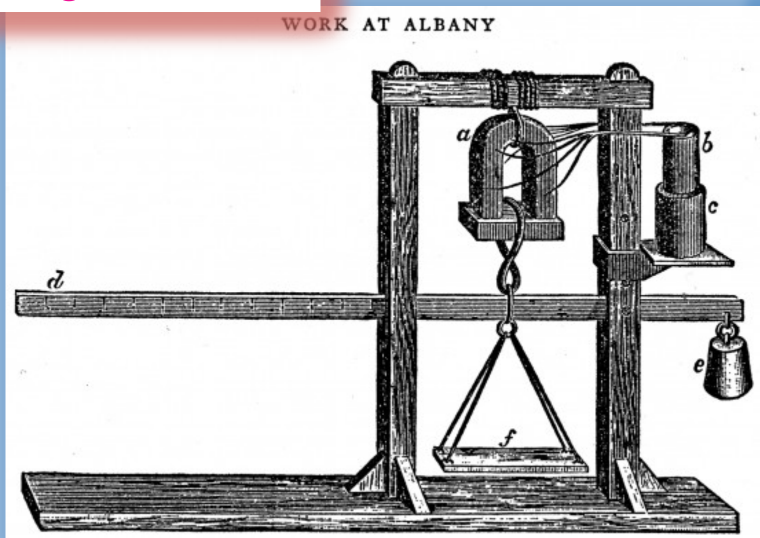


Arago/Ampère 1820

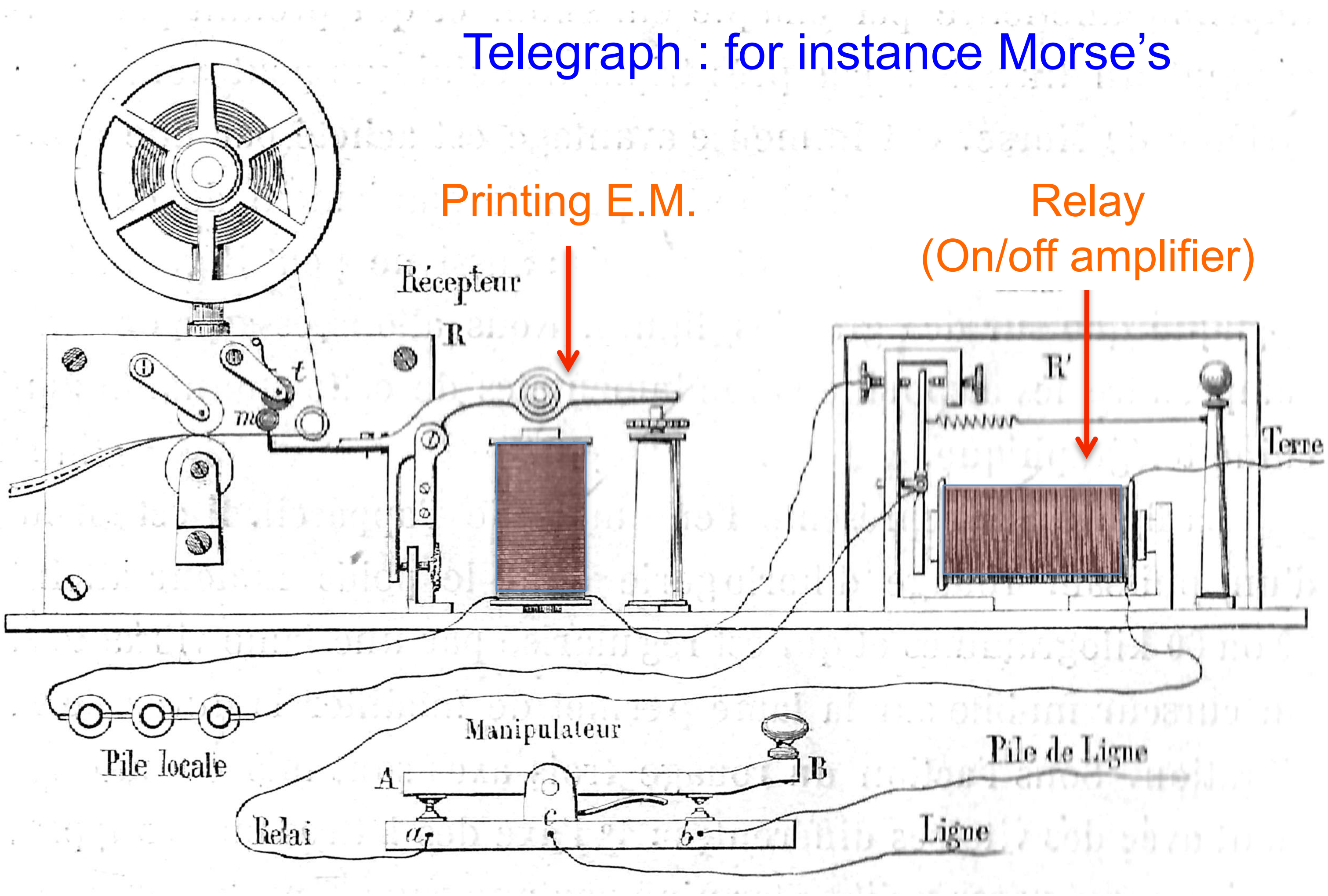


W. Sturgeon 1824

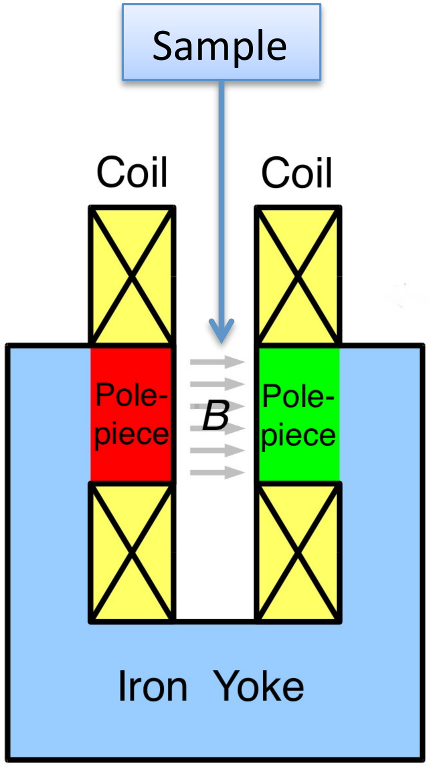
J. Henry 1831: lifting weights



First applications of electromagnets



Also electrical clocks, electric alarm bells, …
all using small electromagnets powered by electrochemical cells

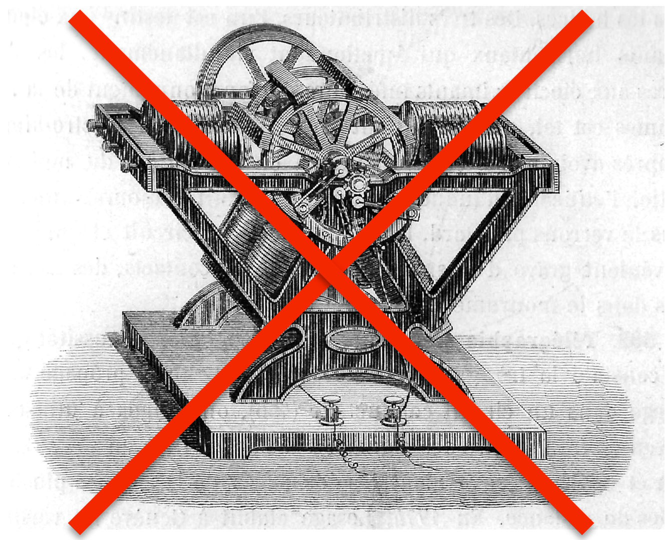


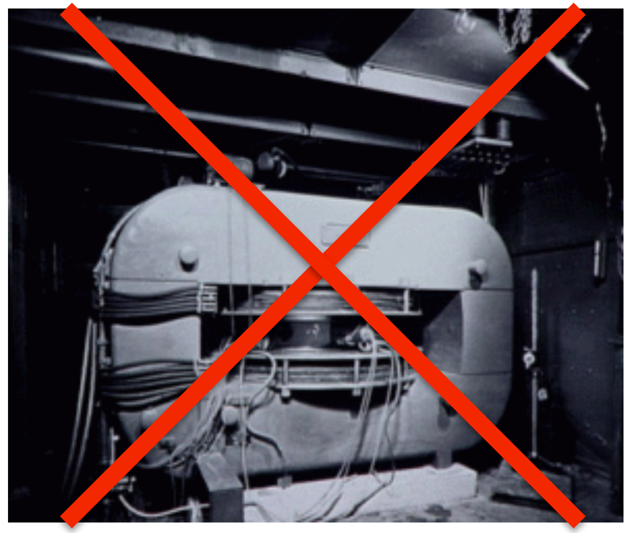
General purpose laboratory electromagnet

Investigation of the properties of a material sample (solid, liquid, gas), in a static or quasi-static magnetic field.
We'll forget the obvious ferro-magnetism,
despite its enormous technological importance.
And no theory – most phenomena discovered before an adequate theory became available!

- Slowly variable magnetic field
- Interchangeable pole-pieces: cylindrical, truncated cones, wedge-shaped, bored-through, …
- Gap width adjustable

Excluded: electromagnets used for their purely mechanical effects





Also excluded: ~~electrotechnology, *i.e.* everything based on induction~~

Michael FARADAY (1791-1867): dia- and para-magnetism

In 1845-1846, 20 years after the construction of the first electromagnets, he is the first to use them to study of properties of matter in a magnetic field.

He (re)discovers the diamagnetism (a word he coined) of material samples, and the paramagnetism of others, putting between the poles of his electromagnets, powered by Grove cells, almost every bit of matter he found in his laboratory at the Royal Institution of London.

Diamagnetic bodies are very weakly repelled by a magnetic field, paramagnetic ones are attracted. We normally don't feel these forces, many orders of magnitude smaller than the ones exerted on iron (ferro-magnetism)

Bismuth and pyrolytic carbon: the strongest room-temperature diamagnetics

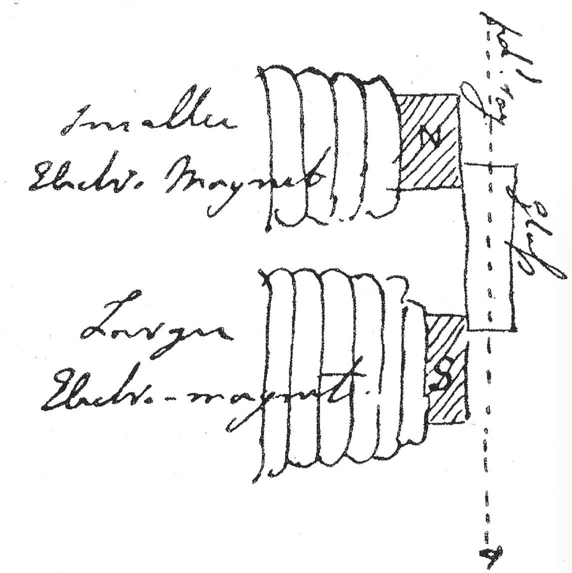
Diamagnetism = repulsion => room-temperature levitation ?!

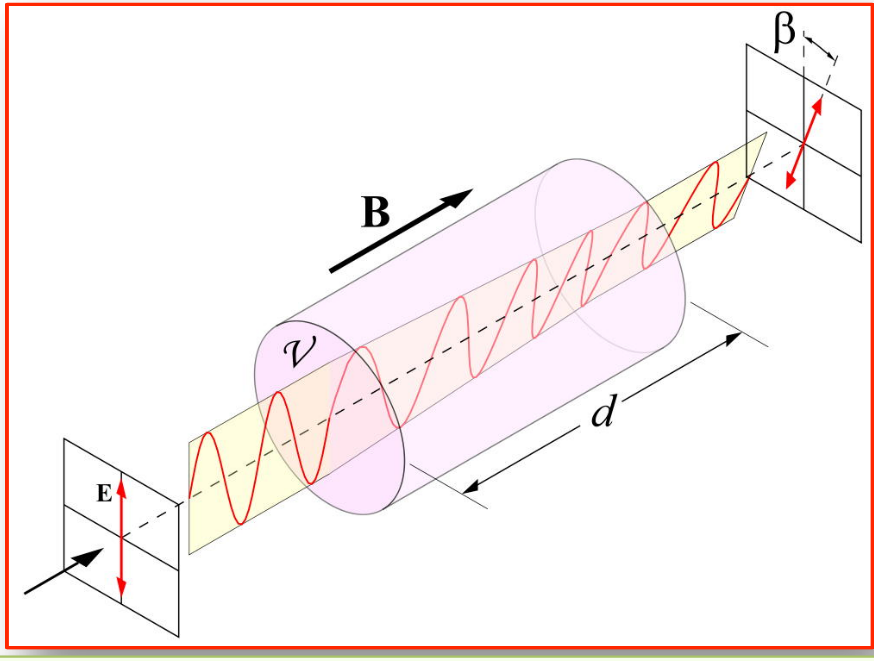
A dream until recently.

Magnet (5 mm side cube)
floating under another magnet
No power!

Living frog levitating
32 mmø bore, 16 T
Enormous power!

Michael FARADAY: first magneto-optical effect





The plane of polarization of monochromatic light rotates proportionally to *B* and *d*.
The angle *β* is *doubled* by reflection on a mirror!

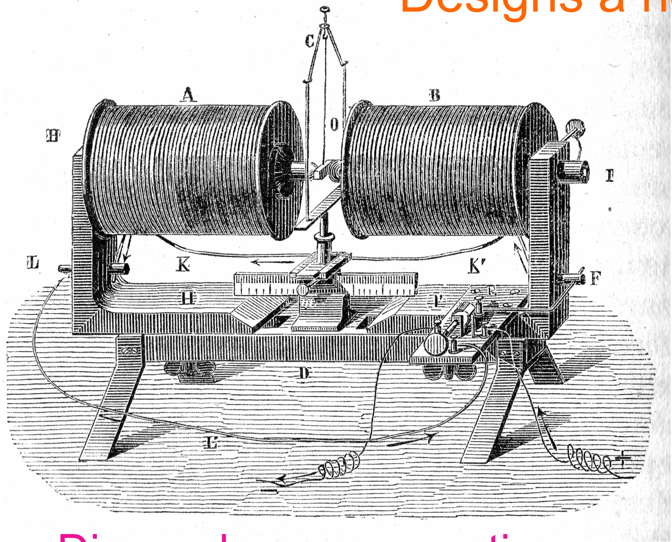
Intensity of the Faraday-effect (wavelength-dependent) described by the Verdet Constant, named after Marcel Emile Verdet (1824-1866)

Applications: measurement of *B* (Verdet constant); optics: Faraday rotators and isolators

Heinrich Daniel Ruhmkorff (1803–1877)

Renowned French instrument maker,
best known for the eponymous induction coil.

Designs a novel E-M, repeats Faraday's experiments



Dia- and para-magnetism

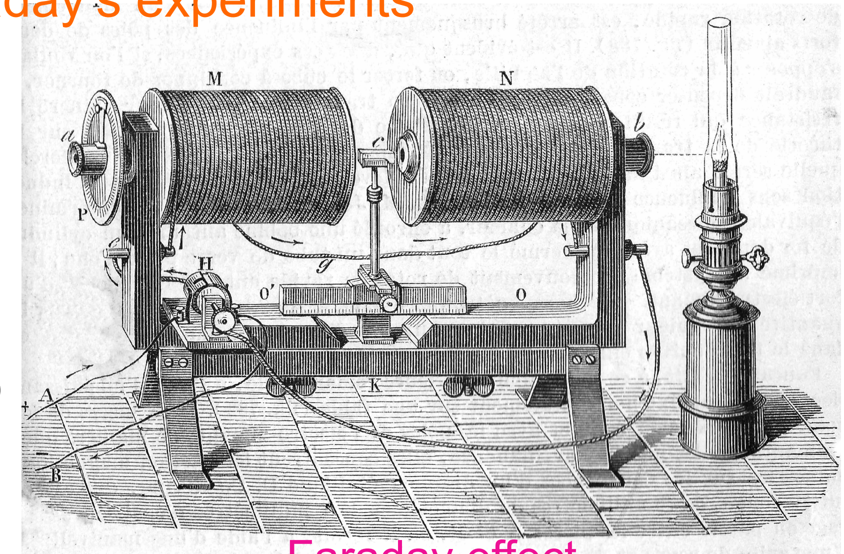
1846!

Still used much later:

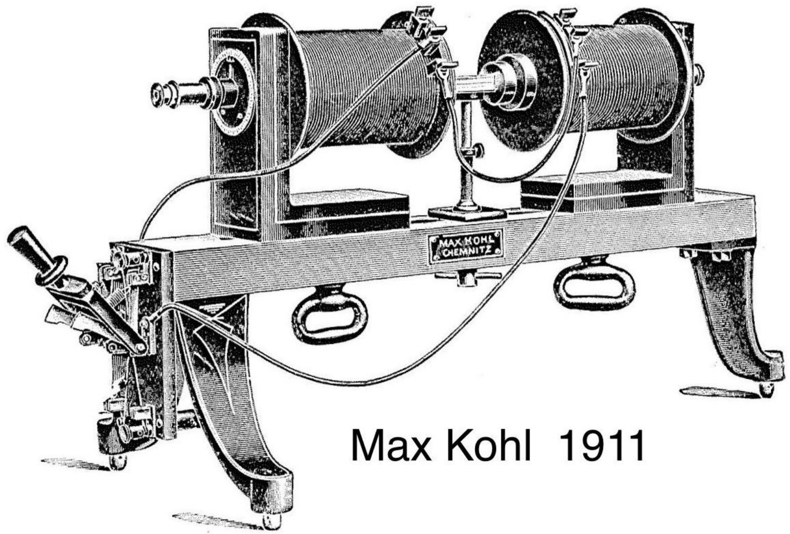
1897: Zeemann (Leiden)

1897: Cotton (Toulouse)

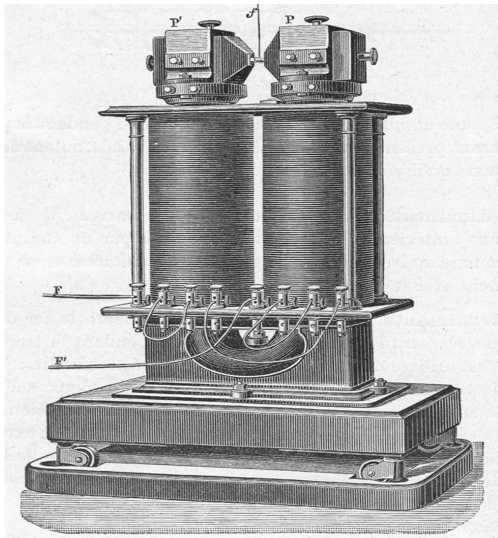
1898: Rigghi, Macaluso, Corbino (Rome), …



Faraday effect



Max Kohl 1911



Horseshoe E-Ms of every size remain popular

Large Ducretet (850 kg) U-shaped magnet, built from 1880, sold well

Demonstration of Faraday effect using a Ruhmkorff electromagnet

Video :
http://www.youtube.com/watch?v=UFEVvsbvIkA

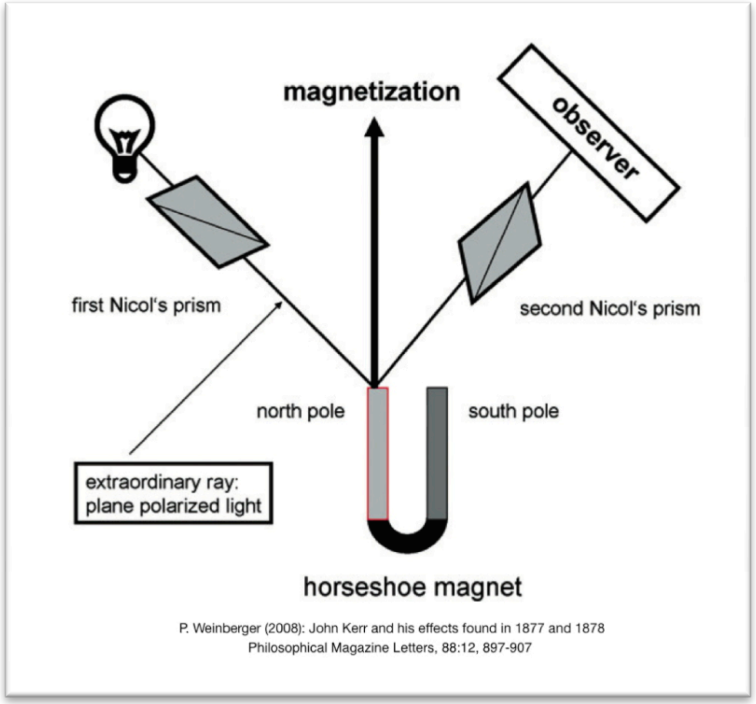
With the kind permission of Paolo Brenni, at the Fondazione Scienza e Tecnica, Firenze

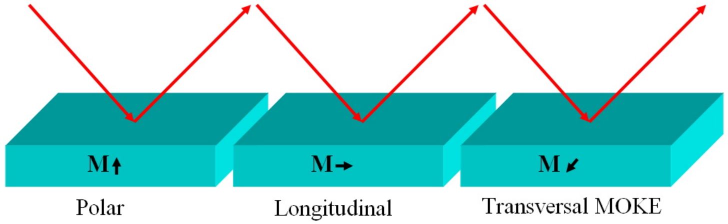
Kerr effect

c. 1860

In 1877-1878, John Kerr (1824-1907) discovers at Glasgow another magneto-optical effect, one year after the (Kerr) electro-optical effect: change of the state of polarization of the light reflected on a magnetized, polished iron surface

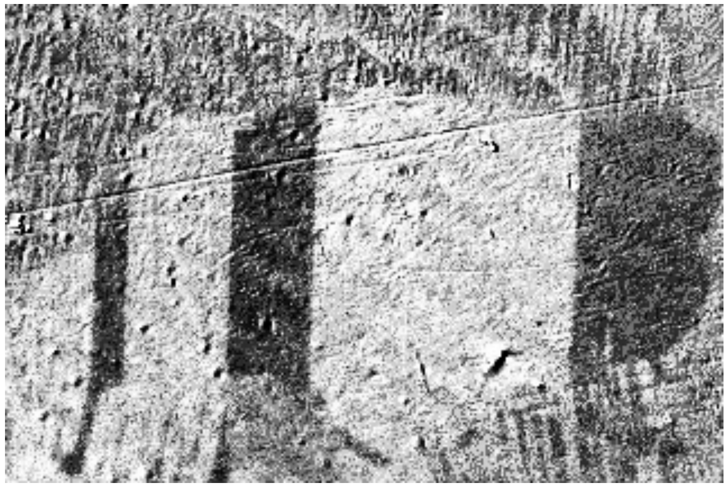
$h \approx 30$ cm





3 modes of "MOKE":
a complex phenomenon!

Magneto-optical disk
for data storage

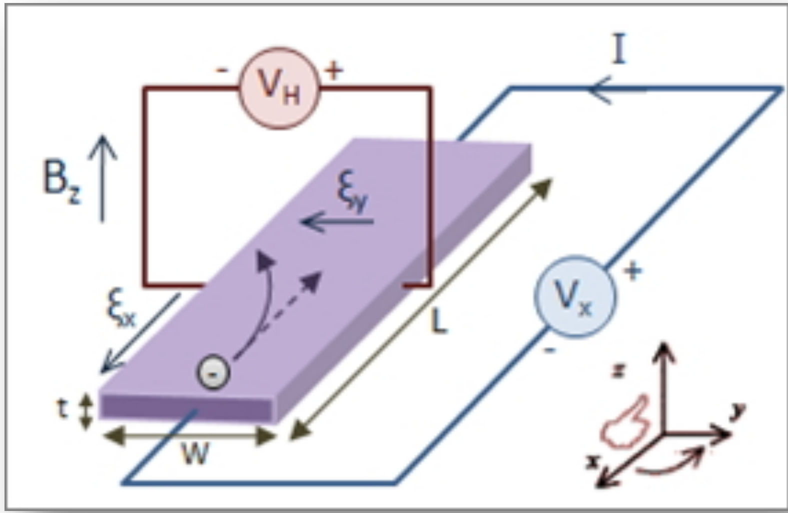


Kerr microscopy:
moving Weiss domains

One more magneto-optical effect was found later: the magnetic birefringence or magnetic double-refraction (Voigt 1902, Cotton-Mouton 1907, Majorana)

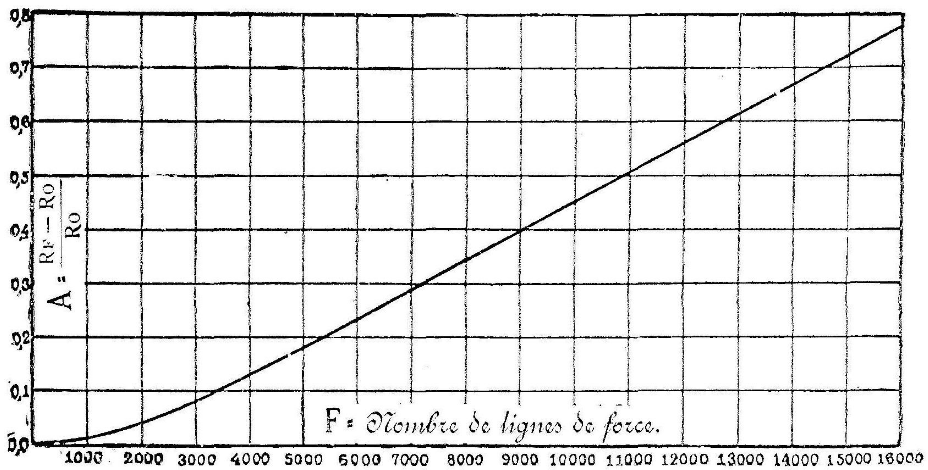
Hall effect

Discovered in 1879 by Edwin Hall (1835-1938)
at John Hopkins University
Gold leaf: low voltage, hard to measure



Bismuth in thin layers is a natural semiconductor.
Hall voltage is much higher, but still hard to measure
until electronic voltmeters became available at the time of WWII

From 1890 until WWII, the measurement of the resistance of a spiral of bismuth
(Lenard's spiral, made by H&B) was a standard way of measuring magnetic fields



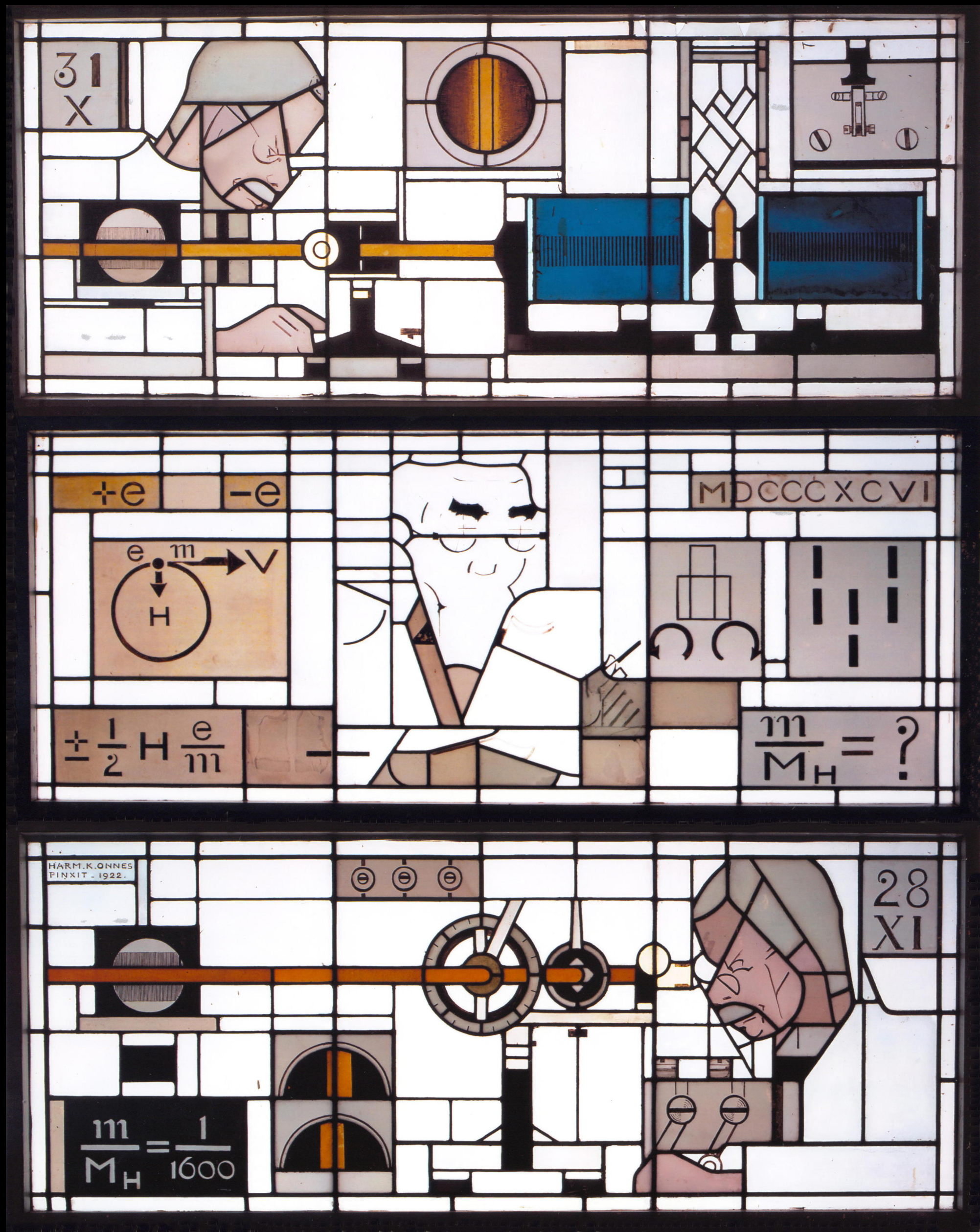
After WWII, good quality semiconductors became available: true "Hall-probes"

Zeeman effect (1896)

Zeeman (1902)

Lorentz (1902)

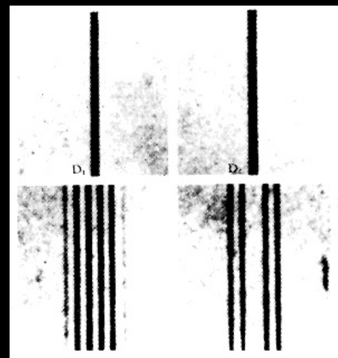
Nobel Prize 1902



Stained-glass window at Leiden (1922), with kind permission of Dirk van Delft

Artist: Harm K. Onnes, Heike's nephew

Ruhmkorff E-M



Na D-lines

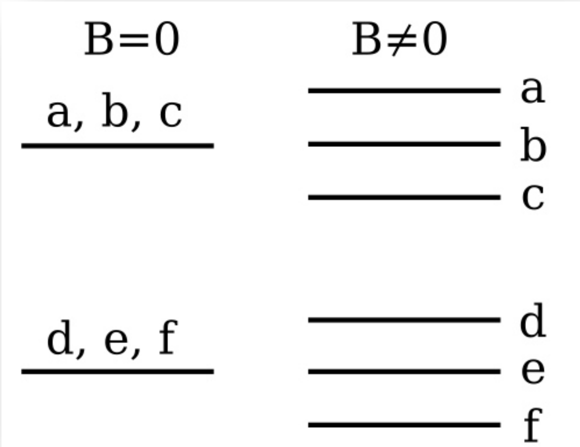
=> Doublets and triplets

=> Polarization

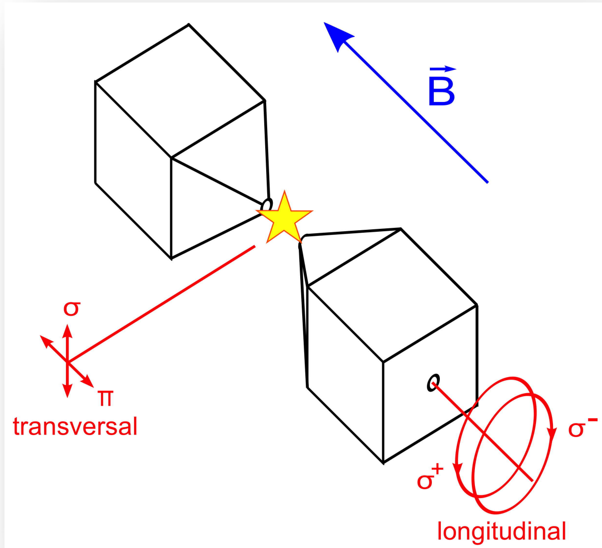
Zeeman effect

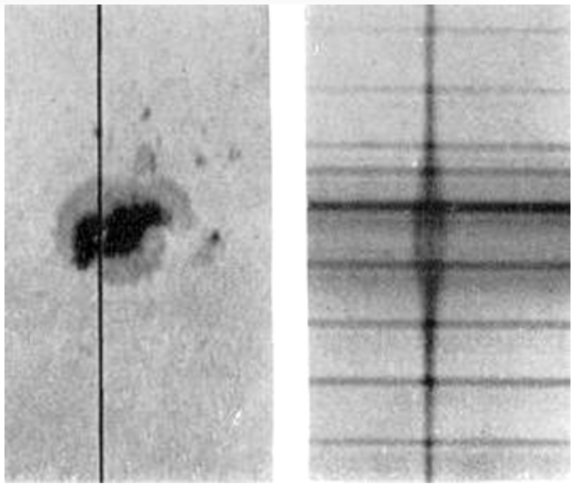
Discovered in 1896 by Pieter Zeeman (1865-1943) while at Leiden.
Soon Hendrik Lorentz (1853-1928) provided a (still classical) theoretical explanation.
Both shared the Nobel Prize in physics in 1902.

Splitting of spectral lines:
doublets, triplets, …



Side-lines are polarized



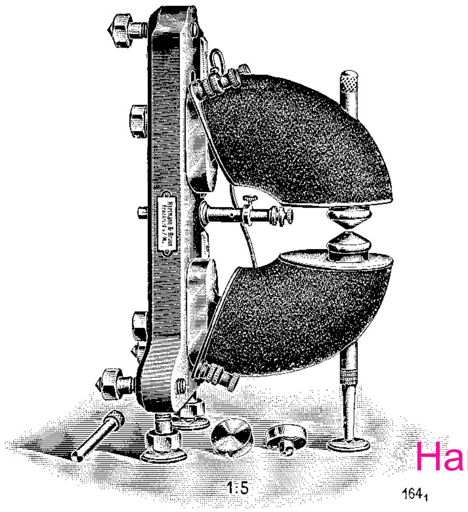


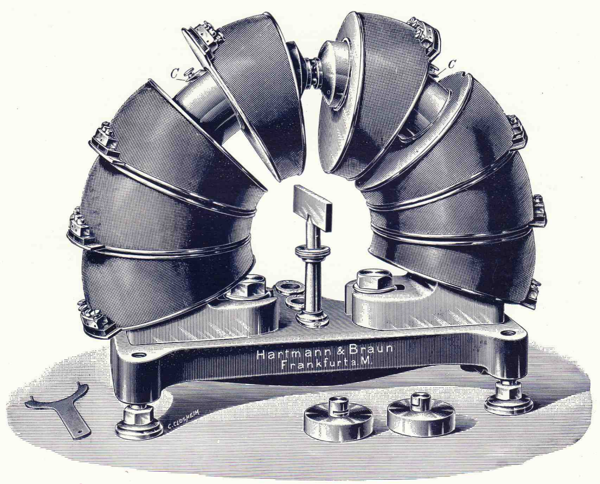
Application to astronomy from 1909,
by George Ellery Hale :
magnetic field in stars

Line widening in a Sun spot (1919)

Modern electromagnets: du Bois

Electro-aimants en demi-cercle





Hartmann & Braun

1:5

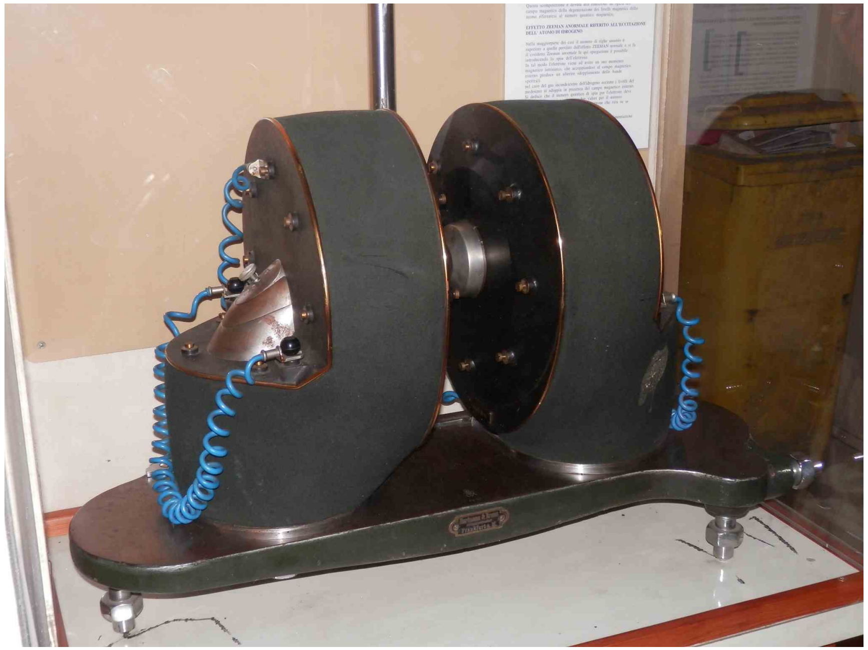
Nº 432. Grand électro-aimant en demi-cercle
de H. du Bois.

Kazan

Henri du Bois (1963-1918):
First scientifically designed E-M
Full-ring E-M (1894) evolved into several successive models of half-ring E-M

Uncooled (excepted maybe the very last ones)
Fixed gap
Awkward form of the coils

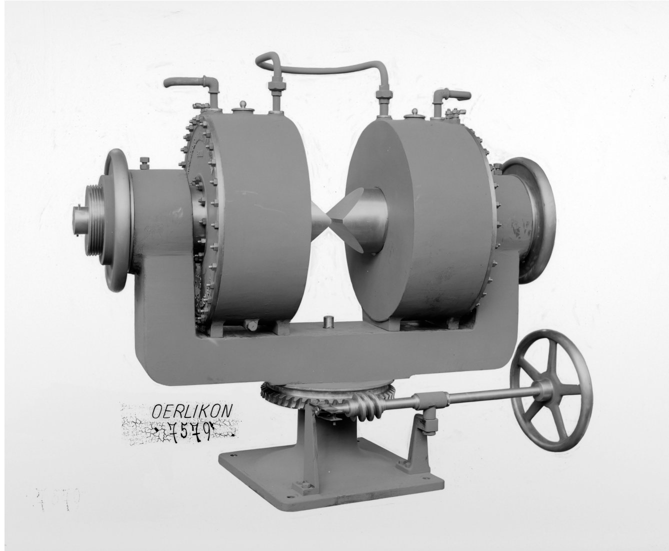
Until the 1930s, the only serious competition to small- and medium-sized Weiss-like E-M



Turin

Modern electromagnets: Pierre Weiss

Pierre Weiss (Mulhouse 1865 - Lyons 1940) dedicated most of his career to magnetism.
While at Rennes, in 1898, he built his first, small E-M (Ruhmkorff-like, but 3 coils as Ewing's);
At the Polytechnikum of Zurich (1902-1918), in collaboration with Maschinenfabrik Oerlikon (MFO), he built the first truly modern, large (1000 kg), water-cooled E-M.



Weiss-MFO electromagnet (1907) for Zurich and ENS (Paris)

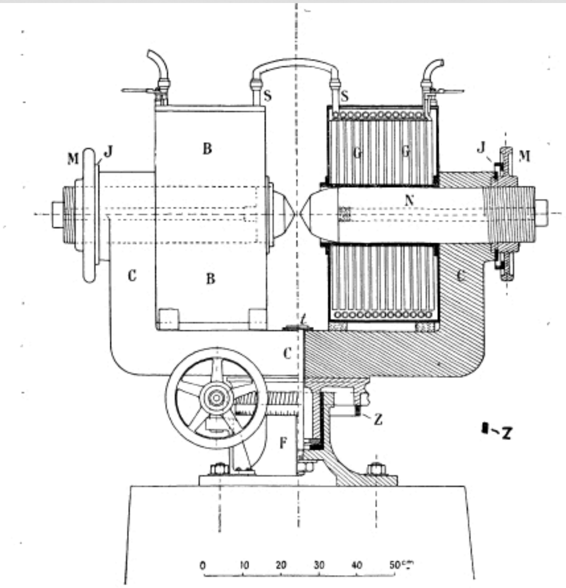


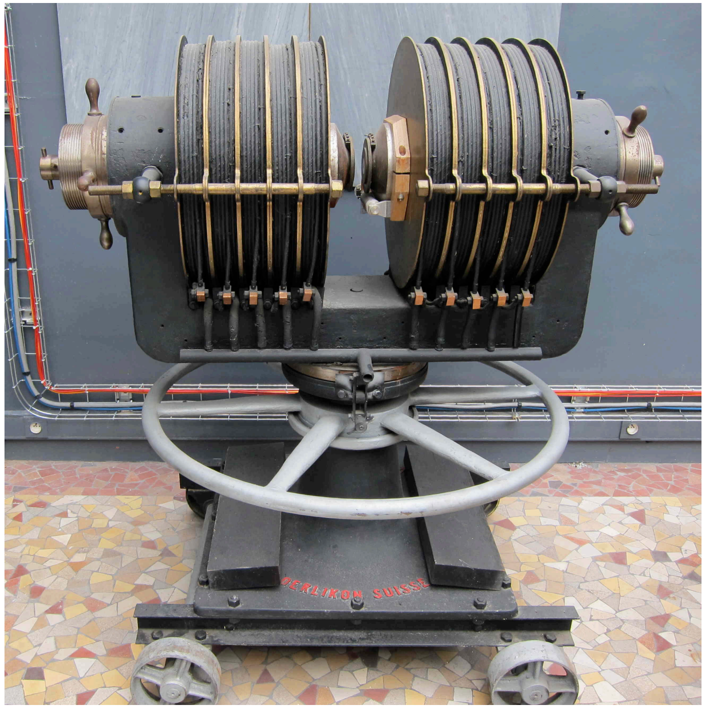
Fig. 3.

Cylindrical poles, bored-through, dia. 150 – 200 mm

Improved Weiss-MFO E-M (1913):

- coils: Cu-tubes with water circulation
- pole-tips: Fe-Co inserts

  First ones for J. Becquerel at the Muséum (Paris) and H. K. Onnes (Leiden)



Archetype of most modern electromagnets!

Small modern electromagnets

1. 100 years ago

Small Weiss E-M (132 kg),
A. Perrier and H. K. Onnes
at Leiden (~ 1913)

Small SIP E-M at UNIL (1913-1923)
Coils ø 300 mm, poles ø 90 mm
In use until 2003

2. Today

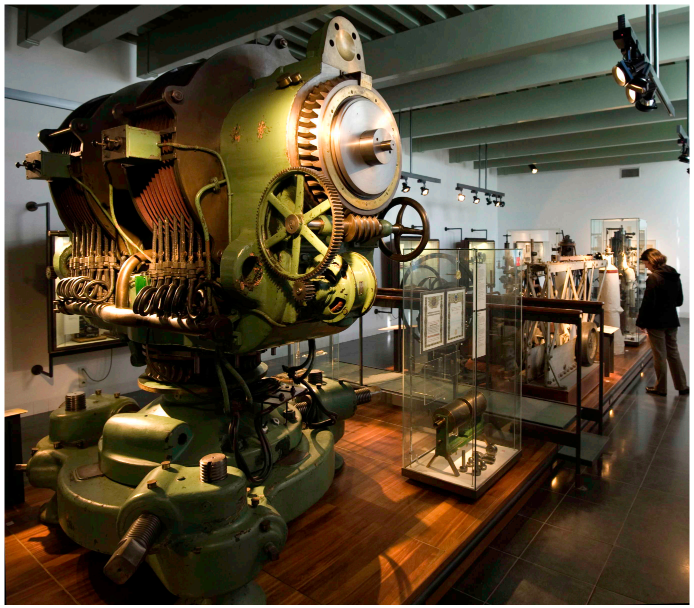
Weiss-inspired E-Ms are as popular as ever, to be found nowadays in most physics laboratories

Giant electromagnets

After WWI, a need was perceived for bigger, even huge general-purpose laboratory electromagnets providing:

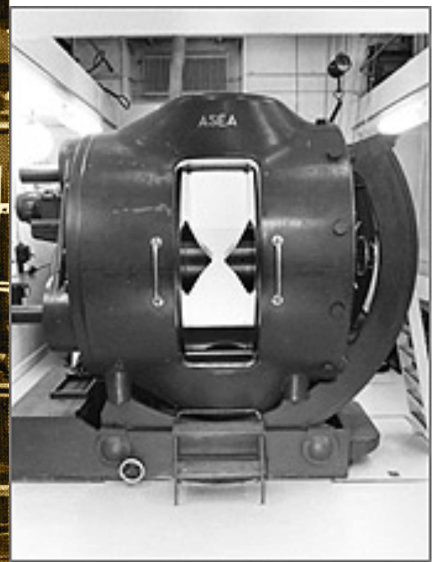
- either a very high field (up to 7 T) in a small volume (~ cm^3),
- or an uniform, moderate field in a large volume,
  to provide room for bulky experimental apparatus

1930s: race to the lowest temperatures, << 1 K:
Cooling of *paramagnetic salts* through adiabatic demagnetization calls for bulky cryostats



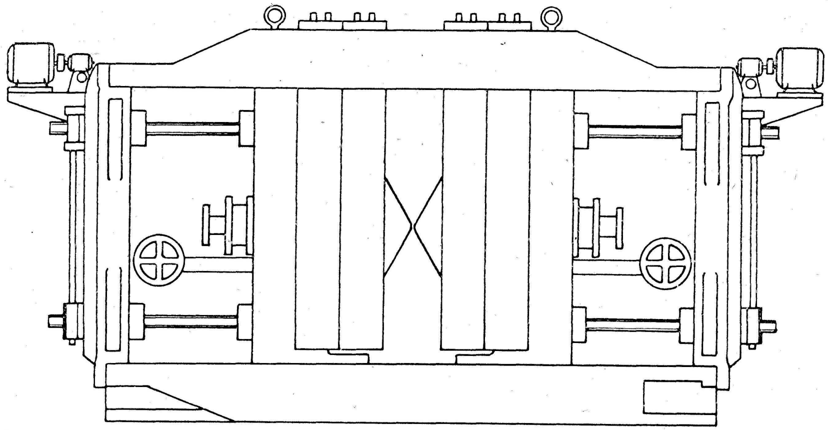
Leiden 1932

Meudon-Bellevue (Académie) 1928



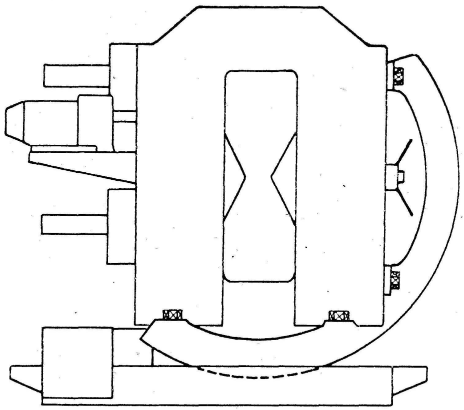
Uppsala 1937

Giant electromagnets: size comparison



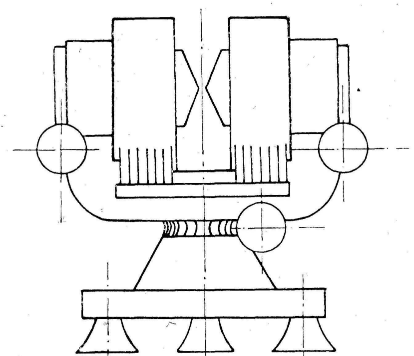
a, Bellevue-Magnet

Académie/Bellevue:
Core ø 750 mm
Coil ø 1.9 m
120 t – 6 T in small volume



b, Uppsala-Magnet

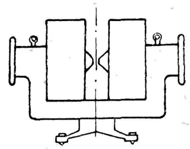
ASEA/Uppsala:
Core ø 590 mm
Height 2.7 m
37 t – max. 6.2 T



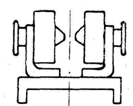
c, Leidener Magnet

S&H/Leiden
Pole ø 400 mm
Height 2.5 m
14 t – max. 6 T

Weiss/SIP or Max Kohl (large):
Pole ø 100 mm



e, großer Weiß-Magnet



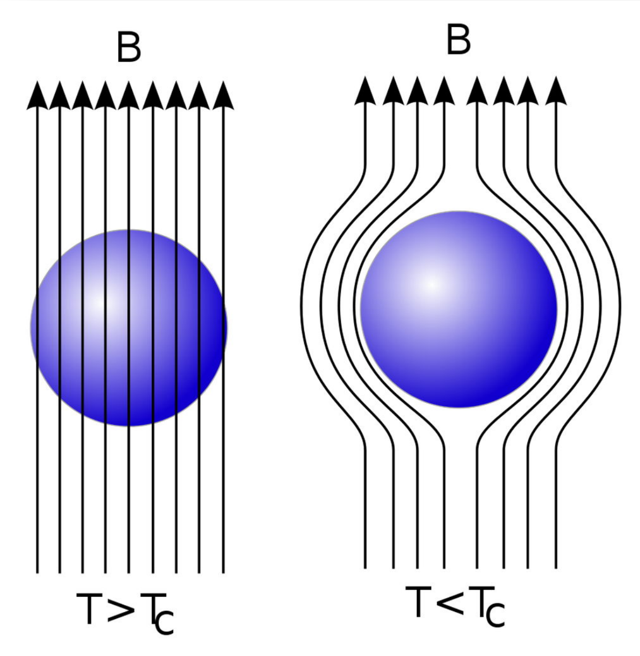
f, kleiner Weiß-Magnet

Weiss/SIP or Max Kohl (small):
Pole ø 80 mm

Maßstäblicher Vergleich (1 : 50) der Größe der stärksten Elektromagneten mit Eisenjoch.
a) Riesenmagnet der Académie Française in Bellevue bei Paris.
b) Riesenmagnet der Technischen Hochschule in Uppsala, gebaut von der Asea.
c) Riesenmagnet des Leidener Kältelaboratoriums, gebaut von Siemens & Halske.
d) Elektromagnet der PTR., gebaut von Boas, Berlin NO.
e) Großer Weißmagnet, gebaut von M. Kohl, Chemnitz.
f) Kleiner Weißmagnet, gebaut von M. Kohl, Chemnitz.

Meissner effect (1933)

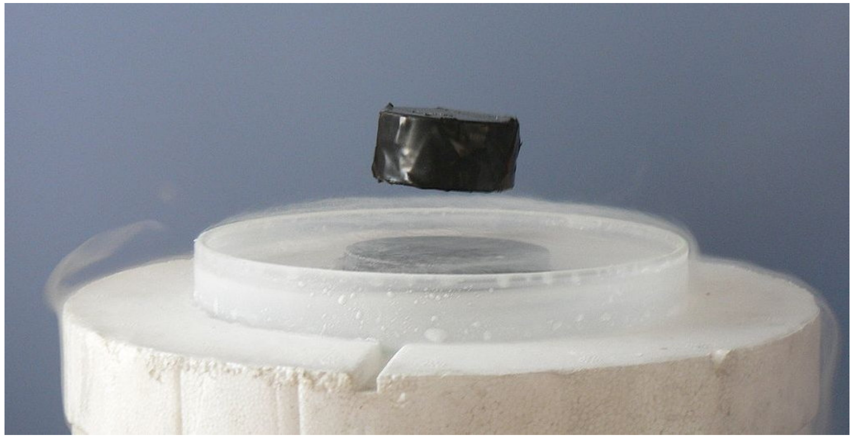
1908 : H. K. Onnes at Leiden liquefies He (T = 4.2 K)
1911 : H. K. Onnes discovers superconductivity in Hg



Walther Meißner (1882-1974) and
Robert Ochsenfeld (1901-1993),
while at PTR-Berlin,
demonstrate in 1933 that
a superconductor expells the magnetic field.
It is perfectly diamagnetic.

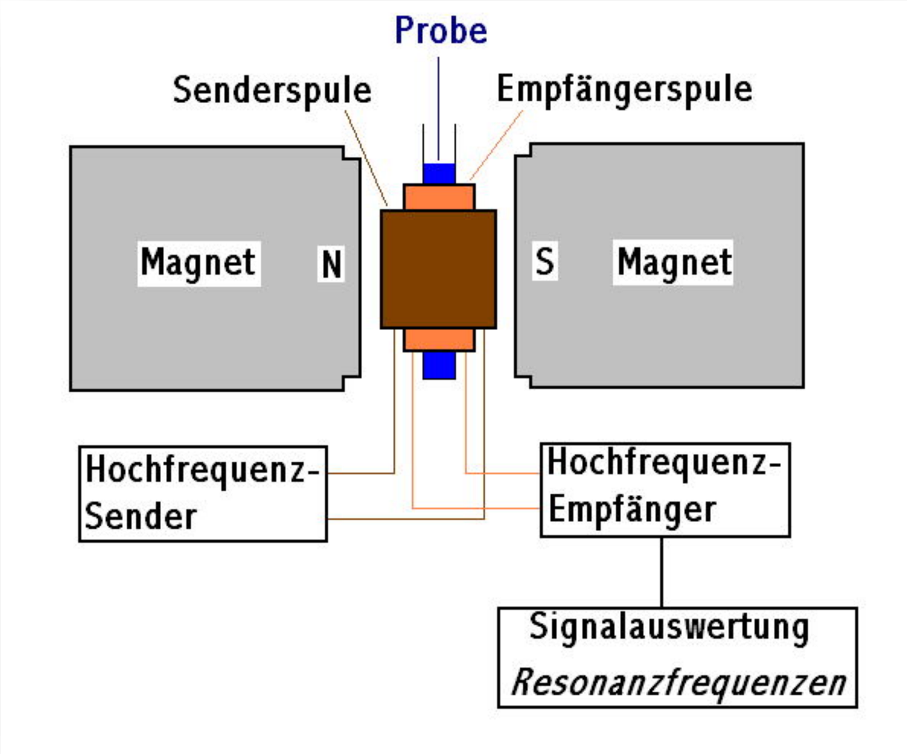
Apply B, then cool under T_c } => no difference!
Cool under T_c, then apply B }

Demonstration:
Magnet levitating above a high-T_c superconductor
cooled by liquid nitrogen (77 K)



Maglev Trains using high-T_c superconductors?

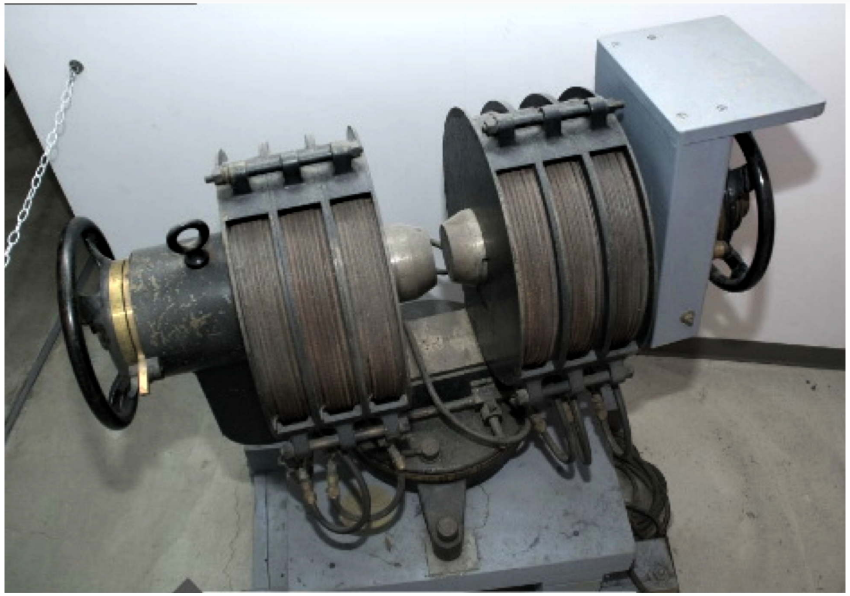
Nuclear Magnetic Resonance



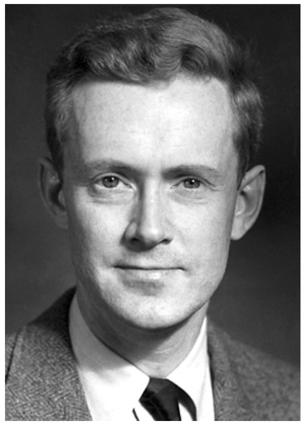
Back to physics at room temperature

Nuclear spins
immersed in B + radiofrequency f

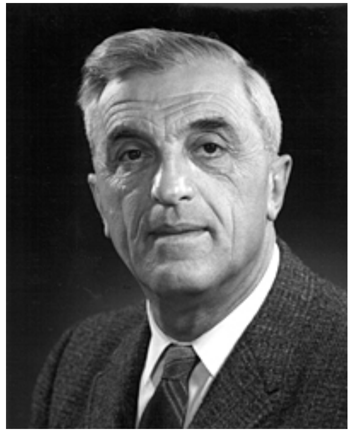
Harvard 1946:
Proton resonance observed
in liquids and solids by
Bloembergen, Purcell and Pound



Old SIP E-M at Harvard
Pole dia. 100 mm



Purcell (1912-1997)



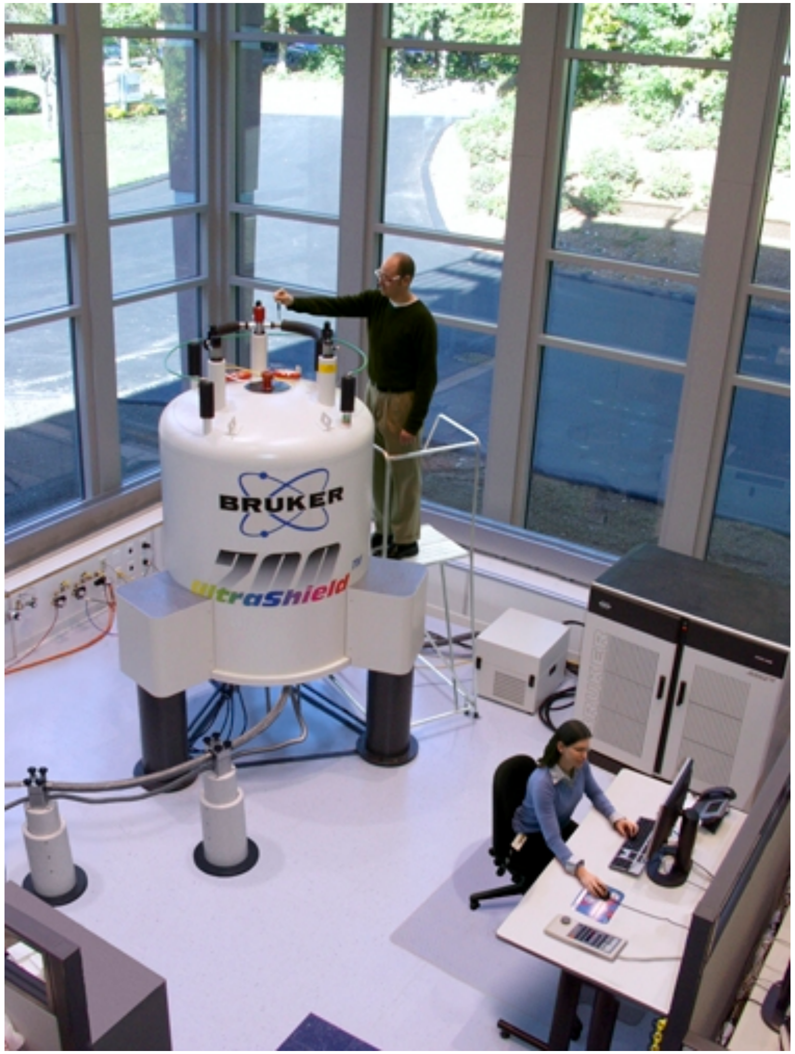
Bloch (1905-1983)

1952:
E. M. Purcell shares the Nobel Prize
with Felix Bloch

Nuclear Magnetic Resonance: applications

1. High-precision magnetometers (proton precession)

2. Li-He cooled superconducting magnets + RF + computers



2a. Chemistry: NMR spectroscopy

2b. Medicine: (Nuclear) Medical Resonance Imaging

Conclusions

Submitting material samples to magnetic fields,
many surprising phenomena have been discovered.

In many cases, fundamental discoveries were made with oldish,
rather inadequate but available electromagnets (Faraday, Zeeman, Purcell,…).

Theory: the observation of experimental effects preceded,
often by a long time, a rigorous theoretical explanation (Q.M.).

A few effects found applications, sometimes much later,
outside the physics laboratories:

Kerr-effect: magneto-optical storage for computers (already obsolete)

Hall-effect: sensors

Meissner-effect: nice demonstrations; MAGLEV transportation???

NMR (+computer): Medical Resonance Imaging, in most hospitals

Bibliography

A long list of the consulted books, manufacturers' catalogues and scientific articles is available from

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Thank you for your attention !