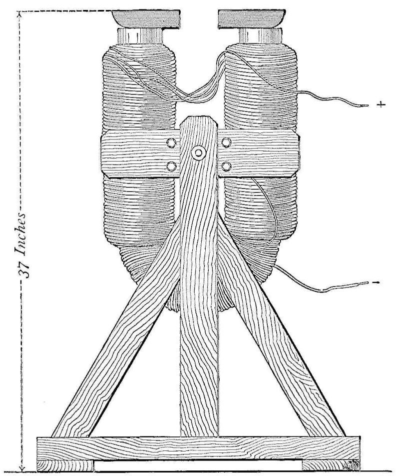
DPG – Fachverband Geschichte der Physik
18th Symposium (Munich 20.03.2019)

LABORATORY ELECTROMAGNETS:
from the beginnings to Electromagnet Laboratories



FARADAY'S ELECTROMAGNET AT THE ROYAL INSTITUTION.

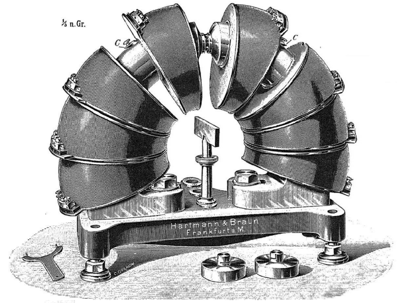
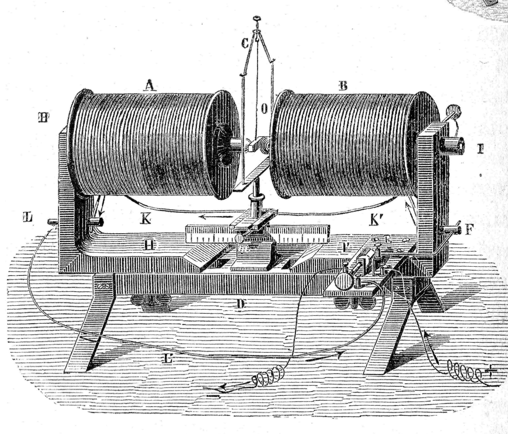
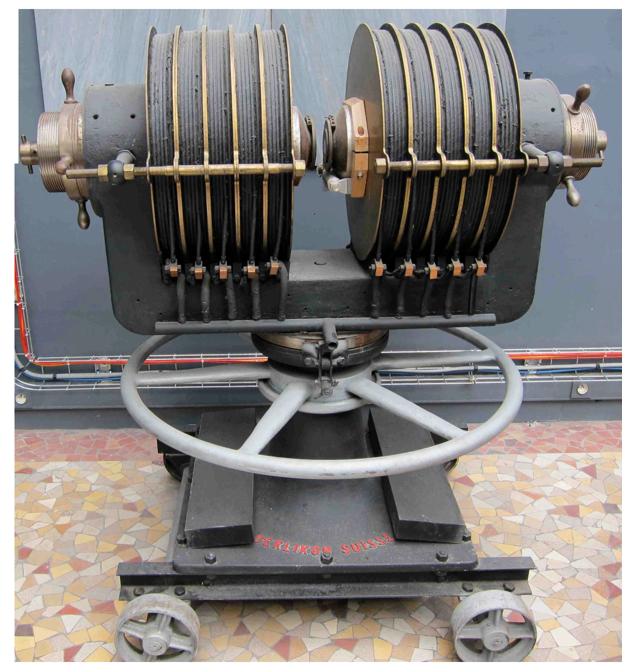


Fig. 609.



Jamin, J. : Cours de physique de l'École polytechnique (2e éd. en 3 vols)
(Paris : Gauthier-Villars, 2e éd., Tome 3, 1869)
Fig. 609, p. 254



Jean-François LOUDE - École Polytechnique Fédérale de Lausanne – Suisse

Dominique BERNARD - Université de Rennes 1 - France

Magnetism before H. C. Oersted

Certain stones ("lodestones") attract iron.
They are naturally (by a lightning bolt?) magnetised pieces of magnetite, an iron ore

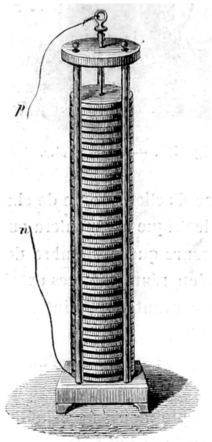
First application: compass, first for geomancy in China, then for navigation

William Gilbert (1600):
De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure
First mention of the Earth as a weak (c. 50 μT) giant magnet

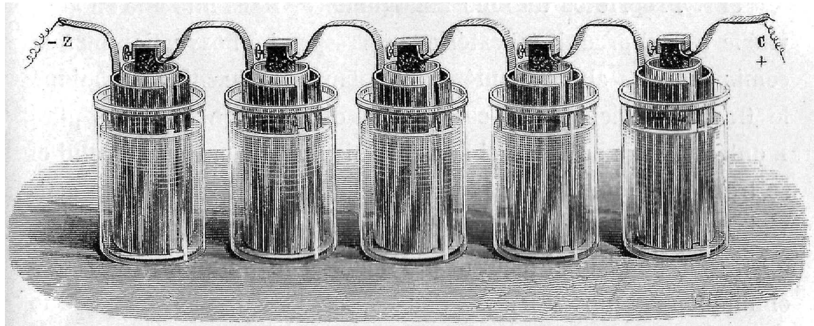
Concerted international studies of geomagnetism begin in the 1880s

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

First discoveries



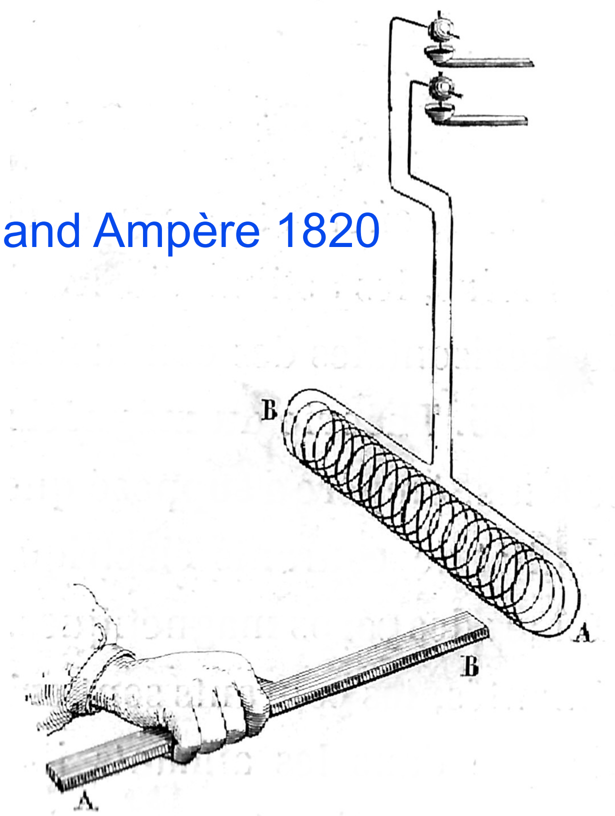
Volta 1800

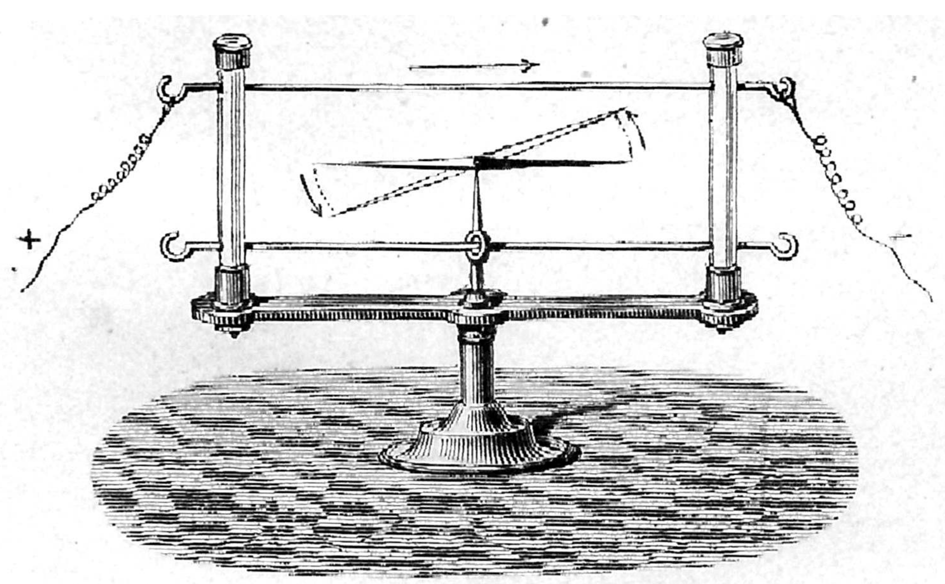


Electrochemical cells (Bunsen, etc.)

Sources of permanent electrical current

Arago and Ampère 1820

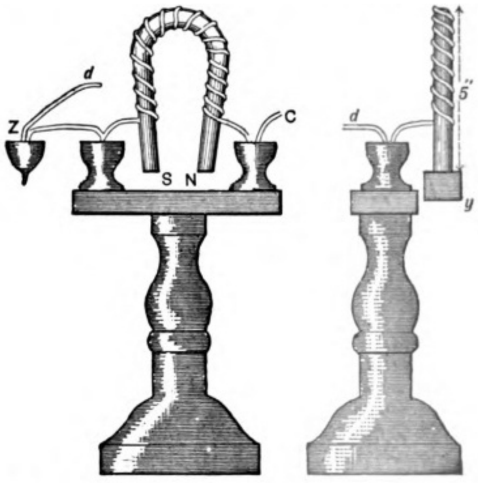




Oersted 1820

The first electromagnets (E-Ms) and their makers

William Sturgeon
(1824)



FIGS. 1 AND 2.—STURGEON'S FIRST ELECTROMAGNET.

Sturgeon's first electromagnet

Joseph Henry
(1831)

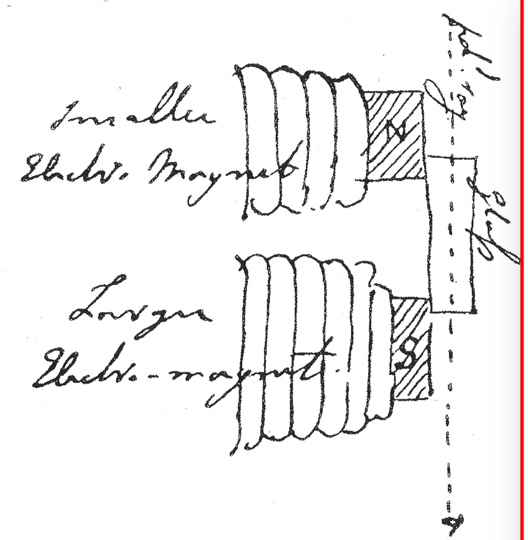
The Yale Magnet (1831) could support 936 kg

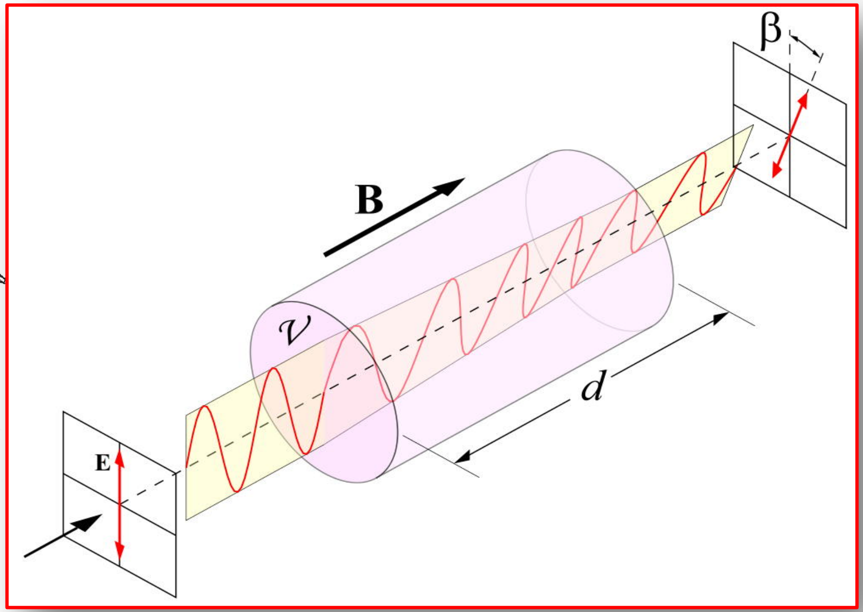
Michael Faraday
(1845 -1846)

Large electromagnet belonging to Michael Faraday (1791-1867) c.1850

Michael FARADAY (1791–1867): first magneto-optical effect (1845)

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





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

FARADAY: dia- and para-magnetism

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 magnet, paramagnetic ones are attracted. We normally don't feel these forces, many orders of magnitude smaller than the ones exerted on iron (ferro-magnetism).

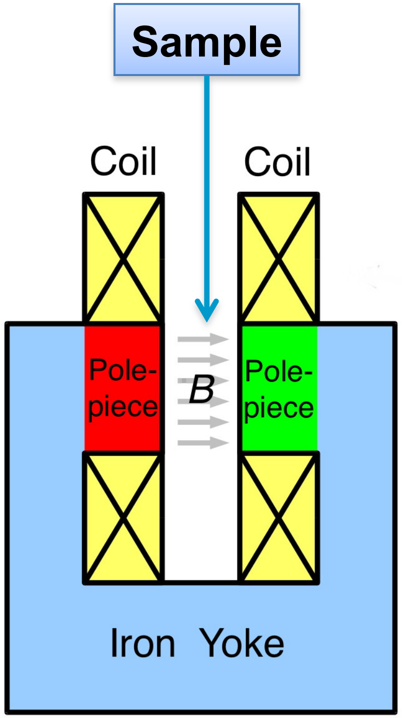
Pyrolytic carbon and bismuth are the strongest room-temperature diamagnetics.

Diamagnetism = repulsion => room-temperature levitation?!
A dream until recently!

Living frog levitating
above an E-M
(32 mmø bore, 16 T)
Enormous power needed!

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

General purpose laboratory electromagnet

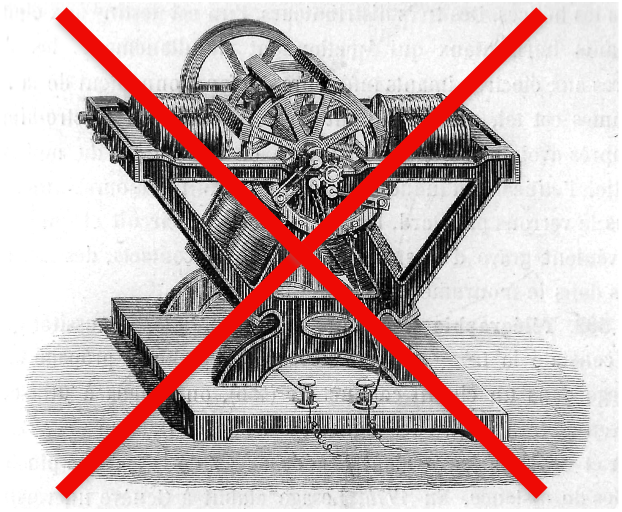


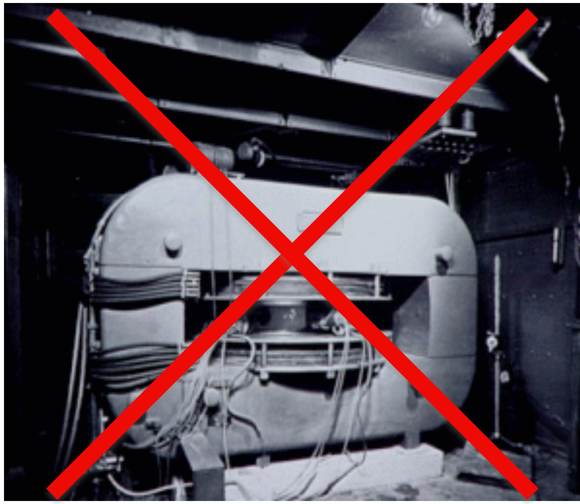
Purpose:
Investigation of the properties of a material sample (solid, liquid, gas), in a static or quasi-static magnetic field.
We'll forget the obvious ferro-magnetism, despite its enormous technological importance.
Theory left out: most phenomena were discovered before an adequate theory became available!

Main requirements:

- Slowly variable *B*, up to the highest possible value
- Interchangeable pole-pieces: cylindrical, truncated cones, wedge-shaped, bored-through, …
- Mechanical adjustments: gap width, position, ...

Excluded: electromagnets used for their purely mechanical effects





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

Heinrich Daniel Ruhmkorff (1803–1877)

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

1846: Designs a novel E-M, repeats Faraday's experiments

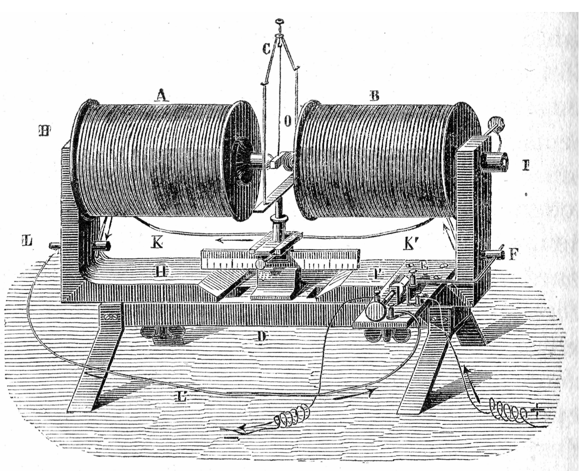
Still used half a century later by well known physicists:

1895: P. Curie (Paris), with Ruhmkorff-inspired E-M

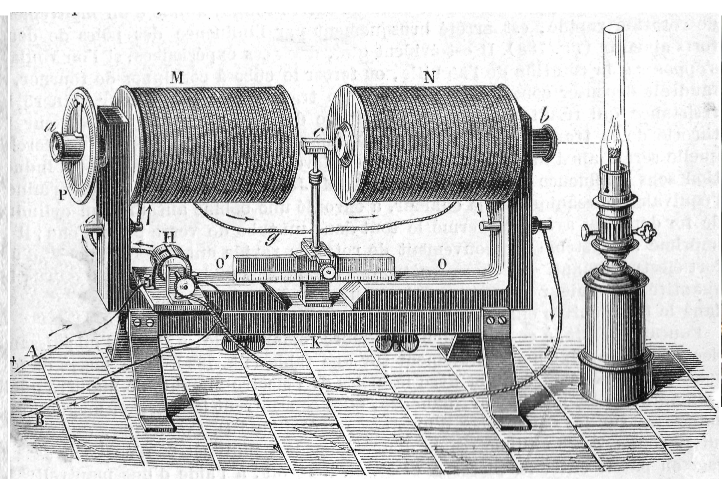
1897: Zeemann (Leiden)

1897: Cotton (Toulouse)

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



Ruhmkorff E-M for
dia- and para-magnetism

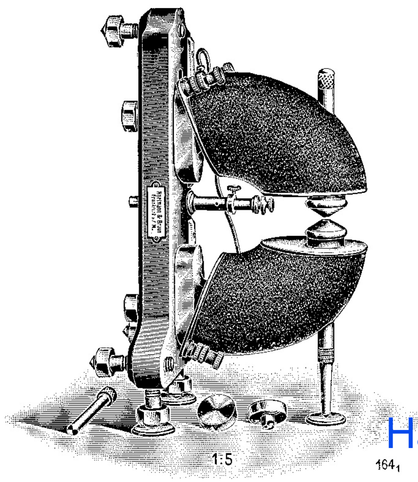


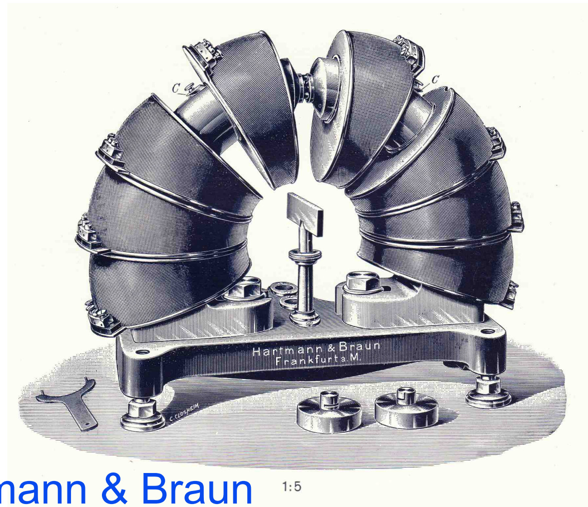
Ruhmkorff E-M for
Faraday effect

Magnetism at
various temperatures
(Pierre Curie, Ph. D., 1895)
Bourbouze E-M (?)

Modern electromagnets: du Bois

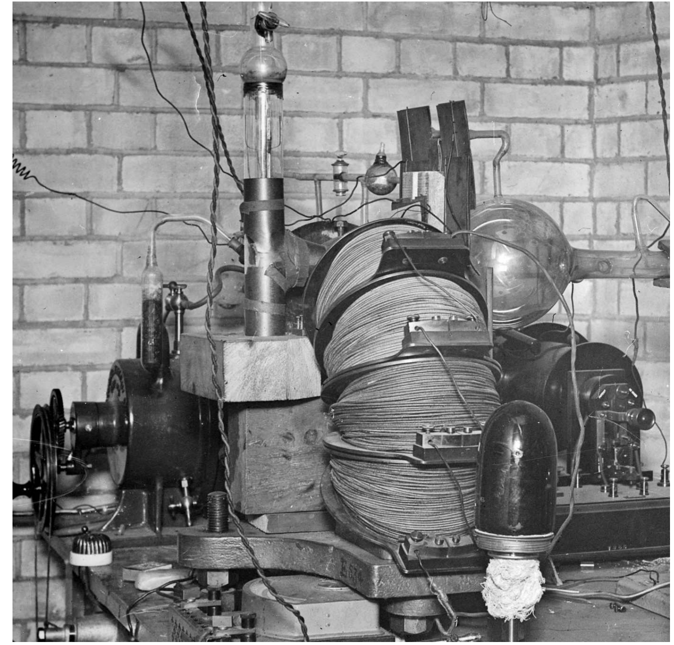
Electro-aimants en demi-cercle





Hartmann & Braun 1:5

N° 432. Grand électro-aimant en demi-cercle
de H. du Bois.

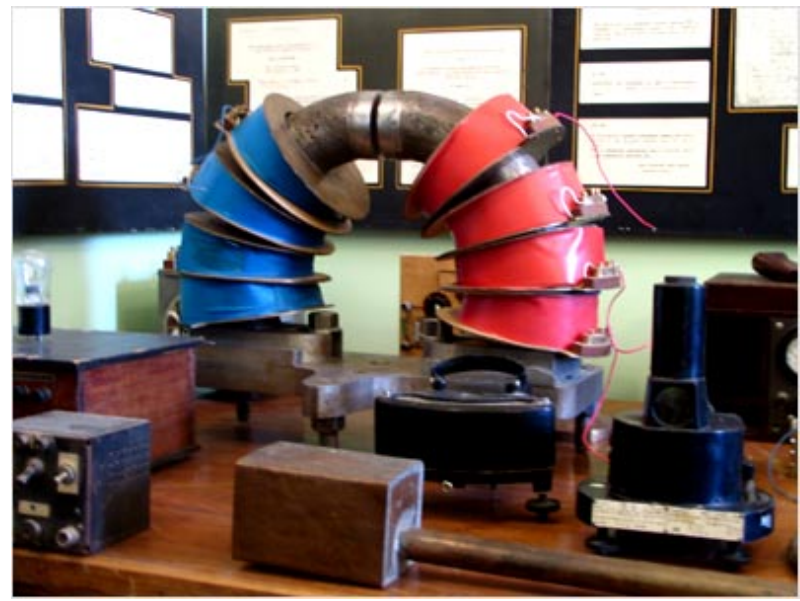


Cavendish Lab 1911-1912
(J.J. Thomson and F.W. Aston)

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)
Almost fixed gap
Awkward form of the coils

Despite these defects, they remained until the 1930s the only serious competition to small- and medium-sized Weiss-like E-Ms and were used by well-known physicists for important work



Kazan (Russia): Zavoisky Laboratory

Physics in magnetic fields after Faraday
1. At or near ambient temperature

– **Kerr effect**: John Kerr (1824-1907) discovers in 1877-1878 at Glasgow another magneto-optical effect. Using a horse-shoe E-M, he observes a change of the state of polarization of the light reflected on the magnetized, polished surface of the pole-piece. Has been used for data storage (magneto-optical disk)

– **Hall effect**: Edwin Hall (1855-1938), working at Johns Hopkins University, discovers in 1879 a magneto-electrical effect, the production of a voltage difference across an electrical conductor, transverse to an electric current in the conductor and a magnetic field perpendicular to the current.
Nowadays, widely used for the measurement of magnetic fields, either in laboratories or in consumer electronics (brushless DC motors)

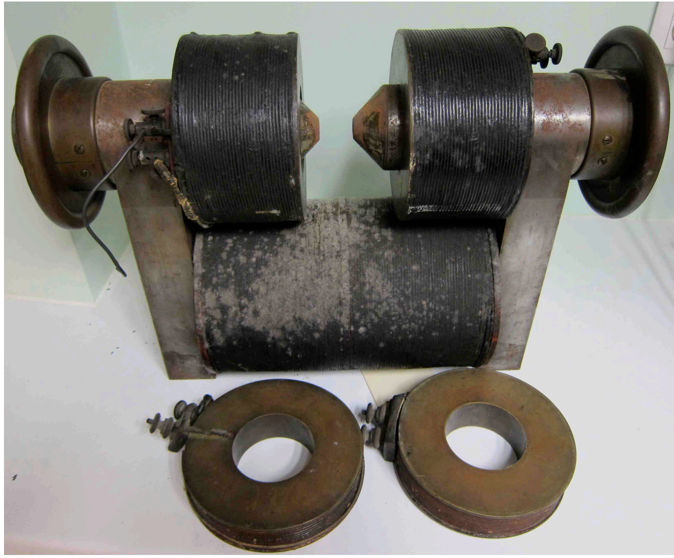
– **Zeeman effect**: Pieter Zeeman (1865-1943) observes in 1897 at Leiden a splitting of atomic spectral lines when the magnetic field of a Ruhmkorff E-M is applied on the source of the light.
He shares with Hendrik Lorentz (1853-1928) the Nobel Prize in physics (1902).
This effect is applied in 1909 by G. E. Hale to measure the magnetic field in stars.

– A few other magneto-optical effects were discovered by Voigt (1898), Cotton-Mouton (1907), Majorana.

Pierre Weiss (1865-1940),
French physicist,
pioneer of magnetism

Weiss ca. 1913
born Mulhouse (FR)

Fac. des Sciences de Rennes
1895 to 1899



1898: 3-coils E-M
Very like Ewing's E-M of 1892
(U. Rennes1)

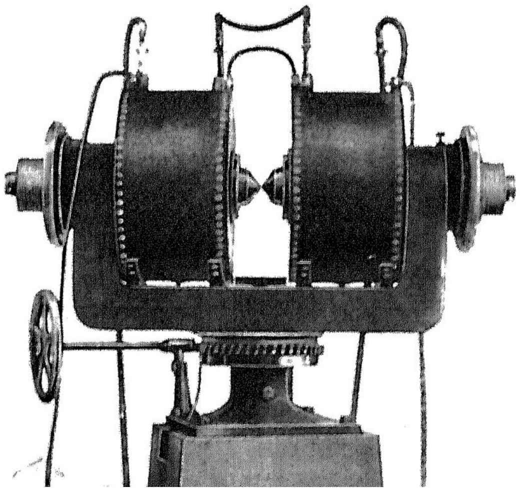
Polytechnikum Zürich
Switzerland
1902 to 1919

1907
– Weiss-MFO Electromagnet
– Magnetic (Weiss) domains

Faculté des Sciences
Strasbourg - France
1919 to 1940
† at Lyon

Modern electromagnets: Pierre Weiss

At the Polytechnikum of Zurich (1902-1918),
in collaboration with Maschinenfabrik Oerlikon (MFO),
Weiss built the first truly modern, large (1000 kg), water-cooled E-M**.**



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

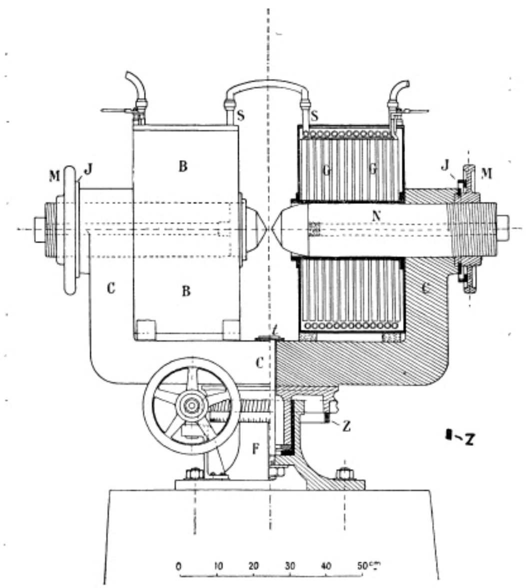


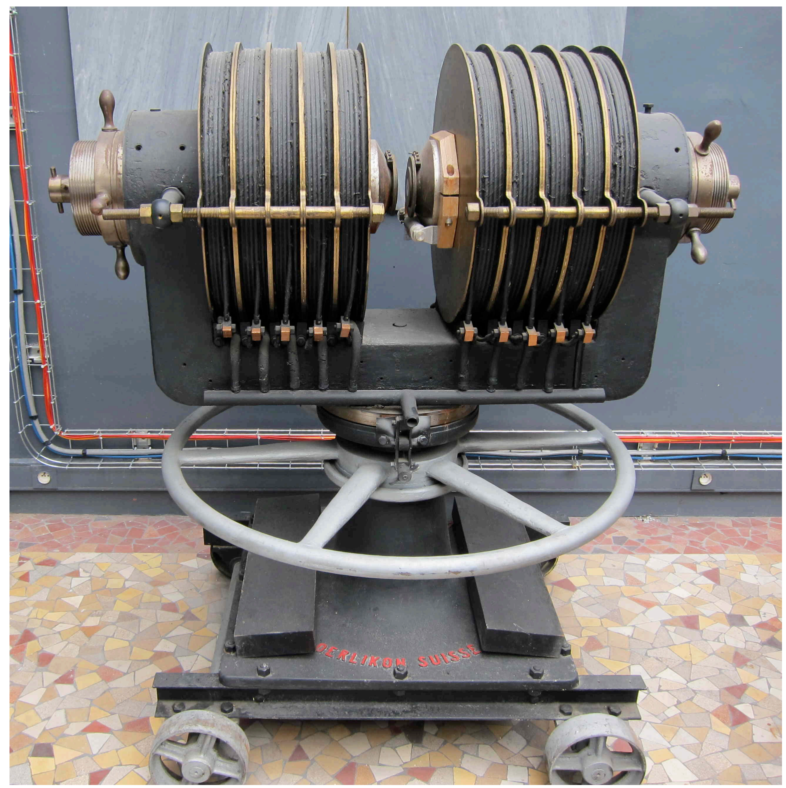
Fig. 3.

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

Improved Weiss-MFO E-M (1913):

- windings: Cu-tubes with H_2O circulation
- poles: Fe-Co inserts

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



Archetype of most modern laboratory E-Ms!

A range of smaller Weiss E-Ms was built by the SIP (Geneva)

SOCIÉTÉ GENEVOISE

POUR LA CONSTRUCTION D'INSTRUMENTS DE PHYSIQUE ET DE MÉCANIQUE

GENÈVE (Suisse)

5, CHEMIN GOURGAS, 5

Electro-aimants de laboratoire (Système du Prof. P. WEISS).

Ces appareils sont construits en quatre grandeurs caractérisées par le diamètre des noyaux polaires, 80, 92, 100 millimètres.

Ce dernier modèle est aussi construit en deux dimensions.

Ils se distinguent des appareils similaires par les points principaux suivants :

Les bobines étant placées directement sur les noyaux polaires concentrent la saturation magnétique uniquement dans cette région, tandis que le reste du circuit magnétique, ayant une section notablement plus forte, travaille avec une induction beaucoup plus faible.

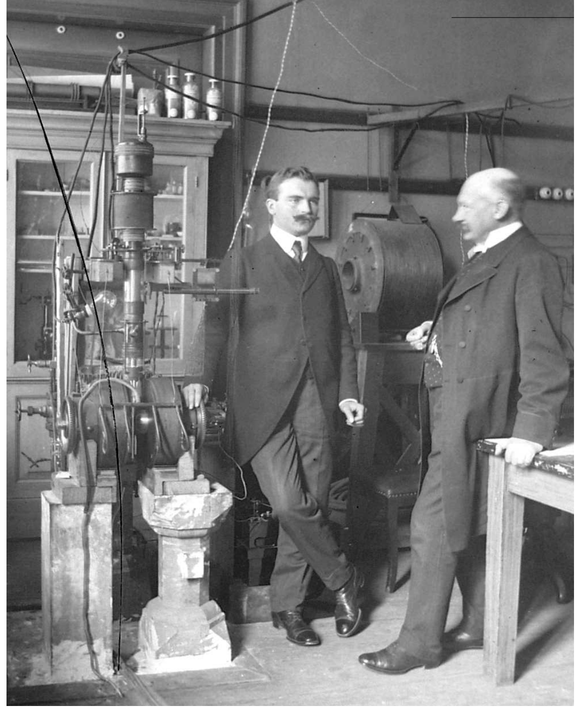
Les noyaux polaires sont susceptibles d'être éloignés ou rapprochés micrométriquement ; la longueur de l'entrefer peut être lue au dixième de millimètre.

Leur prix est sensiblement inférieur aux appareils équivalents d'autres systèmes.

Ces électro-aimants peuvent être livrés montés sur un pied à rotation sur billes, avec cercle de calage divisé en degrés et dispositif de bloquage, ou montés simplement sur un fort plateau de chêne.

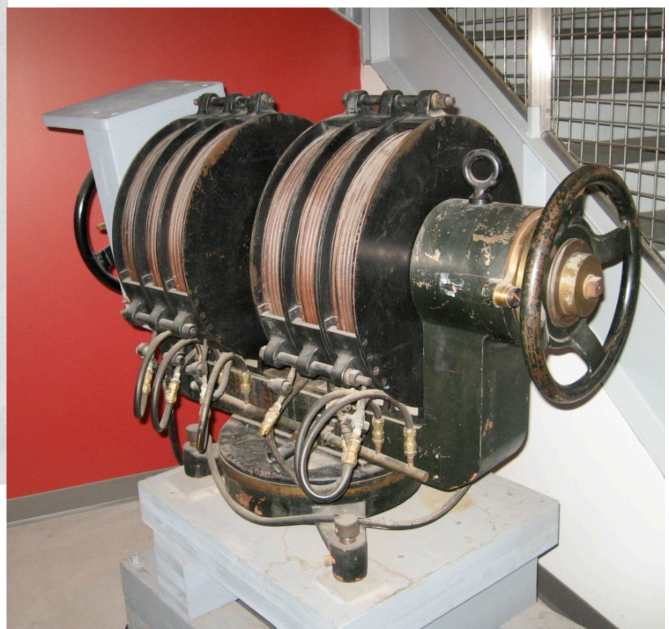
Electro-aimant Weiss monté sur pied tournant.

Les parois des carcasses des bobines sont creuses et sont parcourues par une circulation d'eau, ce qui empêche la chaleur produite par l'échauffement du bobinage de se communiquer aux garnitures polaires. L'entrefer reste *absolument froid*, ce qui est un avantage important pour beaucoup d'expériences.



First SIP E-M
at Leiden (1909-1914)
Pole dia. 90 mm, 132 kg
Left A. Perrier (Lausanne),
right H. Kamerlingh Onnes

Lausanne University
(bought by A. Perrier
before 1923,
in use until 2003)
Pole dia. 90 mm



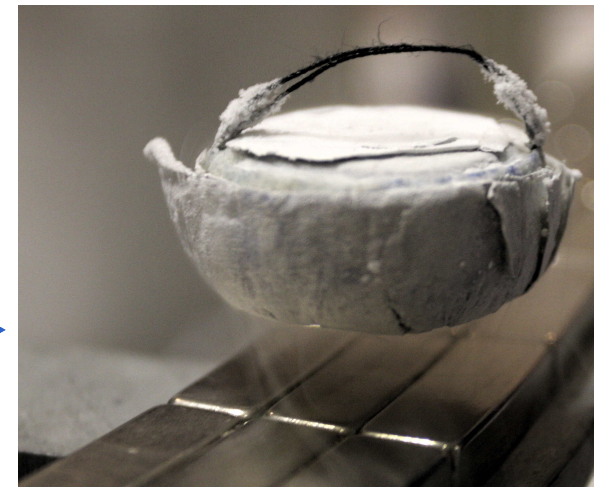
Harvard University
SIP - Model 1913
Water cooled
635 kg
Example of use :
Pole dia. at the gap 10 cm
0.7 T in gap ≈ 20 mm
for a power of 220 watts

Physics in magnetic fields after Faraday
2. At low temperature (≤ 77 K)

– **Meissner effect**: W. Meissner and R. Ochsenfeld at PTR-Berlin find (1933) that a superconductor expells the magnetic field, behaving as a perfect diamagnetic.

Applications: nice demonstrations of levitation; Maglev trains ?

Magnet levitating above a high-T_c superconductor at 77 K



High-T_c superconductor at 77 K levitating above magnets

– **Magneto-caloric effects**:
P. Weiss and A. Piccard (ETHZ, 1917) demonstrate a magneto-caloric effect in Ni at high T
P. Debye (ETHZ, 1926) and W. F. Giauque (UCB, 1927) independently propose a process of magnetic refrigeration by adiabatic demagnetisation
1933: Giauque and MacDougall reach 0.25 K by adiabatic demagnetisation of paramagnetic salts

Applications: Laboratory cooling to extremely low T. Alternative methods of refrigeration?

Race to extremely low temperature still going on

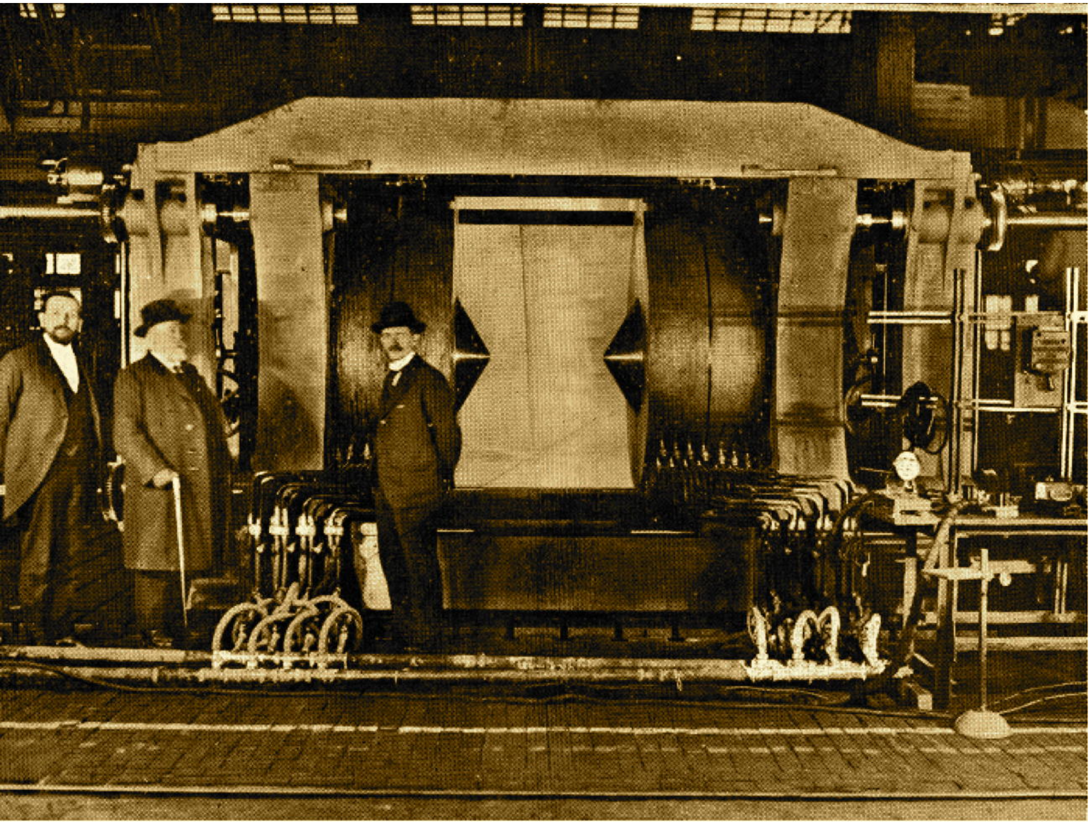
Giant electromagnets (1)

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

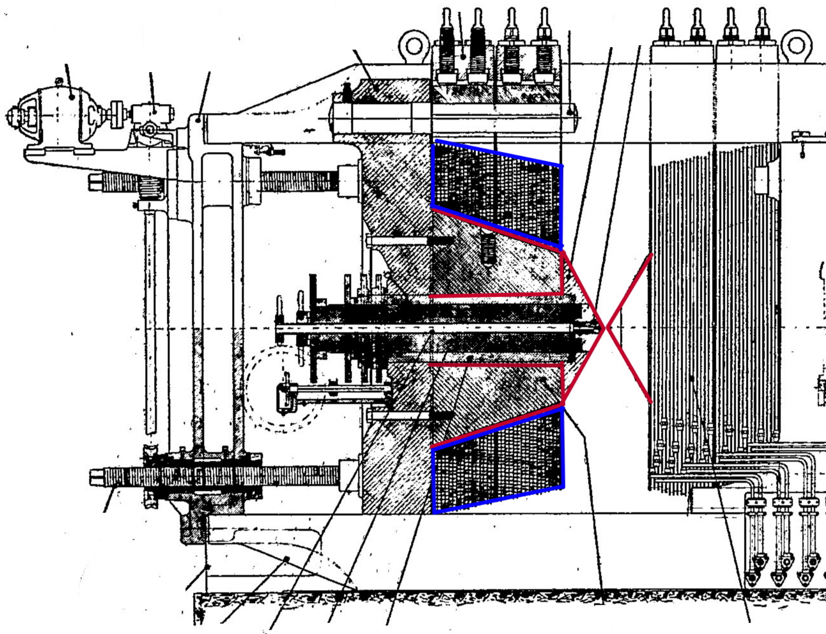
– either a very high field (up to 5 T) in a small volume (~ cm^3),

– or an uniform, moderate field in a large volume, to provide room for bulky experimental apparatus (for instance cryostats, cloud chambers)

The first one was built for the Académie des Sciences de Paris:

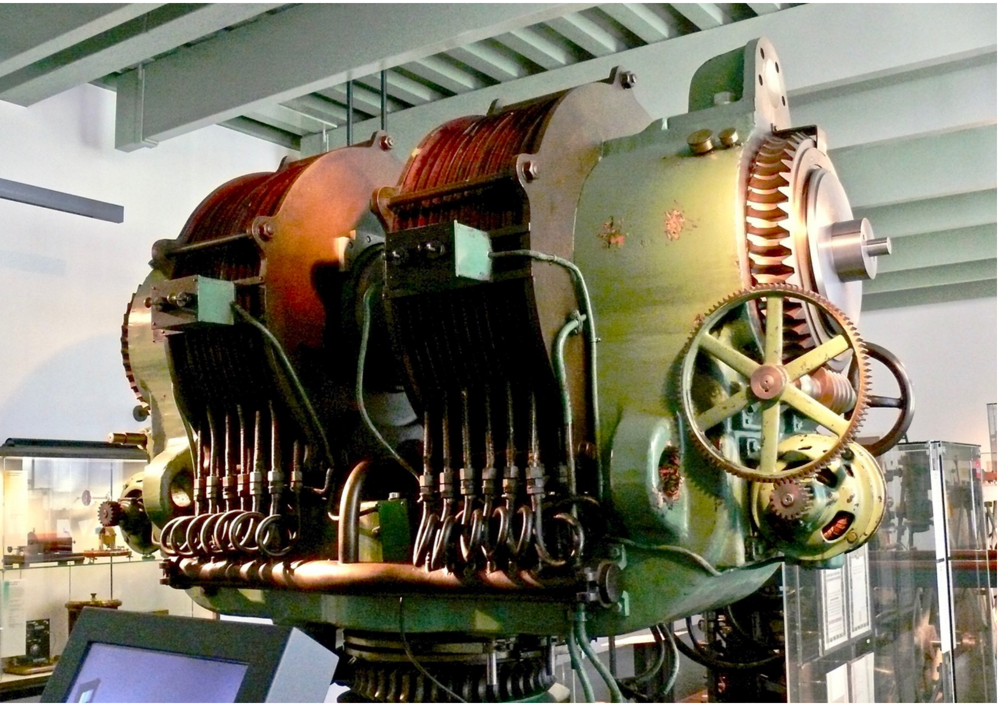


Installed at Meudon-Bellevue in 1928
120 tons – 5.3 T in 20 cm^3

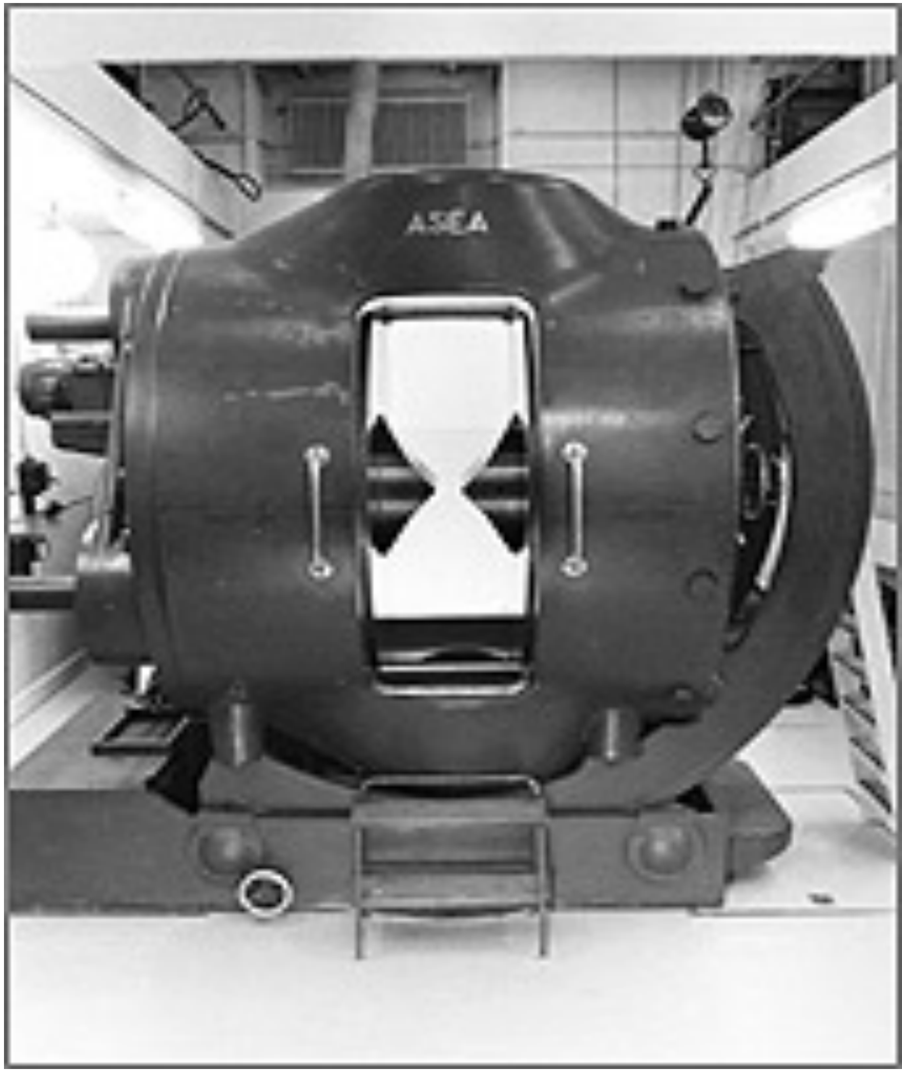


Tronconical pole-pieces
(as already used in 1923 by
Boas and Pederzani at Berlin)

Giant electromagnets (2)



Leiden University
Delivered 1925, inaugurated 1932
Cylindrical pole-pieces
14 tons, max. 6 T
S&H (Berlin)

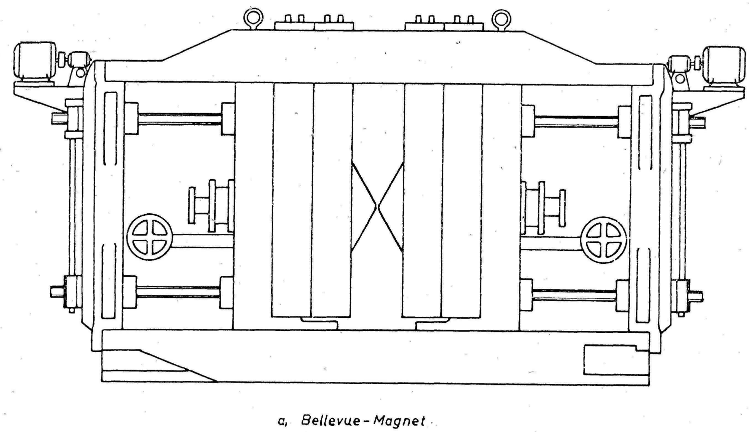


Uppsala University (1935)
Tronconical pole-pieces
37 tons, max. 6.2 T
ASEA (Västerås)

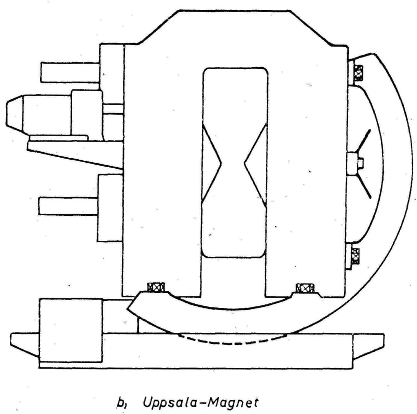
Last general-purpose giant E-Ms.
But very large special-use E-Ms were built for nuclear physics (cyclotrons, ...)

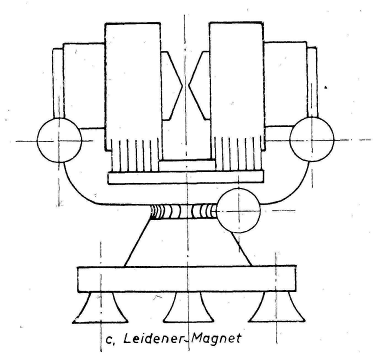
Giant electromagnets: size comparison

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



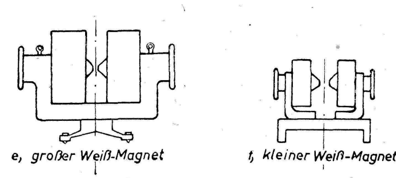
ASEA/Uppsala:
Core ø 590 mm
Height 2.7 m
37 t – max. 6.2 T





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

Weiss E-M by Max Kohl or SIP
(large, pole ø 100 mm)



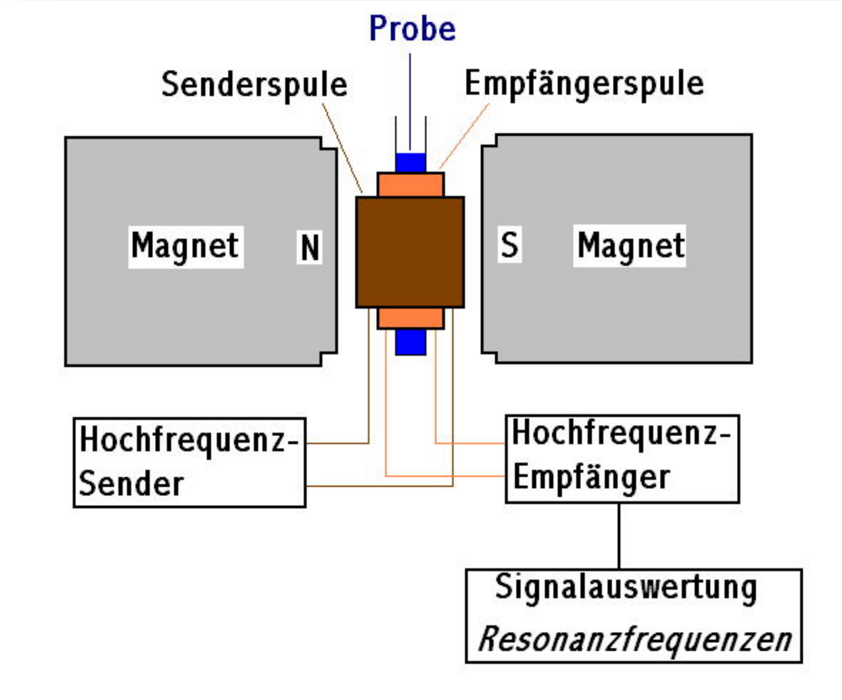
Weiss E-M by Max Kohl or SIP
(small, pole ø 80 mm)

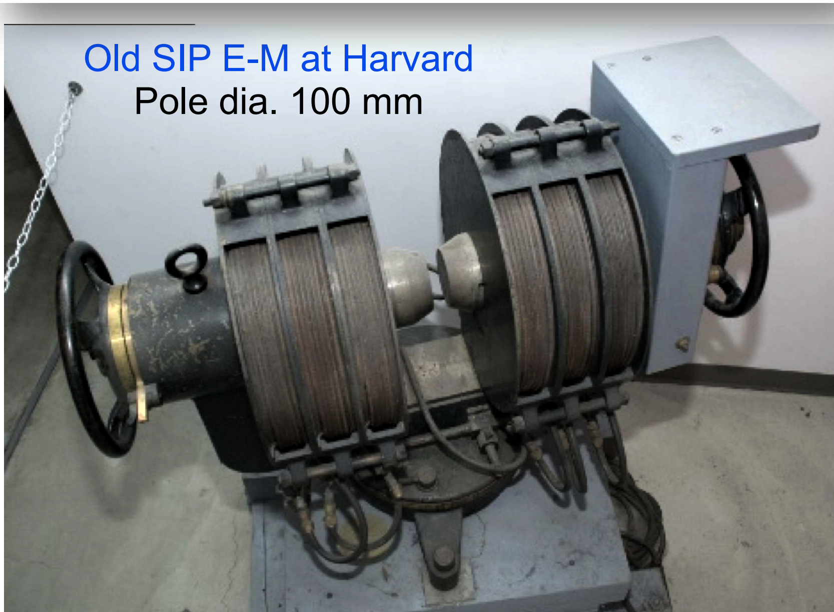
Maßstäblicher Vergleich (1 : 50) der Größe der stärksten Elektromagneten mit Eisenjoch.

At the bottom, the Weiss magnets built by Max Kohl or SIP shown for comparison are standard laboratory ones, provided with a simple cooling system, where in most cases only the sides and bottom of the coils are cooled.

Adapted from Justi, E.: Phys. Zeitschrift 45 (1944) 244-258; Fig. 1

Back to physics at room temperature: **Nuclear Magnetic Resonance**

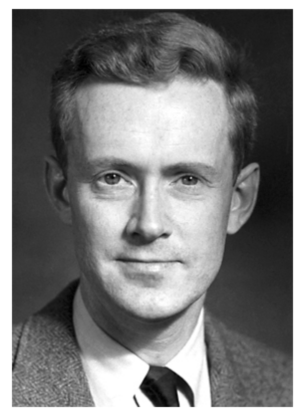




Bloembergen & al. (1948) complain about the *inhomogeneity of the field of their iron-core E-M*

Nuclear spins
immersed in *B* + radiofrequency *f*

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



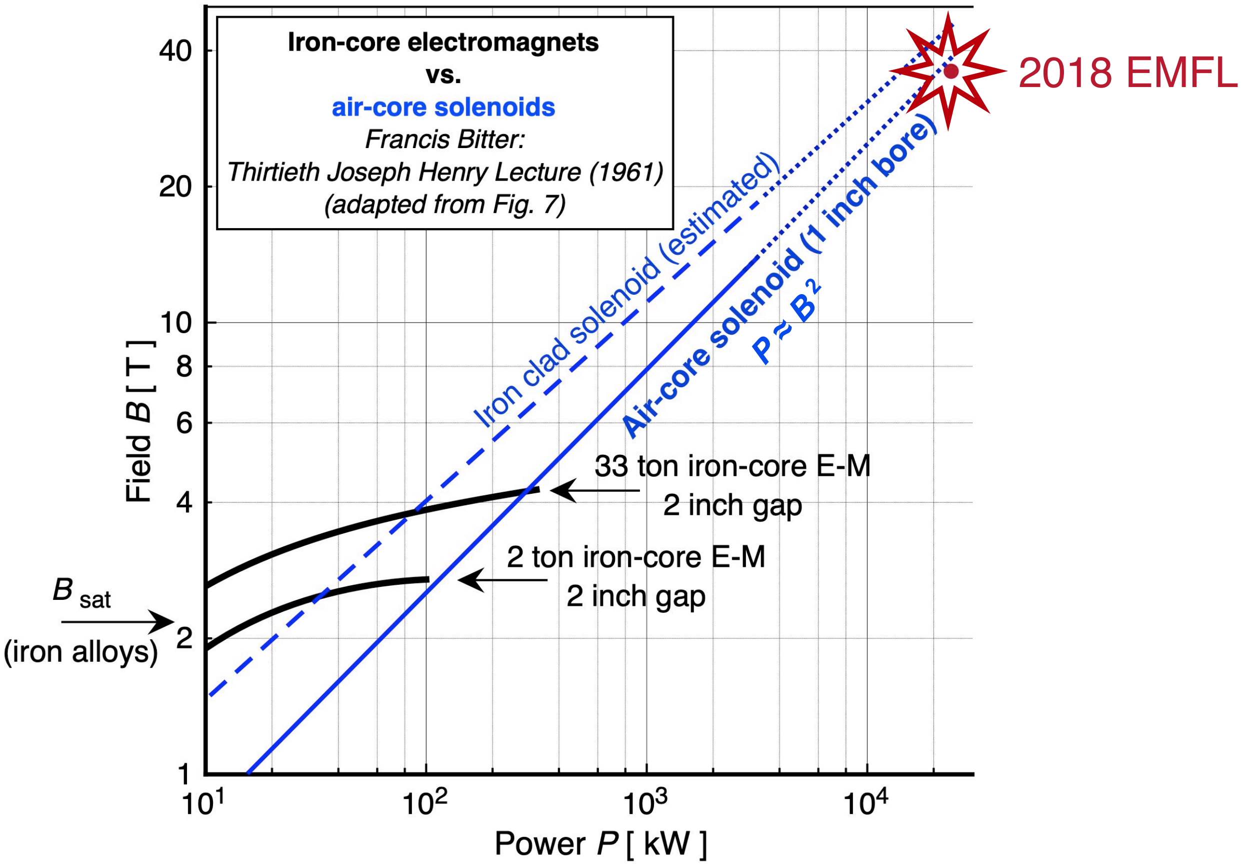
Purcell (1912-1997)

Bloch (1905-1983)

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

How to get higher fields ?

(E–M with resistive windings)



Laboratory E-M

(private use)

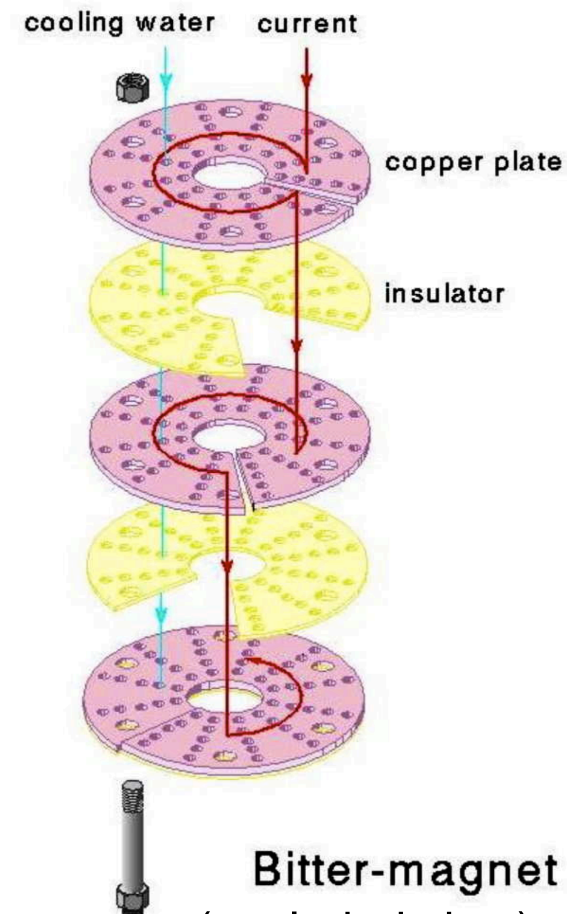
Magnet Laboratory

High Field Laboratory

(competitive use according to proposals submitted)

First air-core solenoid

built by Francis Bitter (1933)



Bitter-magnet

(exploded view)

EMFL: 36 T in 34 mm bore, 24 MW

How to get higher fields ?
(E–M with superconductive windings)

Superconductive (SC) iron-less solenoids:

Superconductivity in Hg discovered by H. Kamerlingh Onnes in 1911

First low-*T* (≤ 4.2 K) SC-solenoids made ca. 1965 (Nb_3Sn or NbTi windings)

No power for *B* = cte (except for cooling and powering up)

Limit on *B*: critical temperature and current of superconductive alloys

2019 : B_{max} at 4.2 K (liquid He) up to about 30 T

Further progress is expected

Still higher permanent fields:

Hybrid magnet:
Bitter magnet inside superconductive solenoid

World record:
45 T in a 32 mm dia. bore
Electrical power 30 MW

Conclusions

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

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

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

The first scientifically designed iron-core E-Ms were those of du Bois and Weiss.
After WWII, the limitation on attainable field due to iron saturation was
overcome by air-core solenoids, first resistive, then superconductive.

* *

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

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

Hall-effect: sensors

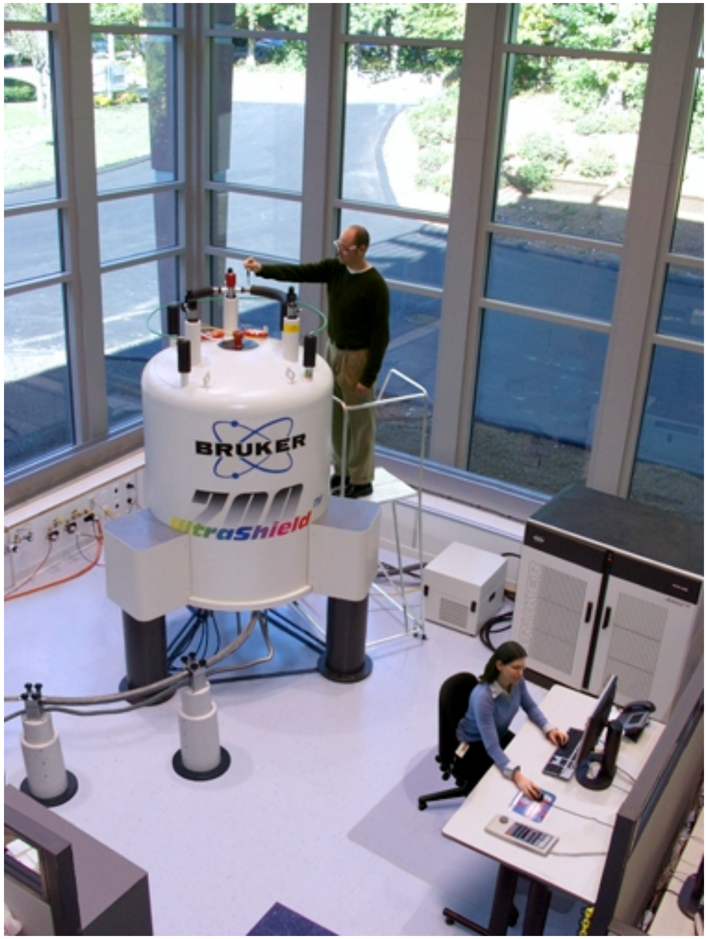
Meissner-effect: nice demonstrations; MAGLEV transportation???

NMR: Magnetic Resonance Imaging, in most medical centers

Nuclear Magnetic Resonance: applications

1. High-precision magnetometers (proton precession)

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



2a. Chemistry: NMR spectroscopy
(up to 22 T / 900 MHz for H nuclei)

2b. Medicine: (Nuclear) Magnetic Resonance Imaging
(typical 1.5 T, homogeneity ≈ **0.2 ppm** in ø 36 cm)

Bibliography

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