КИЇВСЬКИЙ АКАДЕМІЧНИЙ УНІВЕРСИТЕТ

Курс:
Фізичні методи дослідження матеріалів

Тема:
Матеріали в магнітних та електричних полях
(вступна лекція 2)

Лектор: О. А. Кордюк

1. Температура

2. Тиск *+ вимірювання*
+ навантаження

3. Поле

dc

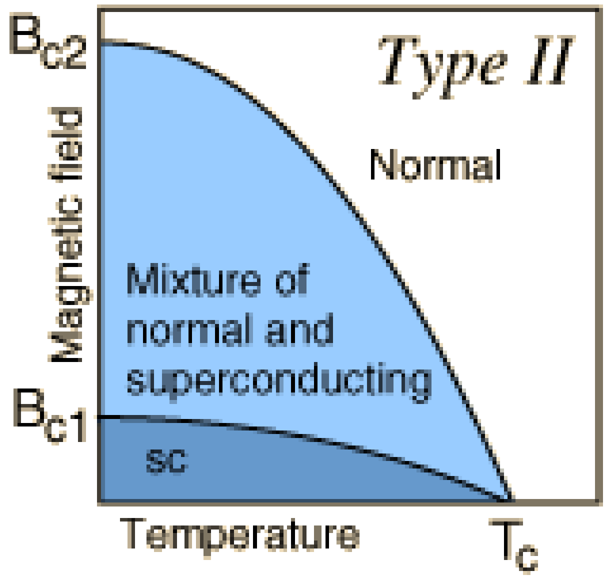
Магнітне

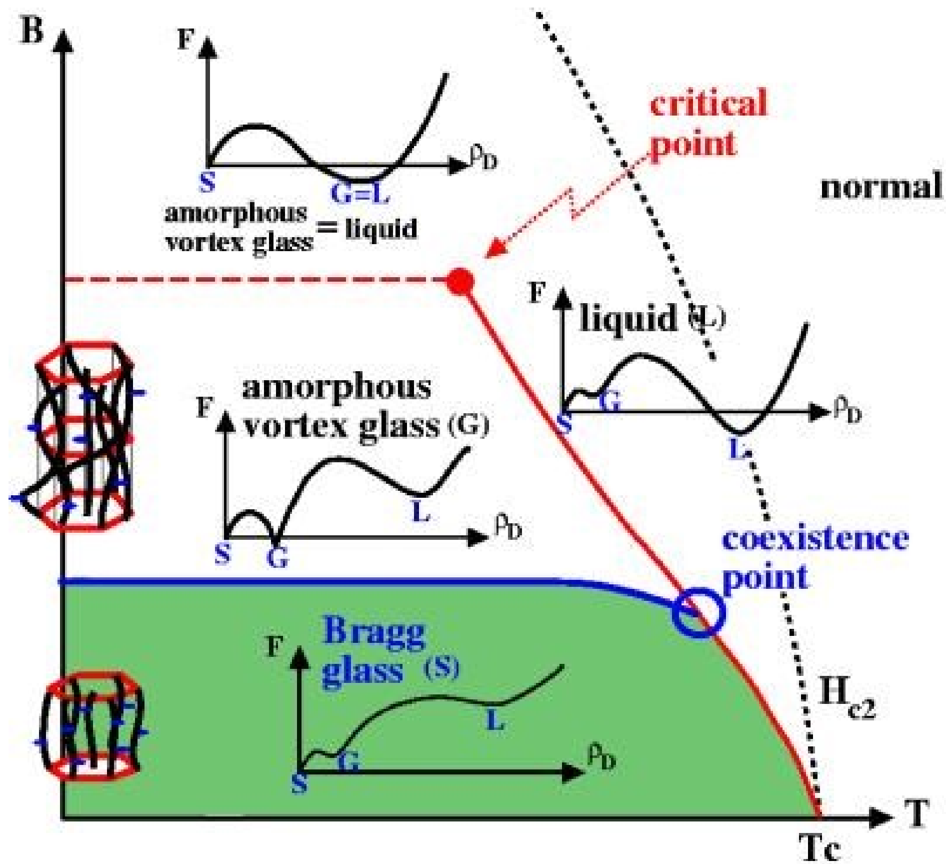
Електричне

ac

Спектроскопії

B-T фазові діаграми: вихорова матерія





Magnetic field

B-field

- Magnetic induction
- Magnetic flux density
- Magnetic field

H-field

- Magnetic field intensity
- Magnetic field strength
- Magnetic field
- Magnetizing field

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$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{B} = \frac{1}{c}\left(4\pi\mathbf{J} + \frac{\partial\mathbf{E}}{\partial t}\right)$$

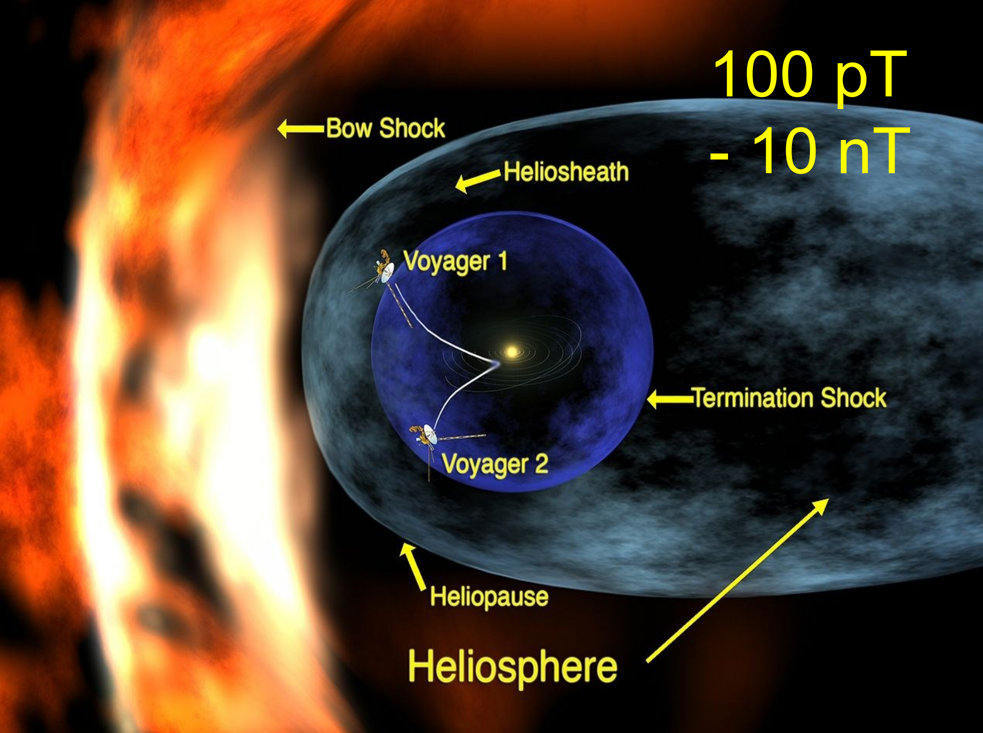
$$(\mathbf{J}_\mathrm{f} + \mathbf{J}_\mathrm{b})$$

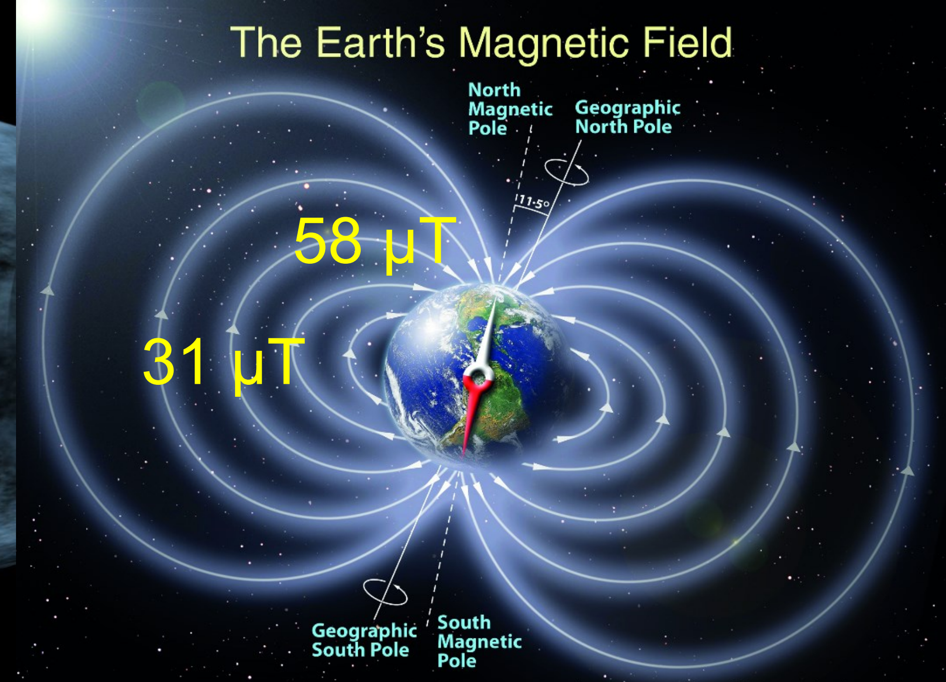
$$\nabla \times \mathbf{H} = \frac{1}{c}\left(4\pi\mathbf{J}_\mathrm{f} + \frac{\partial\mathbf{D}}{\partial t}\right)$$

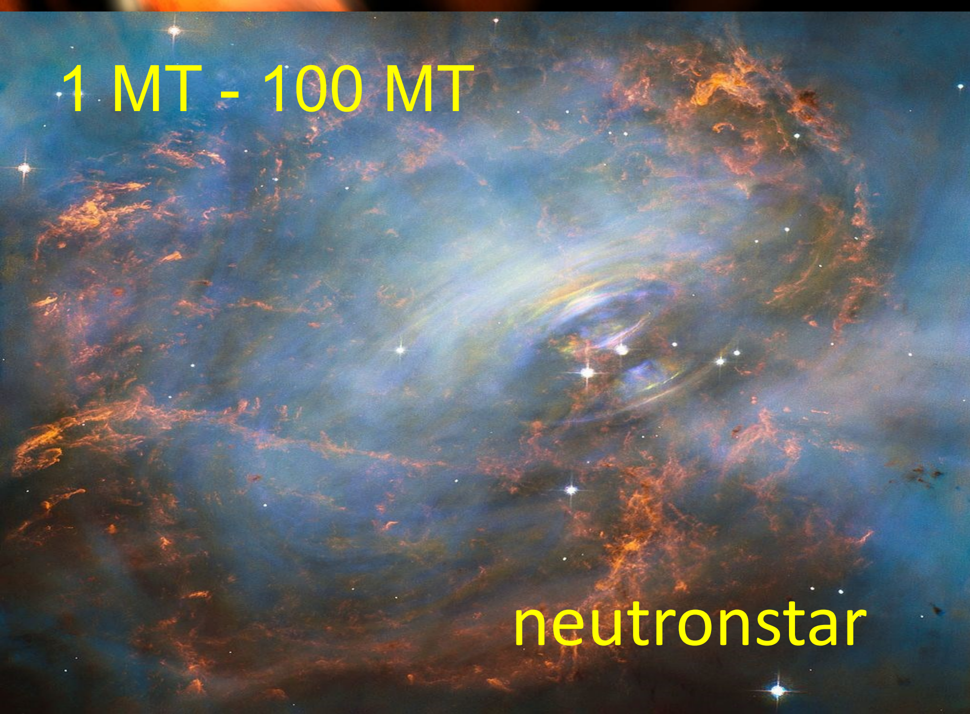
Magnetic field

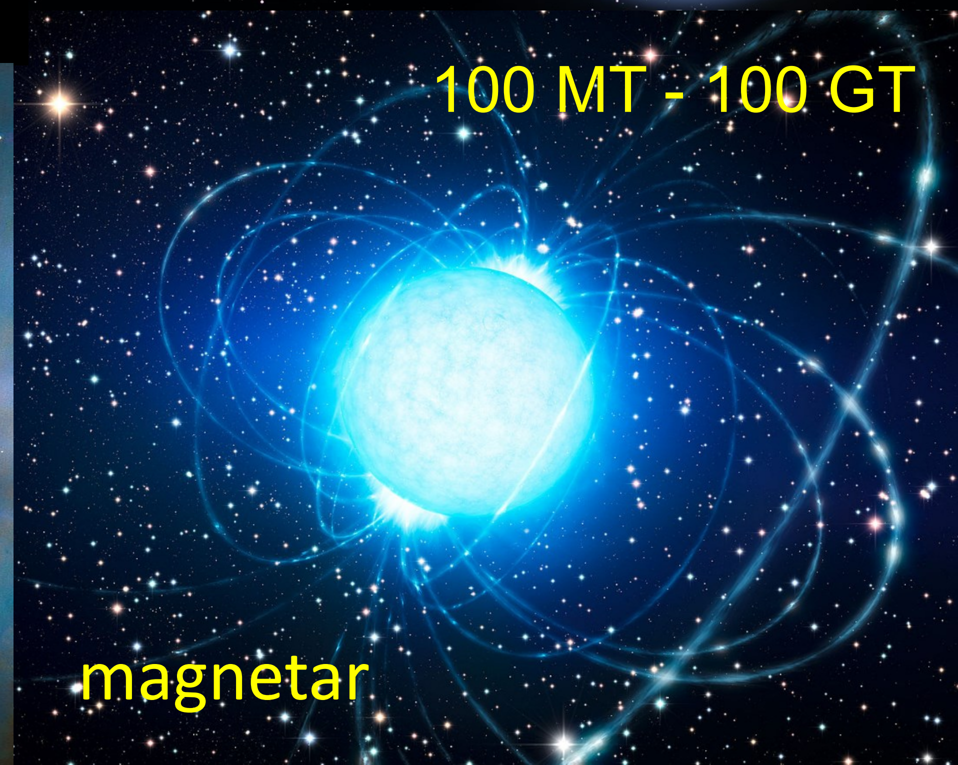
B-field	**H-field**
1 T = 10^4 G	1 kA/m = 4π Oe
1 mT = 10 G	1 kA/m ≈ 12 Oe

Factor (T)	SI prefix	Value (SI units)	Value (CGS units)	Item
10^{-18}	attotesla	5 aT	50 fG	SQUID magnetometers on Gravity Probe B gyroscopes measure fields at this level over several days of averaged measurements
10^{-15}	femtotesla	2 fT	20 pG	SQUID magnetometers on Gravity Probe B gyros measure fields at this level in about one second
10^{-12}	picotesla	100 fT to1 pT	1 nG to 10 nG	Human brain magnetic field
10^{-9}	nanotesla	100 pT to10 nT	1 µG to100 µG	Magnetic field strength in the heliosphere
10^{-6}	microtesla	4 µT to 8 µT	40 mG to80 mG	Magnetic field produced by a microwave oven, in use, at a distance of 30 cm
10^{-5}		31 µT	310 mG	Strength of Earth's magnetic field at 0° latitude (on the equator)
		58 µT	580 mG	Strength of Earth's magnetic field at 50° latitude
10^{-3}	millitesla	5 mT	50 G	The strength of a typical refrigerator magnet
10^{0}	tesla	1.25 T	12.5 kG	Strength of a modern neodymium–iron–boron ($Nd_2Fe_{14}B$) rare earth magnet.
10^{1}	decatesla	16 T	160 kG	Strength used to levitate a frog
		45 T	450 kG	Strongest continuous magnetic field yet produced in a laboratory (National High Magnetic Field Laboratory, USA)
10^{2}	hectotesla	100 T	1 MG	Strongest pulsed non-destructive magnetic field produced in a laboratory, Pulsed Field Facility at National High Magnetic Field Laboratory's, Los Alamos National Laboratory, Los Alamos, NM, USA)
10^{3}	kilotesla	1 kT	100 MG	Strongest (pulsed) magnetic field ever obtained in a laboratory (Z machine, Sandia National Laboratories in Albuquerque, New Mexico)
10^{6}	megatesla	1 MT to100 MT	10 GG to1 TG	Strength of a neutron star
10^{6}	megatesla	2.2 MT	22 GG	Strongest pulsed magnetic field created by destructive measurements in Jablikia , Russia).
10^{8} - 10^{11}	gigatesla	100 MT to100 GT	1 TG to 1 PG	Strength of a magnetar
10^{53}	N/A	2×10^{29} YT	2×10^{33} YG	Planck magnetic field strength


100 pT
- 10 nT
Bow Shock
Heliosheath
Voyager 1
Voyager 2
Termination Shock
Heliopause
Heliosphere


The Earth's Magnetic Field
North Magnetic Pole
Geographic North Pole
11.5°
58 µT
31 µT
Geographic South Pole
South Magnetic Pole


1 MT - 100 MT
neutronstar


100 MT - 100 GT
magnetar

A Room with the Lowest Magnetic Field in the Solar System

TU Munich

H / 7 000 000

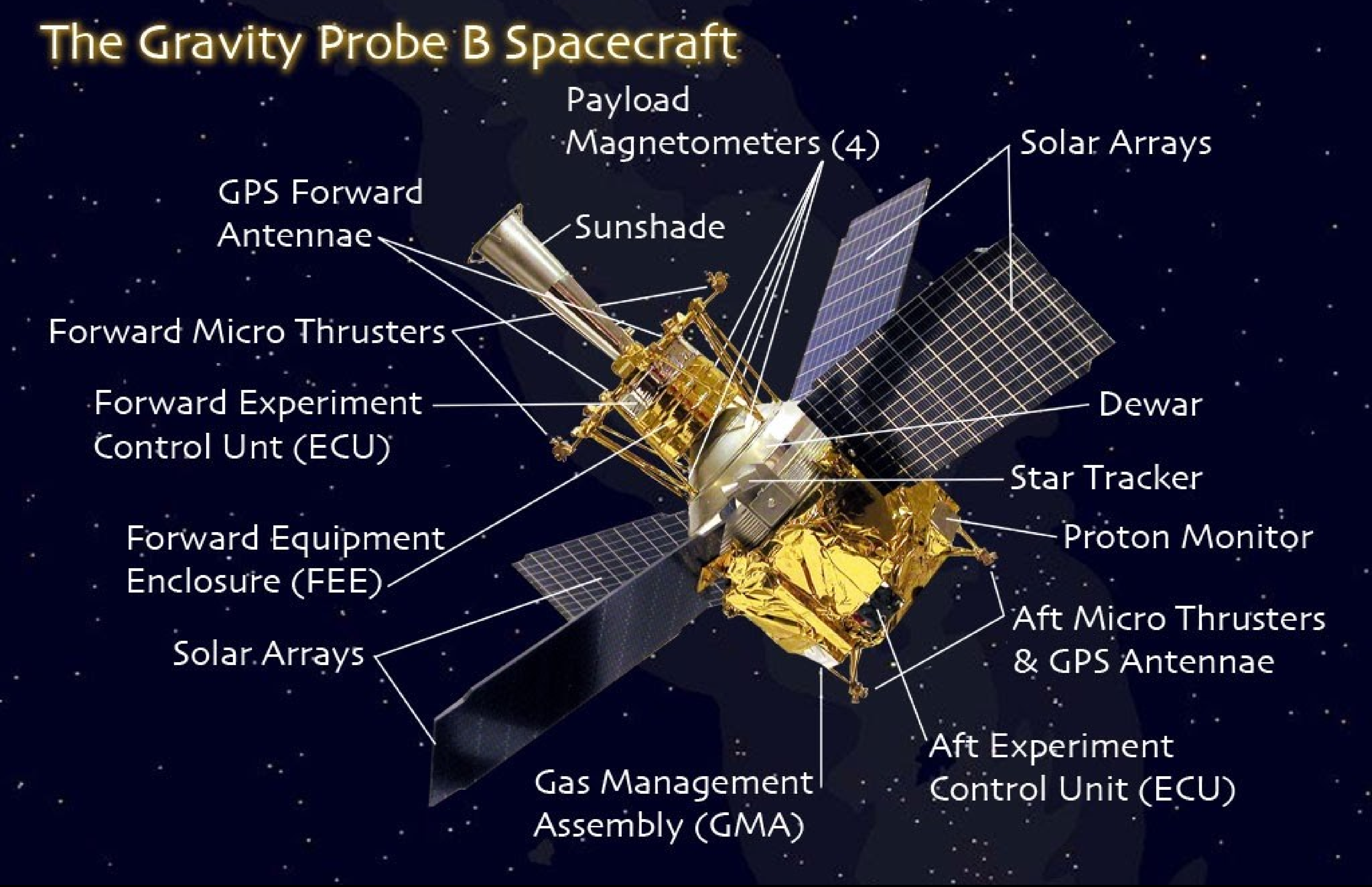
– to measure the electric dipole moment of the neutron

– to explain physics beyond our Standard Model

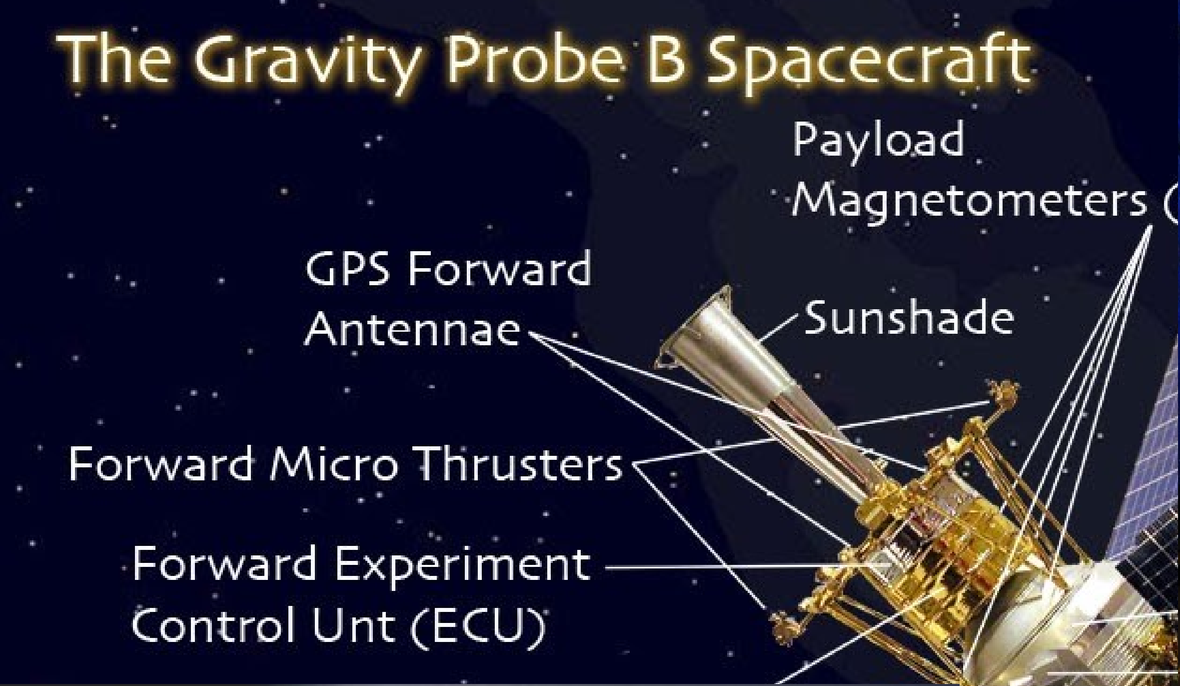
– measuring magnetic signals from the brain with SQUIDs

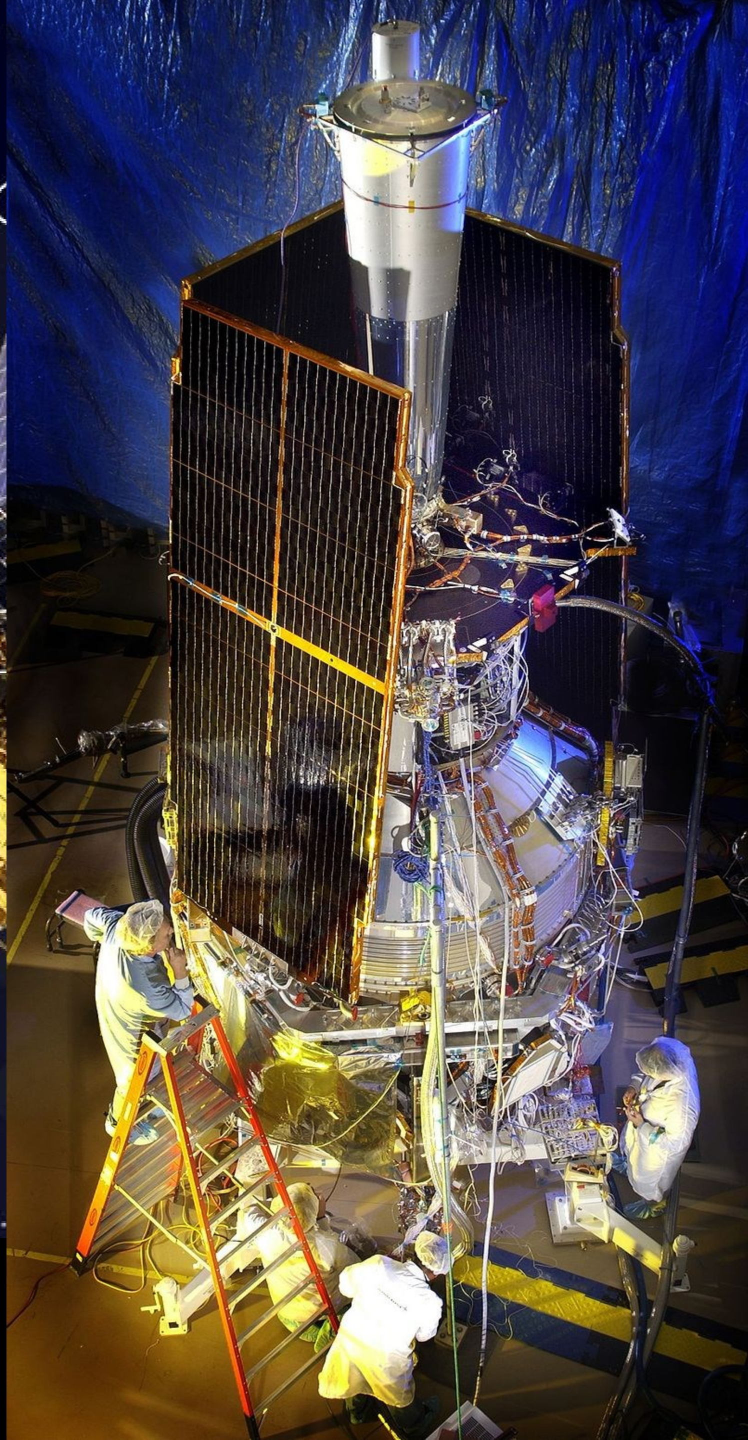
– the design and testing of SQUIDs, superconducting detectors, and low-noise electronics

A large-scale magnetic shield with 10^6 damping at mHz frequencies
J. Appl. Phys. **117**, 183903 (2015)



5 aT = 5×10^{-18} T

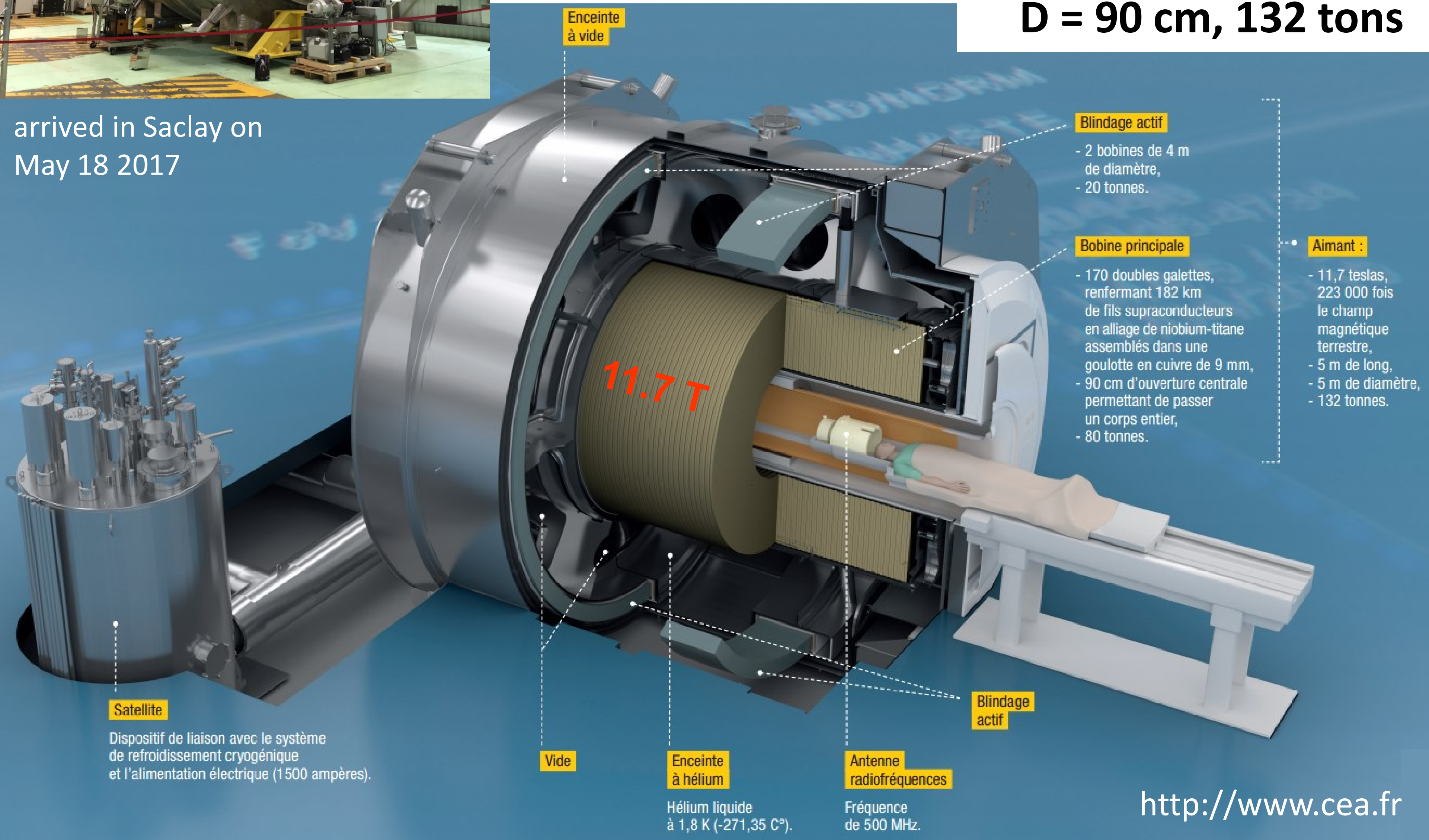

The Gravity Probe B Spacecraft
Payload
Magnetometers
GPS Forward
Antennae
Sunshade
Forward Micro Thrusters
Forward Experiment
Control Unt (ECU)
(GMA)



NeuroSpin research facility at the CEA's Paris-Saclay Center

arrived in Saclay on May 18 2017

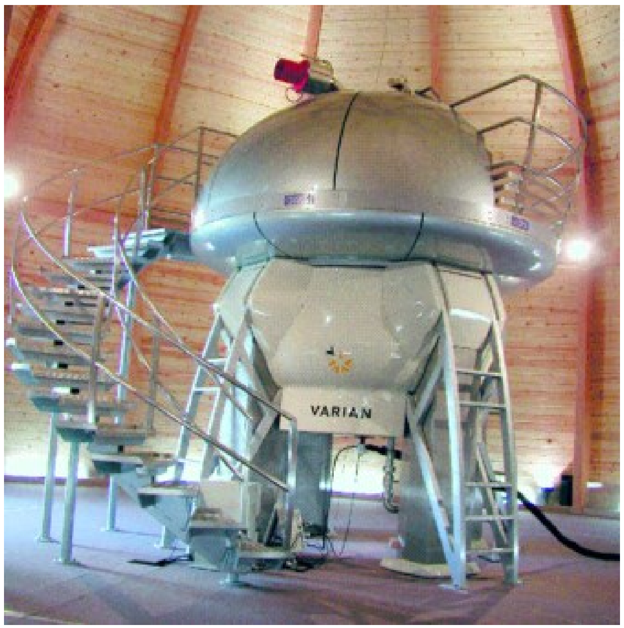
NbTi @ 1.8 K -> 11.7 T
D = 90 cm, 132 tons



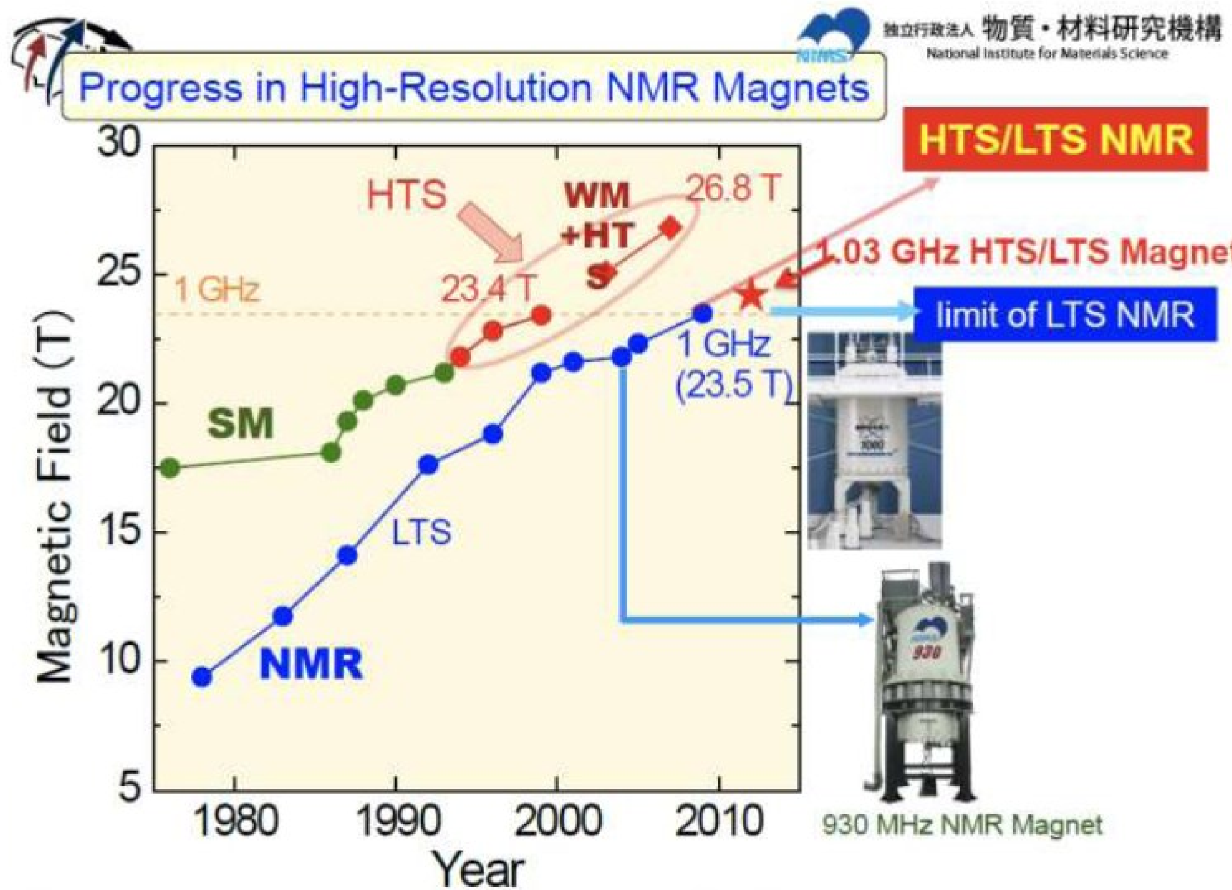
http://www.cea.fr

ЯМР-спектрометри

біологи готові на все щоб отримати високі поля але потенціал НТНП - вже вичерпано



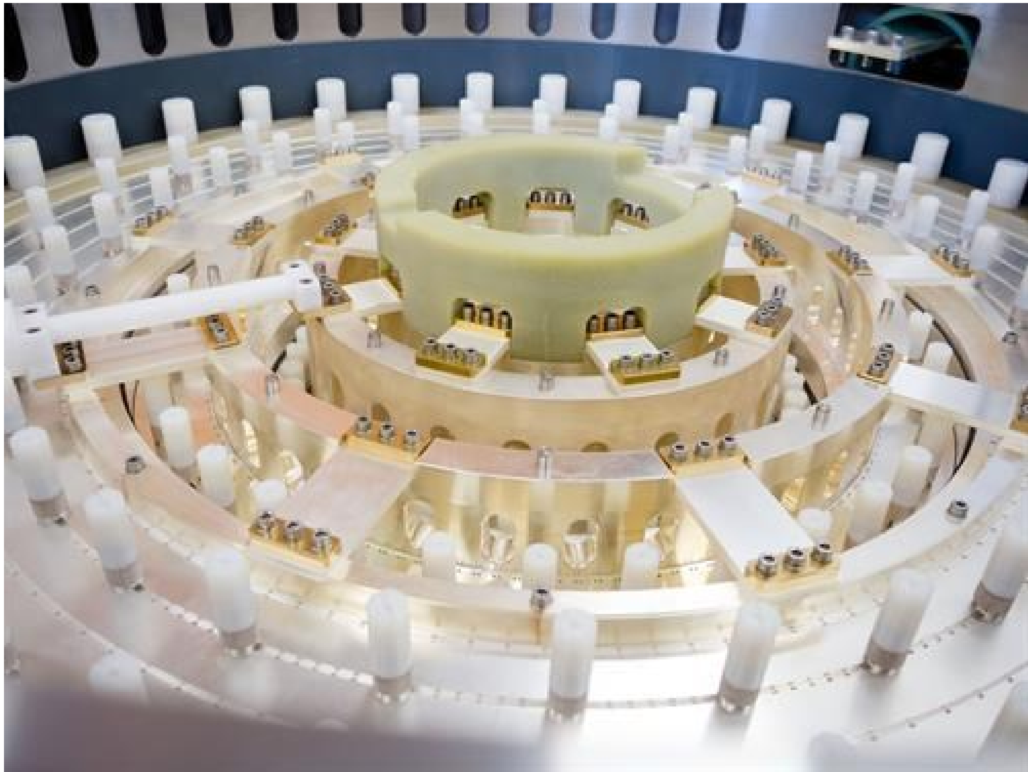
900 МГц надпровідний ЯМР для вивчення біологічних макромолекул в Yokohama City University



dc magnetic field

High Field Magnet Laboratory

@ University of Nijmegen



2014
HFML sets world record with a new **37.5 tesla** magnet

National High Magnetic Field Lab, Los Alamos National Laboratory

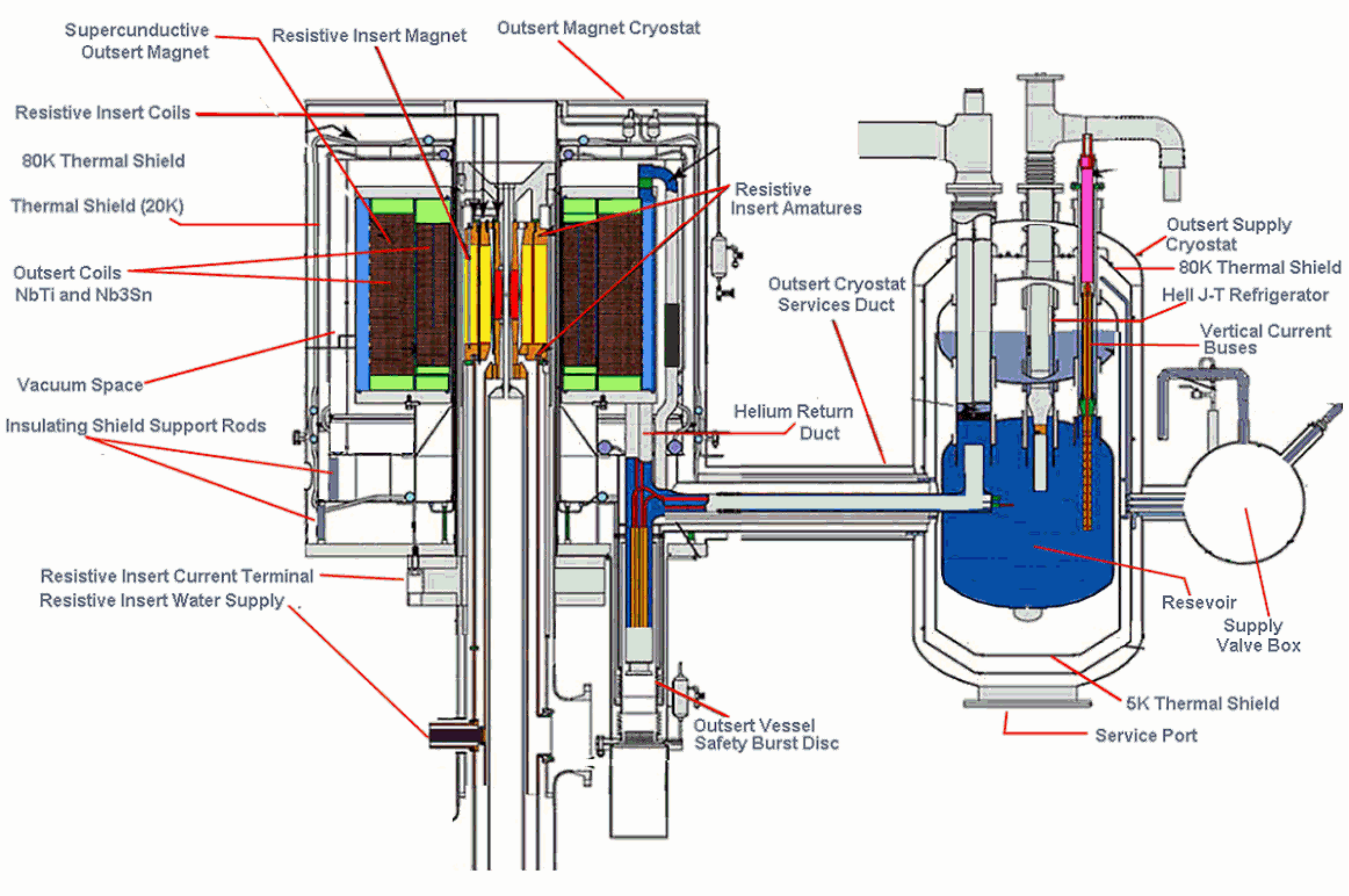
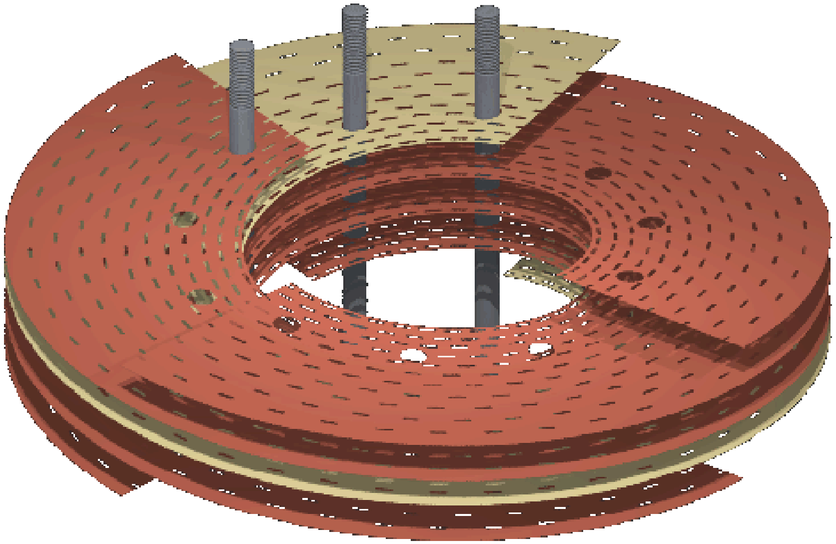


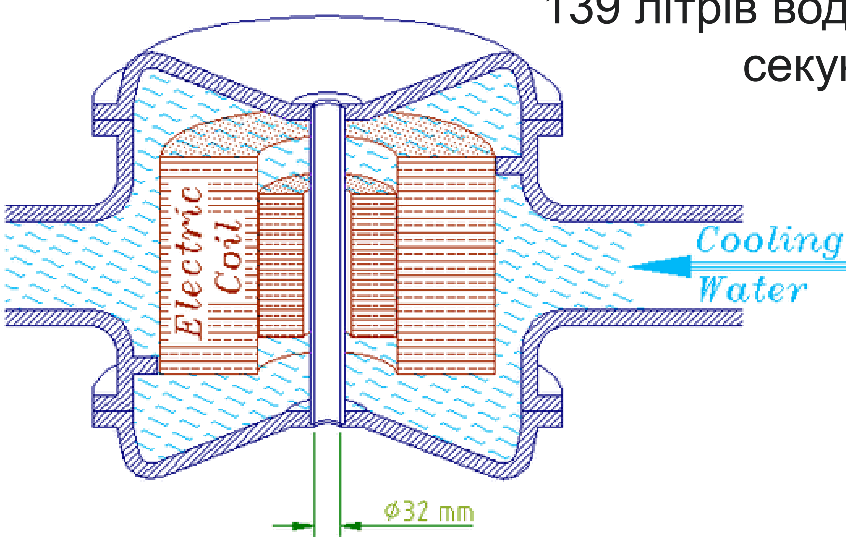
Diagram of the **45 tesla** hybrid magnet

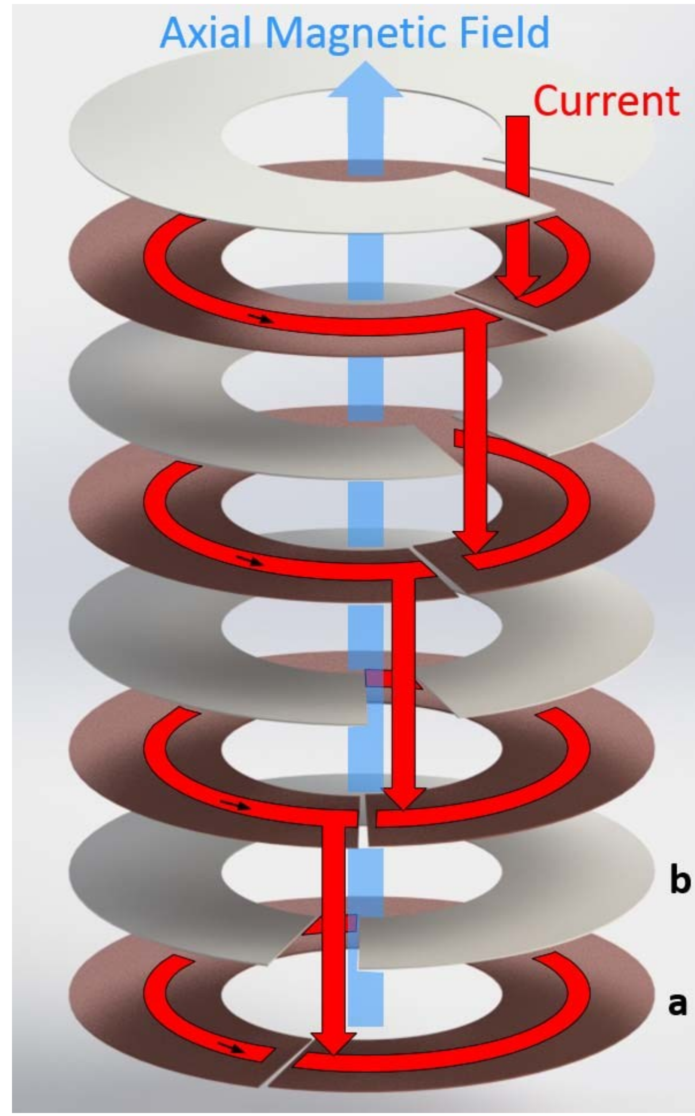
Bitter electromagnets

36.2 Тл (2011) - National High Magnetic Field Laboratory (Tallahassee)

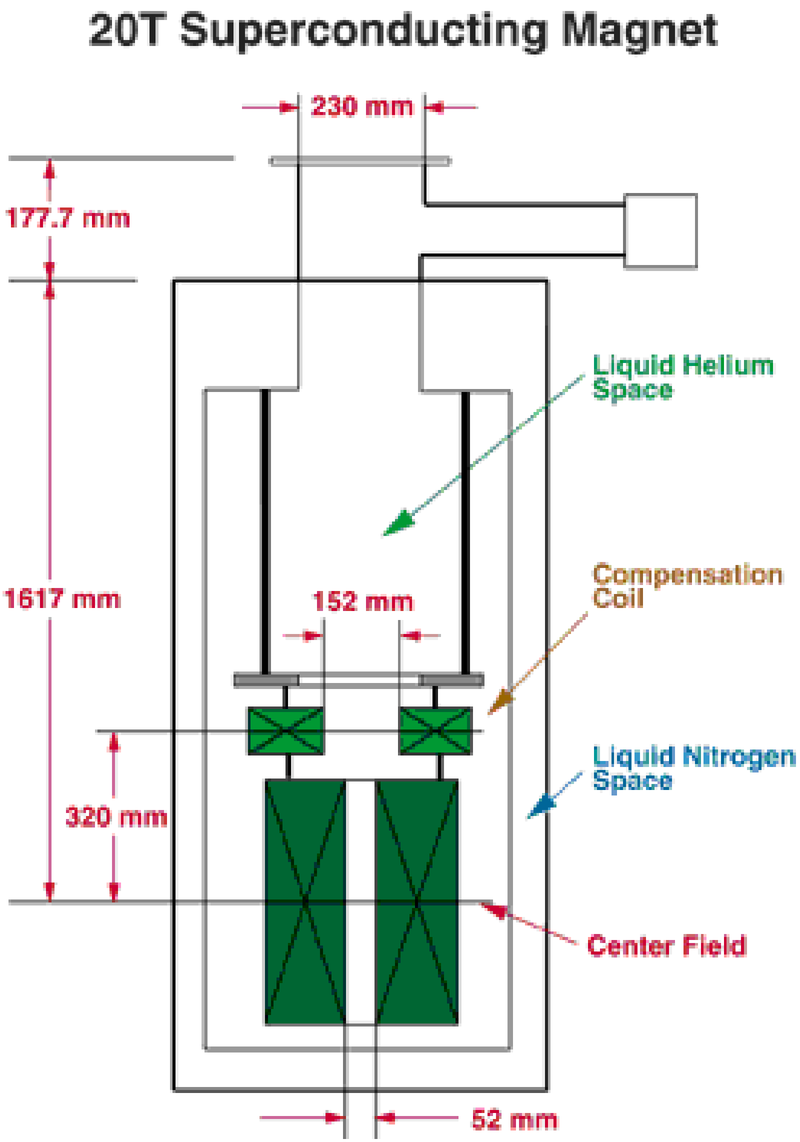


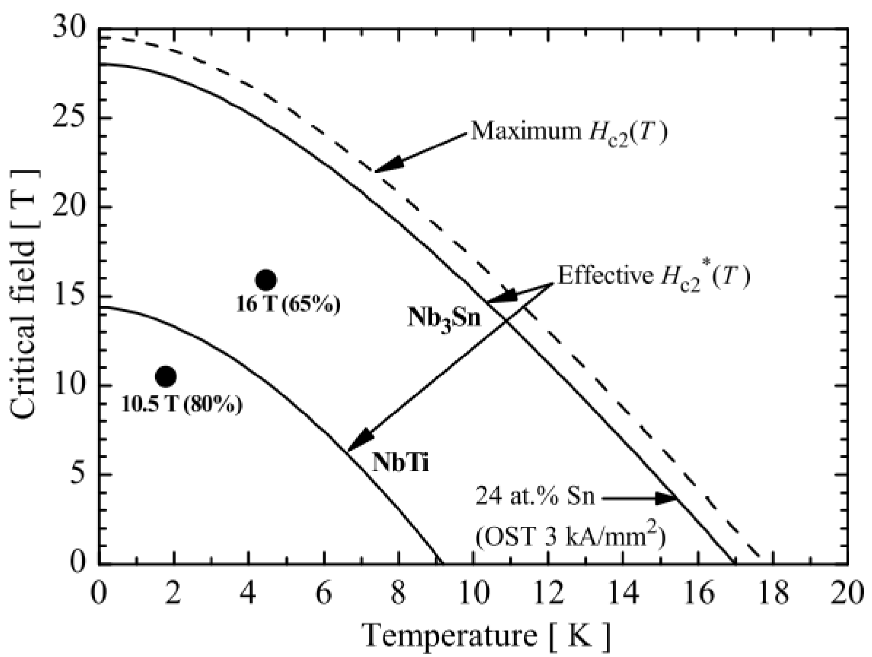
19,6 МВт,
139 літрів води в секунду





Superconducting magnets

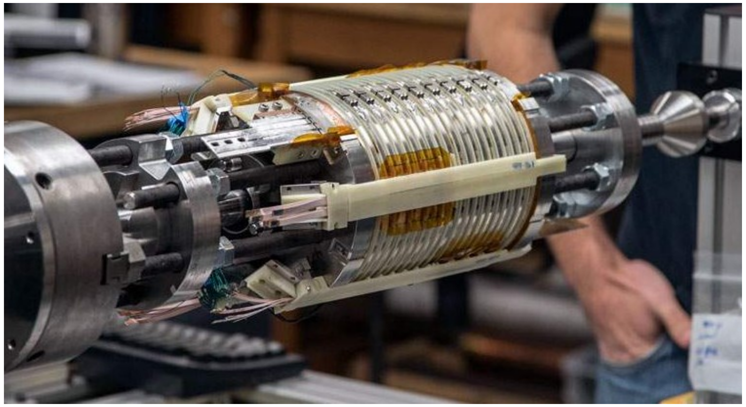




https://www.osti.gov/servlets/purl/937570

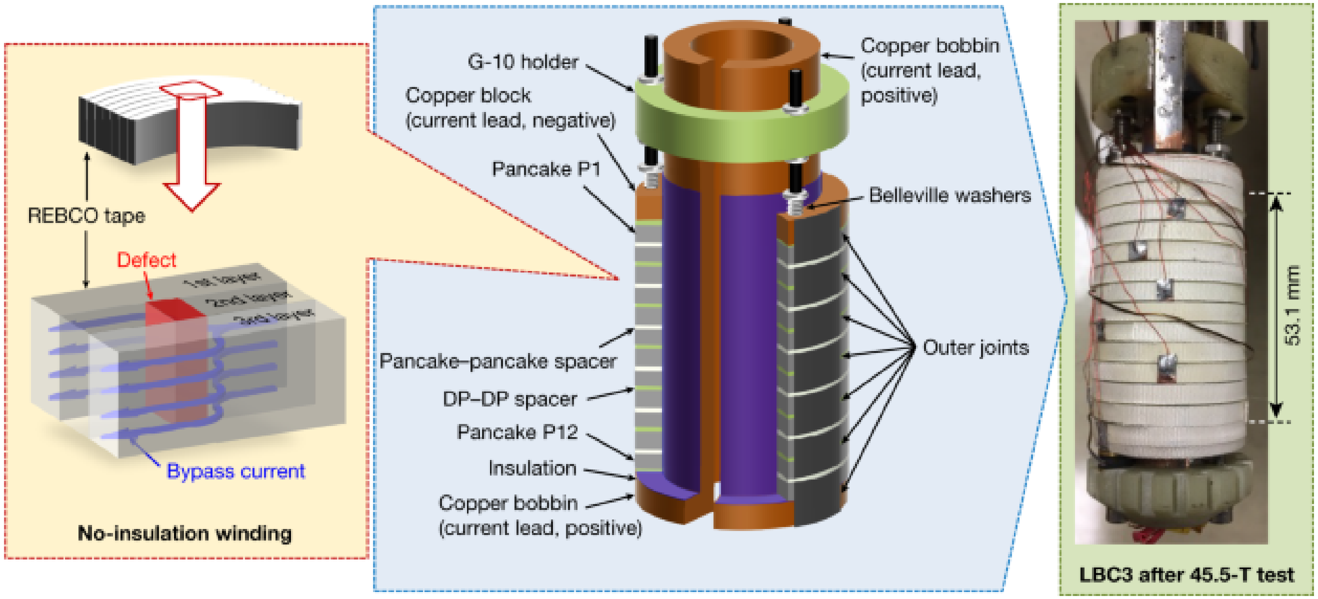
Superconducting magnets

32 Tesla
All-Superconducting
Magnet:
YBCO (2 coils),
NbTi (3 coils)

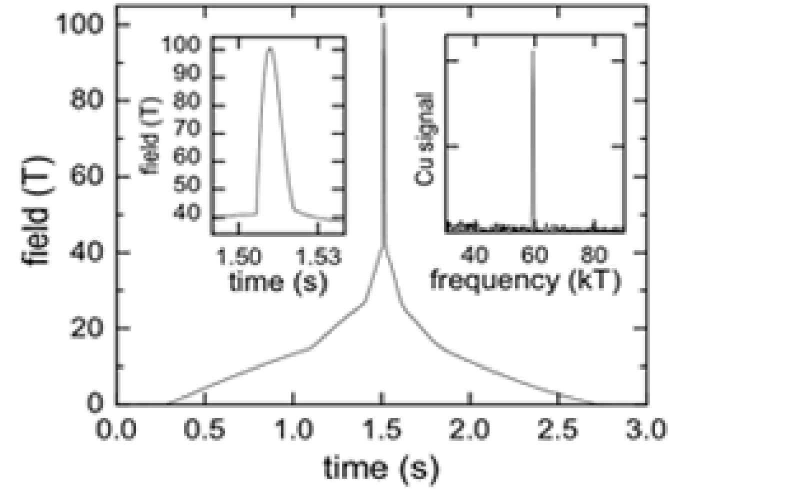


https://nationalmaglab.org/education-magnet-academy/teachers/32-tesla-scm

45.5-tesla direct-current magnetic field generated with a high-temperature superconducting magnet. *Nature* **570**, 496 (2019)

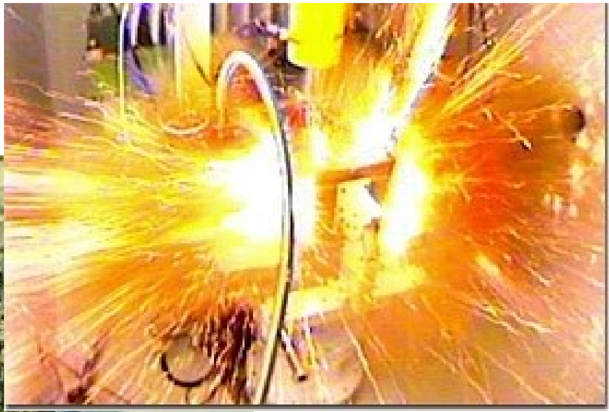


Pulsed Field Facility @ National High Magnetic Field Lab, Los Alamos National Laboratory



HLD.

Dresden High Magnetic Field Laboratory



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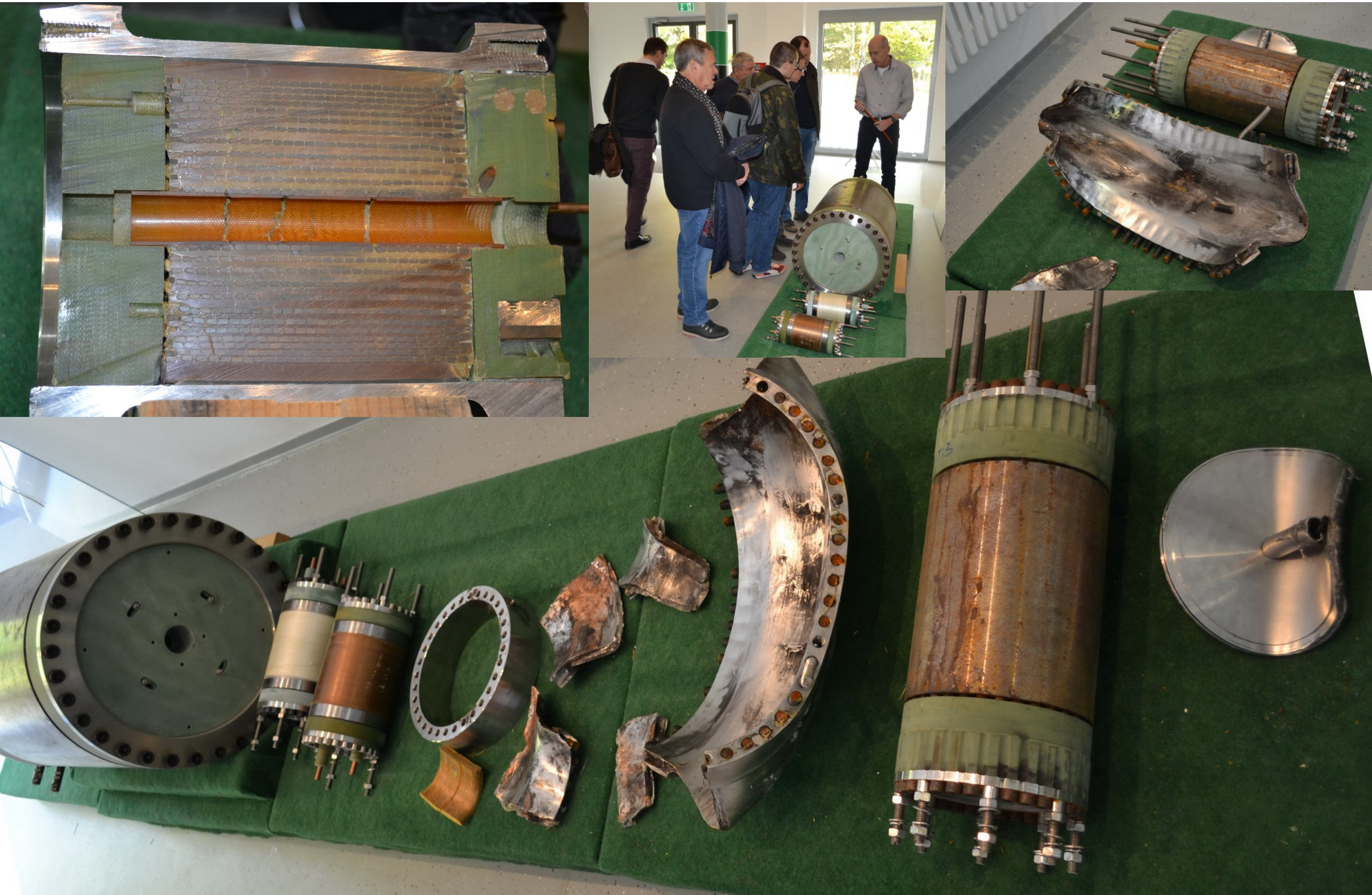
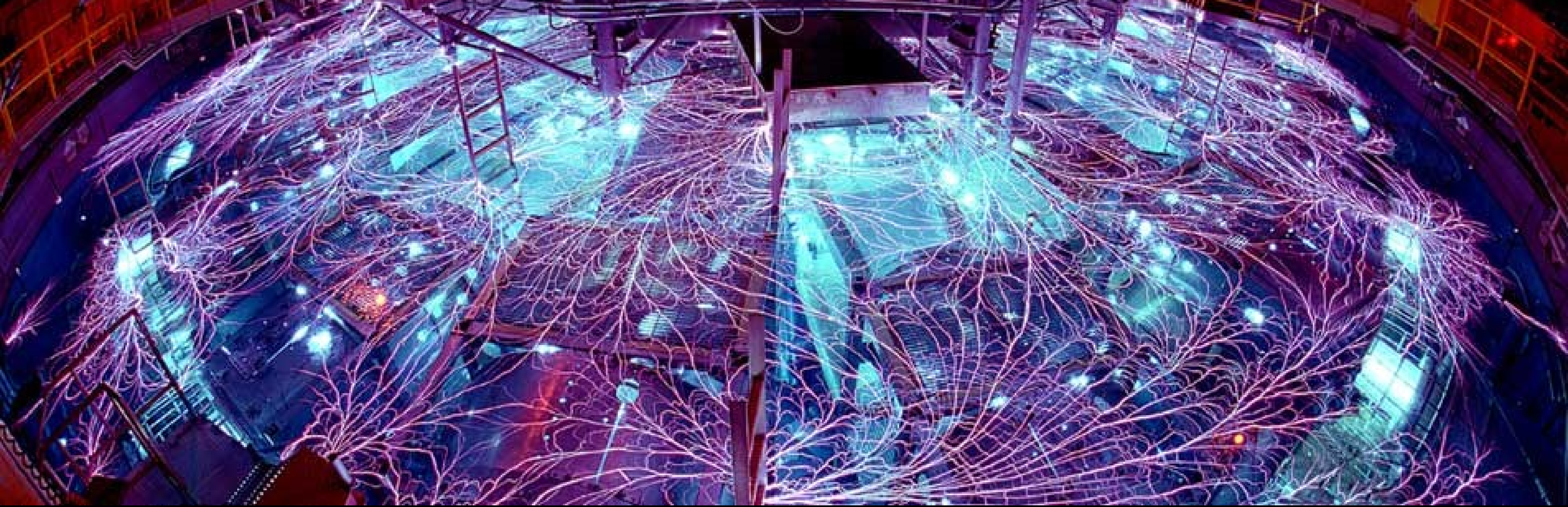
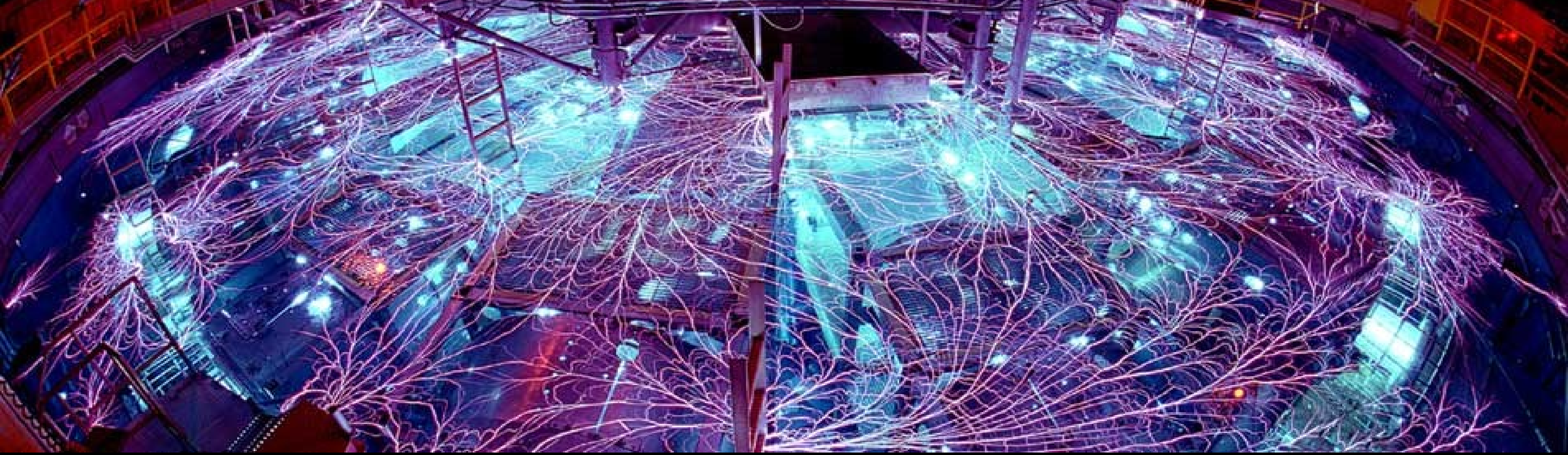
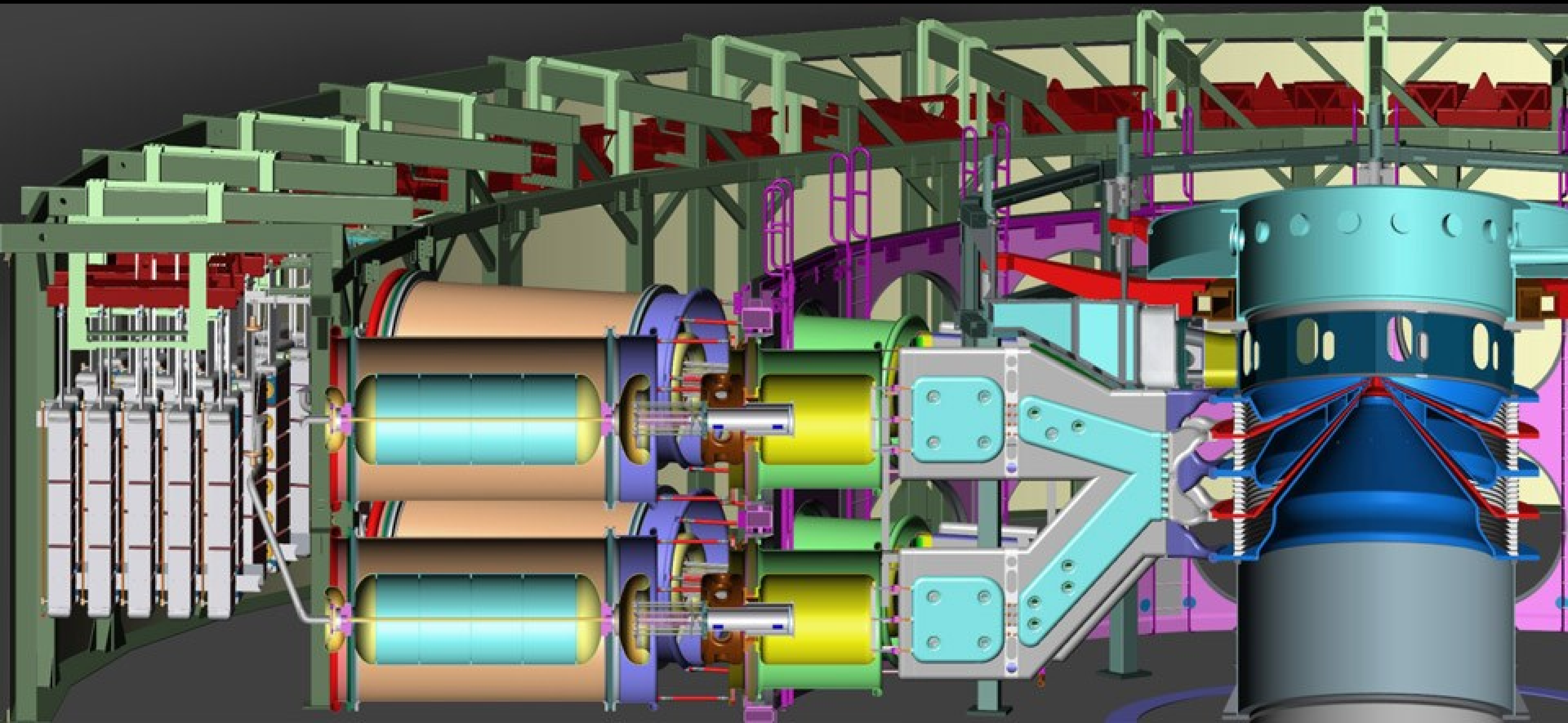




“Z machine” (Z Pulsed Power Facility) 2 GK, 1 kT

https://youtu.be/eaopaLJk3-Y | https://youtu.be/TVaIvAPMd_g





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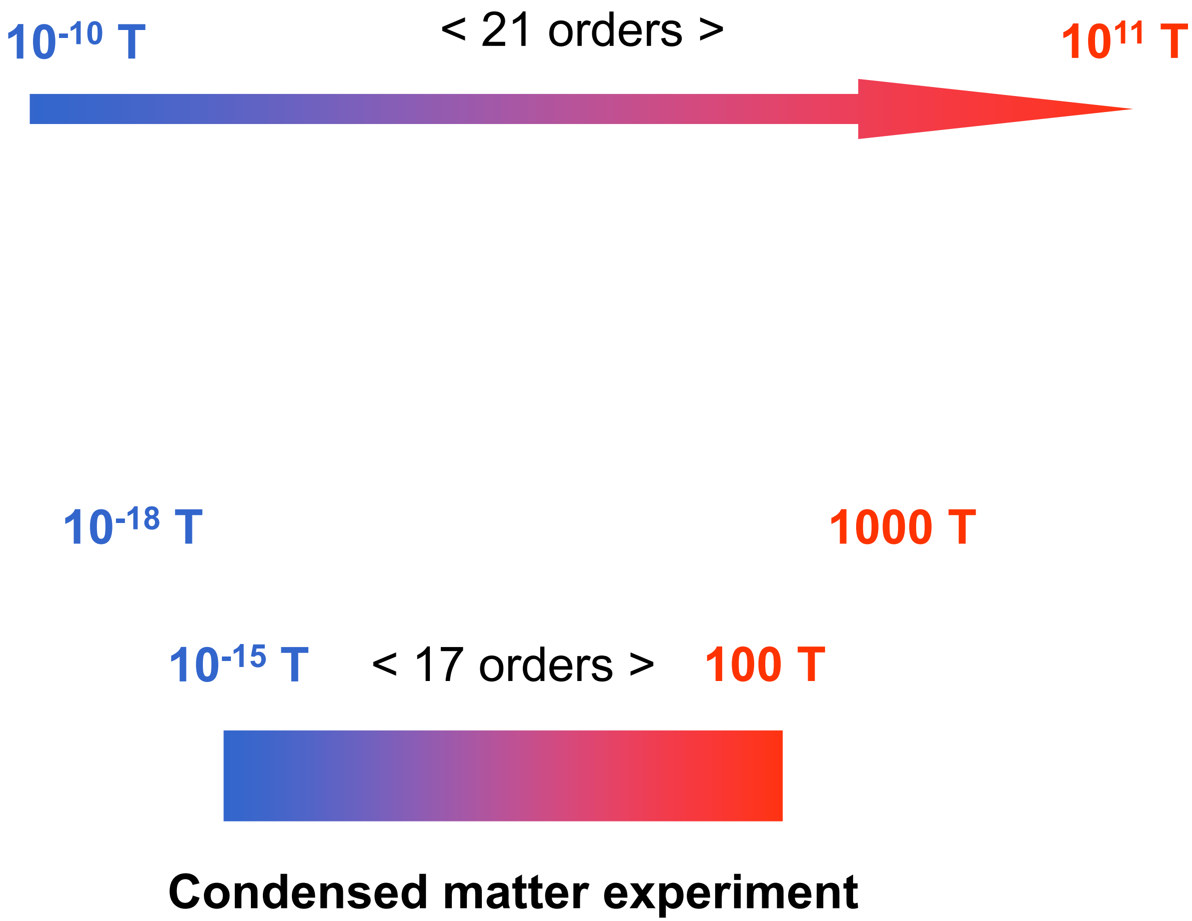
Magnetic field



Методи

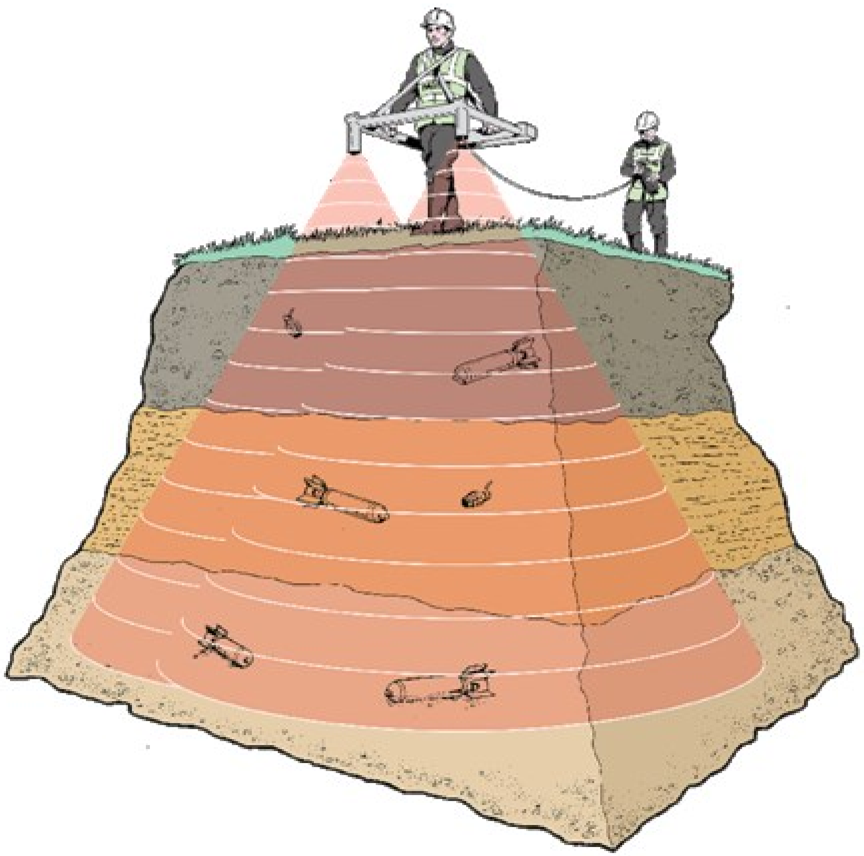
Дмитро Каменський
Radboud University, Nijmegen
23-24 листопада

- магнітні резонанси
- квантові осциляції
- классичний та квантовий ефекти Холла
- фазові перетворення

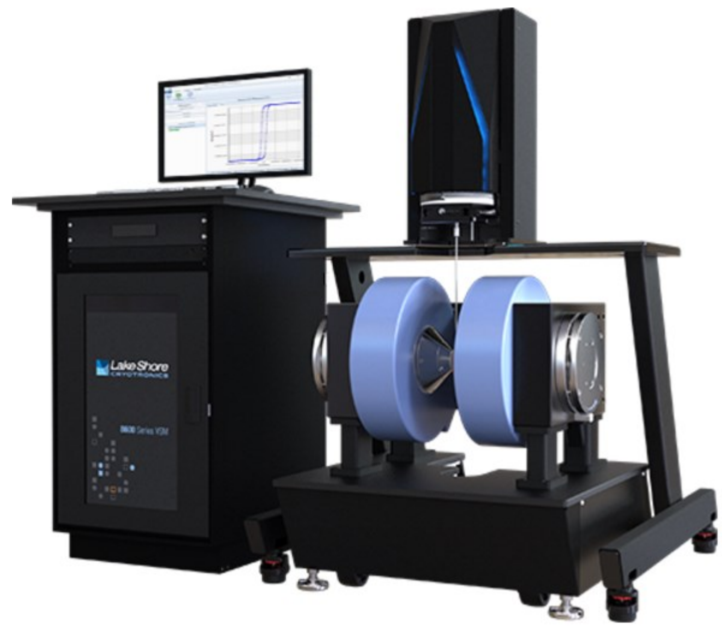
- магнітометрія
- магнетооптика

Magnetometers / Магнітометри

Survey magnetometers
Польові магнетометри



Laboratory magnetometers
Лабораторні магнетометри



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Survey magnetometers
Польові магнетометри

- Proton precession magnetometer
- Caesium vapour magnetometers
- Rotating coil magnetometer
- Fluxgate magnetometer
- Hall sensor
- Magnetoresistive devices
- SQUID magnetometer
- Spin-exchange relaxation-free (SERF) atomic magnetometers

Laboratory magnetometers
Лабораторні магнетометри

- Faraday Force Magnetometry
- VSM (Vibrating Sample Magneto-meter)
- Inductive Pickup Coils
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- SQUID Magnetometer
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- Optical Magnetometry

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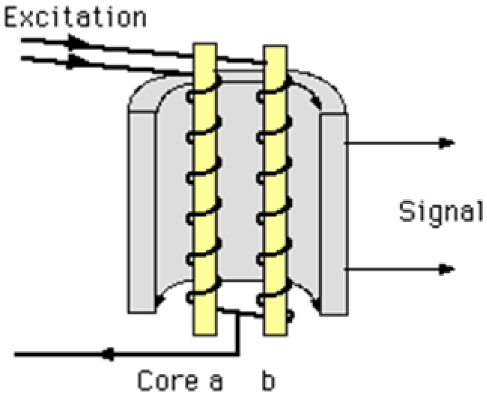
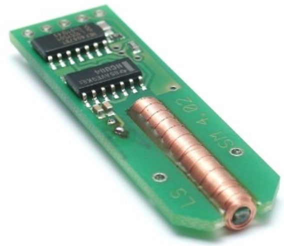
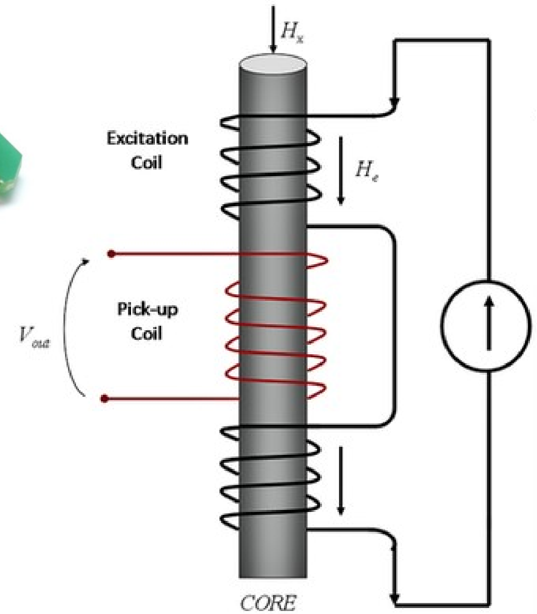
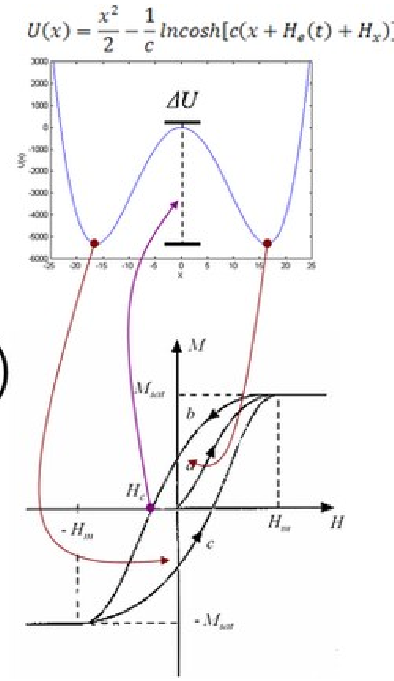
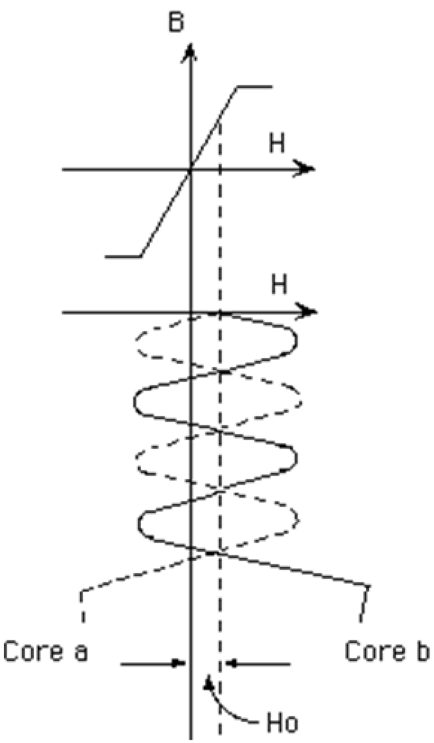
Fluxgate magnetometers

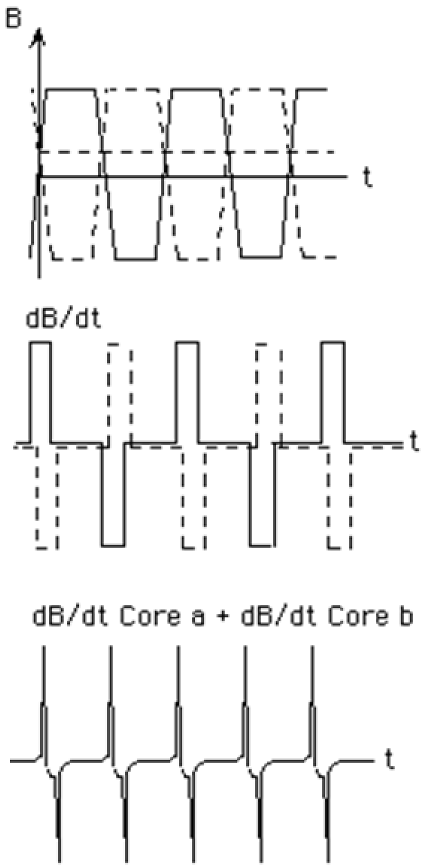


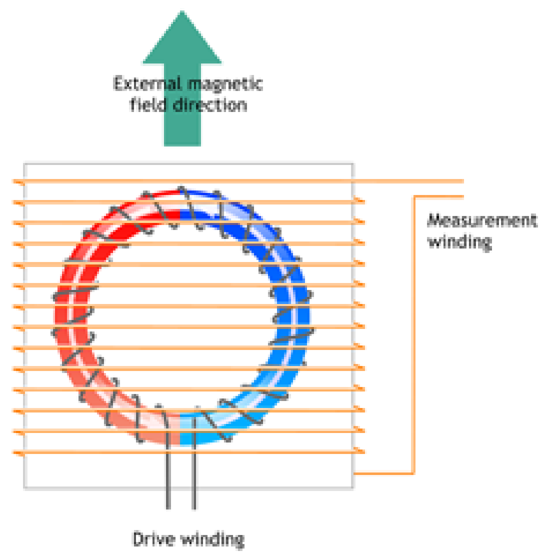












Rediscovering the Lost Art of Fluxgate Magnetometer Cores

NASA SCIENCE
SHARE THE SCIENCE

Published: Jul 6, 2021

PROJECT: MAGnetometers for Innovation and Capability (MAGIC)

SNAPSHOT

A NASA-sponsored team at the University of Iowa is rediscovering and improving lost techniques to develop high-fidelity instruments needed to make the magnetic field measurements that enable many of the nation's space science and space weather missions.

Fluxgate magnetometers are essential and widely-used space science and space weather instruments, but they depend on a legacy component—**a ferromagnetic core**—that was developed and manufactured for the U.S. Navy using technology that has been subsequently lost to the civilian community. The stockpiles of these legacy cores are so depleted that some providers are now exploring destroying old flight-spare hardware to recover and refurbish the cores for use in new missions.

The instrument's performance is limited by the magnetic noise of a specialized ferromagnetic core.

New 'Tesseract' high stability sensor prototype enabled by new styles of fluxgate cores.

https://science.nasa.gov/technology/technology-highlights/rediscovering-the-lost-art-of-fluxgate-magnetometer-cores

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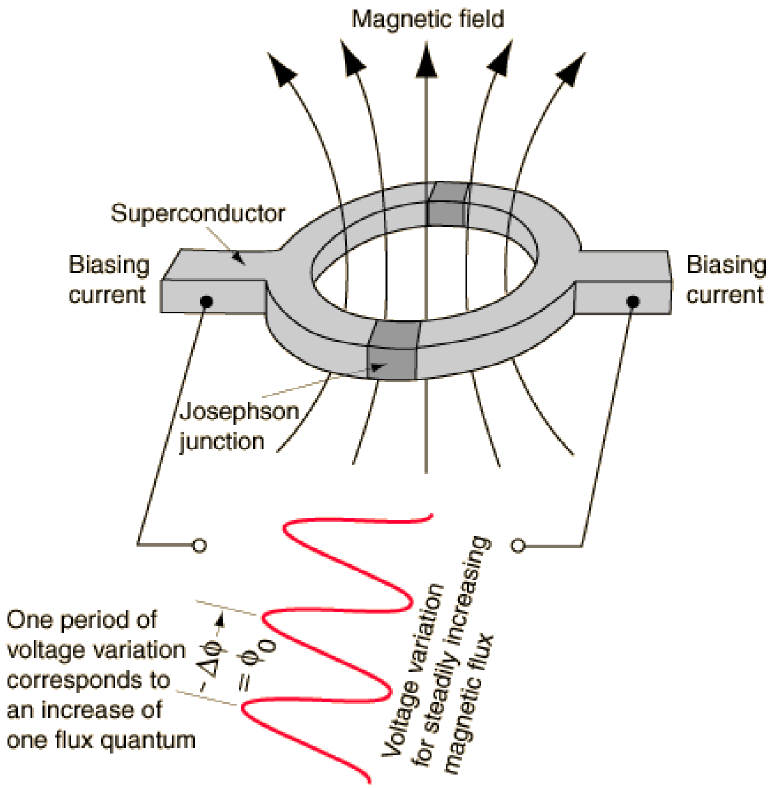
- Optical Magnetometry

SQUID Magnetometer



$$\Phi_0 = \frac{2\pi\hbar}{2e} \cong 2.0678x10^{-15}\, tesla \cdot m^2$$

Threshold for SQUID: 10^{-14} T
Magnetic field of heart: 10^{-10} T
Magnetic field of brain: 10^{-13} T

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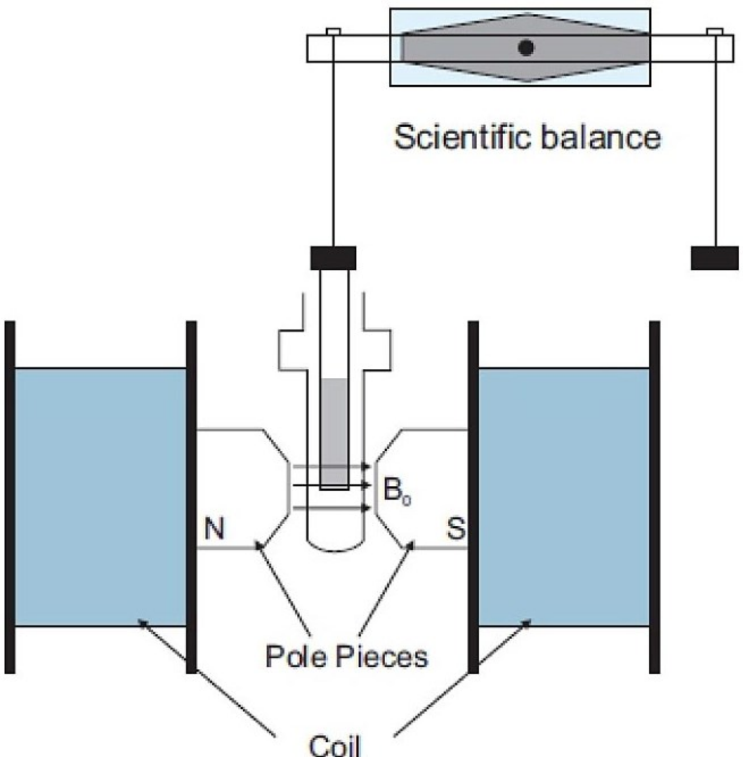
Ваги Фарадея / Gouy balance
Magnetic Susceptibility Balance



doi.org/10.1063/1.4977719

JOURNAL OF APPLIED PHYSICS **121**, 094701 (2017)

Analytical balance-based Faraday magnetometer

Alberto Riminucci,[1,a)] Marc Uhlarz,[2] Roberto De Santis,[3] and Thomas Herrmannsdörfer[2]
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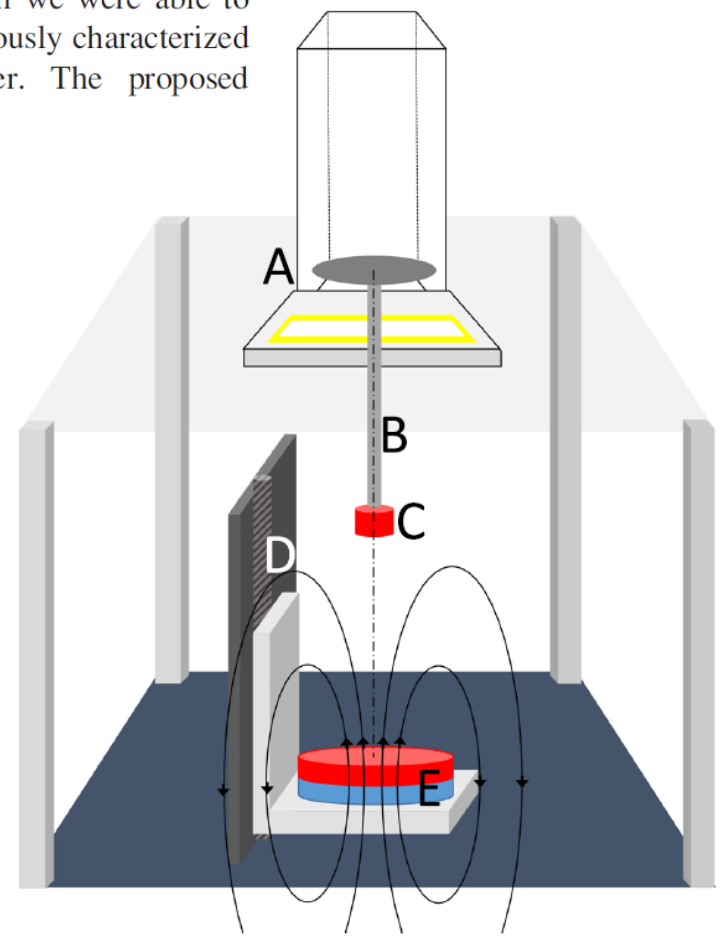
We introduce a Faraday magnetometer based on an analytical balance in which we were able to apply magnetic fields up to 0.14 T. We calibrated it with a 1 mm Ni sphere previously characterized in a superconducting quantum interference device (SQUID) magnetometer. The proposed magnetometer reached a theoretical sensitivity of 3×10^{-8} A m^2.

$$\vec{F} = (\vec{\mu}\,\vec{\nabla})\vec{B}$$

$$\mu = \chi\ \mu_0 H$$

$$F = \mu(B) \times \nabla B \sim H^2$$



Magnetometers / Магнітометри

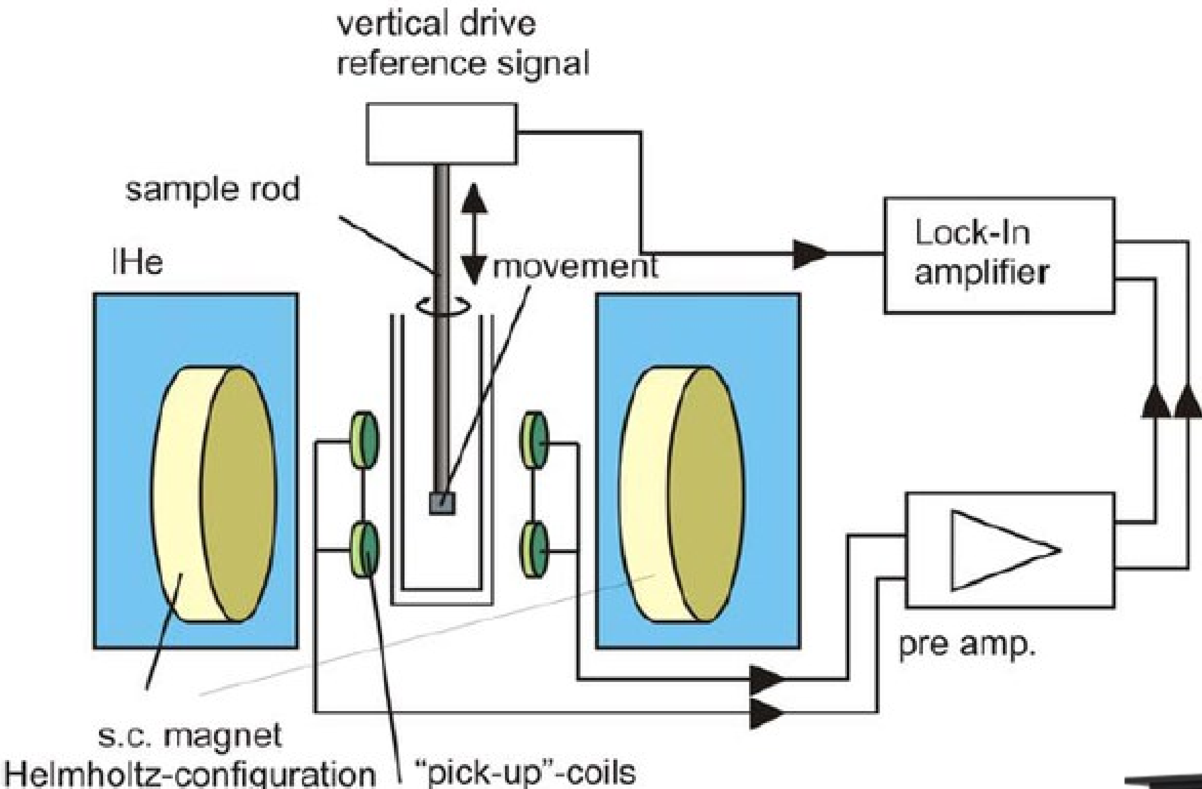
Survey magnetometers
Польові магнетометри

- Proton precession magnetometer
- Caesium vapour magnetometers
- Rotating coil magnetometer
- Fluxgate magnetometer
- Hall sensor
- Magnetoresistive devices
- SQUID magnetometer
- Spin-exchange relaxation-free (SERF) atomic magnetometers

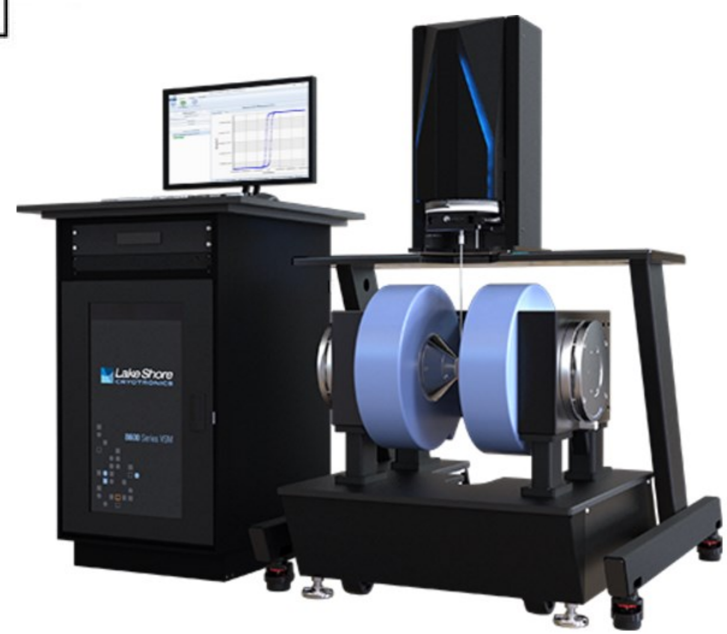
Laboratory magnetometers
Лабораторні магнетометри

- Faraday Force Magnetometry
- **VSM (Vibrating Sample Magneto-meter)**
- Inductive Pickup Coils
- Pulsed Field Magnetometry
- SQUID Magnetometer
- Torque Magnetometry
- Optical Magnetometry

Vibrating Sample Magnetometer (VSM)



$$\mu = \chi \ \mu_0 H$$



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Physical Property Measurement System (PPMS®)
Magnetic Property Measurement System (MPMS®3)

PPMS:
T = 1.9 - 400K, 7, 9, 14 and 16 tesla magnets

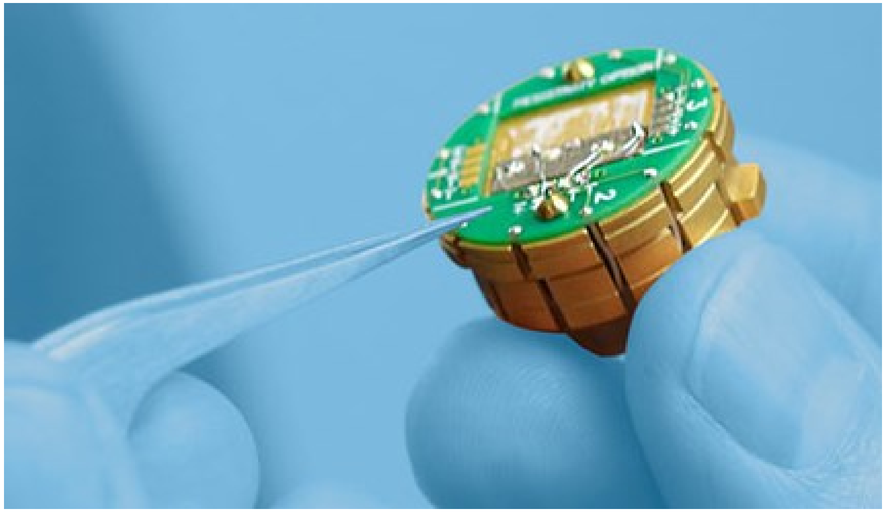
- **Heat Capacity**, **Electrical Transport** and **DC Resistivity** measurements
- Helium-3 Refrigerator Option (down to 0.5 K)
- Dilution Refrigerator Option (from 4 K down to 50 mK)
- Adiabatic Demagnetization Refrigerator (ADR) (from 300 K to ~100 mK in <3 hours)

MPMS: SQUID Magnetometry
T = 1.8 - 400K, B <= 7 T ± 0.05 G

- **Vibrating Sample Magnetometer** (VSM) Oven (up to 1000K)
- **AC Susceptibility** Option (0.005–15 Oe, 0.1 Hz – 1 kHz)
- **Magneto-Optic** Option (UV or IR Rod)
- Horizontal Sample Rotator

Quantum Design

Physical Property Measurement System (PPMS®)
Magnetic Property Measurement System (MPMS®3)



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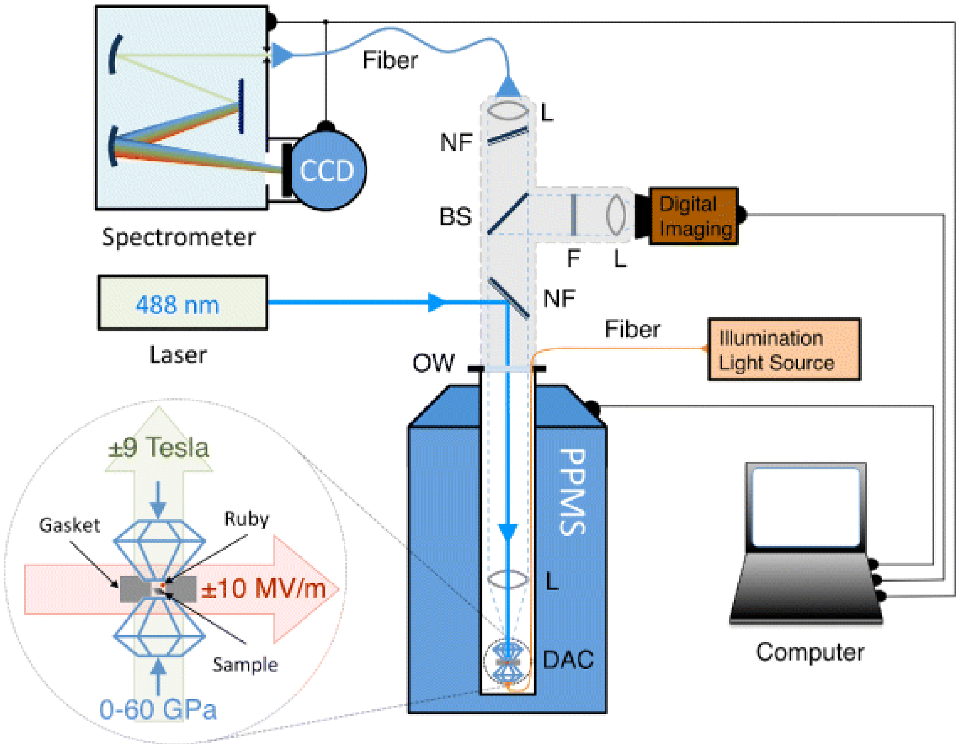
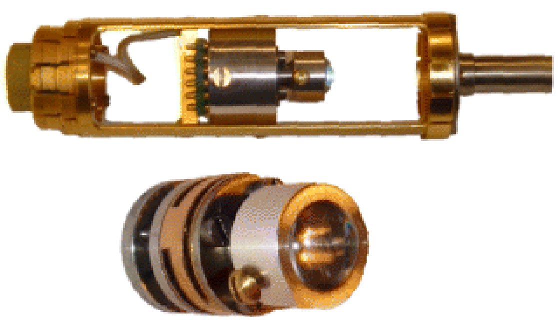
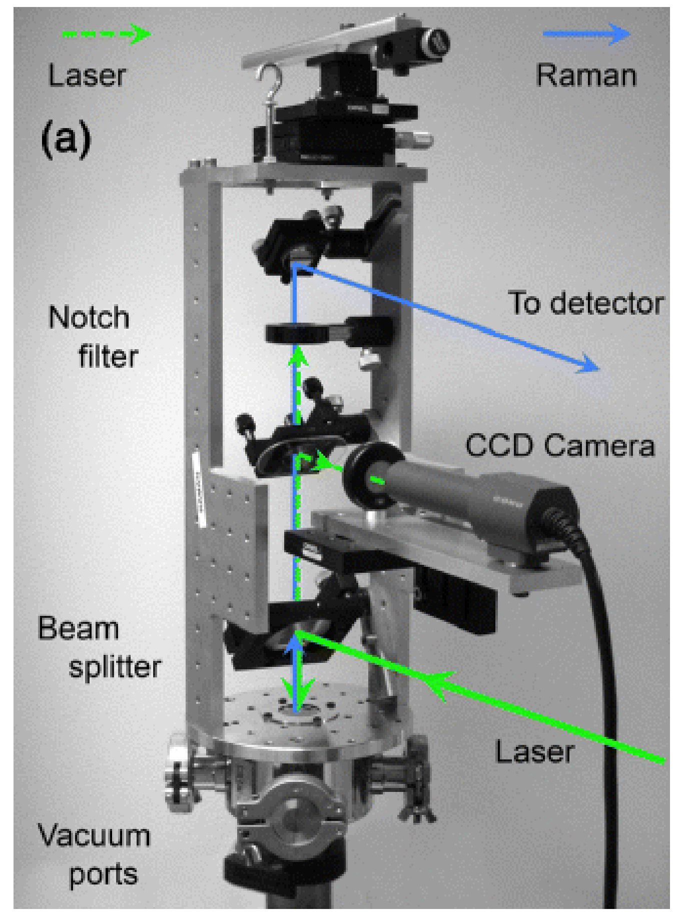


PPMS-based set-up for Raman and luminescence spectroscopy at high magnetic field, high pressure and low temperature





Hudl et al. *EPJ Tech. Instr.* 2015

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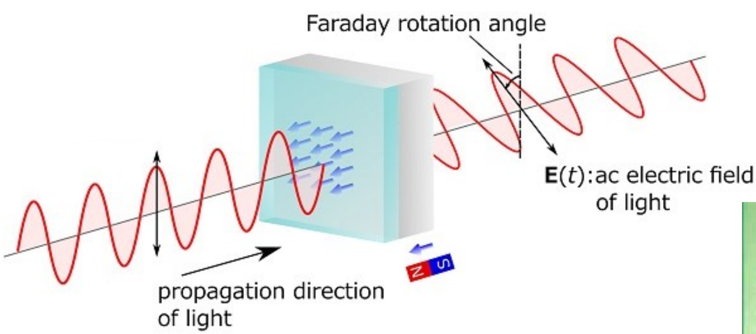
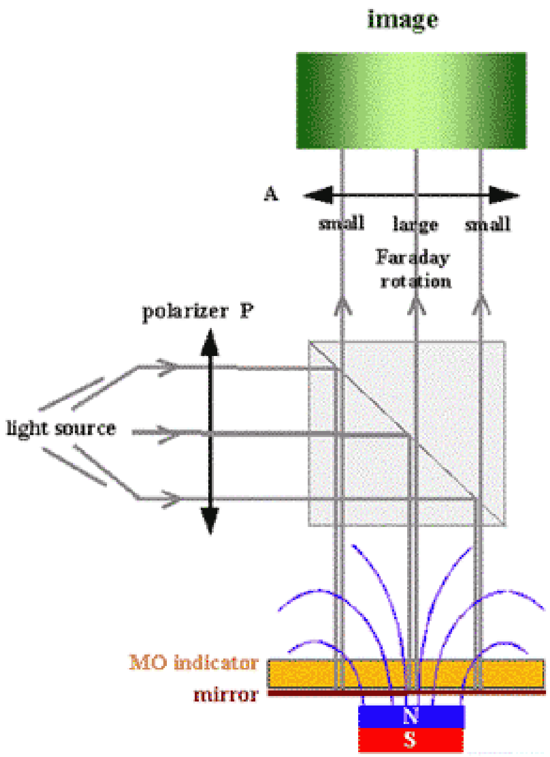
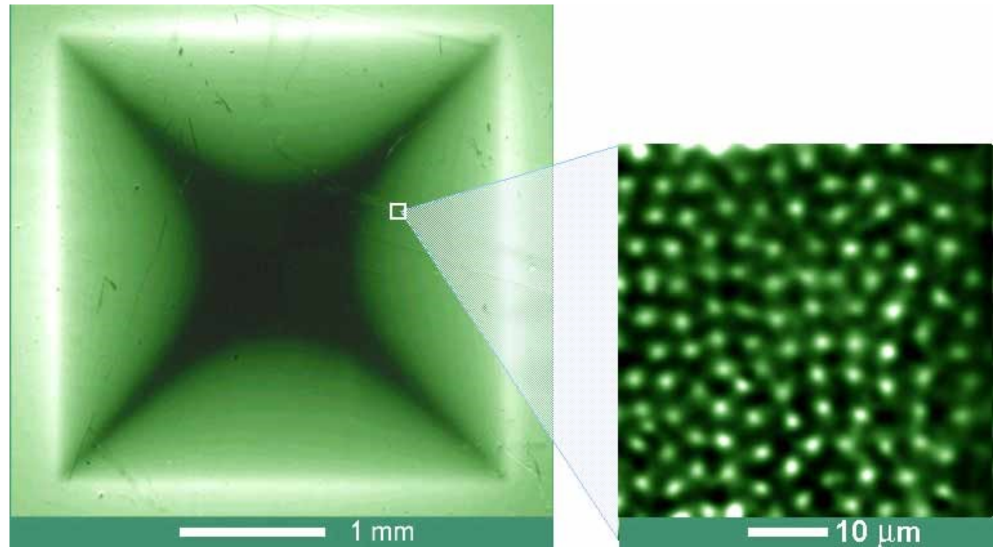
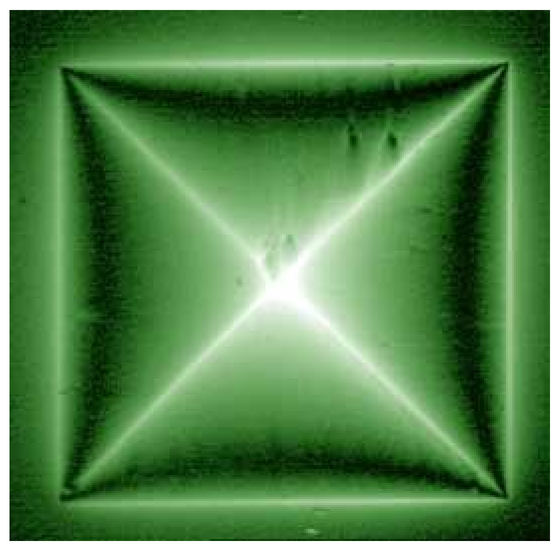
- **Optical Magnetometry**

Magneto optics







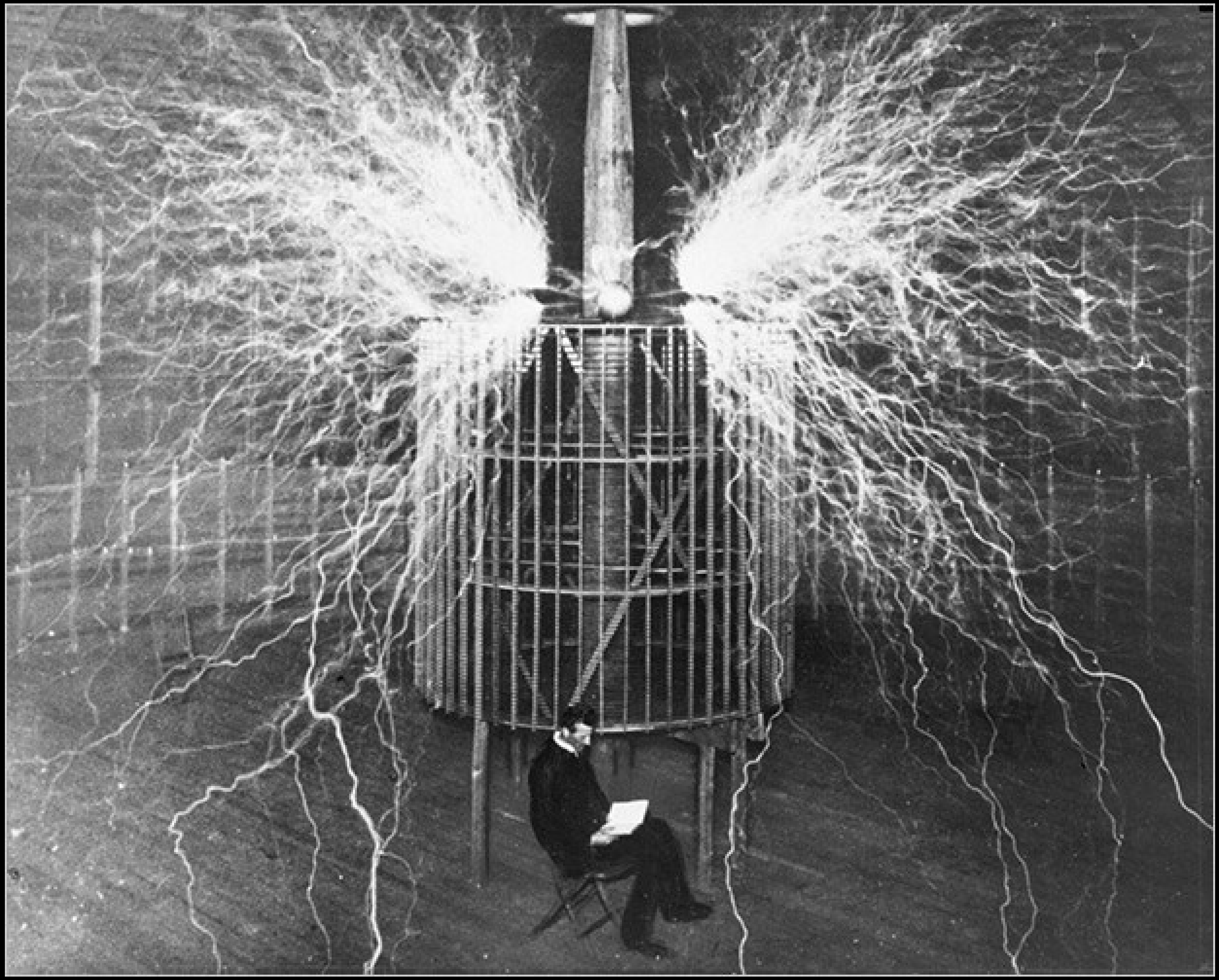


University of Oslo

Materials in Magnetic Field

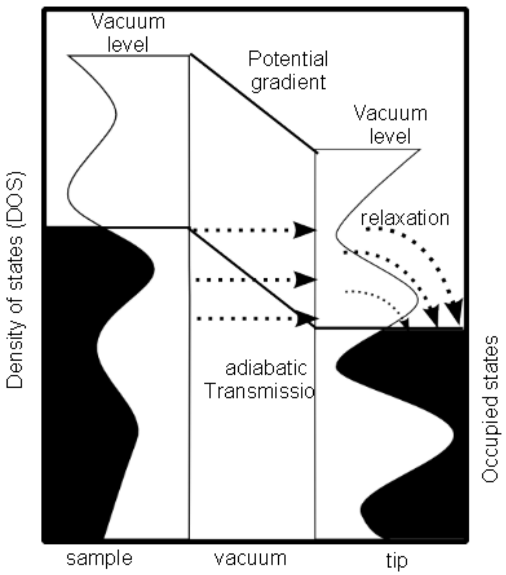
- Resonance spectroscopies:
  - NMR
  - EPR
- Quantum oscillations:
  - resistance (the Shubnikov-de Haas effect)
  - Hall resistance
  - magnetic susceptibility (the de Haas-van Alphen effect)
- Muon spin spectroscopy (μSR)
- Neutron scattering

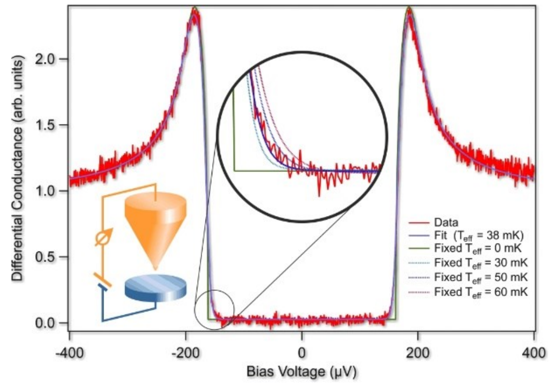
Electric Field

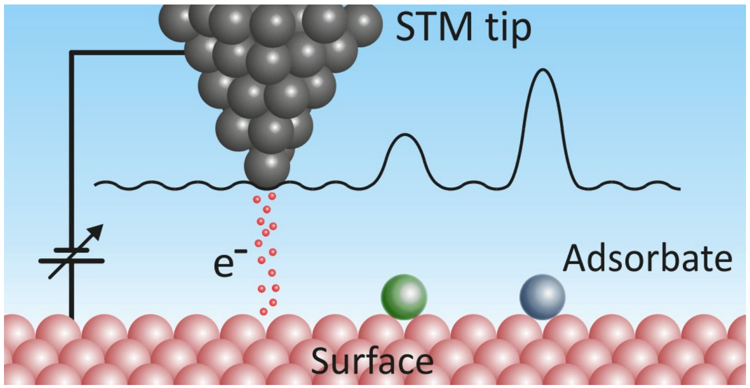


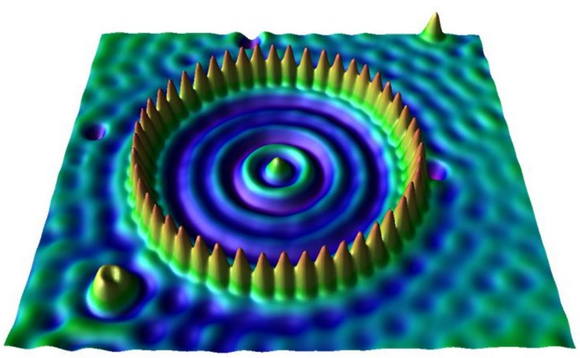
I prefix	Factor (volt)	Value	Item
Micro-	10^{-7}	0.5 μV	Change in nerve cell potential caused by opening a single acetylcholine receptor channel
Milli-	10^{-4}	0.5–1 mV	Miniature endplate potentials, spontaneous fluctuations in neuron potentials
Centi-	10^{-2}	~10–50 mV	Ripple voltage in the output of a good DC power supply
		75 mV	Nerve cell resting potential
N/A	10^{0}	1.5 V	Alkaline battery AA, AAA, C or D battery
Deca-	10^{1}	12 V	Typical car battery
Hecto-	10^{2}	100–240 V	Domestic wall socket voltage
Kilo-	10^{3}	2450 V	Electric chair execution in Nebraska
		3–35 kV	Accelerating voltage for a typical television cathode ray tube
		4160-34,500 V	Typical voltages in North America for distribution of power from distribution substations to end users
	10^{4}	25 kV	European high-speed train overhead power lines
	10^{5}	800 kV	Lowest voltage used by ultra-high voltage (UHV) power transmission systems
Mega-	10^{6}	3 MV	Used by the ultra-high voltage electron microscope at Osaka University
	10^{7}	25.5 MV	The largest man-made voltage – produced in a Van de Graaff generator at Oak Ridge National Laboratory
	10^{8}	100 MV	The potential difference between the ends of a typical lightning bolt
Peta-	10^{15}	7 PV	Voltage around a particular energetic highly magnetized rotating neutron star
N/A	10^{27}	1.04×10^{27} V	Planck voltage

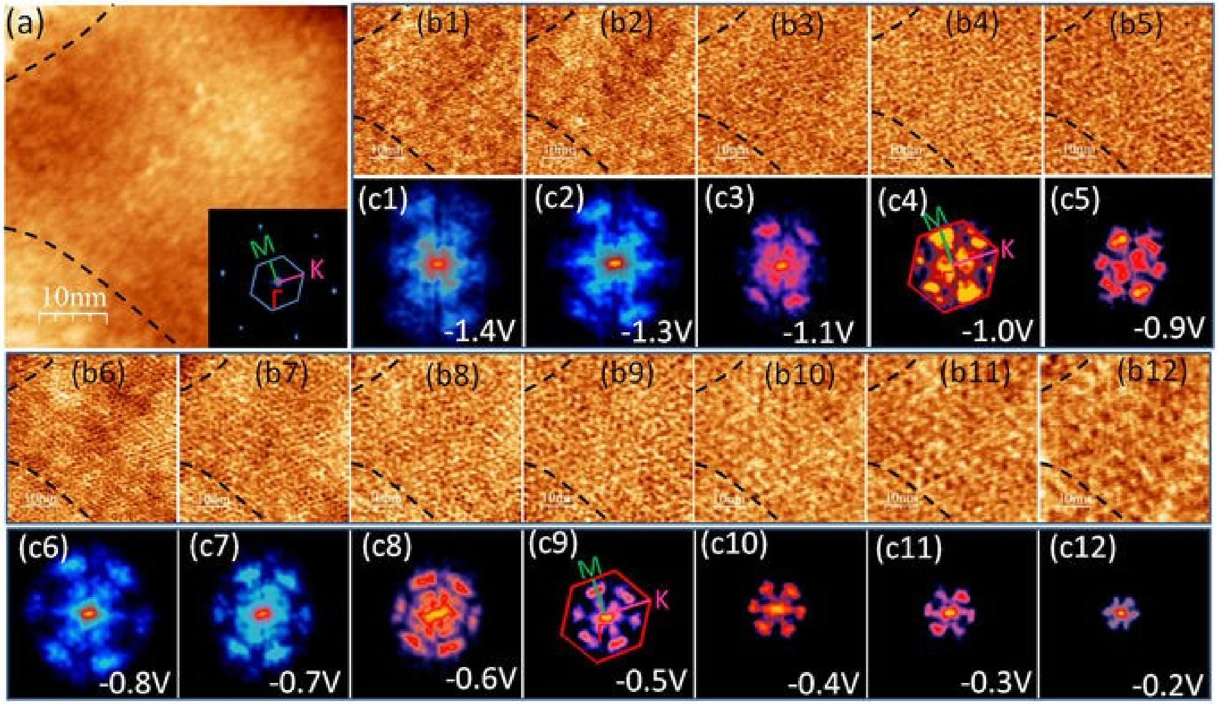
Scanning tunneling spectroscopy (STS)





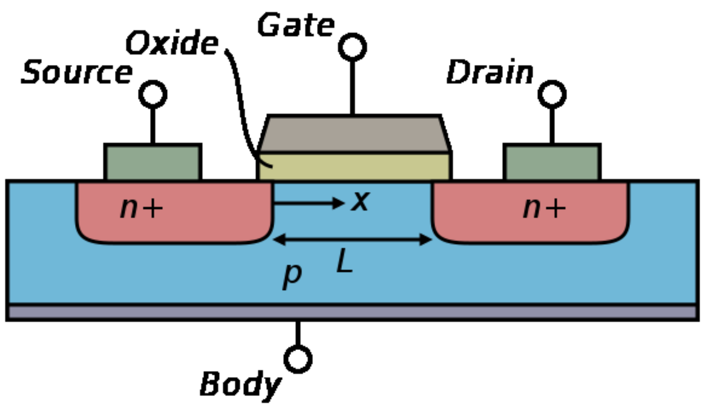


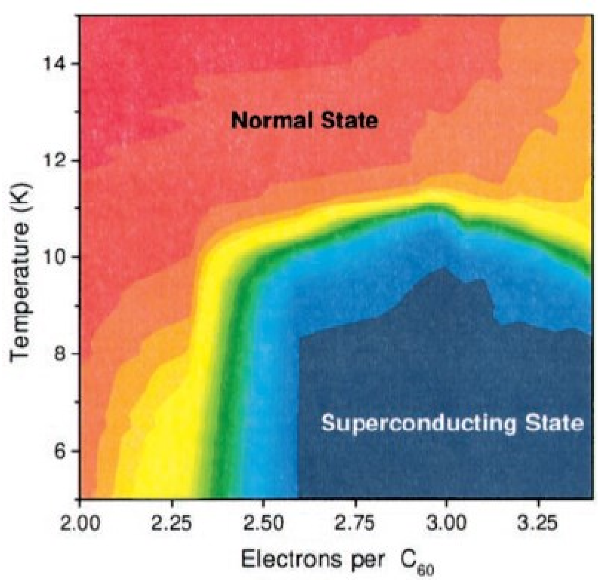




Польовий транзистор / field-effect transistor (FET)

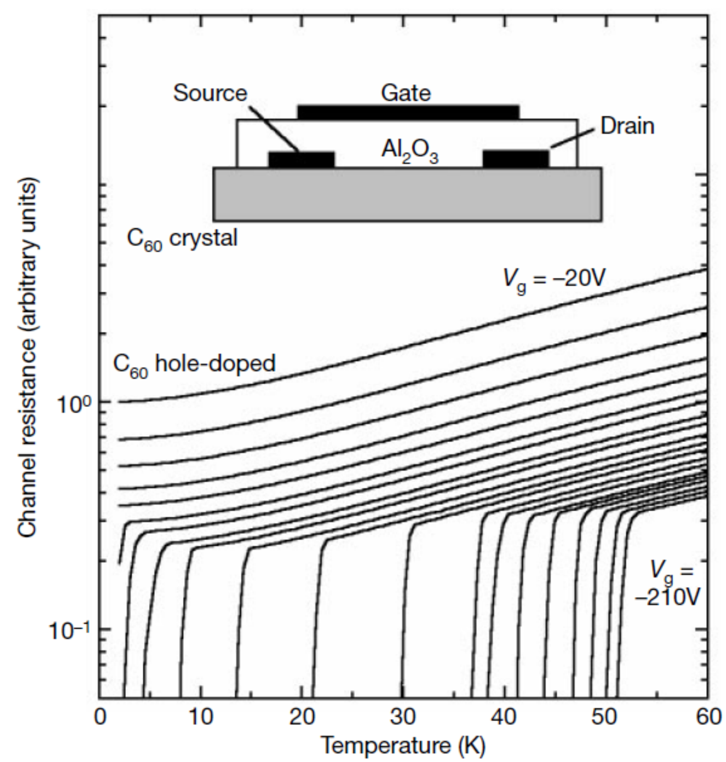
Metal–oxide–semiconductor field-effect transistor (MOSFET)





A Superconducting Field-Effect Switch

J. H. Schön,[1] Ch. Kloc,[1] R. C. Haddon,[2] B. Batlogg[1]



Retraction

… AND J. HENDRIK SCHÖN ***SCIENCE***•1 Nov 2002•Vol 298, Issue 5595•p. 961•DOI: 10.1126/science.298.5595.961b

We are writing as coauthors on the following manuscripts published in *Science*, which were, in part, the subject of an independent investigation conducted at the behest of Bell Laboratories, Lucent Technologies. The independent committee reviewed concerns related to the validity of data associated with the device measurements described in the papers.

1. J. H. Schön, S. Berg, Ch. Kloc, B. Batlogg, Ambipolar pentacene field-effect transistors and inverters, *Science* 287, 1022 (2000).
2. J. H. Schön, Ch. Kloc, R. C. Haddon, B. Batlogg, A superconducting field-effect switch, *Science* 288, 656 (2000).
3. J. H. Schön, Ch. Kloc, B. Batlogg, Fractional quantum Hall effect in organic molecular semiconductors, *Science* 288, 2338 (2000).
4. J. H. Schön, Ch. Kloc, A. Dodabalapur, B. Batlogg, An organic solid state injection laser, *Science* 289, 599 (2000).
5. J. H. Schön, A. Dodabalapur, Ch. Kloc, B. Batlogg, A light-emitting field-effect transistor, *Science* 290, 963 (2000).
6. J. H. Schön, Ch. Kloc, H. Y. Hwang, B. Batlogg, Josephson junctions with tunable weak links, *Science* 292, 252 (2001).
7. J. H. Schön, Ch. Kloc, B. Batlogg, High-temperature superconductivity in lattice-expanded C_{60}, *Science* 293, 2432 (2001).
8. J. H. Schön, H. Meng, Z. Bao, Field-effect modulation of the conductance of single molecules, *Science* 294, 2138 (2001).

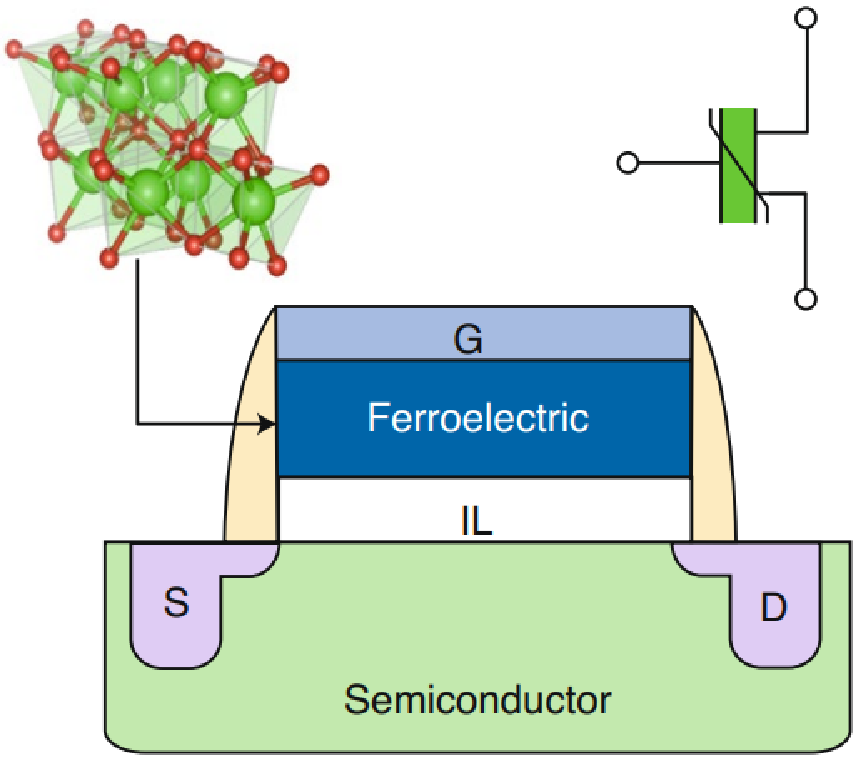
As a result of the committee's findings, we feel obligated to the scientific community to issue a retraction of the above articles. We note that although these papers may contain some legitimate ideas and contributions, we think it best to make a complete retraction.

Note

*Editor's Note:*For more information on the investigation, please see the summary and full report of the committee, which are available at www.lucent.com/news_events/researchreview.html.

Ferroelectric field-effect transistor

Сегнетоеле́ктрики або **фероеле́ктрики** — речовини, які мають спонтанний дипольний електричний момент в одній із кристалічних фаз, що існує в певному діапазоні температур.



A ferroelectric field-effect transistor (FEFET) combines a ferroelectric material with a semiconductor in a transistor structure.

FEFET can be a key hardware component in the future of computing, providing a new approach to electronics that we term ferroelectronics

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