Superconductivity, Trains and SQUIDs

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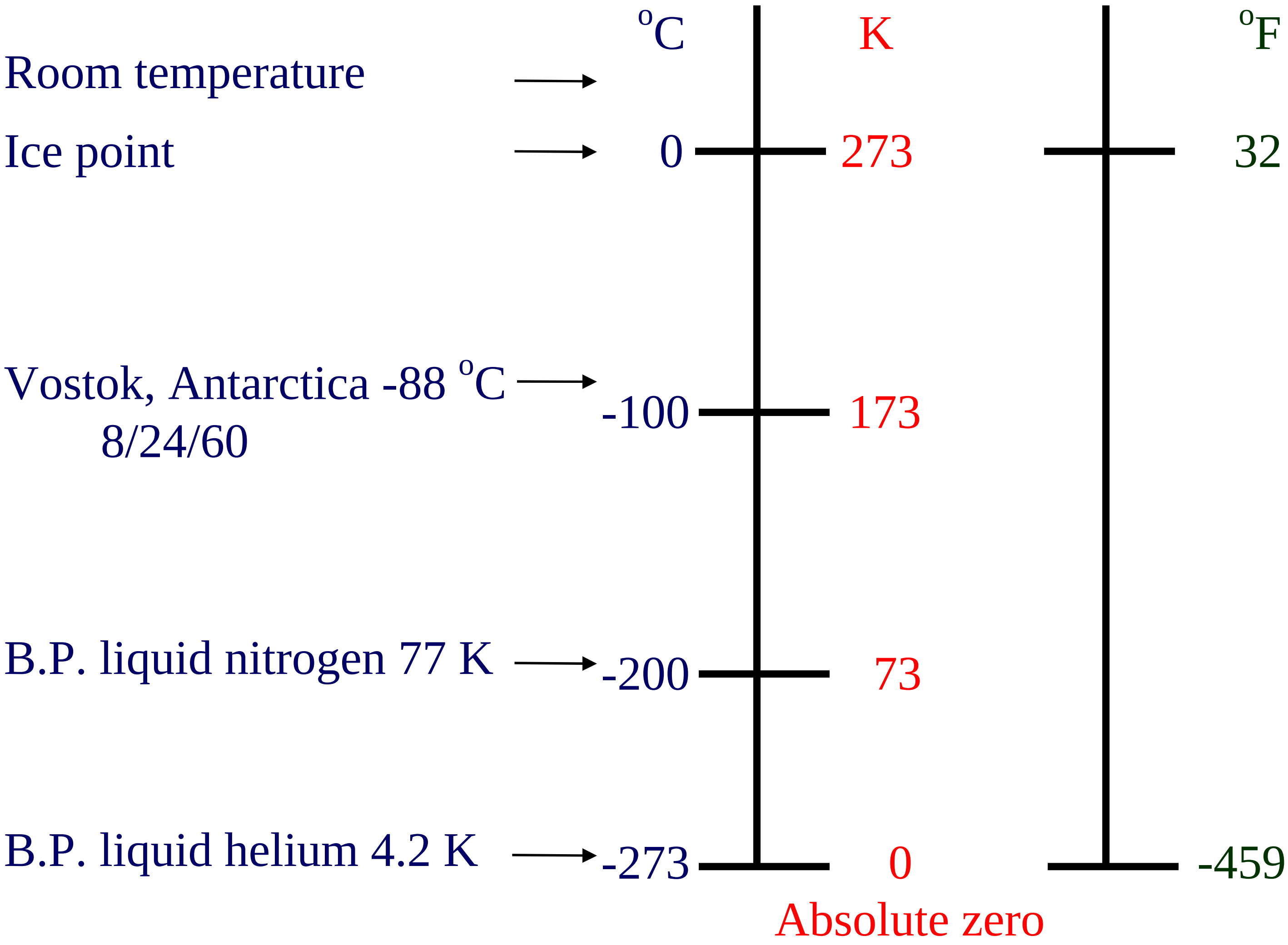
Outline

- Introduction
- Superconductivity: A brief review
- Macroscopic applications: Magnets
- Microscopic applications: SQUIDs
- Closing remarks

Introduction

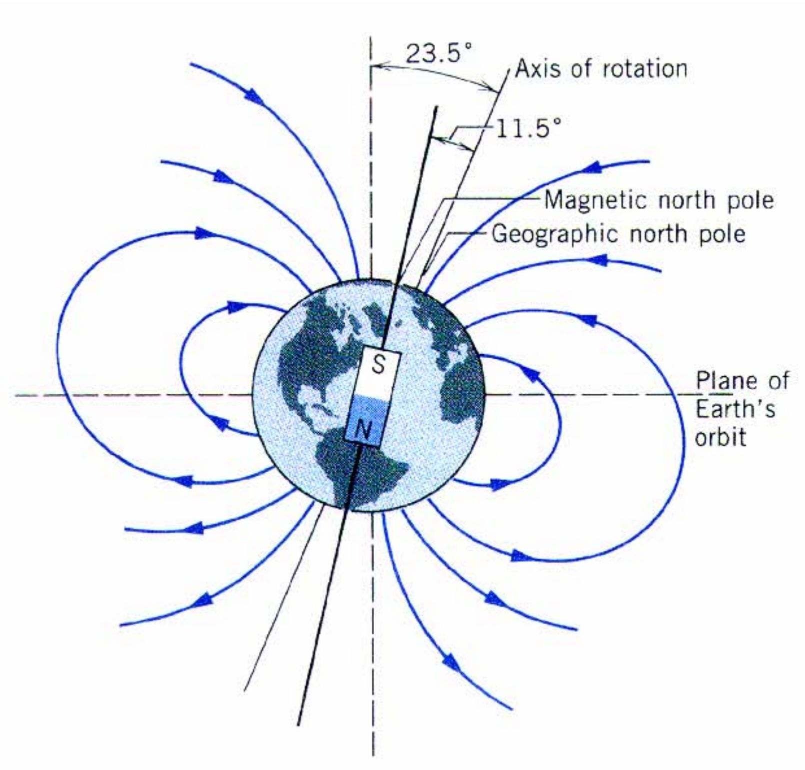
Centigrade/Kelvin/Fahrenheit Temperature Scales

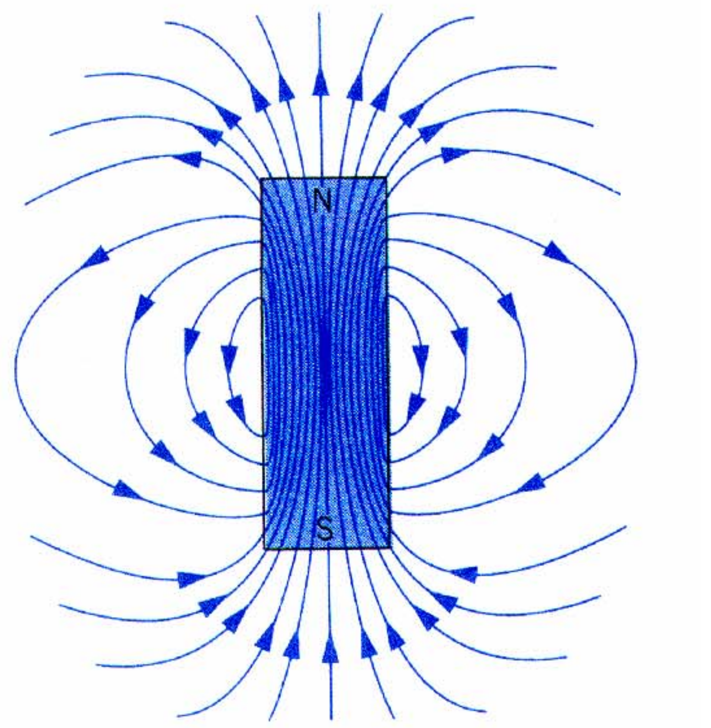


Magnetic Fields

The Earth

Bar magnet





~1 gauss

10^{-4} tesla

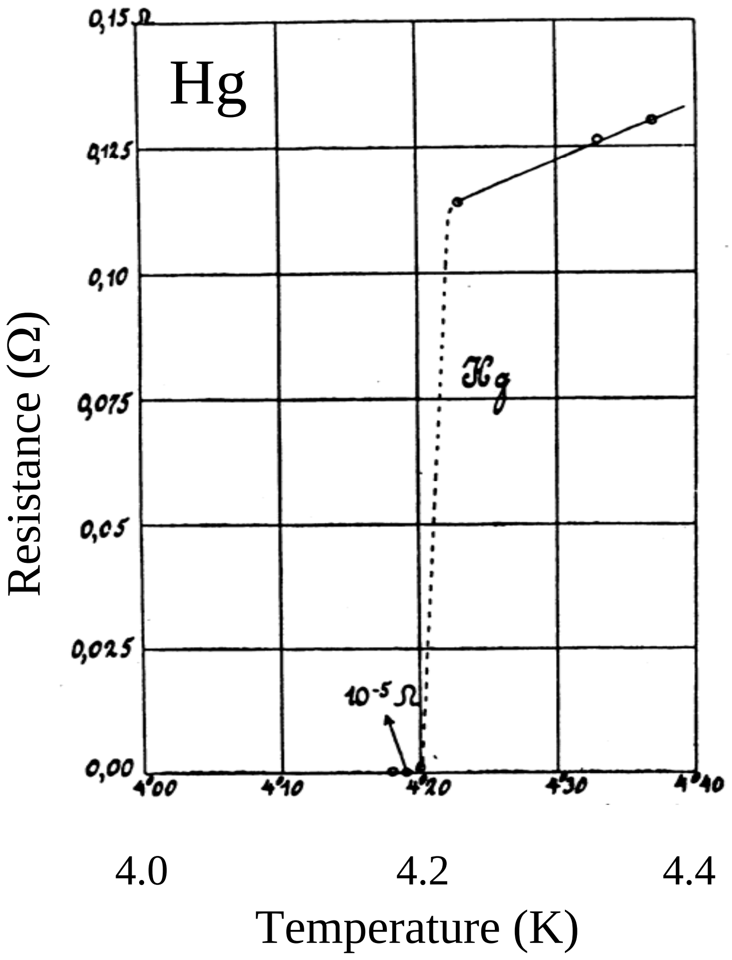
~1000 gauss

0.1 tesla

Superconductivity:
A Brief Review

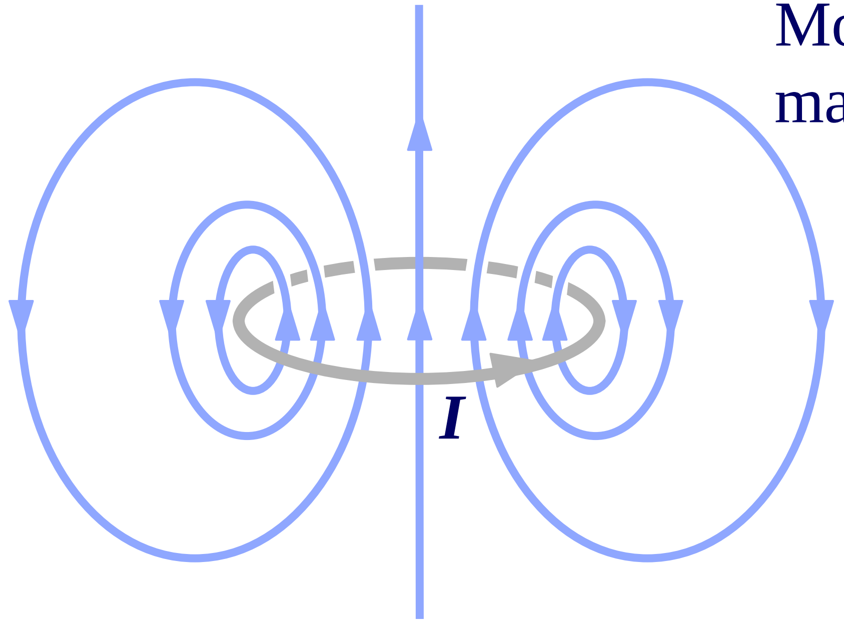
The Discovery of Superconductivity (1911)

Heike Kamerlingh Onnes



Resistance vanishes below the transition (or critical) temperature T_c

Zero Resistance



Monitor the magnetic field

- Current ***I*** persists without loss for years
- Resistivity at least one billion billion times less than that of copper
- **Basis of superconducting magnets**

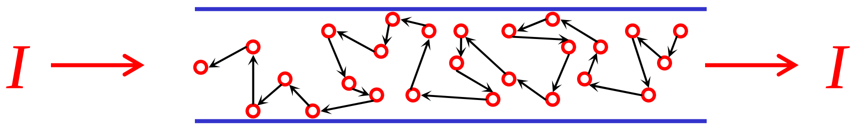
A Few Other Superconductors

Metal	T_c
Aluminium	1.2 K
Indium	3.4 K
Tin	3.7 K
Lead	7.2 K
Niobium	9.2 K
NbN	18 K
Nb_3Ge	23 K

Normal Metals vs. Superconductors

Normal Metals

Electron has charge -*e*

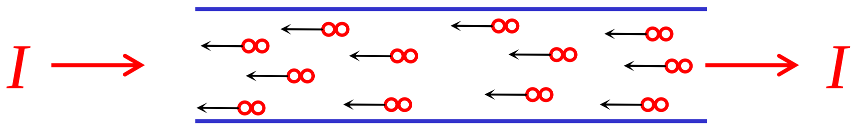


Scattering of electrons produces *resistance*.

A *current* generates a *voltage*, and hence causes *dissipation* (electric heater).

Superconductors

Electrons are paired together :
These Cooper pairs have charge -2*e*



Cooper pairs carry a *supercurrent* which encounters *no resistance*.

A *supercurrent* generates *no voltage*, and hence causes *no dissipation*.

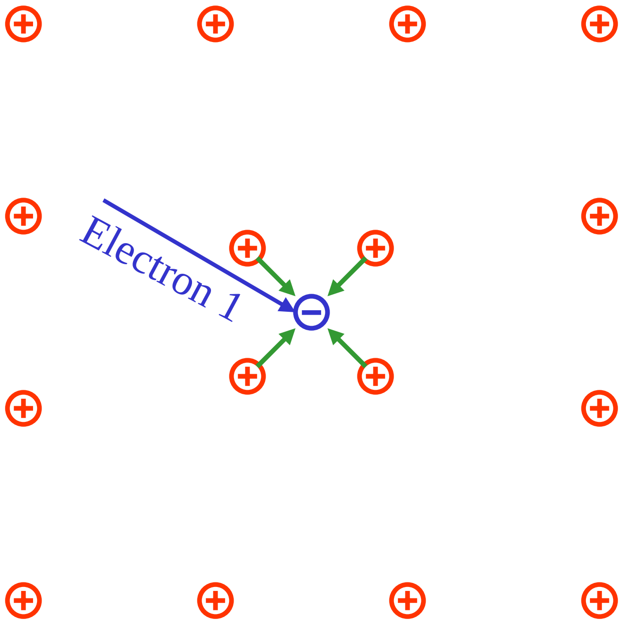
Bardeen-Cooper-Schrieffer BCS Theory (1957)*

In a metal, each atom gives up one electron or more to produce a positively charged ion. The free electrons form a gas.

*50 years old last month!

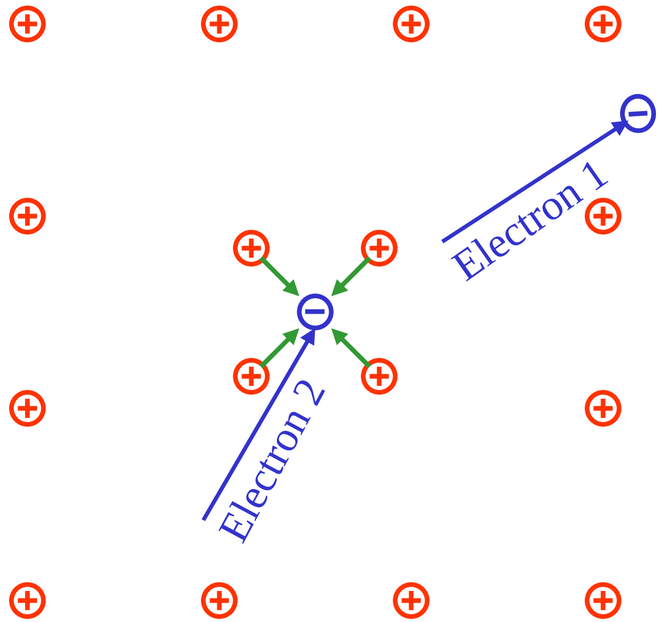
BCS Theory

An electron attracts nearby positive ions towards itself, distorting the lattice.

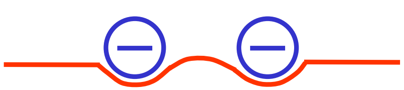


BCS Theory

The distortion of the charged lattice produces an effective attraction between two electrons.

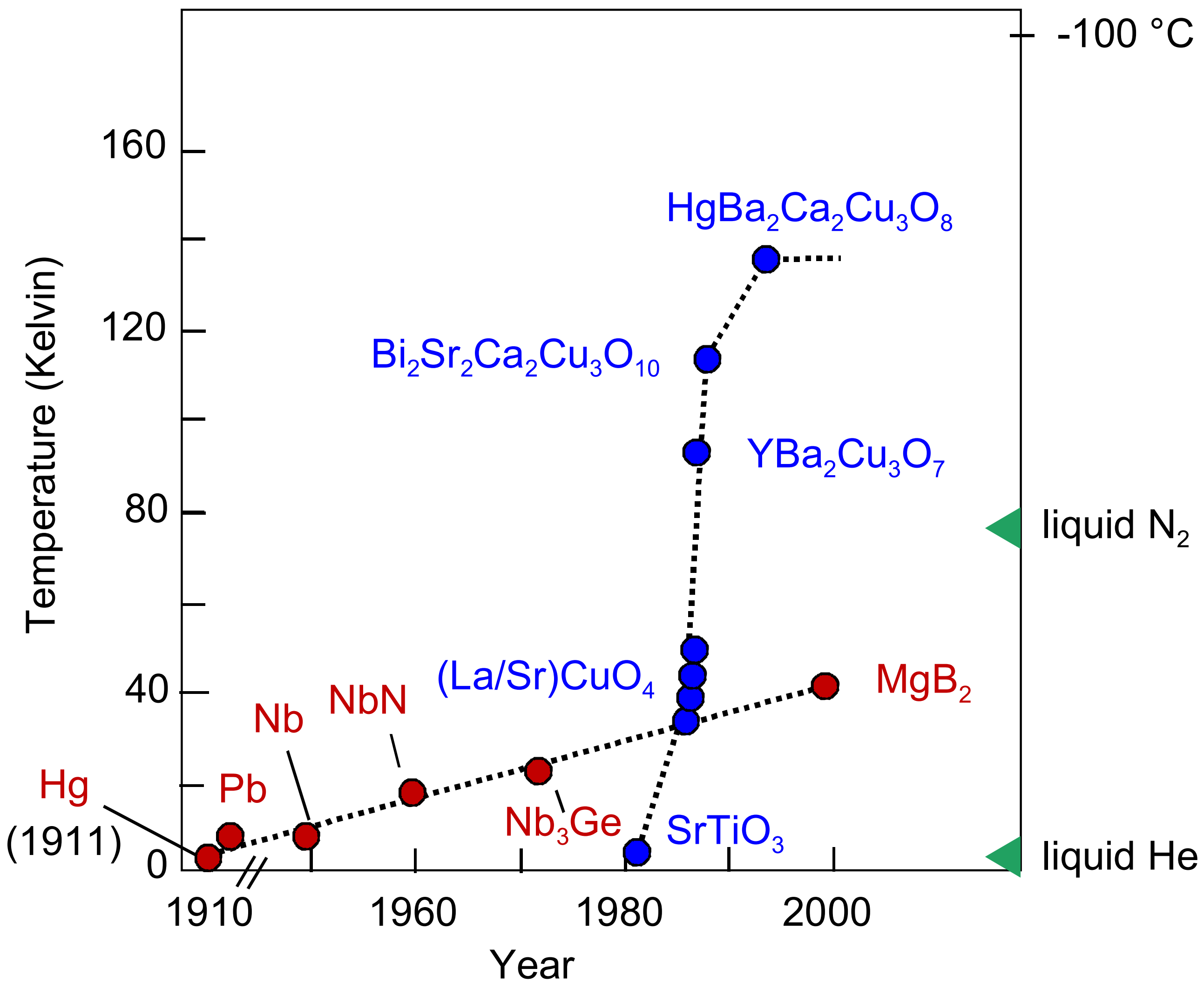


This attractive force is known as the “electron-phonon interaction”.

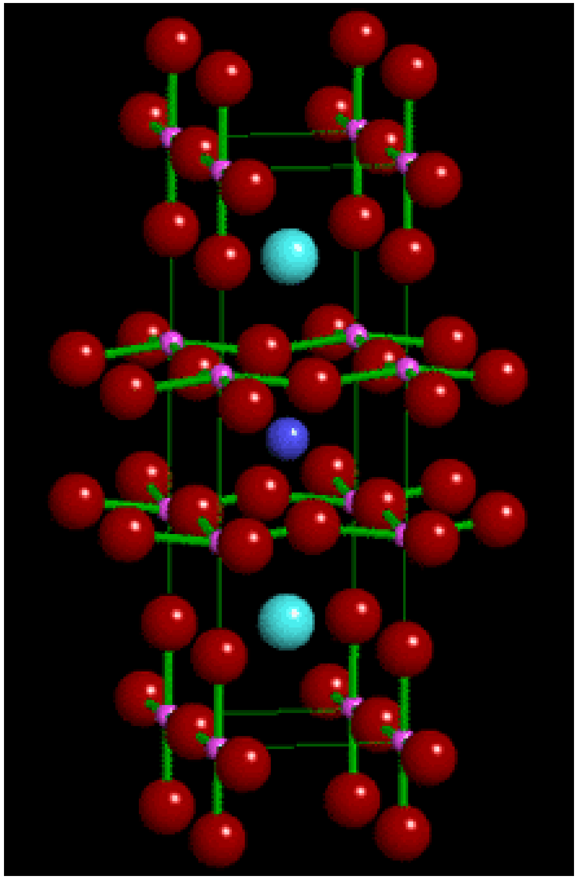


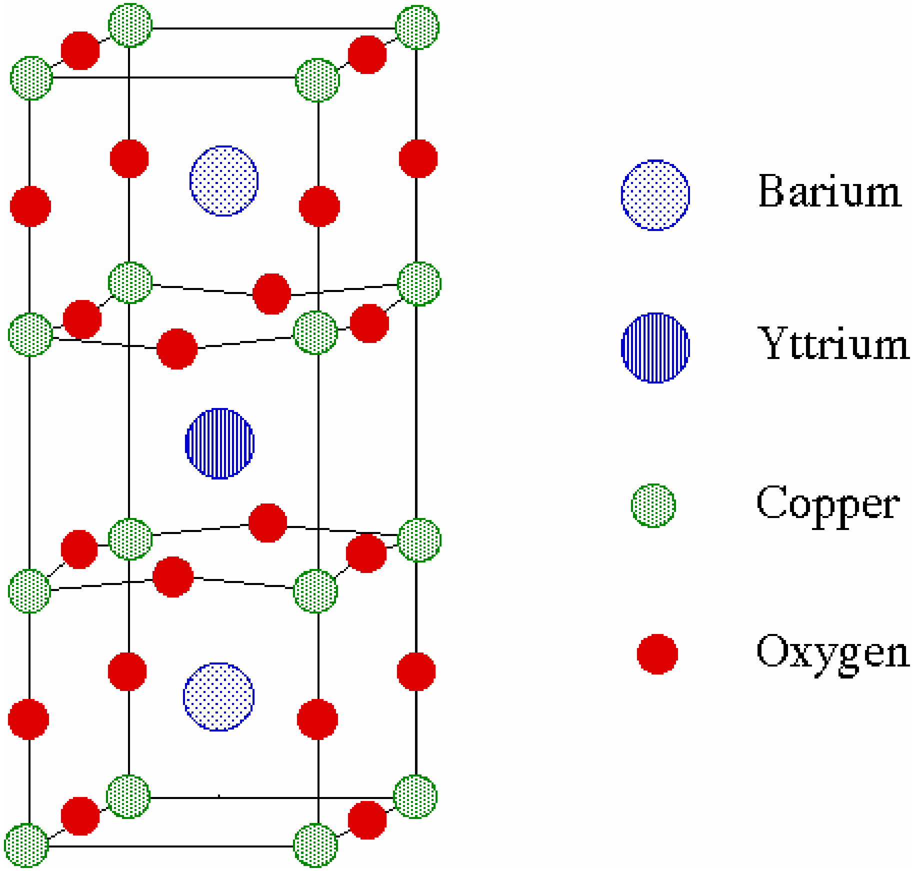
The water bed analogy

Transition Temperature Over the Years: “High-T_c” Superconductivity



$YBa_2Cu_3O_{7-x}$

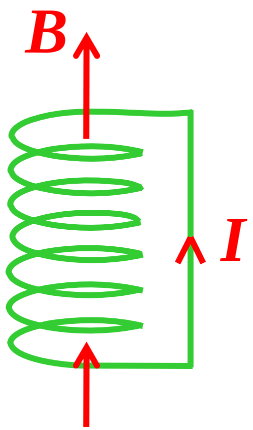




- The mechanism for "high-T_c" superconductivity is not at all understood.

Macroscopic Applications: Magnets

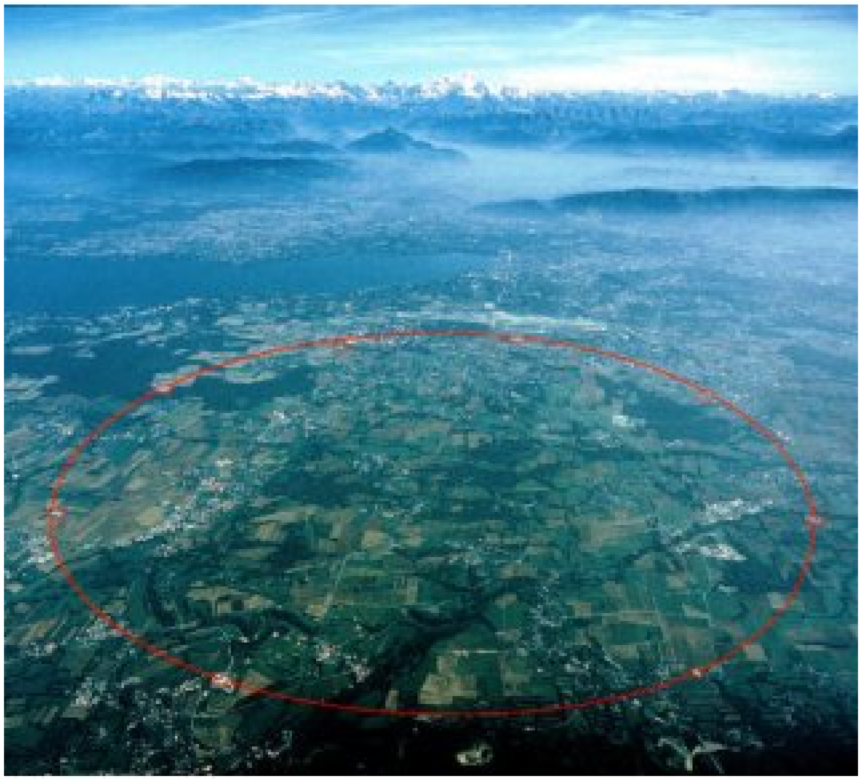
High-Field Magnets



- Persistent current ***I***: No power required to maintain magnetic field ***B***

- Particle accelerators
- Magnetic resonance imaging (~ $3 billion/year)
- Levitated trains

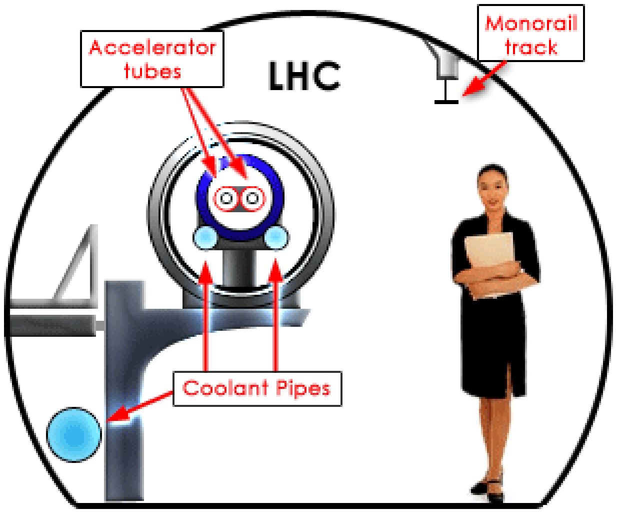
Large Hadron* Collider (LHC)



- CERN: Conseil Européen pour la Recherche Nucléaire—Geneva
- Circumference 27 km
- Will collide beams of protons each with an energy of 7 TeV (7 x 10^{12} eV)
- Goals: To explore the properties of elementary particles at the highest energy ever
- Total cost: 3 billion euros
- Power consumption: 120 MW
- 7000 physicists!

*Hadron: Strongly interacting composite subatomic particle, for example a proton (3 quarks)

LHC Beamline



- The two beams of protons travel in opposite directions in evacuated tubes

- The protons are bent into circular orbits by a strong magnetic field produced by superconducting magnets

Superconducting Dipole Magnet

- Length: 15 meters
- Mass: 35 tonnes
- Wire: niobium-titanium cooled to 1.9 K
- Current: 11,700 ampères
- Magnetic field: 8.3 tesla
- There are 9,300 superconducting magnets in the LHC
- Start-up planned for 2008

Without superconductivity, one could not build particle accelerators on this scale.

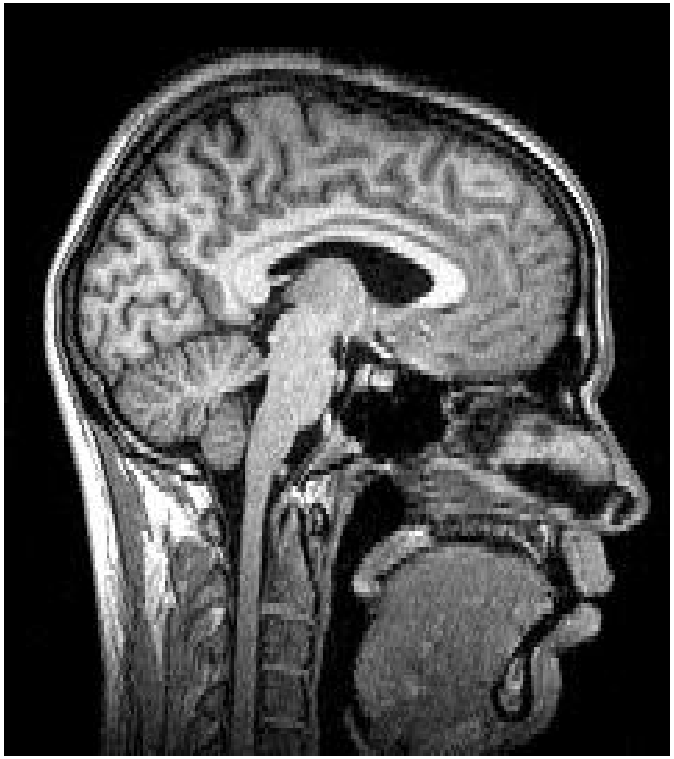
Magnetic Resonance Imaging (MRI)

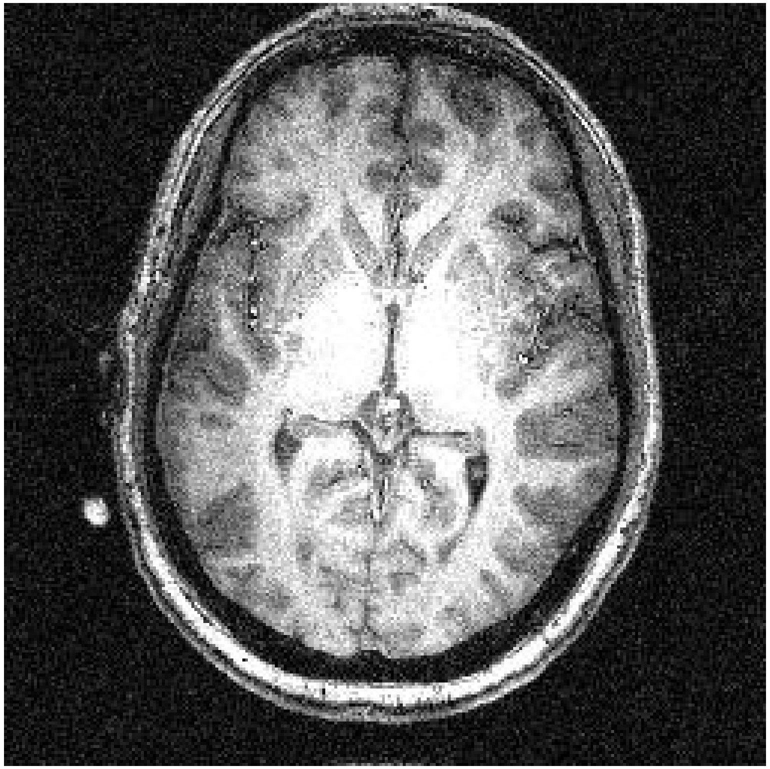
1.5 T MRI scanner (GE)

3 T MRI scanner (GE)

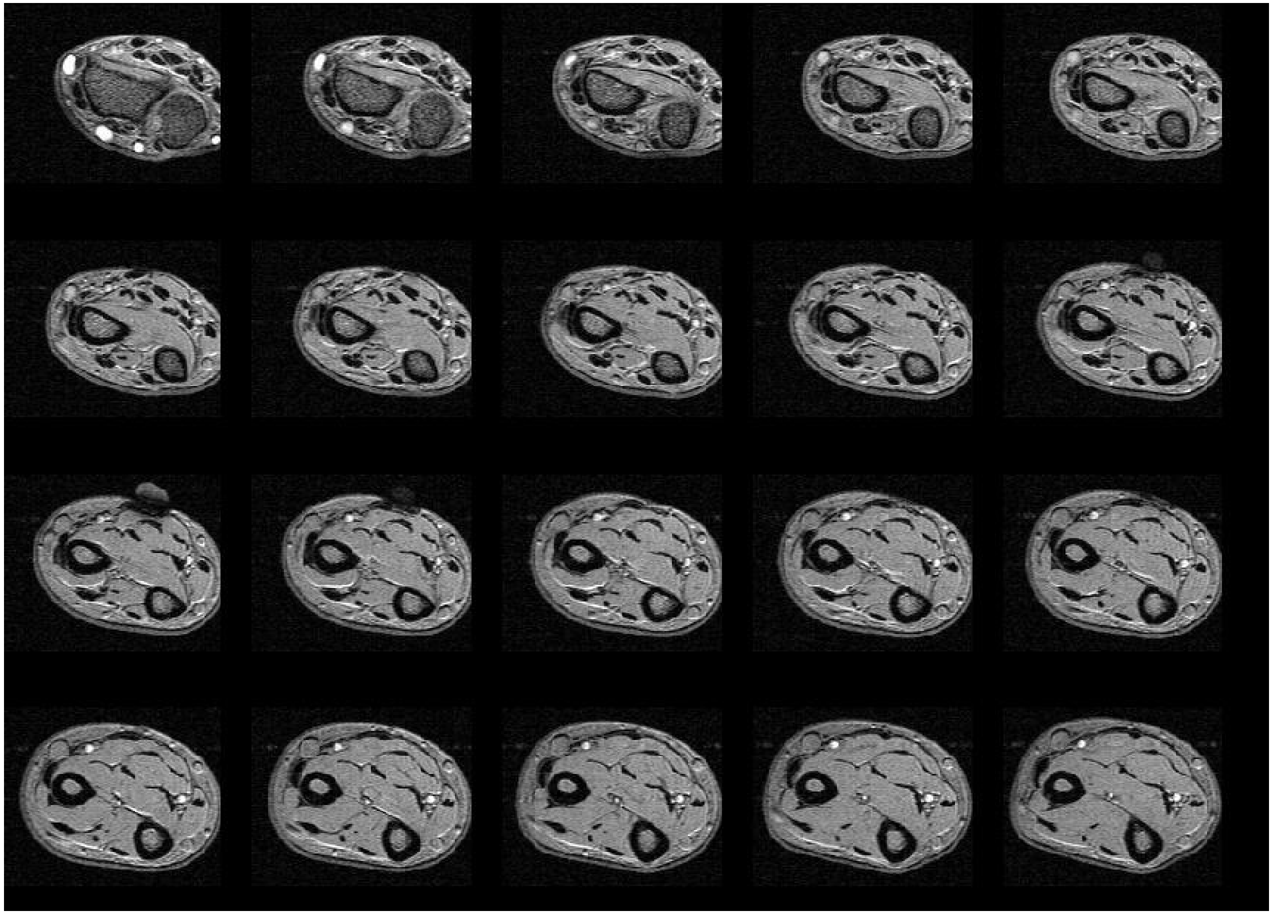
- MRI operates on the principle of nuclear magnetic resonance (NMR)
- Each machine contains 50 km of NbTi wire cooled to 4.2 K
- About 22,000 machines worldwide
- ***Without superconductivity, these systems would not exist***

Images of the Head





Images of the Arm



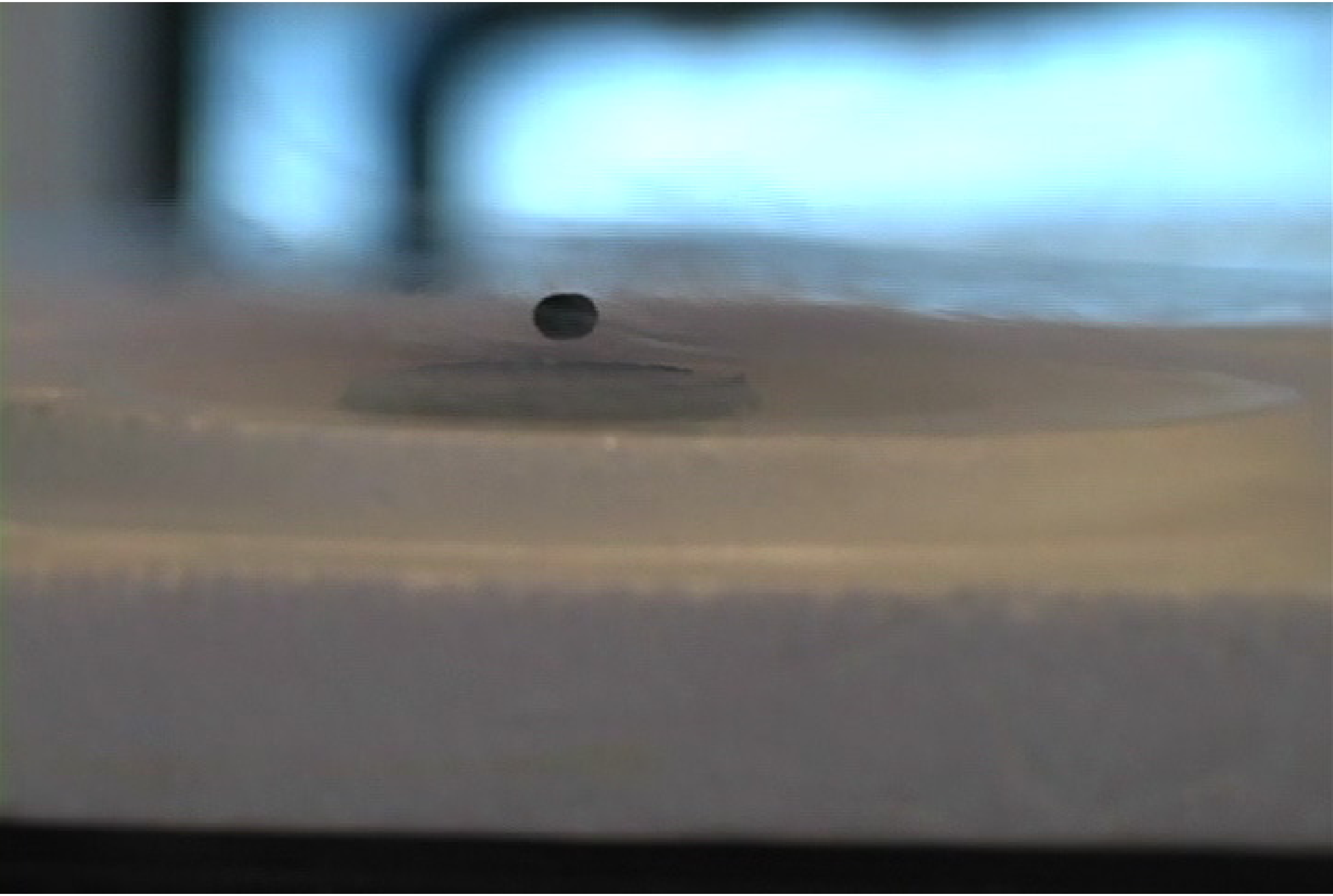
Magnetic field: 4 tesla
Slice thickness: 1.5 mm

Courtesy Ben Inglis (UCB)

Japanese MAGLEV

Maximum speed: 581 km/hour = 361 miles/hour
Planned: Tokyo to Osaka in one hour!

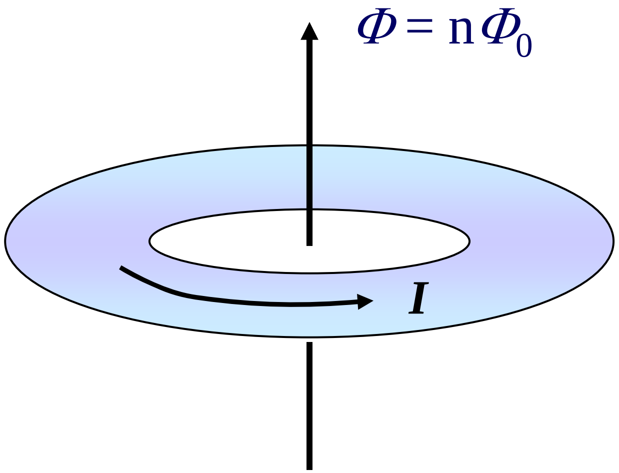
The Floating Superconductor



Microscopic Applications: SQUIDs

Magnetic Flux Quantization

Magnetic flux =
Magnetic field × Area

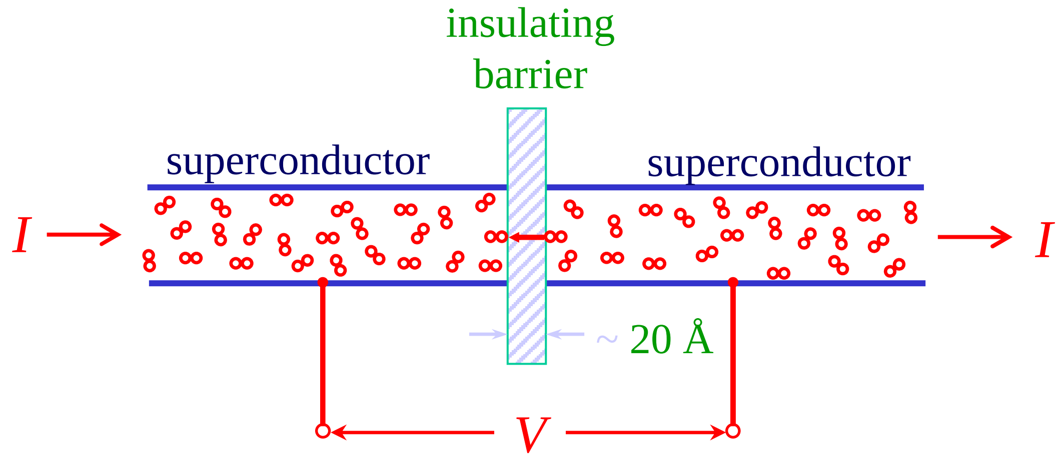


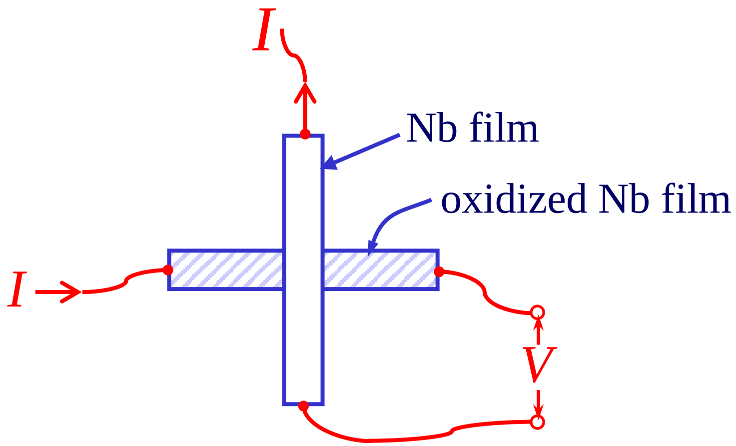
$\Phi = n\Phi_0$ (n = 0, ±1, ±2, ...)
where
$\Phi_0 \equiv h/2e \approx 2 \times 10^{-15}$ Wb
is the flux quantum

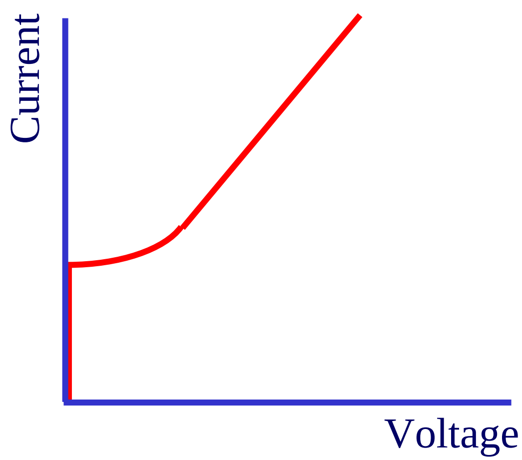
Josephson Tunneling

- Cooper pairs *tunnel* through the barrier

Brian Josephson 1962





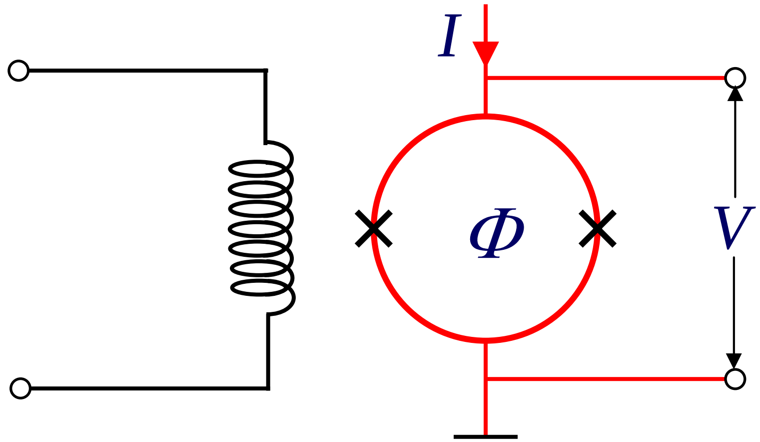


Created the field of superconducting electronics

The dc Superconducting Quantum Interference Device

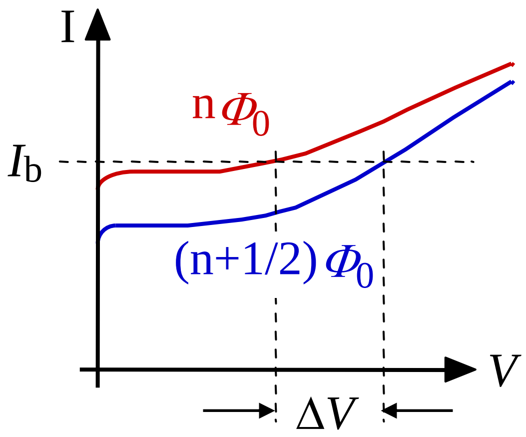
- **DC SQUID**

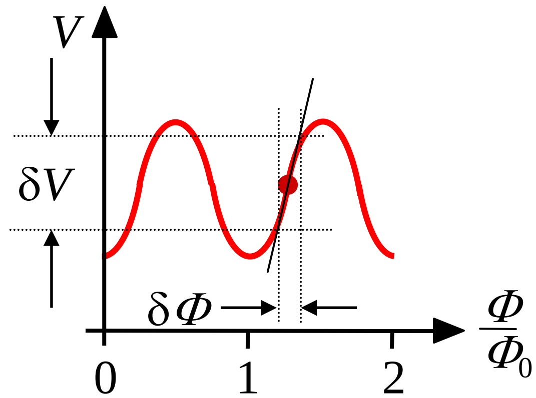
  Two Josephson junctions on a superconducting ring



- **Current-voltage (I-V) characteristic modulated by magnetic flux Φ**

  Period one flux quantum $\Phi_0 = h/2e = 2 \times 10^{-15}$ T m^2





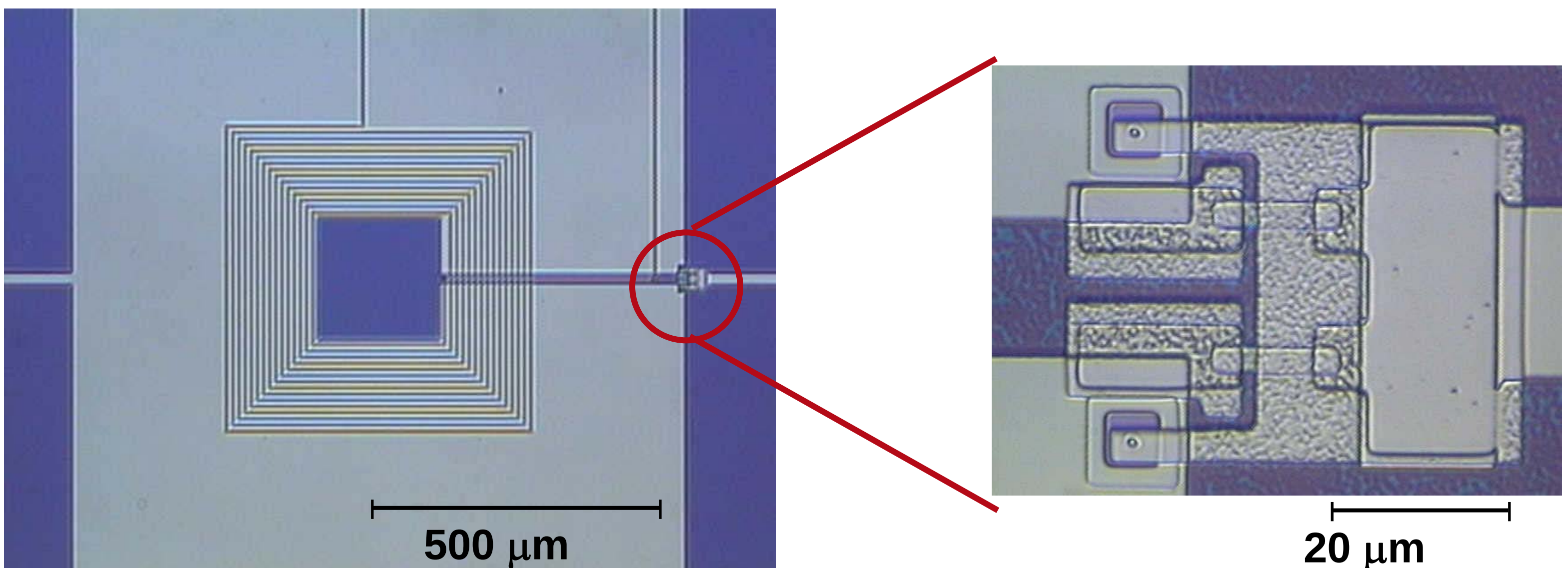
- These oscillations arise from "interference" in a way closely related to the production of optical fringes by Young's slits: Hence the acronym.

Thin-Film SQUID

Operates typically at 4.2 K

Multilayer device

Niobium - aluminum oxide – niobium Josephson junctions

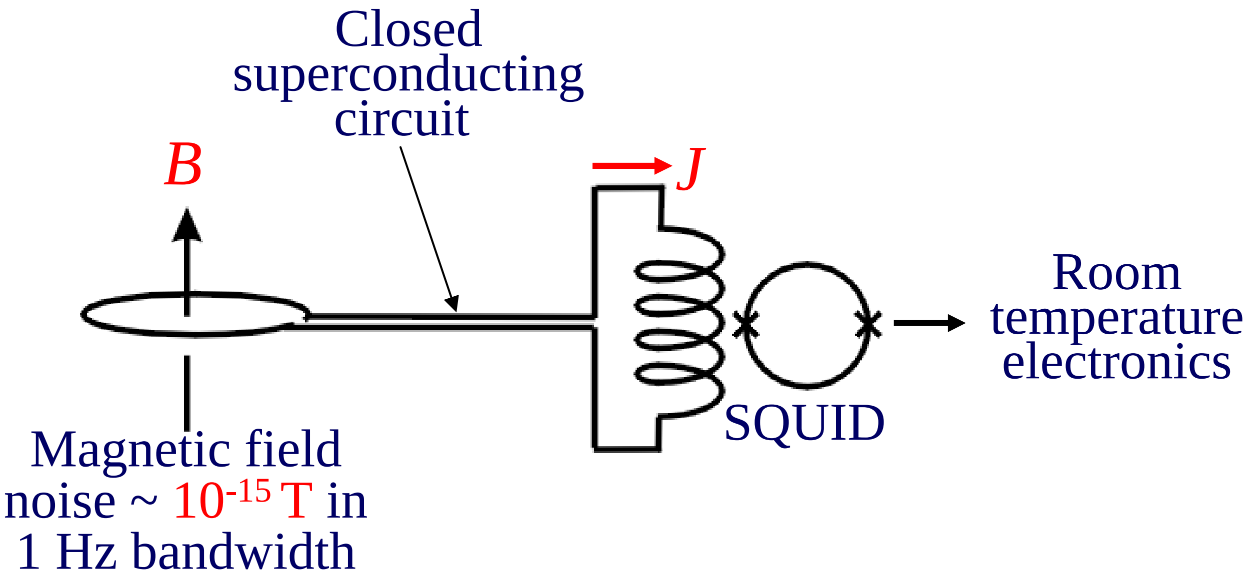


SQUID with input coil

Josephson junctions

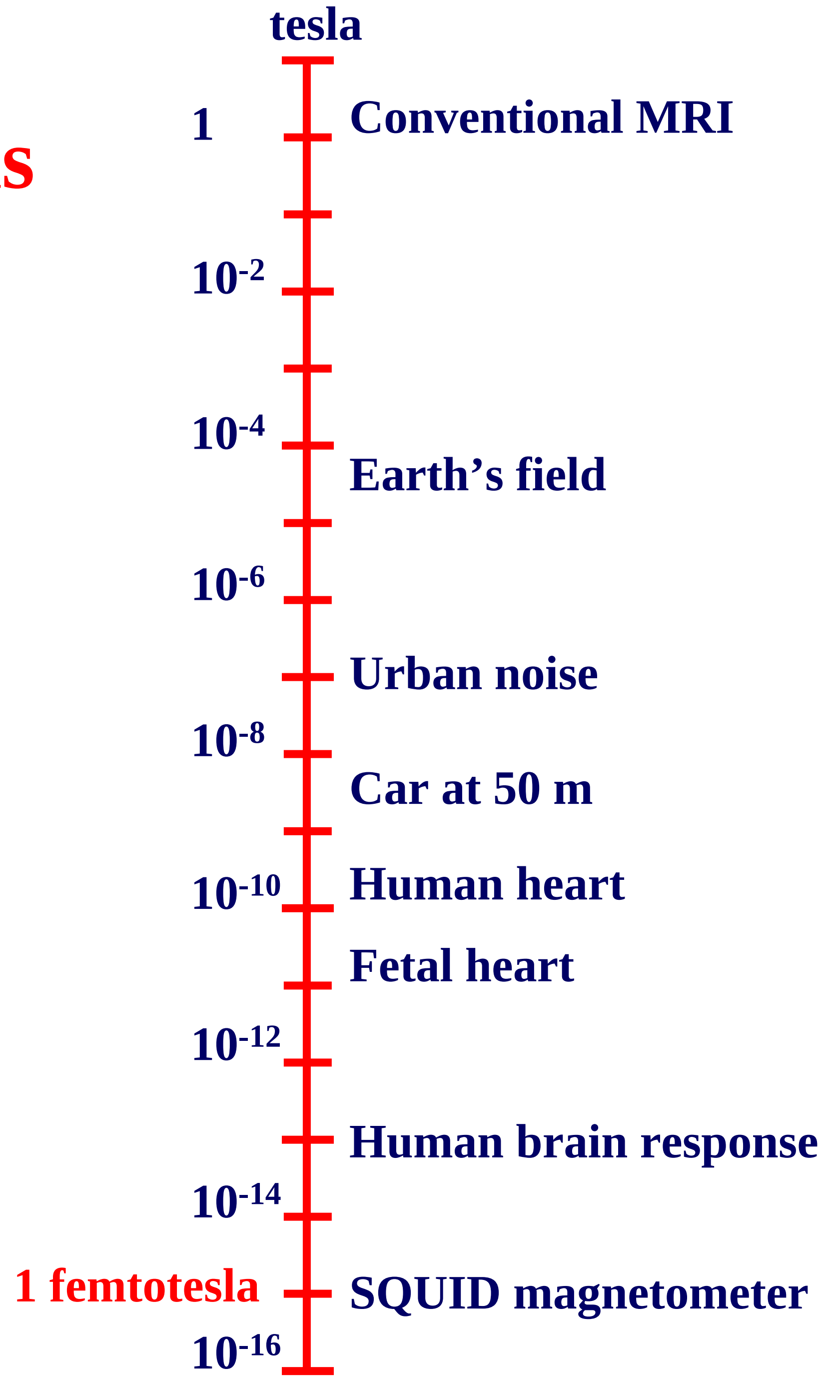
- With appropriate electronics, the SQUID can detect $10^{-6}\ \Phi_0\ \mathrm{Hz}^{-1/2}$

Superconducting Flux Transformer: Magnetometer



- Response to magnetic field is flat down to zero frequency

Magnetic Fields



So: Where's the "Nano"

- In one second, a SQUID can detect a magnetic field
  100,000,000,000 (10 milli-nano)
  times smaller than that of the earth

- In one second, a SQUID can detect an energy
  100,000,000,000,000,000,000,000,000,000,000
  (10 micro-nano-nano-nano)
  times smaller than that consumed by a flashlight bulb

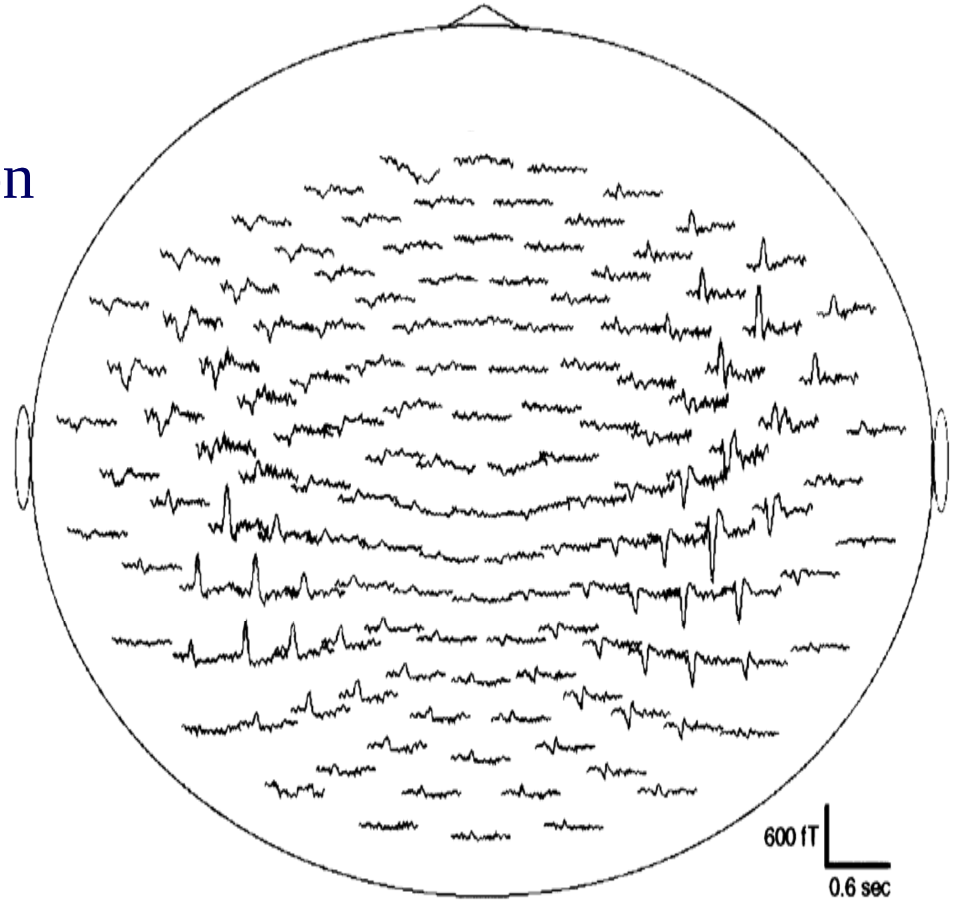
Looking at Your Brain: Magnetoencephalography

300-Channel SQUID Systems for Magnetoencephalography (MEG)

- Presurgical mapping of brain tumors
- Locating epileptic centers
- Monitoring recovery from stroke or brain trauma

Magnetoencephalography Data

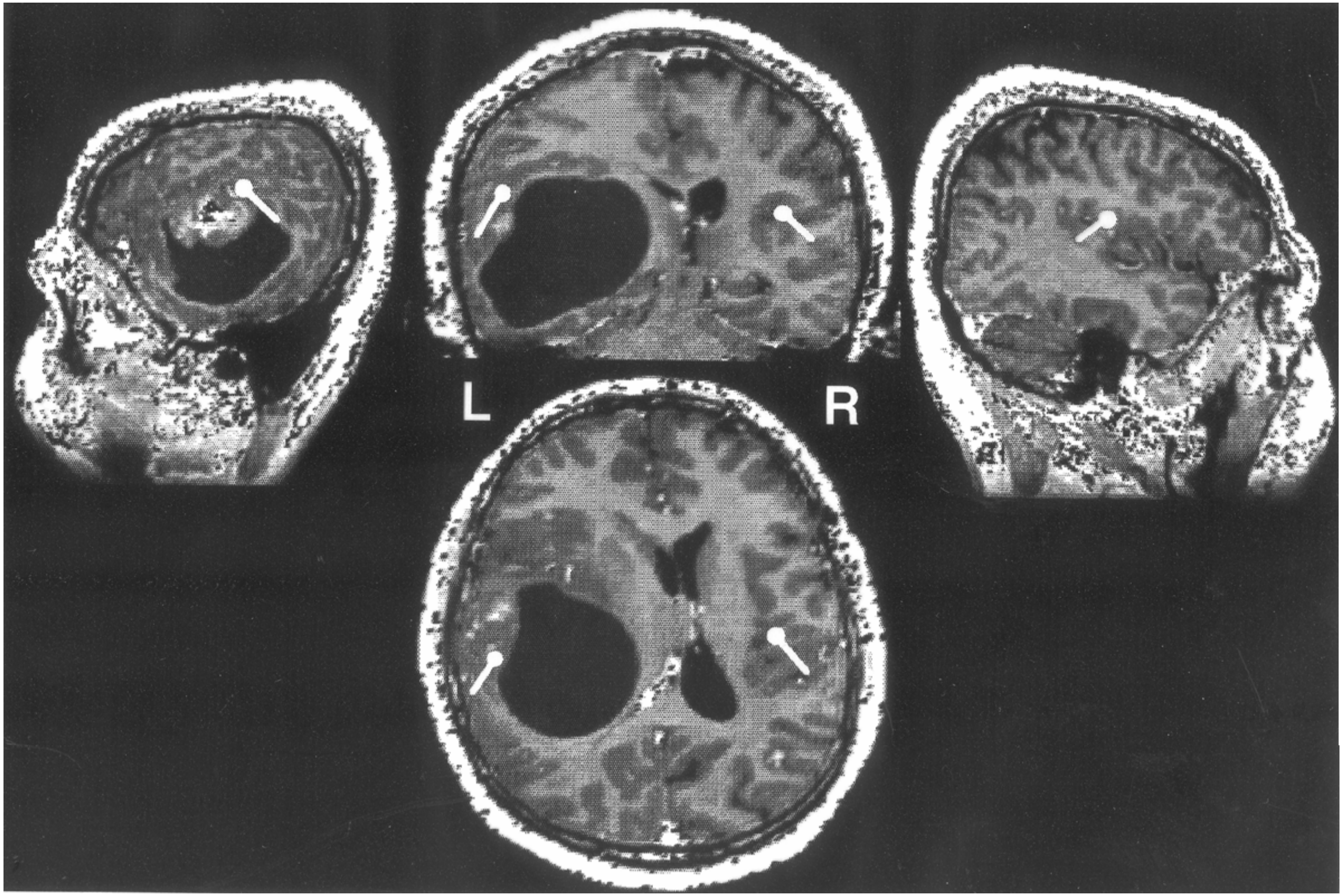
1 kHz tone
0.1 sec duration



Made possible
by the SQUID

Courtesy Jiri Vrba, CTF

Presurgical Screening of Brain Tumors



25-year old male

Courtesy Jiri Vrba, CTF

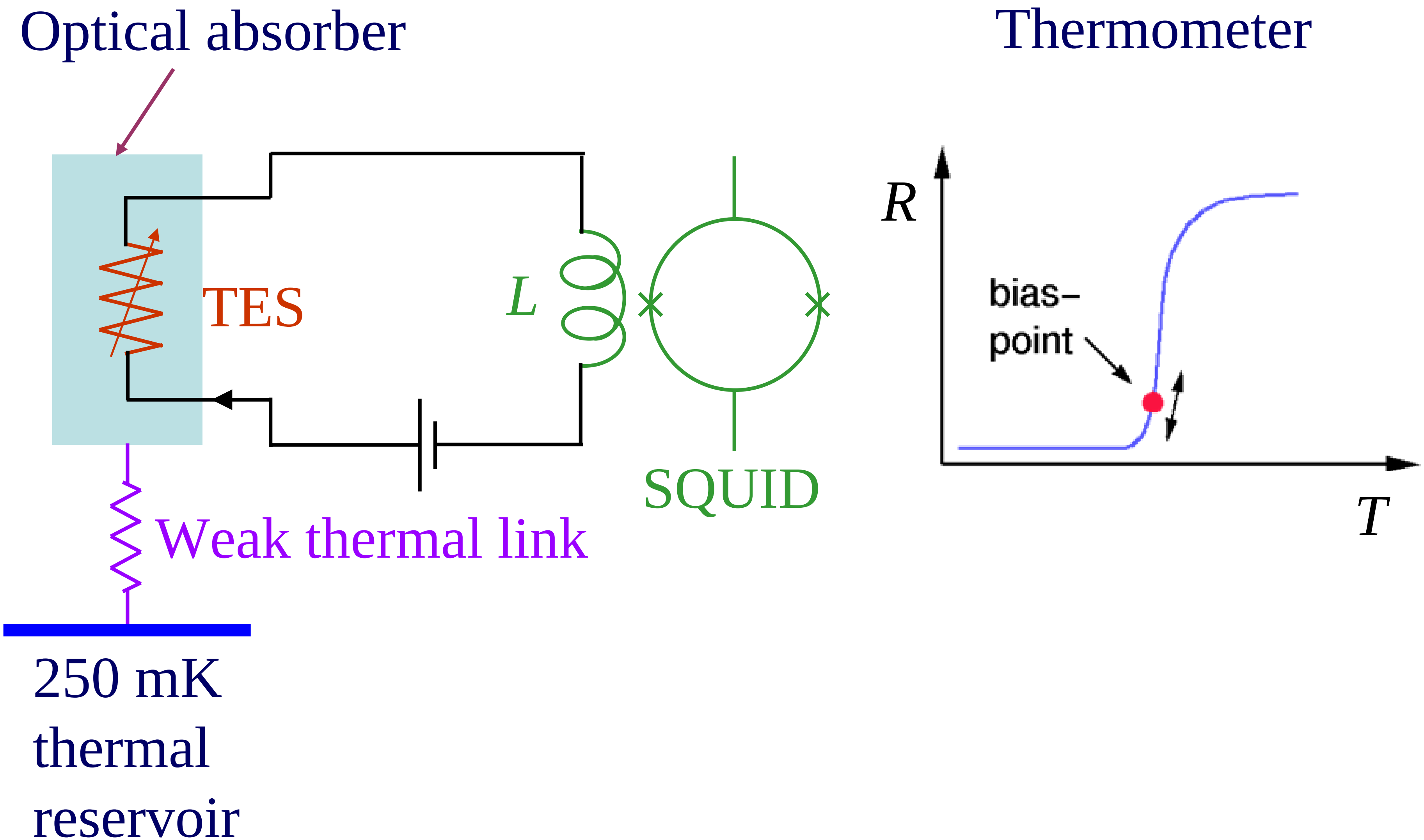
Cosmology:
Searching for Galaxy Clusters

Searching for Galaxy Clusters

Hubble Telescope image of A1689

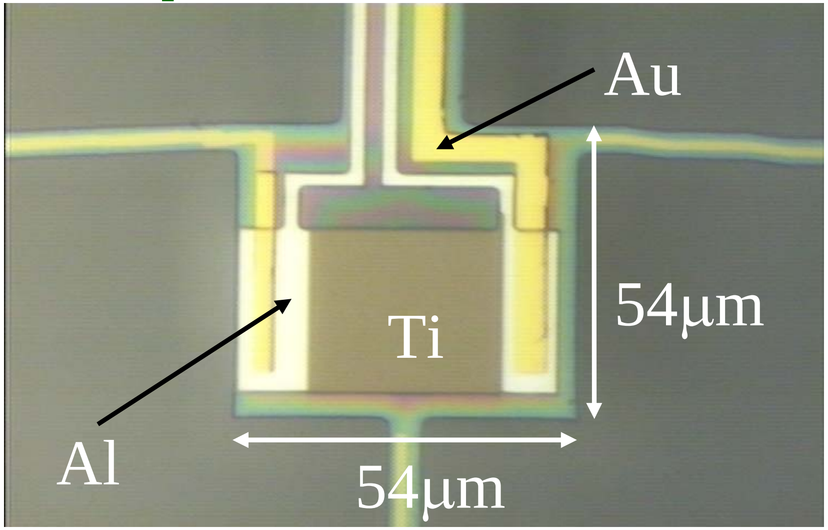
- Several hundred galaxies per galaxy cluster
- Clusters of galaxies, held together by gravity, are the largest objects in the universe ($10^{14} < M_{Sun} < 10^{15}$)
- Galaxy clusters enable one to investigate structure formation on the largest scales in the universe, and test cosmological theories such as equation of state for dark energy
- Search for electromagnetic radiation produced by galaxy clusters in the far infrared (wavelength ~ 1 mm)

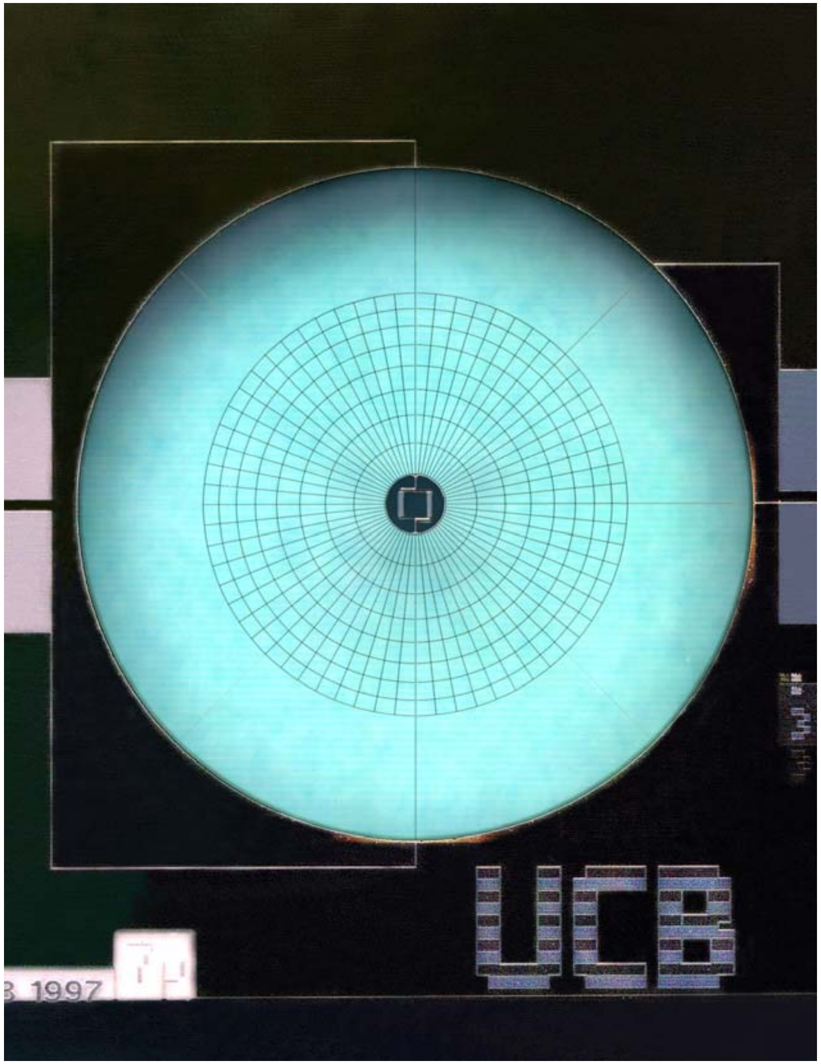
The Transition-Edge Sensor (TES)



Spiderweb Bolometer

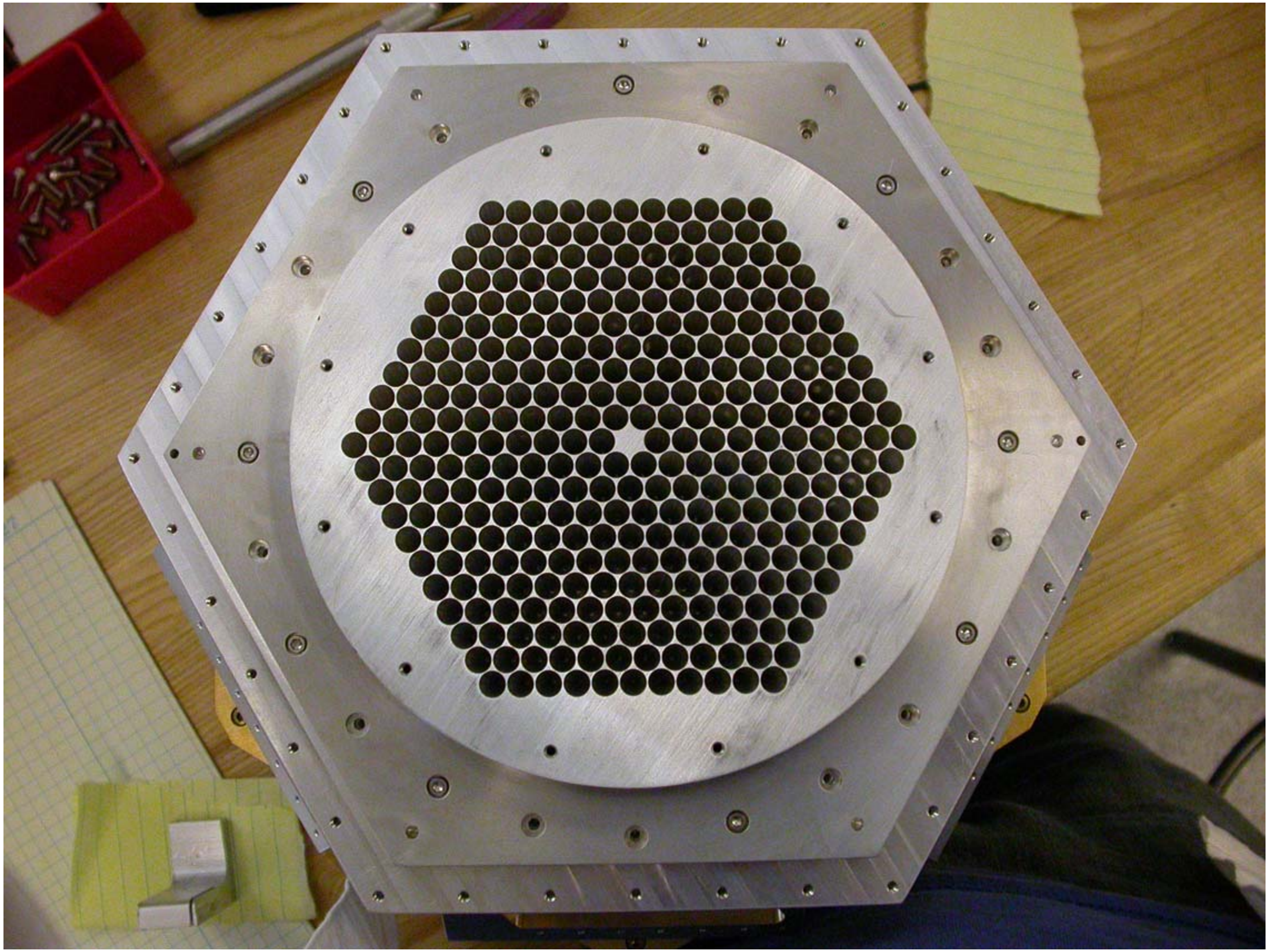
Spiderweb TES bolometer





UCB/LBNL

Horn Array: 330 Elements



UCB/LBNL

SPT (South Pole Telescope)

- Antarctica
- 1000 transition edge sensors
- Goal: locate 1000's of galaxy clusters
- Taking data!

UCB, LBNL, Univ. of Colorado Boulder, Univ. of Chicago, Case Western Reserve Univ., UC Davis, Harvard-Smithsonian, Univ. of Illinois, Jet Propulsion Laboratory

Magnetic Resonance Imaging in Ultralow Magnetic Fields

UCB/LBNL

High Field Magnetic Resonance Imaging

1.5 tesla MRI scanner (GE)
NMR frequency ≈ 64 MHz

- High-field MRI is a wonderful clinical tool
- Highly successful: roughly 22,000 systems worldwide
- Typical cost about $2M
- System is large and heavy—installation costs can exceed cost of the system
- The bore is confining—roughly 10% of the population is not able to be imaged

What if we lowered the magnetic field by a factor of 10,000 to, say, 150 microtesla? –Three Times the Earth's field

- System would be cheaper—eliminating the need for a large, expensive magnet and high installation costs
- It could be less confining
- Could we still obtain magnetic resonance images?

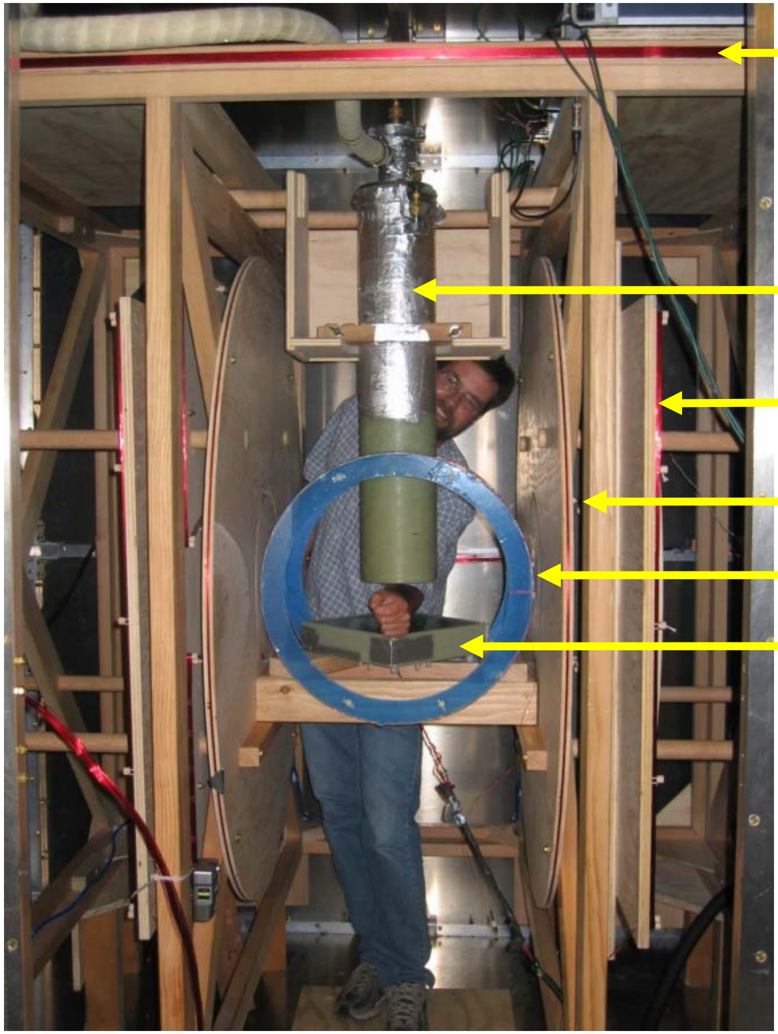
Timeline

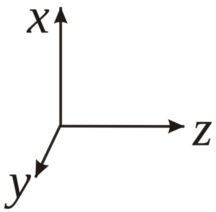
Michael Crichton, 1999

"Most people", Gordon said, "don't realize that the ordinary hospital MRI works by changing the quantum state of atoms in your body ... But the ordinary MRI does this with a very powerful magnetic field – say 1.5 tesla, about twenty-five thousand times as strong as the earth's magnetic field. We don't need that. We use Superconducting QUantum Interference Devices, or SQUIDs, that are so sensitive they can measure resonance just from the earth's magnetic field. We don't have any magnets in there".

“The Cube”

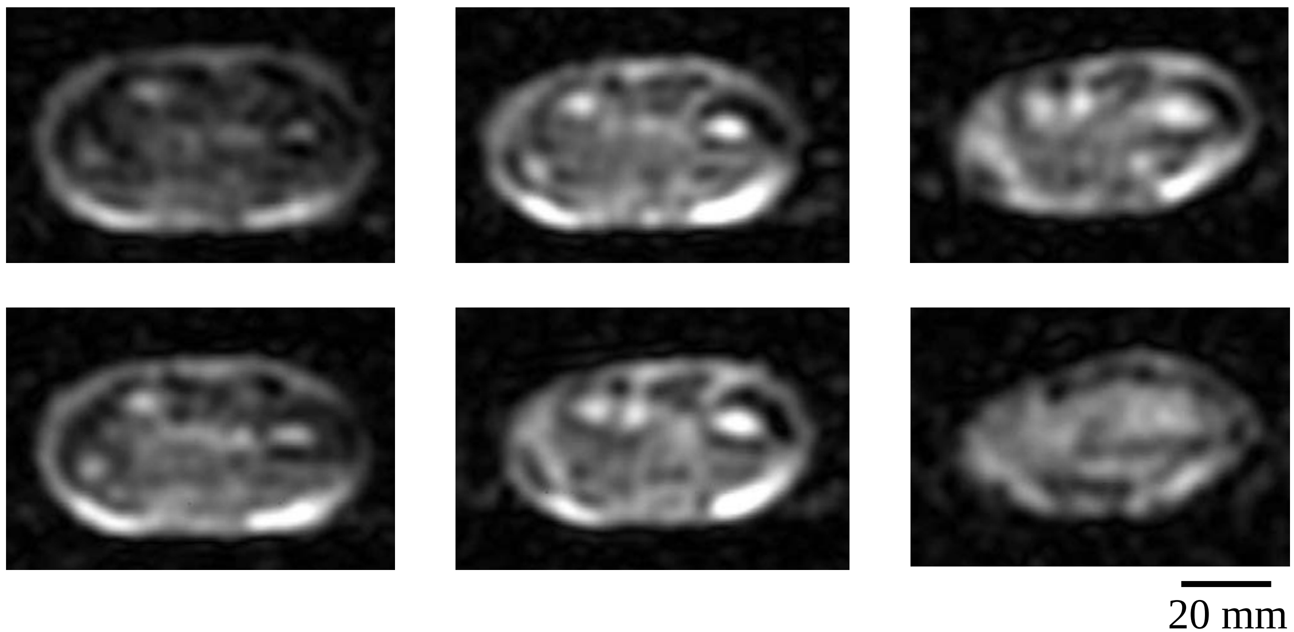
MRI Coil Geometry





- Gradient fields define voxels in space in the same way as in high-field MRI

Three-Dimensional *In Vivo* Images of the Arm



B_0 = 132 μT
B_p = 40 mT
Gradients: 150 μT/m
Acquisition time: 6 min
Slice thickness: 10 mm
In-plane resolution ~ 2mm

Future Prospects

- Microtesla MRI is potentially lower in cost, lower in weight, and more open than conventional MRI.
- It has significantly better capabilities to distinguish different types of tissue–for example tumors and healthy tissue–than high-field MRI.
- Microtesla MRI may have application to screening for cancer, and to monitoring the progression of tumors during treatment.

- A new European Union project is aimed at imaging the brain by combining microtesla MRI with existing 300-channel systems for magnetoencephalography.

Closing Remarks

- Nearly a century after its discovery, superconductivity remains extraordinarily rich in fundamental science as well as in its diverse applications—from the massively large to the exquisitely small.

- Superconducting magnets are essential to both the world's most powerful particle accelerators and systems to image the human body in exquisite detail.

- SQUIDs — the world's most sensitive sensors — make possible an amazing array of scientific measurements, ranging from detecting minute magnetic signals from the human brain to searching for electromagnetic radiation that started its journey through space shortly after the Universe was created.