



# Superconductivity, from discovery to applications

Philippe Lebrun

*CERN*

Visit of CERN Special Award winners from ISEF 2013

24 June 2013



# 1911: First Solvay physics congress, Brussels

« ...to discuss questions pertaining to the kinetic theory of matter  
and the quantum theory of radiation » (Nernst)





# First liquefaction of « permanent » gases: the way to low temperatures



When	What	Temperature [°C]	Temperature [K]	Who	Where
1877	Oxygen (mist)	-183	90	Cailletet	Châtillon-sur-Seine
1877	Oxygen (jet)	-183	90	Pictet	Genève
1883	Oxygen	-183	90	Wroblewski Olszewski	Cracow
1883	Nitrogen	-196	77	Wroblewski Olszewski	Cracow
1898	Hydrogen	-253	20	Dewar	London
1908	Helium	-269	4	Kamerlingh Onnes	Leyden



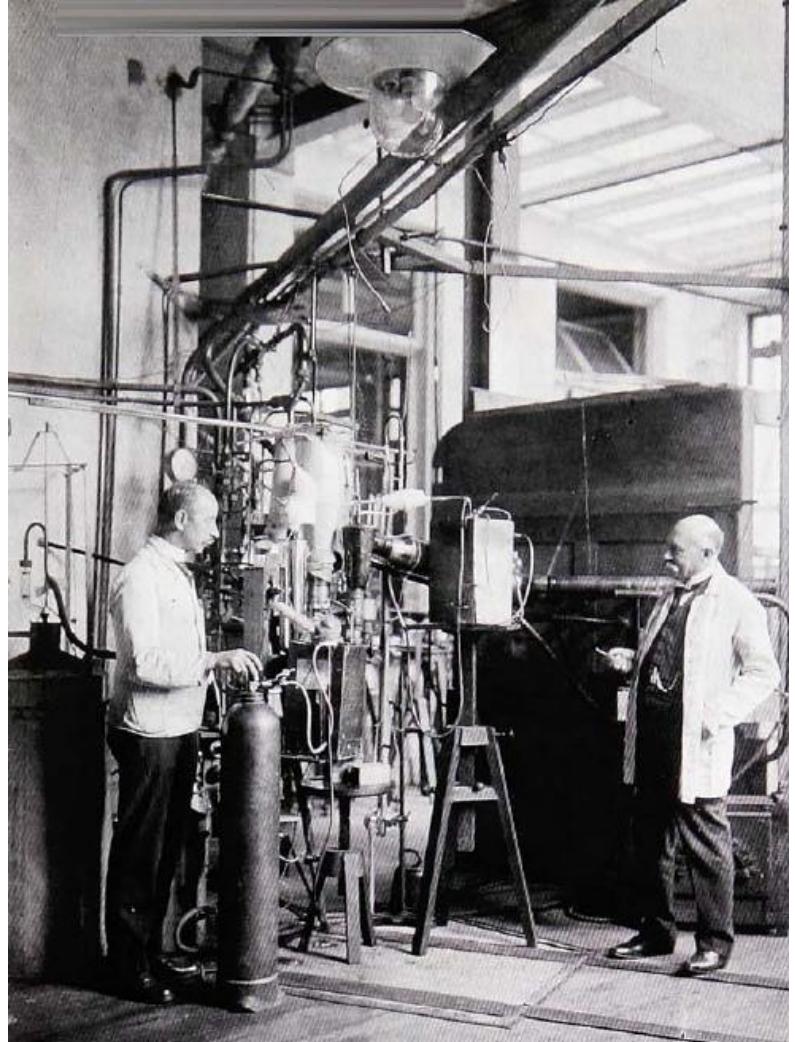
# Liquefaction of helium at Leyden laboratory allows to study matter close to absolute zero



Heike Kamerlingh Onnes



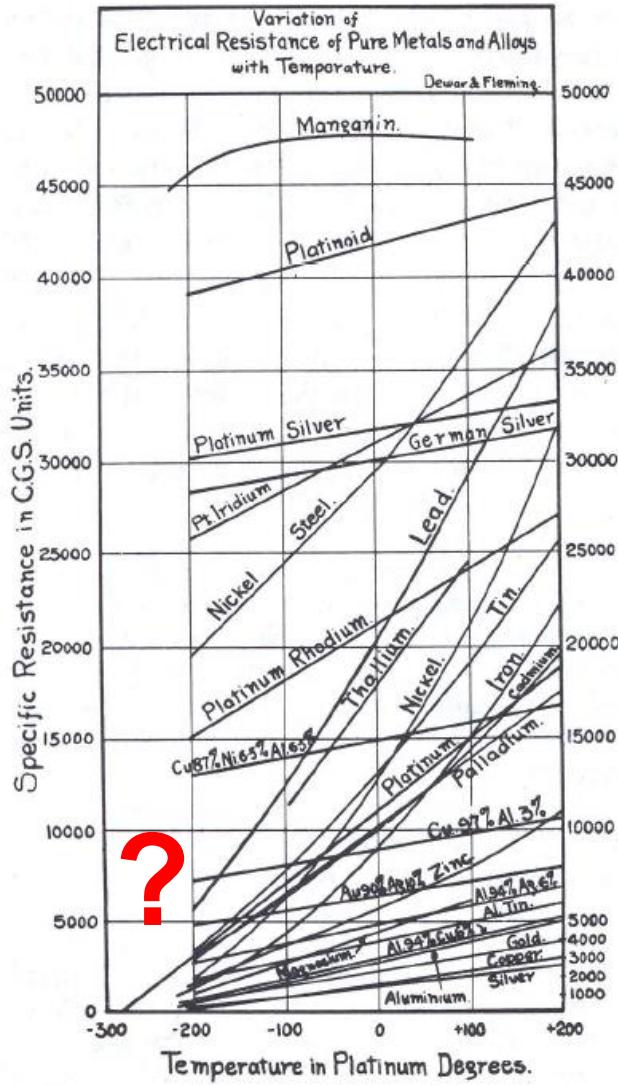
*"Door meten tot weten"*  
Knowledge by measurement



# Dewar studies variation of electrical resistivity of metals and alloys with temperature



James Dewar



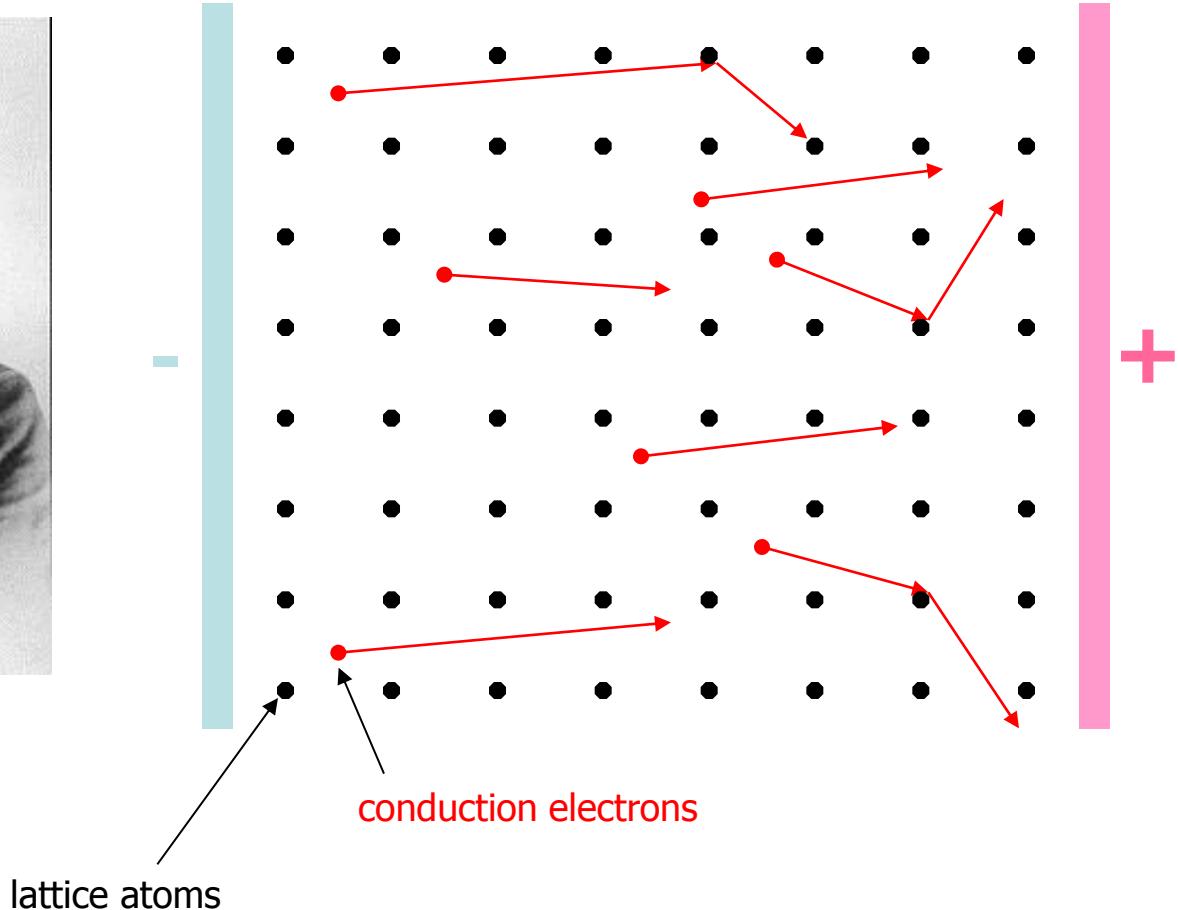
J. Dewar & J.A. Fleming, Phil. Mag. **36** (1893)

# Electrical resistance of pure metals

## Drude's electron gas model (1900)



Paul Drude

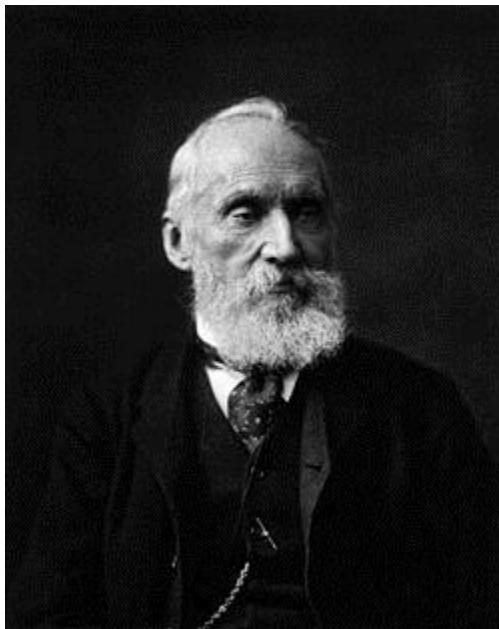


Resistivity of metals increases with temperature (scattering of conduction electrons by vibrations of the crystal lattice)

# William Thomson (Lord Kelvin)

*Aepinus atomized*, Phil. Mag. 3 (1902) 272

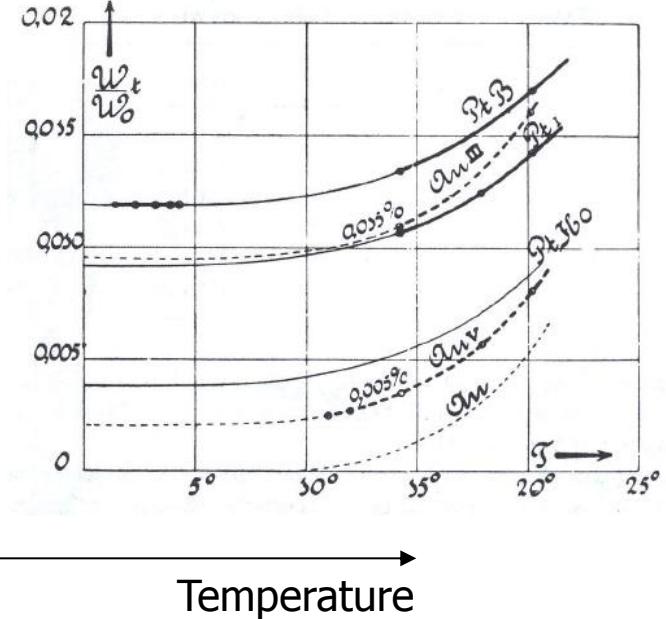
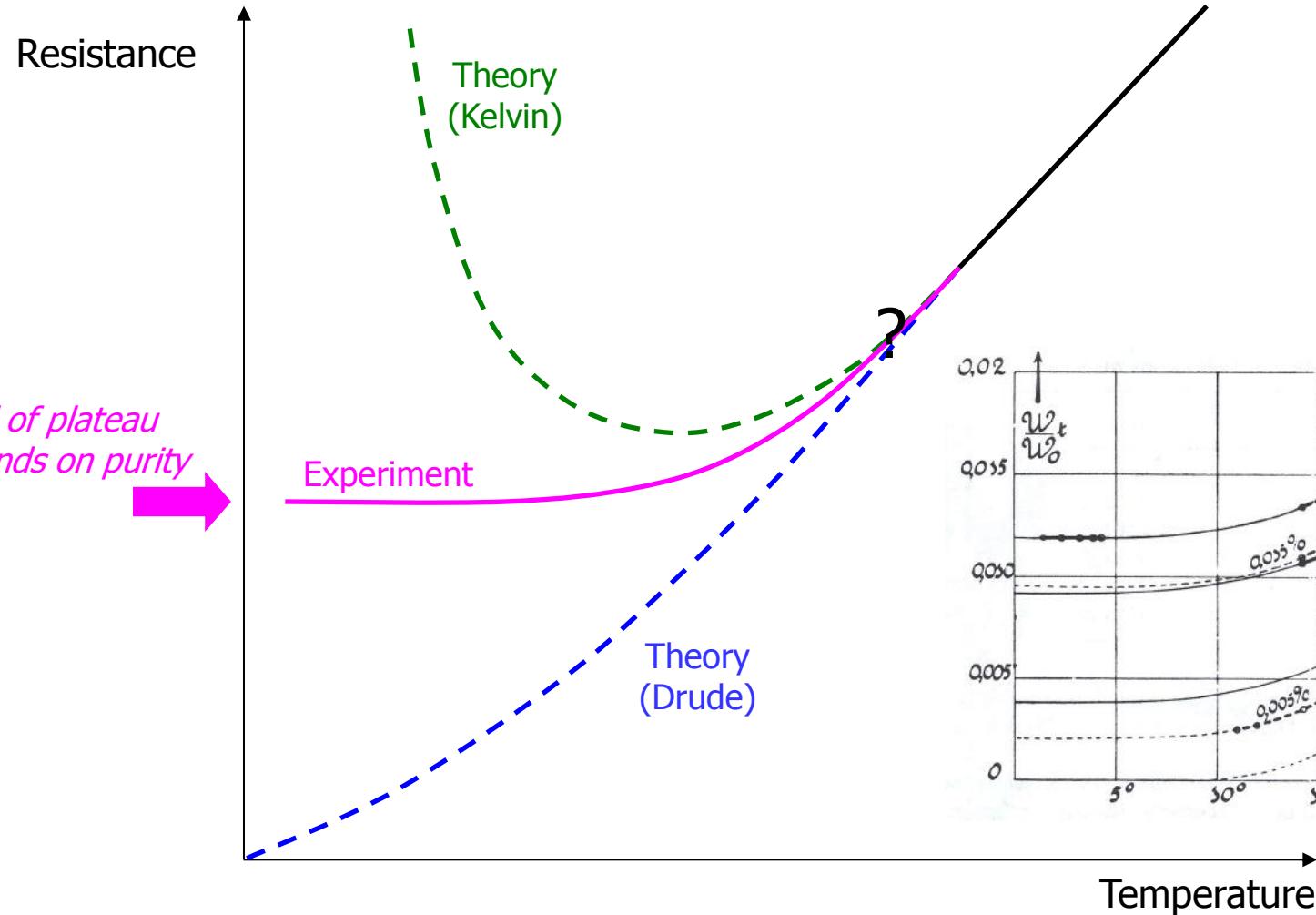
Electrical resistivity of metals increase as one approaches absolute zero  
(the « gas » of conduction electrons « condenses » on the atoms)



§ 27. Consider lastly a solid; that is to say, an assemblage in which the atoms have no relative motions, except through ranges small in comparison with the shortest distances between their centres. The first thing that we remark is that **every solid would, at zero of absolute temperature** (that is to say all its atoms and electrons at rest), **be a perfect insulator of electricity under the influence of electric forces, moderate enough not to pluck electrons out of the atoms** in which they rest stably when there is no disturbing force.

§ 29. Raise the temperature now to anything under that at which the solid would melt. This sets the **electrons** to performing wildly irregular vibrations, so that some of them will occasionally be shot out of their atoms. Each **electron** thus shot out will quickly either fall back into the atom from which it has been ejected, or will find its way into another atom. If the body be in an electric field  $F$ , a considerable proportion of the **electrons** which are shot out will find their way into other atoms in the direction in which they are pulled by  $F$ ; that is to say, the body which was an infinitely perfect insulator at zero absolute temperature has now some degree of electric conductivity, which is greater the higher the temperature.

# Electrical resistance of metals

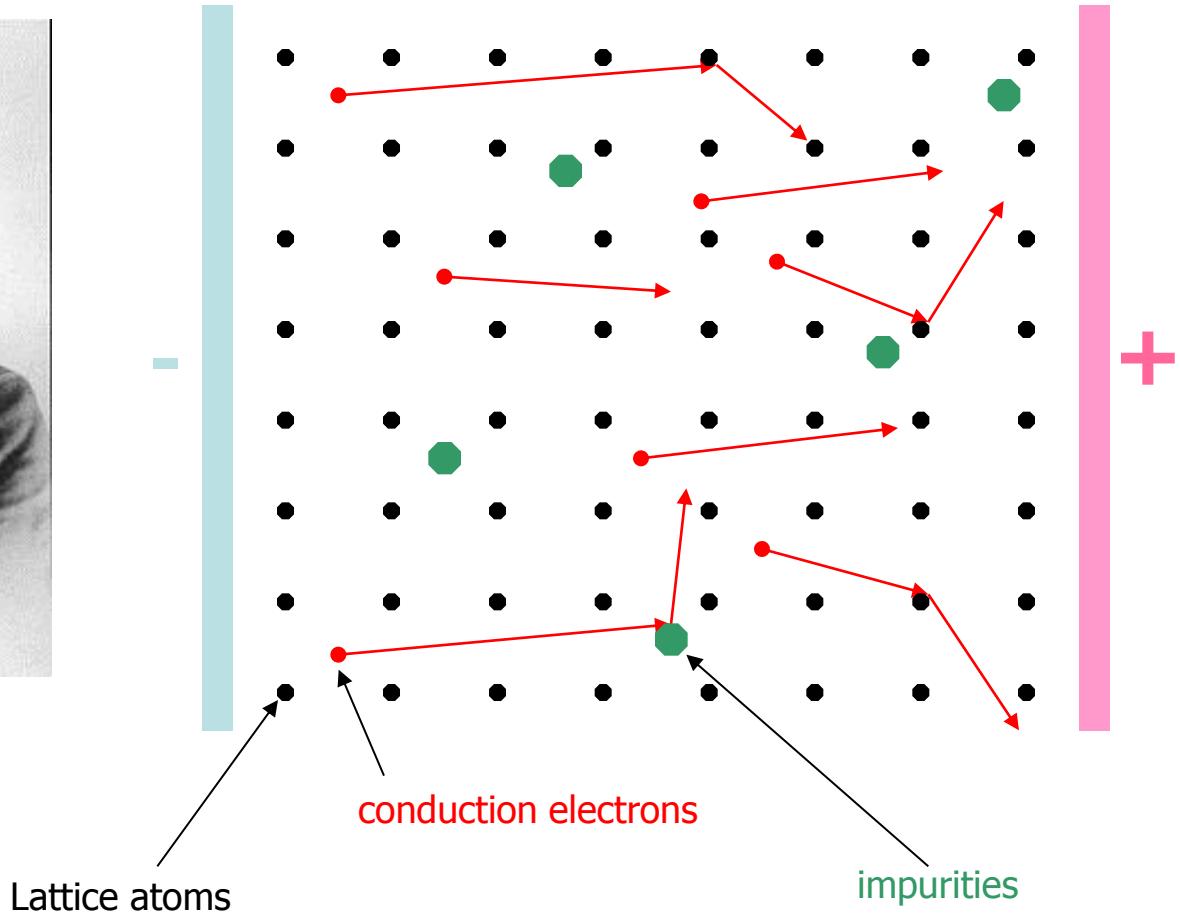


# Electrical resistance of real metals

## Drudes's electron gas model and Mathiessen's rule

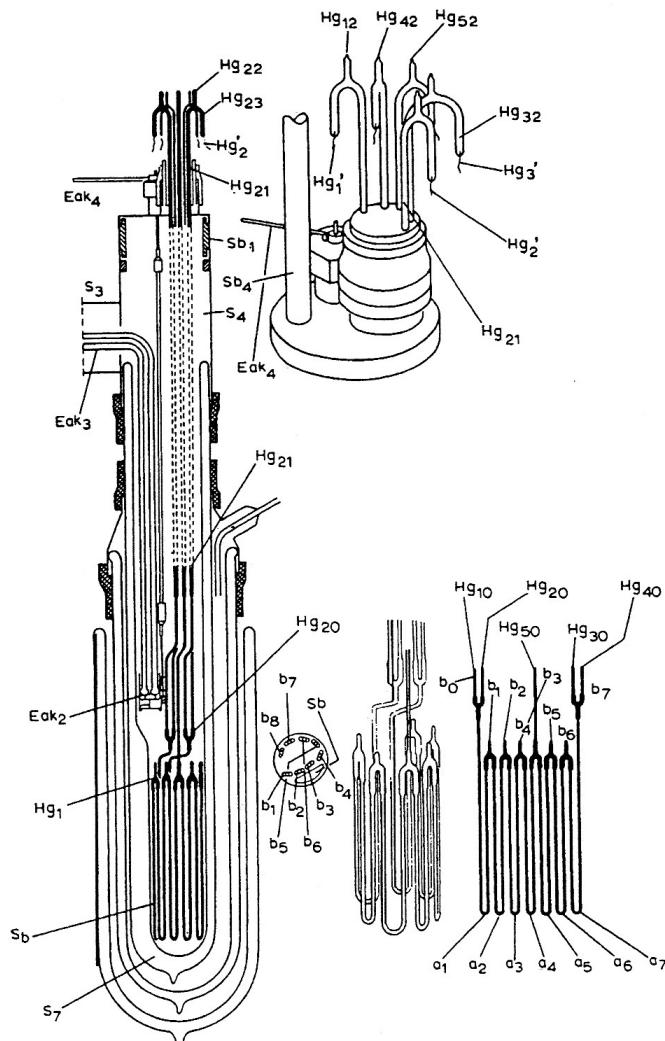


Paul Drude



Resistivity of metals increases with temperature (scattering of conduction electrons by vibrations of the crystal lattice) and with impurity content (scattering of conduction electrons by foreign atoms)

# Onnes' measurement of electrical resistivity of mercury at low temperature



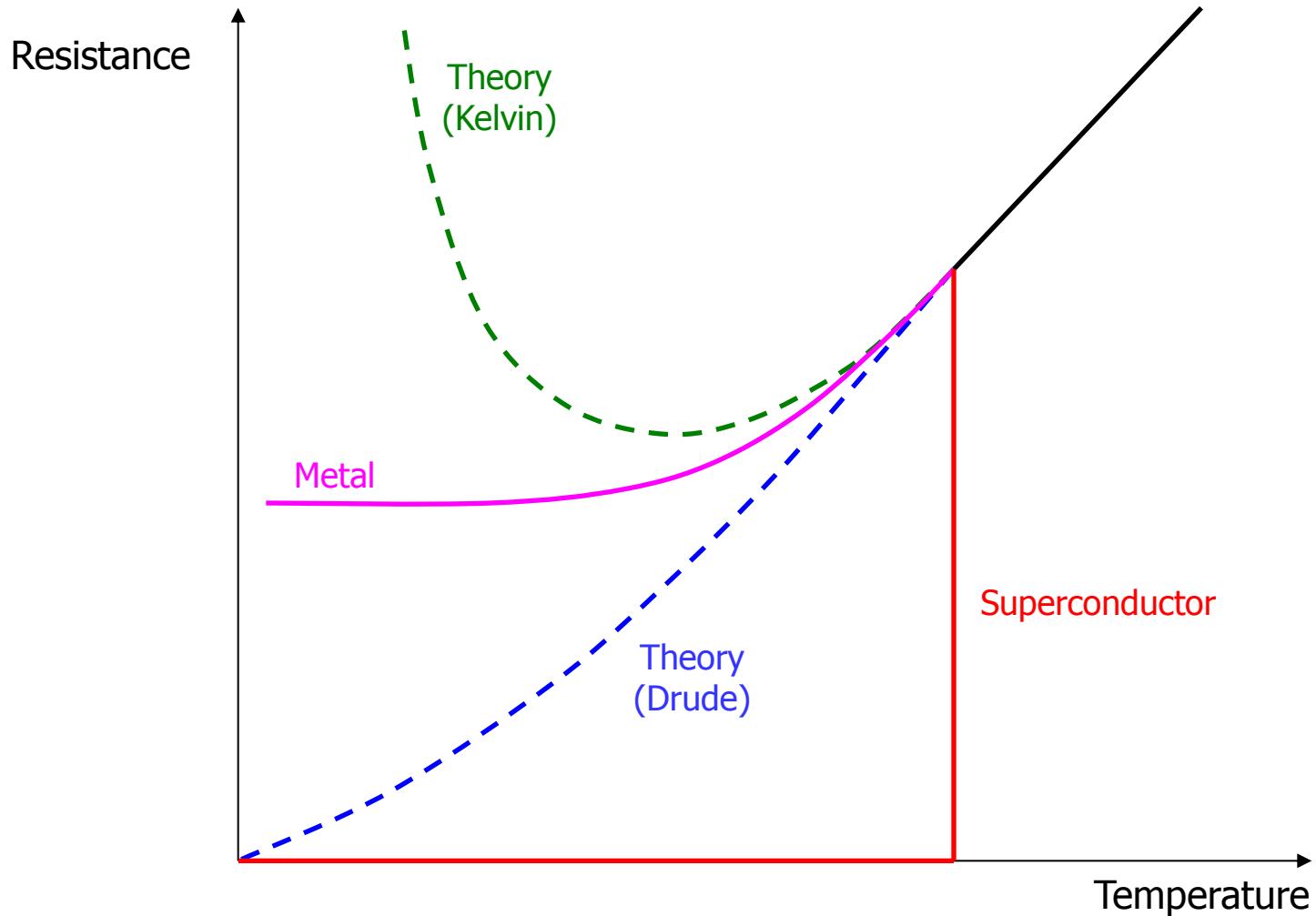
To study properly the effect of temperature, the sample must be free from impurities

Mercury, a metal in the liquid state at room temperature, can be easily purified by distillation (it boils at 357 °C)

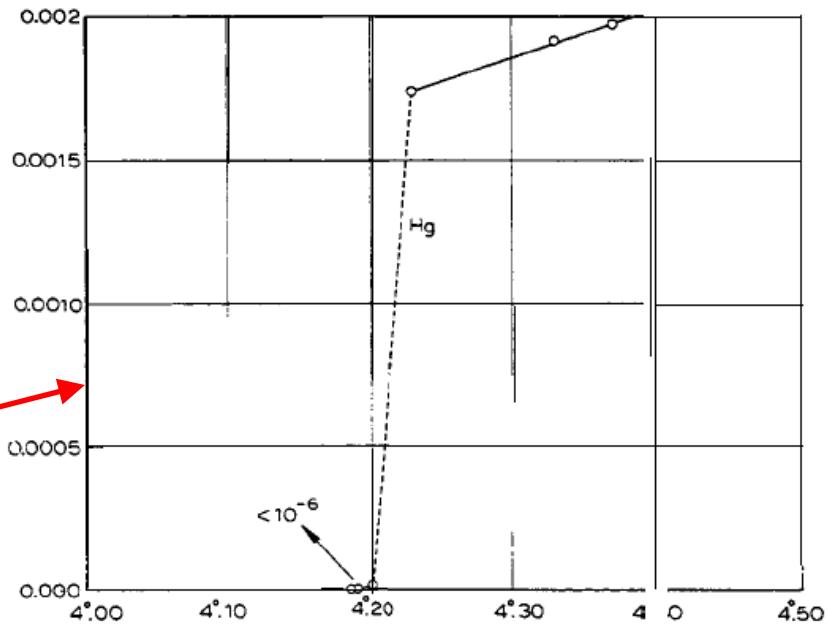
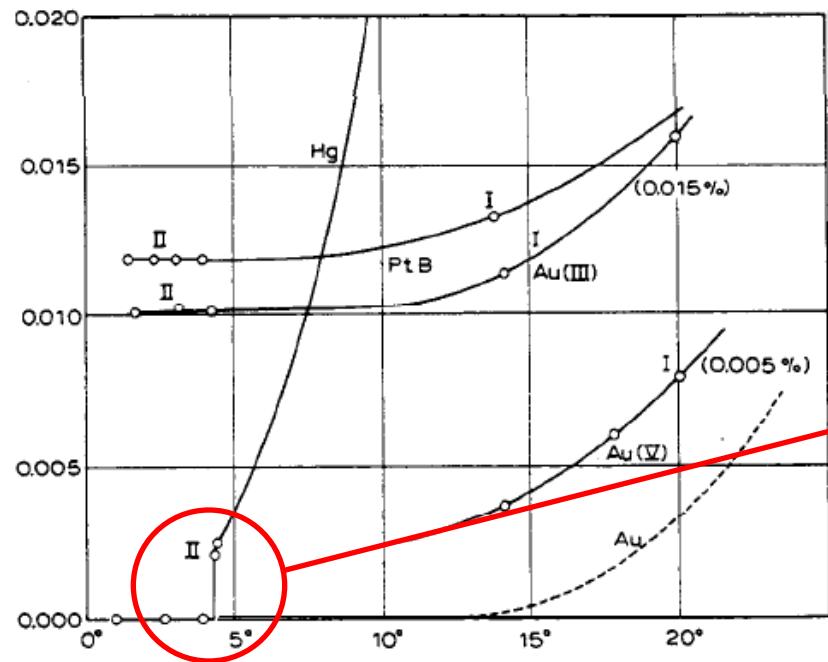
H.K. Onnes produced « wires » of mercury by filling glass tubes with connection electrodes: the « wires » get solid upon cooling at -39 °C



# Sudden disappearance of electrical resistance

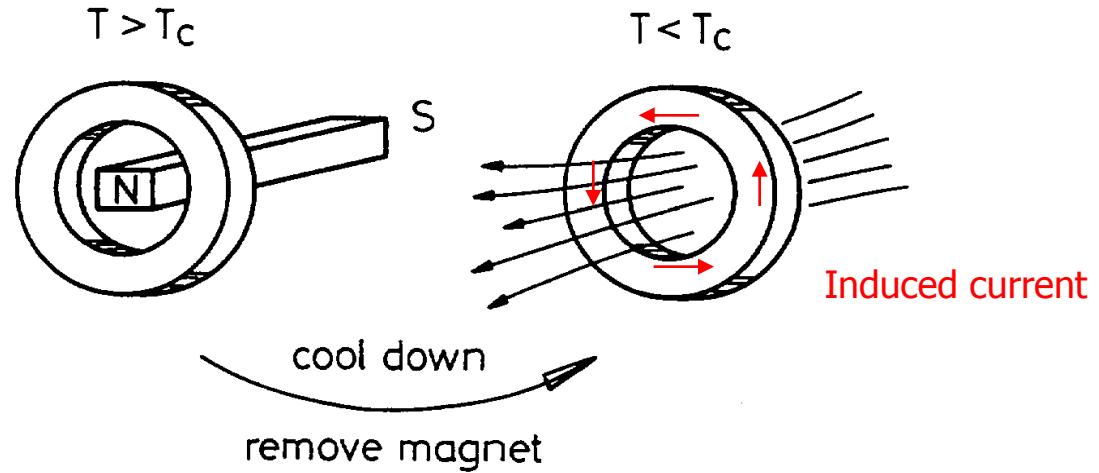


# Discovery of superconductivity (1911)



Thus the mercury at 4.2°K has entered a new state, which, owing to its particular electrical properties, can be called the state of superconductivity.

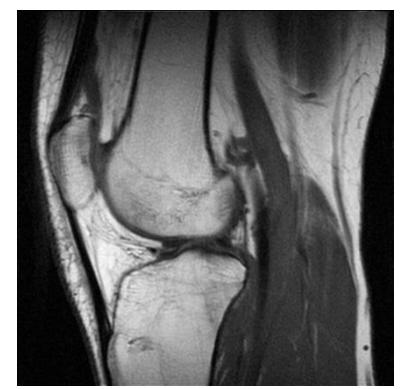
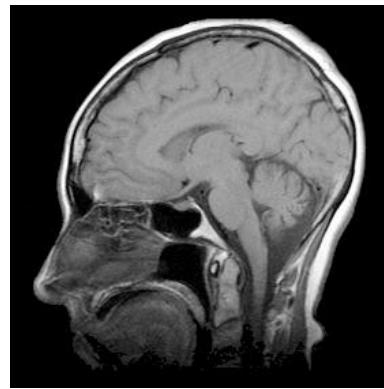
# A superconductor shows zero resistance



The current induced in a ring of superconducting material flows without losses almost indefinitely. Measurements showed a typical time constant for current decay of 100'000 years, i.e. a few billionths per hour!



# Superconducting magnets for MRI use the stability of « persistent » currents



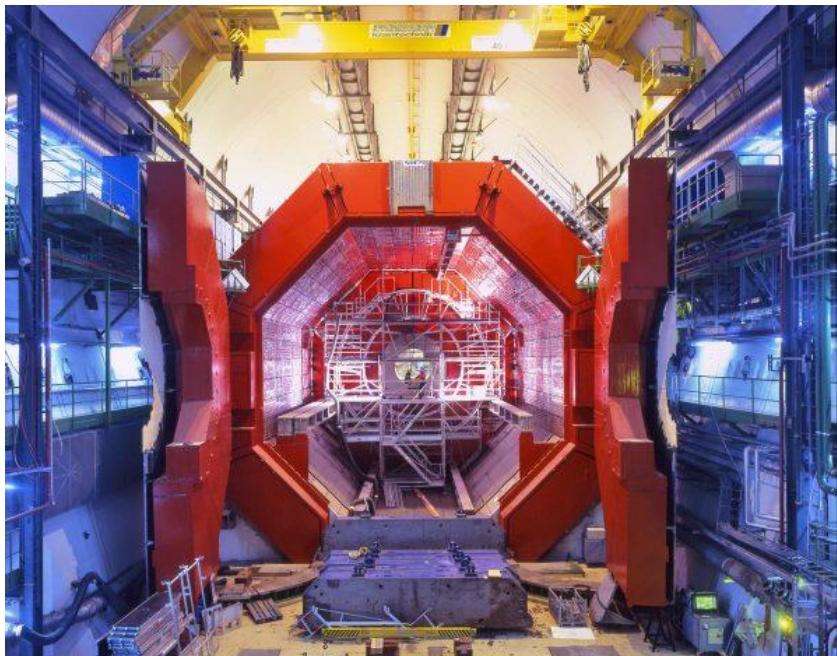
# Saving energy

## No resistance = no losses

Superconducting devices do not exhibit Joule losses. The refrigeration system which keeps them cold however consumes energy

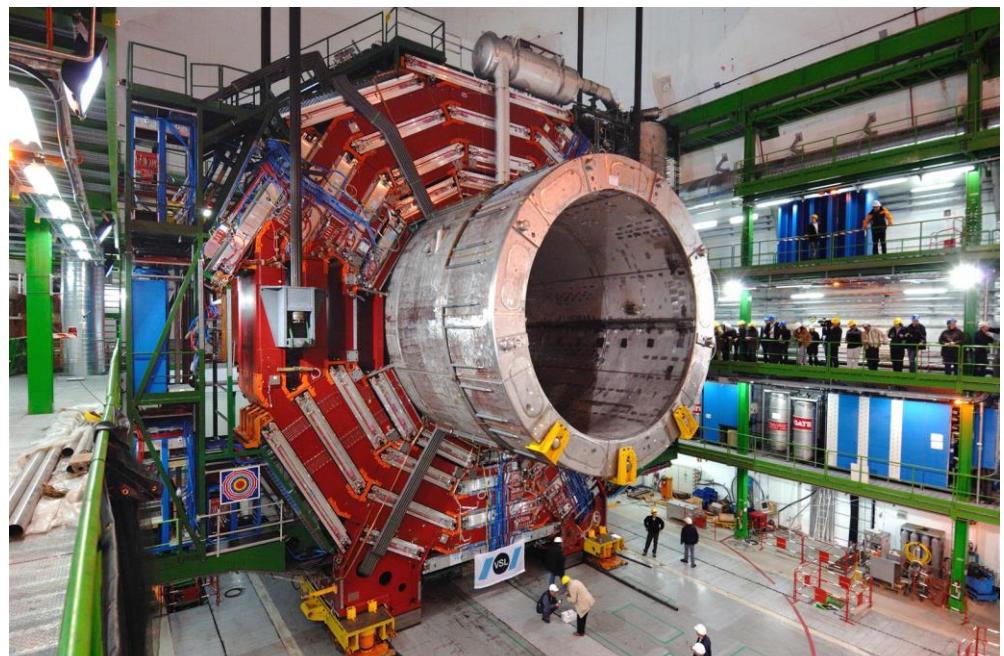
ALICE experiment at CERN

« Classical » electromagnet uses 4.2 MW

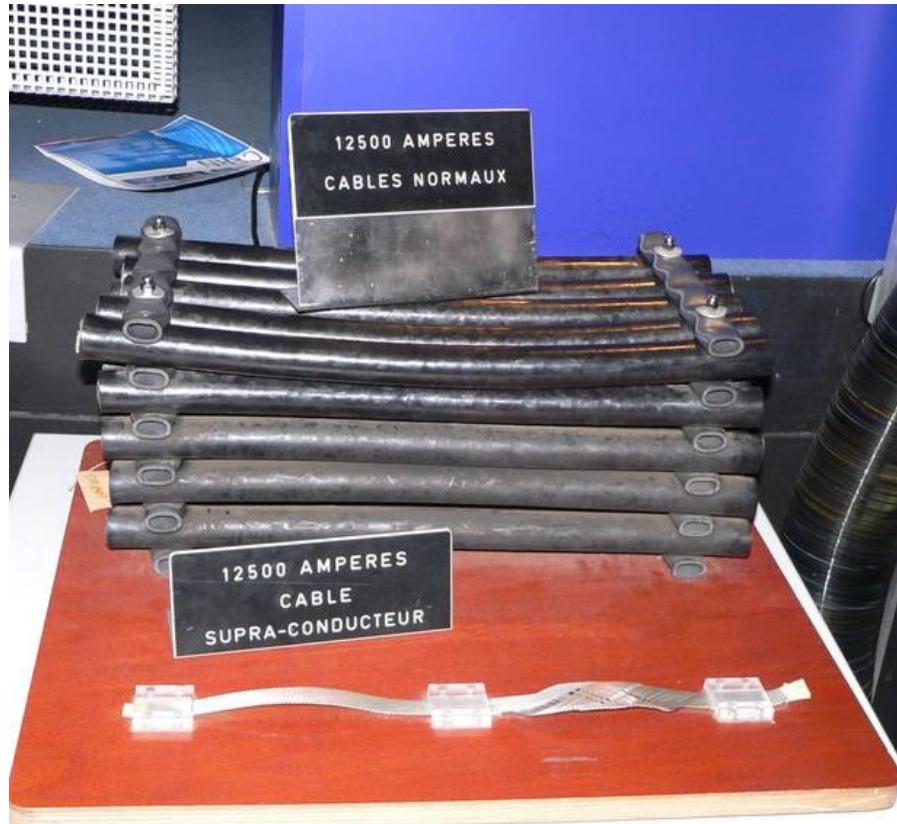


CMS experiment at CERN

Superconducting magnet with refrigerator of 0.5 MW



# Saving materials



**No resistance = no losses**

**No losses → high current density**

In absence of losses, superconductors do not heat, so that higher currents can be transported in the same cross-section of material

- Copper:  $\sim \text{A/mm}^2$
  - Superconductor:  $\sim \text{kA/mm}^2$
- $\Rightarrow$  *factor 1000*



## Onnes immediately tries to use superconductivity for making high-field magnets...



dendum 2.) There is also the question as to whether the absence of Joule heat makes feasible the production of strong magnetic fields using coils without iron, \* for a current of very great density can be sent through very fine, closely wound wire spirals. Thus we were successful in sending a current of 0.8 amperes, i.e. of 56 amperes per square millimetre, through a coil, which contained 1,000 turns of a diameter of 1/70 square mm per square centimetre at right angles to the turns.

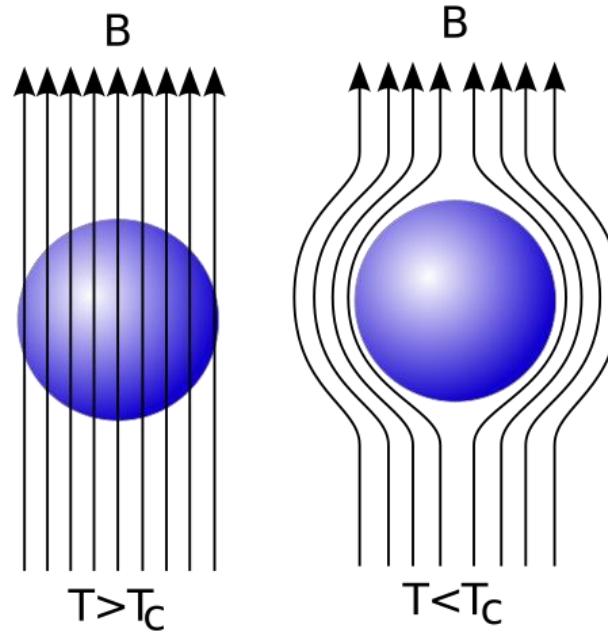
**...but stumbles upon their « critical field »!**

after this lecture was given and produced surprising results. In fields below a threshold value (for lead at the boiling point of helium 600 Gauss), which was not reached during the experiment with the small coil mentioned in the text, there is no magnetic resistance at all. In fields above this threshold value a relatively large resistance arises at once, and grows considerably with the field. Thus in an unexpected way a difficulty in the production of intensive magnetic fields with coils without iron faced us. The discovery of the

# Discovery of the Meissner effect (1933)



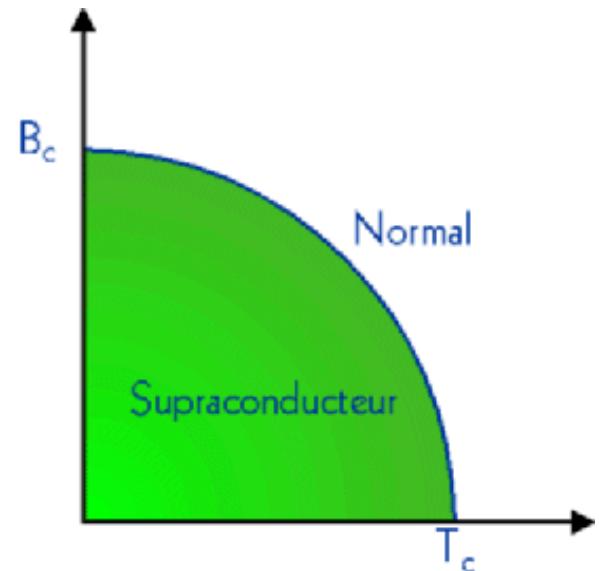
Walther Meissner



A superconductor excludes magnetic field from its interior

Application of a magnetic field above a limit value  $B_c$  destroys superconductivity

The superconducting state only exists in a limited domain of temperature and magnetic field

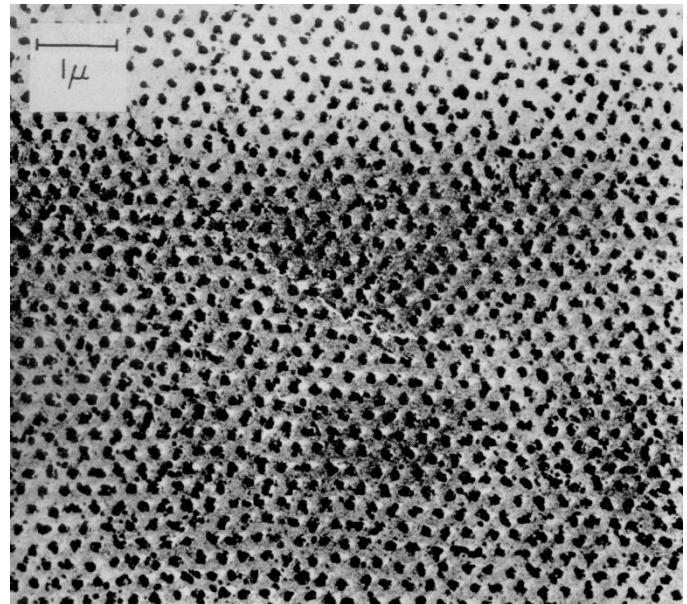
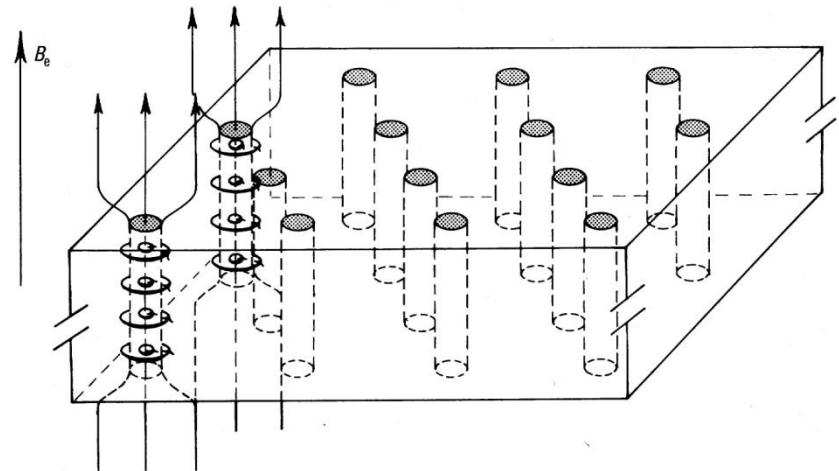
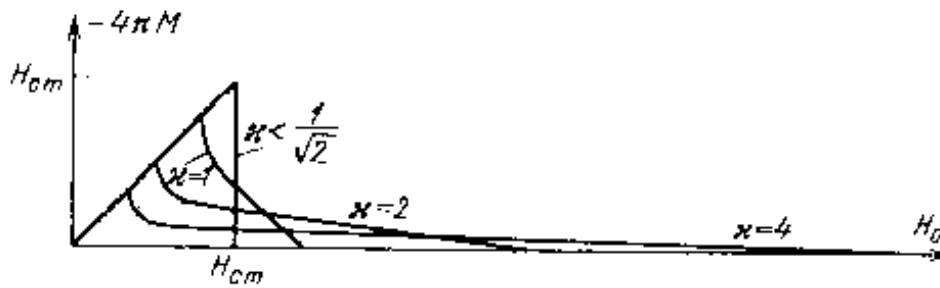


# (Limited) penetration of the magnetic field

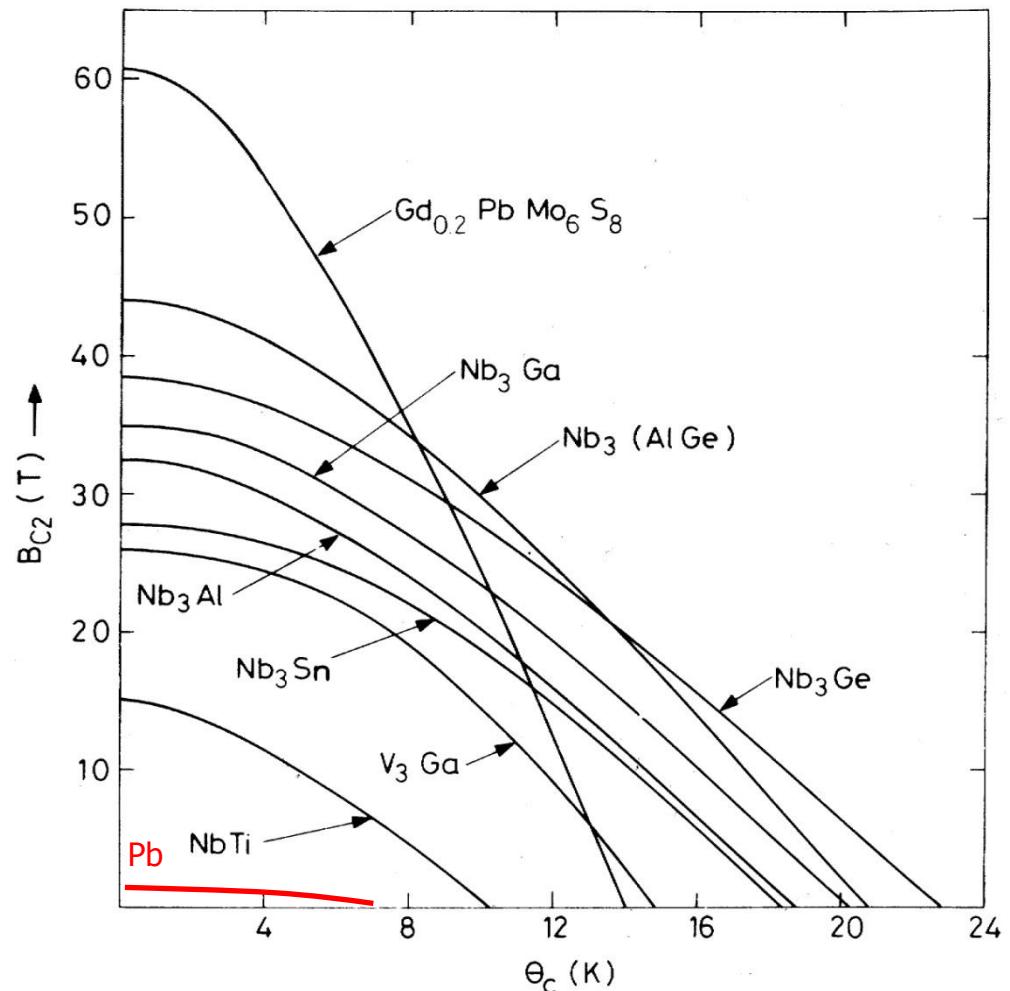
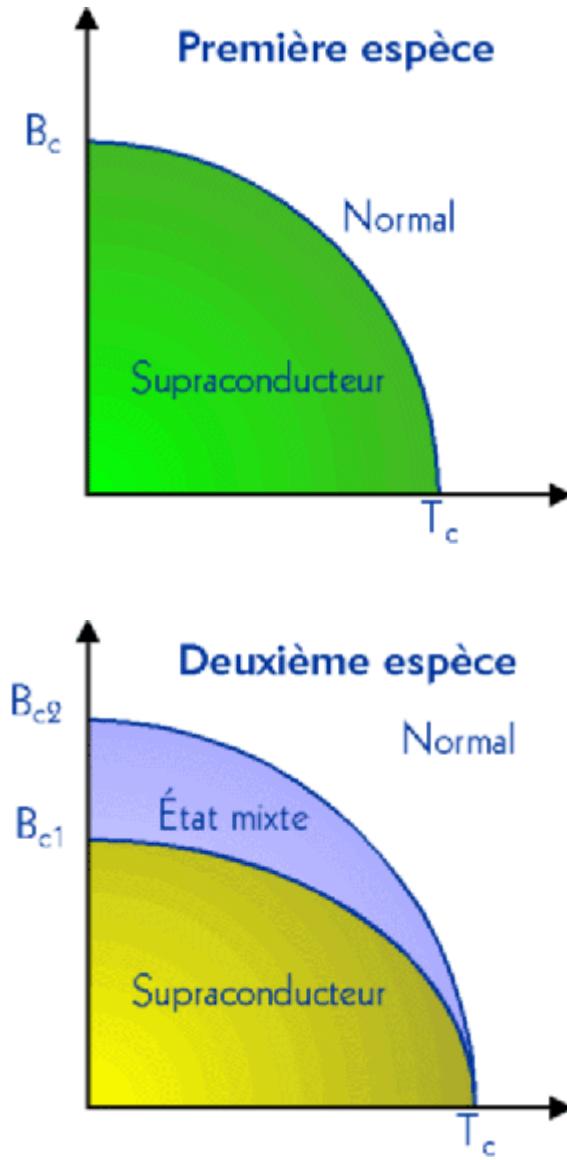
## The « mixed » state of type II superconductors (1954)



Alexei Abrikosov



# Type II superconductors are practical materials





# The first « high-field » superconducting magnet (1960)



April 14, 1964

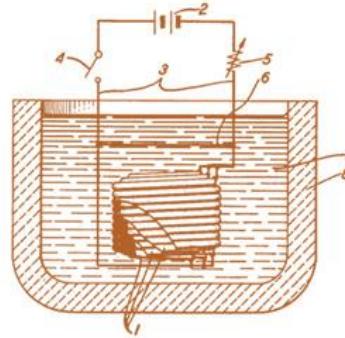
J. E. KUNZLER

3,129,359

SUPERCONDUCTING MAGNET CONFIGURATION

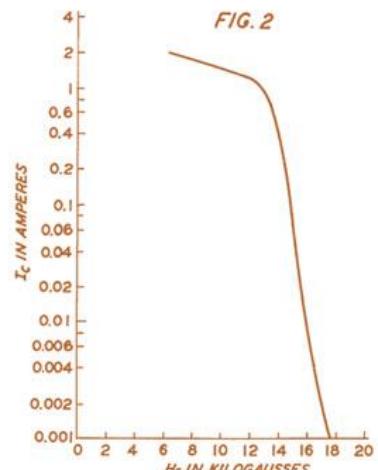
Filed Sept. 19, 1960

FIG. 1



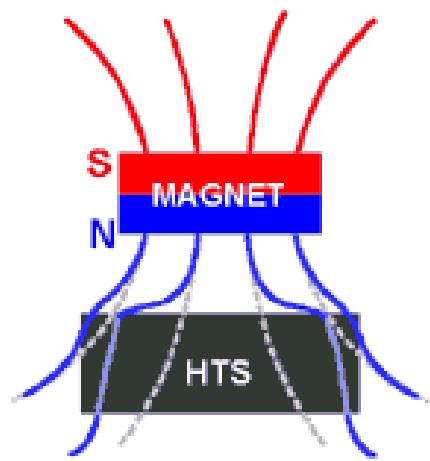
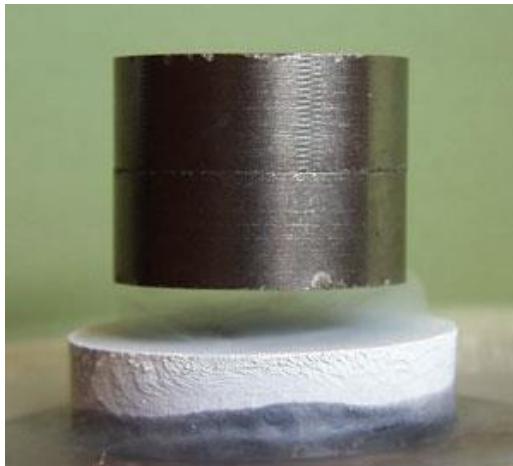
Patent 1960 (registered 1964) by J. Kunzler of Bell Laboratories

The magnet wound with a molybdenum-ruthenium wire reaches 1,5 T (15'000 gauss)



INVENTOR  
BY J. E. KUNZLER  
George S. Brady  
ATTORNEY

# An application of the Meissner effect and the « mixed » state: magnetic levitation



« Floating » magnet experiment

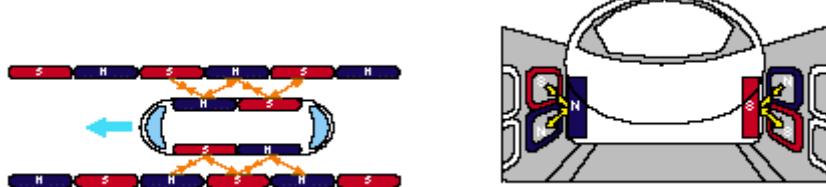
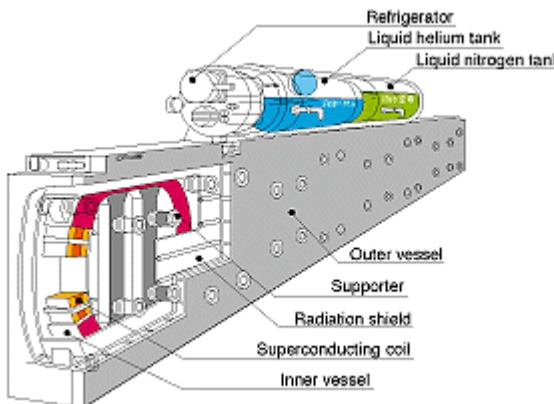


142 kg sumotori + 60 kg  
magnetized disk = 202 kg levitated



# Superconducting magnet levitation train

## Yamanashi test line of JNR (550 km/h)





# Microscopic theory of superconductivity (1957)



PHYSICAL REVIEW

VOLUME 108, NUMBER 5

DECEMBER 1, 1957

## Theory of Superconductivity\*

J. BARDEEN, L. N. COOPER,<sup>†</sup> AND J. R. SCHRIEFFER<sup>‡</sup>  
*Department of Physics, University of Illinois, Urbana, Illinois*

(Received July 8, 1957)

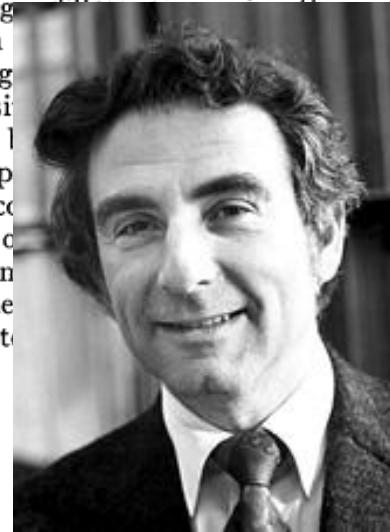
A theory of superconductivity is presented, based on the fact that the interaction between electrons resulting from virtual exchange of phonons is attractive and less than the energy,  $\hbar\omega$ . In this attractive Coulomb interaction individual-pair formation is formed from in which electron and moment amount properties of isotopes effect

the energy of the conducting electrons. The repulsion described by the state of a superconductor is due to the normal state consisting of pairs of electrons in the normal state ( $\psi^2$ ), consisting of excited

one-to-one correspondence with those of the normal phase is obtained by specifying occupation of certain Bloch states and by allowing the electrons to form a d-wave combination of orbital pair conservation and transition and Calculated their temperature. There is a decrease of matrix elements of excited-state transition given.



John Bardeen

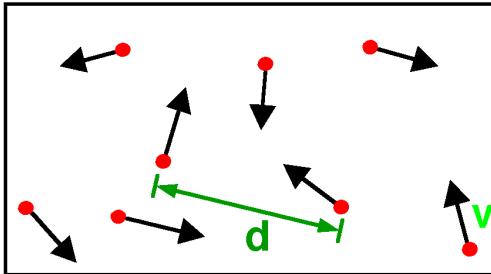


Leon Neil Cooper

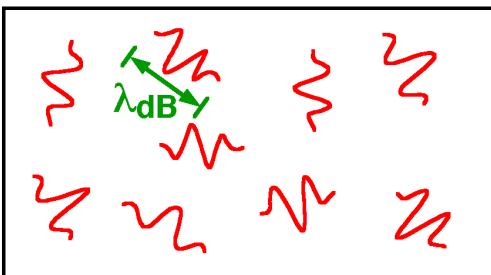


John Robert Schrieffer

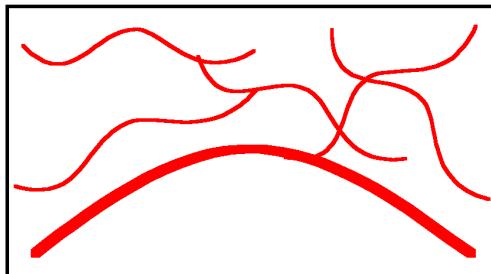
# A gas of quantum particles



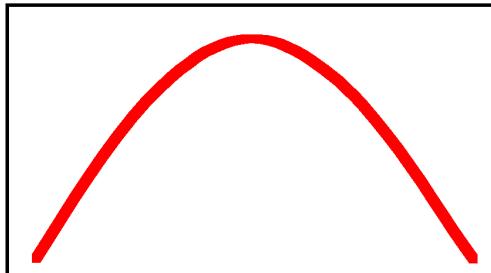
At high temperature, the particles behave as hard « billiard balls », independant from each other



At low temperature, the particles behave as « wave packets », with fuzzy contours but still preserving their individuality



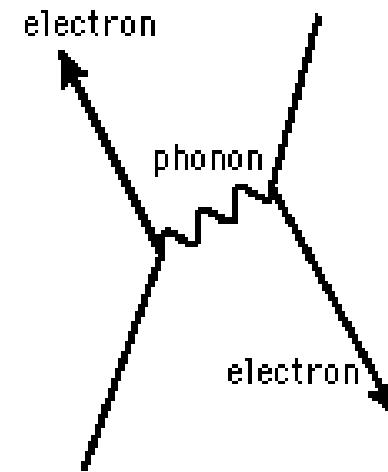
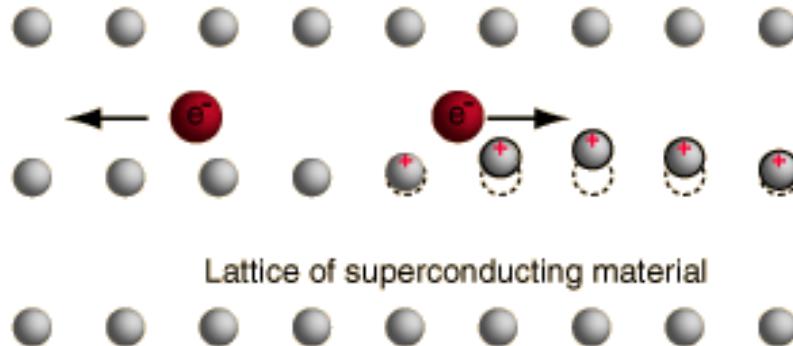
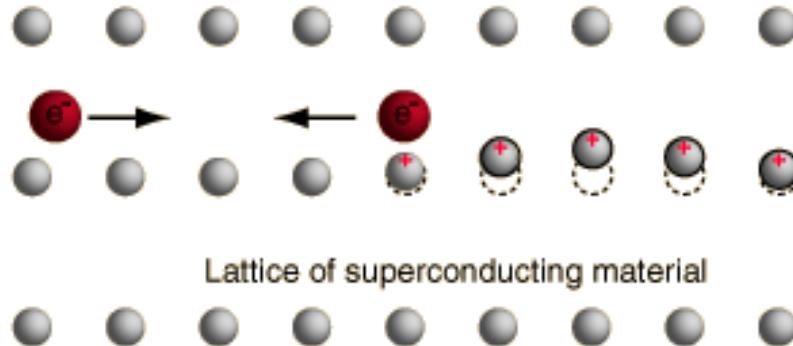
Below a « critical » temperature, the wave packets tend to overlap and lose their individuality: the behaviour of the particles is strongly correlated; if they are «bosons» (particles of integer spin), they tend to «condense» in the lowest-energy state



At absolute zero, all particles are in the « condensed » state and show identical behaviour

From W. Ketterle

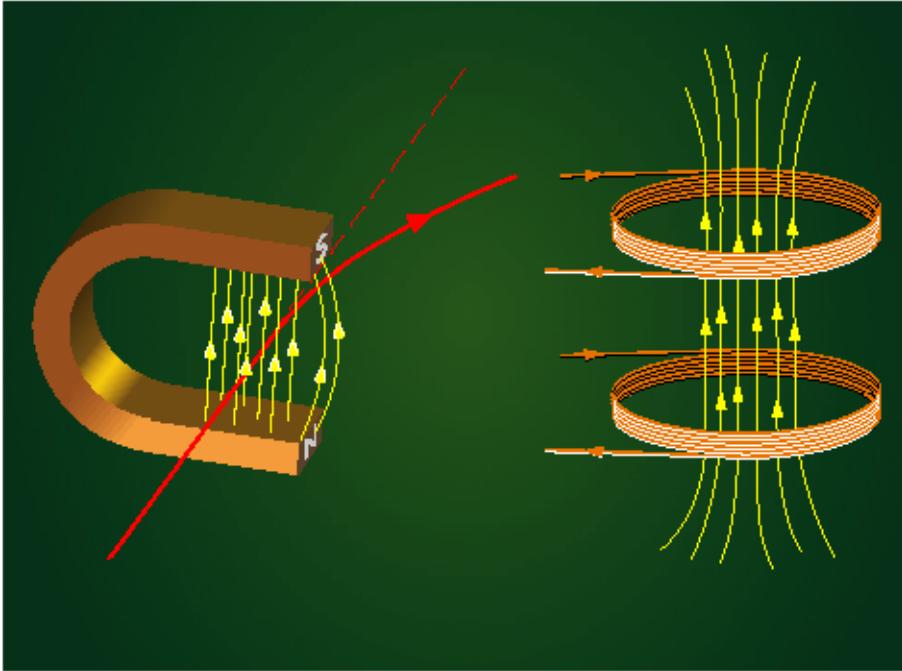
# Formation of electron pairs



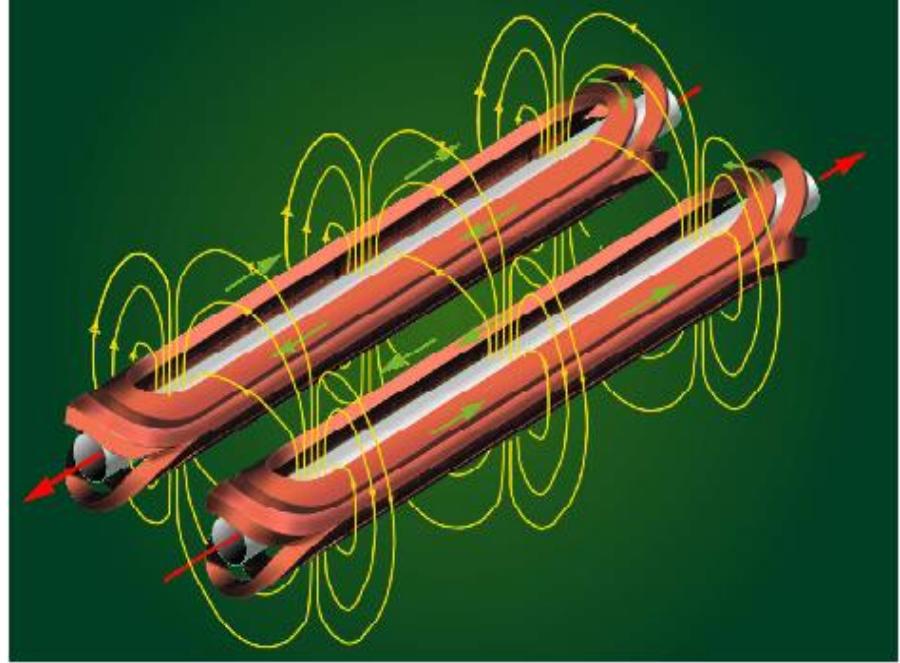
Electrons (fermions) get coupled by the lattice vibrations (so-called « phonons ») thus constituting « Cooper pairs », thus behaving as bosons

The current carriers in a superconductor are the Cooper pairs

# Superconducting magnets for particle accelerators



In a particle accelerator, electromagnets produce fields for guiding and focussing the beams



Superconducting magnet coils fit along the beam pipes to produce a high magnetic field in the useful volume

Superconductivity permits to produce higher fields for reducing the size and the electrical energy consumption of accelerators

# The Tevatron at Fermilab (Chicago)

## The first superconducting particle accelerator



Started operation in 1983

Circumference 6,3 km

Magnetic field 4,4 T

990 main superconducting magnets, cooled  
at 4,4 K by supercritical helium





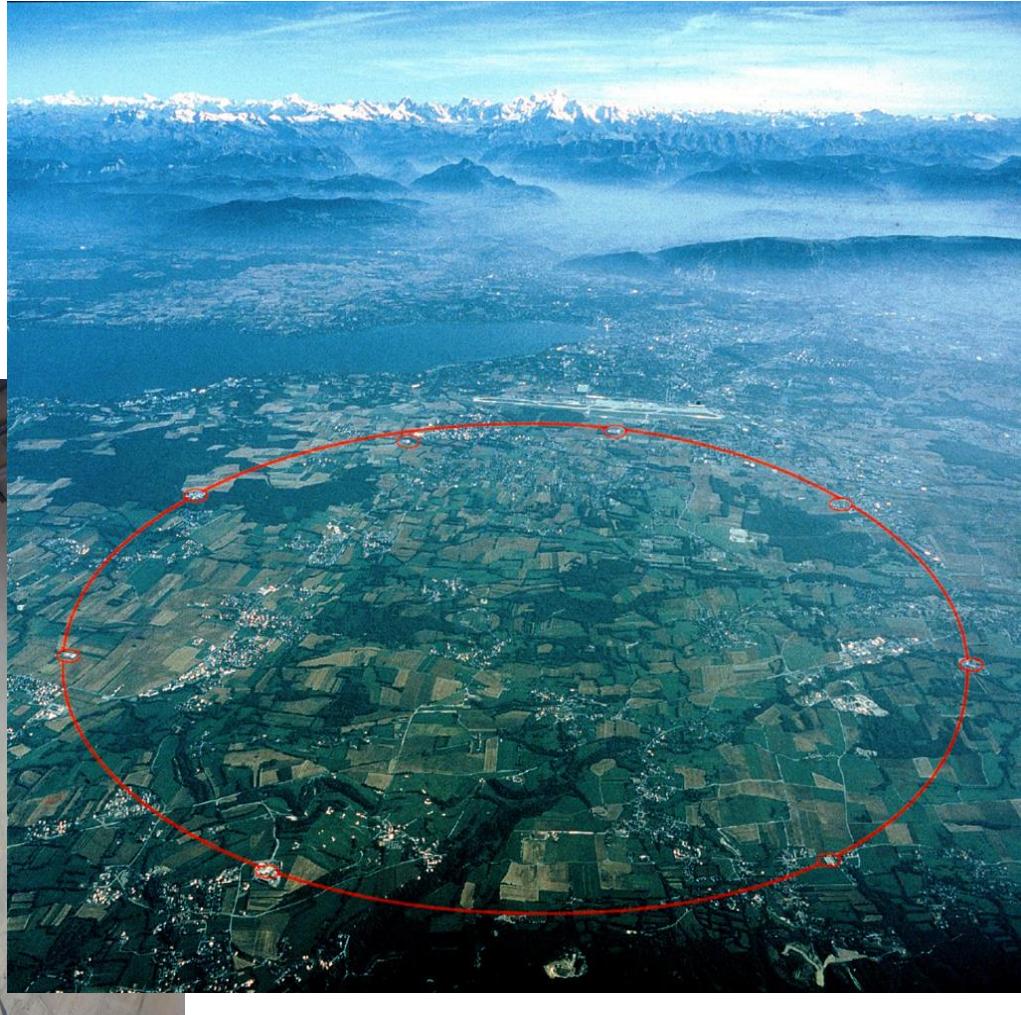
# The LHC at CERN

## The largest scientific instrument in the world

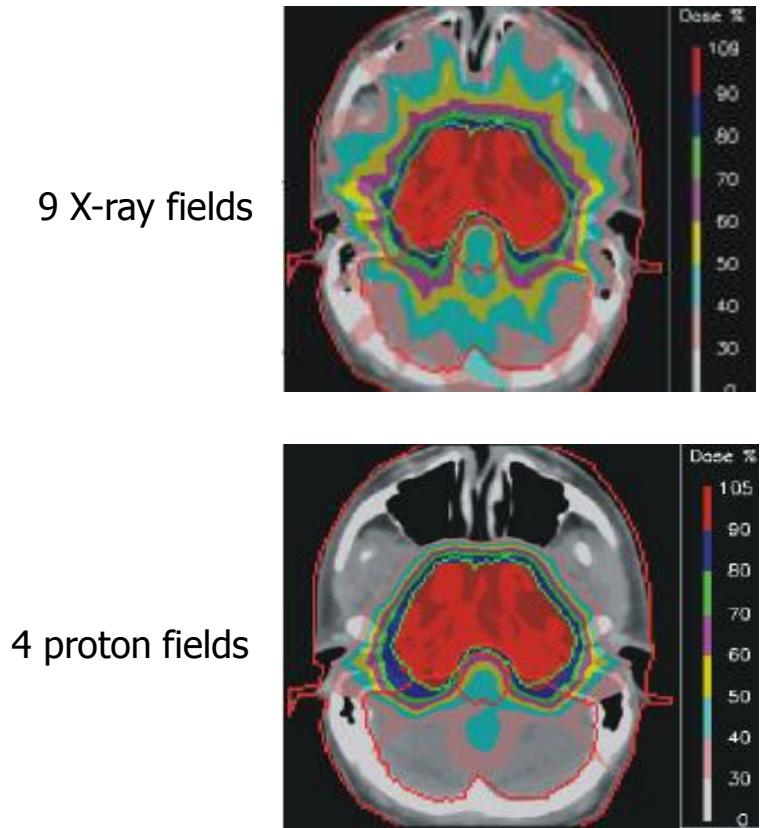
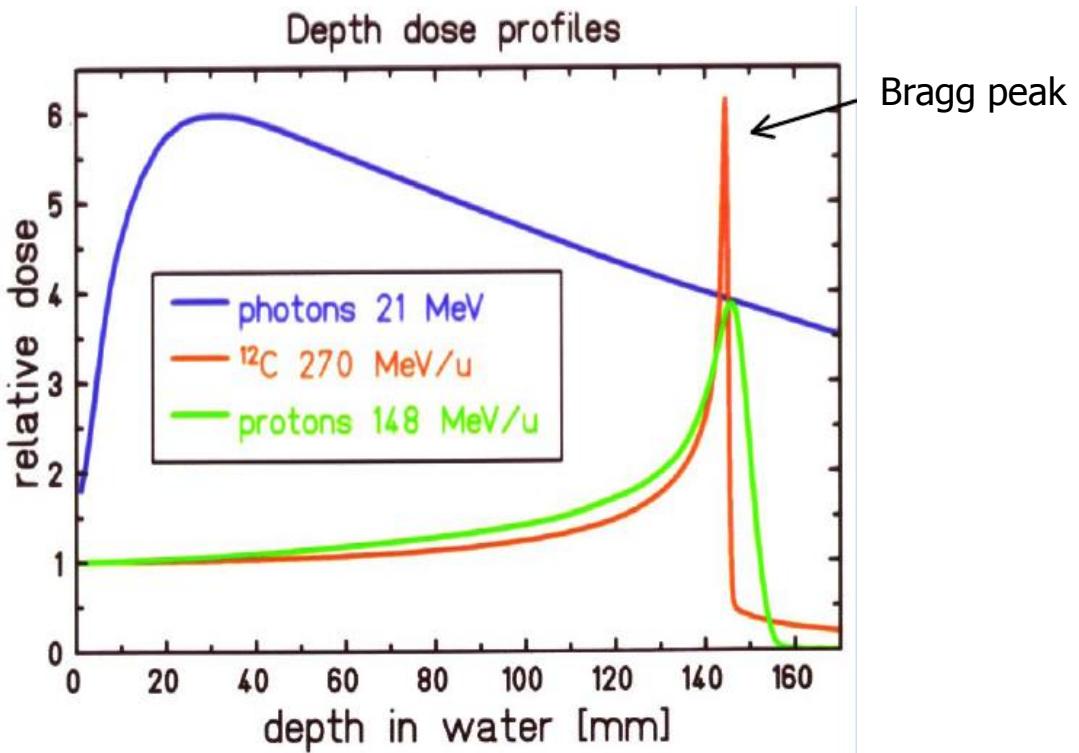
Circumference 26,7 km

Magnetic field 8,3 T

1706 main superconducting magnets, cooled at 1,9 K by superfluid helium



# Hadrontherapy: tumor treatment by particle beams



Hadron beams enable better targeting of the tumor than X-rays



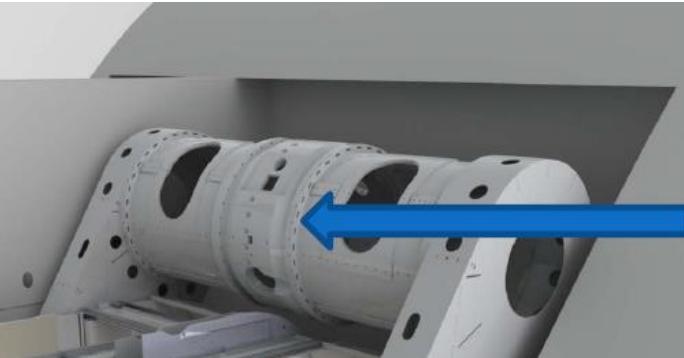
# Compact superconducting synrocyclotron for hadrontherapy (*Still River Systems*)



- 250 MeV protons
- 20 t mass allowing integration in gantry
- cooled by cryorefrigerators (no liquid helium)



Gantry manufacturing



Synrocyclotron

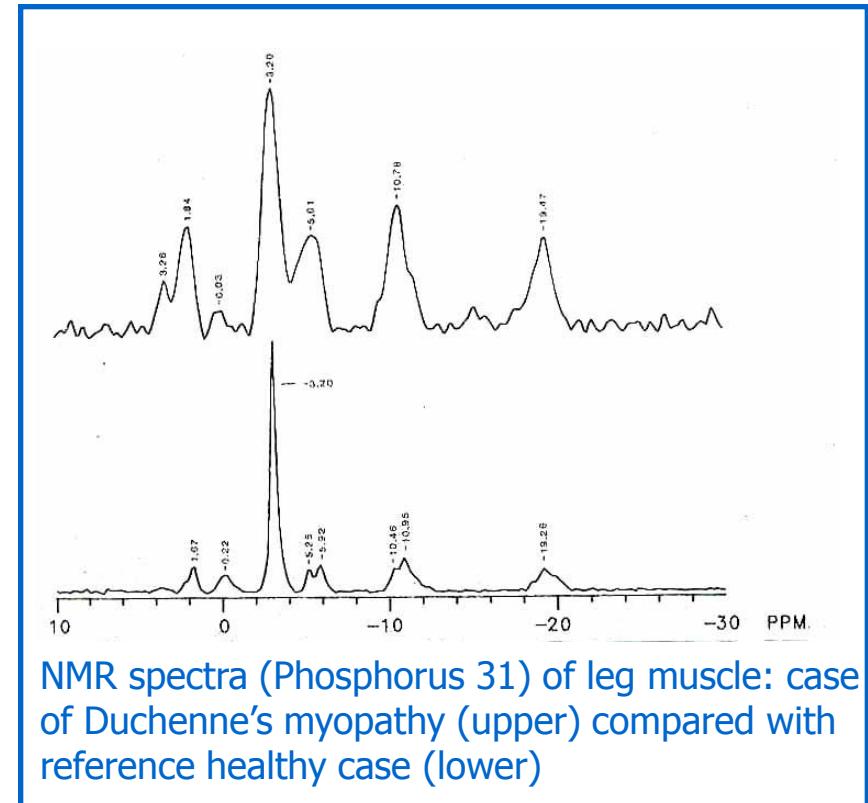


# NMR analysis magnets (*Bruker*)

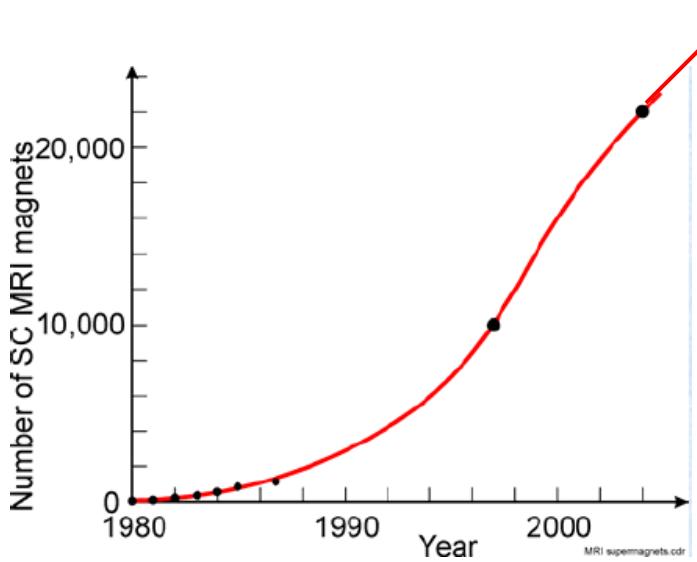


Very powerful analysis technique in chemistry, biology, pharmacology

Resolution increases with the strength of the magnetic field (21 T at 900 MHz)



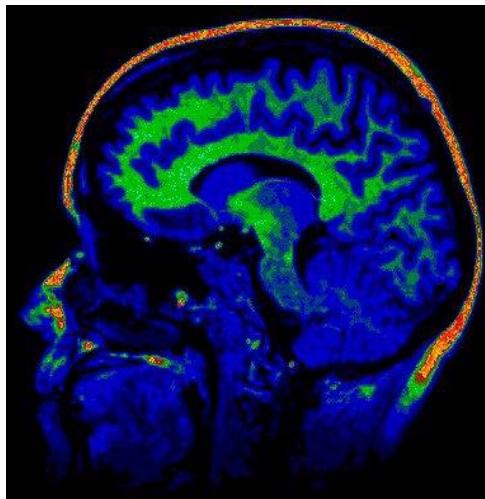
# Superconducting magnets for MRI



More than 25'000 operating in the world

Yearly market ~ 1 billion euros

« Open » magnet for surgical intervention under MRI





# A very frequent phenomenon... at low enough temperature

KNOWN SUPERCONDUCTIVE ELEMENTS																		0	
1	IA																		He
2	H	Li	Be																Ne
3	Na	Mg		III B	IV B	V B	VI B	VIIB	VII				IB	II B	5	6	7	8	9
4	K	Ca	Sc	Ti	Y	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	
6	Cs	Ba	*La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn	
7	Fr	Ra	+Ac	Rf	Ha	106	107	108	109	110	111	112							

■ BLUE = AT AMBIENT PRESSURE  
■ GREEN = ONLY UNDER HIGH PRESSURE

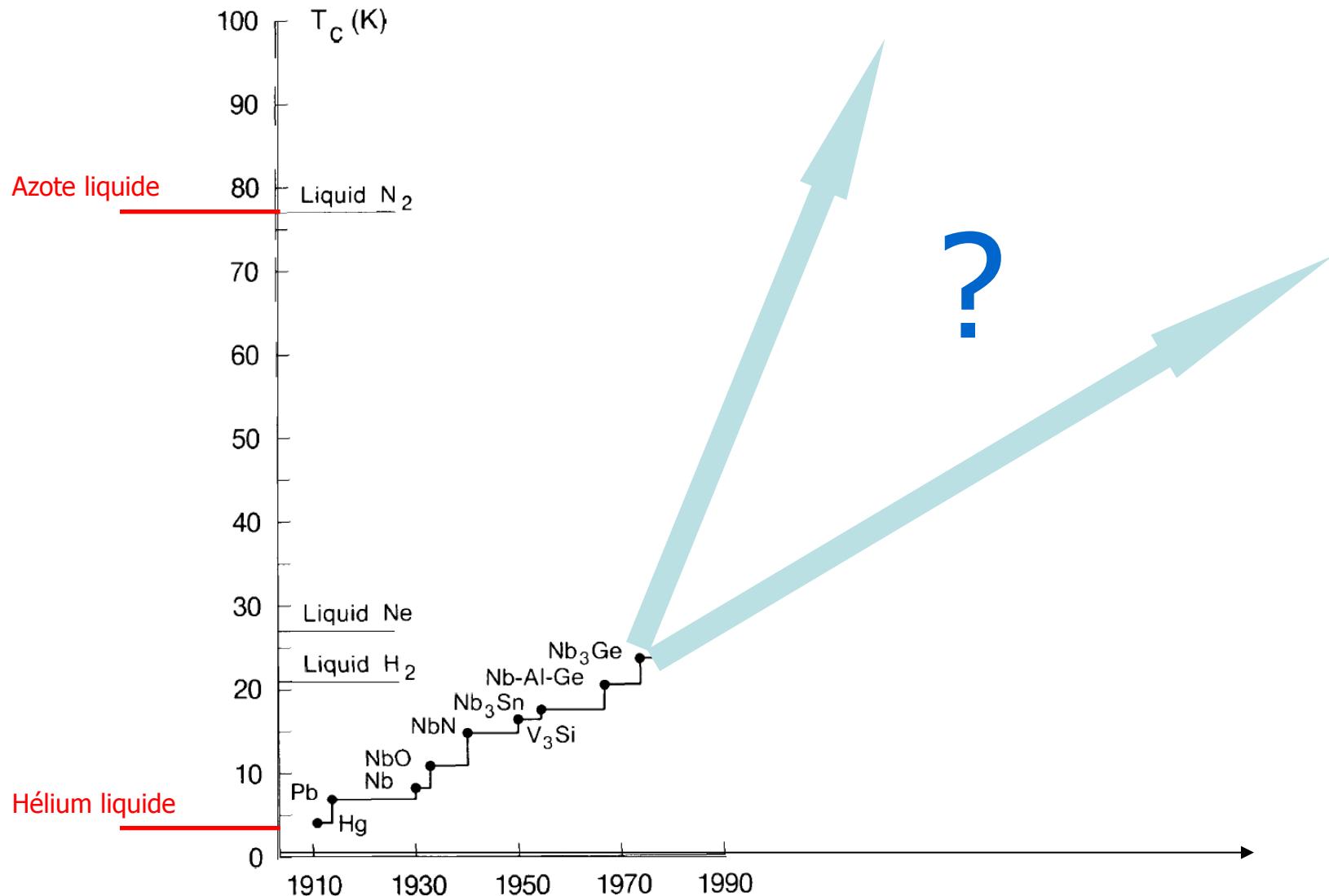
*SUPERCONDUCTORS.ORG*

\* Lanthanide  
Series

58	59	60	61	62	63	64	65	66	67	68	69	70	71
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
90	91	92	93	94	95	96	97	98	99	100	101	102	103
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

+ Actinide  
Series

# Towards higher temperatures?





# Discovery of « high » temperature superconductors (1986)

Z. Phys. B – Condensed Matter 64, 189–193 (1986)

## Possible High $T_c$ Superconductivity in the Ba – La – Cu – O System



J. Georg Bednorz

J.G. Bednorz and K.A. Müller

IBM Zürich Research Laboratory, Rüschlikon, Switzerland

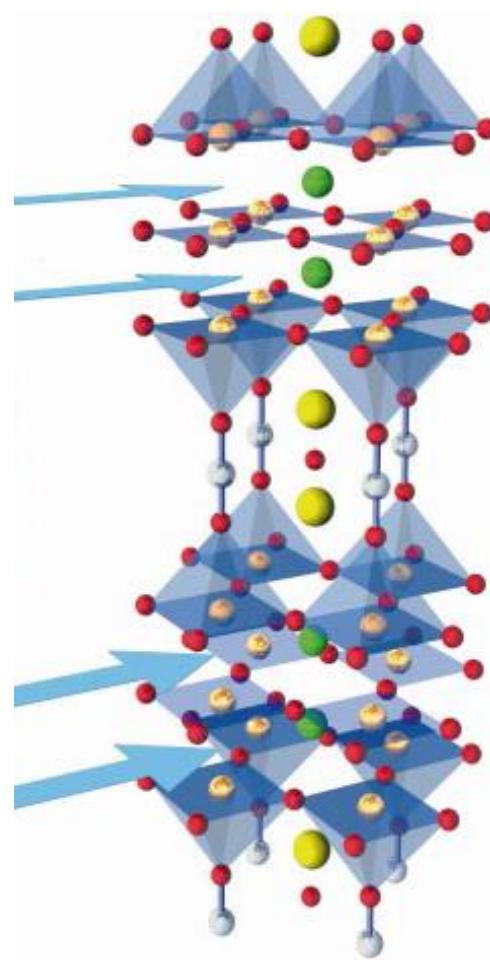
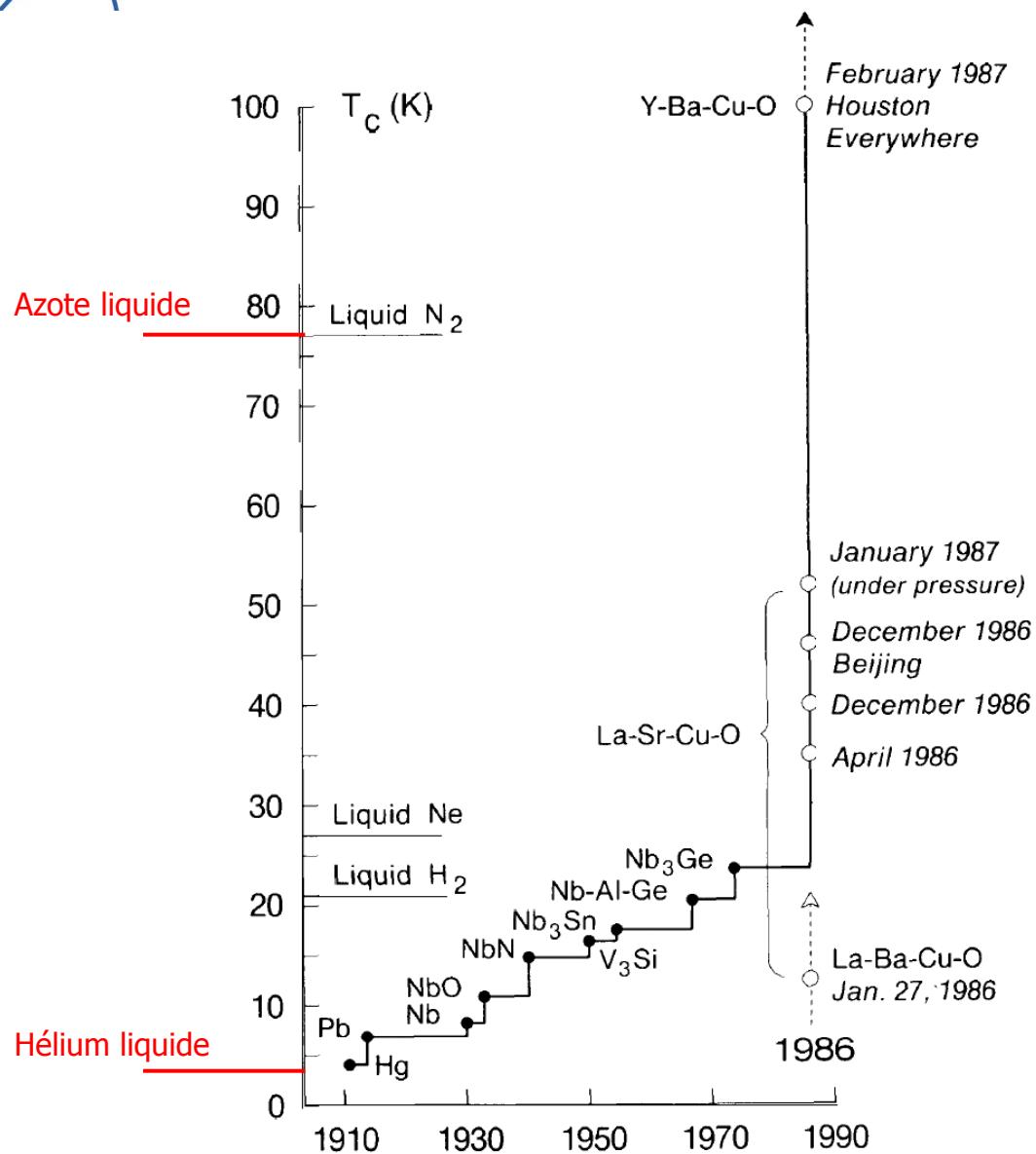
Received April 17, 1986

Metallic, oxygen-deficient compounds in the Ba – La – Cu – O system, with the composition  $\text{Ba}_x\text{La}_{5-x}\text{Cu}_5\text{O}_{5(3-y)}$ , have been prepared in polycrystalline form. Samples with  $x=1$  and  $0.75$ ,  $y>0$ , annealed below  $900^\circ\text{C}$  under reducing conditions, consist of three phases, one of them a perovskite-like mixed-valent copper compound. Upon cooling, the samples show a linear decrease in resistivity, then an approximately logarithmic increase, interpreted as a beginning of localization. Finally an abrupt decrease by up to three orders of magnitude occurs, reminiscent of the onset of percolative superconductivity. The highest onset temperature is observed in the 30 K range. It is markedly reduced by high current densities. Thus, it results partially from the percolative nature, but possibly also from 2D superconducting fluctuations of double perovskite layers of one of the phases present.

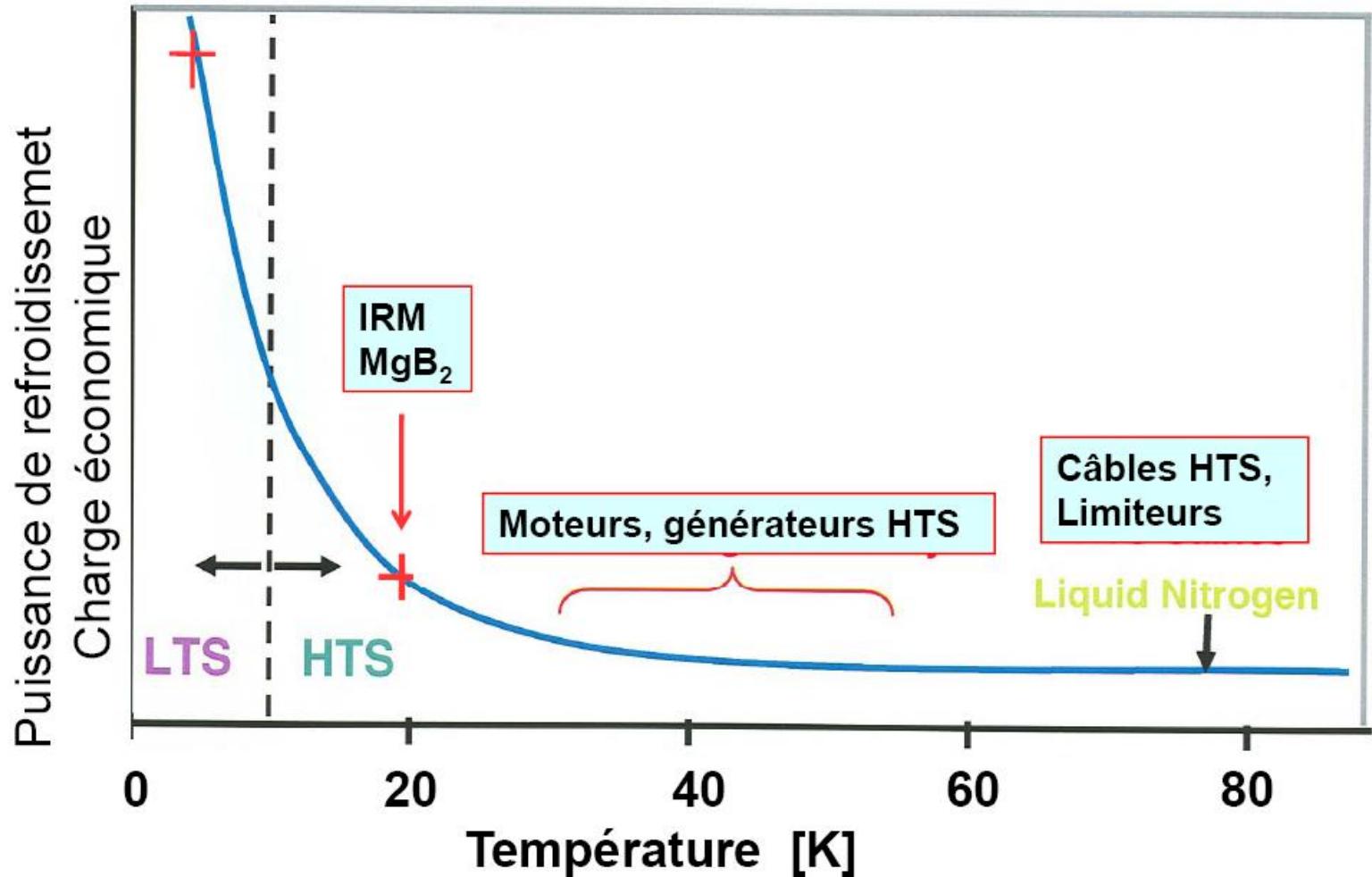


K. Alexander Müller

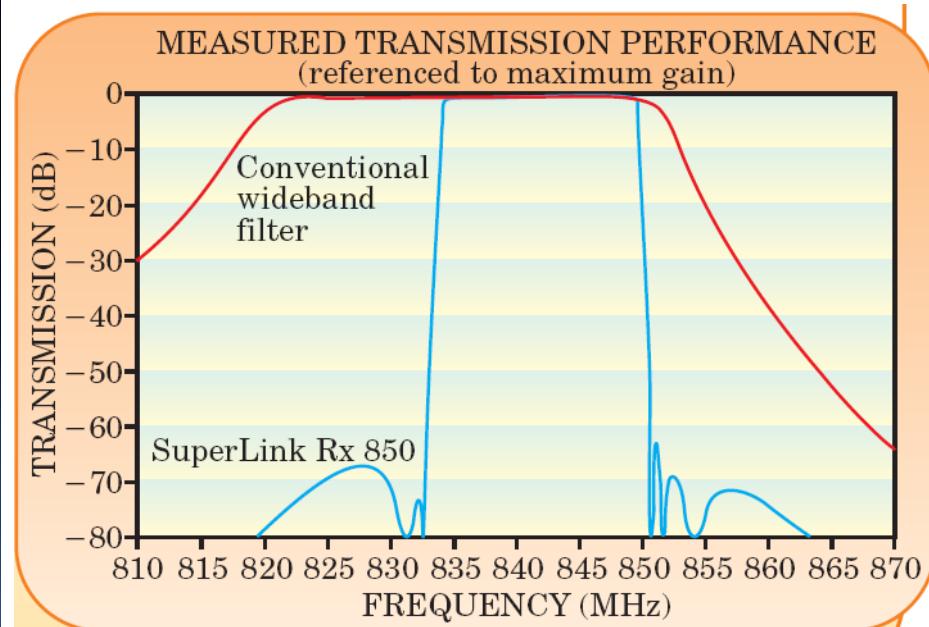
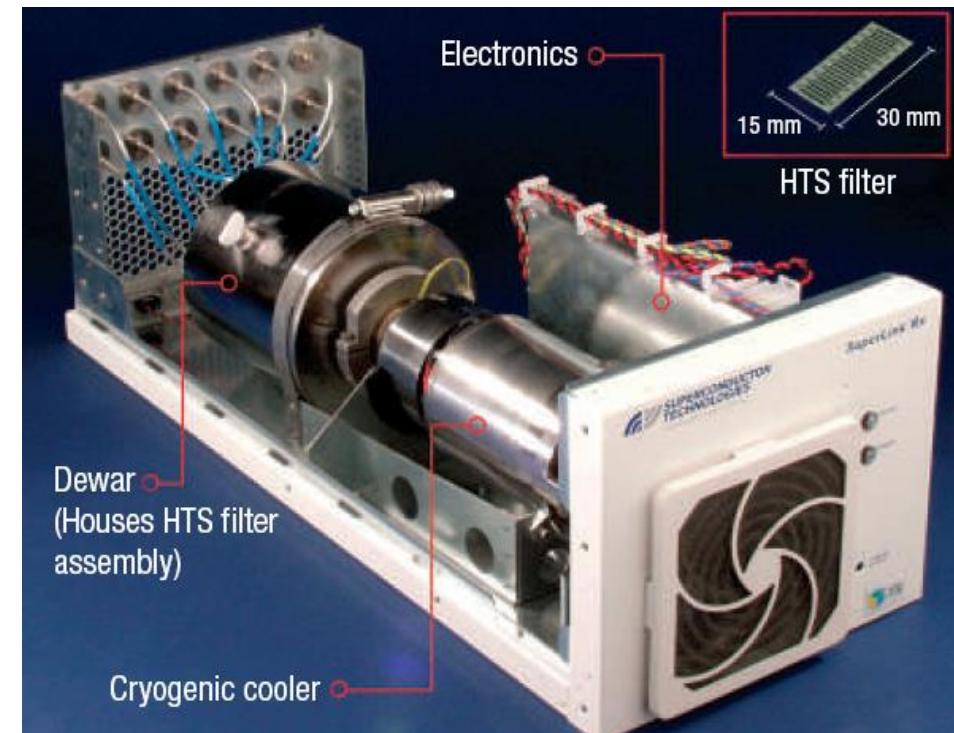
# « High » temperature superconductors



# Cost of refrigeration and applications of superconductivity



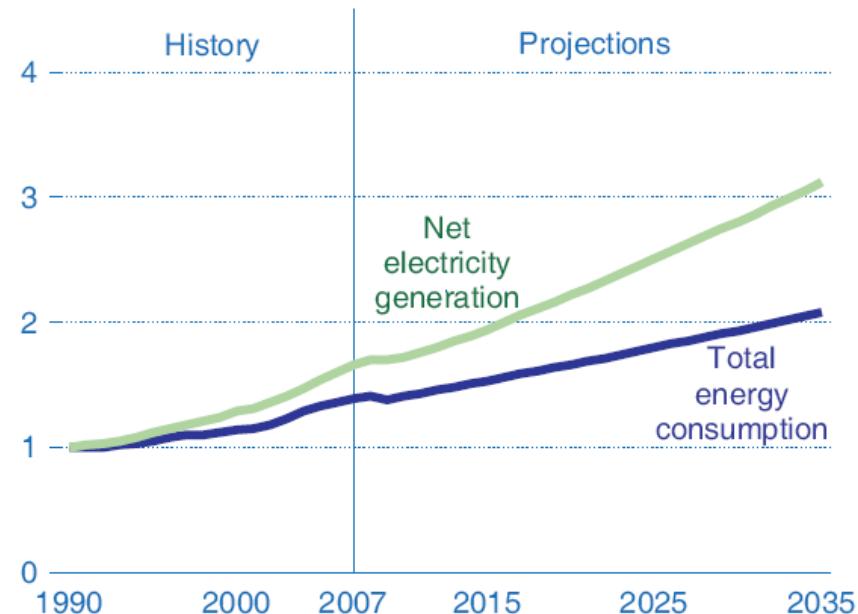
# HTS filter for cell phone station: more channels per bandwidth





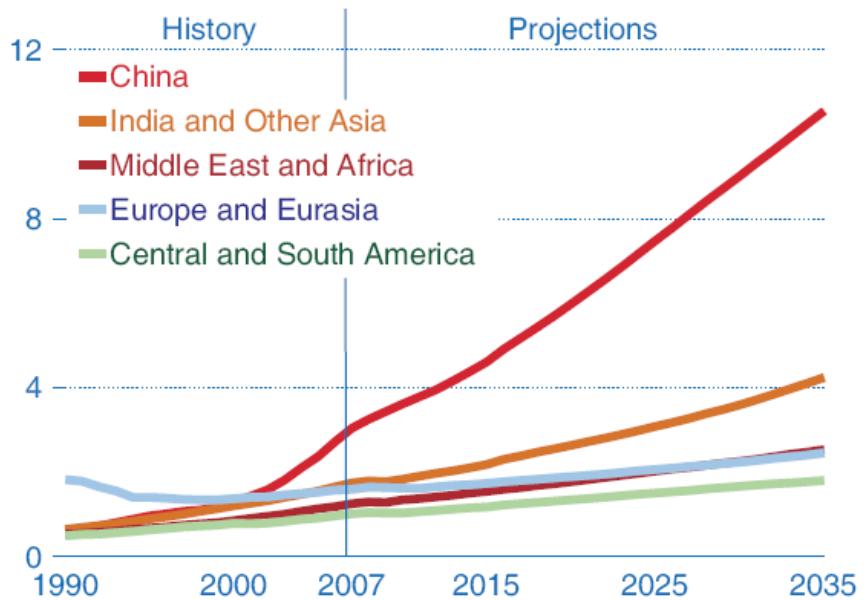
# Use of electricity and economic development

Figure 67. Growth in world electric power generation and total energy consumption, 1990-2035 (index, 1990 = 1)

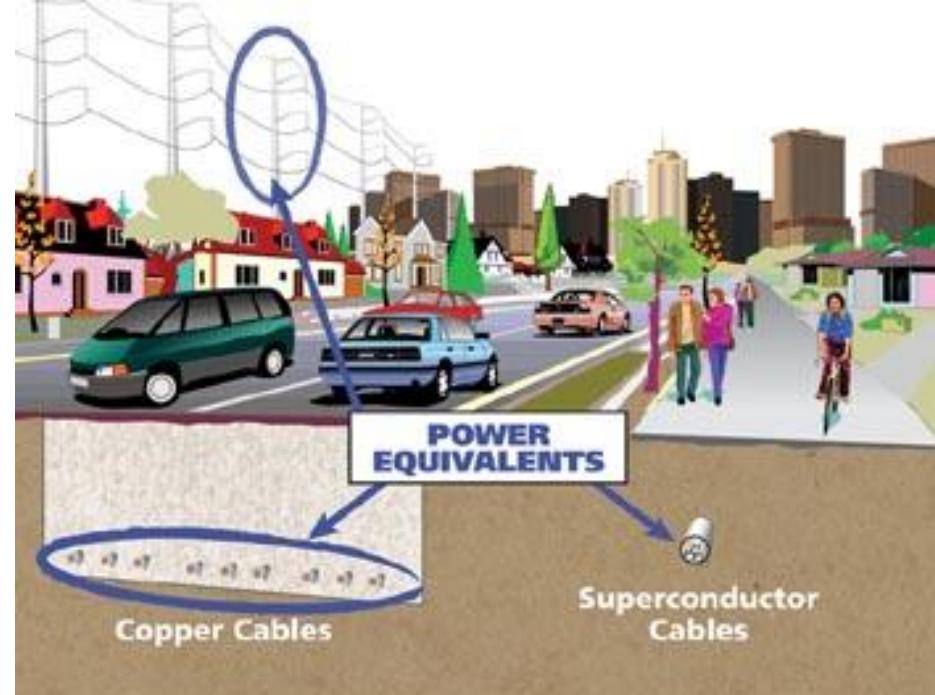


U.S. Energy Information Administration / International Energy Outlook 2010

Figure 69. Non-OECD net electricity generation by region, 1990-2035 (trillion kilowatthours)



# Superconducting power lines



Increase power transported in dense urban areas

Reduce electricity transport losses

Reduce visual impact and electromagnetic pollution of overhead lines

# Power line using high-temperature superconductors, connected to electrical network (2008)



Section du ruban de Bi-2223 supraconducteur



Three-phase 138 kV, 574 MVA (LIPA)



# Intercontinental interconnexion of power networks requires low-loss, long-distance lines



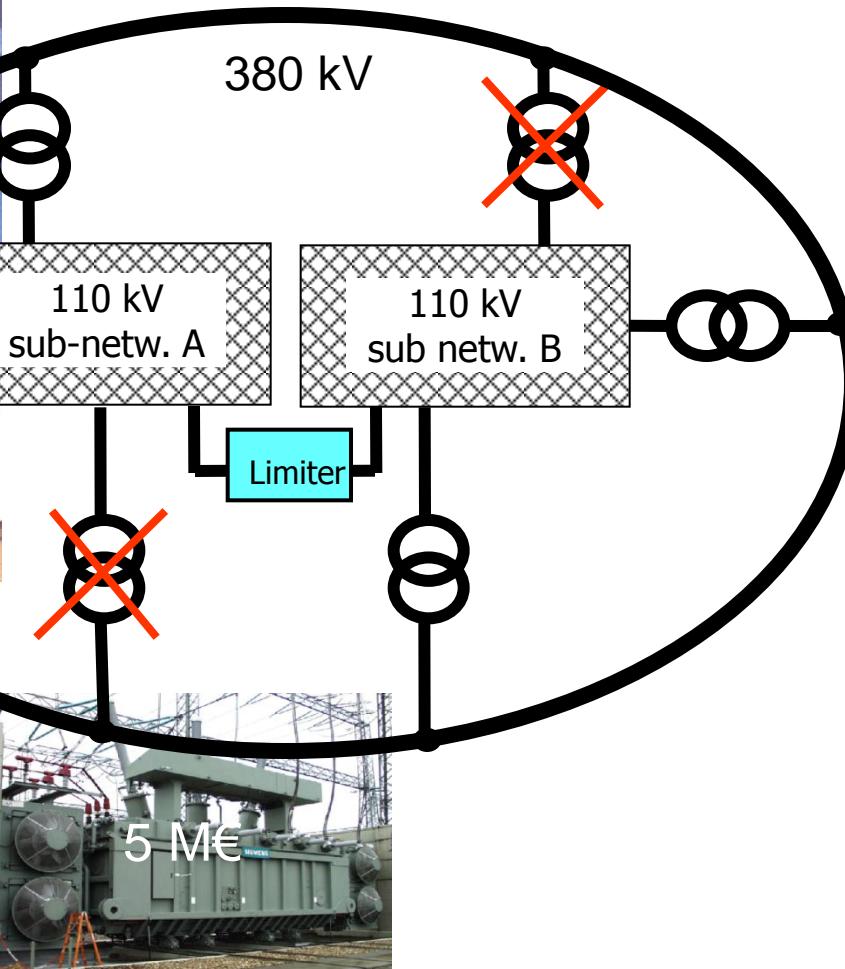
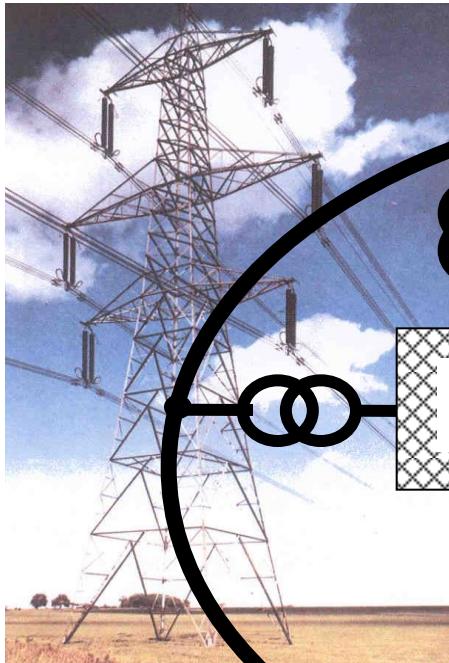


## 28 September 2003: blackout over Italy



# Interconnection increases short-circuit risks: need « smart » grids

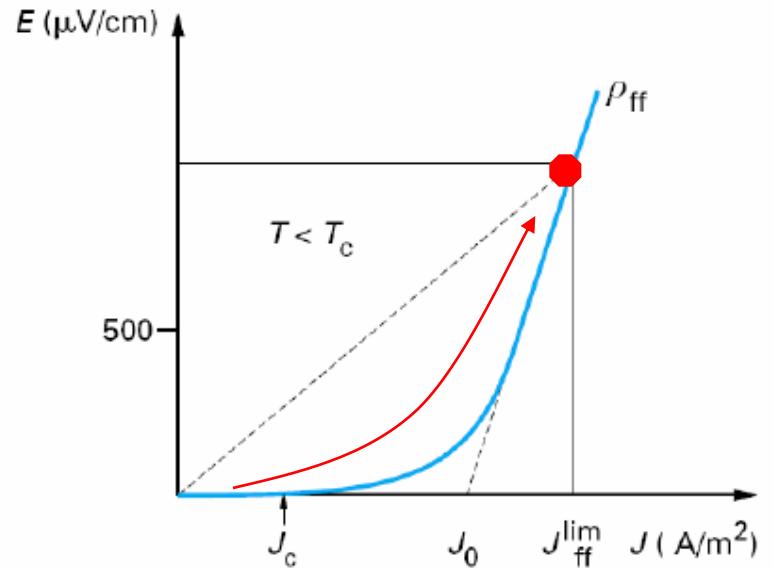
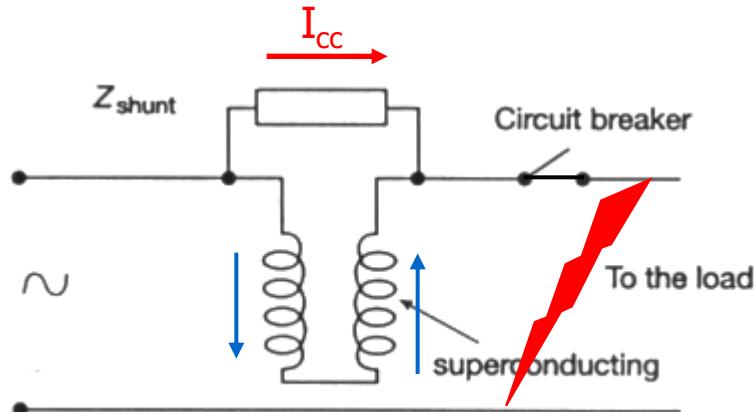
Interconnected grids  $\Rightarrow$  short-circuit currents add up!



Thanks to fault current limiter :

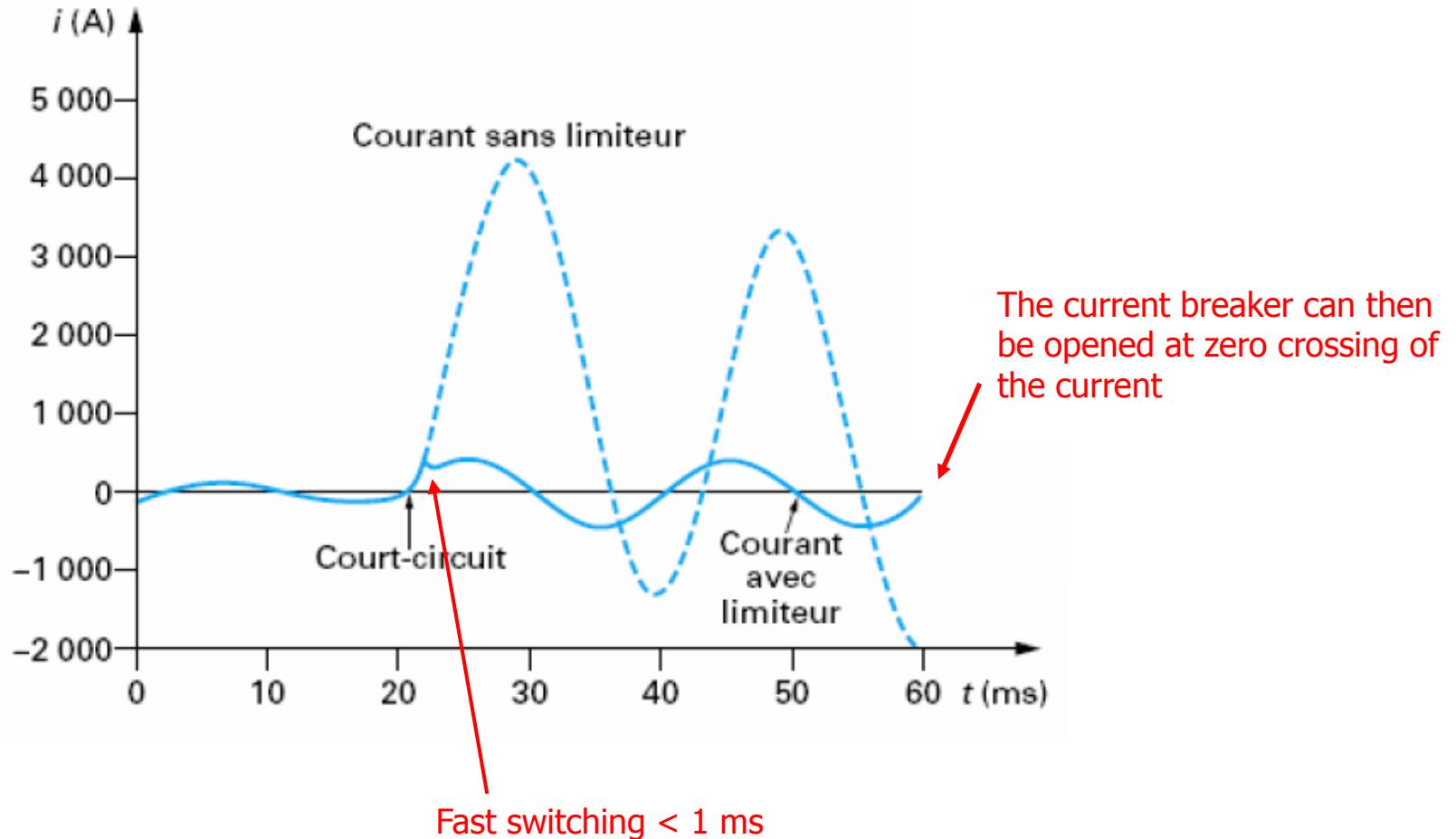
- Reduced need for redundancy in sub-grids
- Optimized operation of interconnected grid

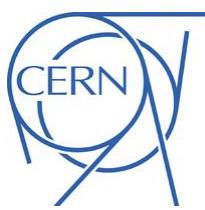
# Superconducting fault-current limiter



The abrupt change of resistance from the superconducting to the normal state is used for rapid switching in of a shunt resistor, thus limiting short-circuit current until the circuit breaker can be opened at the next zero-crossing

# Operation of a superconducting fault-current limiter





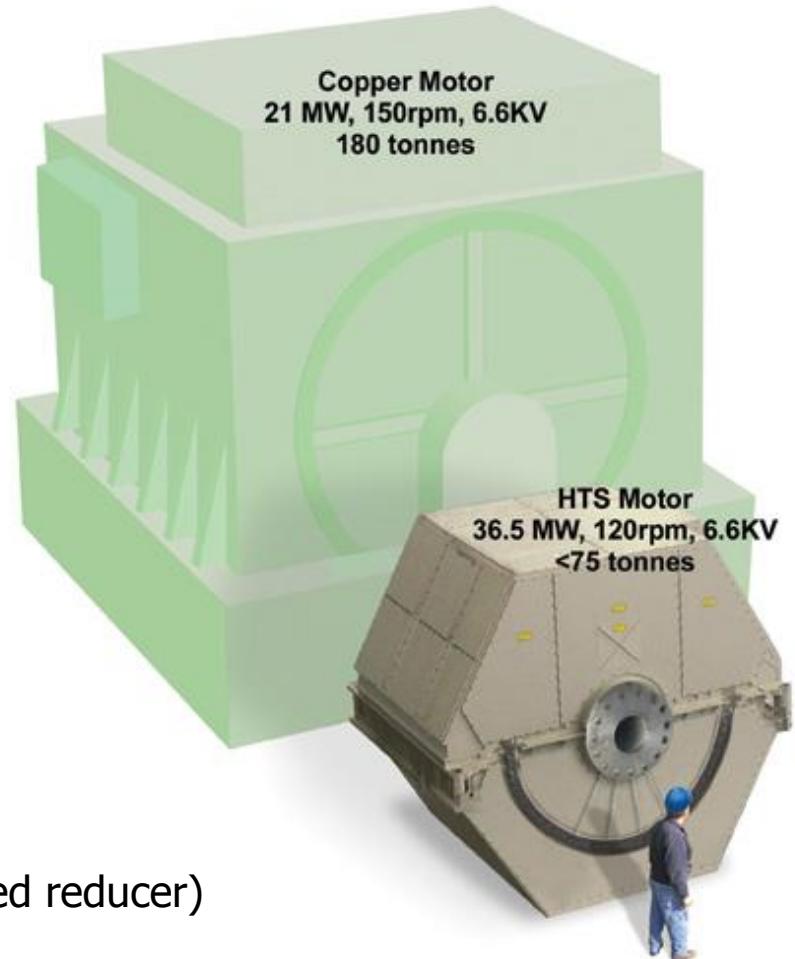
# HTS fault limiter 12 kV, 800 A (*Nexans-Vattenfall*)



# Electrical motor for naval propulsion (AMSC)



36,5 MW, 120 rpm motor



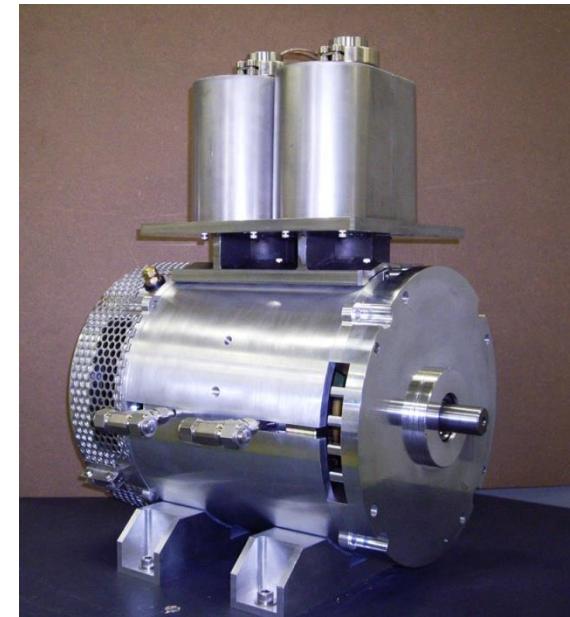
Reduction of on-board mass

Simpler mechanics (propeller shaft line, speed reducer)

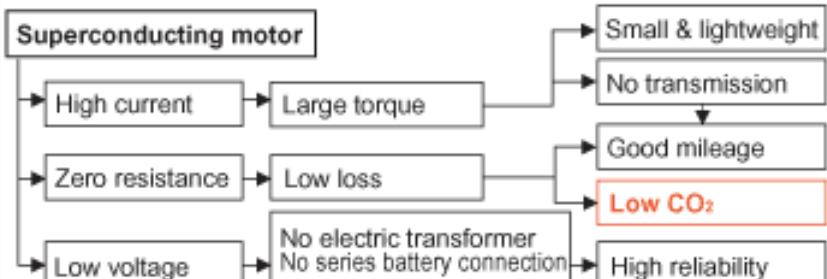
Lower acoustical signature → stealth

High torque → acceleration

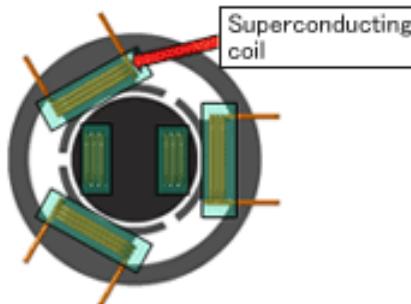
# Electrical car with superconducting motor (Sumitomo)



## < Advantages of superconducting motor >



## < Structure of typical superconducting motor >



50 & 345 kW motors

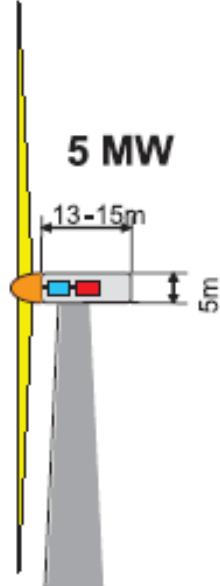
Autonomy gain 13 %

# Compact superconducting generators for wind turbines (*SeaTitan*)

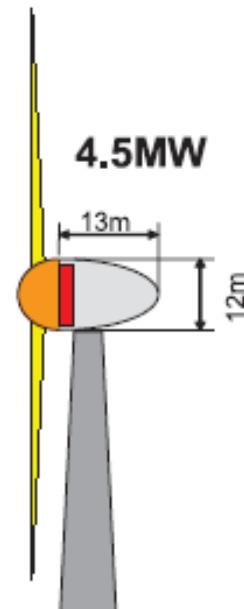


- Generator
- Gearbox
- Hub
- Blade
- Nacelle
- Tower

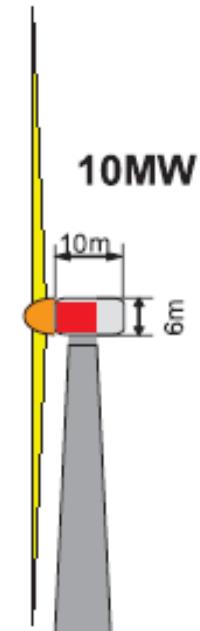
**Main Stream  
Geared**



**Conventional  
Direct Drive**



**Optimized HTS  
Direct Drive  
(AMSC)**



Possible  
to go as  
large as  
20MW  
with HTS

**Mass of Nacelle**

+ Hub

+ Blades

$m_{\text{Top}} \sim 310 \text{ to } 430 \text{t}$

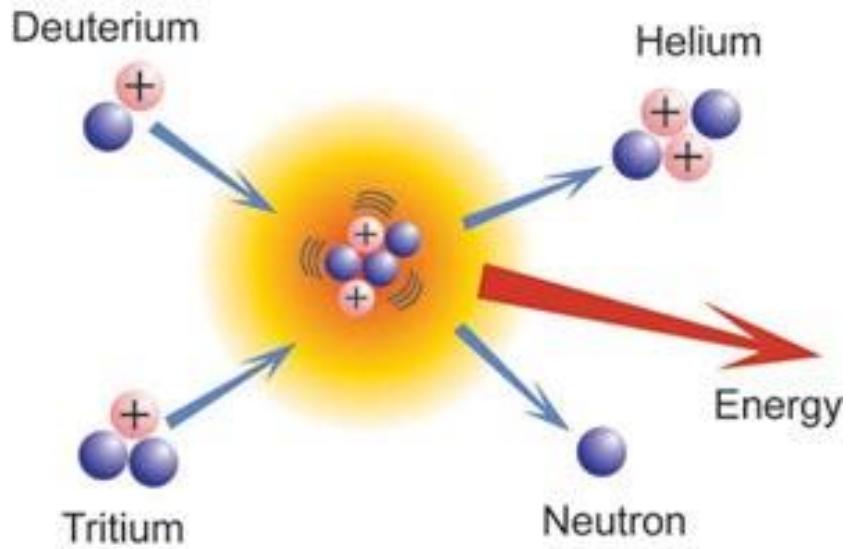
Extrapolated for 10 MW  $m_{\text{Top}} \sim 750 \text{t} - 850 \text{t}$

$m_{\text{Top}} \sim 500 \text{t}$

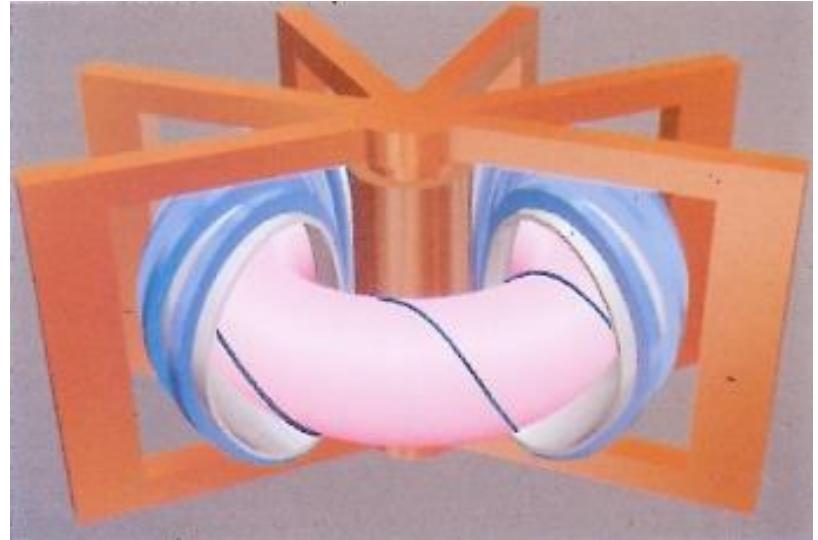
$m_{\text{Top}} \sim 800 \text{t}-900 \text{t}$

$m_{\text{Top}} < 500 \text{t}$

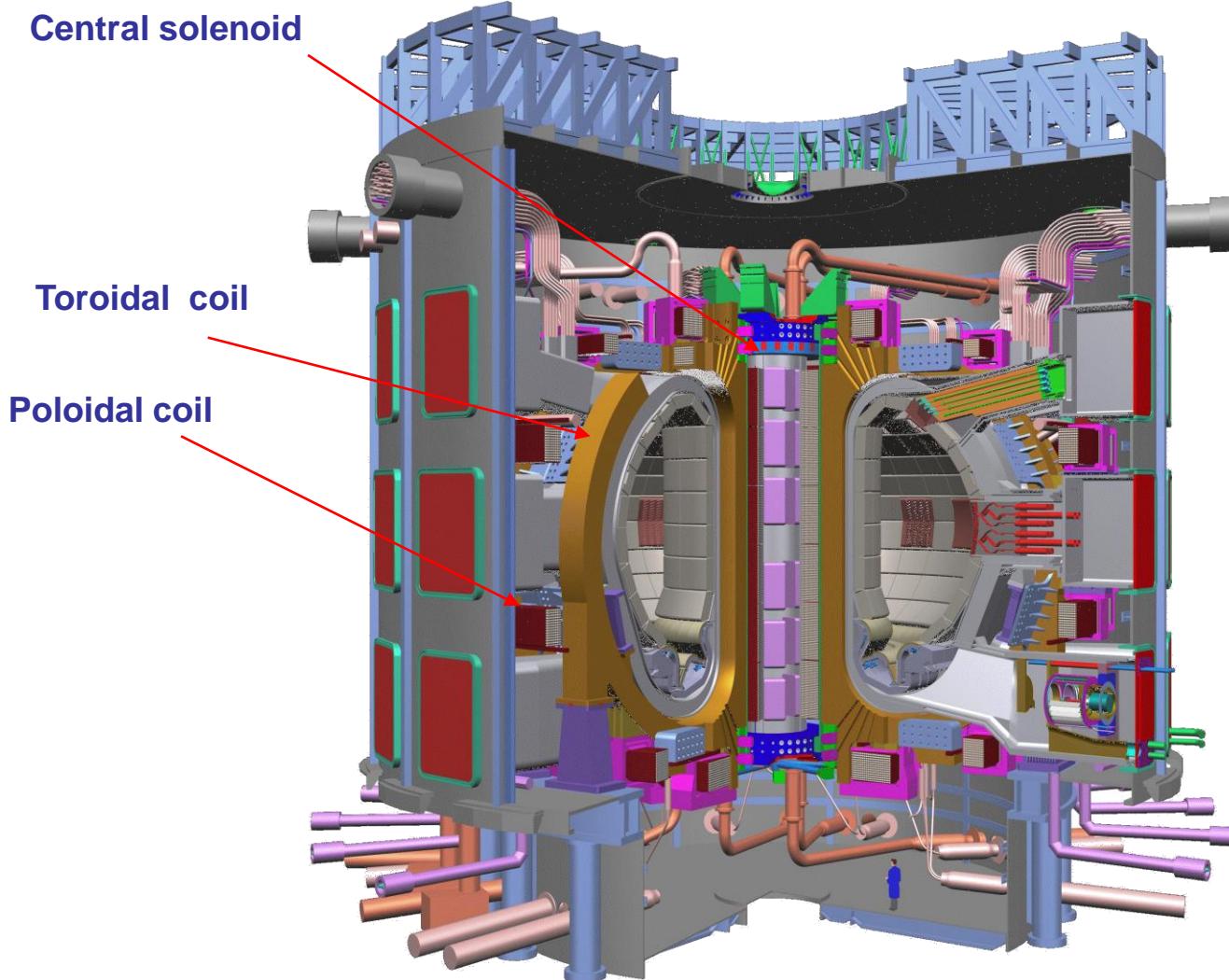
# Nuclear fusion, energy for tomorrow ?



Sustaining nuclear fusion requires a temperature of some 100 million degrees: one thus needs a « magnetic bottle », the tokamak, to contain the D-T plasma



# ITER needs large superconducting magnets





## Conclusion

- Superconductivity is 100 years old: its history is an integral part of the development of science and technology in the twentieth century
  - A « magical » phenomenon which could only be explained with the application of quantum physics to condensed matter
  - A key technology for producing high magnetic fields
  - Very few applications in the technical system of the twentieth century, inherited from the second industrial revolution
- With the discovery of new material and the emergence of new applications, superconductivity can contribute to answer main societal issues of the twenty-first century
  - health
  - mobility
  - energy efficiency
  - reduction of GHG emissions and climate change



## Some readings



- H. Kamelingh Onnes, *Investigations into the properties of substances at low temperatures, which have led, amongst other things, to the preparation of liquid helium*, Nobel Lecture (1913)  
[http://nobelprize.org/nobel\\_prizes/physics/laureates/1913/onnes-lecture.pdf](http://nobelprize.org/nobel_prizes/physics/laureates/1913/onnes-lecture.pdf)
- P.F. Dahl, *Superconductivity, its historical roots and developments from mercury to the ceramic oxydes*, AIP, New York (1992)
- J. Matricon & G. Waysand, *La guerre du froid, une histoire de la supraconductivité*, Seuil, Paris (1994)
- D. van Delft, *Freezing physics, Heike Kamerlingh Onnes and the quest for cold*, Royal Netherlands Academy of Arts and Sciences, Amsterdam (2007)
- D. van Delft & P. Kes, *The discovery of superconductivity*, Physics Today, September 2010, 38-43
- P. Tixador & Ph. Lebrun, *La supraconductivité à l'ère industrielle*, Pour la Science **402**, Avril 2011, 76-83