Supergeleiding wordt steeds “hotter”

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Universiteit van Amsterdam

Science Park FNWI-UvA

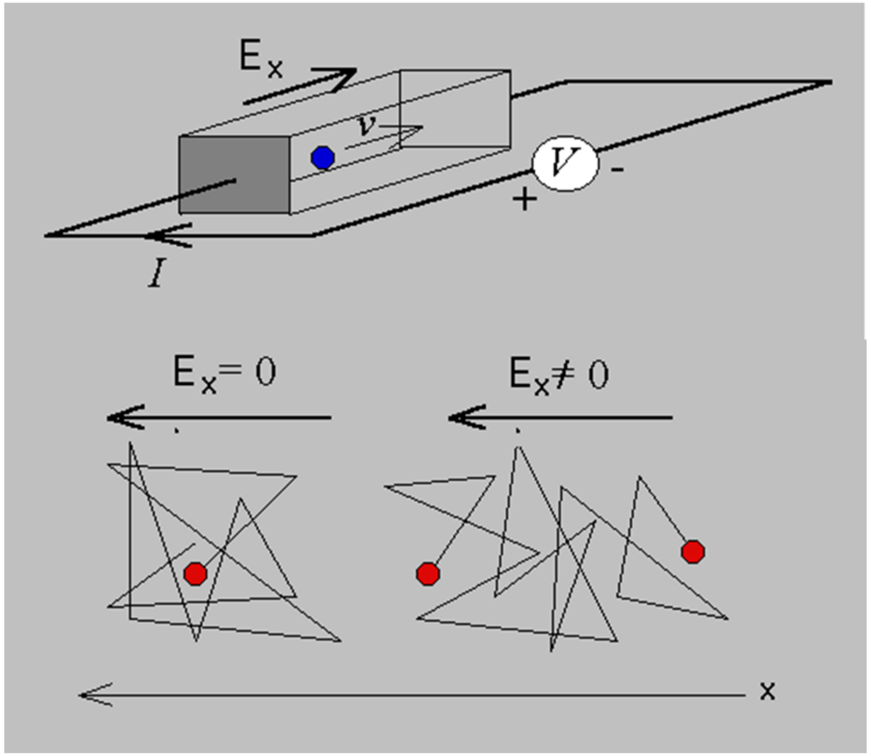
- Klassieke supergeleiders
- Het “standaard” model: BCS
- Hoge temperatuur supergeleiding
- Supergeleiding toegepast
- “Hot-topics” supergeleiding

Klassieke supergeleiders

Geleiding in metalen omstreeks 1900

- Drude model, klassiek model:
  - verdund gas van electronen
  - verstrooien aan atoomkernen

Paul Drude
1863-1906



$$\boxed{\sigma = \frac{ne^2\tau}{m}}$$

geleiding

$$\boxed{\rho = \frac{m}{ne^2\tau}}$$

weerstand *R*;
τ = verstrooiingstijd

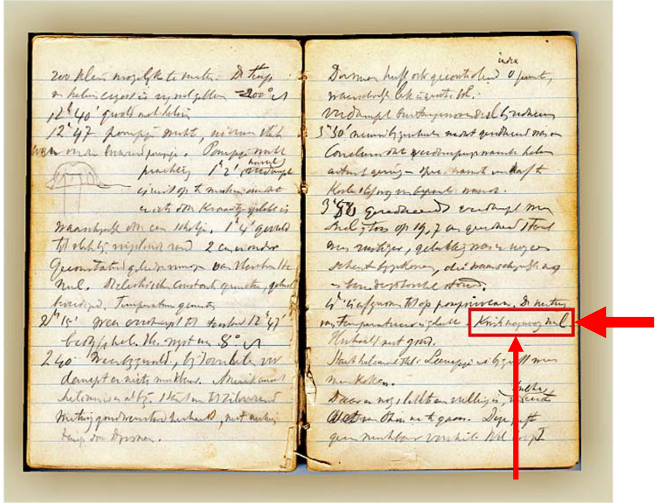
$$\boxed{\vec{j} = \sigma\,\vec{E} = \frac{1}{\rho}\vec{E}}$$

stroomdichtheid

Ontdekking van supergeleiding in 1911

- Omstreeks ~1900:
  Wat gebeurt er met de weerstand van een metaal wanneer $T \to 0$?
  - toename verstrooiingstijd τ: $\rho \to 0$??
  - afname mobiliteit: $\rho \to \infty$??

- 1911 Kamerlingh Onnes
  - weerstand verdwijnt abrupt



kwik nagenoeg nul

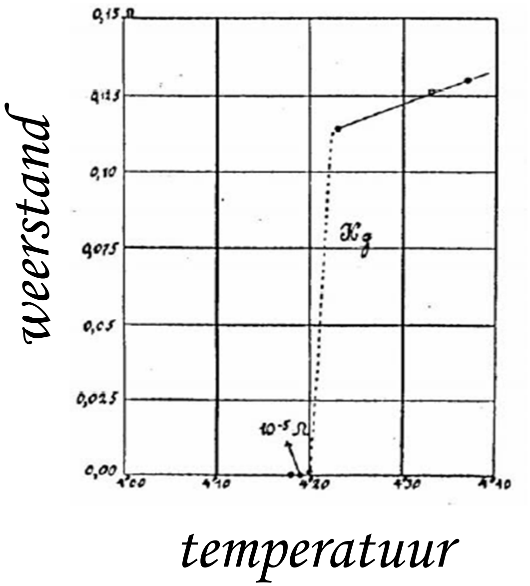
H. Kamerlingh Onnes
1853-1926
Nobelprijs 1913

G. Holst
1886-1968

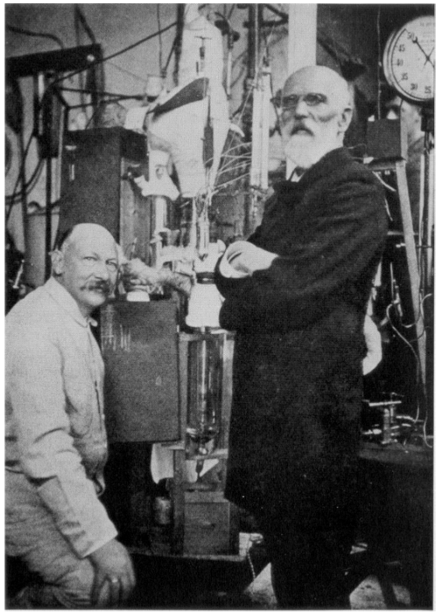
kwikzilver
T_s= 4.2 K

$$\boxed{R = 0}$$

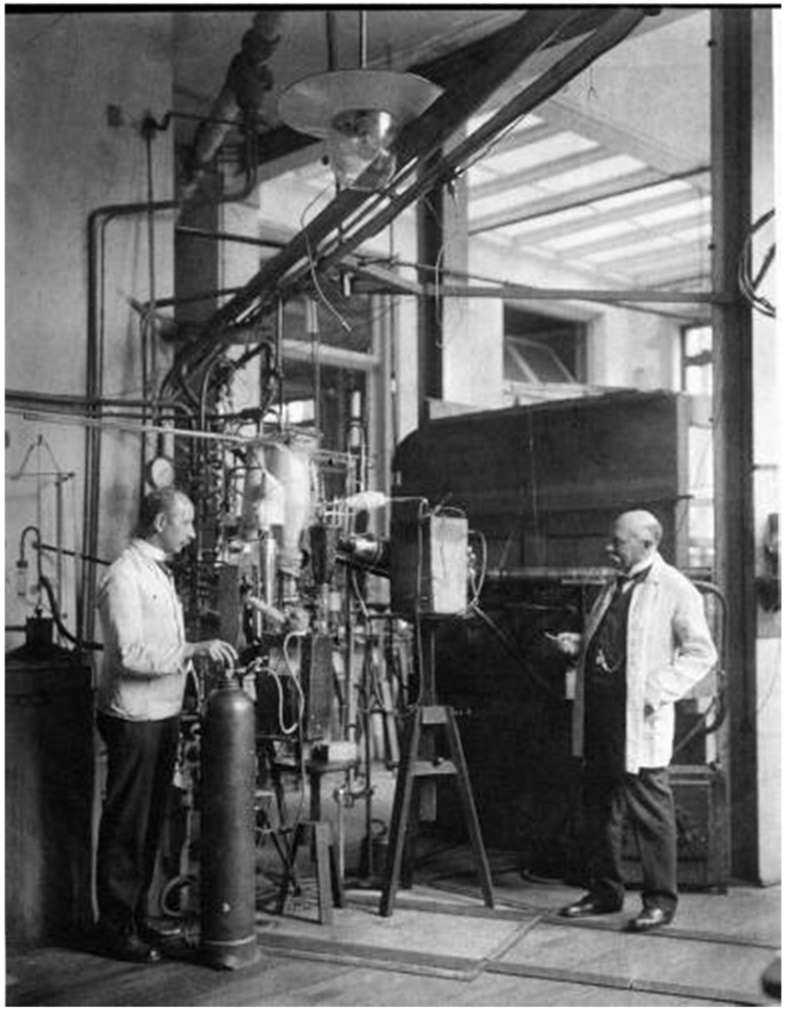
ontdekking van supergeleiding op 8 april 1911
Van Delft & Kes, Physics Today, Sept. 2010



Ontdekking van supergeleiding in 1911



Heike Kamerlingh Onnes met Van der Waals

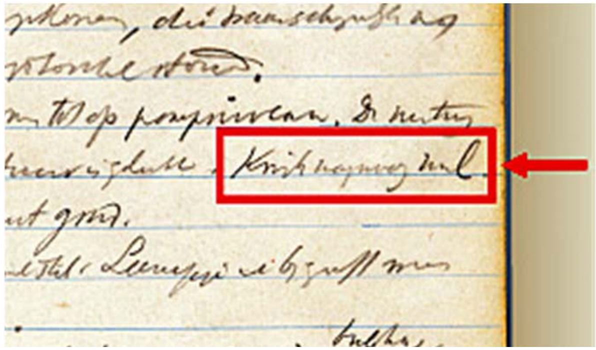


HKO en Gerrit Jan Flim

Laboratorium aan de
Steenschuur, Leiden

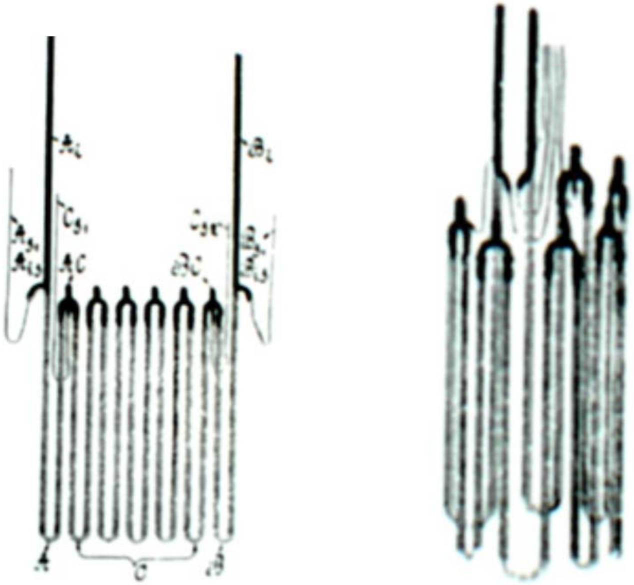
Rapenburg, na de explosie van het kruitschip op 12 jan.1807

Ontdekking van supergeleiding in 1911

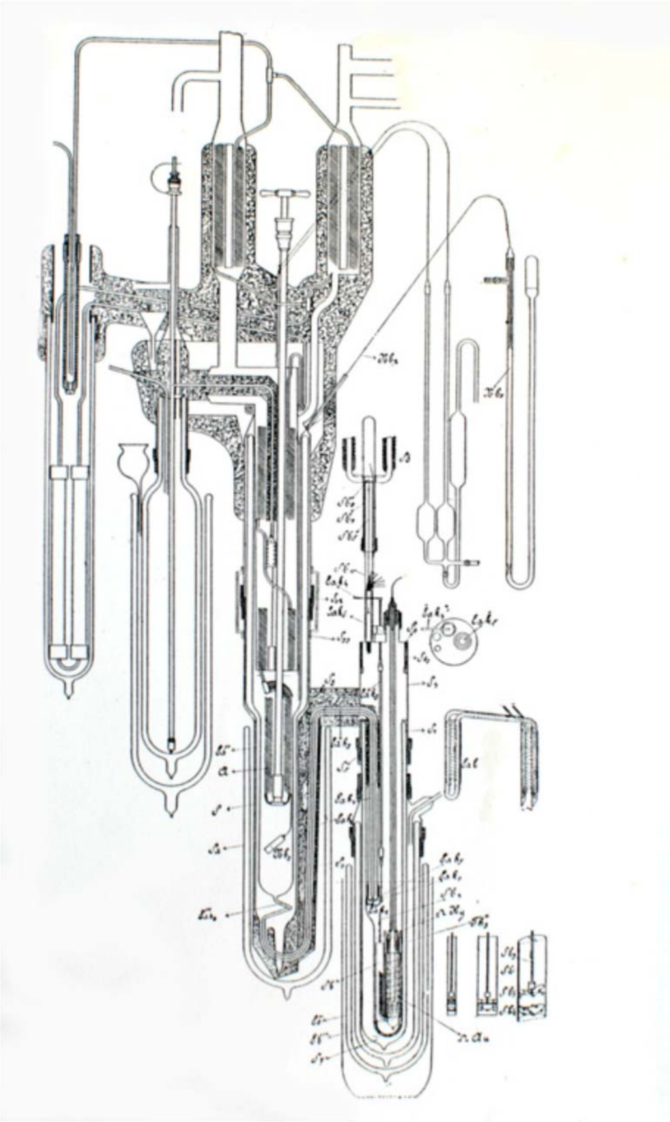


Kwik nagenoeg nul

kwik
nagenoeg
nul

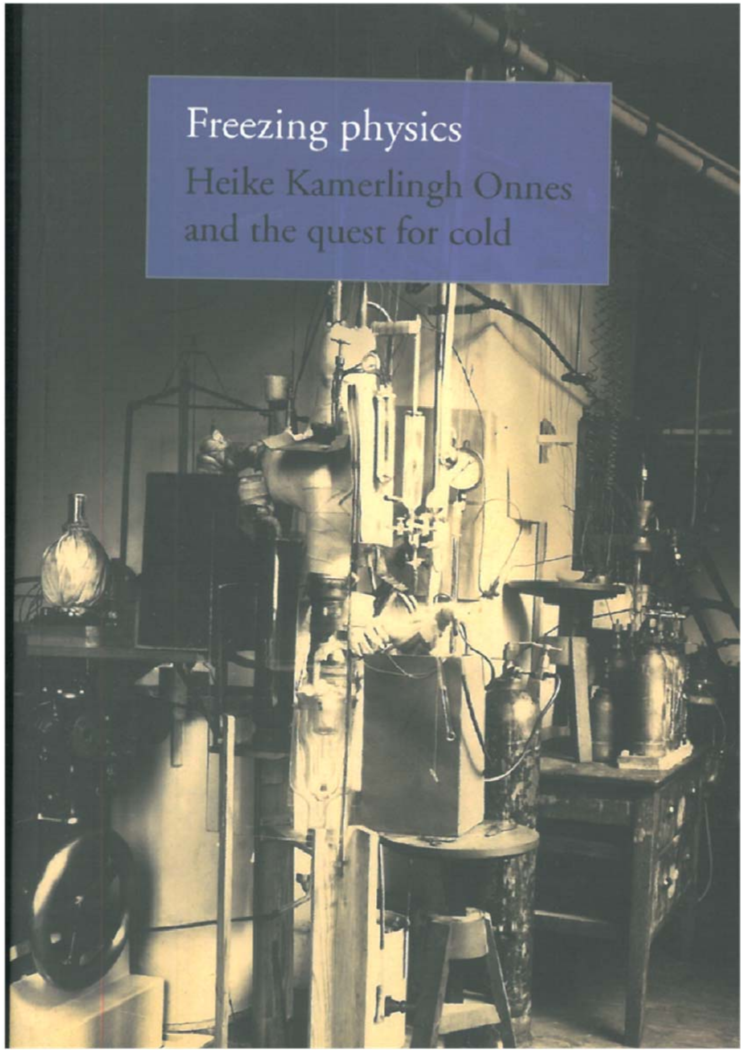


kwik preparaat in glazen capillair



de “cryostaat”

Biografie van Kamerlingh Onnes

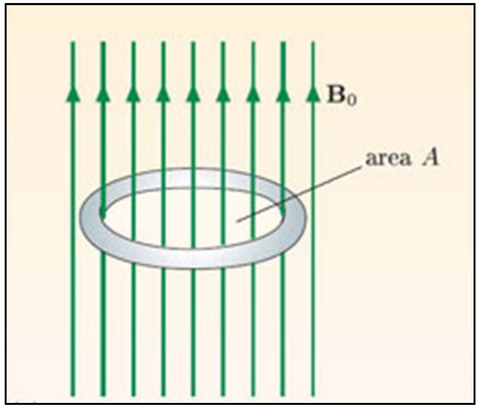


Freezing physics
Heike Kamerlingh Onnes
and the quest for cold

Dirk van Delft,
(Bert Bakker, Amsterdam, 2005)

Weerstand nul & eeuwigdurende stroom

- Magnetische flux in een metalen ring voor $T > T_s$
  - flux $\boxed{\phi = \int \vec{B} \cdot d\vec{A}}$



- Magnetische flux voor $T < T_s$
  - flux verandering

$$\boxed{\nabla \times \vec{E} = -\frac{d\vec{B}}{dt}}$$

Maxwell

$$\boxed{-\frac{d\phi}{dt} = -\int \frac{d\vec{B}}{dt} \cdot d\vec{A} = \int (\nabla \times \vec{E}) \cdot d\vec{A} = \oint \vec{E} \cdot d\vec{r} = 0} \leftarrow$$

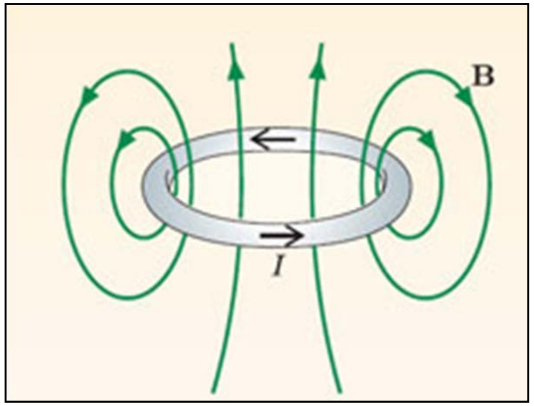
$$\boxed{\int (\nabla \times \vec{E}) \cdot d\vec{A} = \oint \vec{E} \cdot d\vec{r}}$$

Stokes

$$\uparrow$$

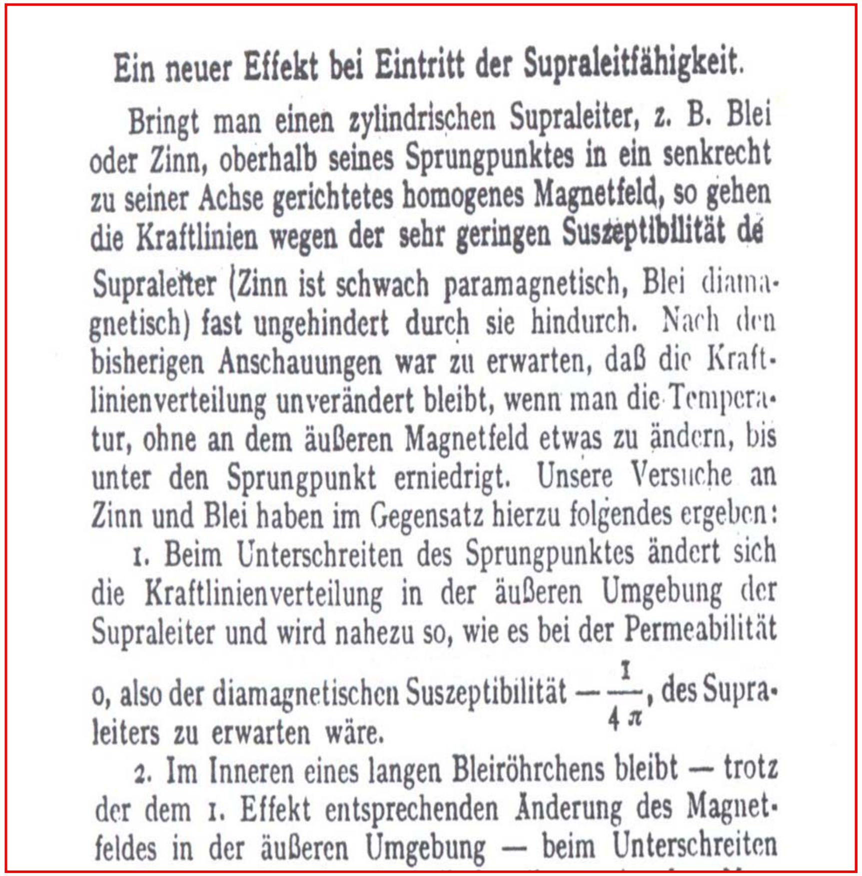
$$\boxed{\vec{E} = 0} \quad \boxed{\vec{j} = \frac{1}{\rho} \vec{E}}$$

- Voor $T < T_s$: wanneer $B_{ext} \rightarrow 0$ dan ontstaat een eeuwigdurende stroom want flux ϕ is constant



Het Meissner-Ochsenfeld effect 1933

Meissner en Ochsenfeld in
Naturwissenschaften 21, 787 (1933)



Ein neuer Effekt bei Eintritt der Supraleitfähigkeit.

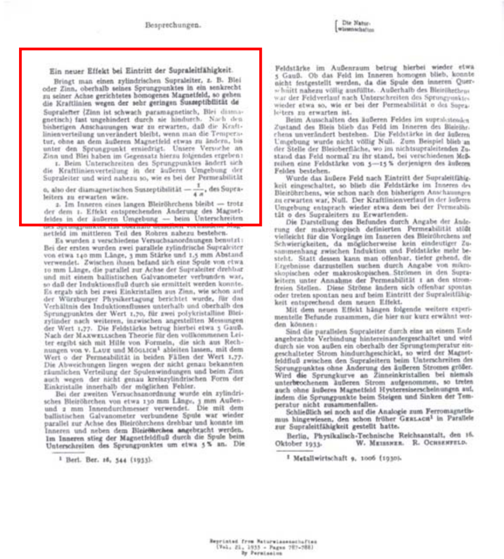
Bringt man einen zylindrischen Supraleiter, z. B. Blei oder Zinn, oberhalb seines Sprungpunktes in ein senkrecht zu seiner Achse gerichtetes homogenes Magnetfeld, so gehen die Kraftlinien wegen der sehr geringen Suszeptibilität de Supraleiter (Zinn ist schwach paramagnetisch, Blei diamagnetisch) fast ungehindert durch sie hindurch. Nach den bisherigen Anschauungen war zu erwarten, daß die Kraftlinienverteilung unverändert bleibt, wenn man die Temperatur, ohne an dem äußeren Magnetfeld etwas zu ändern, bis unter den Sprungpunkt erniedrigt. Unsere Versuche an Zinn und Blei haben im Gegensatz hierzu folgendes ergeben:

1. Beim Unterschreiten des Sprungpunktes ändert sich die Kraftlinienverteilung in der äußeren Umgebung der Supraleiter und wird nahezu so, wie es bei der Permeabilität 0, also der diamagnetischen Suszeptibilität $-\frac{1}{4\pi}$, des Supraleiters zu erwarten wäre.

2. Im Inneren eines langen Bleiröhrchens bleibt — trotz der dem 1. Effekt entsprechenden Änderung des Magnetfeldes in der äußeren Umgebung — beim Unterschreiten

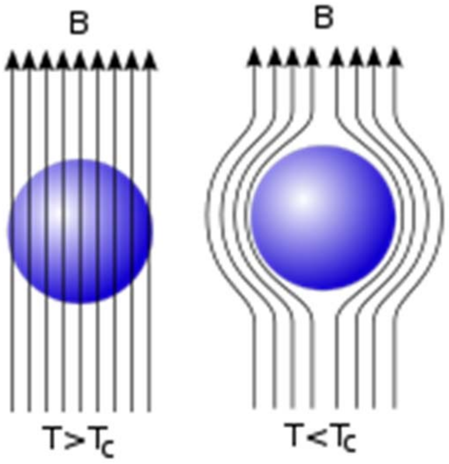
W. Meissner
1882-1974

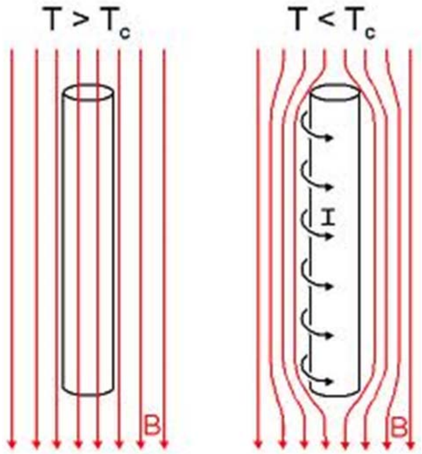
R.Ochsenfeld
1901-1993



Het Meissner-Ochsenfeld effect

- Een supergeleider stoot een zwak magneetveld uit bij koelen naar $T < T_c$





afscherm stromen op oppervlak

- Perfecte diamagneet
  - magneetveld geinduceerd door afschermstromen compenseert aangelegde magneetveld

$$\boxed{\vec{B} = \mu_0(\vec{M} + \vec{H}) = 0} \;\Rightarrow\; \boxed{\vec{M} = -\vec{H}}$$

$$\boxed{\chi_M = \left.\frac{dM}{dH}\right|_{H=0} = -1}$$

susceptibiliteit

Electrodynamica supergeleider 1934

H. London
1907-1970

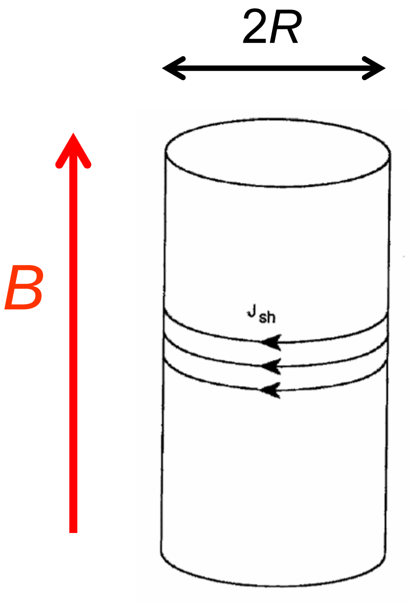
F. London
1900-1954

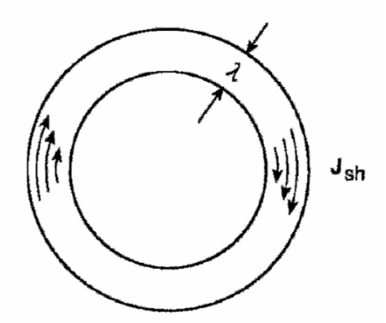
- London vergelijking

$$\cancel{\vec{j} = \frac{ne^2\tau}{m}\vec{E}} \Rightarrow \boxed{\vec{j} = -\frac{ne^2}{m}\vec{A}}$$

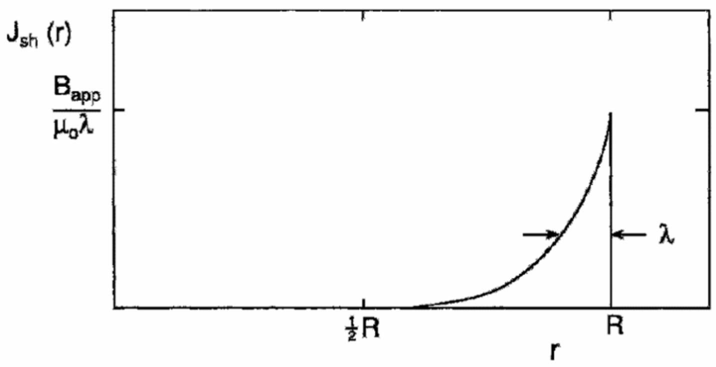
$$\boxed{\vec{B} = \nabla \times \vec{A}}$$

A = vector potentiaal





boven aanzicht



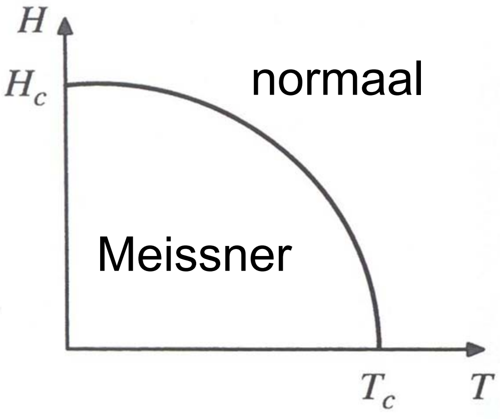
penetratie diepte

$\lambda \sim 1\ \mu\text{m}$

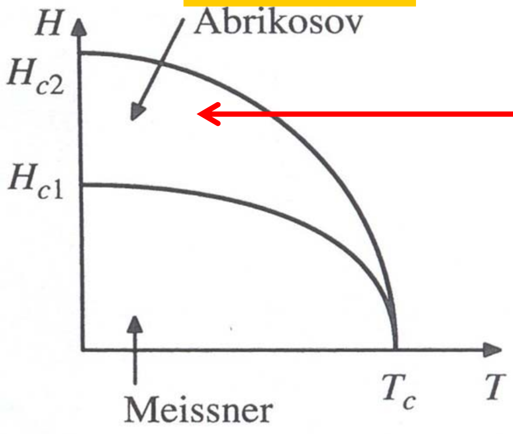
Meissner effect

Type I en Type II supergeleiders

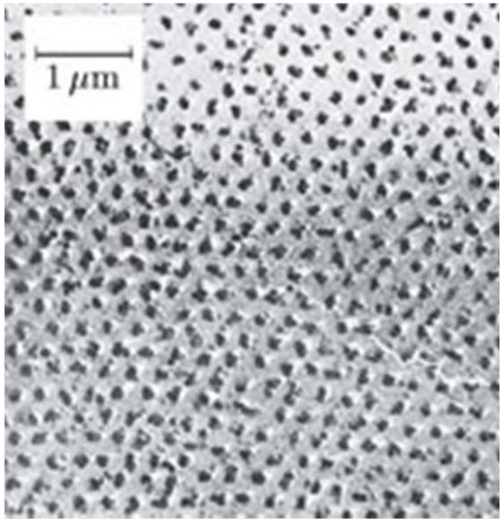
Type I



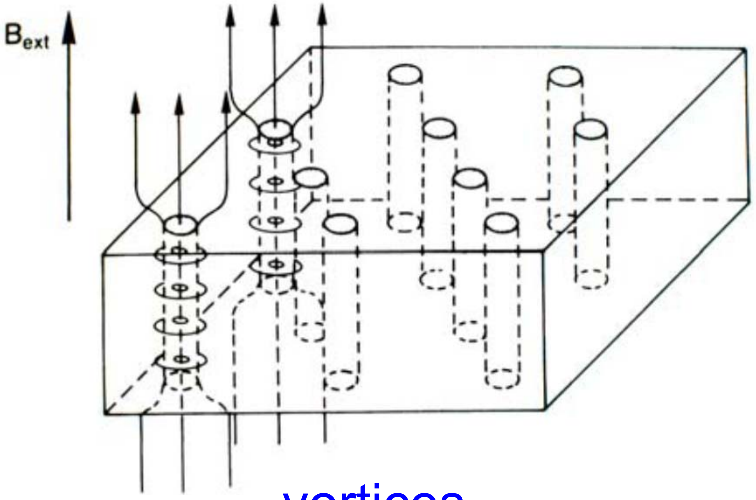
Type II



B= 20 mT



Abrikosov fase
fluxlijn rooster



vortices

A. Abrikosov
1928-…
Nobelprijs 2003

$$a_\Delta = \left(\frac{4}{3}\right)^{1/4}\left(\frac{\Phi_0}{B}\right)^{1/2}$$

$$\Phi_0 = \frac{h}{2e}$$

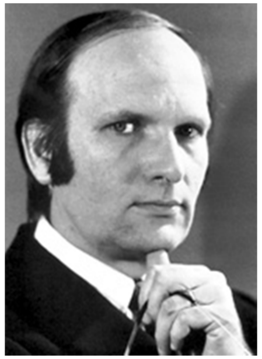
flux quantum

Het “standaard” model voor supergeleiding

1957: De BCS theorie voor supergeleiding

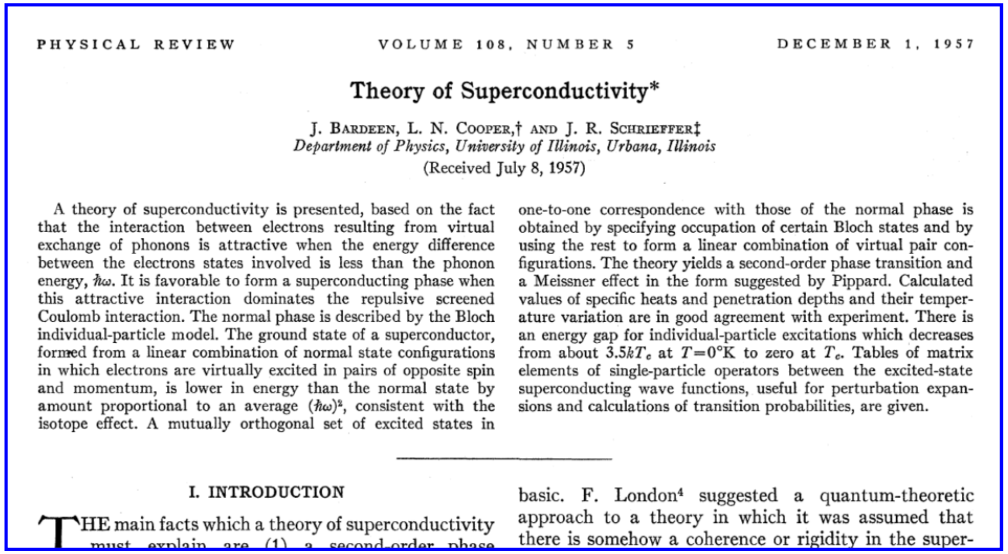
John Bardeen
1908-1991

Leon Cooper
1930- …



Robert Schrieffer
1931- ...

Nobelprijs 1972
"for their jointly developed theory of superconductivity, usually called the BCS-theory"



PHYSICAL REVIEW VOLUME 108, NUMBER 5 DECEMBER 1, 1957

Theory of Superconductivity*

J. BARDEEN, L. N. COOPER,† AND J. R. SCHRIEFFER‡
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 when the energy difference between the electrons states involved is less than the phonon energy, $\hbar\omega$. It is favorable to form a superconducting phase when this attractive interaction dominates the repulsive screened Coulomb interaction. The normal phase is described by the Bloch individual-particle model. The ground state of a superconductor, formed from a linear combination of normal state configurations in which electrons are virtually excited in pairs of opposite spin and momentum, is lower in energy than the normal state by amount proportional to an average $(\hbar\omega)^2$, consistent with the isotope effect. A mutually orthogonal set of excited states in one-to-one correspondence with those of the normal phase is obtained by specifying occupation of certain Bloch states and by using the rest to form a linear combination of virtual pair configurations. The theory yields a second-order phase transition and a Meissner effect in the form suggested by Pippard. Calculated values of specific heats and penetration depths and their temperature variation are in good agreement with experiment. There is an energy gap for individual-particle excitations which decreases from about $3.5kT_c$ at $T=0°K$ to zero at T_c. Tables of matrix elements of single-particle operators between the excited-state superconducting wave functions, useful for perturbation expansions and calculations of transition probabilities, are given.

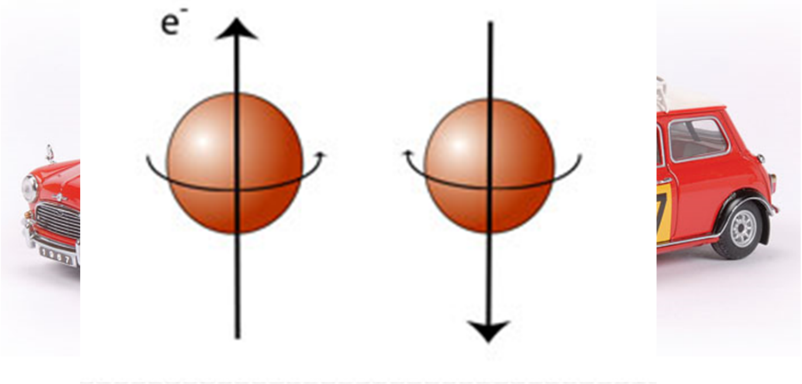
I. INTRODUCTION

THE main facts which a theory of superconductivity must explain are (1) a second-order phase

basic. F. London[4] suggested a quantum-theoretic approach to a theory in which it was assumed that there is somehow a coherence or rigidity in the super-

Het “standaard” model

- Attractieve interactie tussen electronen door roostertrillingen
  - Cooper paren
  - spin-singlet toestand



spin-singlet paar
$L=0$, $S=0$

$$\boxed{\frac{1}{\sqrt{2}}\left(\downarrow\uparrow - \uparrow\downarrow\right)}$$

animatie: superconductors.org

BCS → formule voor T_s

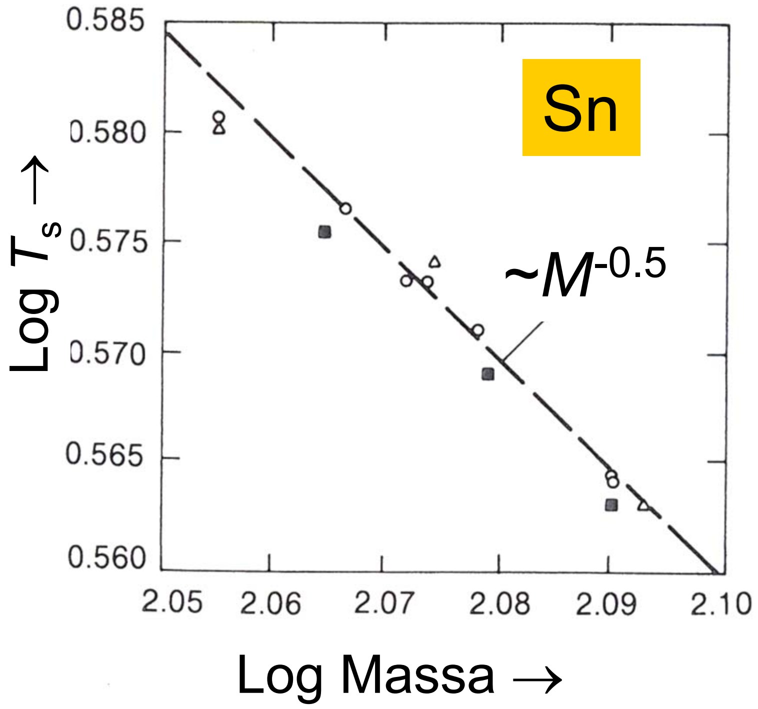
$$\boxed{T_s = 1.13\frac{\hbar\omega_D}{k_B}e^{-1/N(E_F)V}}$$

$$\boxed{T_s = 1.13\times\theta_D\times e^{-1/N(E_F)V}}$$

V = interactie parameter

Voorspelling van de BCS theorie: isotoop effect

T_s als functie van de atomaire massa M

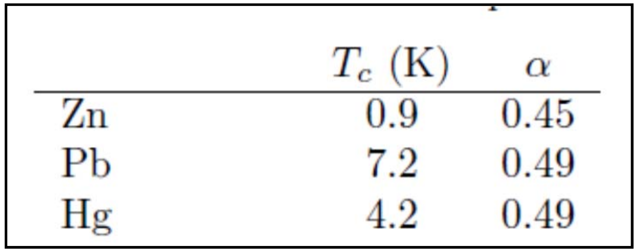


Ibach & Lüth,
Solid State Physics
(Springer, 2002)

$$\omega_D \propto \sqrt{\frac{1}{M}}$$

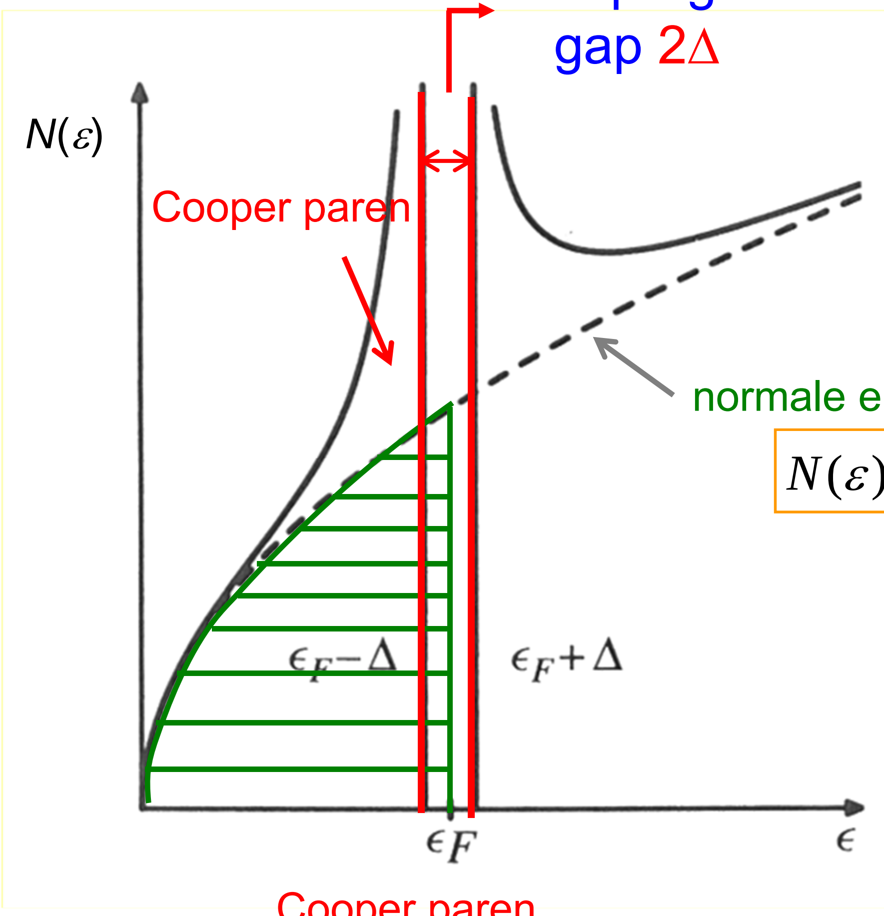
$$T_s = 1.13 \frac{\hbar \omega_D}{k_B} e^{-1/N(E_F)V}$$

$$T_c \propto M^{-\alpha} \quad \text{with} \quad \alpha \approx 0.5$$



	T_c (K)	α
Zn	0.9	0.45
Pb	7.2	0.49
Hg	4.2	0.49

Voorspelling van de BCS theorie: supergeleidende gap



supergeleidende gap 2Δ

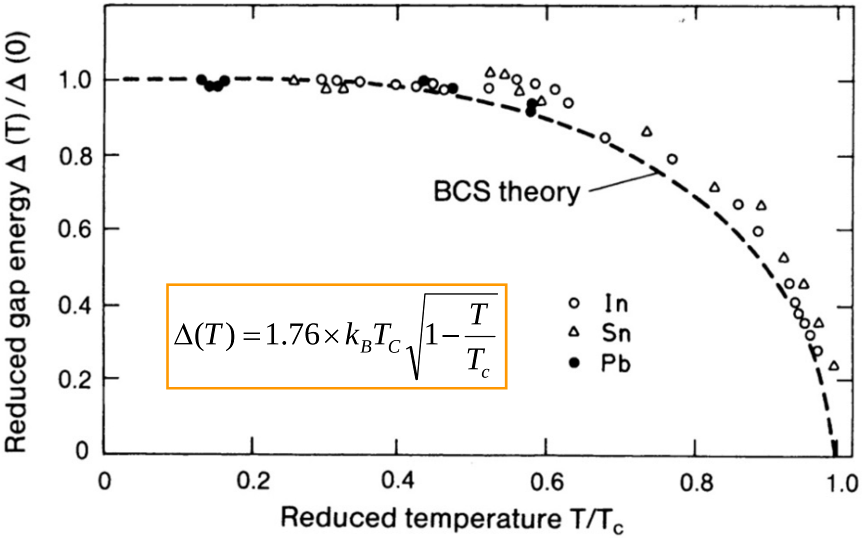
Cooper paren

normale electronen

$$N(\varepsilon) \propto \sqrt{\varepsilon}$$

Cooper paren
kunnen niet verstrooien
$R = 0$

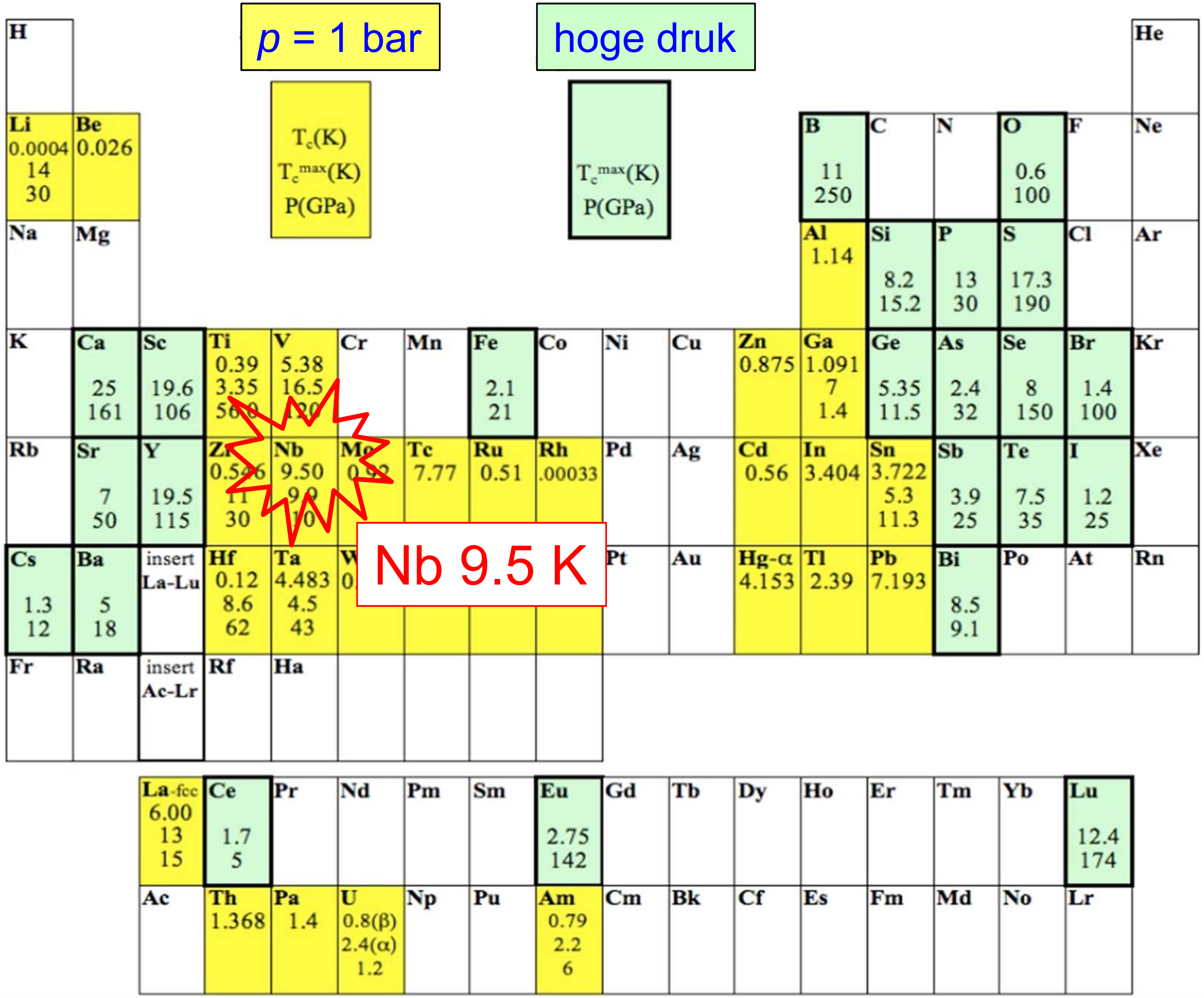
Temperatuur afhankelijkheid van de gap



$$\Delta(T) = 1.76 \times k_B T_C \sqrt{1 - \frac{T}{T_c}}$$

Hoge temperatuur supergeleiding

Supergeleiding in het periodiek systeem



p = 1 bar

T_c(K)
T_c^{max}(K)
P(GPa)

hoge druk

T_c^{max}(K)
P(GPa)

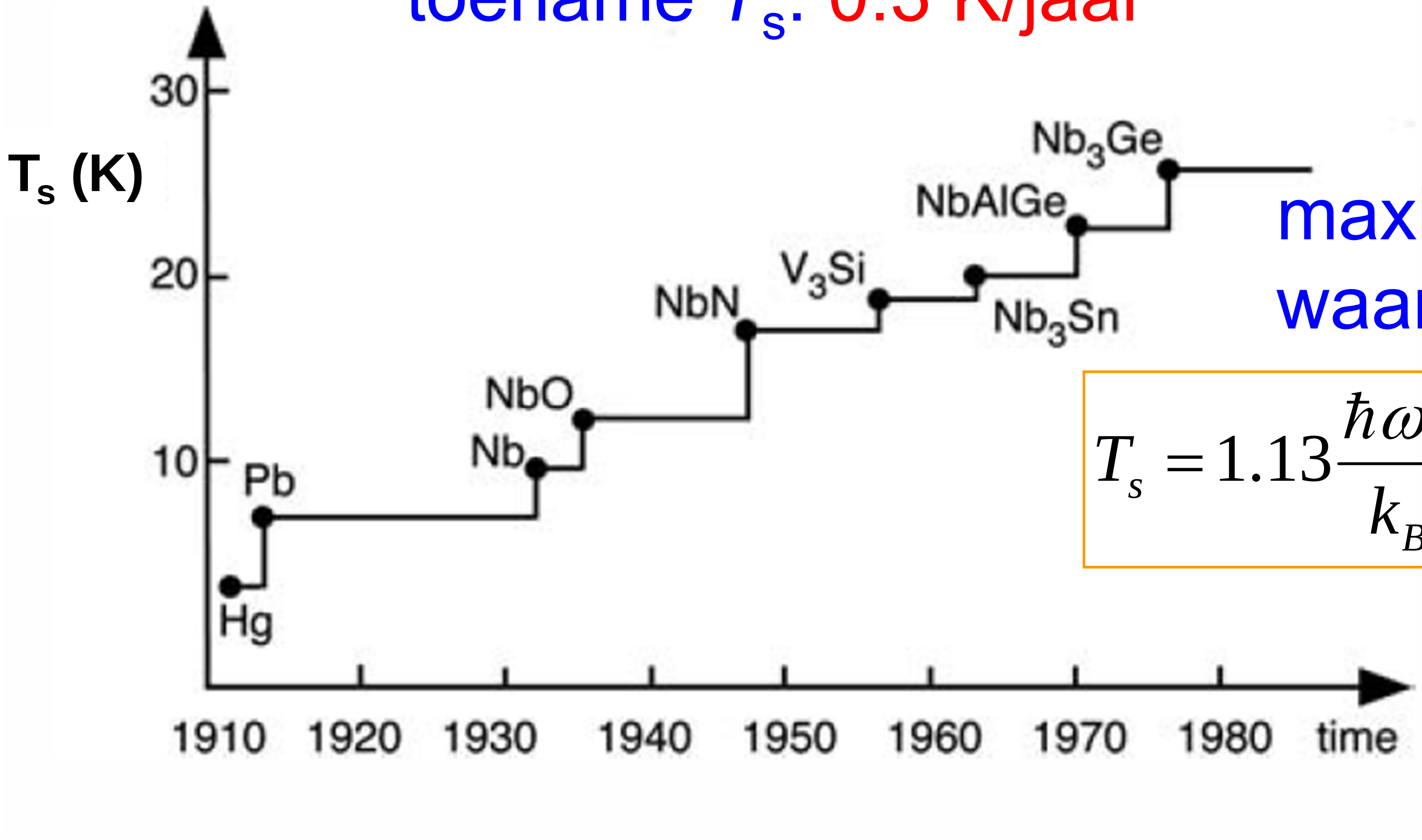
H																	**He**
Li 0.0004 14 30	**Be** 0.026											**B** 11 250	**C**	**N**	**O** 0.6 100	**F**	**Ne**
Na	**Mg**											**Al** 1.14	**Si** 8.2 15.2	**P** 13 30	**S** 17.3 190	**Cl**	**Ar**
K	**Ca** 25 161	**Sc** 19.6 106	**Ti** 0.39 3.35 56.0	**V** 5.38 16.5 120	**Cr**	**Mn**	**Fe** 2.1 21	**Co**	**Ni**	**Cu**	**Zn** 0.875	**Ga** 1.091 7 1.4	**Ge** 5.35 11.5	**As** 2.4 32	**Se** 8 150	**Br** 1.4 100	**Kr**
Rb	**Sr** 7 50	**Y** 19.5 115	**Zr** 0.546 11 30	**Nb** 9.50 9.9 10	**Mo** 0.92	**Tc** 7.77	**Ru** 0.51	**Rh** .00033	**Pd**	**Ag**	**Cd** 0.56	**In** 3.404	**Sn** 3.722 5.3 11.3	**Sb** 3.9 25	**Te** 7.5 35	**I** 1.2 25	**Xe**
Cs 1.3 12	**Ba** 5 18	insert **La-Lu**	**Hf** 0.12 8.6 62	**Ta** 4.483 4.5 43	**W** 0				**Pt**	**Au**	**Hg-α** 4.153	**Tl** 2.39	**Pb** 7.193	**Bi** 8.5 9.1	**Po**	**At**	**Rn**
Fr	**Ra**	insert **Ac-Lr**	**Rf**	**Ha**													

La-fcc 6.00 13 15	**Ce** 1.7 5	**Pr**	**Nd**	**Pm**	**Sm**	**Eu** 2.75 142	**Gd**	**Tb**	**Dy**	**Ho**	**Er**	**Tm**	**Yb**	**Lu** 12.4 174
Ac	**Th** 1.368	**Pa** 1.4	**U** 0.8(β) 2.4(α) 1.2	**Np**	**Pu**	**Am** 0.79 2.2 6	**Cm**	**Bk**	**Cf**	**Es**	**Fm**	**Md**	**No**	**Lr**

Nb 9.5 K

Supergeleiding in metalen

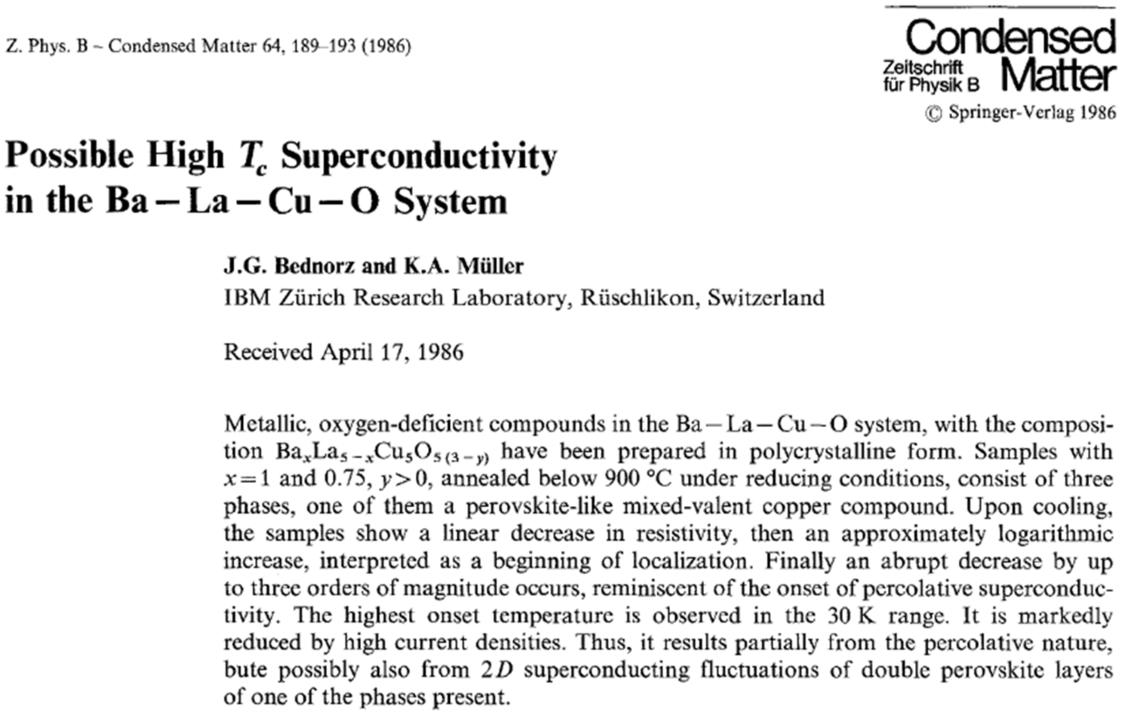
toename T_s: 0.3 K/jaar



maximum
waarde BCS

$$T_s = 1.13 \frac{\hbar \omega_D}{k_B} e^{-1/N(E_F)V}$$

Supergeleiding in koper-oxiden: Hoge-T_c supergeleiders



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

Condensed Matter
Zeitschrift für Physik B
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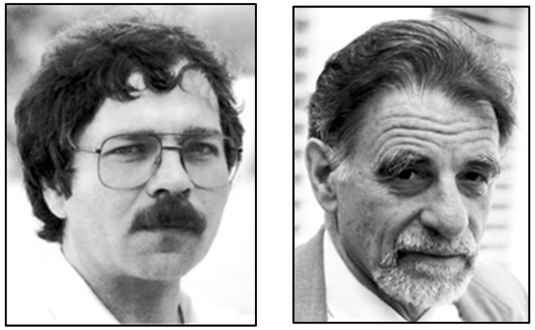
Possible High T_c Superconductivity in the Ba – La – Cu – O System

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 $Ba_xLa_{5-x}Cu_5O_{5(3-y)}$ have been prepared in polycrystalline form. Samples with $x=1$ and 0.75, $y>0$, annealed below 900 °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, bute possibly also from $2D$ superconducting fluctuations of double perovskite layers of one of the phases present.

- supergeleiding in Ba-La-Cu-O verbinding bij 30 K
- nieuw wereld record T_s na 12 jaar Nb_3Ge
- in $(La,Sr)_2CuO_4 \rightarrow T_s = 40$ K



Nobelprijs 1987

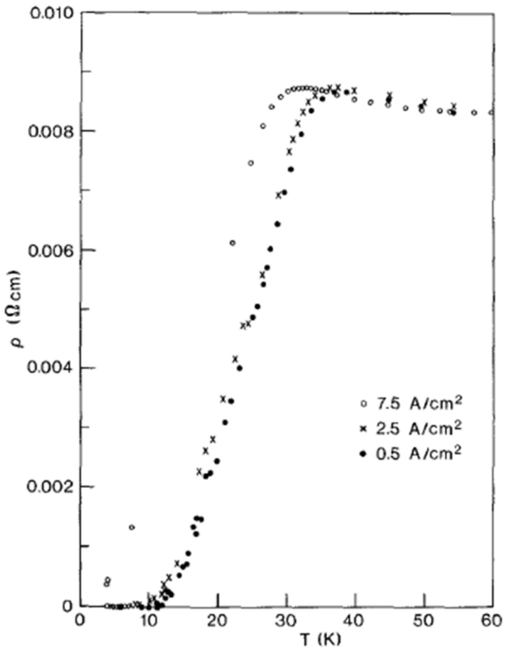
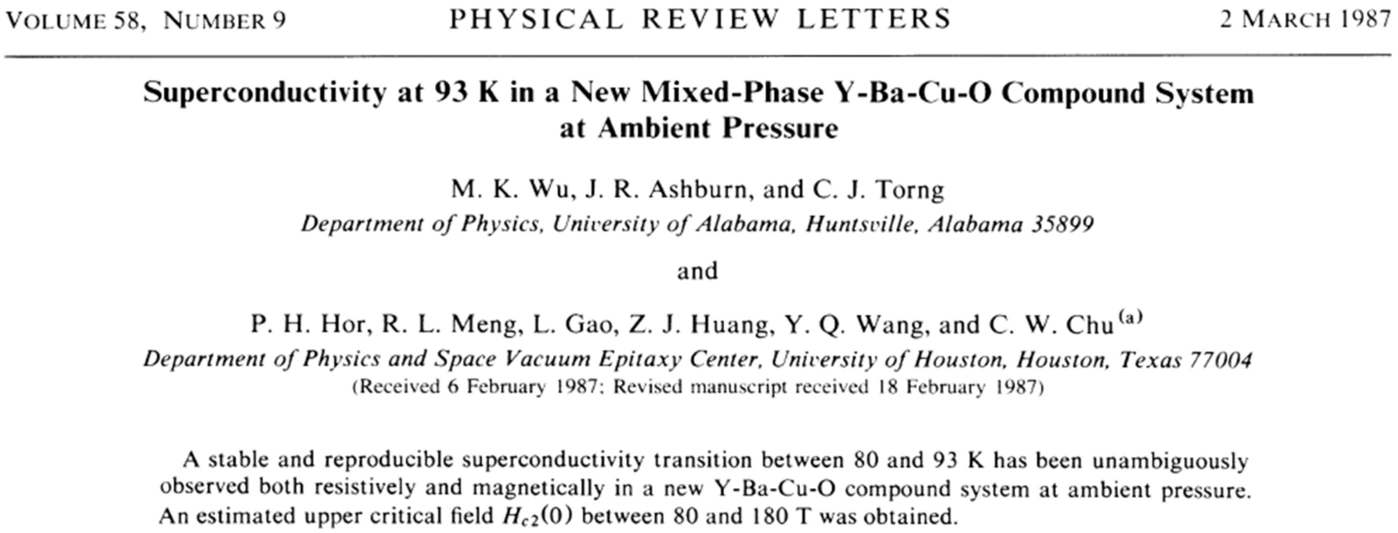


Fig. 3. Low-temperature resistivity of a sample with $x(Ba)=0.75$, recorded for different current densities

Supergeleiding in koper-oxiden: Hoge-T_c supergeleiders



VOLUME 58, NUMBER 9 PHYSICAL REVIEW LETTERS 2 MARCH 1987

Superconductivity at 93 K in a New Mixed-Phase Y-Ba-Cu-O Compound System at Ambient Pressure

M. K. Wu, J. R. Ashburn, and C. J. Torng
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and

P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, Y. Q. Wang, and C. W. Chu (a)
Department of Physics and Space Vacuum Epitaxy Center, University of Houston, Houston, Texas 77004

(Received 6 February 1987; Revised manuscript received 18 February 1987)

A stable and reproducible superconductivity transition between 80 and 93 K has been unambiguously observed both resistively and magnetically in a new Y-Ba-Cu-O compound system at ambient pressure. An estimated upper critical field $H_{c2}(0)$ between 80 and 180 T was obtained.

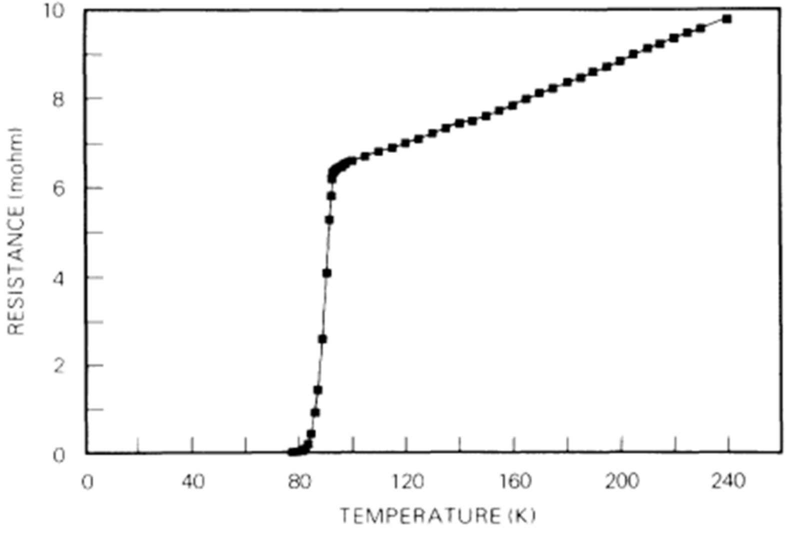
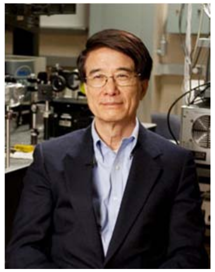


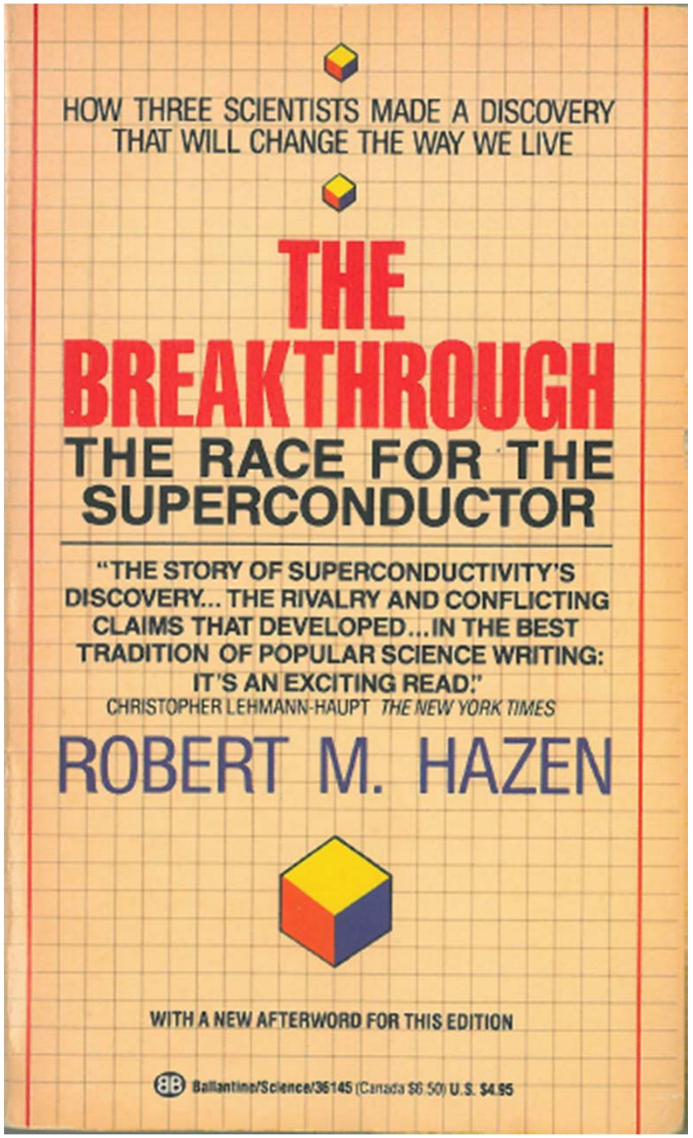
FIG. 1. Temperature dependence of resistance determined in a simple liquid-nitrogen Dewar.



C.W. Paul Chu

- supergeleiding in Y-Ba-Cu-O verbinding bij $T_c = 93$ K
- supergeleiding met vloeibare stikstof (kookpunt 77 K)

Supergeleiding in koper-oxiden: Hoge-T_c supergeleiders



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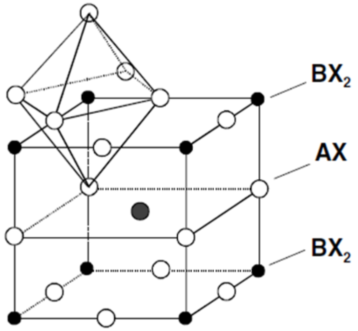
Ballentine books
New York, 1988

Supergeleiding in koper-oxiden: kristal structuur

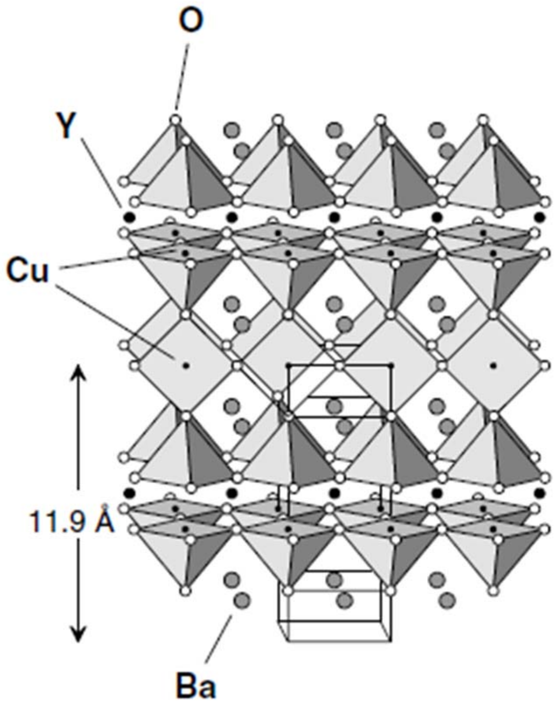
Buckel & Kleiner, Superconductivity (Wiley, 2004)



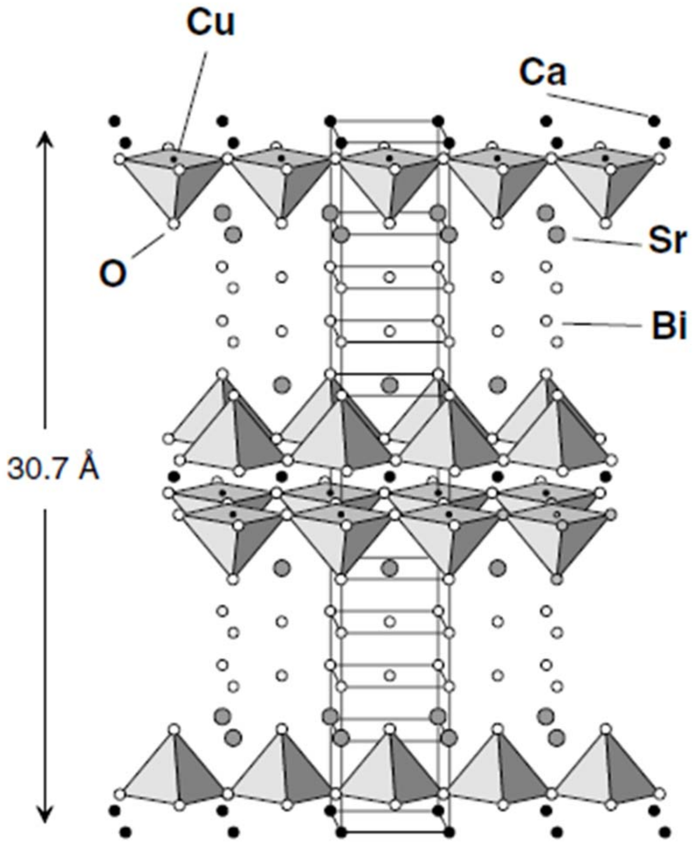
- perovskiet bouwstenen ABX_3

  B atoom omringd door octahedron met X atomen
- gelaagd materiaal

  met CuO_2 vlakken



$YBa_2Cu_3O_7$

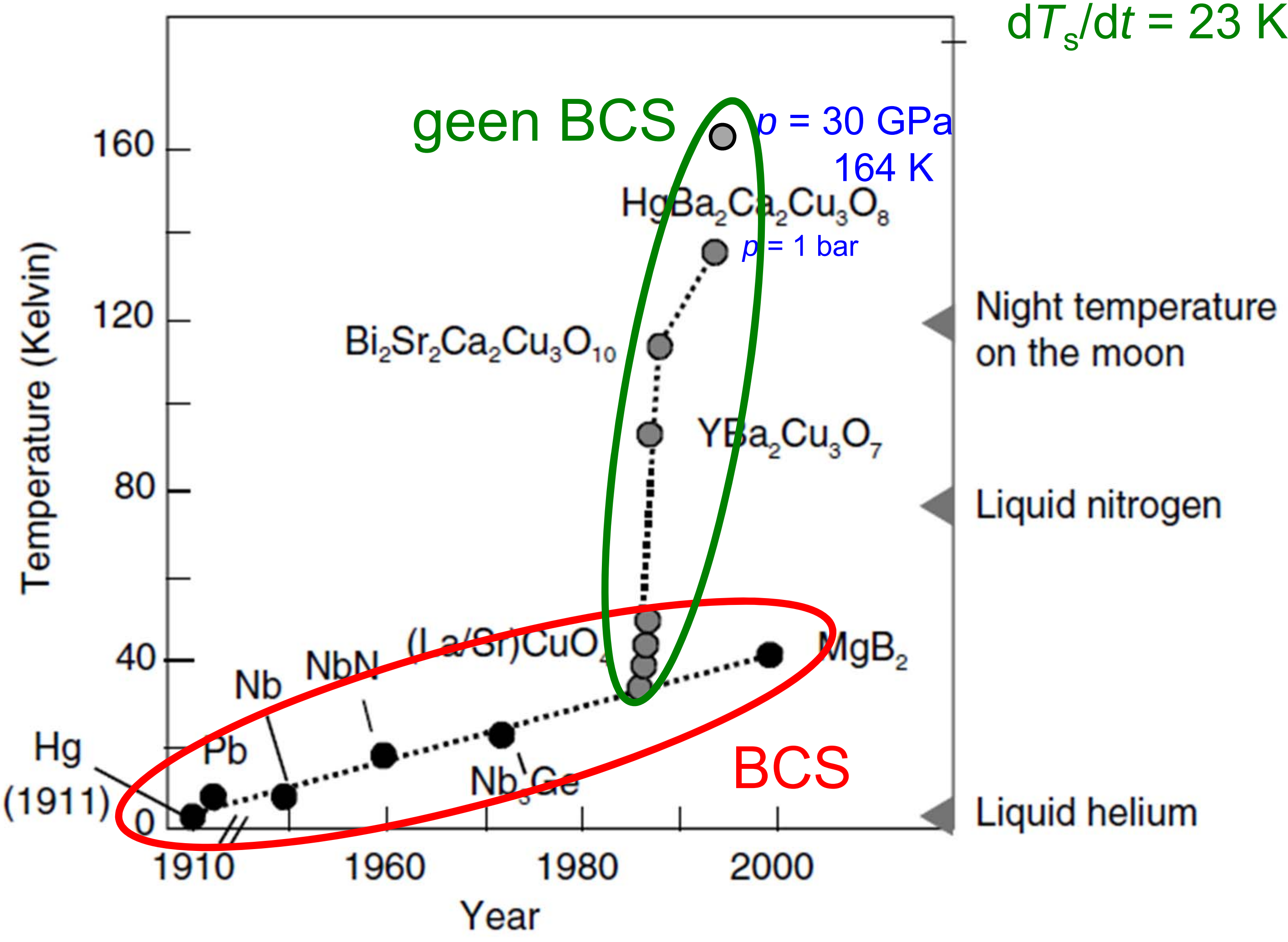


$Bi_2Sr_2CaCu_2O_8$

Supergeleiding in koper-oxiden

Buckel & Kleiner, Superconductivity (Wiley, 2004)

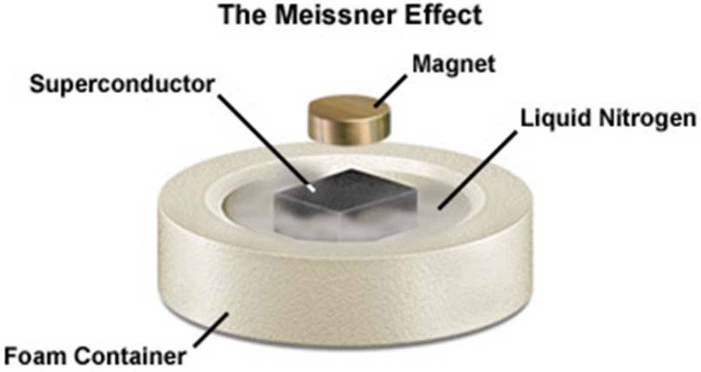
dT_s/dt = 23 K/jaar



Toepassingen van supergeleiding

Leviteren

zie: www.fys.uio.no/super/levitation/



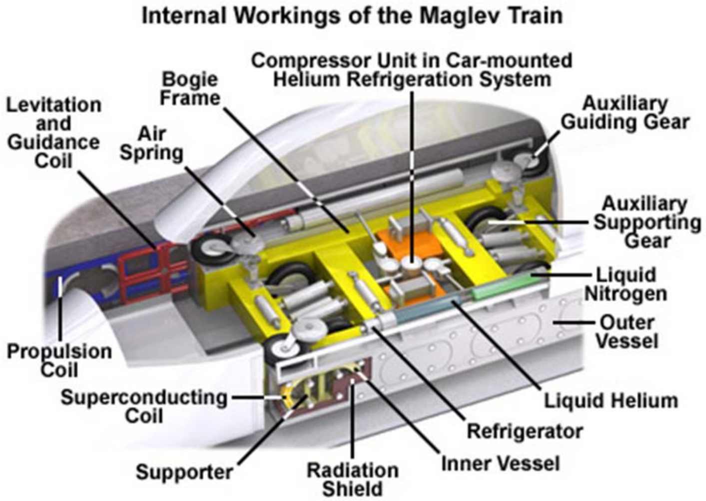
TOSANOUMI
(Sumo Wrestler)

Height of Tosanoumi	186cm
Weight of Tosanoumi	142kg
Weight of disk	60kg
Total weight	202kg

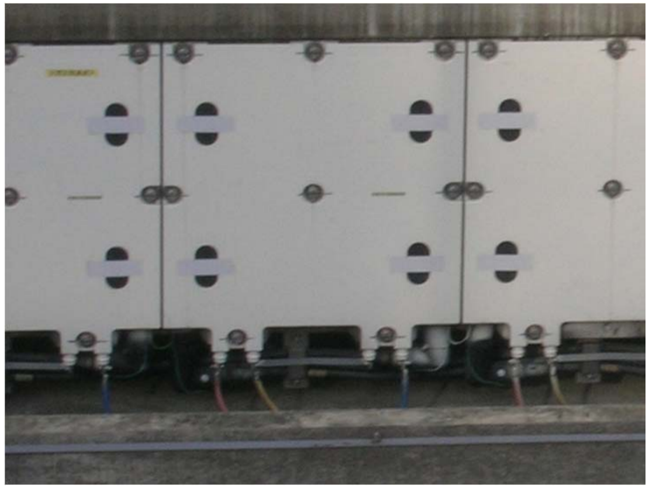
As of February '96

totaal 202 kg

Supergeleidende zweeftrein



guiding coils system



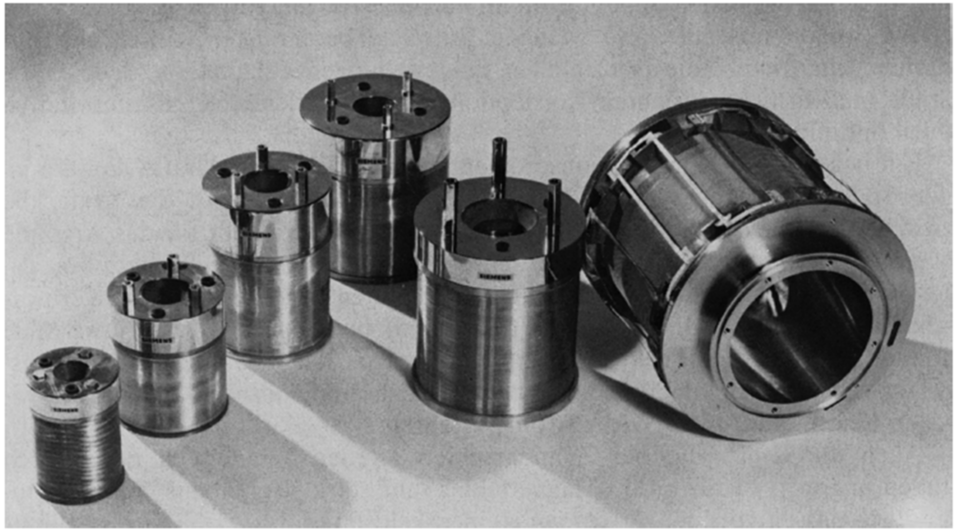
Japan Rail Maglev MLX-01

snelheid: 581 km/h

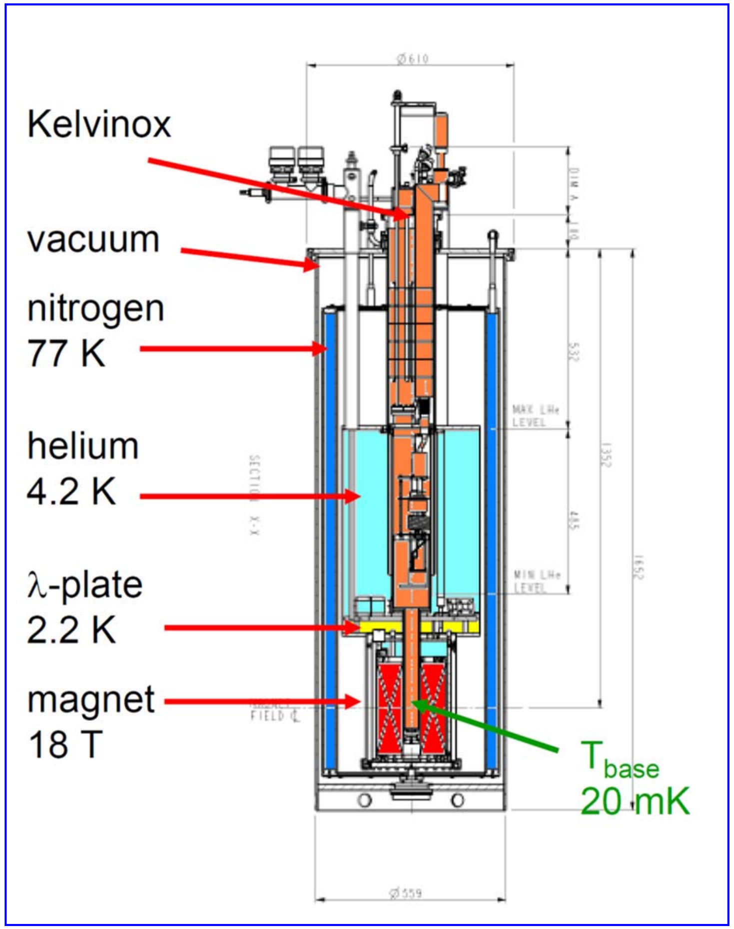
operationeel 1997

Maglev Washington – New York
http://www.usjmaglev.com/usjmaglev/Home.html

Supergeleidende magneten



standaard laboratorium magneten



Kelvinox

vacuum

nitrogen
77 K

helium
4.2 K

λ-plate
2.2 K

magnet
18 T

T_{base}
20 mK

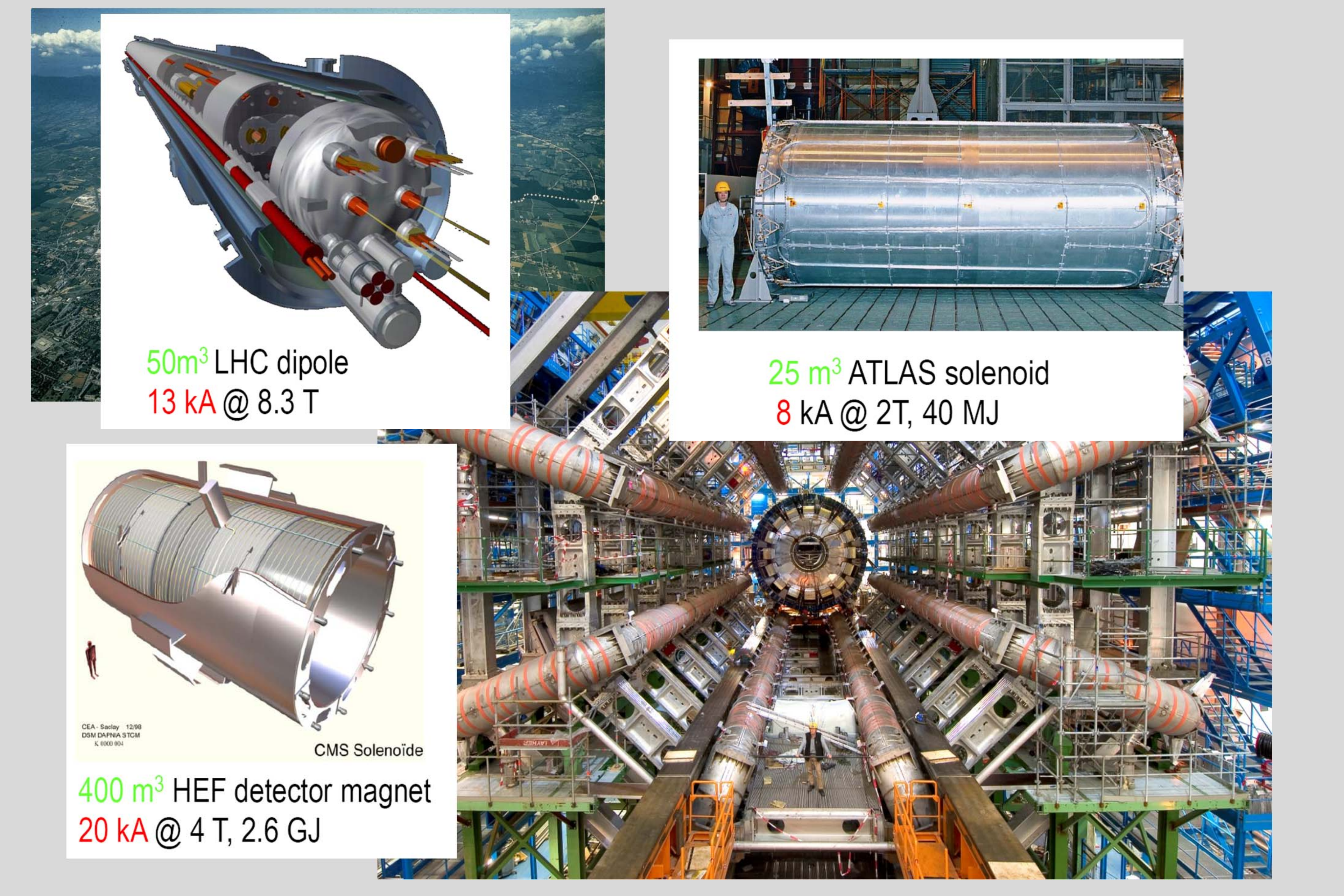
Kelvinox mengkoeler
met supergeleidende magneet UvA
16 T bij 4.2 K
18 T bij 2.2 K

Supergeleidende magneten: quench

opgeslagen energie $E = ½LI^2$
~100 kJ voor 10 Tesla

WND Conferentie, Noordwijkerhout, 12 dec. 2015

Toepassing supergeleidende magneten: deeltjesversnellers/detectoren



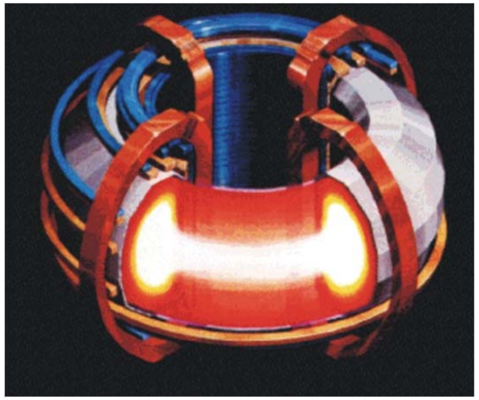
50m^3 LHC dipole
13 kA @ 8.3 T

25 m^3 ATLAS solenoid
8 kA @ 2T, 40 MJ

400 m^3 HEF detector magnet
20 kA @ 4 T, 2.6 GJ

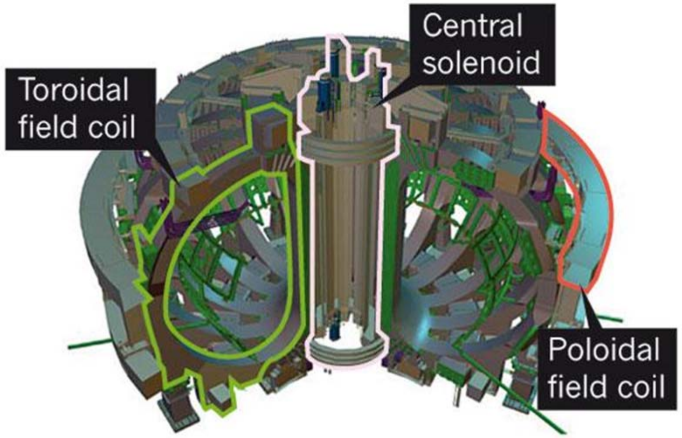
Toepassing supergeleidende magneten: Energie - kernfusie

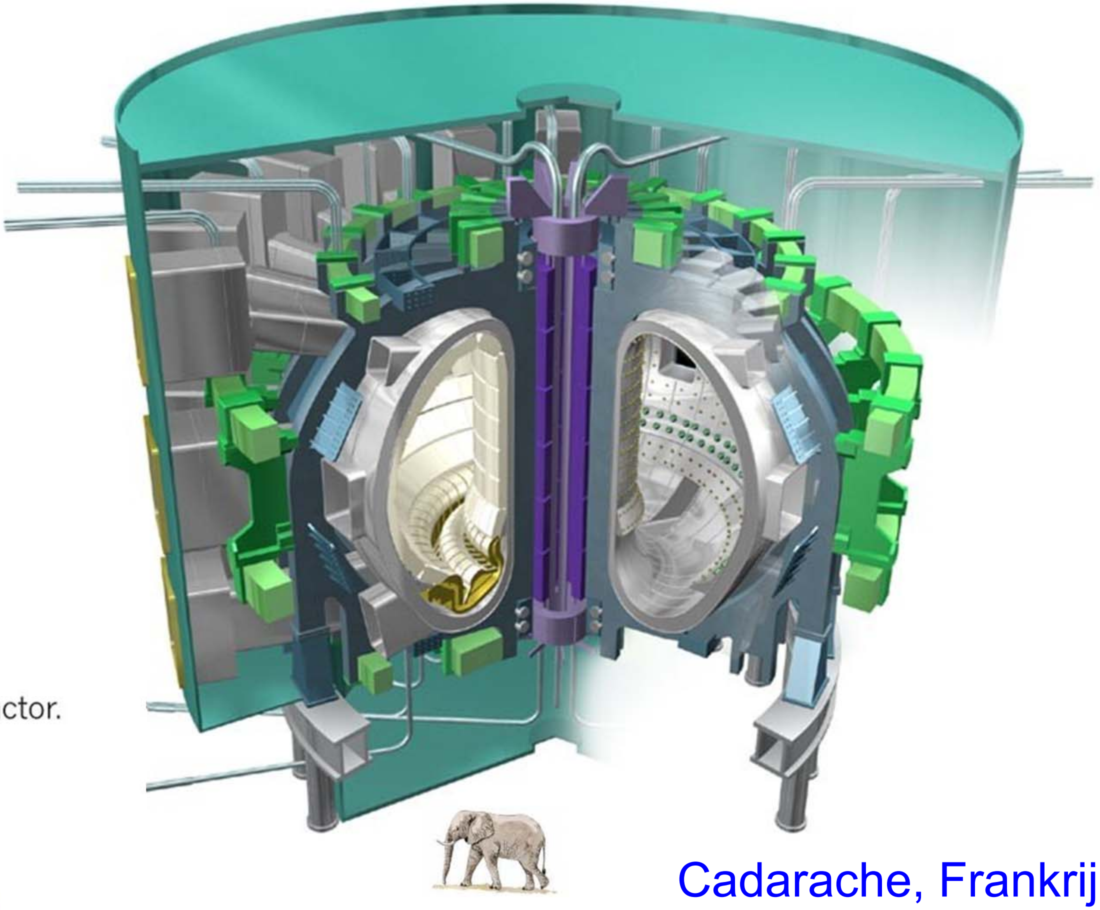
temperatuur plasma:
100-200 miljoen °C



ITER'S BEATING HEART

The superconducting cables of the central solenoid are a crucial part of the fusion reactor.



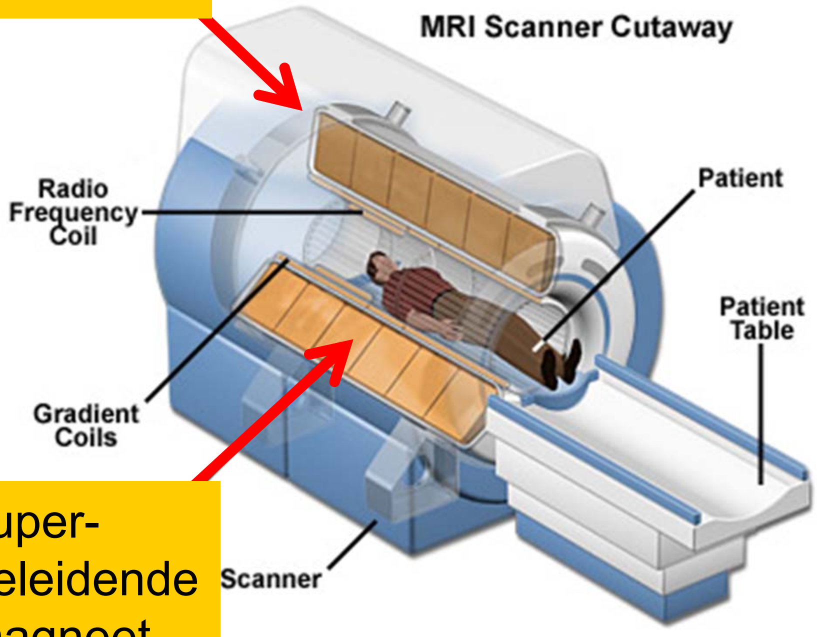


Cadarache, Frankrijk

$1000\ m^3$ ITER magnets
40-70 kA @ 10-13T , 50 GJ

Toepassing supergeleidende magneten: MRI scanner

vloeibaar helium



super-geleidende magneet

magnetic resonance imaging (=NMR)

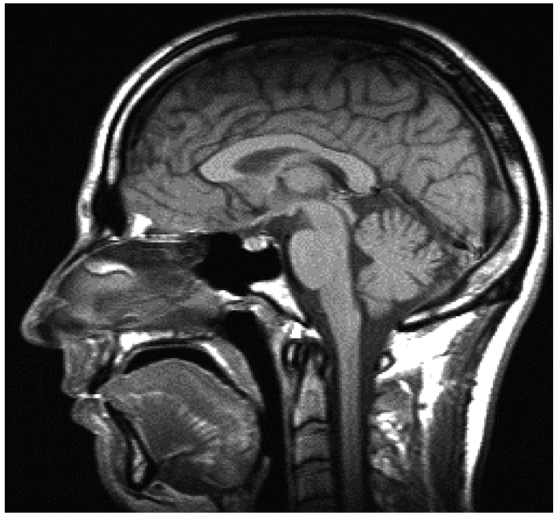
- verschuiving resonantie frequentie van proton door verschil in chemische omgeving

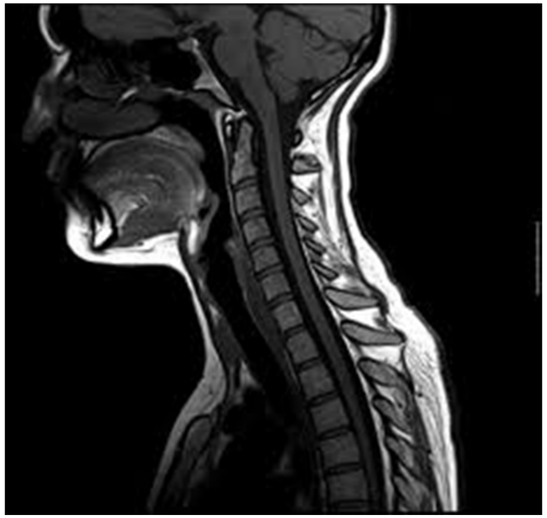
nucleaire spin tomografie

supergeleidende magneet

B = 3-8 T

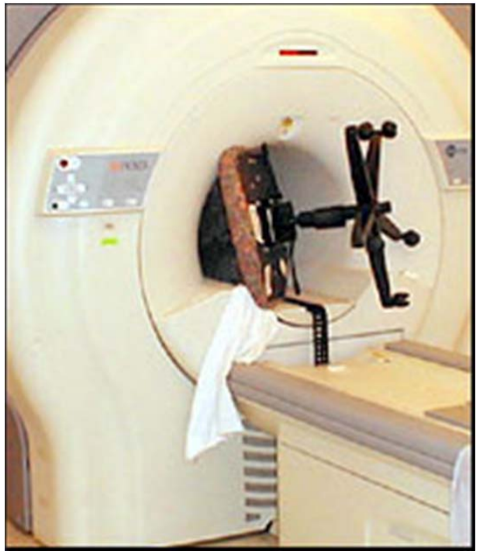
Toepassing supergeleidende magneten: MRI scanner





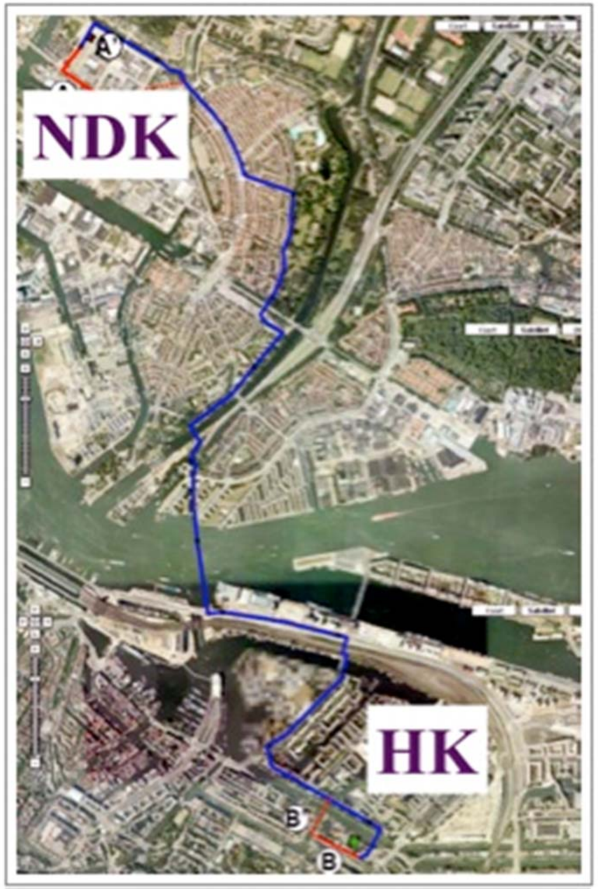
resolutie 160 μm

Toepassing supergeleidende magneten: MRI scanner ongelukjes

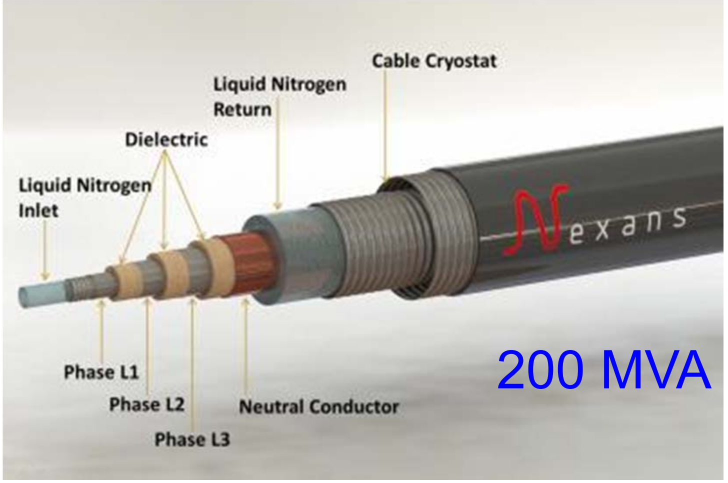


Supergeleidende kabels voor energie transport

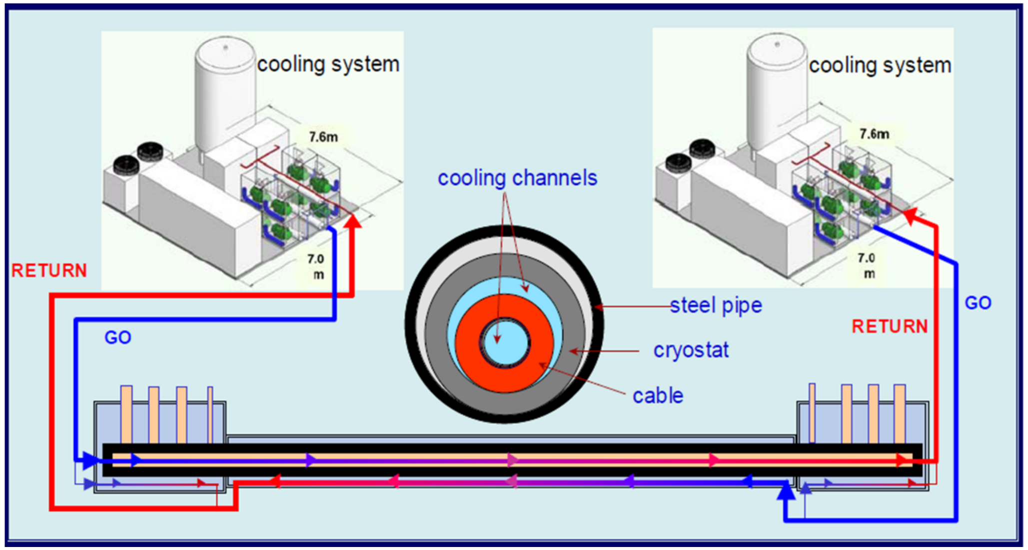
Amsterdam!



Alliander & Ultera



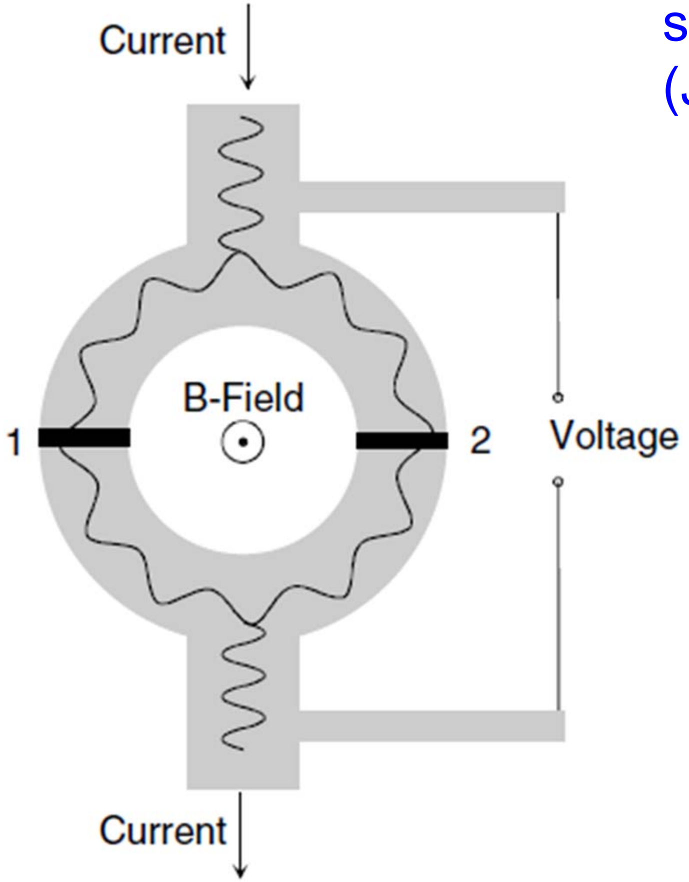
200 MVA



Journal of Physics: Conf. Series 234 (2010) 032037

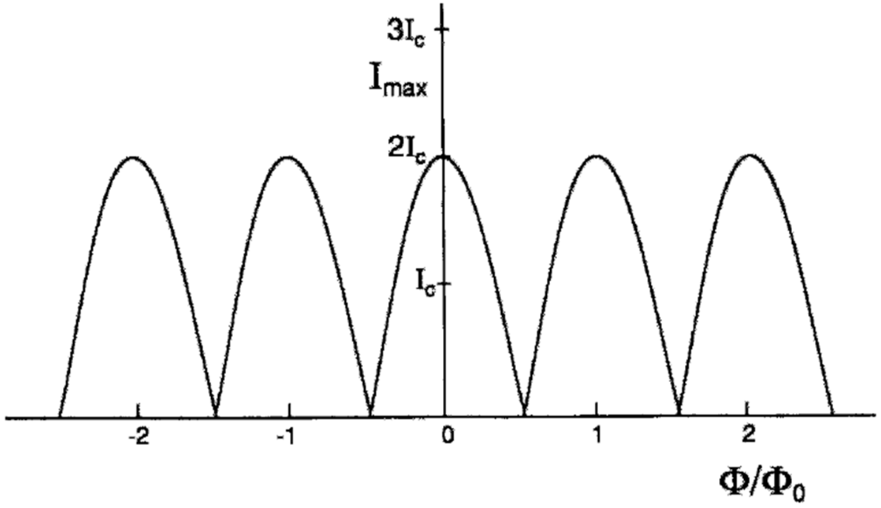
http://www.liandon.nl/liandon/producten_en_diensten/hoog_en_middenspaning/product_supergeleidende_kabel.htm

SQUIDS – Superconducting QUantum Interference Device



supergeleidende ring met 2 “weak links” (Josephson juncties)

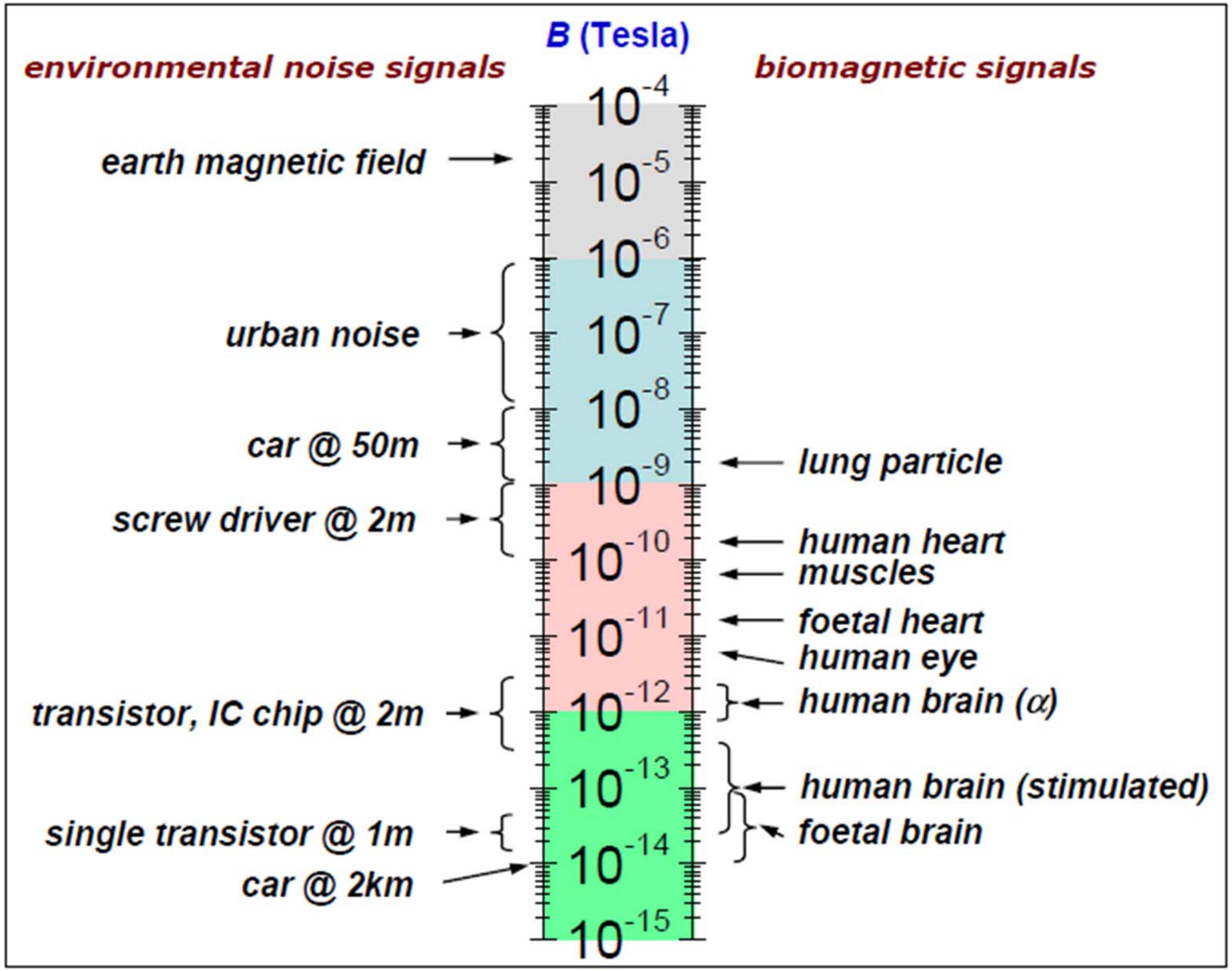
$$I_{\max} = 2I_c \left|\cos\left(\frac{\pi\Phi}{\Phi_0}\right)\right|$$



optica: zelfde patroon als bij dubbel-spleet experiment (Young)

SQUID gevoeligheid

resolutie $10^{-6}\ \Phi_0$; voor 1 mm^2 oppervlak: $B = 10^{-6}\ \Phi_0/10^{-6} \approx 10^{-15}$ Tesla



Gross and Marx: Lecture Applied Superconductivity, Walther Meissner Inst.

SQUID applications: Multichannel squid systemen

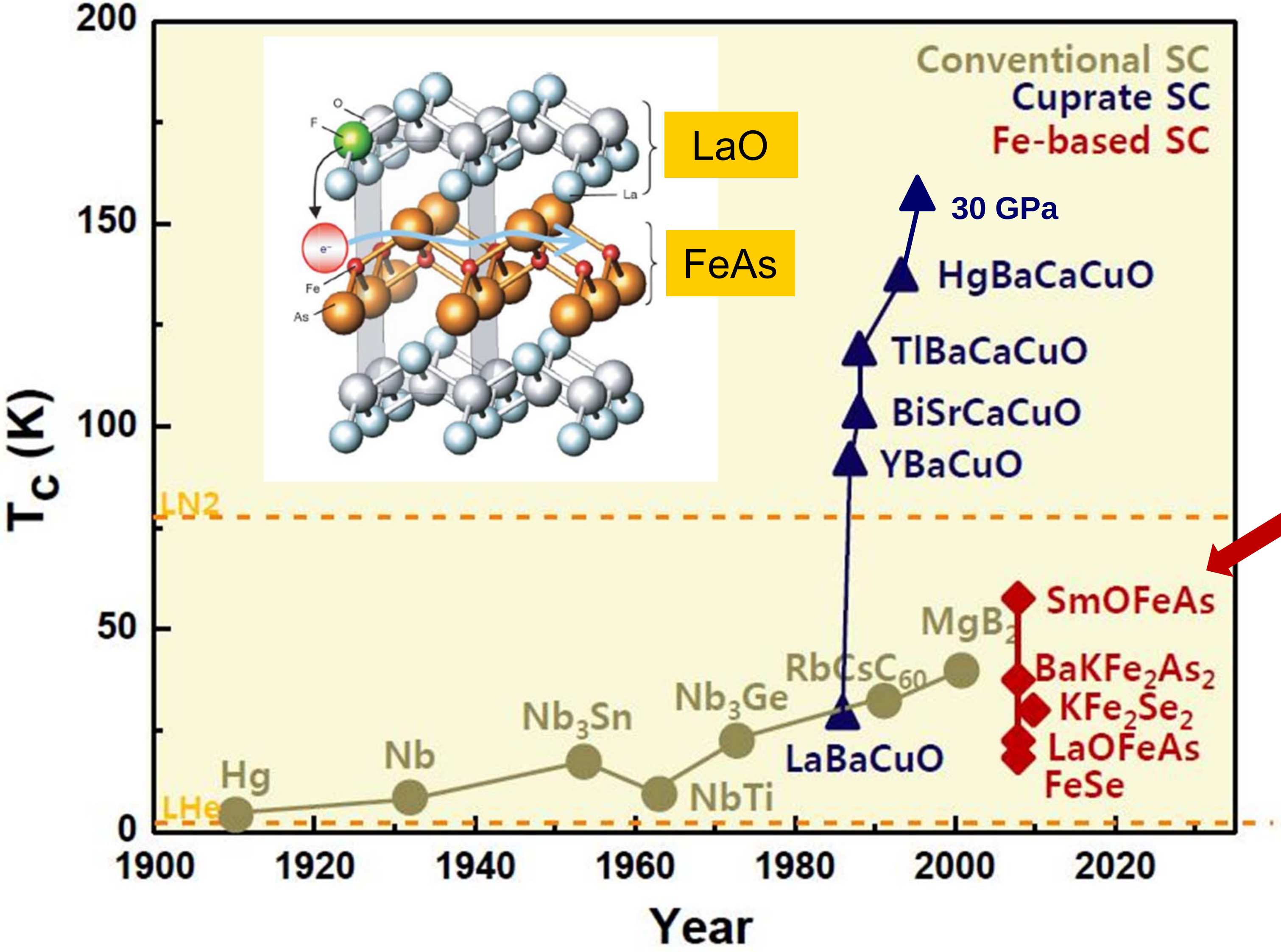
multichannel SQUID systemen
voor magnetoencephalografie en magnetocardiografie

CTF Systems Inc.,
Vancouver, Canada

Biomagnetic Technologies,
San Diego, USA

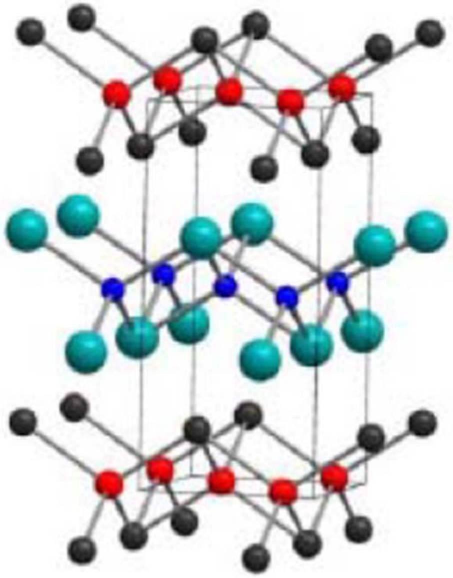
“Hot-topics ” supergeleiding

Supergeleiding in ijzerpnictiden

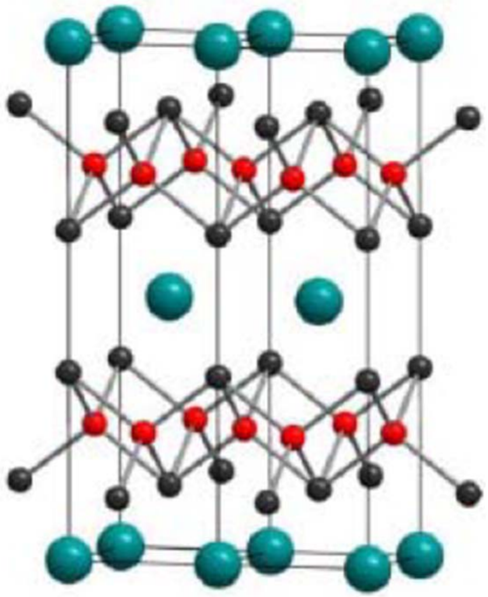


H. Hosono
2008

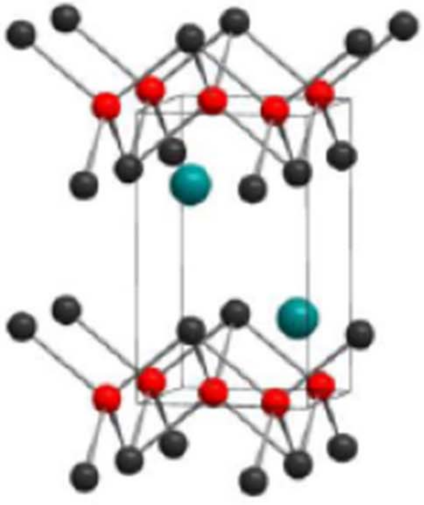
Supergeleiding in ijzerpnictiden: gelaagd met FeAs vlakken



LaFeAsO

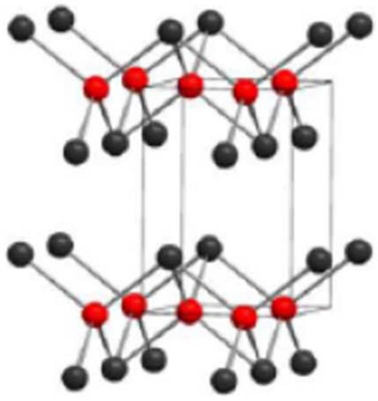


$Ba(FeAs)_2$



LiFeAs

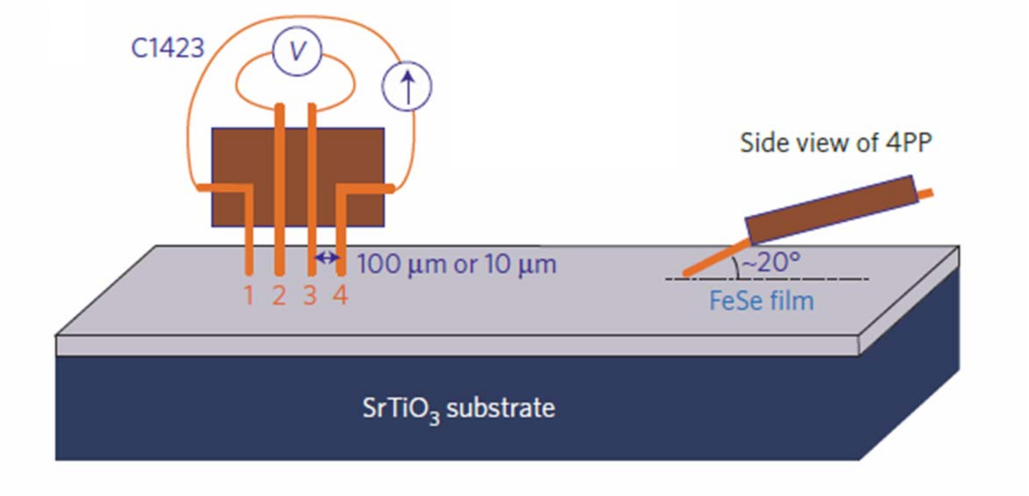
- 1111, 122, 111 en 11 kristalstructuur
- supergeleiding in FeAs of FeSe lagen

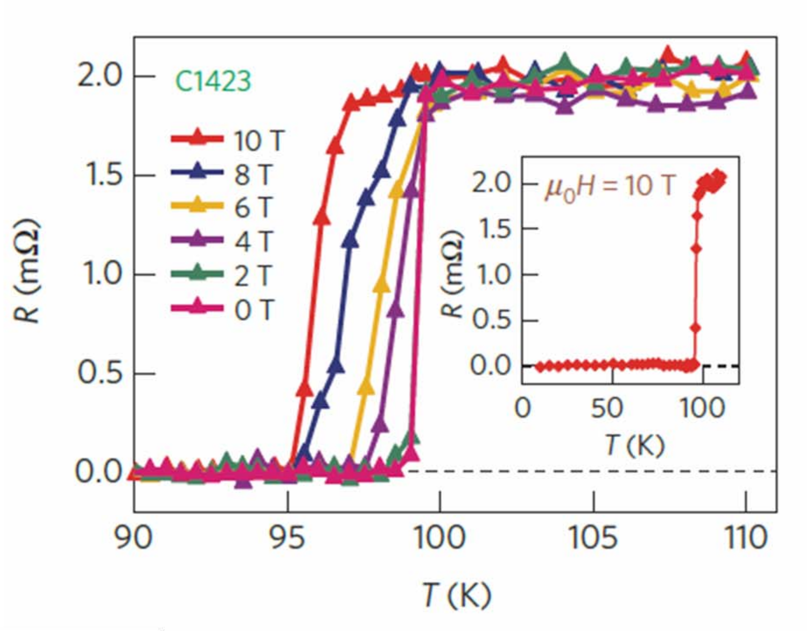


FeSe

2015: Supergeleiding bij 100 K in monolaag FeSe dunne film

J.-F. Ge *et al*., Nature Materials 14 (2015) 285

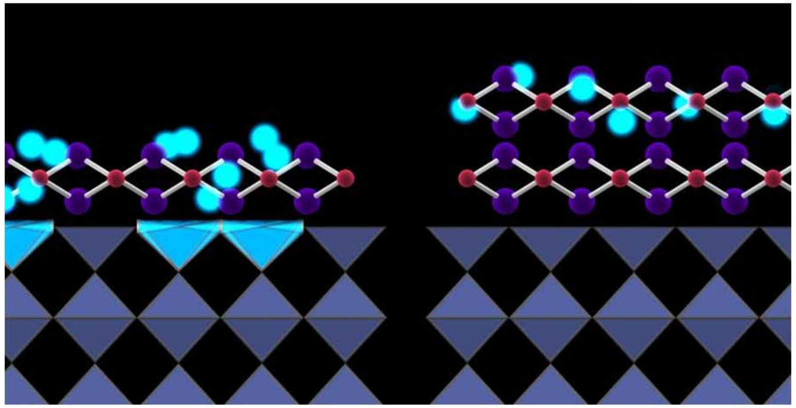




T_s = 100 K!

1 laag FeSe

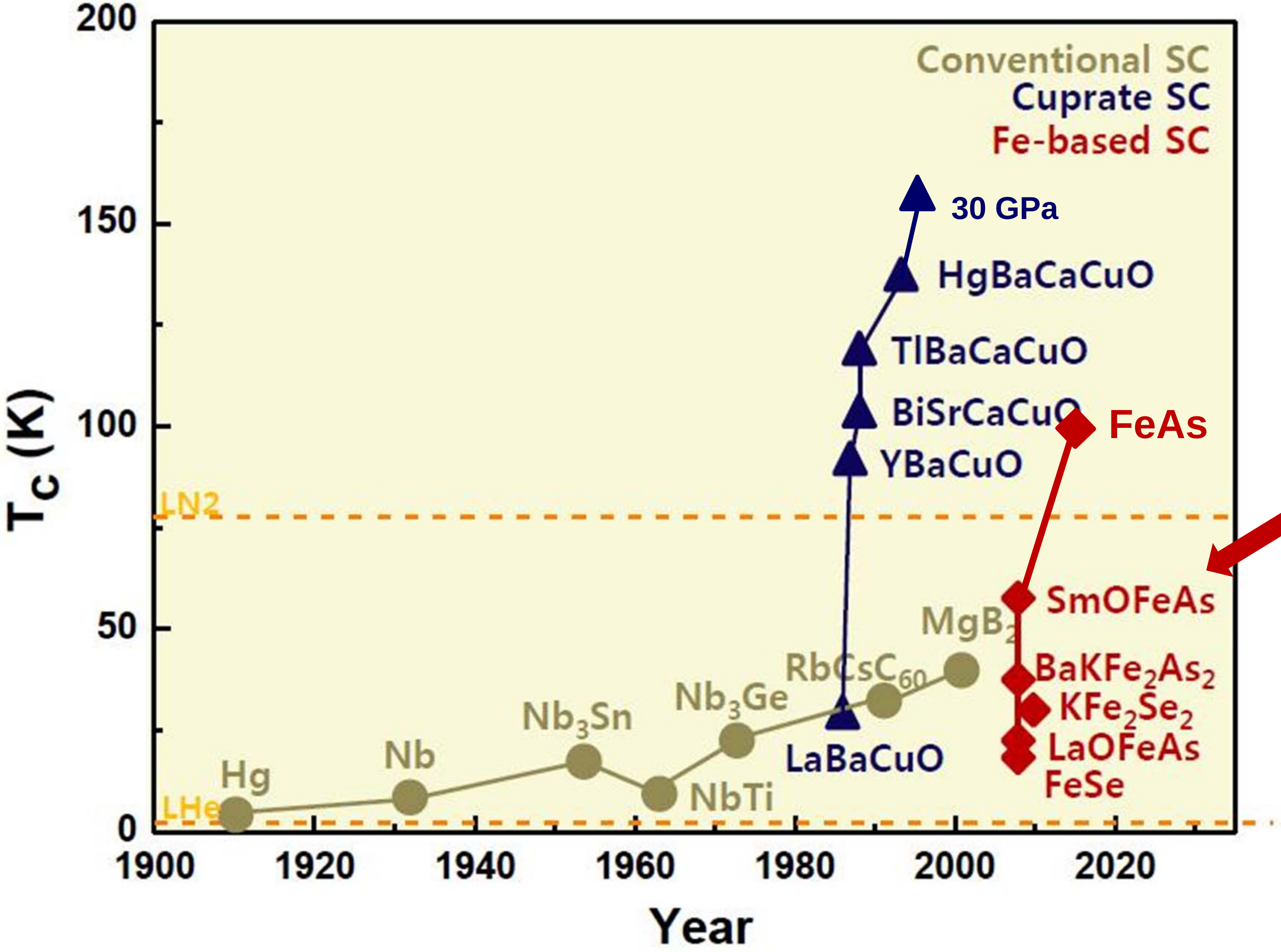
substraat



2 lagen FeSe

geen supergeleiding

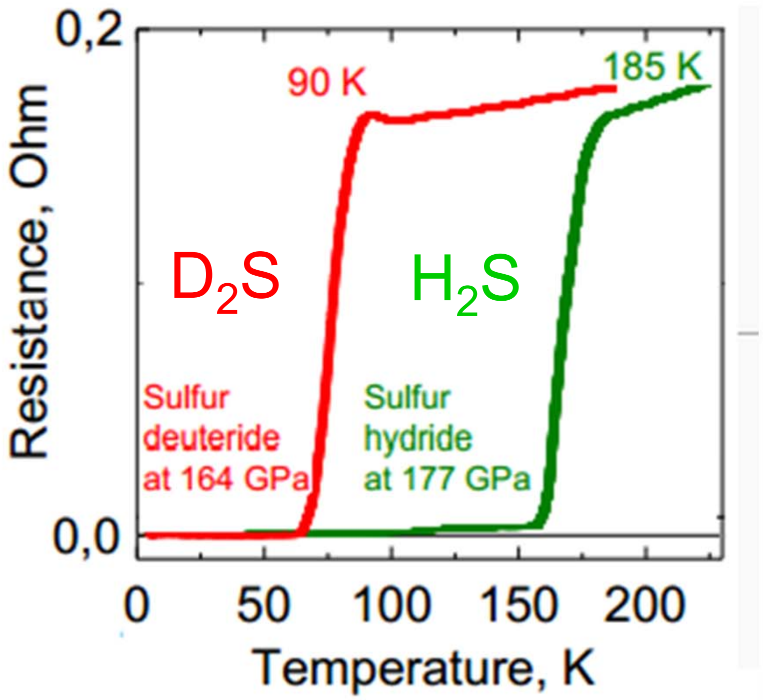
Supergeleiding in ijzerpnictiden



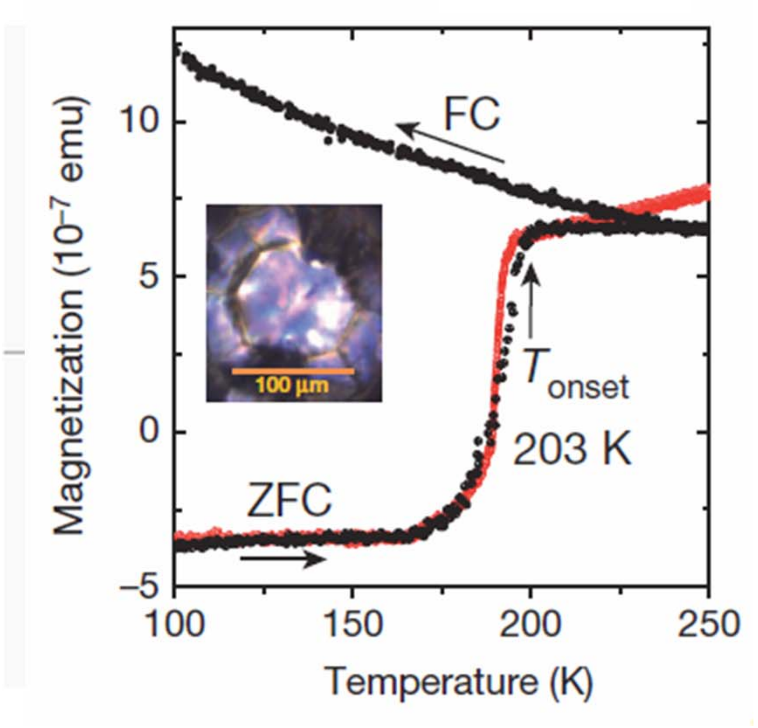
H. Hosono
2008

2015: Supergeleiding bij 203 K in H_2S onder hoge druk ~1.8 miljoen atm.

Drozdov *et al*., Nature 525 (2015) 73

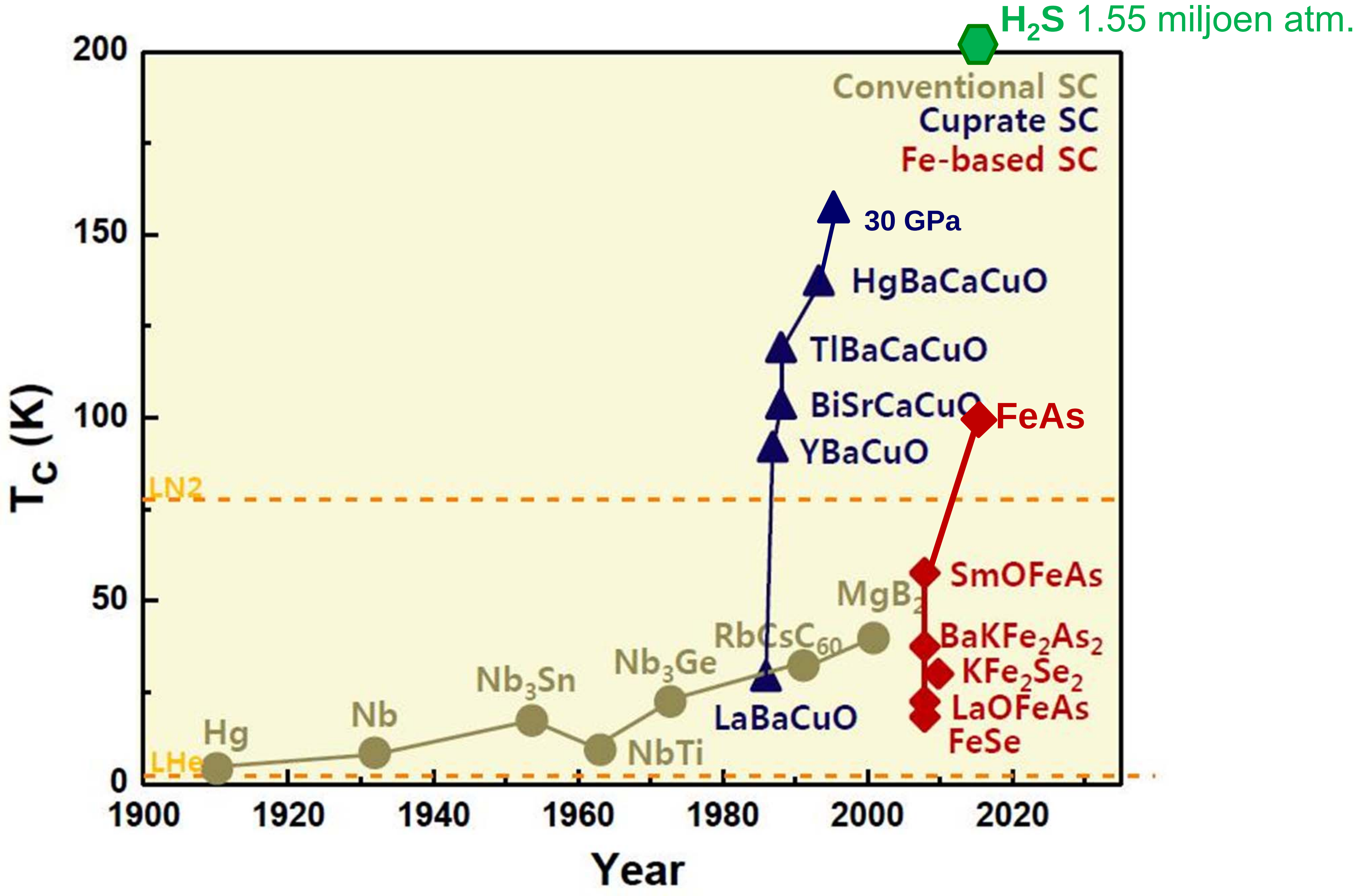


155 GPa



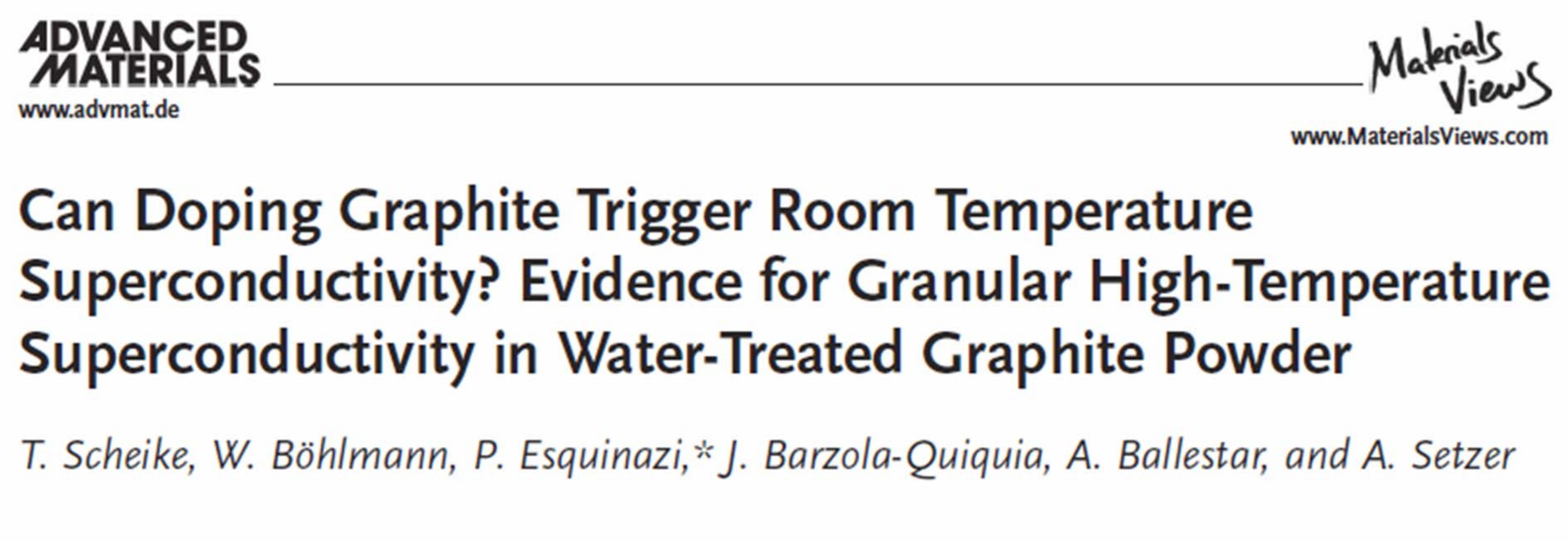
groot isotoop effect
→ BCS model?

Supergeleiding in H_2S onder druk



Supergeleiding bij kamertemperatuur?

Scheike *et al*., Adv. Mat. 24 (2012) 5826

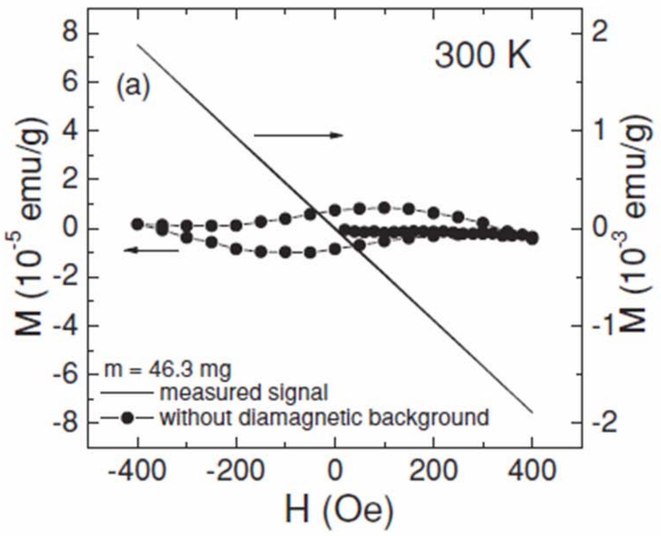


ADVANCED MATERIALS
www.advmat.de

Materials Views
www.MaterialsViews.com

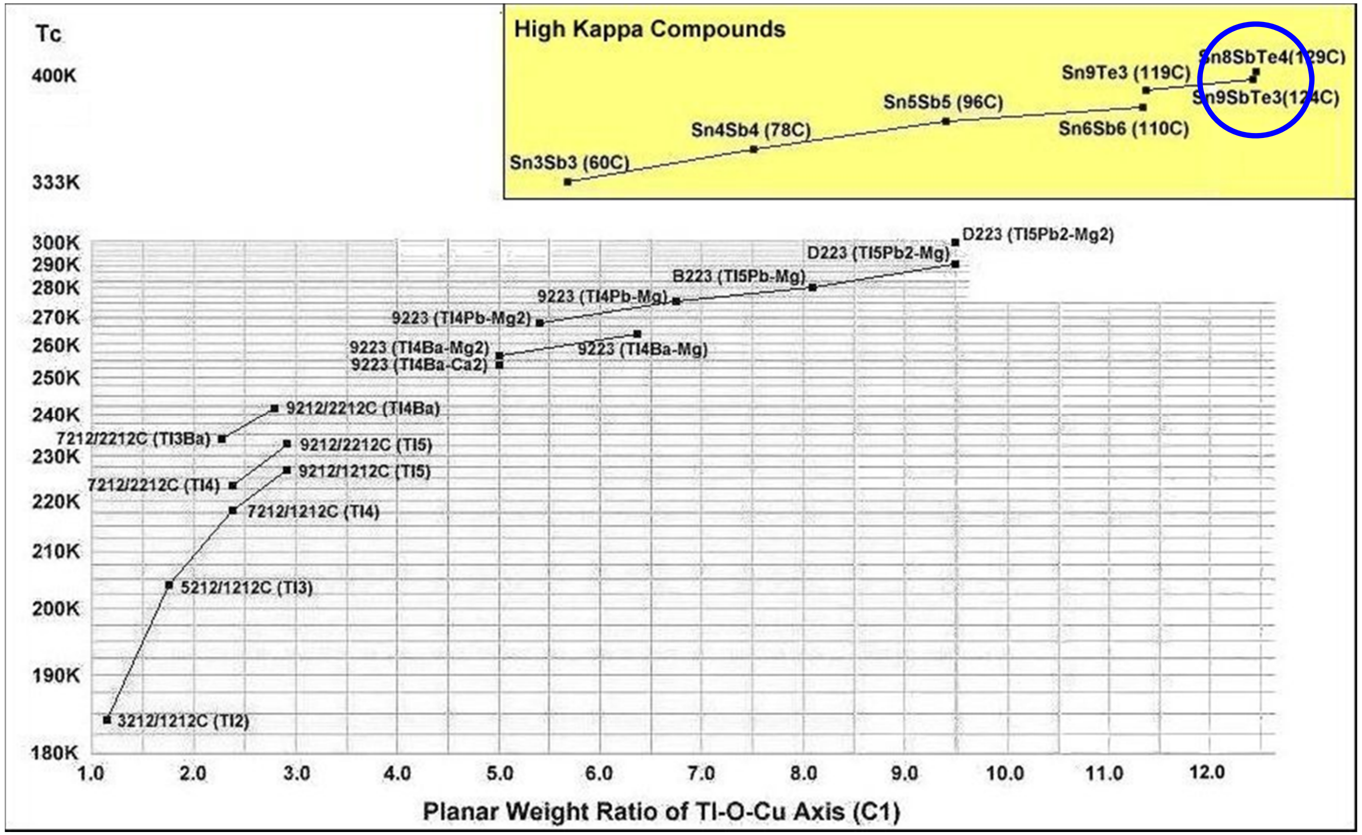
Can Doping Graphite Trigger Room Temperature Superconductivity? Evidence for Granular High-Temperature Superconductivity in Water-Treated Graphite Powder

T. Scheike, W. Böhlmann, P. Esquinazi, J. Barzola-Quiquia, A. Ballestar, and A. Setzer*

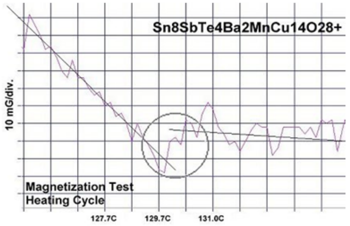


Supergeleiding boven kamertemperatuur?

www.superconductors.org



eerste
400 K
supergeleider?



Nee! USO’s: Unidentified Superconducting Objects

Supergeleiding wordt steeds “hotter”, nog slechts 100 K te gaan …