UNIVERSITY OF TWENTE.

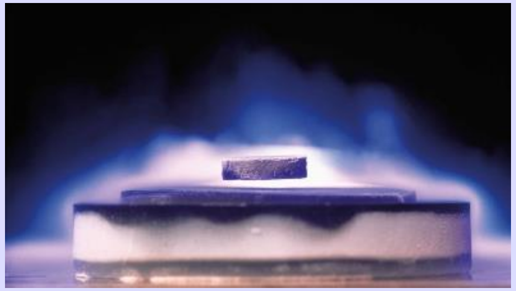
European Course of Cryogenics 2022

Thursday 25/08

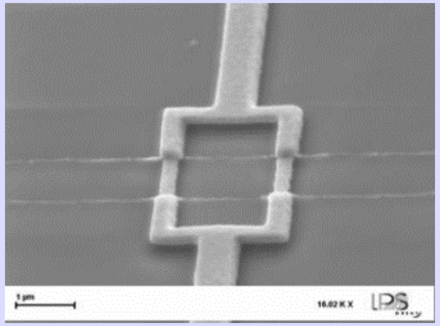
Superconductivity & Cryogenics

Dr. Marc Dhallé, EMS UTwente

1. Phenomenology & understanding
2. Materials & applications
3. Cooling requirements & - strategies



Physics World



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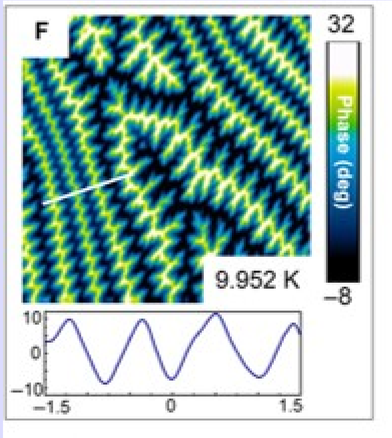
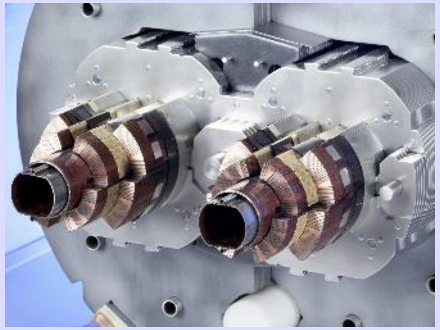


Science Advances



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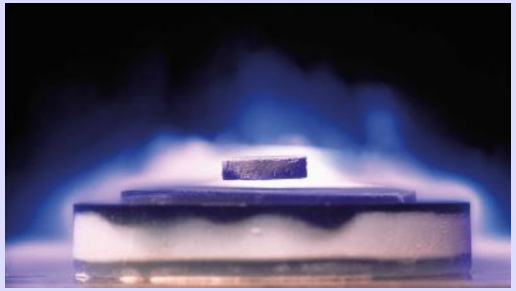
Want to know more?

- V.L. Ginzburg and E.A. Andryushin, "*Superconductivity*" (1994)

  Excellent layman's primer.

- V.V. Schmidt "*The Physics of Superconductors*" (1997)
- M. Cyrot and D. Pavuna, "*Introduction to Superconductivity and high-Tc materials*" (1992)
- M. Tinkham, "*Introduction to Superconductivity*" (1975)
- P.G. De Gennes, "*Superconductivity of metals and alloys*" (1966)

… and many more books of varying level of detail.



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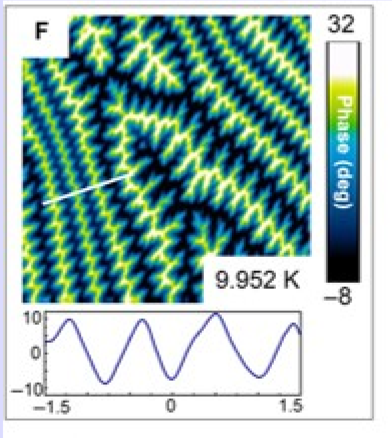

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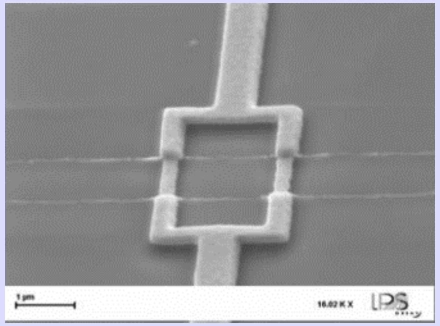

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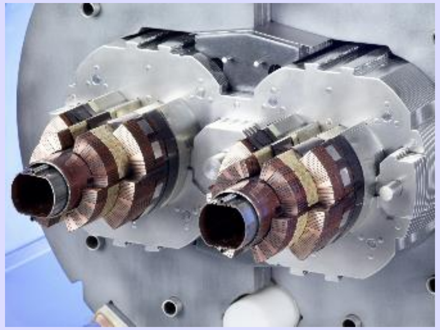

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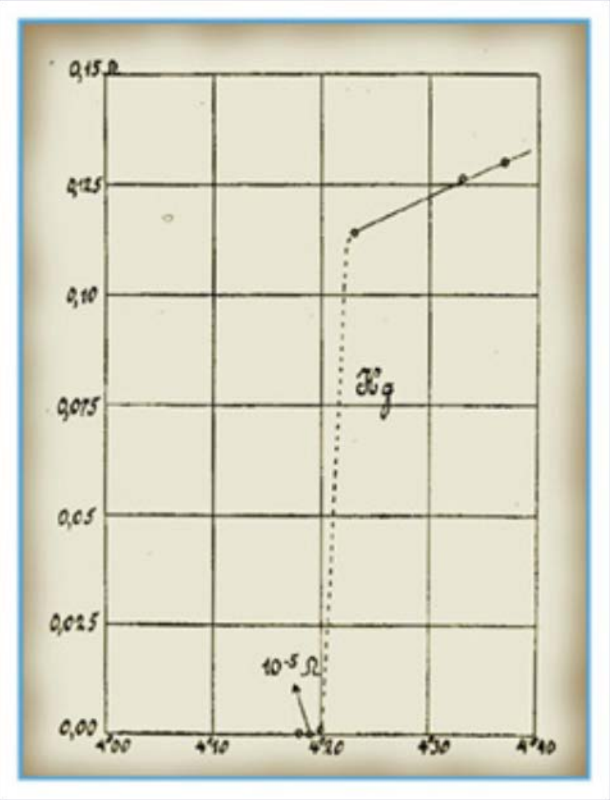
… or contact us: *https://www.utwente.nl/en/tnw/ems/*

Disappearance of electrical resistivity

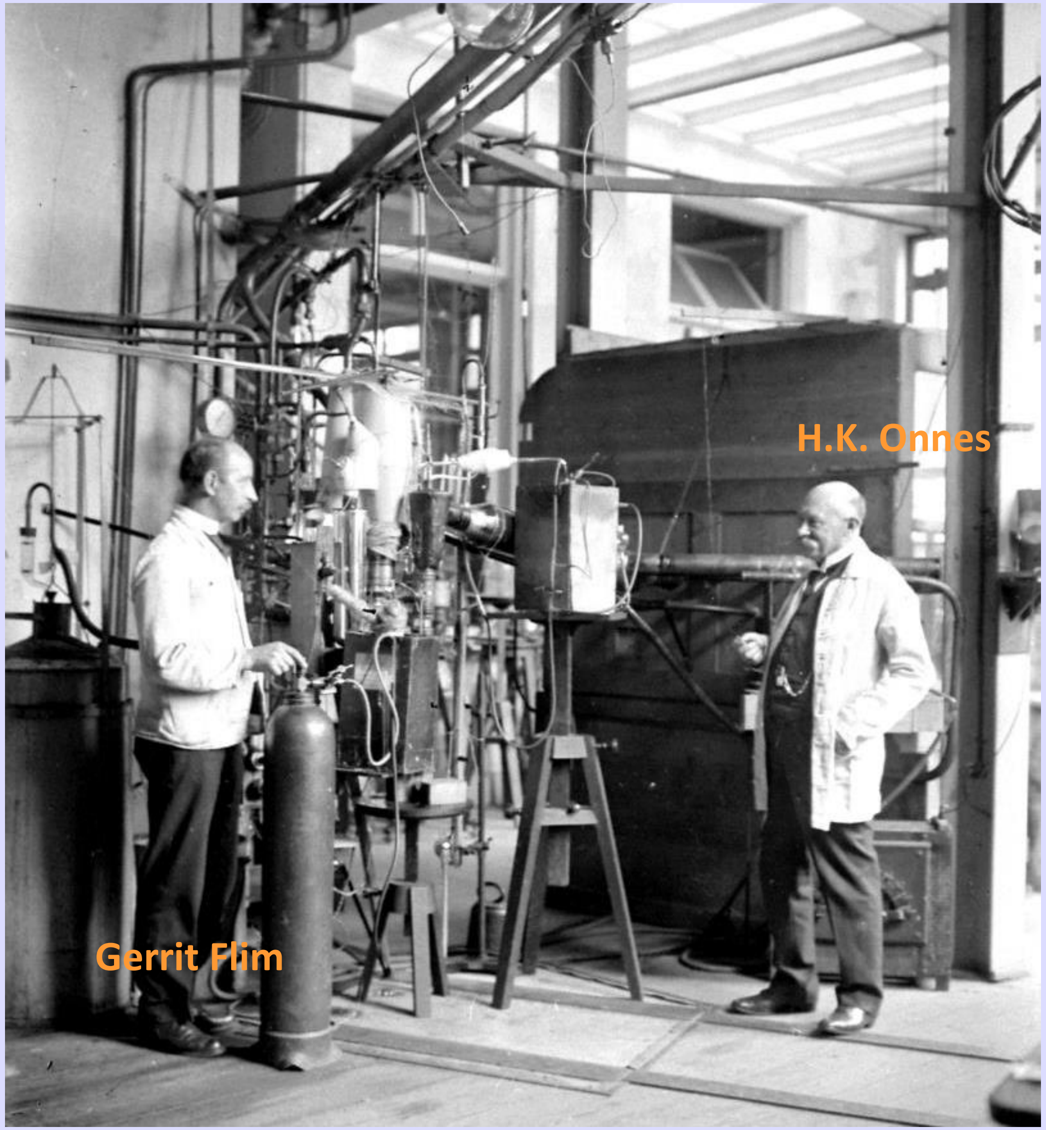


Onnes, 1911

Below a ***critical temperature*** T_c :

$$\rho = 0$$

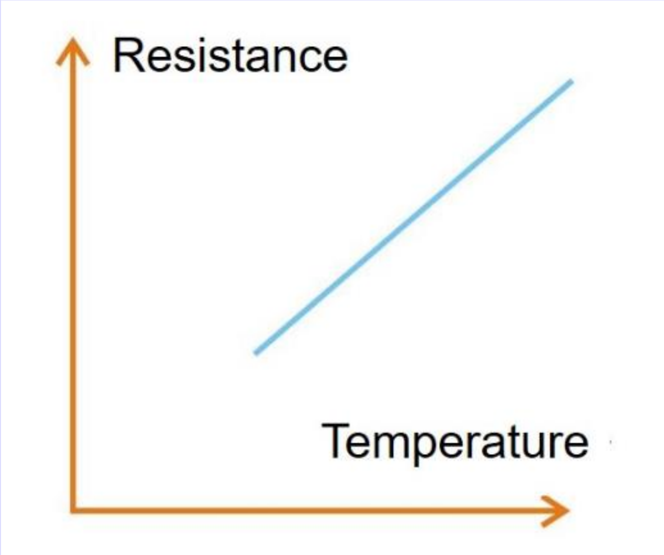
No scattering of charge carriers at lattice imperfections



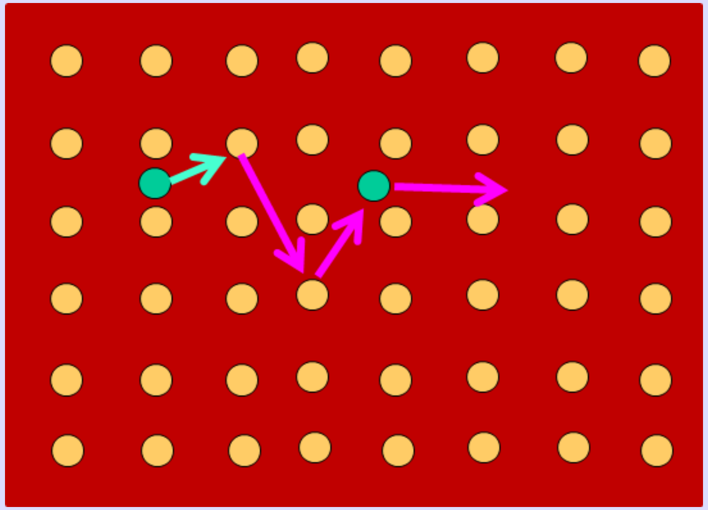
Lorentz.leidenuniv.nl

Liquid helium
4.2 Kelvin (1908)

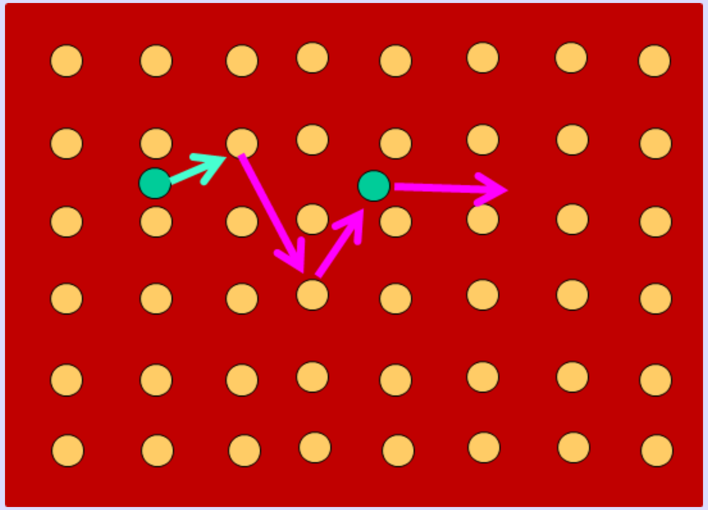
https://www.youtube.com/watch?v=9FudzqfpLLs

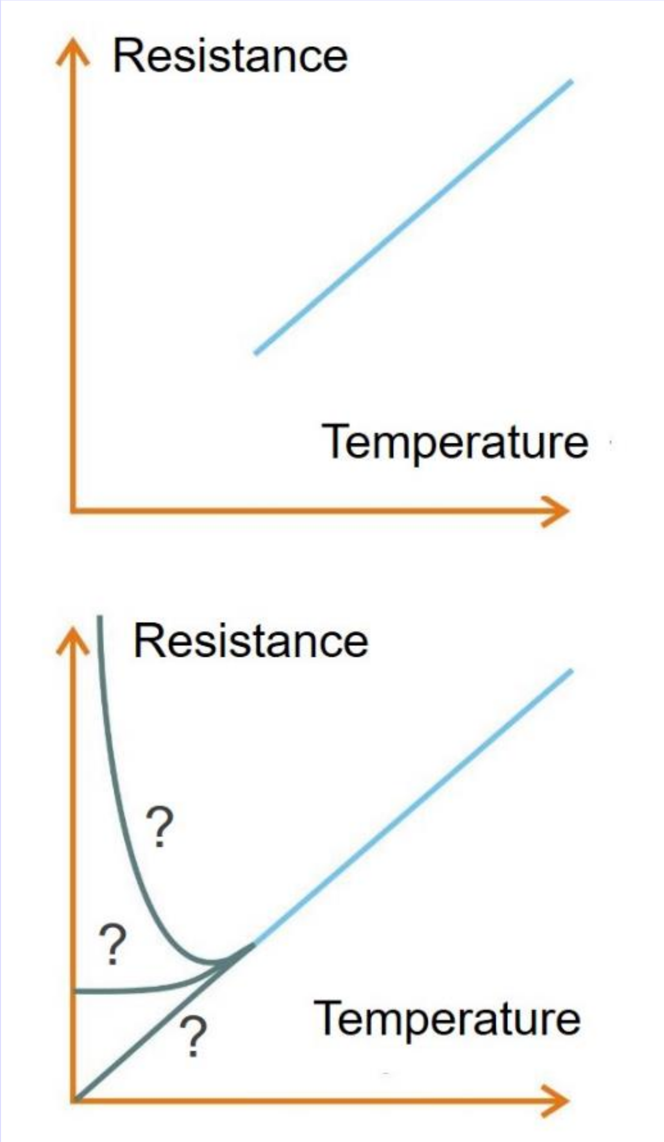


Electrical conductivity & resistivity



Electrical conductivity & resistivity





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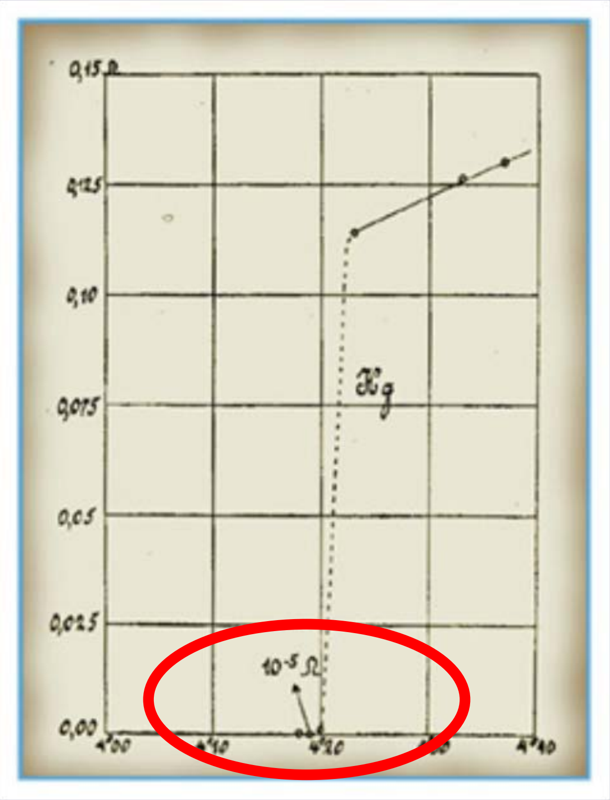

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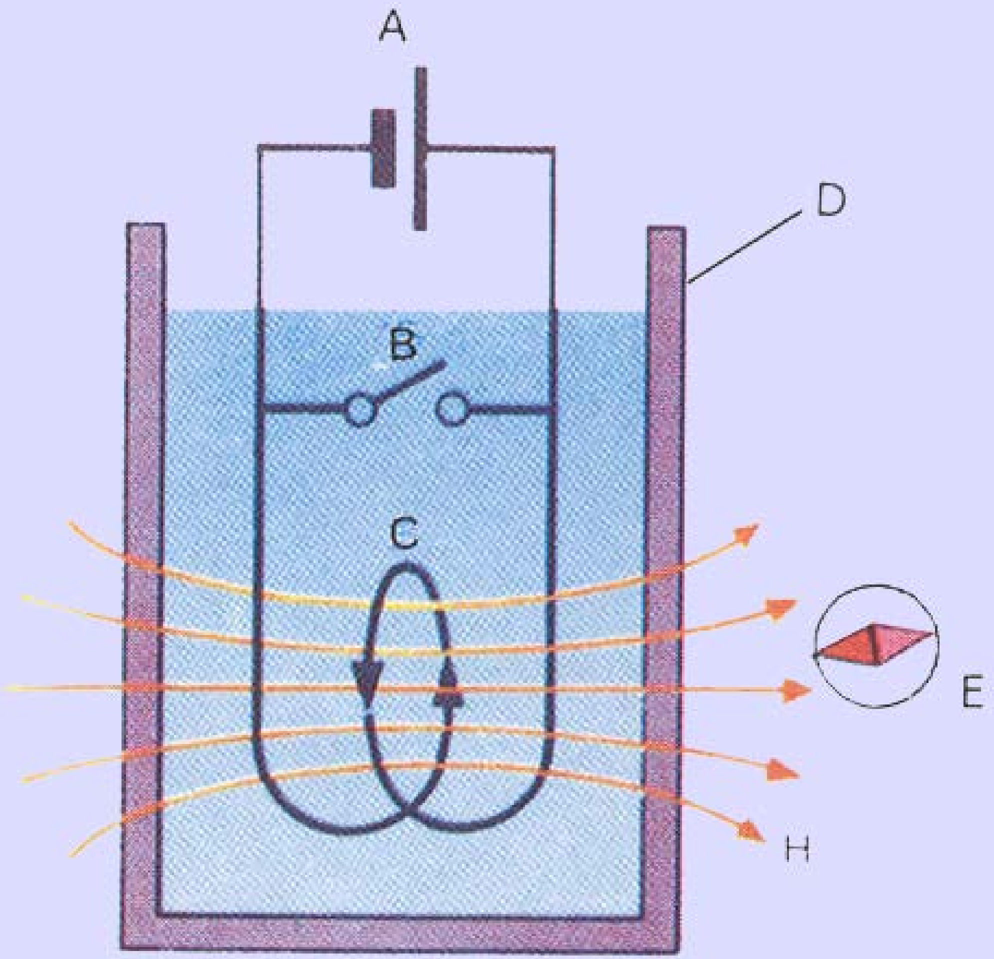
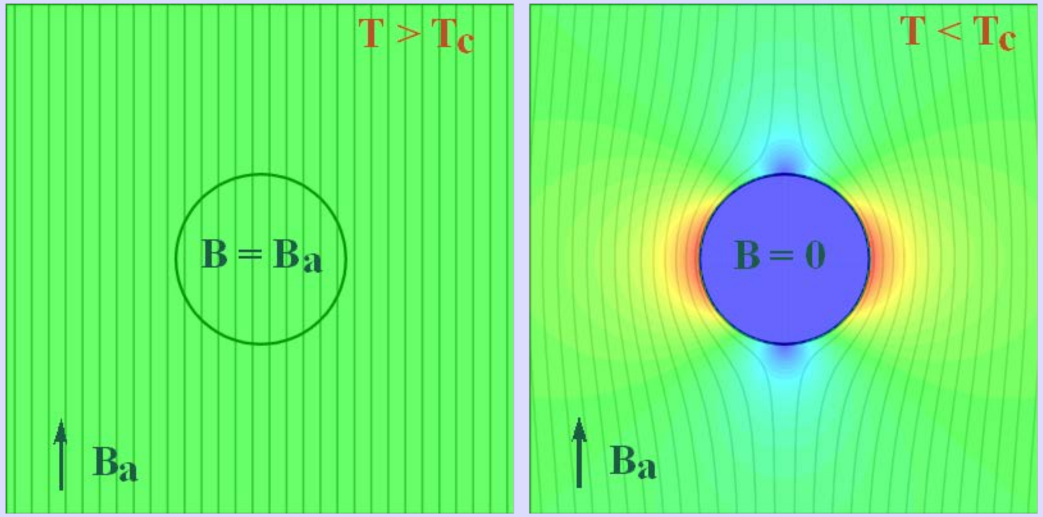


Ginzburg & Andryushin, 1994

Resistance is at least 10^{17} times smaller than that of copper

Meissner effect

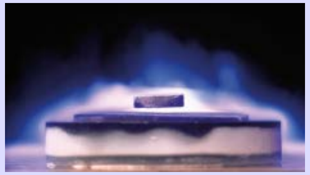


Perfect *diamagnetism*

$$B = 0$$

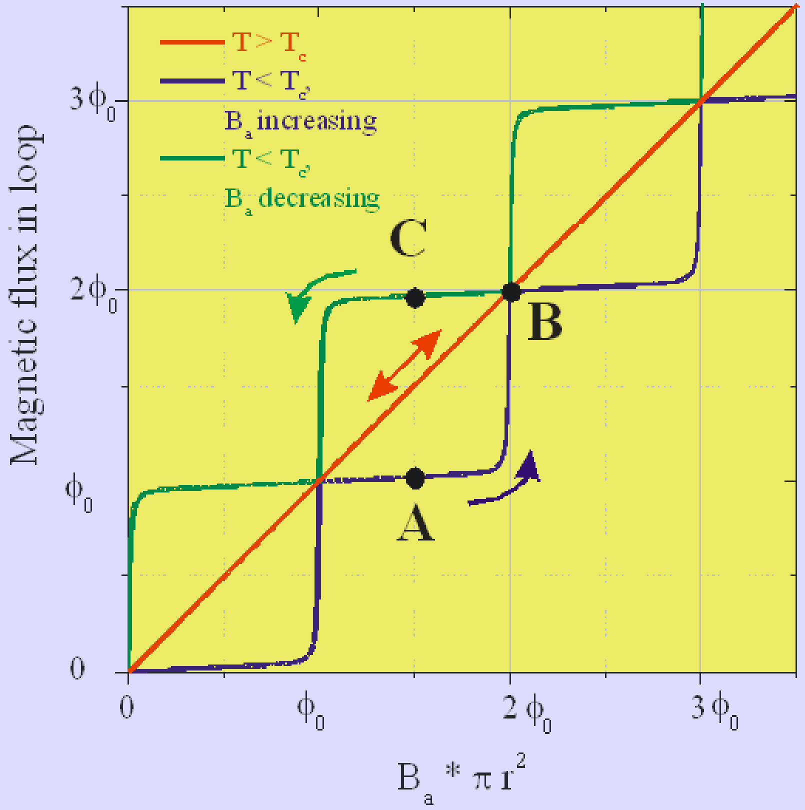
Magnetic fields are screened out by surface currents (*)

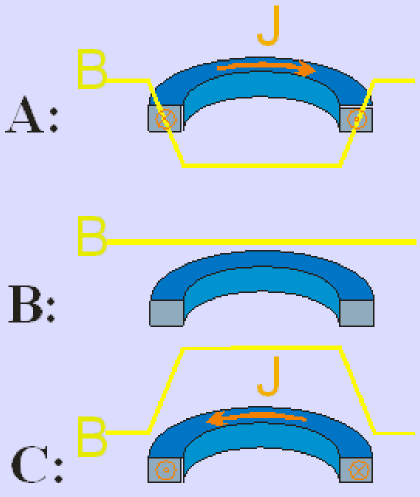
W. Meissner and R. Ochsenfeld, 1933



(*) up to a *critical field* H_{c1}

Flux Quantization





Only integer multiples

$$\Phi = n\phi_0$$

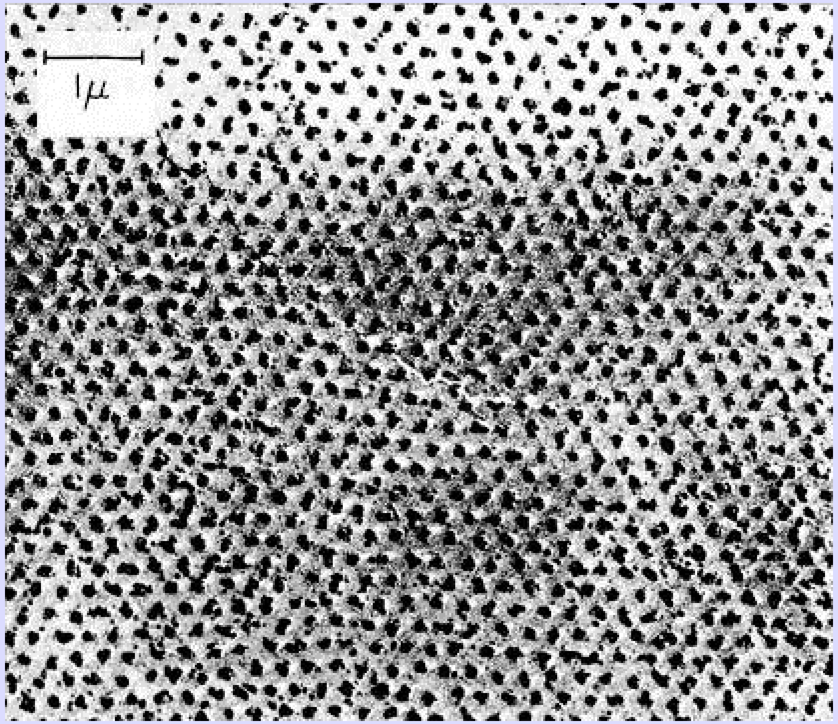
of the *flux quantum*

$$\phi_0 = \frac{h}{2e}$$

are allowed inside a superconducting ring.

F. London, 1950
W. A. Little and R.D. Parks, 1962

Flux Quantization



A.A. Abrikosov, 1957
Essman and Traube, 1967

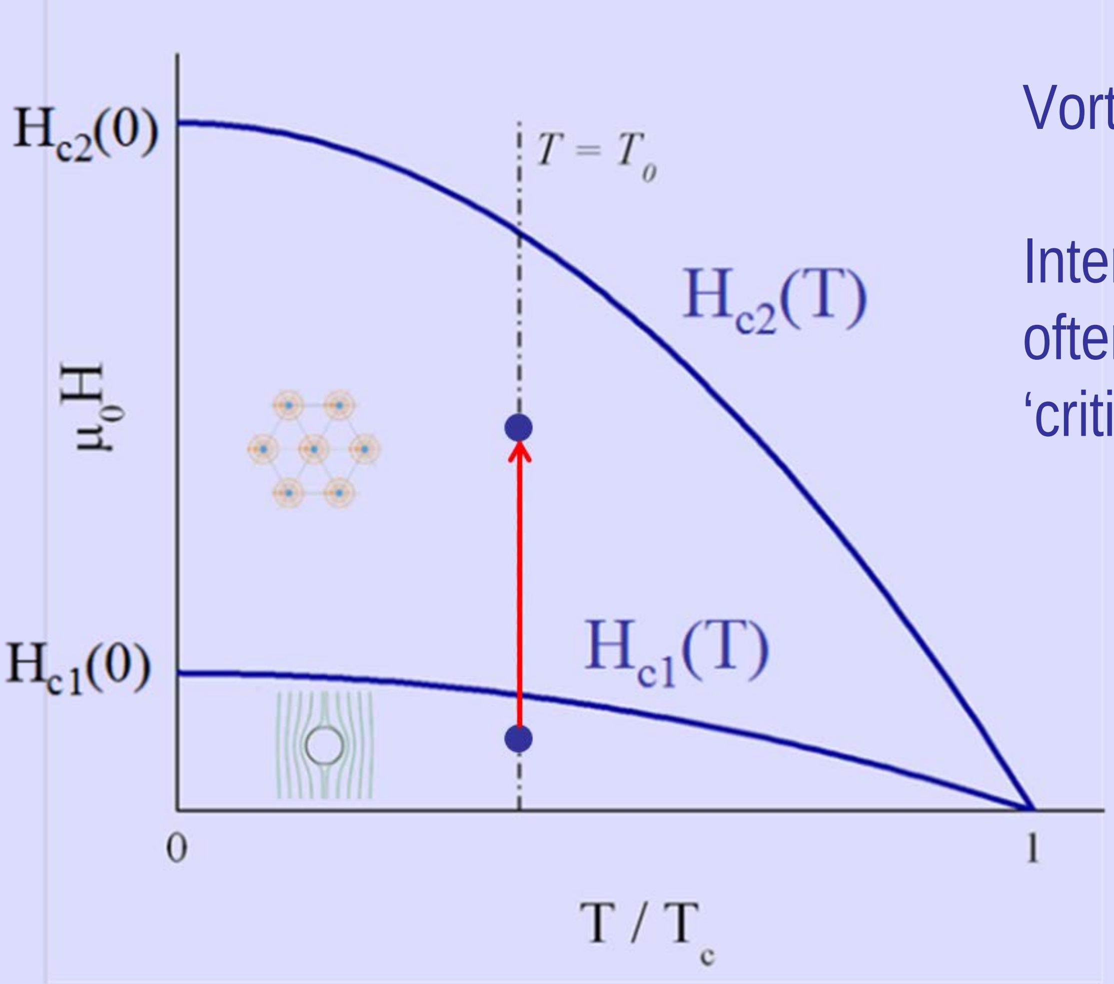
For “type II” superconducting materials:

$$B = n\,A\,\phi_0$$

Fields higher than H_{c1} are admitted in the form of mutually repulsive flux tubes (*), generated by current vortices

(*) up to a second *critical field* H_{c2}

Flux Quantization



Vortex- or ‘Abrikosov’- state.

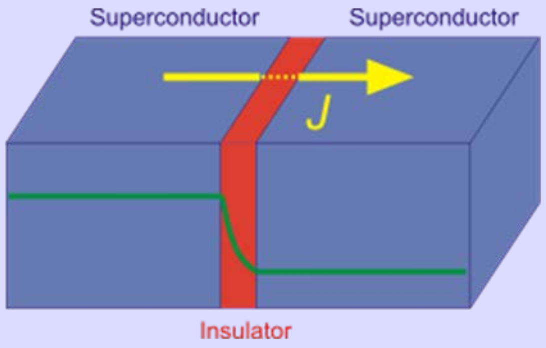
Interactions between vortices and current often determine maximal or ‘critical’ current density J_c

Josephson effect

Current can 'leak' through a barrier:

$$J_c = J_0 \sin \delta$$

$$\delta(t) = \delta(0) + \frac{Vt}{\phi_0}$$



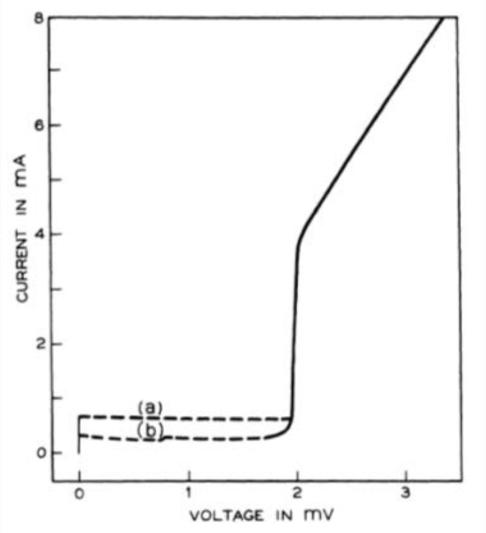
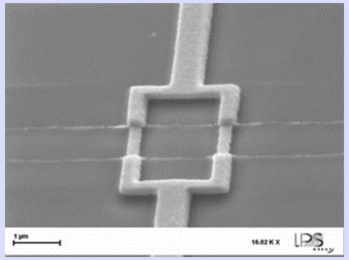


FIG. 1. Current-voltage characteristic for a tin-tin oxide-lead tunnel structure at ~1.5°K, (a) for a field of 6×10^{-3} gauss and (b) for a field 0.4 gauss.

The maximum *tunneling current* is modulated by a "*phase difference*" across the barrier that depends on magnetic field.

B.D. Josephson, 1962
P.W. Anderson and J.M.Rowell, 1963



1. Phenomenology & *understanding*
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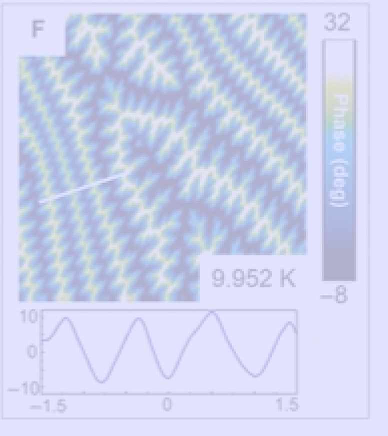

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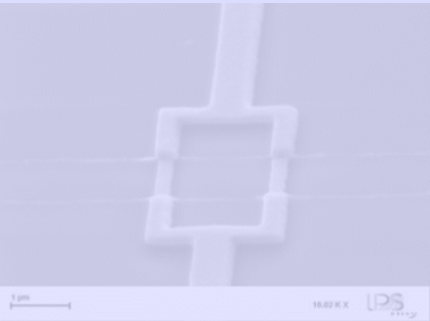

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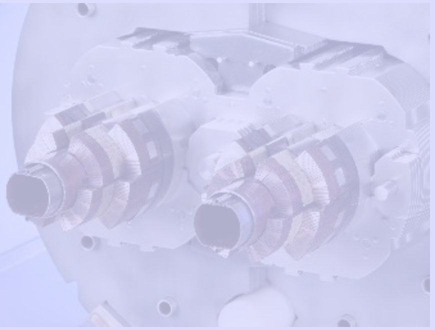

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The London theory

H. London and F. London, 1935

$$\lambda^2(\nabla \times J_s) + H = 0$$

Equation of motion for "superelectrons"

→ penetration depth λ

$$n_s = n_0\left(1 - {}^{T}/_{T_c}\right) \;\; ; \quad n_n = n_0\, {}^{T}/_{T_c}$$

"2 fluid"-model

→ *kinetic inductance, surface impedance*

Ginzburg-Landau theory

V.L. Ginzburg and L.D. Landau, 1950

$$\psi(\vec{r}) = |\psi(\vec{r})| \mathrm{e}^{\mathrm{i}\varphi(\vec{r})} \quad \text{with} \quad |\psi|^2 = {}^{n_s}/_{2}$$

complex "order parameter"

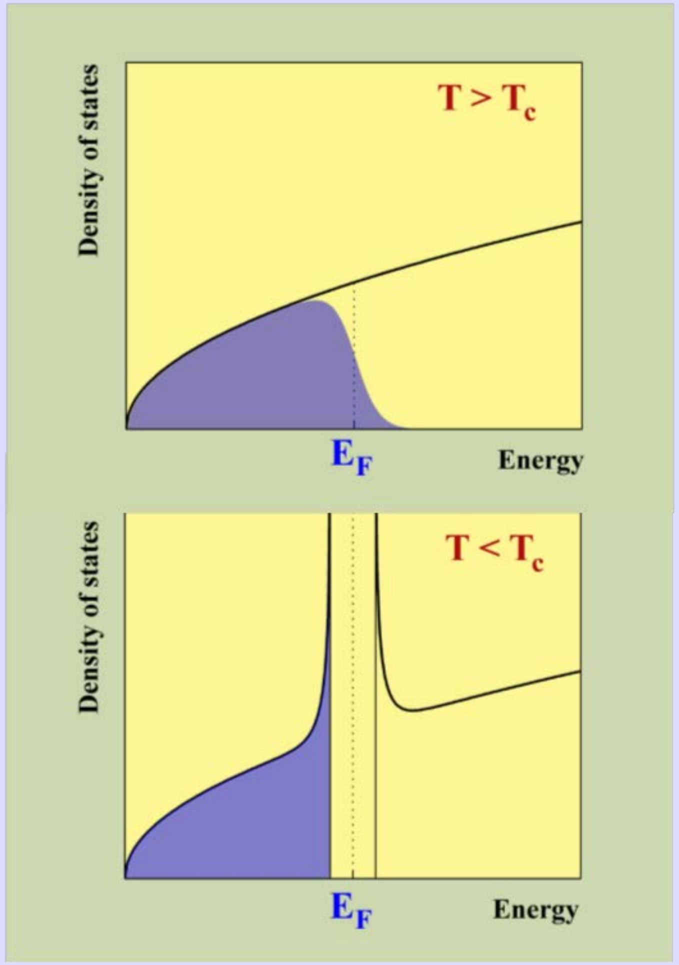
$$\Delta F = F_s - F_s = \alpha|\psi|^2 + \beta|\psi|^4 + \frac{1}{2m}\left|\left(i\hbar\nabla + 2e\vec{A}\right)\psi\right|^2 + \frac{\mu_0 H^2}{2}$$

Minimization of free energy *F* ⟶

flux quantization; coherence length ξ; penetration depth; vortex state

BCS theory (1)

L.N. Cooper, 1956



Bound Electron Pairs in a Degenerate Fermi Gas*

LEON N. COOPER

Consider a pair of electrons which interact above a quiescent Fermi sphere with an interaction of the kind that might be expected due to the phonon and the screened Coulomb fields. If there is a net attraction between the electrons, it turns out that they can form a bound state, though their total energy is larger than

In the presence of an attractive interaction, electrons can 'team up', they form "Cooper pairs".

Cooper pairs are bosons.

To break them up, one needs to overcome an energy gap Δ.

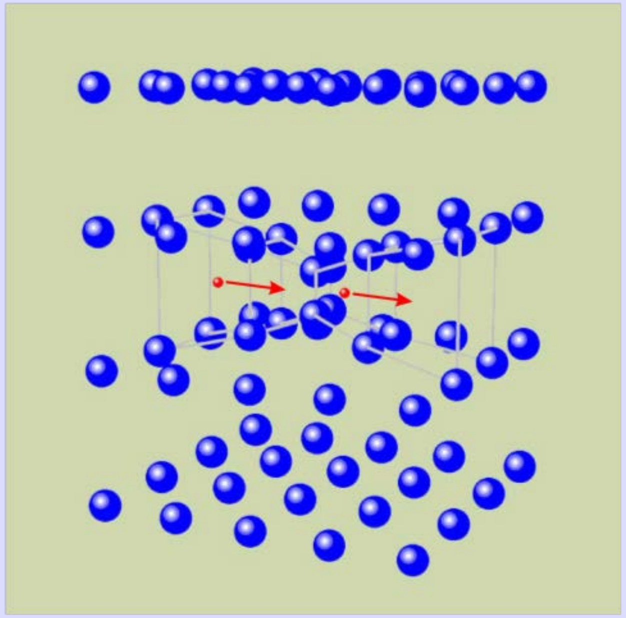
BCS theory (2)

J. Bardeen, L.N. Cooper, J.R. Schrieffer 1957

Theory of Superconductivity*

J. Bardeen, L. N. Cooper,† and J. R. Schrieffer‡

We shall call the interaction, H_2, between electrons resulting from the electron-phonon interaction the "phonon interaction." This interaction is attractive when the energy difference, $\Delta\epsilon$, between the electron states involved is less than $\hbar\omega$. Diagonal or self-energy



The attractive interaction comes about through interactions with lattice vibrations ("*phonons*").

⇒

- T_c (*isotope effect*), critical field H_c
- Gap Δ
- Cooper pair density
- penetration depth λ, coherence length ξ

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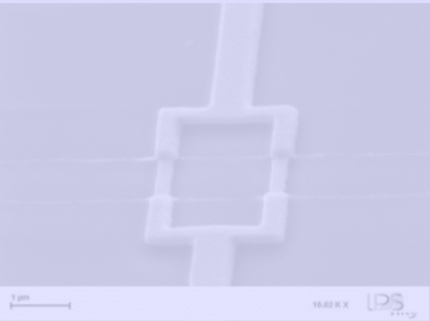

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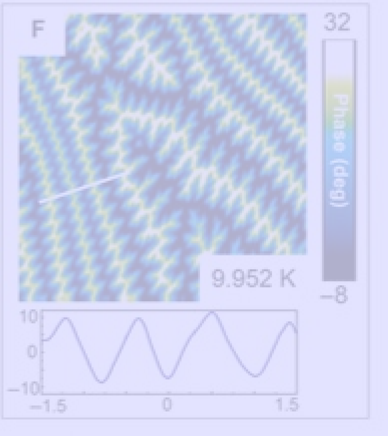
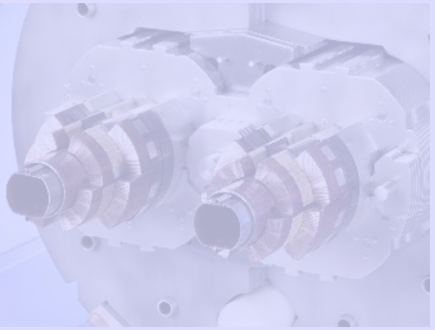


Science Advances



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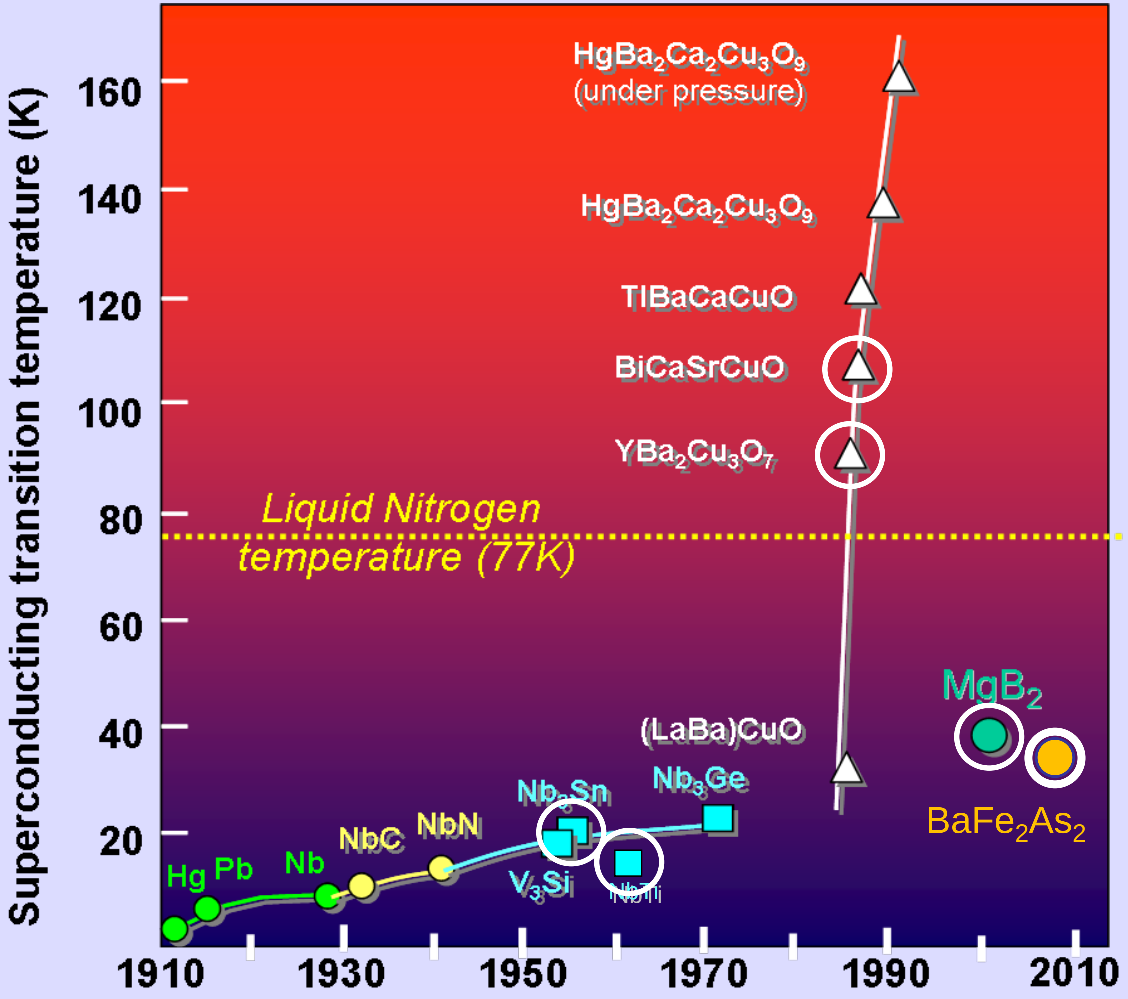
The history of superconducting materials (only a selected materials are shown)

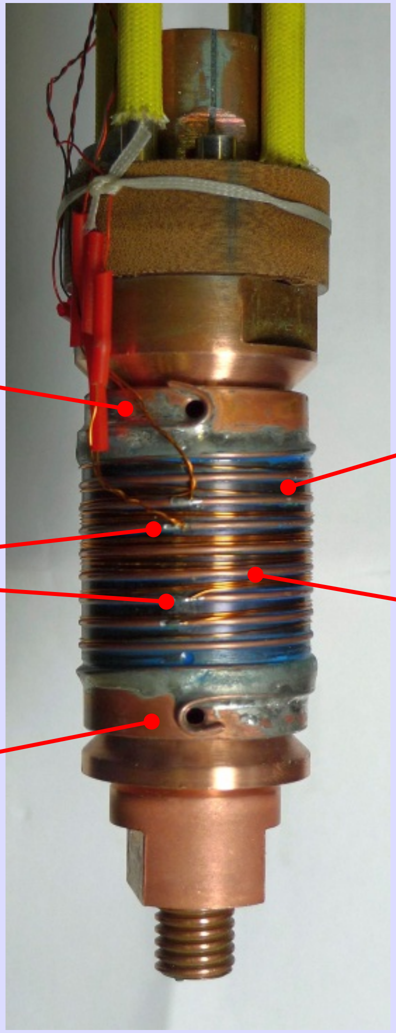


○ : Materials that are developed / commercialized into ***practical*** superconductors

"*Practical* " = >1 km long wires (*) with stable and uniform properties that can be used on coil windings

(*) see lecture 2

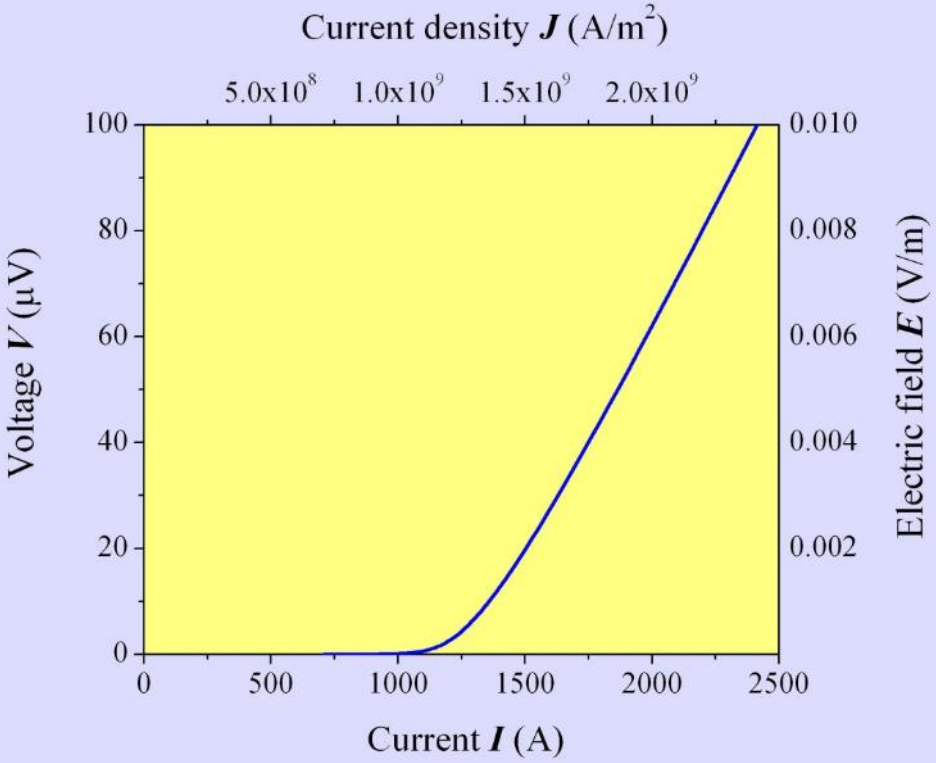
Intermezzo

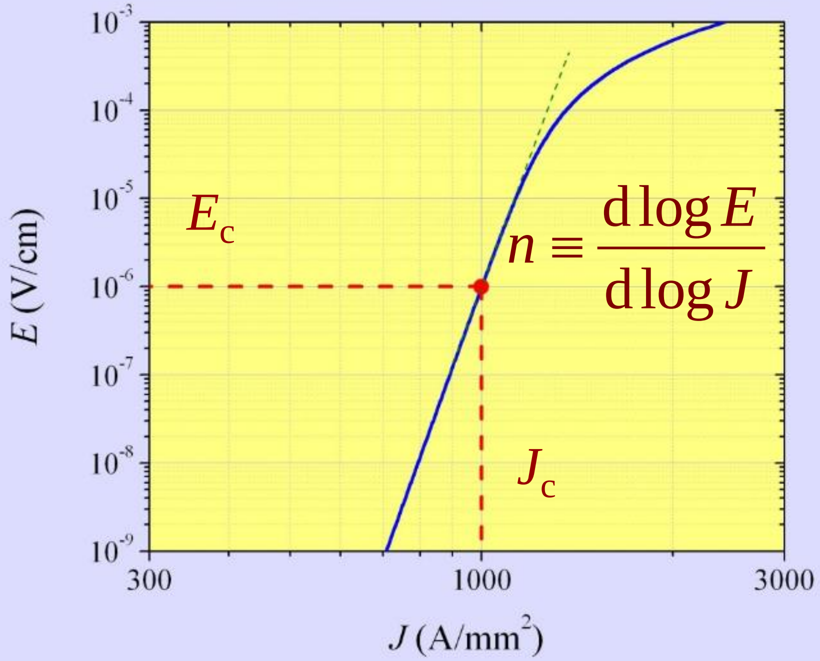


- Probing the limit of loss-less charge transport:
  the **critical current I_c**;
  the **critical current density J_c**
- Place the sample holder in a controlled *T*- and *H* – environment
  (often a SC solenoid in liquid or gaseous He)
- At each desired *T*- and *H*- value, slowly increase the current *I* and record the voltage *V* across the test section (IV-measurement)

Voltage-current relation of a superconductor: “sudden” appearance of voltage

~ power-law relation (curved on lin-lin VI scale, but linear on log-log VI scale)

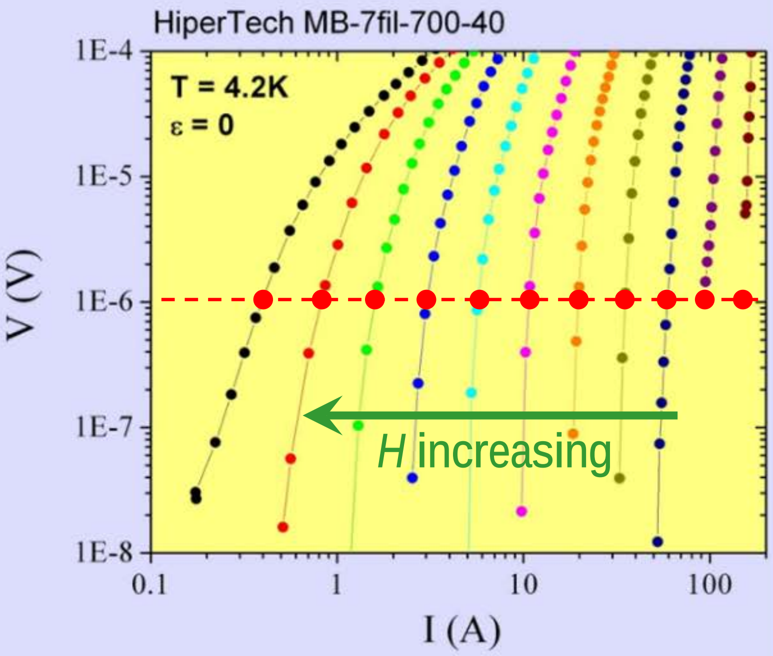


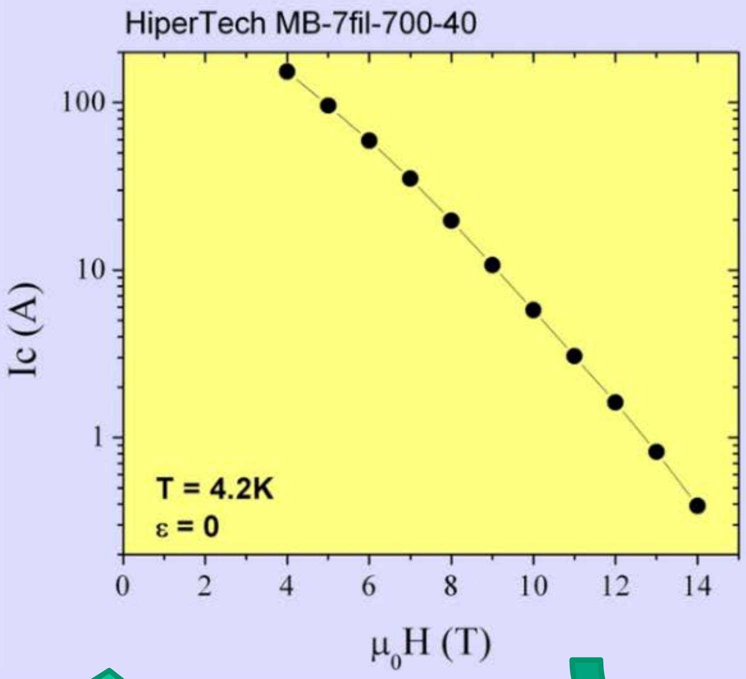


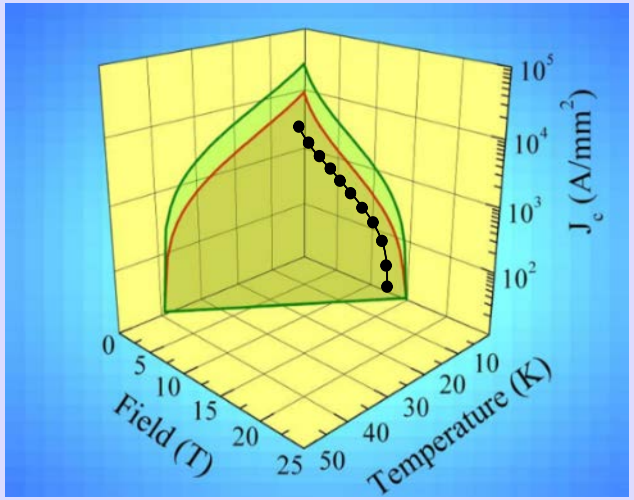
Note:

1. *Not infinitely steep ($n < \infty$); needs **criterion** (E_c or ρ_c)*
2. *Use of E and J instead of V and I*

Measure VI-curves across a range of magnetic fields H and temperatures T, extract I_c (B,T) and from this the ***critical surface Jc(T,H)*** *of a superconductor*







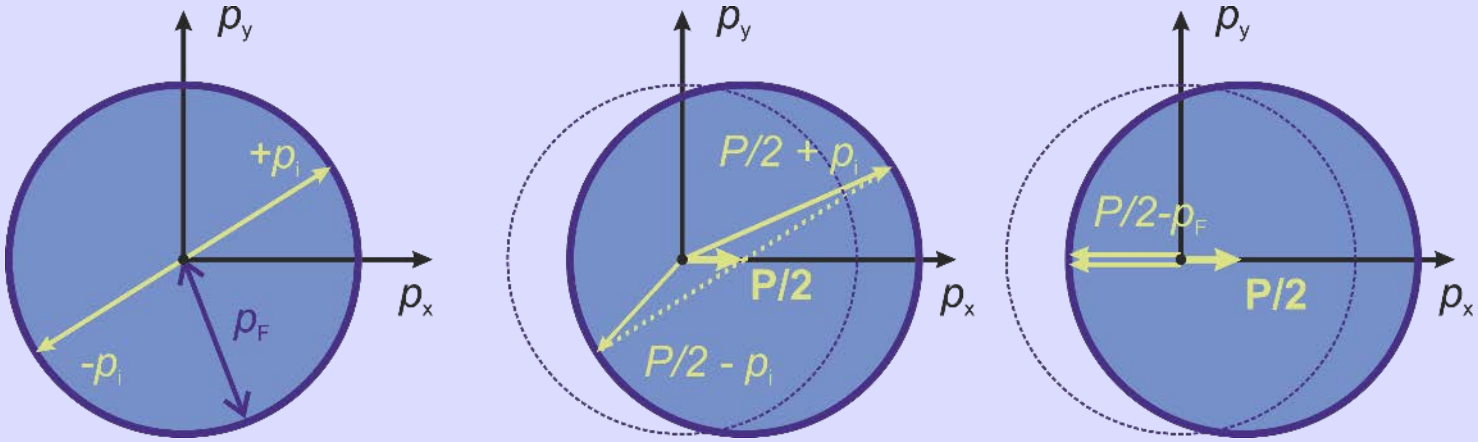
Loss-less transport = bodily shifting of Fermi surface in k-space

$$E_0 = \frac{1}{2m}\left[\left(\mathbf{P}/2+\mathbf{p}_i\right)^2 + \left(\mathbf{P}/2-\mathbf{p}_i\right)^2\right] = \frac{1}{2m}\left(P^2/2+2p_F{}^2\right)$$

Depairing current:

- $10^4 – 10^6$ A/mm^2 ;
- Fundamental upper limit;
- Never reached in practical SC

$$J_{c,depairing} = 2n_s e\,{}^{\Delta}/_{p_F}$$



Non current-carrying — Paired : $E = E_0$ — Unpaired : $E = E_0 + 2\Delta - Pv_F$

after Rose-Innes & Rhoderick, 1974

Scattering of a pair to the state with lowest available E lowers E_{kin}, but costs condensation energy 2Δ

$$E_{scattered} = 2\frac{\left(\mathbf{P}/2-\mathbf{p}_F\right)^2}{2\text{m}} + 2\Delta(T) = E_o - \frac{P\,p_F}{m} + 2\Delta(T)$$

Depinning current:

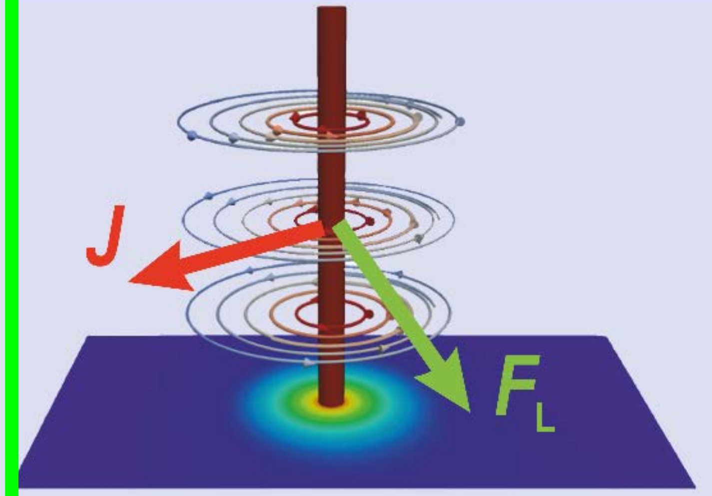
- 10^2 – 10^4 A/mm^2 ;
- Sample-dependent;
- Usual limit in practical SC

Current J + vortices ⟶ Lorentz force F_L

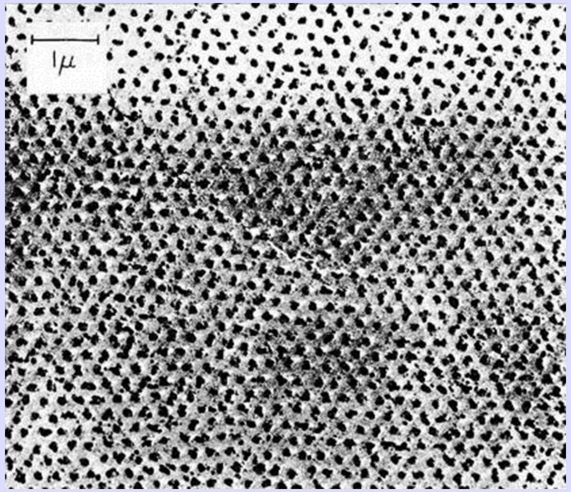
Moving vortex → Dissipation

See Maxwell's equations: $\nabla \times \mathbf{B} = \mu \mathbf{J}$, $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$ *and* $P = \mathbf{E} \cdot \mathbf{J}$

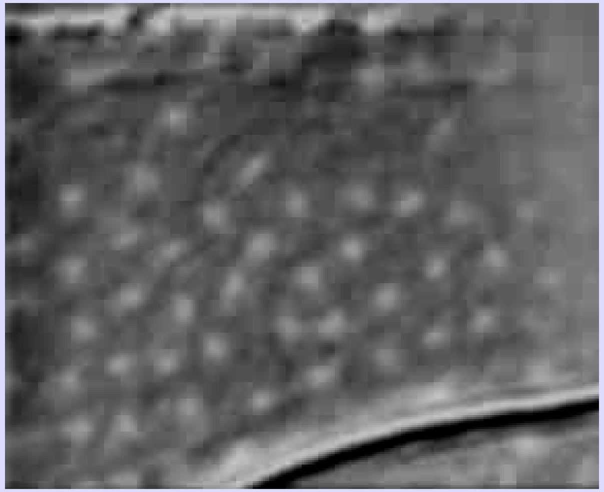
High current density can only be maintained loss-less when vortices are adequately pinned



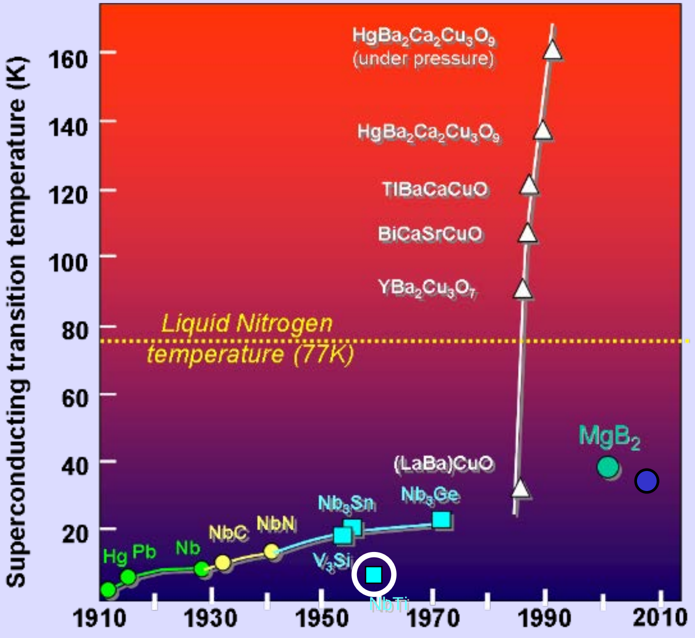
after Glatz et al, 2019



Essman and Traube, 1967



Olsen et al, 2004



NbTi : niobium-titanium alloy

T_c = ***9 K***

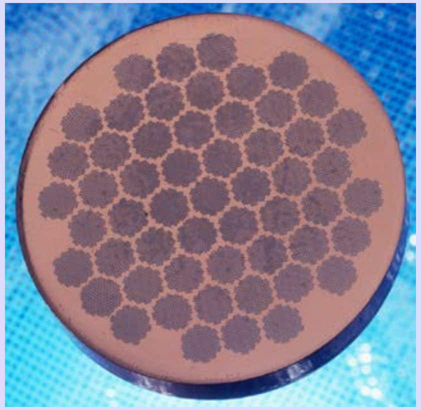
B_{c2} = 11 T at 4.2K and ***14T*** at 0K

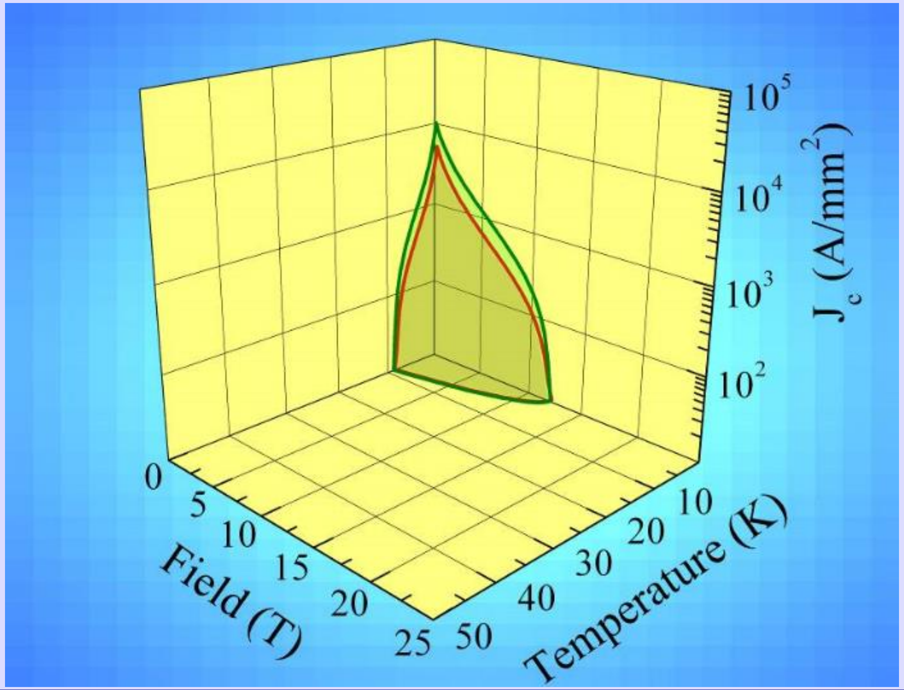
well-developed

costs ~1 €/kA.m at 4.2K, 5T (*)

(*) L. Cooley et al., 2005

Cubic alloy, isotropic





EMS

Pinning in NbTi: very finely distributed Ti-precipitates

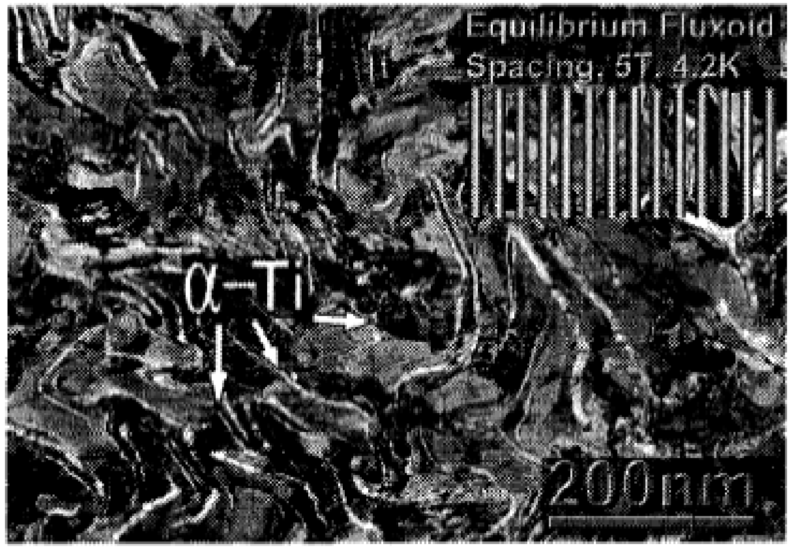
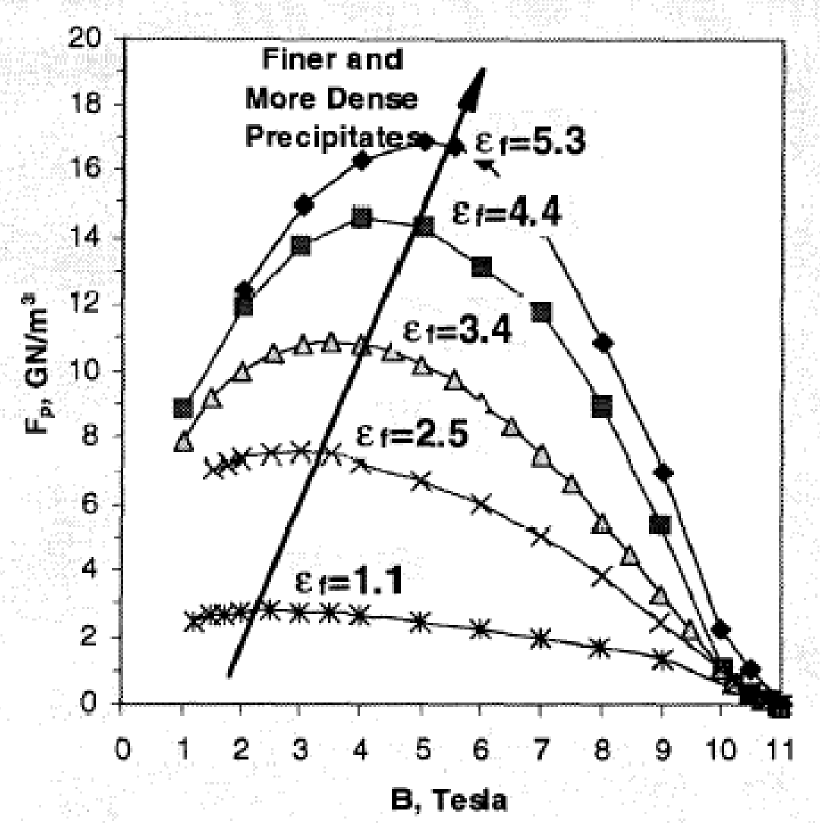
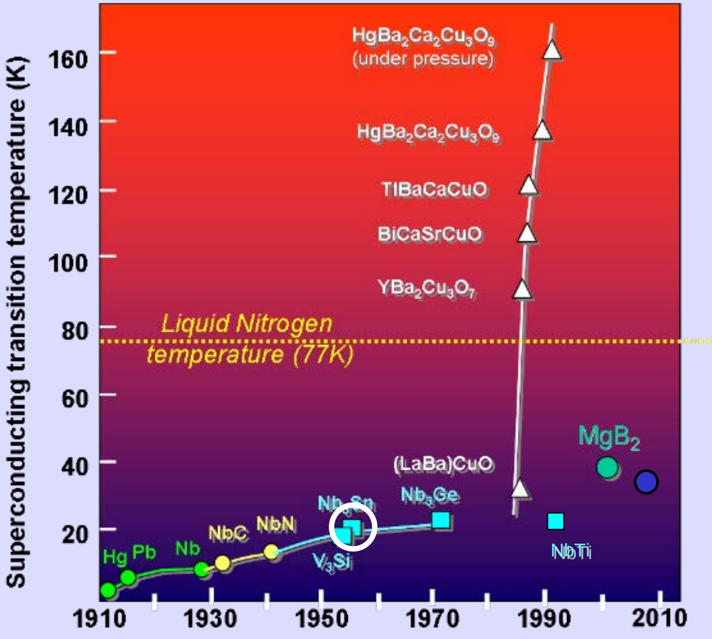


Figure 2 Typical Nb-47wt.%Ti high critical current microstructure (in transverse cross-section) showing the densely folded sheets of α-Ti pinning centers dispersed within the superconducting β-Nb-Ti matrix. Superimposed is a schematic illustration of the equilibrium fluxoid spacing and dimensions appropriate to Nb-47wt.%Ti at 5T, 4.2K.



Larbalestier et al, *1995*

$F_p = J_c \times B$ = *“maximum pinning force”*



Nb_3Sn : niobium three tin

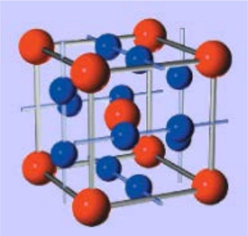
T_c = **18 K**

B_{c2} = 23-26 T at 4.2K and **30T** at 0K

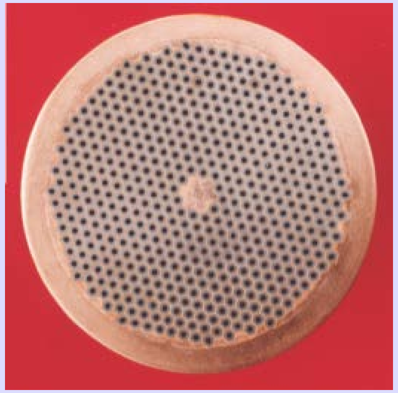
well developed, still in progress

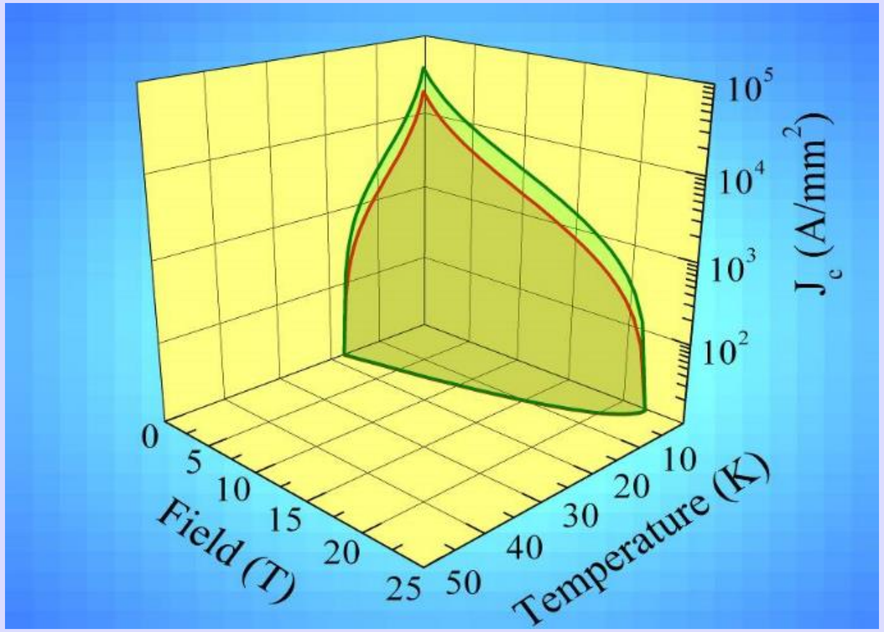
cost ~5-25 €/kA.m at 4.2K, 5T (*)

(*) L. Cooley et al., 2005



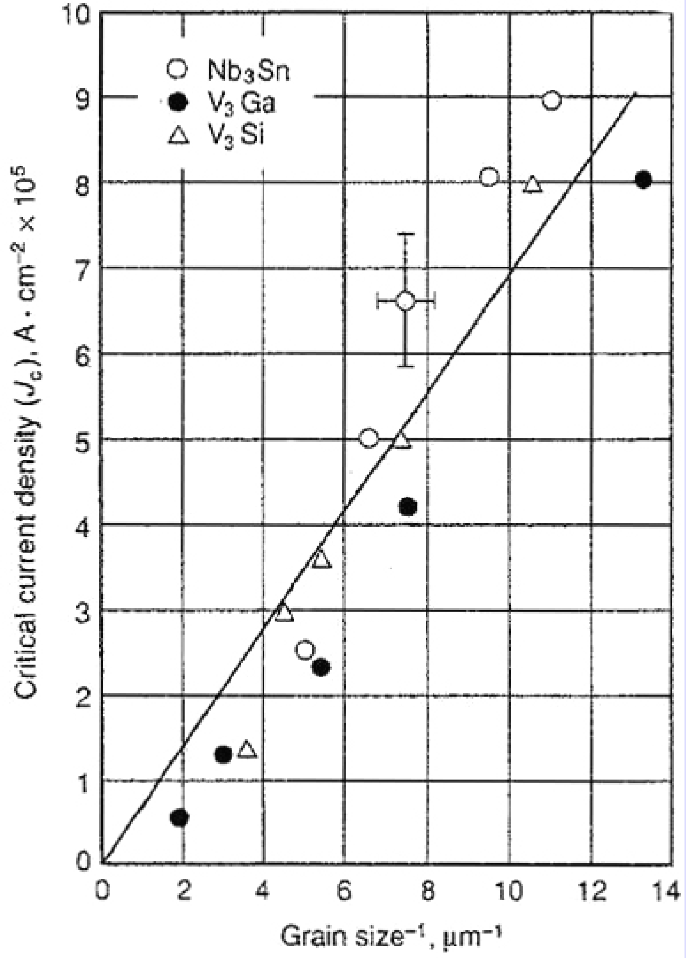
Cubic inter-metallic, isotropic

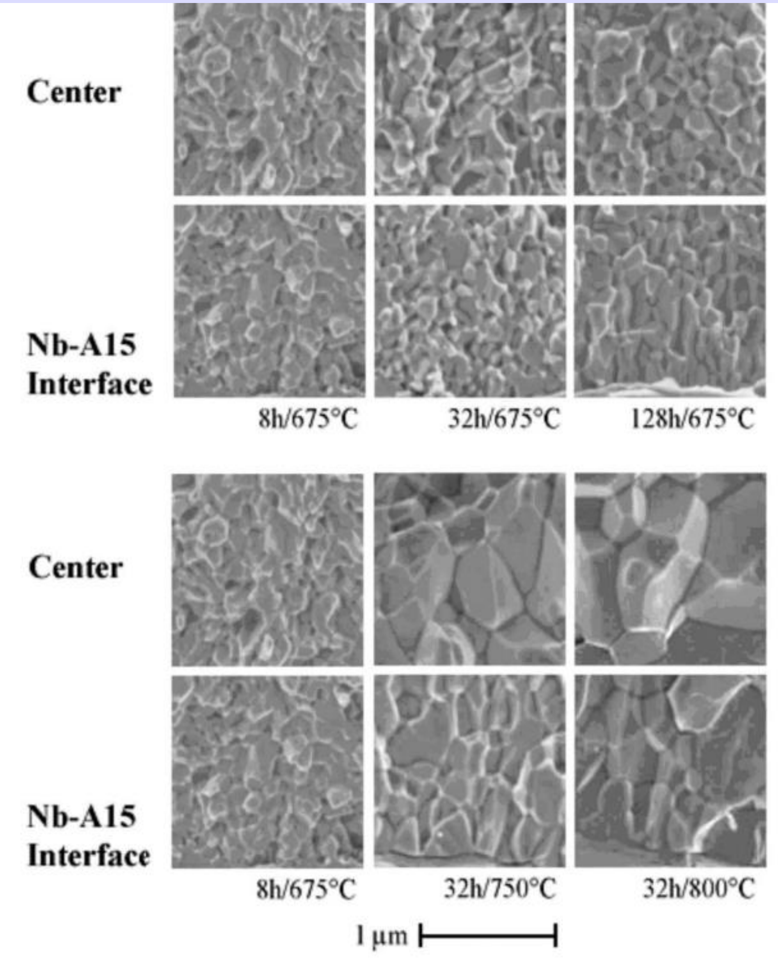




EMS

Pinning in Nb_3Sn: grain boundaries

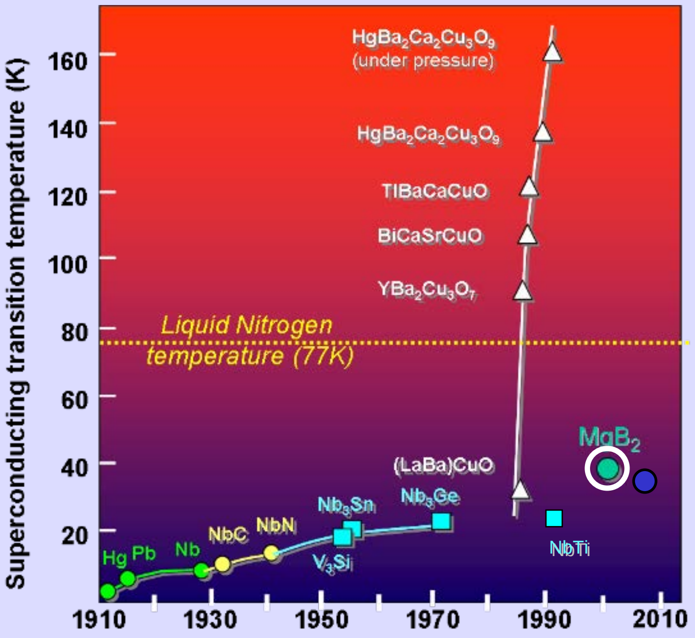




Reaction temperature [°C]	Average grain size [nm]
675	150
750	275
800	400
850	500
1000	1500

Suenaga et al, 1981

Fischer et al, 2002



MgB_2 : magnesium di-boride

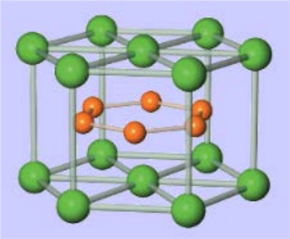
T_c = 38 K

B_{c2} = 20-25 T at 4.2K and 25-30T at 0K

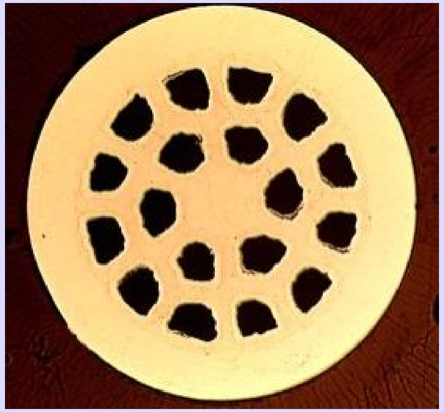
Development in progress

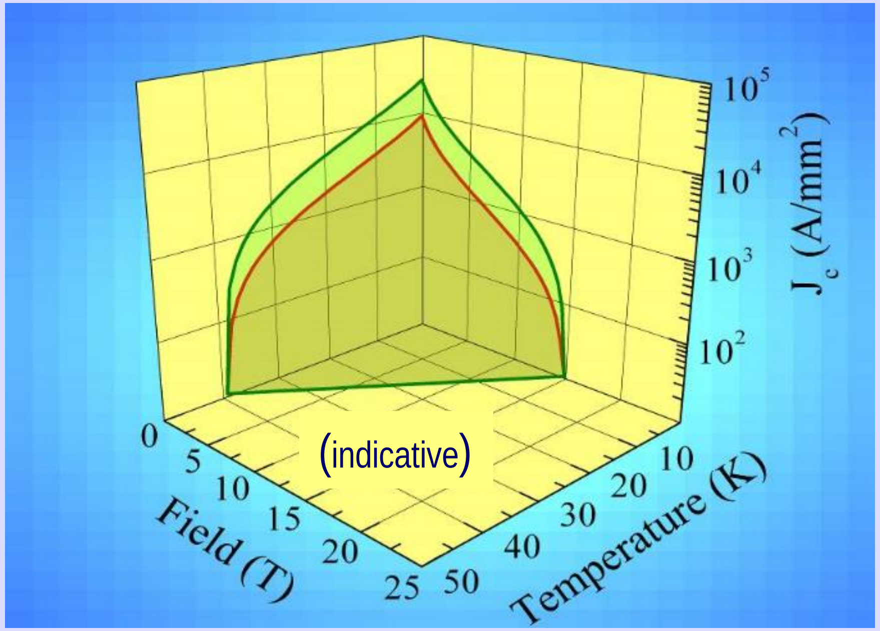
cost ~1 €/kA.m at 4.2K, 5T (*)

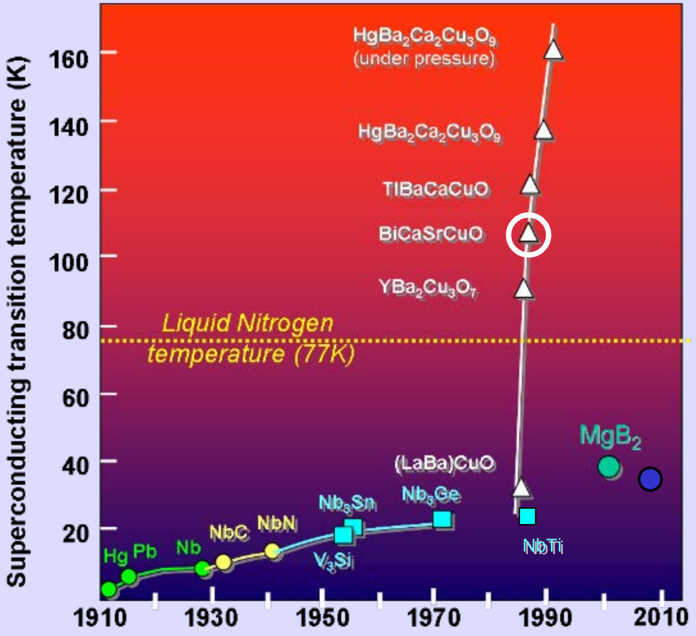
(*) L. Cooley et al., 2005



Hexagonal inter-metallic, anisotropic





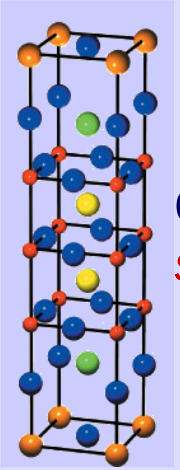


"BSCCO" : bismuth-strontium-calcium-copper-oxide "Bi-2212" and "Bi-2223" (*)

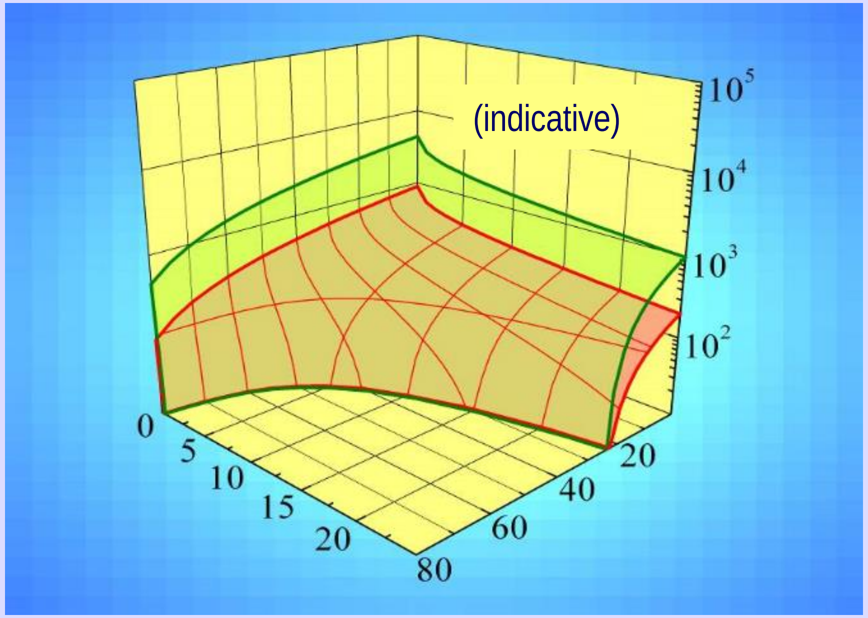
T_c = **80 K** (2212) or **110 K** (2223)

B_{c2} = **> 100 T**

under development , cost ~ 50 €/kAm (**)

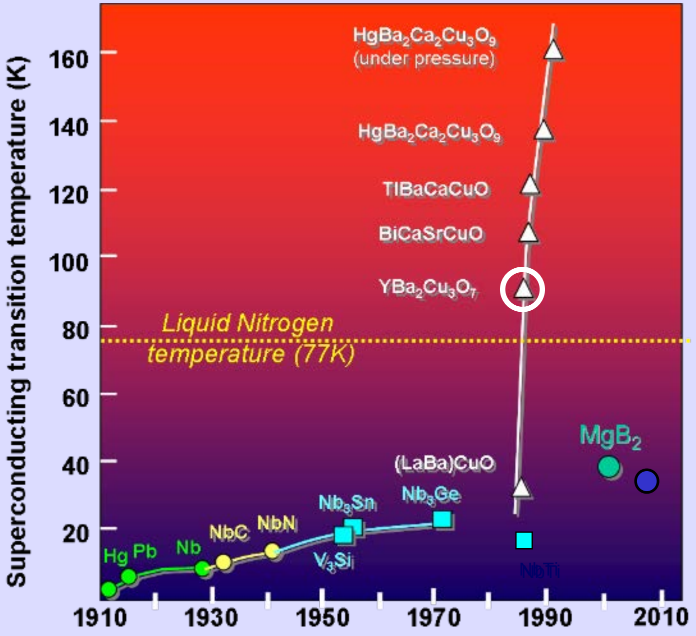


Orthorhombic oxide; *strongly* anisotropic



(*) $Bi_2Sr_2CaCu_2O_8$ & $Bi_2Sr_2Ca_2Cu_3O_{10}$

(**) L. Cooley et al., 2005



"ReBCO" : ytrium-barium-copper-oxide (*)

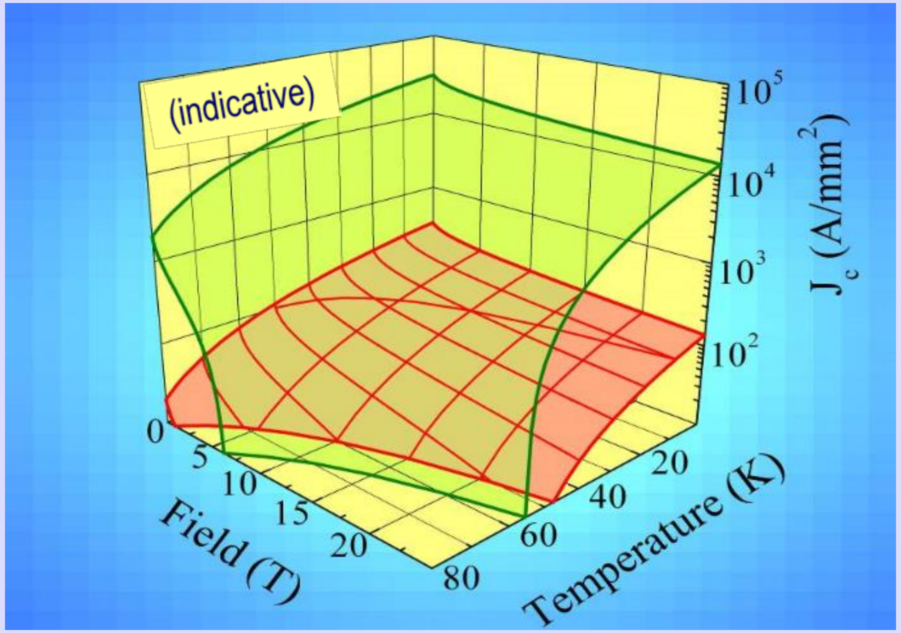
T_c = *90 K*

B_{c2} = *> 100 T*

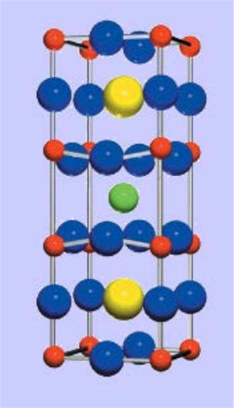
Under development

cost ~100-200 €/kAm (**)

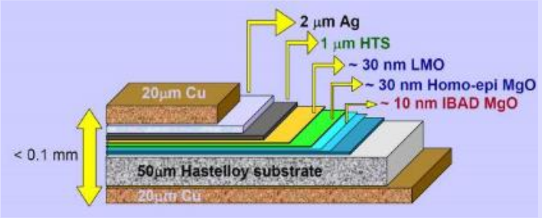
(*) "*Re*" = rare earth,
used to be $YBa_2Cu_3O_7$,
now often $GdBa_2Cu_3O_7$



(**) at 30K, 2T;
N. Bykowsky 2016,
J.H. Kim 2016



Orthorhombic oxide; anisotropic



Pinning in $YBa_2Cu_3O_7$: "correlated" disorder (anisotropy!)

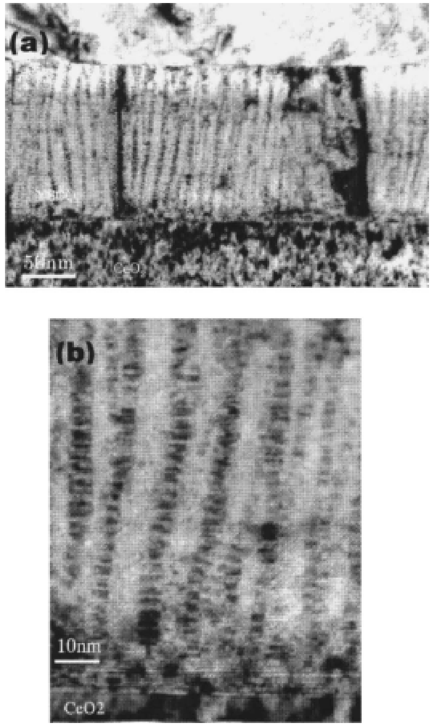
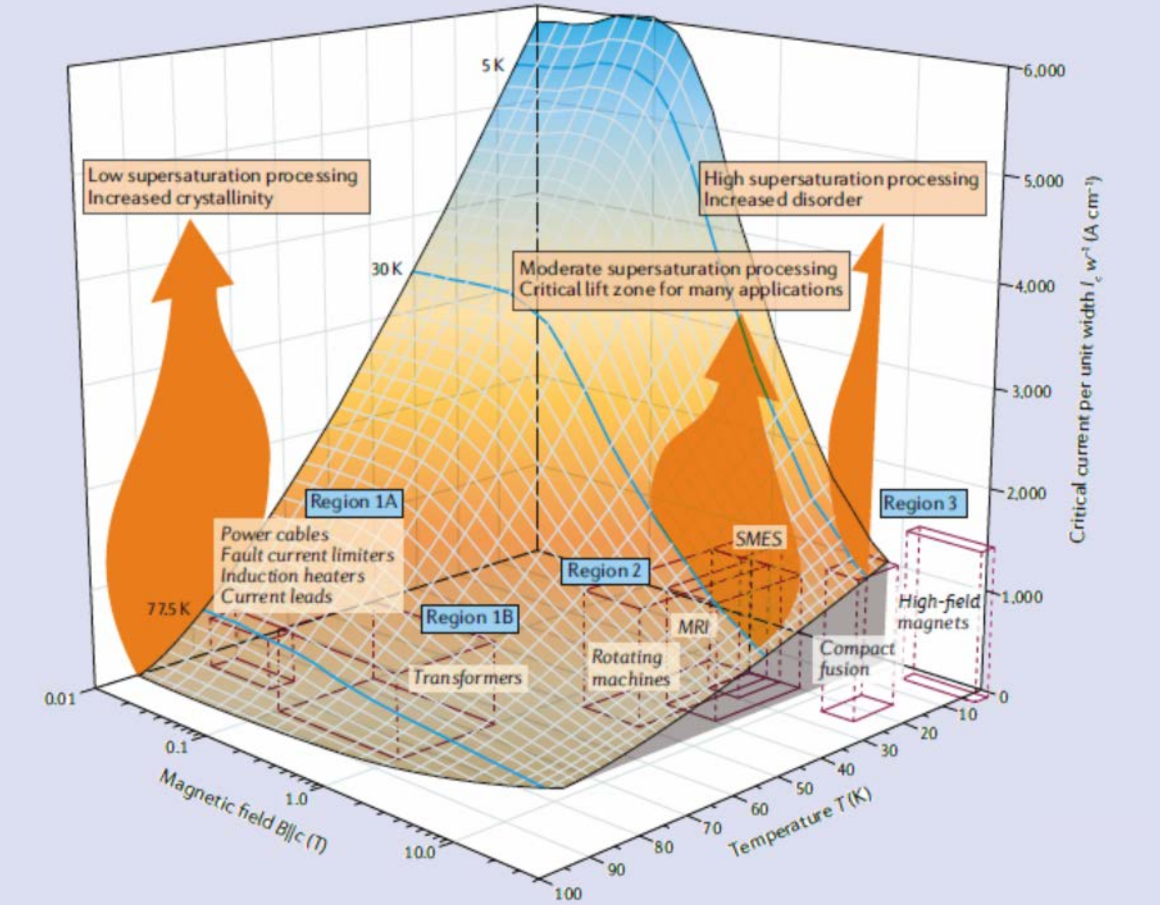


FIG. 1. Transmission electron micrographs (TEM) of the cross section of the (Y123+YSZ) sample with the $BaZrO_3$/Y123 multilayer structure, the bamboo structure: (a) the whole sample, showing the bamboo structure grown up to the surface of the film; (b) the bamboo structure near the buffer layer of CeO_2 started from the substrate. The dark region in the knots of the bamboo suggests the stress fields surrounding Zr-included structures such as $BaZrO_3$. Y123 layers are epitaxially inserted between them.

Yamada et al *Appl. Phys. Lett. 2005*



MacManus-Driscoll, 2021

"Ba122" : barium-iron-arsenic (*)

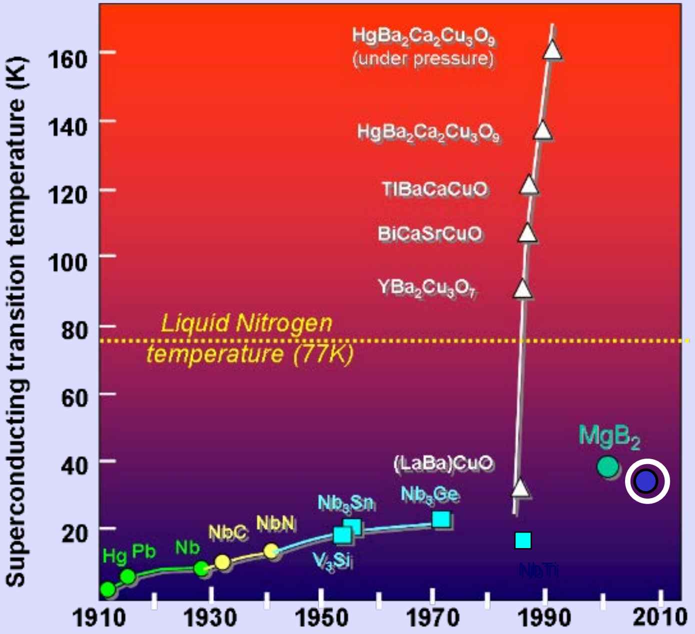
T_c = ***39 K***

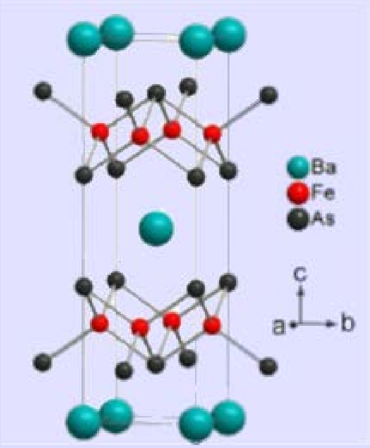
$B_{c2} \approx$ ***100 T***

Early development

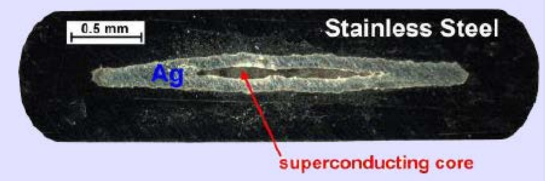
not yet commercialized

(*) $Ba_{0.55}K_{0.45}Fe_2As_2$

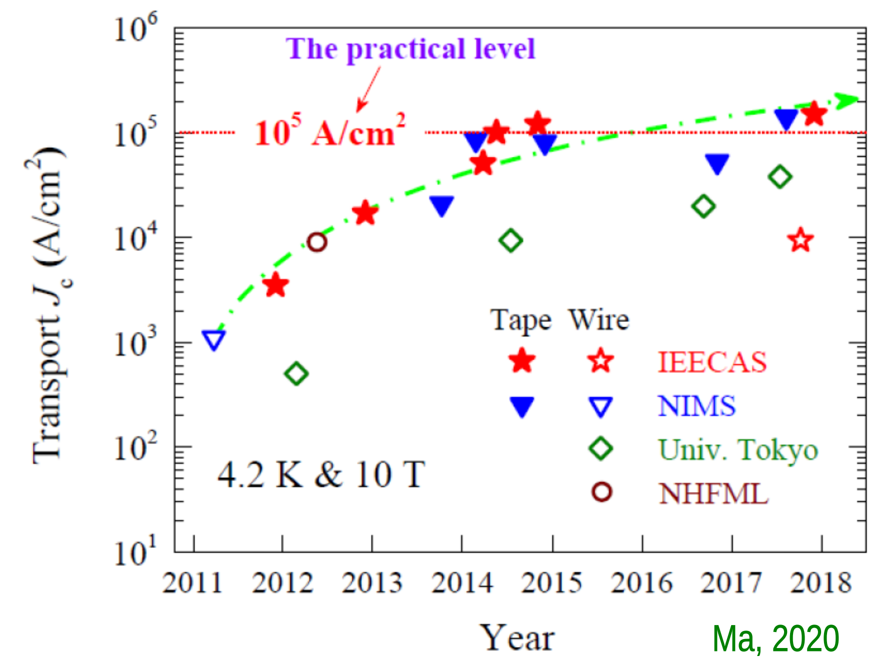




Orthorhombic pnictide;
near-isotropic (!)



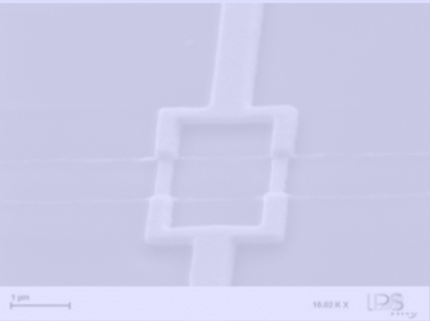
Ma, 2020



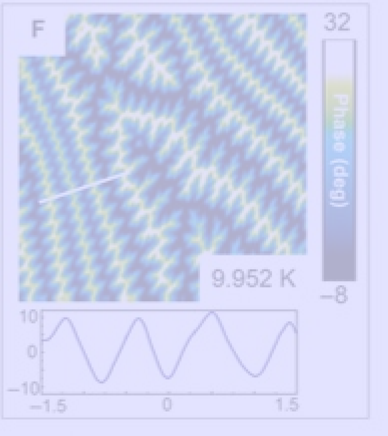
Ma, 2020

1. Phenomenology & understanding
2. Materials & *applications*
3. Cooling requirements & - strategies

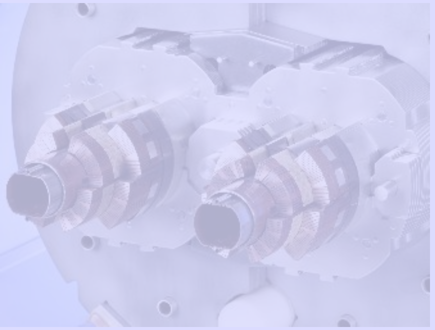
Physics World



Supraconductivité.fr



Science Advances



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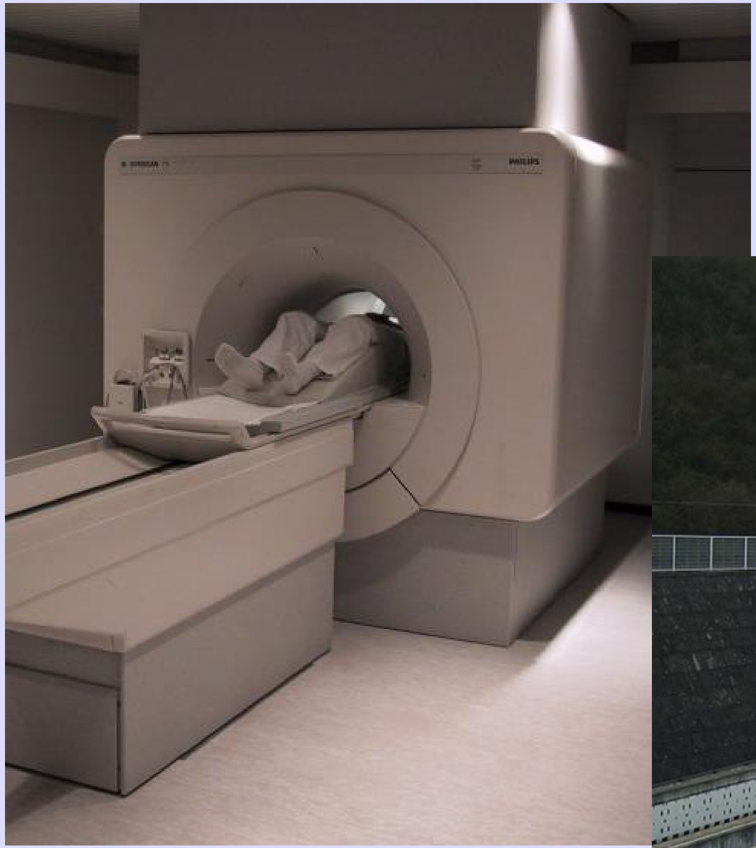
Large scale (1)

High current density without ohmic heating

($J \sim 100 - 1000$ A/mm^2 instead of ~ 1 A/mm^2)



Large scale (2)

High current density without ohmic heating

($J \sim 100 - 1000$ A/mm^2 instead of ~ 1 A/mm^2)

⇒ Powerful electro-magnets
(MRI, NMR, HEP, fusion,…)

⇒ Compact electro-technical devices
(cables, FCL, generators, motors…)

Large scale (3)

High current density without ohmic heating

($J \sim 100 - 1000$ A/mm^2 instead of ~ 1 A/mm^2)

⇒ Powerful electro-magnets
(MRI, NMR, HEP, fusion,…)

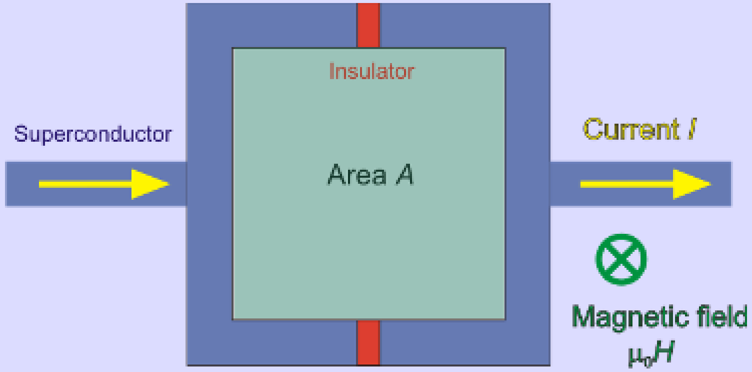
⇒ Compact electro-technical devices
(cables, FCL, generators, motors…)

ecoswing

Horizon 2020
European Union Funding
for Research & Innovation

Small scale (1)

Quantum interference with EM fields

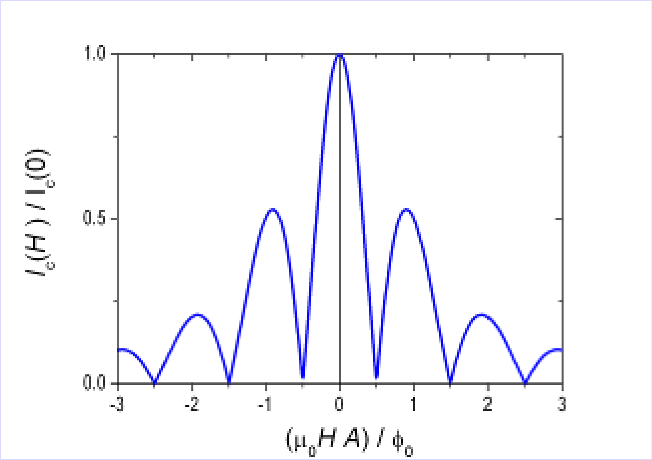


⇒ Superconducting Quantum Interference Device ('SQUID')

more precise magnetic field measurements

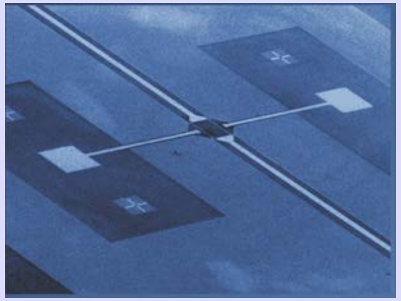
⇒ Measurement standards

(SI 'volt' definition)



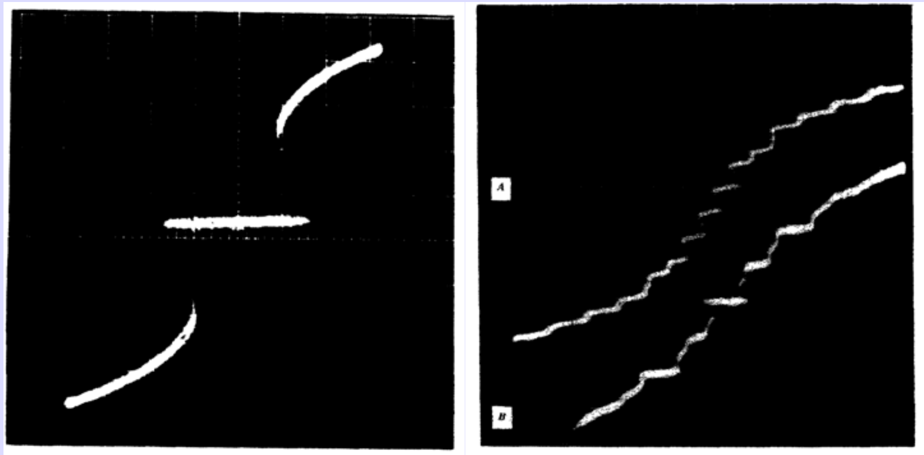
⇒ Faster and compacter electronics

⇒ Qubits, quantum computing

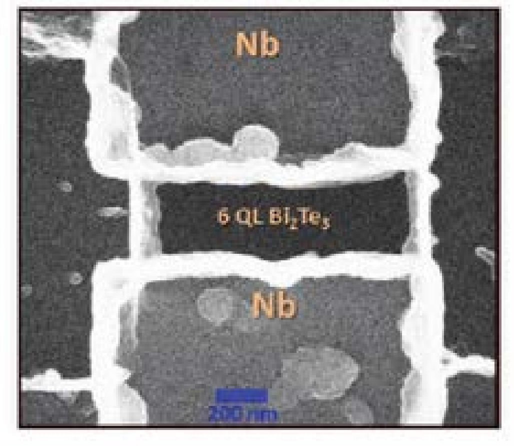


Small scale (2)

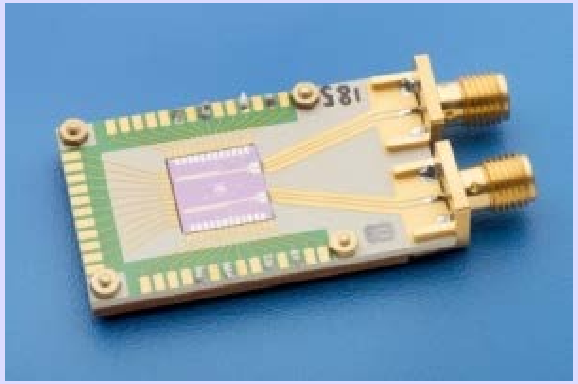
Quantum interference with EM fields



S. Shapiro, 1963



M.P. Stehno, Adv. Mater. 2020



www.PTB.de

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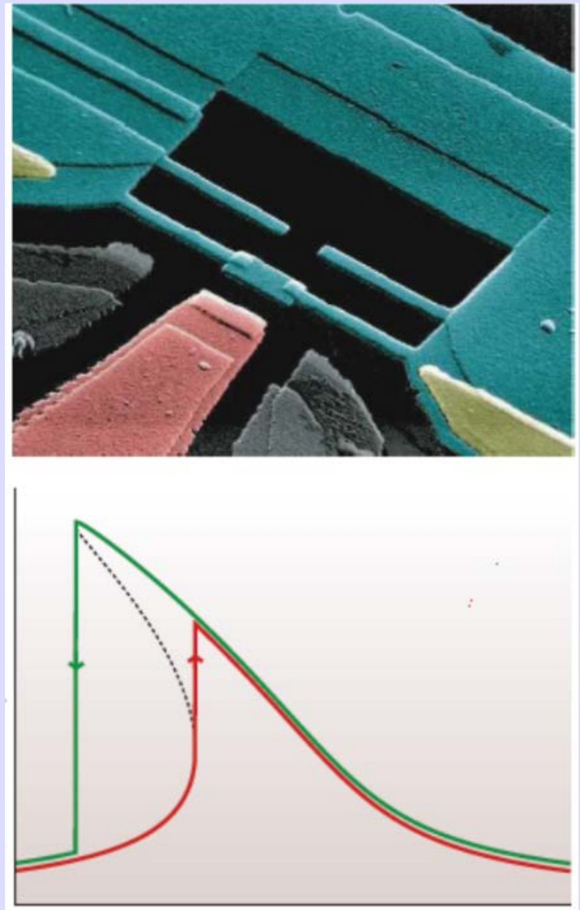
Small scale (3)

Quantum interference with EM fields



Clarke & Wilhelm, Nature 2008

⇒ Superconducting Quantum Interference Device ('SQUID')

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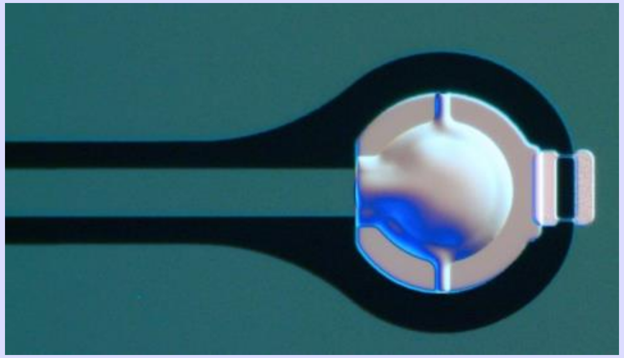

Bosman et al, Nature 2017

1. Phenomenology & understanding
2. Materials & applications
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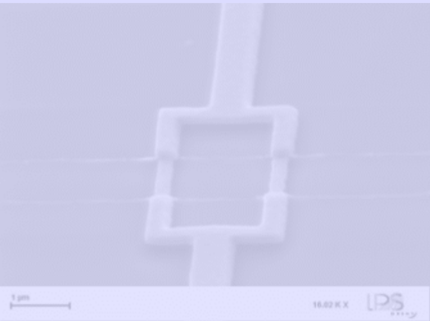
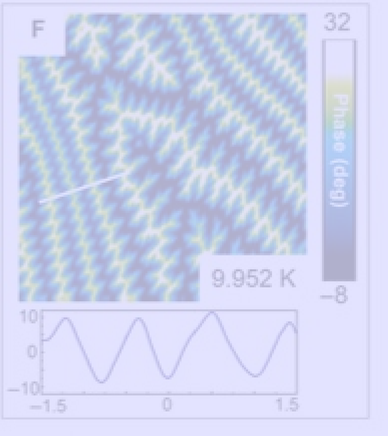
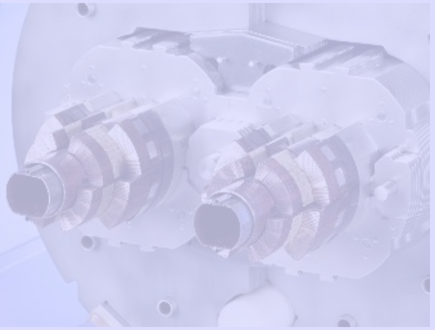
Physics World



Supraconductivité.fr



Science Advances



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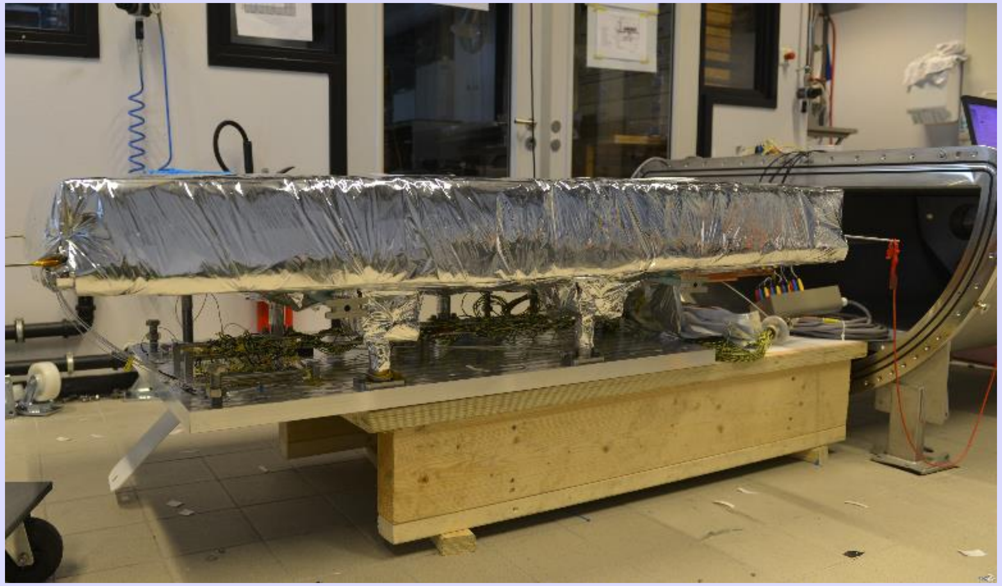
Heat loads:

❑ in-leak through cryostat enclosure	➢ in common with other cryogenic systems
❑ ramp- or AC losses	➢ unavoidable, but strongly application-dependent
❑ external current leads	➢ perennial worry
❑ 'warm-cold' structural elements	➢ application-dependent
❑ 'accidental'	➢ "quench"-detection and - protection

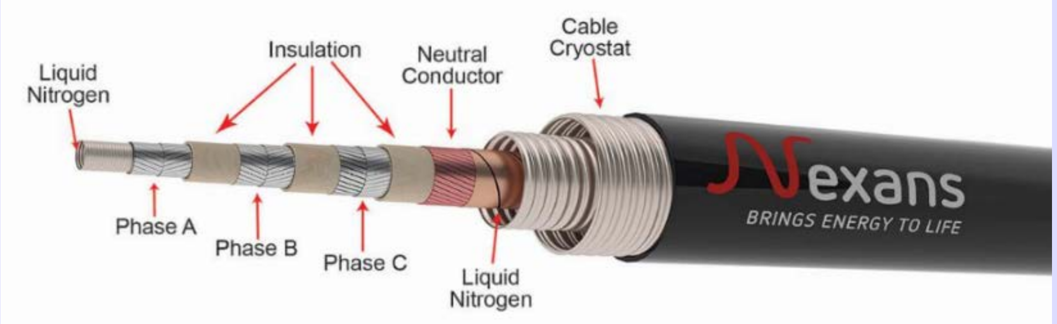
In-leak through cryostat enclosure



MDS separator

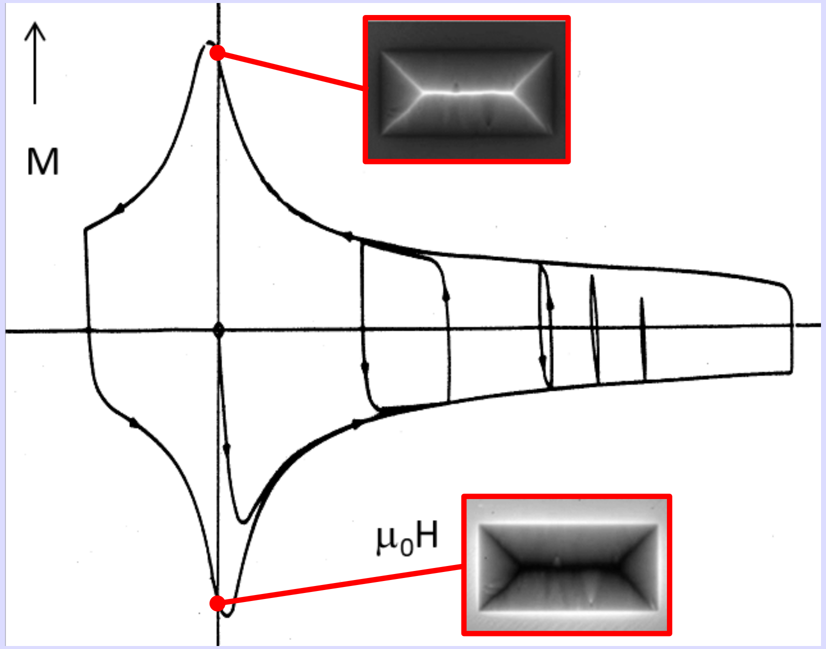
Ecoswing rotor

- Typically vacuum + MLI;
- Challenge: minimize the 'air' gap
- ~ 0.1 - 1 W/m^2 between 293 & 4.2 K (chambers);
  ~ 0.1 - 1 W/m between 293 & 77 K (flex tubes)

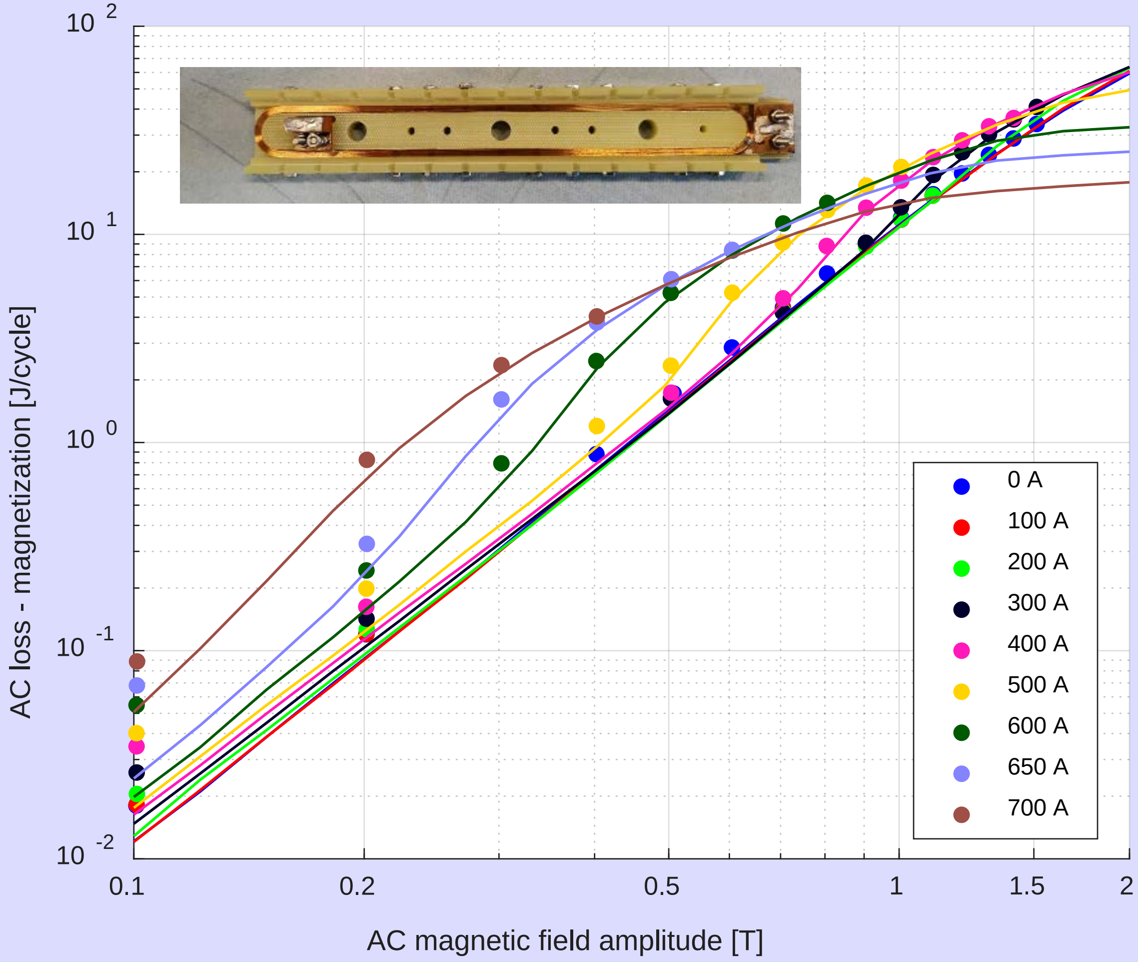


www.nexans.com

Ramp- or AC losses



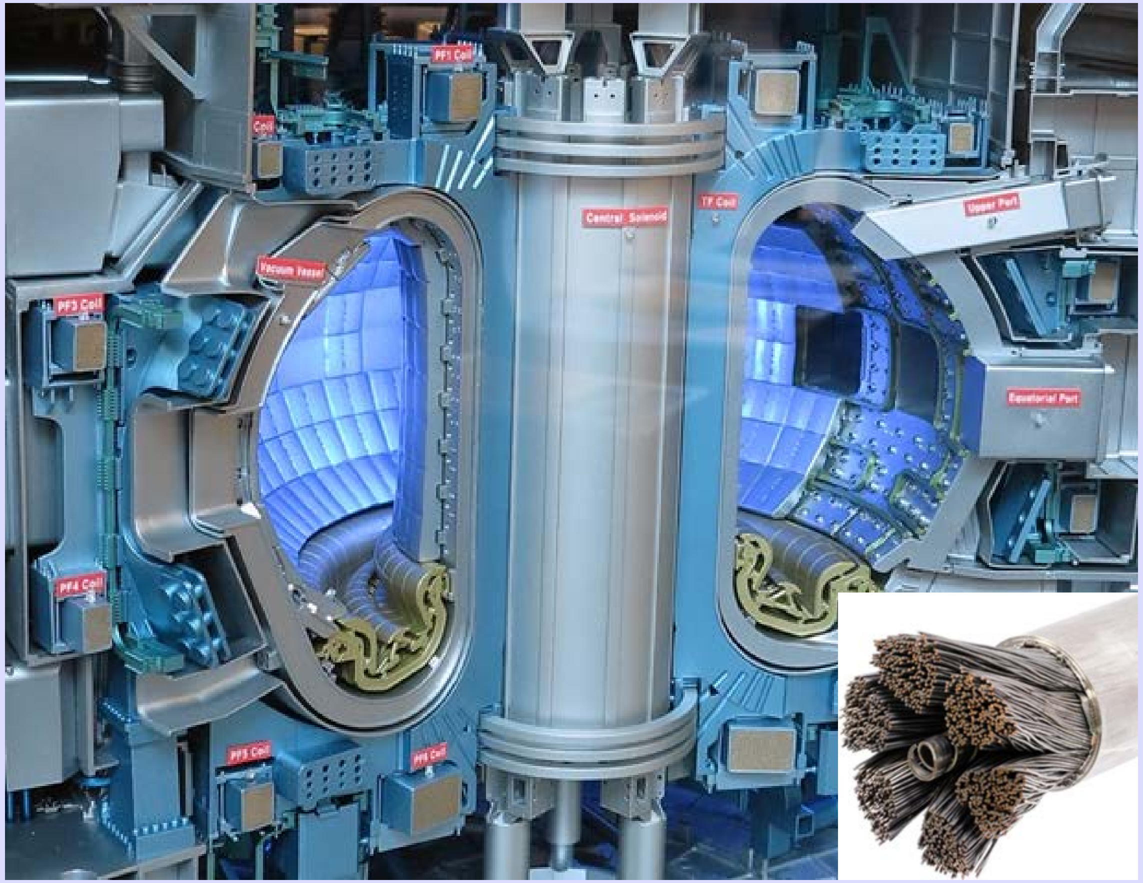
after Jooss et al, 2001



Hyseresis losses in linear actuator coil

- Time-varying magnetic fields or currents lead to hysteretic internal flux profiles
- Motion of vortices → dissipation …
- *Hysteresis loss*

Ramp- or AC losses



www.anl.gov

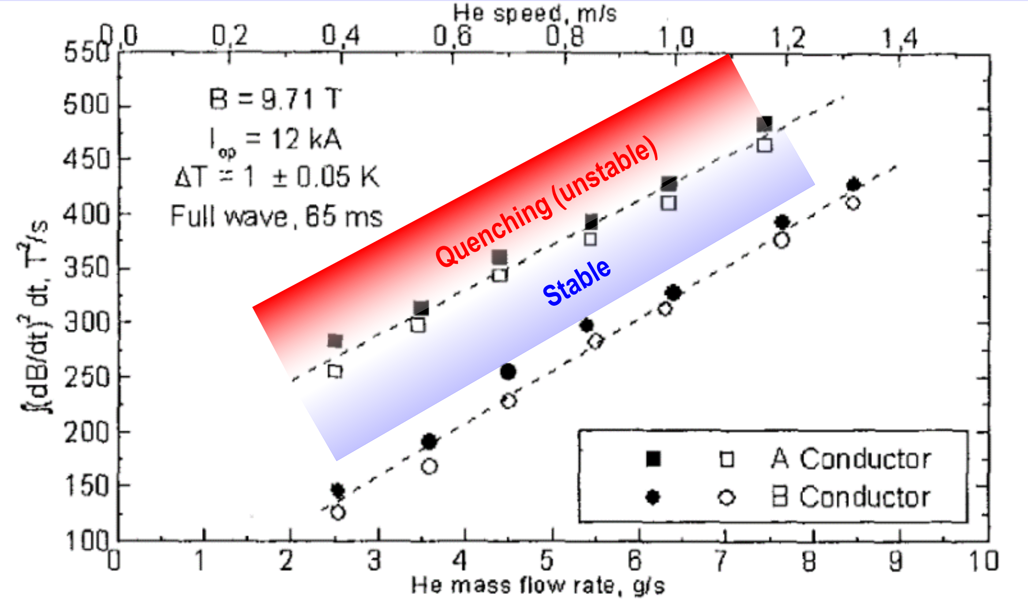
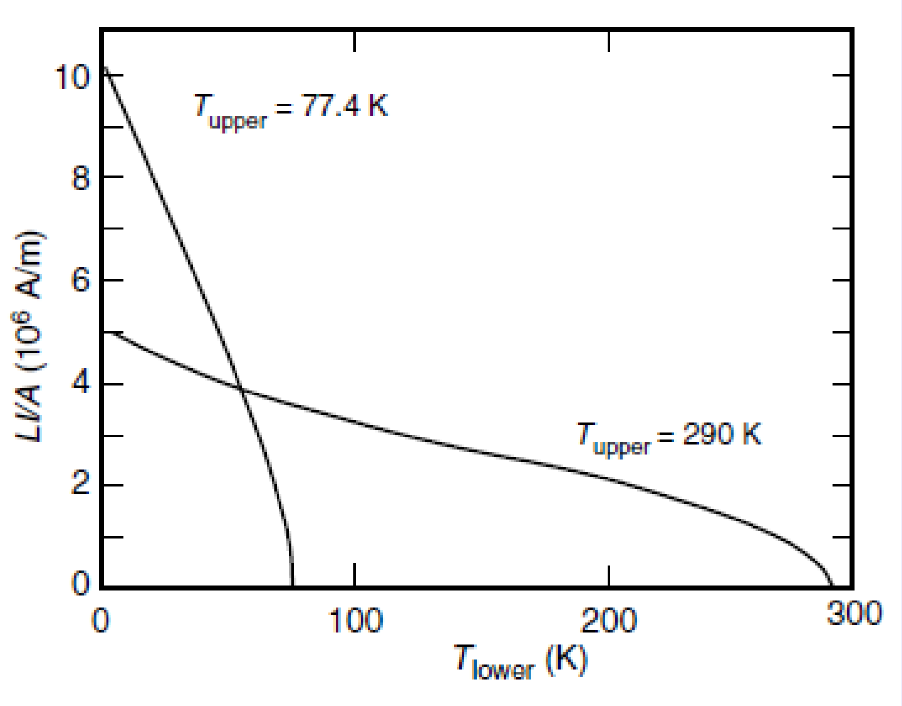


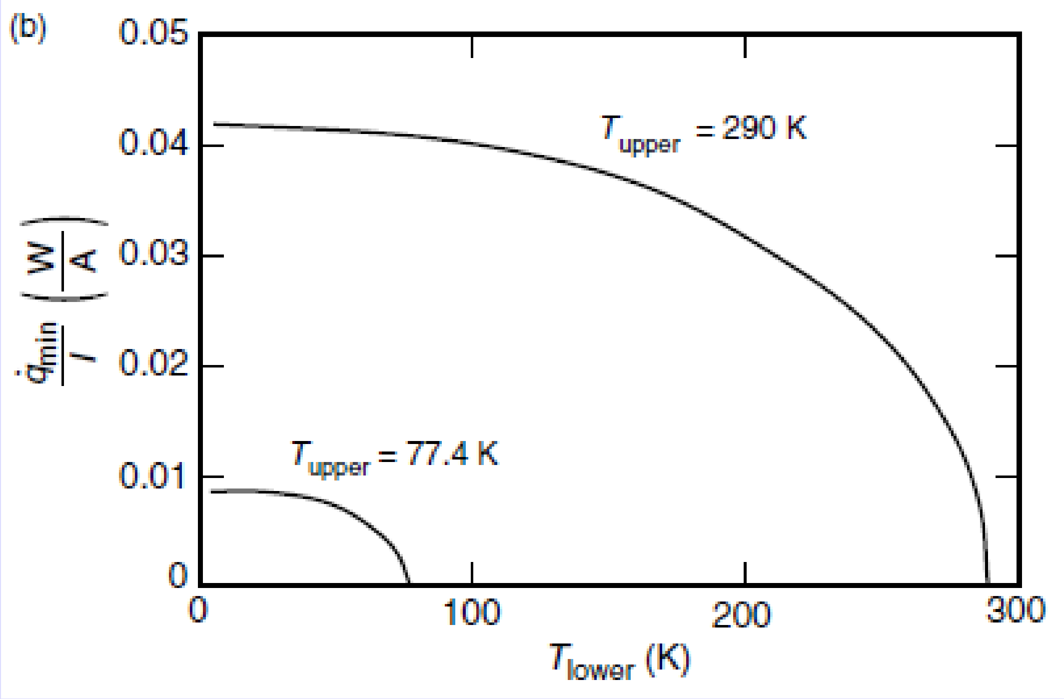
Fig. 8 Stability vs. mass flow rate at constant temperature margin

after P. Bruzzone et al, 2001

- … in addition, induced currents between strands in cabled structures lead to ohmic loss
- *'Coupling' loss*

External current leads *between RT power supply and cryogenic SC device*





J. Ekin, “Experimental techniques for low-temperature measurements” 2006

- Minimizing heat conduction calls for long length L and small cross-section A;
- Minimizing ohmic heating calls for short length L and large cross-section A

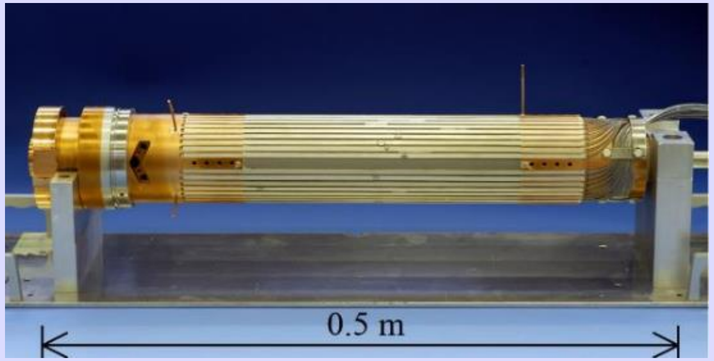
- Optimal geometry L/A
- Unavoidable loss level

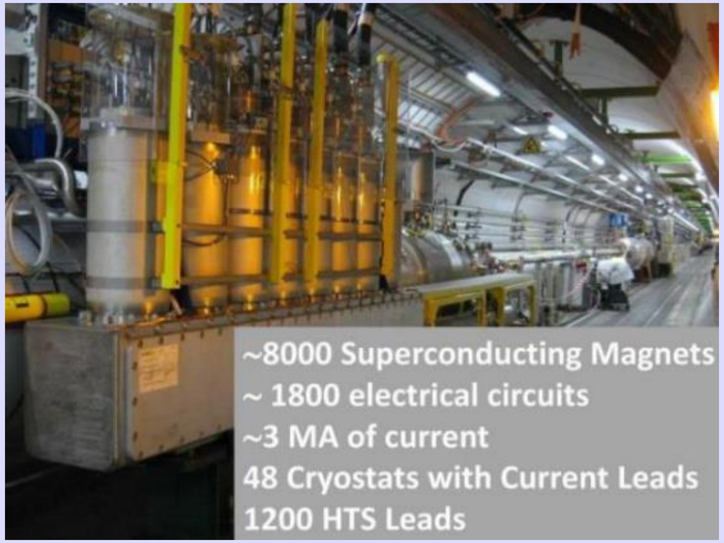
External current leads

Possible escape (1) :

intercept in-leak a.s.a.p. &
continue with HTS SC leads to actual device

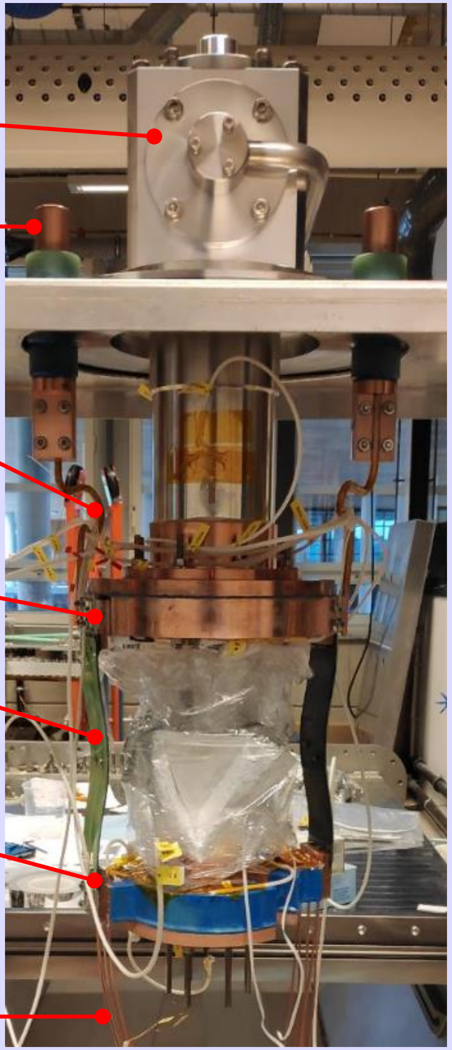
CERN LHC current feedthroughs





A. Ballarino, 2004

A. Ballarino, 2013



MDS current feedthroughs

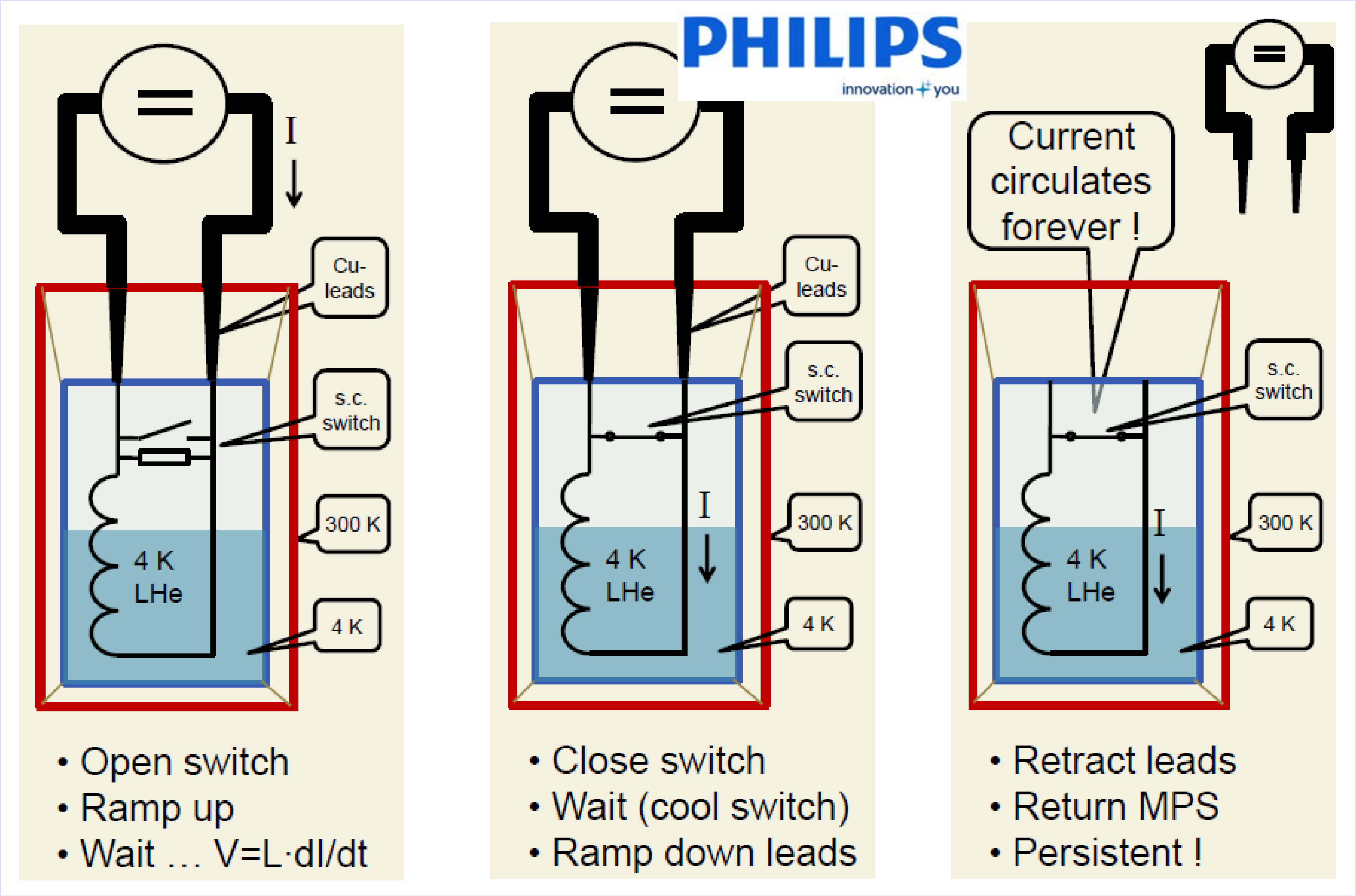
External current leads

Possible escape (2) :

retract RT connection after charging of the device

persistent mode

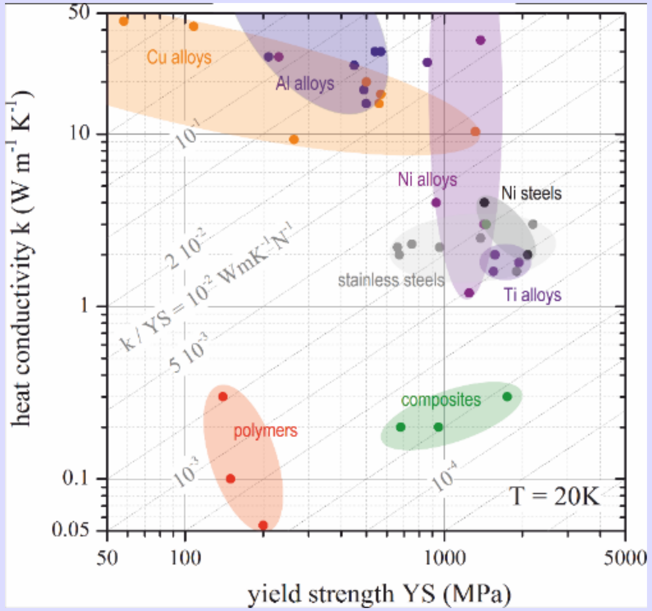
G. Mulder, 2018



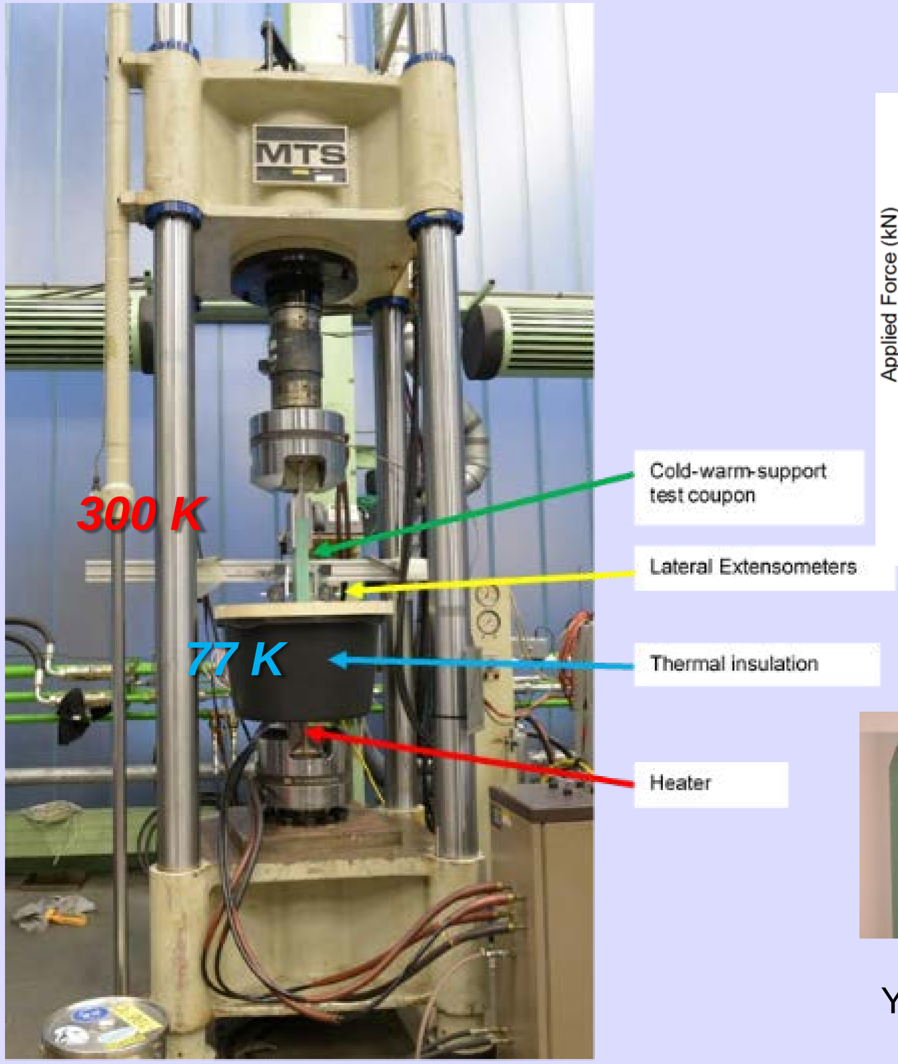
G. Mulder, 2018

Warm-cold supports

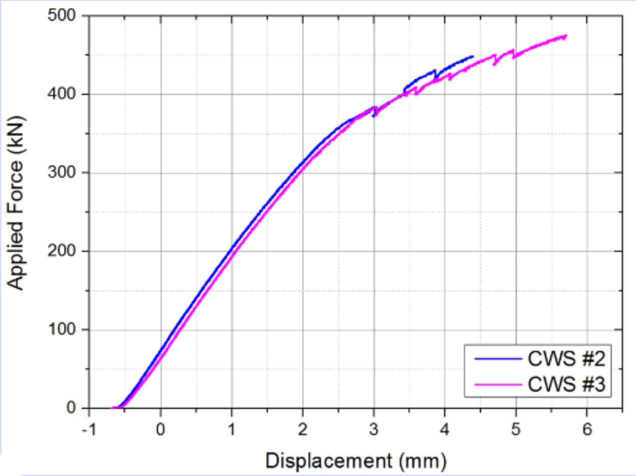
- Especially in electrical machinery (high torque)
- high E_Y – low κ material
- *reinforced polymers*



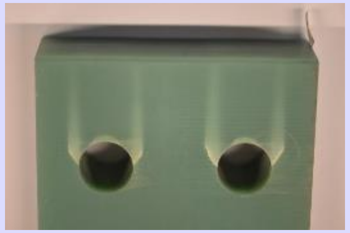
Cryogenic strength vs heat conductivity



Tensile / compressive loading test coupons @ TNO Delft



Tensile yield test



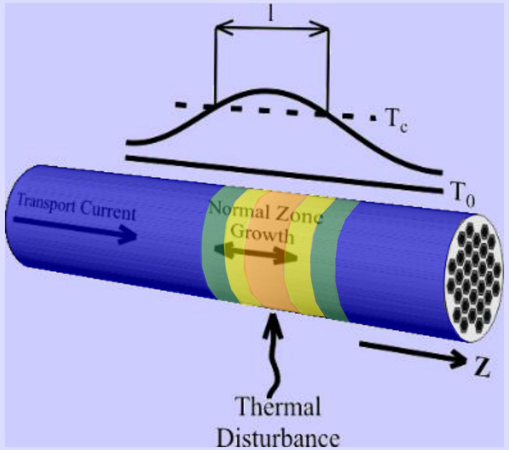
Yielding on warm side, not cold side

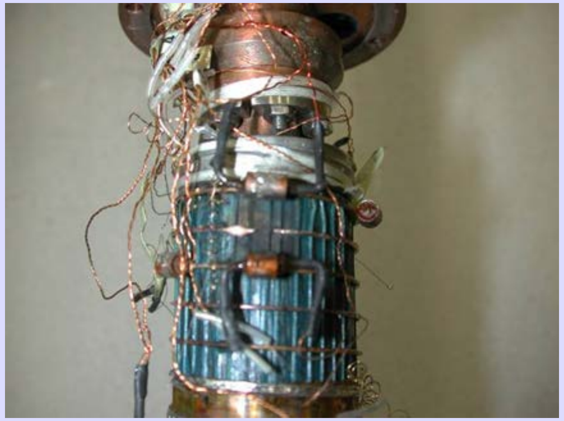
UNIVERSITY OF TWENTE.

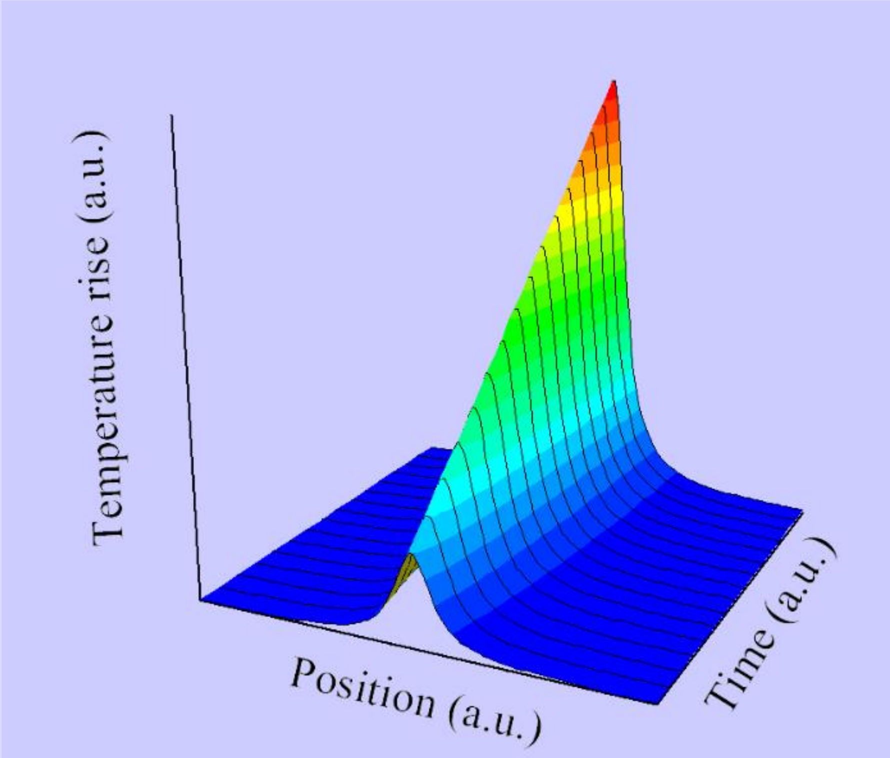
Quench-detection and protection

$$C\frac{\partial T}{\partial t} = \frac{\partial}{\partial t}\left(\kappa\frac{\partial T}{\partial x}\right) + \rho J^2 + p_{initial}$$

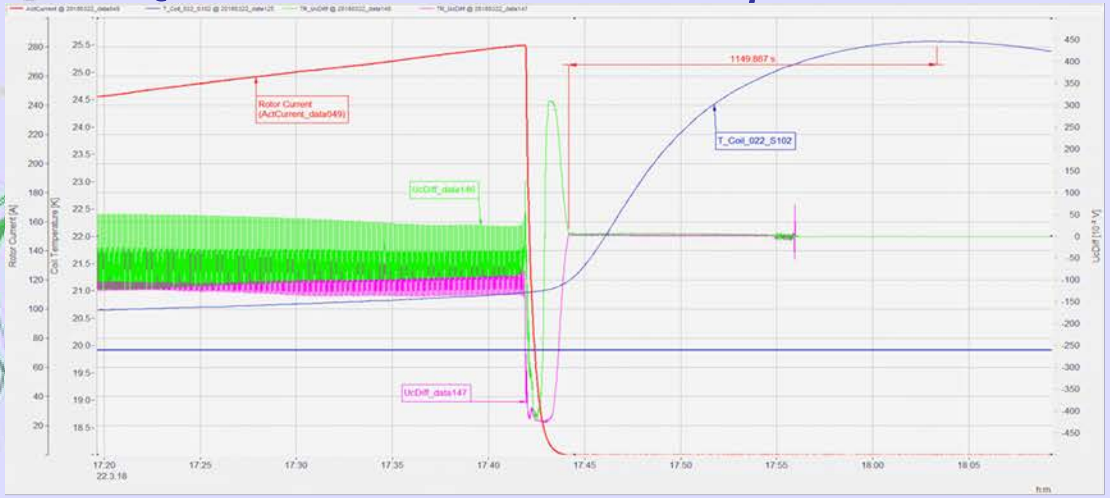
- An unexpected local disturbance can initiate a 'thermal avalanche', a quench
- Such a disturbance must be detected a.s.a.p. and the stored energy safely extracted







Quench-detection and protection



Temperature rise sub-standard coil after ***quench***

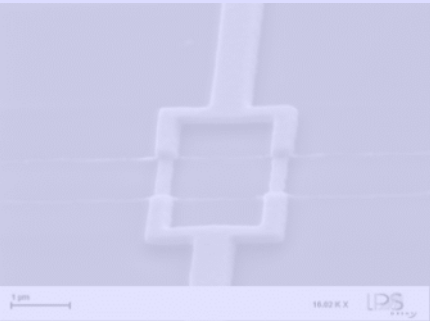
- Sub-standard coil had passed (accelerated) acceptance test …
- … and failed during power-up ramp;
- Inadequate 'quench-detection' (EM interference)
  - ➢ **Required coil replacement & protection upgrade**

Repair action at Boessenkool Almelo

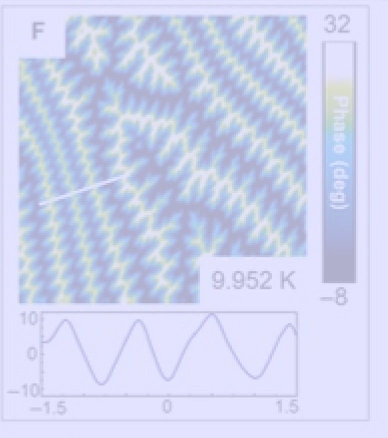
UNIVERSITY OF TWENTE. THEVA JEUMONT Electric

1. Phenomenology & understanding
2. Materials & applications
3. Cooling requirements & - *strategies*

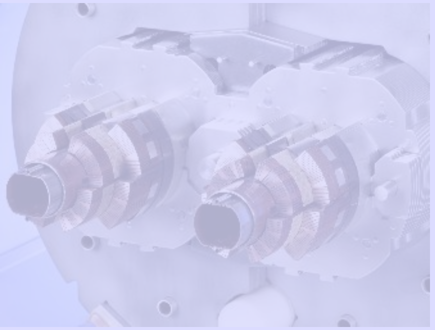
Physics World



Supraconductivité.fr



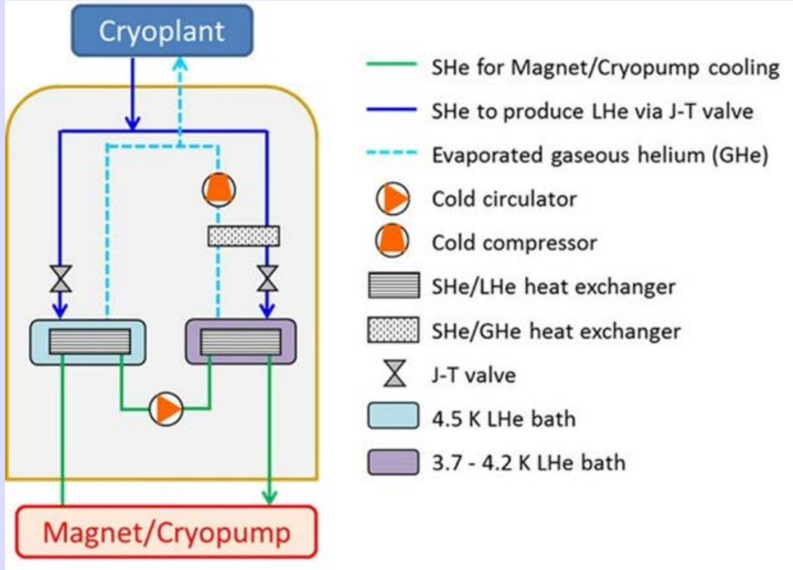
Science Advances



CERN.ch

Large systems ('Big Science')

- Forced-flow of (possibly superfluid) He
- Extended cryo-plants for re-liquification



www.iter.org

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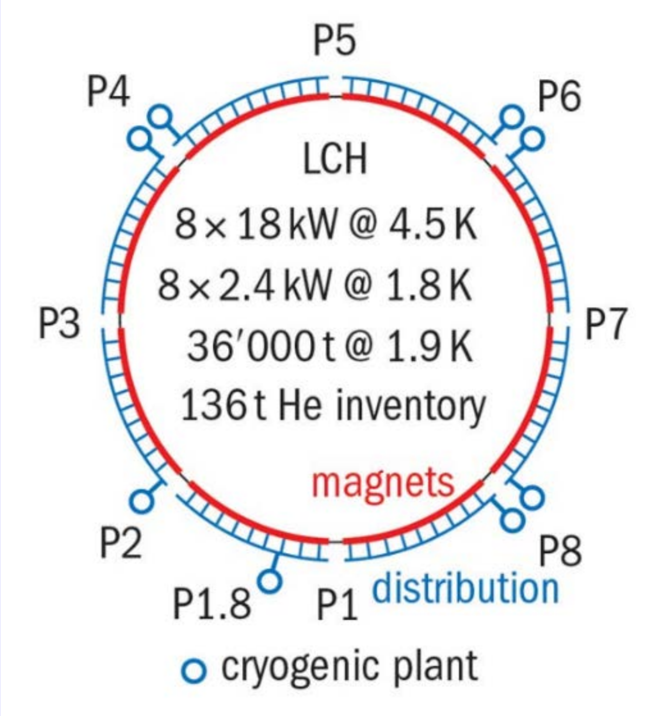
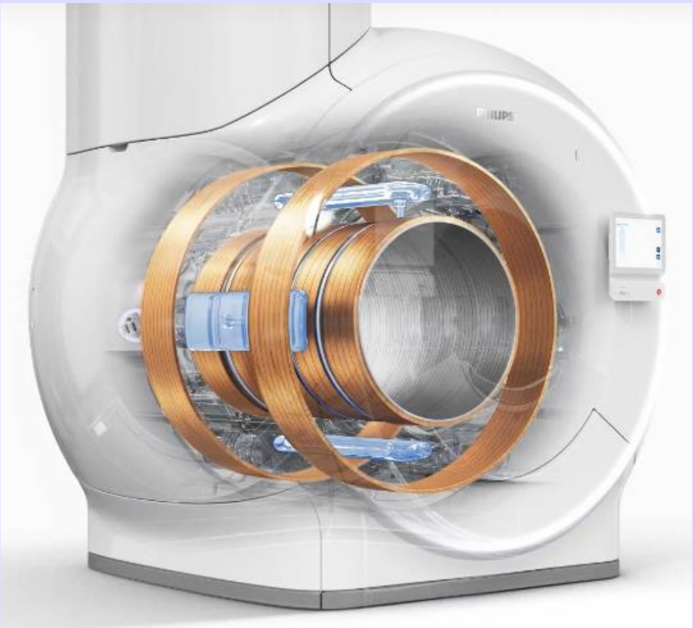


CERNCOURIER, 2013

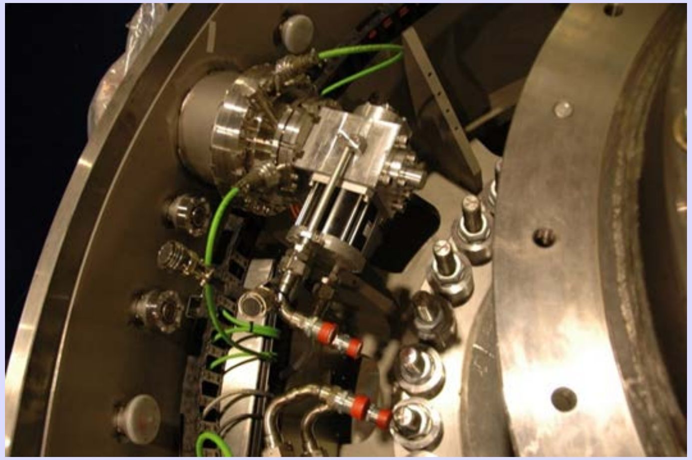
Medical systems (stand-alone)



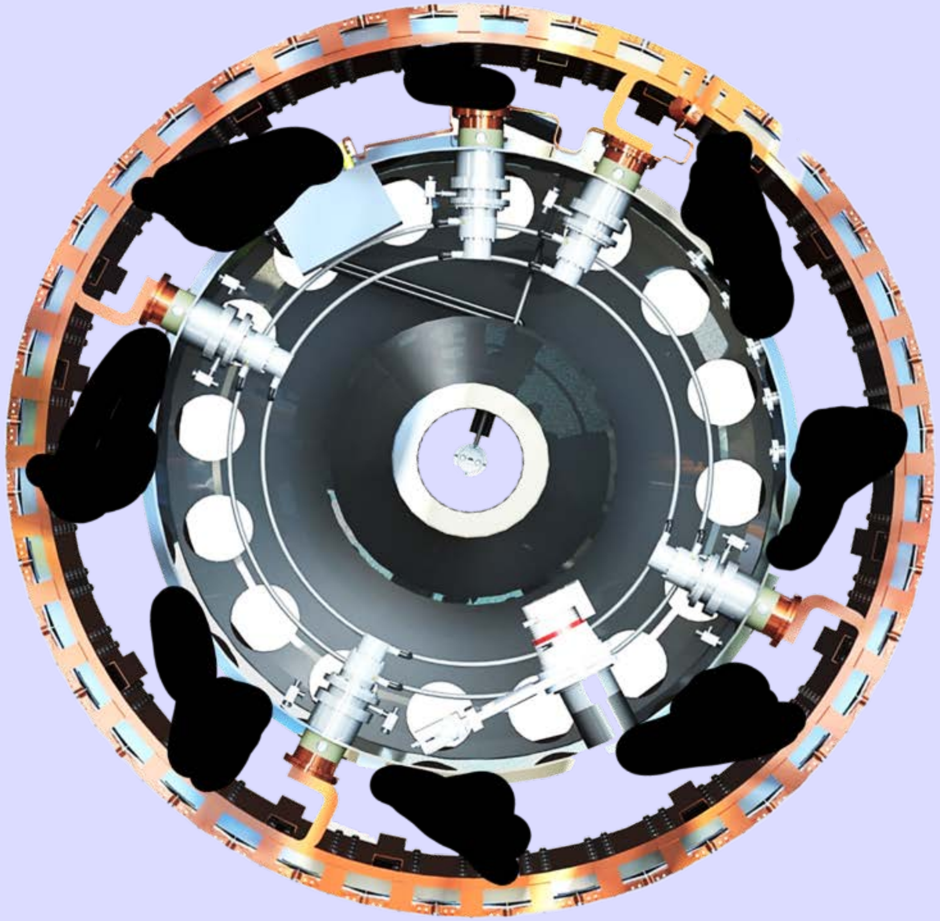
www.philips.com

- Liquid He bath cooling
- "Zero boil-off" technology (cryocooler-based re-condenser)
- Trend towards less & less He on-board (e.g. Philips 'BlueSeal' MRI system)

'Industrial' machines (stand-alone) : cryocoolers + conduction cooling



GM cold-heads & compressors

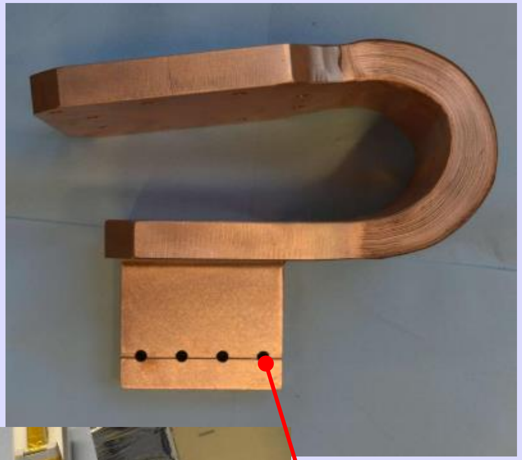


Cryogenic rotor design
(Cu cold-bus, distributed coolers)

- Cu 'cold-bus' monted on cold back-iron
- 'On-board' rotating GM coolers
- Static compressors
- ***Rotating He gas coupling!*** (Sumitomo)

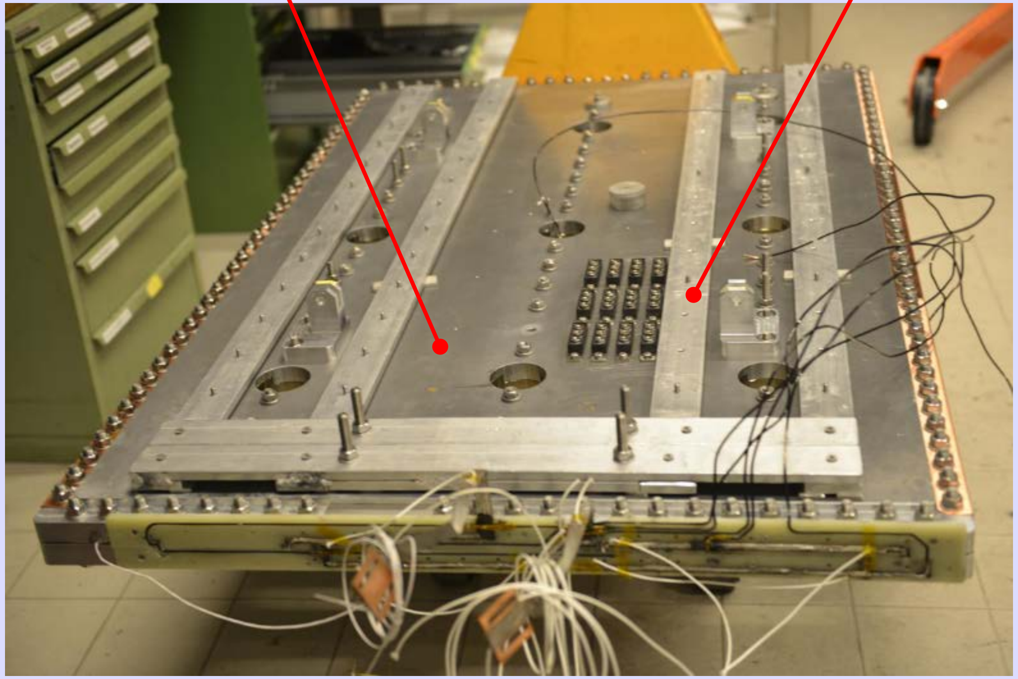
'Industrial' machines (stand-alone) : cryocoolers + conduction cooling

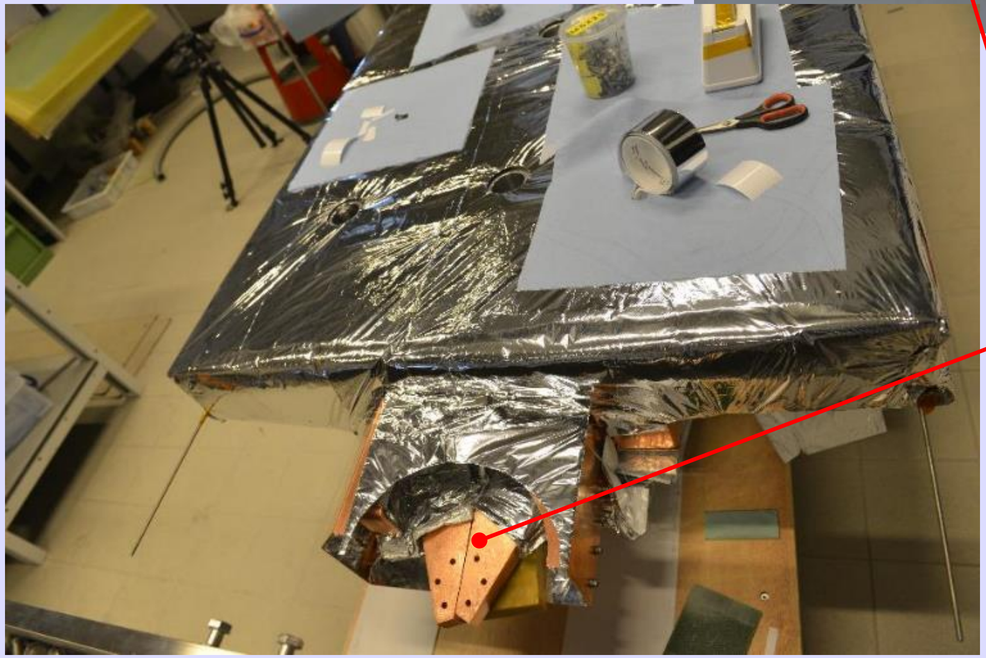
- Thermal gradients need to be kept as low as possible
- High-purity metal flex-links & thermal shunts …



Al alloy cassette (pre-compression)

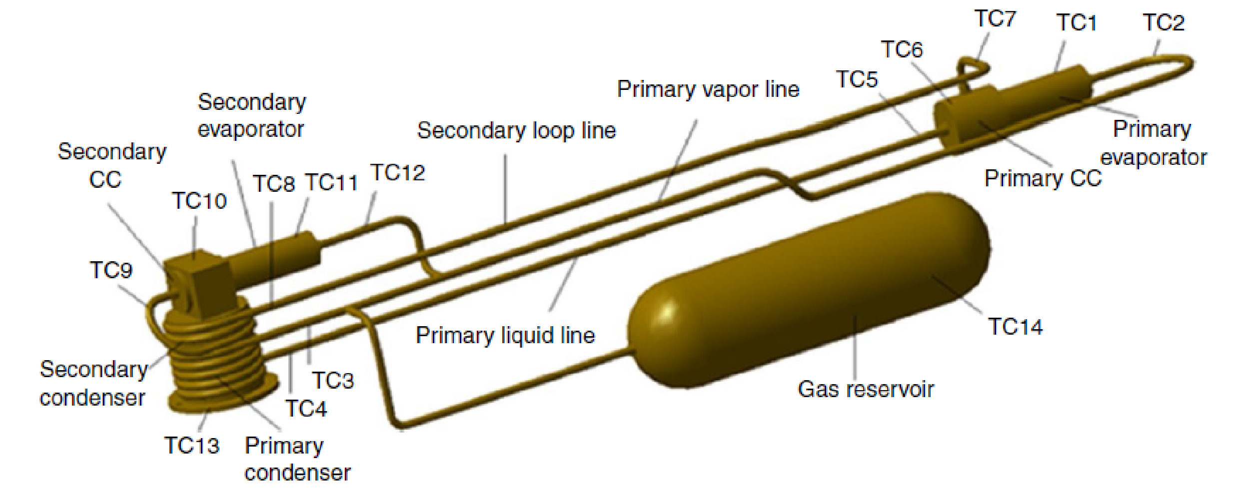
high-purity Al shunts

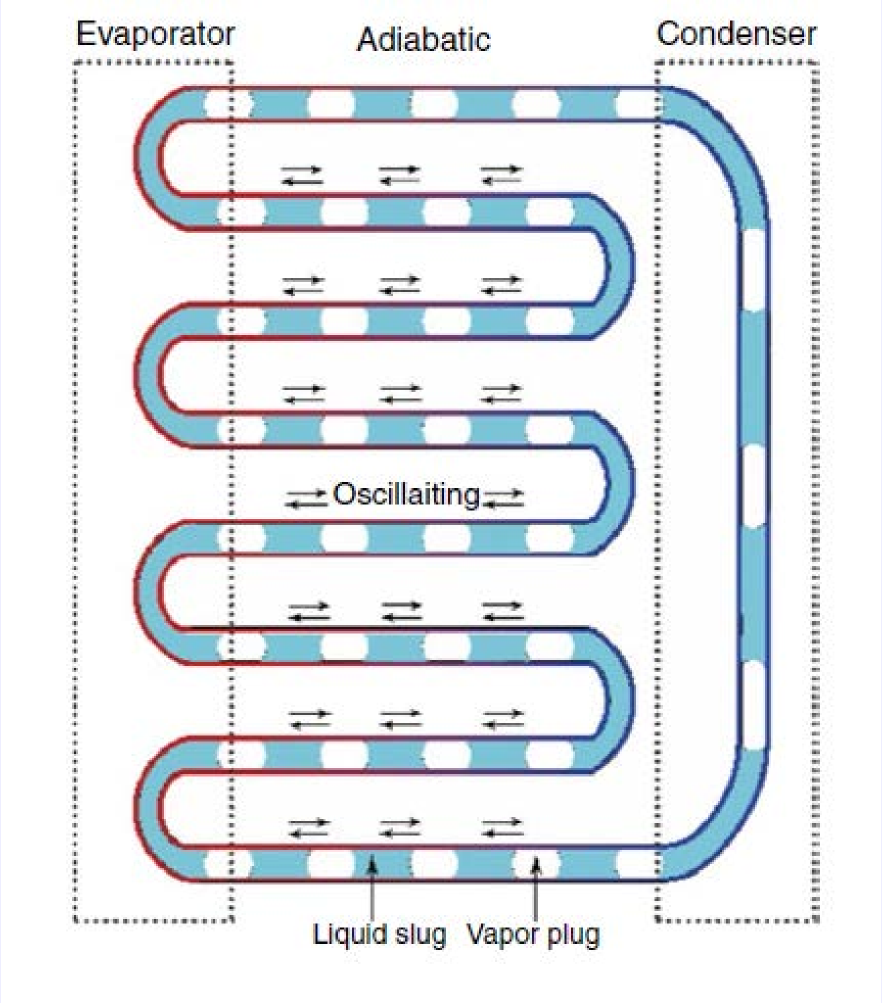




Cu flex-link

Cryogenic heat-pipes as thermal links for the most demanding SC applications?





A. Haghighi et al, 2022