Superconductivity in High-Energy Particle Accelerators

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Motivation for superconductor technology in accelerators

Basics of superconductivity

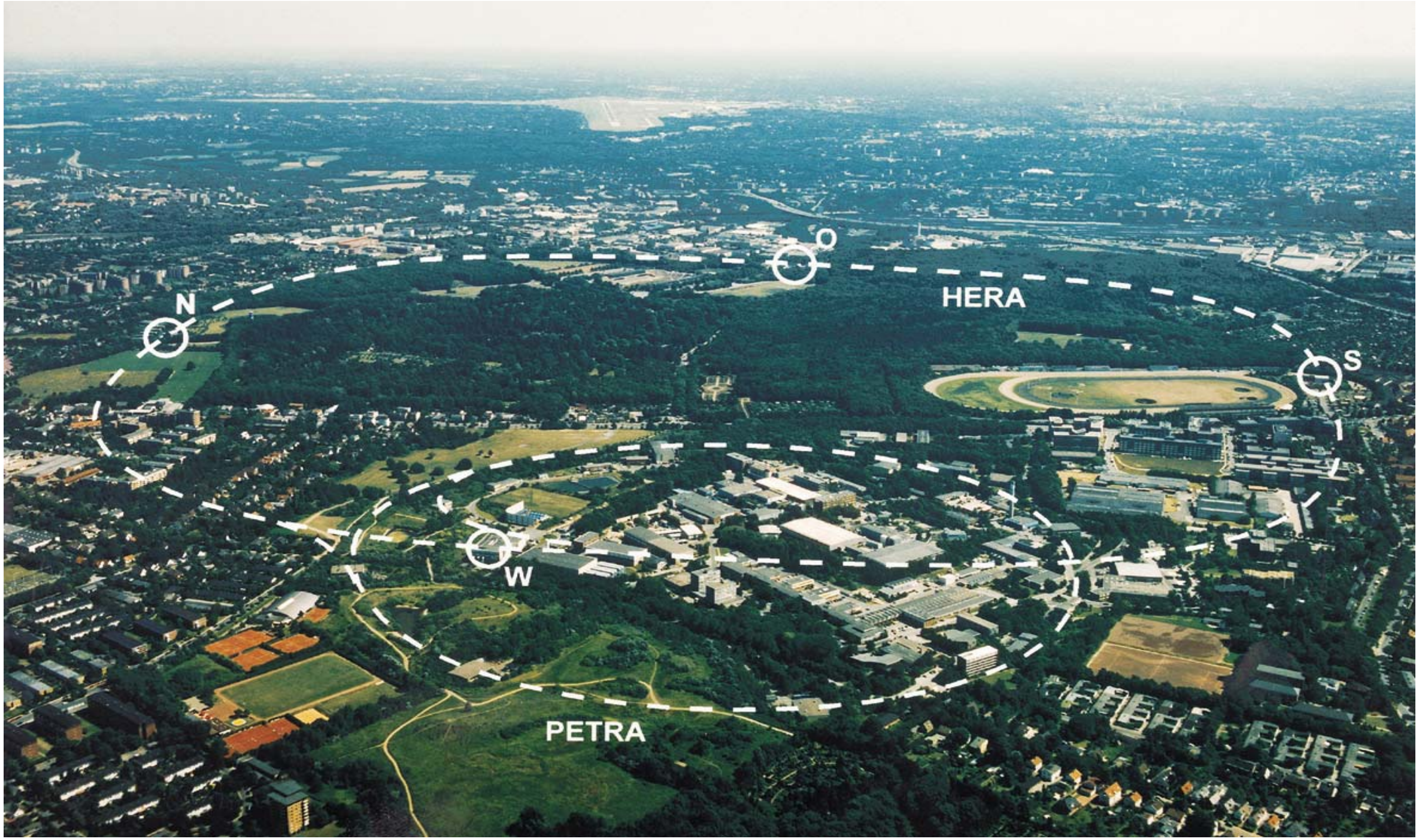
Superconducting magnets

Superconducting cavities

Magnet installation at LHC
With normal magnets, the energy
would be only 1.5 TeV

HERA: a 900 GeV Superconducting Proton Storage Ring in a Big City

Impossible with normal electromagnets,
HERA would extend beyond the airport of Hamburg



Superconductor technology in accelerators

Superconducting Magnets: far superior to normal magnets

sc magnets are indispensible for large hadron ring accelerators
far higher field than in normal magnets: 5 – 8 Tesla vs. 2 Tesla
much lower power consumption

HERA-p 800 GeV: 6 MW electrical power needed by helium plant
CERN SPS at 300 GeV: 52 MW power dissipation in magnet coils

Superconducting Cavities: advantage not as obvious

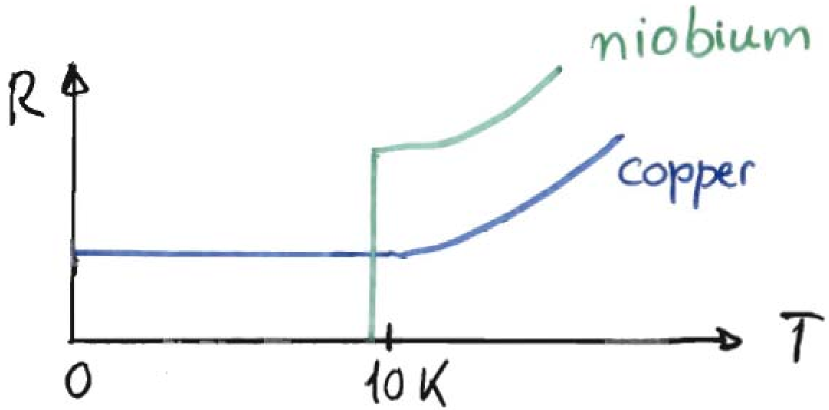
Superconductors have small but finite resistance in microwave fields
Accelerating fields lower than in Cu cavities

For linear electron-positron colliders two different concepts have been pursued for a long time:
Next Linear Collider (SLAC): 11 GHz normal conducting accelerating structures
TESLA (DESY, Fermilab, Saclay, Cornell, INFN etc): 1.3 GHz superconducting cavities

International Linear Collider ILC based on TESLA technology

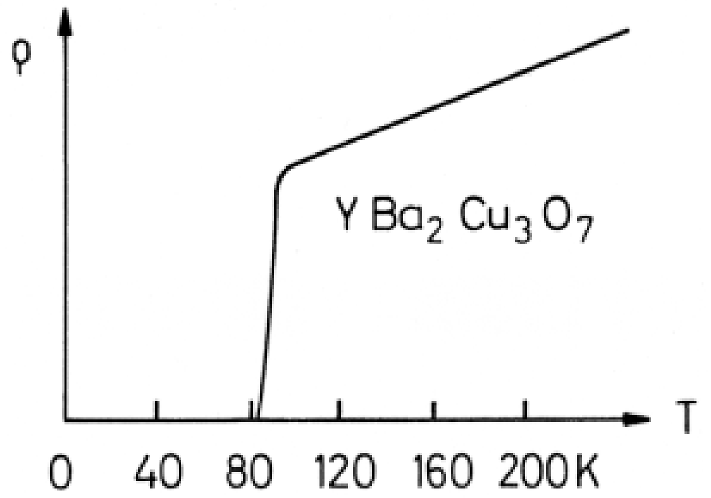
Basics of Superconductivity

Low-temperature superconductor niobium
normal conductor copper



critical temperature Tc = 9.2 K for Nb

High-temperature superconductor

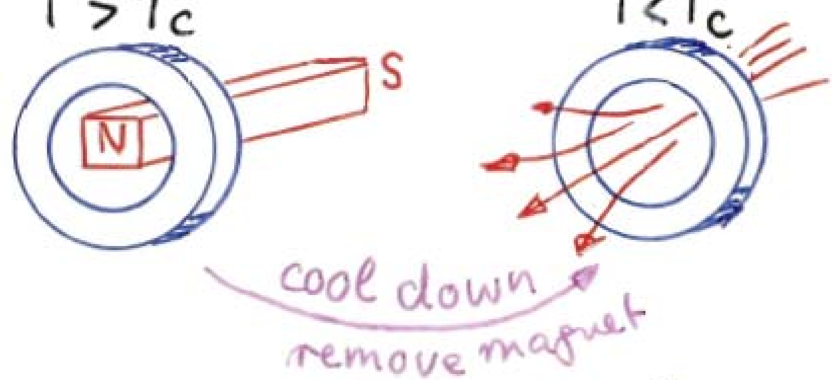


Interesting observation: excellent normal conductors such as Cu and Ag do not become superconductive

Heuristic argument: Cooper pair formation requires strong coupling between electrons and phonons
Consequence: resistance in normal state is high

Is the resistivity really zero?

Induce current in a superconducting ring and measure decay of magnetic field.



The induced current in the ring decays exponentially.

$$I(t) = I(0)\exp(-t/\tau) \qquad \tau = \frac{L}{R}$$

Copper: $\tau < 100\,\mu s$ typically

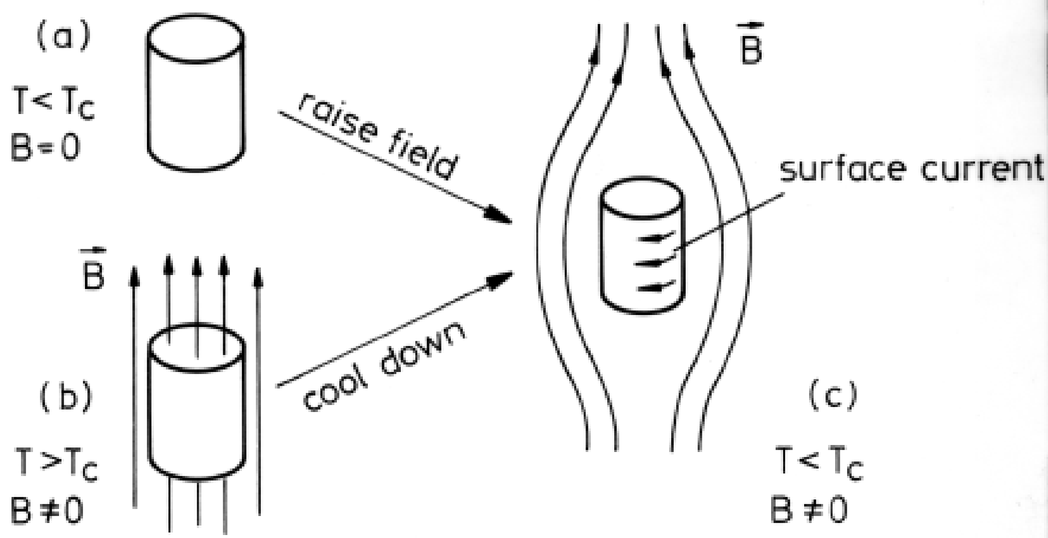
superconductor $\tau \simeq 10^5$ years

File, Mills Phys Rev Lett 10 (1963)

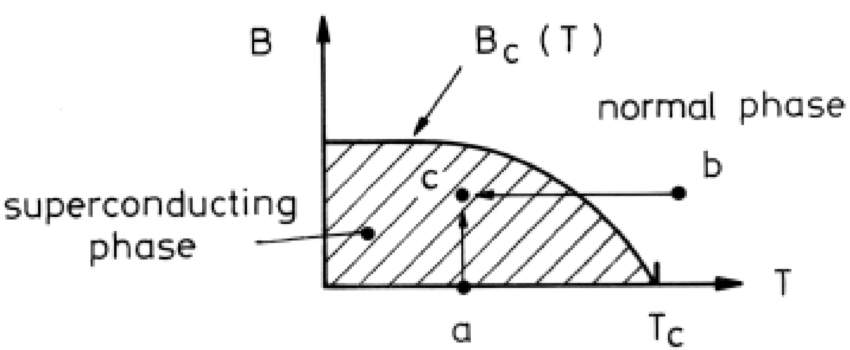
Application: operation of sc coils in short-circuit mode, $3 \cdot 10^{-9}$/hour

Superconductor in magnetig field: Meisner-Ochsenfeld effect

Below T_C a weak magnetic field is expelled from the superconductor



This applies for type I superconductors pure elements (lead, tin, aluminum…)



London equations

Heinz and Fritz London proposed 1935 two equations which offer a phenomenological description of the Meissner effect.

Super-electrons experience no friction:

$$\Rightarrow \quad m\dot{\vec{v}} = -e\vec{E}$$ equation of motion in electric field

Call $\vec{j}_s = -en_s\vec{v}$ the current density of the super-electrons, then we get

$$\boxed{\frac{\partial \vec{j}_s}{\partial t} = \frac{n_s e^2}{m}\vec{E}}$$ London equation (1)

Now we use the Maxwell equation

$$\vec{\nabla}\times\vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

and take the curl (rotation) of (1):

$$\frac{\partial}{\partial t}\left(\frac{m}{n_s e^2}\vec{\nabla}\times\vec{j}_s + \vec{B}\right) = 0$$

Integrating over time and <u>assuming</u> that the integration constant vanishes, one gets the important **second** London equation

$$\boxed{\vec{\nabla}\times\vec{j}_s = -\frac{n_s e^2}{m}\vec{B}}$$ London equation (2)

Combine the Maxwell equation

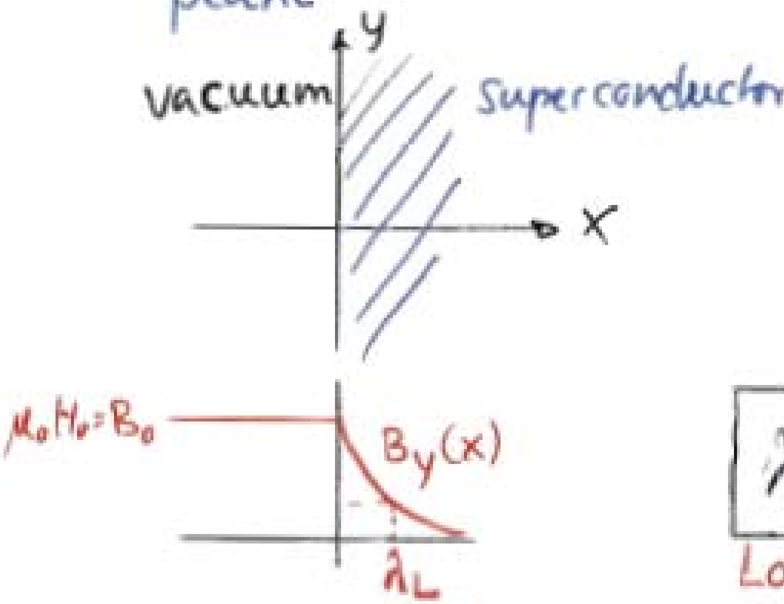
$$\vec{\nabla} \times \vec{B} = +\mu_0 \vec{j}_s$$

and London eq. (2):

$$\underbrace{\vec{\nabla} \times (\vec{\nabla} \times \vec{B})}_{-\nabla^2 \vec{B} \text{ since } \vec{\nabla}\cdot\vec{B} = 0} = +\mu_0 \vec{\nabla} \times \vec{j}_s = +\frac{\mu_0 n_s e^2}{m} \vec{B}$$

$$\boxed{\nabla^2 \vec{B} - \frac{\mu_0 n_s e^2}{m} \vec{B} = 0}$$

Consider special case of superconducting half plane



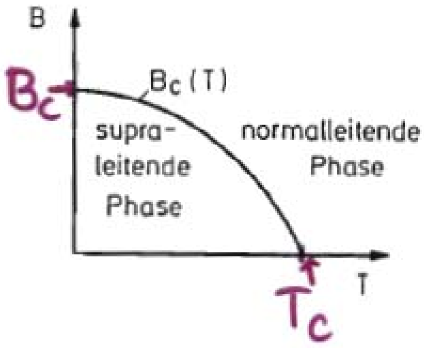
$$\frac{d^2 B_y}{dx^2} = \frac{1}{\lambda_L^2} B_y$$

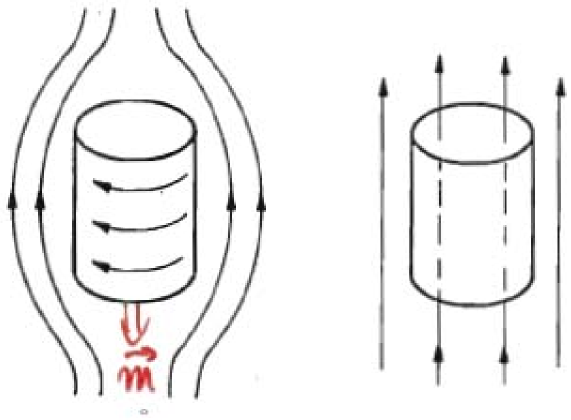
$$B_y(x) = B_0 e^{-x/\lambda_L}$$

$$\boxed{\lambda_L = \sqrt{\frac{m}{\mu_0 n_s e^2}}}$$

London penetration depth

Type I superconductors: pure elements (lead, indium, tin..) but not niobium



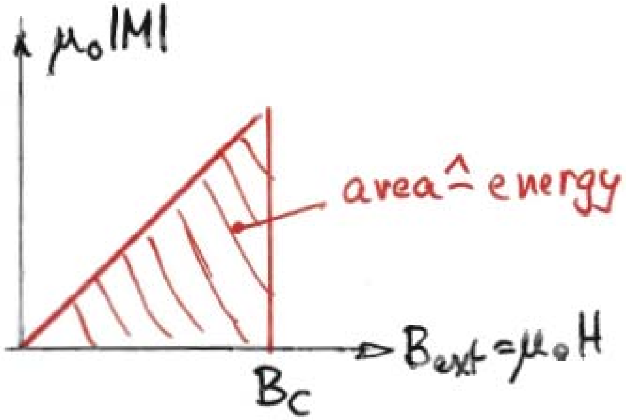


$B < B_c(T)$ $\qquad$ $B > B_c(T)$

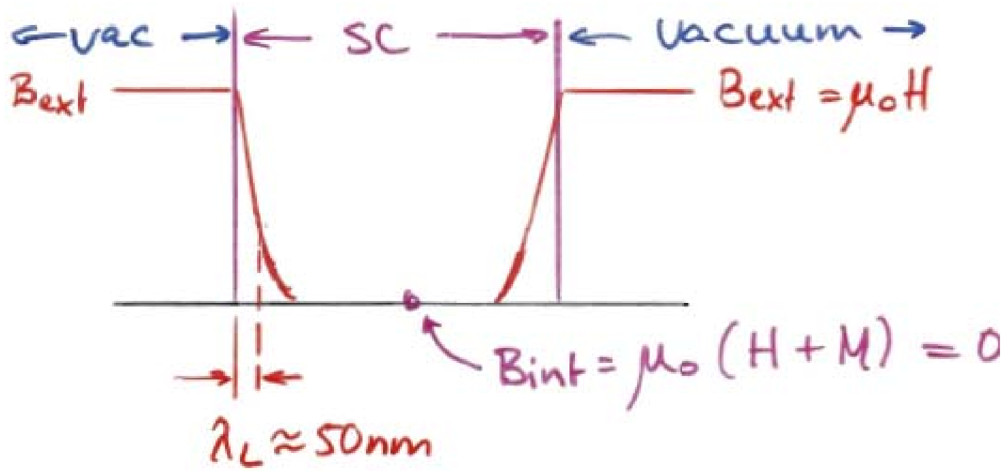
Meissner effect:

$B = \mu_0 (H + M) = 0$ inside supercond.

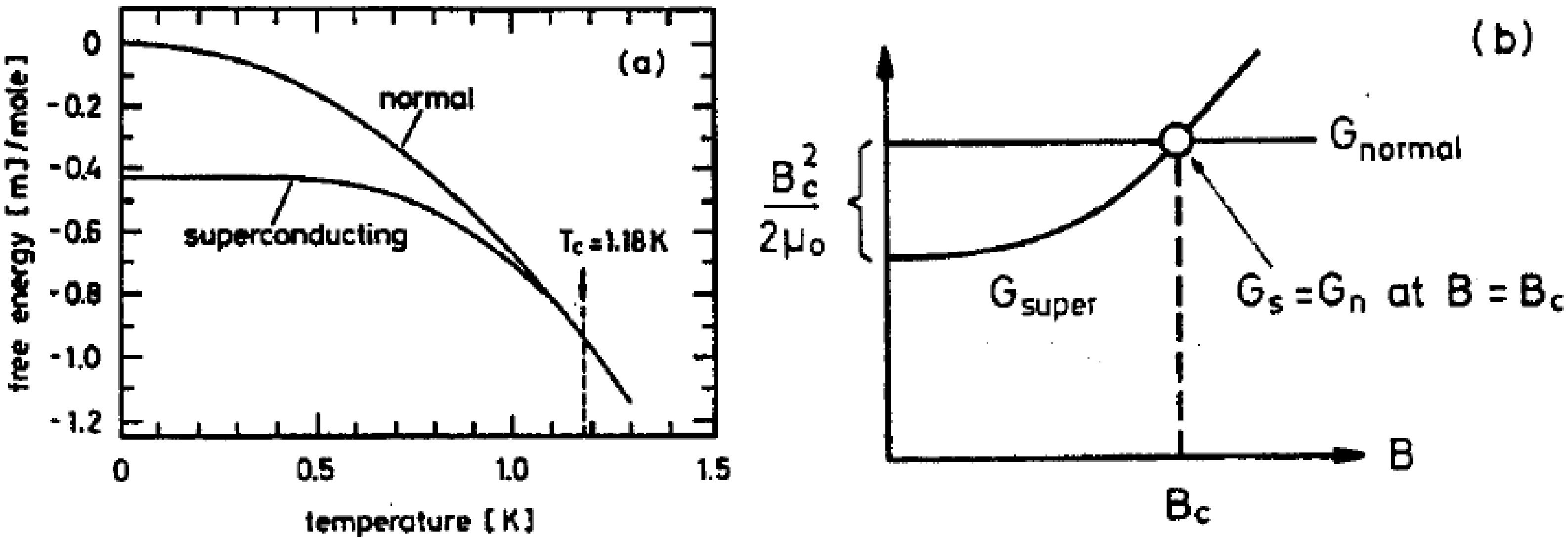
except for thin surface layer



$M = -H$ for $H < H_c$



Critical magnetic field of type I superconductor

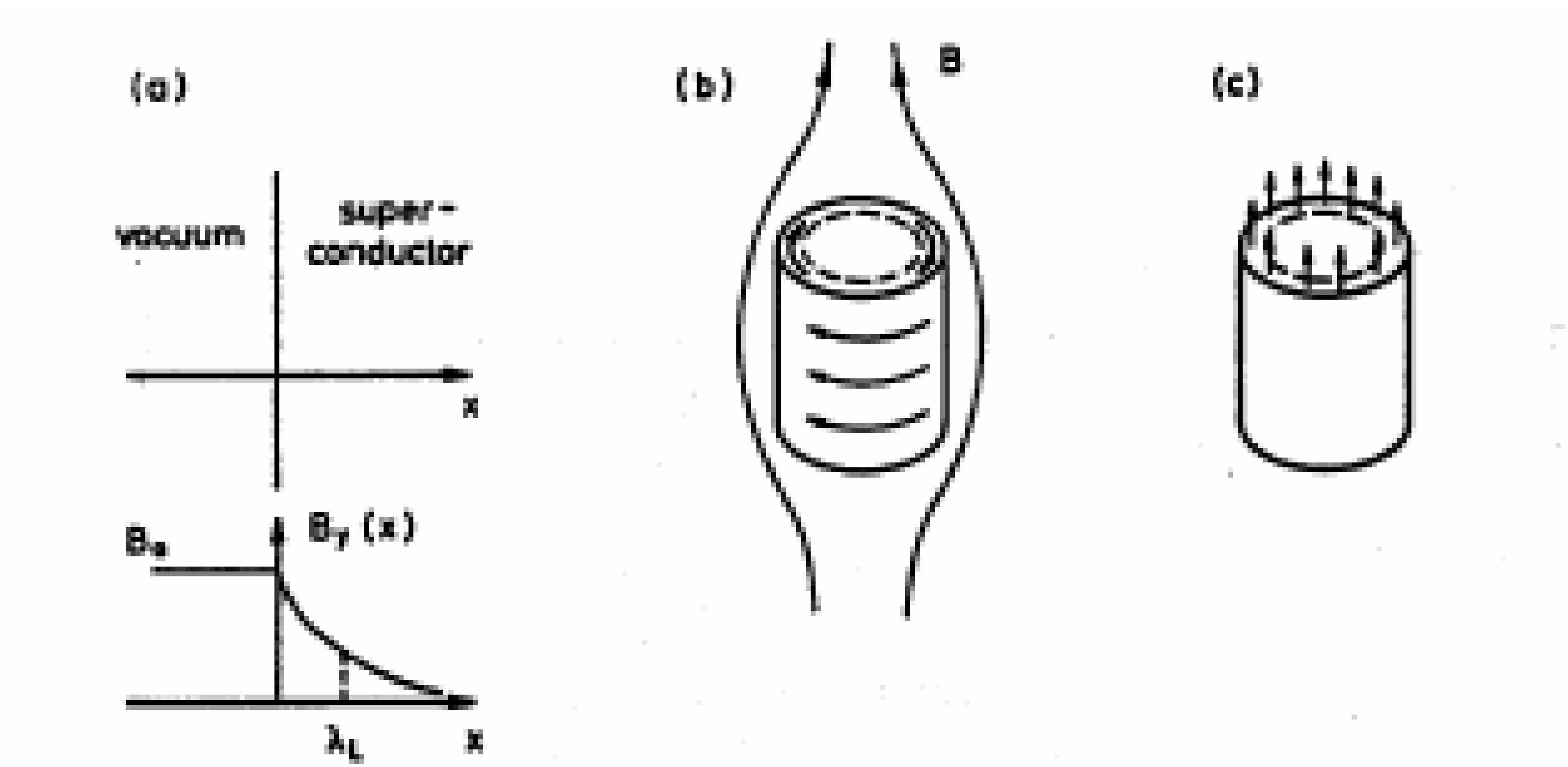


$$G_{sup}(H) = G_{sup}(0) + \frac{\mu_0}{2} H^2$$

$$\frac{\mu_0}{2} H_c^2 = G_{norm} - G_{sup}(0)$$

G is the Gibbs free energy

Is a type I superconductor good for magnets?

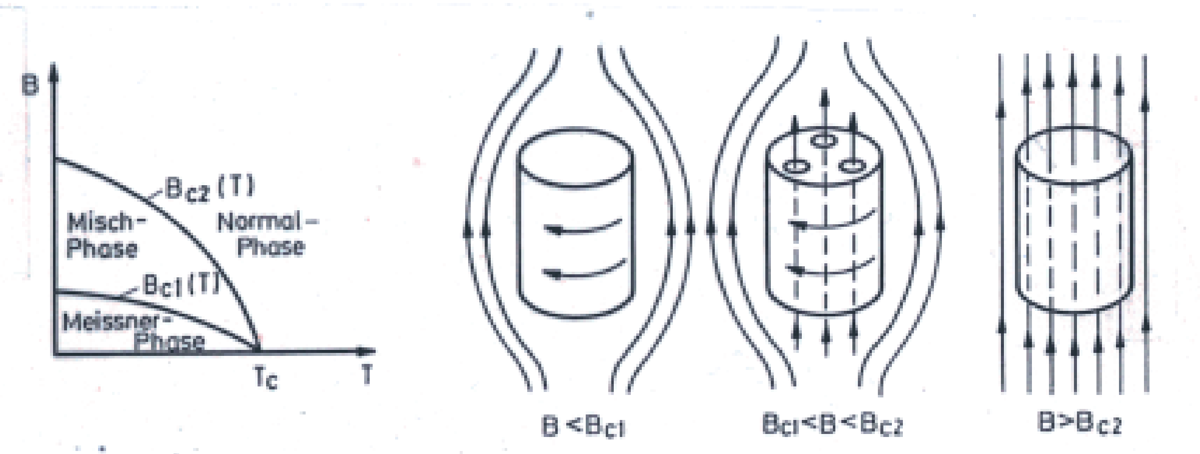


Answer: no

1) critical field too low: 0.08 Tesla in lead, the best type I conductor
2) current flows only in a 50 nanometer thin surface layer

Type II Superconductors

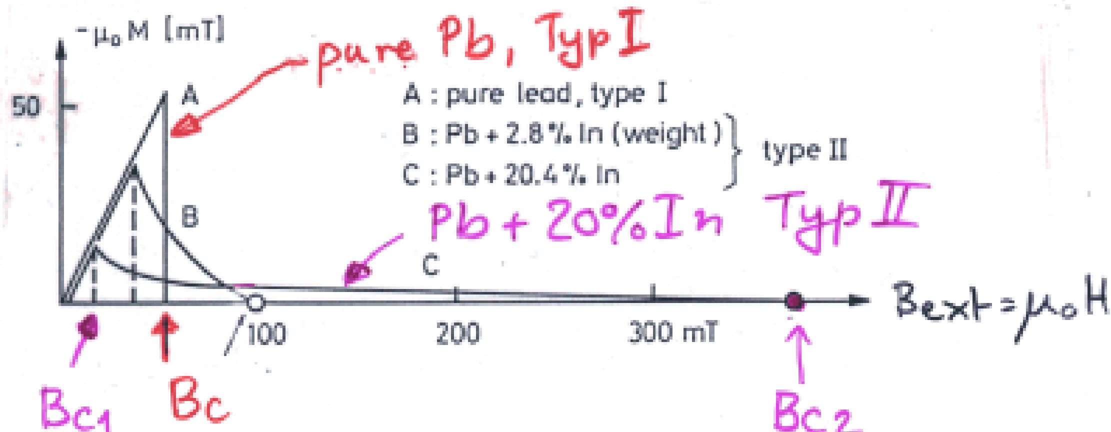
niobium, all alloys (NbTi, Nb_3Sn...)



2 critical fields

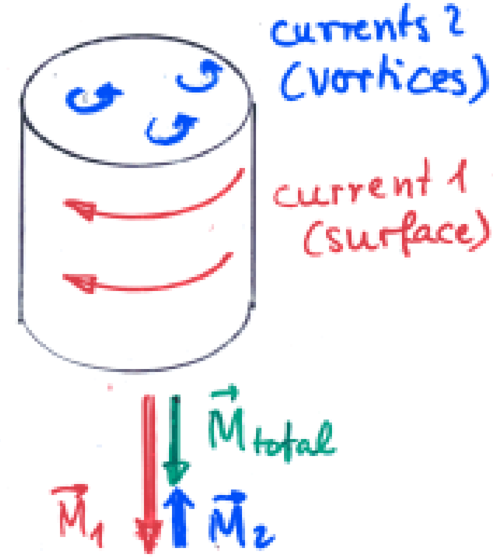
$B < B_{c1}$ Meissner phase

$B_{c1} < B < B_{c2}$ mixed phase

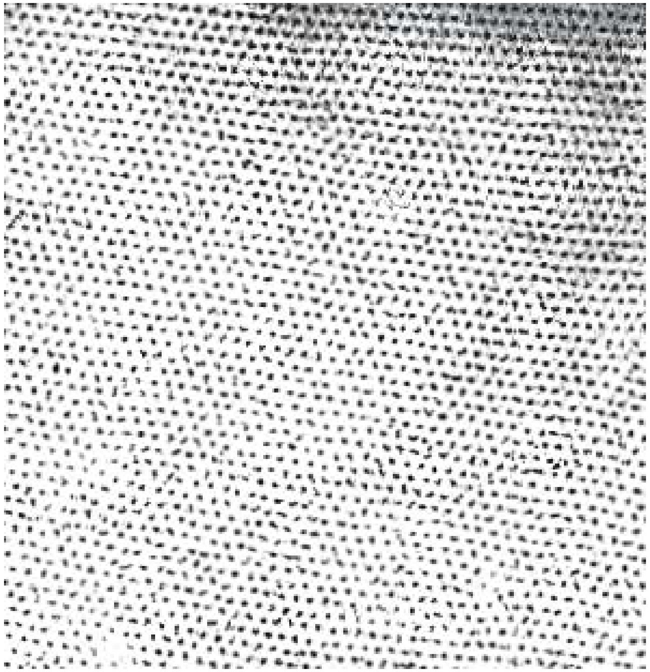


high B_{c2} : excellent for magnets

lower magnetization in mixed phase



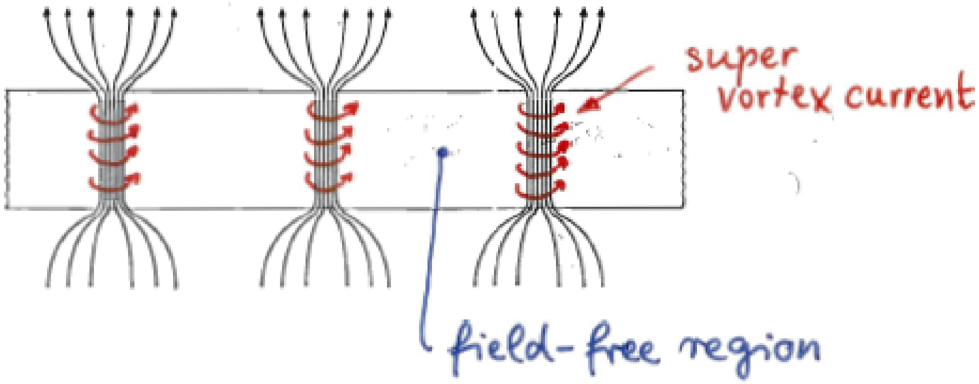
Magnetic flux through type II superconductor



Flux line lattice in niobium
U. Essmann, MPI Stuttgart

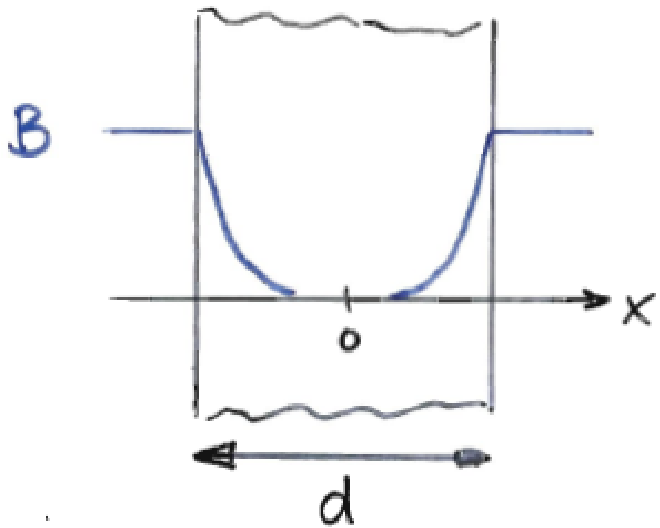
separation 0.2 μm

each flux line contains one
flux quantum h/2e



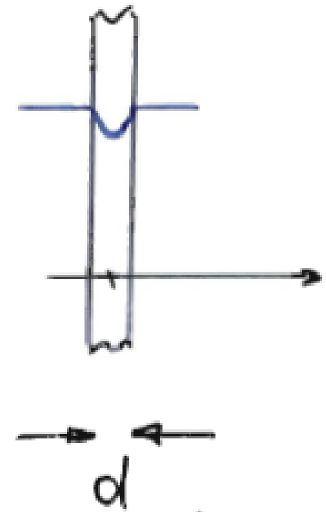
Distinction between type I and type II supercond.

Consider first a very thin sheet of type I s.c. in field parallel to the surface



thick slab : $d \gg \lambda_L$

$B = 0$ inside



very thin slab

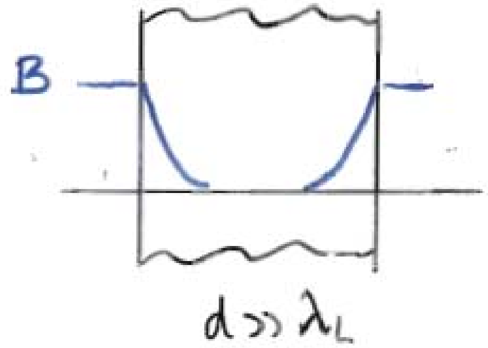
$d < \lambda_L$

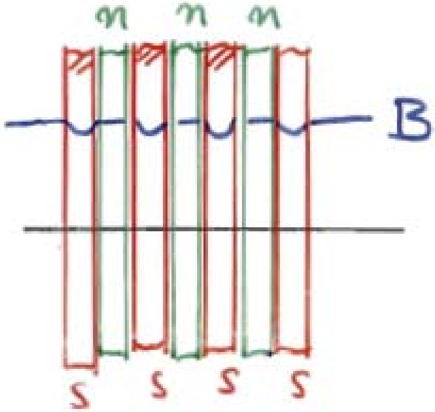
B no more zero at center

Since $B \neq 0$ in thin slab: less energy needed to expel field. This has two consequences:

(1) critical field $> B_c$ for thin slab

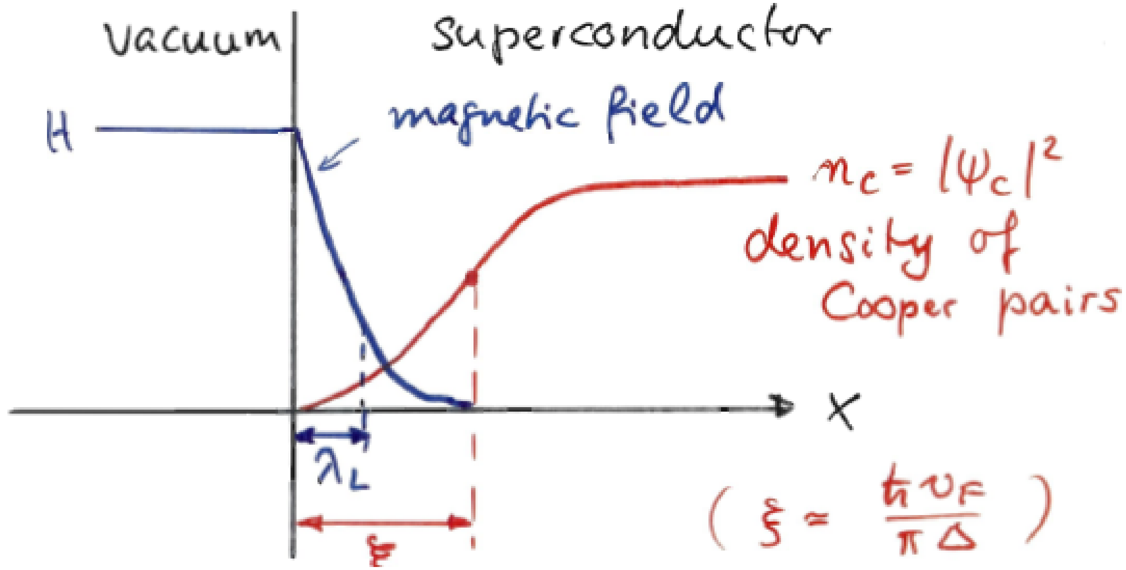
(2) it may appear energetically favourable to subdivide a thick type I s.c. into thin slices that are alternatingly normal and superconductive





Counterargument: a surface energy is associated with the subdivision which is larger than the gain in magnetic energy

Coherence length ξ



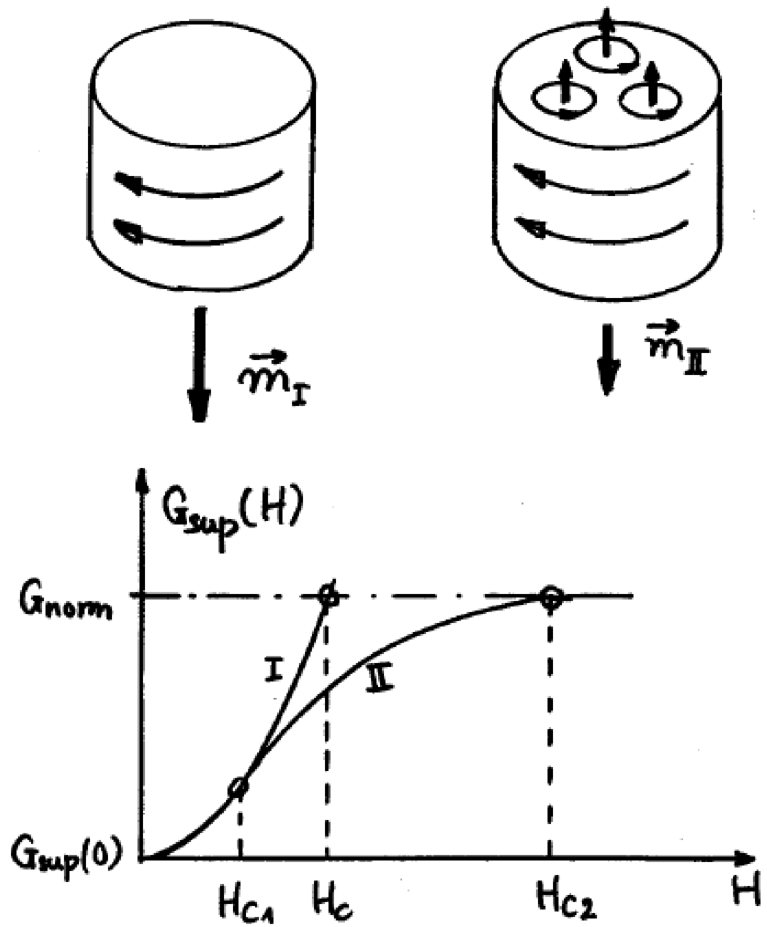
So a subdivision in alternating normal and s.c. layers is energetically favourable if the London penetration depth exceeds the coherence length.

Refined treatment : Ginsburg - Landau theory

$$K = \frac{\lambda_L}{\xi} < \frac{1}{\sqrt{2}} \quad \text{type I superconductor}$$

$$K = \frac{\lambda_L}{\xi} > \frac{1}{\sqrt{2}} \quad \text{type II} \quad \text{"}$$

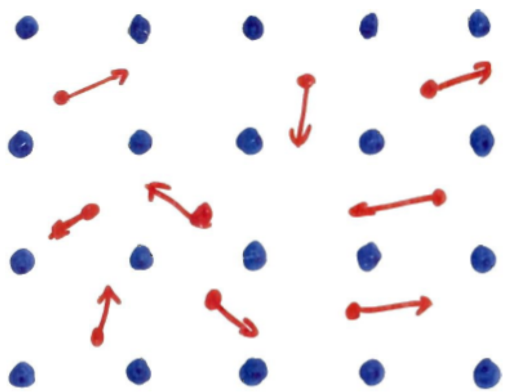
Critical magnetic fields in type I and type II superconductors



Basic ideas of Bardeen-Cooper-Schrieffer (BCS) theory

I. Electron gas in normal metals

Copper : Cu^+ ions form a regular lattice
1 conduction electron per atom



electrons move like gas molecules
random directions
($\sum \vec{v} = 0$)
$\Rightarrow$ no net current

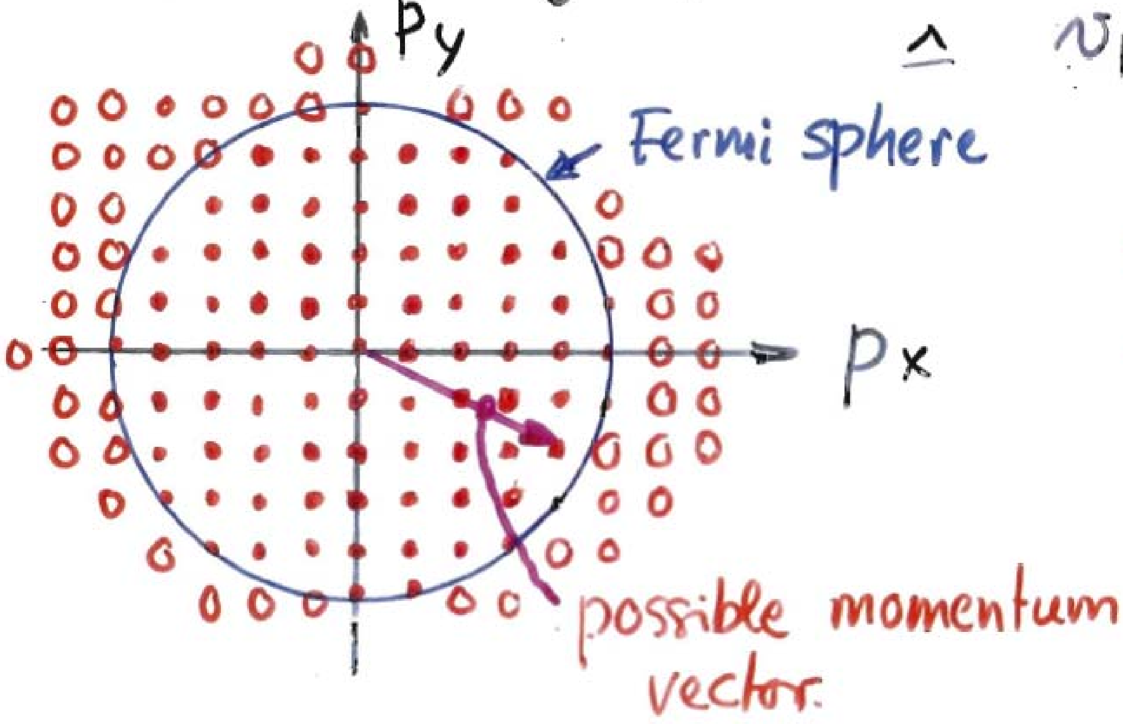
Important : application of Pauli exclusion principle (Fermi - Dirac statistics)

Important: application of Pauli exclusion principle (Fermi-Dirac statistics)

Electrons have very high energy (≈Fermi energy):

$$\frac{1}{2} m \overline{v^2} = \frac{3}{5} E_F \qquad E_F = 7\,eV \text{ for Cu}$$

$$\hat{=} \quad v_F \approx 1.6 \cdot 10^6 \, m/s$$



• occupied states

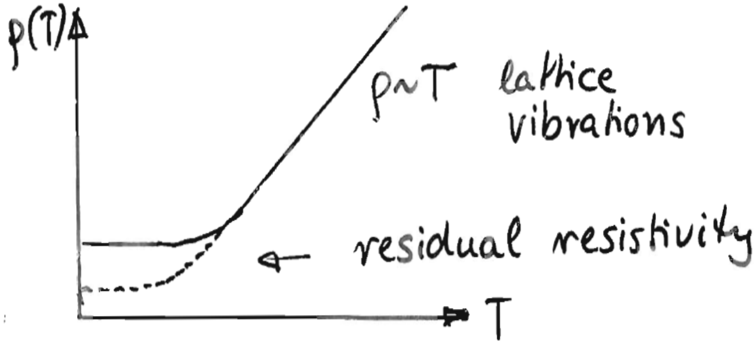
o free states

Origin of Ohm's law: collisions

Only the electrons near the Fermi sphere can be accelerated in an electric field because only these have free states in their vicinity.

Quantum theory: describe electrons by wave function. In an ideal lattice, these waves move without resistance.

$\Rightarrow$ $\rho = 0$ in an ideal crystal



Where does resistance come from?

Any irregularity leads to collisions

(a) foreign atoms or lattice defects

(b) thermal vibration of the atoms

Typical wave length of electrons

$$\lambda = \frac{2\pi\hbar}{m\, v_F} \simeq \text{lattice constant}$$

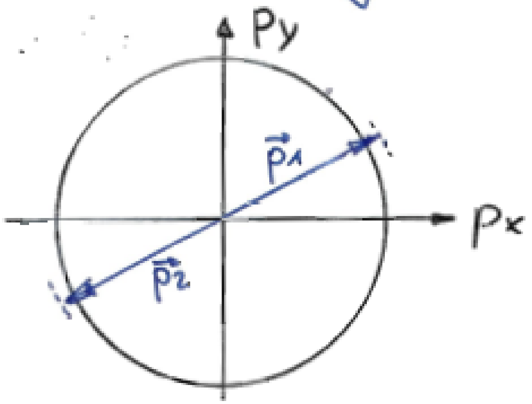
$(\simeq 0.5\,\text{nm})$

So for the "conduction" electrons a single foreign atom acts already as scattering center because λ is so small.

Cooper pairs

In a normal metal at $T \to 0$ all states inside the Fermi sphere are filled with electrons, all states outside are empty.

Cooper (1956): if there exists a weak attractive force between two electrons at or just outside the Fermi sphere, which have opposite momenta $\vec{p}_1 = -\vec{p}_2$ ($p_1 = p_2 \gtrsim p_F$), then these form a bound system whose energy is $< 2E_F$.



Cooper pair

$(\vec{p}_1 \Uparrow, -\vec{p}_1 \Downarrow)$

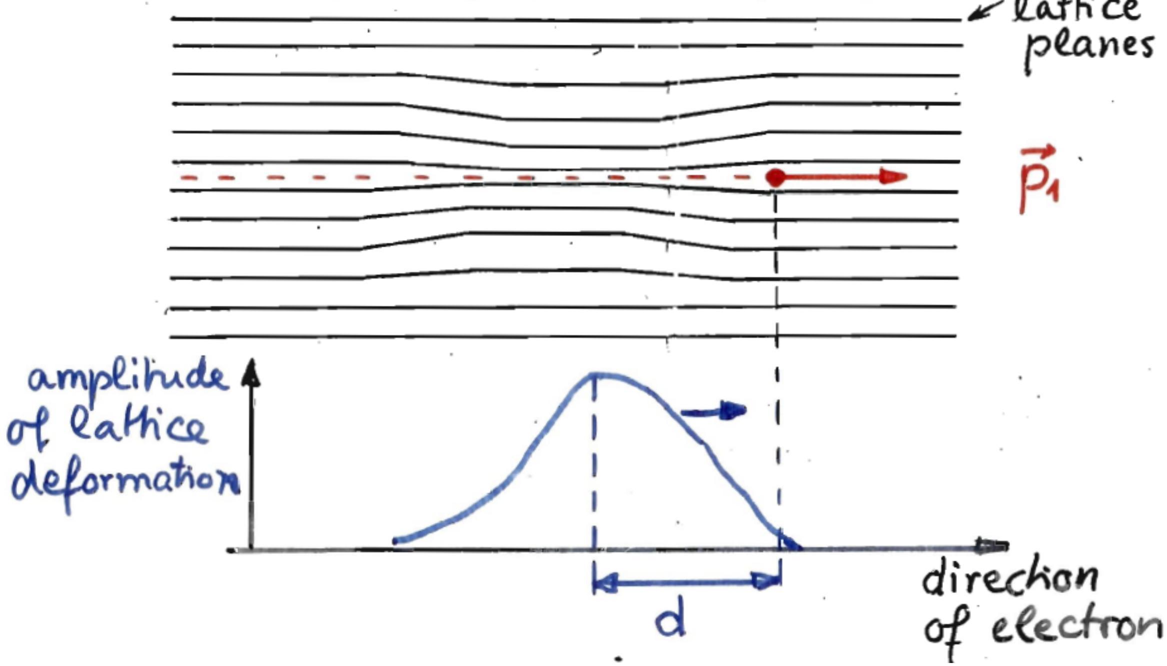
$\uparrow$ Spin

The binding energy is very small ($\sim 10^{-4}$ eV $\ll E_F$) so the two electrons are far apart in the metal. Their Coulomb repulsion is shielded but how does the attraction come about?

Interaction between electrons via lattice deformation (phonon exchange)

Schematic view of lattice deformation

(Ibach, Lüth, Festkörperphysik)



The first electron attracts the positive ions along its path. Because of its high velocity $v \approx v_F \approx 10^6\,m/s$ the ions do not respond immediately but at best with the highest lattice vibration frequency, the Debye frequency.

Consequence: the maximum lattice deformation lags behind the electron by a distance

$$d \approx v_F \cdot \left(\frac{\omega_D}{2\pi}\right)^{-1} \approx 100\ nm\ (= 1000\ \mathring{A})$$

Lattice deformation has strongest attraction for second electron if :

(a) electron 2 is flying in the same direction as electron 1

($\vec{p}_2 = \vec{p}_1$ seems best , but $\vec{p}_2 = -\vec{p}_1$ not so bad either)

(b) distance between e_1 and e_2 $\approx d = v_F \frac{\omega_D}{2\pi}$

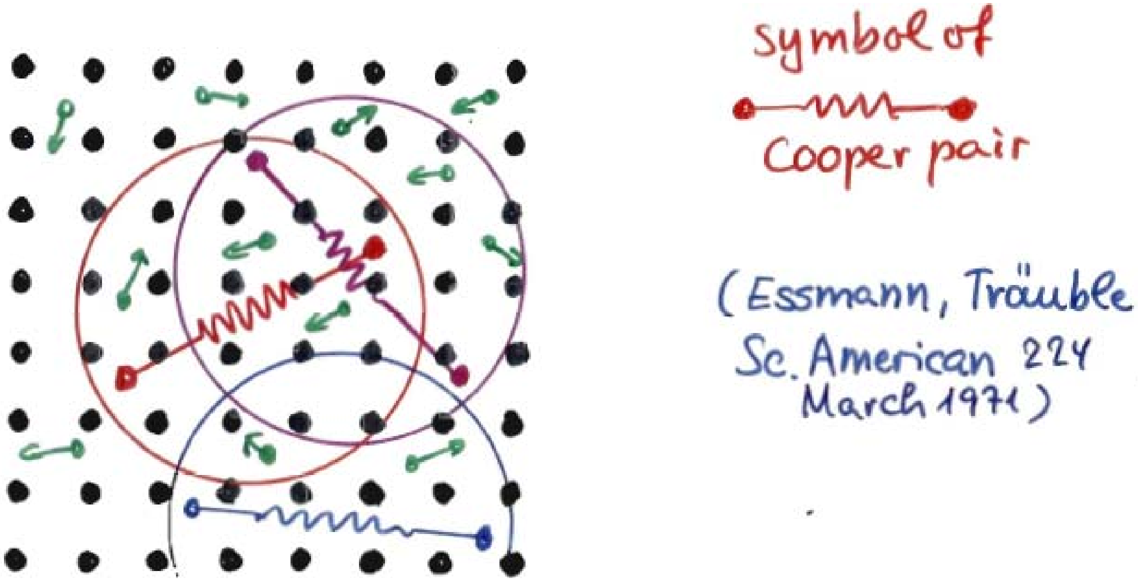
Quantum theory plus Pauli principle require

$\vec{p}_2 = -\vec{p}_1$ and spins antiparallel

(I don't know any intuitive argument for this).

According to the lag between the first electron and the lattice deformation one expects a large extension of a Cooper pair, ≈ 1000 Å or about 200 lattice constants.

Intuitive picture of Cooper pairs



(Essmann, Träuble
Sc. American 224
March 1971)

Obviously, Cooper pairs are no well-defined and separated particles. In the volume occupied by a Cooper pair there ≈ a million other electrons or Cooper pairs.

BCS : the electrons in Cooper pairs frequently change partners. Possible because of strong overlap.

III. Main results of the BCS theory

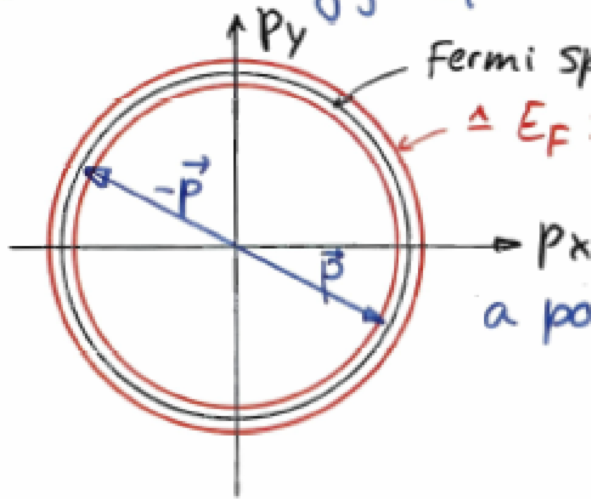
The Cooper pair attraction is provided by lattice vibrations.

Maximum energy of a phonon

$$\varepsilon \equiv \hbar\omega_D = k_B \cdot \Theta_D \quad \approx 0.01 - 0.02\ \mathrm{eV}$$

(Θ_D Debye temperature, k_B Boltzmann constant)

Only the electrons in a shell of $\pm\,\varepsilon$ around the Fermi energy E_F can be paired.



Fermi sphere, $\vec{p}^{\,2}/2m = E_F$

$\hat{=}\ E_F \pm \hbar\omega_D$

a possible Cooper pair

At $T \to 0$ all electrons in this shell condense into Cooper pairs ($T = 4.2\,K$: unpaired electr. exist)

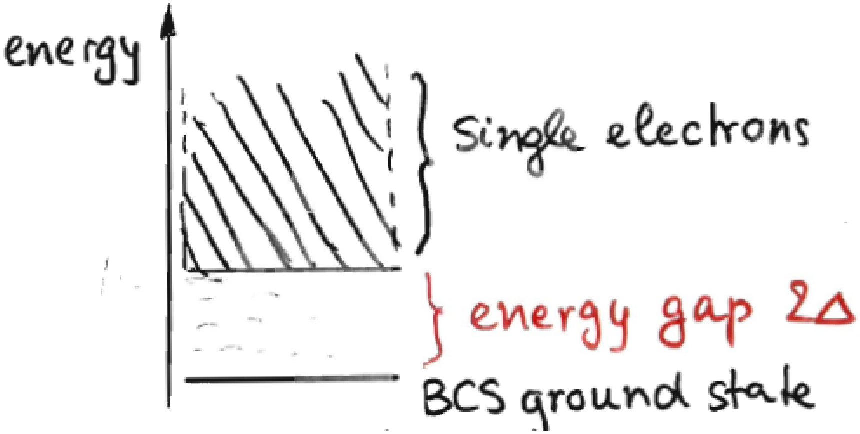
Cooper pair : momentum $\vec{P} = \vec{p} - \vec{p} = 0$

In a vanishing electric field, all Cooper pairs have momentum $\vec{P} = 0$. They can be described by a macroscopic wave function ψ, similar to a radio wave.

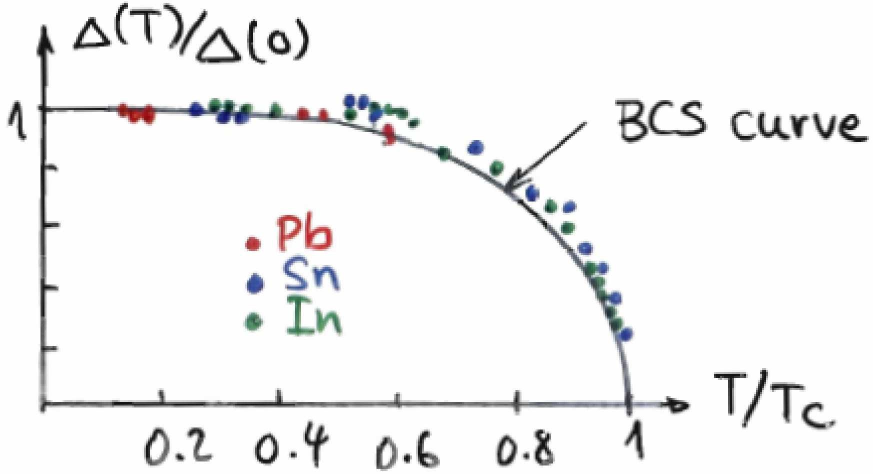
This is the BCS ground state.

The ground state energy is lower by an amount 2Δ (per pair) than the energy levels of unpaired electrons.

There exists no excited Cooper pair state.



Energy gap depends on temperature **(difference to semiconductors)**



Important formulas

$$\Delta = \Delta(0) = 2\hbar\omega_D \exp\left(-\frac{1}{V_{latt.} \cdot N(E_F)}\right)$$

$V_{lattice}$ = interaction potential of lattice vibrations

$N(E_F)$ = density of single electron states at E_F

$$k_B T_C = 1.14 \cdot \hbar\omega_D \cdot \exp\left(-\frac{1}{V_{latt} \cdot N(E_F)}\right)$$

$$\Rightarrow \boxed{\Delta(0) = 1.76 \cdot k_B T_C}$$

relation between energy gap and critical temperature

element	Sn	In	Tl	Ta	Nb	Hg	Pb
$2\Delta(0)/k_B T_c$	3.5	3.5	3.6	3.5	3.5	4.6	4.3

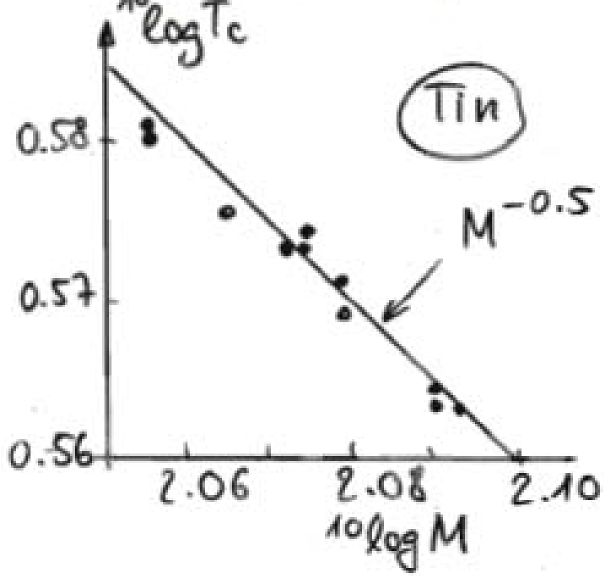
So generally very good agreement with BCS value 3.5.

(2Δ measured by tunnel experiments, ultrasound or light absorption)

Are lattice vibrations really responsible?

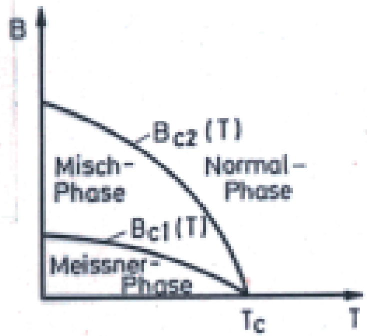
$$T_c \propto \omega_{Debye} \propto \frac{1}{\sqrt{M}} \qquad M = \text{Mass of ion}$$

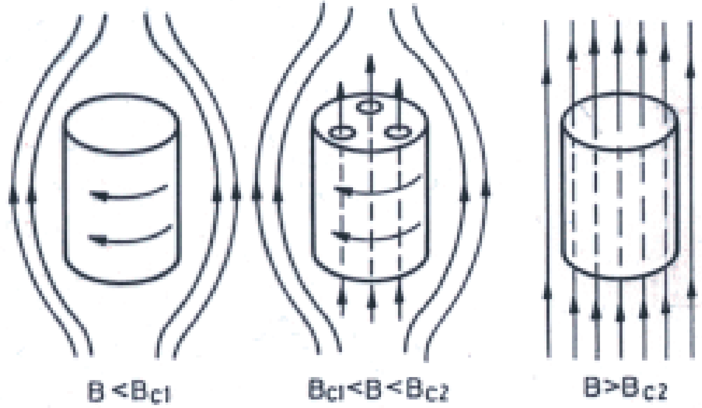
Compare different isotopes



Type II Superconductors

niobium, all alloys (NbTi, Nb_3Sn...)

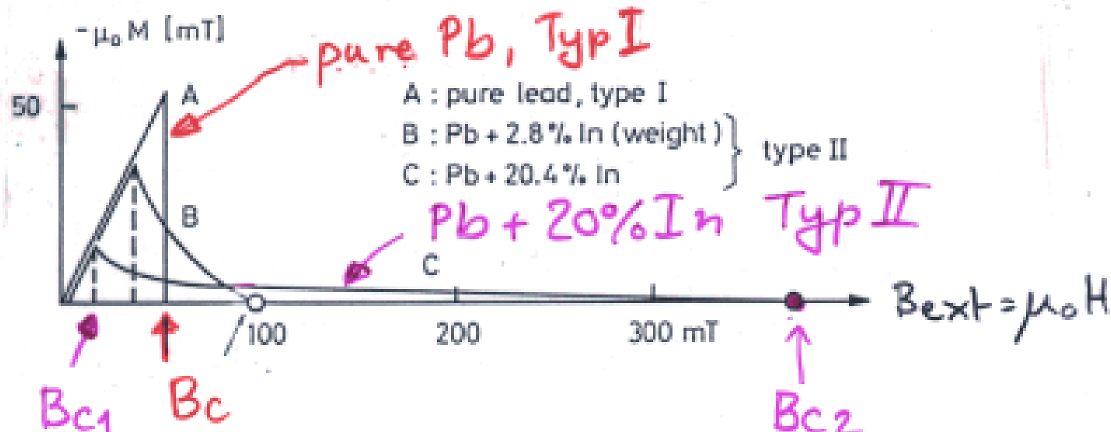




2 critical fields

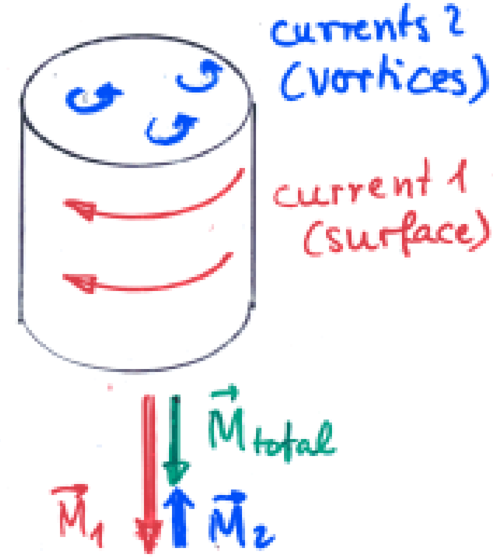
$B < B_{c1}$ Meissner phase

$B_{c1} < B < B_{c2}$ mixed phase



high B_{c2} : excellent for magnets

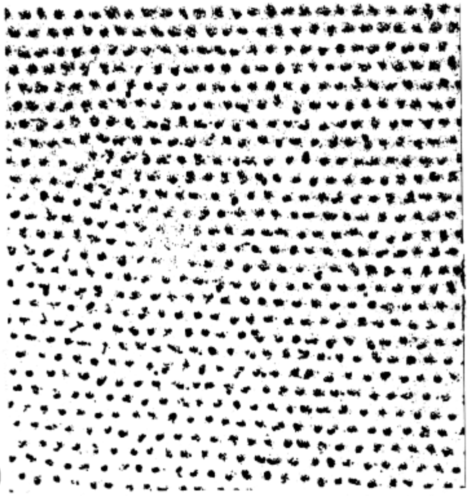
lower magnetization in mixed phase



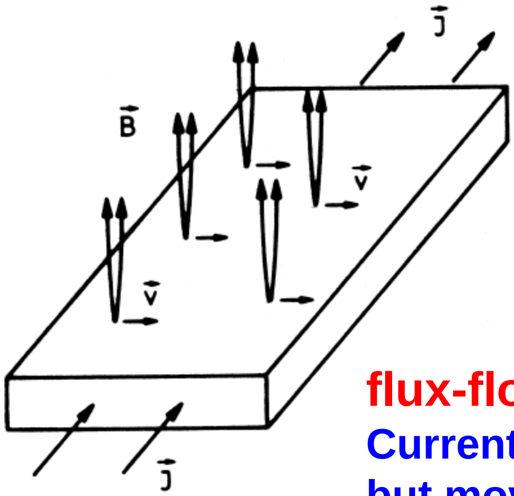
Hard superconductors: type II superconductors with strong flux pinning

magnetic flux tube pattern

(a)



(b)



flux-flow resistance

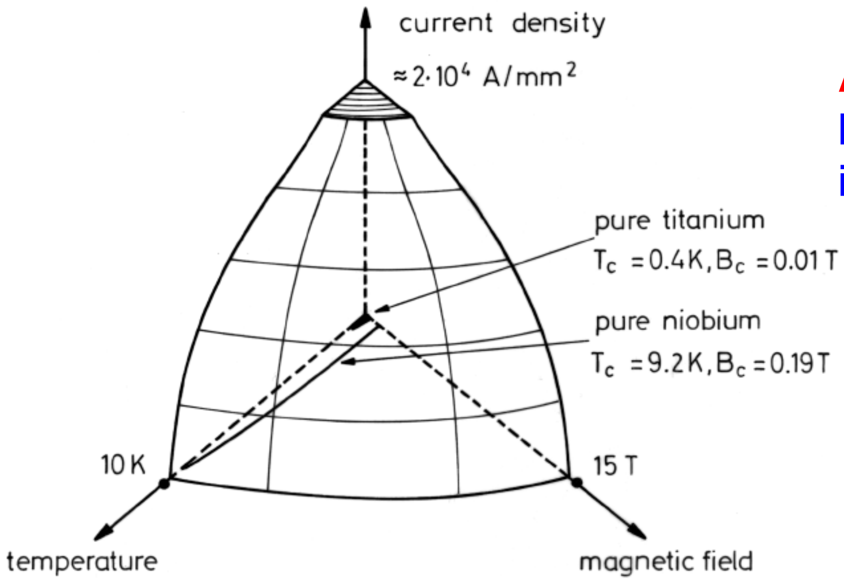
Current flows without resistance
but moving flux tubes produce heat

Pinning centers inhibit flux tube motion

Most effective pinning centers in NbTi are
normal-conducting Ti precipitates
(the micron-size white „worms“ in the micrograph)

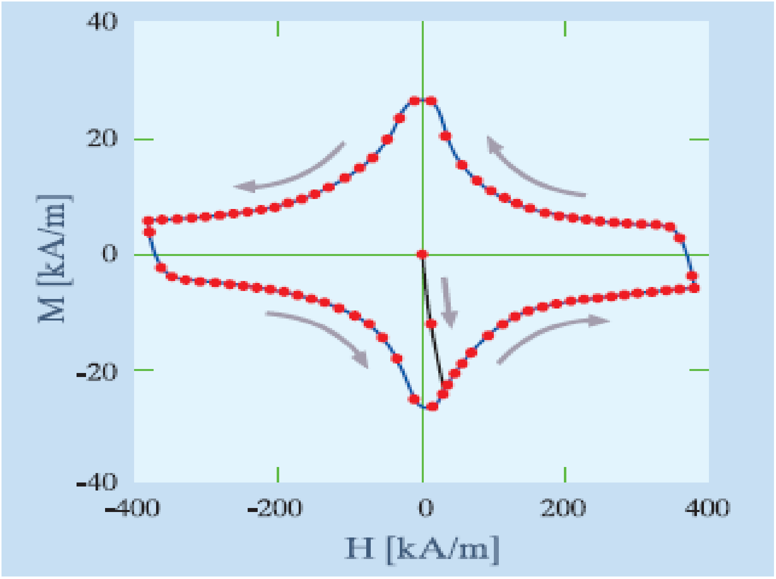
Micrograph of niobium-titanium
Larbalestier et al., Univ. of Wisconsin

Niobium-titanium: the standard superconductor for magnets



Advantage of strong flux pinning:
high current can flow without any dissipation in the presence of a large magnetic field

current density > 2500 A / mm²
at 4.5 Kelvin and 5 Tesla



Disadvantage of strong flux pinning:
magnetic hysteresis similar to ferromagnet

enclosed area is dissipated heat

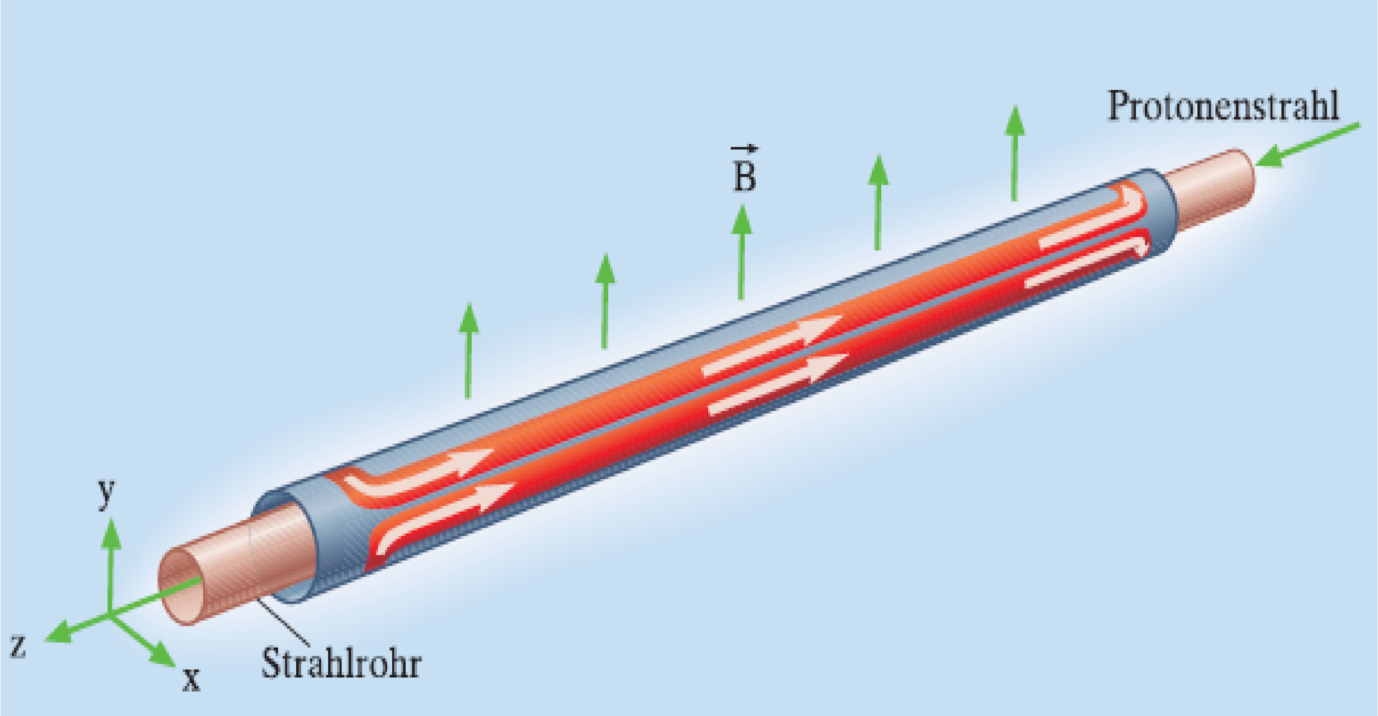
Conclusion:

hard superconductor is good for dc magnets but bad for microwave cavities

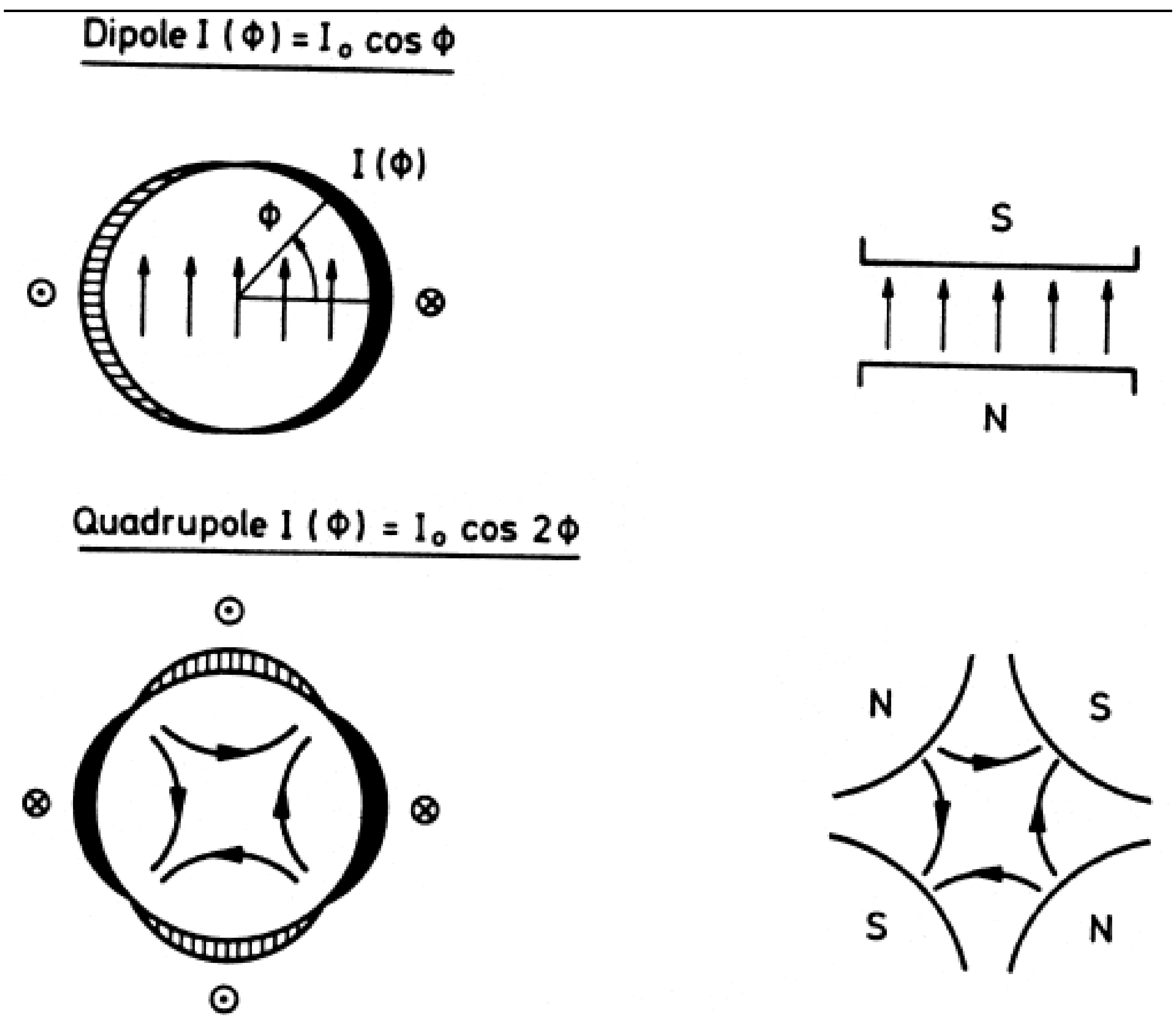
5 - 8 Tesla superconducting accelerator magnets

In contrast to conventional electromagnets these magnets are current-dominated.
Desired field pattern is generated by suitable arrangement of conductors.
Iron yoke plays minor role. Coil must be extremely precise.

schematic view of superconducting dipole



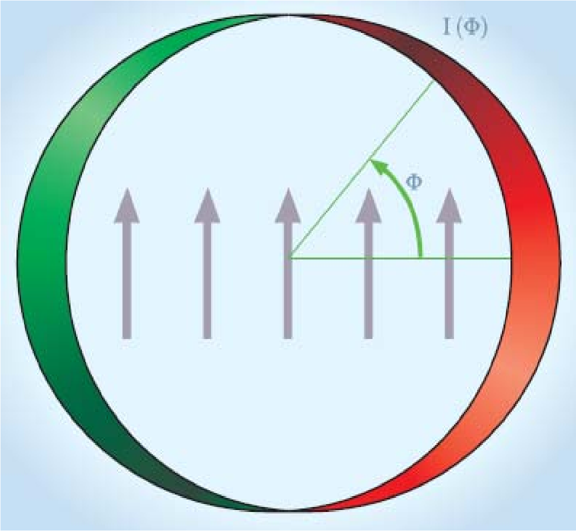
Generation of pure dipole and quadrupole fields by current distributions $I(\phi) = I_0 \cos(n\,\phi)$ with n=1 resp. n=2



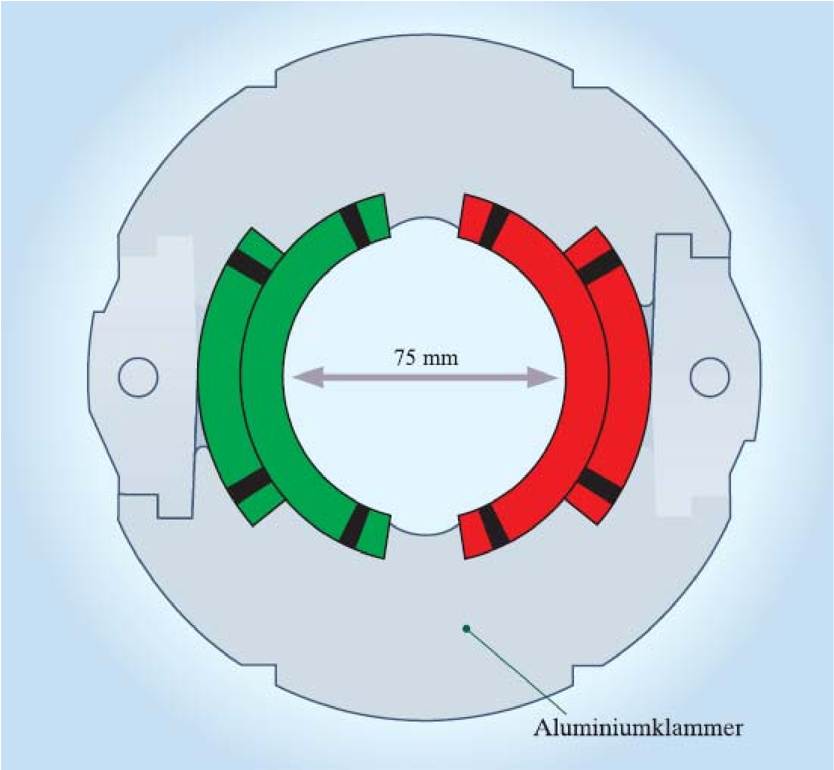
Cross section of dipole coil

pure dipole field

$I(\phi) = I_0 \cos(\phi)$



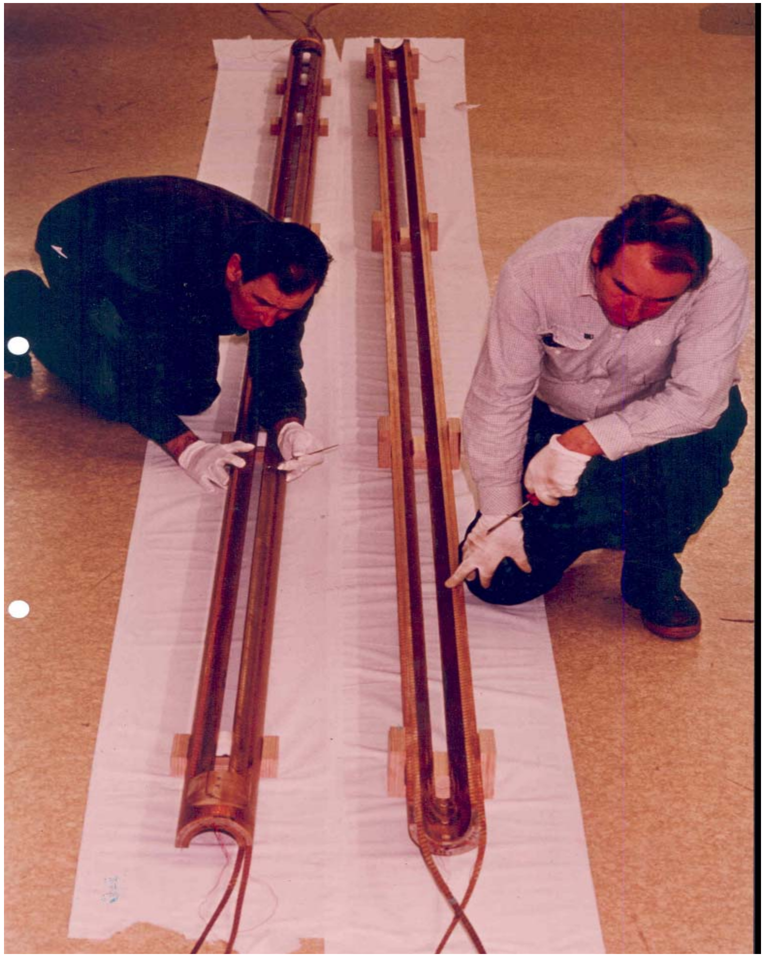
Cross section of the HERA dipole coil



Very strong clamps define precise coil geometry and sustain huge Lorentz forces (>100 tons per meter)
Field errors less than 0.01%

Dipole coil winding at DESY with professional tooling

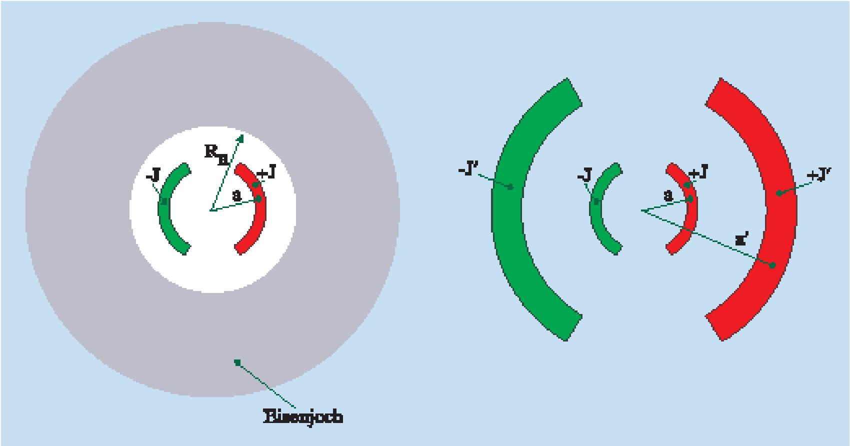
Winding of 6 m long dipole half-coils in DESY Hall 3



This winding machine was later shipped to BBC Mannheim

Iron yoke: cylindrical inner bore

use method of image currents to compute field

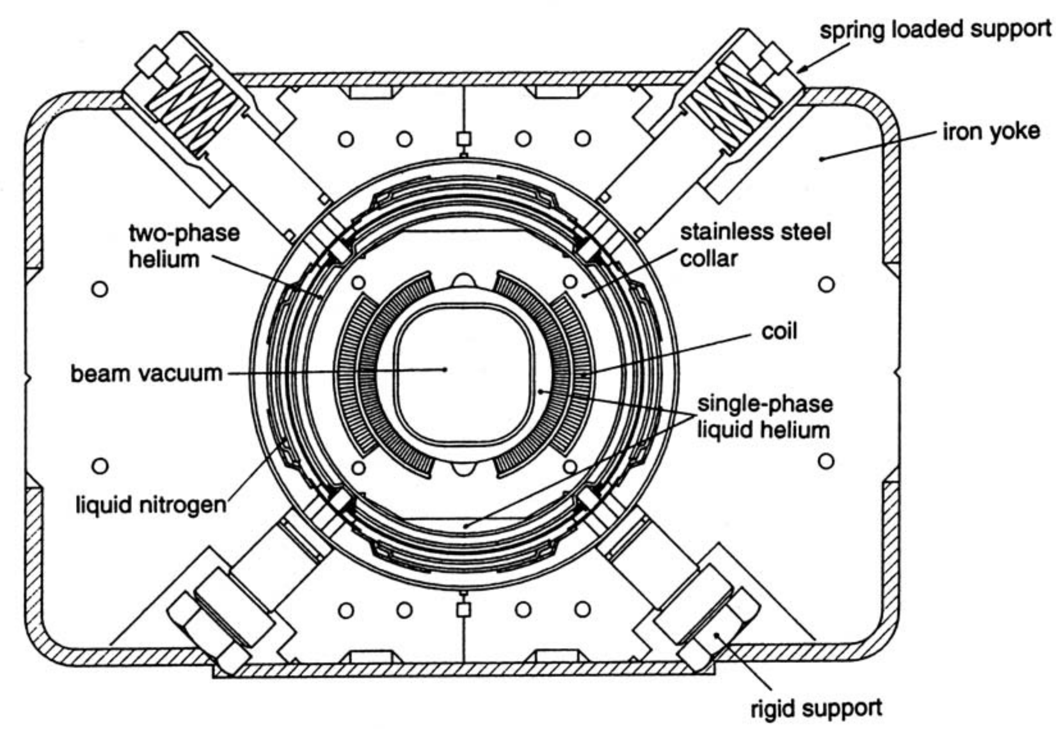


Important:

unsaturated yoke

increases dipole field

preserves field quality



Tevatron dipole

warm yoke surrounding cryostat

field enhancement about 10%

This was the initial magnet design for HERA

Very demanding task: quench protection system

(at DESY K.-H. Mess, R. Bacher and others)

In case of a quench (transition to normal-conducting state):
5000 A current must be reduced to zero in a fraction of a second to prevent destruction of the coil

But: In a long string of magnets the current must be reduced to zero in a much longer time (about 20 s in HERA) to avoid excessive inductive voltages (tolerable induced voltage is 1000 V)

Solution: current is guided around the quenched coil.
At HERA, the bypass is provided by a „cold diode“ mounted inside cryostat.

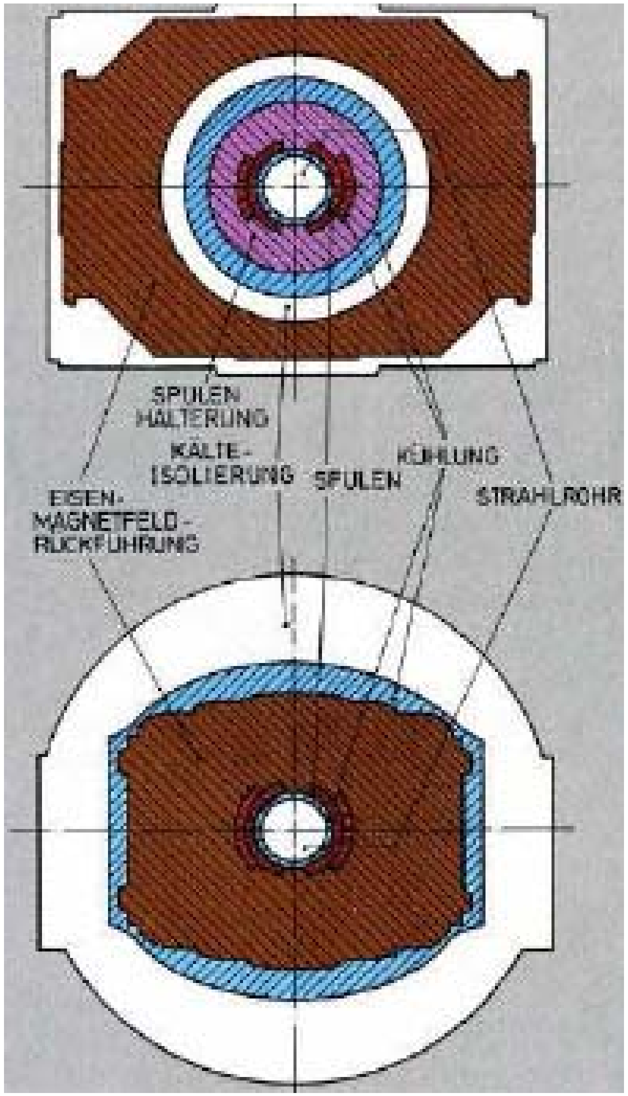
This is a „passive system“ like an automatic safety valve in a steam engine.
No electronics, thyristor switches or computer action are needed.

Each HERA magnet can absorb ist own stored field energy of about 1 MegaJoule

Very important: fast detection of quench, triggering of quench heaters to spread energy along the whole coil, controlled run-down of current.

An important decision for HERA in spring 1984

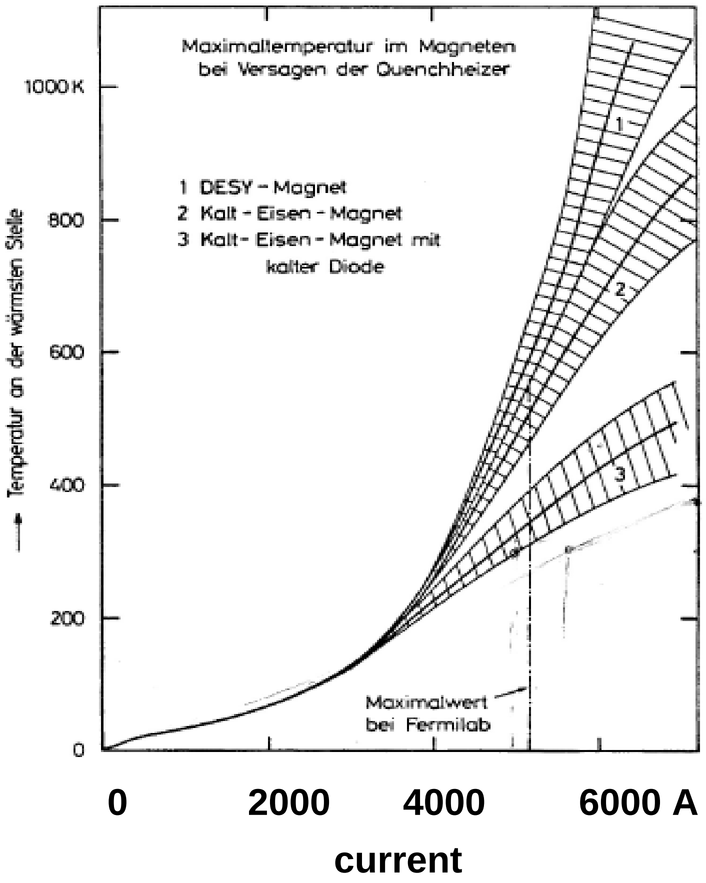
Two development lines for superconducting dipoles in early 1984



warm-iron dipole a la Tevatron
designed and produced at DESY

cold-iron dipole a la Brookhaven
designed and produced at BBC Mannheim
(Dr. C.-H. Dustmann)

Quench safety considerations (K.-H. Mess, PS, January 1984)



Maximum coil temperature after a quench
in case of failing quench heaters

DESY magnet 1000 Kelvin
BBC magnet 850 Kelvin

BBC magnet with cold diode 500 K

Temperatures above 700 K very dangerous
Only cold-iron magnet can be protected by cold diode bypassing the current

Strong recommendation by K.-H. Mess, PS:

Use cold-iron magnet

The „hybrid“ magnet

K. Balewski (diploma thesis), H. Kaiser, PS

Ein Kalt-Eisen-Magnet mit Aluminium-Klammer

K.Balewski, H.Kaiser, P.Schmüser

2. Beschreibung des Hybridmagneten

Die guten Erfahrungen mit den aluminiumgeklammerten Dipolspulen bei DESY legen es nahe, ein Magnetkonzept zu untersuchen, bei dem eine solche Spule direkt von einem kalten Eisenjoch umgeben ist. Abb. 1 zeigt einen Vorschlag für einen solchen "Hybridmagneten"; es wird die DESY-Spule mit geringfügig geänderter Geometrie verwendet.

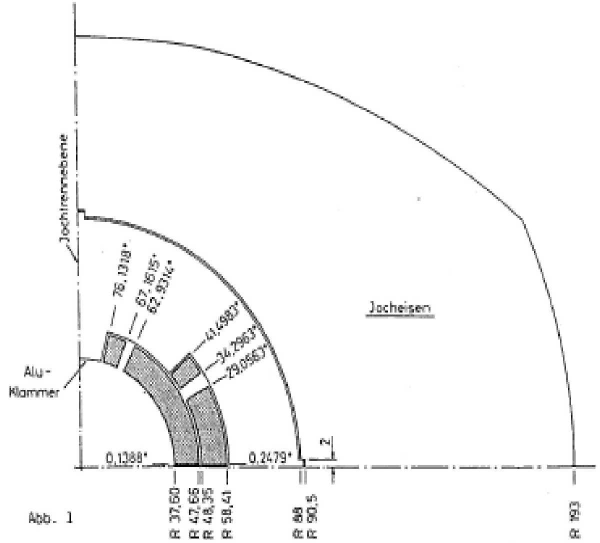
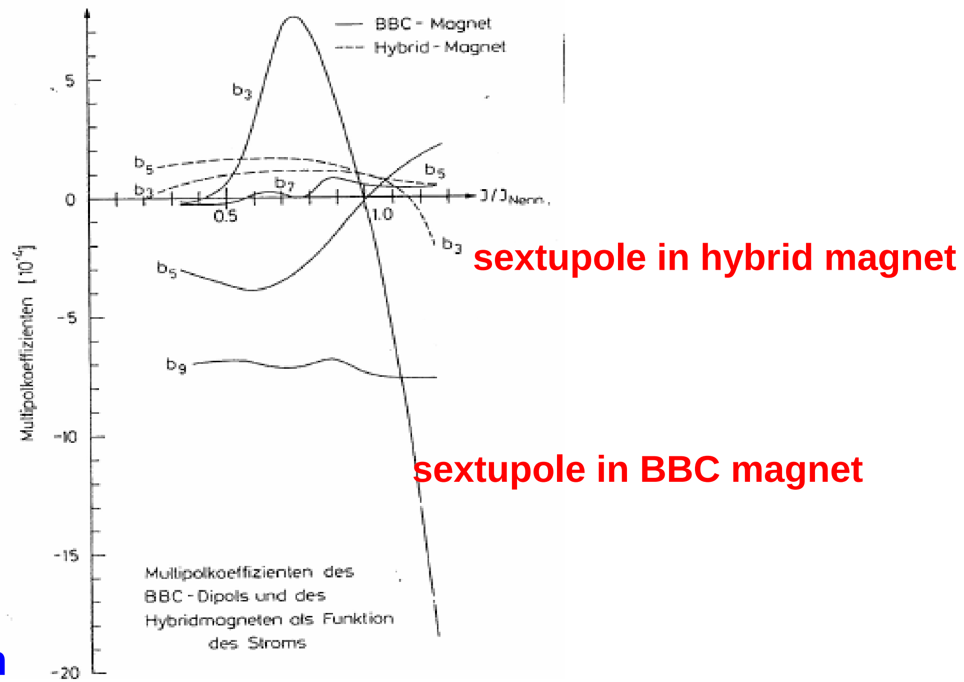


Abb. 1

Cold-iron dipole suffers from strong yoke saturation
field quality very bad above 4 Tesla

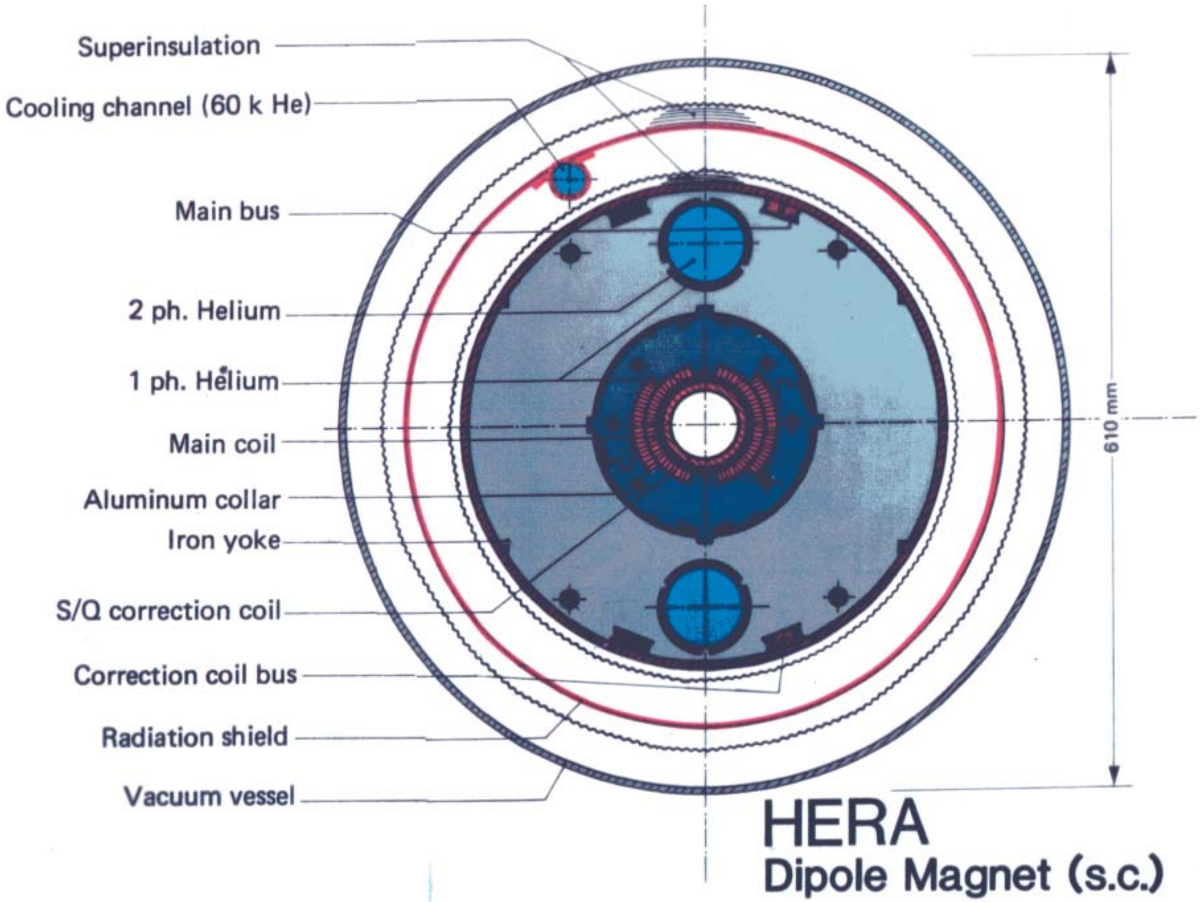


Basic idea:

surround Al-collared coil of DESY design with iron yoke inside cryostat

The HERA Dipole

Coil is confined and pres-stressed by non-magnetic clamps
The collared coil is surrounded with an iron yoke inside the cryostat



iron yoke contributes 22% to dipole field

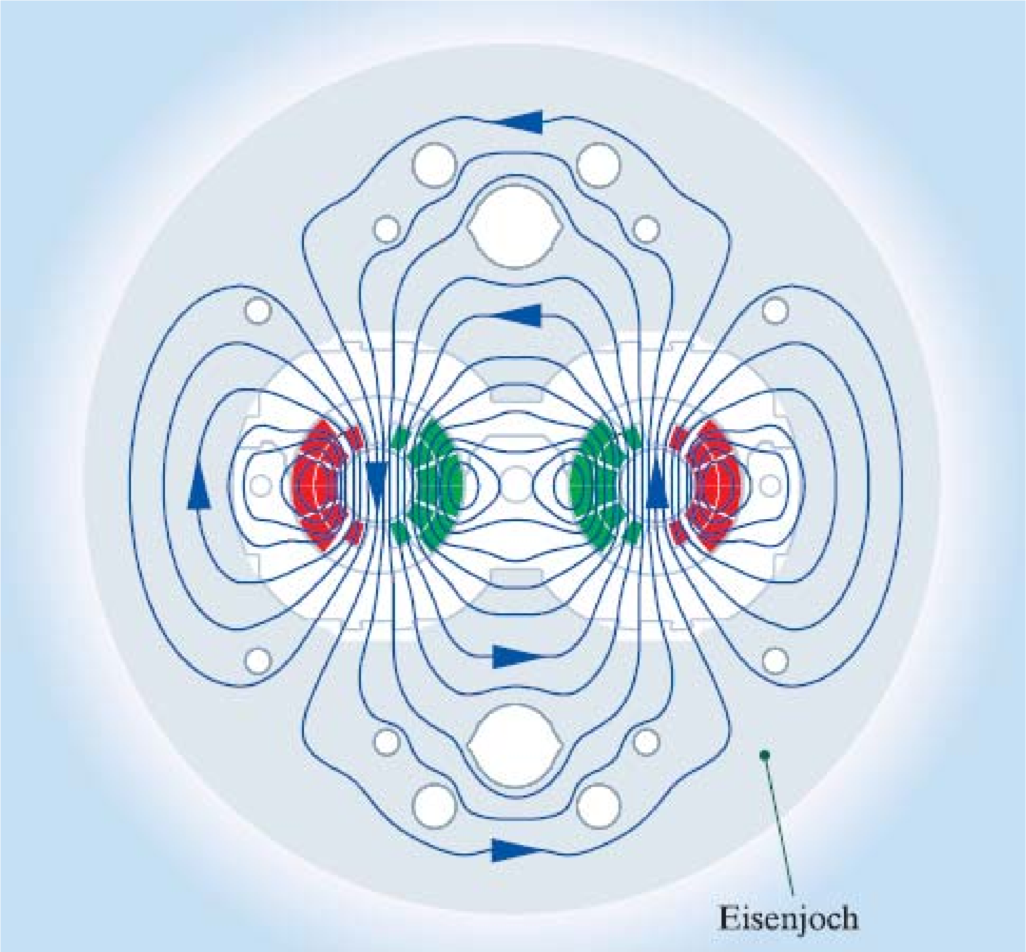
field errors below 0.01%

Only disadvantage:
large cold mass

Hybrid design cheaper than warm-iron design because of its much simpler cryostat

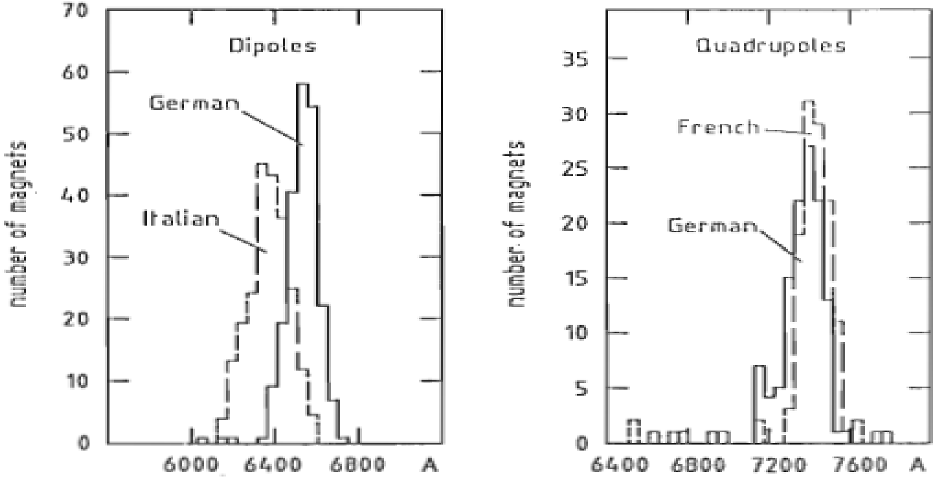
The twin-aperture LHC magnet

impossible with warm iron yoke



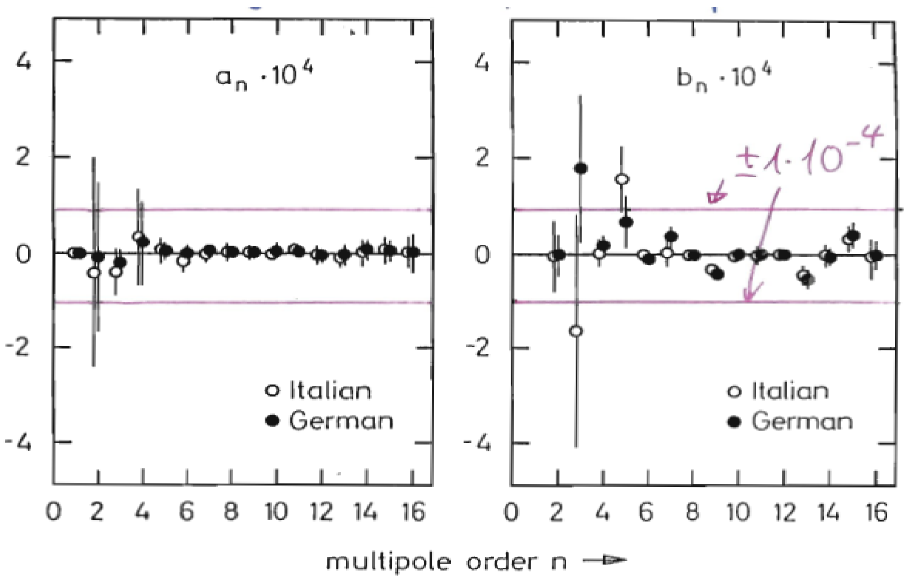
Remark: the iron yoke goes partly into saturation. The field line pattern inside the iron is computed numerically.
Courtesy S. Russenschuck, CERN

Excellent performance of HERA dipoles and quadrupoles



all dipoles exceed nominal current of 5000 A by 25%

quadrupoles go even higher



multipoles of 440 dipoles all within specified limits

Exception: sextupole, decapole these are compensated by correction coils

The tolerable field errors were determined in elaborate „dynamic aperture“ calculations by F. Schmidt (PhD thesis), F. Willeke and F. Zimmermann (PhD thesis)

Installation work in the HERA tunnel

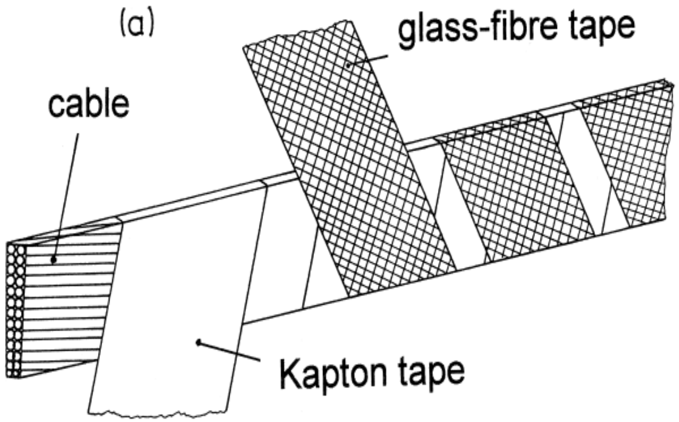
Two of our excellent technicians:
Gerd Tödten, Jürgen Holz

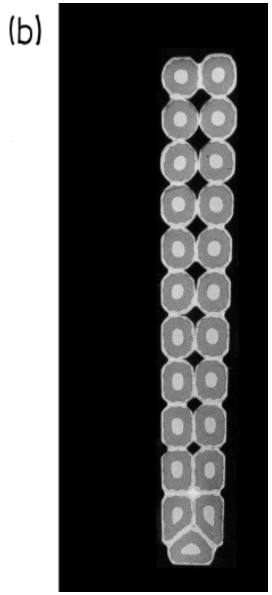
QY 518 is a superconducting quadrupole

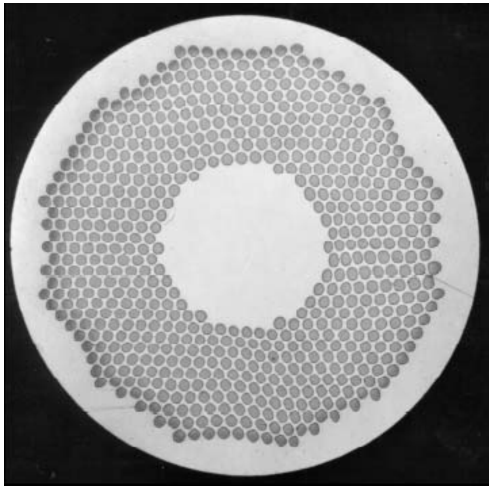
Below: module of electron ring
Sextupole, quadrupole and dipole
Design: H. Kaiser

Jürgen Holz and his people made all superconductor solder connections with extreme care, not a single failure

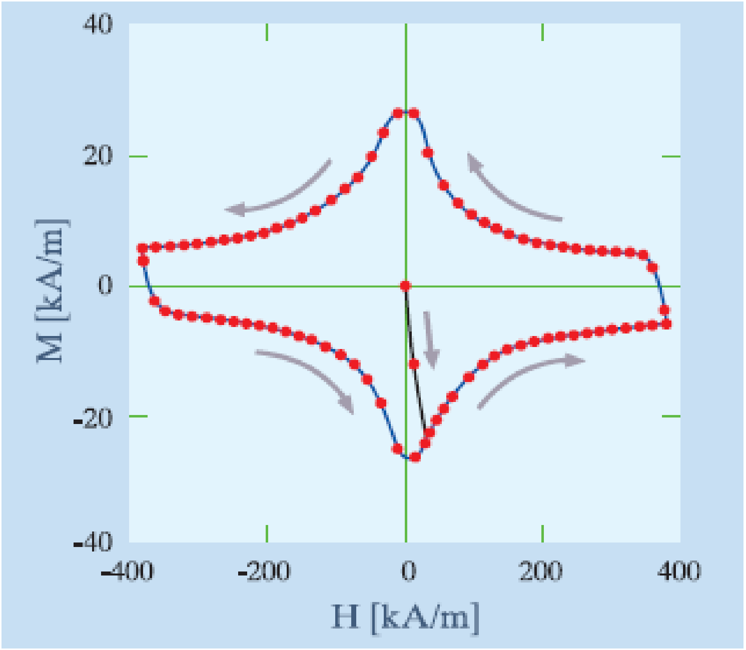
The superconducting cable



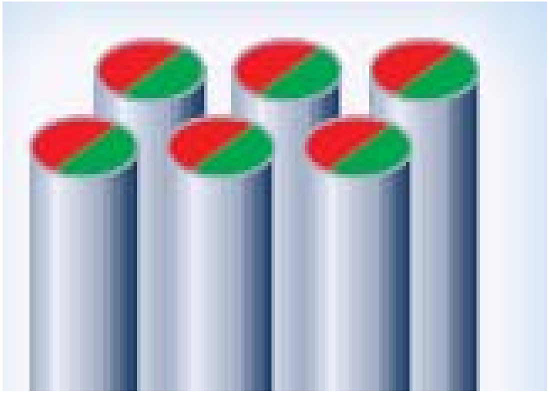




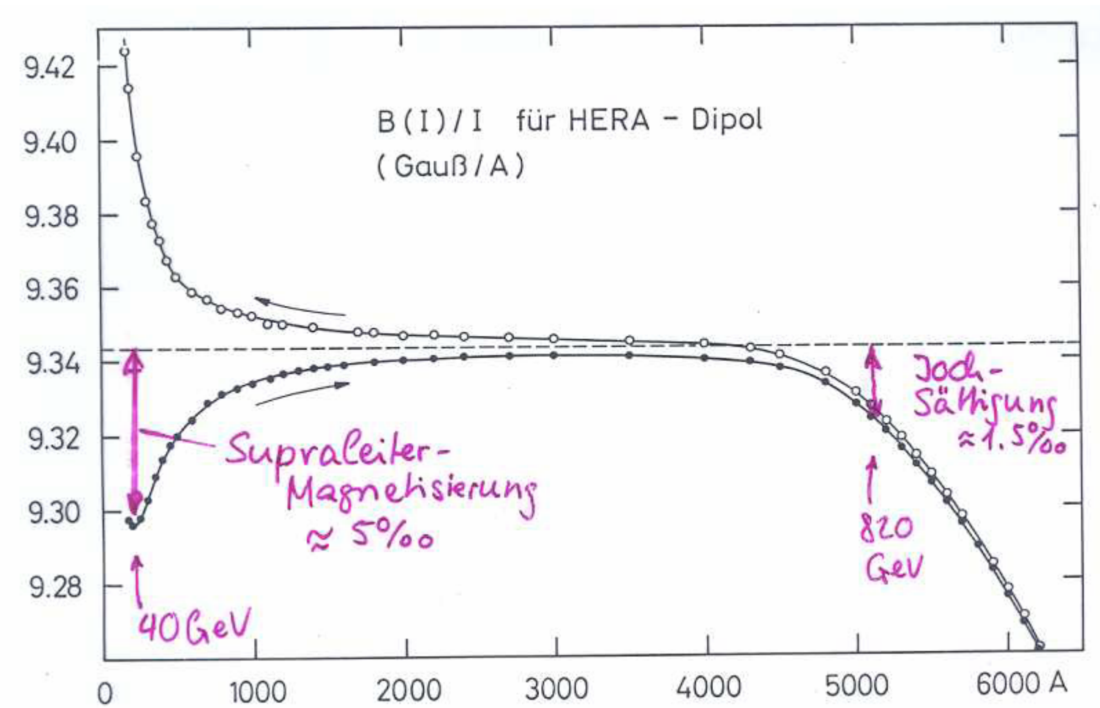
NbTi filaments in copper matrix

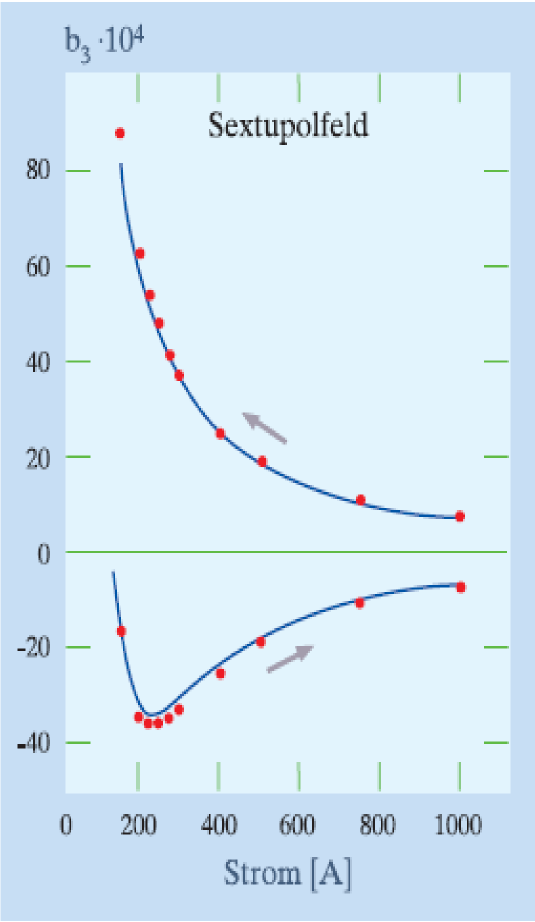


Persistent currents in the 14 μm thick NbTi filaments



Influence of persistent magnetization currents on dipole field





Dipole field B_1 at injection 0.5% lower

Remedy: correction magnets with non-linear current control

Strong sextupole component 30 times larger than tolerable

Solid curves:
absolute model prediction
diploma thesis Felix Müller

Nature, Feb. 1990

HERA magnets may need to be upgraded

- 'Eddy currents' spoil magnetic field
- Upgrade to cost $300 million **(at SSC)**

Munich & Washington

UNFORESEEN problems with the superconducting magnets in the nearly completed HERA (hadron electron ring *anlage*) electron–proton collider in Hamburg, West Germany, may force a costly eleventh-hour upgrade. The technical difficulties are similar to those encountered on prototype magnets for the US Superconducting Super Collider (SSC), which last month led to a costly redesign. But HERA physicists are still optimistic that they can solve the problems with minor, and relatively inexpensive, modifications.

For both HERA and the SSC, the problem begins with the fact that protons are fed by a lower energy accelerator — the injector — into the main ring at an energy much lower than the final energy at which collisions are to take place. Designers of both machines have found that at the injection energy, when only a small current is passed through the superconducting main ring magnets, unexpectedly large 'eddy currents' spoil the magnetic field quality and send the protons crashing into the beam-pipe walls.

Both HERA and the SSC were initially planned with the final energy a factor of twenty higher than the injection energy.

HERA accelerates protons from 40 GeV up to 820 GeV, and the SSC was to take protons from its injector at 1,000 GeV, or 1 TeV, to a collision energy of 20 TeV.

The eddy current problem was discovered in the SSC magnets in the prototyping phase, and SSC officials have decided to double the injector energy to 2 TeV so that the main ring magnets do not need to be run at such low currents. The upgrade, which will cost nearly $300 million, has led to concern that the project's cost might pass its 'political threshold' and lose it congressional support (see *Nature* **343**, 103; 1990).

Early tests on the superconducting magnets at HERA have revealed the same problem. The difficulty would be avoided if the protons were injected at 80 to 100 GeV, making the injection to final energy ratio about 10, as in the redesigned SSC. But in HERA's current design, the injector is an existing machine known as PETRA, and redesigning it would mean throwing PETRA away and building a wholly new injector. The cost of such an overhaul would be about DM30 million ($18 million has already been spent on the machine.

Nevertheless, physicists at HERA are still optimistic that they will be able to avoid the SSC's problems and are now trying to build additional magnets that will counteract the eddies.

Unfortunately, the task is not simple. The eddies vary irregularly with time, making it difficult to build compensating magnets.

The problem is made worse because HERA includes ostensibly identical magnets made by separate teams in Italy and West Germany. The magnitude and behaviour of the eddies depends strongly on the internal structure of the superconducting cable, and it turns out that magnets made in Italy behave differently from those made in West Germany. Two different strategies for compensation have had to be developed, and Italian magnets and West German magnets will be bunched in alternating octants around the ring. HERA officials will make no decision on an injector upgrade until the main ring is finished, later this year, and are hoping that some combination of these small alterations will dispose of the eddy problem.

US researchers familiar with the project are sceptical that the West German scientists will solve a problem that stumped teams of SSC planners. "It's clear that they'll get some particles to go around, but the question is how many", says SSC physicist Roger Koons. One of the key factors in a collider is the rate at which collisions occur, which depends on the beam luminosity. An accelerator that directs particles onto a fixed target can overcome a low luminosity by running for longer times, but for colliders such as HERA and the SSC, a certain minimum luminosity is essential if any collisions at all are to be produced.

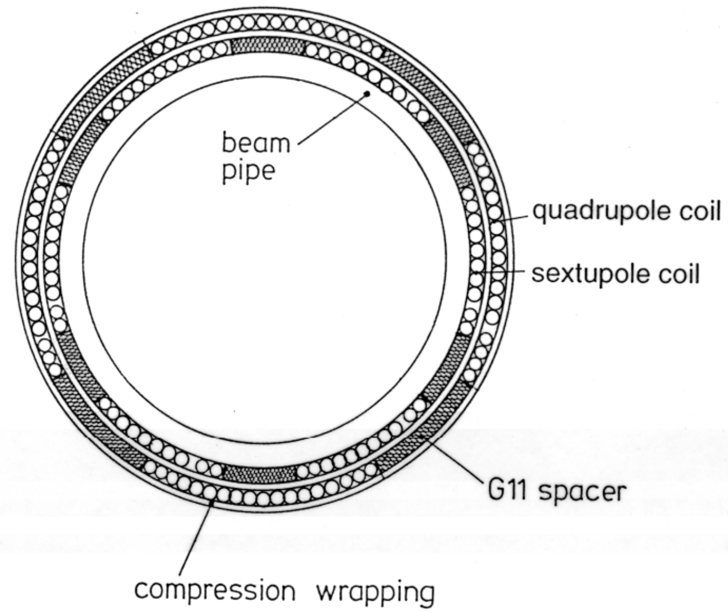
SSC researchers say they are watching the developments at HERA closely. One lesson the US researchers have already learned is not to mix superconducting cable from different sources. Because of HERA's difficulties, the SSC will only use cable either manufactured or supervised by a single vendor.

"If you don't understand the physics of superconducting cable, the next best thing is to make it all exactly the same", says Paul Mantsch, a physicist at the Fermi National Laboratory where the SSC magnets are being designed.

Problem:
ratio 1:20 between field at injection and maximum field
persistent currents very large at injection

SSC solution:
raise injection energy from 1 to 2 TeV

HERA solution:
(found long before Nature article appeared)
beam pipe correction coils

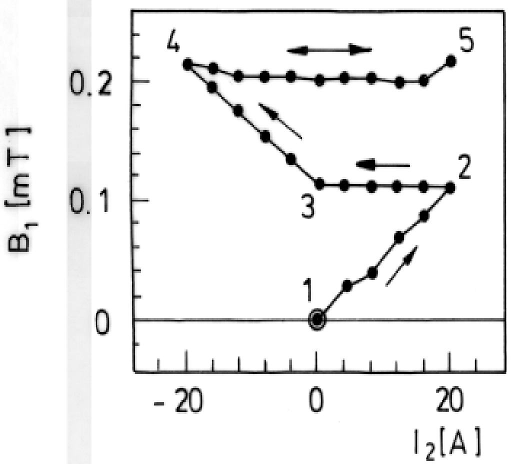


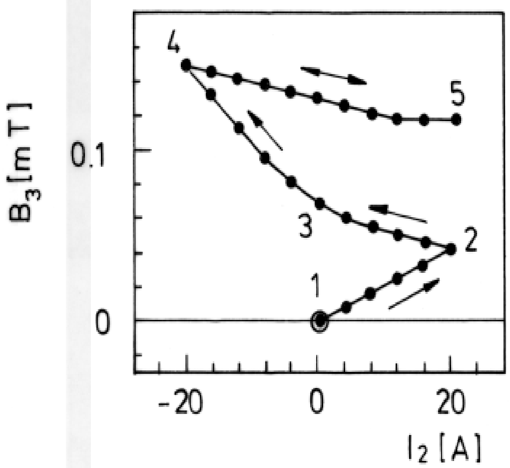
Design by Cornelis Daum (NIKHEF), PS
Built by Dutch industry

The unexpected behaviour of beam pipe correction coils

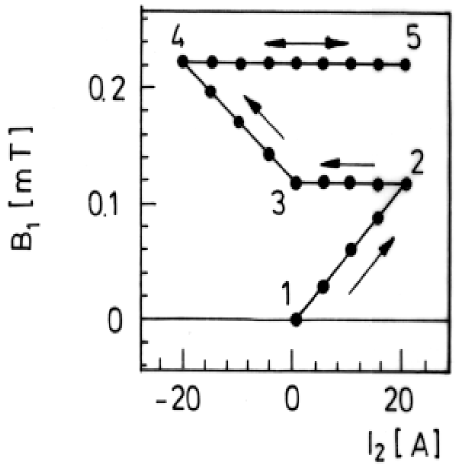
the coils may easily ruin the field quality of the dipole, and nobody realizes ist

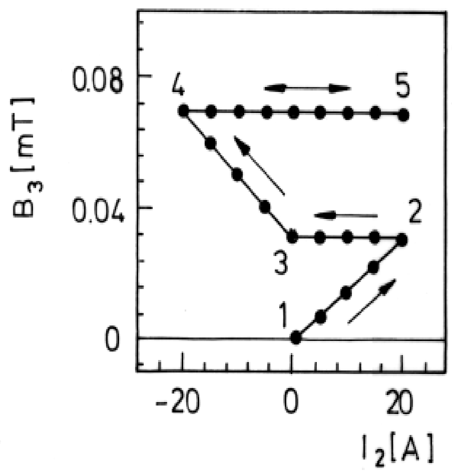
measurement





theoretical model





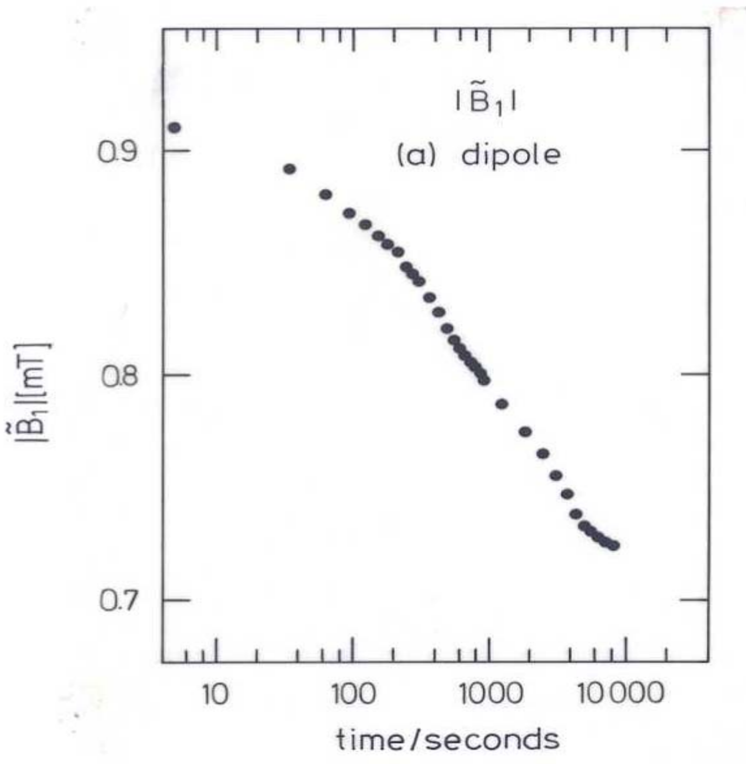
diploma thesis
Michael Pekeler

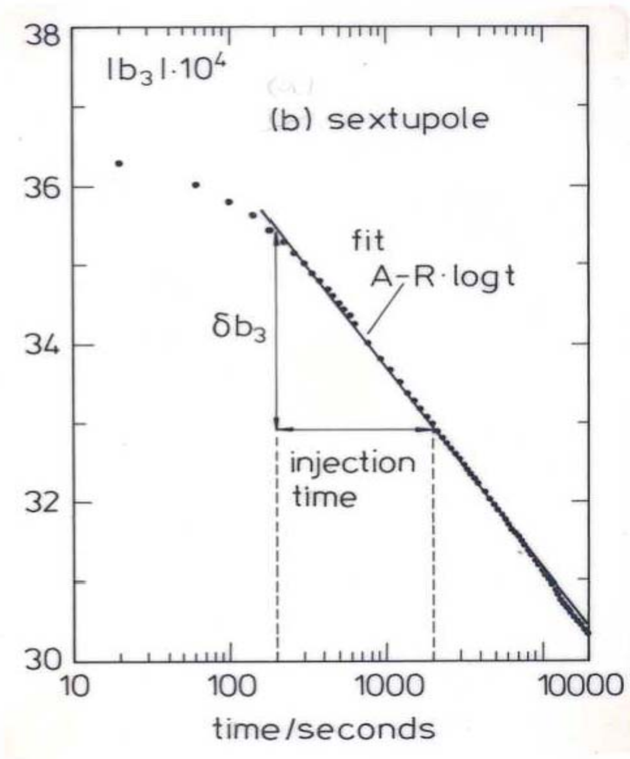
Remedy: large current cycle of main dipole removes all these field distortions

Explanation:
The correction coils generate a field outside the beam pipe which induces strange persistent-currrent patterns in the conductor of the main dipole coil. These patterns persist even if the correction coil current is reduced to zero. But they are wiped out by the main dipole current cycle that is routinely carried out after a luminosity run and before injection of a new proton beam.

The next surprise: persistent current multipoles are time-dependent

discovered at the FNALTevatron, chromaticity changed with time





Theoretical explanation was found in 1995 at CERN (thesis A. Verweij):
time dependence results from complicated interplay between „superconducting" magetization currents in NbTi and „normal" eddy currents in Cu

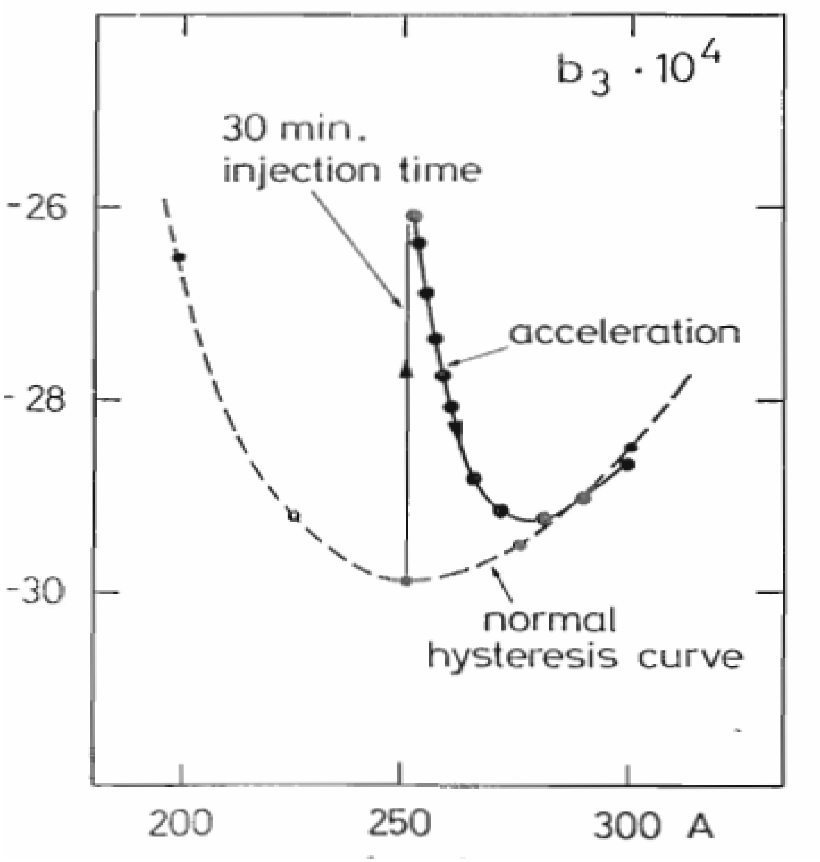
Injection and initial acceleration in HERA

Injection at 40 Gev lasts 30 minutes, dipole and sextupole field drift away.
When acceleration starts they immediately re-approach the hysteresis curve

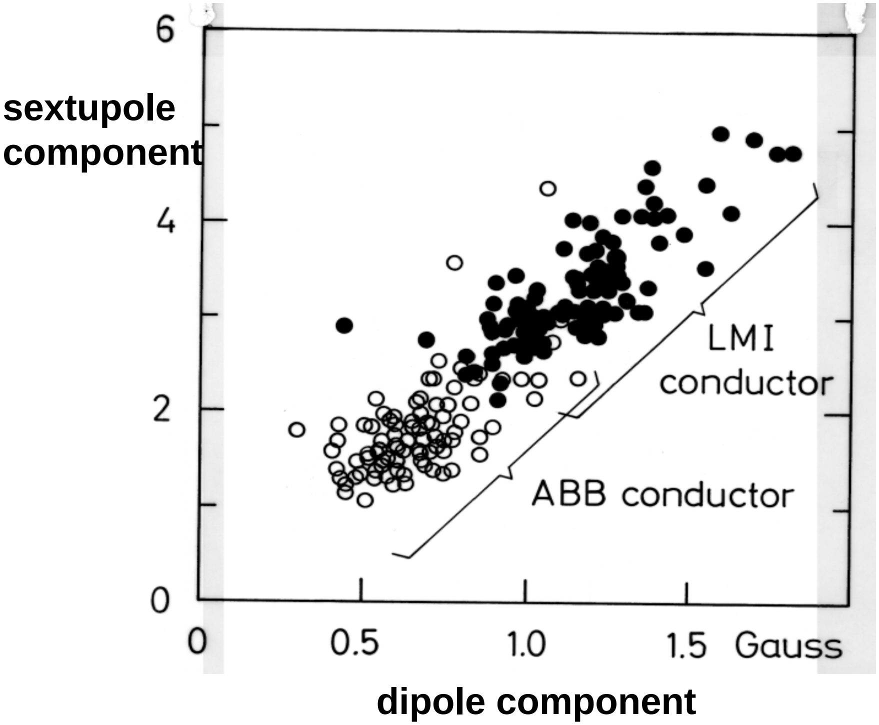
So one has to track rapid field changes

Big complication:
decay rates vary from magnet to magnet, different for German and Italian dipoles

Sextupole component



decay rates in all HERA dipoles



The reference magnets for controlling the magnets currents

proposed by D. Degele, PS

Installed in HERA Hall West:
1 ABB and 1 Ansaldo dipole
connected in series with main ring

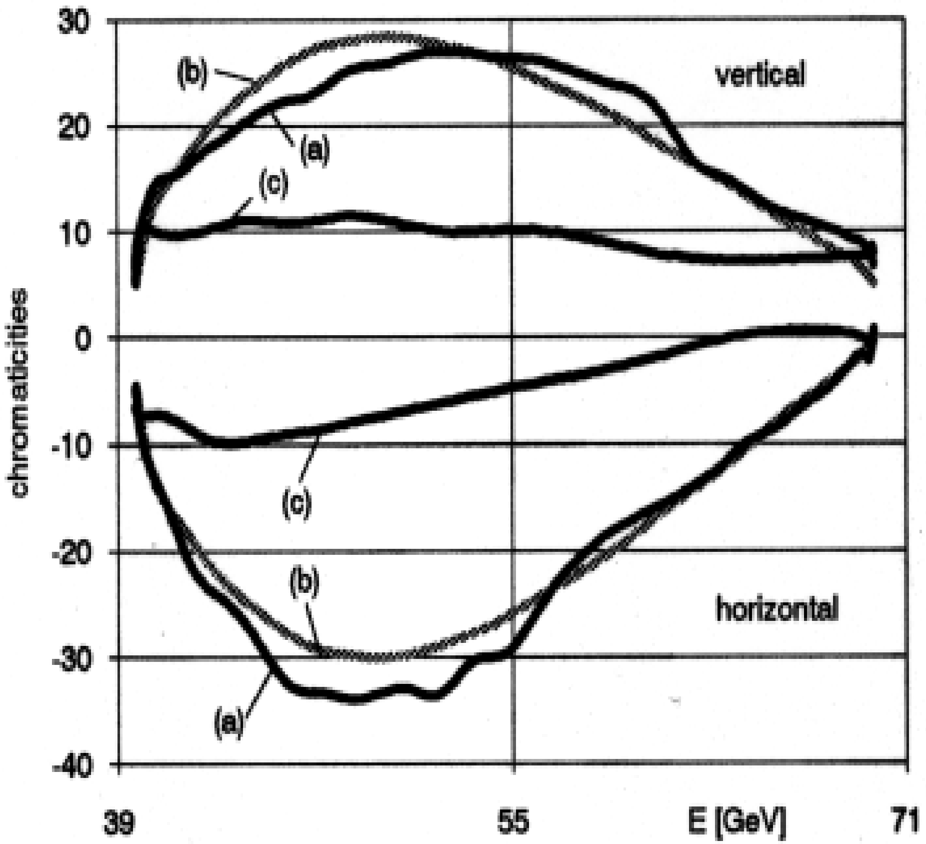
NMR measures B_1 at injection
Pickup coil provides dB/dt pulses
which control currents in all
correction coils and in all normal
magnets of HERA-p

Rotating coil measures sextupole
field in real-time,
controls sextupole correctors

H. Brück, M. Stolper

Acceleration from 40 to 70 GEV

Vertical and horizontal chromaticity without and with control by reference magnets



Diploma thesis Olaf Meincke

(a) Without control
(c) with control

Chromaticity is the momentum dependence of the number of betatron oscillations per revolution. For stable operation the chromaticity must be close to zero.
The chromatic errors of the quadrupoles are corrected by sextupoles.

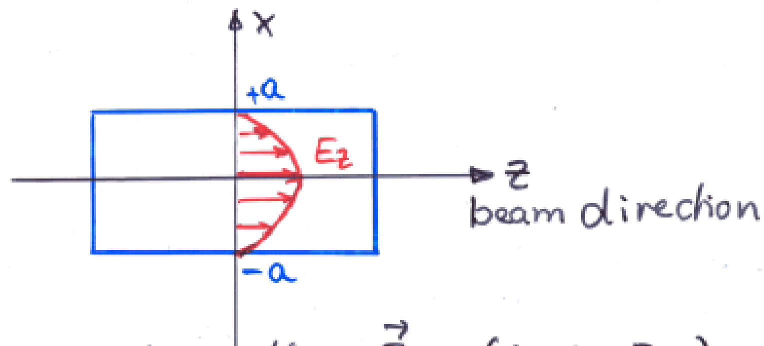
Microwave cavity for particle acceleration

$\boxed{\text{Rectangular cavity}}$

wave number $|\vec{k}| = \frac{2\pi}{\lambda}$

eigenfrequency

$$\omega_0 = 2\pi f_0 = c\,|\vec{k}|$$



eigenmode with $\vec{E} = (0, 0, E_z)$

wave equation:

$$\frac{\partial^2 E_z}{\partial x^2} + \frac{\partial^2 E_z}{\partial y^2} + \frac{\partial^2 E_z}{\partial z^2} = \frac{1}{c^2}\frac{\partial^2 E_z}{\partial t^2}$$

boundary conditions: $E_z = 0$ at $x = \pm a$, $y = \pm a$

simplest solution

$$E_z(x, y, z, t) = E_0 \cos(k_1 x)\cos(k_2 y)\cos(\omega_0 t)$$

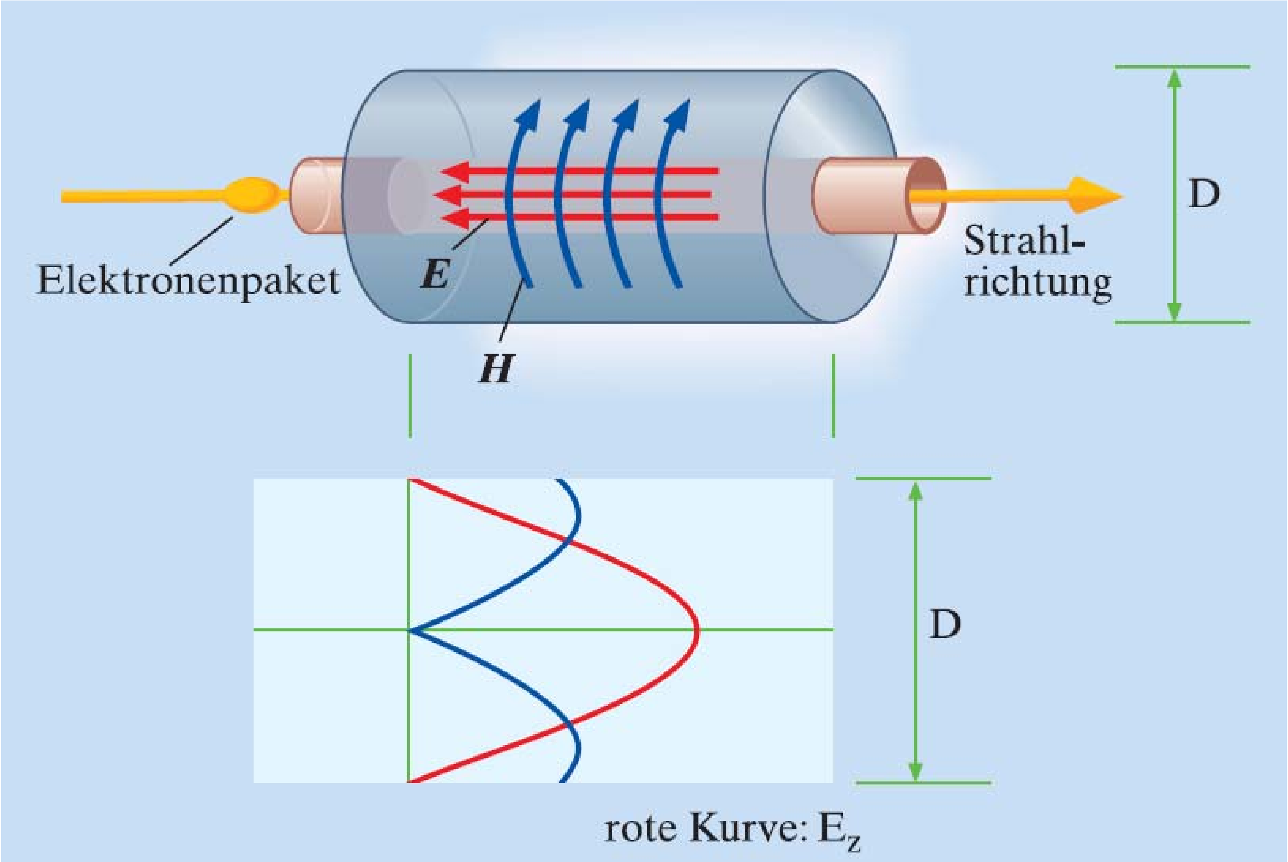
bound. cond. $\Rightarrow k_1, k_2 = \frac{\pi}{2a}$

$$\left.\begin{array}{l} \vec{k}^2 = k_1^2 + k_2^2 = \frac{\pi^2}{2a^2} \end{array}\right\}$$

resonant frequency

$$\omega_0 = c\,\frac{\pi}{\sqrt{2}\,a}$$

Cylindrical cavity (pill box)

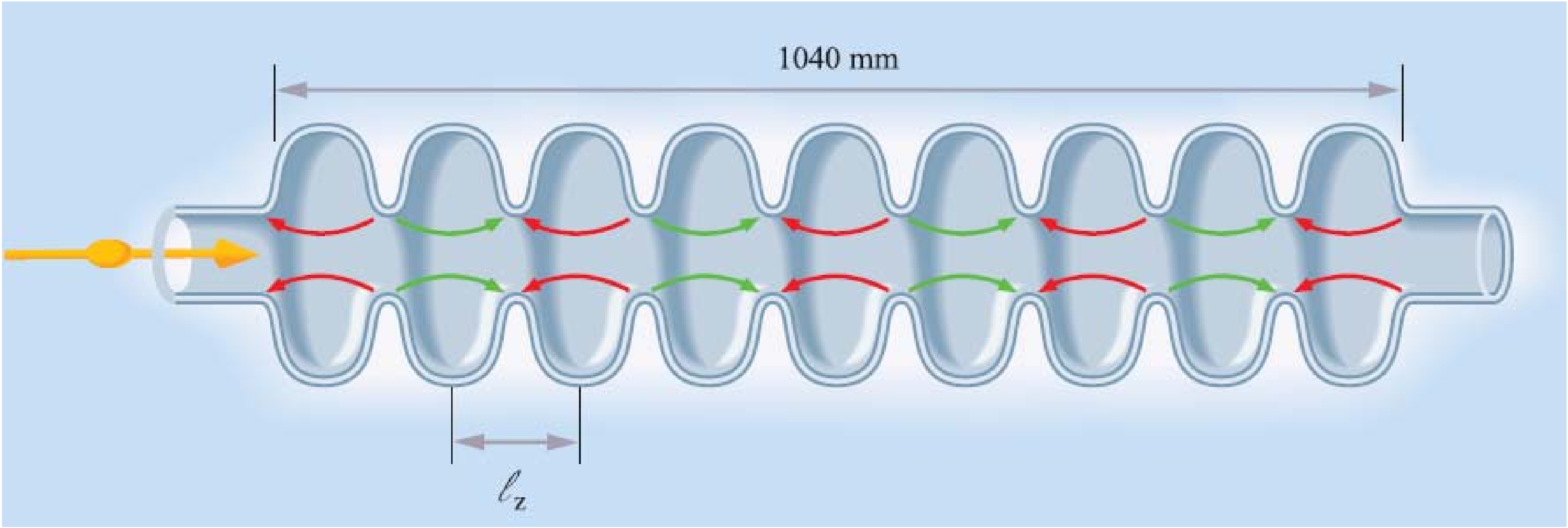


$$E_z(r,t) = E_0 J_0\left(\frac{\omega_0 r}{c}\right)\cos(\omega_0 t)\;,$$

$$H_\theta(r,t) = -\frac{E_0}{\mu_0 c} J_1\left(\frac{\omega_0 r}{c}\right)\sin(\omega_0 t)$$

Nine-cell TESLA cavity

excited in π mode with 180^0 phase advance from cell to cell



Figures of merit of cylindrical cavity

$$f_0 = \frac{2.405c}{2\pi R_c}$$

resonance frequency, determined by cavity radius

$$U = \frac{\varepsilon_0}{2} E_0^2 (J_1(2.405))^2 \, \pi R_c^2 L_c$$

stored field energy

$$P_{diss} = R_{surf} \cdot \frac{E_0^2}{2\,\mu_0^2\, c^2} (J_1(2.405))^2 \, 2\pi R_c \, L_c \, (1 + R_c / L_c)$$

dissipated power

$$R_{surf} = \frac{1}{\sigma \delta}$$

surface resistance of copper cavity
σ conductivity, δ skin depth

$$Q_0 = 2\pi \cdot \frac{U \, f_0}{P_{diss}} = \frac{f_0}{\Delta f}$$

quality factor

Q_0 is roughly the number of free oscillations needed to dissipate the stored energy

What is the surface resistance of a superconducting cavity?

Instead of skin depth we can use the London penetration length.
But if we assume infinite conductivity we get surface resistance zero.
This is wrong! The surface resistance is small but non-zero.

Use two-fluid model in analogy with liquid helium below 2.17 K
superfluid: Cooper pairs
normal fluid: unbound conduction electrons

Complex conductivity

$$\sigma = \sigma_n + i\sigma_s \quad \text{with} \quad \sigma_s = \frac{2\, n_c e^2}{m_e\, \omega} = \frac{1}{\mu_0 \lambda_L^2\, \omega}$$

RF surface resistance of superconductor

$$R_{surf} = Re\left(\frac{1}{\lambda_L(\sigma_n + i\sigma_s)}\right) = \frac{1}{\lambda_L} \cdot \frac{\sigma_n}{\sigma_n^2 + \sigma_s^2}$$

Unpaired electrons are created by thermal breakup of Cooper pairs
Energy gap $E_g = 2\Delta$ between the superconducting (BCS) ground state and the free electron states
By analogy with the conductivity of an intrinsic (undoped) semiconductor we get

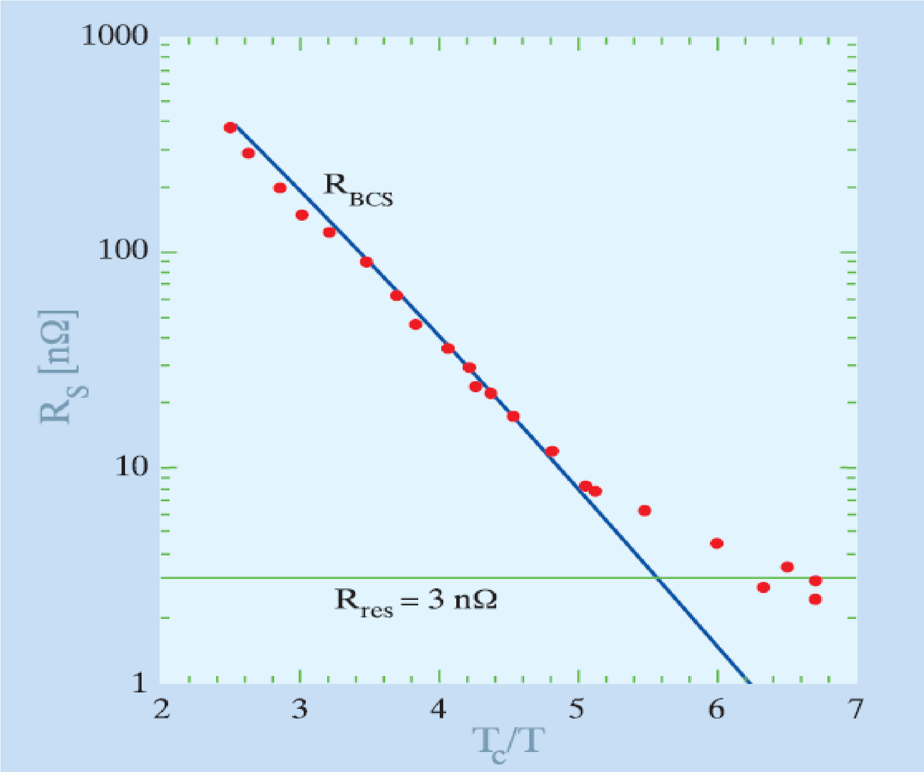
$$n_n \propto \exp(-E_g/(2k_B T))$$

and hence

$$\sigma_n \propto \ell \exp(-\Delta/(k_B T)) \; . \qquad (2$$

Using $1/\sigma_s = \mu_0 \lambda_L^2 \omega$ and $\Delta = 1.76 k_B T_c$ we finally obtain for the BCS surface resistance

$$\boxed{R_{BCS} \propto \lambda_L^3 \, \omega^2 \, \ell \, \exp(-1.76 \, T_c/T)}$$



Advantage of superconducting cavities compared to copper cavities

Surface resistance of Nb at 2 Kelvin is five to six orders of magnitude lower than for copper

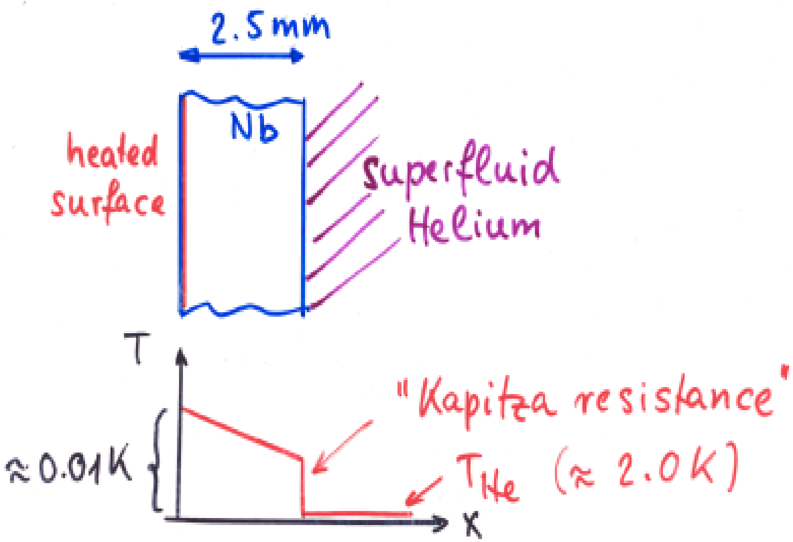
Example: 9-cell TESLA cavity at accelerating field of 25 MV/m, quality factor > 10^{10} and beam current of 8 mA

RF power going to beam is 200 kW
Dissipated power in cavity walls is only about 20 W
In copper cavities beam power and dissipated power about equal

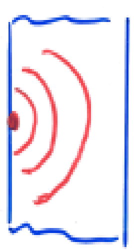
Big but: 1 W of heat flux into liquid helium at 2 K requires about 1000 W of electrical power in refrigerator

In a superconducting linear collider the conversion of primary electrical power into beam power is about twice as efficient than in a normal-conducting machine

Heat transfer to liquid He

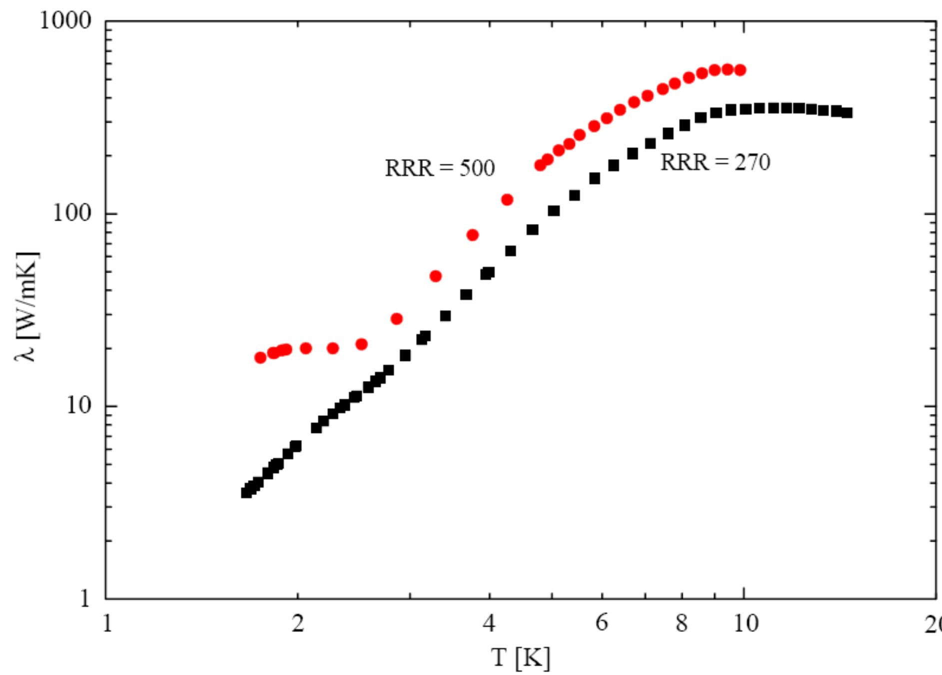


Much stronger heating due to small normal-conducting defects



area of defect $< 10^{-6}$ area of cavity

Very unfortunate:
heat conductivity tends to zero at very low temperatures

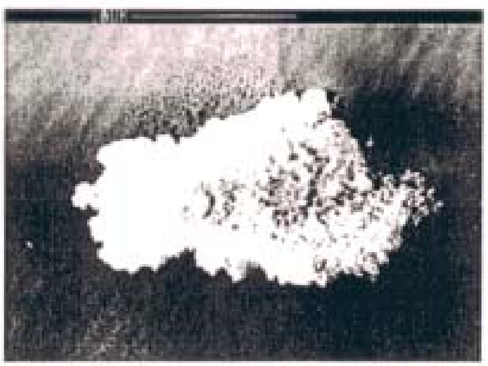


one needs very pure niobium

Strong limitation in many practical cavities

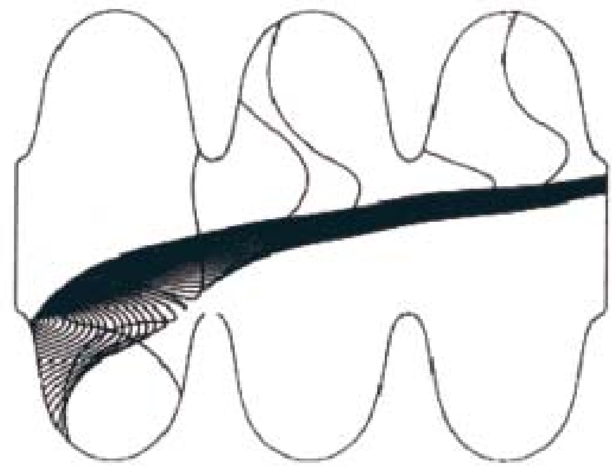
Field Emission

Pictures taken from: H. Padamsee, Supercond. Sci. Technol., 14 (2001), R28 –R51



Particle causing field emission

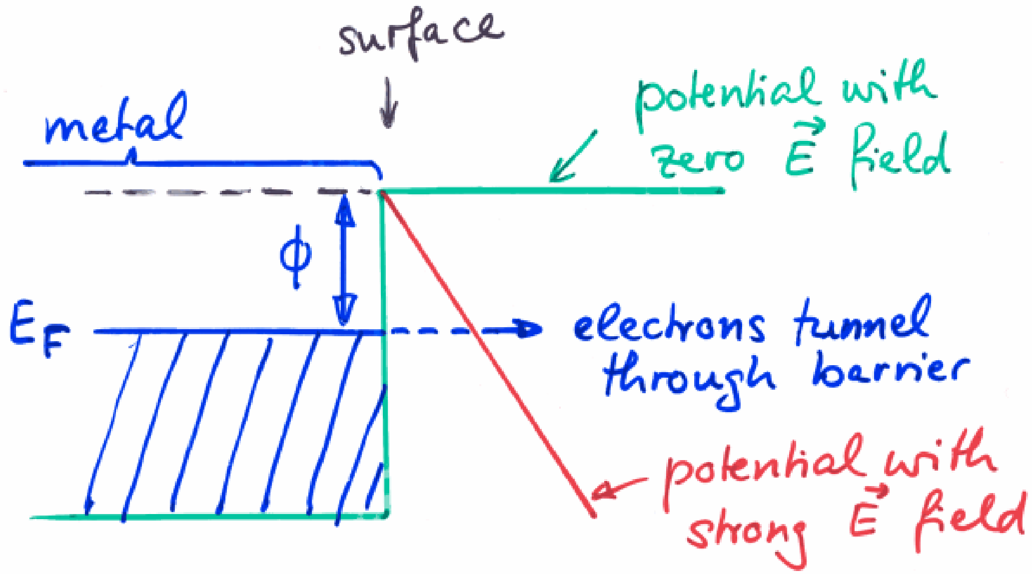
Temperature map of a field emitter



Simulation of electron trajectories in a cavity

What is field emission:

extraction of electrons by high electric fields via the tunnel effect



current density given by Fowler-Nordheim equation

$$j(E) = \frac{A}{\phi}\,(\beta_{FN}\cdot E)^2\,\exp\left(-\frac{B\cdot\phi^{3/2}}{\beta_{FN}\cdot E}\right)$$

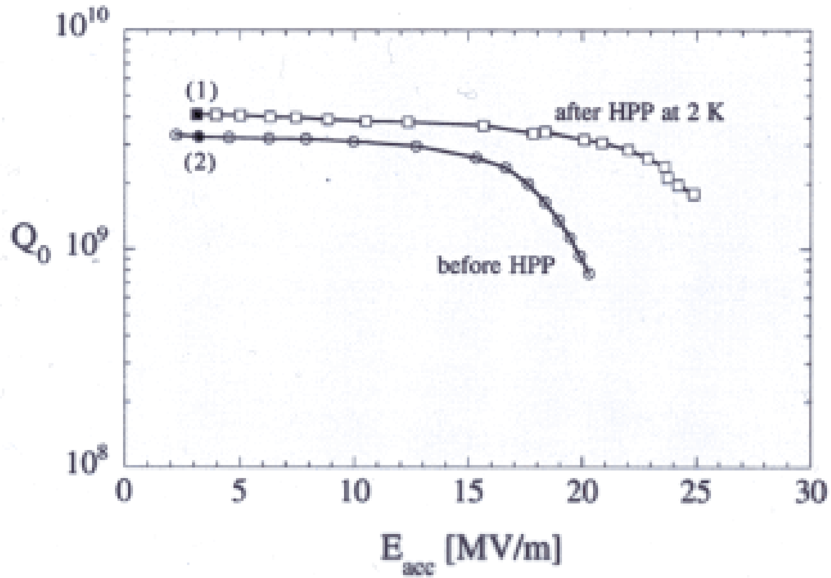
ϕ work function of metal

β_{FN} : empirical field enhancement factor

Destruction of field emitters by High Power Processing (HPP)

Cornell Univ., H. Padamsee

Apply short ($\geq 100 \mu s$) rf pulses of several 100 kW instantaneous power



dissertation Michael Pekeler
U. of Hamburg

Clean room for cavity preparation

Destruction of field emitters by high peak power (HPP) processing
(several 100 kW for ≈ 100 μs)

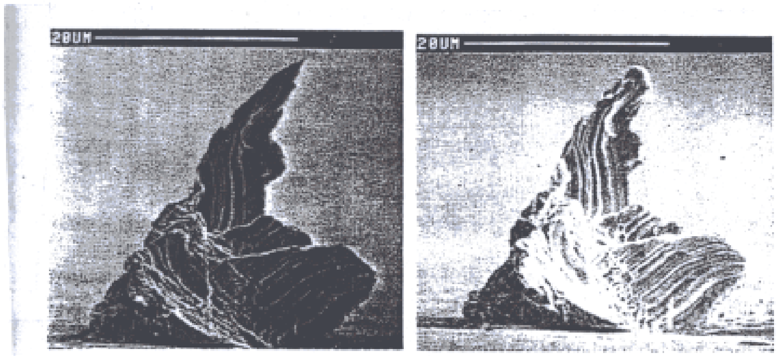
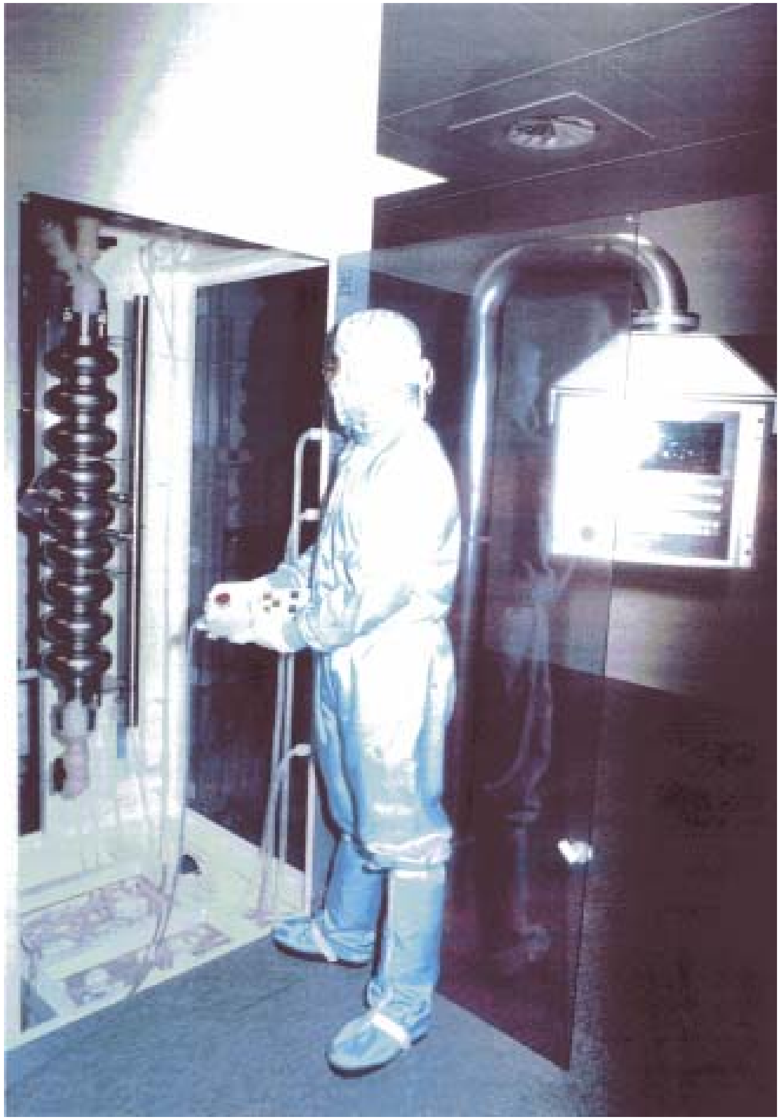


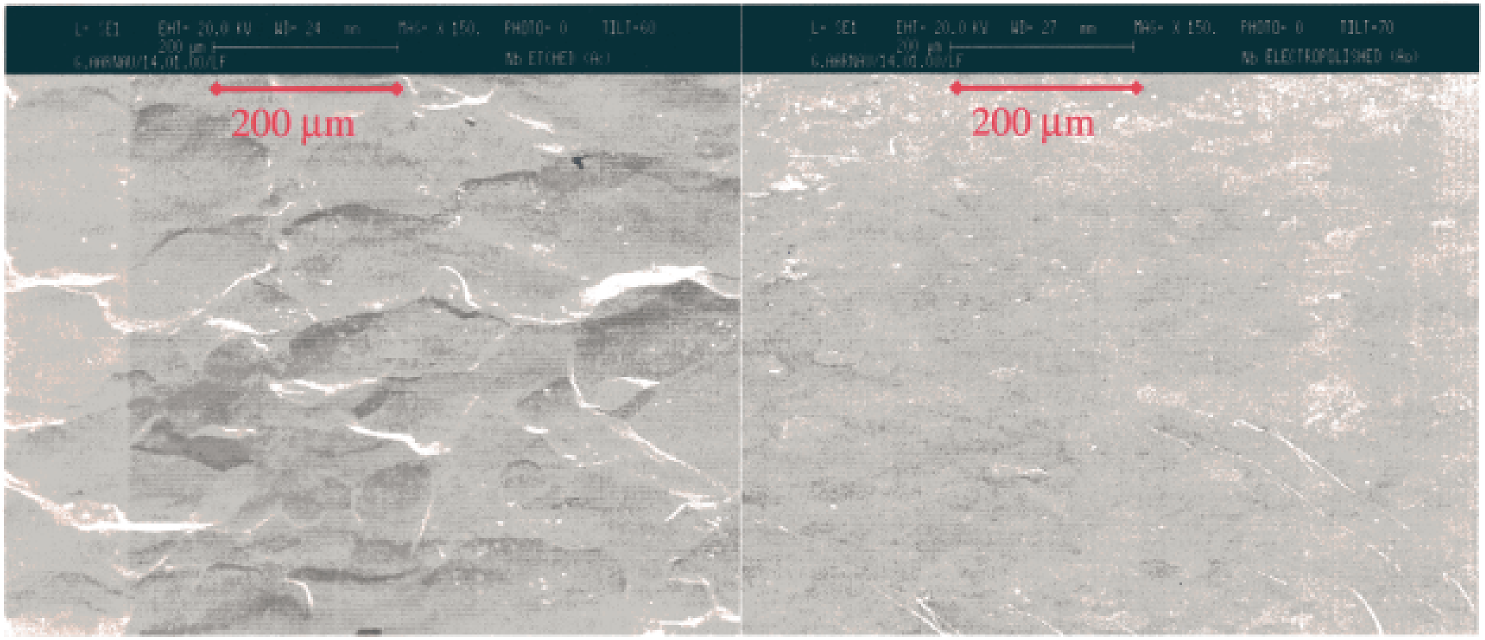
Fig. 6 Microphotograph of an emitting site: a) before emission; b) after emission. Note the apex melting.

B. Bonin (Saclay): melting of a sharp tip by HPP



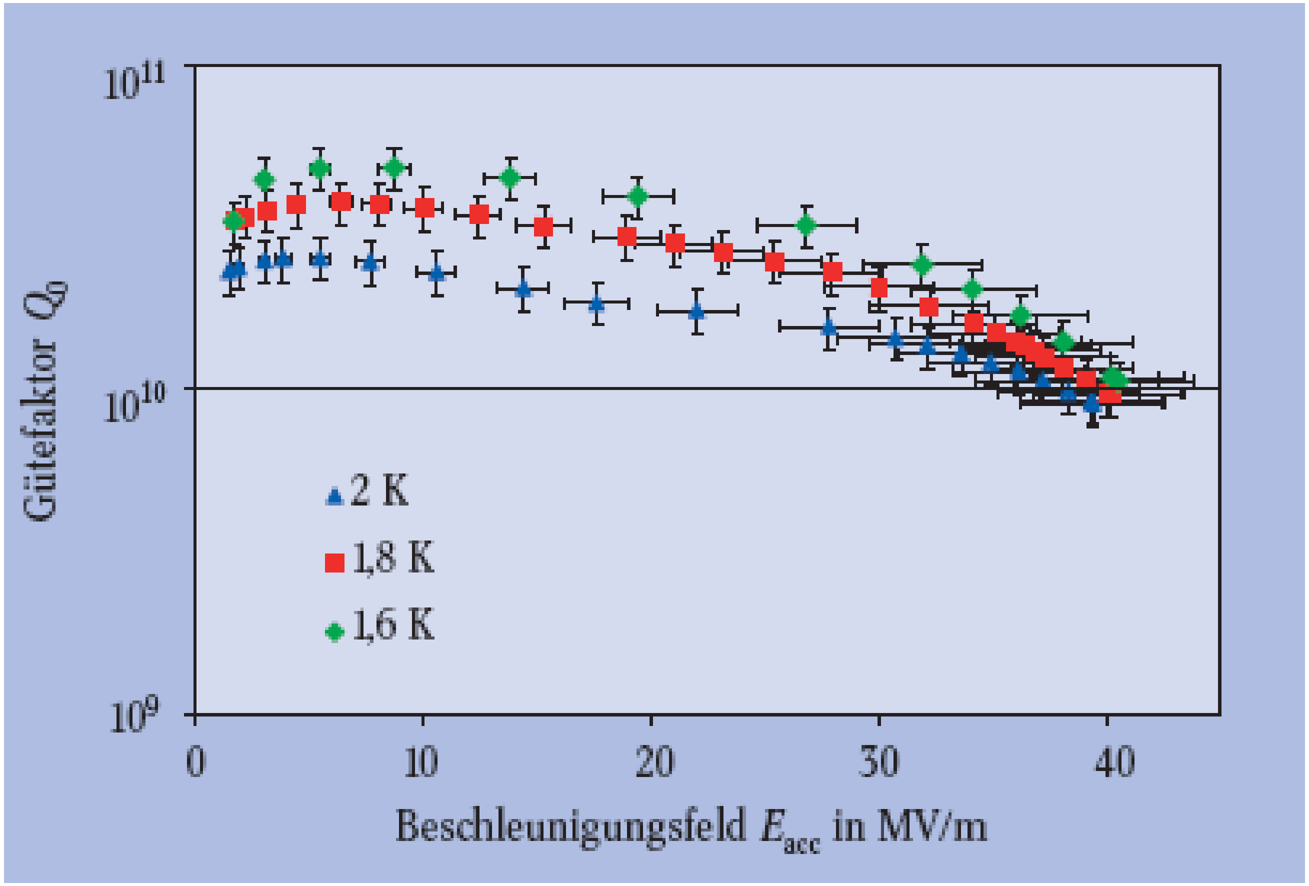
Improvement by electrolytic polishing of inner cavity surface

Niobium surfaces



- Etching (Buffered chemical polish)
  - HF, HNO_3, H_3PO_4
- Electropolishing

An excellent nine-cell cavity



Manufactured by ACCEL, electrolytic polishing at DESY

Lutz Lilje, DESY

What is the highest accelerating field?

Cavity breaks down when the RF magnetic field exceeds the critical field of the superconductor

Lead: **type I conductor with Bc = 0.08 T**
accelerating field < 20 MV/m

Niobium: **type II conductor**
At T = 2 K:
lower critical field Bc1 = 160 mT **acc. field about 40 MV/m**
upper critical field Bc2 = 350 mT
thermodynamical field Bc = 200 mT **acc. field almost 50 MV/m**

> 50 MV/m have been reached in 1-cell cavities of special shape

Requirements on technical superconductors

General: critical temperature as high as possible
But: present-day high Tc conductors are badly suited both for magnets and for cavities
Useful as current leads in LHC magnets

Accelerator magnets

large critical field, hence only type II sc
alloys and not pure elements
strong flux pinning: lattice defects

One needs a „dirty superconductor“

NbTi $T_C = 9.2$ K $B_{C2} = 14$ T
very ductile, easily extruded with copper
the standard sc for magnets

Nb_3Sn $T_C = 18$ K, $B_{C2} = 20$ T
brittle material, very difficult to use and
very expensive in accel. magnets

Niobium-titanium is the best choice

Microwave cavities

no magnetic flux inside bulk sc
no flux pinning to avoid hysteresis loss
high heat conductivity

One needs a „clean superconductor“

Pb $T_C = 7.2$ K $B_C = 0.08$ T

Nb $T_C = 9.2$ K $B_C = 0.2$ T

Niobium is the best choice

Nb is a type II conductor