Superconductivity in High-Energy Particle Accelerators

Peter Schmüser, Univ. Hamburg and DESY

Motivation for superconductor technology in accelerators

Basic properties of superconductors

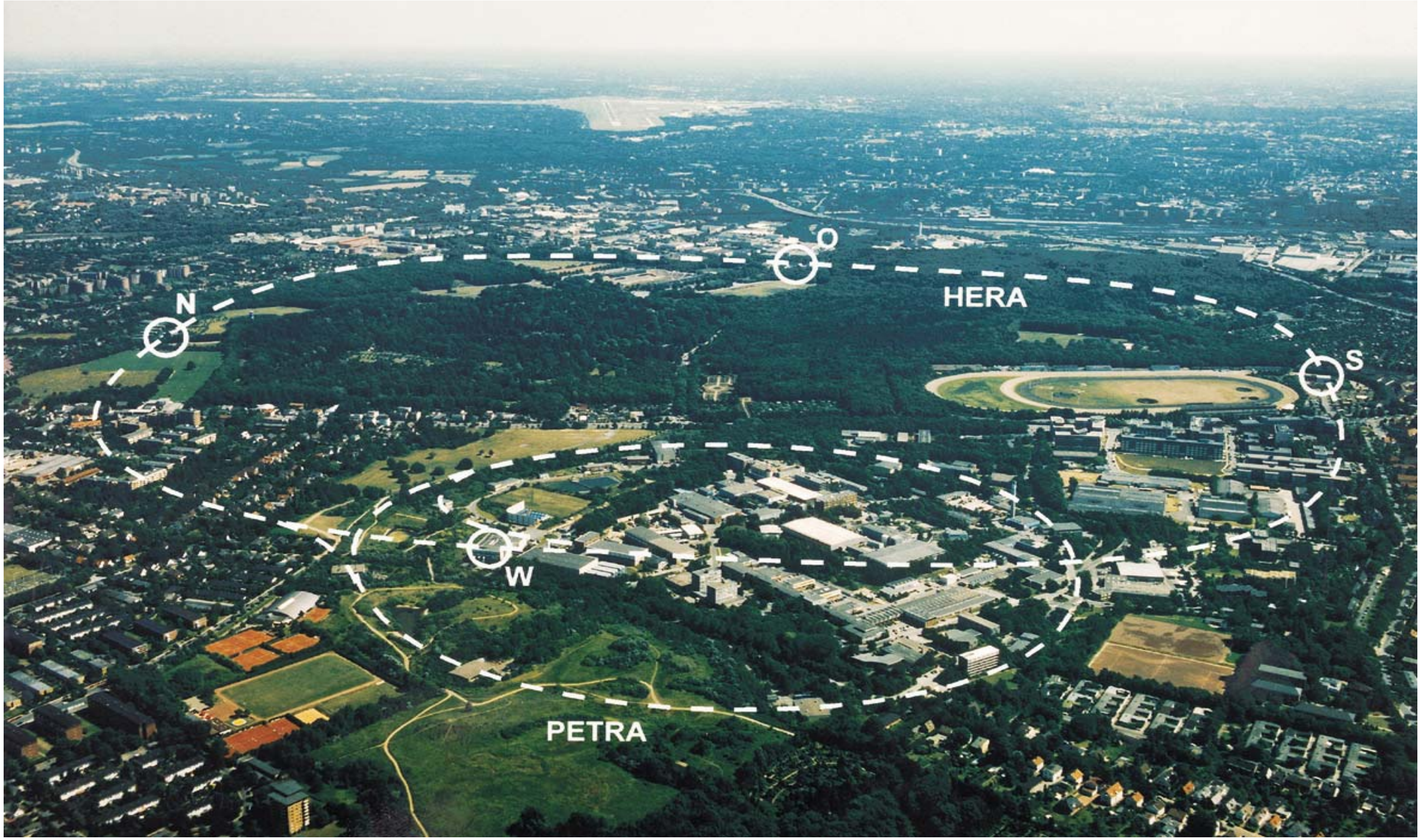
Superconducting magnets

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

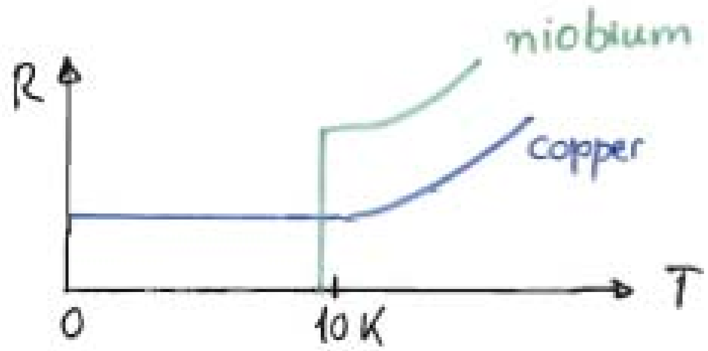
Superconductors have small but finite resistance in microwave fields
Accelerating fields lower than in Cu cavities

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

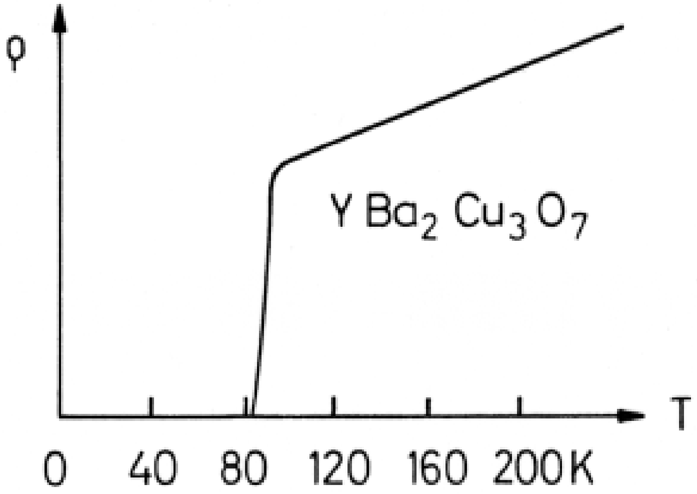
Basics of Superconductivity

Low-temperature superconductor niobium
normal conductor copper



critical temperature Tc = 9.2 K for Nb

High-temperature superconductor

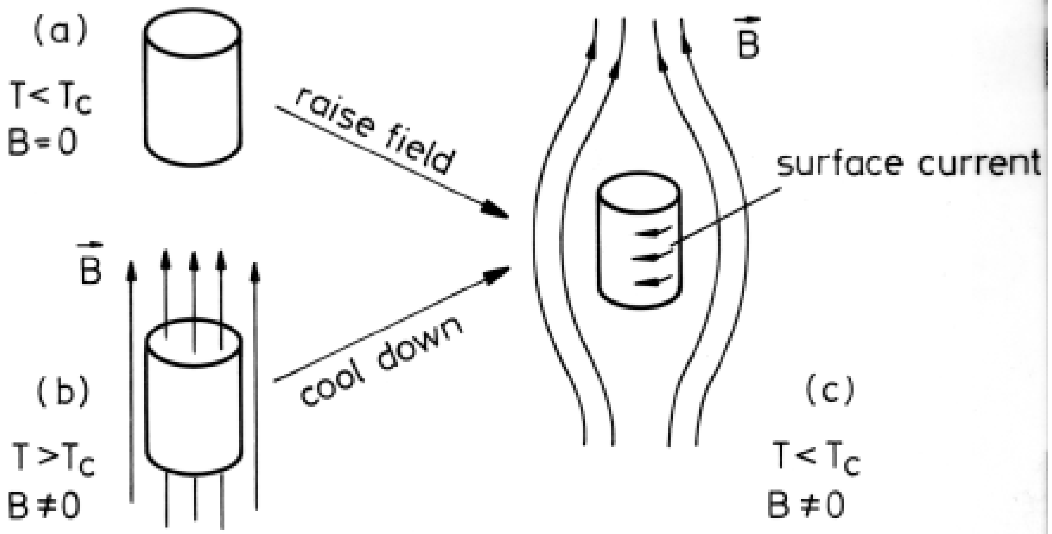


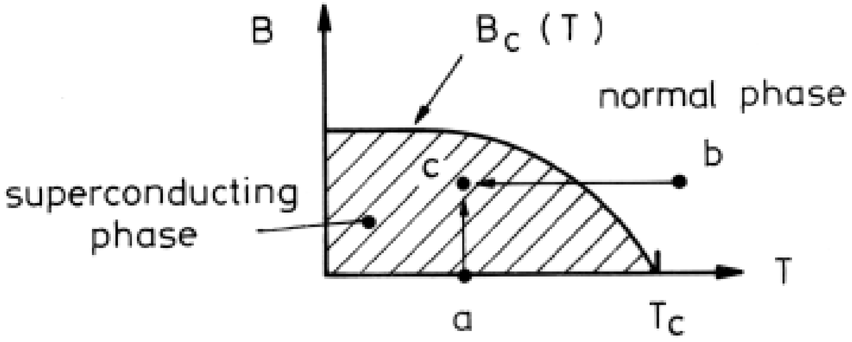
Interesting observation: excellent normal conductors such as Cu and Ag do not become superconductive

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

Superconductor in magnetig field: Meisner-Ochsenfeld effect

Below T_C a weak magnetic field is expelled from the superconductor

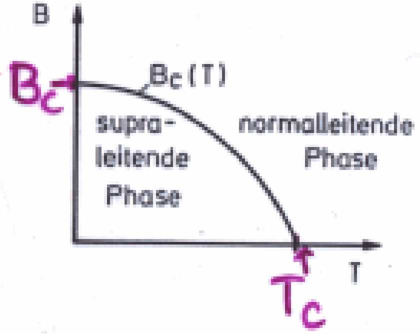


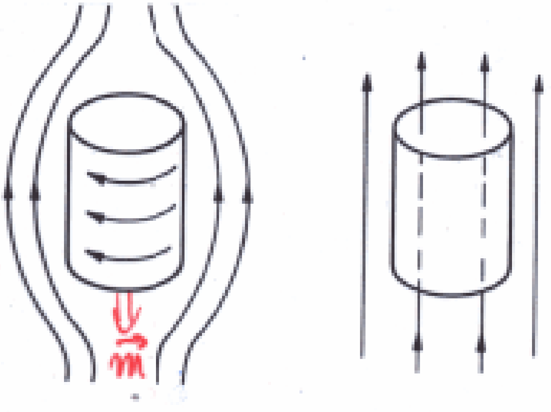


This applies for type I superconductors pure elements (lead, tin, aluminum…)

Type I Superconductors

pure elements: lead, indium, tin,.. but not niobium!



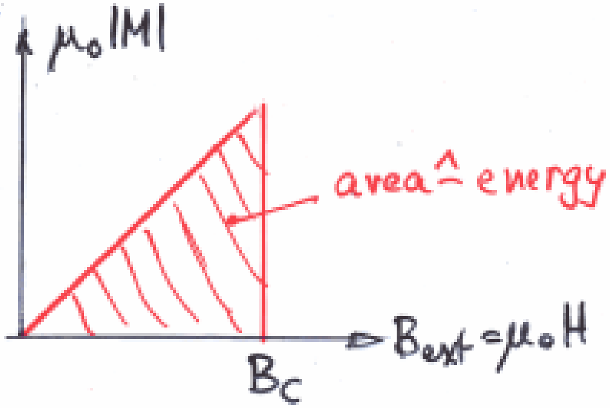


$B < B_c(T)$ $B > B_c(T)$

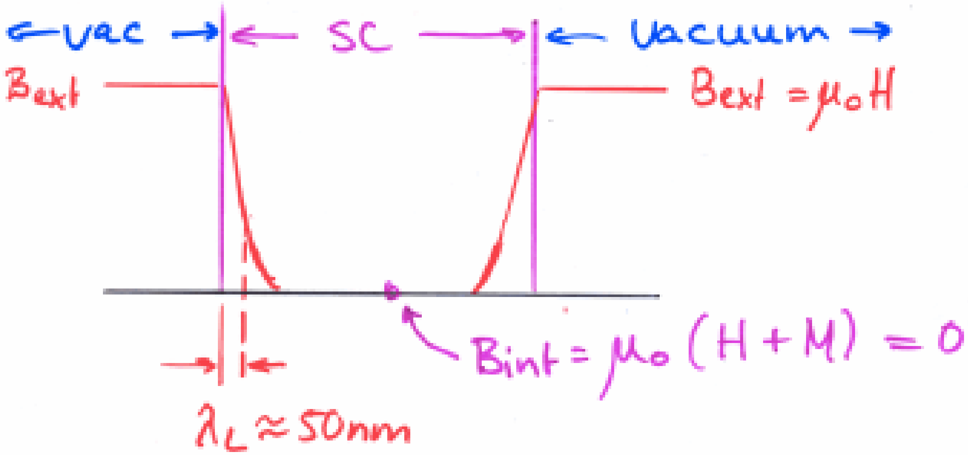
Meissner effect:

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

except for thin surface layer

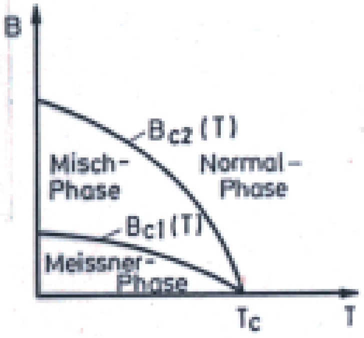


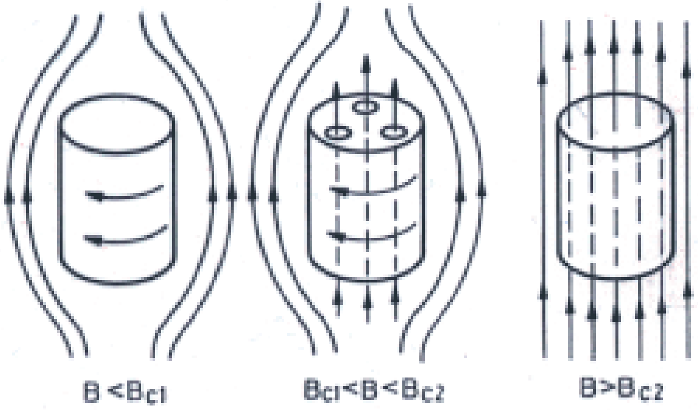
$M = -H$ for $H < H_c$



Type II Superconductors

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

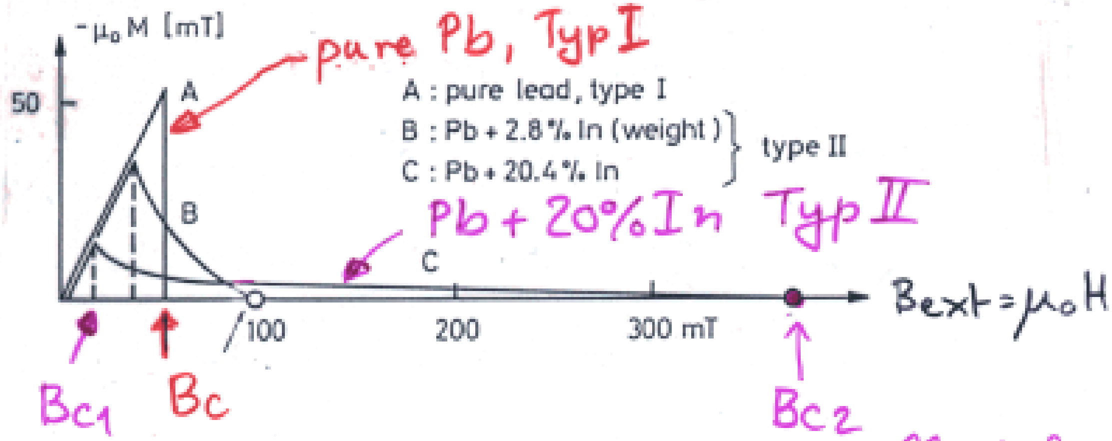




2 critical fields

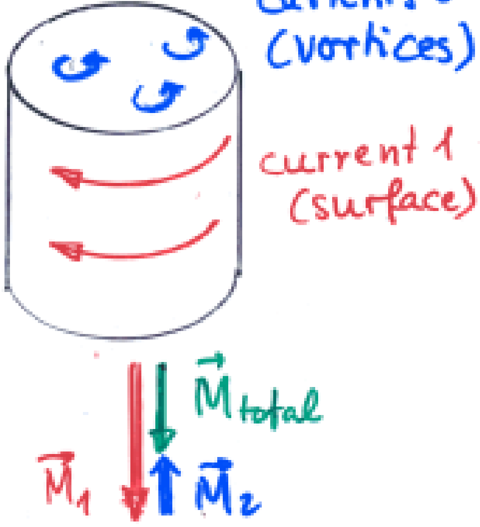
$B < B_{c1}$ Meissner phase

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



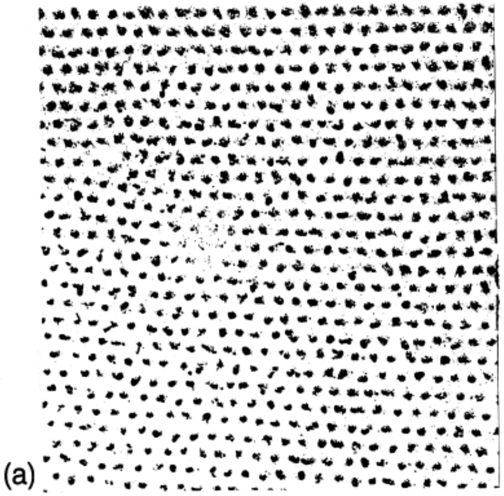
high B_{c2} : excellent for magnets

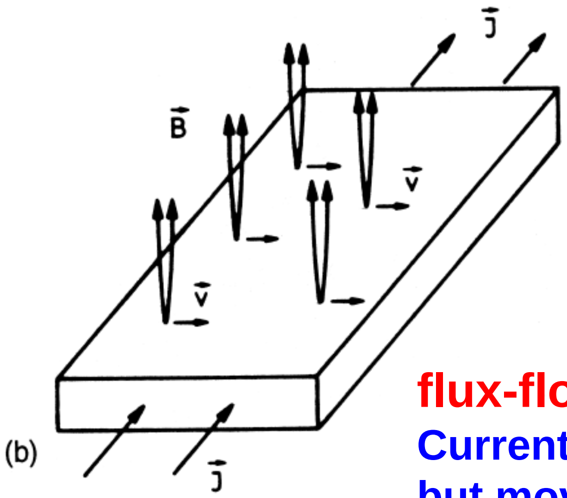
lower magnetization in mixed phase



Hard superconductors: type II superconductors with strong flux pinning

magnetic flux tube pattern





flux-flow resistance

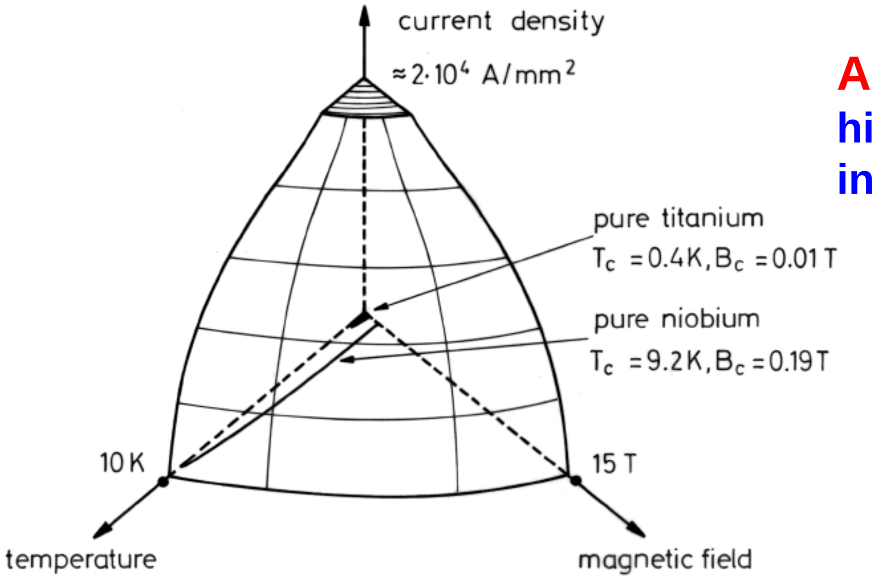
Current flows without resistance
but moving flux tubes produce heat

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

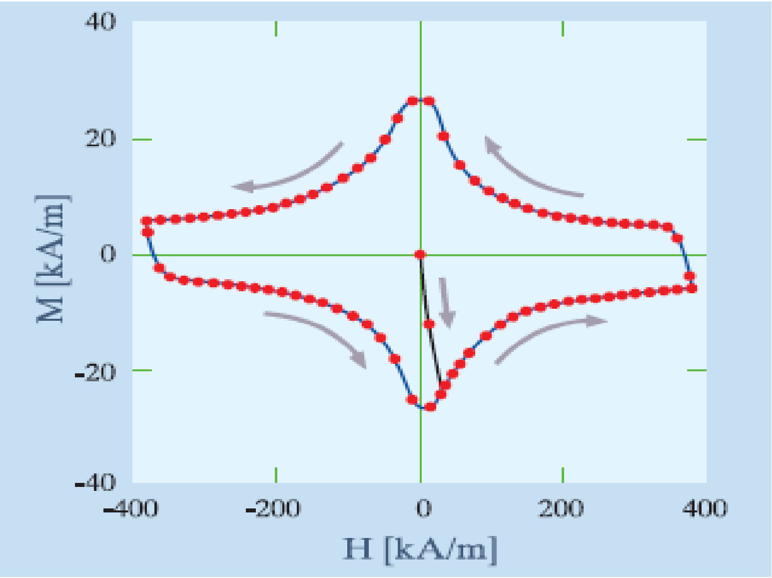
Niobium-titanium: the standard superconductor for magnets



Advantage of strong flux pinning:

high current can flow without any dissipation in the presence of a large magnetic field

current density > 2500 A / mm^2
at 4.5 Kelvin and 5 Tesla



Disadvantage of strong flux pinning:

magnetic hysteresis similar to ferromagnet

enclosed area is dissipated heat

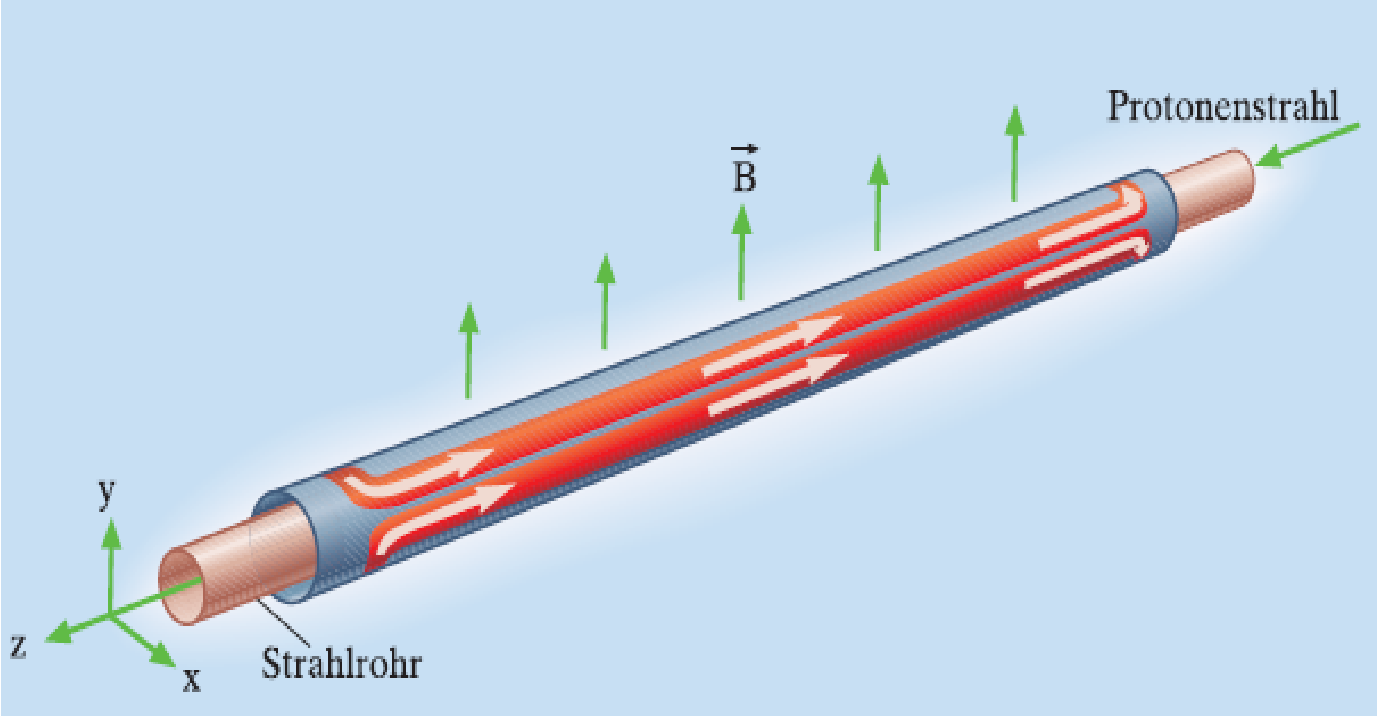
Conclusion:

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

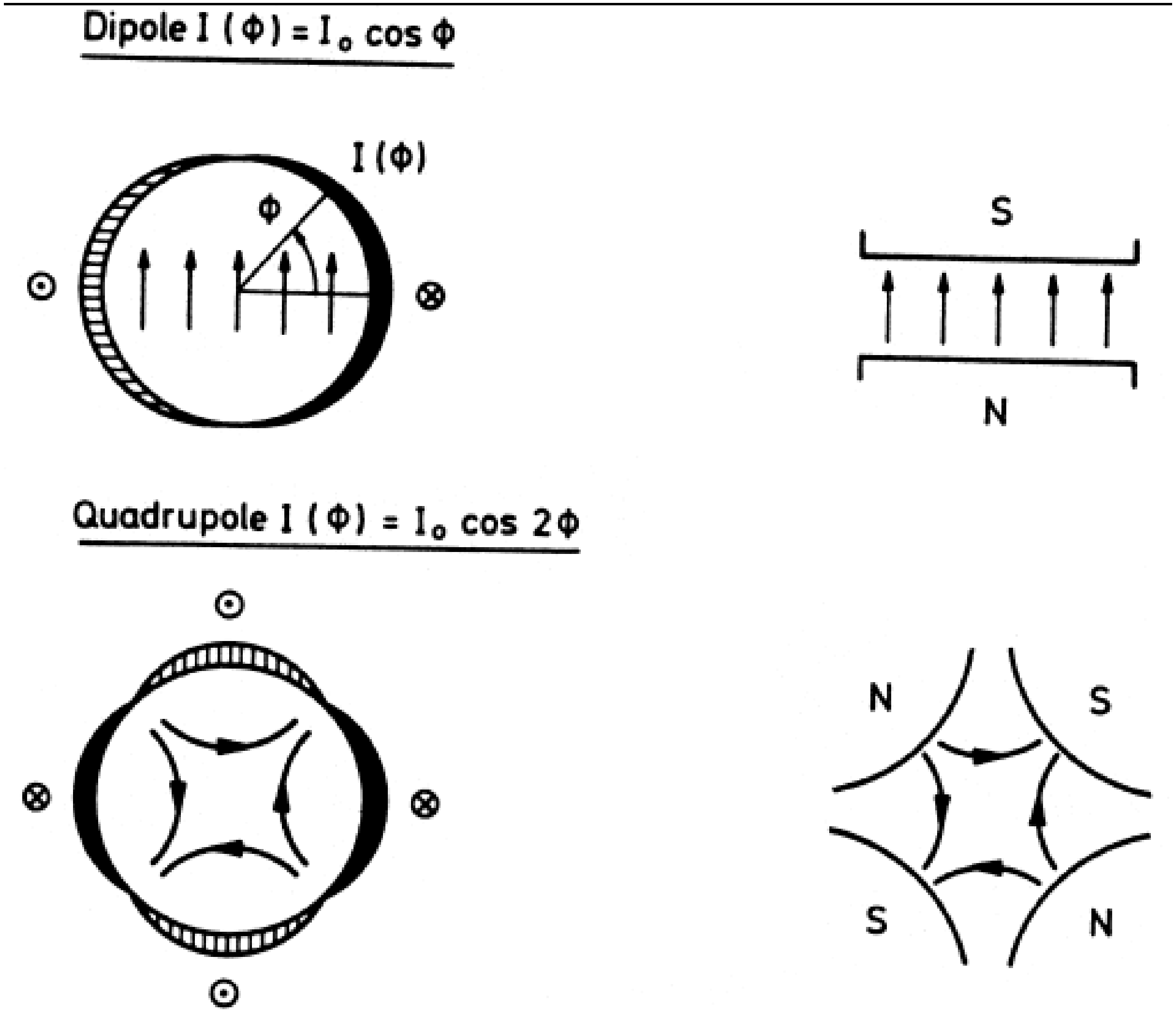
5 - 8 Tesla superconducting accelerator magnets

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



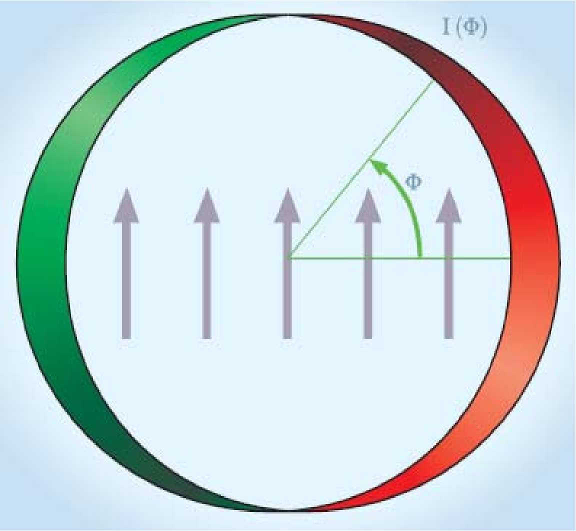
Generation of pure dipole and quadrupole fields by current distributions
$I(\phi) = I_0 \cos(n\,\phi)$ with n=1 resp. n=2



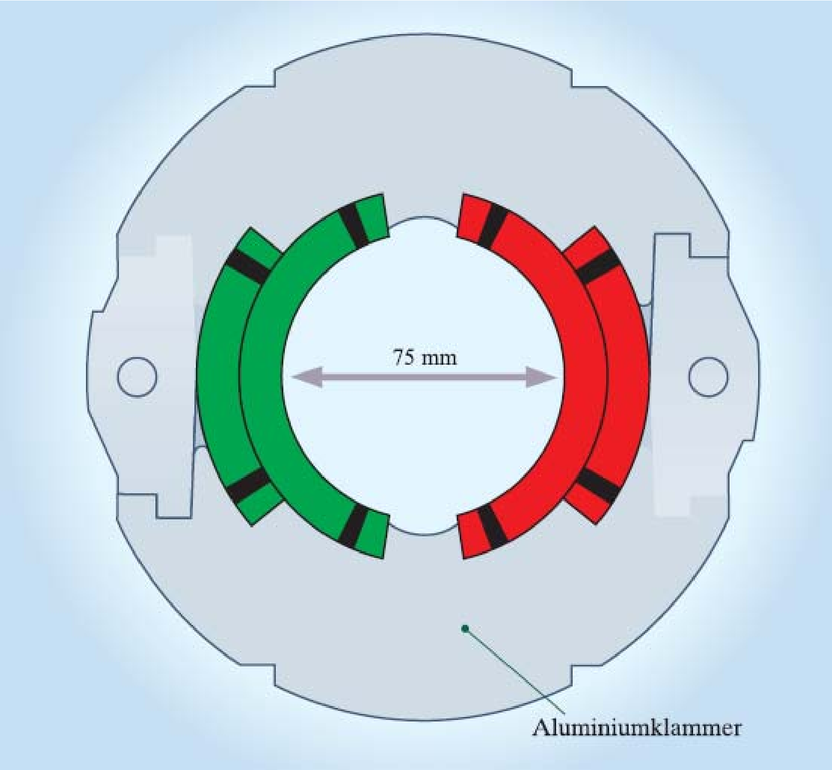
Cross section of dipole coil

pure dipole field

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



Cross section of the HERA dipole coil

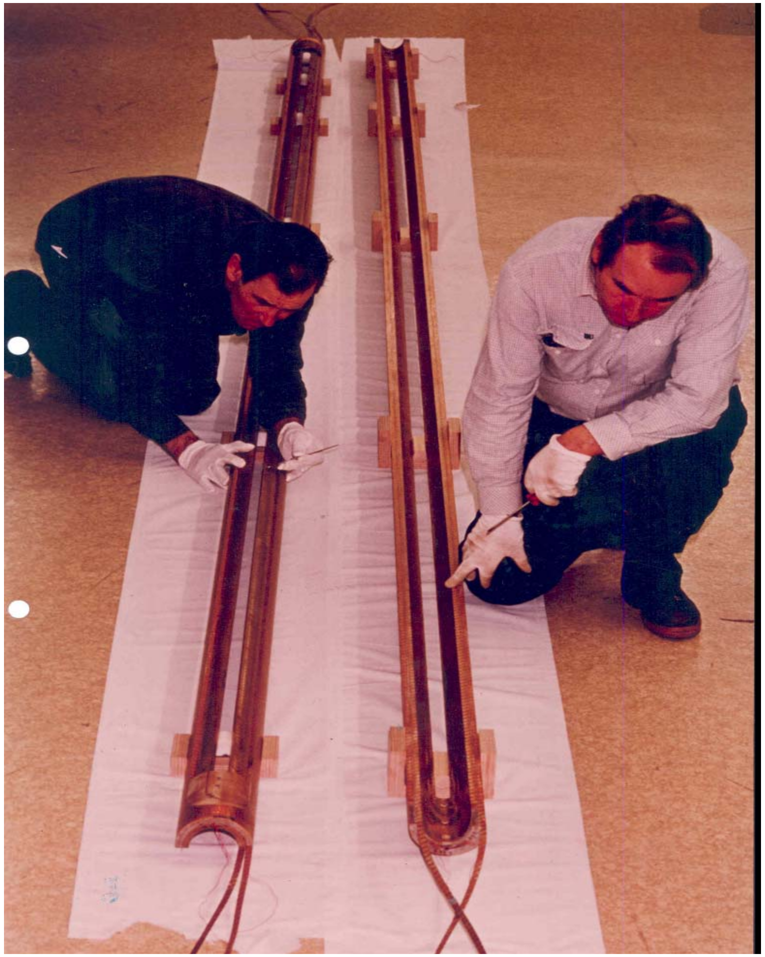


Very strong clamps define precise coil geometry and sustain huge Lorentz forces (>100 tons per meter)

Field errors less than 0.01%

Dipole coil winding at DESY with professional tooling

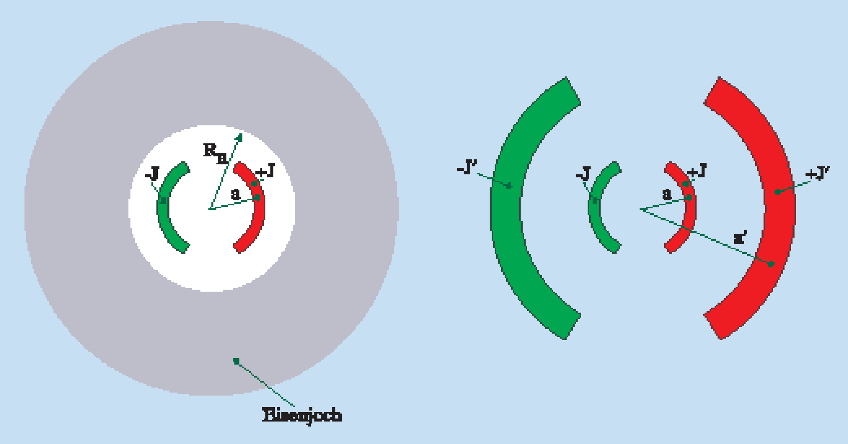
Winding of 6 m long dipole half-coils in DESY Hall 3



This winding machine was later shipped to BBC Mannheim

Iron yoke: cylindrical inner bore

use method of image currents to compute field

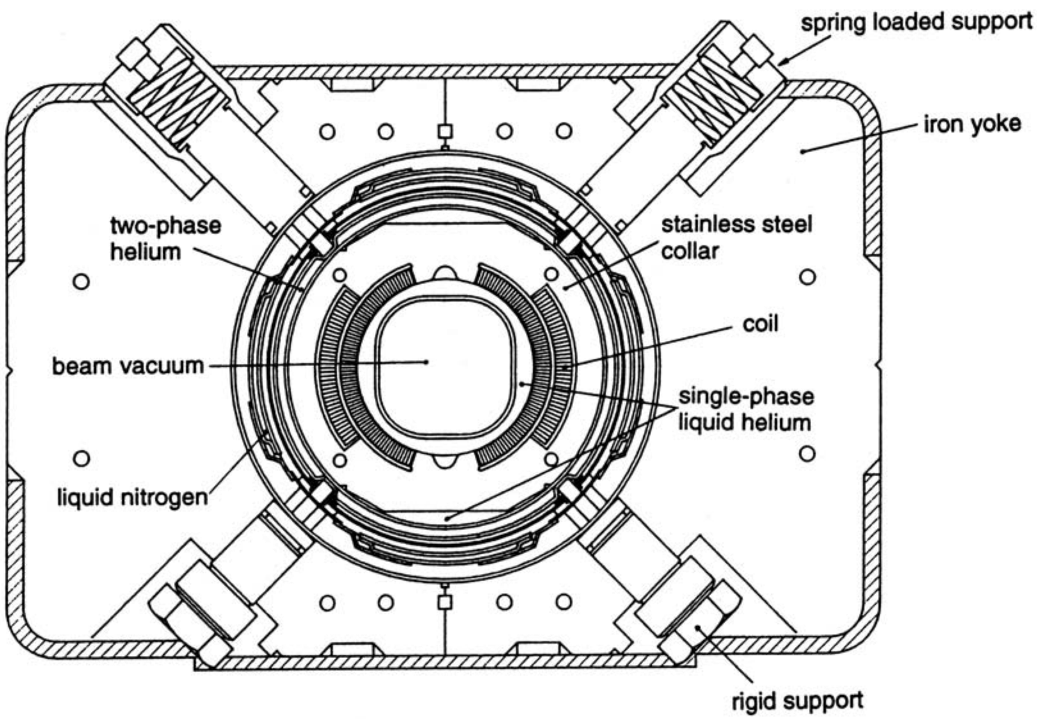


Important:

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.

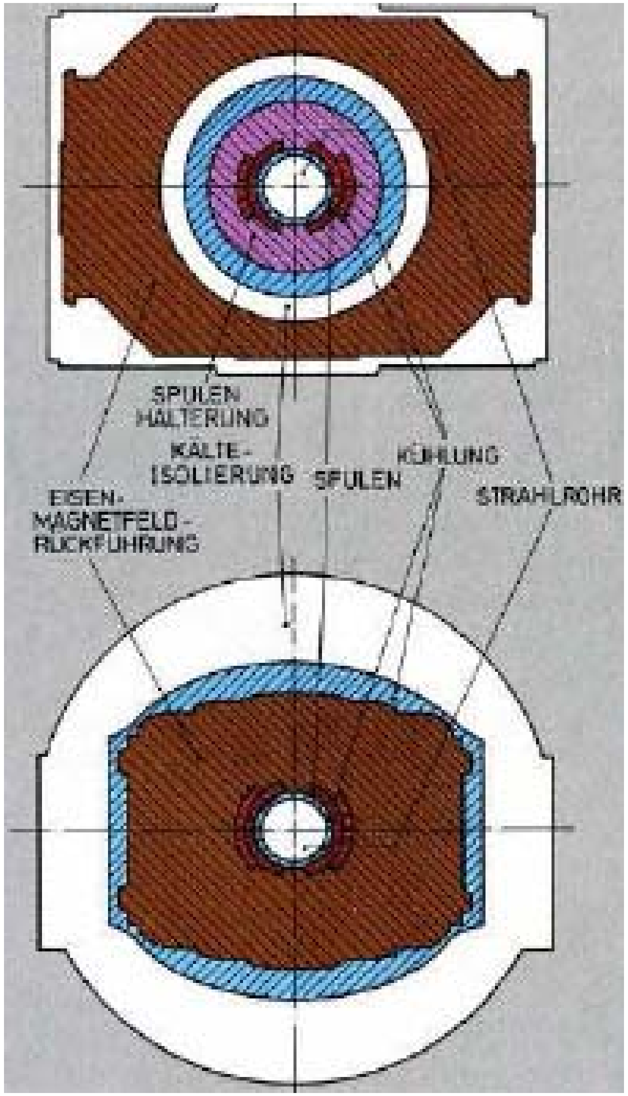
This is a „passive system“ like an automatic safety valve in a steam engine.
No electronics, thyristor switches or computer action are needed.

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

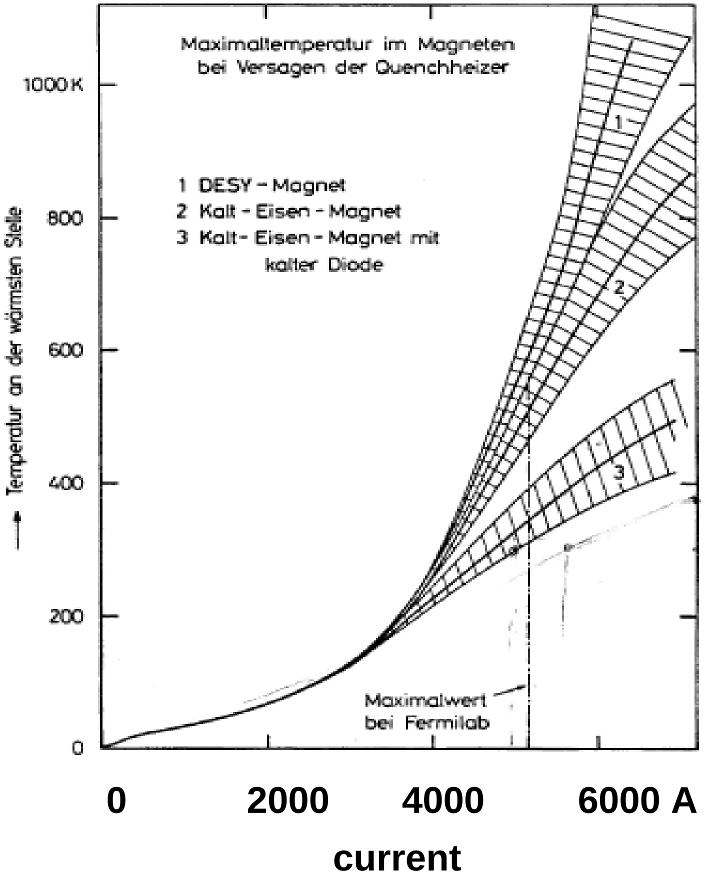
Two development lines for superconducting dipoles in early 1984



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.

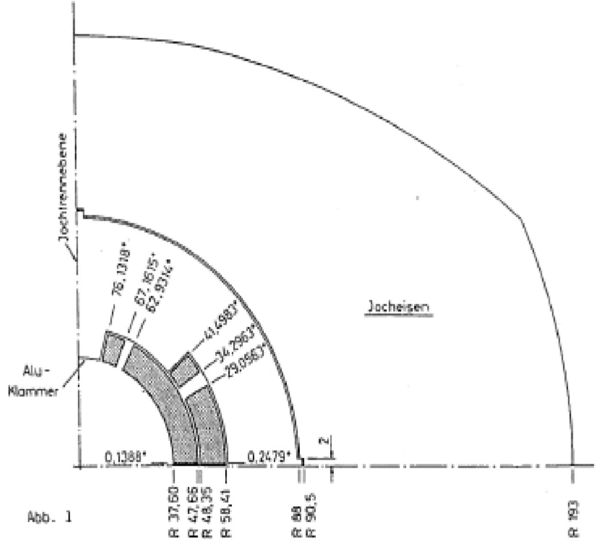
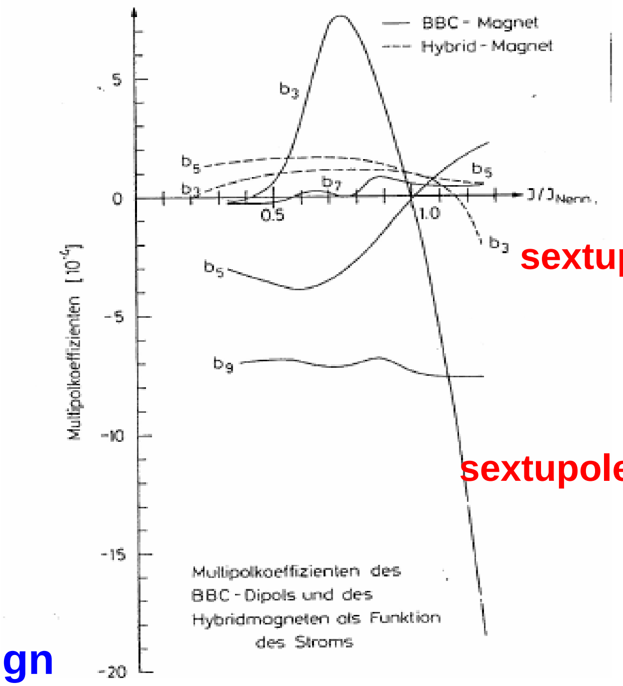


Abb. 1

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



Multipolkoeffizienten des BBC-Dipols und des Hybridmagneten als Funktion des Stroms

sextupole in hybrid magnet

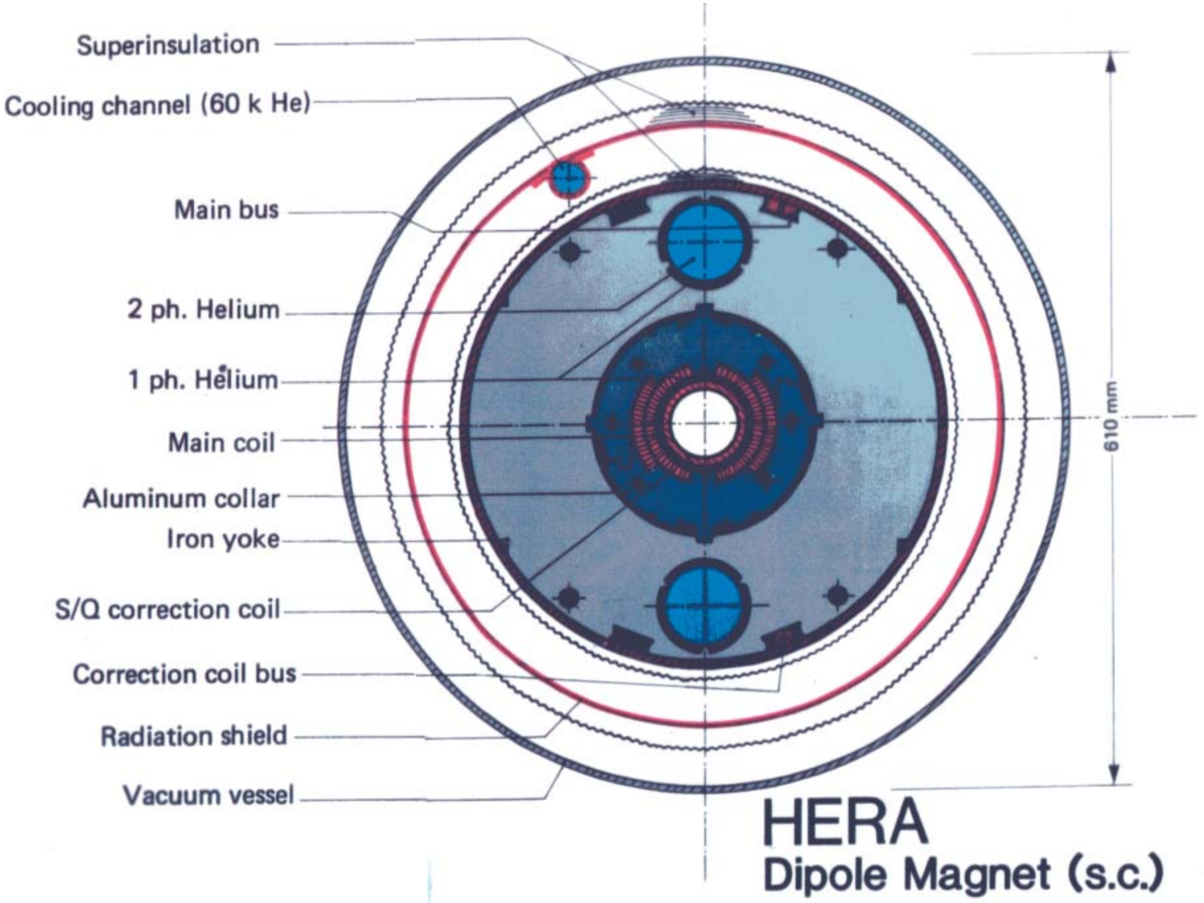
sextupole in BBC magnet

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

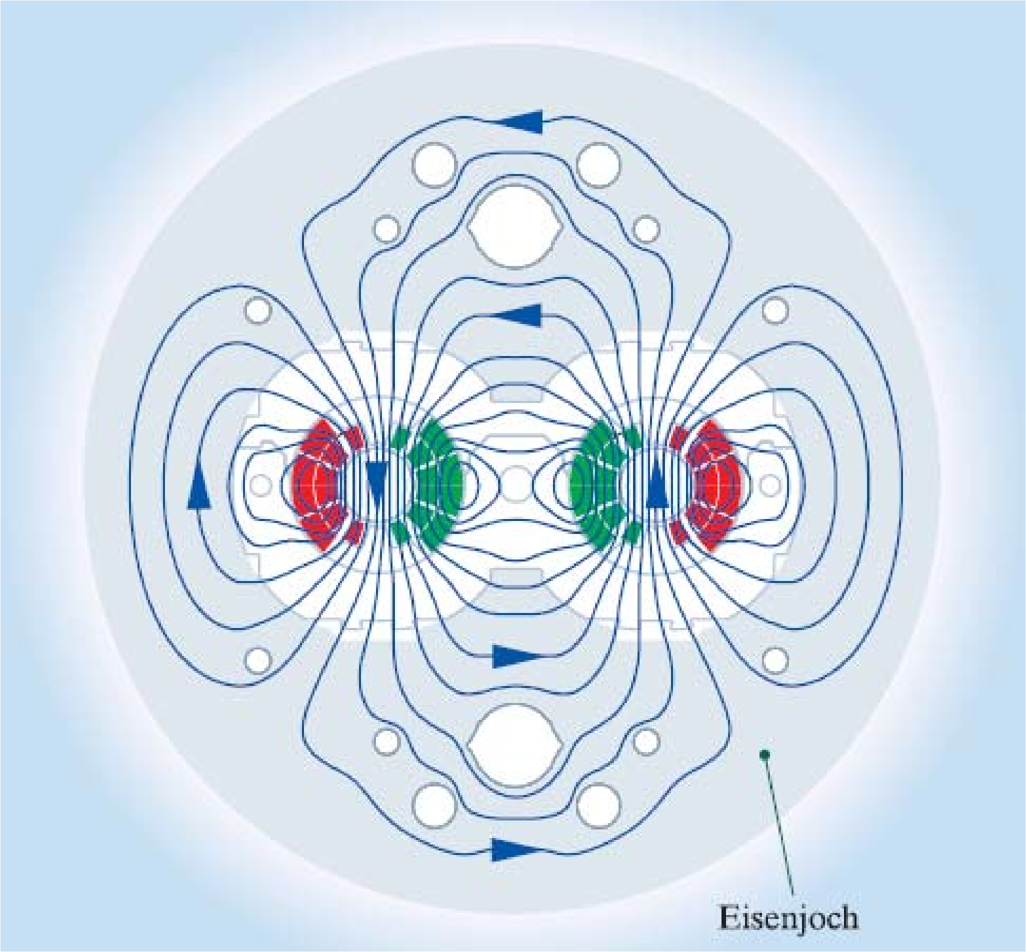
field errors below 0.01%

Only disadvantage:
large cold mass

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

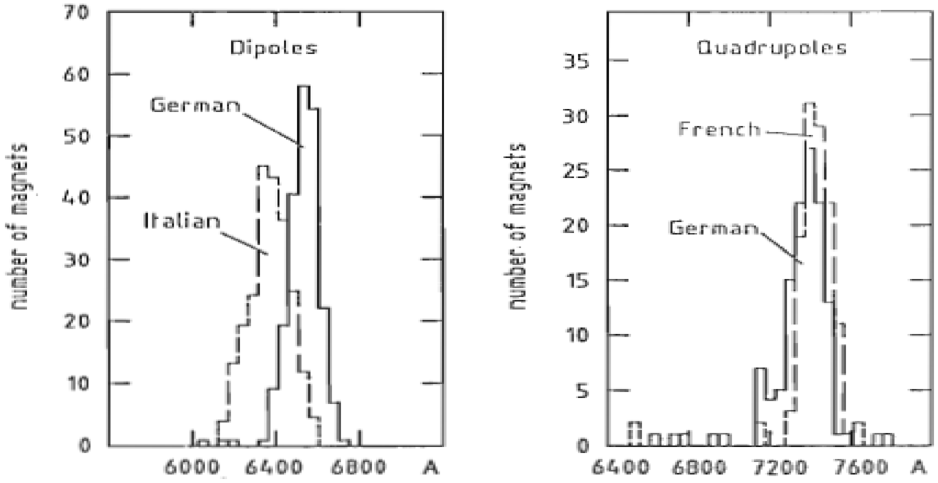
The twin-aperture LHC magnet

impossible with warm iron yoke



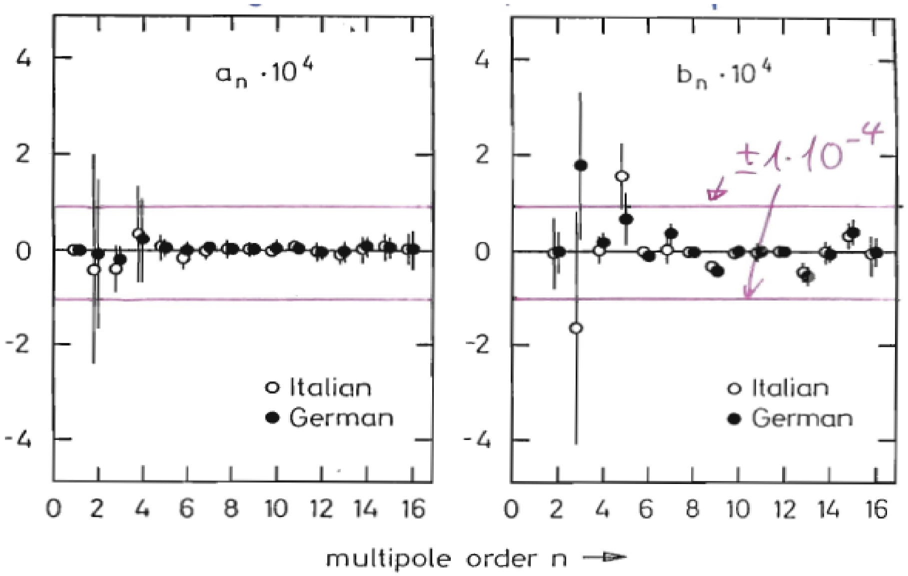
Remark: the iron yoke goes partly into saturation. The field line pattern inside the iron is computed numerically.
Courtesy S. Russenschuck, CERN

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

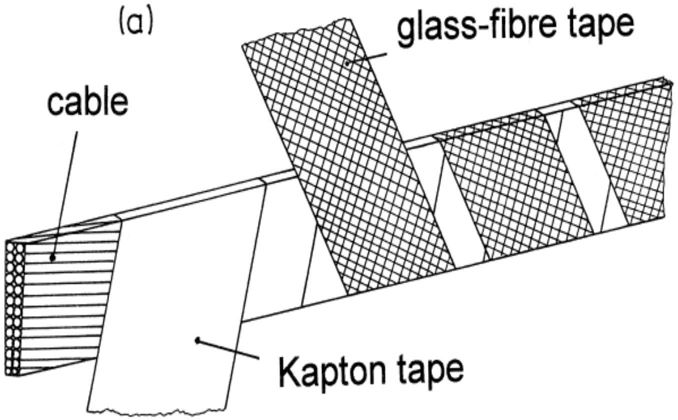
Two of our excellent technicians:
Gerd Tödten, Jürgen Holz

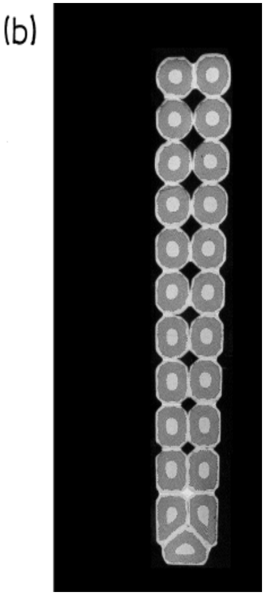
QY 518 is a superconducting quadrupole

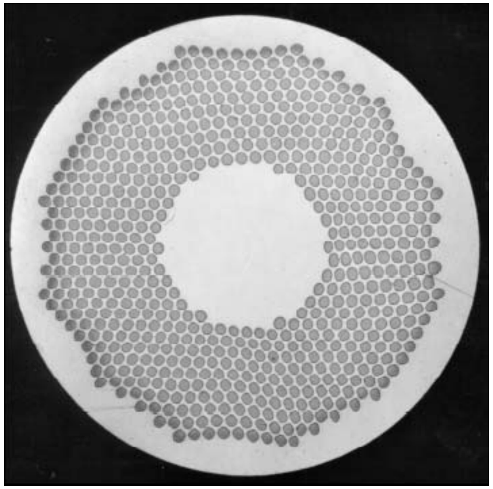
Below: module of electron ring
Sextupole, quadrupole and dipole
Design: H. Kaiser

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

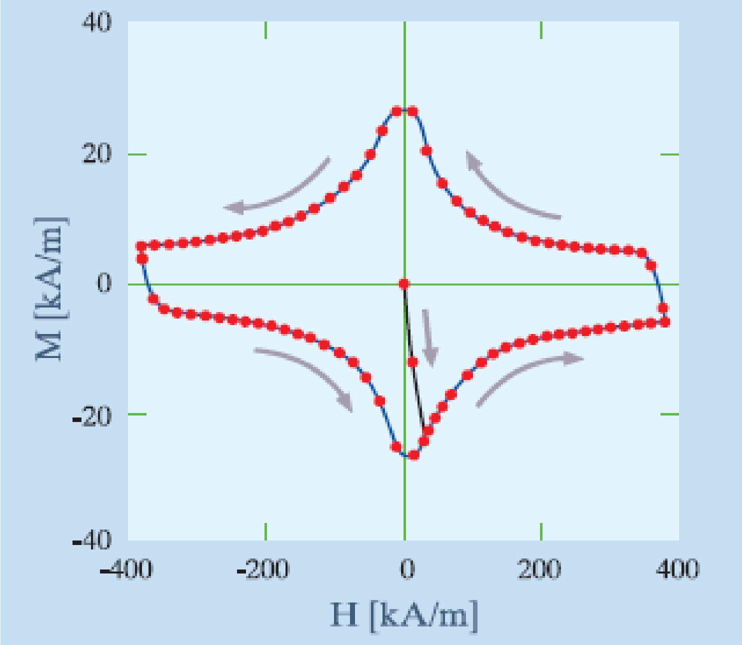
The superconducting cable



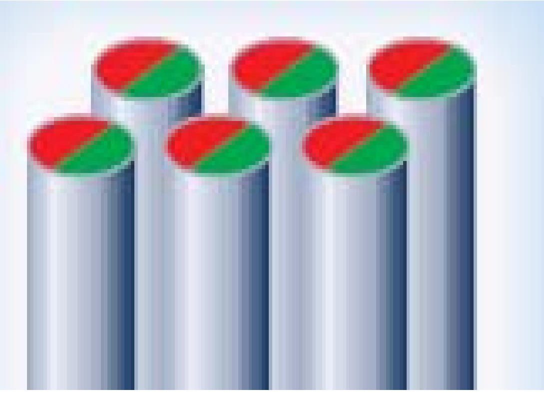




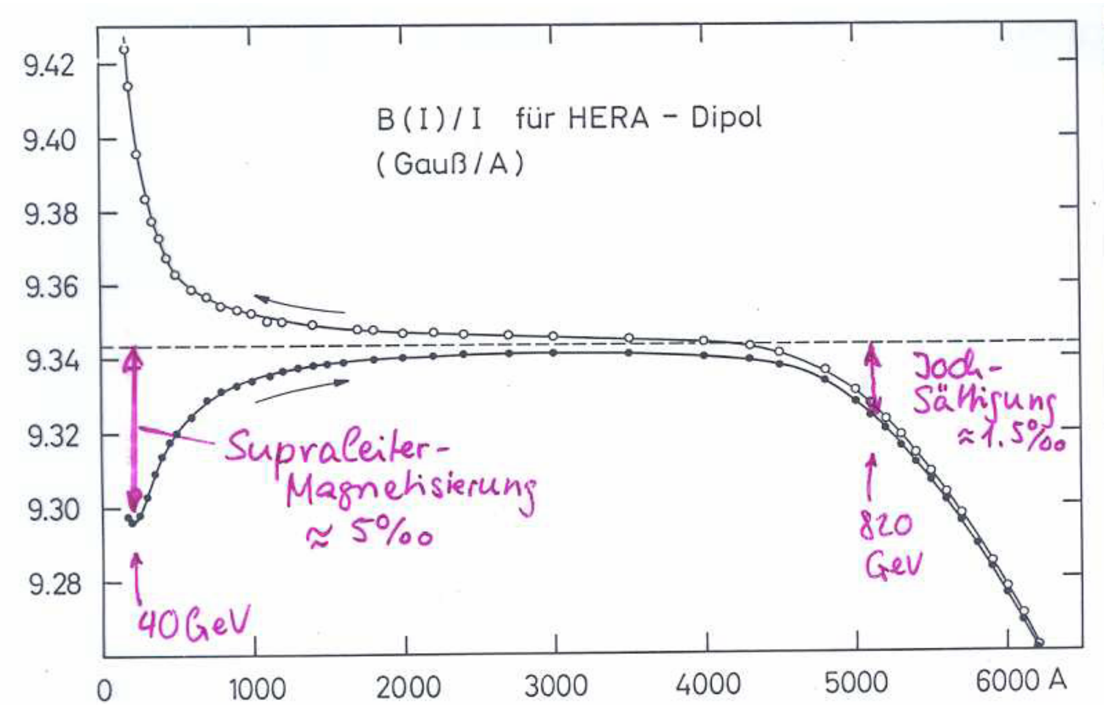
NbTi filaments in copper matrix

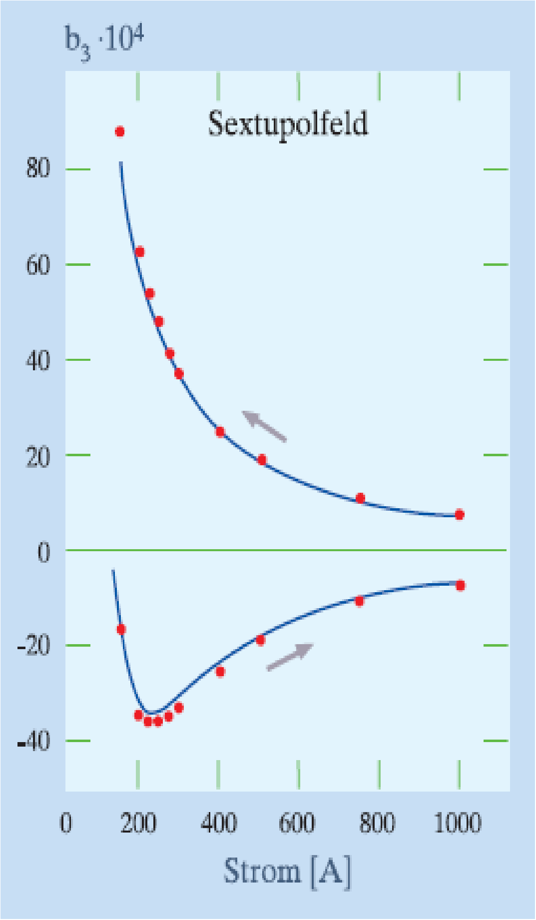


Persistent currents in the 14 μm thick NbTi filaments



Influence of persistent magnetization currents on dipole field





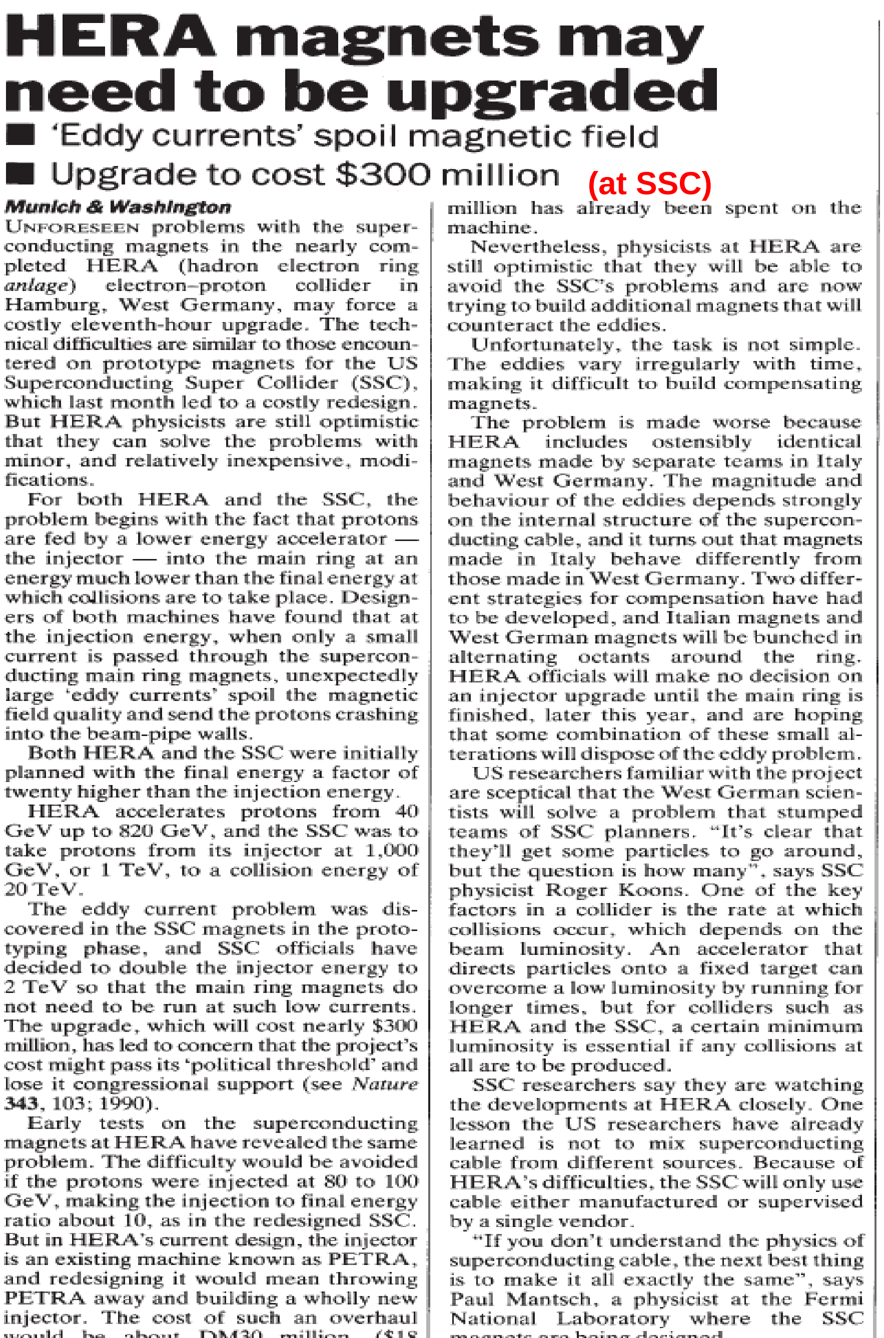
Dipole field B_1 at injection 0.5% lower

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

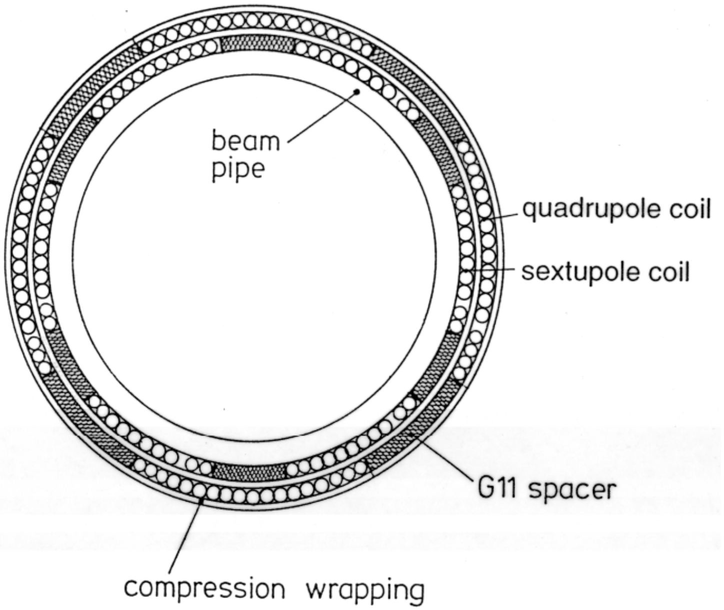
SSC solution:

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

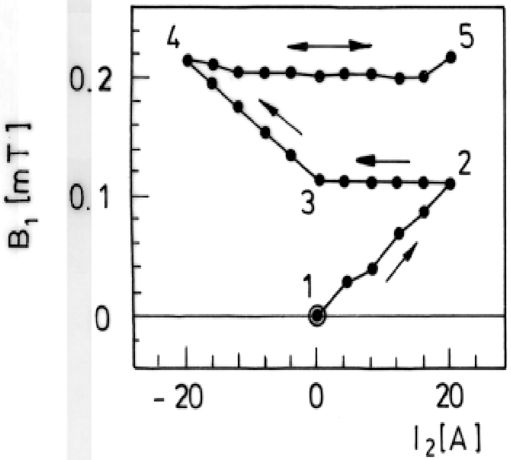
Built by Dutch industry

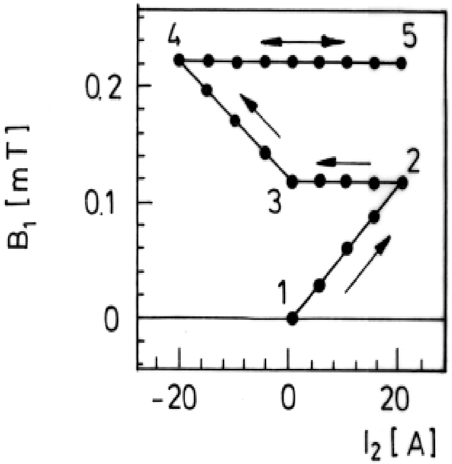
The unexpected behaviour of beam pipe correction coils

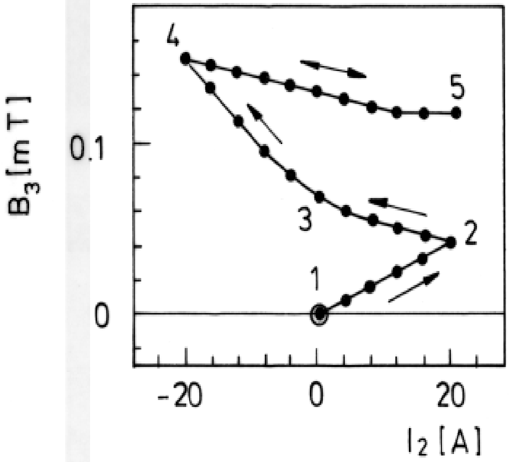
the coils may easily ruin the field quality of the dipole, and nobody realizes ist

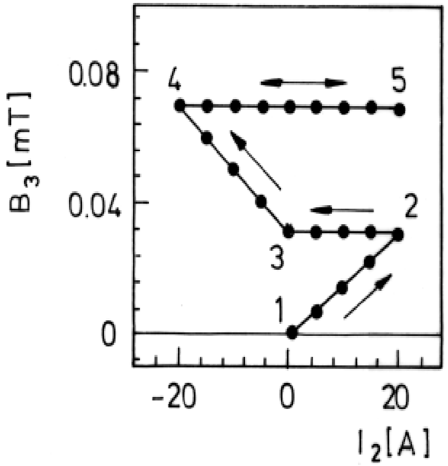
measurement

theoretical model









diploma thesis
Michael Pekeler

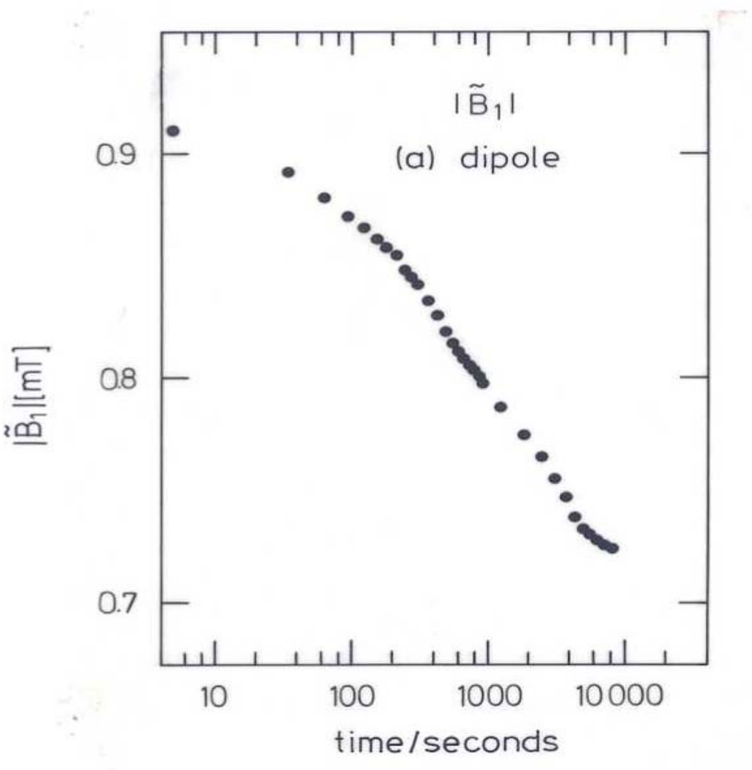
Remedy: large current cycle of main dipole removes all these field distortions

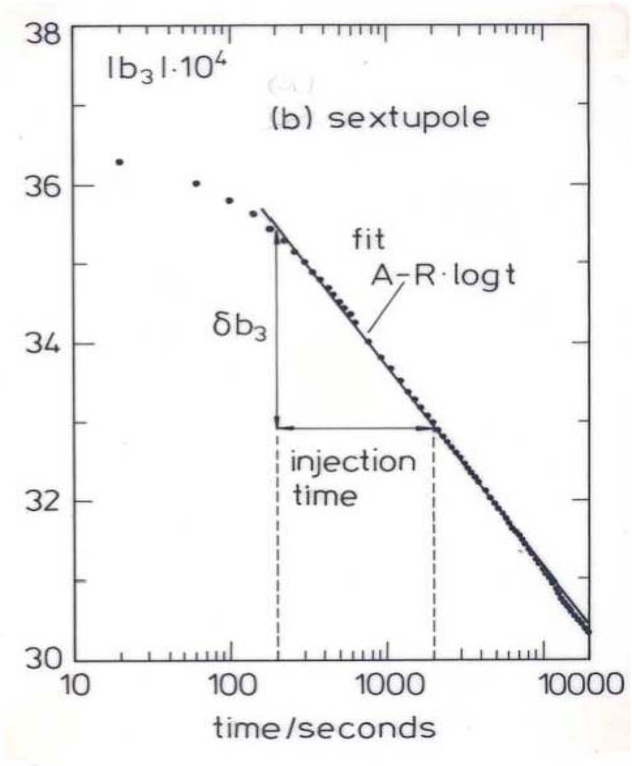
Explanation:

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

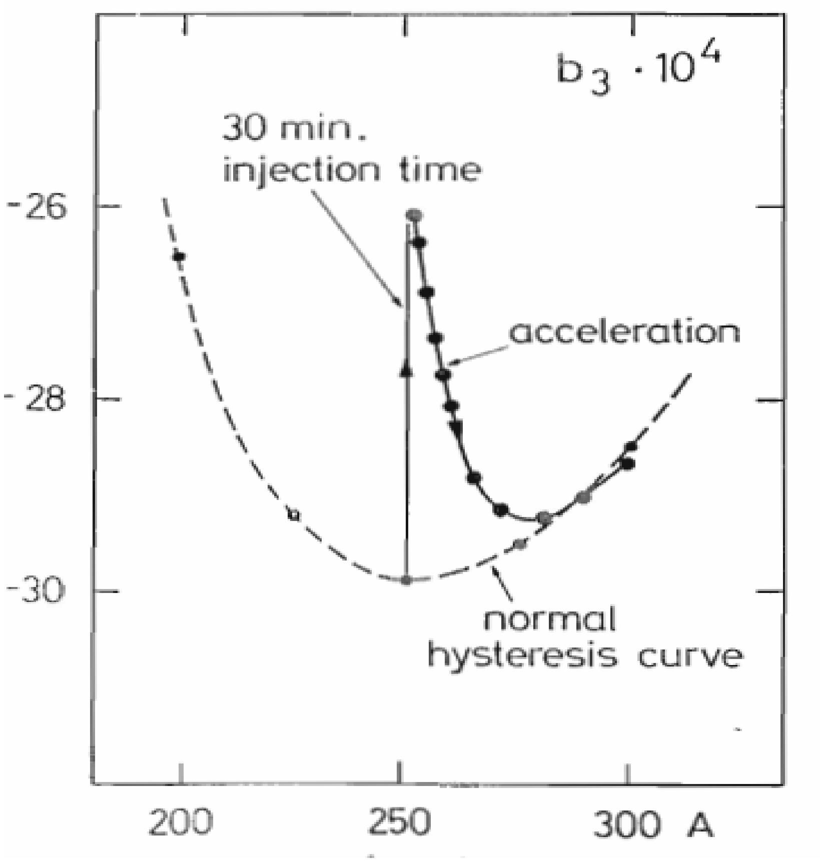
Injection and initial acceleration in HERA

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

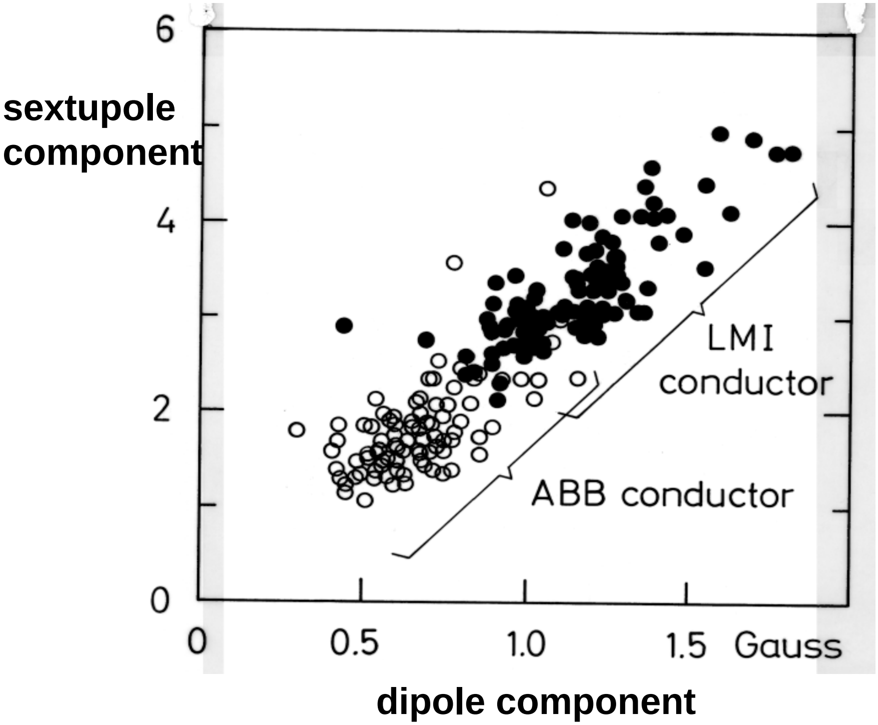
So one has to track rapid field changes

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

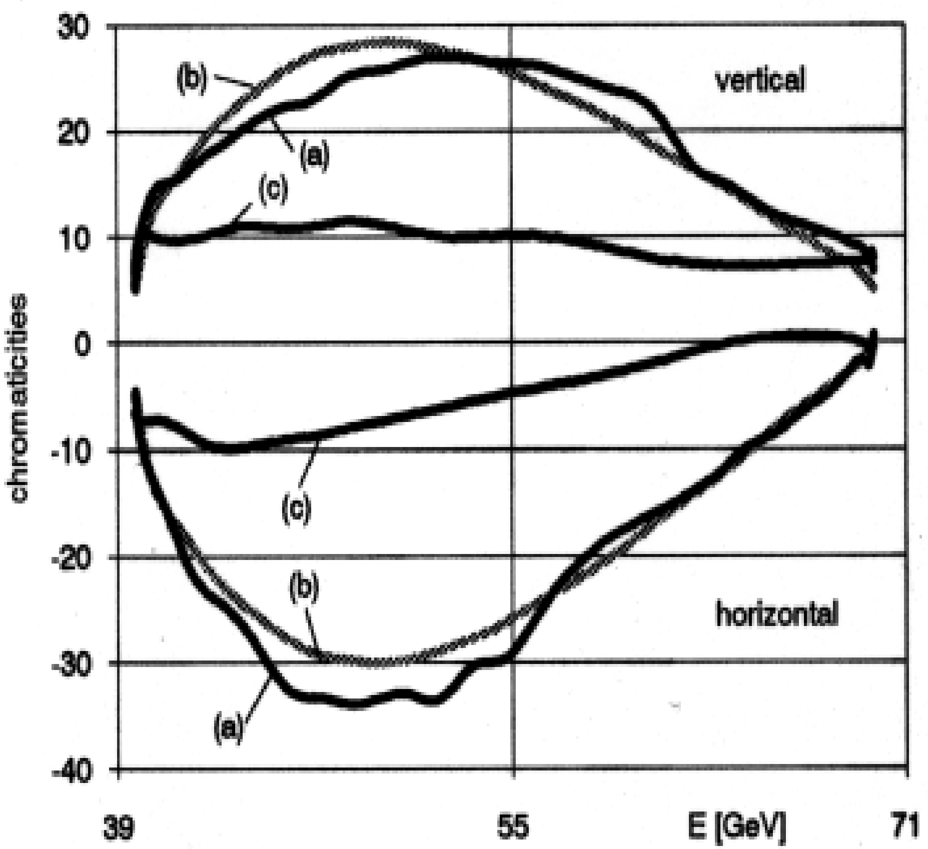
NMR measures B_1 at injection
Pickup coil provides dB/dt pulses which control currents in all correction coils and in all normal magnets of HERA-p

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.

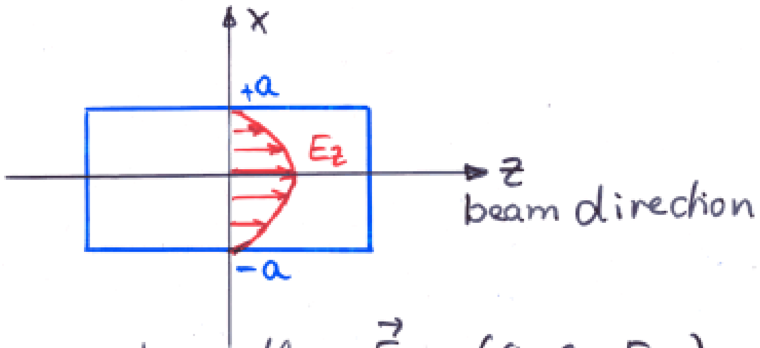
Microwave cavity for particle acceleration

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

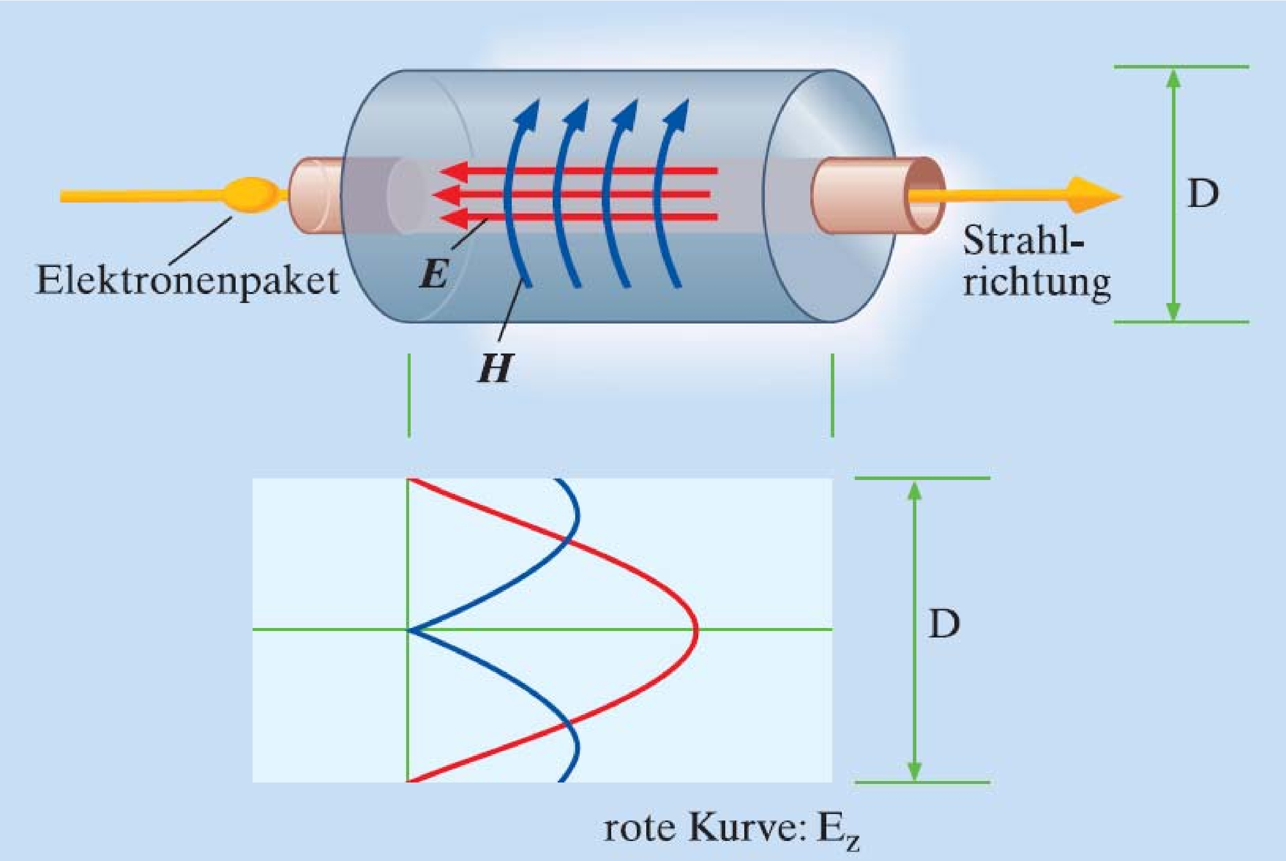
$$E_z(x, y, z, t) = E_0 \cos(k_1 x)\cos(k_2 y)\cos(\omega_0 t)$$

$$\left.\begin{aligned} &\text{bound. cond.} \Rightarrow k_1, k_2 = \frac{\pi}{2a} \\ &\vec{k}^2 = k_1^2 + k_2^2 = \frac{\pi^2}{2a^2} \end{aligned}\right\}$$

resonant frequency

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

Cylindrical cavity (pill box)

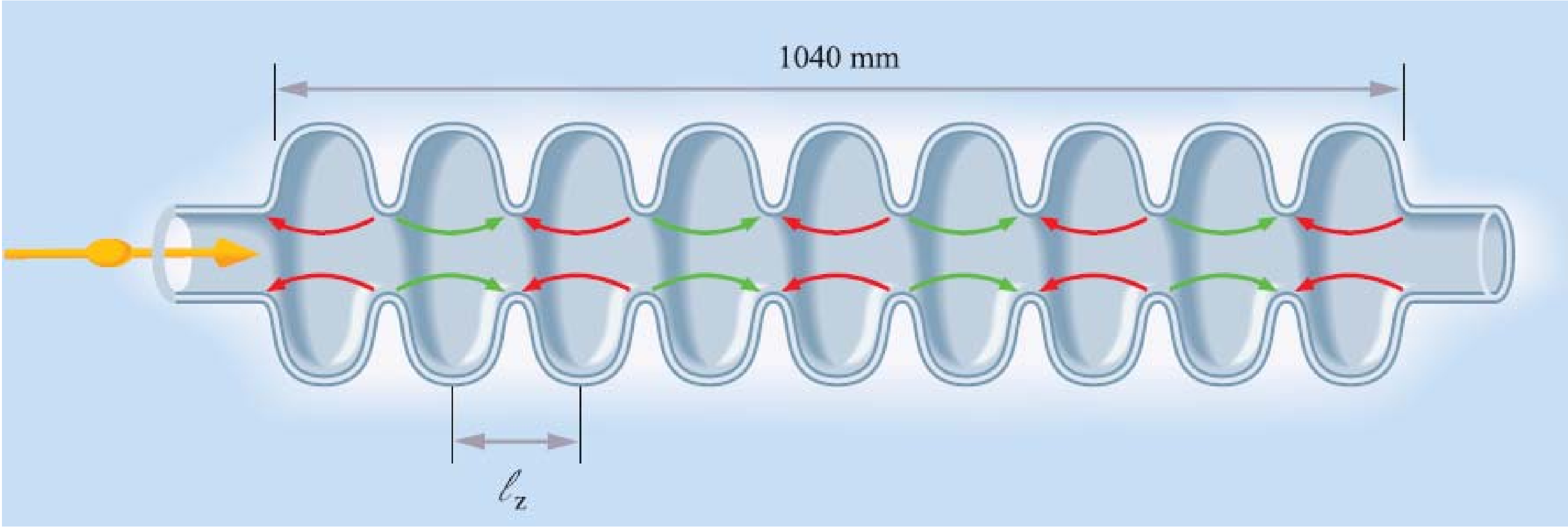


$$E_z(r,t) = E_0 J_0(\frac{\omega_0 r}{c}) \cos(\omega_0 t) \,,$$

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

Nine-cell TESLA cavity

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



Figures of merit of cylindrical cavity

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

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

$$Q_0 = \frac{G}{R_{surf}} \quad \text{with} \quad G = \frac{2.405\,\mu_0\,c}{2(1 + R_c/L_c)}$$

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

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

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

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

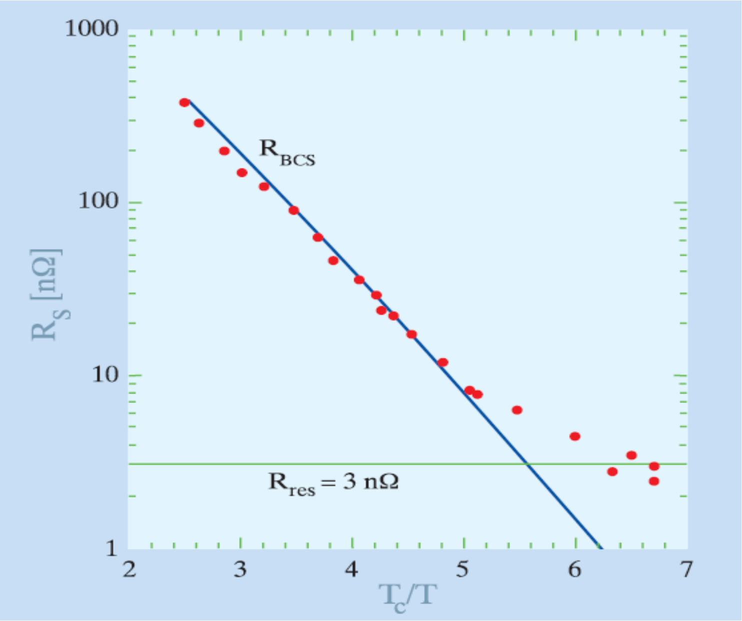
$$n_n \propto \exp(-E_g/(2k_BT))$$

and hence

$$\sigma_n \;\propto\; \ell\, \exp(-\Delta/(k_BT))\;. \tag{22}$$

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

$$\boxed{R_{BCS} \;\propto\; \lambda_L^3\,\omega^2\,\ell\,\exp(-1.76\,T_c/T)} \tag{23}$$



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

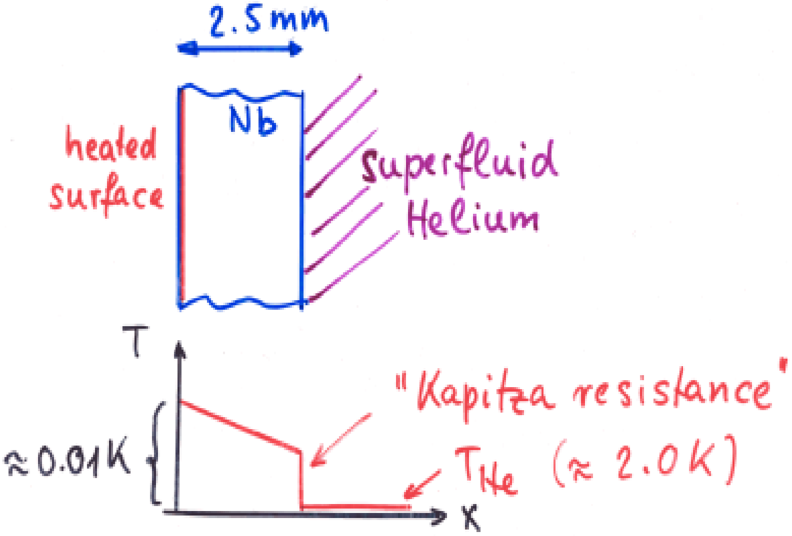
Example: 9-cell TESLA cavity at accelerating field of 25 MV/m,
quality factor > 10^{10} and beam current of 8 mA

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

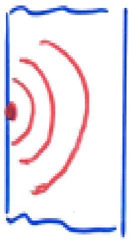
Big but: **1 W of heat flux into liquid helium at 2 K requires about 1000 W of electrical power in refrigerator**

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

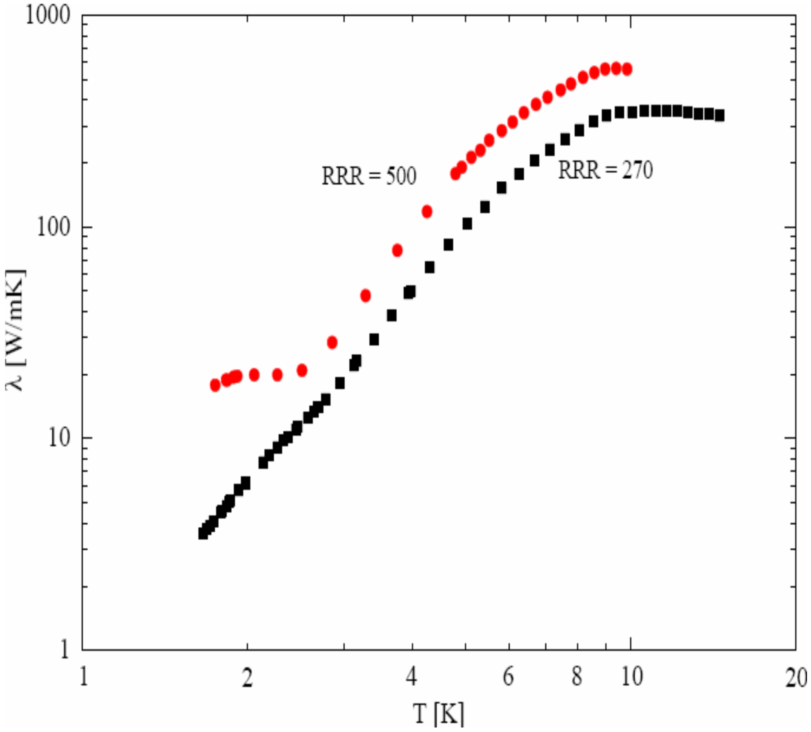


Much stronger heating due to small normal-conducting defects



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

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

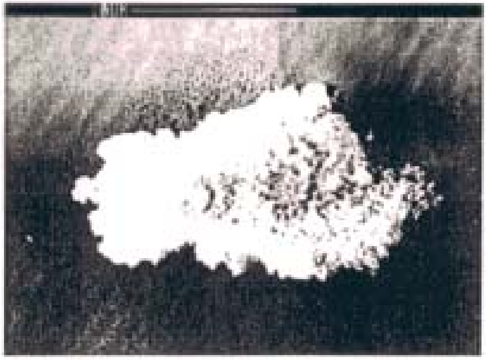


one needs very pure niobium

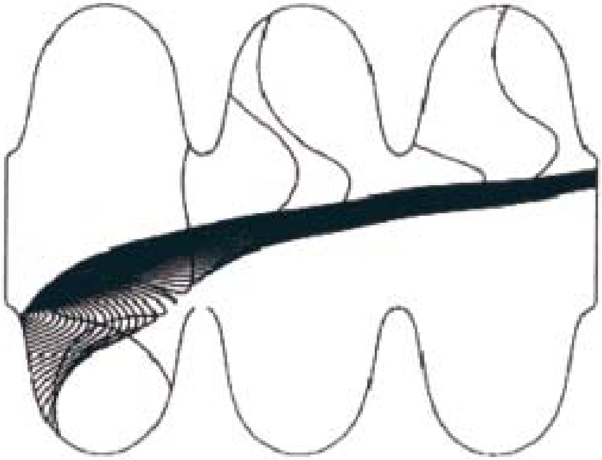
Strong limitation in many practical cavities

Field Emission

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

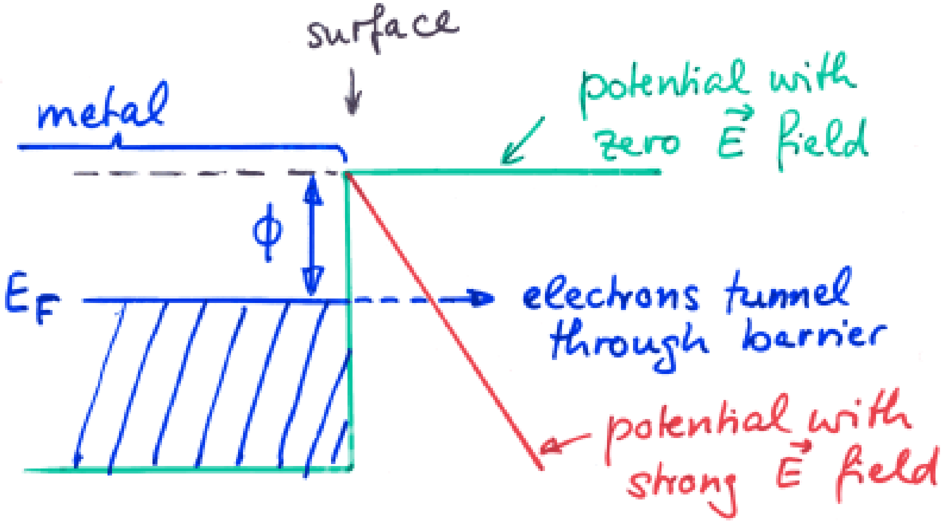

Particle causing field emission

Temperature map of a field emitter


Simulation of electron trajectories in a cavity

What is field emission?

Extraction of electrons from a metal via the quantum mechanical tunnel effect



current density given by Fowler-Nordheim equation

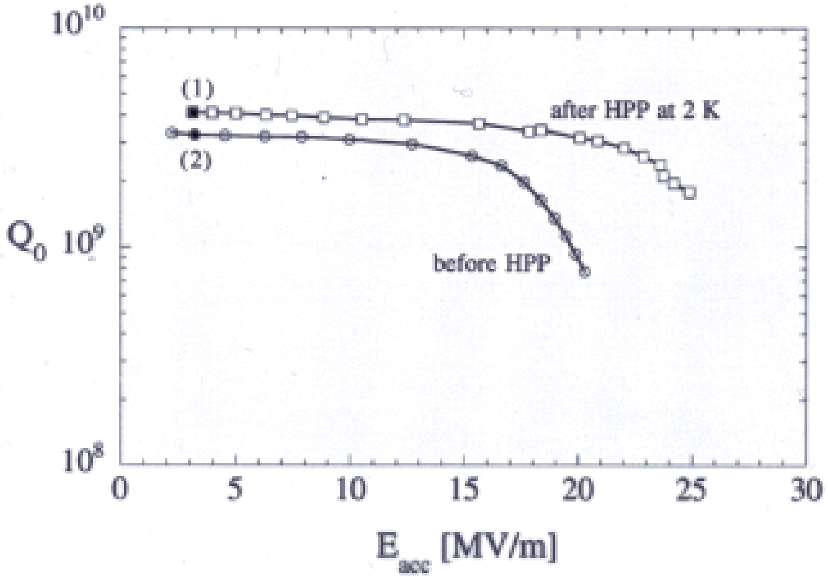
$$j(E) = \frac{A}{\phi} \left(\beta_{FN} \cdot E\right)^2 \exp\left(- \frac{B \cdot \phi^{3/2}}{\beta_{FN} \cdot E}\right)$$

ϕ: work function of metal

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



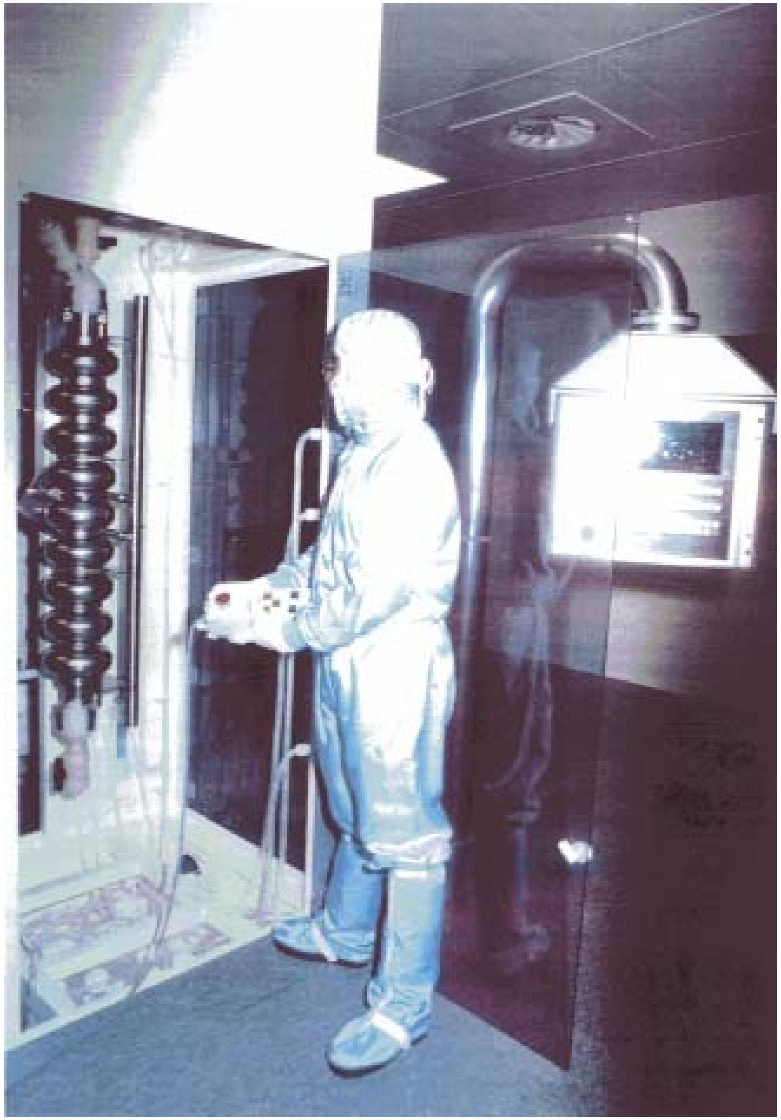
dissertation Michael Pekeler
U. of Hamburg

Clean room for cavity preparation

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

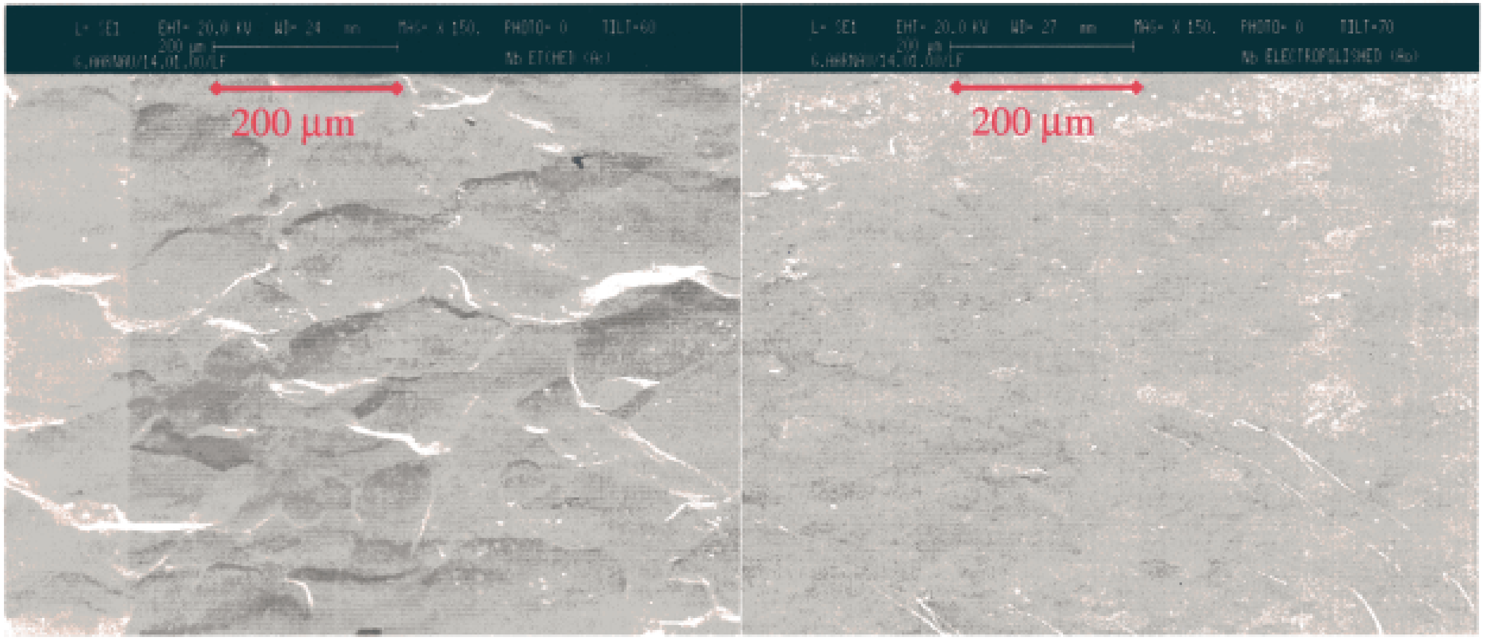
Fig. 6 Microphotograph of an emitting site: a) before emission; b) after emission. Note the apex melting.

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



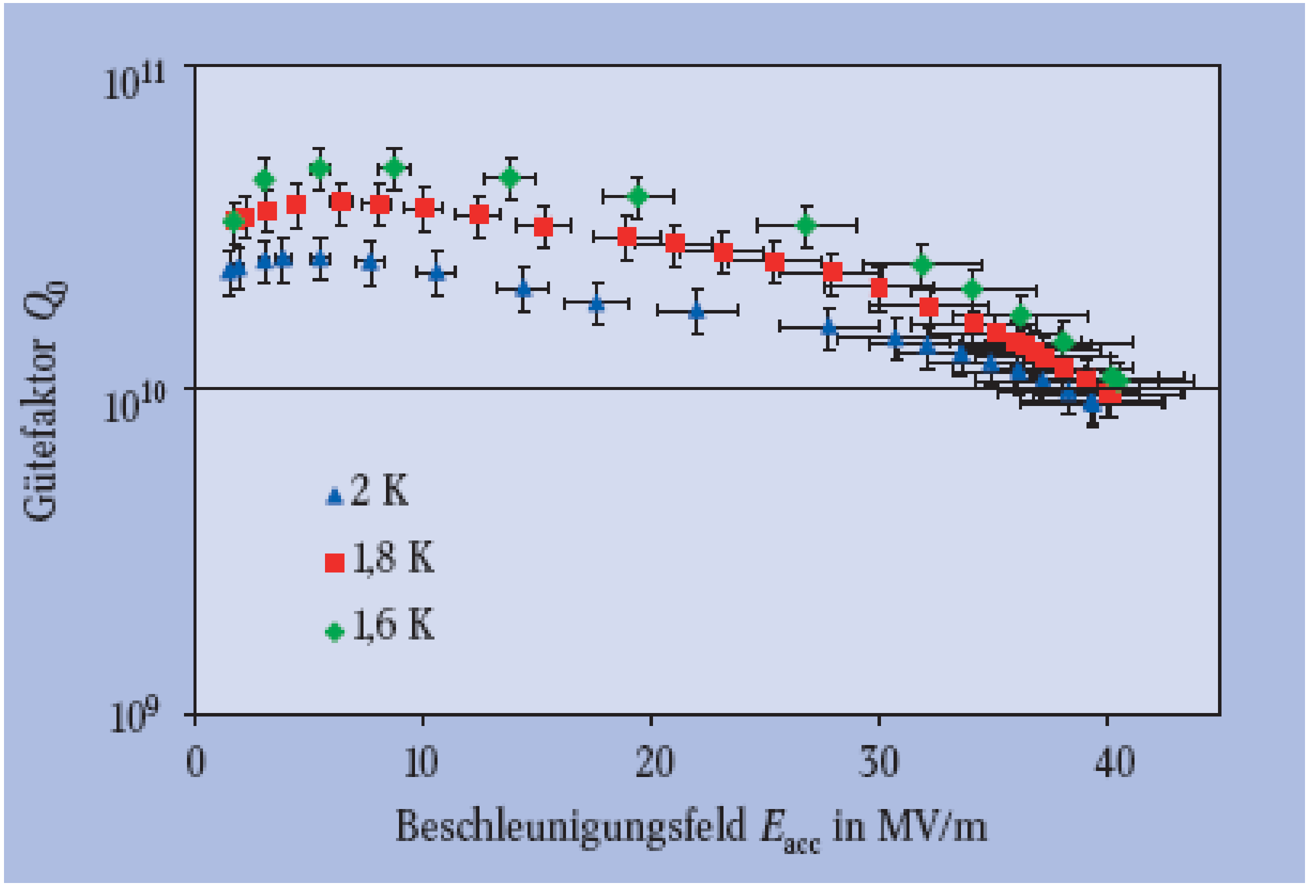
Improvement by electrolytic polishing of inner cavity surface

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 $B_c = 0.08$ T**
accelerating field < 20 MV/m

Niobium: **type II conductor**
At T = 2 K:
lower critical field $B_{c1} = 160$ mT **acc. field about 40 MV/m**
upper critical field $B_{c2} = 350$ mT
thermodynamical field $B_c = 200$ mT **acc. field almost 50 MV/m**

> 45 MV/m have been reached in 1-cell cavities

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