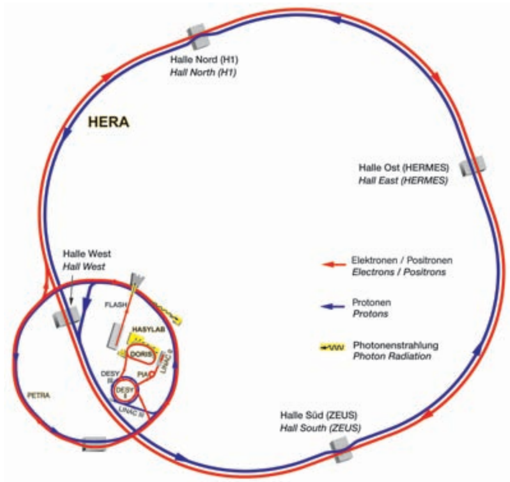
Superconductivity at DESY in Hamburg

Peter Schmüser, DESY and Univ. of Hamburg

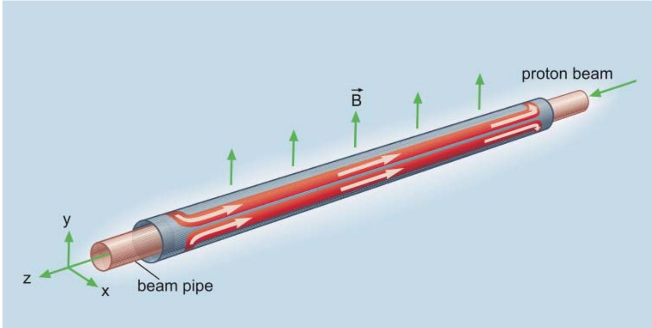
1) Superconducting magnets for proton storage ring
2) Superconducting cavities for linear electron accelerators

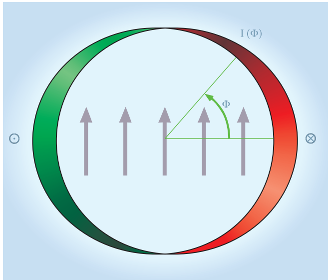
Electron-Proton Collider HERA

Superconducting proton storage ring, 920 GeV, field 5.3 Tesla
normal conducting electron storage ring, 27.5 GeV, field 0.17 Tesla
circumference 6.3 km

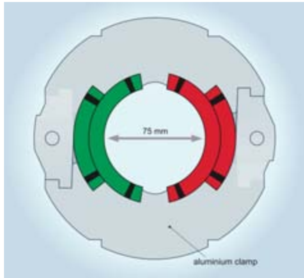


Schematic view of superconducting dipole coil





ideal coil: $I(\varphi) = I_0 \cos\varphi$



cross section of HERA coil

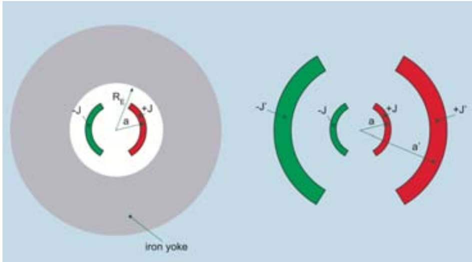
Dipole coil winding at DESY with professional tooling

Tooling was designed for industrial production
(H. Böttcher, M. Rüter, G. Deppe, S.Wolff, O. Peters, PS)

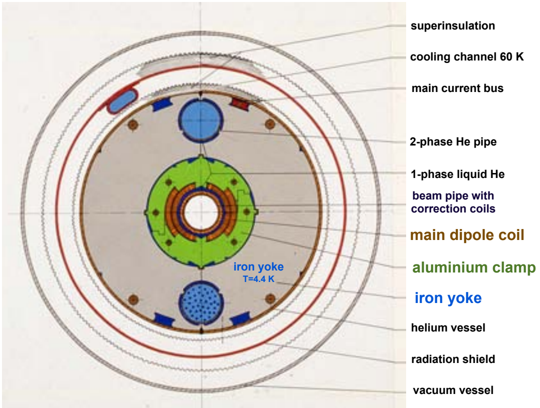
Winding of 6 m long dipole half-coils at DESY

This winding machine was later shipped to BBC Mannheim

Iron yoke: soft-iron cylinder with cylindrical inner bore



Field pattern dominated by coil
Iron yoke contribution computed
by image current-method



Cross section of HERA dipole:

coil, yoke, cryostat

The magnet measurement hall

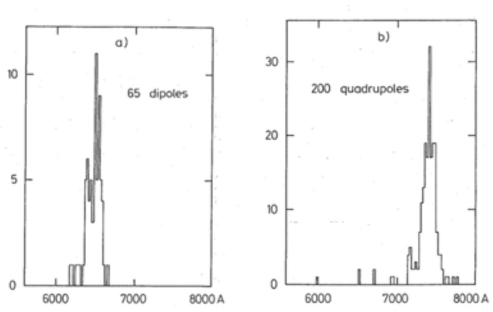
Helium refrigerator

All magnets were quench-tested

extensive field measurements:
Field integral, multipoles,
persistent-current effects

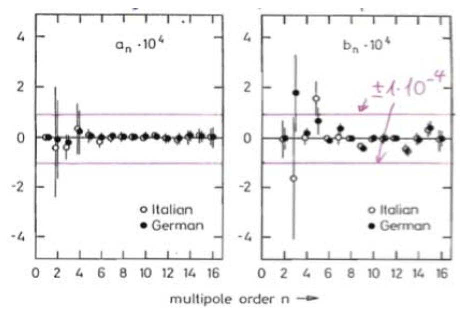
Installation in the tunnel

Excellent performance of supercond. dipoles and quadrupoles



all dipoles exceed nominal current of 5000 A by 25%

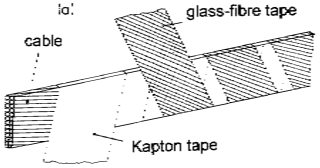
quadrupoles go even higher

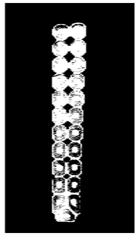


multipoles of 440 dipoles all within specified limits

Exception: sextupole, decapole these are compensated by correction coils

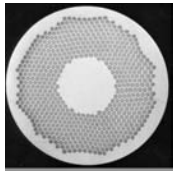
Superconducting cable





Niobium-titanium filaments in copper matrix
Rutherford-type cable with 24 strands
1230 filaments per strand
Critical current about 6000 A at T = 4.5 K and B = 5.5 T

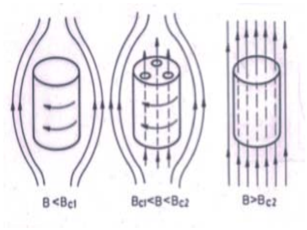
HERA magnets are cooled with pressurized normal liquid helium of 4.3 Kelvin

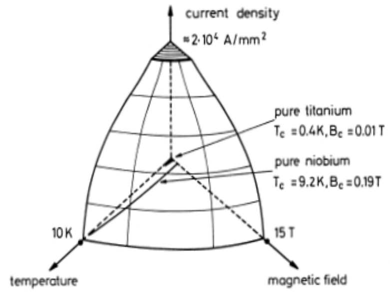


strand diameter 0.82 mm

The niobium-titanium superconductor

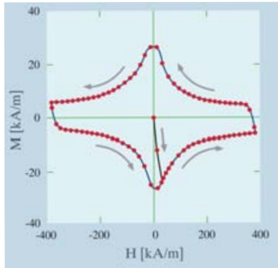
Type II superconductor with strong flux pinning





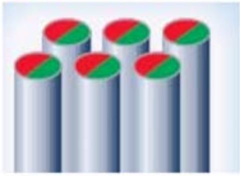
Flux pinning is indispensible to achieve large current density, but is has a price:

Magnetic hysteresis

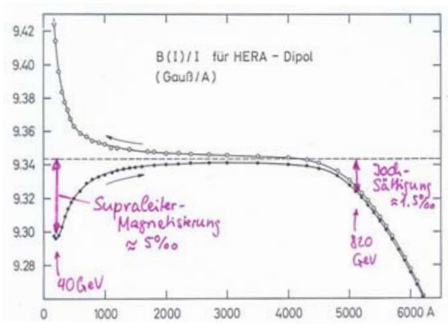


magnetization of superconductor hysteresis

Persistent currents in the 14 μm thick NbTi filaments



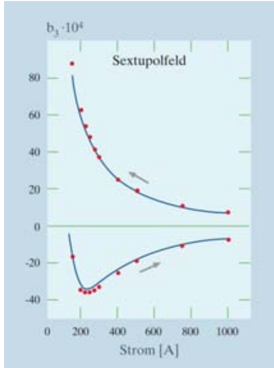
Influence of persistent magnetization currents on dipole field



Dipole field B_1 at injection 0.5% lower

Remedy: correction magnets with non-linear current control

These correction magnets (dipoles, quadrupoles, sextupoles) were built by Dutch industry

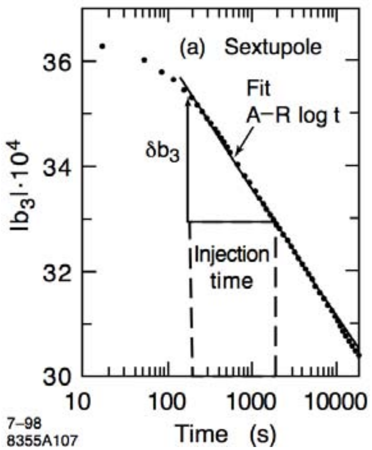


Strong sextupole component 30 times larger than tolerable

Solid curves:
absolute model prediction

The next surprise: persistent current multipoles are time-dependent

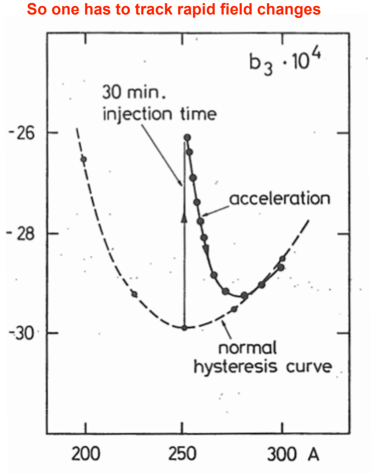
discovered at the FNALTevatron, chromaticity changed with time



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



The reference magnets for controlling the magnets currents

proposed by D. Degele, PS

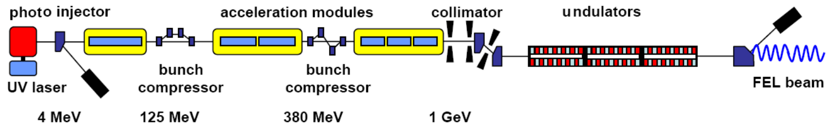
Installed in HERA Hall West:
1 ABB and 1 Ansaldo dipole
connected in series with main ring

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

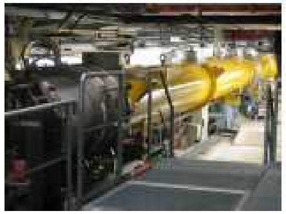
Rotating coil measures sextupole field in real-time,
controls sextupole correctors

Free-Electron Laser FLASH, aerial view

Layout of the FLASH machine



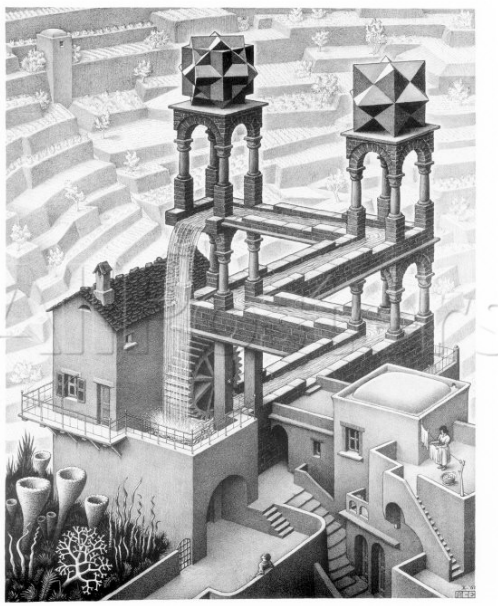
Electron source



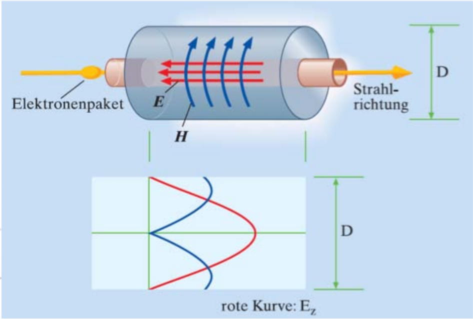
Superconducting linear accelerator

Undulator magnet system

The perpetuum mobile of Maurits Cornelis Escher

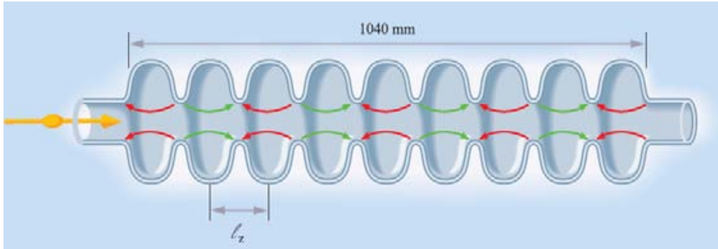


In practice we need radio-frequency cavities to accelerate particles



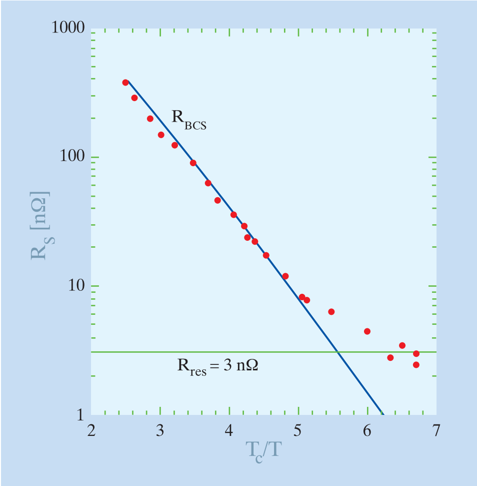
Nine-cell superconducting 1.3 GHz cavity

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



Cavity made from ultrapure niobium
operated with superfluid helium at 2 Kelvin
accelerating field more than 25 MV/m
quality factor > 10^{10}

Microwave surface resistance



superconductors have R = 0 in dc fields
but R > 0 in ac fields

Bardeen-Cooper-Schrieffer theory:
BCS surface resistance drops
exponentially with temperature

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

Quality factor of Nb cavity is > 10^{10} at 2 Kelvin
but 100 times smaller at 4 Kelvin

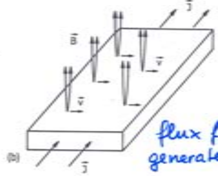
Cooling with superfluid helium (low pressure) at 1.9 - 2 Kelvin

Requirements on superconductor

flux tubes in Nb

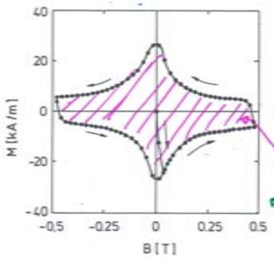
(U. Essmann)

Hard Superconductors



flux flow generates heat

force ~ $\vec{J} \times \vec{B}$



produced heat is

$\mu_0 \oint M(H)\, dH$

area enclosed by the loop

hysteresis in NbTi

For sc-magnets: flux-flow inbited by pinning centers

Not good for micro-wave cavities: magn. hysteresis causes energy dissipation

→ use "soft" supercond.

Requirements on superconductor

Requirements on Superconductor:

general : high critical temper. T_c

(but not "High-T_c" ceramic S.C.)

Accelerator magnets

B_c large ⇒ only type II, alloys

strong flux pinning ⇒ lattice defects etc

⇒ need "dirty" superconductor

NbTi $T_c = 9.2K$, $B_{c2} \approx 14T$

very ductile, easily extruded with Cu

the "Standard conductor"

Nb_3Sn $T_c = 18K$, $B_{c2} \approx 20T$

brittle material, difficult to use in accelerator magnets

Microwave cavities

high heat conductivity, no flux pinning

⇒ need very pure superconductor

Pb $T_c = 7.2K$ $B_c = 80mT$

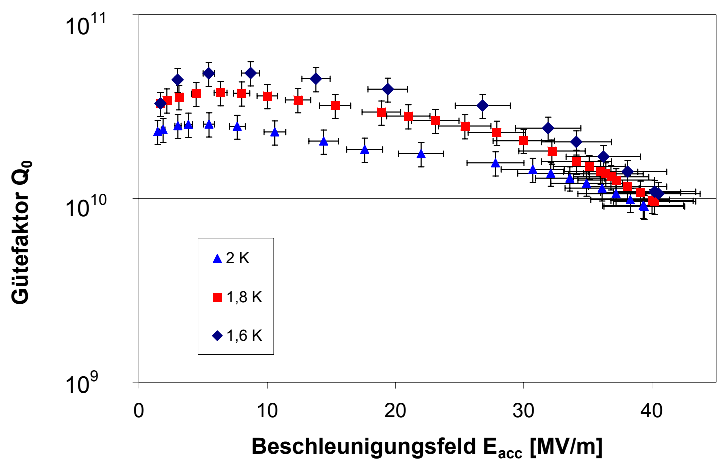
Nb $T_c = 9.2K$ $B_c^{th} = 200mT$

B_c = 200 mT corresponds to accelerating field of 45 - 50 MV/m

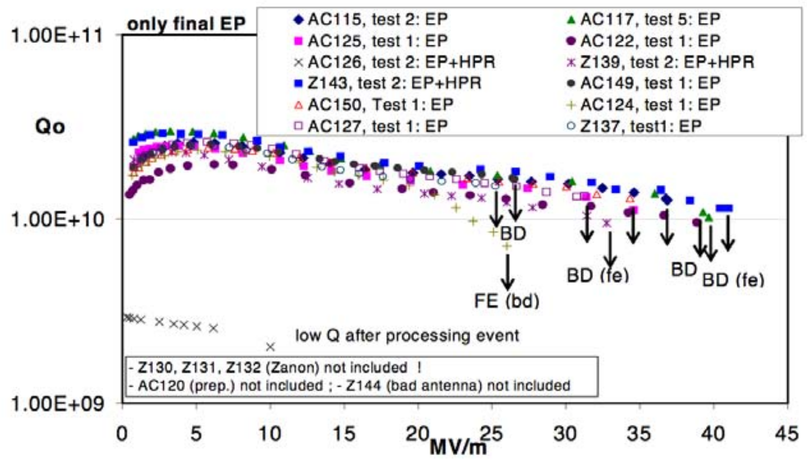
(depending on cavity geometry)

Accelerating field in nine-cell 1.3 GHz niobium cavity

Quality factor as function of gradient



Recent industrial cavity production for X-Ray FEL



These cavities are close to the physical limit

Installation of acceleration module in FLASH linac
contains 8 nine-cell cavities each 1 m long