Lecture 5: The hardware

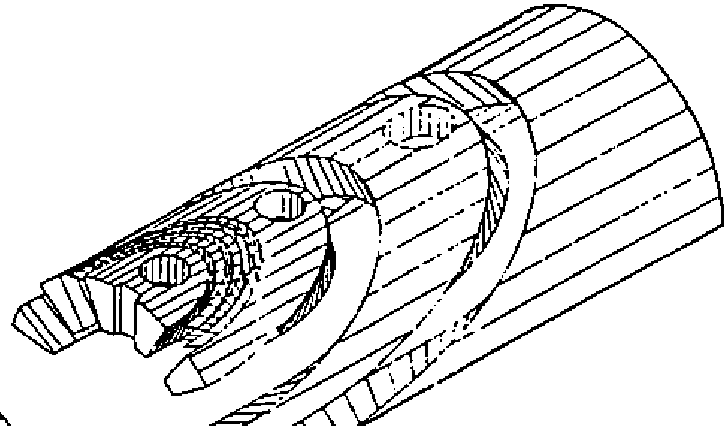
Plan

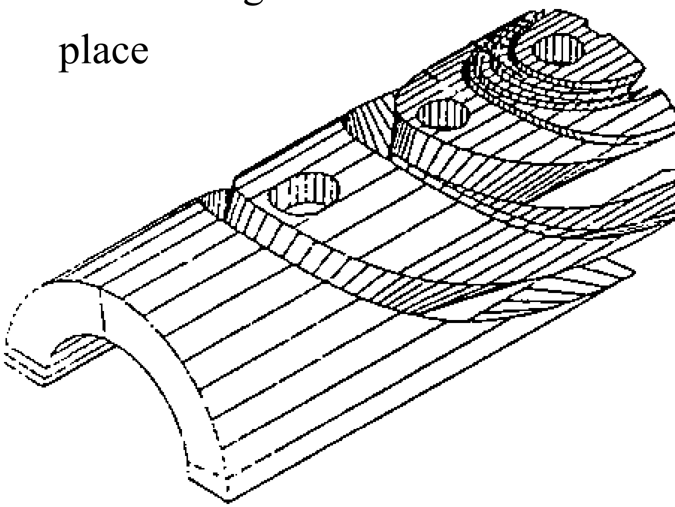
- coil winding and curing
- forces and clamping
- magnet assembly, collars and iron
- cryostats
- installation
- current leads
- some superconducting accelerators

Winding the LHC dipoles

End turns

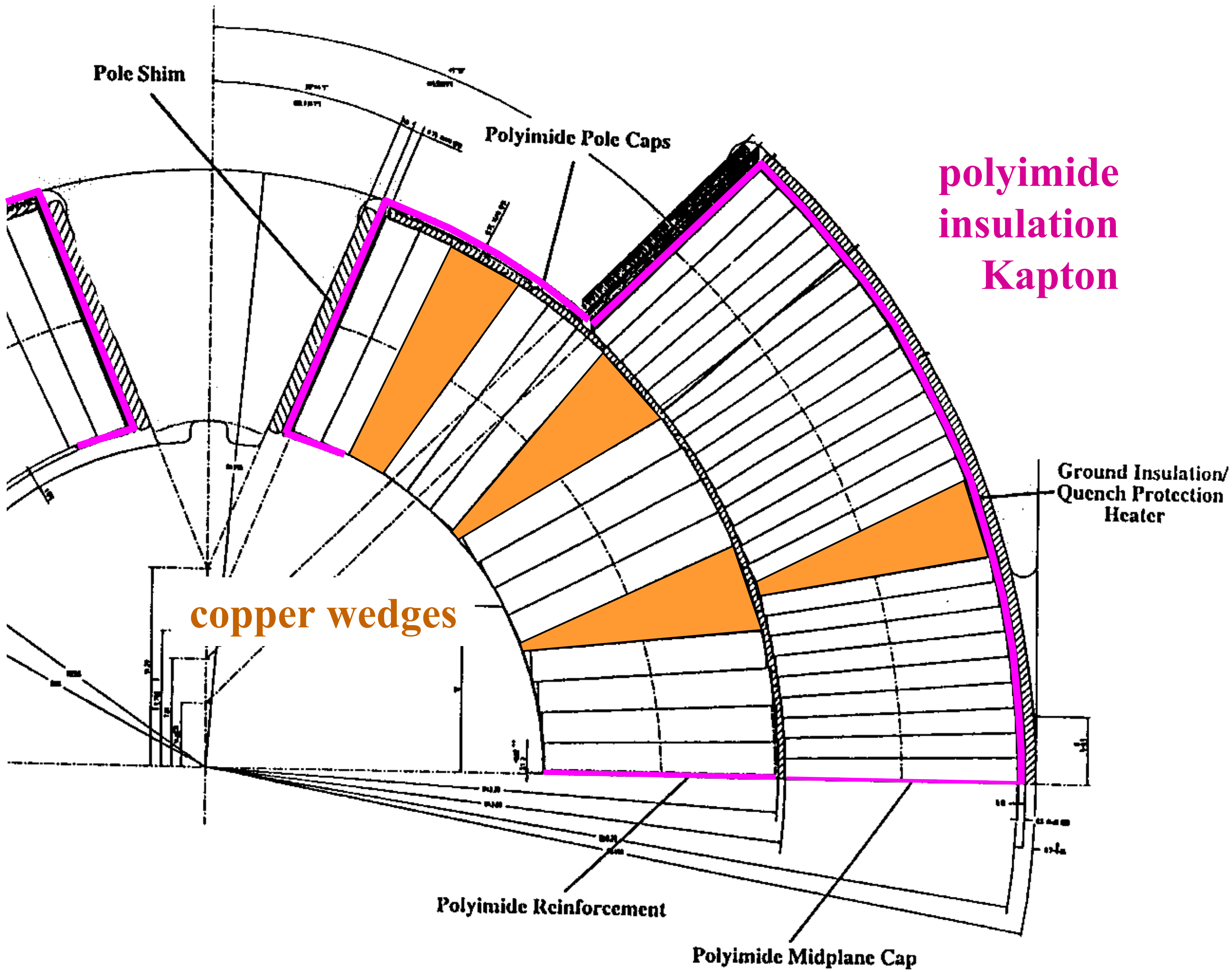
constant perimeter end spacers
help in winding the end turns
because, if the cable is
pulled tight, it will
sit in the right
place





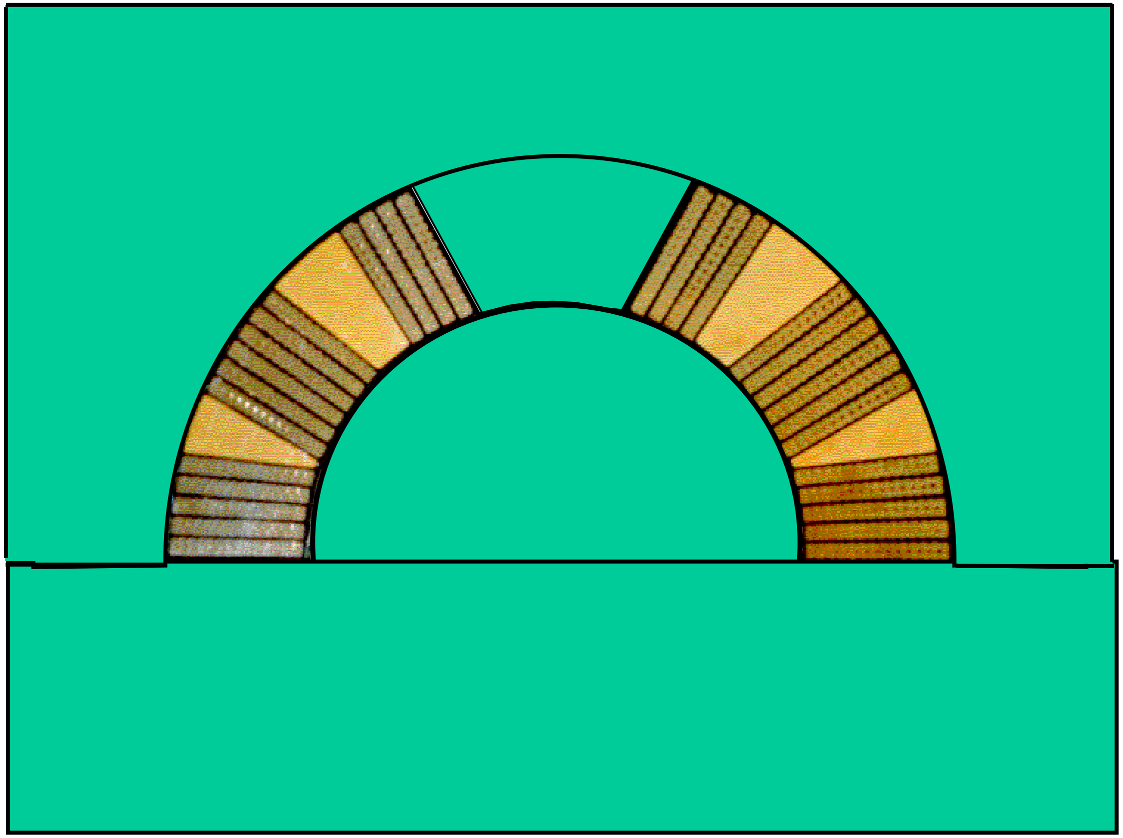
Spacers and insulation

- copper wedges are placed between blocks of winding
- beware of voltages at quench
- great care needed with the insulation, between turns and ground plane
- example: FAIR dipole quench voltage = 340V over 148 turns



Compacting and curing

- After winding is complete, the half coil, which is still very 'floppy' is placed within an accurately machined tool and put into the curing press.
- Here it is compacted to the exact outer dimensions and heated to activate the bonding agent on the insulation. With Kapton insulation this is usually a polyimide adhesive
- After curing, the half coil is quite rigid and easy to handle



Curing press

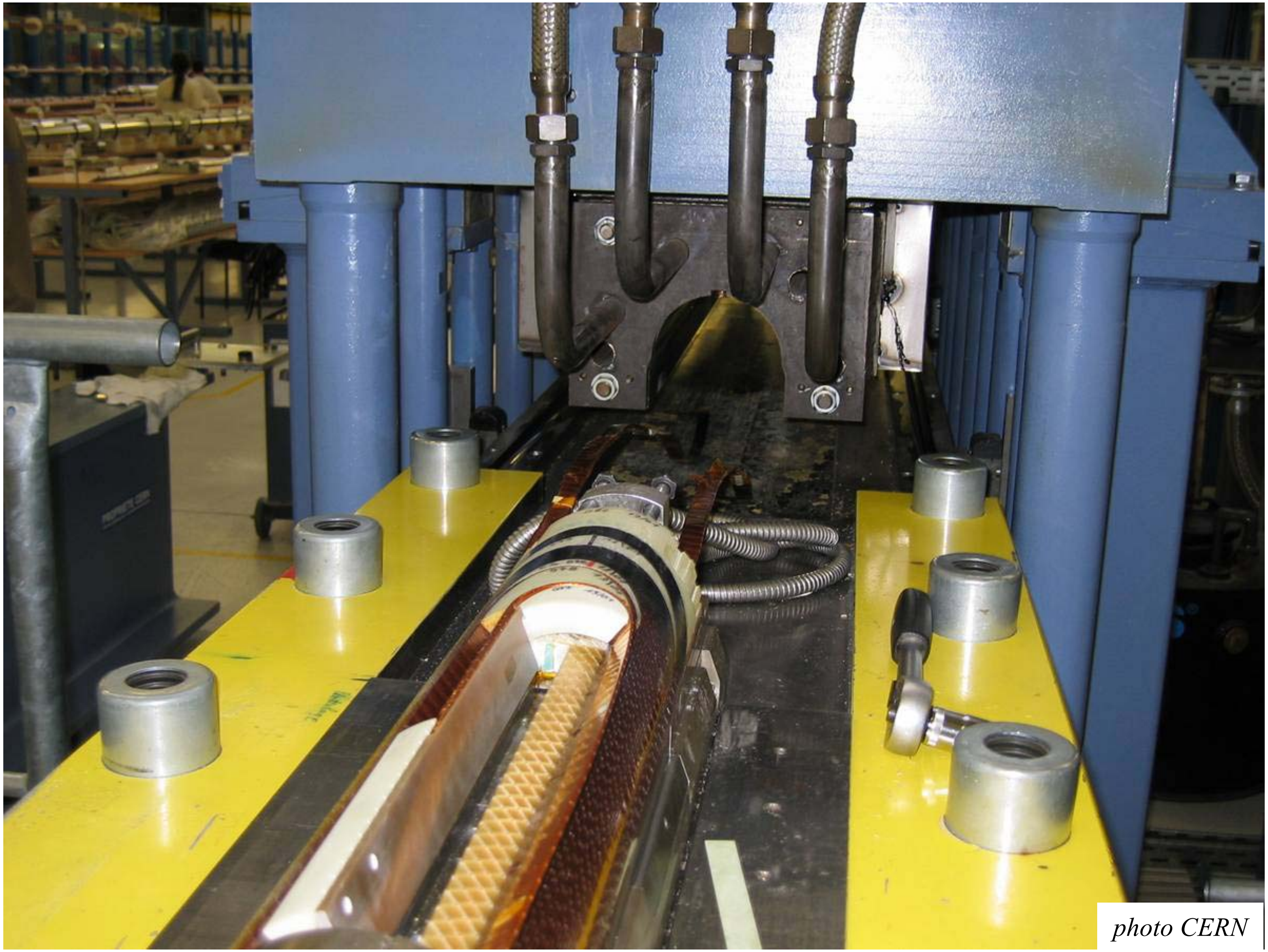


photo CERN

Finished coils

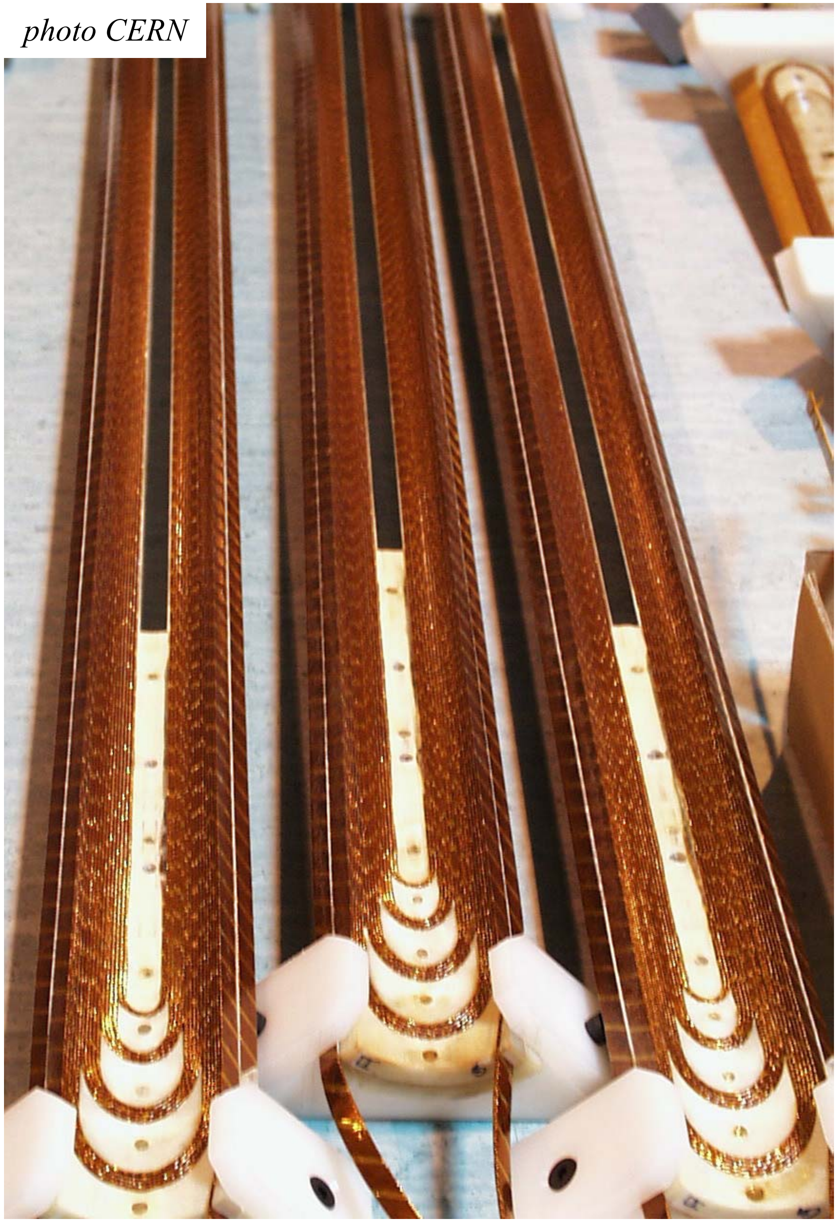


photo CERN

after curing, the coil package is rigid and relatively easy to handle

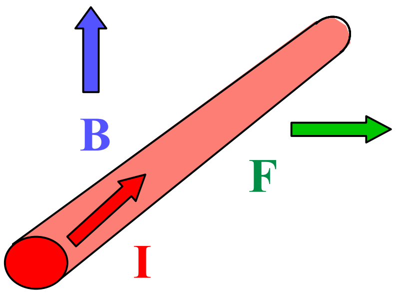
photo CERN

Coils for correction magnets

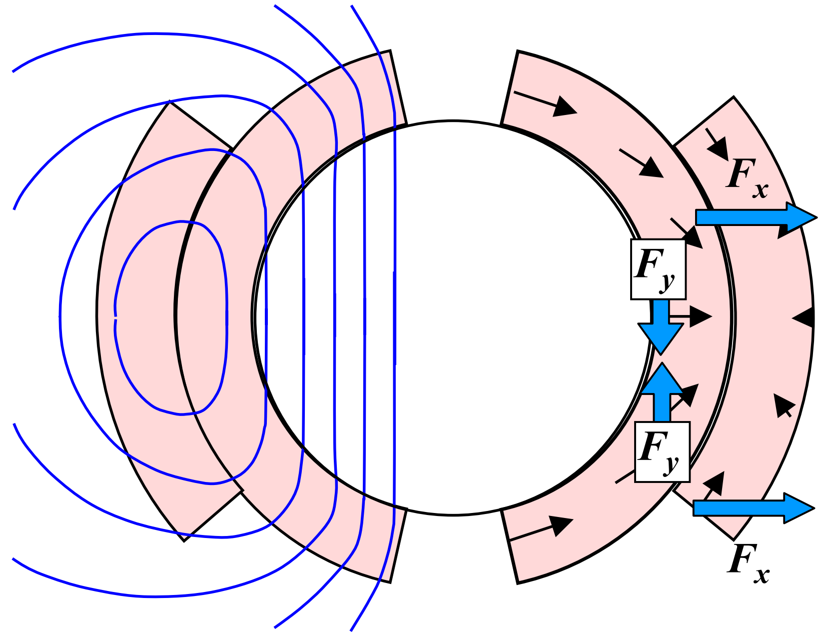
photo CERN

On a smaller scale, but in great number and variety, many different types of superconducting correction coils are needed at a large accelerator

Electromagnetic forces in dipoles



$\underline{F} = \underline{B} \wedge \underline{I}$



- forces in a dipole are horizontally outwards and vertically towards the median plane
- approximately for a thin winding

LHC dipole $F_x \sim 1.6 \times 10^6$ N/m = 160 tonne/m

total outward force *per quadrant*

$$F_x = \frac{B_i^2}{2\mu_o}\frac{4a}{3}$$

total vertical force *per quadrant*

$$F_y = -\frac{B_i^2}{2\mu_o}\frac{4a}{3}$$

- the outward force must be supported by an external structure
- both forces cause compressive stress in the conductor and insulation
- apart from the ends, there is no tension in the conductor

Collars

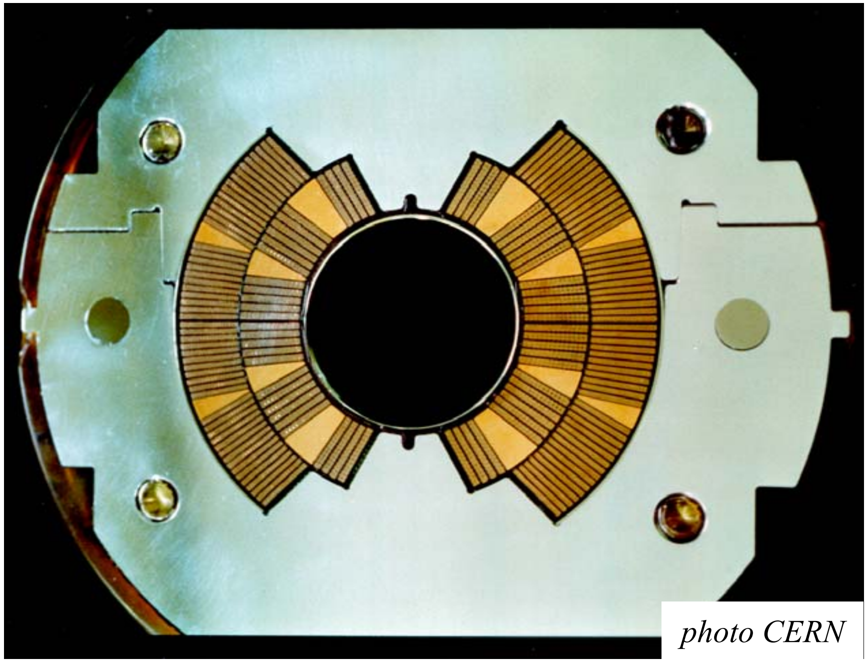


photo CERN

to support the electromagnetic forces, the coils are enclosed in a structure consisting of laminated **collars**

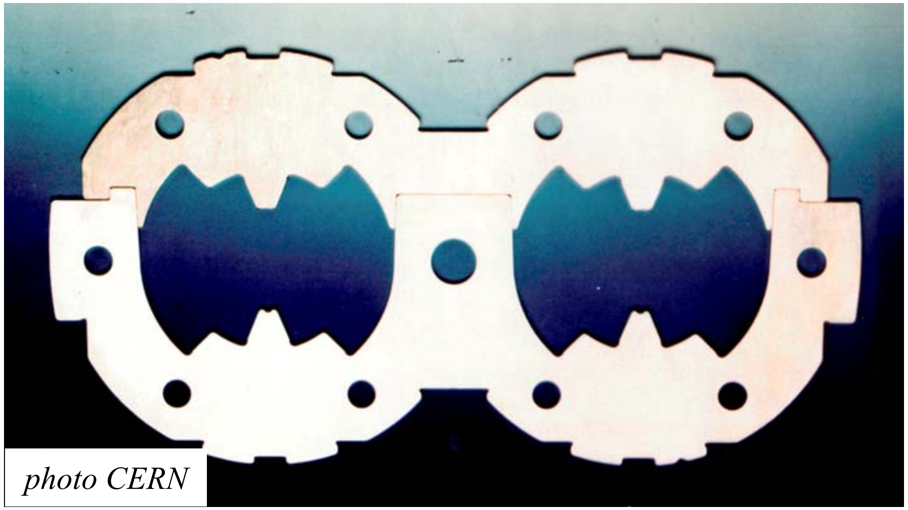


photo CERN

12 million produced
for LHC

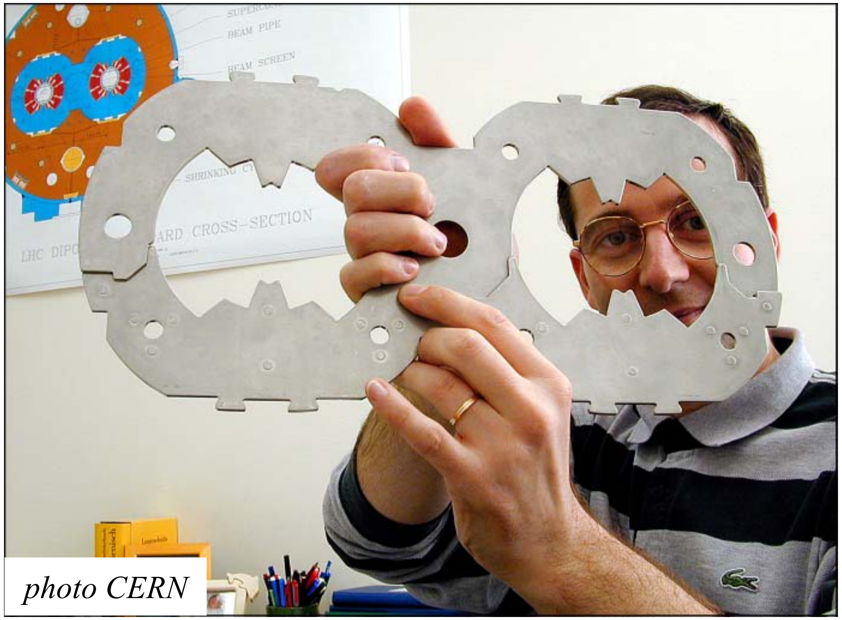


photo CERN

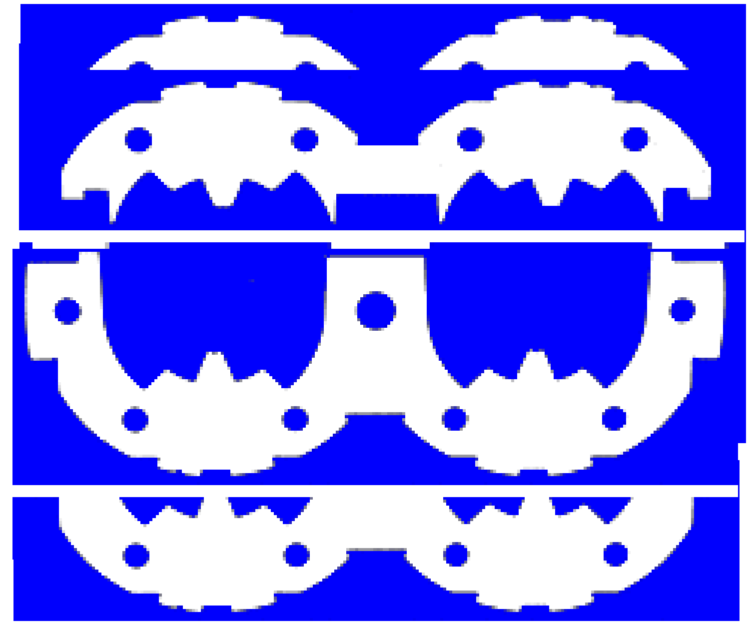
Collars

How to make an external structure that

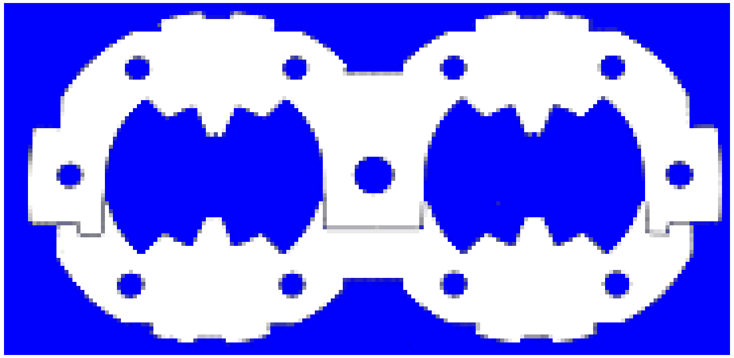
- fits tightly round the coil
- presses it into an accurate shape
- has low ac losses
- can be mass produced cheaply
- ???

- Answer make collars by precision stamping of stainless steel or aluminium alloy plate a few mm thick

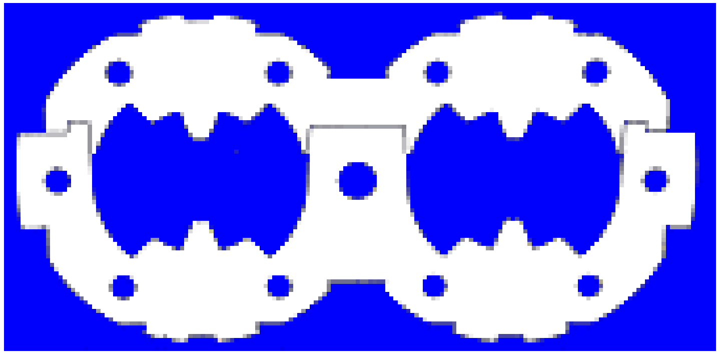
- inherited from conventional magnet laminations



press collars over coil from above and below



invert alternate pairs so that they interlock



push steel rods through holes to lock in position

LHC dipole collars

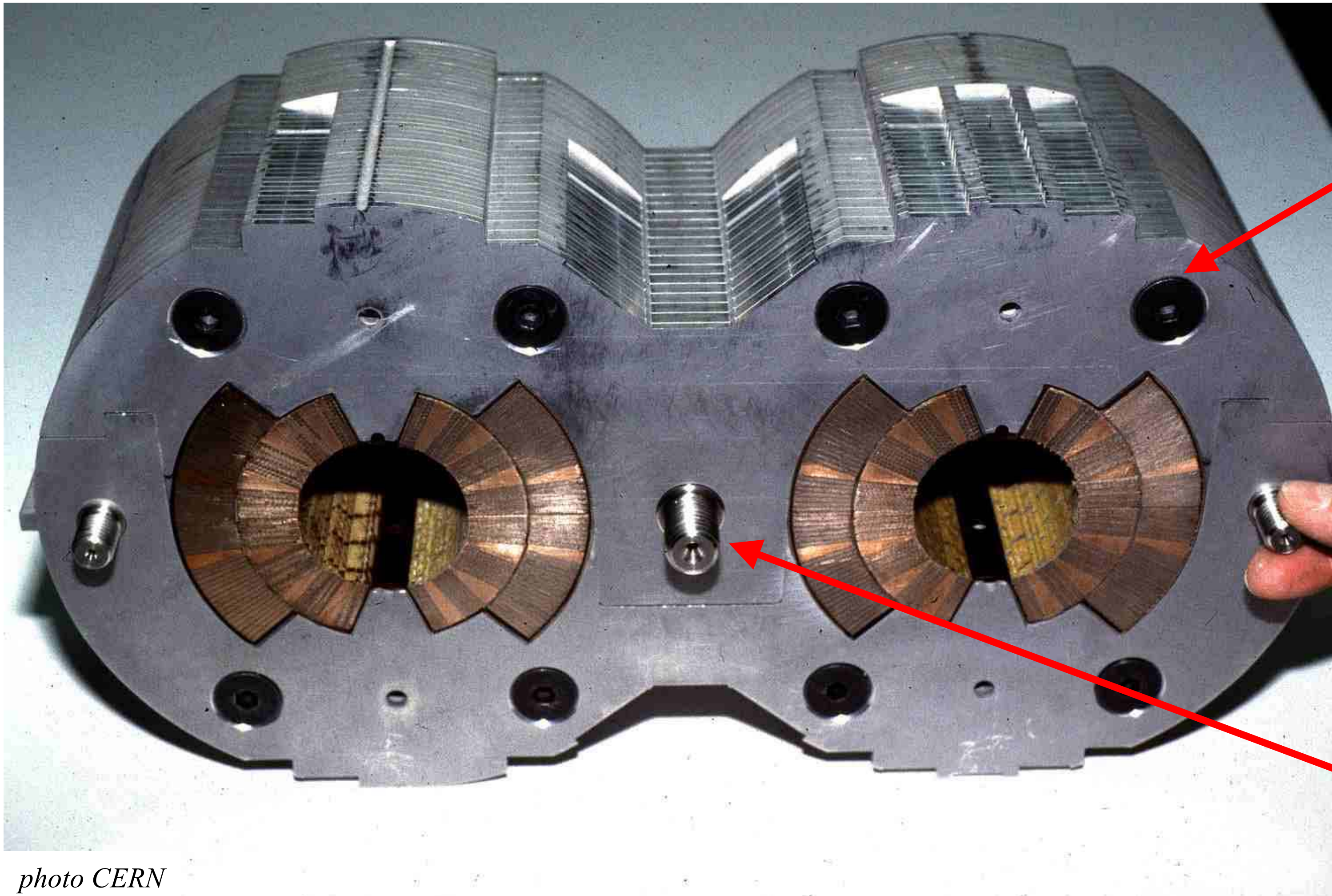


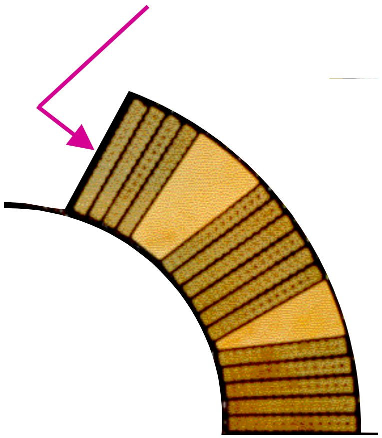
photo CERN

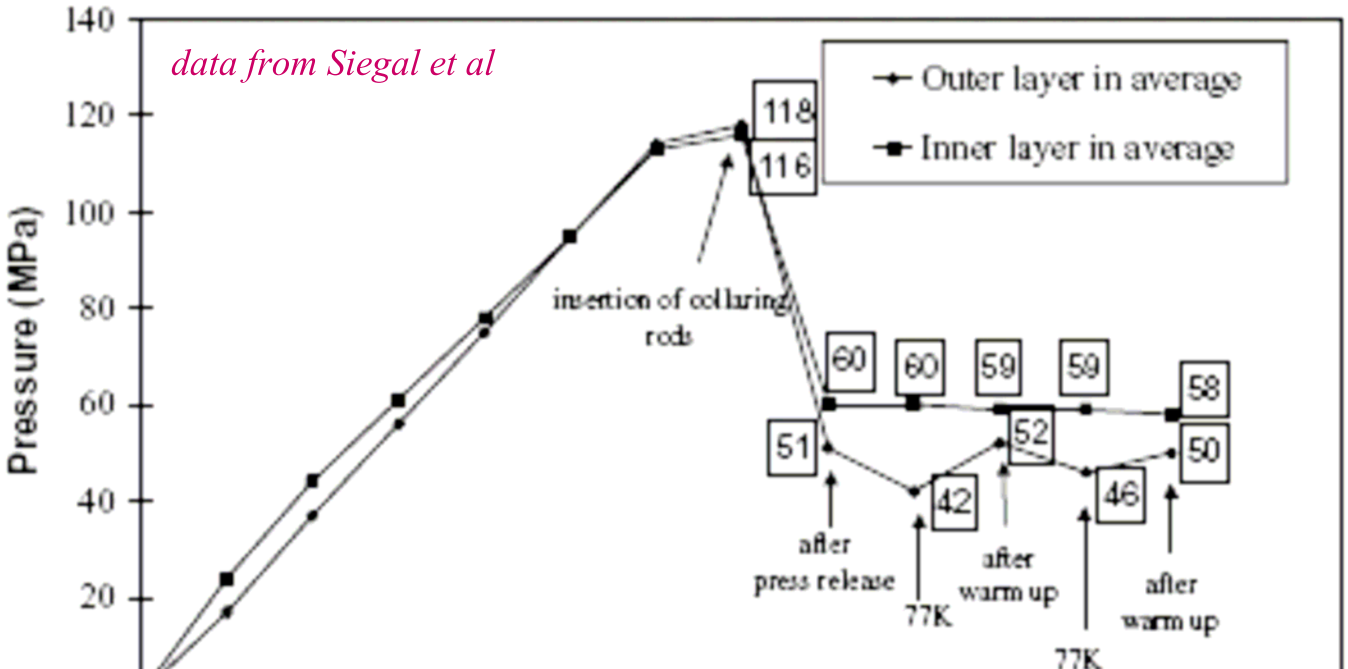
sub-units of several alternating pairs are riveted together

stainless rods lock the sub-units together

Coil internal stresses

measure the pressure here





CERN data during manufacture and operation

data from Modena et al

	after collaring at 293K		after yoking at 293K		at 1.9K		at 1.9K and 8.3T	
	inner	outer	inner	outer	inner	outer	inner	outer
MBP2N2	62Mpa	77Mpa	72Mpa	85Mpa	26MPa	32MPa	2MPa	8Mpa
MBP2O1	51MPa	55MPa	62MPa	62MPa	24MPa	22MPa	0MPa	2MPa

Collars and end plate (LHC dipole)

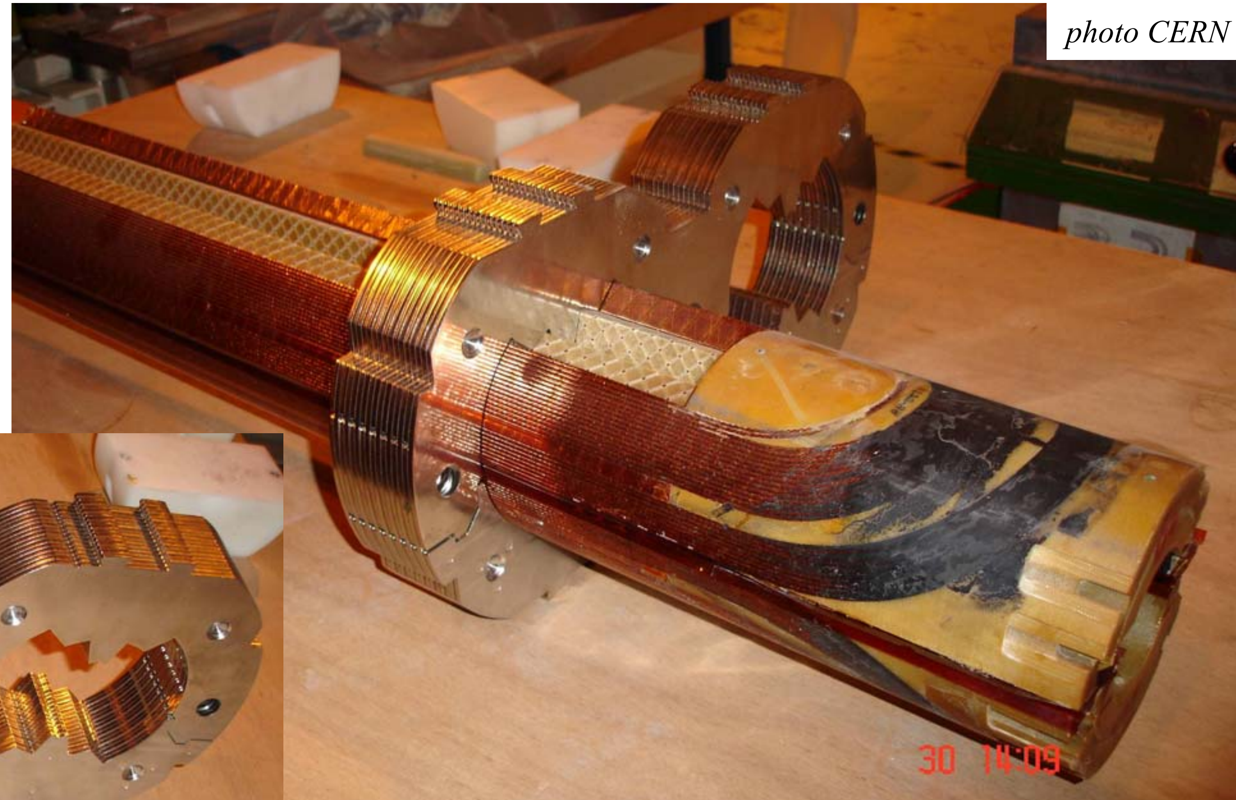


photo CERN

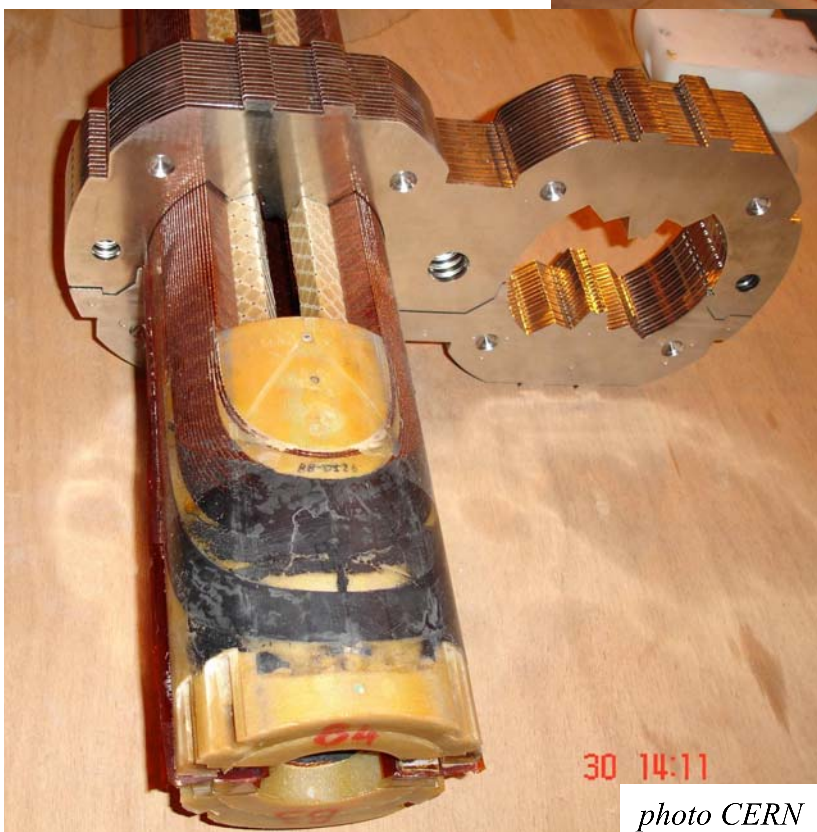
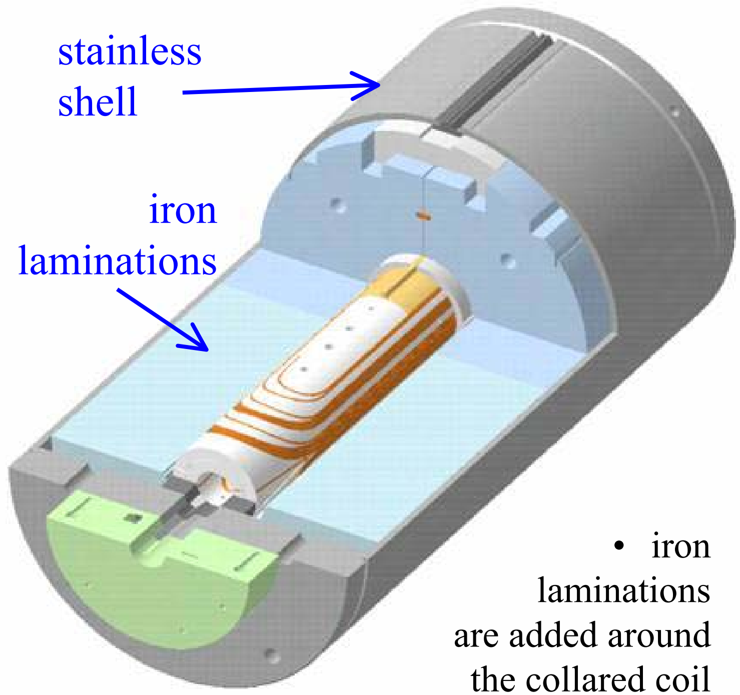
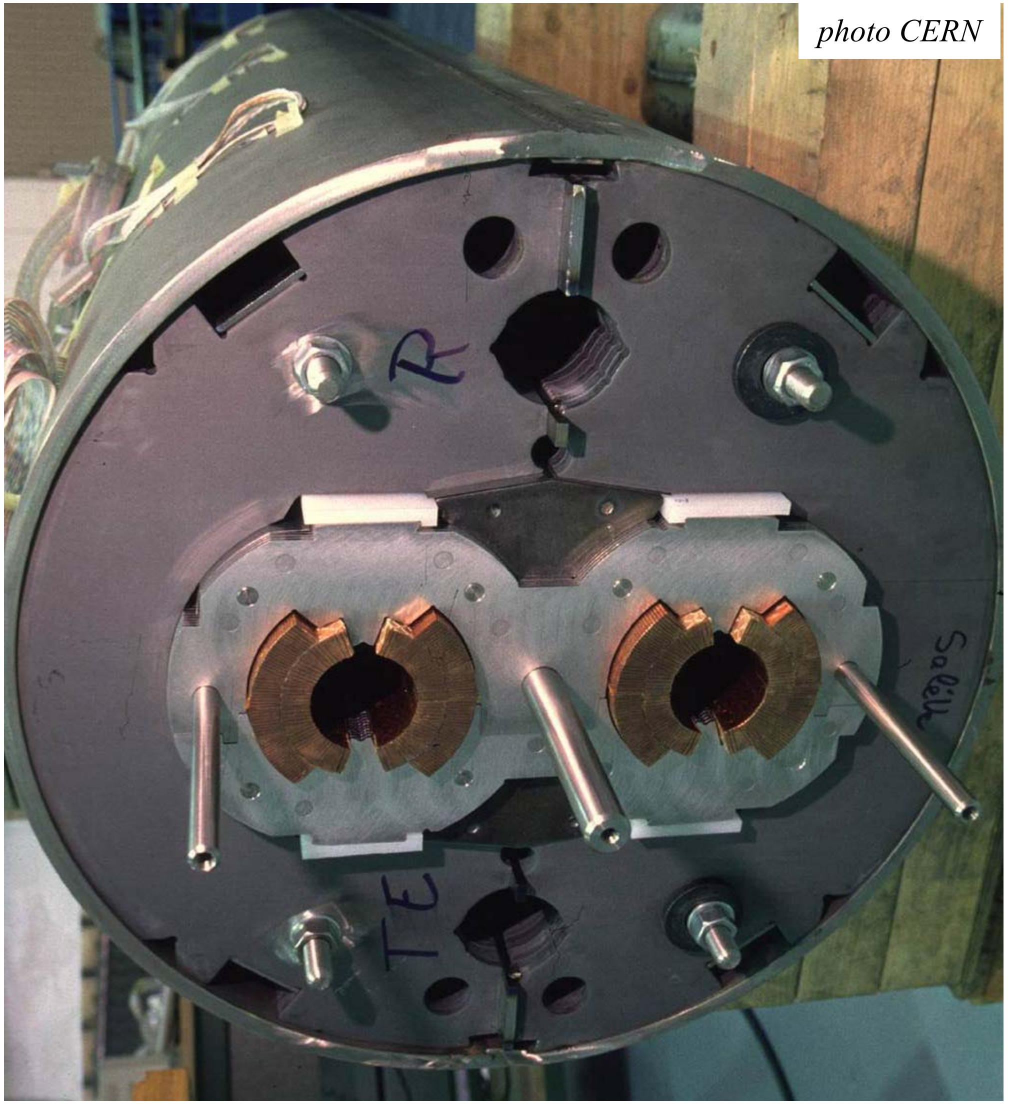


photo CERN

Adding the iron

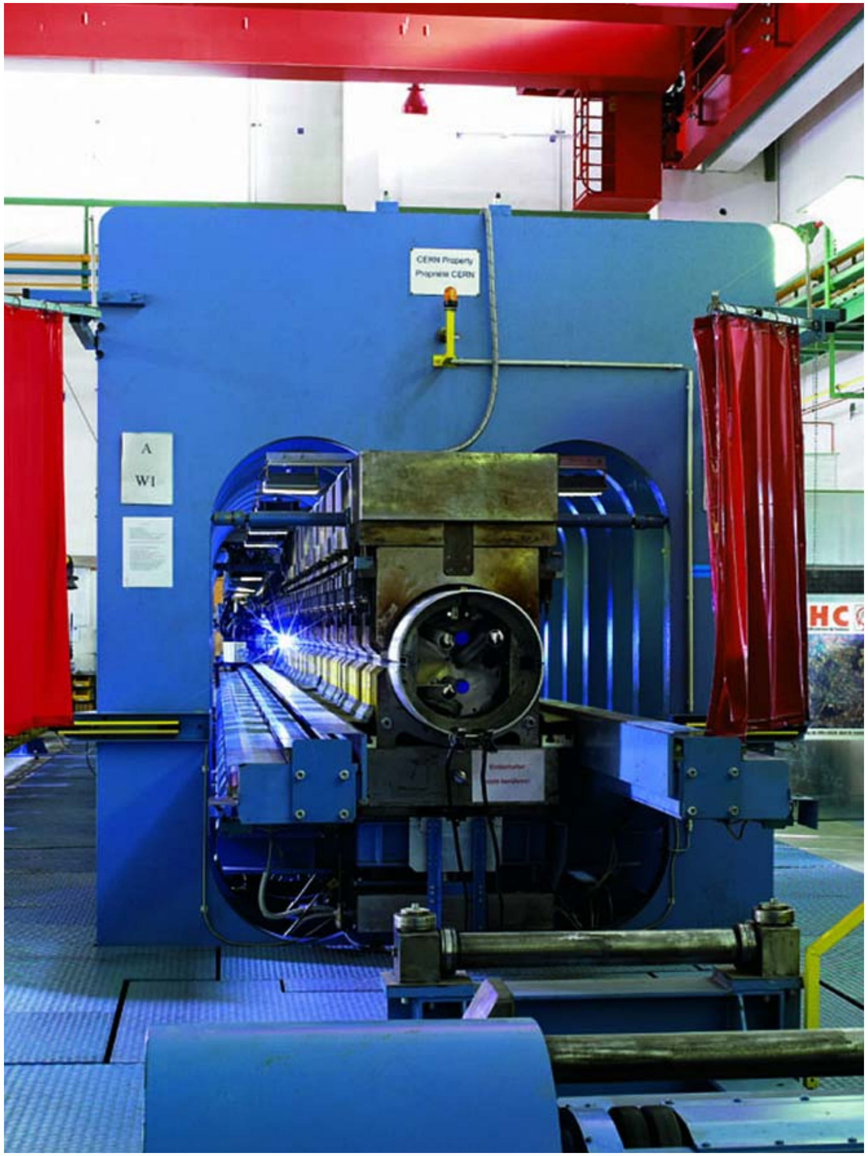


- iron laminations are added around the collared coil

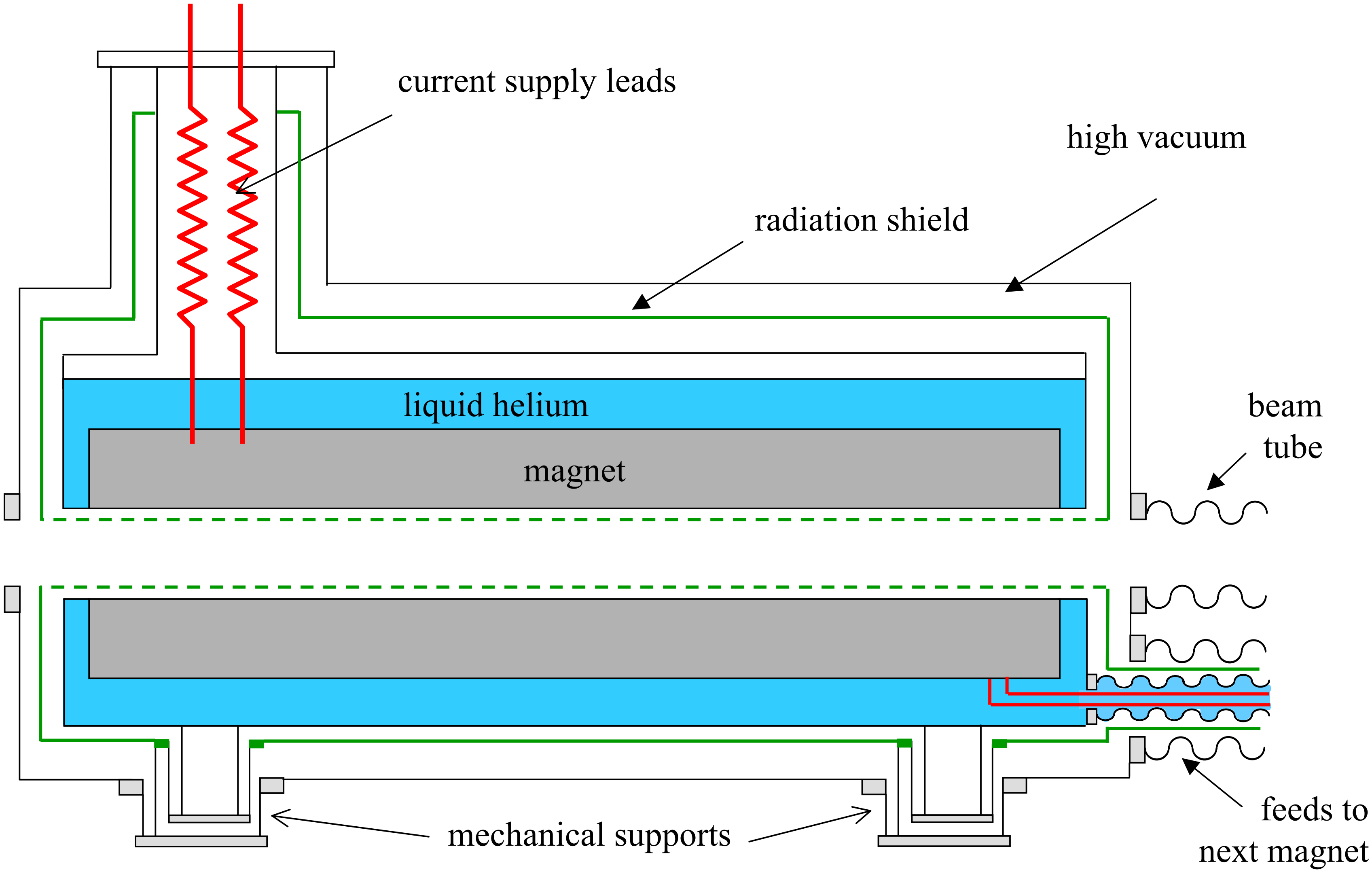


- they are forced into place, again using the collaring press
- remember however that pure iron becomes brittle at low temperature
- the tensile forces are therefore taken by a stainless steel shell which is welded around the iron, while still in the press
- this stainless shell can also serve as the helium vessel

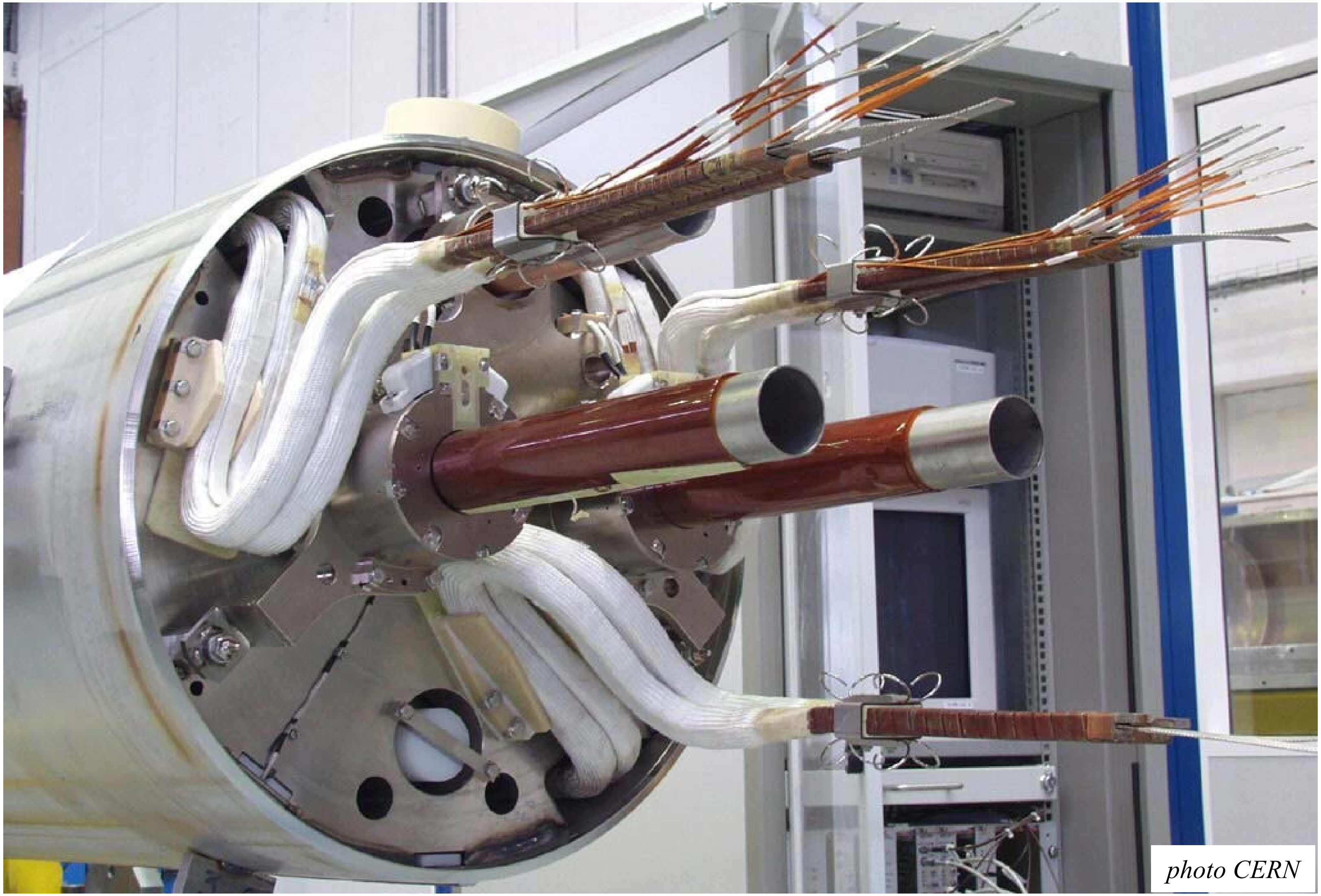
Compressing and welding the outer shell



Cryostat essentials



Dipole inside its stainless shell



Cryogenic supports

'feet' used to support the cold mass inside its cryostat (LHC dipole)

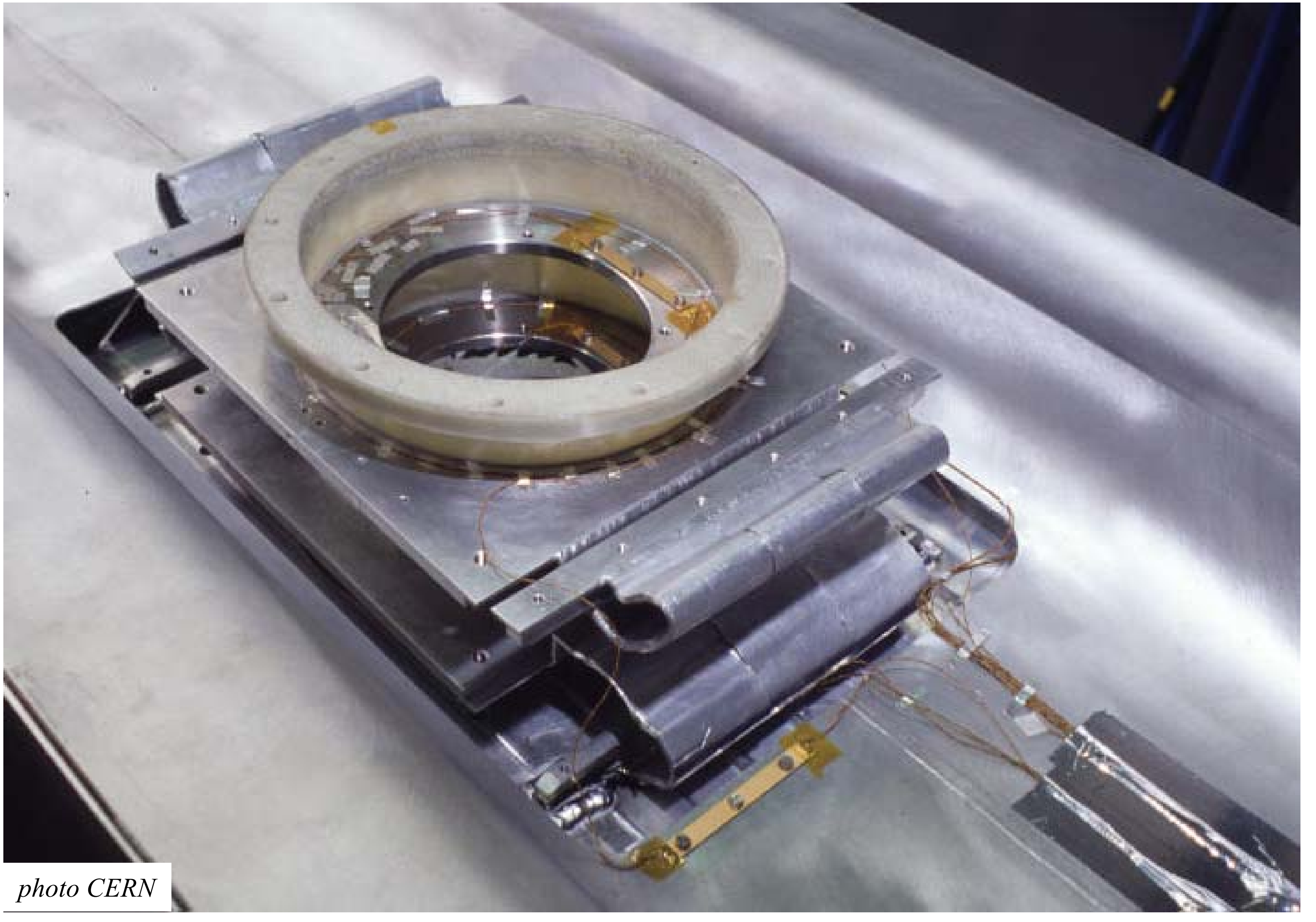


photo CERN

Complete magnet in cryostat

photo CERN

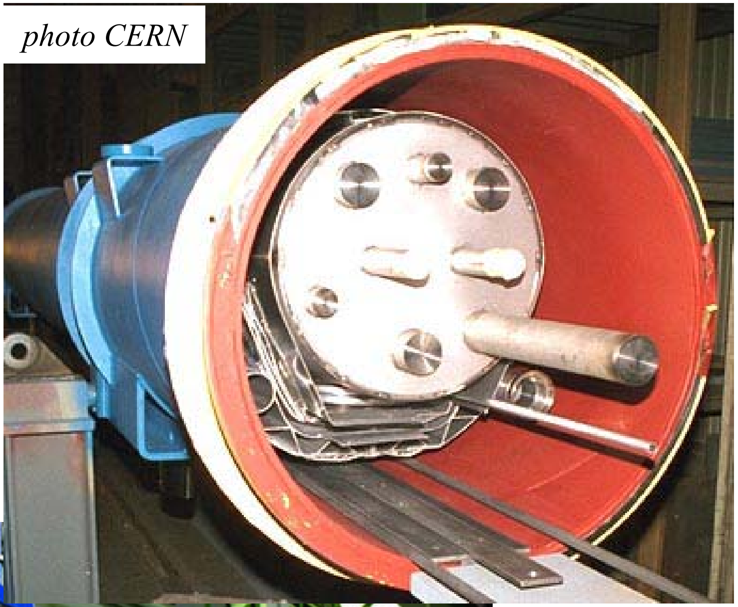


photo CERN

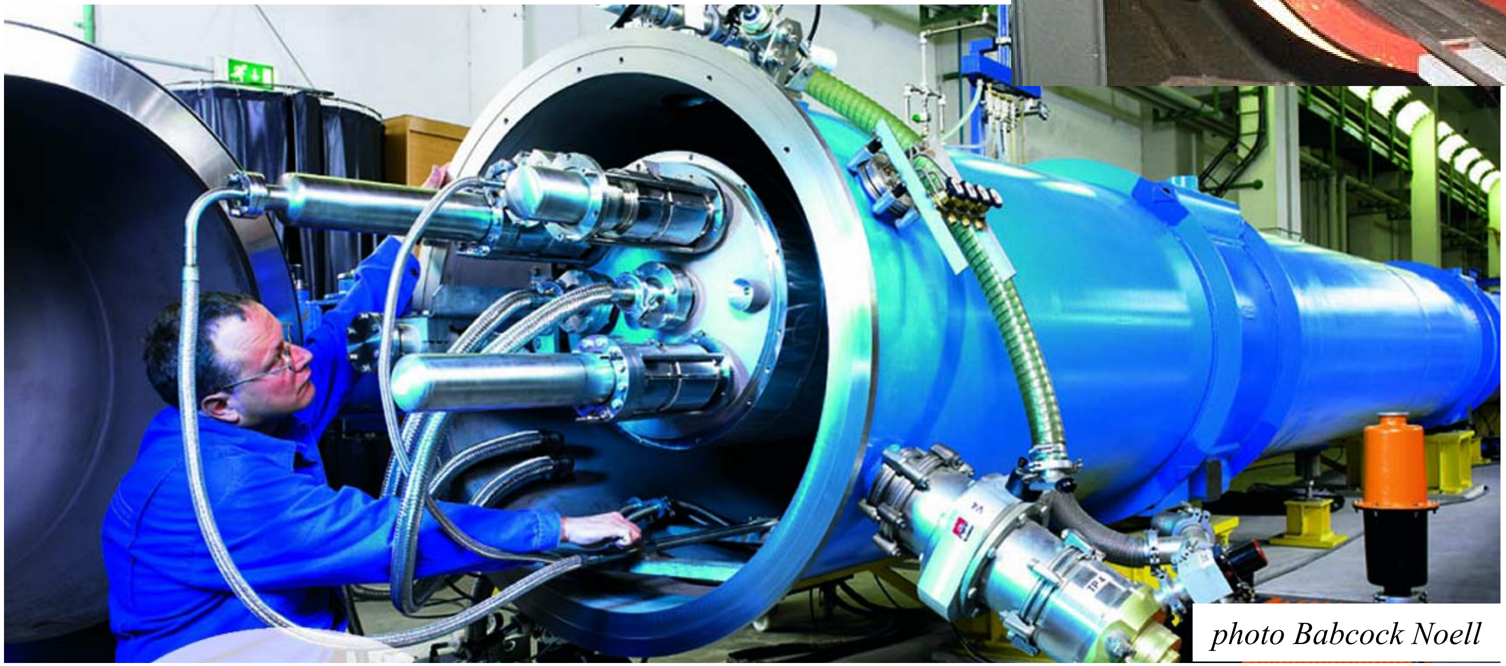
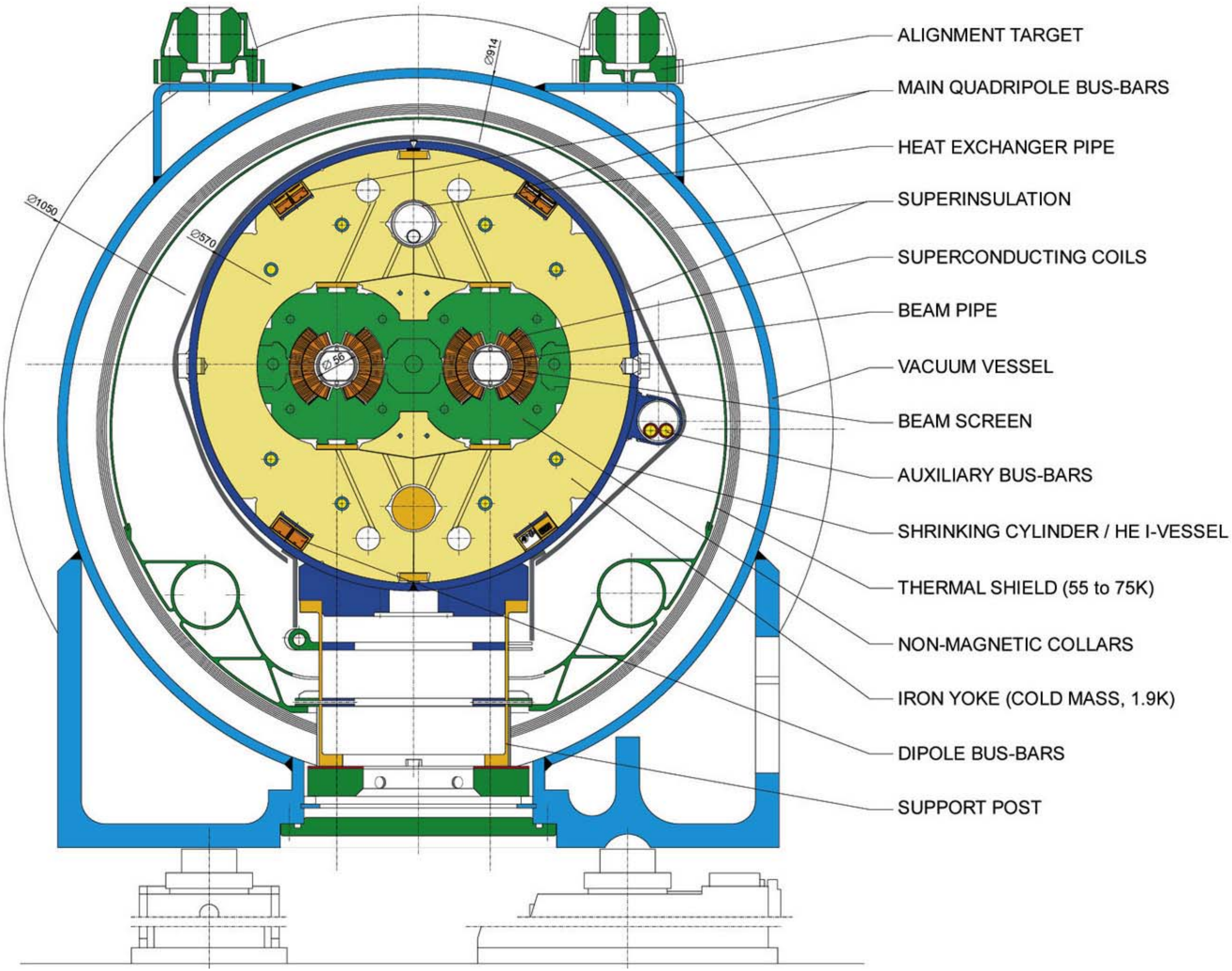


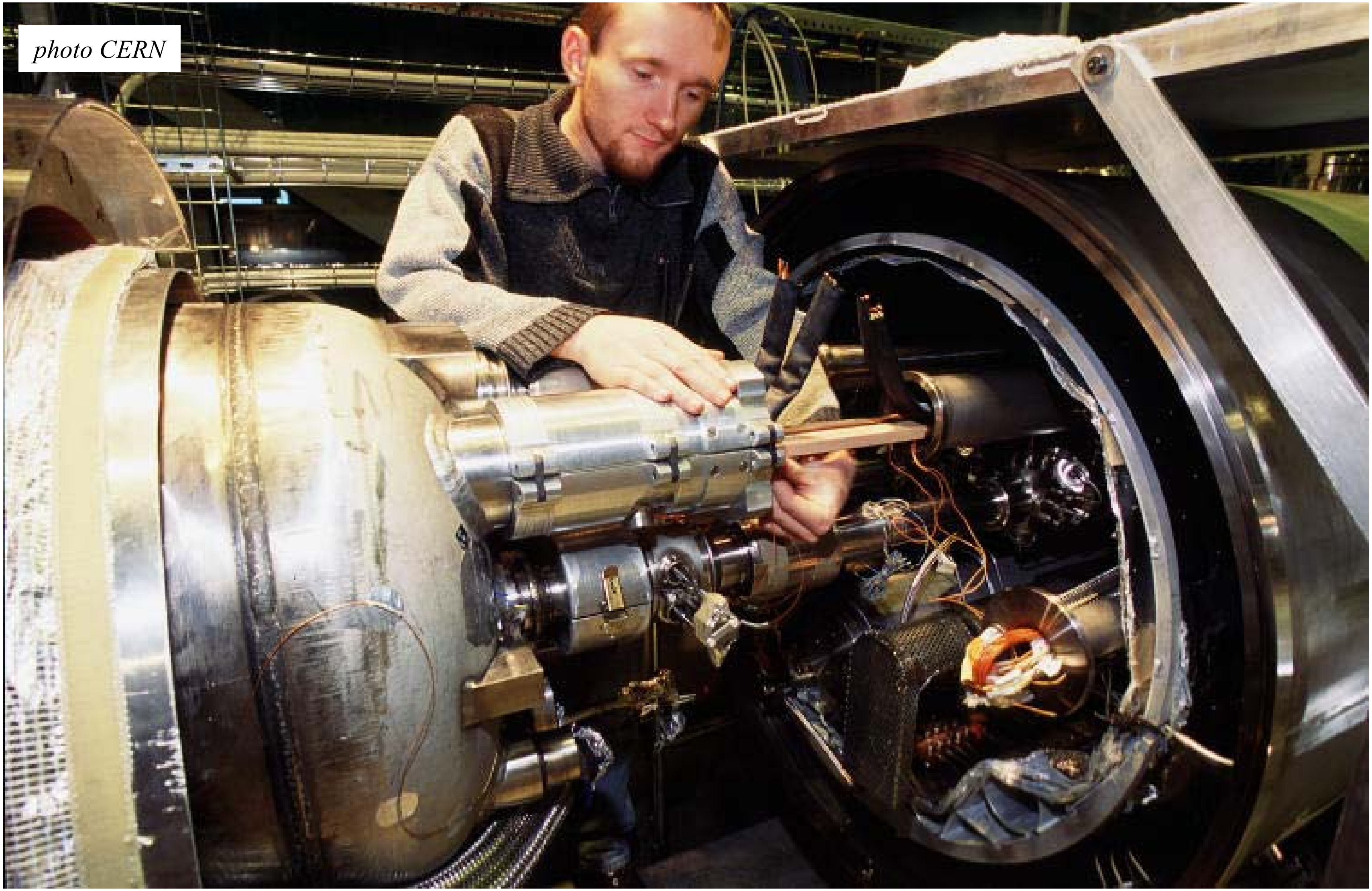
photo Babcock Noell

LHC DIPOLE : STANDARD CROSS-SECTION

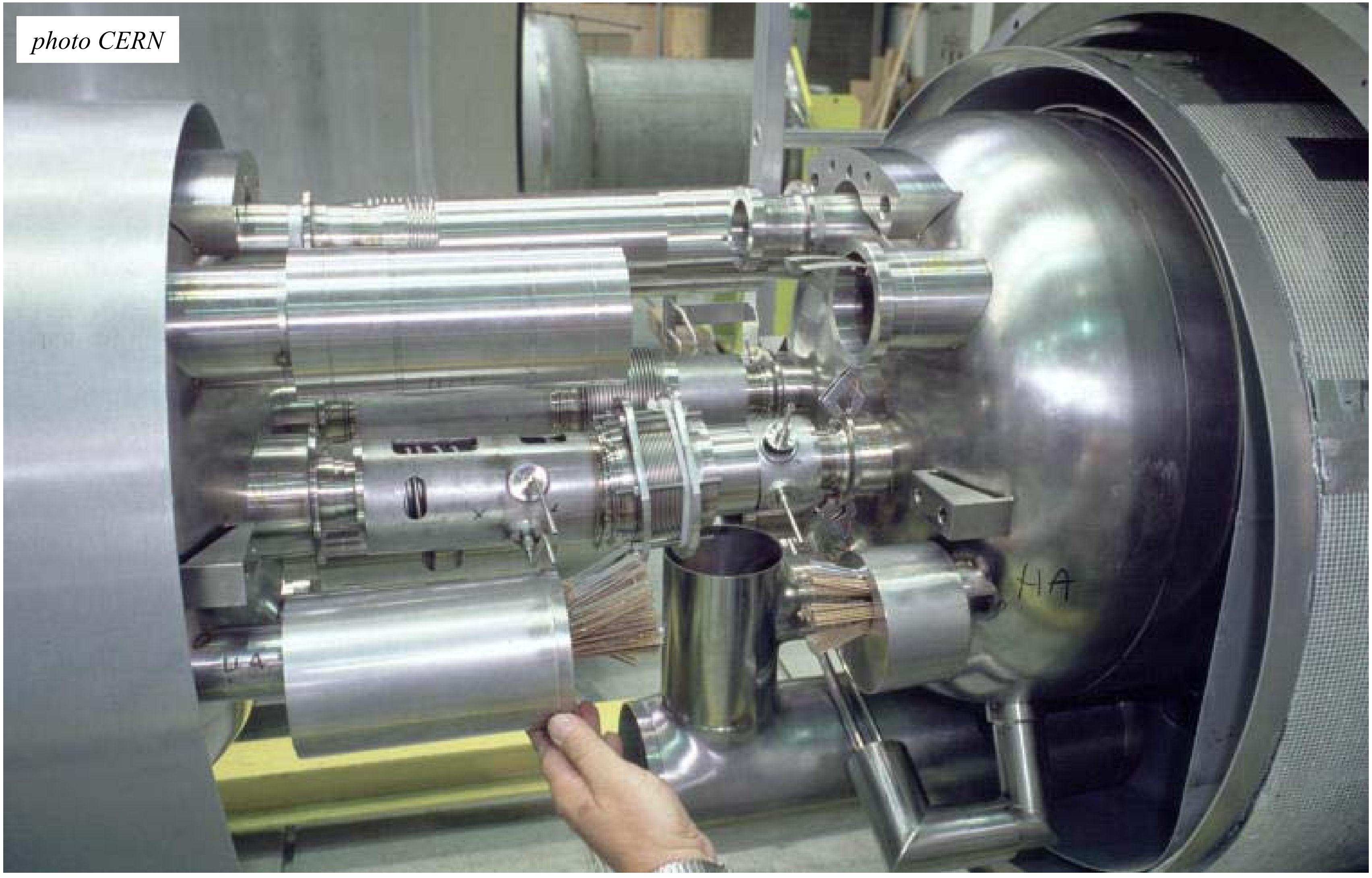
CERN AC/DI/MM - HE107 - 30 04 1999



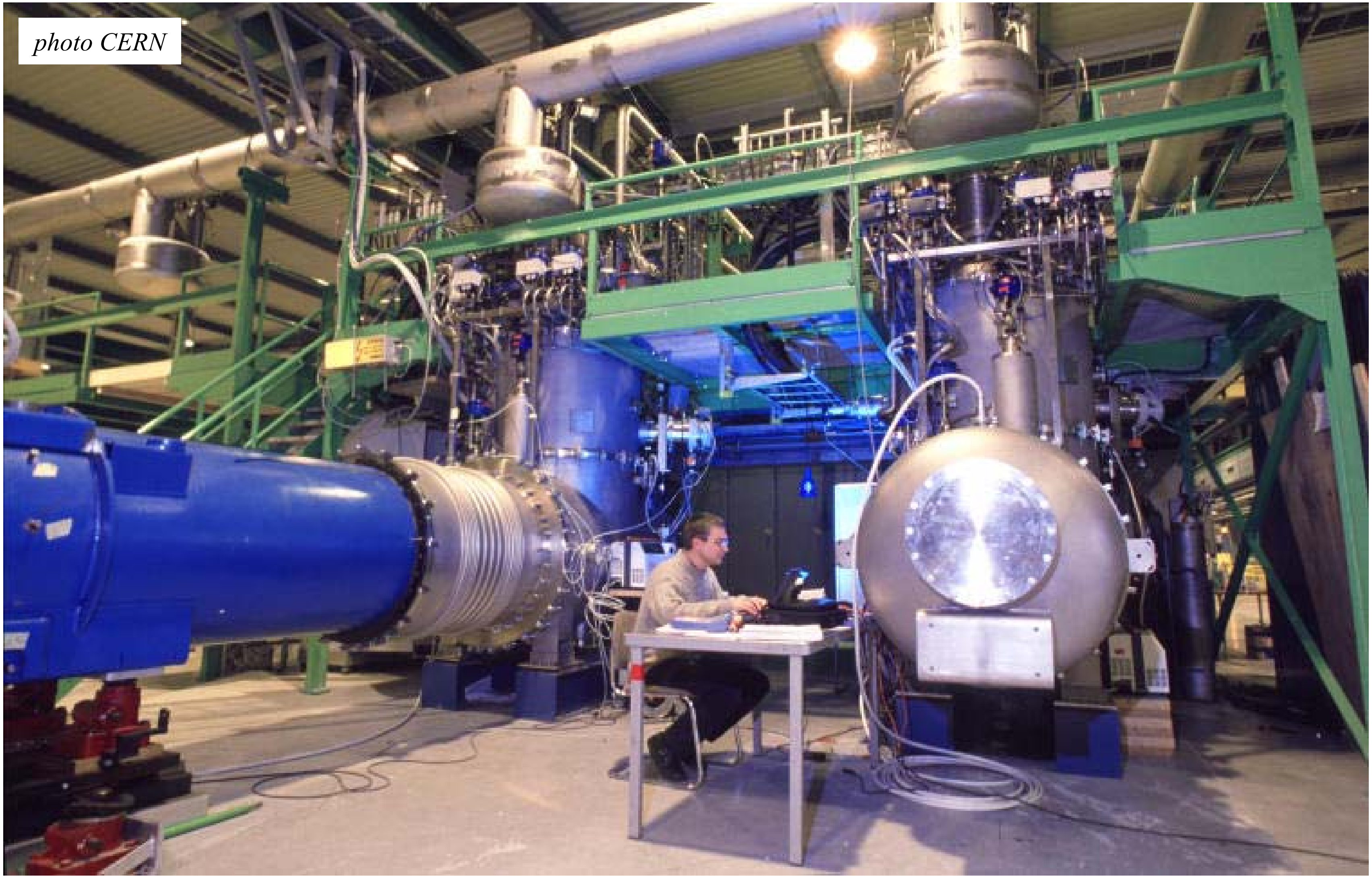
Make the interconnections - electrical



Make interconnections - cryogenic



Connect to the cryogenic feed and current leads

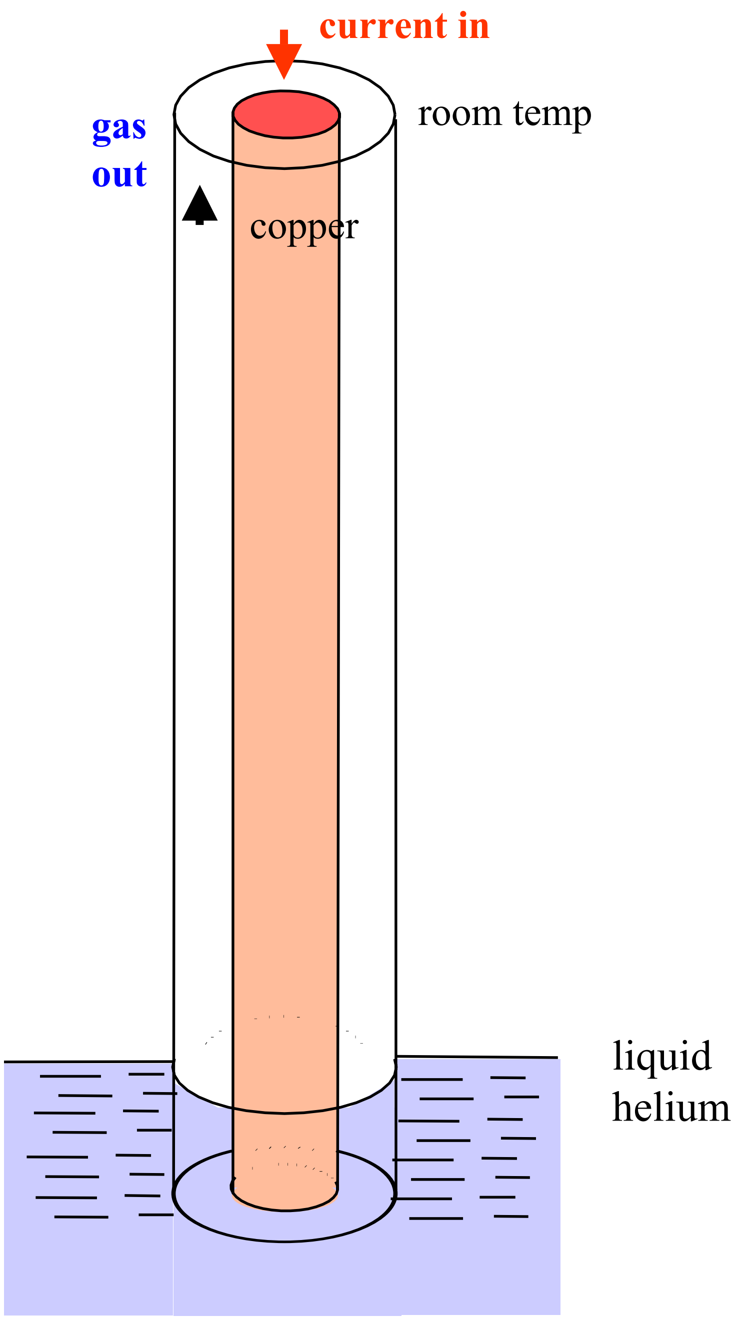


Current Leads

- we want to have low heat inleak, ie low ohmic heating and low heat conduction from room temperature. This implies low *k* and ρ
  - but Wiedemann Franz

$$k(\theta)\rho(\theta) = L_o\theta$$

- so the only variable we have left is the shape
- Recap helium properties
  ratio Δenthalpy/latent heat = 72
- so it would seem a good idea to use the enthalpy of the cold gas which is boiled off to reduce the heat leak to the liquid
- we make the lead as a heat exchanger



Current lead theory

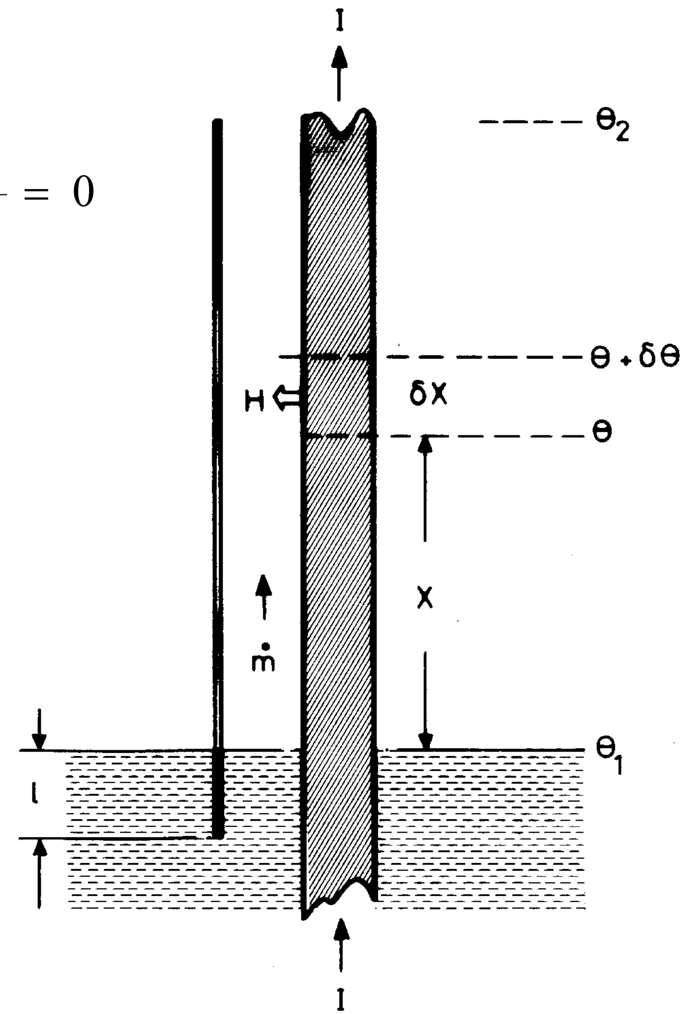
equation of heat conduction

$$\frac{d}{dx}\left(k(\theta) A \frac{d\theta}{dx} \right) - f \overset{\circ}{m} C_p \frac{d\theta}{dx} + \frac{I^2 \rho(\theta)}{A} = 0$$

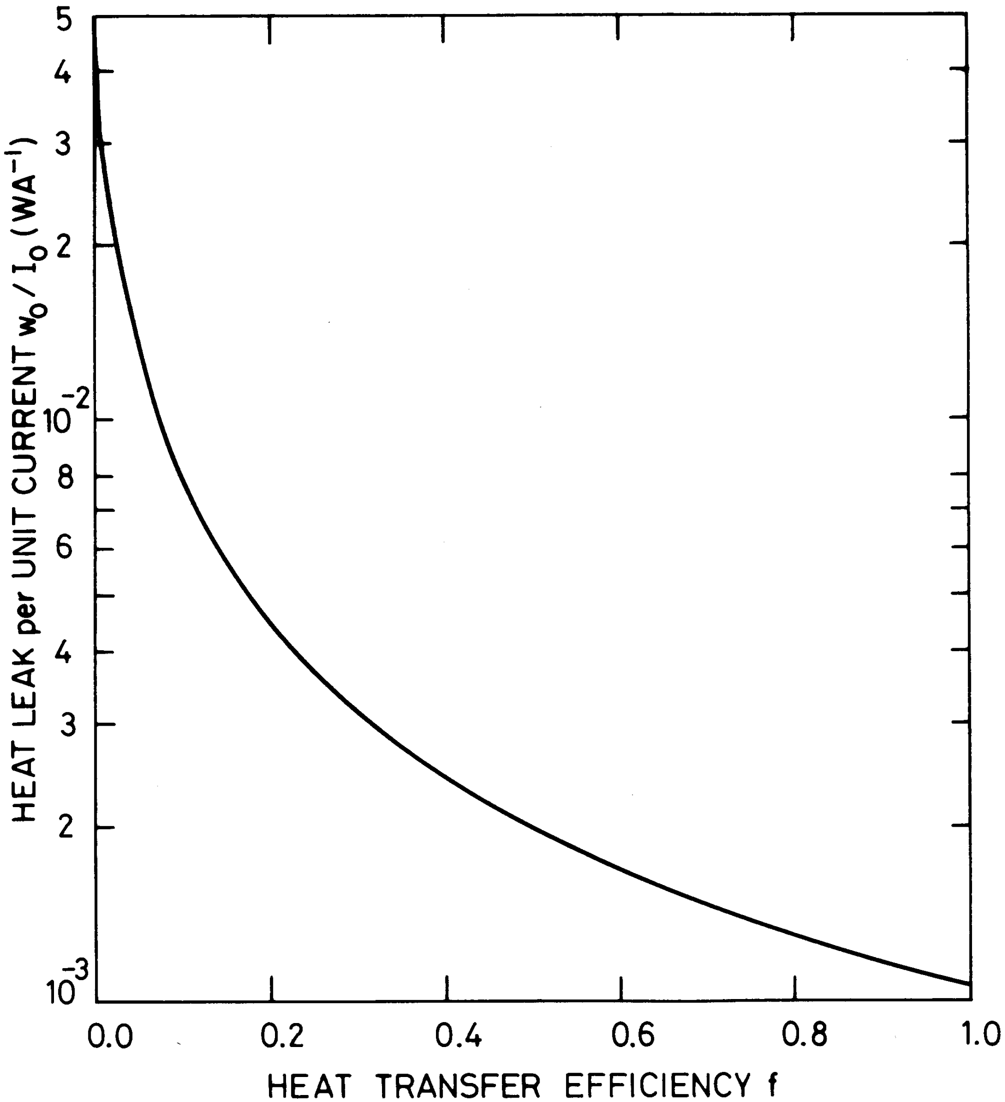
where:

f = efficiency of heat transfer to helium gas
m^o = helium mass flow
C_p = specific heat of gas

- solution to this equation in 'Superconducting Magnets p 257.
- we find there is an optimum shape for the lead which gives the minimum heat leak
  - 'Watts per Amp per lead'
- at optimum shape the heat leak is a strong function of the efficiency of heat transfer f to the boiled off gas



Heat leak of an optimised lead



- with optimum shape and 100% efficient heat transfer the heat leak is

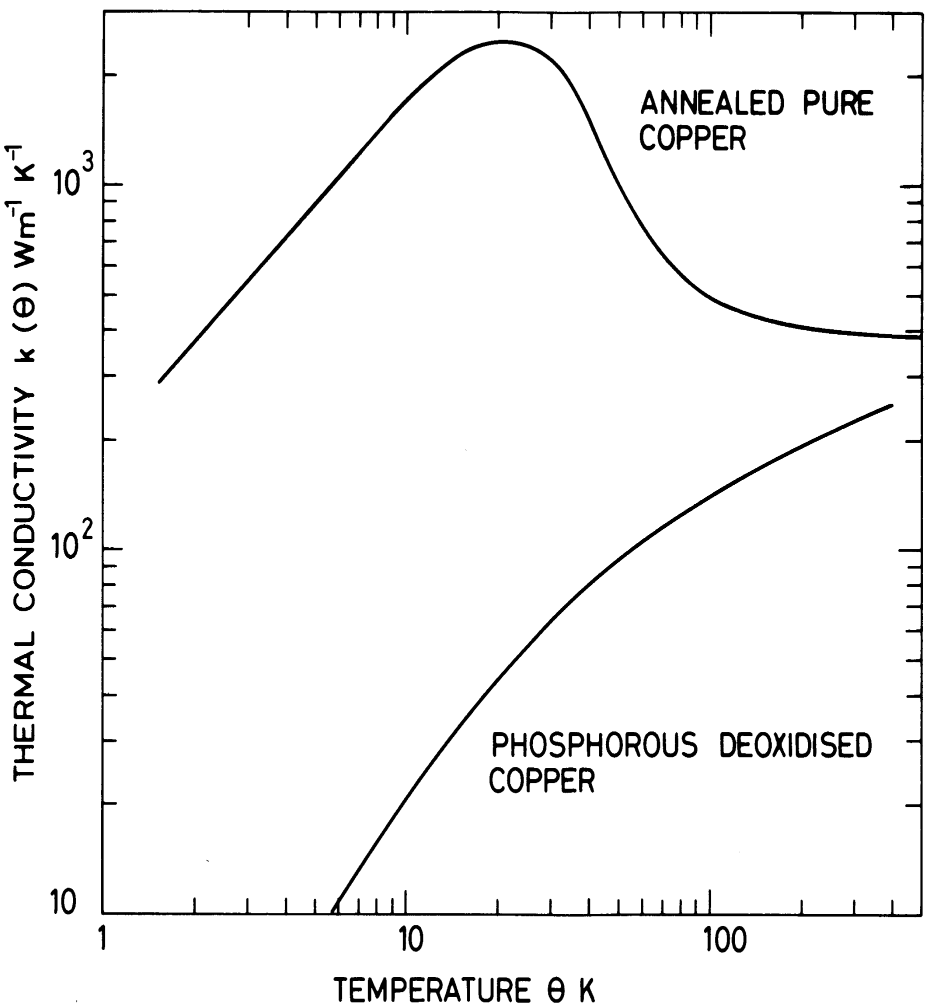
  1.04 mW/Amp

- with optimum shape and no heat transfer the heat leak is

  47 mW/Amp

- Note the optimum shape varies with the heat transfer efficiency

Optimum shape of lead



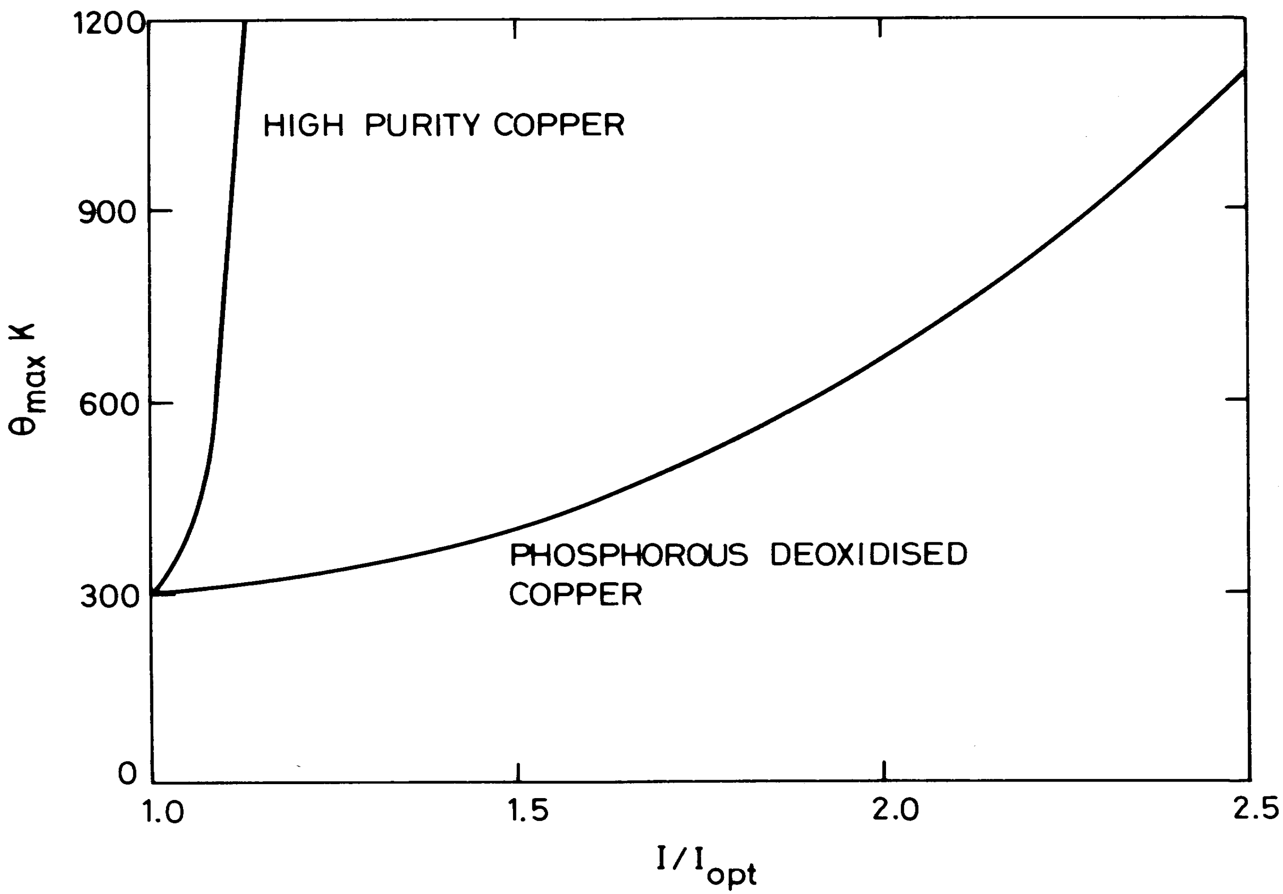
- the optimum shape is a function of temperature and material properties, particularly thermal conductivity.
- for a lead running between 300K and 4.2K the optimum shape is as follows
  - for a lead of annealed high purity copper

$$\left\{ \frac{L}{A} \right\}_{optimum} = \frac{2.6x10^7}{I}$$

  - for a lead of impure phosphorous deoxised copper

$$\left\{ \frac{L}{A} \right\}_{optimum} = \frac{3.5x10^6}{I}$$

Impure materials make more stable leads



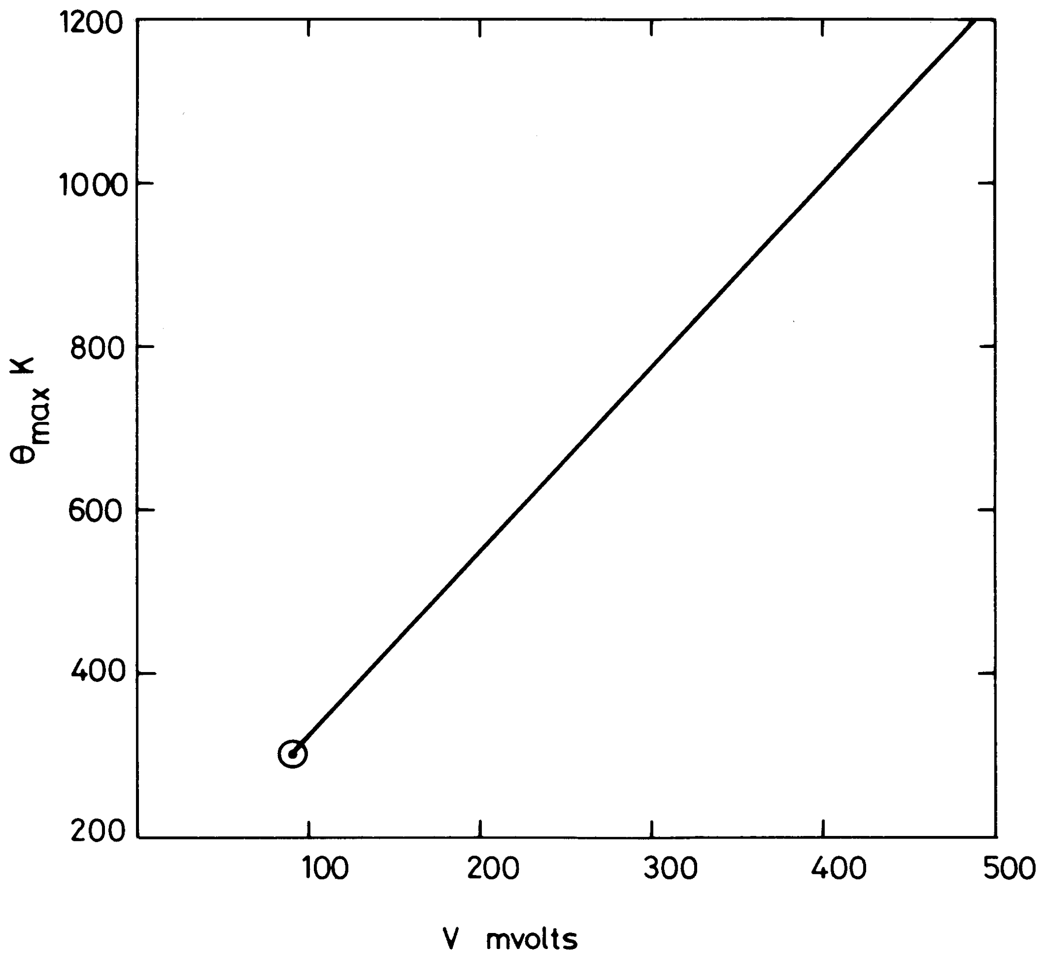
- for an optimized lead, the maximum temperature is room temperature (at the top of the lead)
- when the lead is not optimized, the temperature of an intermediate region rises above room temperature
- the optimum for pure metals is more sensitive than for impure metals

current lead burns out ⇒ magnet open circuit

⇒ large voltages

⇒ disaster

Health monitoring



- it turns out that all leads between the same temperatures and with the same cooling efficiency drop the same voltage at optimum
- for a lead between 300K and 4.2K with with 100% cooling efficiency, the voltage drop at optimum is **75mV**
- measure the volts across your lead to see if it is optimised
- if a lead burns out, the resulting high voltage and arcing (magnet inductance) can be disastrous
- monitor your lead and trip the power supply if it goes too high

HTS (high temperature superconductor) current leads

- HTS materials have a low thermal conductivity
- thus we can make the lower section, below ~ 70K of the current lead from HTS material
- heat leak down the lead is the same but it may be taken at a higher temperature, which uses less refrigeration
- LHC will use HTS leads for all main ring magnets
- savings on capital cost of the refrigerator will pay for the extra cost of the leads and reduced running cost will be a benefit thereafter

⇐13kA lead for LHC

600A lead for LHC ⇒

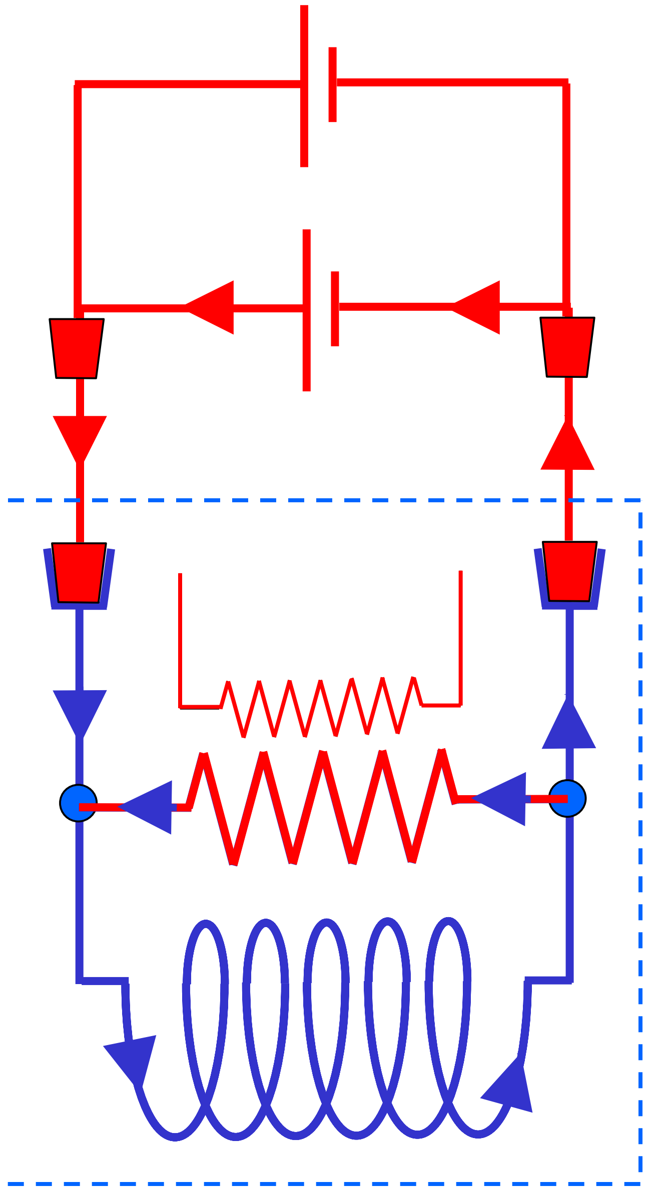
Persistent current operation

1) Heater energized, persistent switch resistive, magnet charged up to operating current by power supply at room temperature

2) Heater switched off, persistent switch cools down and becomes superconducting

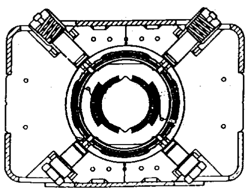
3) Power supply current reduced to zero, magnet current diverts to persistent switch

4) Power supply and current leads may be removed, magnet current continues to circulate in a closed loop (almost) for ever. Small resistances in the joints and superconductor give decay rates of ~ 10^8 hours ~ 10,000 years

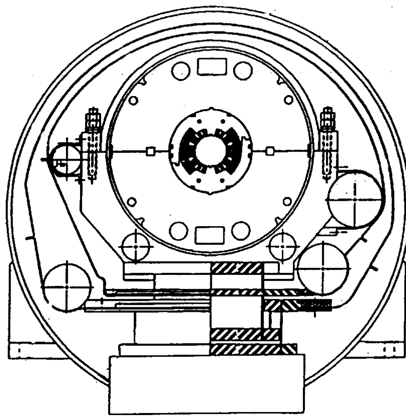


No use for accelerators of course because they need repetitive ramping

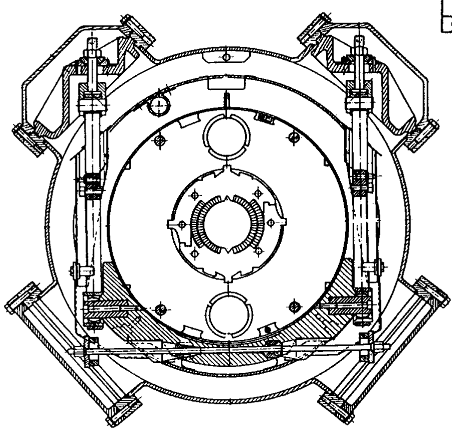
The world's superconducting accelerator dipoles



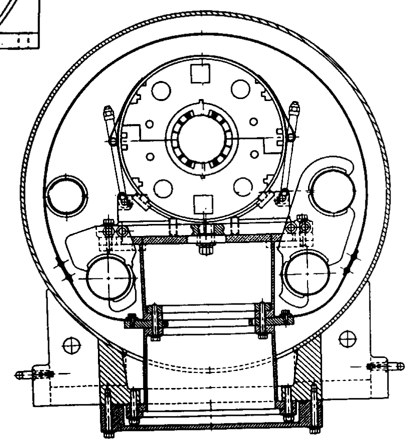
Tevatron



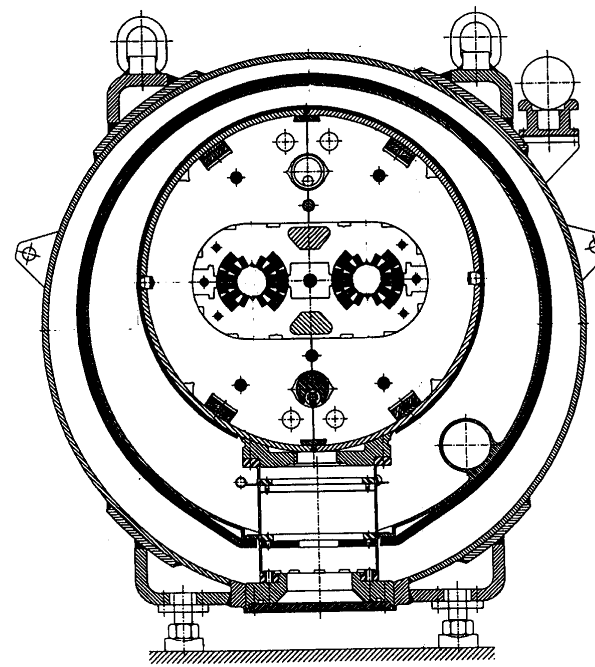
SSC



HERA



RHIC

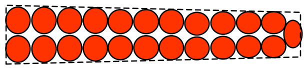
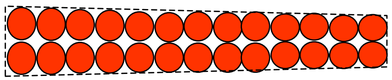
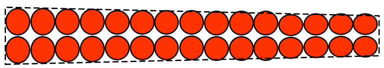
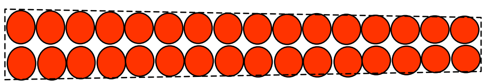
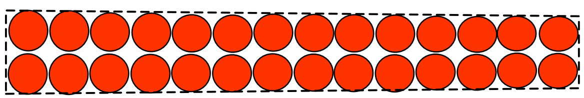
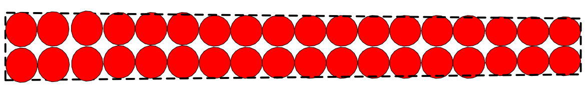
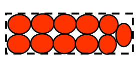
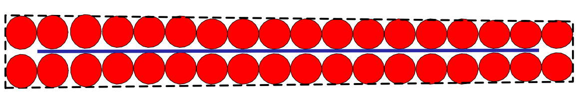


LHC

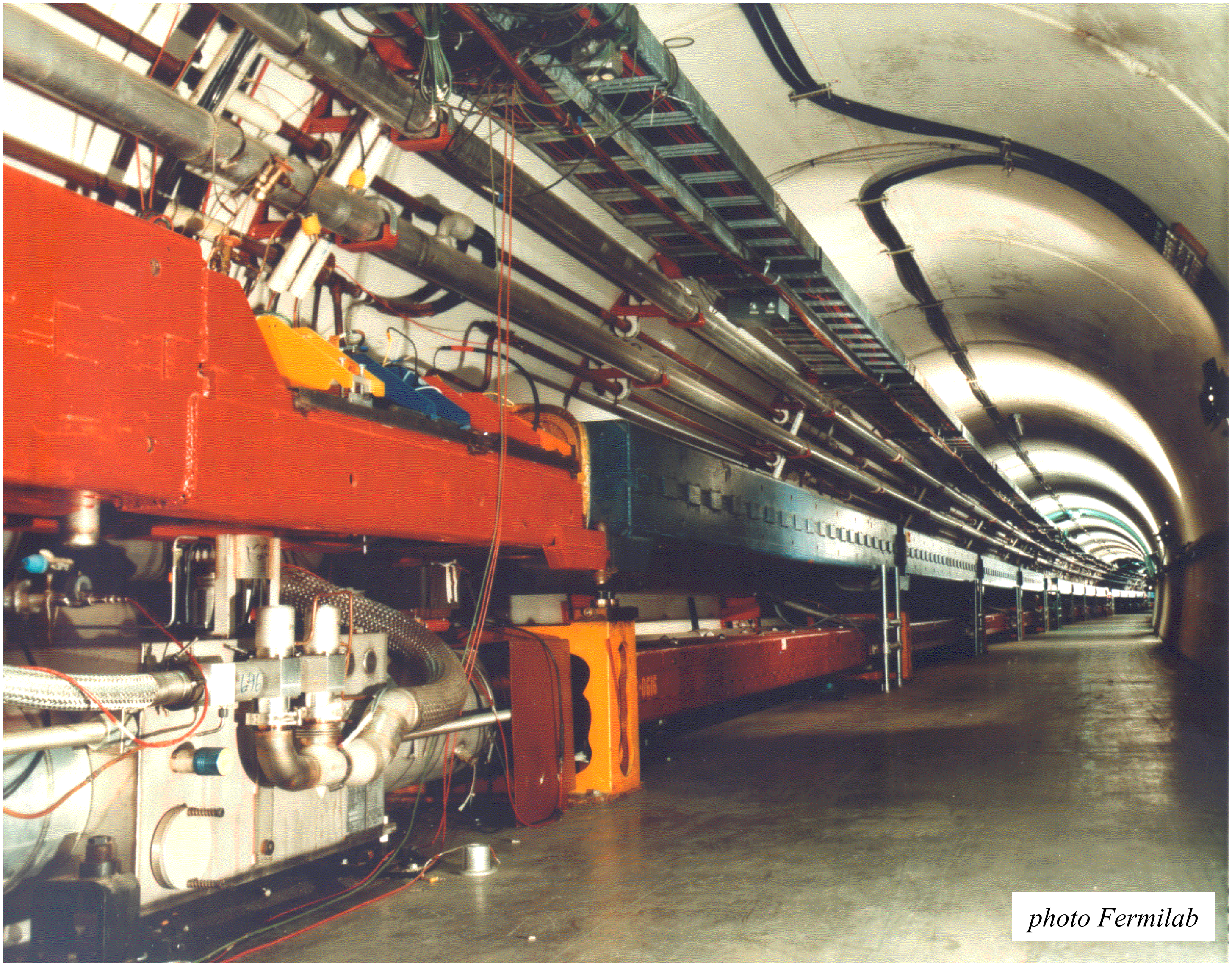
Key parameters of accelerator dipoles

		Tevatron	HERA	SSC	RHIC	LHC	Helios	FAIR
max energy	GeV	950	820	20,000 x 2	250 x 2	7,000 x 2	0.7	300 T.m
max field	T	4.2	4.68	6.79	3.46	8.36	4.5	6.0
max current	kA	4.2	5.03	6.5	5.09	11.5	1.04	6.62
injection field	T	0.66	0.23	0.68	0.4	0.58	0.64	1.6
ramp rate	T/s	0.22	0.009	0.004	0.04	0.066	0.021	1.0
aperture	mm	76	75	50	80	56	58	100
length	m	6.1	8.8	15.2	9.4	14.2	1.6	2.91
operating temperature	K	4.6	4.5	4.35	4.6	1.9	4.5	4.5
number off		774	422	3972	396	1232	2	108

Superconducting cables of the world's accelerators

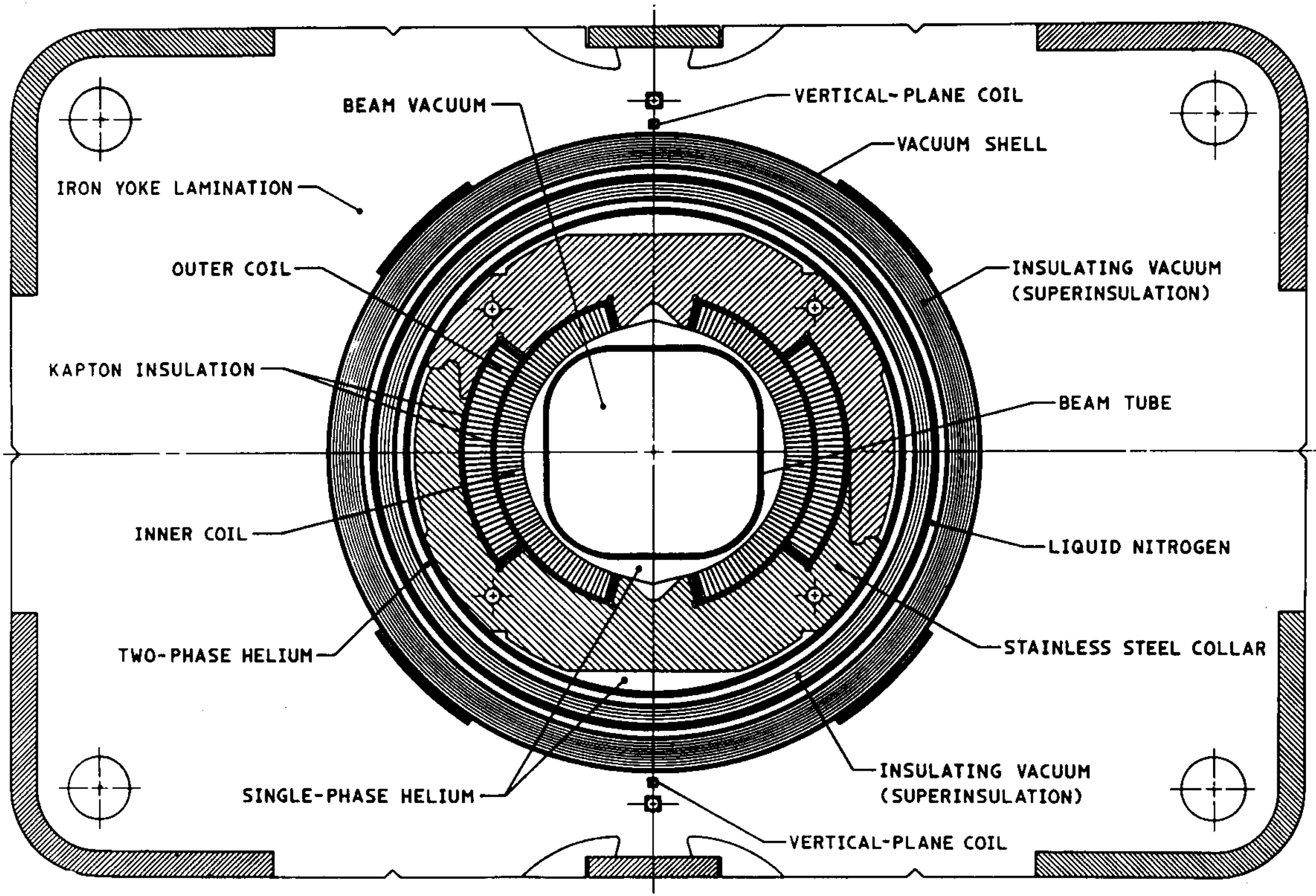
Ring	cable	filament dia µm	cable width mm	twist pitch mm	wire surface	ramp rate T/s
Tevatron		6	7.8	66	zebra	0.22
HERA		14-16	10	95	SnAg	0.009
RHIC		6	9.7	73	copper	0.04
SSC		6	12.3	79	copper	0.004
LHC	 	7 6	15 15	110 100	SnAg pre-ox	0.066
Helios		8.5	3.2	40	copper	0.021
FAIR		2.5 - 3.5	15	110	SnAg pre-ox with SS core	1.0

The Fermilab Tevatron

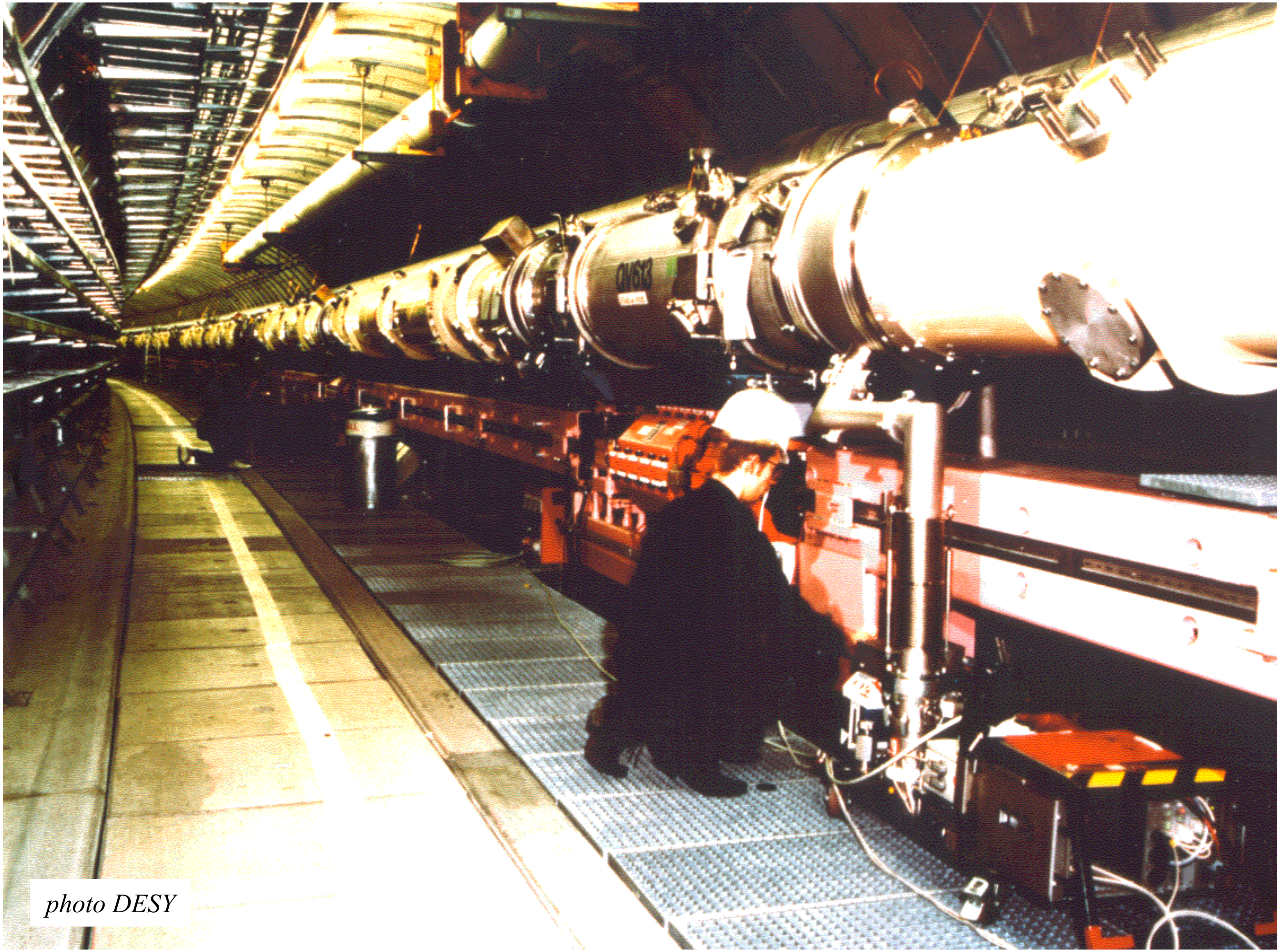


the world's first superconducting accelerator

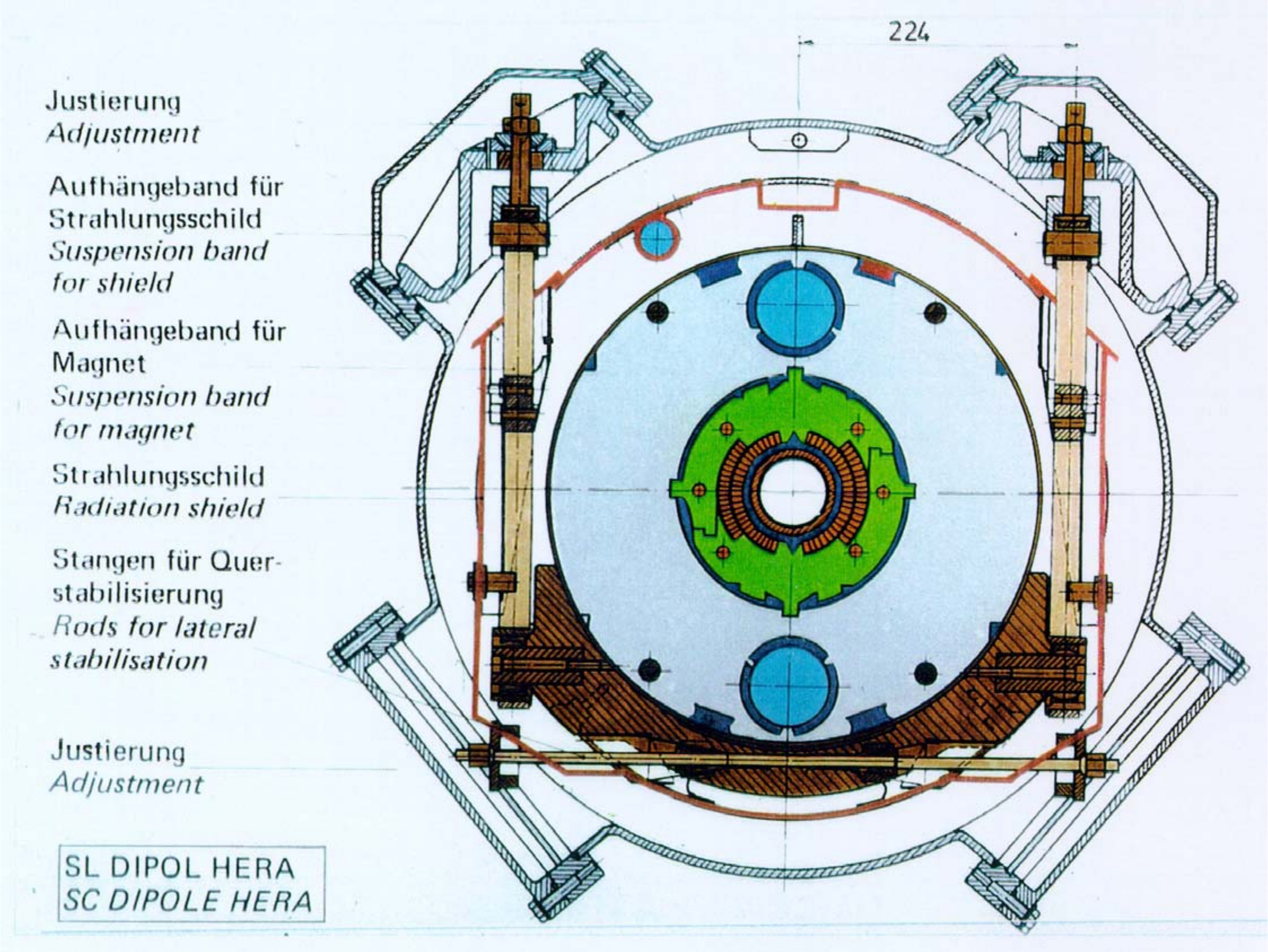
Tevatron dipole



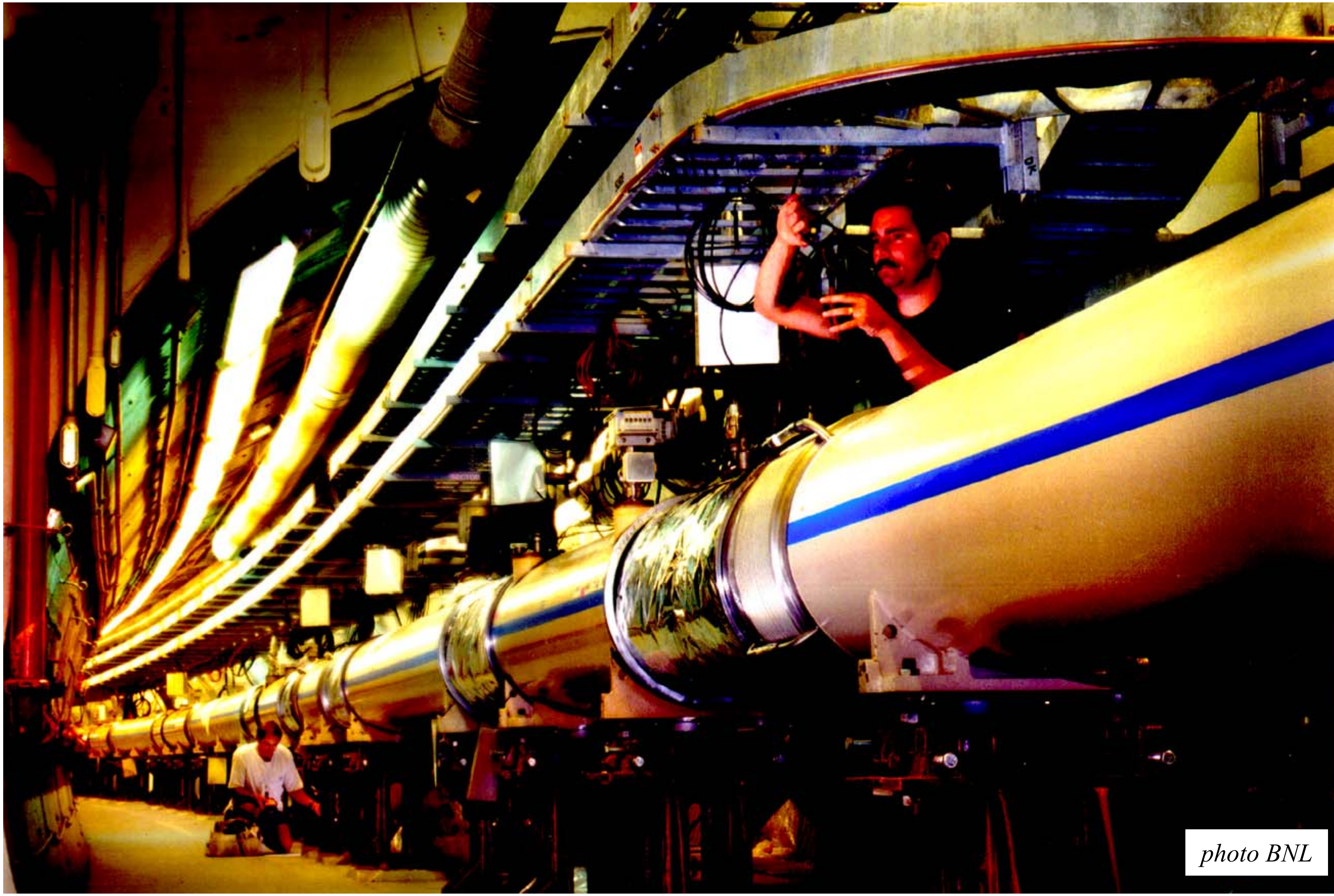
Hera



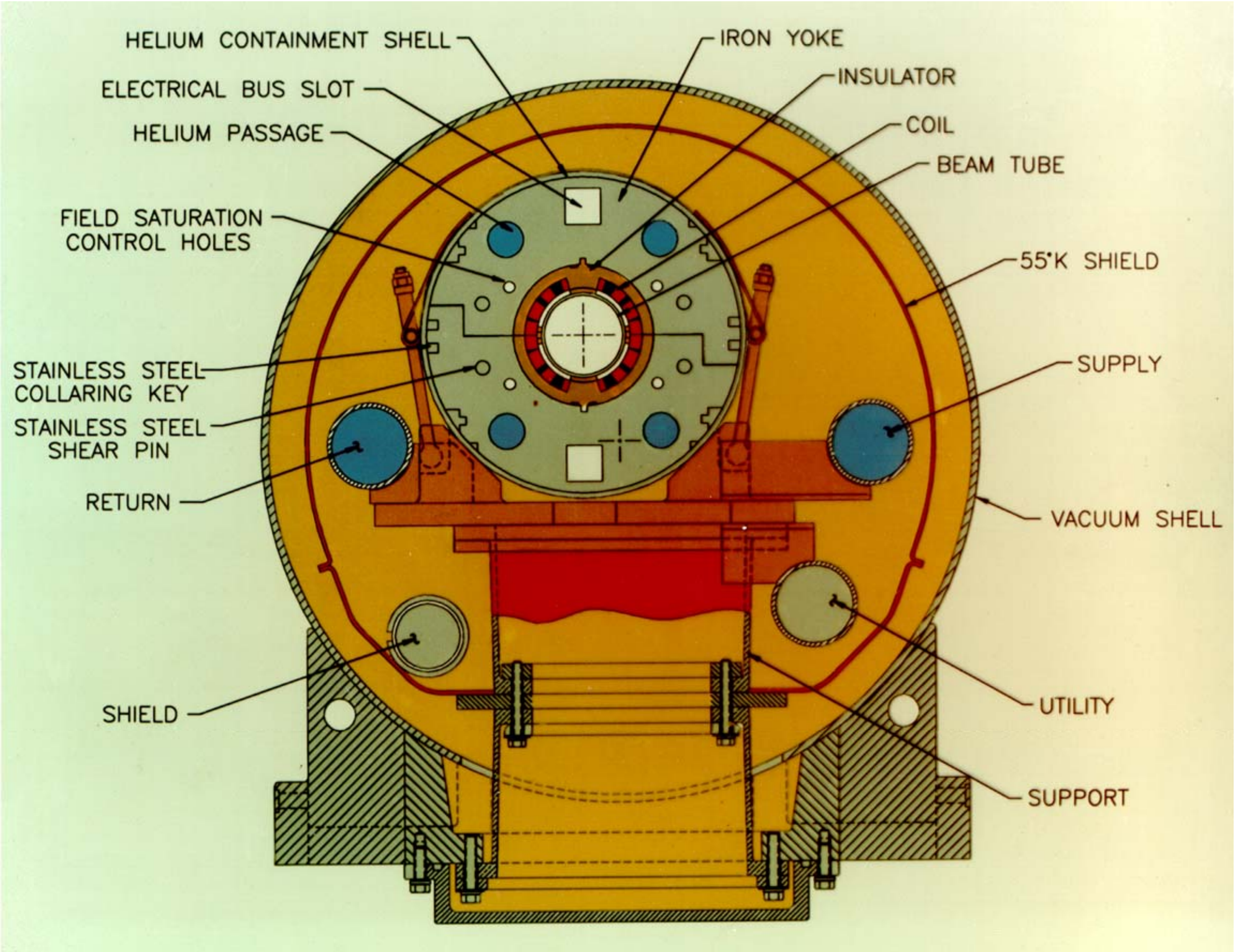
Hera dipole


224
Justierung
Adjustment
Aufhängeband für
Strahlungsschild
Suspension band
for shield
Aufhängeband für
Magnet
Suspension band
for magnet
Strahlungsschild
Radiation shield
Stangen für Quer-
stabilisierung
Rods for lateral
stabilisation
Justierung
Adjustment
SL DIPOL HERA
SC DIPOLE HERA

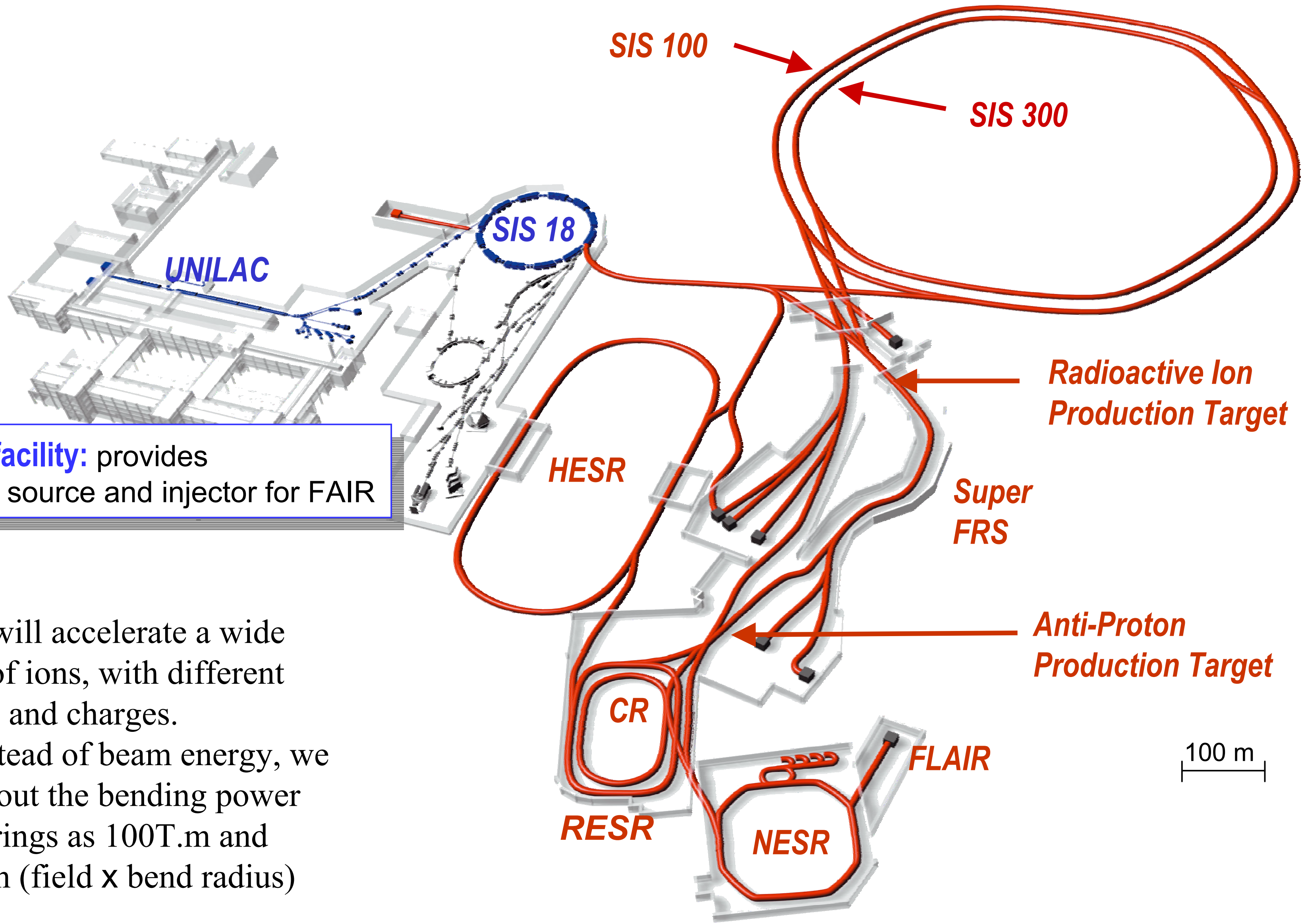
RHIC



RHIC Dipole


HELIUM CONTAINMENT SHELL
ELECTRICAL BUS SLOT
HELIUM PASSAGE
FIELD SATURATION CONTROL HOLES
STAINLESS STEEL COLLARING KEY
STAINLESS STEEL SHEAR PIN
RETURN
SHIELD
IRON YOKE
INSULATOR
COIL
BEAM TUBE
55°K SHIELD
SUPPLY
VACUUM SHELL
UTILITY
SUPPORT

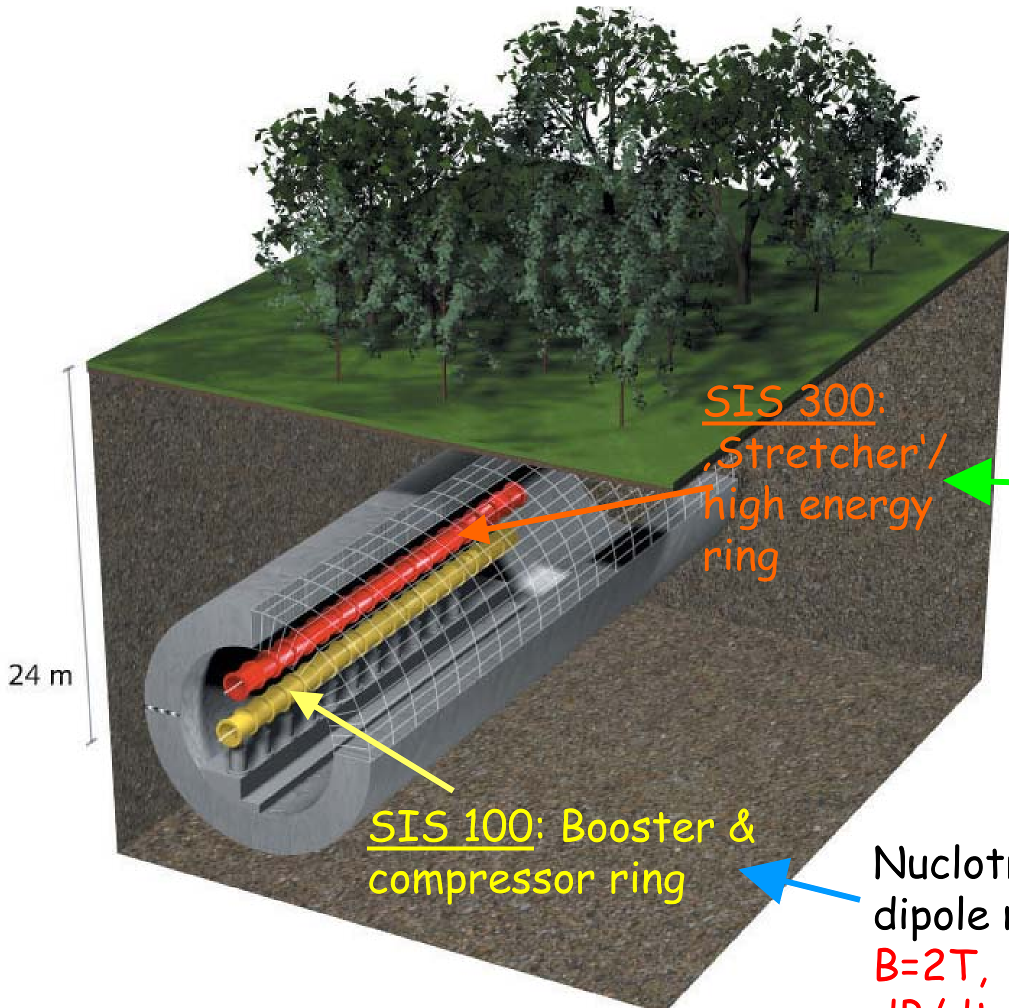
Facility for Antiproton and ion research FAIR



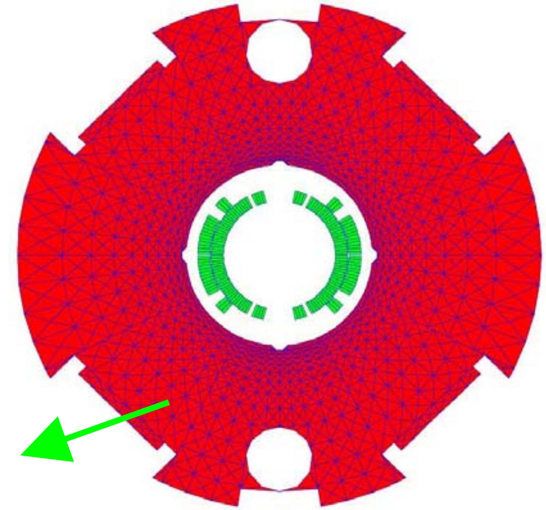
Existing facility: provides ion-beam source and injector for FAIR

FAIR will accelerate a wide range of ions, with different masses and charges.
So, instead of beam energy, we talk about the bending power of the rings as 100T.m and 300T.m (field x bend radius)

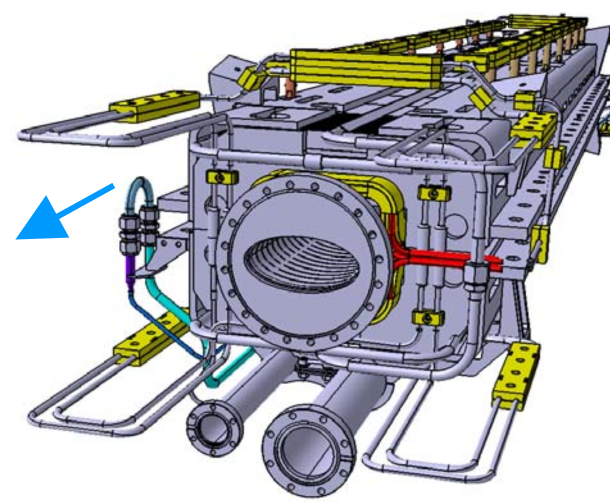
FAIR: two rings in one tunnel



Modified UNK dipole
6T at 1T/s

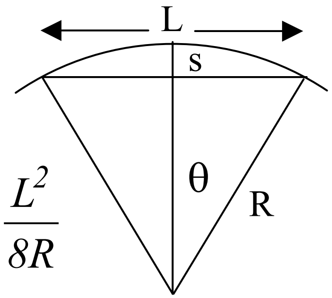


Nuclotron-type dipole magnet:
B=2T,
dB/dt=4T/s

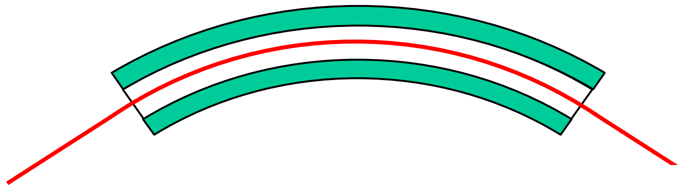


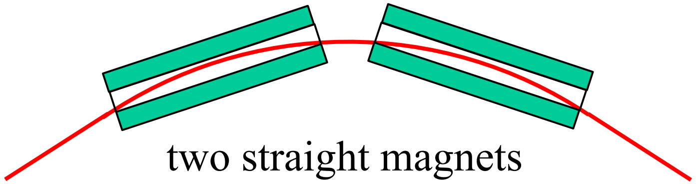
2x120 superconducting dipole magnets
132+162 SC quadrupole magnets

Problem of the sagitta in SIS300



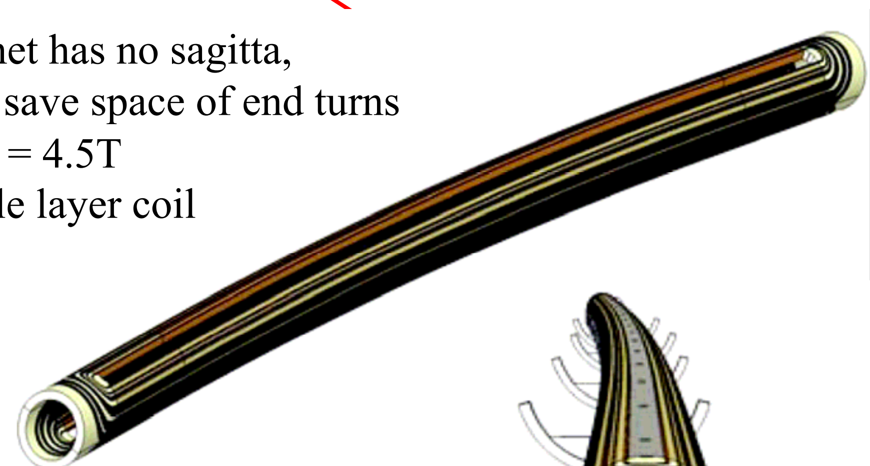
$$s = \frac{L^2}{8R}$$

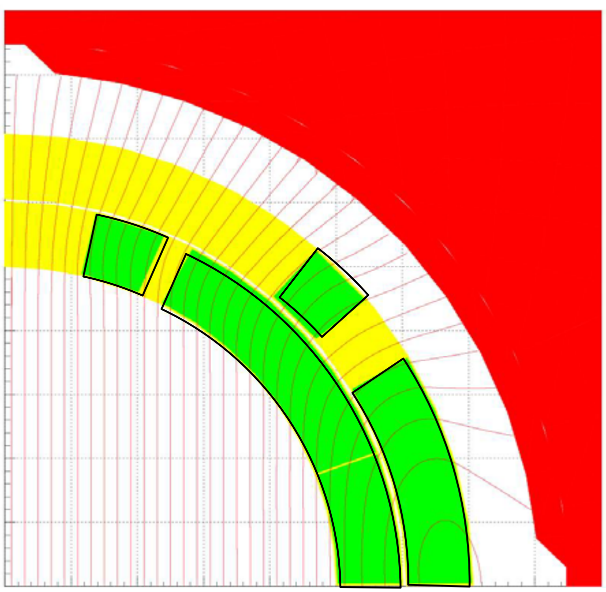


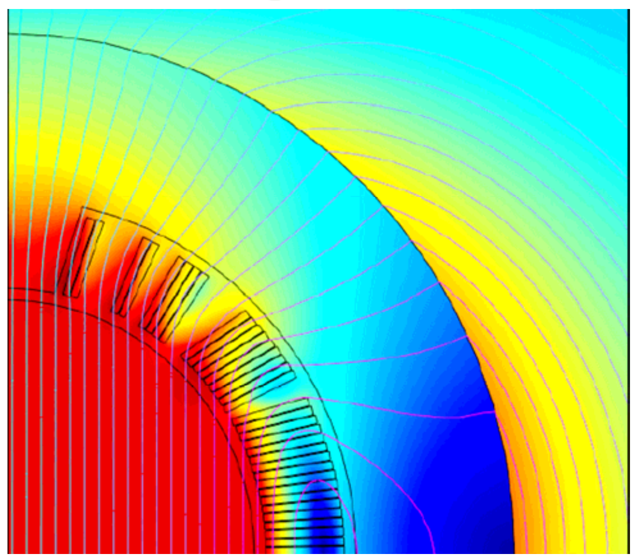


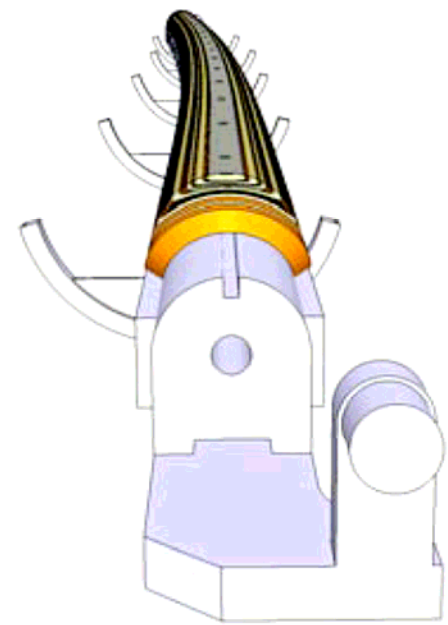
two straight magnets
must be short because of sagitta
$\Rightarrow$ B = 6T
must use double layer coil

curved magnet has no sagitta,
can be long, save space of end turns
$\Rightarrow$ B = 4.5T
can use single layer coil





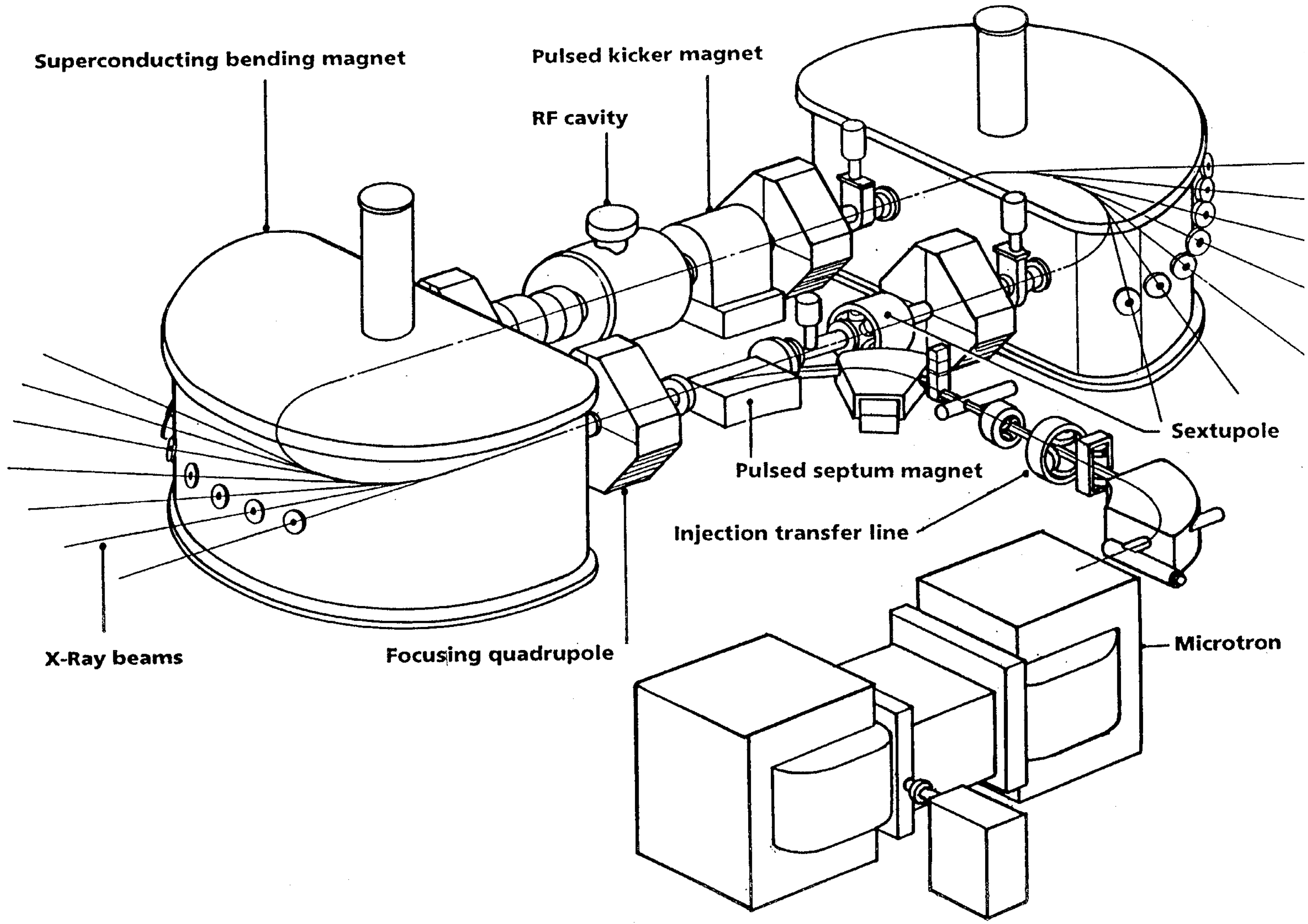




just one problem
- how to make it!

X-ray beams for microchip lithography:

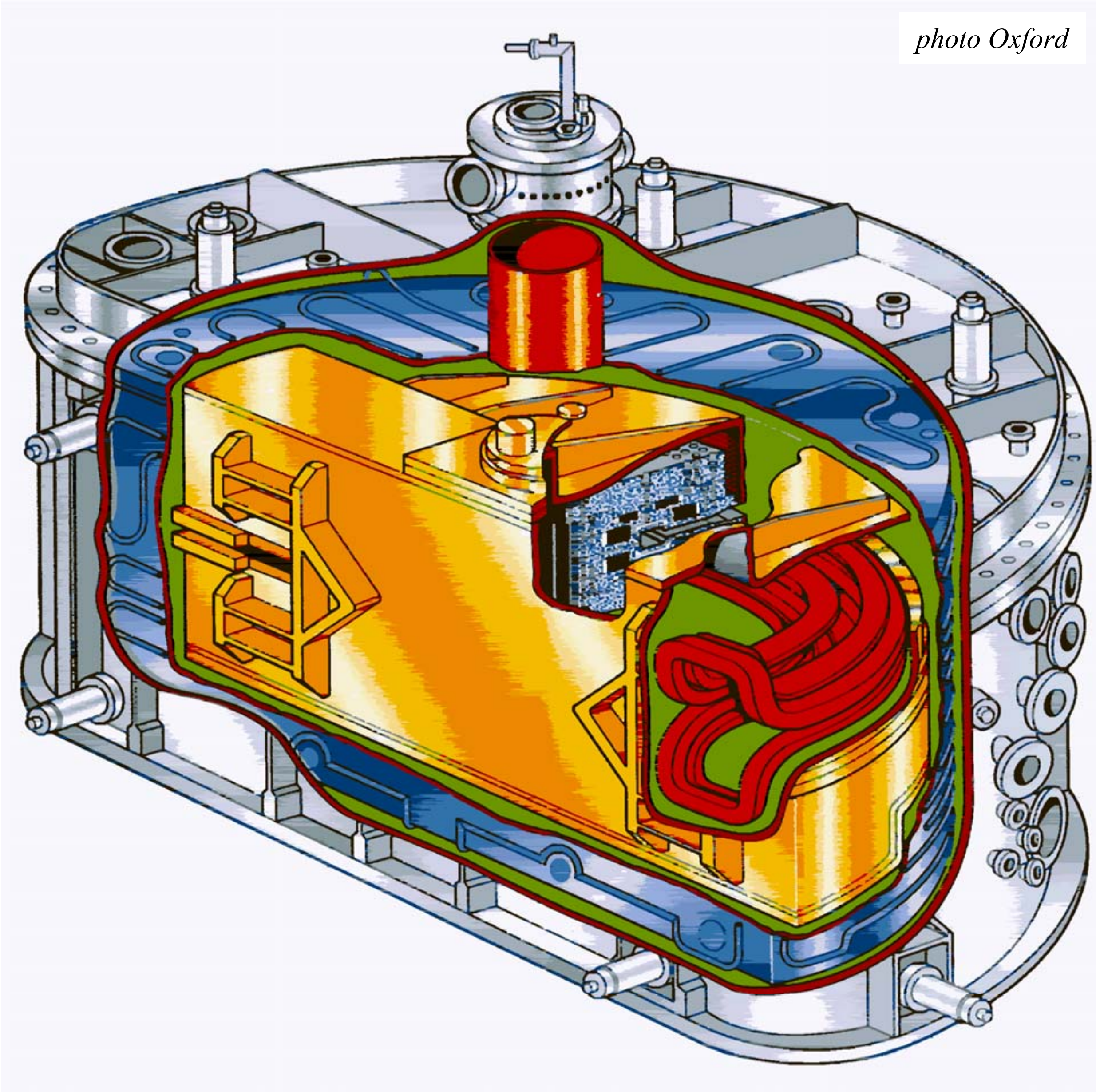
the compact electron storage ring Helios



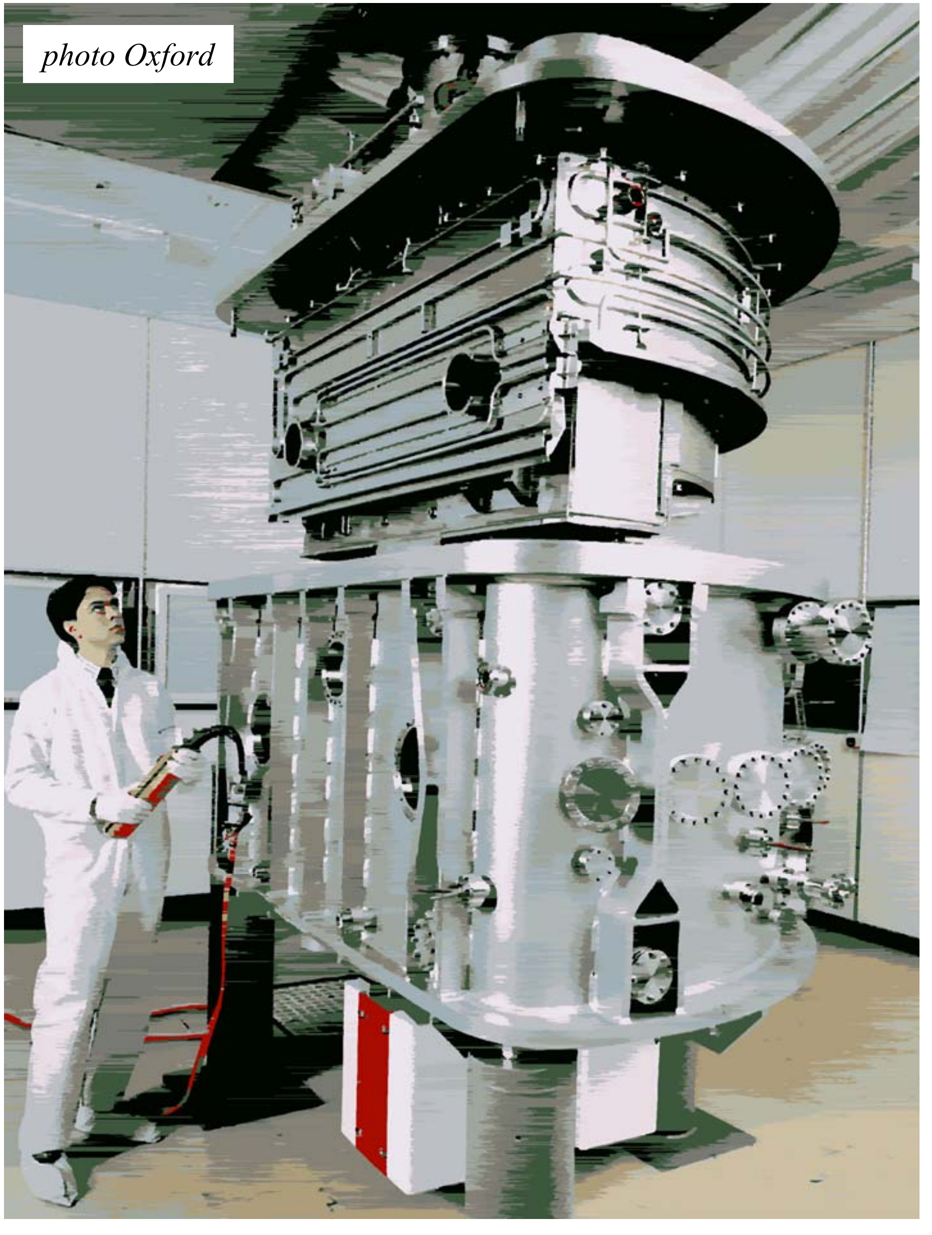
Helios

superconductivity
⇒
compact size
⇒
transportability

Helios dipole



- bent around180°
- rectangular block coil section
- totally clear gap on outer mid plane for emerging X-rays (12 kW)



Helios dipole assembly

ultra clean conditions because UHV needed for beam lifetime

Hardware: concluding remarks

- coils for accelerator magnets are made in accelerator labs and industry
- after winding, compact the finished winding to exact size and 'cure' it
- electrical insulation to ground plane is important during quench
- fit collars, compress to that stress needed for correct loading at 4K - then lock in place
- fit iron and outer shell, compress to size and weld
- install within operating cryostat
- current leads should be gas cooled and the optimum shape for minimum heat leak,
  - shape depends on the material used
  - impure material is less likely to burn out
  - use HTS to reduce heat leak at the bottom end
- in recent years the largest accelerators have all been superconducting

what comes next is up to you!

customer support line:
m-wilson@dsl.pipex.com