

# *Lecture 5: Practical matters*

## **Plan**

- LHC quench protection
- current leads
- accelerator coil winding and curing
- forces and clamping
- magnet assembly, collars and iron
- installation
- some superconducting accelerators



# *LHC dipole protection: practical implementation*

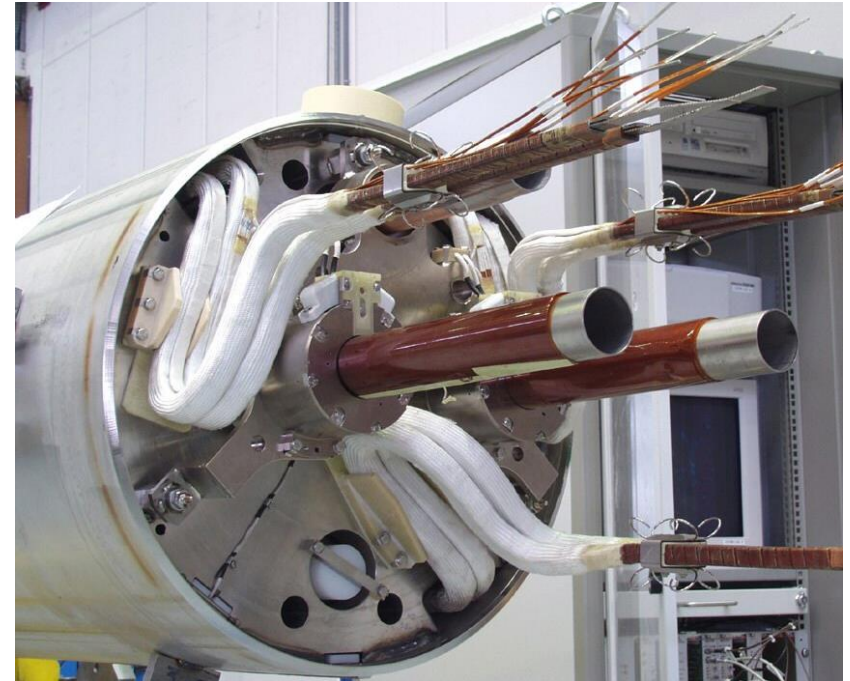
**It's difficult! - the main challenges are:**

## **1) Series connection of many magnets**

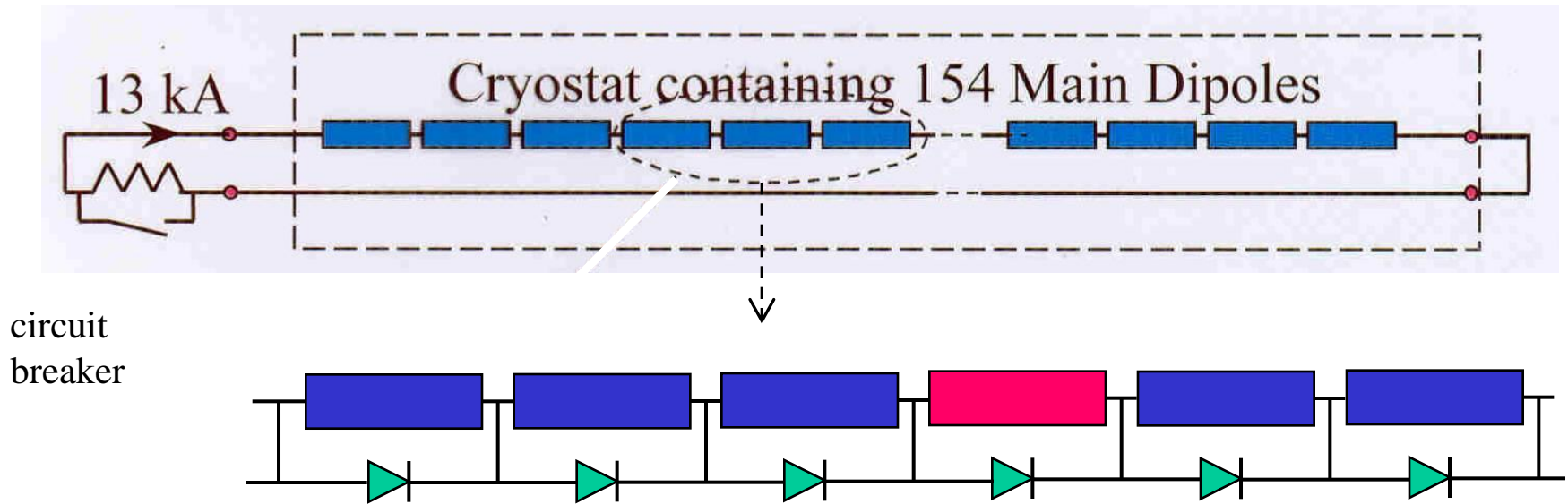
- In each octant, 154 dipoles are connected in series. If one magnet quenches, the combined energy of the others will be dumped in that magnet  $\Rightarrow$  vaporization!
- **Solution 1:** cold diodes across the terminals of each magnet. Diodes normally block  $\Rightarrow$  magnets track accurately. If a magnet quenches, its diodes conduct  $\Rightarrow$  octant current by-passes.
- **Solution 2:** open a circuit breaker onto a resistor (several tonnes) so that octant energy is dumped in  $\sim 100$  secs.

## **2) High current density, high stored energy and long length**

- Individual magnets may burn out even when quenching alone.
- **Solution 3:** Quench heaters on top and bottom halves of every magnet.



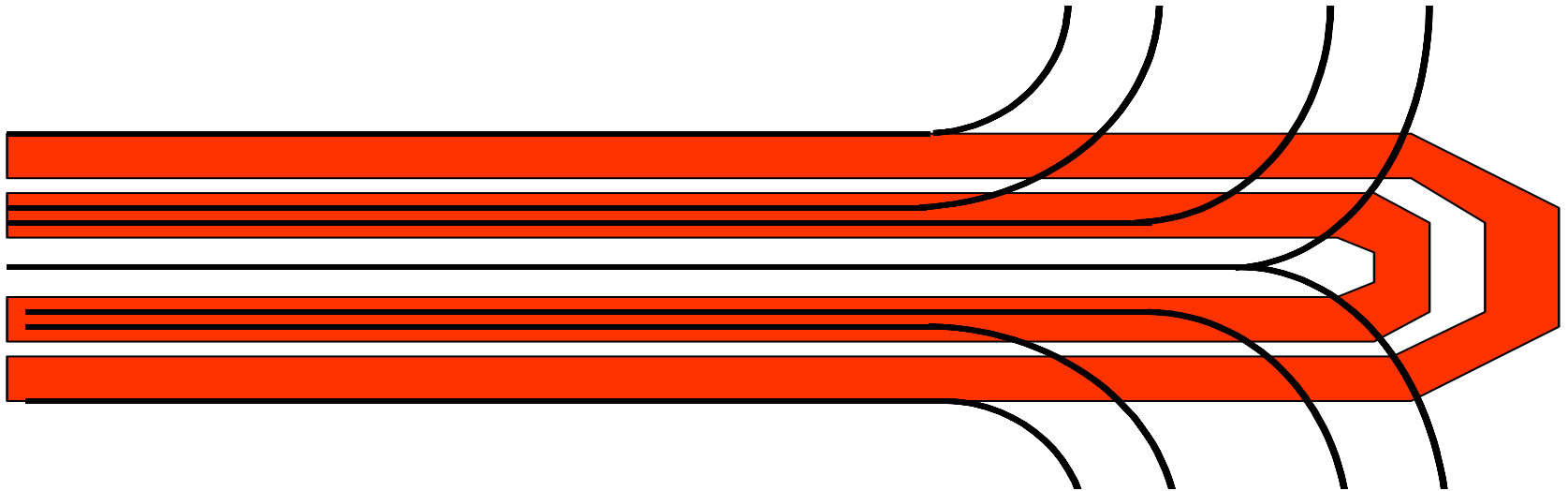
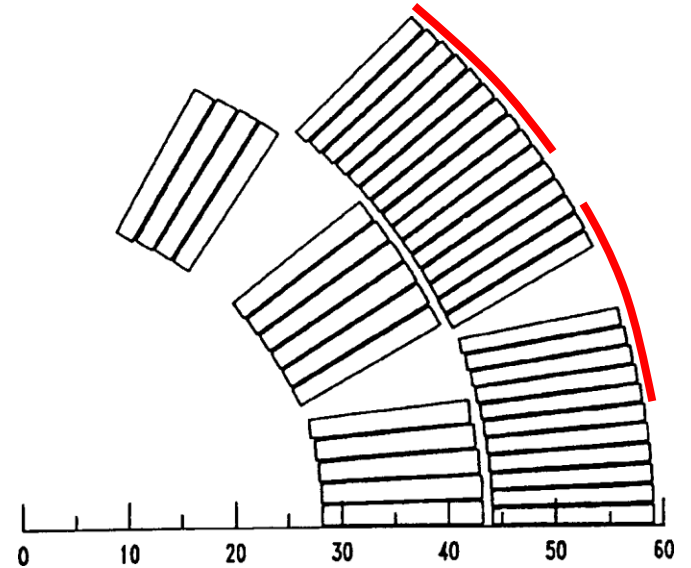
# *LHC power supply circuit for one octant*



- in normal operation, diodes block  $\Rightarrow$  magnets track accurately
- if a magnet quenches, diodes allow the octant current to by-pass
- circuit breaker reduces to octant current to zero with a time constant of 100 sec
- initial voltage across breaker = 2000V
- stored energy of the octant = 1.33GJ

# LHC quench-back heaters

- stainless steel foil 15mm x 25  $\mu\text{m}$  glued to outer surface of winding
- insulated by Kapton
- pulsed by capacitor 2 x 3.3 mF at 400 V = 500 J
- quench delay
  - at rated current = 30msec
  - at 60% of rated current = 50msec
- copper plated 'stripes' to reduce resistance





# *Diodes to by-pass the main ring current*

Installing the cold diode package on the end of an LHC dipole



# Current Leads

## Optimization

- want to have low heat inleak, ie low ohmic heating *and* low heat conduction from room temperature. This requires low  $\rho$  and  $k$  - but Wiedemann Franz says

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

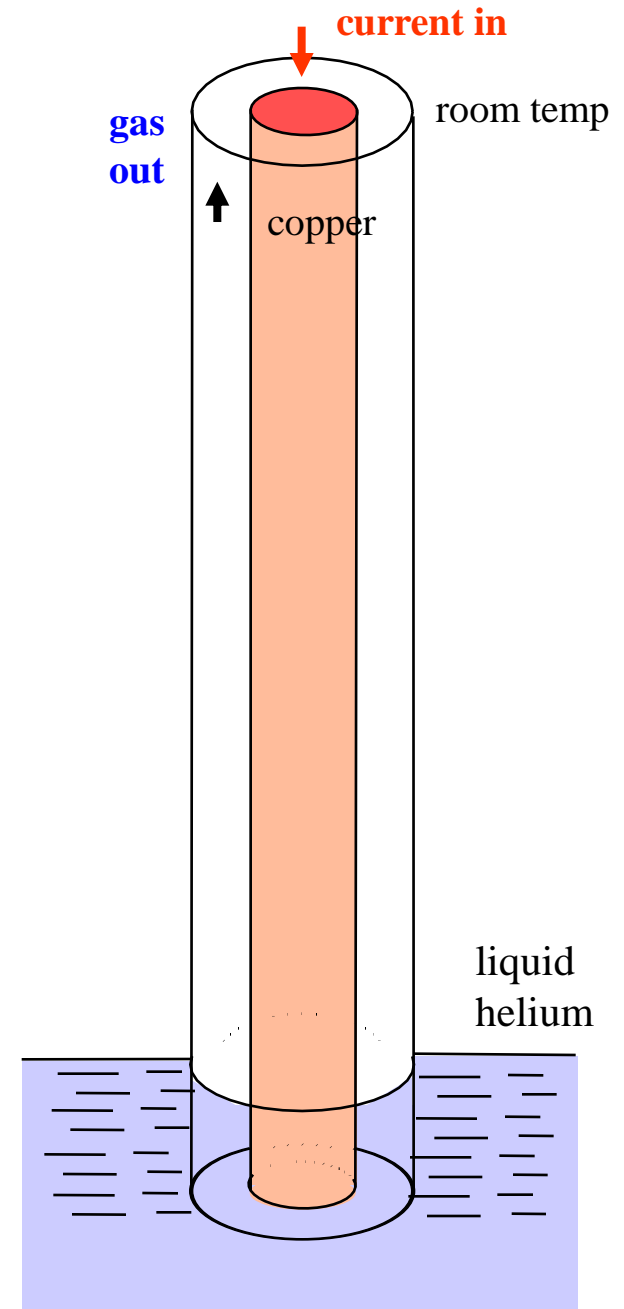
- so all metals are the same and the only variable we can optimize is the *shape*

## Gas cooling helps (recap helium properties Lecture 4)

- $\Delta$ enthalpy gas / latent heat of boiling = 73.4 - lots more cold in the boil off gas

$$\Delta H = \int_{4.2}^{293} C(\theta) d\theta$$

- so use the enthalpy of the cold gas which is boiled off to cool the lead
- we make the lead as a heat exchanger



# Current lead theory

equation of heat conduction

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

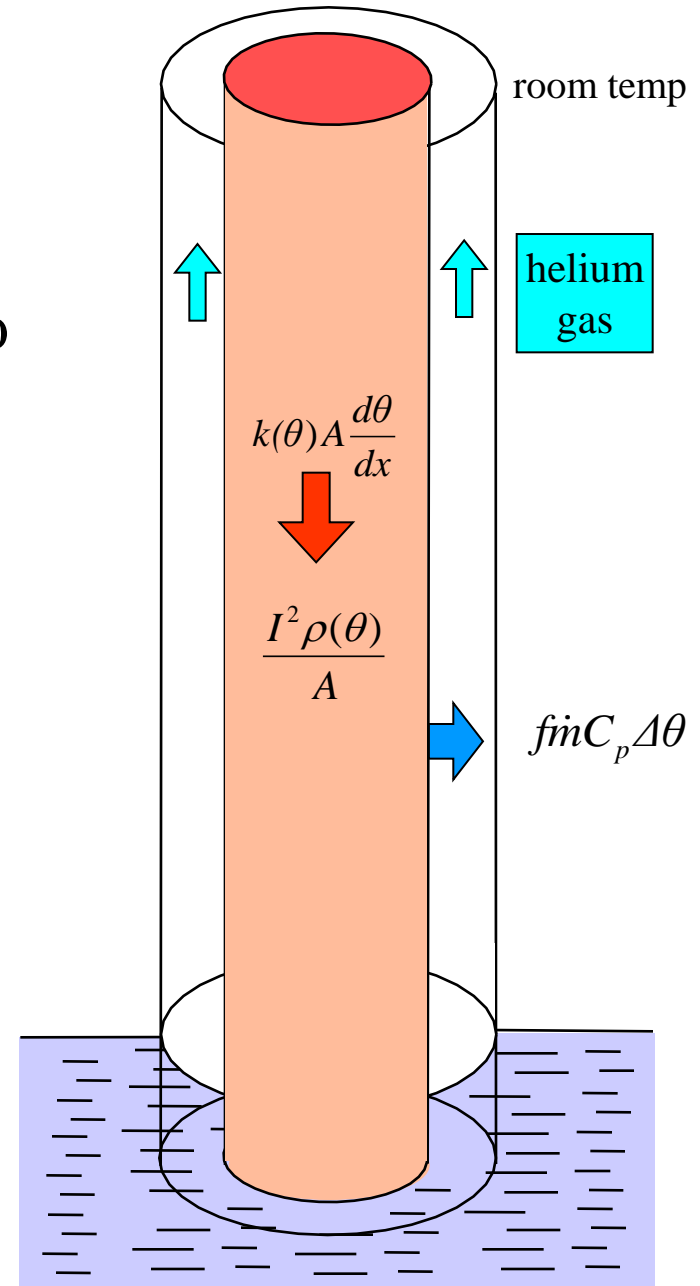
where:

$f$  = efficiency of heat transfer to helium gas

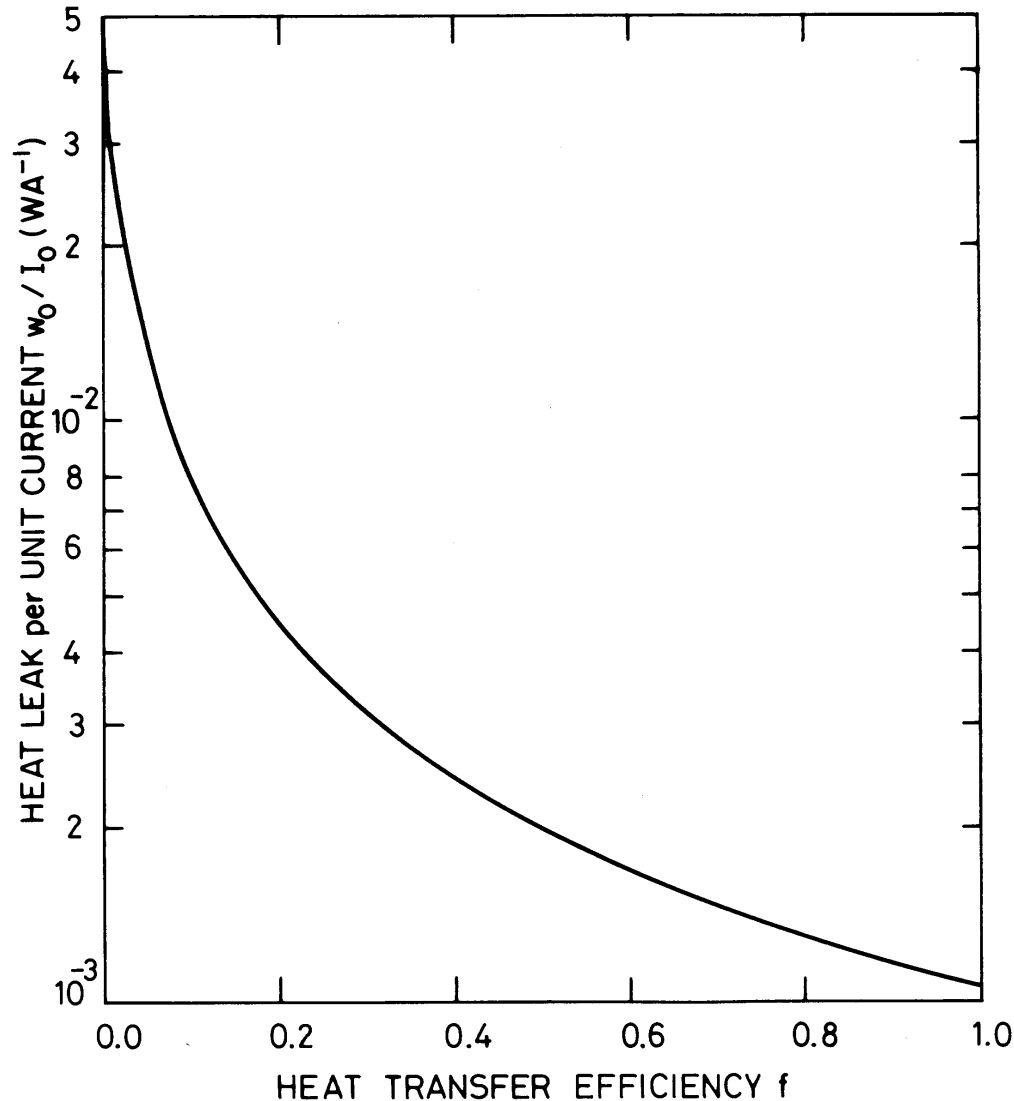
$\dot{m}$  = helium mass flow

$C_p$  = specific heat of gas

- solution to this equation in 'Superconducting Magnets p 257.
- there is an optimum shape (length/area) which gives the minimum heat leak
  - 'Watts per Amp per lead'
- heat leak is a strong function of the efficiency of heat transfer  $f$  to the cold gas



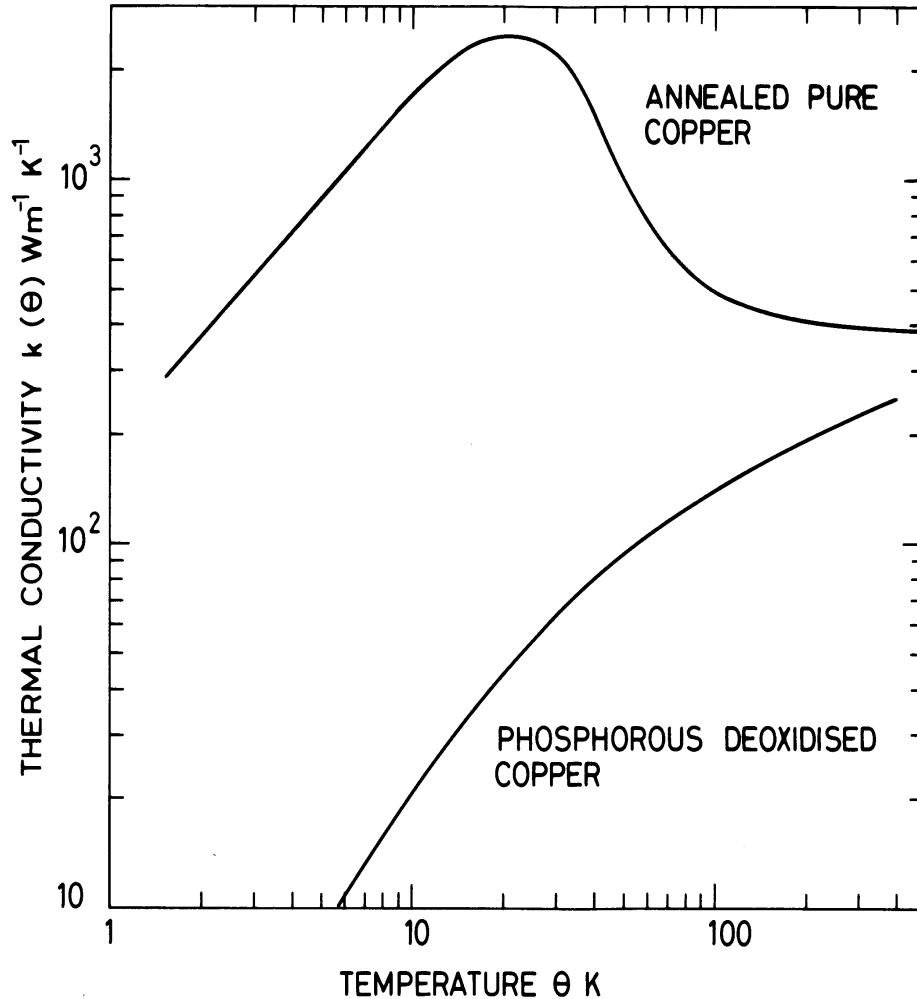
# Heat leak of an optimised lead



- with optimum shape and 100% efficient heat transfer the heat leak is  
**1.04 mW/Amp**  
*per lead*
- 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



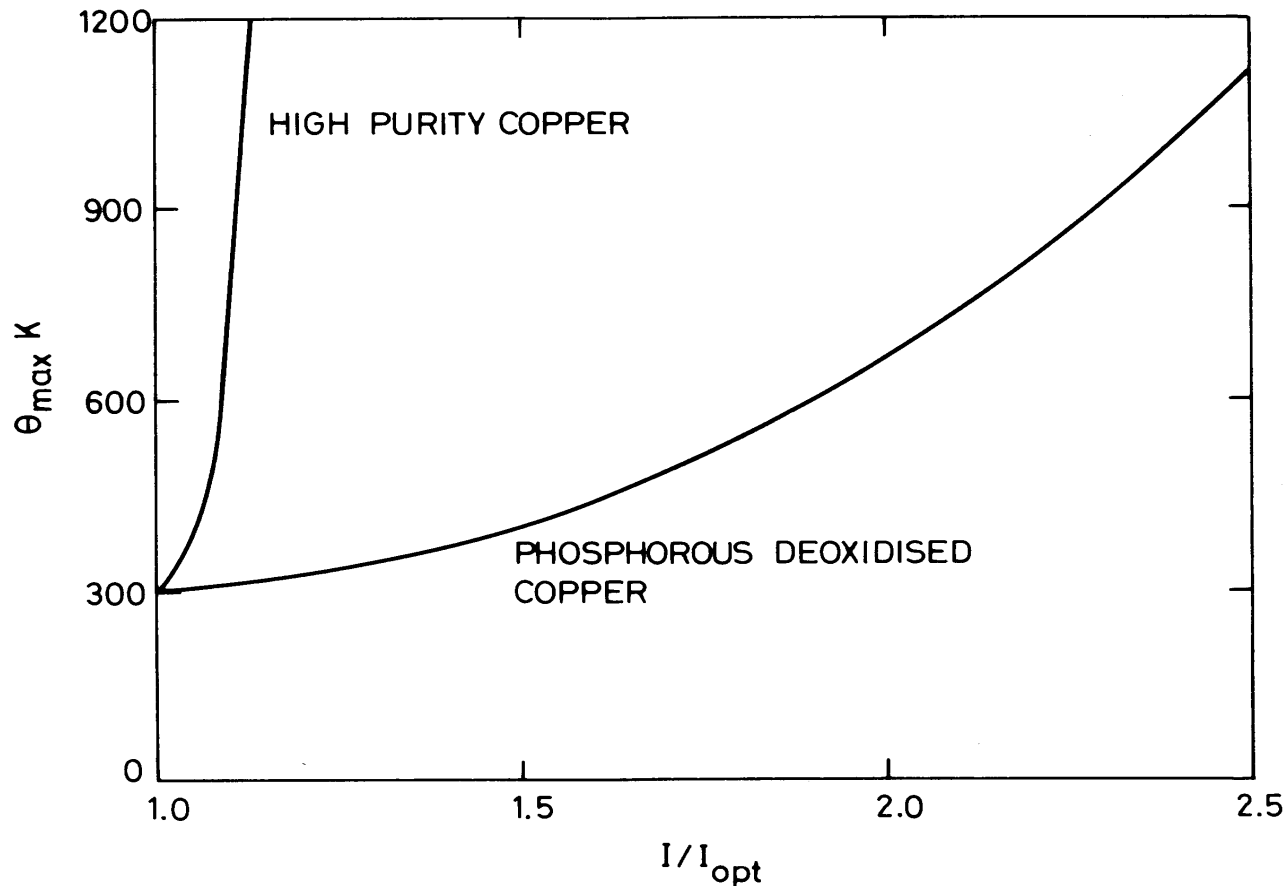
- the optimum shape depends on temperature and material properties, particularly thermal conductivity.
- for a lead between 300K and 4.2K the optimum shape is
  - for a lead of annealed high purity copper

$$\left\{ \frac{L}{A} \right\}_{\text{optimum}} = \frac{2.6 \times 10^7}{I}$$

- for a lead of impure phosphorous deoxidised copper (preferred)

$$\left\{ \frac{L}{A} \right\}_{\text{optimum}} = \frac{3.5 \times 10^6}{I}$$

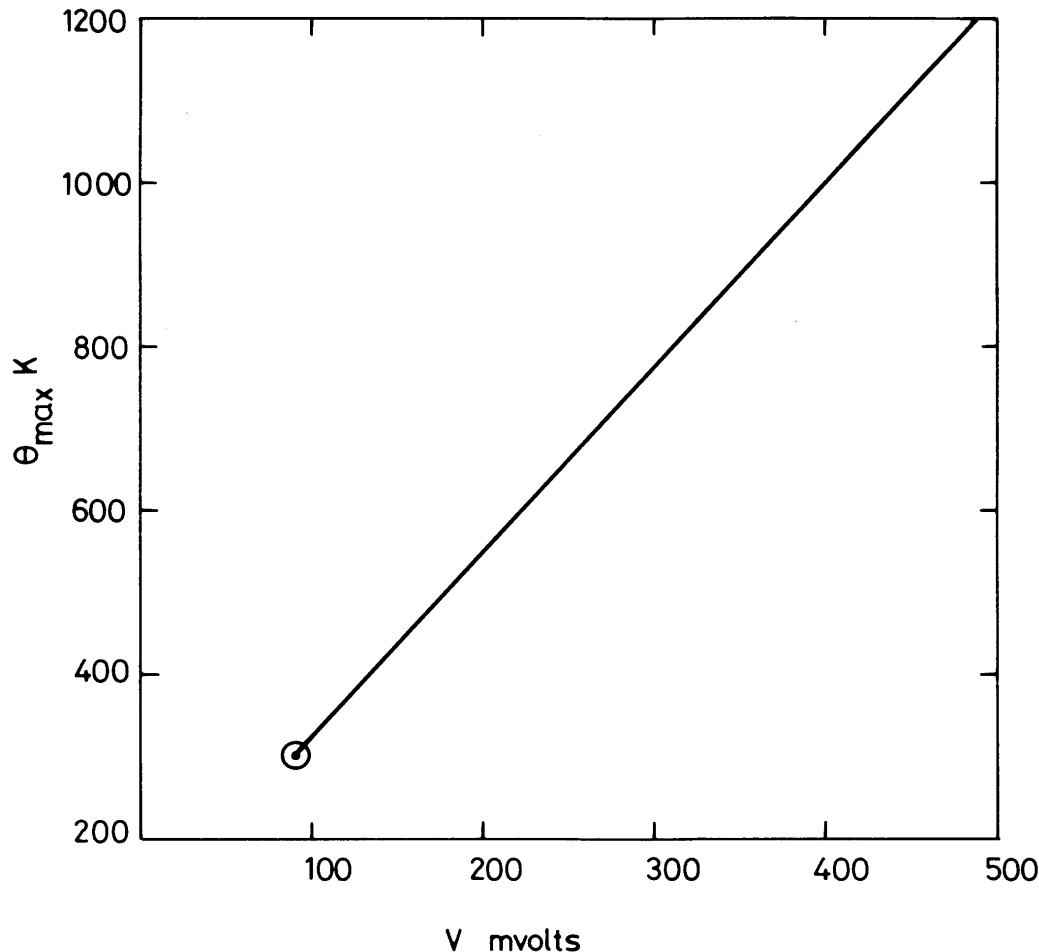
# *Impure materials make more stable leads*



- 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

*if current lead burns out  $\Rightarrow$  magnet open circuit  
 $\Rightarrow$  large voltages  
 $\Rightarrow$  disaster*

# Health monitoring



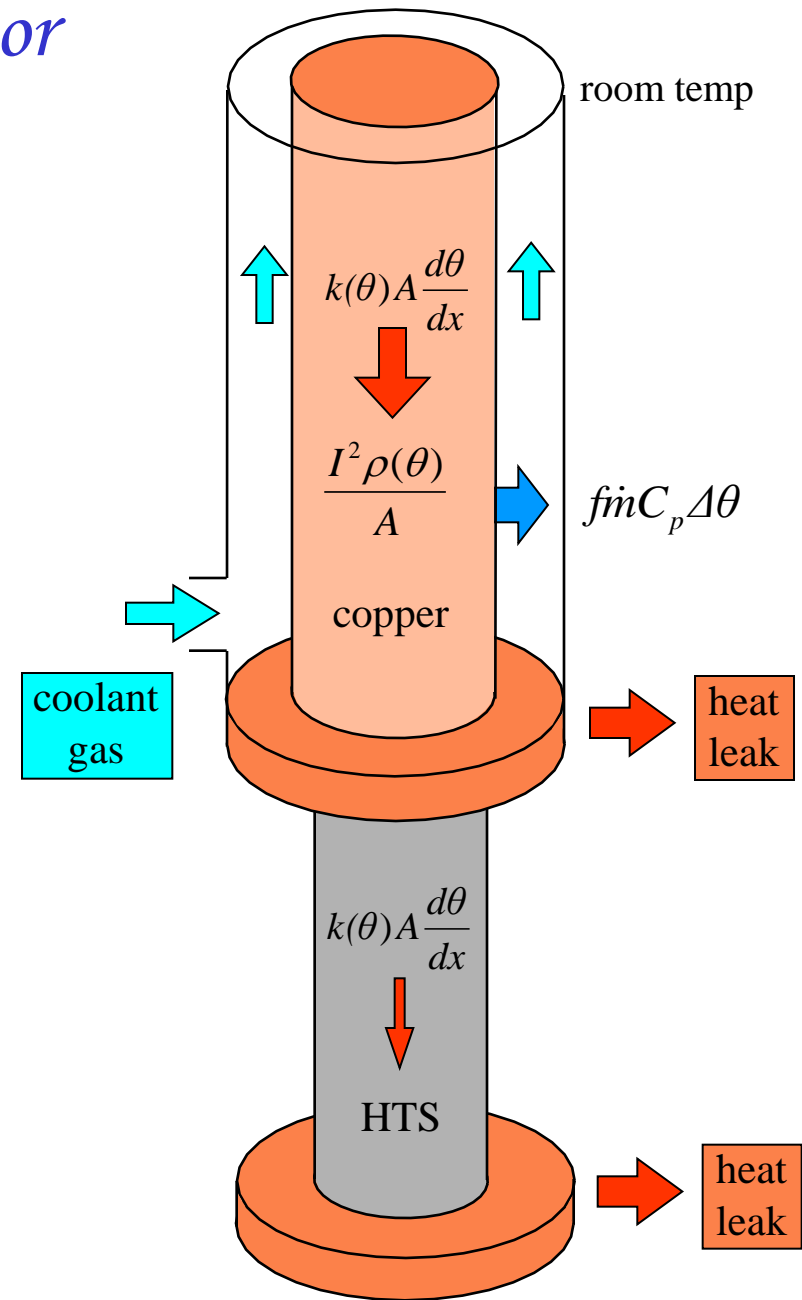
- all leads between the same temperatures and with the same cooling efficiency drop the same voltage at optimum
- for a lead between 300K and 4.2K with 100% cooling efficiency, the voltage drop at optimum is **75mV**
- measure the volts across your lead to see if it is optimised
- if a lead burns out,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

# High temperature superconductor HTS Current leads

- at temperatures below 50 -70K can use HTS
- material has very low thermal conductivity
- no Ohmic heat generation
- but from room temperature to 50 – 70 K must have copper leads
- the 50 – 70 K junction must be cooled or its temperature will drift up and quench the HTS

*For the HTS section beware of*

- *overheating if quenches*
- *fringe field from magnet*





# HTS (high temperature superconductor) current leads



- HTS materials have a low thermal conductivity
- make the section of lead below  $\sim 70\text{K}$  from HTS material
- heat leak down the upper lead is similar, but it is taken at a higher temperature  
 $\Rightarrow$  less refrigeration power
- LHC uses HTS leads for all main ring magnets
- savings on capital cost of the refrigerator  $>$  cost of the leads
- reduced running cost is a continuing benefit

$\Leftarrow 13\text{kA}$  lead for LHC

$600\text{A}$  lead for LHC  $\Rightarrow$



# *Winding the LHC dipoles*

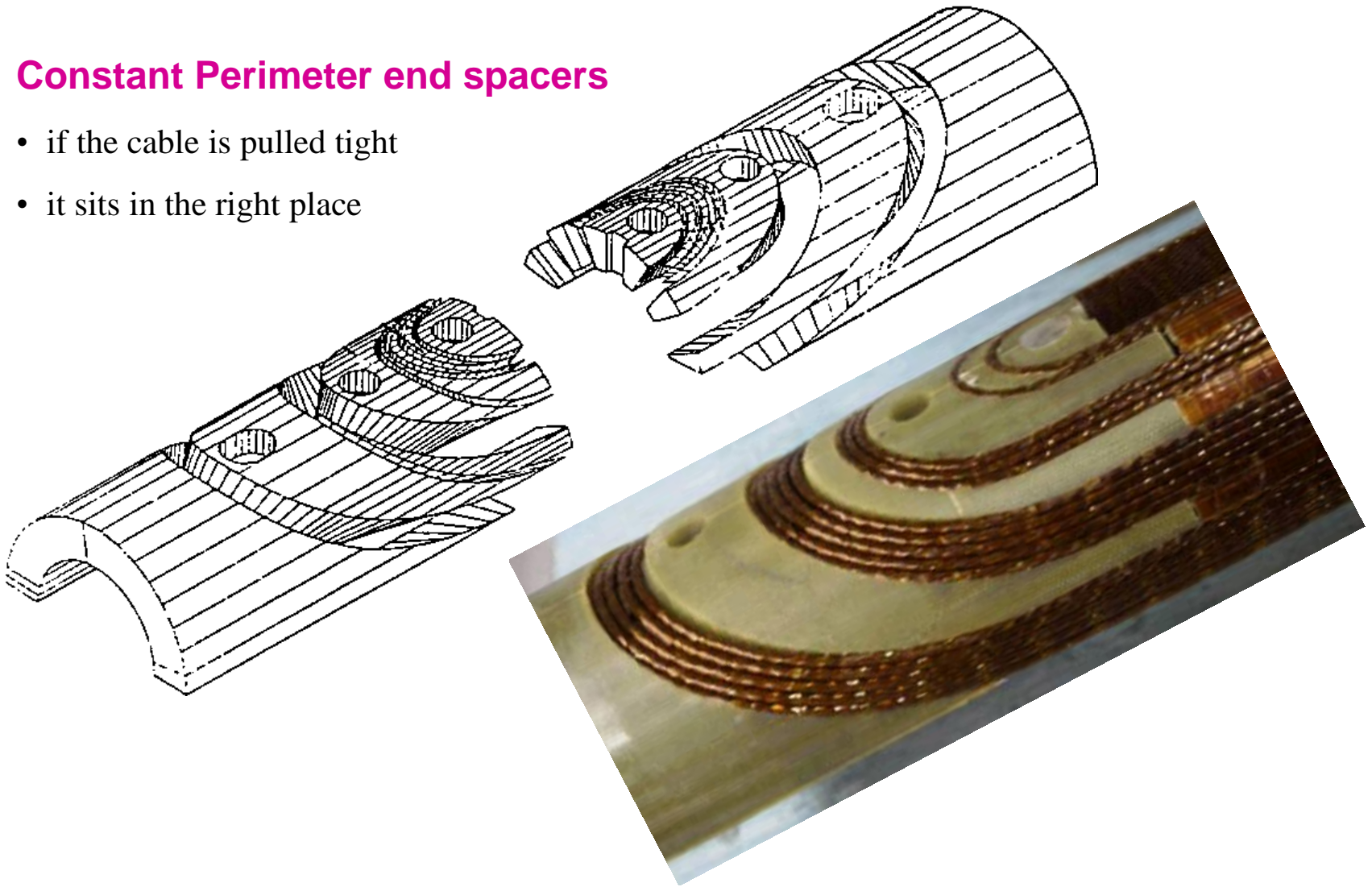


*photo courtesy of Babcock Noell*

# End turns

## Constant Perimeter end spacers

- if the cable is pulled tight
- it sits in the right place





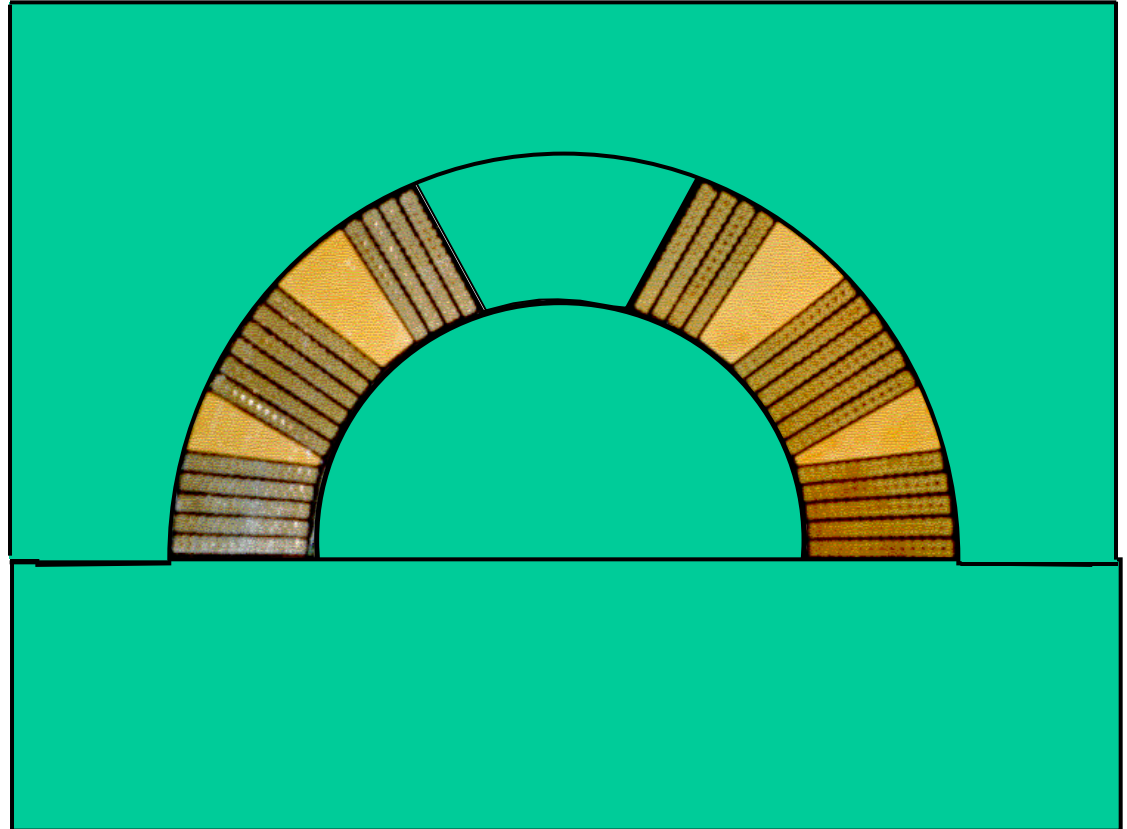
[illegible]

- polyimide  
insulation  
Kapton**



# Compacting and curing

- After winding, the half coil, (still very 'floppy') is placed in an accurately machined tool
- Tool put into a curing press, compacted to the exact dimensions and heated to 'cure' the polyimide adhesive on the Kapton insulation.
- After curing, the half coil is quite rigid and easy to handle



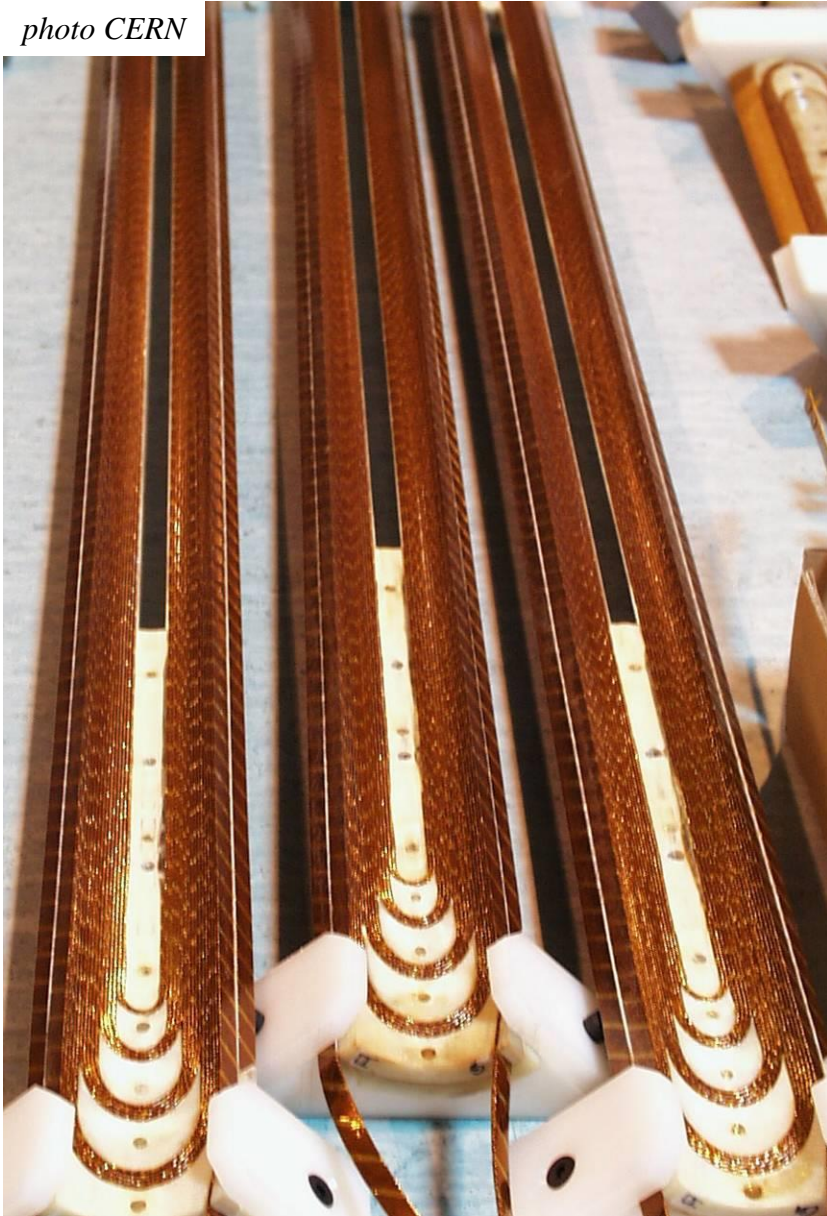
# *Curing press*



*photo CERN*



photo CERN



## *Finished coils*

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



photo CERN

# Coils for correction magnets

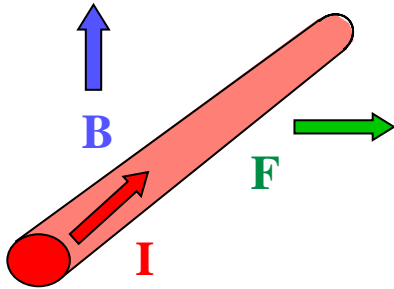


photo CERN

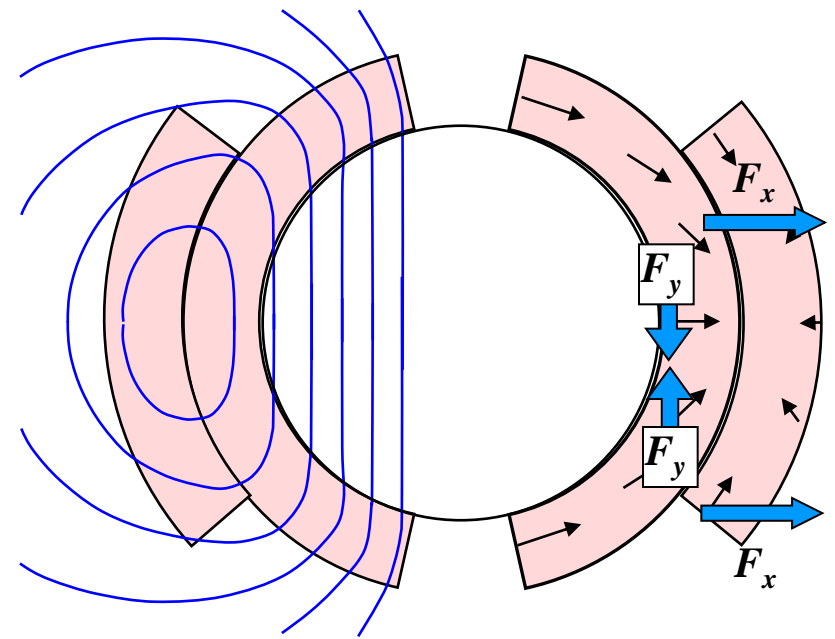
On a smaller scale, but in great number and variety, many different types of superconducting correction coils are needed at a large accelerator



# Electromagnetic forces in dipoles



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



- forces in a dipole are horizontally outwards and vertically towards the median plane
- recap lecture 2 slide 12, for a *thin* winding

total outward force  
*per quadrant*

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

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

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
- $F_x$  and  $F_y$  cause compressive stress in the conductor and insulation
- apart from the ends, there is no tension in the conductor

*for thick winding take ~  
mean radius - or better use  
formulae of Paolo Ferracin:  
Friday Magnet Workshop*

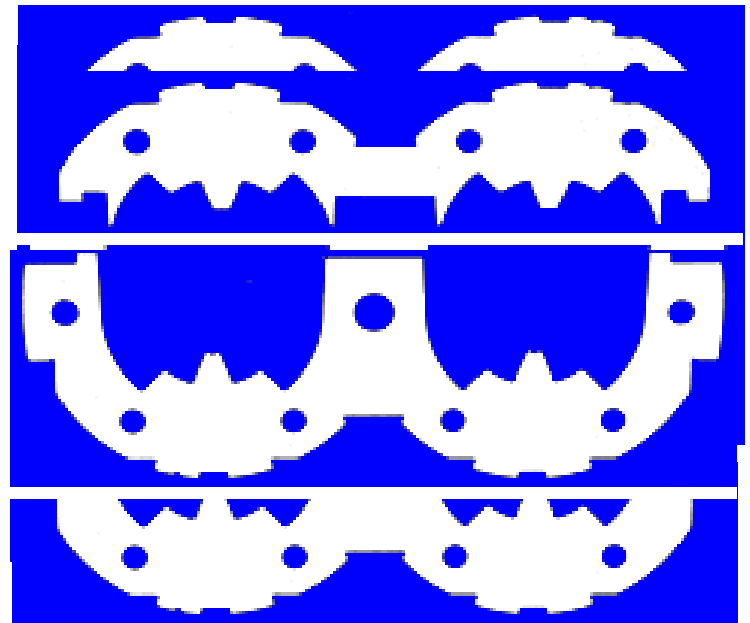
# Collars

**Question:** how to make a force support structure that

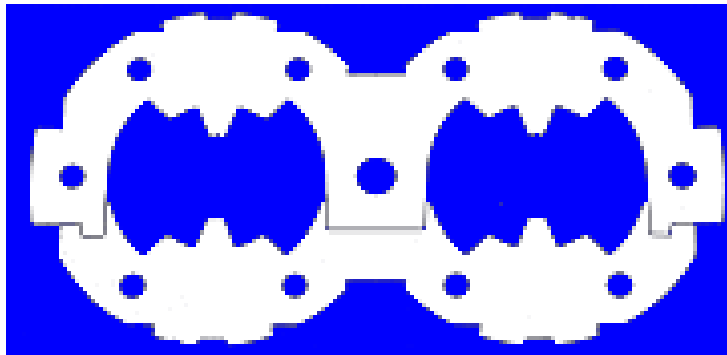
- fits tightly round the coil
- presses it into an accurate shape
- has low ac losses - laminated
- can be mass produced cheaply

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

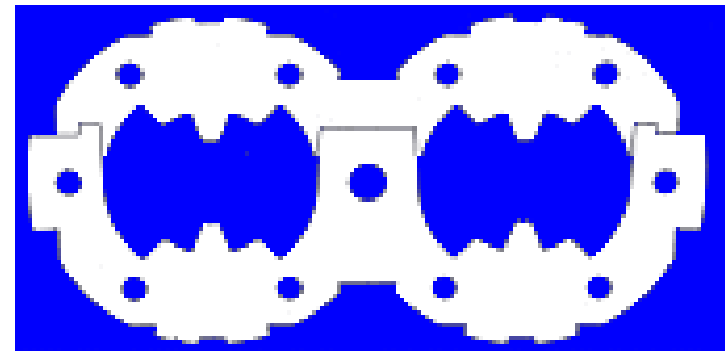
- inherited from conventional magnet laminations



*press collars over coil from above and below*



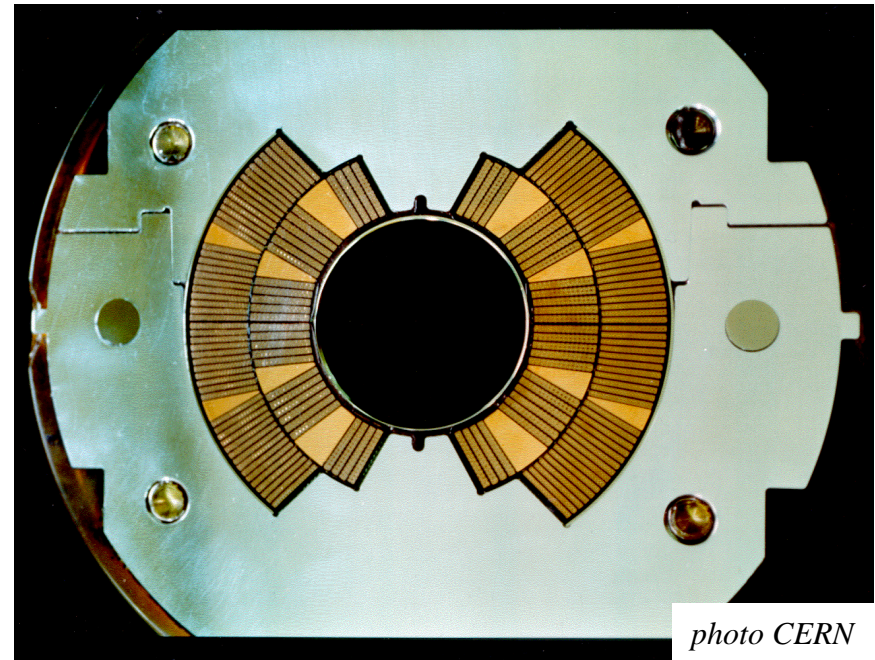
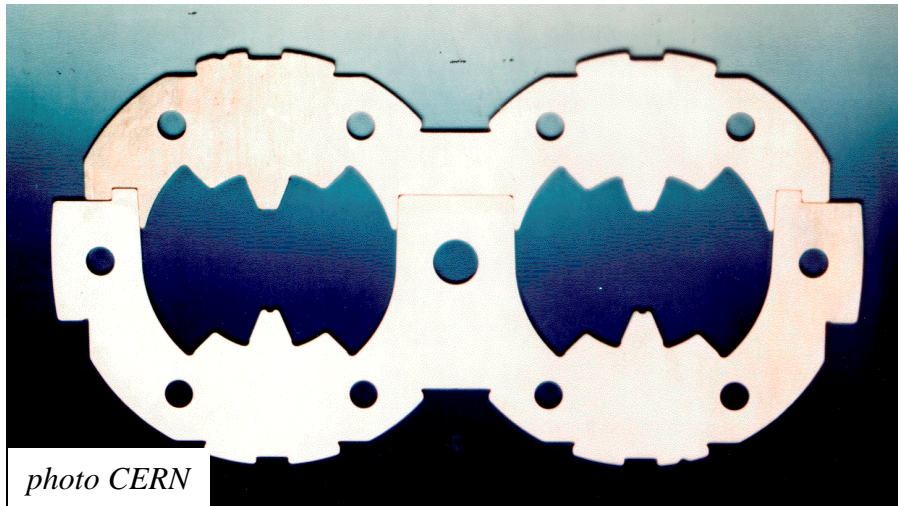
*invert alternate pairs so that they interlock*



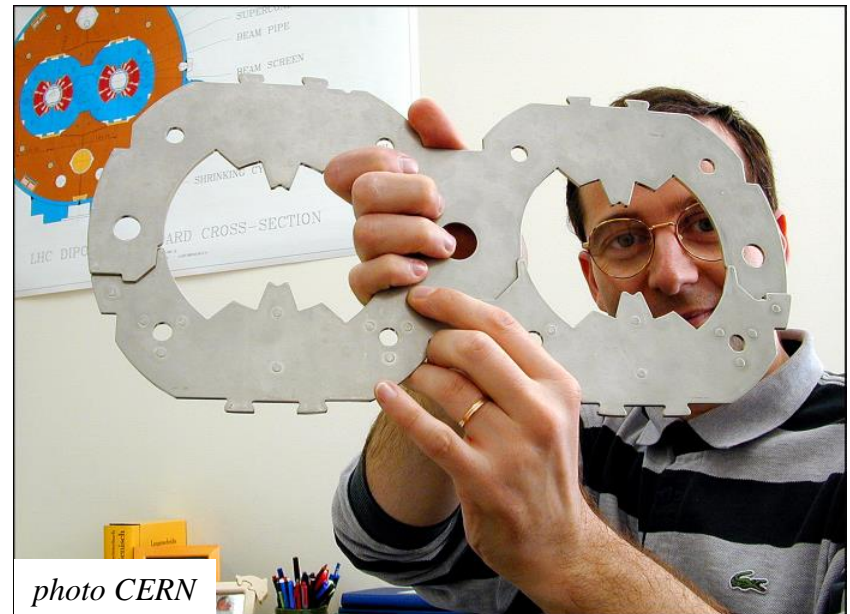
*push steel rods through holes to lock in position*

# Collars

LHC dipole collars support the twin aperture coils in a single unit

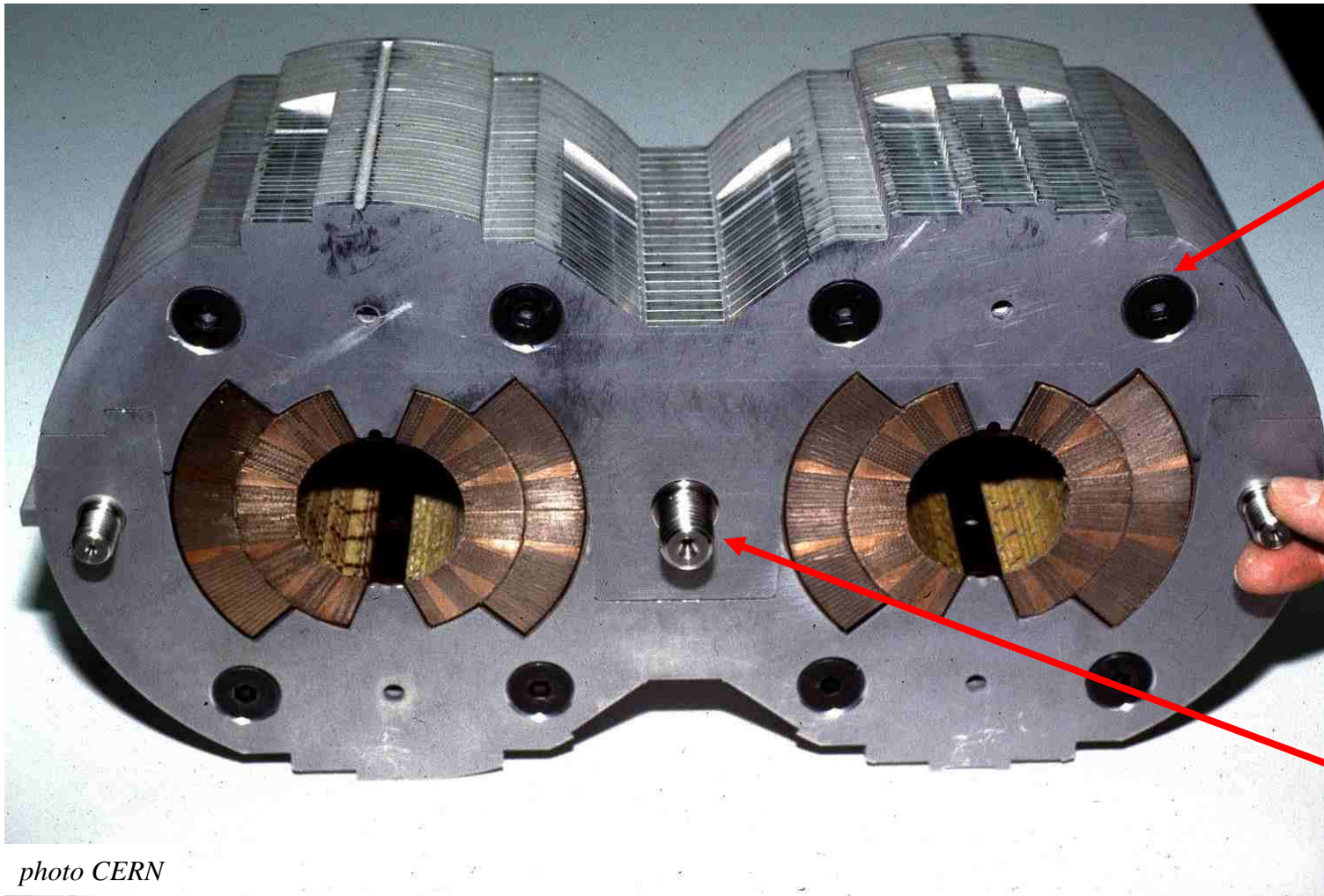


12 million produced  
for LHC



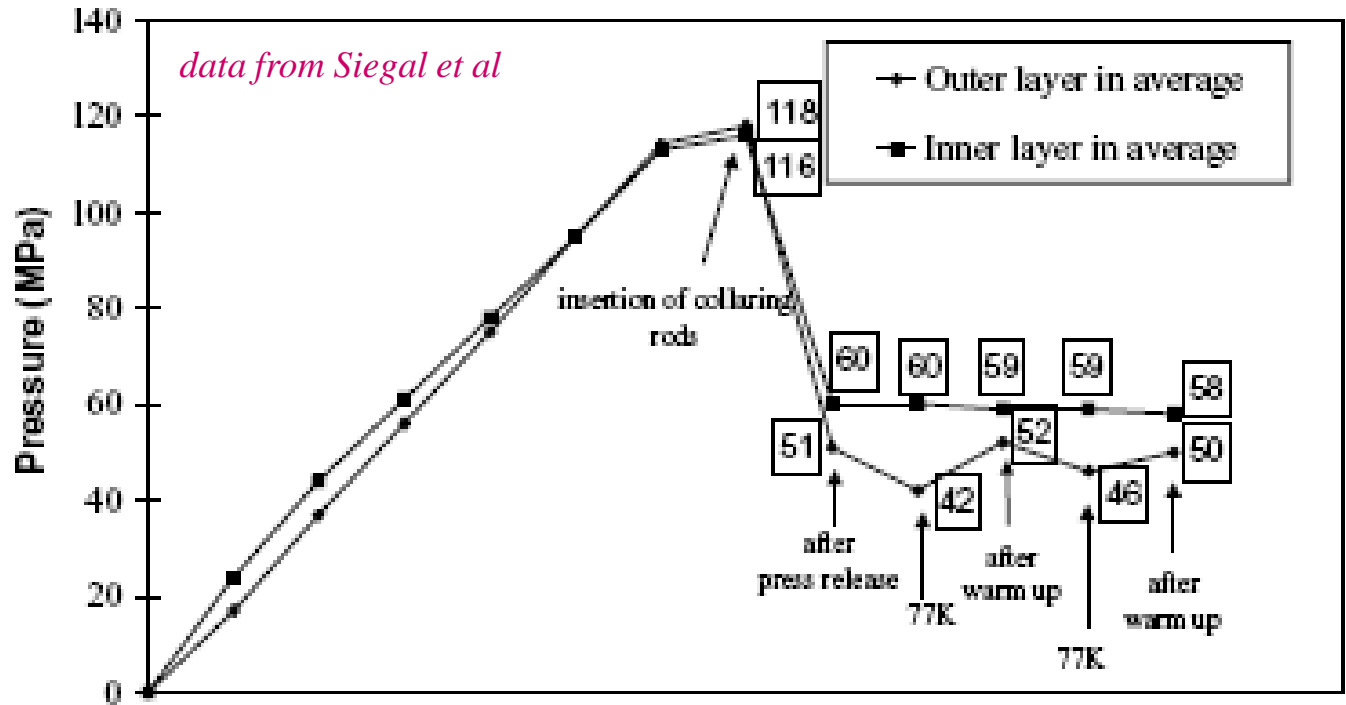
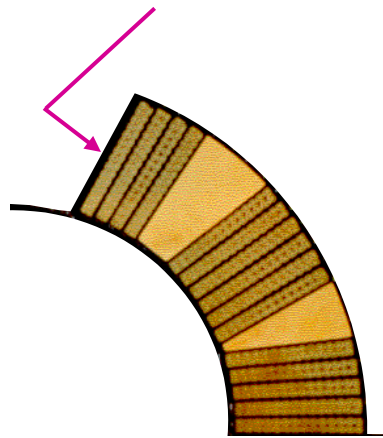


# *LHC dipole collars*



# Pre-loading the coil

measure the pressure here



## CERN data during manufacture and operation

*data from Modena et al*

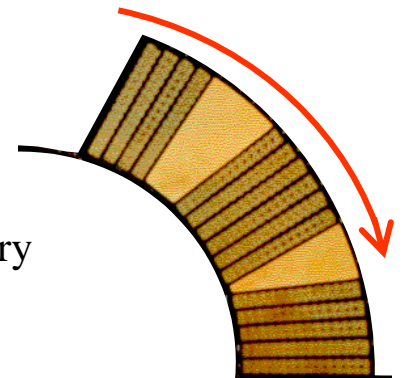
	after collaring at 293K		after yoking at 293K		at 1.9K		at 1.9K and 8.3T	
	inner	outer	inner	outer	inner	outer	inner	outer
MBP2N2	62Mpa	77Mpa	72Mpa	85Mpa	26MPa	32MPa	2MPa	8Mpa
MBP2O1	51MPa	55MPa	62MPa	62MPa	24MPa	22MPa	0MPa	2MPa



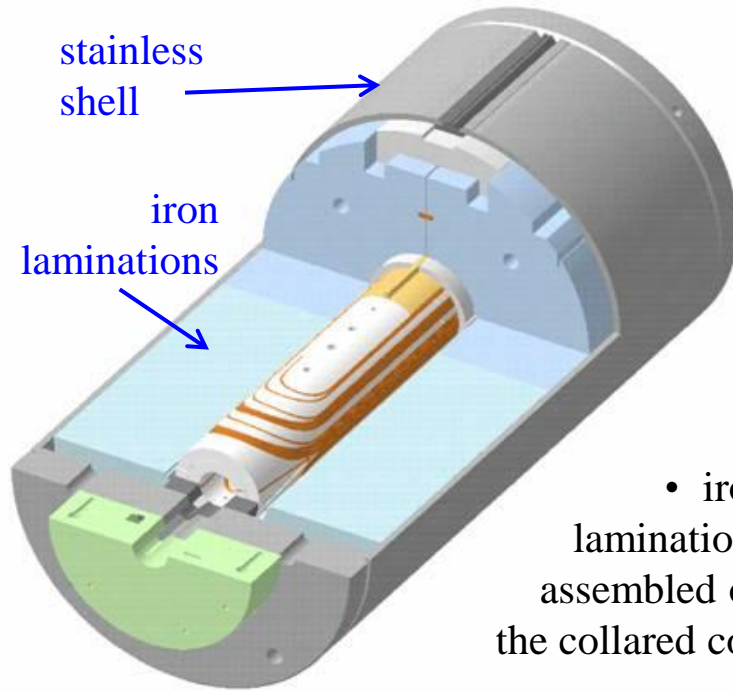
# Collars and end plate (LHC dipole)



- sliding at the outer boundary  
⇒ friction heating
- use kapton layers

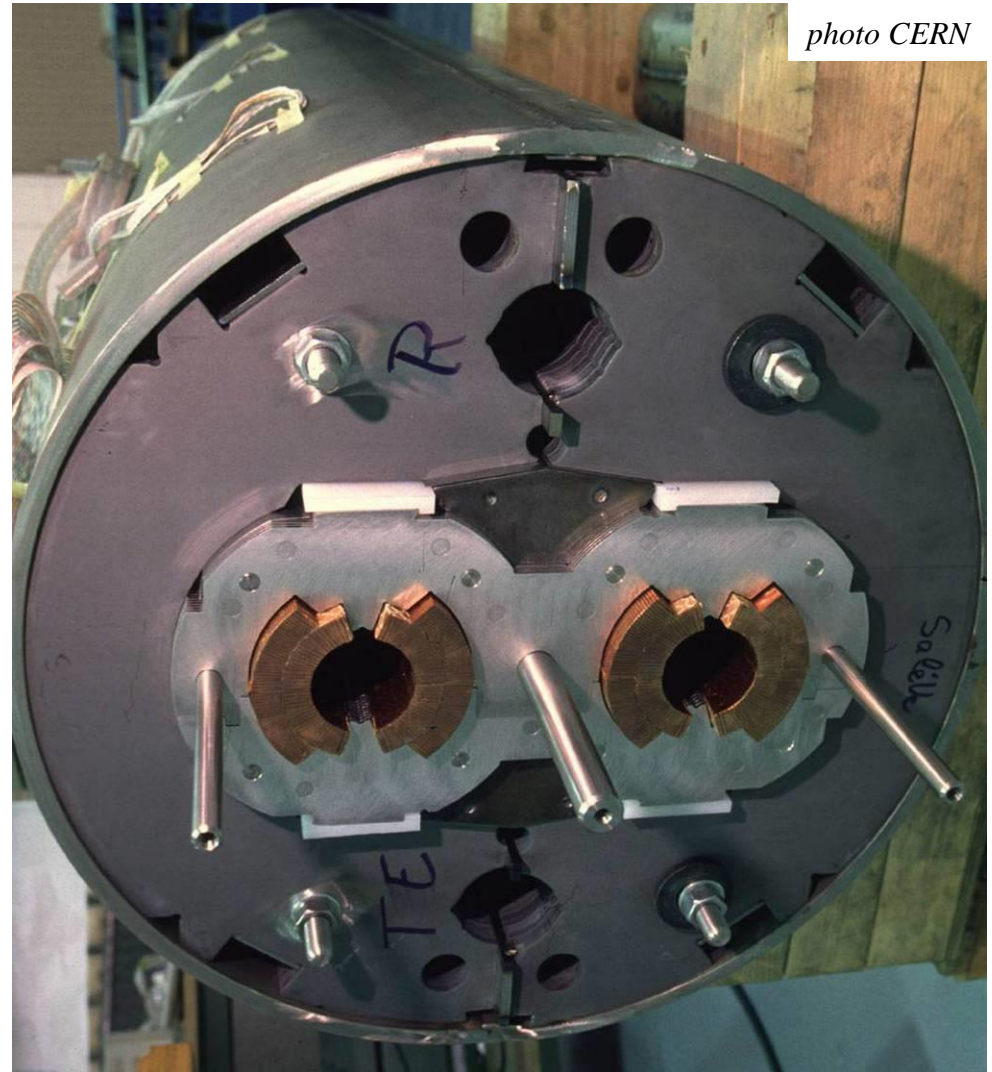


# Adding the iron



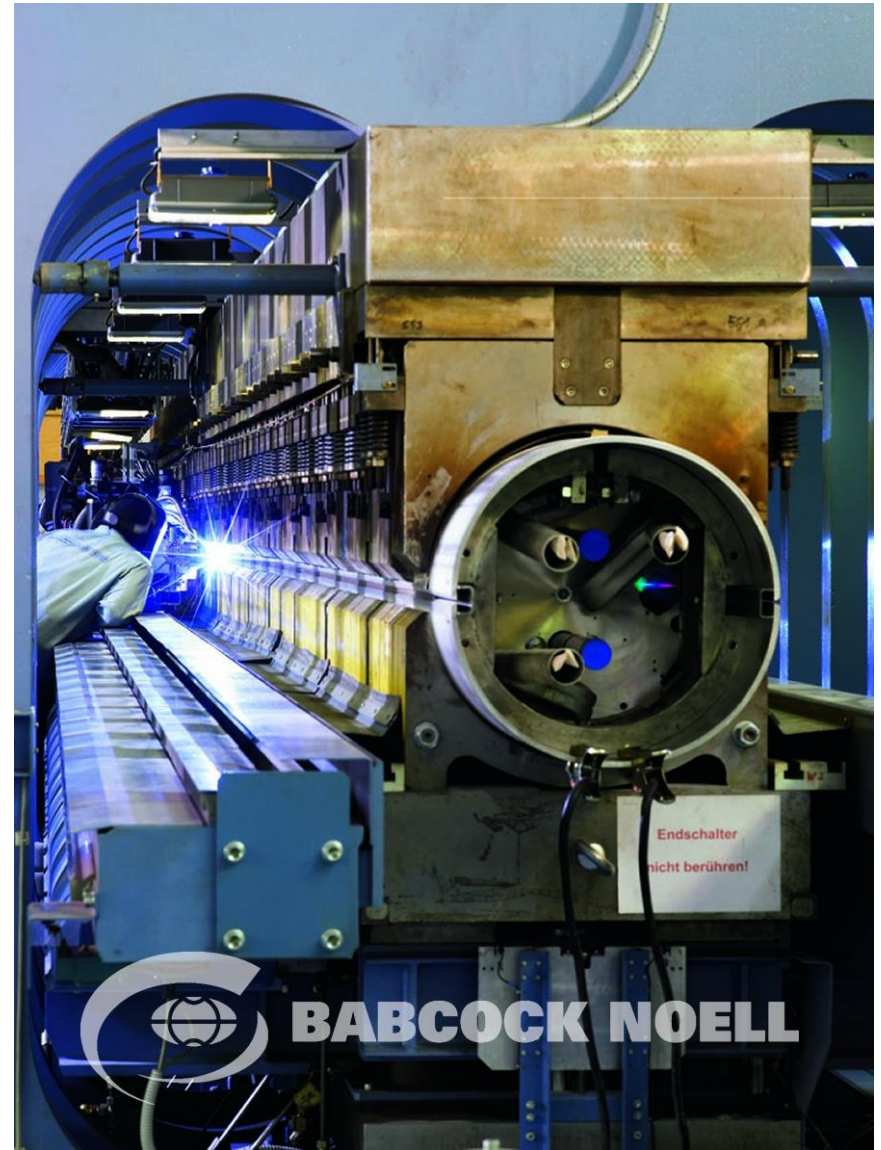
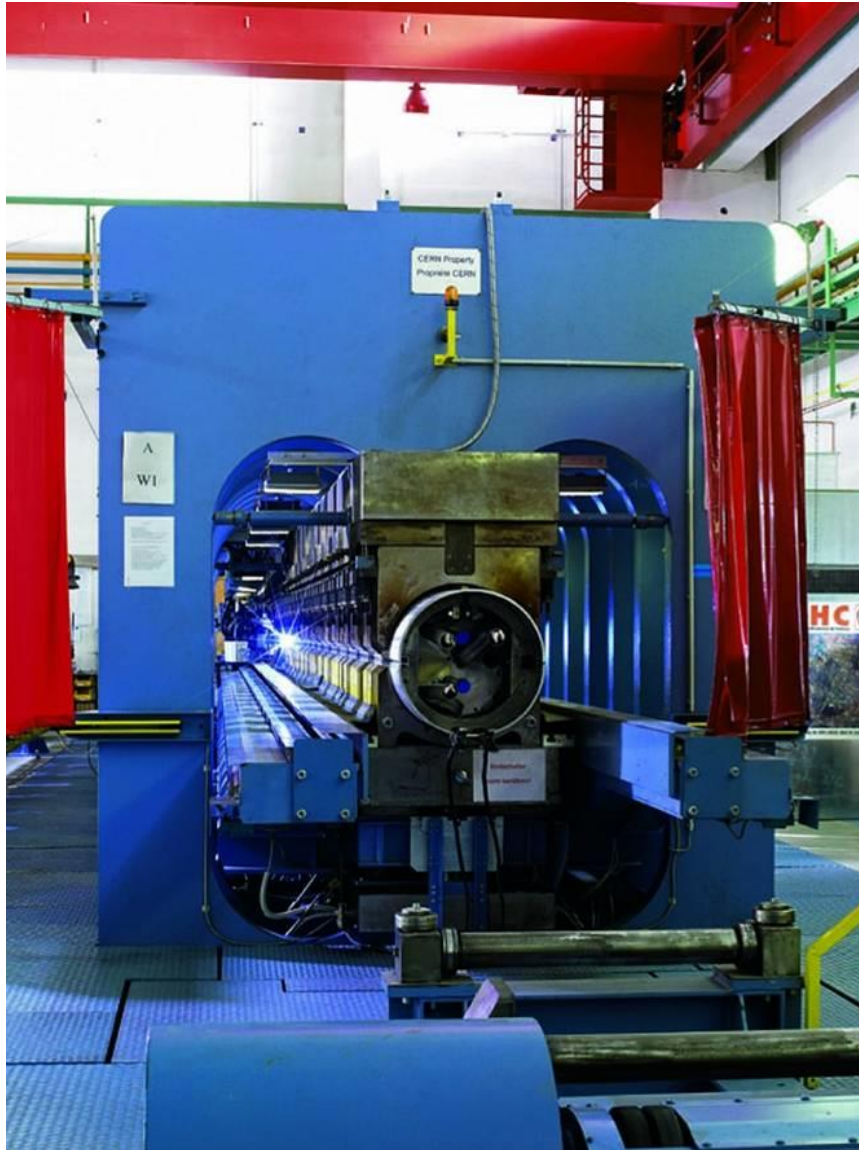
- iron laminations assembled on the collared coil

- pushed into place using the collaring press
- **BUT** pure iron becomes brittle at low temperature
- tensile forces are therefore taken by a stainless steel shell which is welded around the iron, while still in the press
- stainless shell also serves as the helium vessel





# *Compressing and welding the outer shell*



# *Dipole inside its stainless shell*

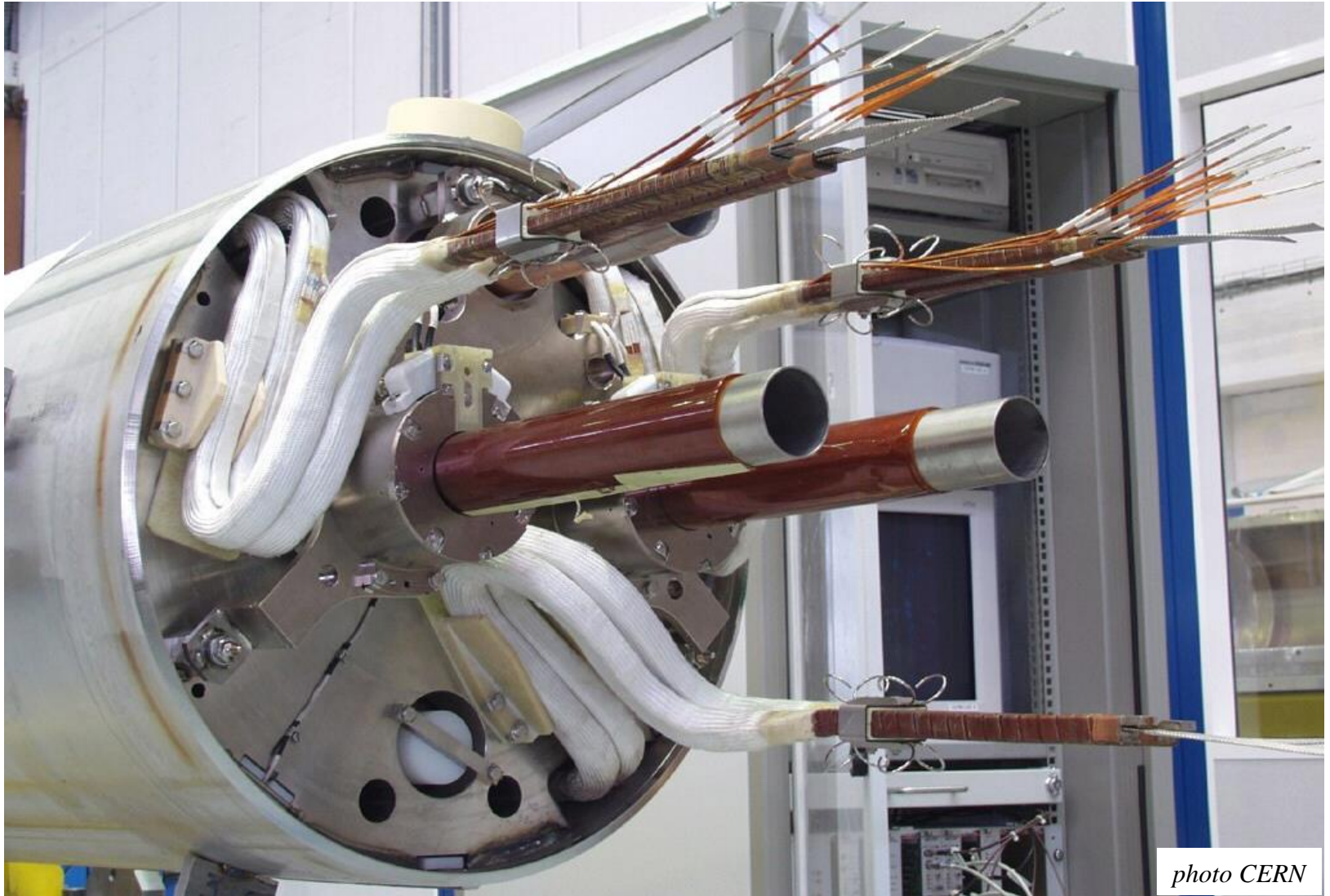
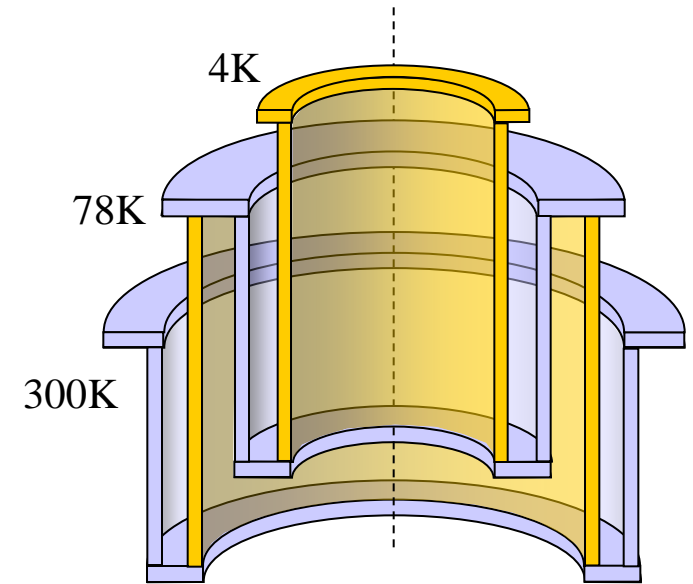
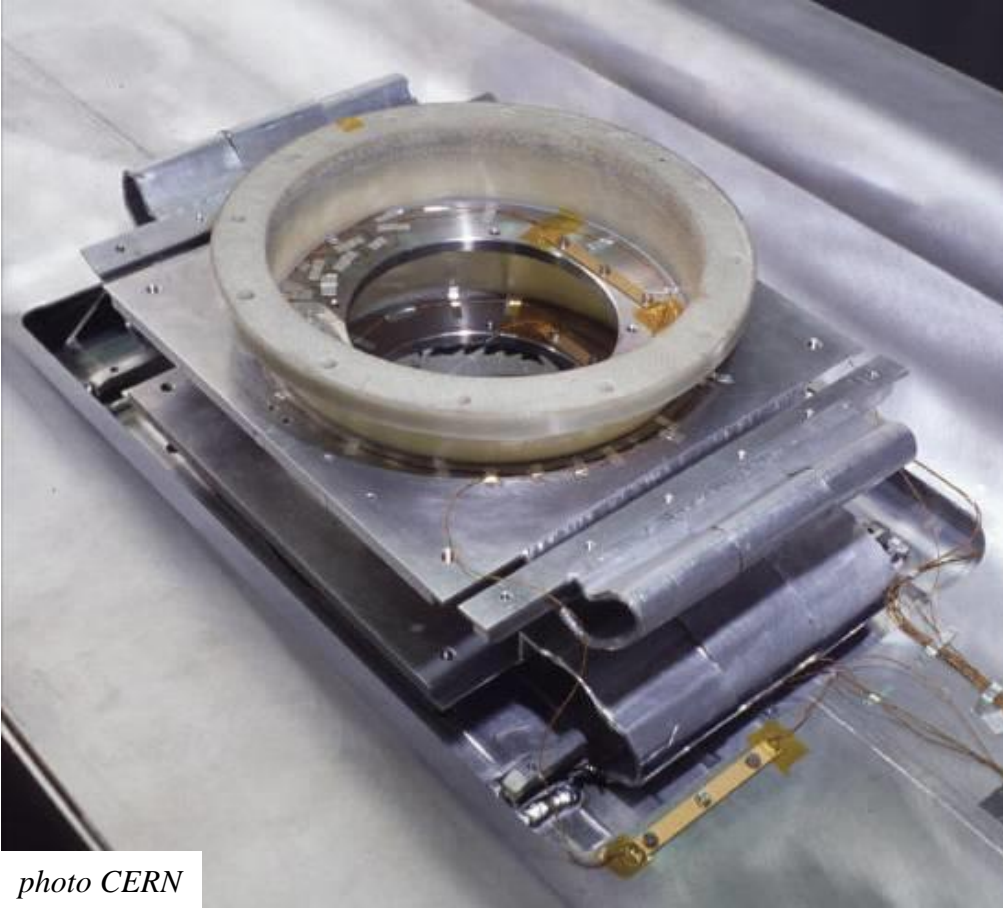


photo CERN



# Cryogenic supports



*the Heim column*

- long path length in short distance
- mechanical stiffness of tubes
- by choosing different material contractions can achieve zero thermal movement

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



# Complete magnet in cryostat



*photo CERN*

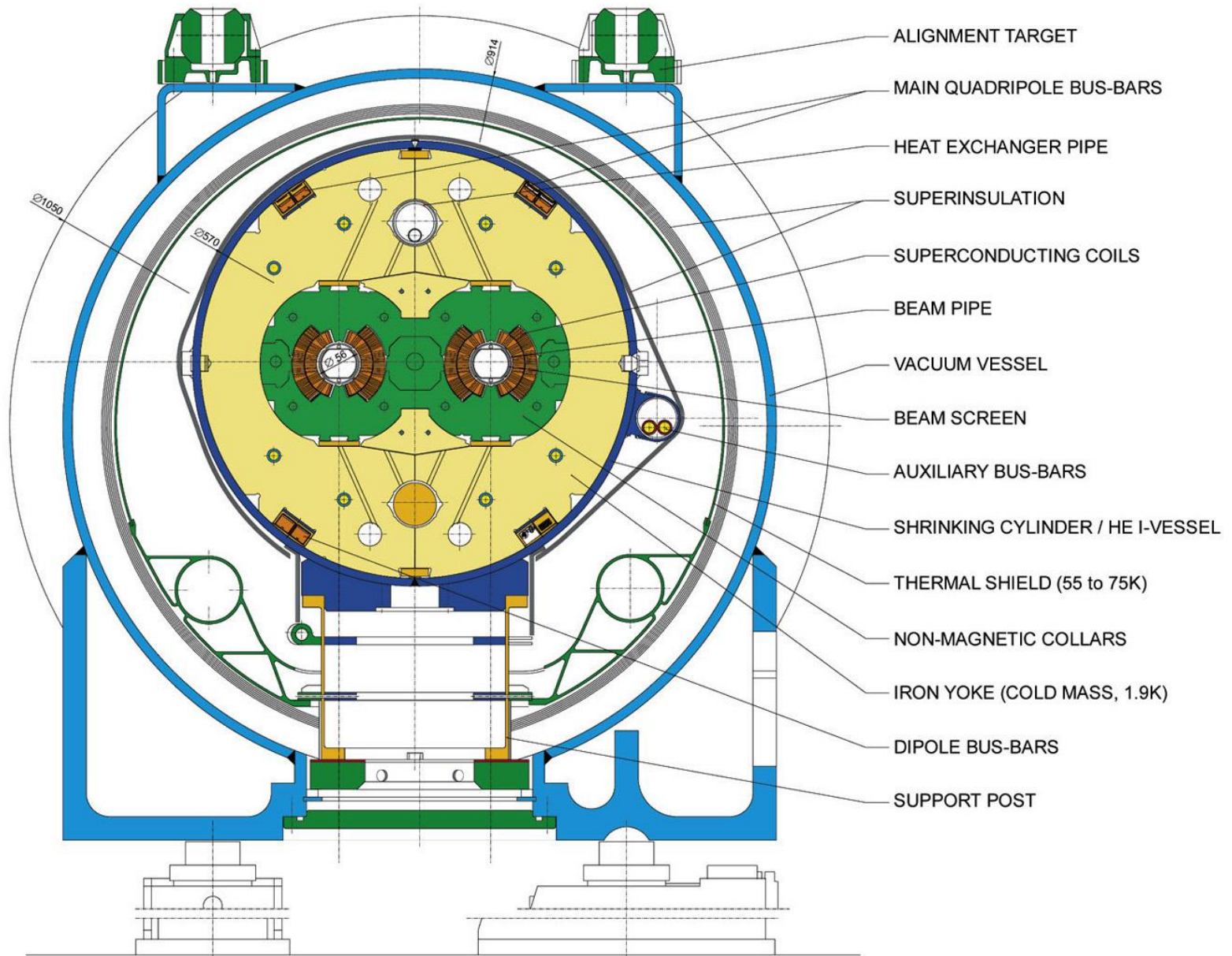
*photo CERN*



*photo Babcock Noell*

# LHC DIPOLE : STANDARD CROSS-SECTION

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



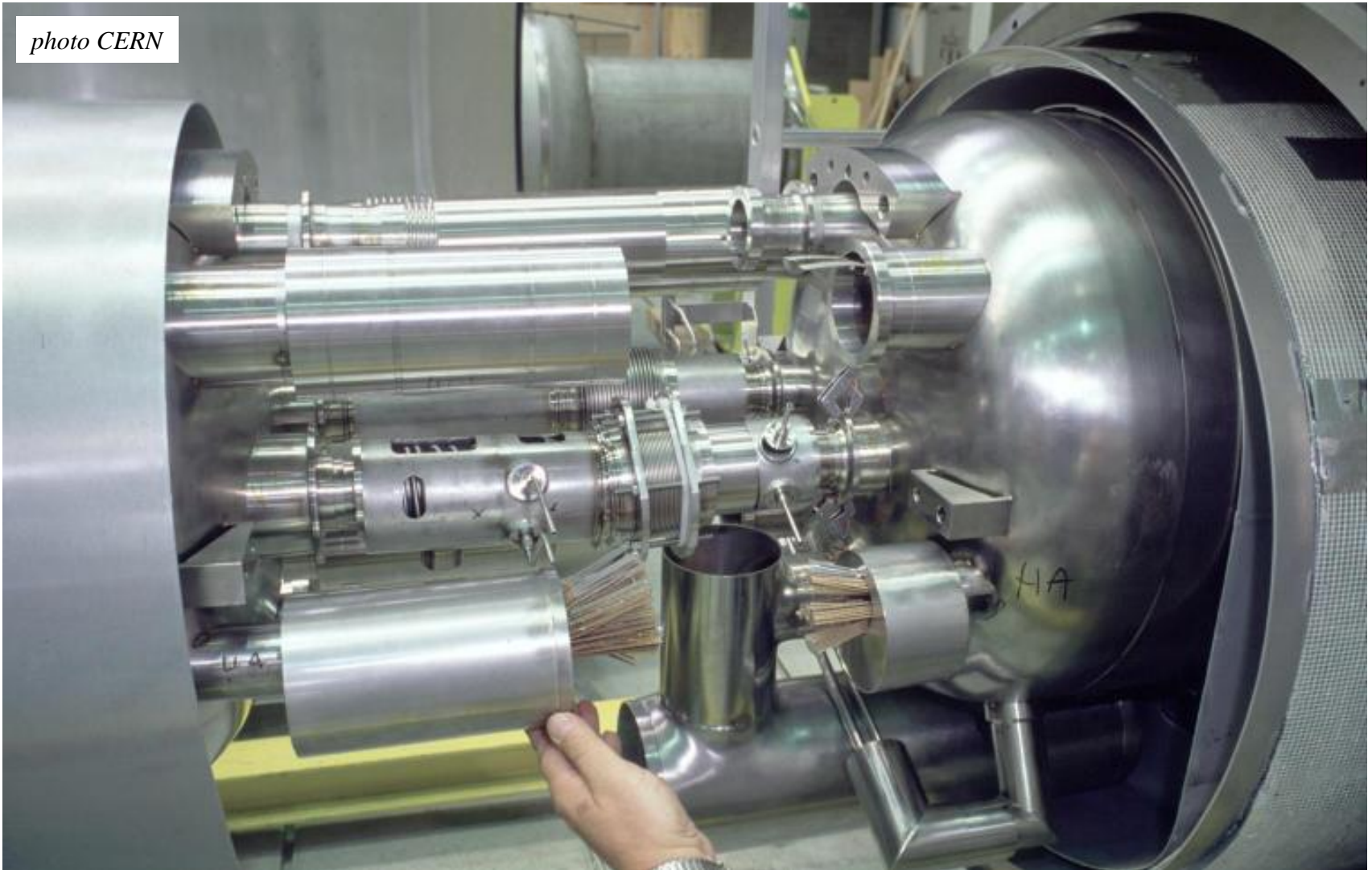


# *Make the interconnections - electrical*



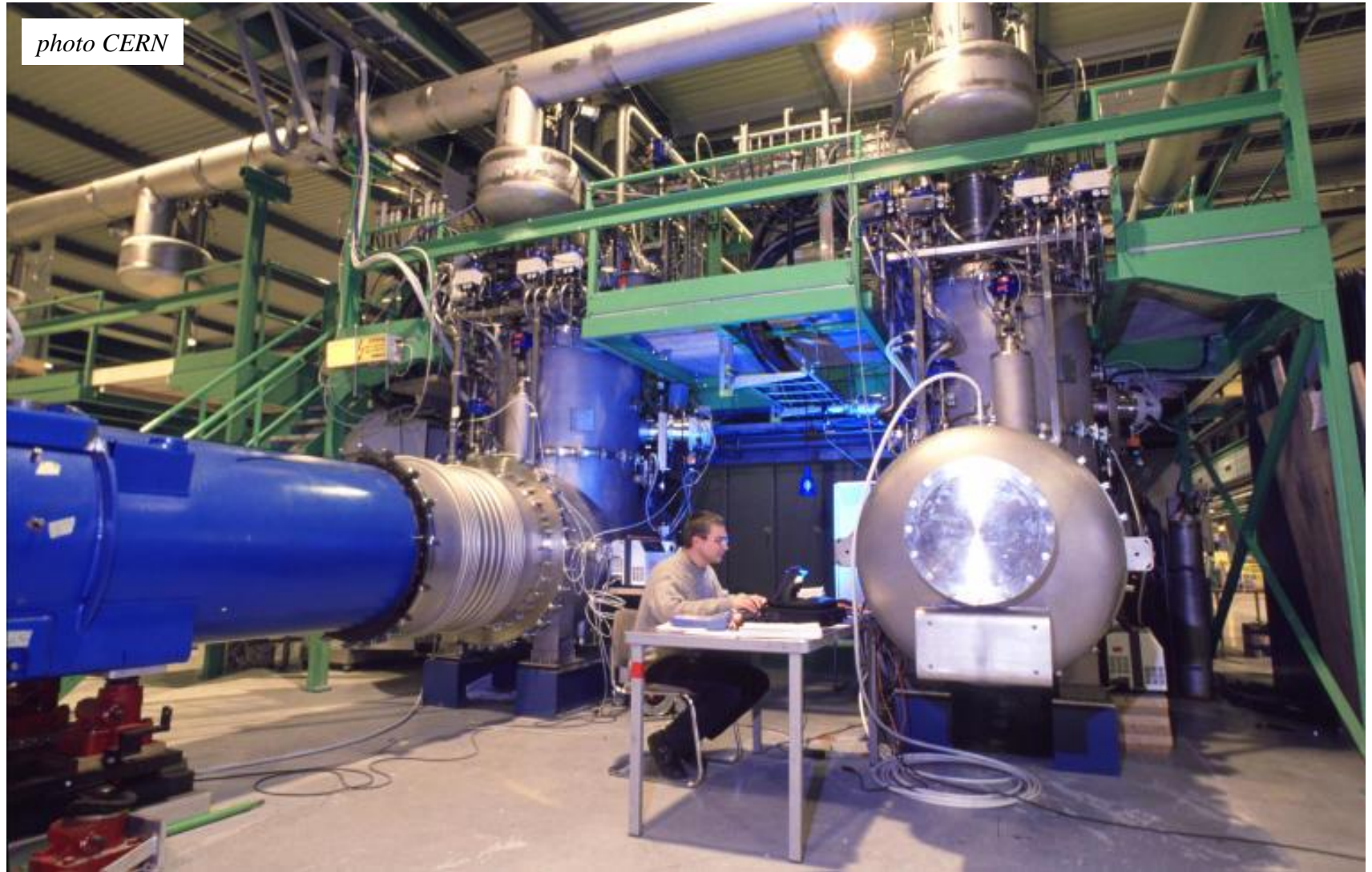
# *Make interconnections - cryogenic*

*photo CERN*





# *Connect to the cryogenic feed and current leads*





# *The Fermilab Tevatron*

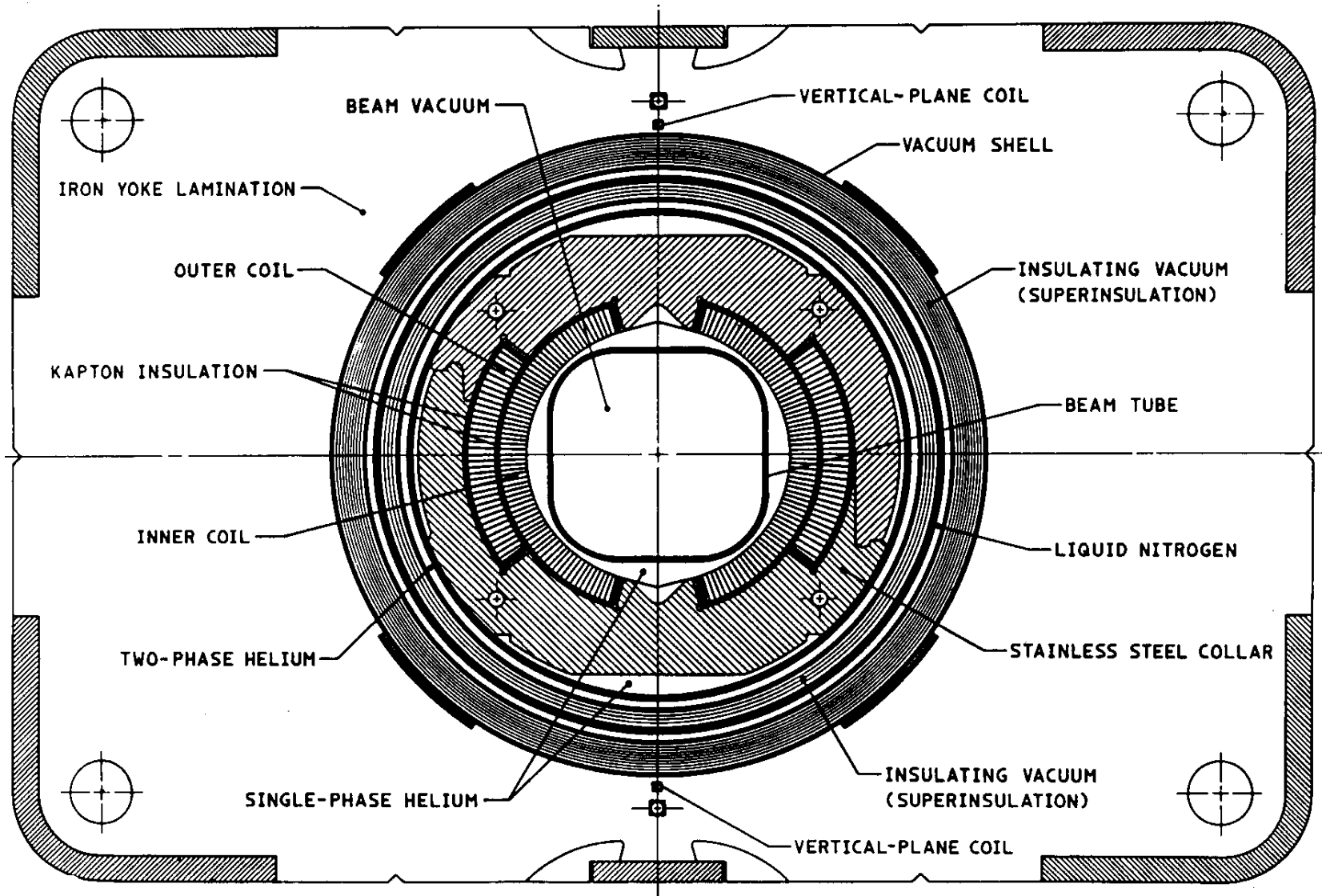


*the world's first  
superconducting  
accelerator*

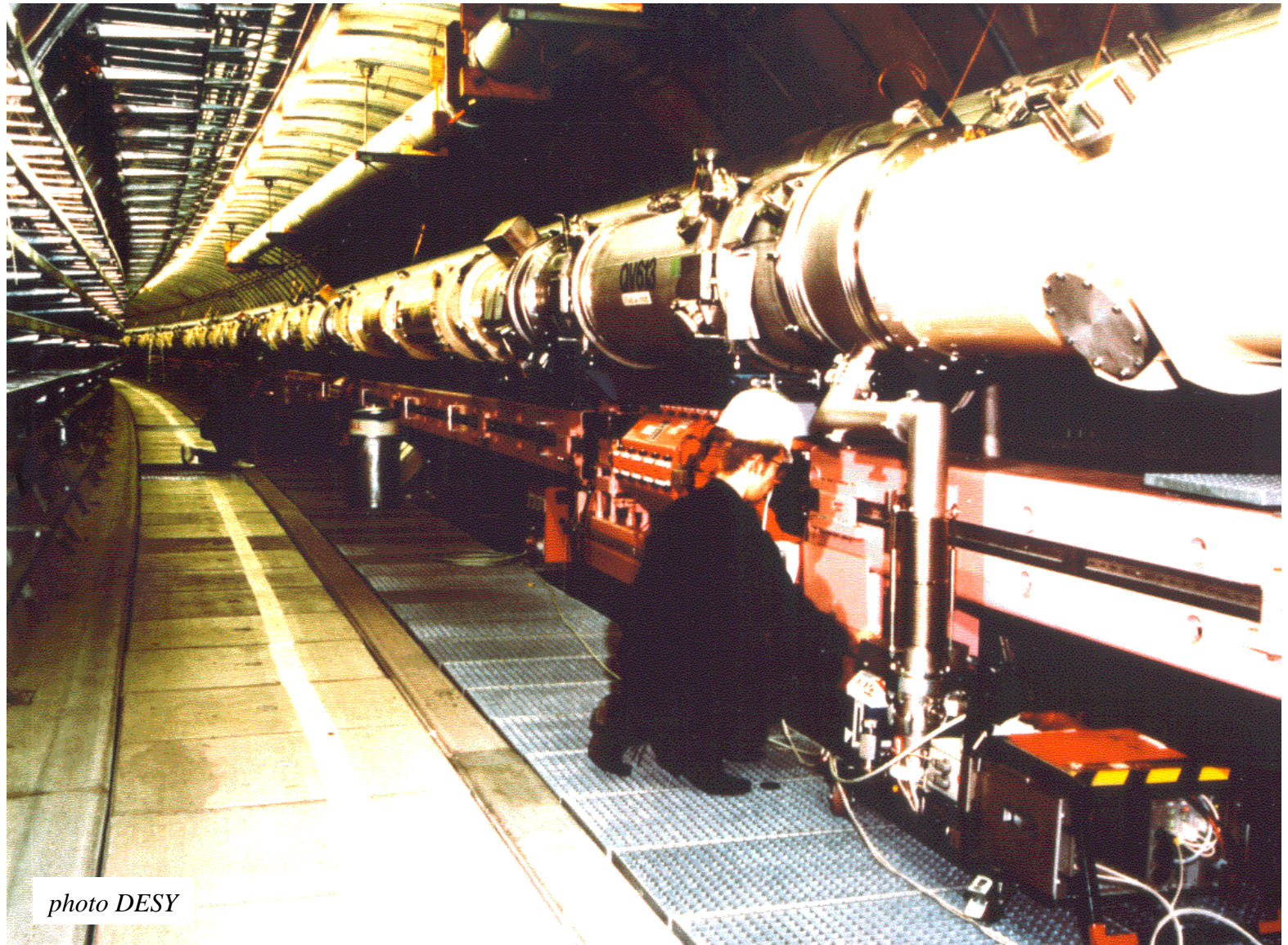
*photo Fermilab*



# *Tevatron dipole*



# Hera



*photo DESY*

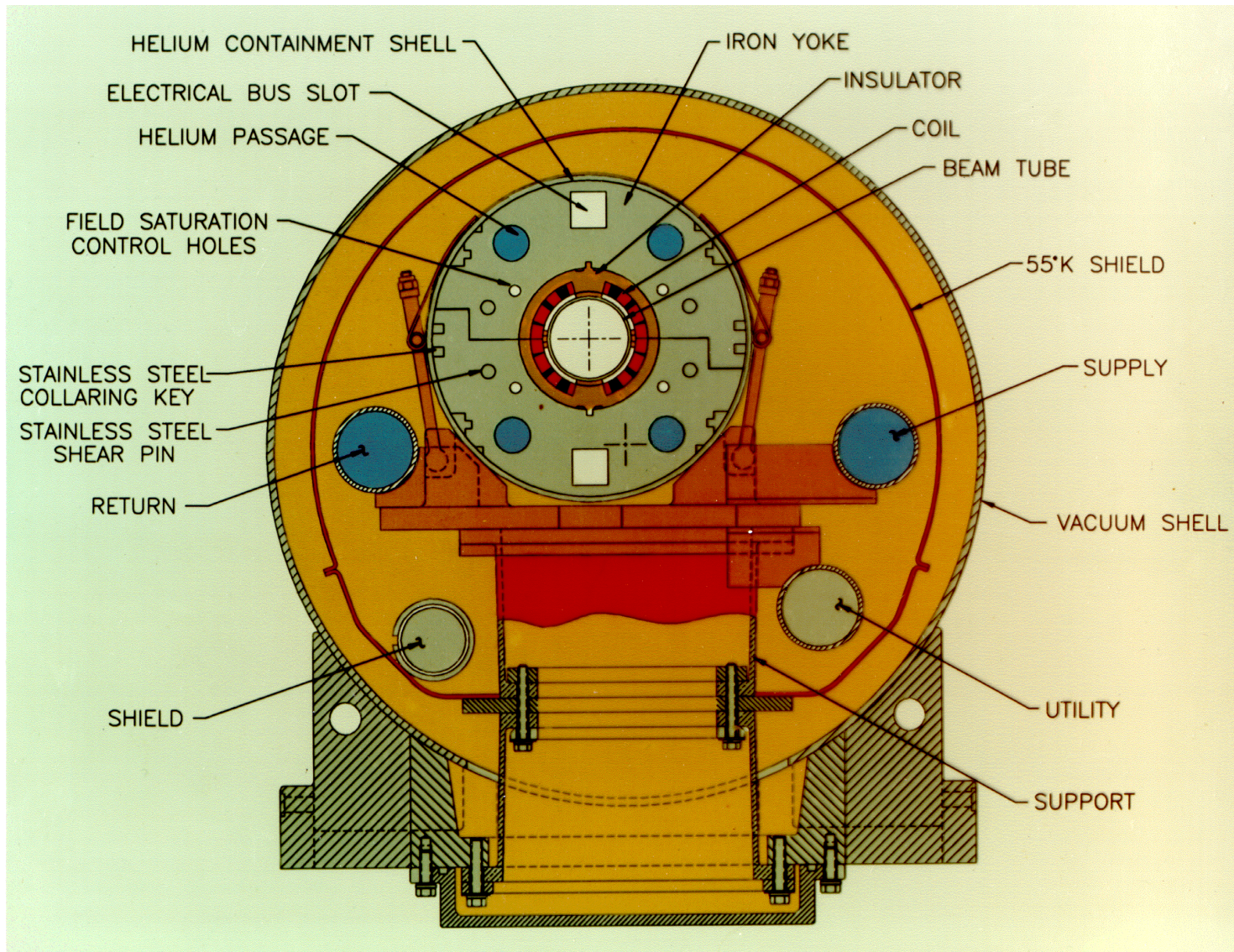




*photo BNL*

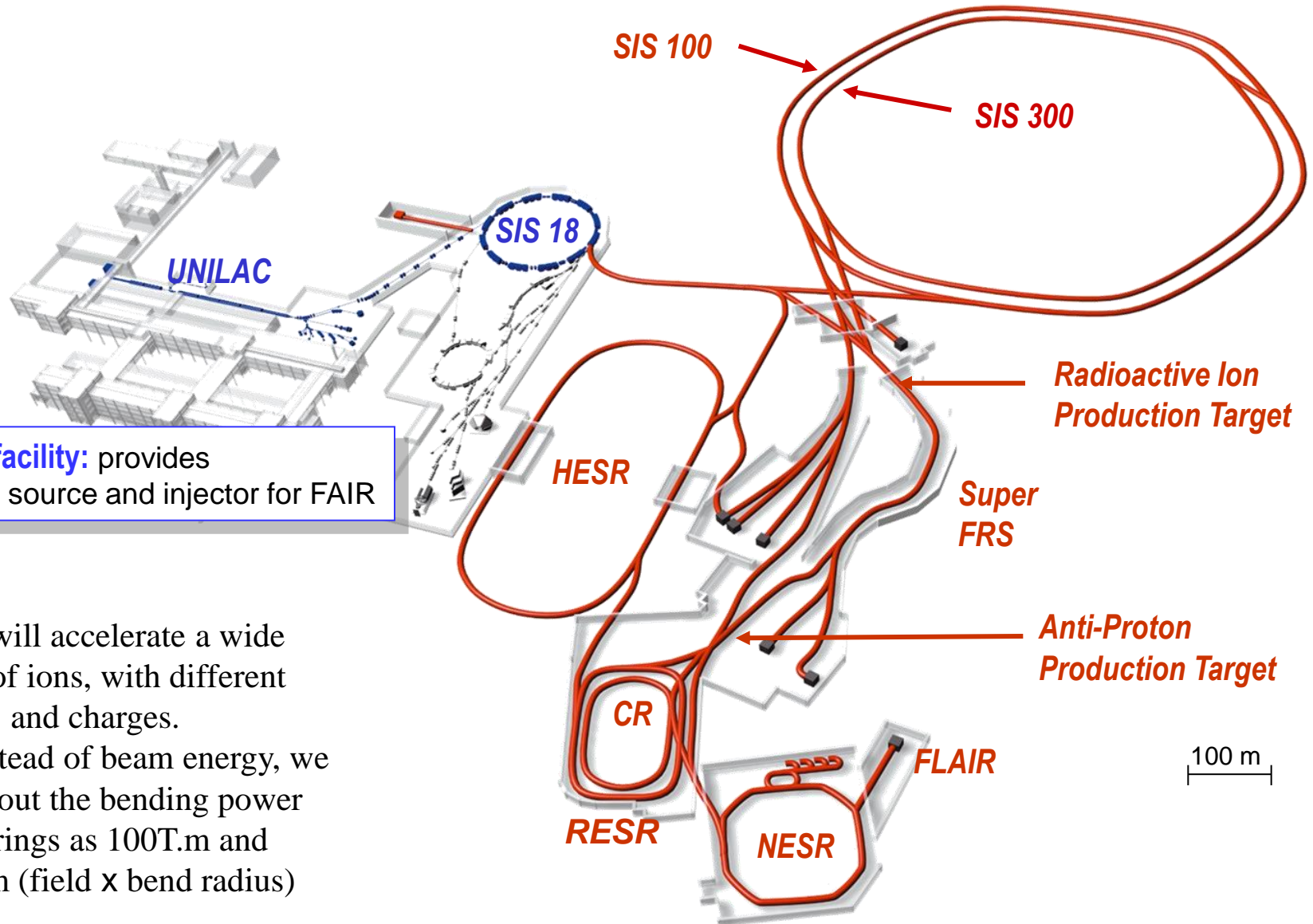


# RHIC Dipole





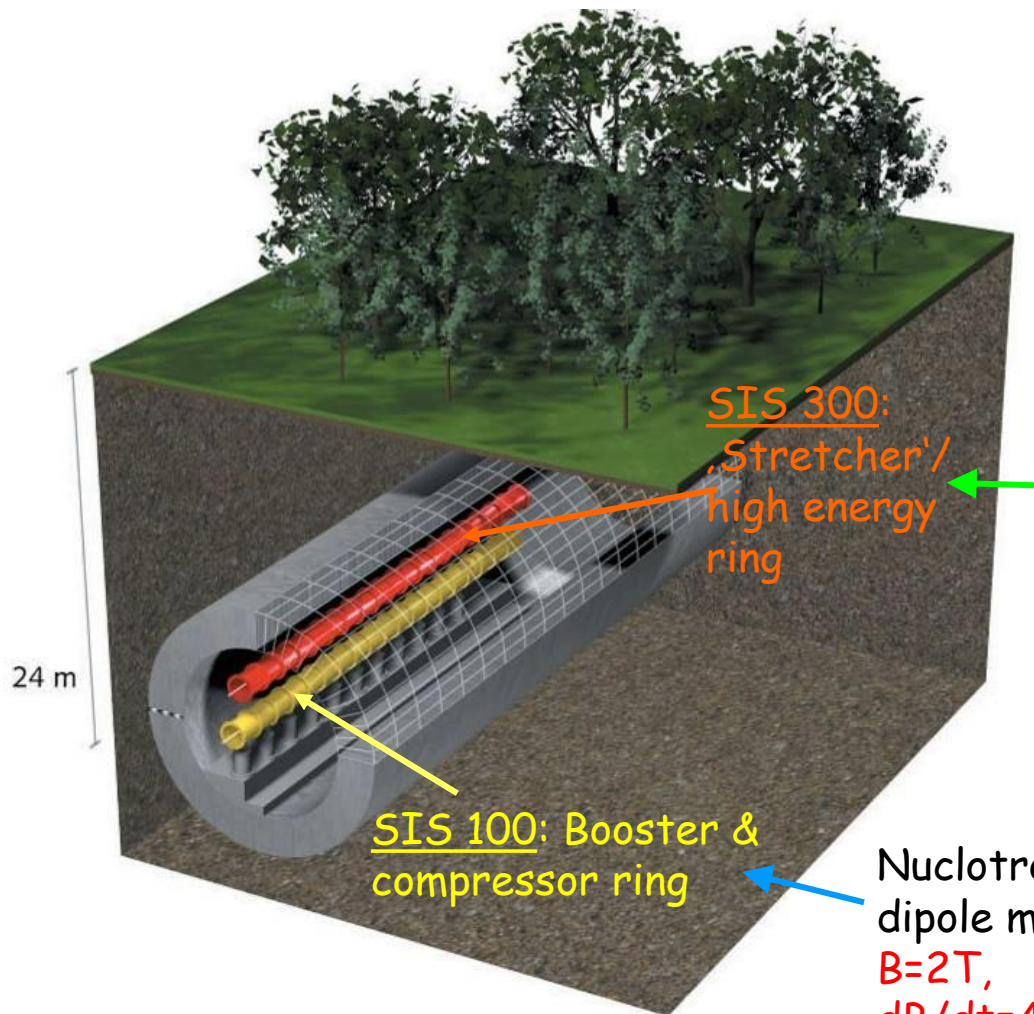
# Facility for Antiproton and ion research FAIR



**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*

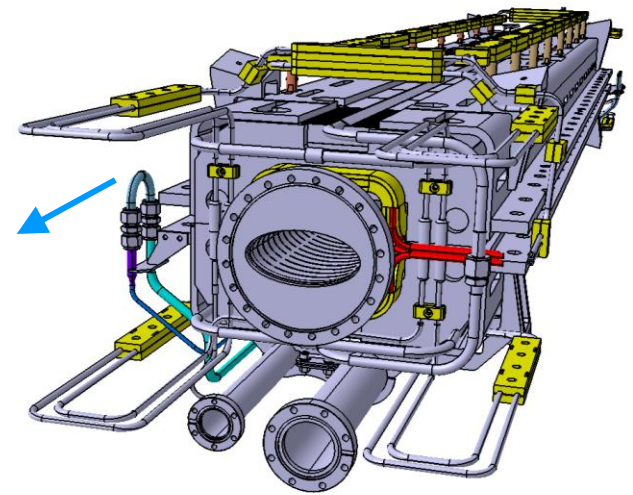
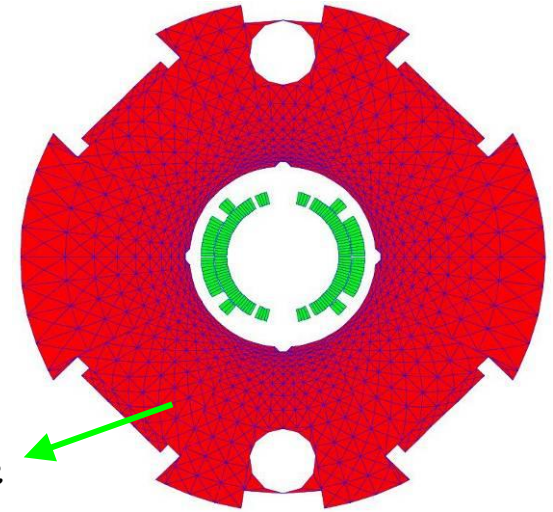


SIS 300:  
„Stretcher“/  
high energy  
ring

SIS 100: Booster &  
compressor ring

Modified  
UNK dipole  
6T at 1T/s

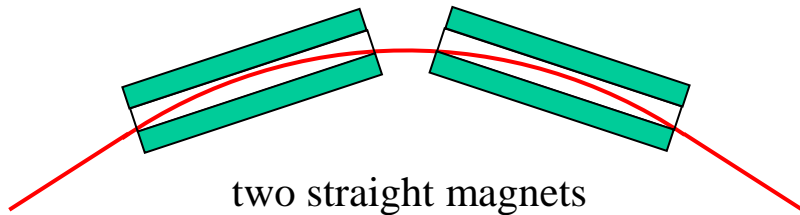
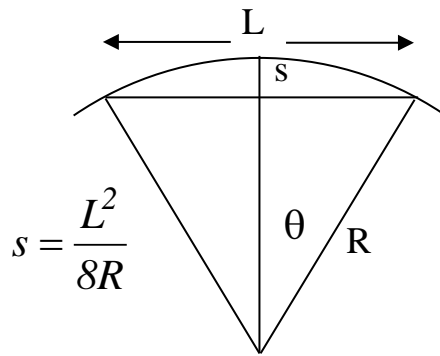
Nuclotron-type  
dipole magnet:  
 $B=2\text{T}$ ,  
 $dB/dt=4\text{T/s}$



2x120 superconducting dipole magnets  
132+162 SC quadrupole magnets



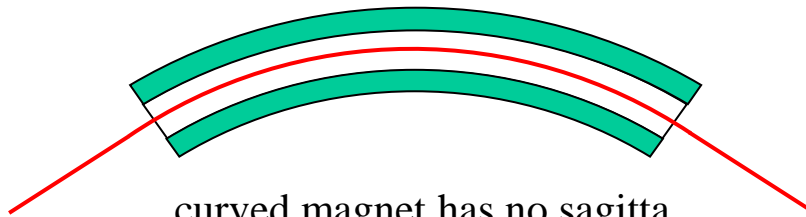
# Problem of the sagitta in SIS300



two straight magnets  
must be short because of sagitta

$$\Rightarrow B = 6\text{T}$$

must use double layer coil



curved magnet has no sagitta,  
can be long, save space of end turns

$$\Rightarrow B = 4.5\text{T}$$

can use single layer coil

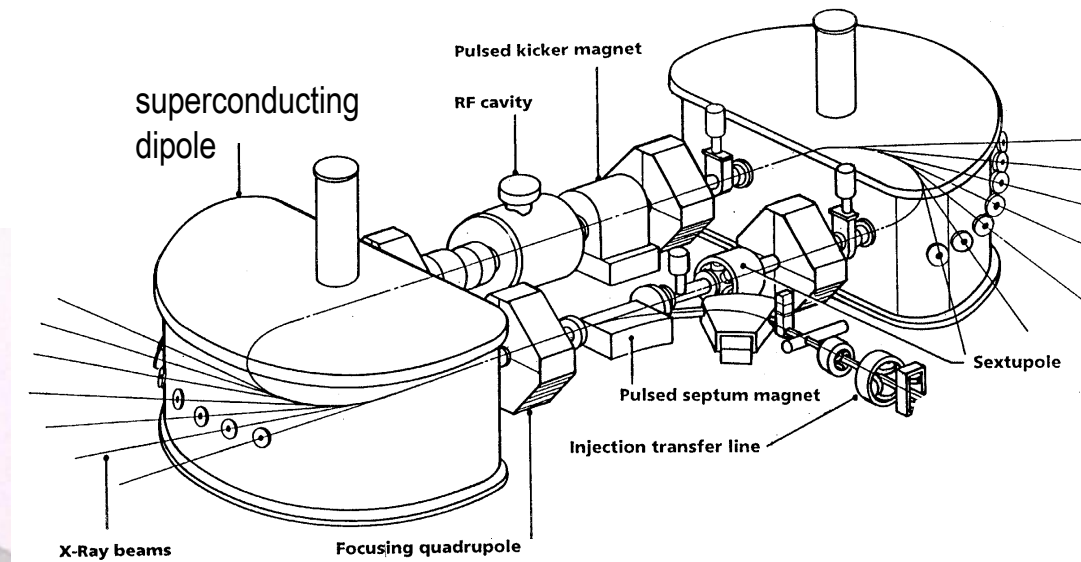
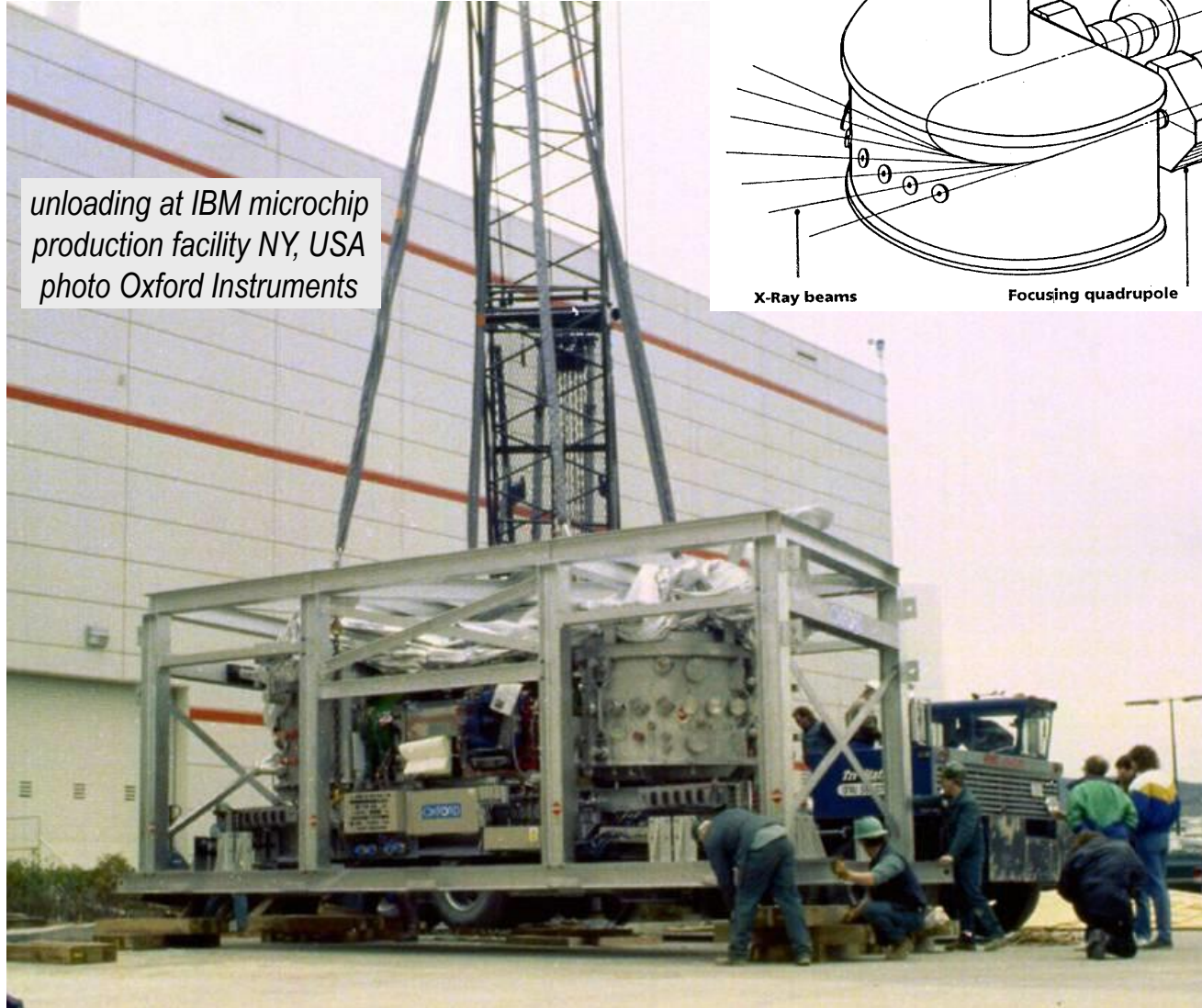


*Discorap curved dipole INFN Frascati / Ansaldo*

# Helios

*synchrotron X-ray source*

unloading at IBM microchip  
production facility NY, USA  
photo Oxford Instruments



superconducting  
dipoles

⇒ high field

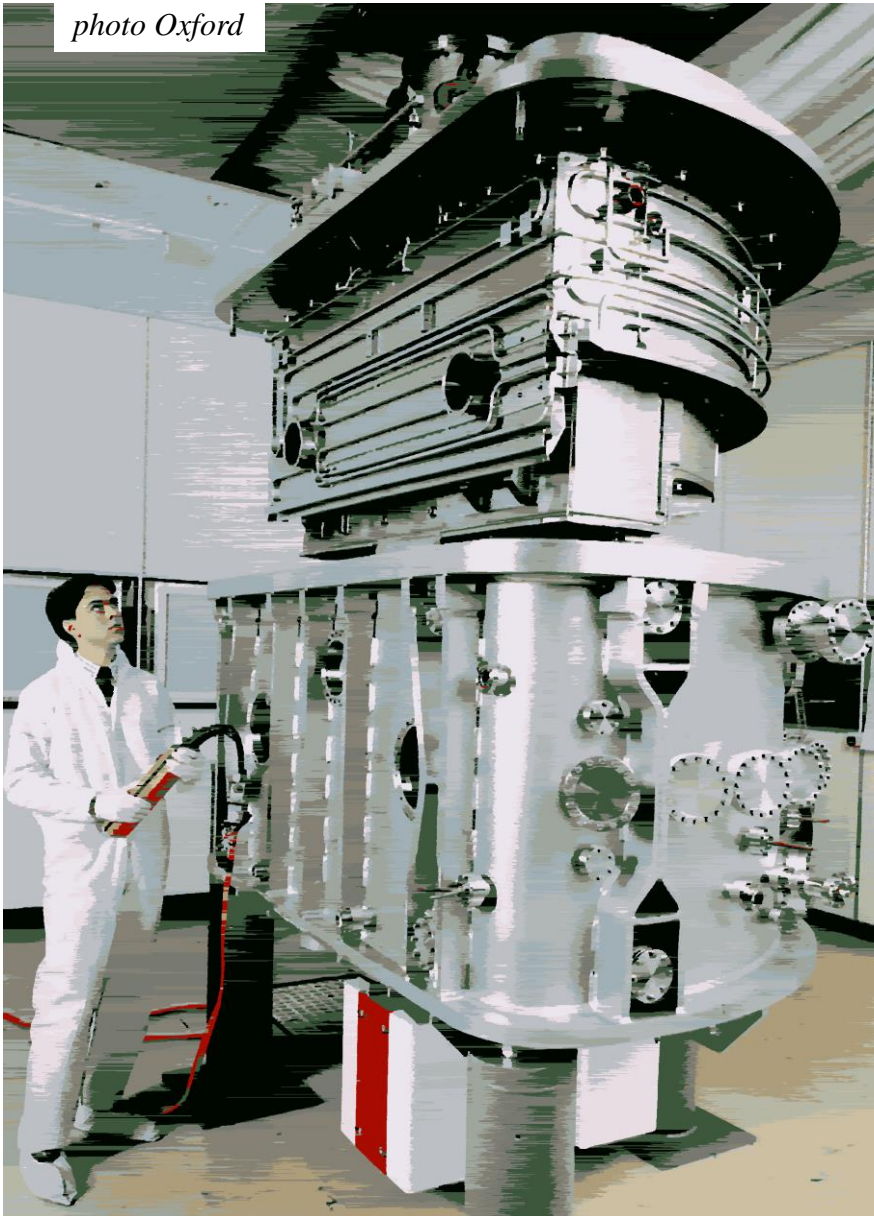
⇒ tight bending radius

⇒ compact size

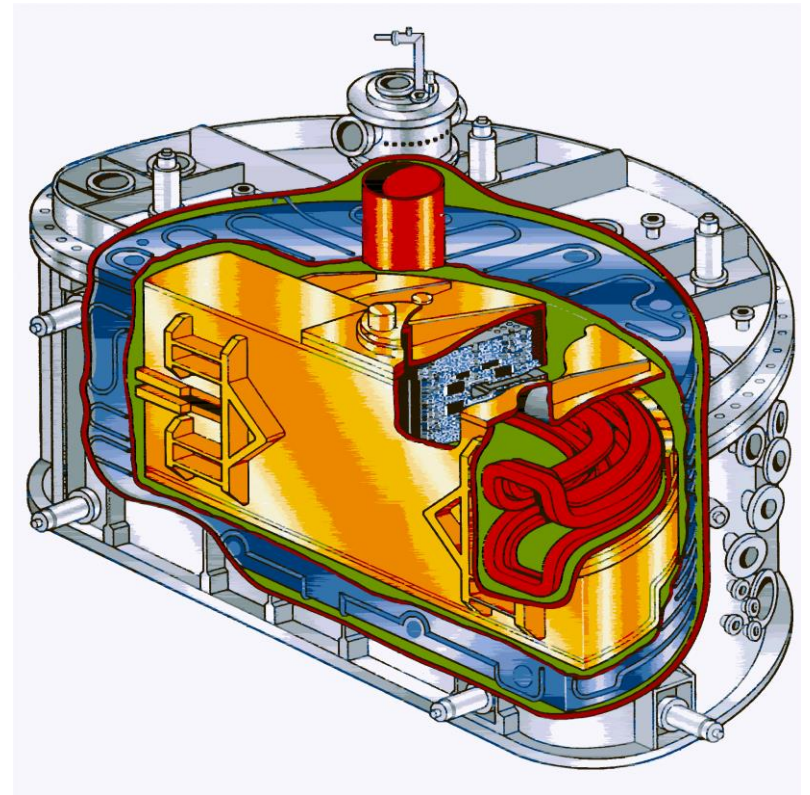
⇒ transportability



photo Oxford



## *Helios dipole*

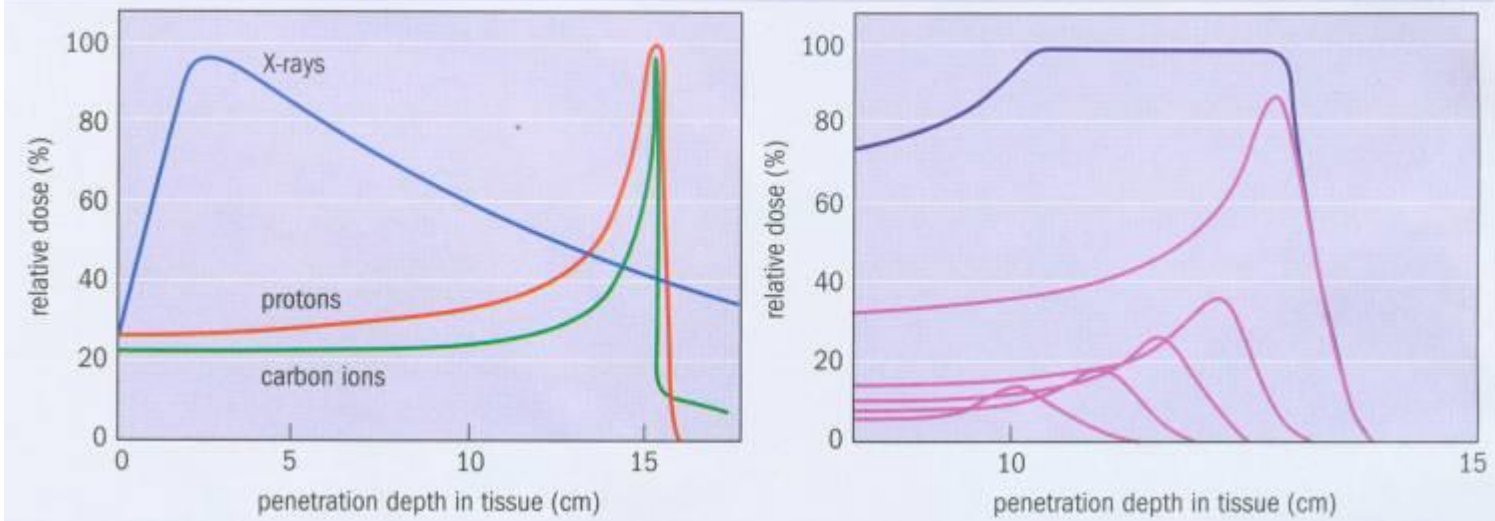


- bent around  $180^\circ$
- rectangular block coil section
- totally clear gap on outer mid plane for emerging X-rays (12 kW)

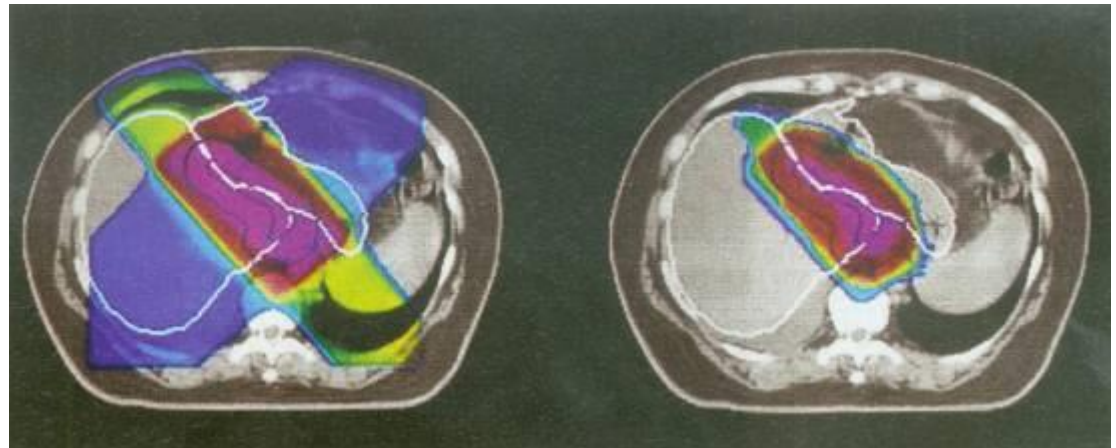


# Cancer therapy by charged particle beams

## 1 Bragg curves and photon absorption in water

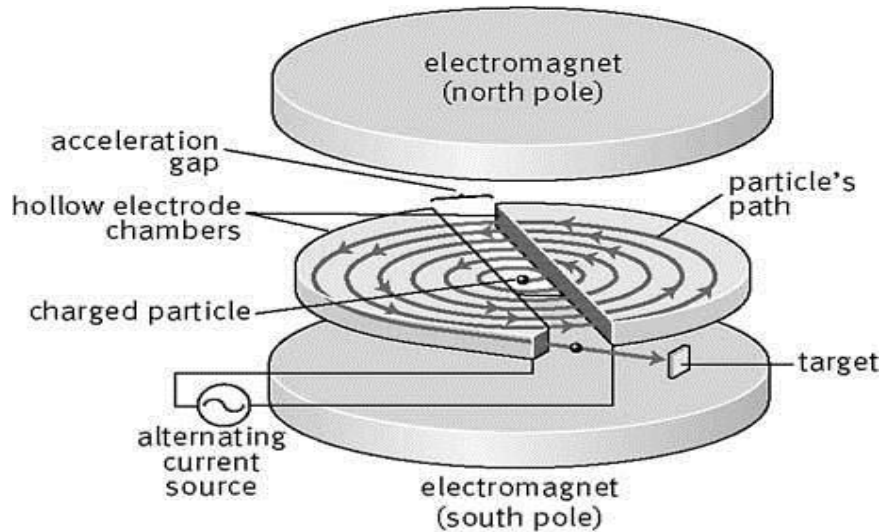


- photons (X-rays) deposit most energy at surface (skin)
- protons deposit most energy at depth
- adjust energy to make depth = tumour
- carbon ions are even better



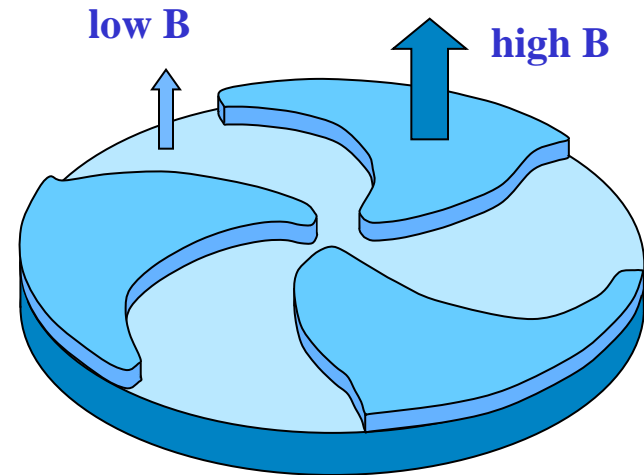
# *Cyclotron: the most popular source for proton therapy*

## Synchrocyclotron



- particles spiral outwards as their energy increases
- field decreases with radius  $\Rightarrow$  focussing
- particles get out of synchronism because field decreases and their (relativistic) mass increases
- ramp the rf frequency to keep in synchronism
- must be pulsed  $\Rightarrow$  low average beam current

## Isochronous cyclotron



- focussing provided by azimuthally varying field AVF
- field can increase with radius to keep pace with relativistic mass increase
- synchronism at all radii
- continuous dc beam

# *Cyclotrons for proton therapy*



## **IBA Proteus 235**

Isochronous cyclotron  
235MeV  
conventional magnet  
1.7 - 2.2T  
220 tonne



## **Varian / Accel**

Isochronous cyclotron  
250MeV  
superconducting magnet  
2.4 - 3.1T  
90 tonne

## **Mevion**

Synchrocyclotron  
250MeV  
superconducting magnet  
8.9T  
20 tonne





# *Practical Matters: concluding remarks*

- LHC quench problems come from series connection of many magnets and high current density
  - diodes across each coil, dump resistor and quench heaters
- 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
- making accelerator magnets is now a well established industrial process
  - winding  $\Rightarrow$  compact to exact size  $\Rightarrow$  heat to cure adhesive
  - fit collars  $\Rightarrow$  compress to required stress  $\Rightarrow$  lock in place
  - fit iron  $\Rightarrow$  add outer shell  $\Rightarrow$  compress to size  $\Rightarrow$  weld
  - assemble in cryostat  $\Rightarrow$  install in tunnel  $\Rightarrow$  make interconnects
- in recent years all the largest accelerators (and some small ones) have been superconducting

what comes next up to you

customer helpline  
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