Lecture 5: Practical matters

Plan

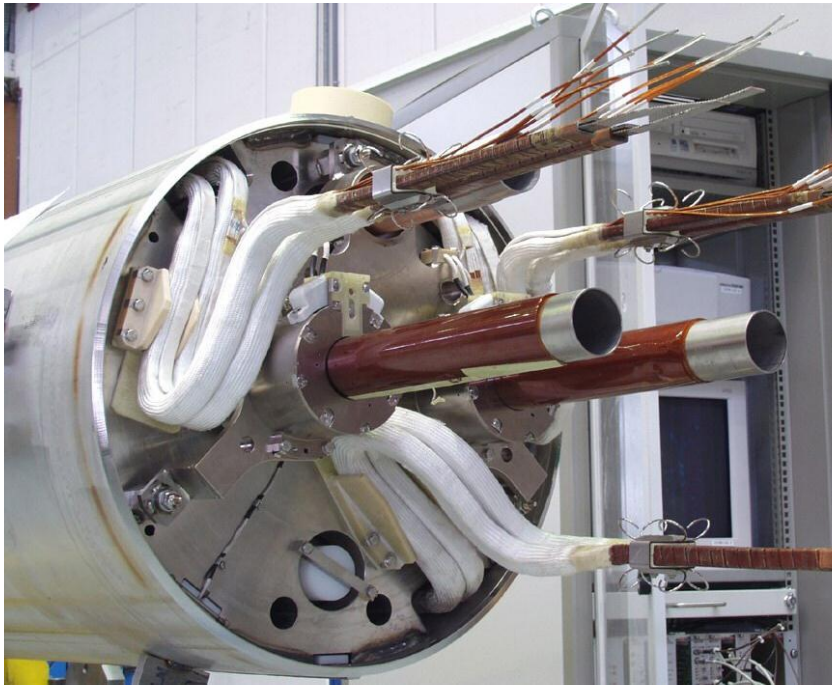
- LHC quench protection
- current leads
- accelerator coil winding and curing
- forces and clamping
- magnet assembly, collars and iron
- installation
- some superconducting accelerators

LHC dipole protection: practical implementation

It's difficult! - the main challenges are:

1) Series connection of many magnets

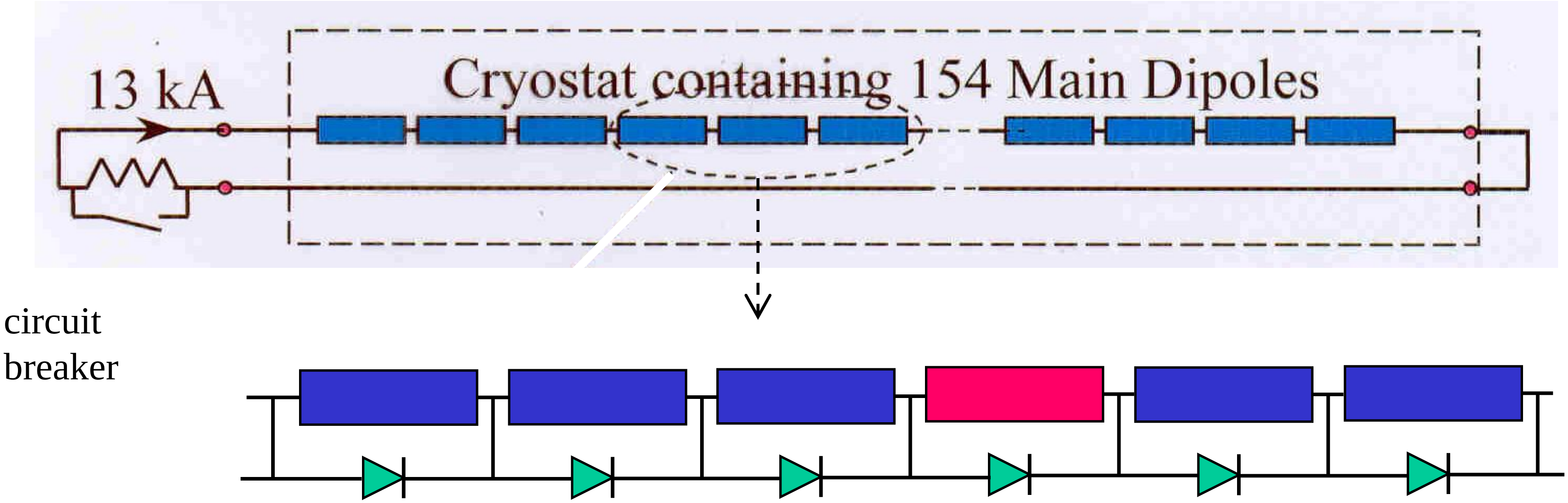
- In each octant, 154 dipoles are connected in series. If one magnet quenches, the combined energy of the others will be dumped in that magnet ⇒ vaporization!
- **Solution 1**: cold diodes across the terminals of each magnet. Diodes normally block ⇒ magnets track accurately. If a magnet quenches, it's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

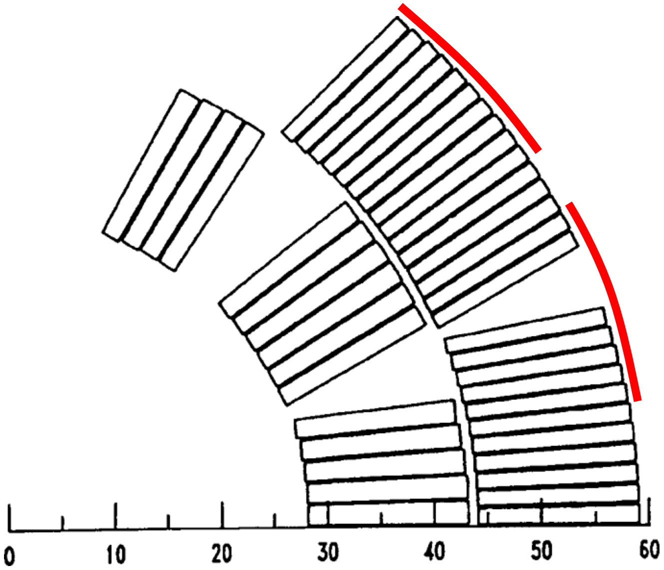
LHC power supply circuit for one octant

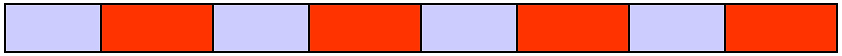


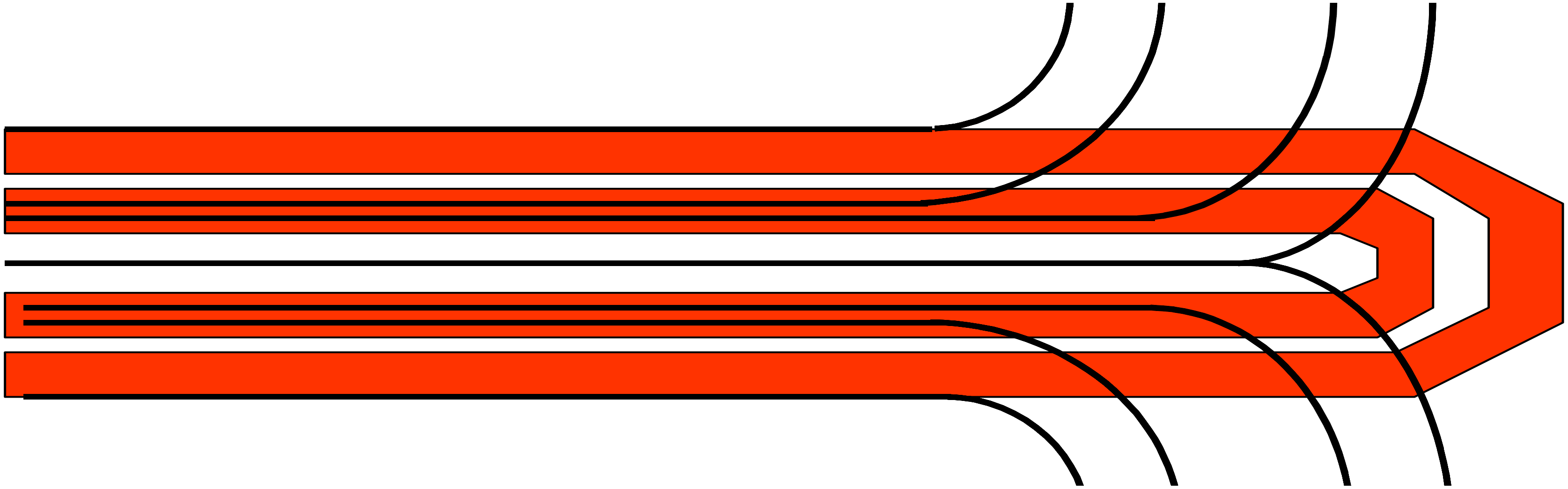
- in normal operation, diodes block ⇒ magnets track accurately
- if a magnet quenches, diodes allow the octant current to by-pass
- circuit breaker reduces to octant current to zero with a time constant of 100 sec
- initial voltage across breaker = 2000V
- stored energy of the octant = 1.33GJ

LHC quench-back heaters

- stainless steel foil 15mm x 25 µm 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

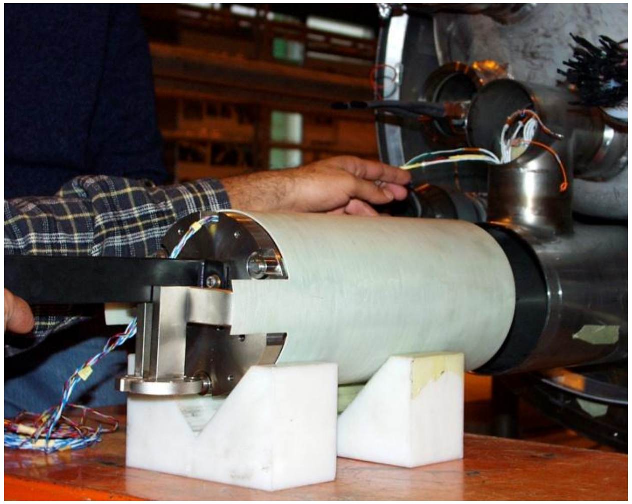






Diodes to by-pass the main ring current

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

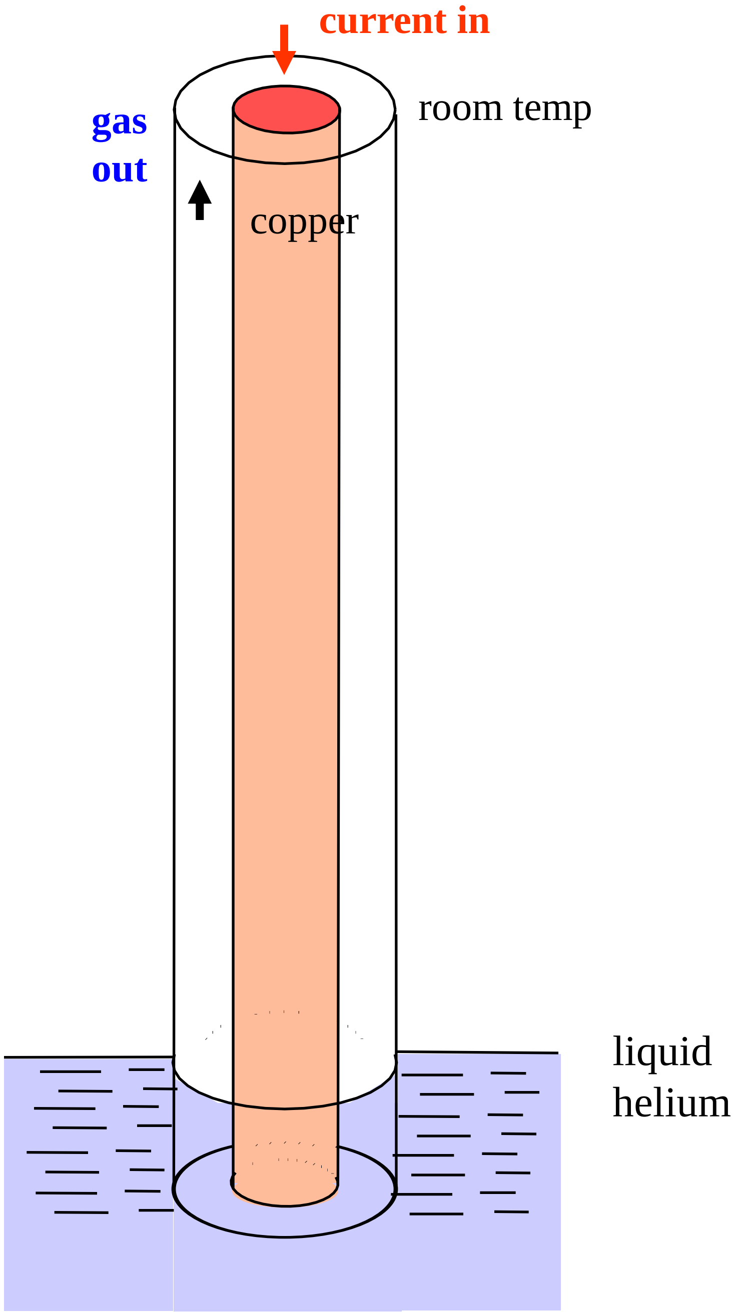


Current Leads

- we want to have low heat inleak, ie low ohmic heating ***and*** low heat conduction from room temperature. This requires low ρ 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
- recap helium properties
  ratio Δenthalpy/latent heat = 72
  there's lots of cold in the boil off gas
- 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

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

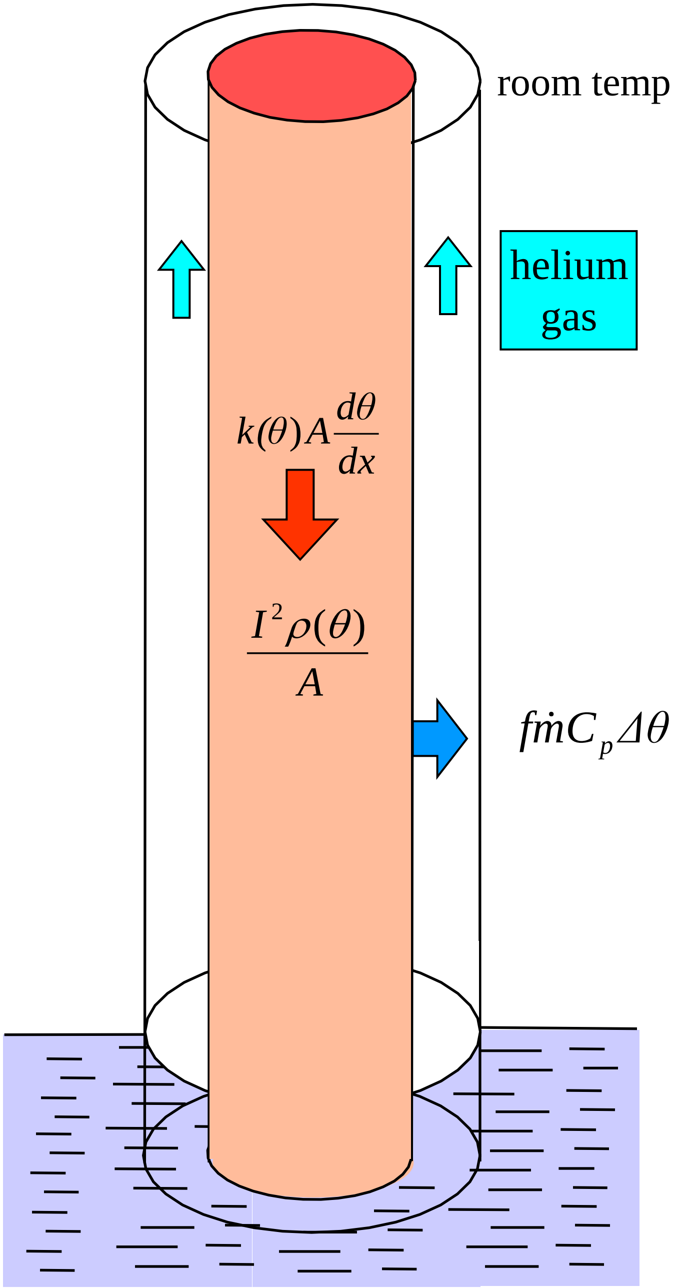
where:

f = efficiency of heat transfer to helium gas

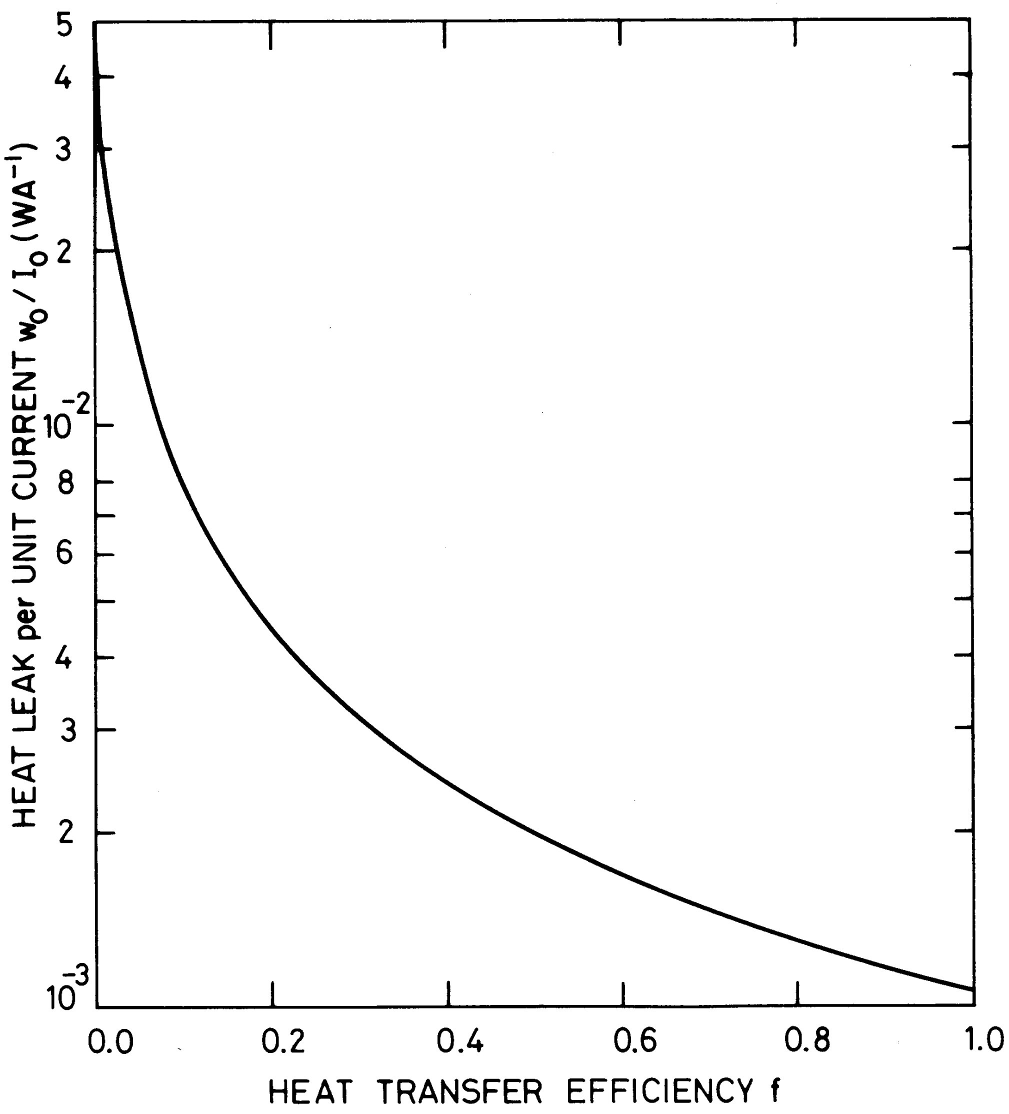
$\dot{m}$ = helium mass flow

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

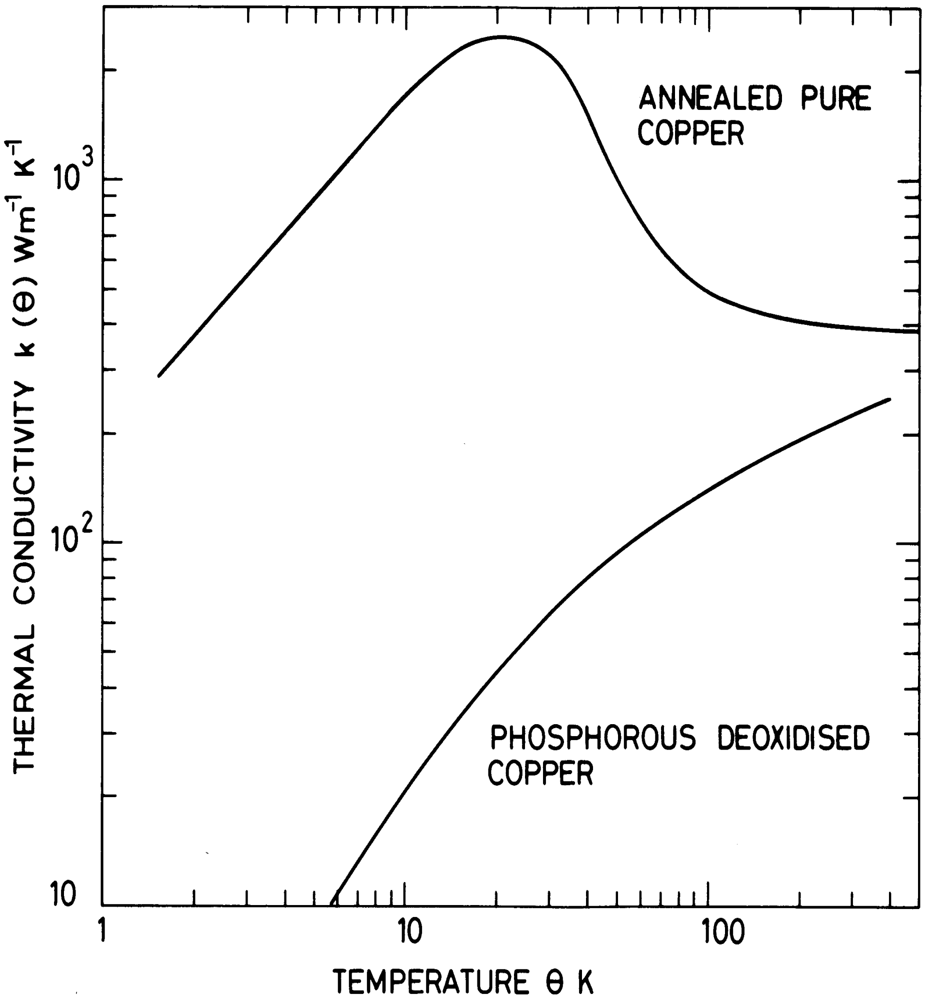
  per lead

- 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



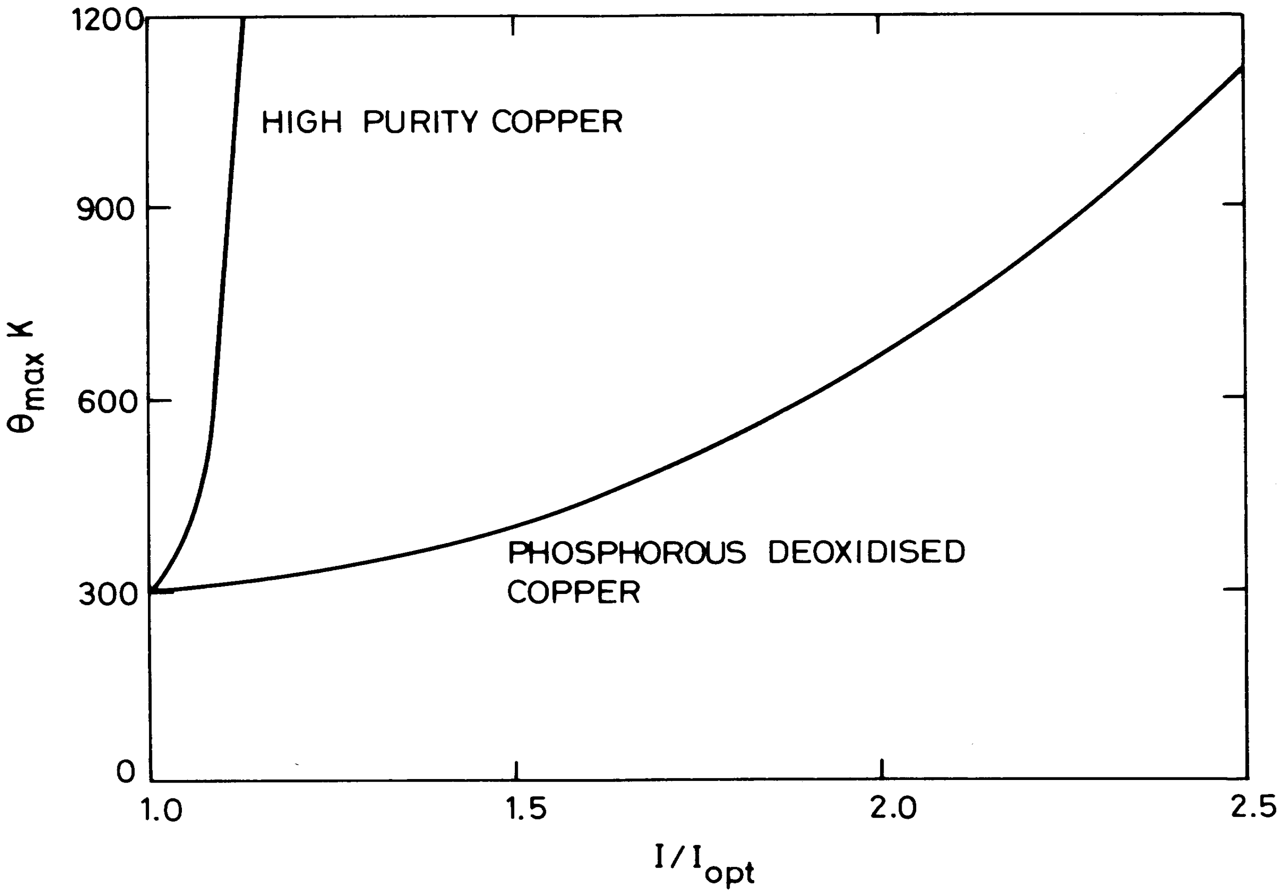
- the optimum shape is a function of temperature and material properties, particularly thermal conductivity.
- for a lead running between 300K and 4.2K the optimum shape is as follows
  - for a lead of annealed high purity copper

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

  - 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



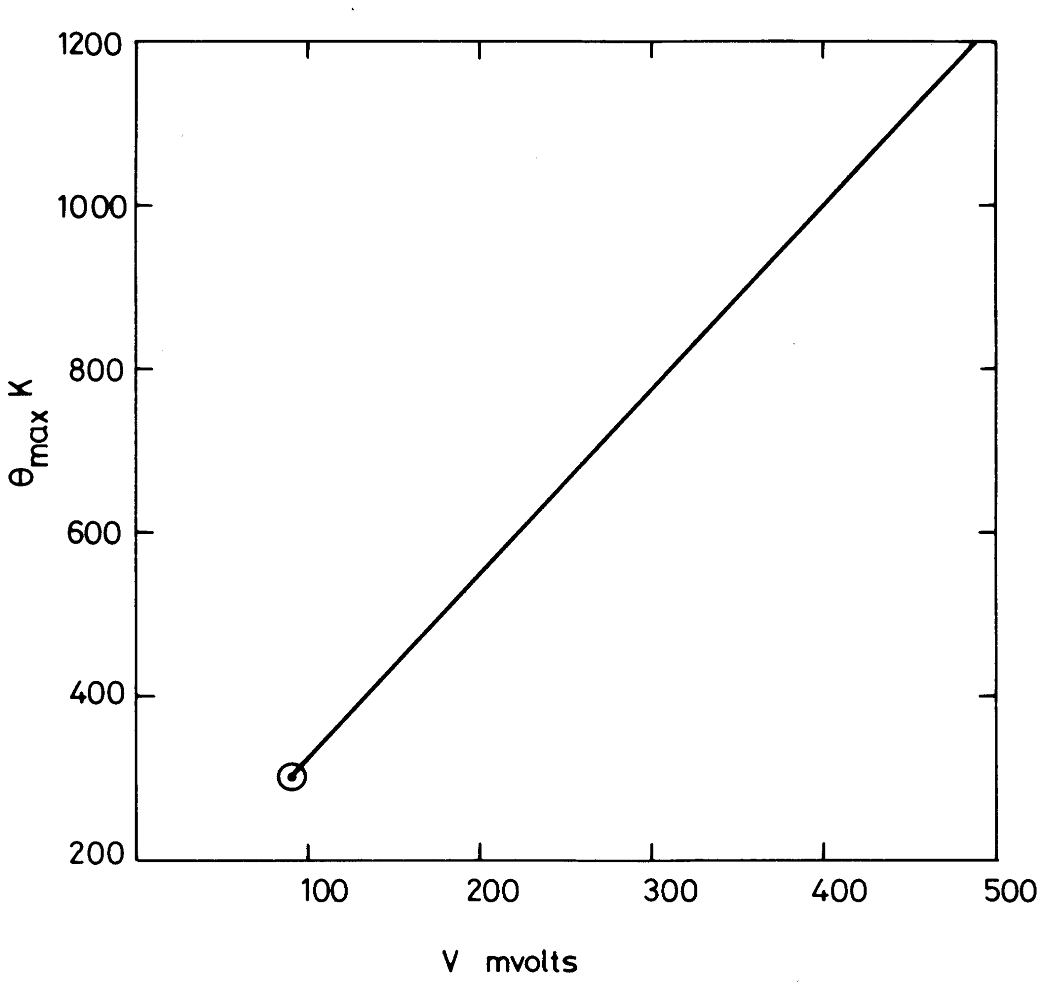
- for an optimized lead, the maximum temperature is room temperature (at the top of the lead)
- when the lead is not optimized, the temperature of an intermediate region rises above room temperature
- the optimum for pure metals is more sensitive than for impure metals

if current lead burns out ⇒ magnet open circuit

⇒ large voltages

⇒ disaster

Health monitoring



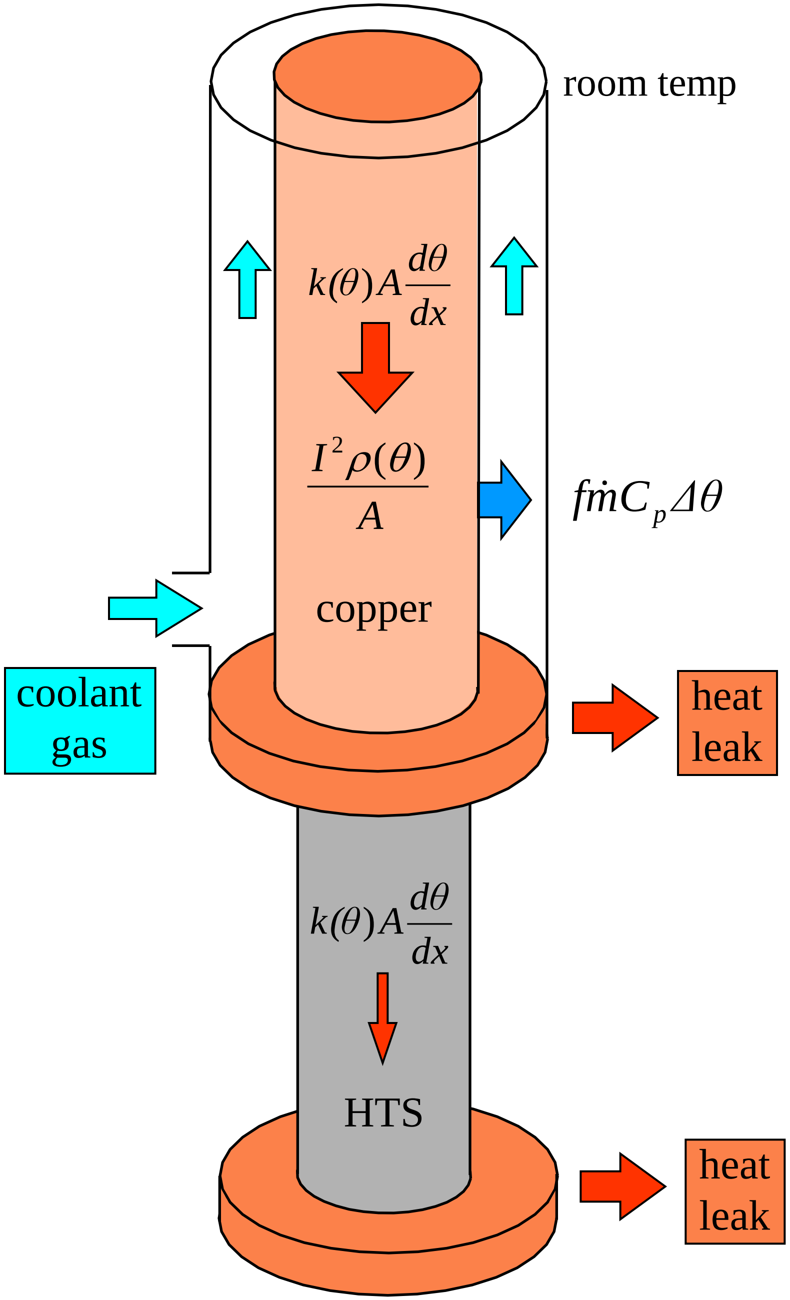
- all leads between the same temperatures and with the same cooling efficiency drop the same voltage at optimum
- for a lead between 300K and 4.2K with with 100% cooling efficiency, the voltage drop at optimum is **75mV**
- measure the volts across your lead to see if it is optimised
- if a lead burns 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
- beneficial to use gas cooling – eg nitrogen

For the HTS section beware of

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



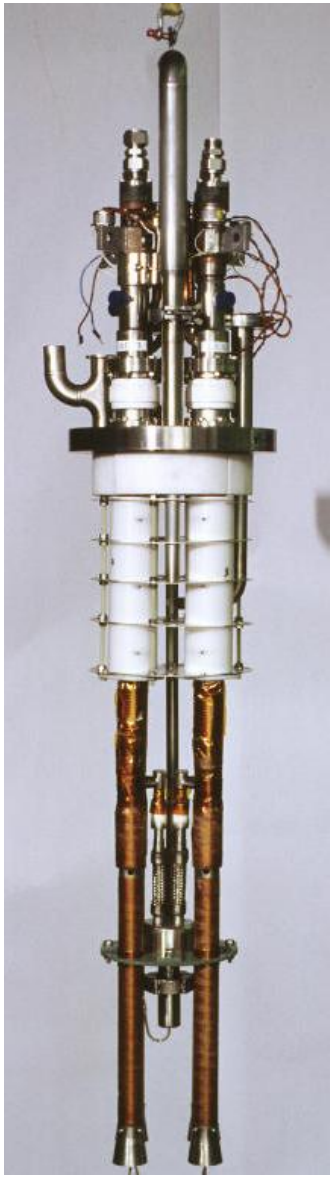
HTS (high temperature superconductor) current leads


photo CERN

- HTS materials have a low thermal conductivity
- make the section of lead below ~ 70K from HTS material
- heat leak down the 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$13kA lead for LHC

600A lead for LHC $\Rightarrow$



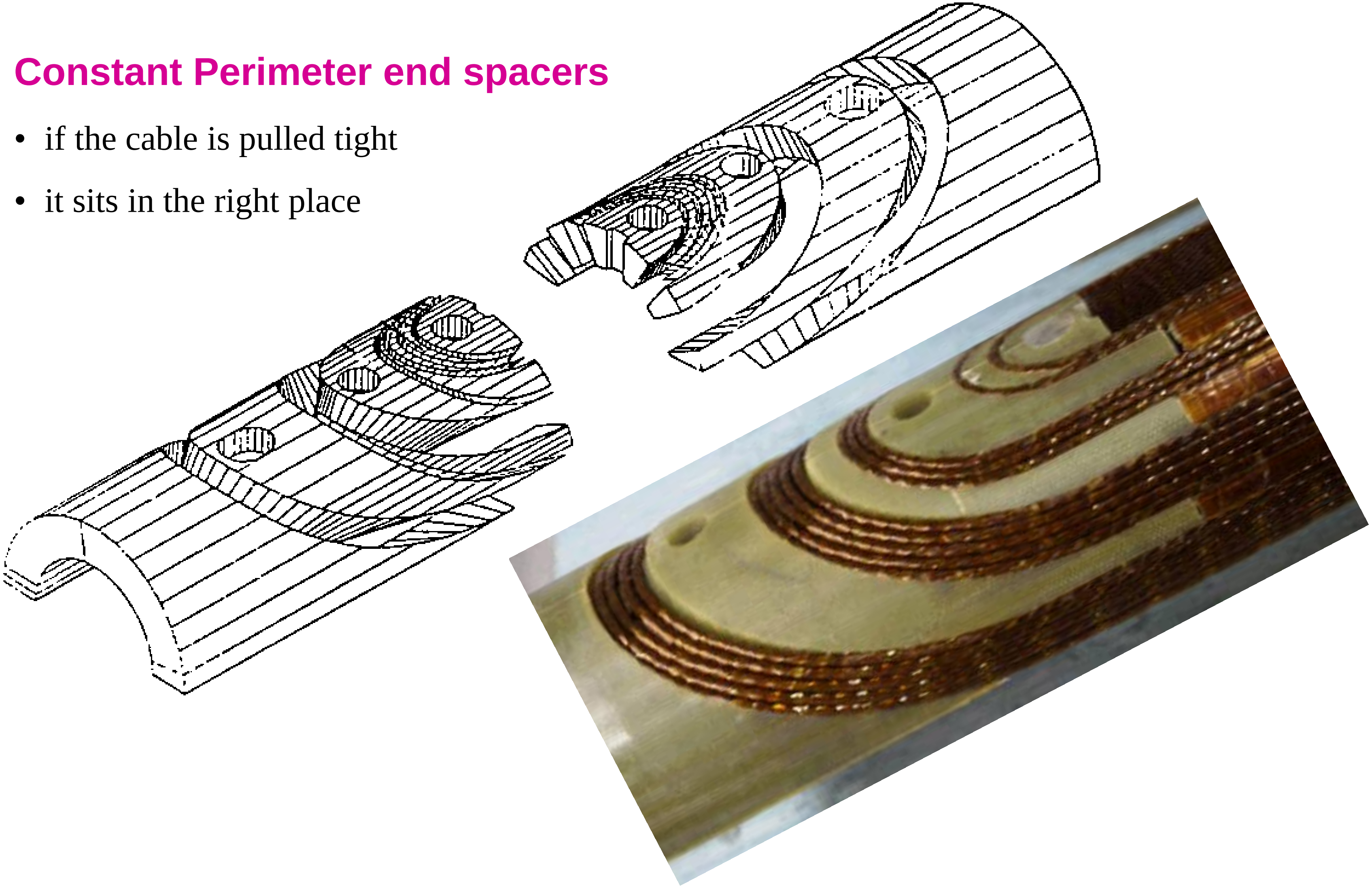
Winding the LHC dipoles

photo courtesy of Babcock Noell

End turns

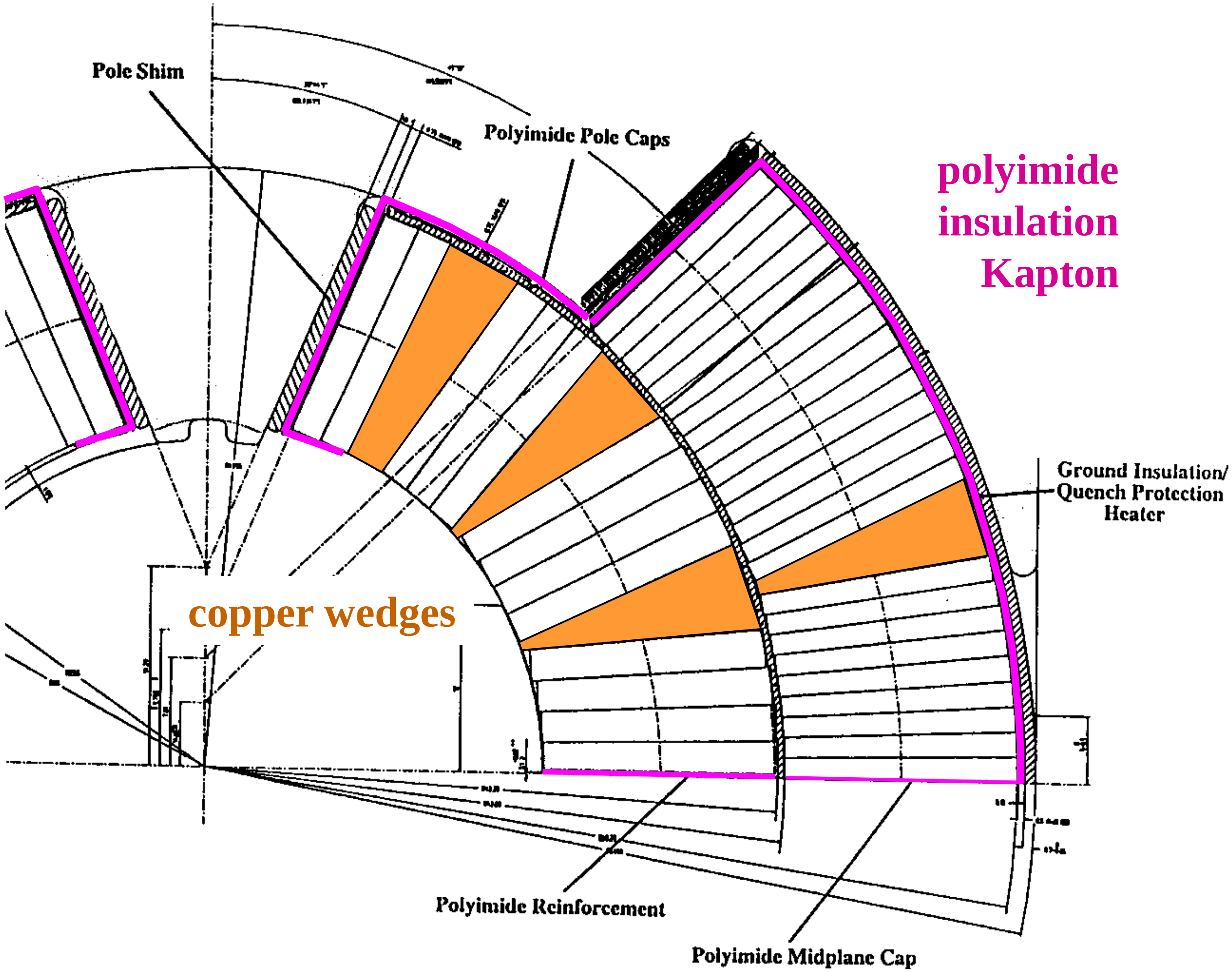
Constant Perimeter end spacers

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



Spacers and insulation

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

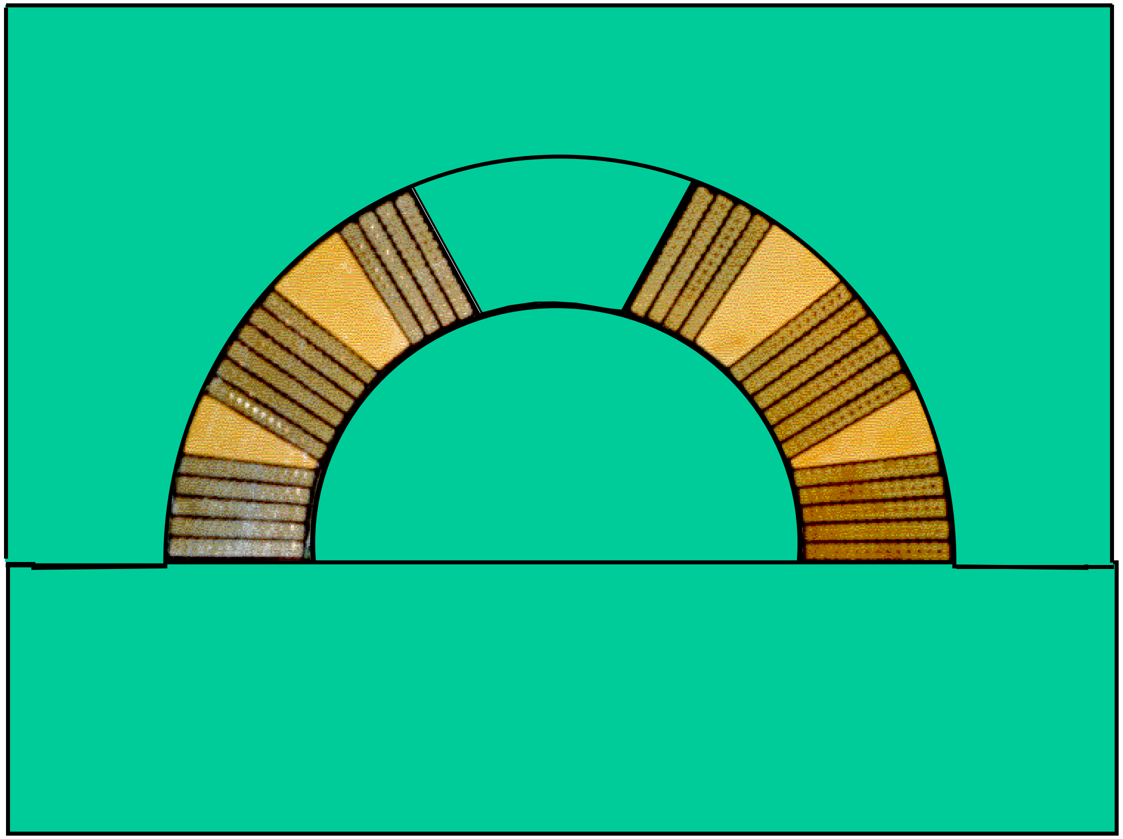


Compacting and curing

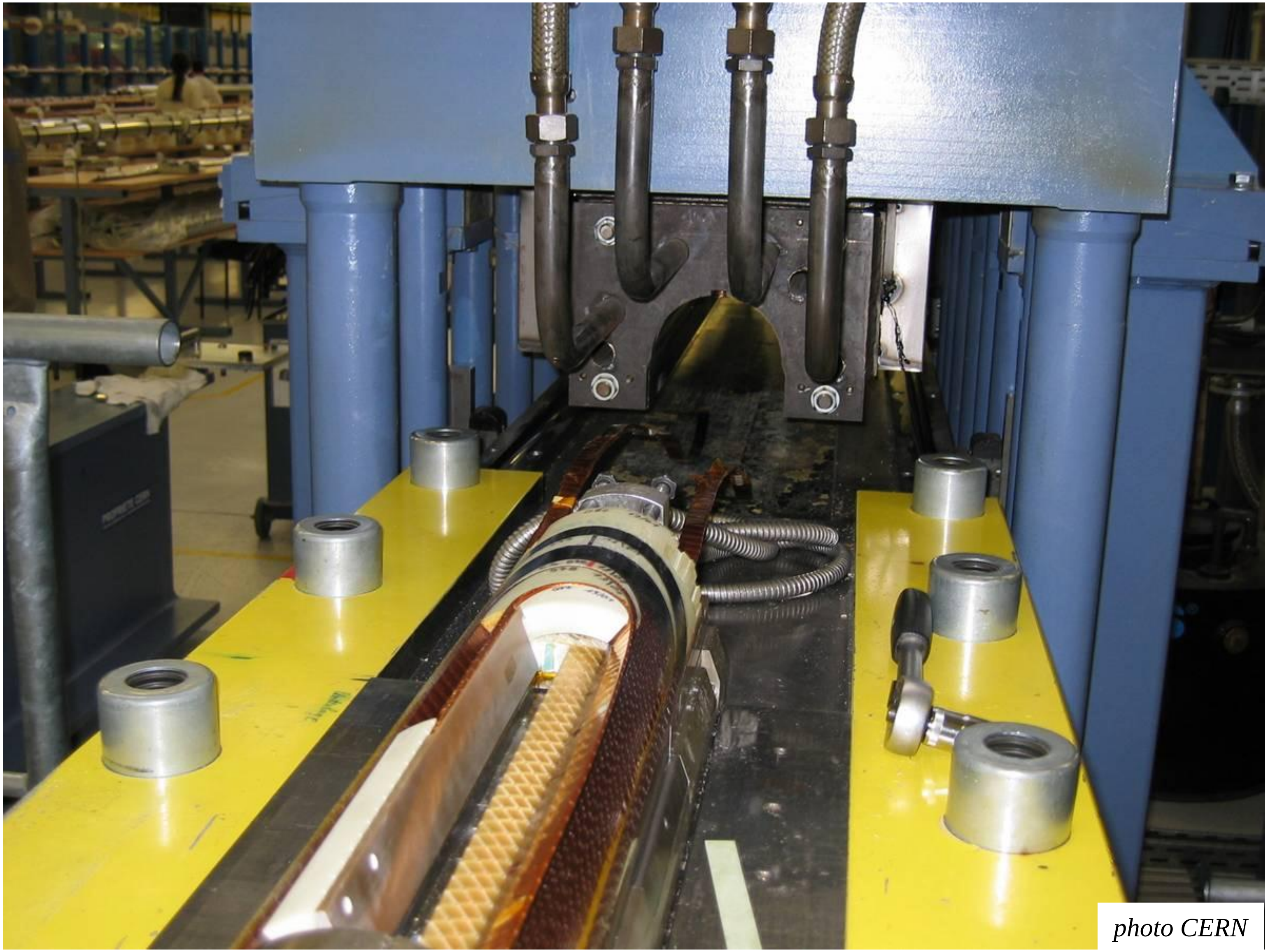
- After winding, the half coil, (still very 'floppy') is placed in an accurately machined tool

- 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



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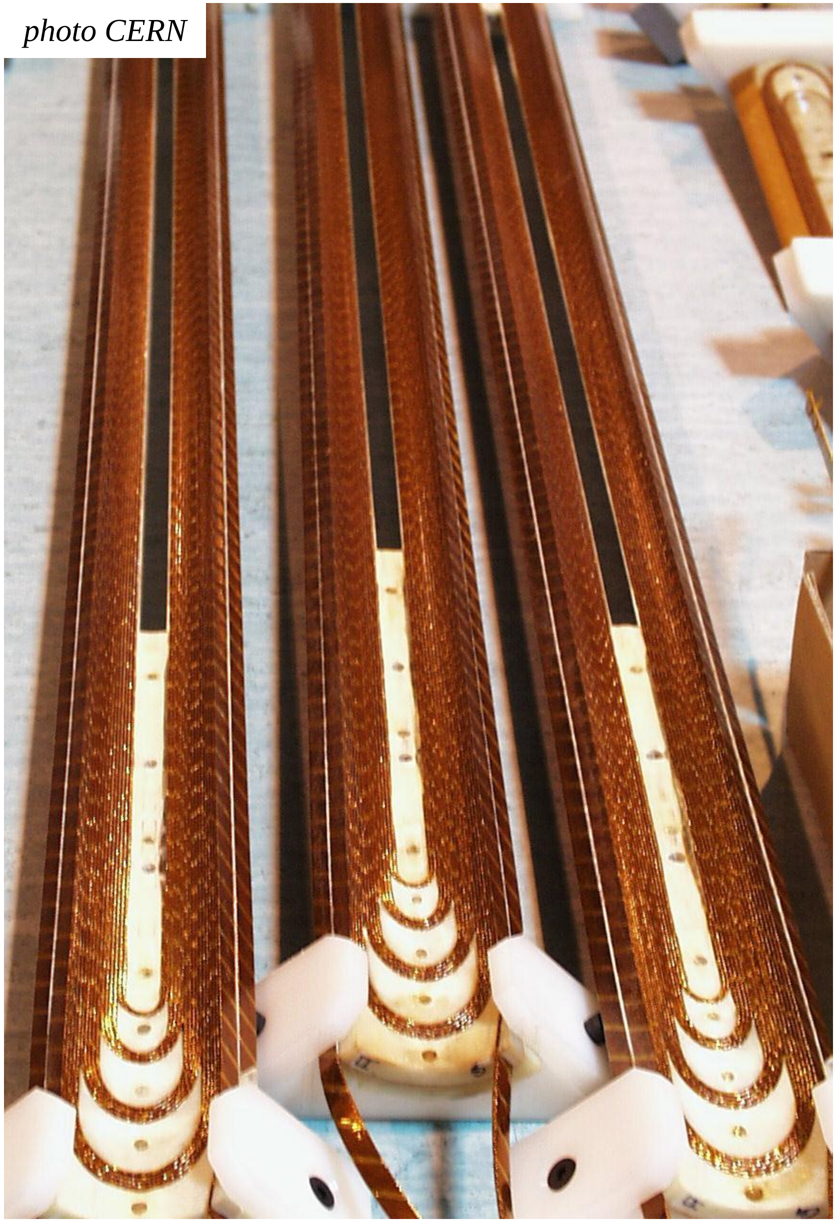
Finished coils



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

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Coils for correction magnets

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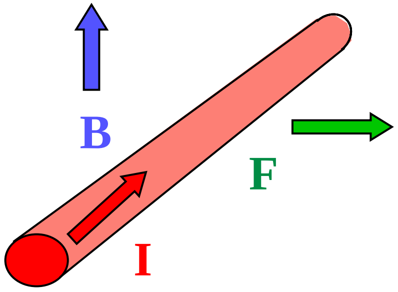
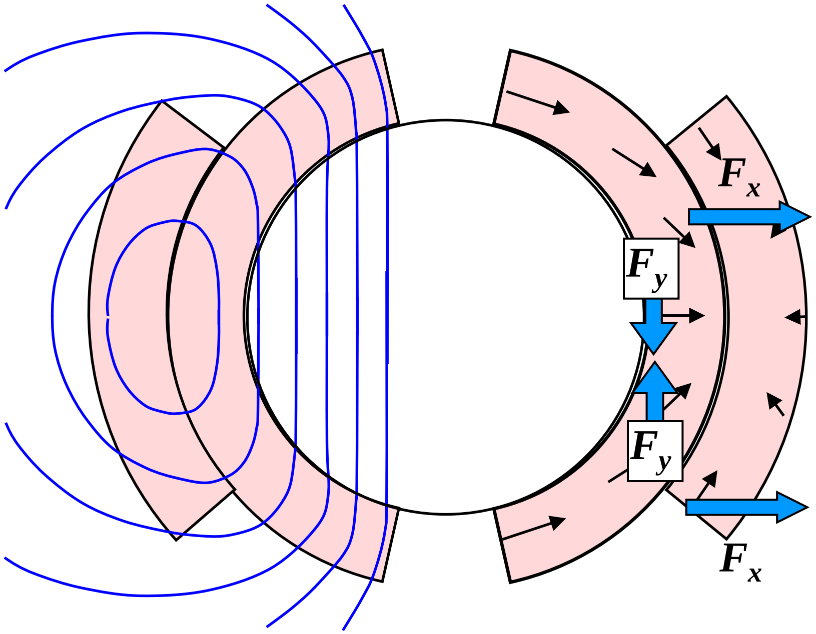
On a smaller scale, but in great number and variety, many different types of superconducting correction coils are needed at a large accelerator

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

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

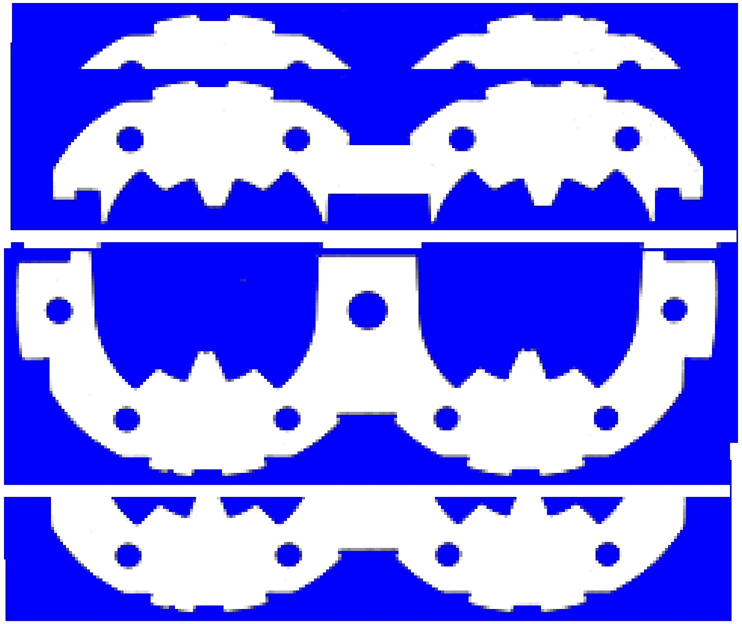
Collars

Question: how to make a force support structure that

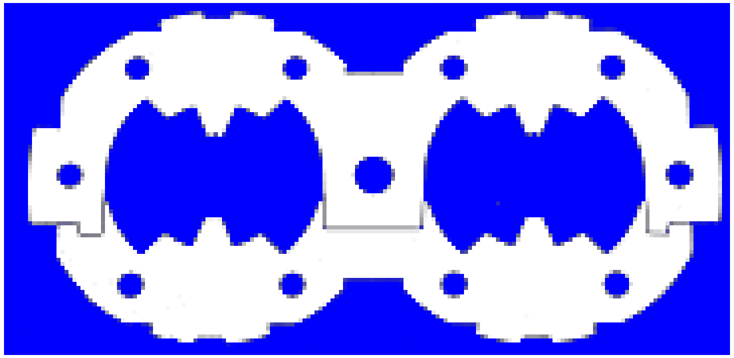
- fits tightly round the coil
- presses it into an accurate shape
- has low ac losses - laminated
- can be mass produced cheaply

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

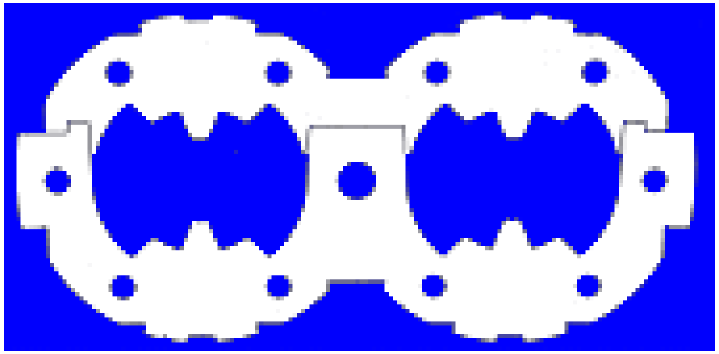
- inherited from conventional magnet laminations



press collars over coil from above and below



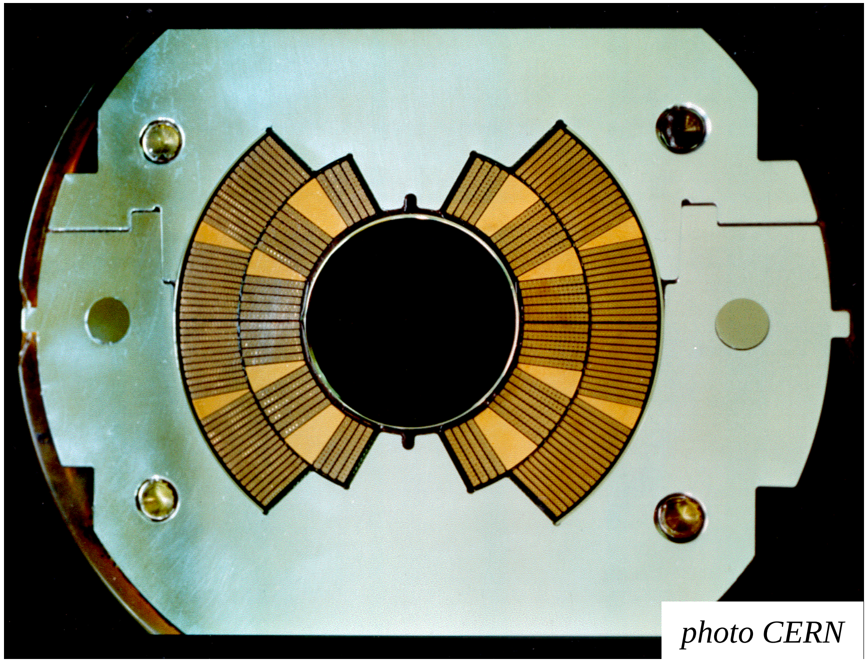
invert alternate pairs so that they interlock



push steel rods through holes to lock in position

Collars

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



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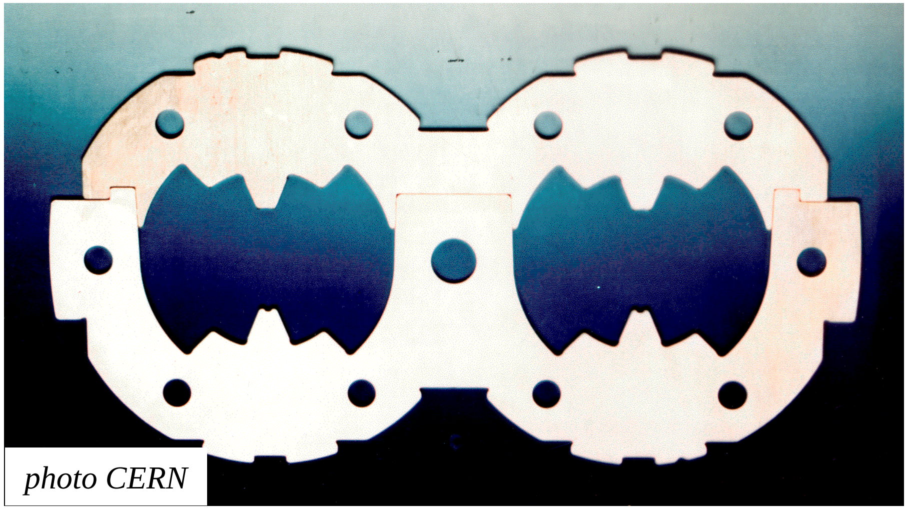

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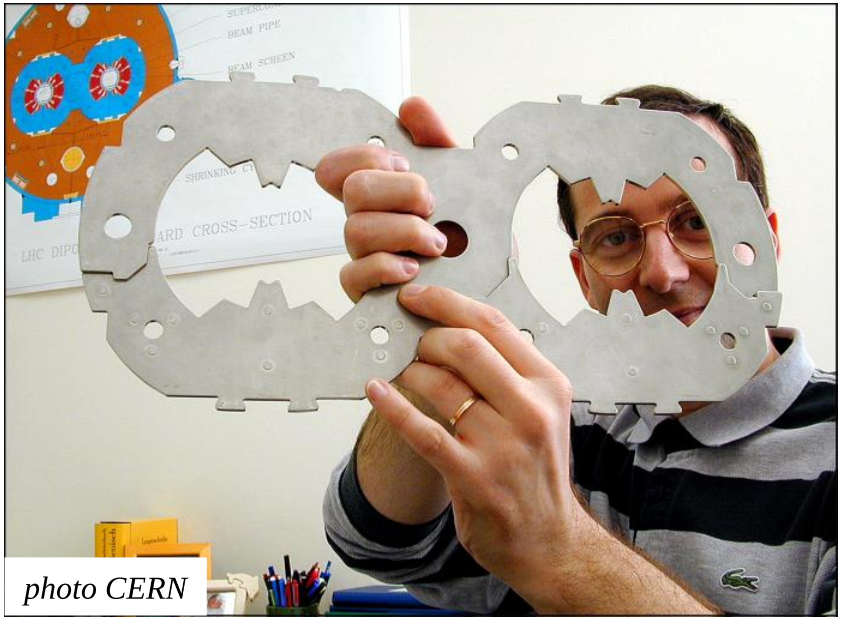
12 million produced
for LHC



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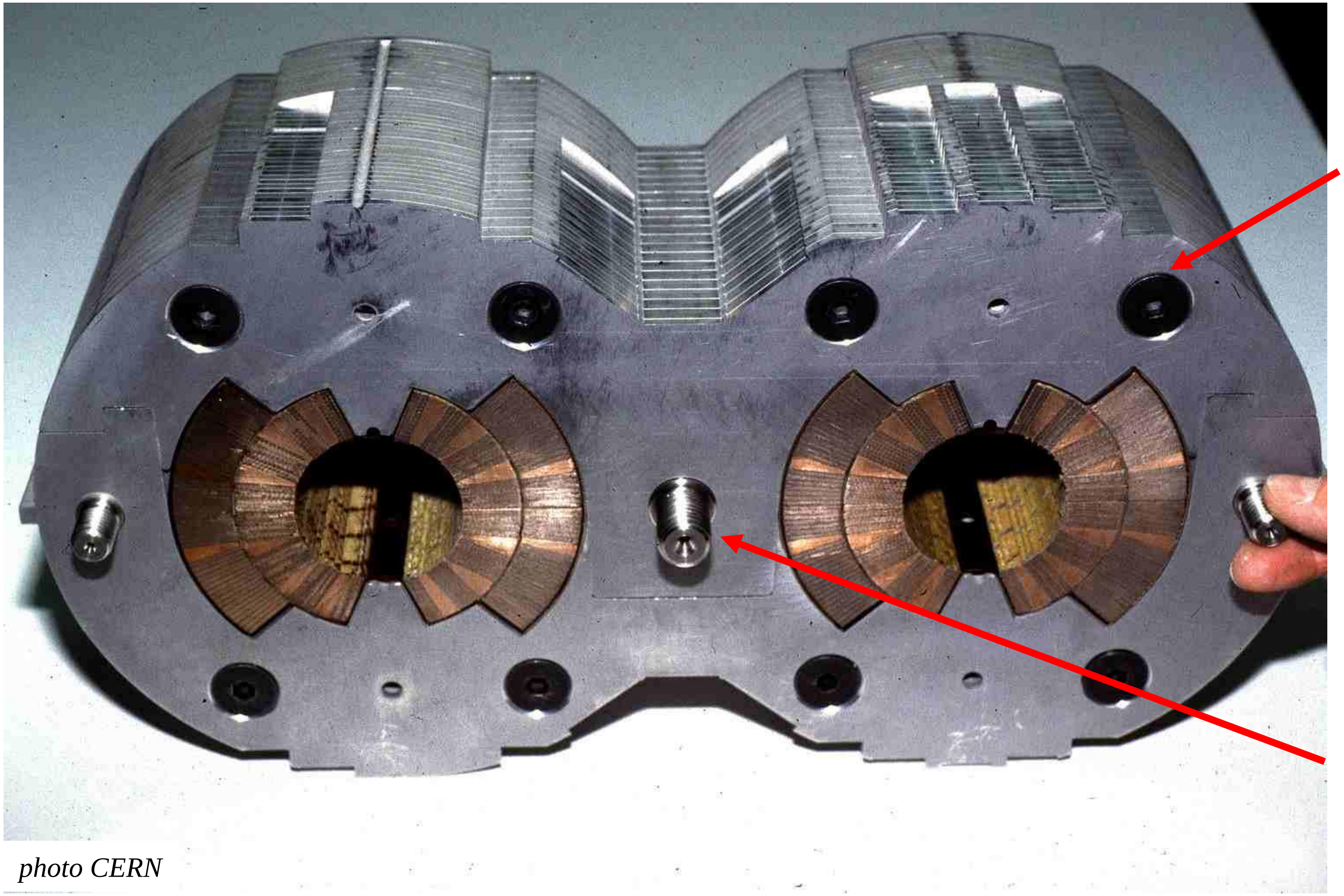
LHC dipole collars



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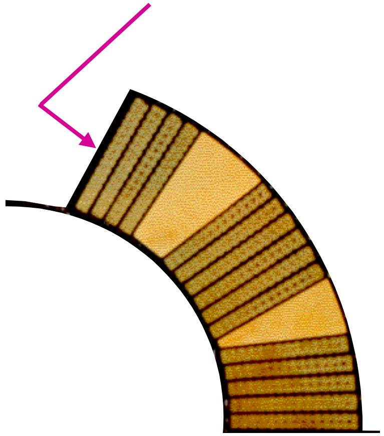
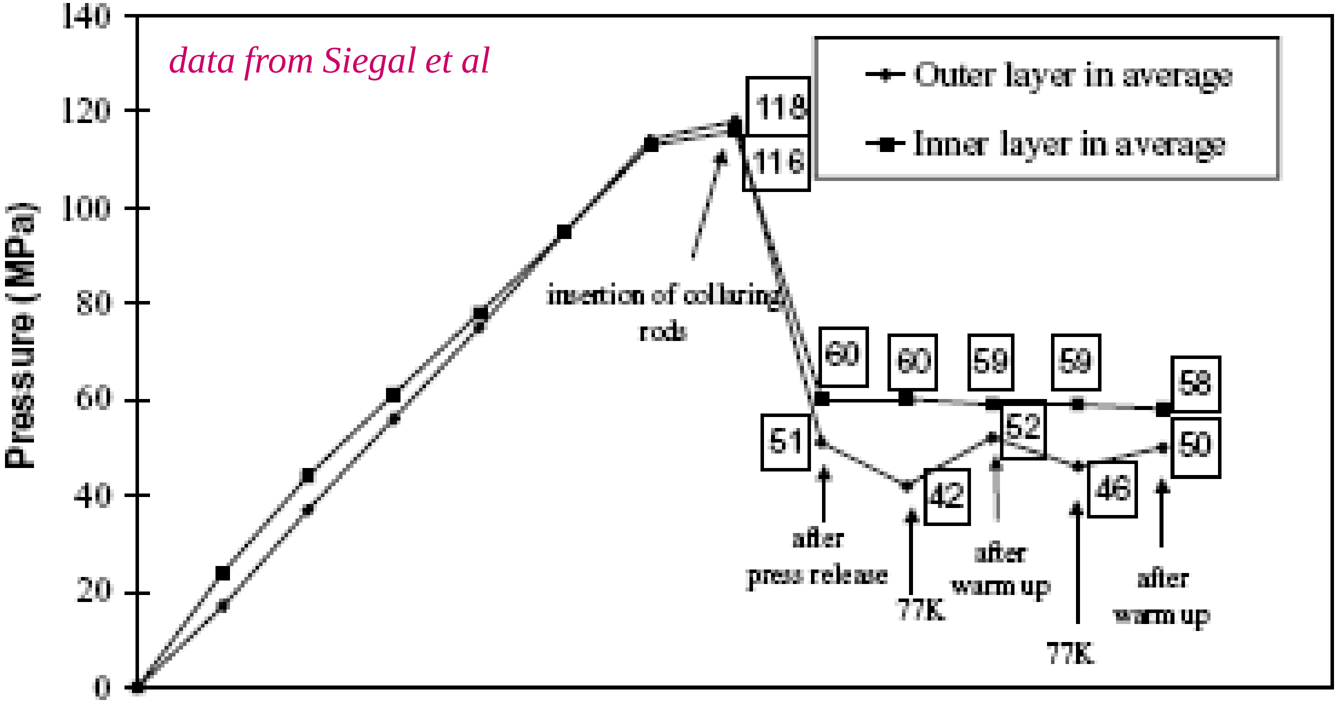
sub-units of several alternating pairs are riveted together

stainless rods lock the sub-units together

Pre-loading the coil

measure the pressure here





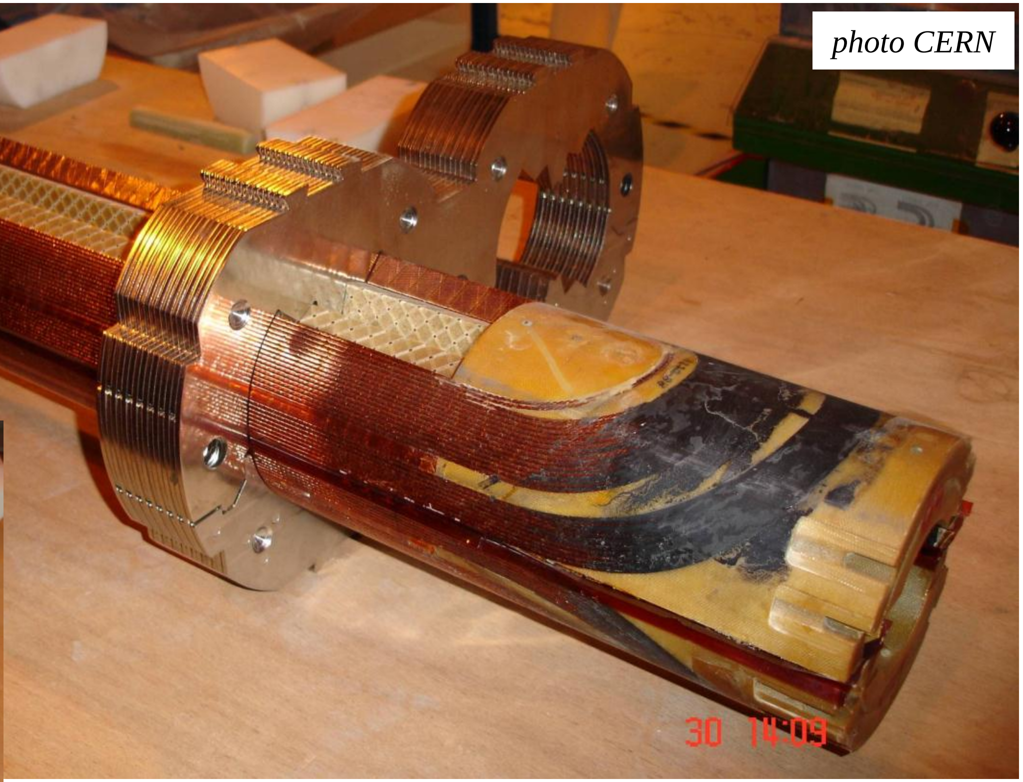
data from Siegal et al

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)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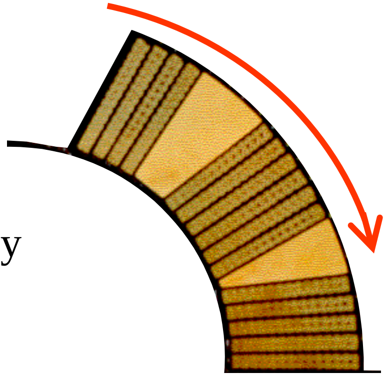

- sliding at the outer boundary
  ⇒ friction heating

- use kapton layers