Lecture 5: Cryogenics and Practical Matters

Plan

- cryogenic working fluids
- refrigeration
- cryostat design principles
- current leads
- accelerator coil winding and curing
- forces and clamping
- magnet assembly, collars and iron
- installation
- some superconducting accelerators

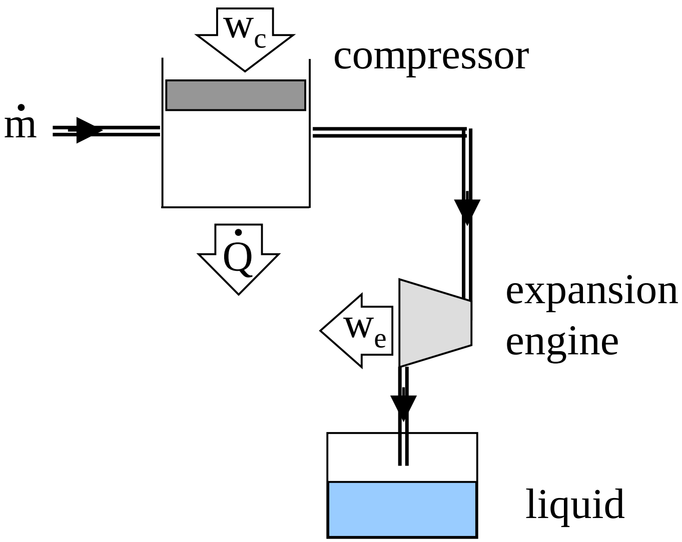
Cryogenics: the working fluids

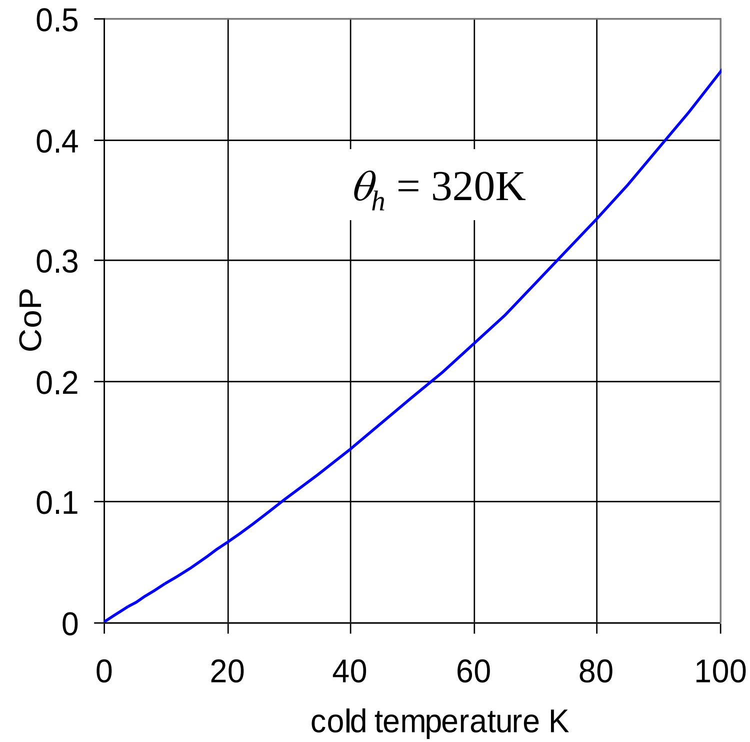
	boiling temper-ature K	critical temper-ature K	melting temper-ature K	latent heat of boiling L kJ kg^{-1}	* enthalpy change ΔH BP ⇒ room kJ kg^{-1}K^{-1}	ratio ΔH / L	liquid density kg m^{-3}
Helium	4.22	5.2		20.5	1506	73.4	125
Hydrogen	20.4	32.9	13.8	449	3872	7.6	71
Neon	27.1	44.5	24.6	85.8	363	3.2	1207
the gap							
Nitrogen	77.4	126.2	63.2	199	304	1.1	806
Argon	87.3	150.7	83.8	161	153	0.7	1395
Oxygen	90.2	154.6	54.4	213	268	0.9	1141

* enthalpy change of gas from boiling point to room temperature $\Delta H = \int_{boiling}^{room} C_p(\theta)d\theta$

represents the amount of 'cold' left in the gas after boiling
- sometimes called 'sensible heat'

Refrigeration



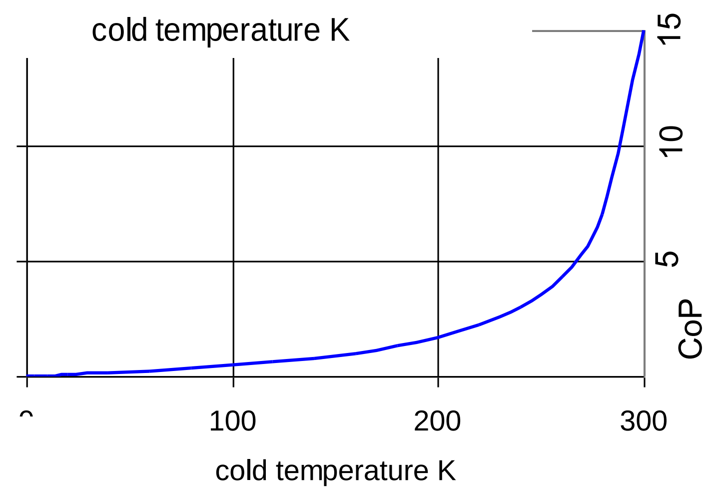


- the most basic refrigerator uses compressor power to extract heat from low temperature and reject a larger quantity of heat at room temperature
- Carnot says the **Coefficient of Performance CoP**

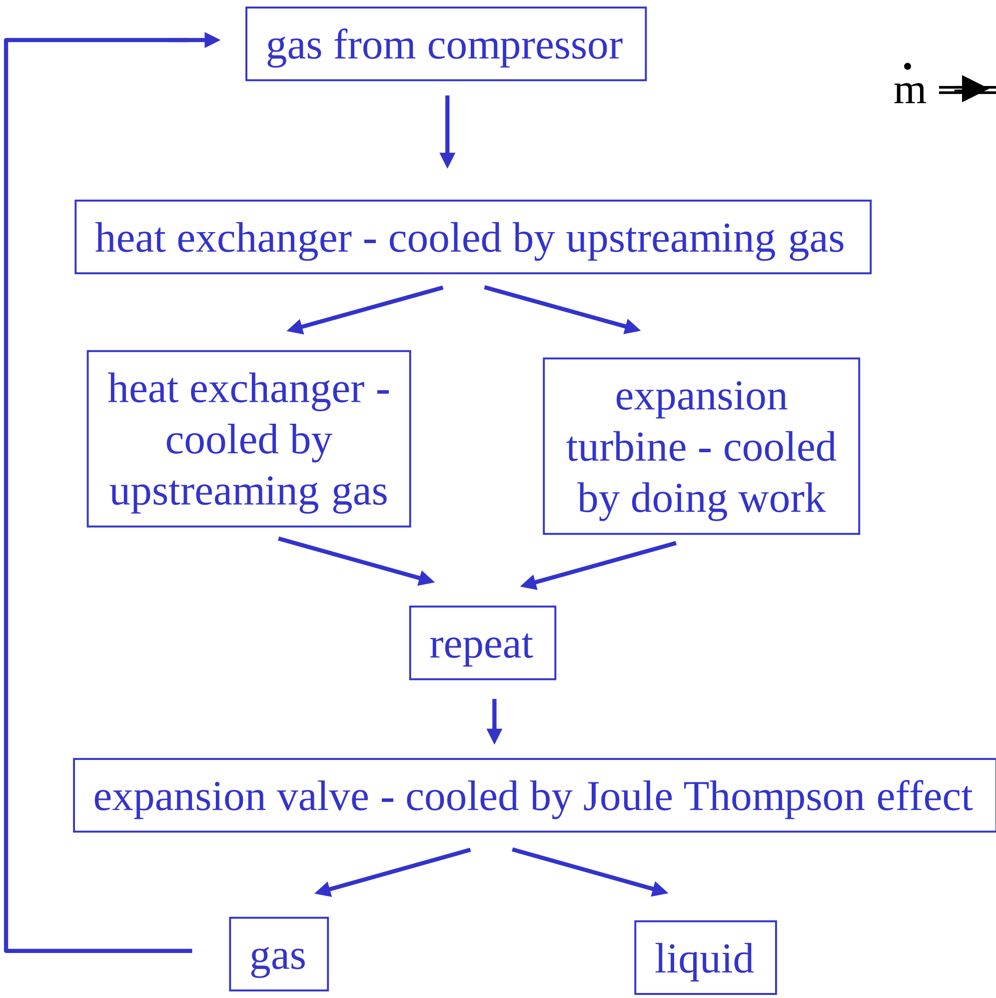
  = cooling power / input power

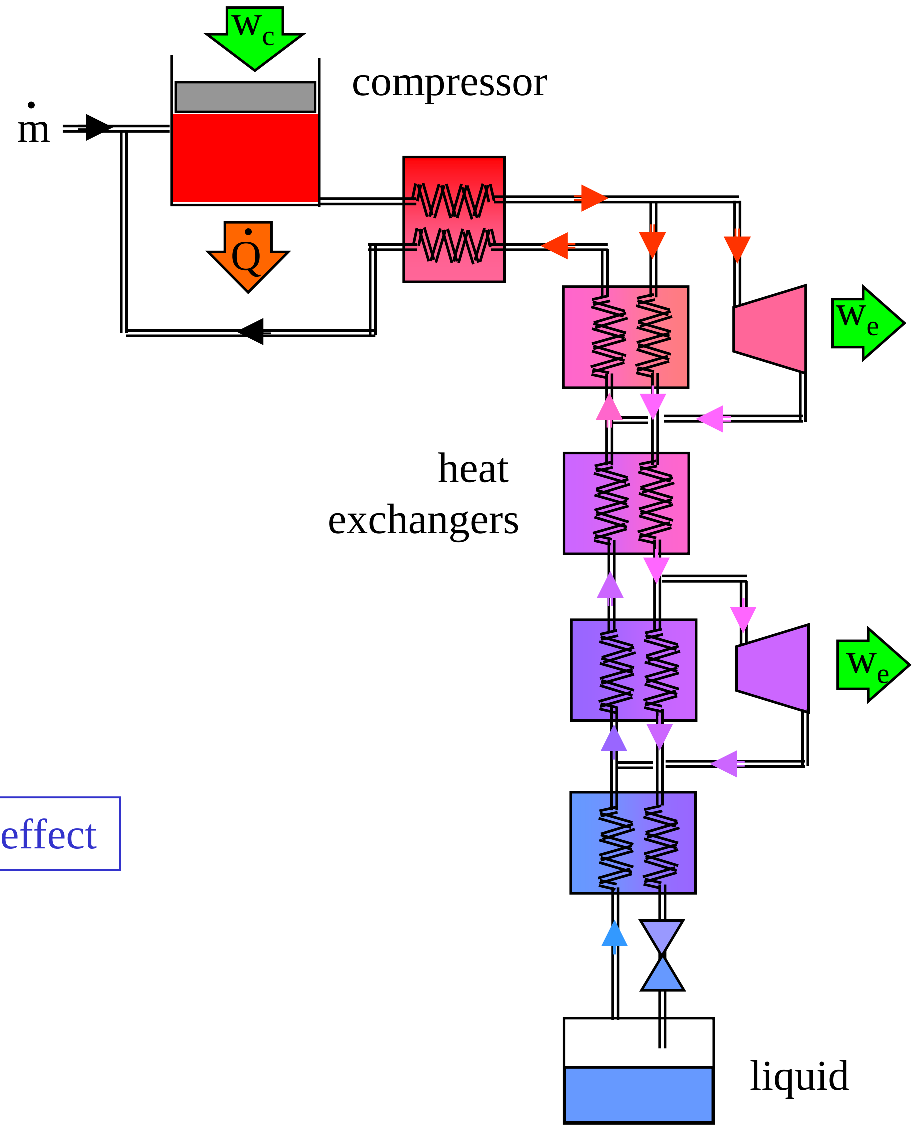
$$CoP = \frac{\theta_c}{\theta_h - \theta_c}$$

at 4.2K CoP = 1.3%



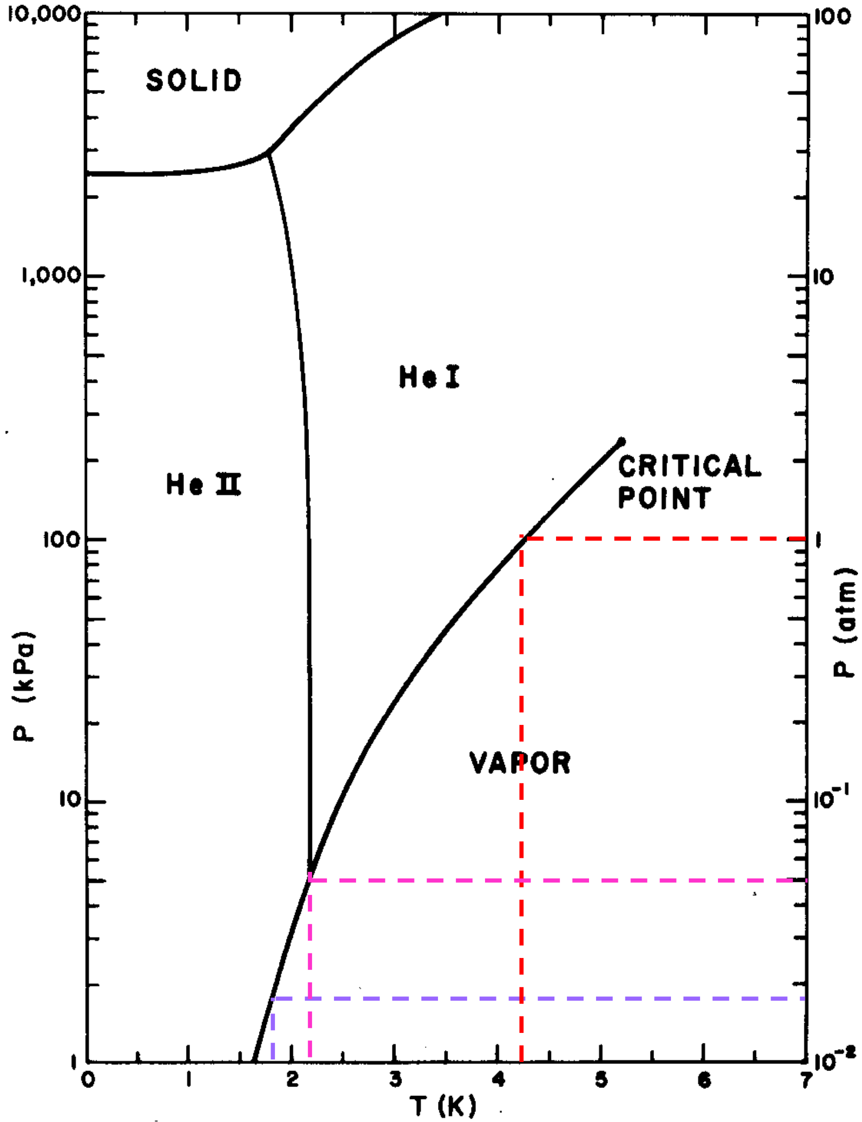
Collins helium liquefier





from Helium Cryogenics SW Van Sciver pub Plenum 1986

Properties of Helium



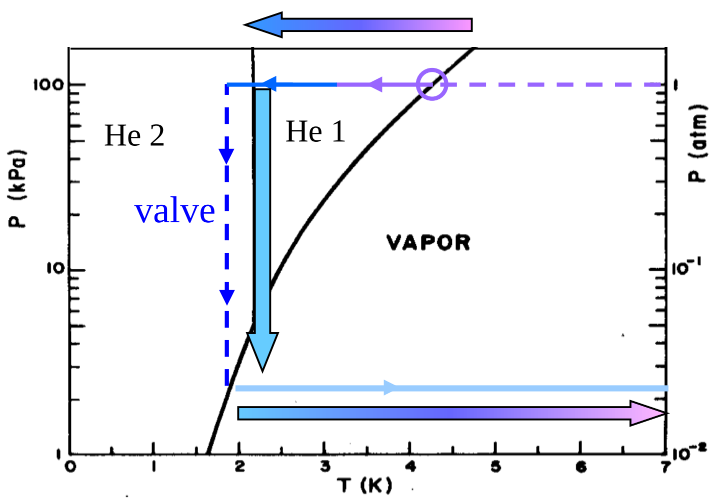
- helium has the lowest boiling point of all gases and is therefore used for cooling superconducting magnets
- below the **lamda point** a second liquid phase forms, known as **Helium 2 or superfluid**
- it has **zero viscosity** and very **high thermal conductivity**

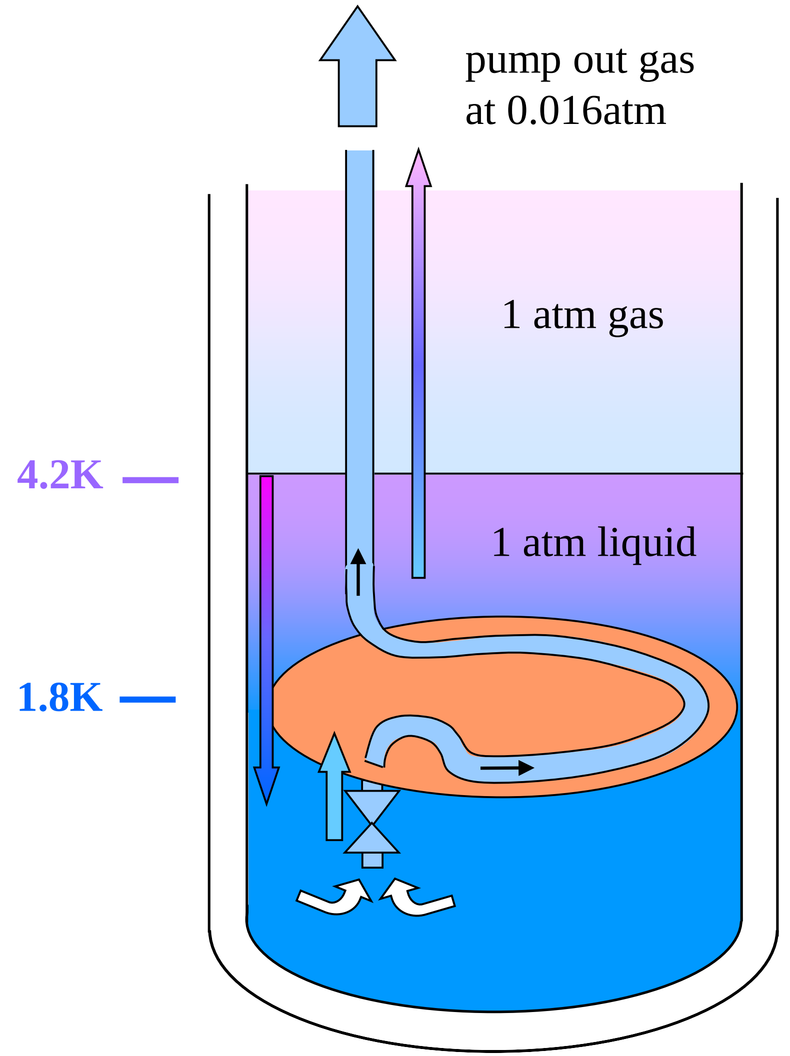
<u>Some numbers for helium</u>

boiling point at 1 atmos	4.22K
lamda point at 0.0497 atmos	2.17K
density of liquid at 4.22K	0.125 gm/cc
density of gas at 4.22K	0.0169gm/cc
density of gas at NTP	1.66×10^{-4}gm/cc
latent heat of vaporization	20.8J/gm
enthalpy change 4.2K⇒293K	1506J/gm
ratio Δenthalpy/latent heat	72

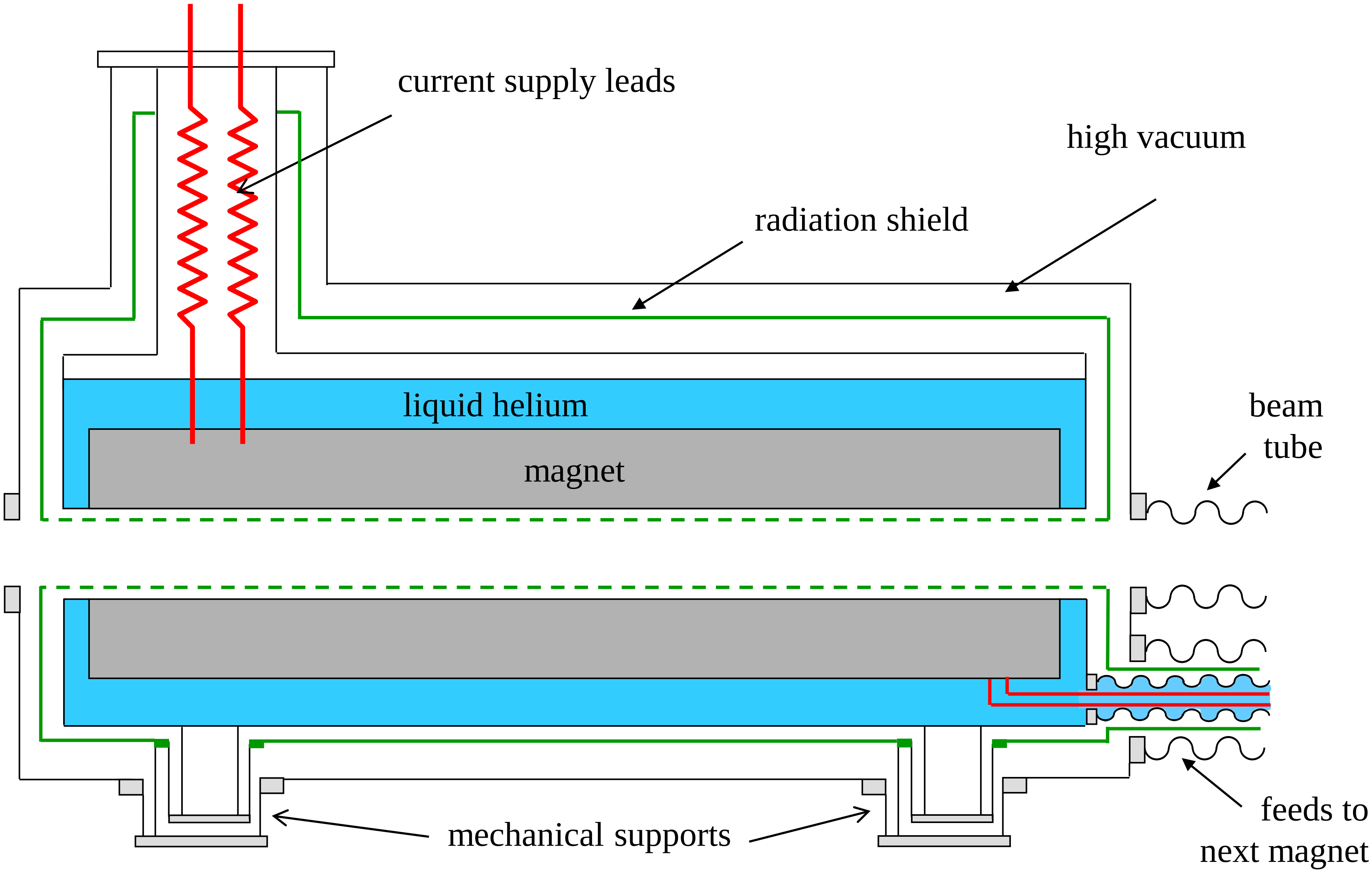
Subcooled Helium II

- HeII is an excellent coolant because of its high thermal conductivity and specific heat
- NbTi works much better at the lower temperature
- but for practical engineering, it is inconvenient operate at pressures below atmospheric
- the 'lamda plate' allows us to produce HeII in a system operating at atmospheric pressure
- used in LHC and commercial NMR magnets





Accelerator magnet cryostat essentials



Cryogenic heat leaks

1) Gas conduction

at low pressures (<10Pa or 10^{-4} torr), that is when the mean free path ~ 1m > distance between hot and cold surfaces

$$\frac{Q}{A} = \eta_g P_g \Delta\theta$$

where η_g depends on the accommodation coefficient; typical values for helium ⇒

$\theta_{cold} \sim \theta_{hot}$	η_g (W.m^{-2}.Pa.K)
4 ~ 20K	0.35
4 ~ 80K	0.21
4 ~ 300K	0.12
80 ~ 300K	0.04

not usually a significant problem, check that pressure is low enough and use a sorb

2) Solid conduction

$$\frac{Q}{A} = k(\theta)\frac{d\theta}{dx}$$

a more convenient form is

$$Q\frac{L}{A} = \int_{\theta_c}^{\theta_h} k(\theta)\, d\theta$$

look up tables of conductivity integrals

3) Radiation

heat flux $$\frac{Q'}{A} = \varepsilon\sigma\theta^4$$

transfer between two surfaces

$$\frac{Q'}{A} = \left\{\frac{\varepsilon_c\varepsilon_h}{\varepsilon_c + \varepsilon_h - \varepsilon_c\varepsilon_h}\right\}\sigma\,(\theta_h^4 - \theta_c^4) = \varepsilon_r\sigma\,(\theta_h^4 - \theta_c^4)$$

Stefan Boltzmann constant $\sigma = 5.67\text{x}10^{-8}$ Wm^{-2}K^{-4}

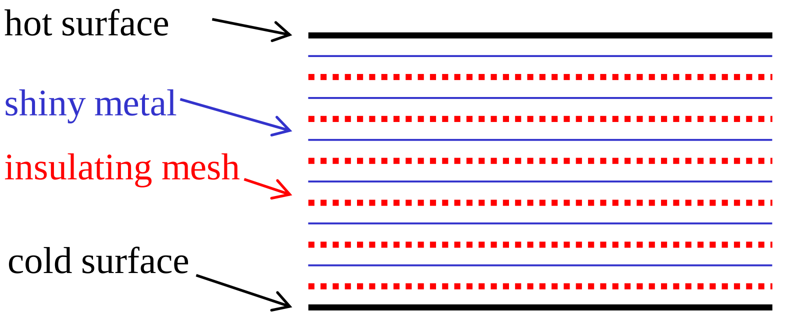
4) Current Leads

optimization problem; trade off Ohmic heating against conducted heat – coming up

5) Other sources

ac losses, resistive joints, particle heating etc

Superinsulation



Some typical values of effective emissivity ε_r for superinsulation

$$\frac{Q}{A} = \varepsilon_r \sigma \left(\theta_h^4 - \theta_c^4\right)$$

- radiated power goes as θ^4
- can reduce it by subdividing the gap between hot and cold surface using alternating layers of shiny metal foil or aluminized Mylar and insulating mesh.
- structure must be open for vacuum pumping.

1 layer of aluminized Mylar	0.028
5 layers of crinkled aluminized Mylar	0.017
10 layers of crinkled Mylar interleaved with glass fibre mesh	0.0072
5 layers of aluminium foil interleaved with glass fibre mesh	0.0094
10 layers of aluminium foil interleaved with glass fibre mesh	0.017
20 layers of NRC2	0.005
200 layers of NRC2	0.004
2 x 24 layer Jehier* blankets	0.002

* Jehier SA BP 29-49120 Chemille France

Current Leads

Optimization

- want low heat inleak, ie low ohmic heating ***and*** low heat conduction from room temperature.
- requires low ρ and k - but Wiedemann Franz law says

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

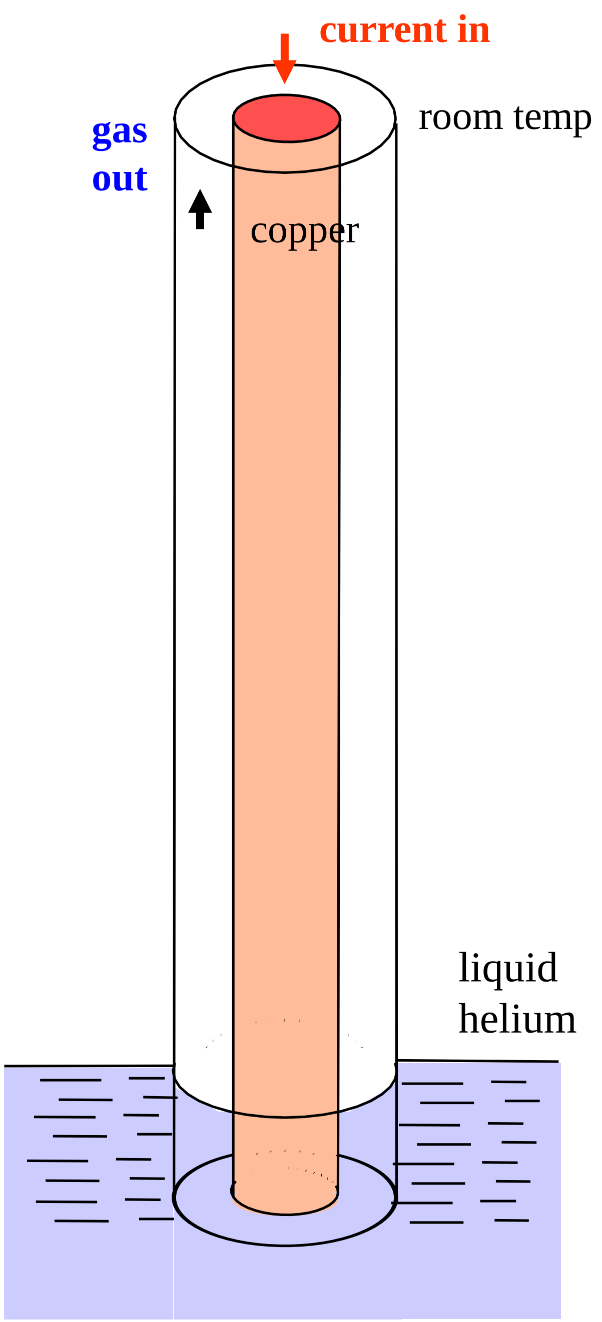
- so all metals are the same and the only variable we can optimize is the ***shape***

Gas cooling helps *(recap helium properties above)*

- Δenthalpy 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 enthalpy of cold gas boiled off to cool the lead
- make the lead as a heat exchanger



Current lead theory

equation of heat conduction

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

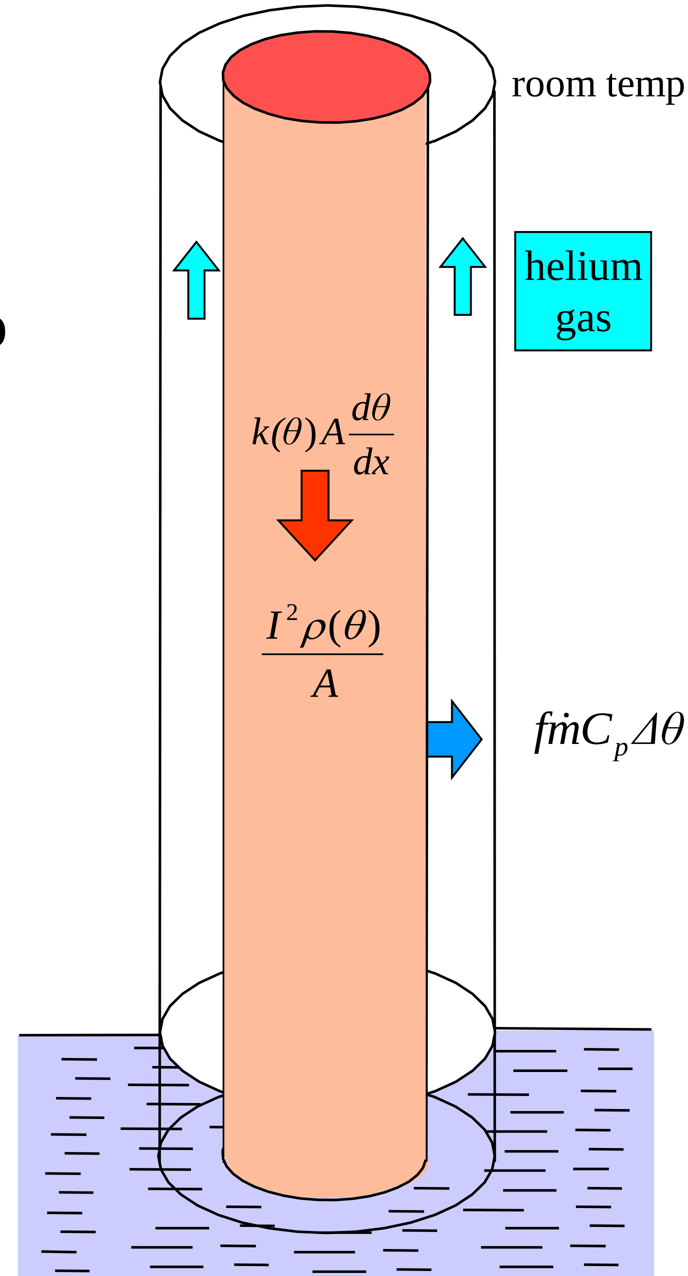
where:

f = efficiency of heat transfer to helium gas

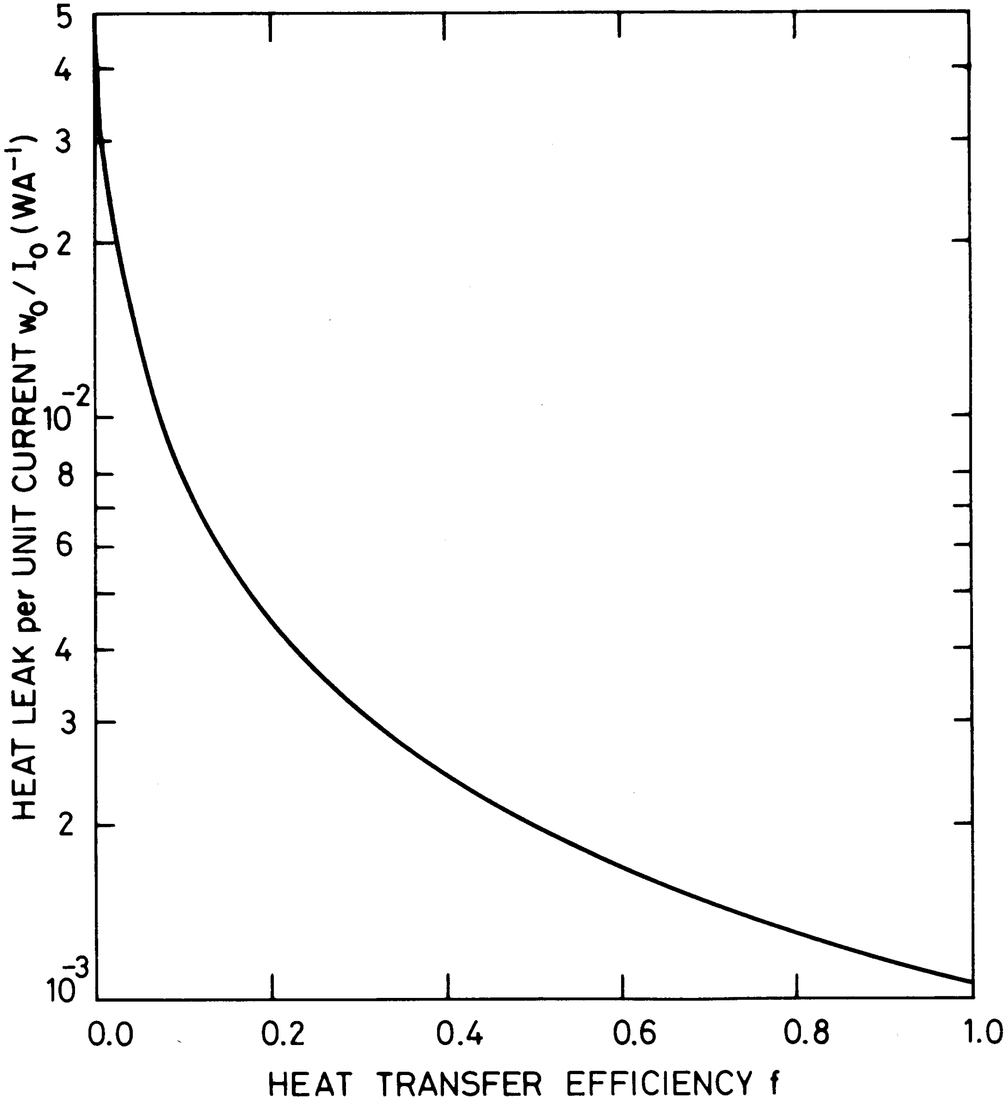
$\dot{m}$ = helium mass flow

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

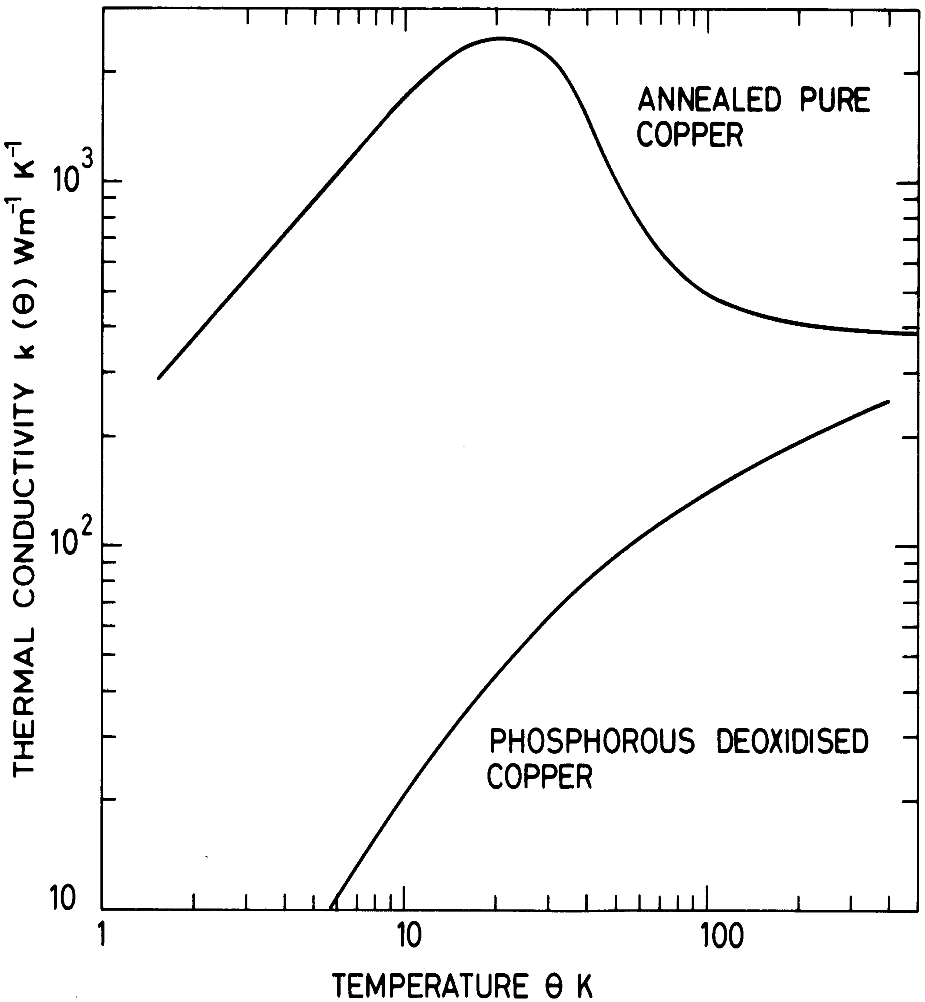
  per lead

- 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 with perfect heat transfer the optimum shape is

  - for a lead of annealed high purity copper

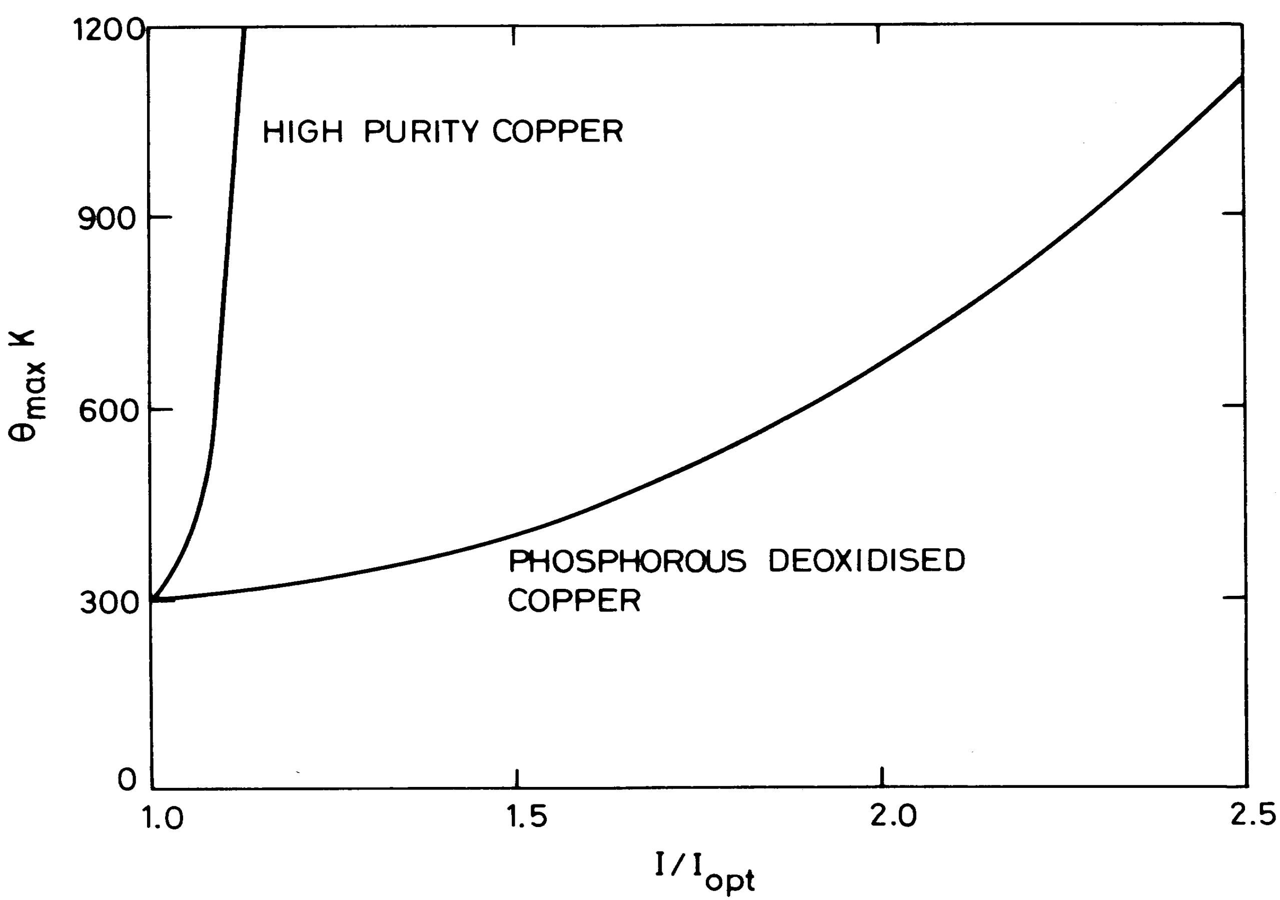
$$\left\{\frac{L}{A}\right\}_{optimum} = \frac{2.6x10^7}{I}$$

L = length, A = area of cross section, A = area

  - 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

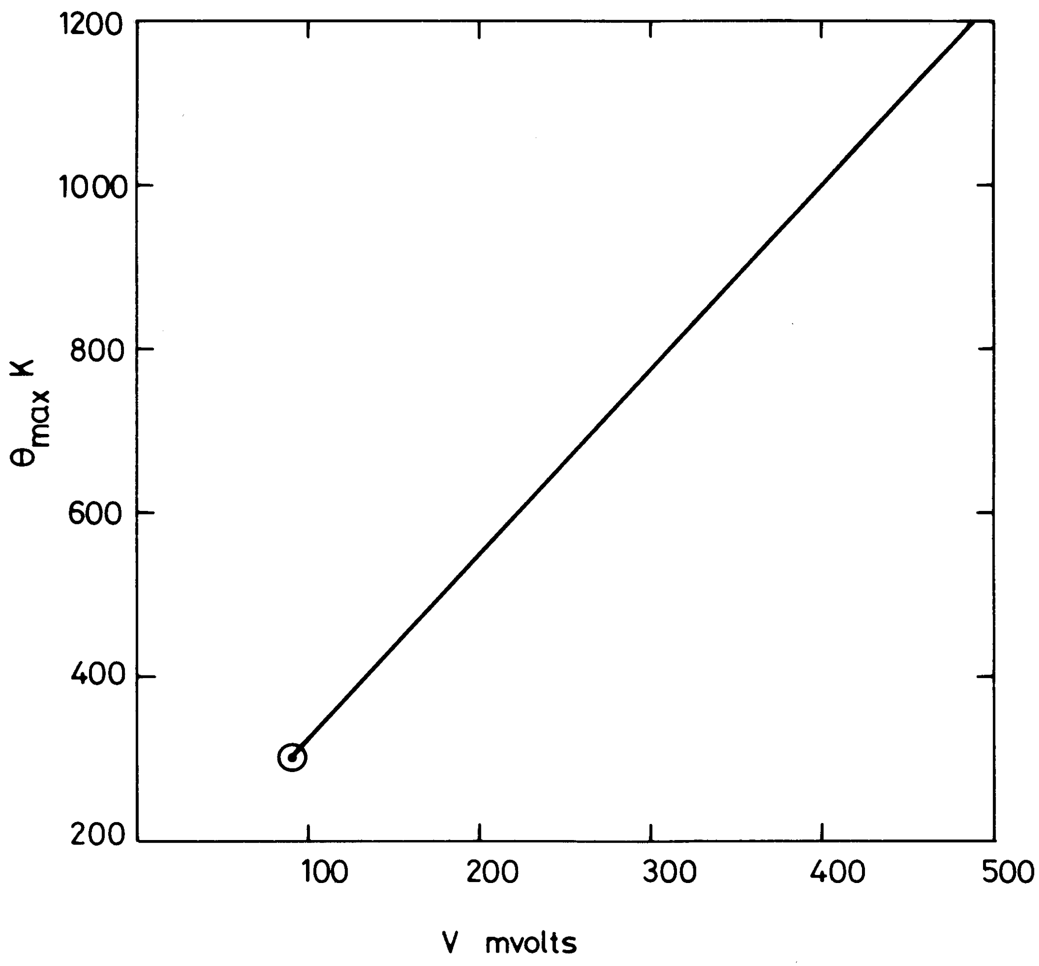


- for an optimized lead, the maximum temperature is room temperature (at the top of the lead)
- when the lead is not optimized, the temperature of an intermediate region rises above room temperature
- the optimum for pure metals is more sensitive than for impure metals

current lead burns out ⇒ magnet open circuit

⇒ large voltages ⇒

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
- monitor your lead and trip the power supply if it goes too high
- if a lead burns out, the resulting high voltage and arcing (magnet inductance) can be disastrous

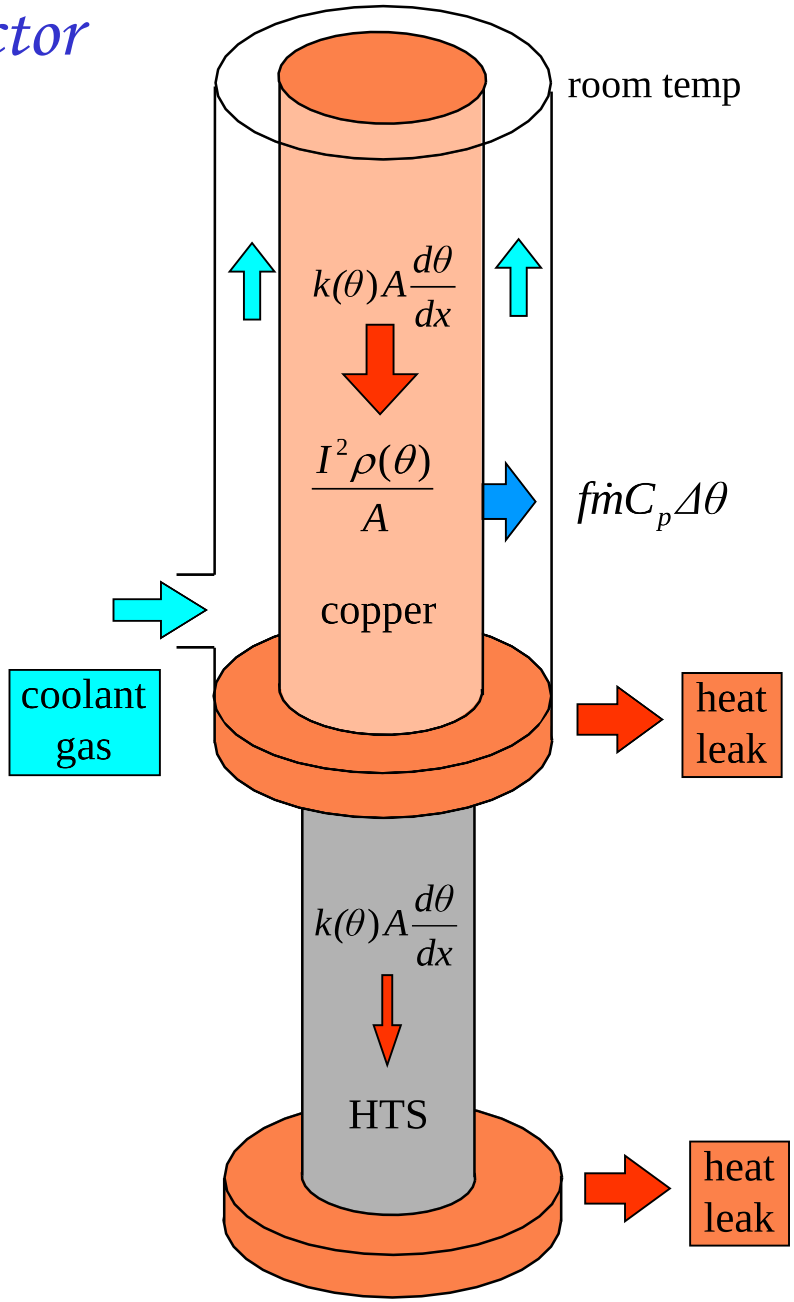
HTS High Temperature Superconductor
Current leads

- 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

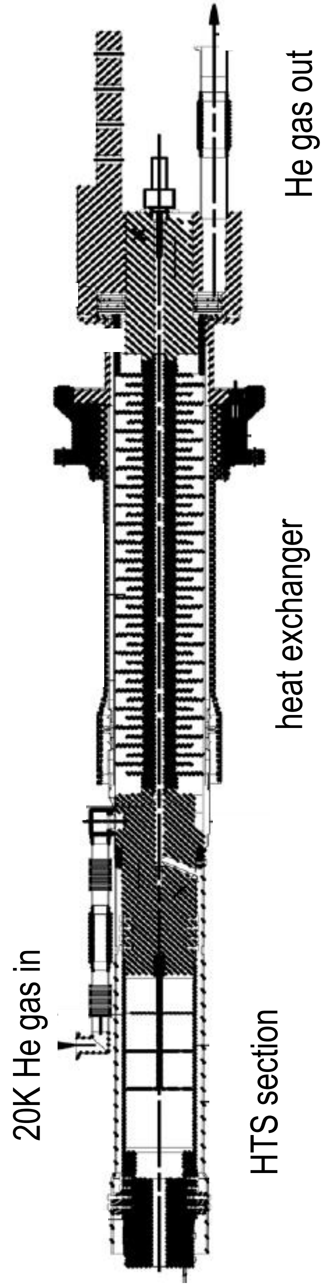
For the HTS section beware of

• overheating if it quenches

• fringe field from magnet



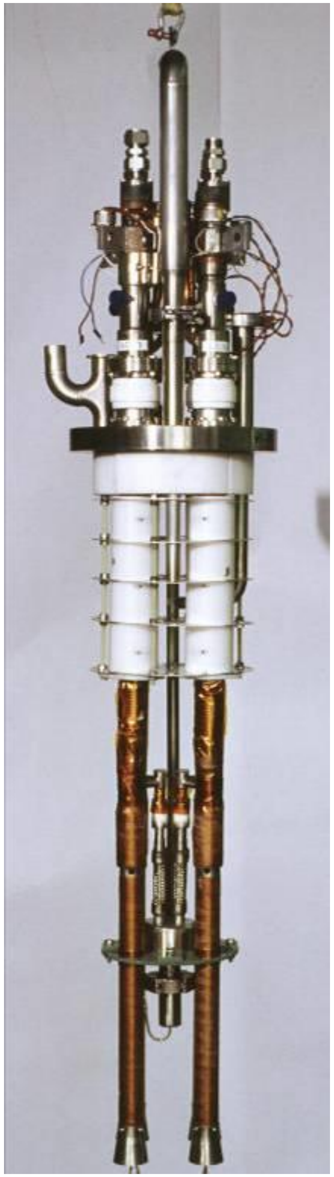
HTS current leads for LHC



- HTS materials have a low thermal conductivity
- make section of lead below ~ 70K from HTS material
- heat leak down the upper lead is similar, but it is taken at a higher temperature
  ⇒ 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

⇐13kA lead for LHC

600A lead for LHC ⇒



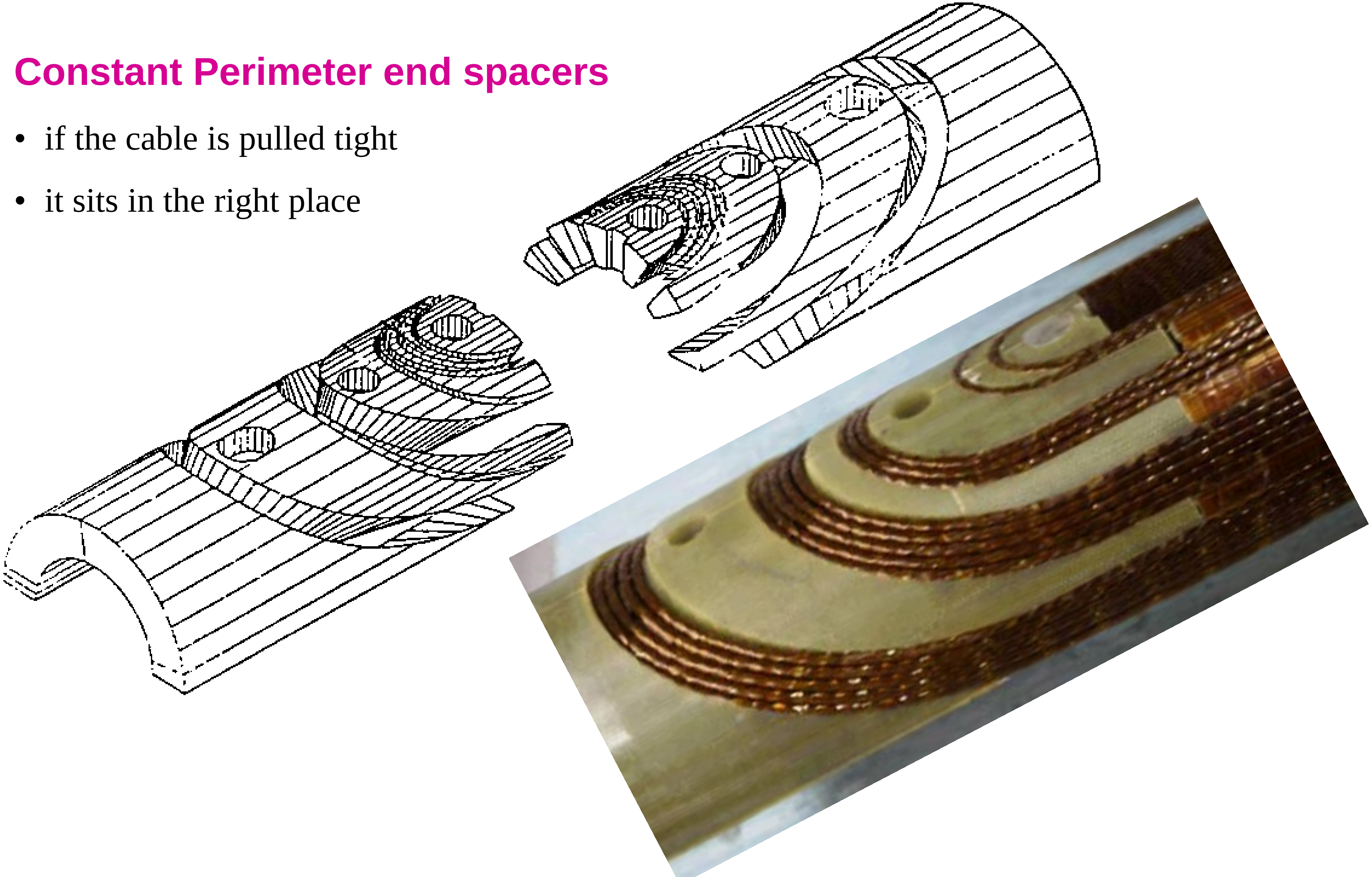
pictures from A Ballarino CERN

Winding the LHC dipoles

End turns

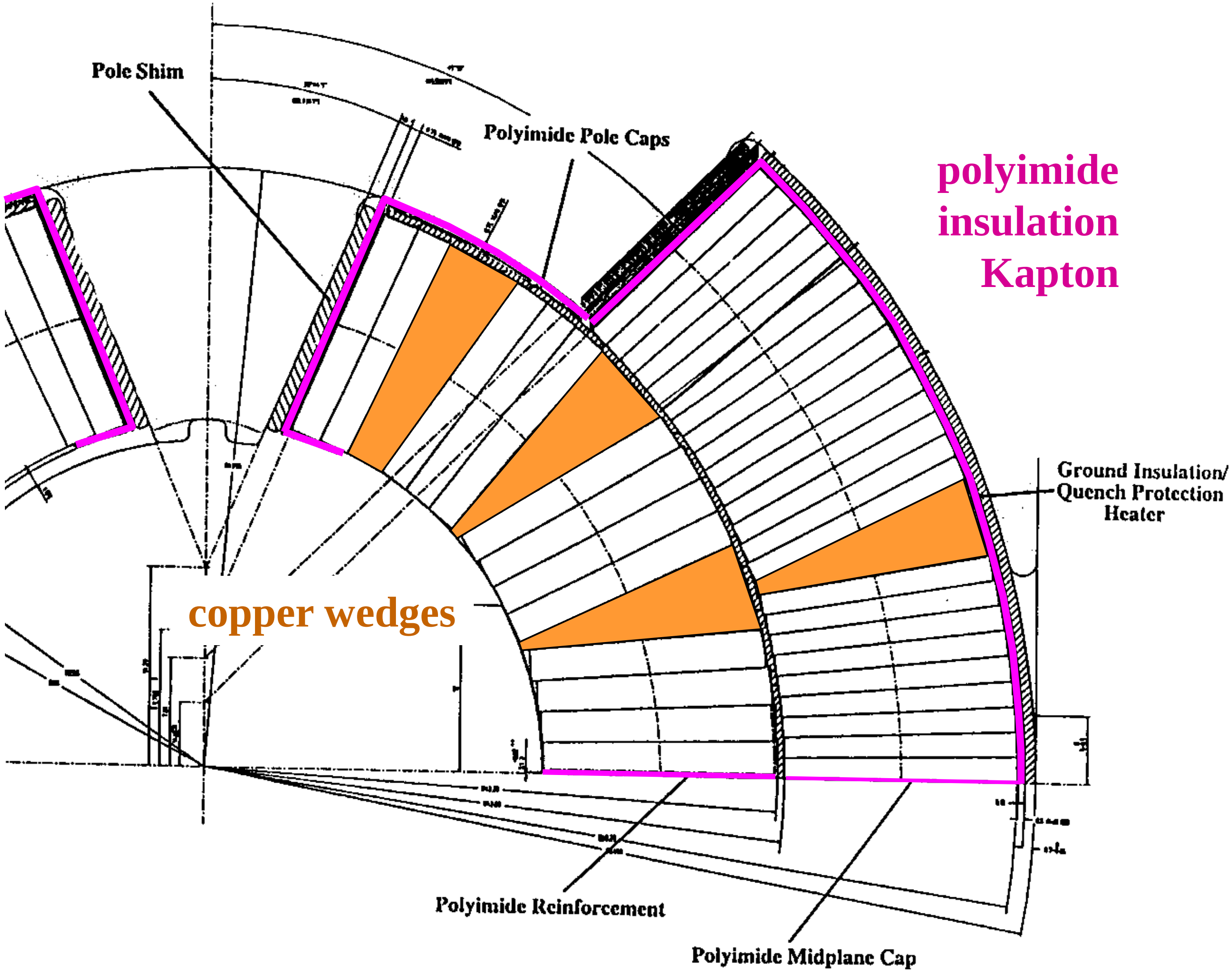
Constant Perimeter end spacers

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



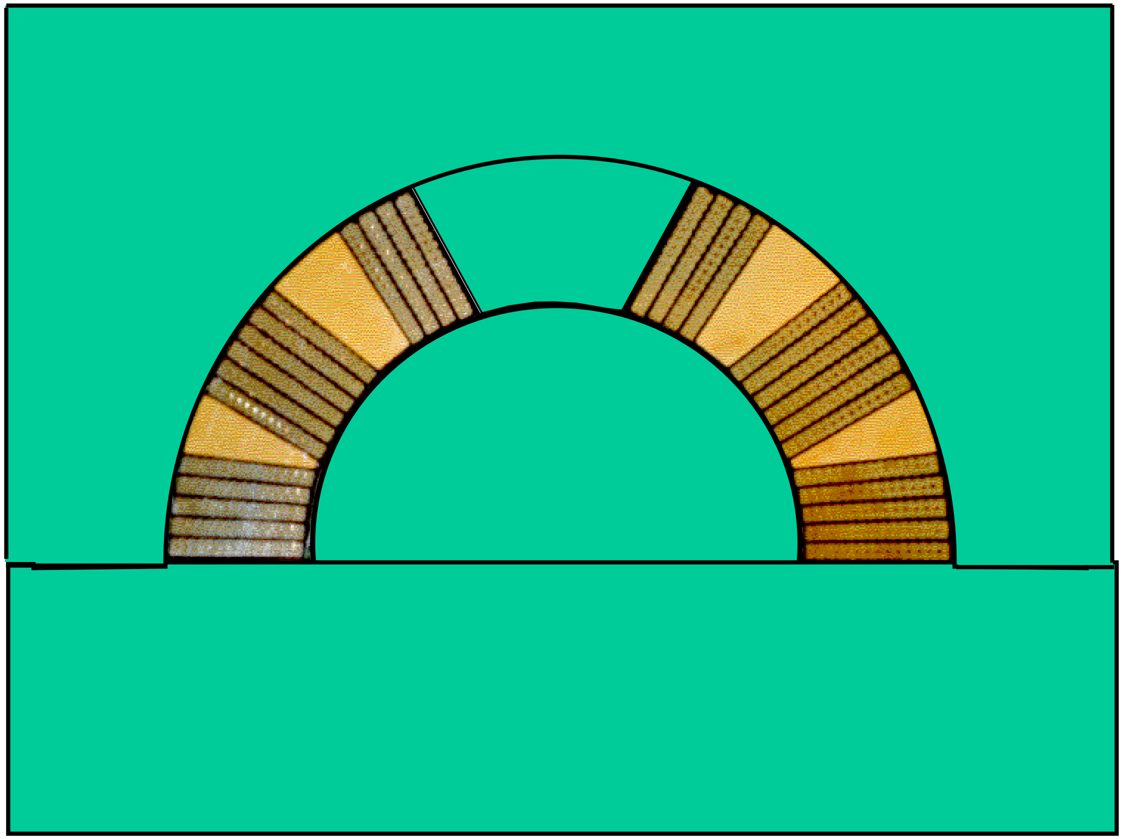
Spacers and insulation

- 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

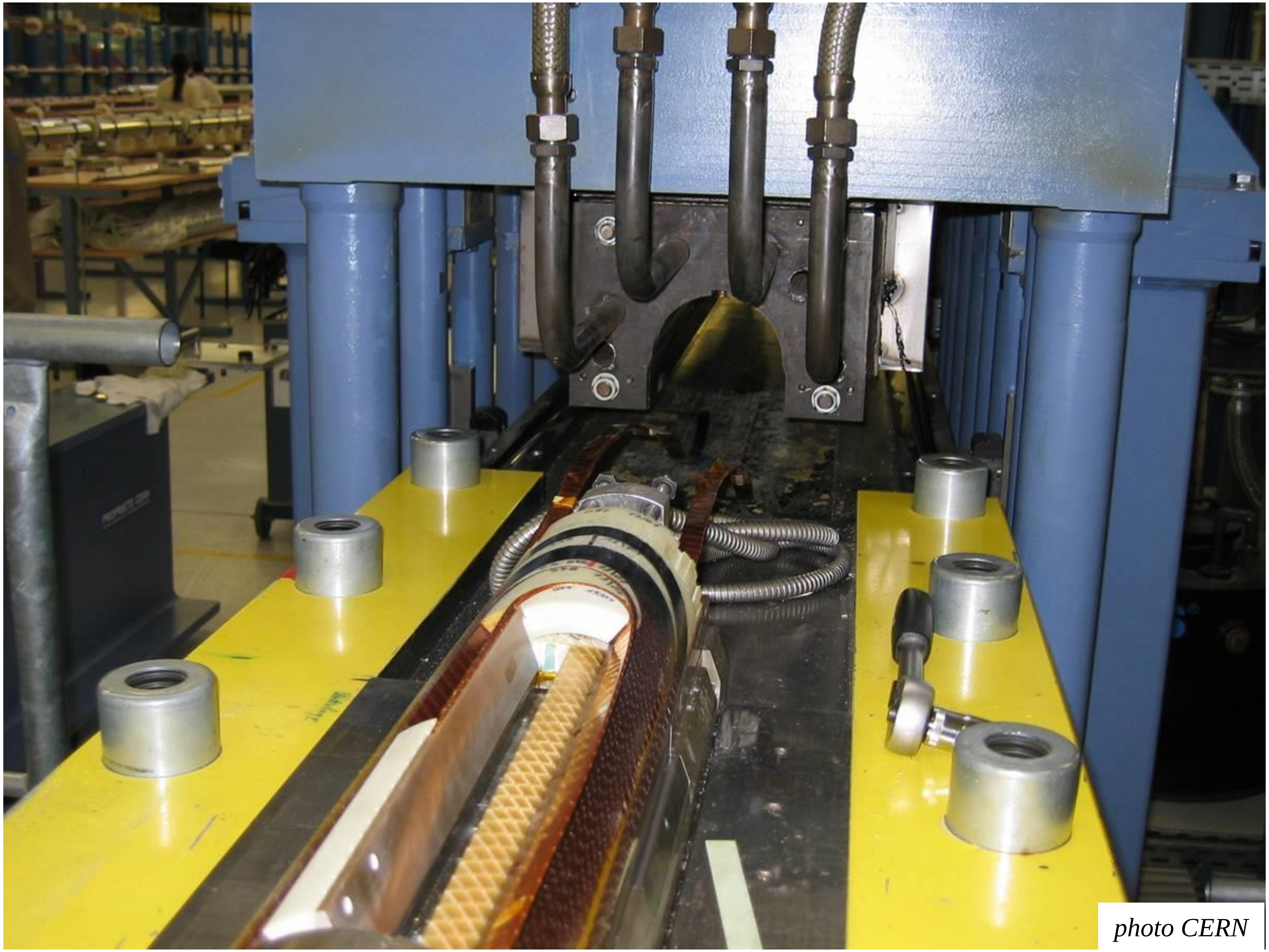


Compacting and curing

- 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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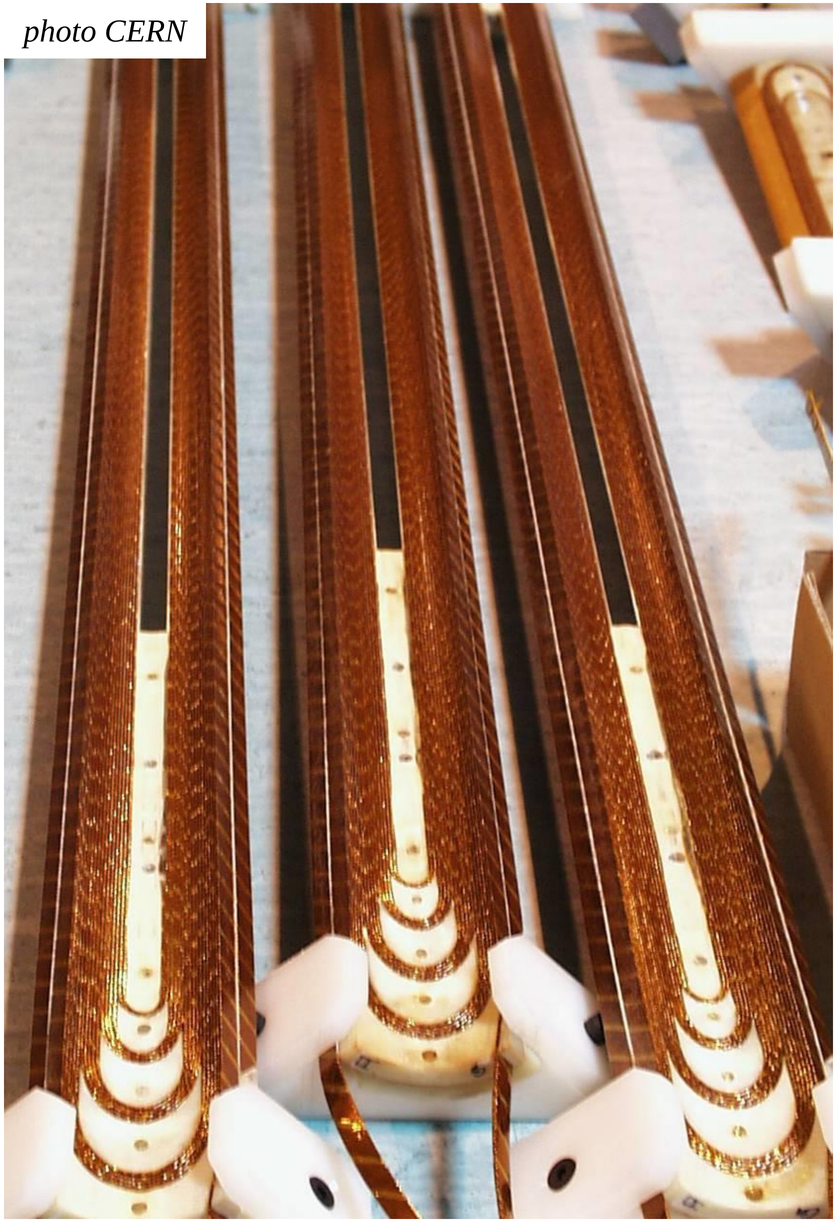
Finished coils



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

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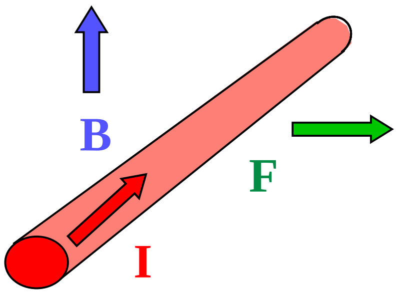
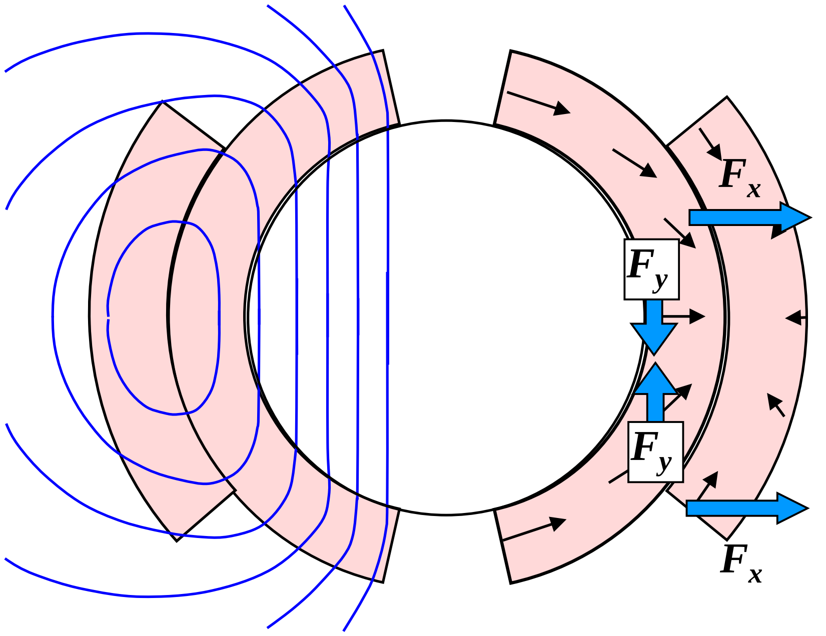
Coils for correction magnets

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 3 slide 11, 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

for thick winding take ~ mean radius

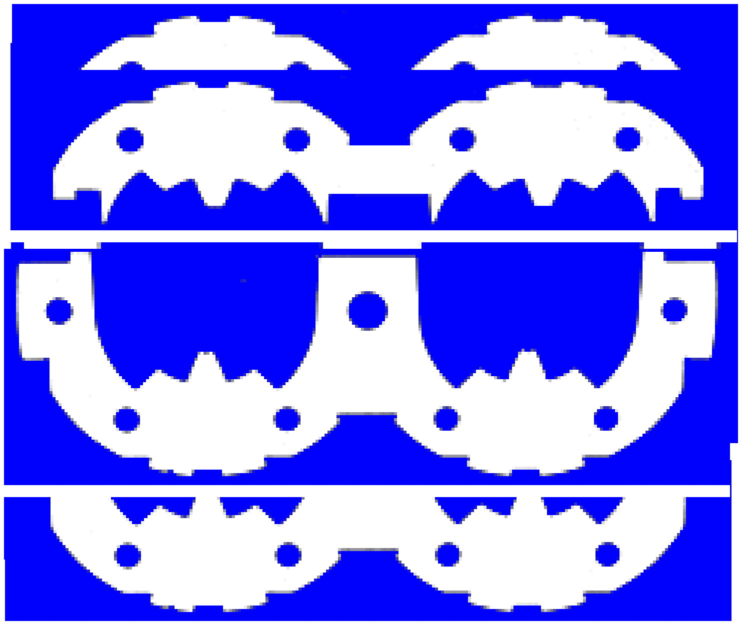
Collars

Question: how to make a force support structure that

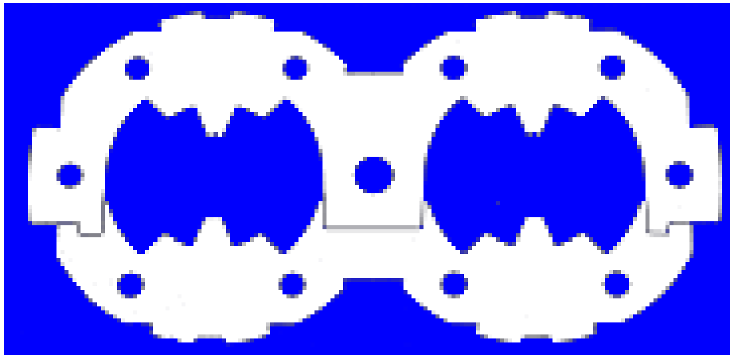
- fits tightly round the coil
- presses it into an accurate shape
- has low ac losses - laminated
- can be mass produced cheaply

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

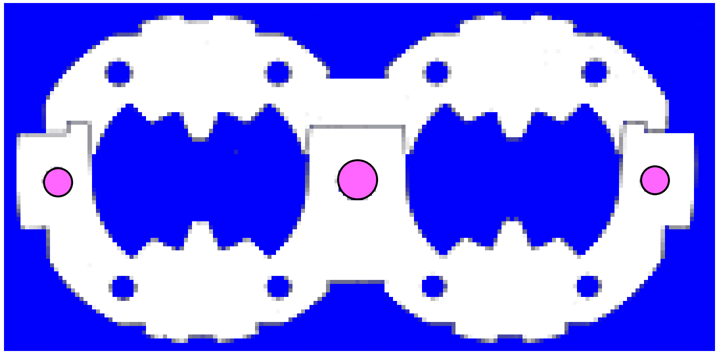
- inherited from conventional magnet laminations



press collars over coil from above and below

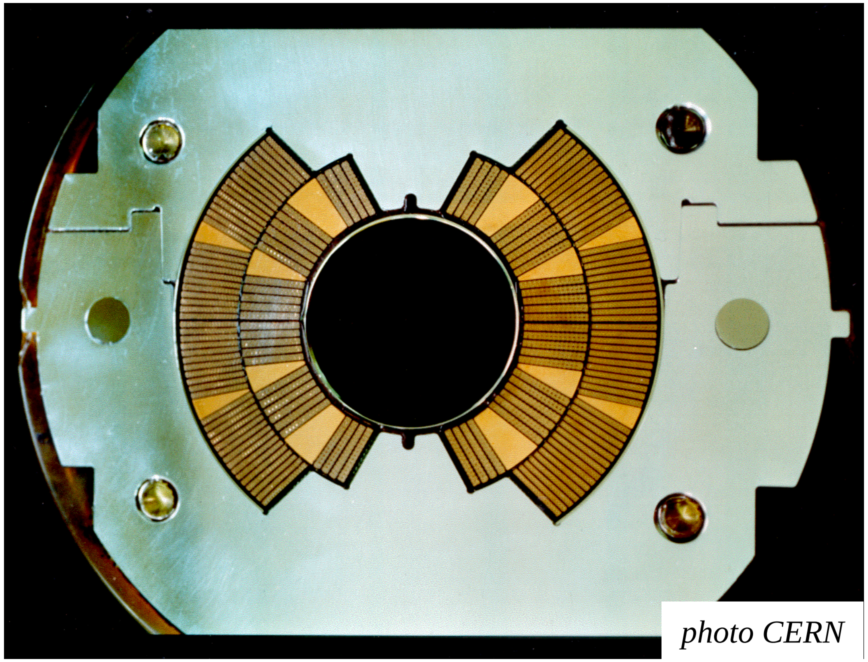


invert alternate pairs so that they interlock



push steel rods through holes to lock in position

Collars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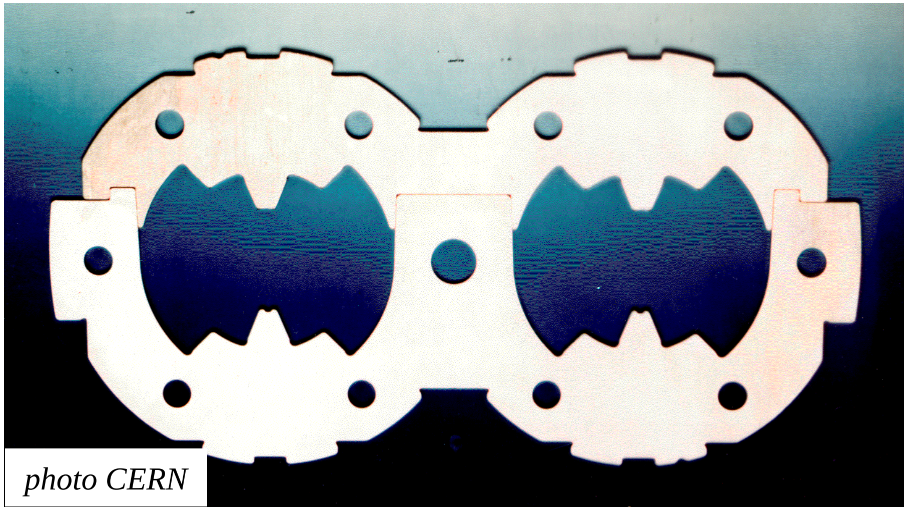
LHC dipole collars support the twin aperture coils in a single unit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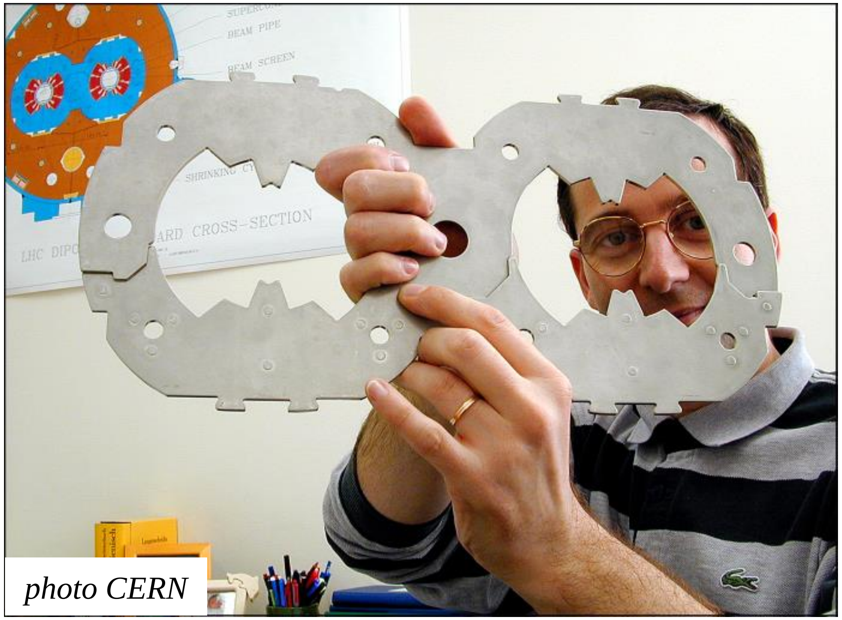
12 million produced for LHC



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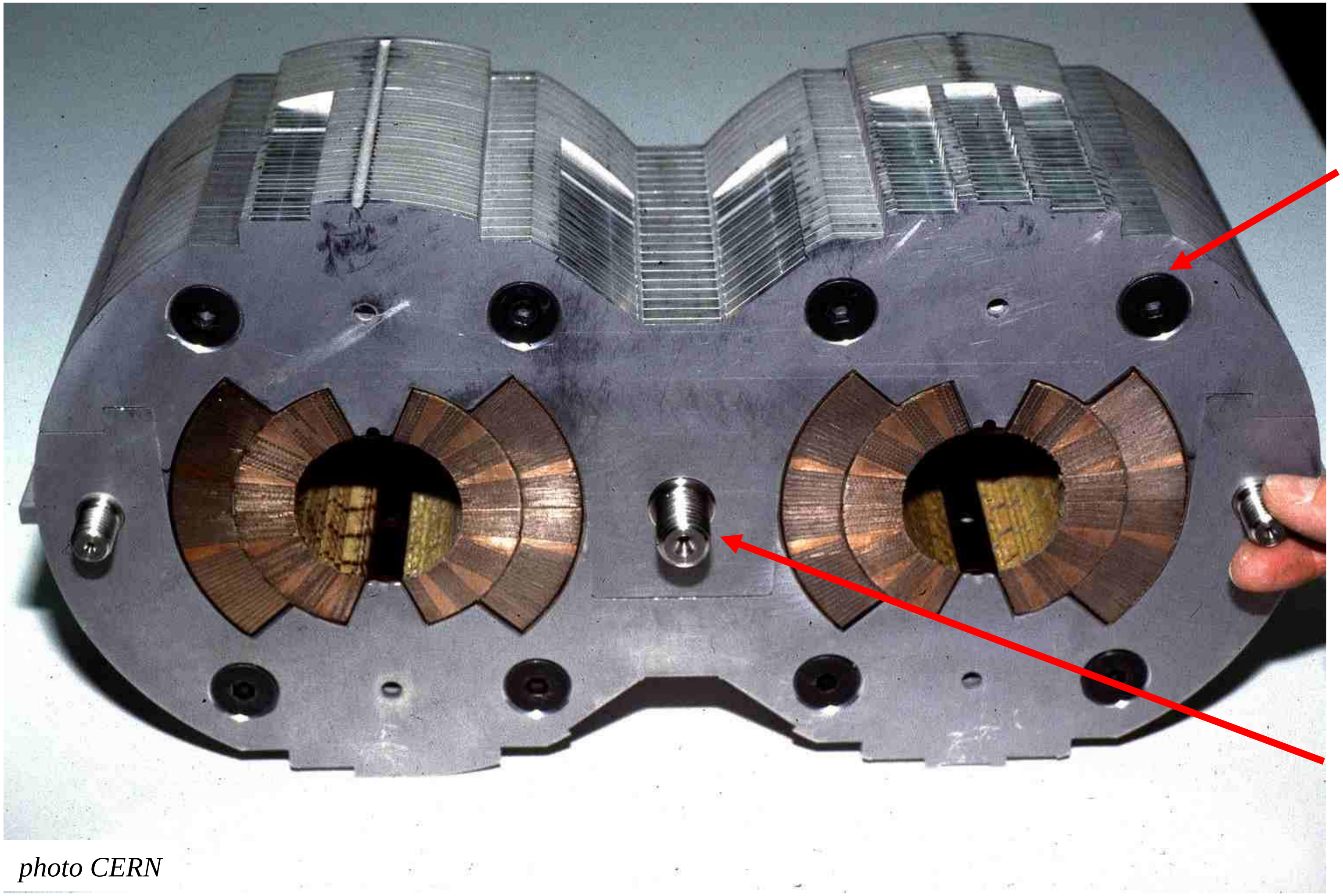
LHC dipole collars



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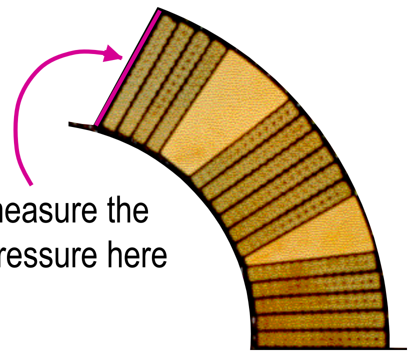
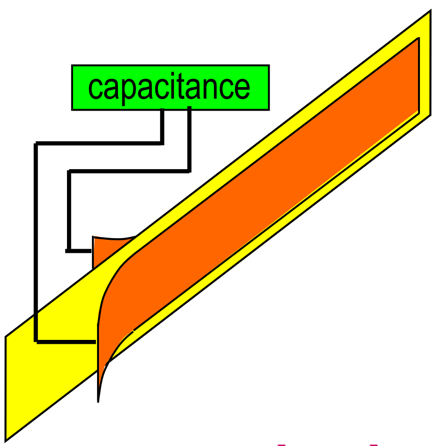
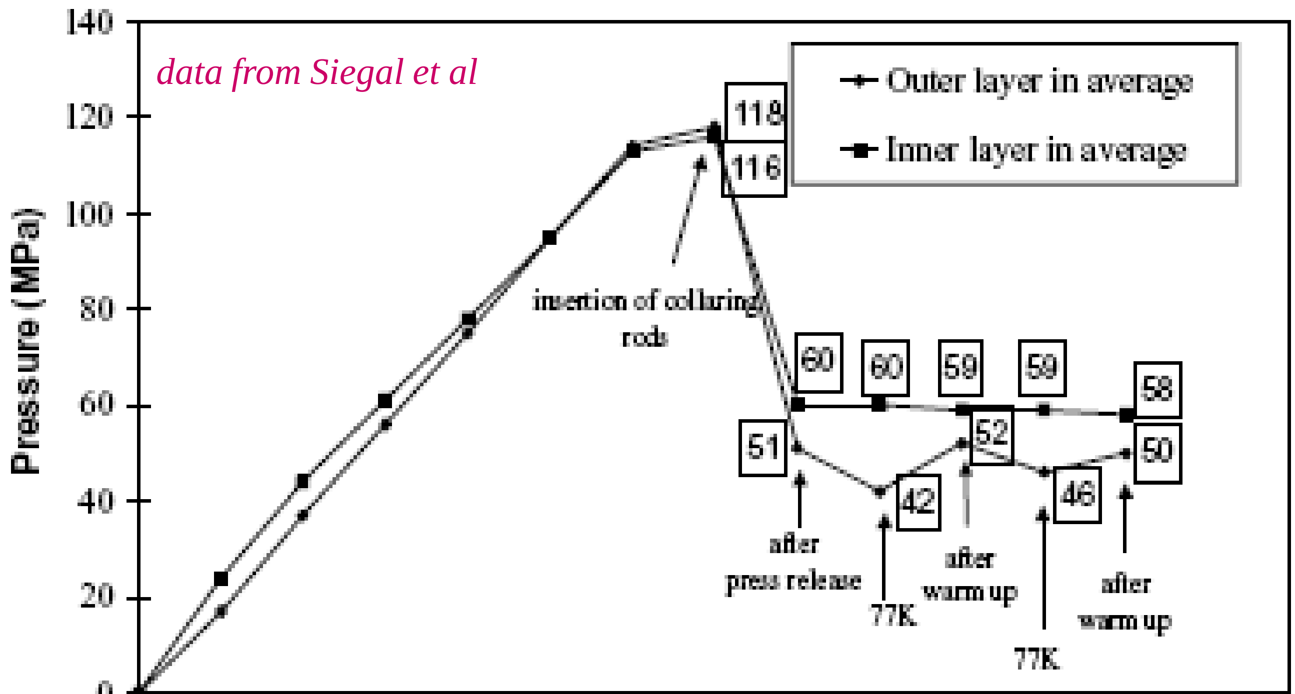
sub-units of several alternating pairs are riveted together

stainless rods lock the sub-units together

Pre-loading the coil





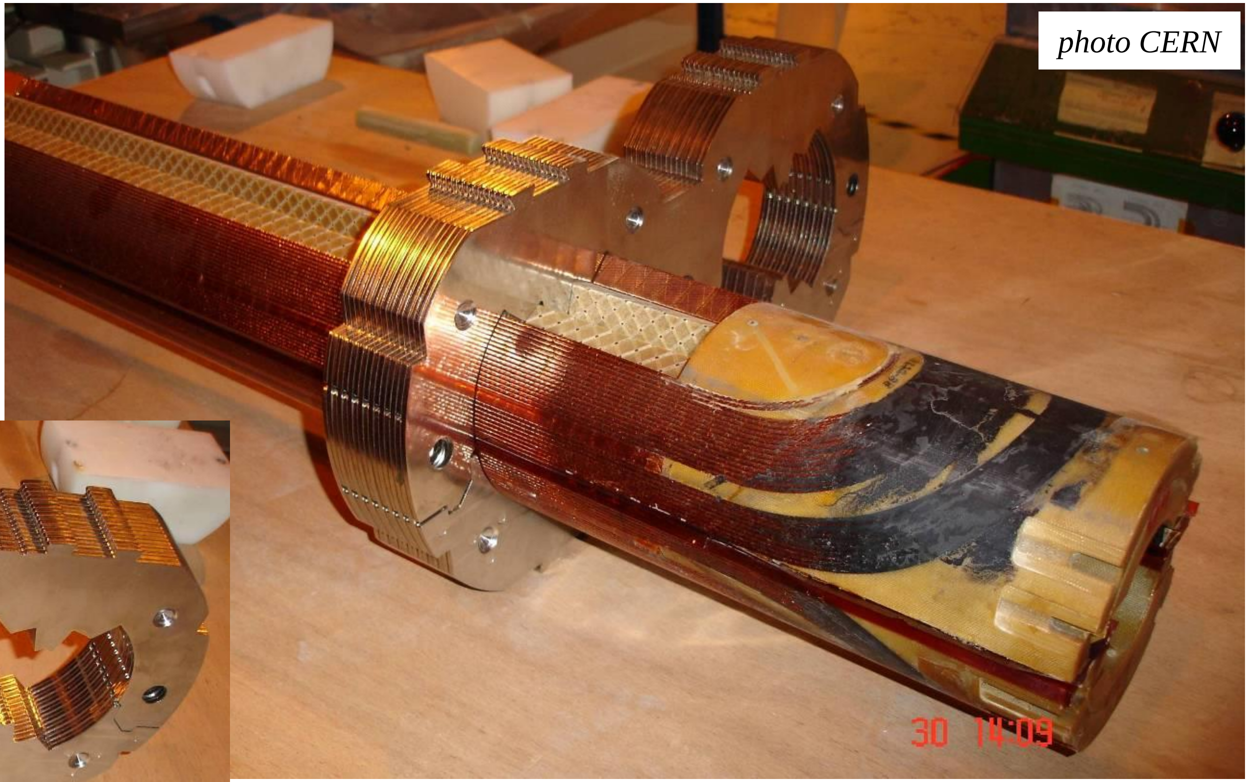


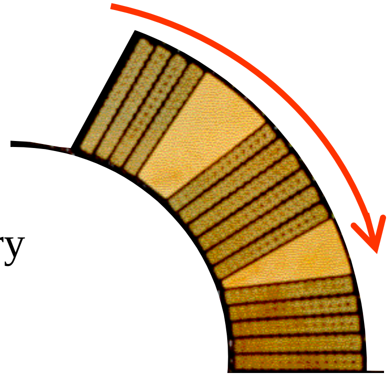
CERN data during manufacture and operation

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)

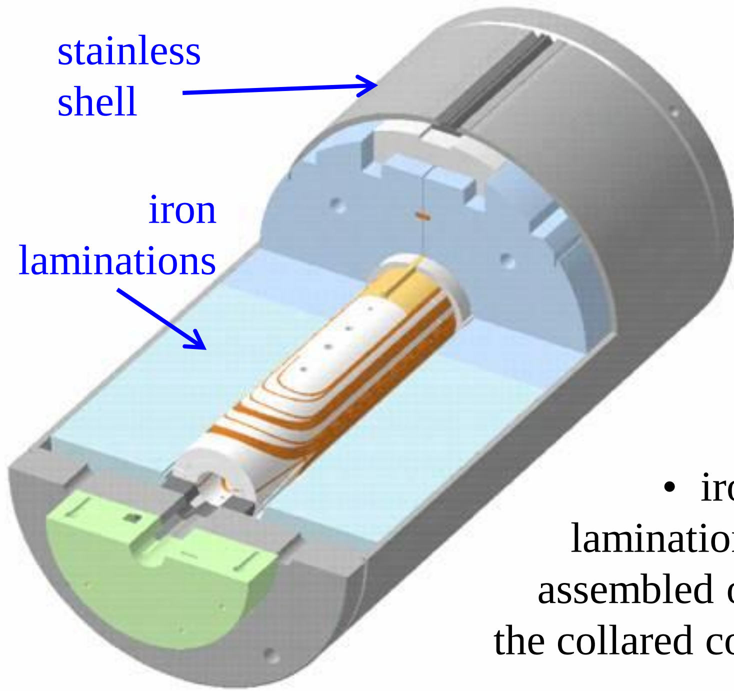




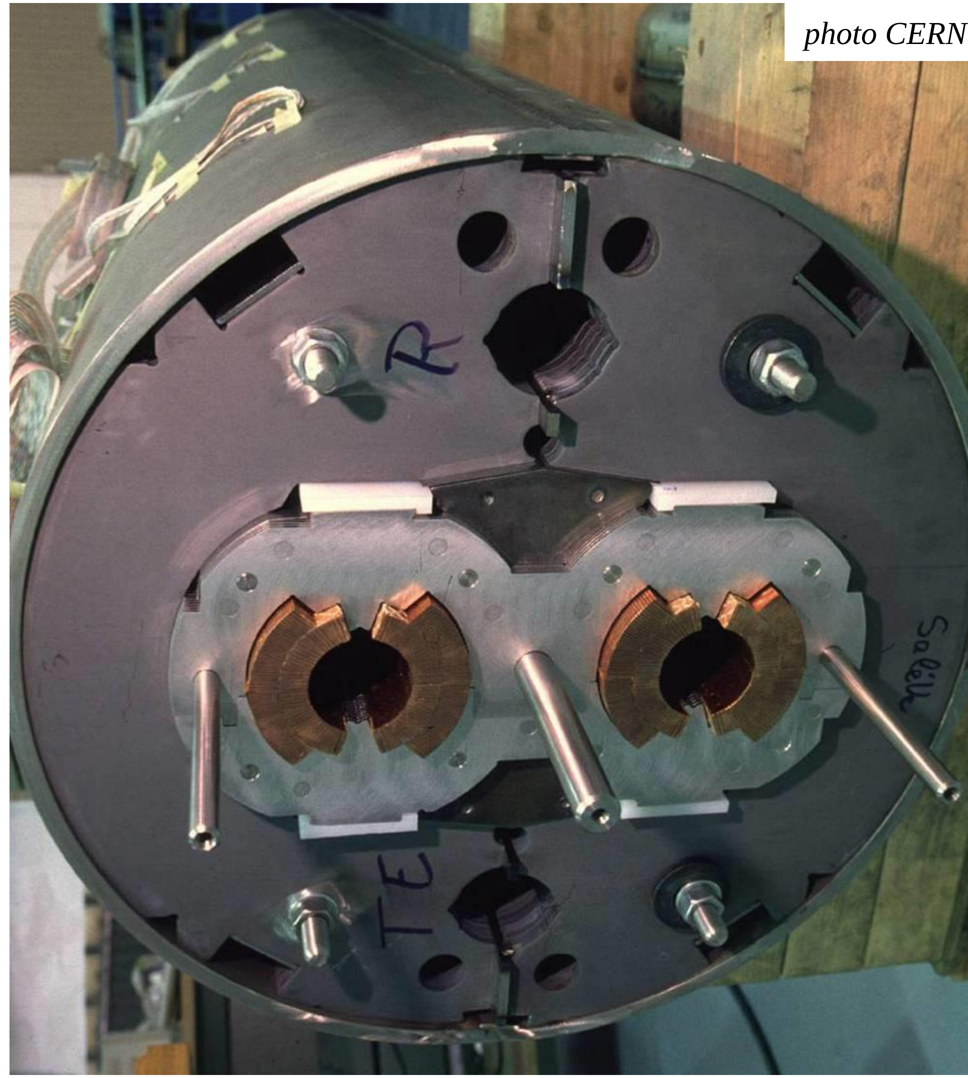
- sliding at the outer boundary
  ⇒ friction heating

- use kapton layers

Adding the iron



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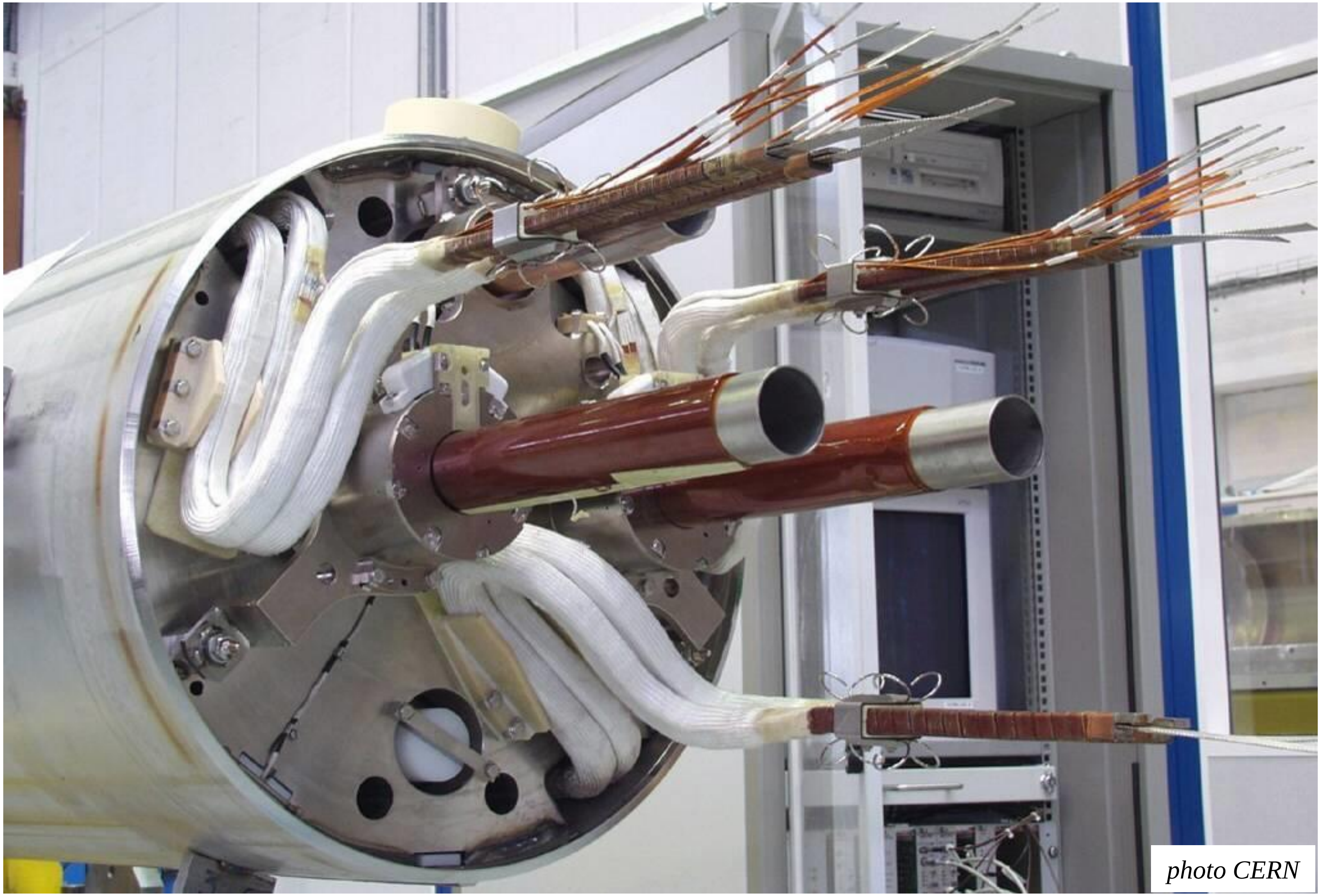
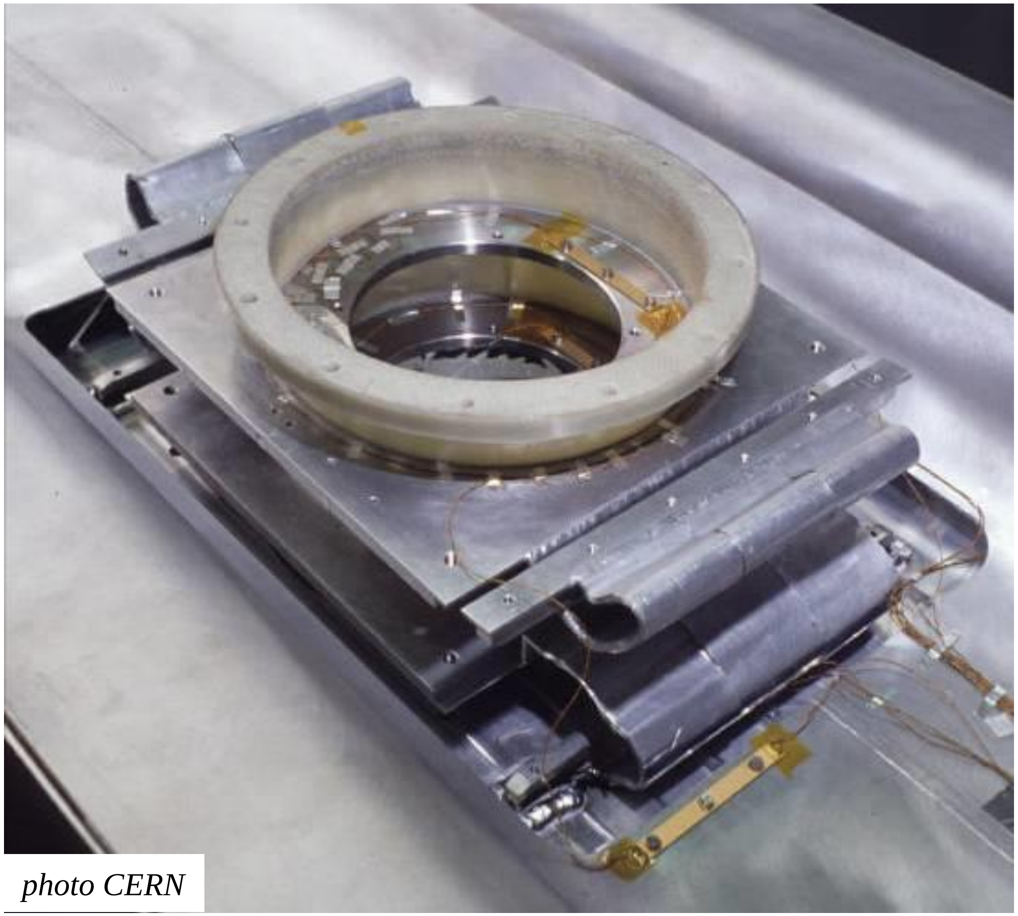
- pushed into place using the collaring press
- **BUT** pure iron becomes brittle at low temperature
- tensile forces are therefore taken by a stainless steel shell which is welded around the iron, while still in the press
- stainless shell also serves as the helium vessel

Compressing and welding the outer shell

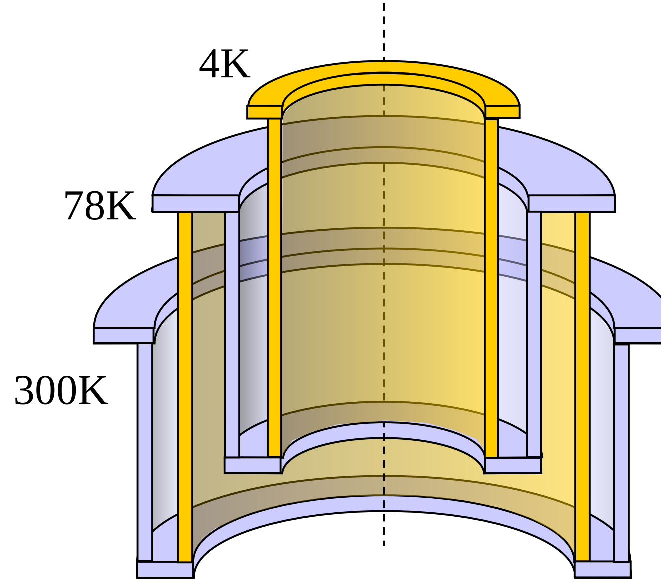
Dipole inside its stainless shell



Cryogenic supports



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



the Heim column

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

Complete magnet in cryostat


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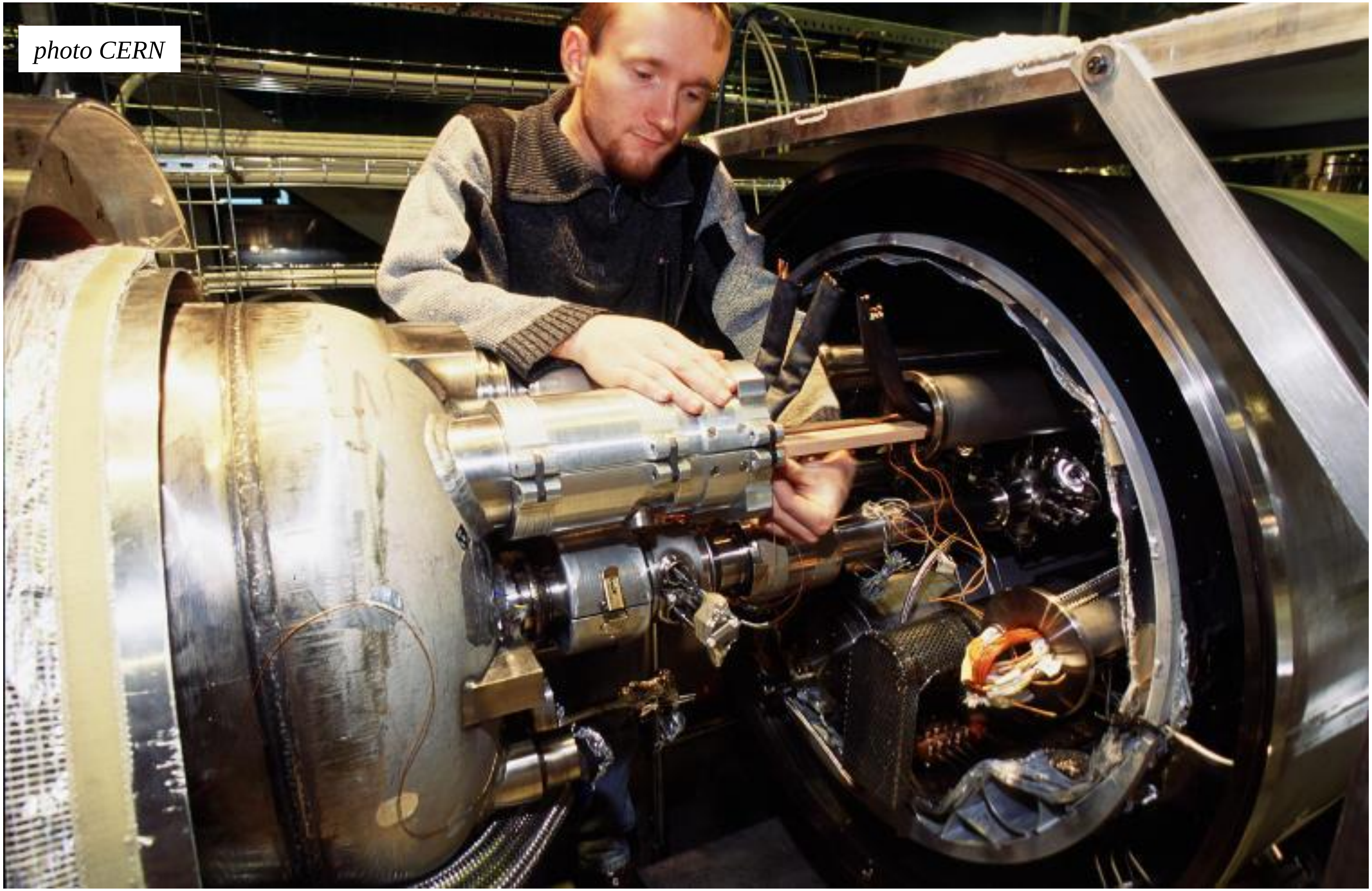
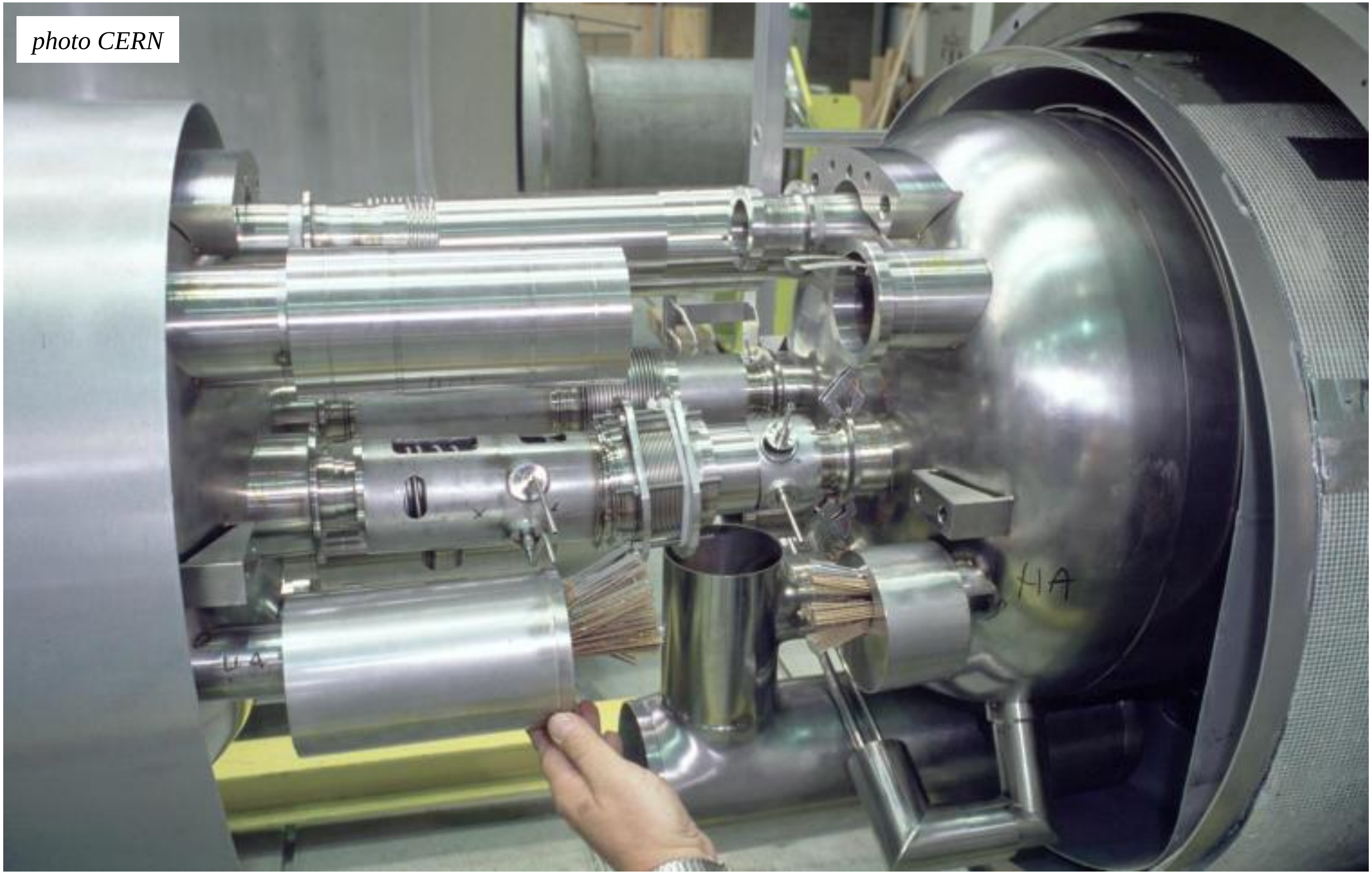
photo CERN


photo Babcock Noell

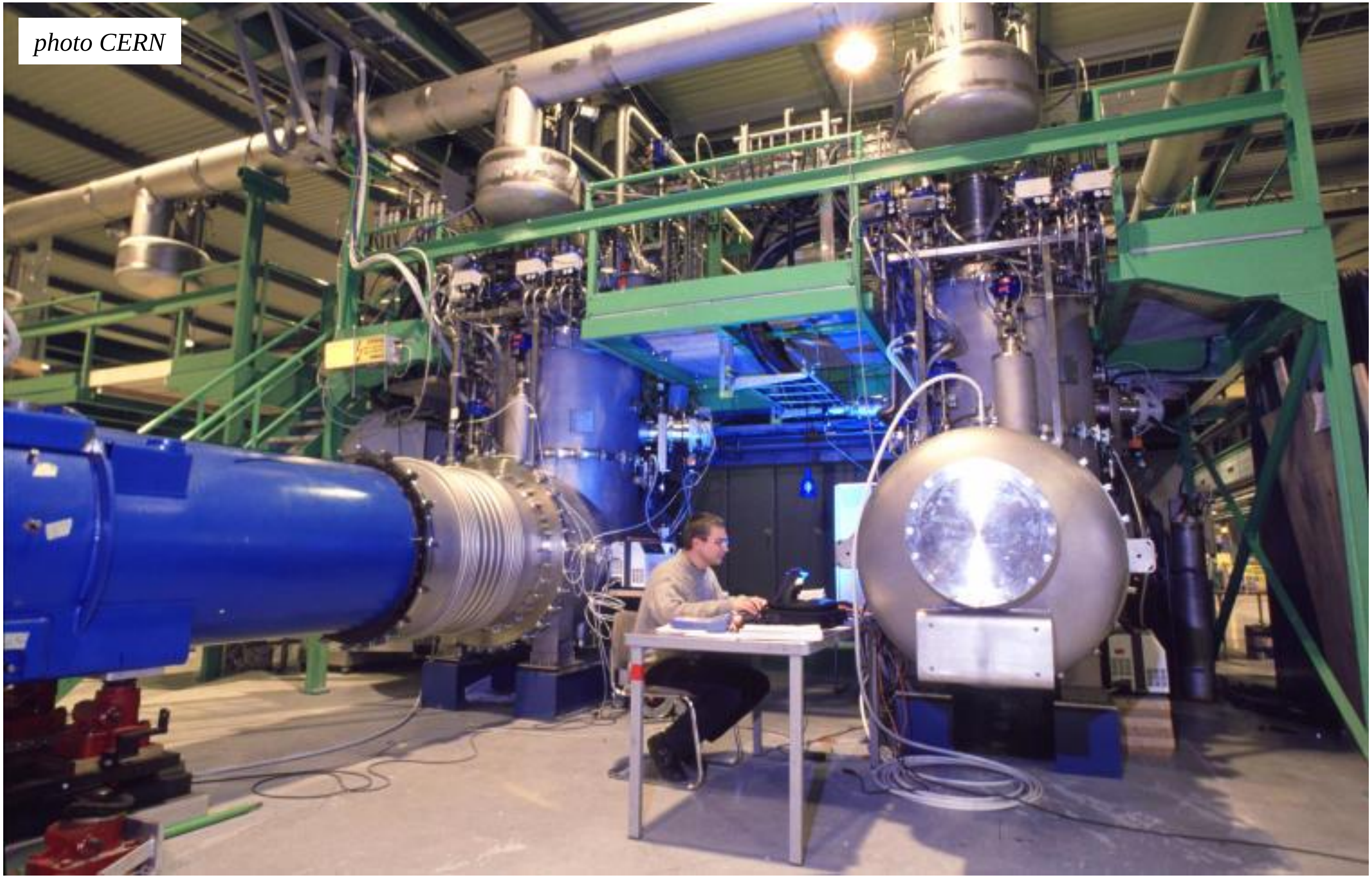
Make the interconnections - electrical



Make interconnections - cryogenic



Connect to the cryogenic feed and current leads



Fermilab Tevatron

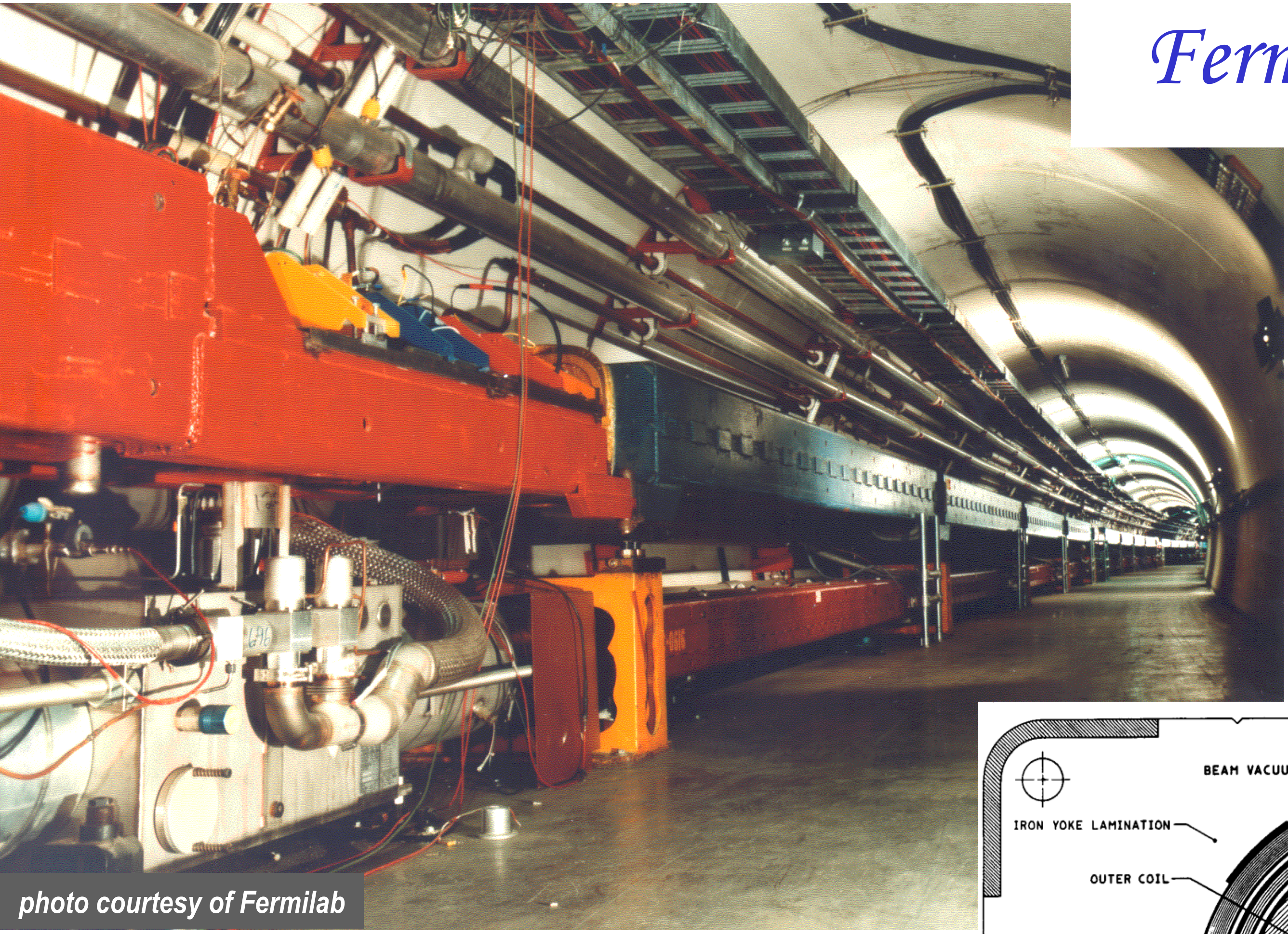
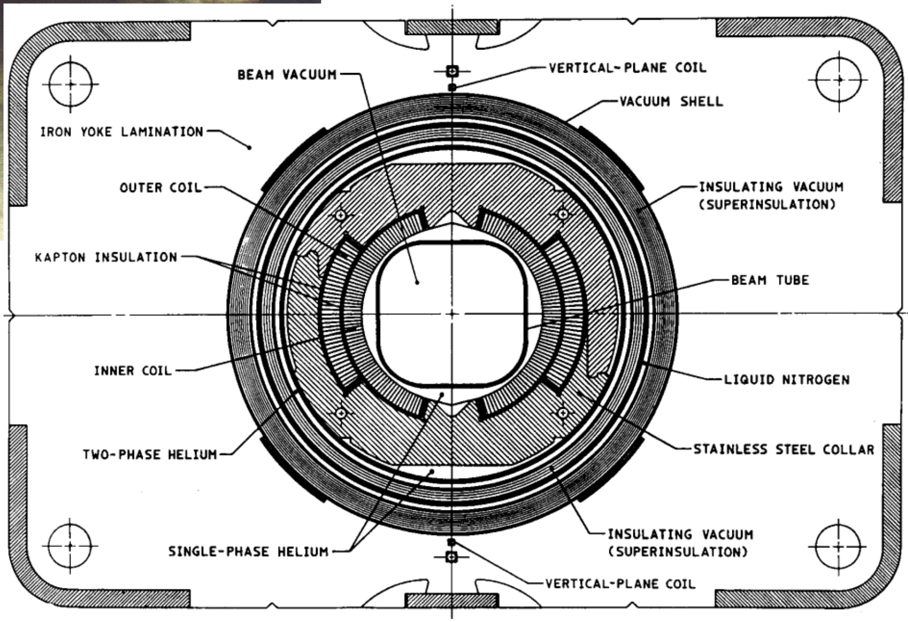
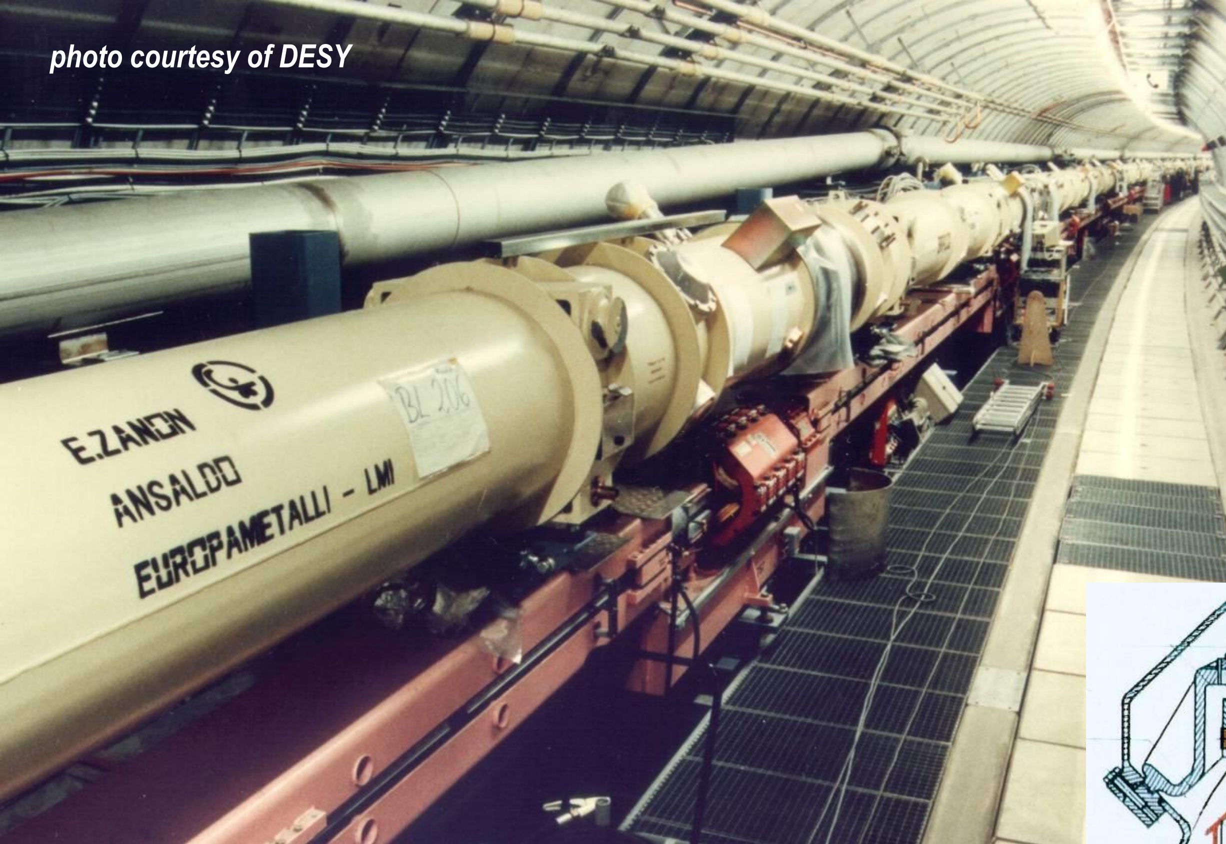


photo courtesy of Fermilab

the world's first superconducting accelerator

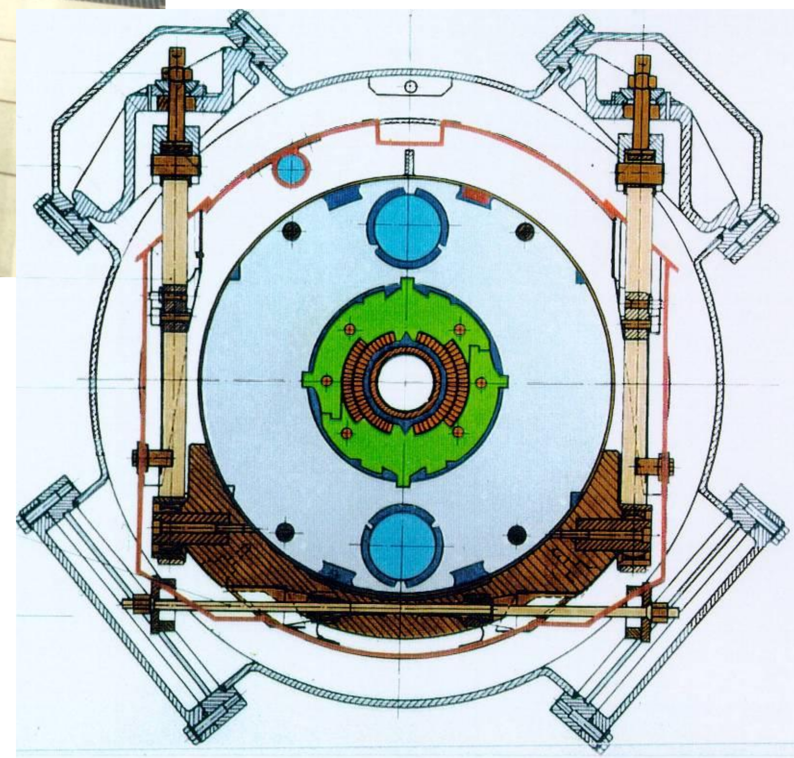


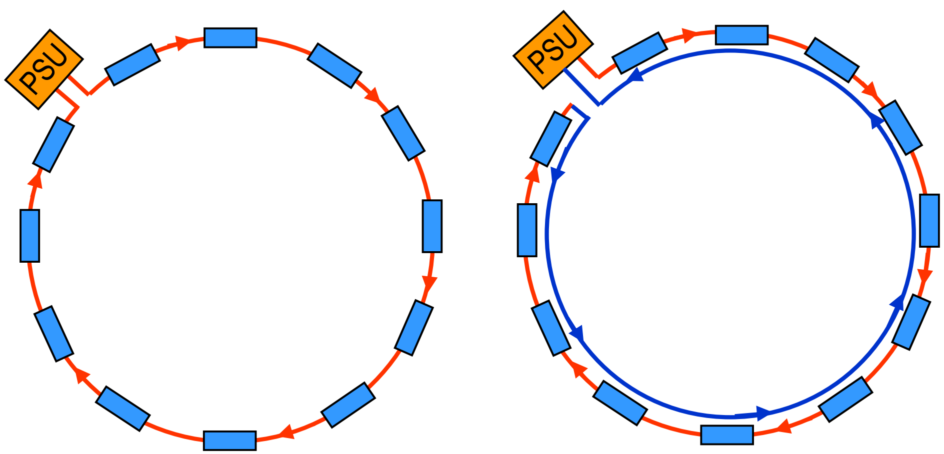
- Rutherford cable
- porous winding
- force supporting collars
- warm iron



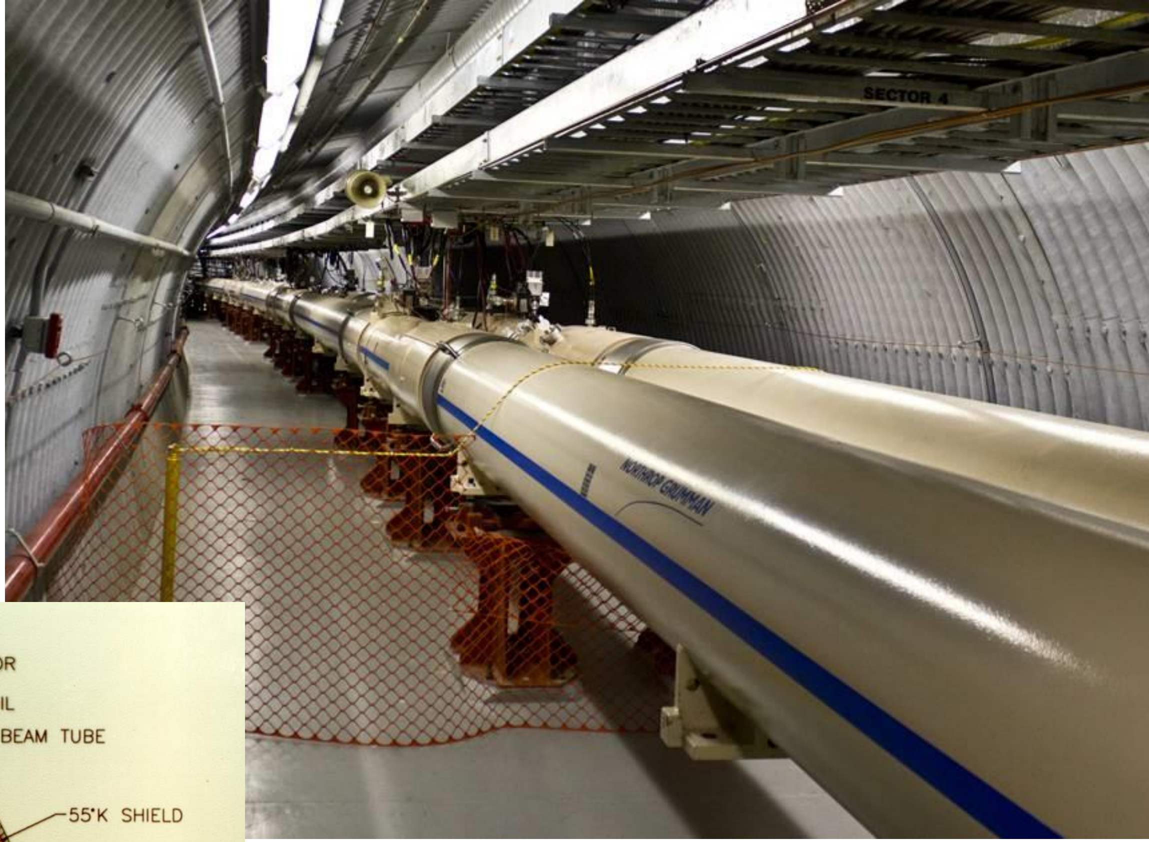
DESY Hera

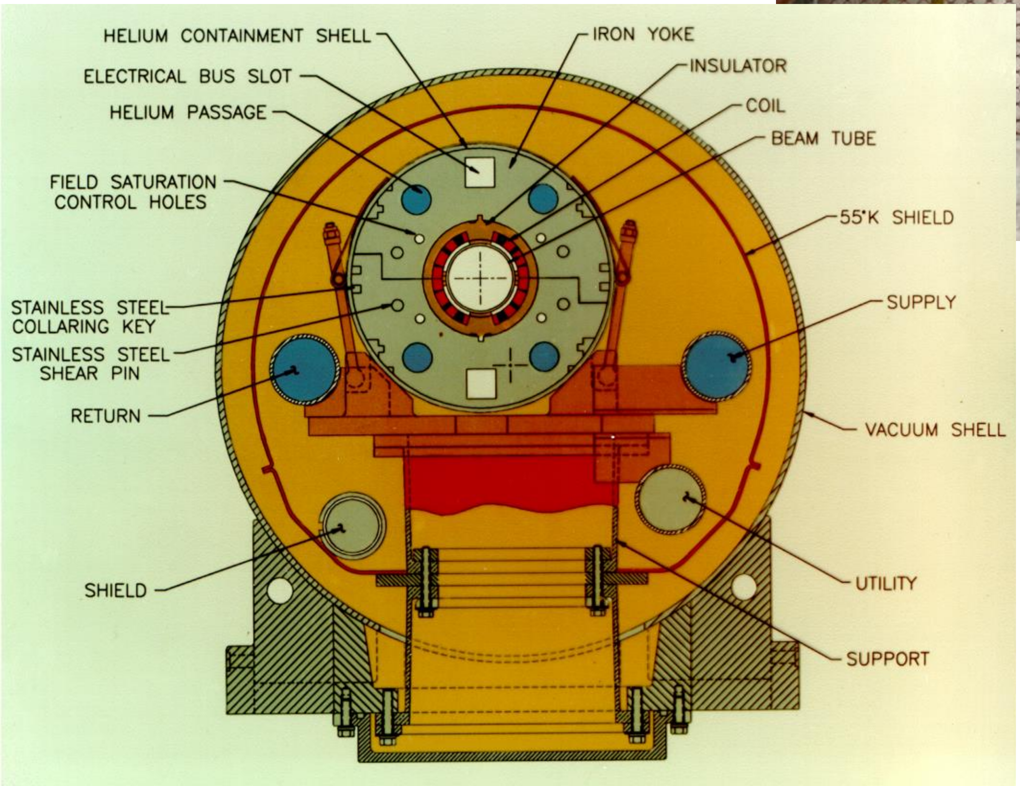
- Rutherford cable
- porous winding
- force supporting collars
- cold iron

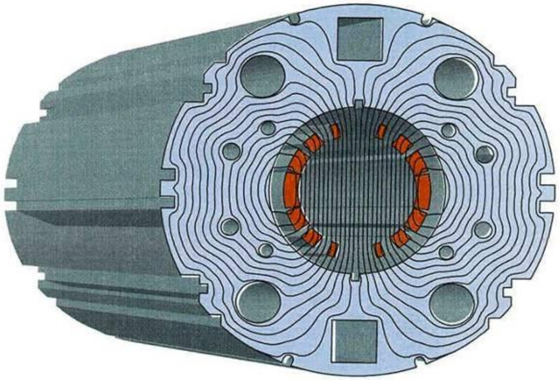




RHIC: Relativistic Heavy Ion Collider







photos BNL

CERN LHC

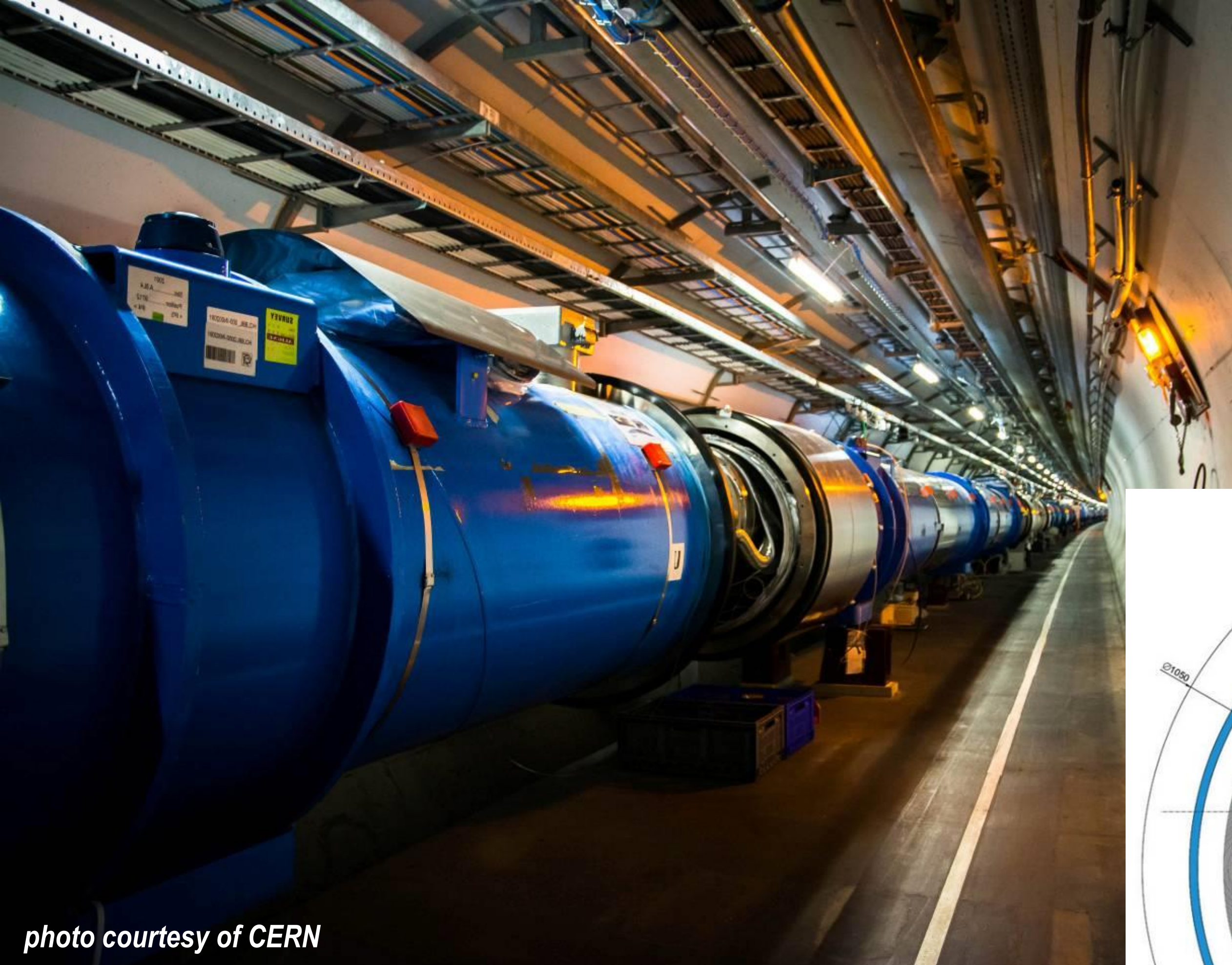
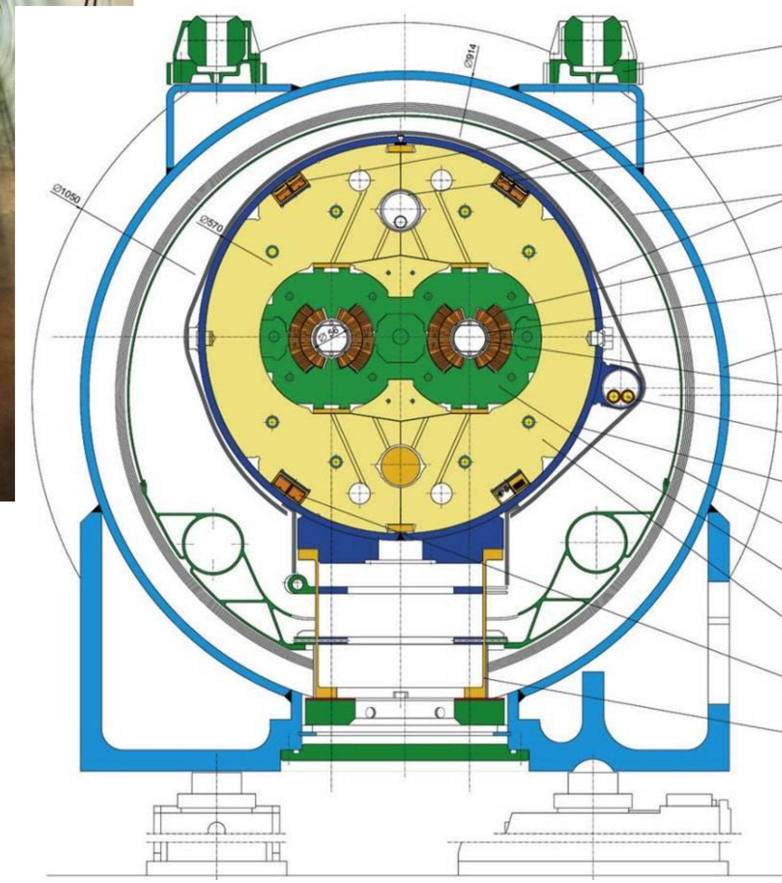
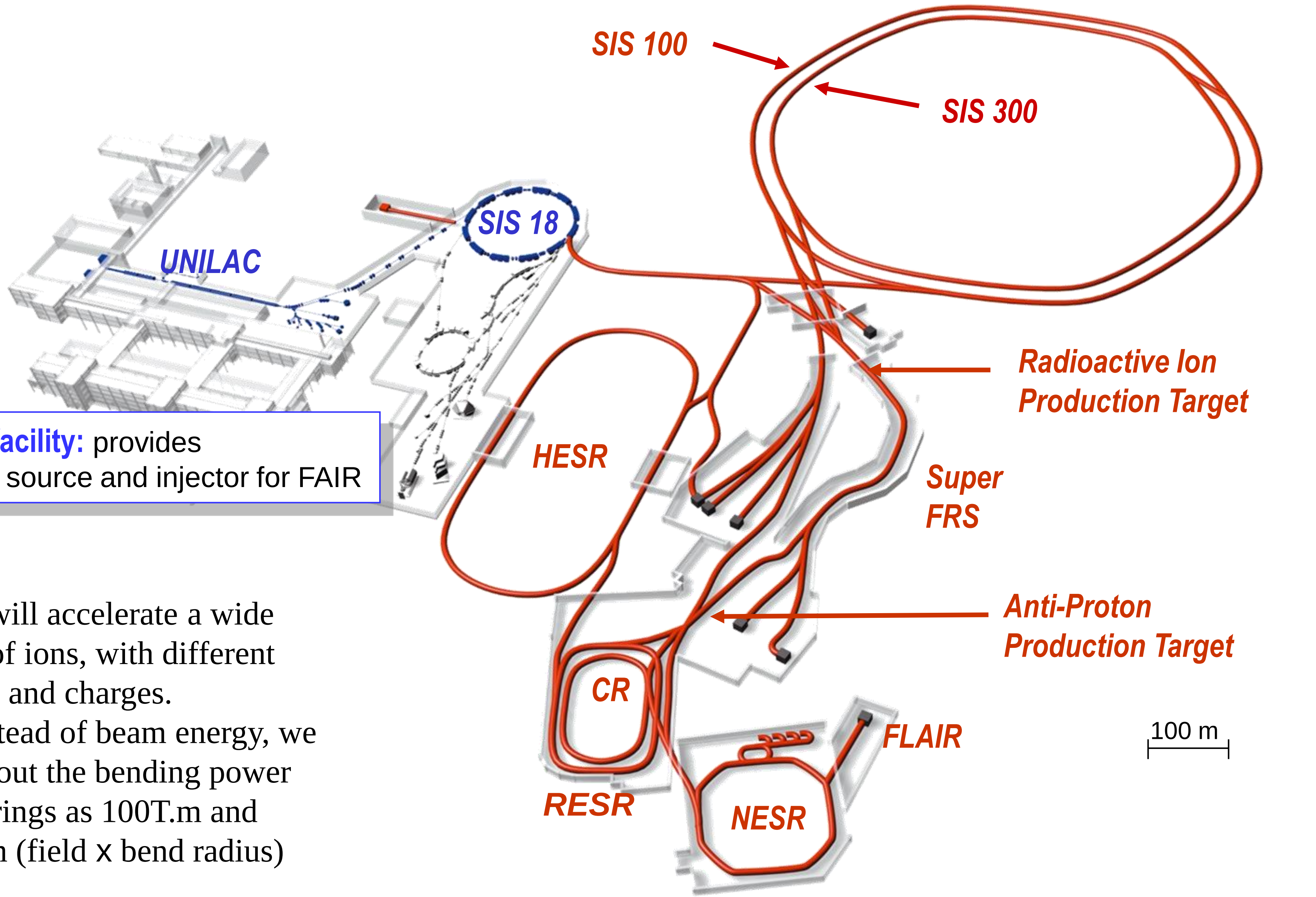


photo courtesy of CERN



- Rutherford cable
- porous winding and He 2
- force supporting collars and cold iron
- two coils in one structure

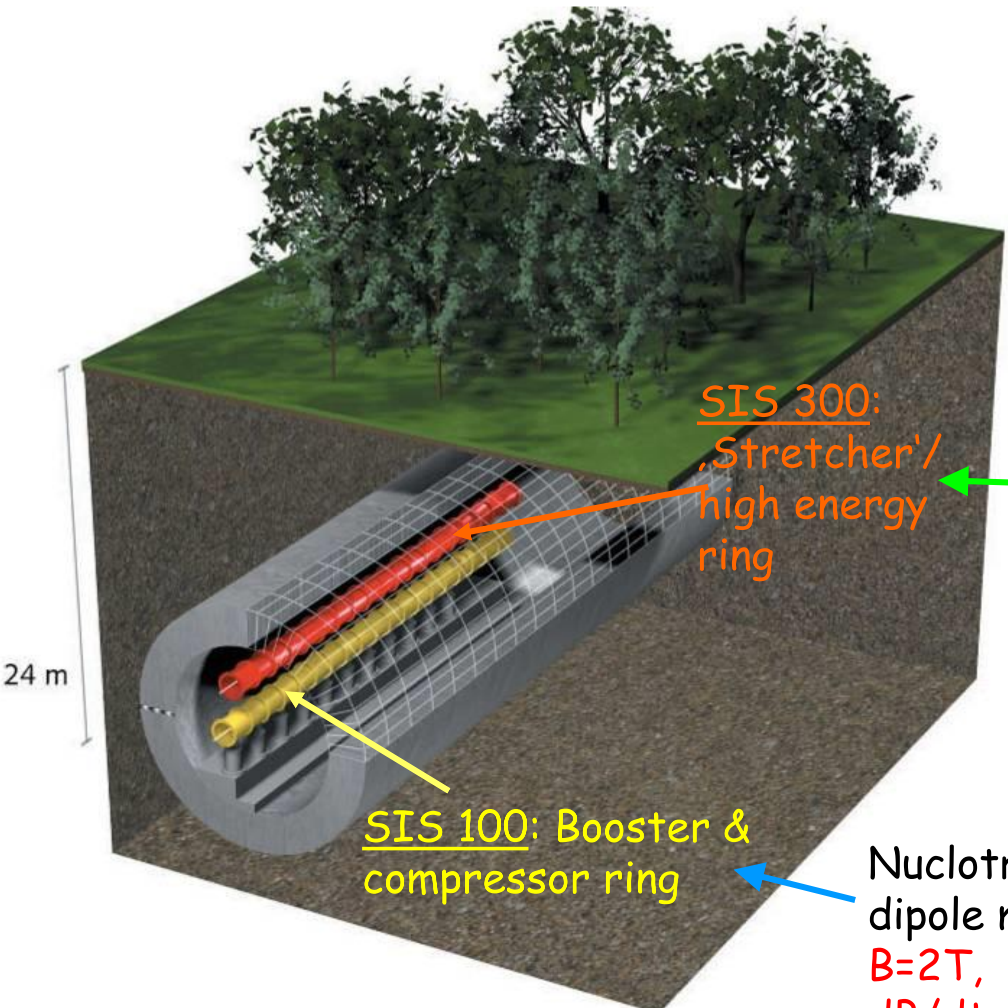
Facility for Antiproton and ion research FAIR

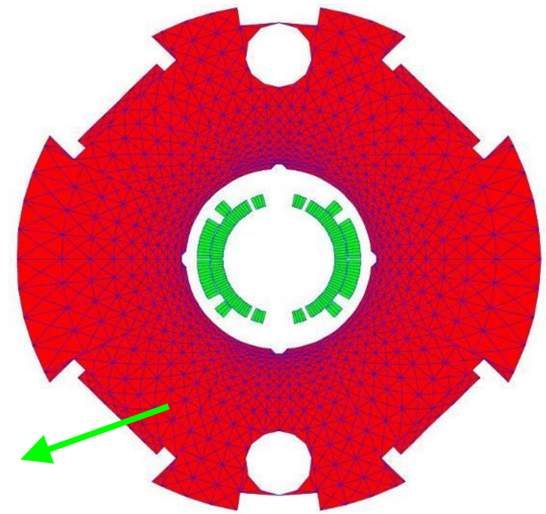


Existing facility: provides
ion-beam source and injector for FAIR

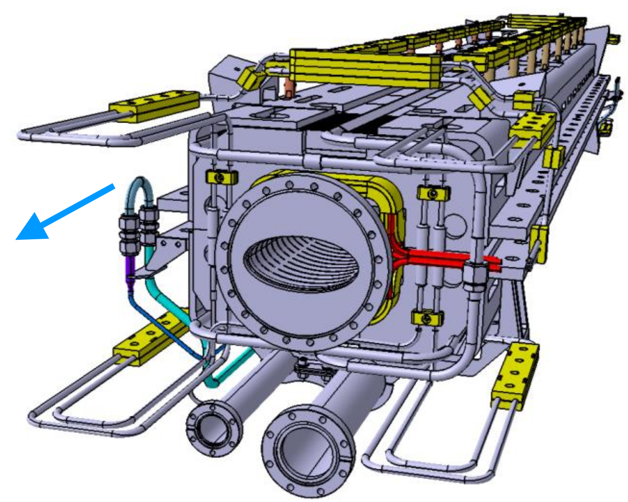
FAIR will accelerate a wide range of ions, with different masses and charges.
So, instead of beam energy, we talk about the bending power of the rings as 100T.m and 300T.m (field x bend radius)

FAIR: two rings in one tunnel





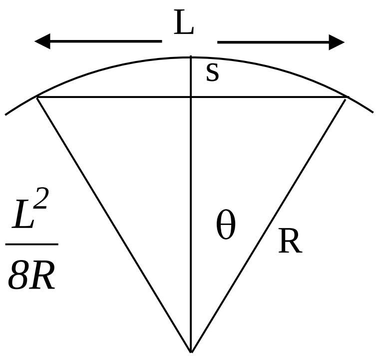
Modified UNK dipole
6T at 1T/s



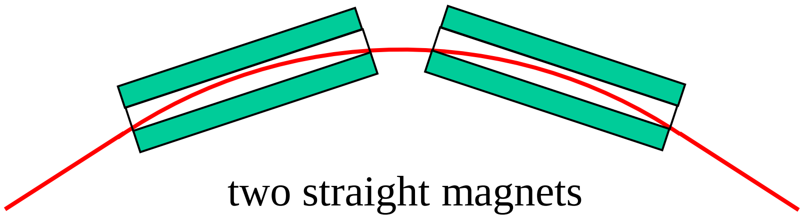
Nuclotron-type dipole magnet:
B=2T,
dB/dt=4T/s

2x120 superconducting dipole magnets
132+162 SC quadrupole magnets

Problem of the sagitta in SIS300



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

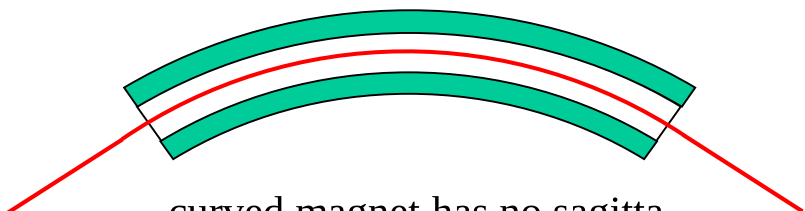


two straight magnets

must be short because of sagitta

$\Rightarrow$ B = 6T

must use double layer coil



curved magnet has no sagitta,

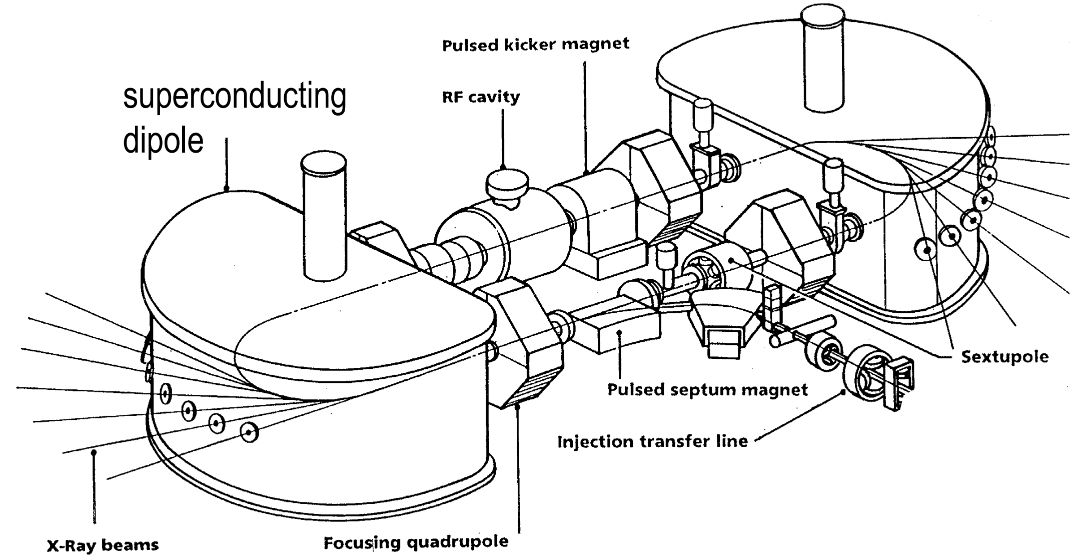
can be long, save space of end turns

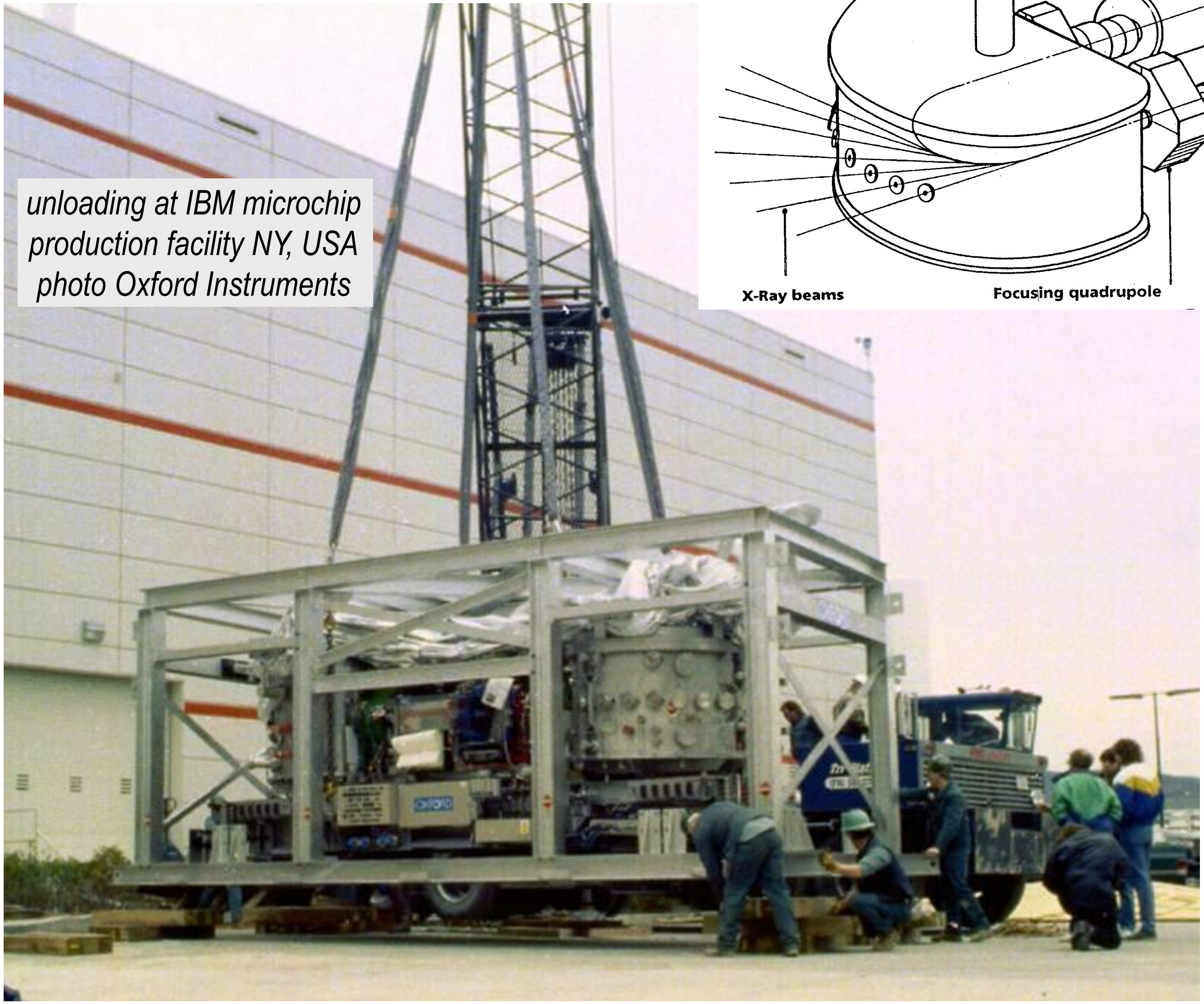
$\Rightarrow$ B = 4.5T

can use single layer coil

Discorap curved dipole INFN Frascati / Ansaldo

Helios
synchrotron X-ray source





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

superconducting dipoles

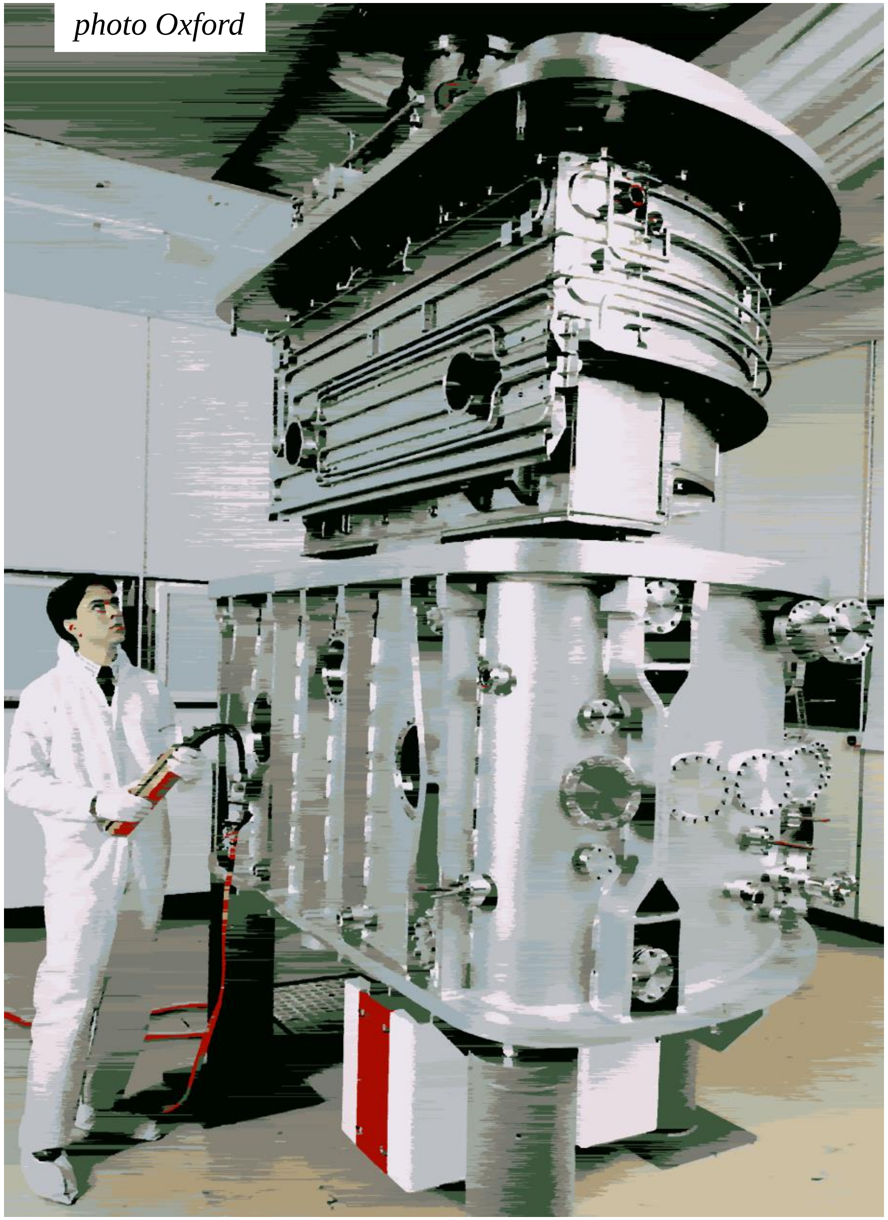
⇒ high field

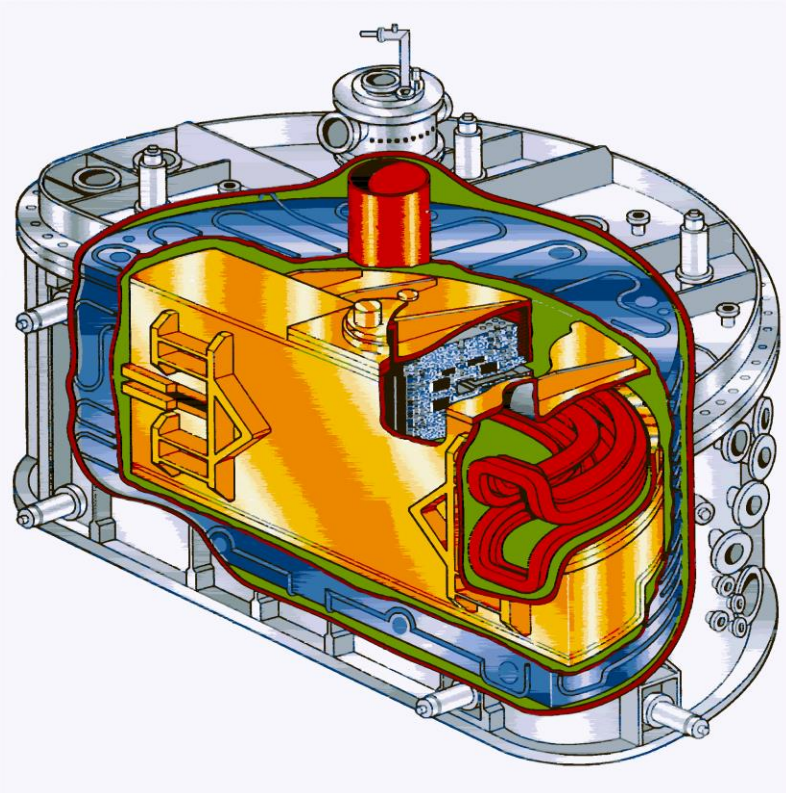
⇒ tight bending radius

⇒ compact size

⇒ transportability

Helios dipole





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

Cryogenics & Practical Matters: concluding remarks

- liquid helium for low temperature and liquid nitrogen for higher – but a gap for HTS
- making cold takes a lot of energy – the colder you go the more it takes
  - ⇨ so must minimize heat leaks to all cryogenic systems - conduction – convection - radiation
- 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
  - ⇨ wind ⇨ compact ⇨ collar ⇨ iron ⇨ cryostat ⇨ install ⇨ interconnect
- in recent years all the largest accelerators (and some small ones) have been superconducting

what comes next up to you

customer helpline
martnwil@gmail.com