

# Introduction to Accelerator Physics

## Part 4

Pedro Castro / Accelerator Physics Group (MPY)  
Hamburg, 3rd February 2023



# LHC commissioning



**April 2008**  
Last dipole down  
(Total: 1232 dipoles)



**September 10, 2008**  
First beams around

2008

2009

2010

**September 30, 2008**  
First collisions planned ...

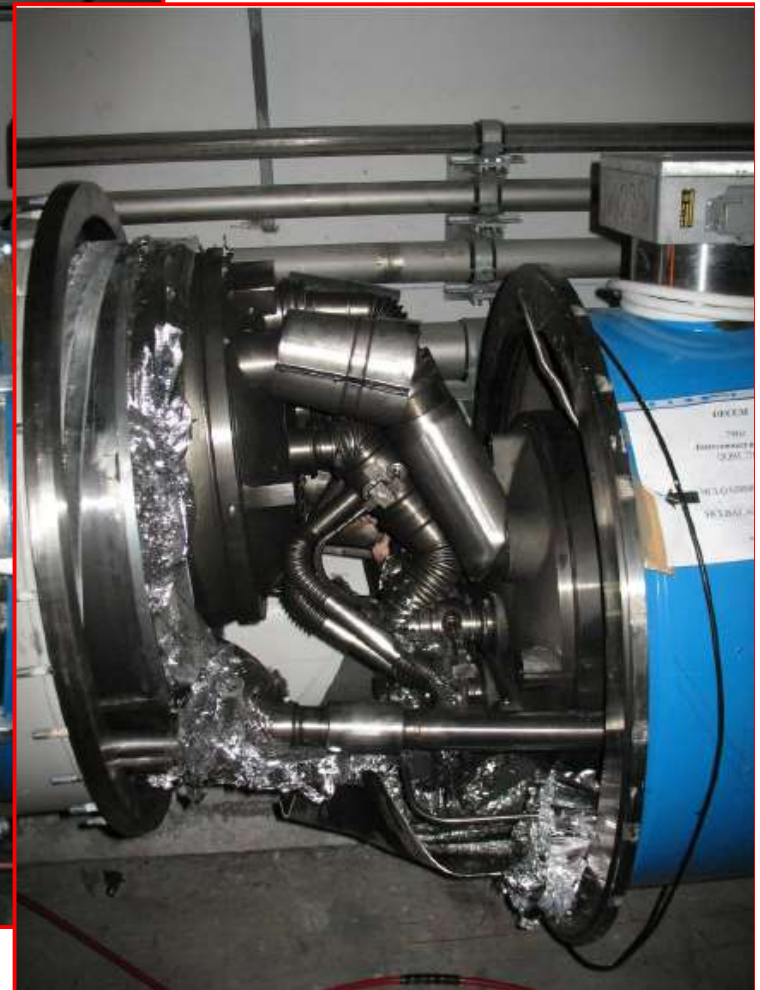
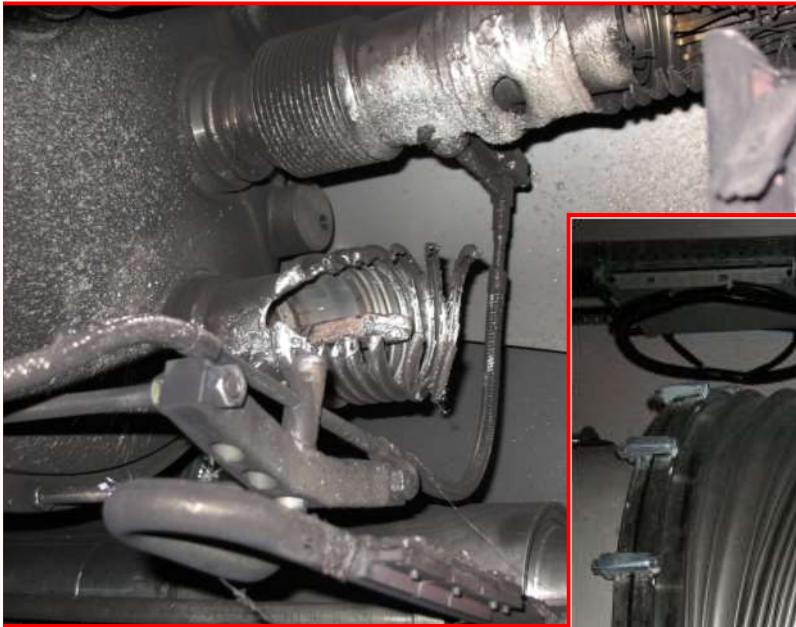
**September 19, 2008**

Disaster:

- Ramping the dipole current to 9.3 kA (6.5 T)
- At 8.7 kA, an electrical arc developed in a LHC dipole magnet interconnection

# Electrical arc between C24 and Q24

- ~6 tonnes of liquid He lost
- contamination of the vacuum tube
- damage of 53 superconducting magnets



# LHC commissioning



**April 2008**  
Last dipole down  
(Total: 1232 dipoles)



**September 10, 2008**  
First beams around

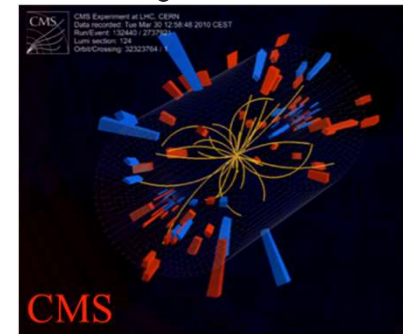
## Repair and Consolidation

**November 20, 2009**  
Beam back

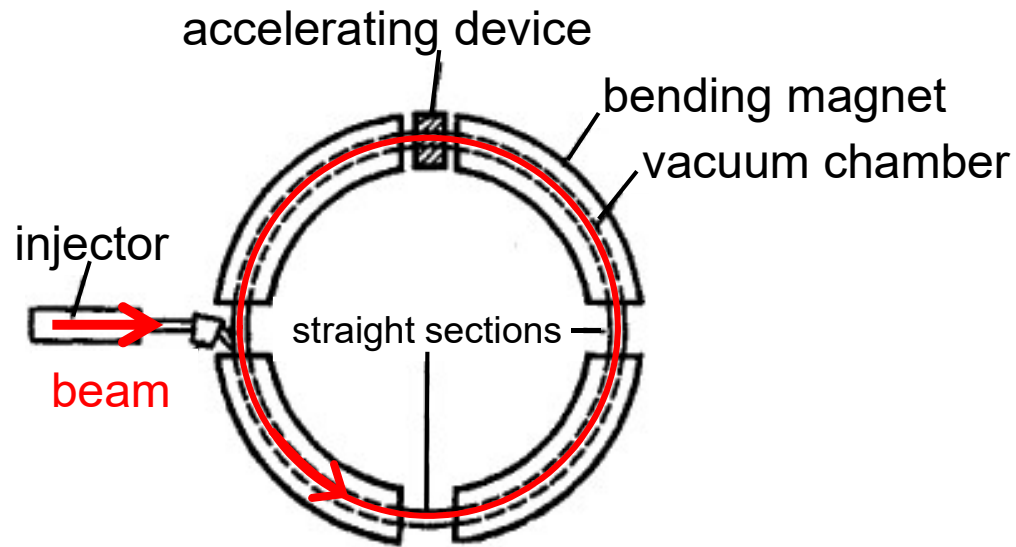


**September 19, 2008**  
**Disaster**  
Electrical arc developed in a LHC  
dipole magnet interconnection

**March 30, 2010**  
First collisions at 3.5 TeV

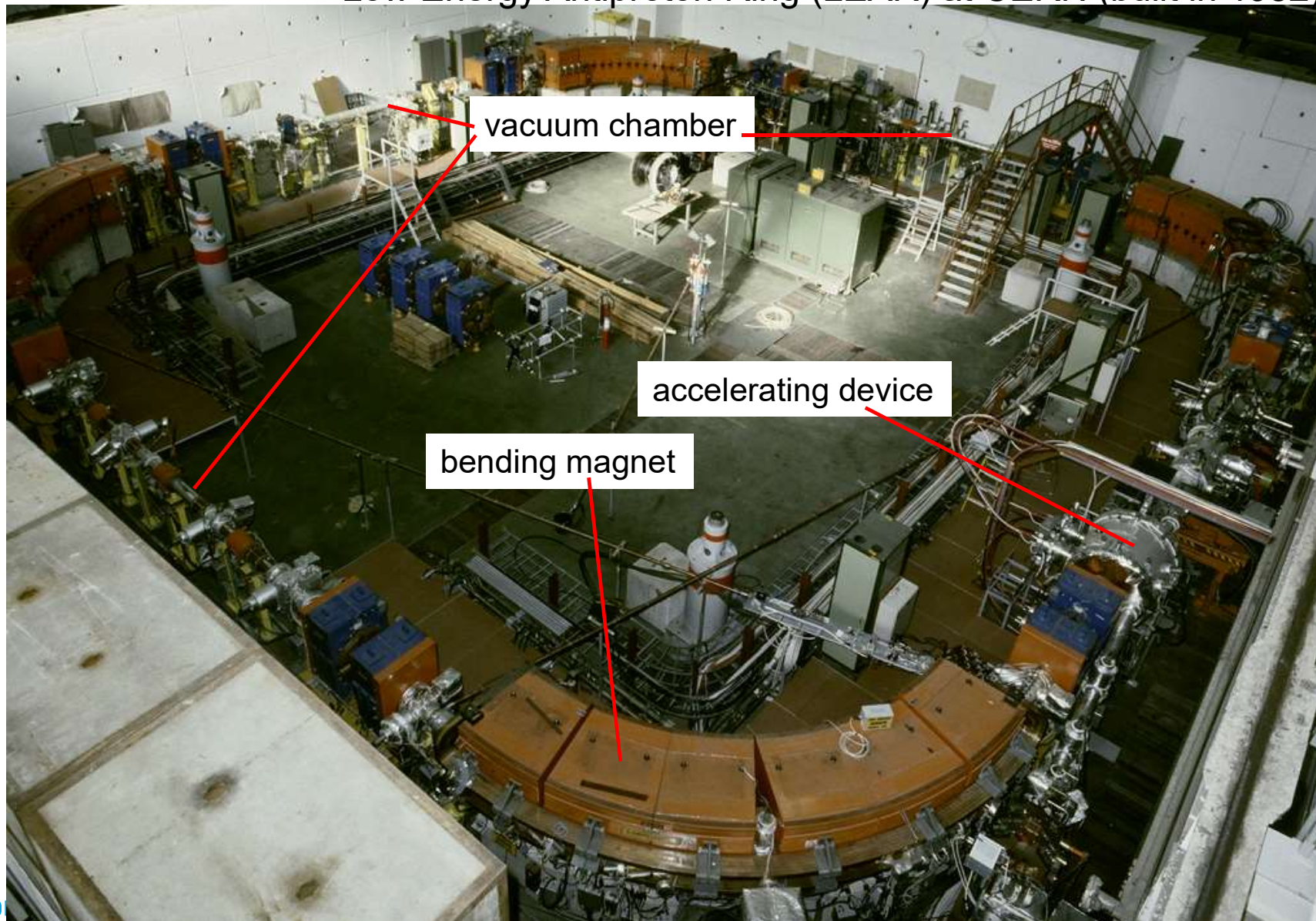


# Circular accelerators: the synchrotron

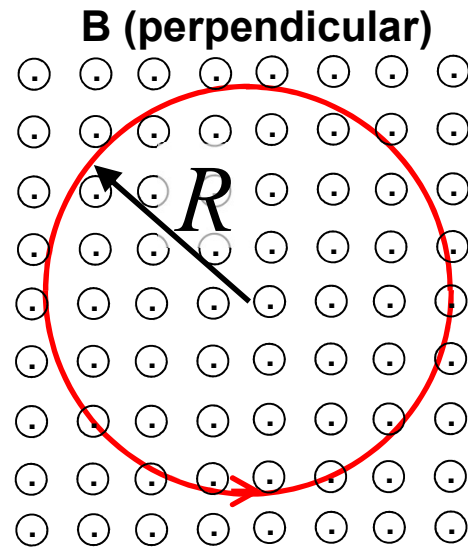


# Circular accelerators: the synchrotron

Low Energy Antiproton Ring (LEAR) at CERN (built in 1982)



# Circular accelerators: the synchrotron



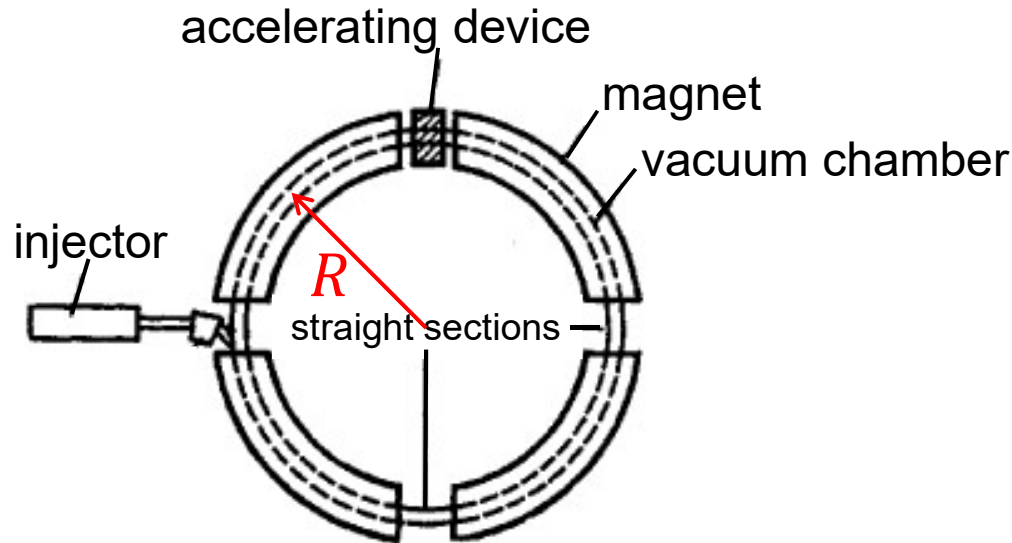
$$\vec{F} = \frac{d\vec{p}}{dt} = q\vec{v} \times \vec{B}$$

momentum
charge
velocity
magnetic field

of the particle

$$\left. \begin{array}{l} \vec{B} \perp \vec{v} \rightarrow F = qvB \\ \vec{F} \perp \vec{v} \rightarrow F = m \frac{v^2}{R} \\ \text{(circular motion)} \end{array} \right\} qB = \frac{mv}{R} \rightarrow R = \frac{mv}{qB}$$

# Circular accelerators: the synchrotron



$$\vec{B} \perp \vec{v} \rightarrow F = qvB$$
$$\vec{F} \perp \vec{v} \rightarrow F = m \frac{v^2}{R}$$

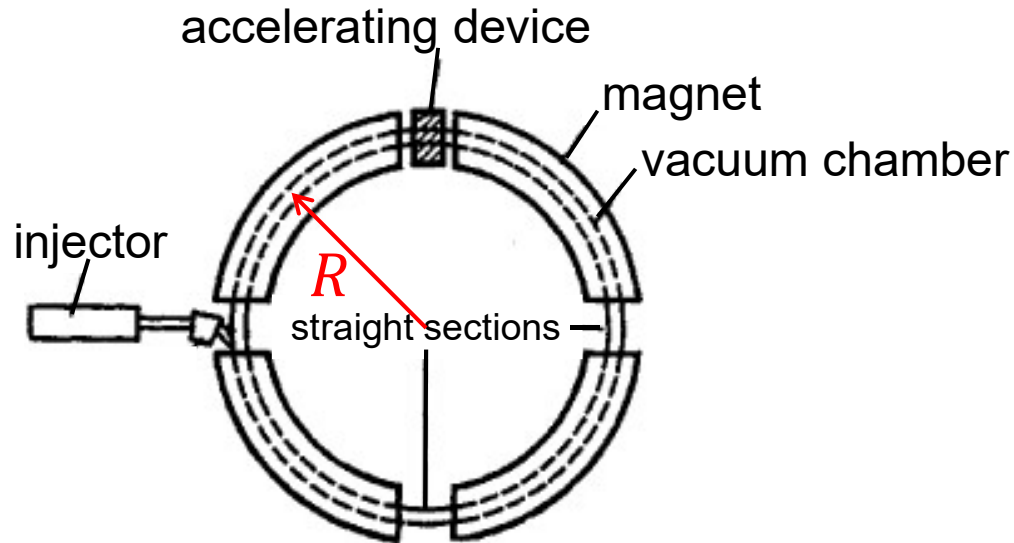
(circular motion)

$$qB = \frac{mv}{R} \rightarrow R = \frac{mv}{qB} = \text{constant}$$

→ increase B **synchronously**  
with  $p = mv$  of particle

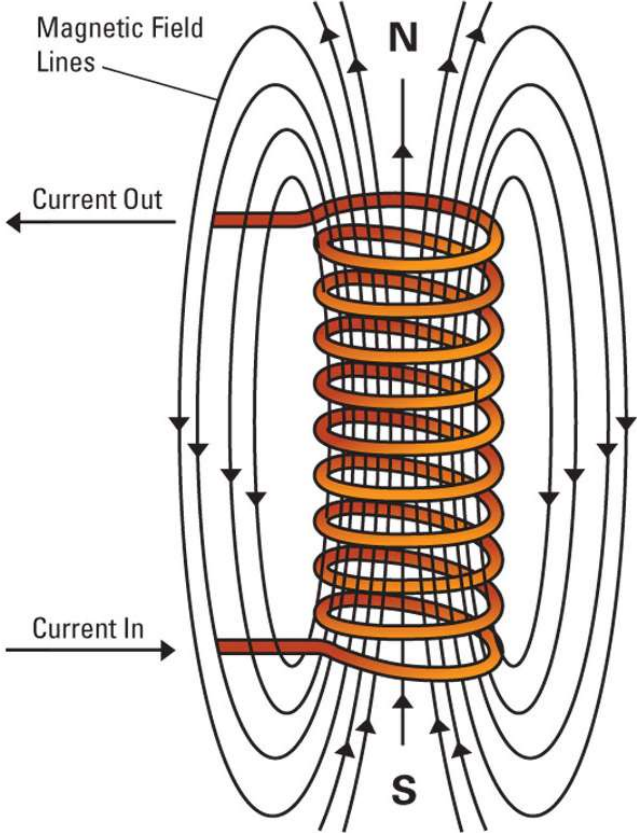


# Circular accelerators: the synchrotron

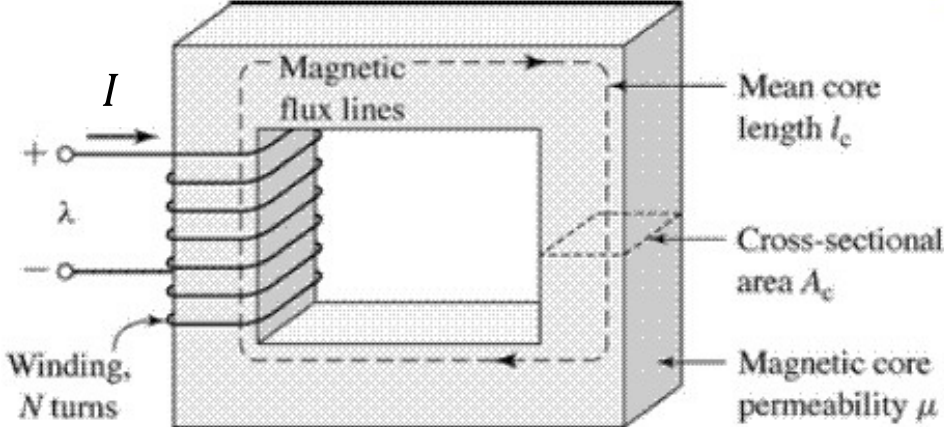


$$\left. \begin{array}{l} \vec{B} \perp \vec{v} \rightarrow F = qvB \\ \vec{F} \perp \vec{v} \rightarrow F = m \frac{v^2}{R} \\ \text{(circular motion)} \end{array} \right\} qB = \frac{mv}{R} \rightarrow R = \frac{(mv)_{max}}{qB_{max}} = \text{constant}$$

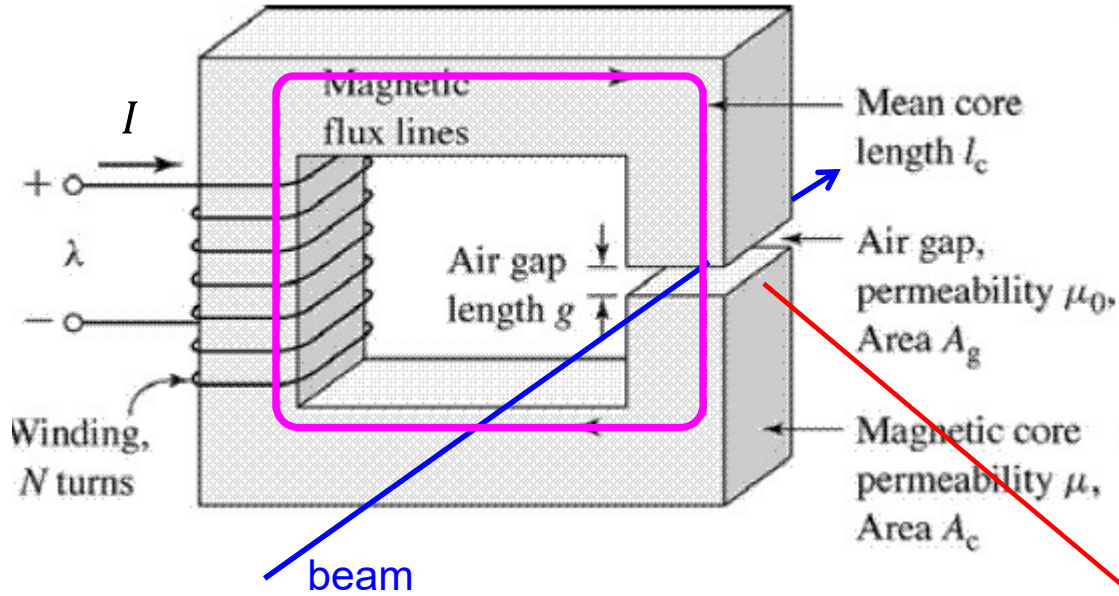
# Electromagnet



permeability of iron = 300...10000 larger than air



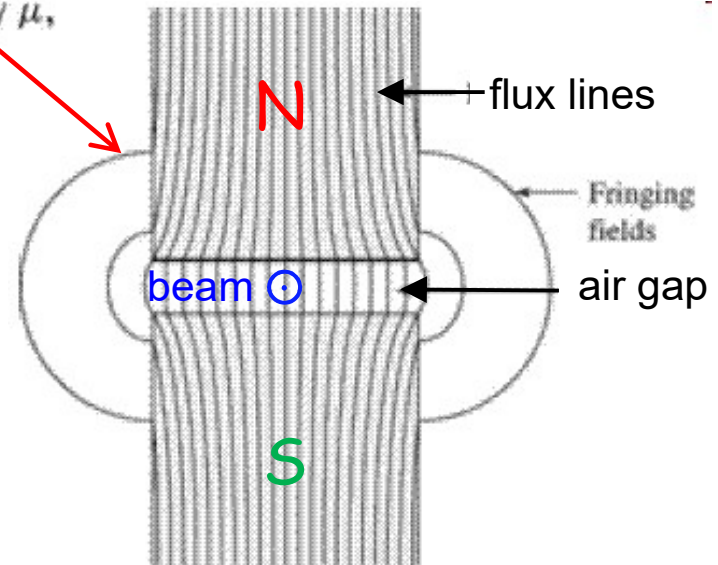
# Dipole magnet



$$\int_{gap} \frac{\vec{B}}{\mu_0} \cdot d\vec{s} = \frac{Bg}{\mu_0} = NI$$

$$B = \frac{\mu_0 N I}{g}$$

gap height



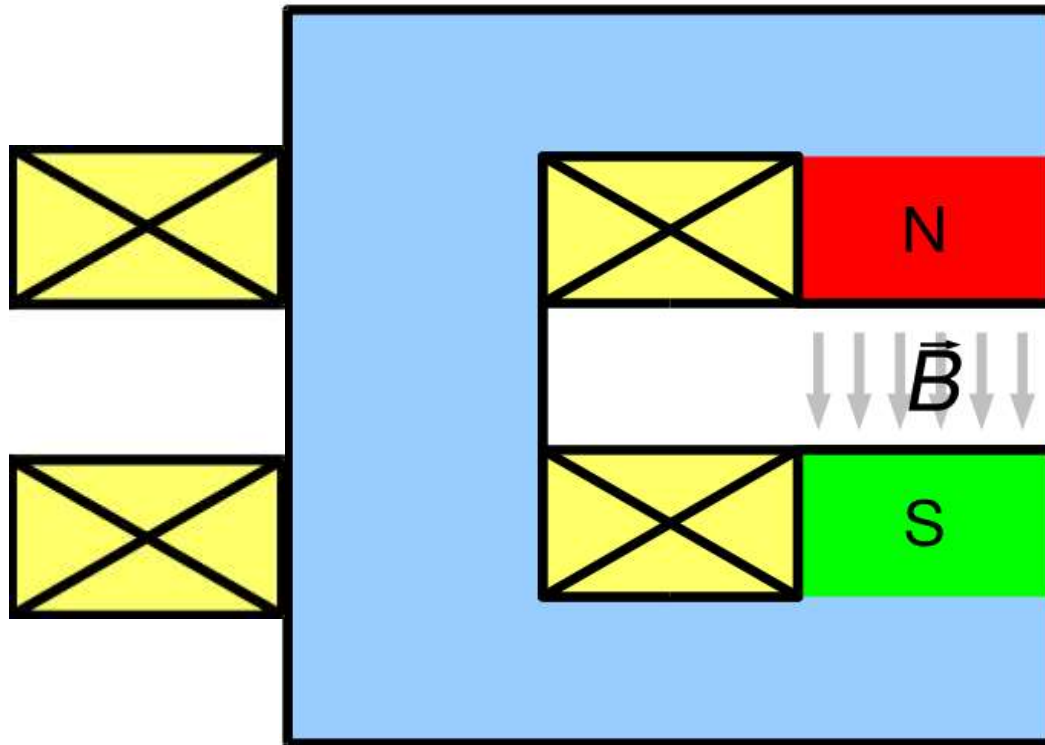
Ampere's law:

$$\oint \vec{H} \cdot d\vec{s} = I_{enclosed} = NI$$

$$\oint \vec{H} \cdot d\vec{s} = \int_{iron} \vec{H} \cdot d\vec{s} + \int_{gap} \vec{H} \cdot d\vec{s} = NI$$

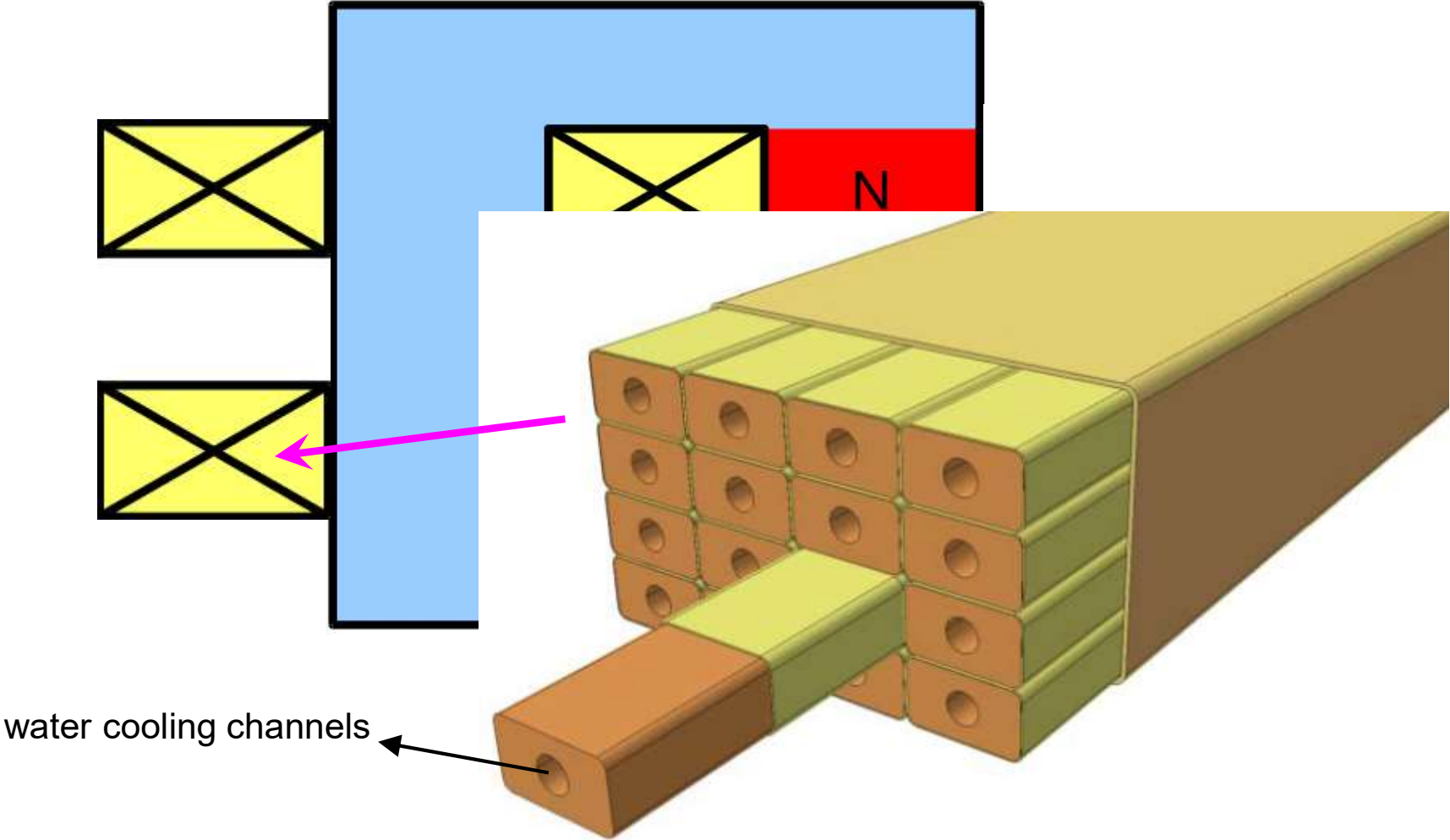
~~$$\int_{iron} \frac{\vec{B}}{\mu_{iron}} \cdot d\vec{s} + \int_{gap} \frac{\vec{B}}{\mu_0} \cdot d\vec{s} = NI$$~~

# Dipole magnet cross section

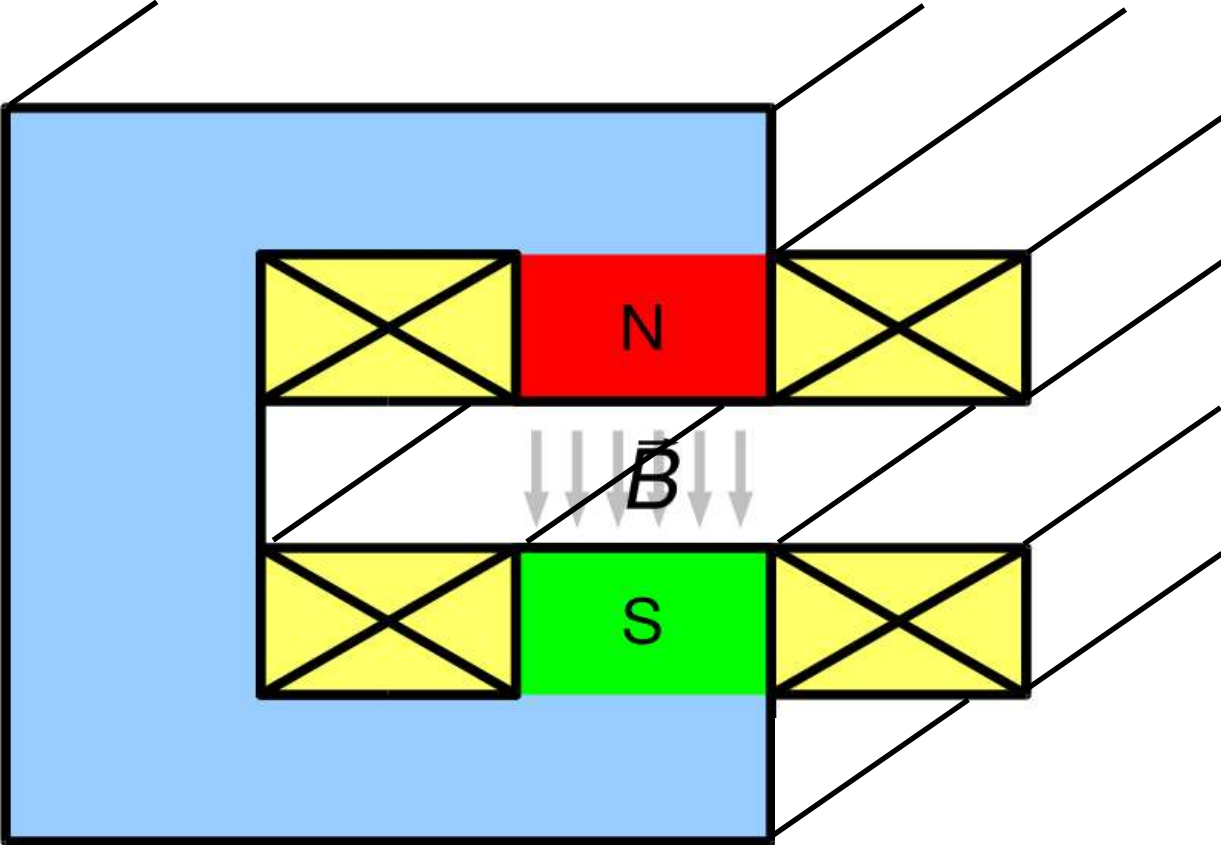


increase  $B \rightarrow$  increase current, but power dissipated  $P = R \cdot I^2$   
 $\rightarrow$  large conductor cables

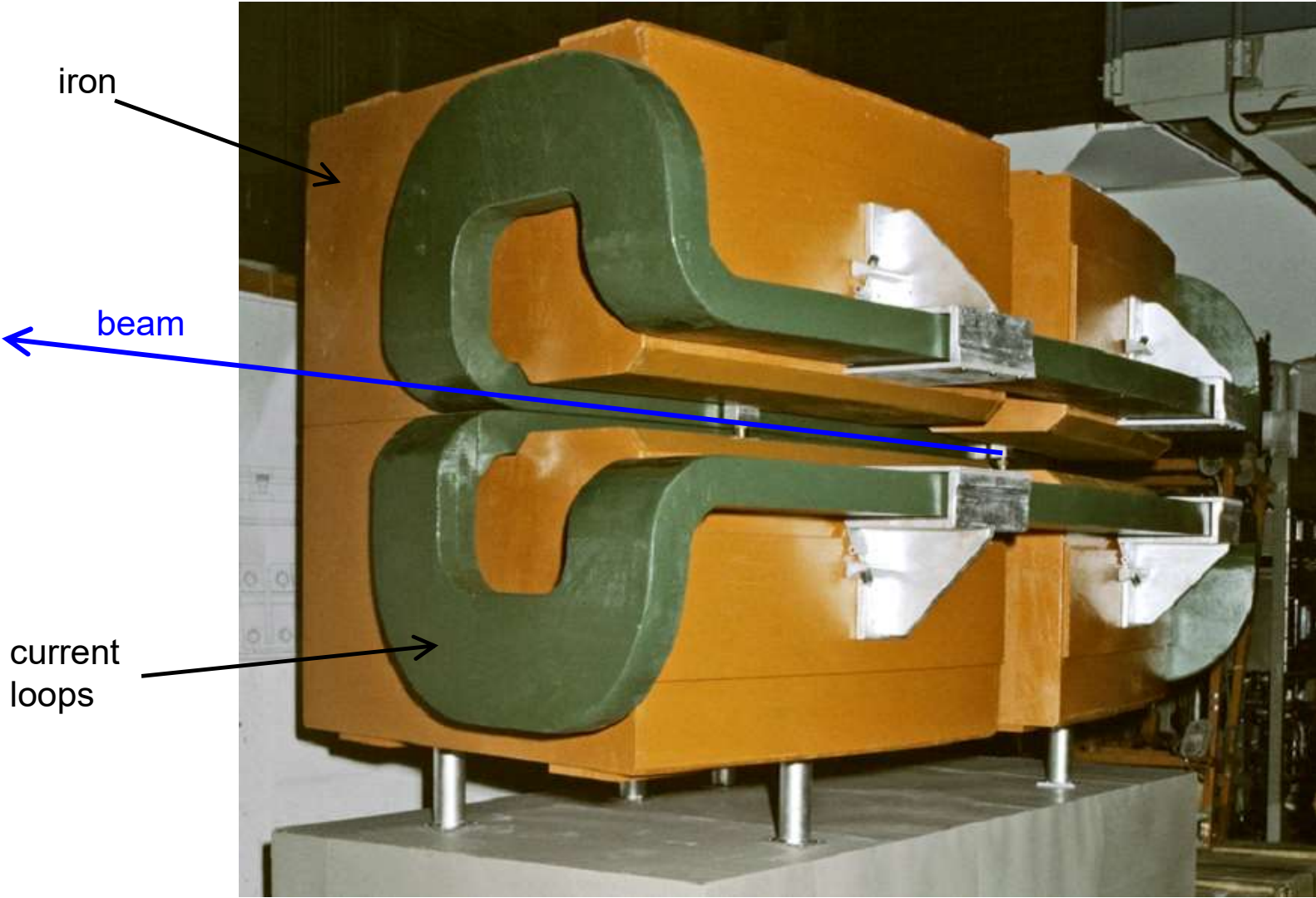
# Dipole magnet cross section



# Dipole magnet cross section

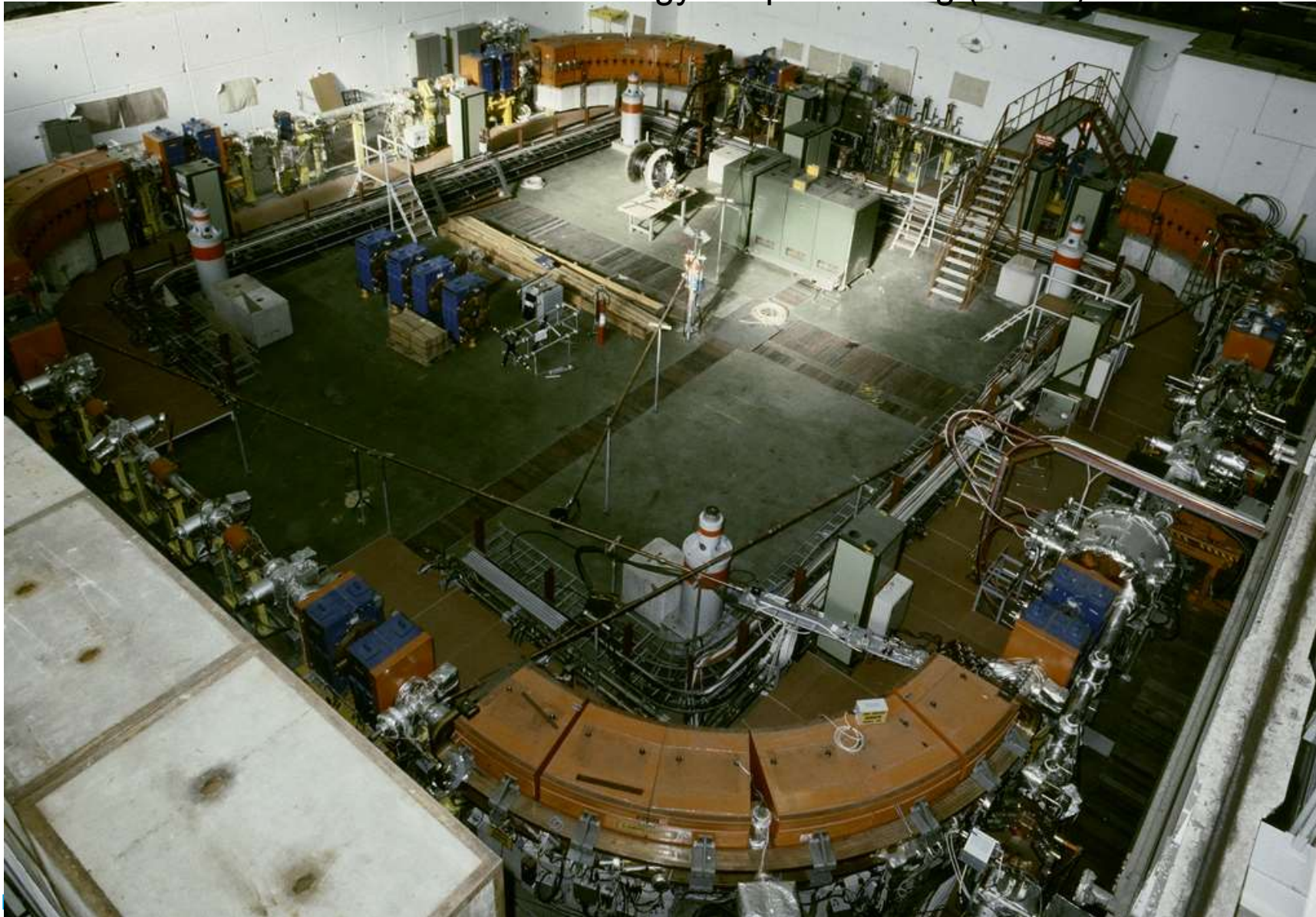


# Dipole magnet



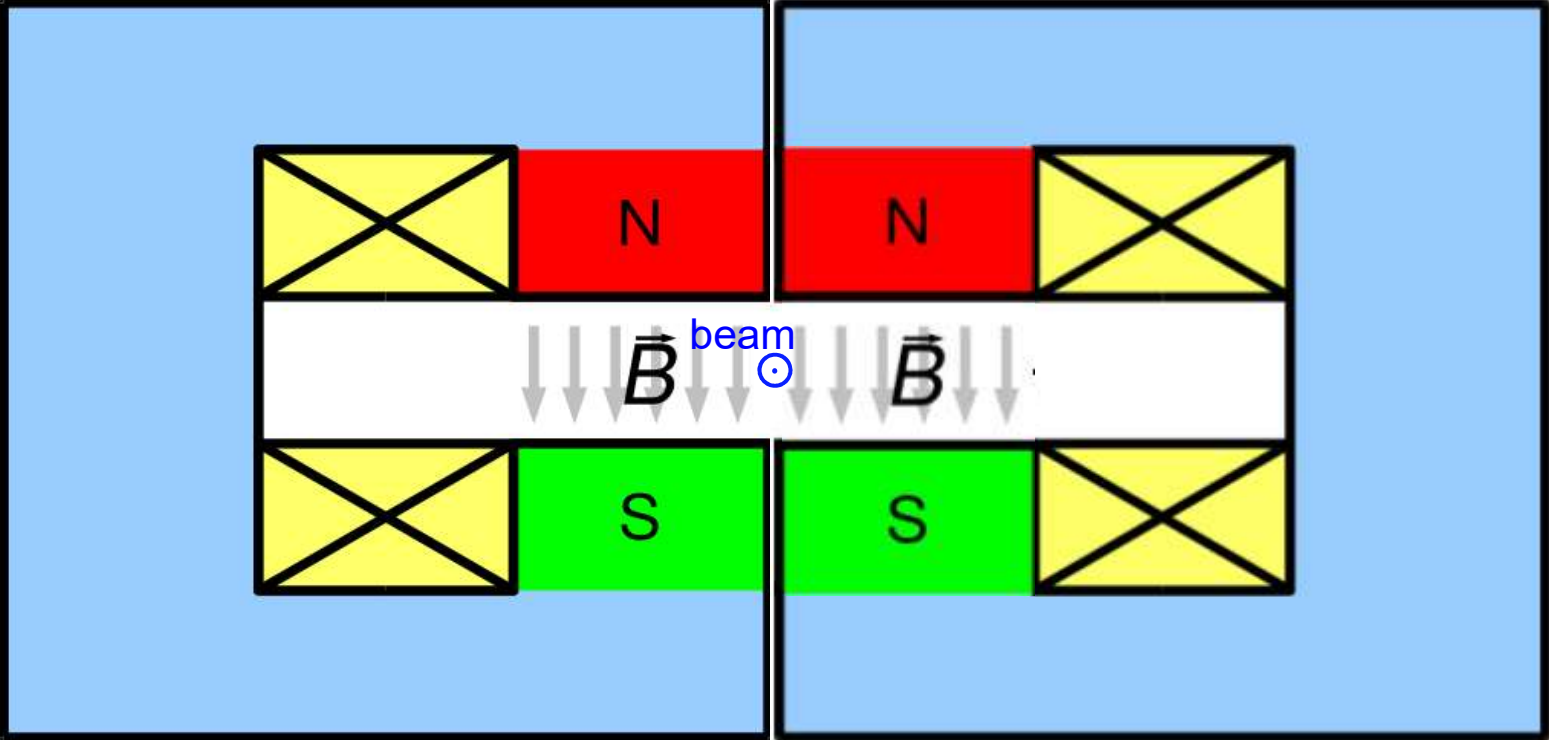
# Dipole magnet

Low Energy Antiproton Ring (LEAR) at CERN



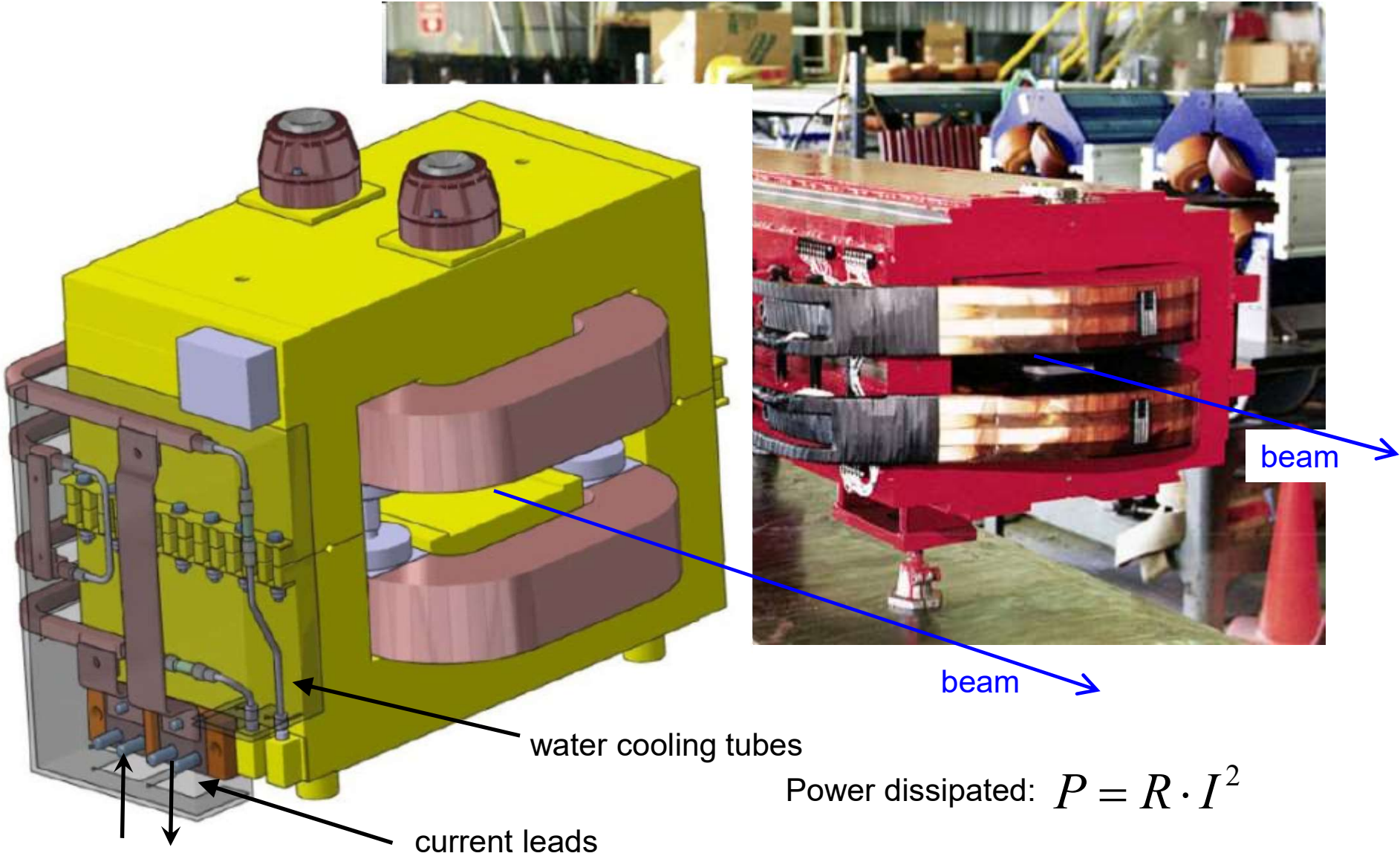


# Dipole magnet cross section



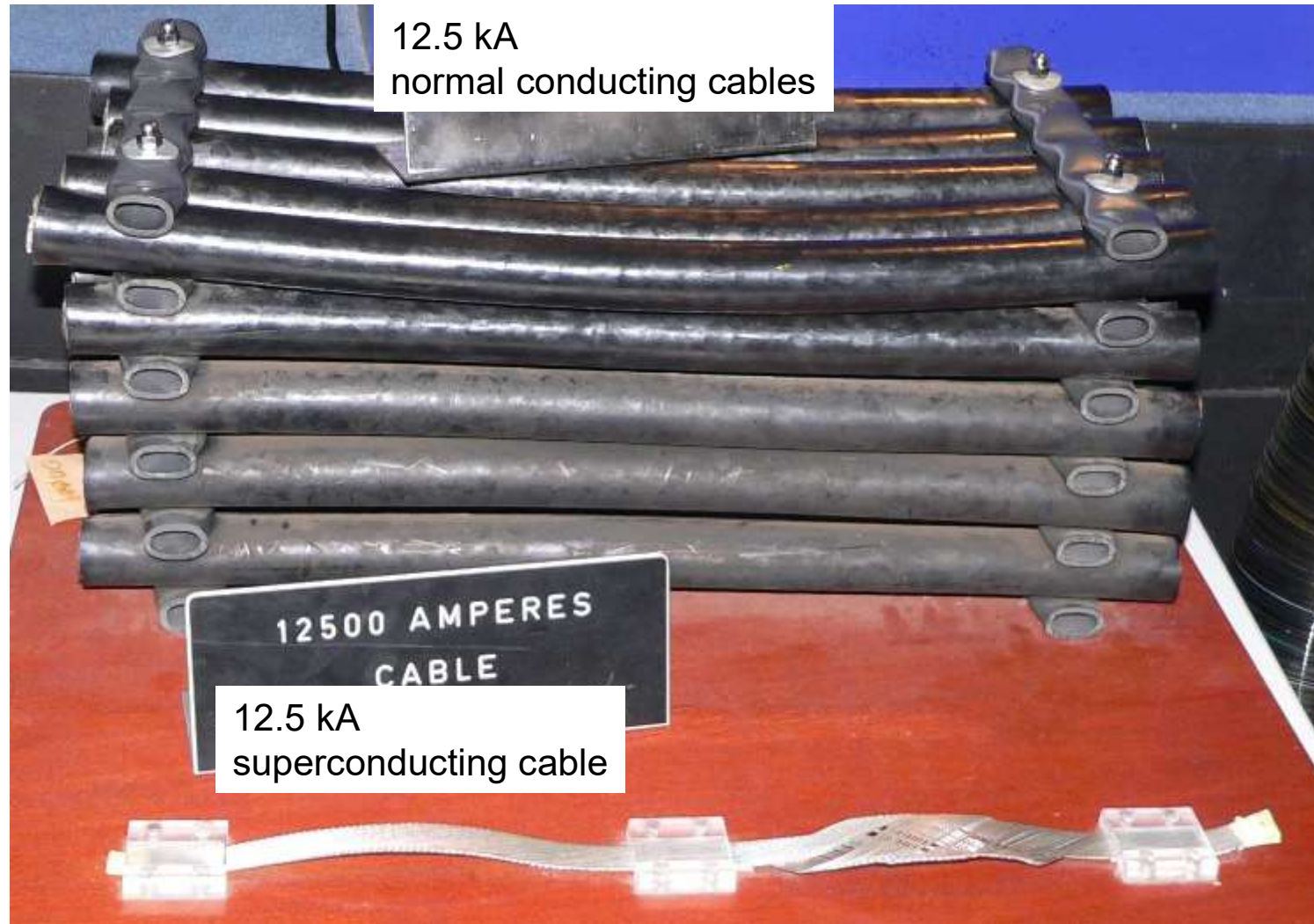
C magnet + C magnet = H magnet

# Dipole magnet cross section (another design)

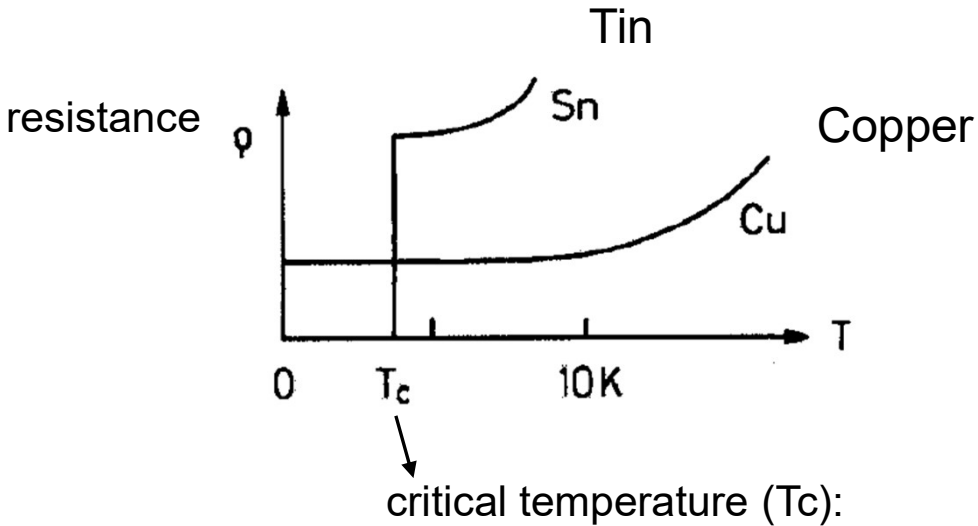


Power dissipated:  $P = R \cdot I^2$

# Superconductivity



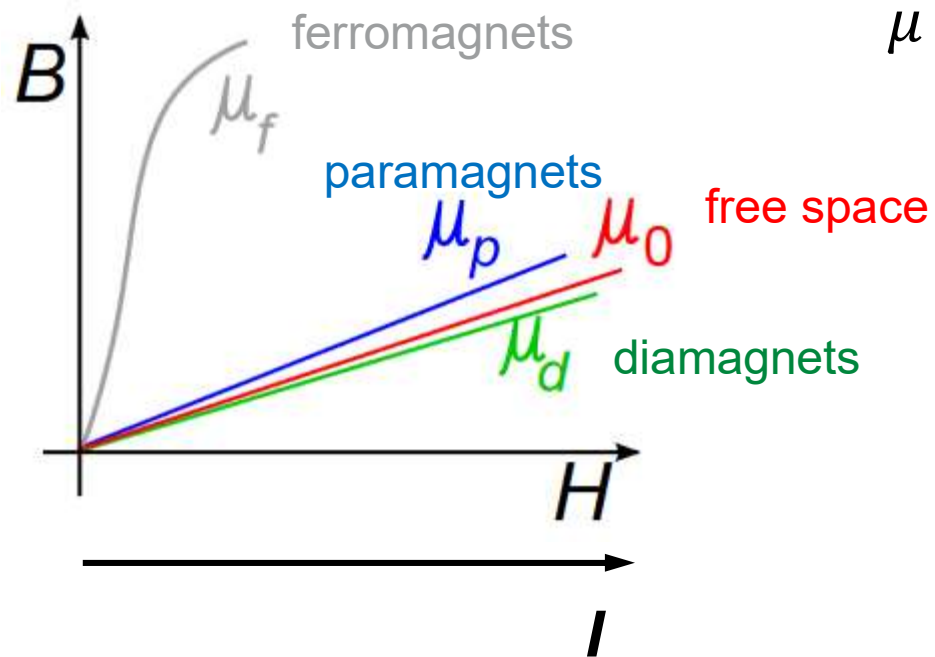
# Superconductivity



using superconducting cables

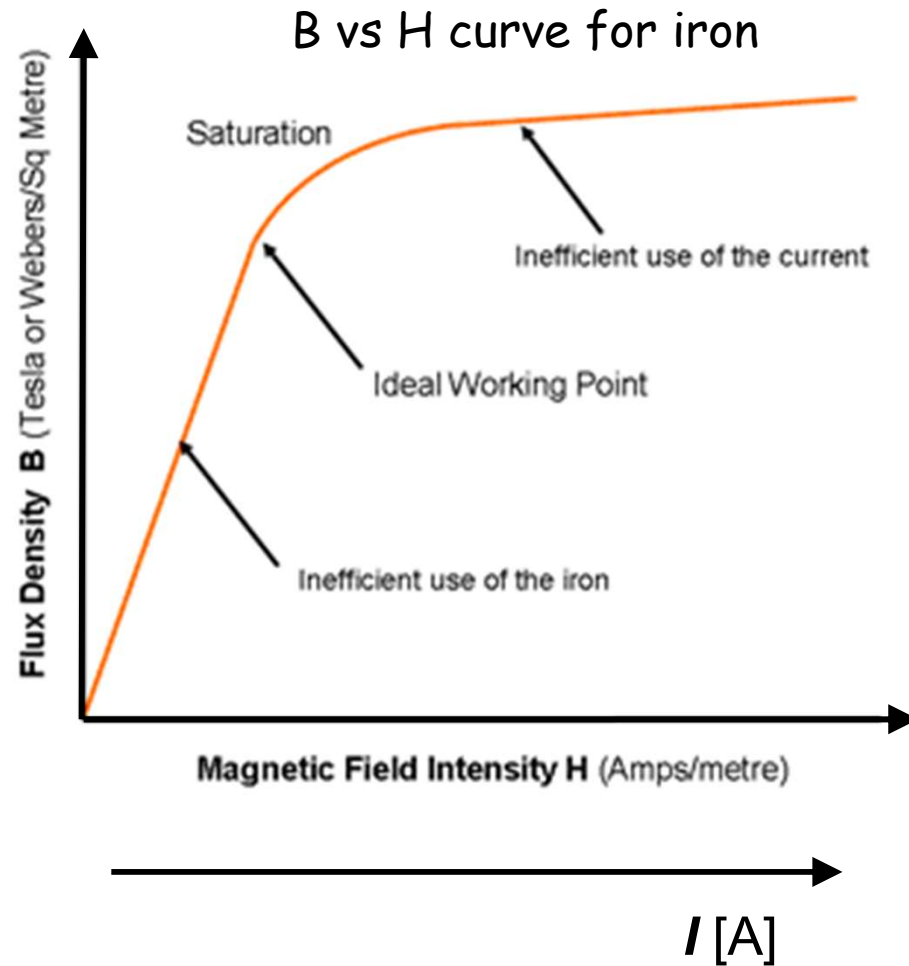
increase B → ~~increase current, but power dissipated  $P = R \cdot I^2$~~   
→ ~~large conductor cables~~  
→ ~~saturation effects~~

- increase  $B \rightarrow$  increase current, but power dissipated  $P = R \cdot I^2$
- $\rightarrow$  large conductor cables
  - $\rightarrow$  saturation effects

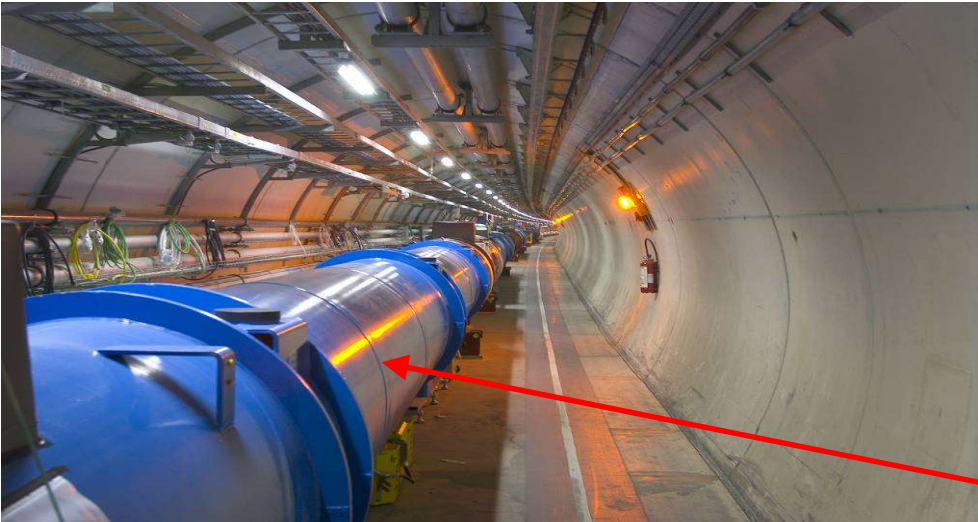


$\mu$  : permeability

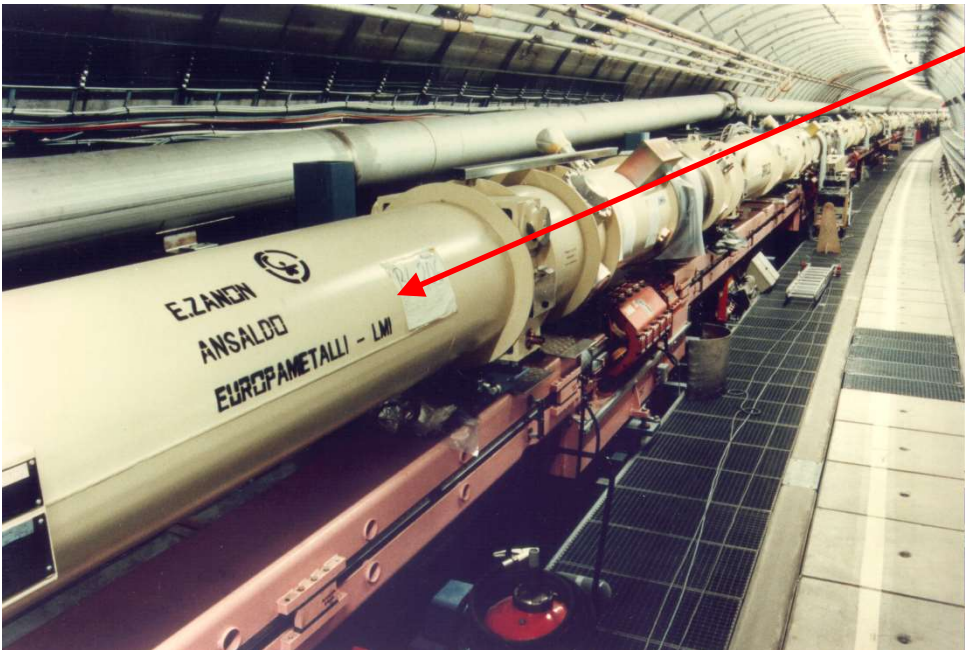
# Saturation of iron: 1.6 – 2 T



# Superconducting dipole magnets



LHC

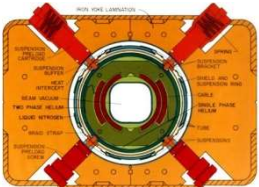
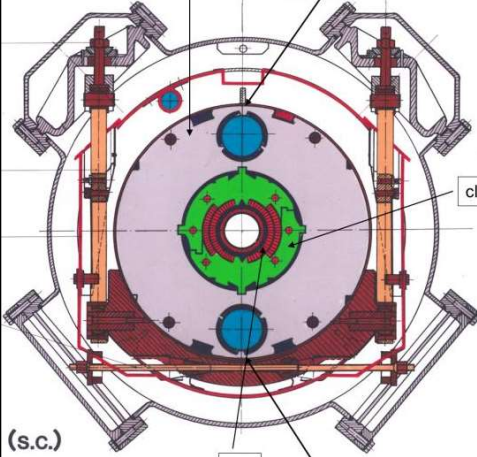
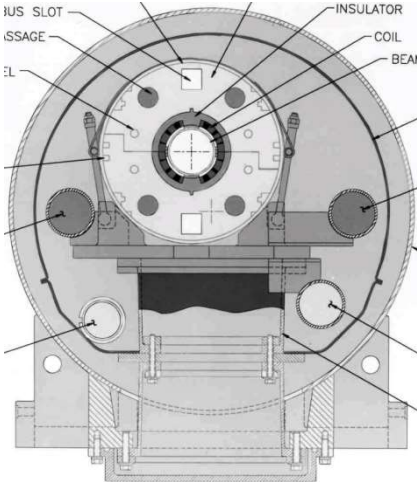
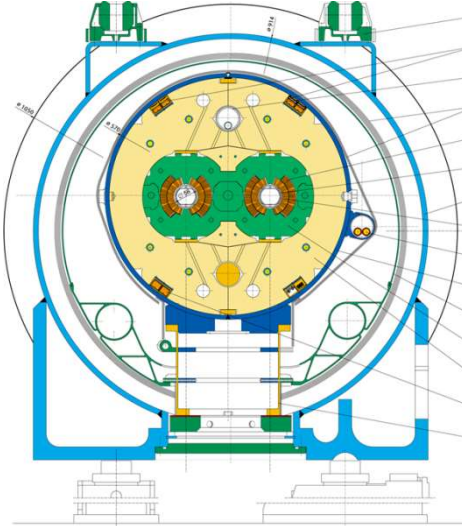


HERA

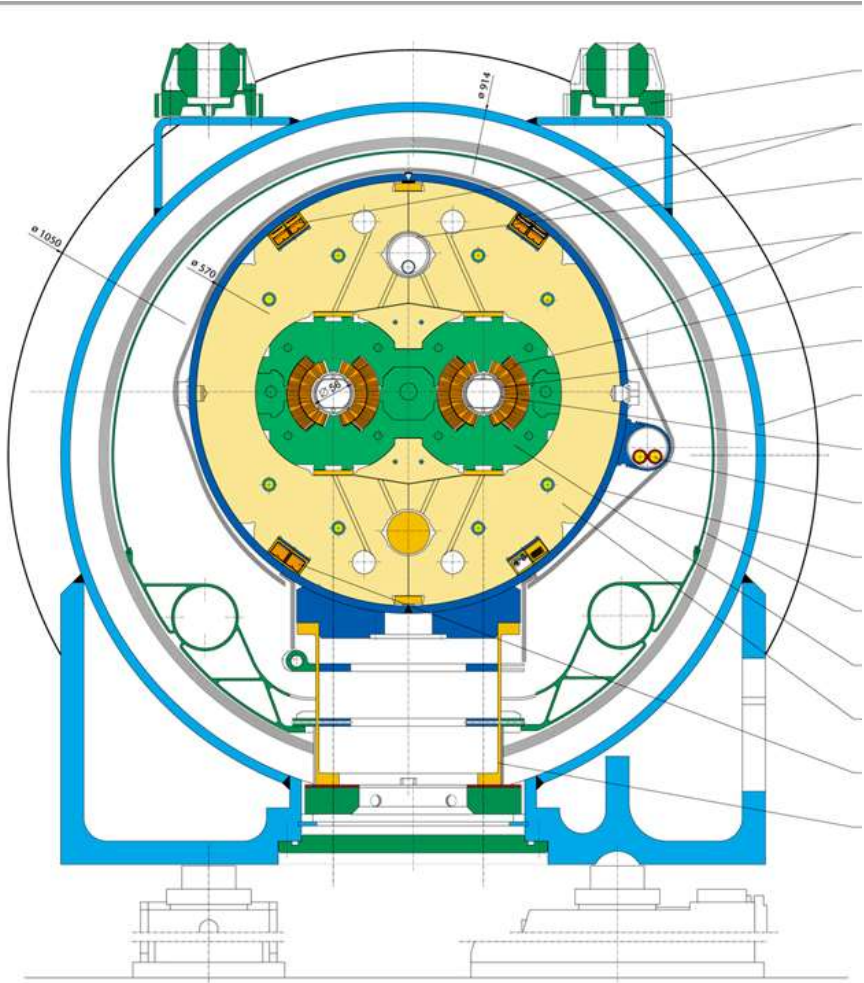
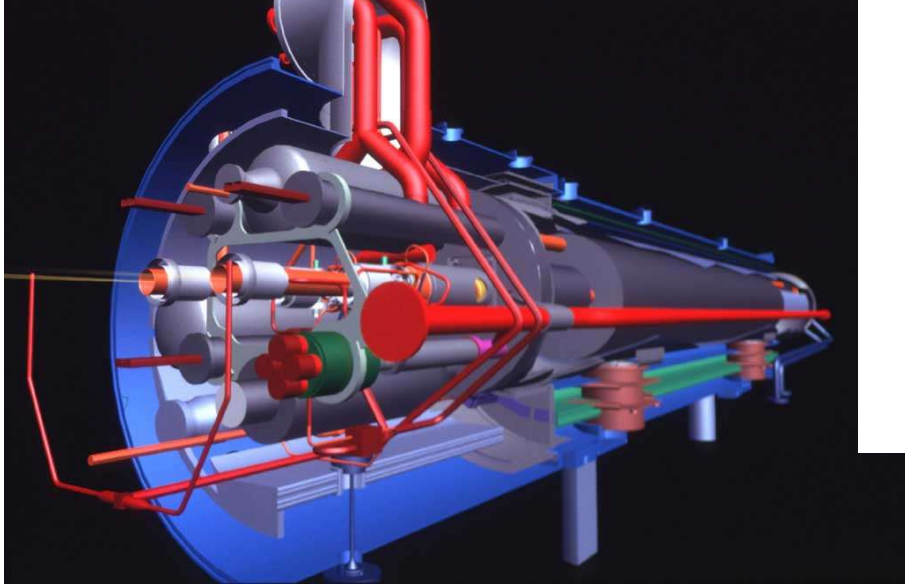
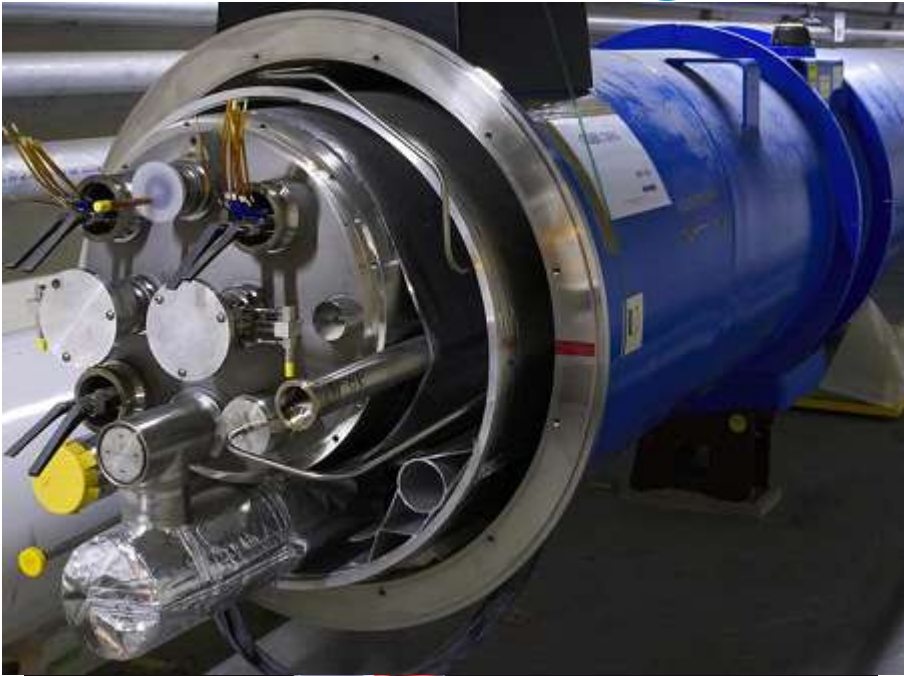
superconducting dipoles



# Superconducting dipole magnets: cross section

Tevatron	HERA	RHIC	LHC
Fermilab Chicago (USA)	DESY Hamburg (Germany)	Brookhaven Long Island (USA)	CERN Geneva (Switzerland)
4.5 T	5.3 T	3.5 T	8.3 T
			

# Superconducting dipole magnets

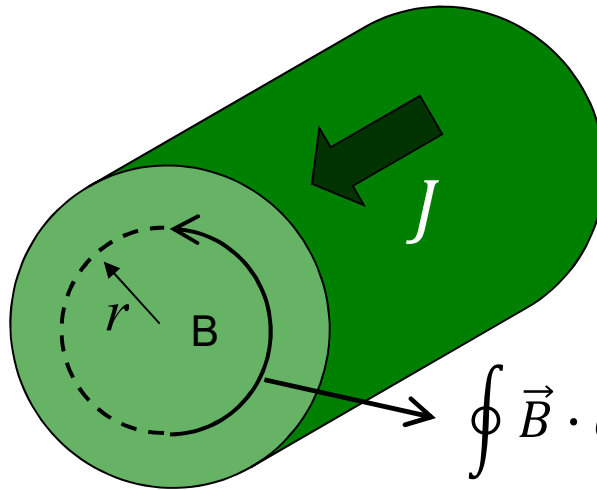


# Dipole field inside 1 conductor

$J$ : uniform current density

Ampere's law:

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{\text{enclosed}}$$



$$\oint \vec{B} \cdot d\vec{s} = \oint B ds = 2\pi r B = \mu_0 \pi r^2 J$$

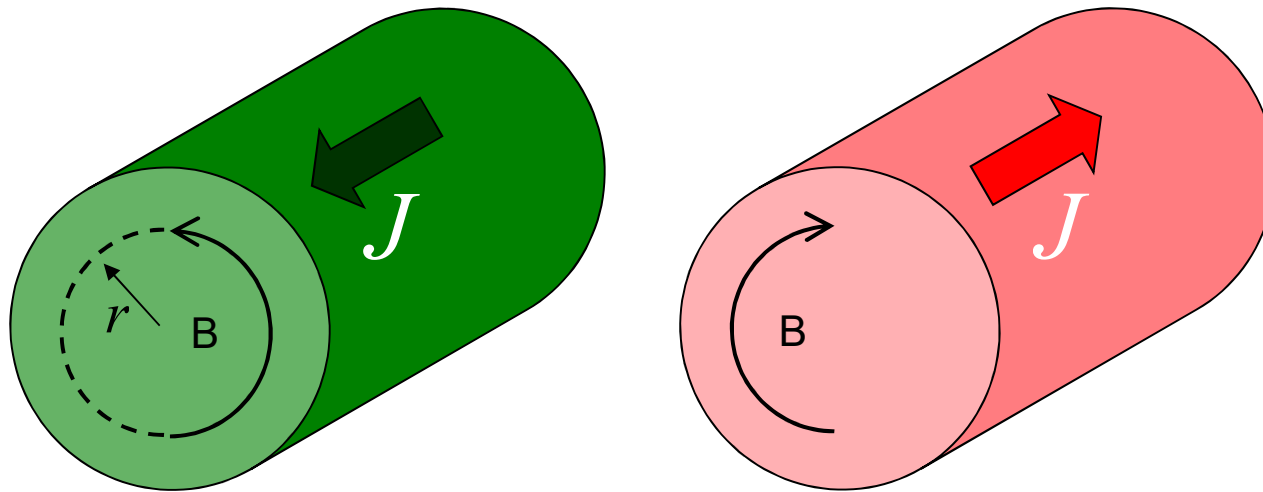
$$B = \frac{\mu_0 J}{2} r$$

A 2D vector diagram showing a position vector  $r$  at an angle  $\theta$  to the horizontal. A differential area element  $d\vec{s}$  is shown as a small arrow pointing tangentially to the path of the magnetic field  $\vec{B}$ . The components of the magnetic field are given by:

$$\left\{ \begin{array}{l} B_x = -\frac{\mu_0 J}{2} r \sin \theta \\ B_y = \frac{\mu_0 J}{2} r \cos \theta \end{array} \right.$$

# Dipole field inside 2 conductors

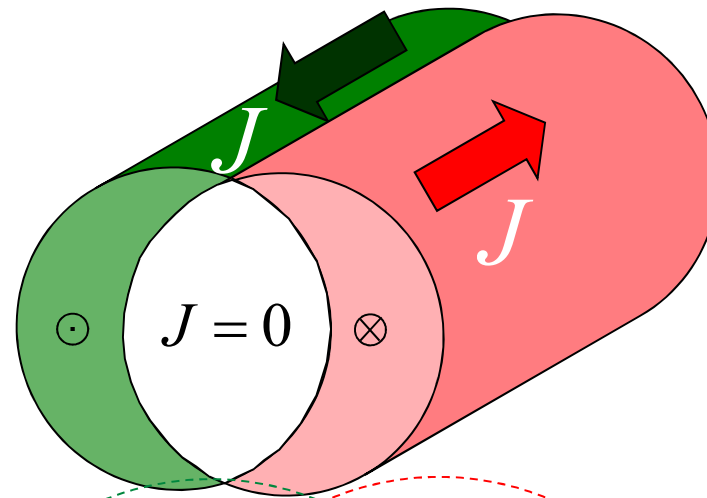
$J$  = uniform current density



# Dipole field inside 2 conductors

$J$  = uniform current density

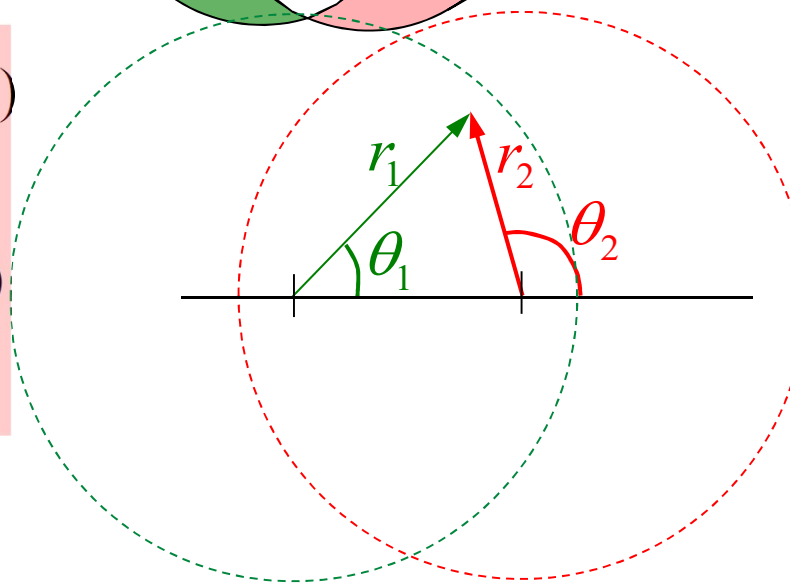
one conductor: 
$$\begin{cases} B_x = -\frac{\mu_0 J}{2} r \sin \theta \\ B_y = \frac{\mu_0 J}{2} r \cos \theta \end{cases}$$



superposition:

$$B_x = \frac{\mu_0 J}{2} (-r_1 \sin \theta_1 + r_2 \sin \theta_2)$$

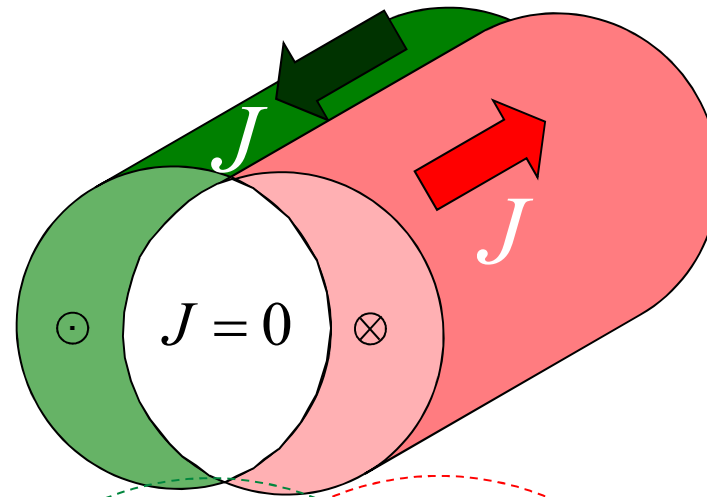
$$B_y = \frac{\mu_0 J}{2} (r_1 \cos \theta_1 - r_2 \cos \theta_2)$$



# Dipole field inside 2 conductors

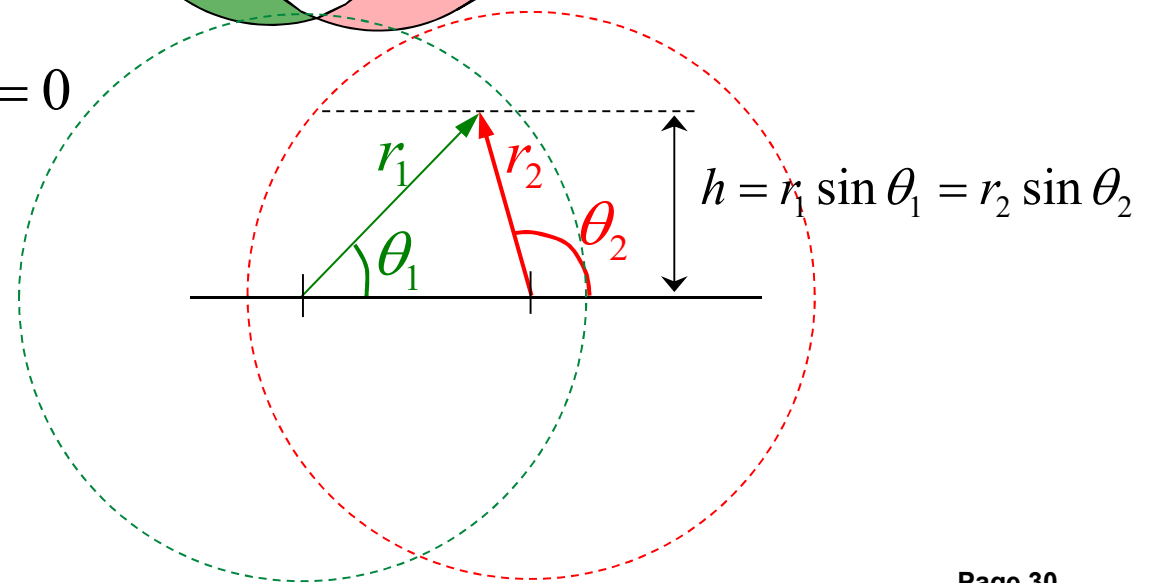
$J = \text{uniform current density}$

one conductor: 
$$\begin{cases} B_x = -\frac{\mu_0 J}{2} r \sin \theta \\ B_y = \frac{\mu_0 J}{2} r \cos \theta \end{cases}$$



$$B_x = \frac{\mu_0 J}{2} (-r_1 \sin \theta_1 + r_2 \sin \theta_2) = 0$$

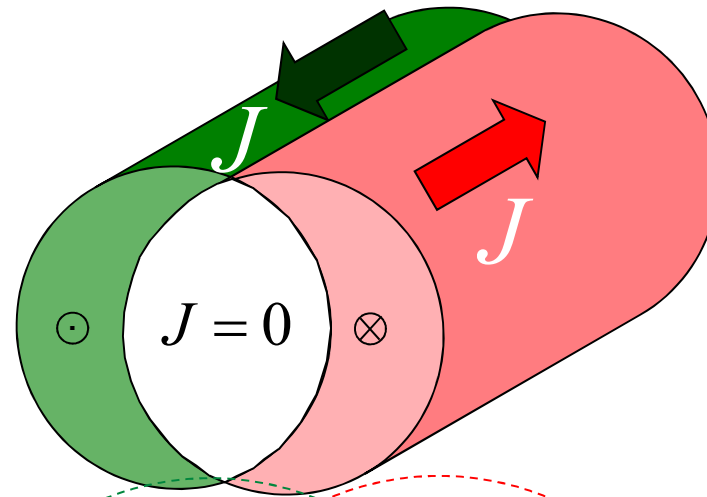
$$B_y = \frac{\mu_0 J}{2} (r_1 \cos \theta_1 - r_2 \cos \theta_2)$$



# Dipole field inside 2 conductors

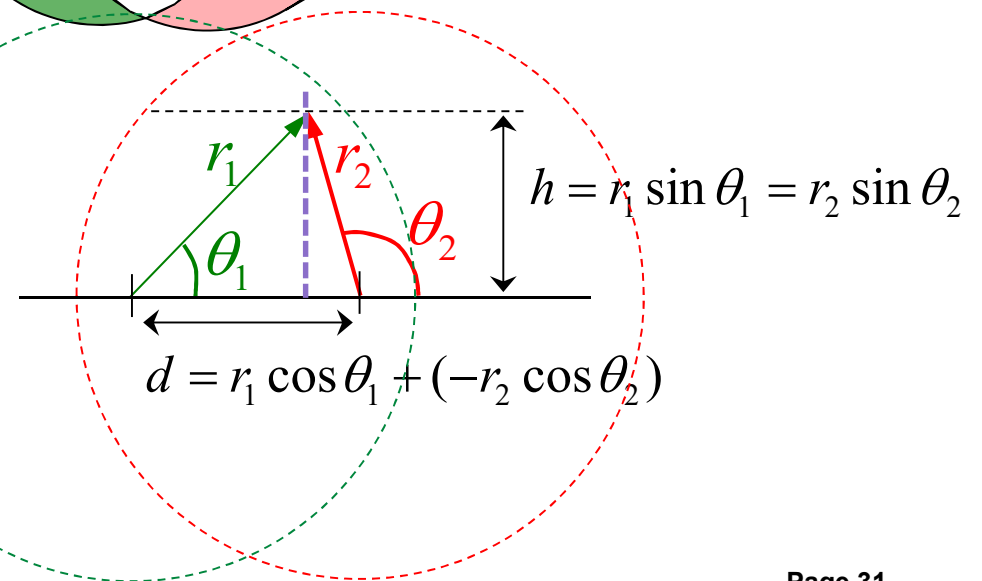
$J = \text{uniform current density}$

one conductor: 
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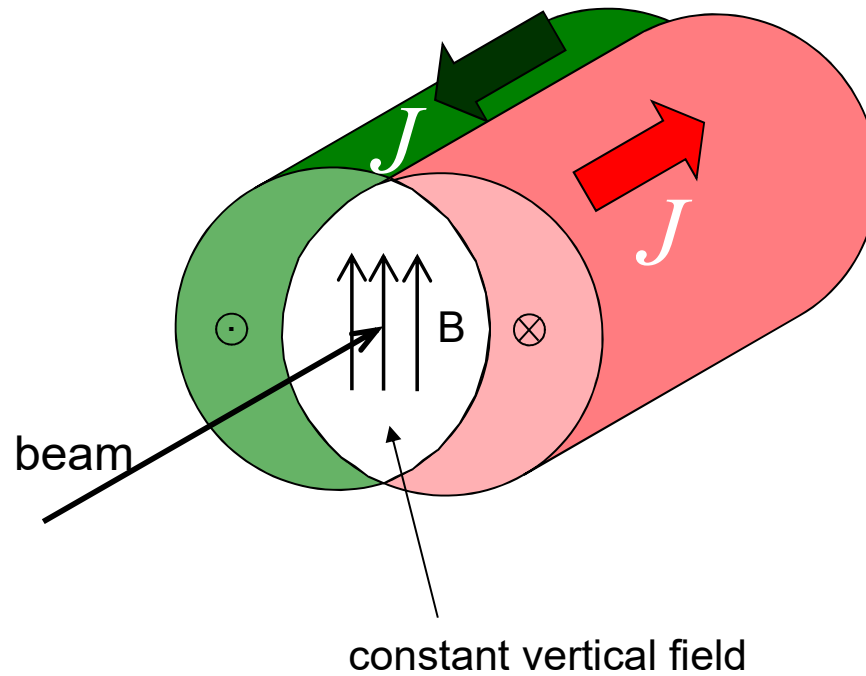


$$B_x = \frac{\mu_0 J}{2} (-r_1 \sin \theta_1 + r_2 \sin \theta_2) = 0$$

$$B_y = \frac{\mu_0 J}{2} (r_1 \cos \theta_1 - r_2 \cos \theta_2) = \frac{\mu_0 J}{2} d$$



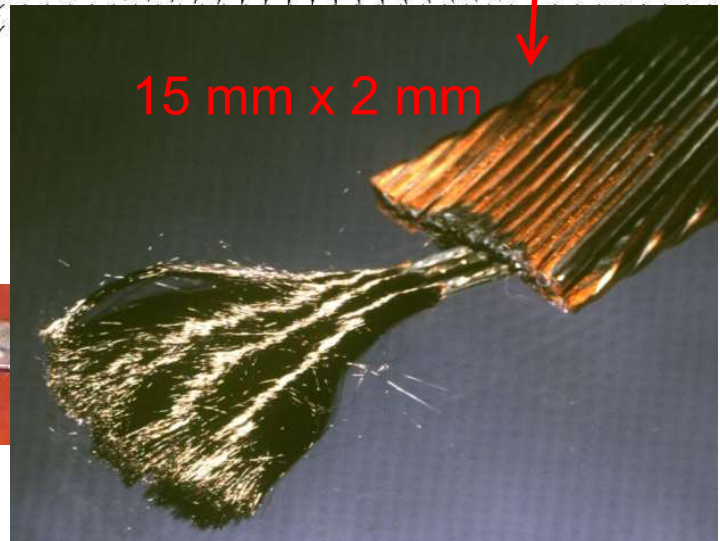
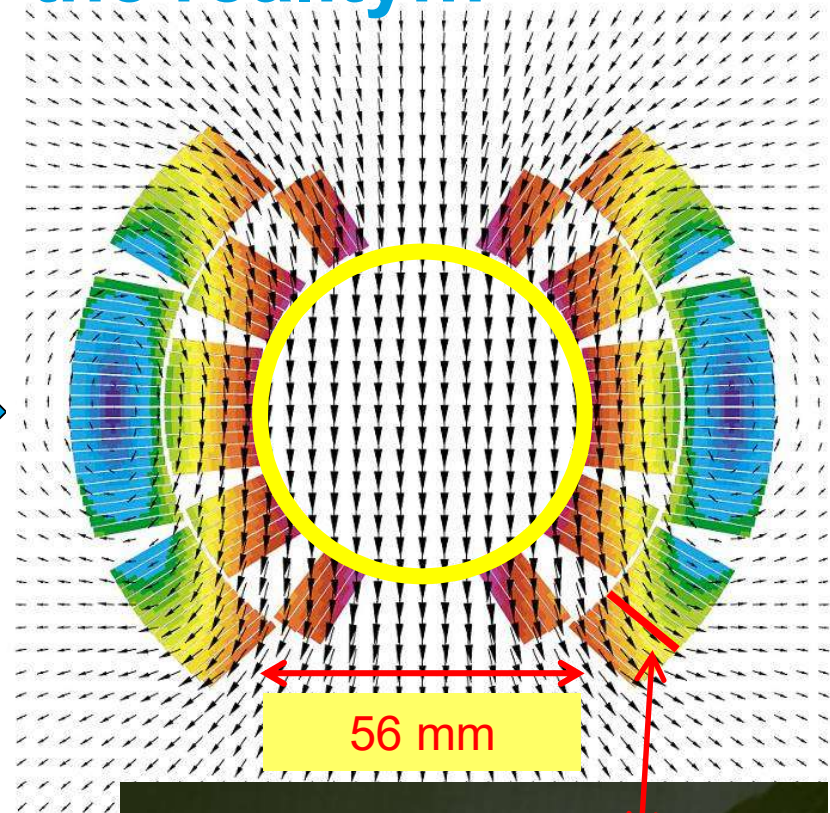
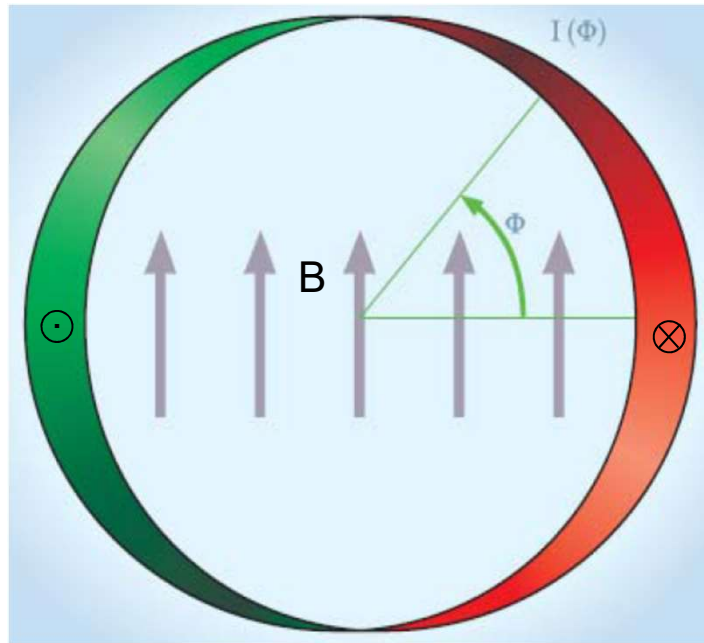
# Dipole field inside 2 conductors



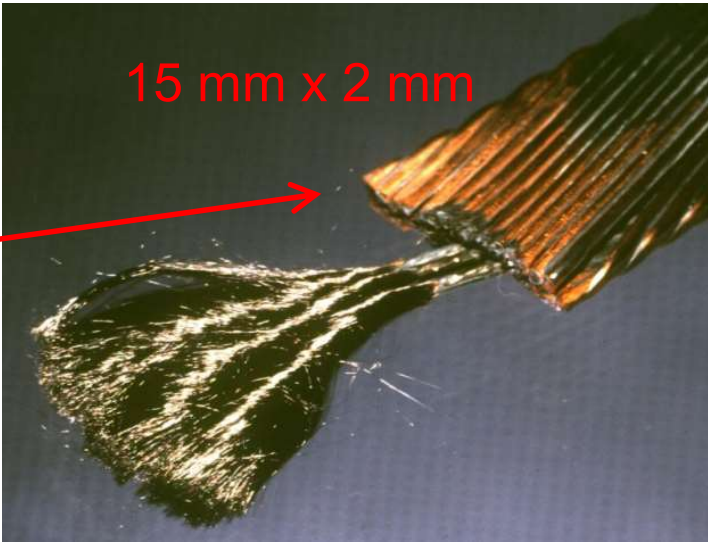
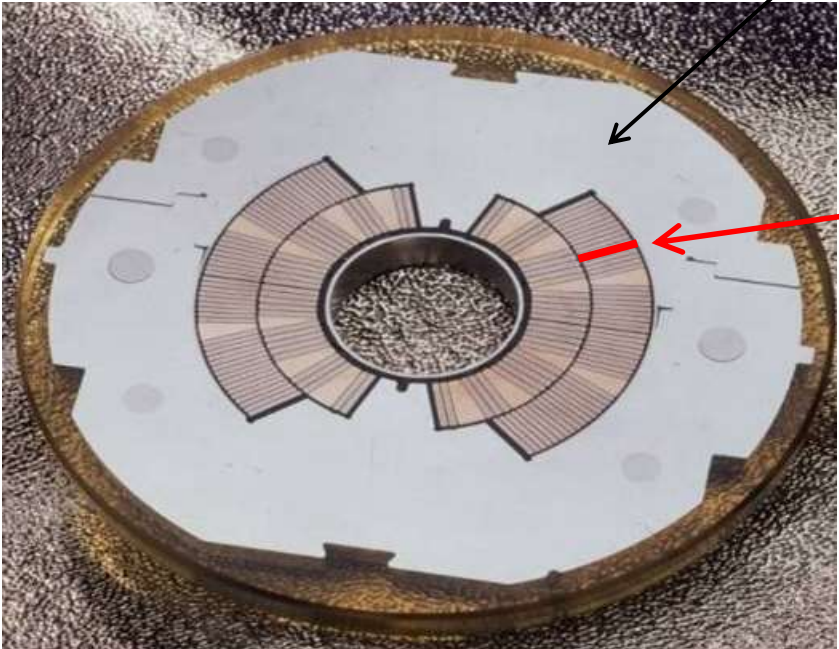
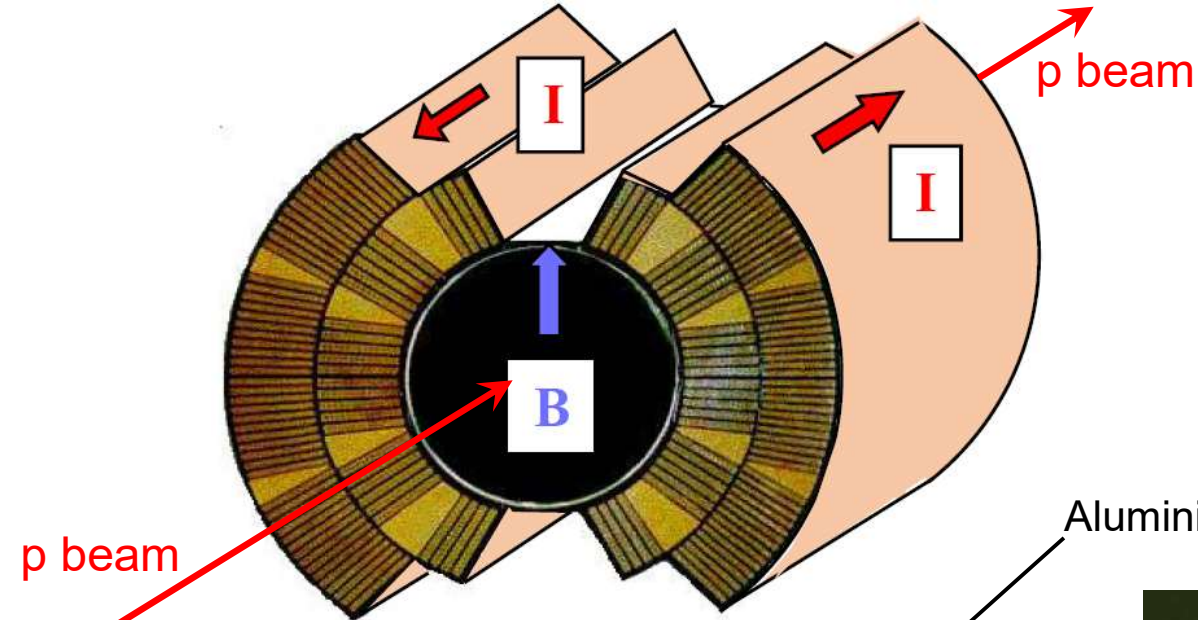
$$B_y = \frac{\mu_0 J}{2} d$$



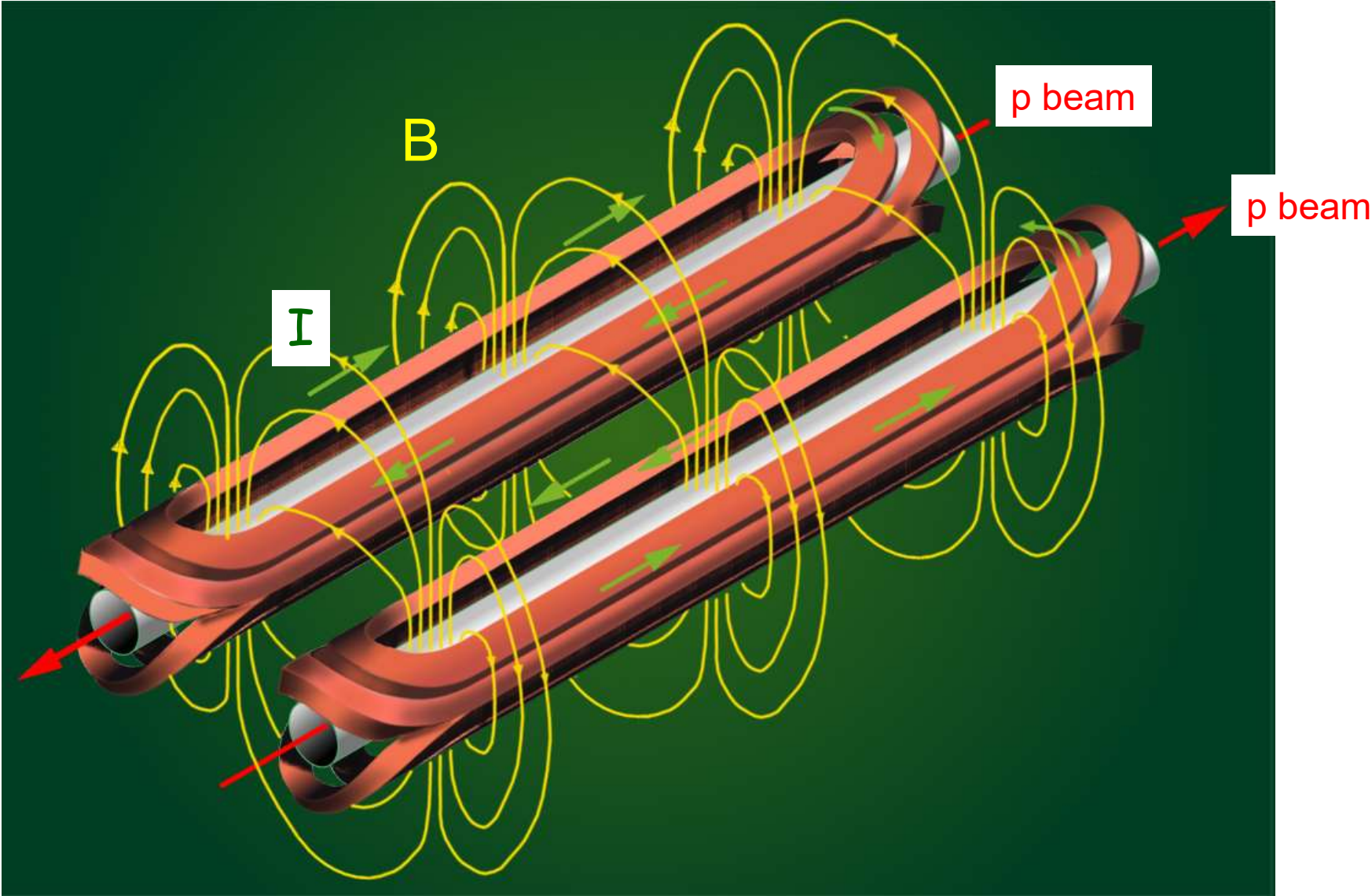
# From the principle ... to the reality...



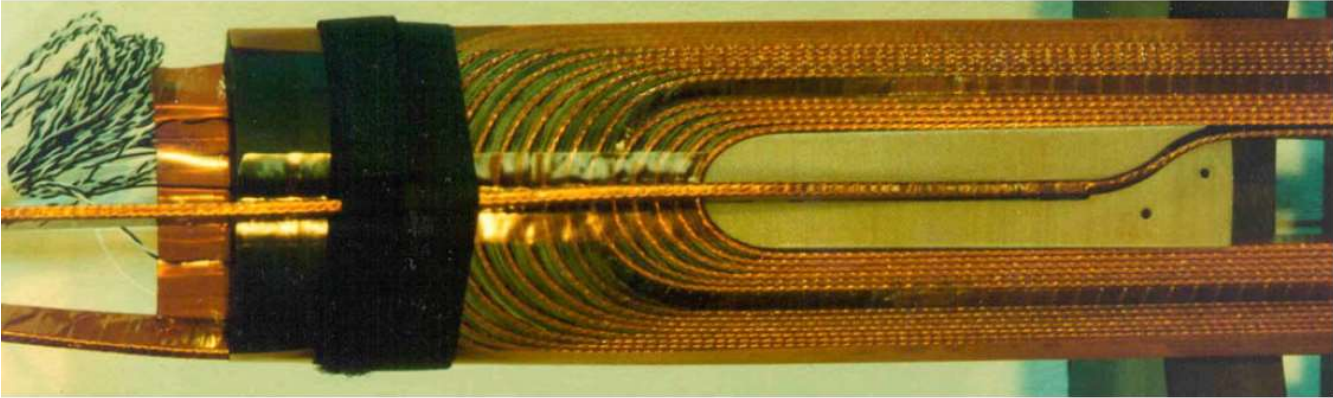
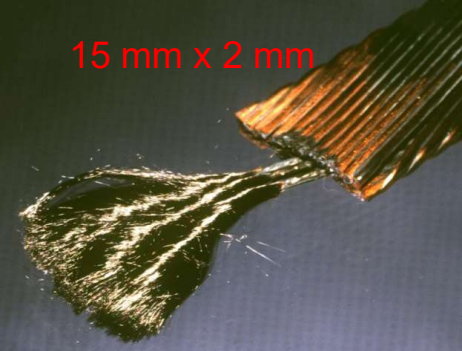
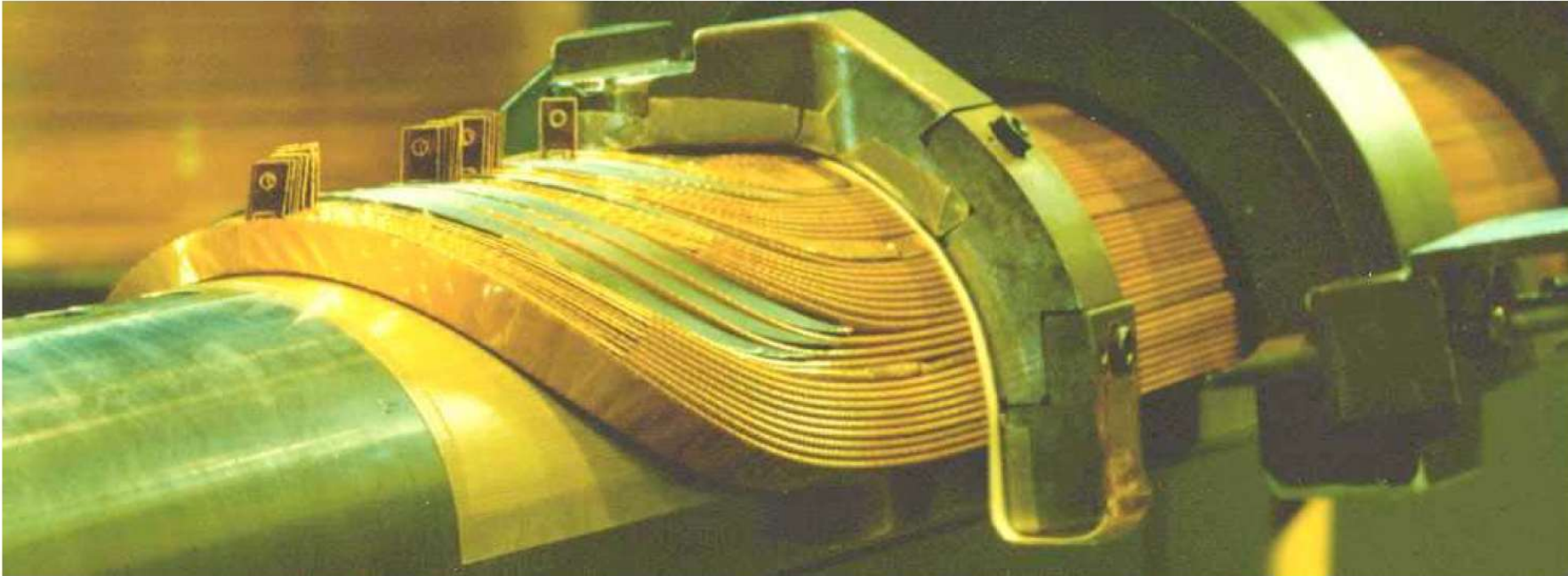
# LHC dipole coils in 3D



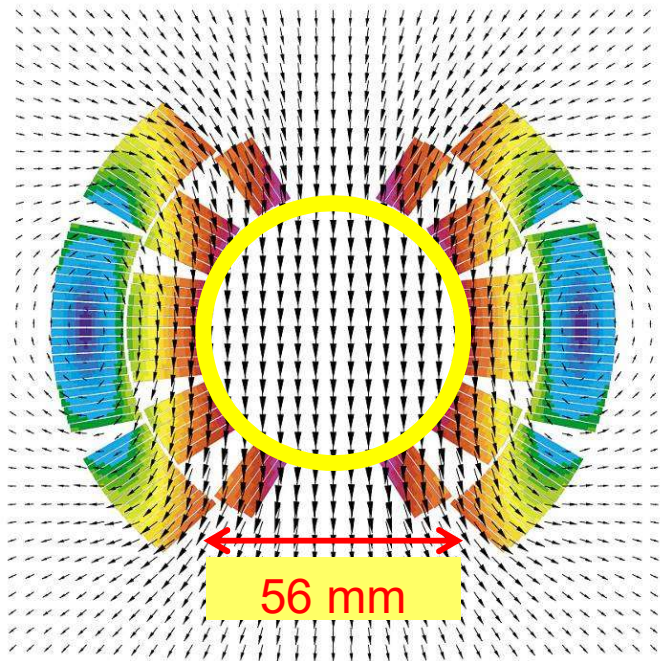
# LHC dipole coils in 3D



# LHC dipole coils in 3D

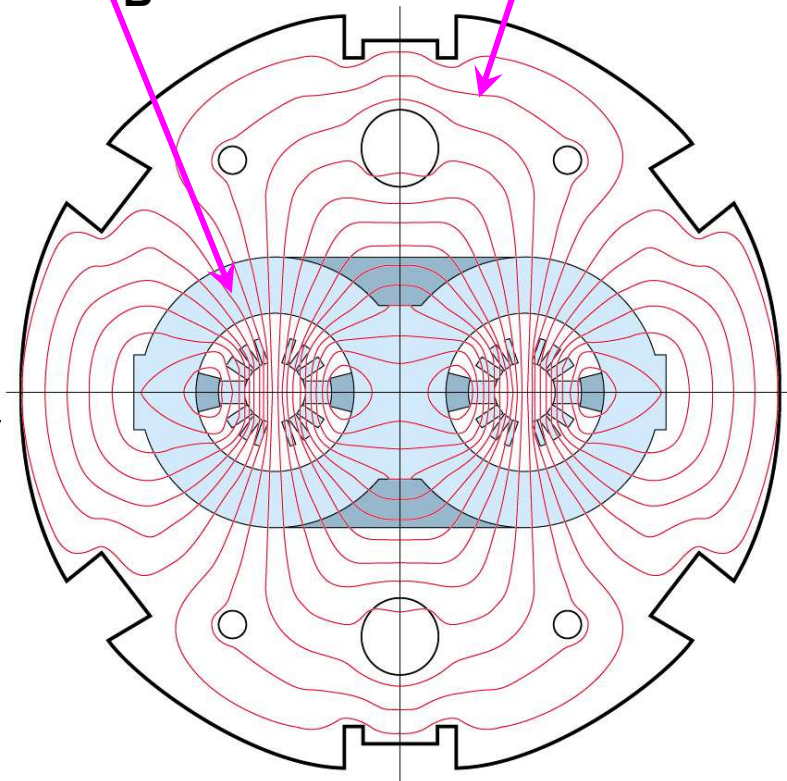


# Computed magnetic field

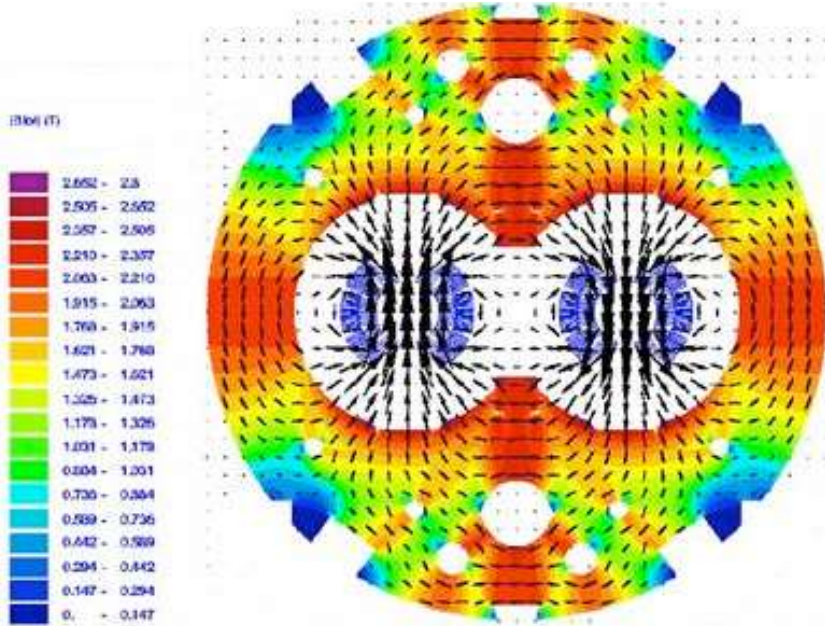


nonmagnetic collars

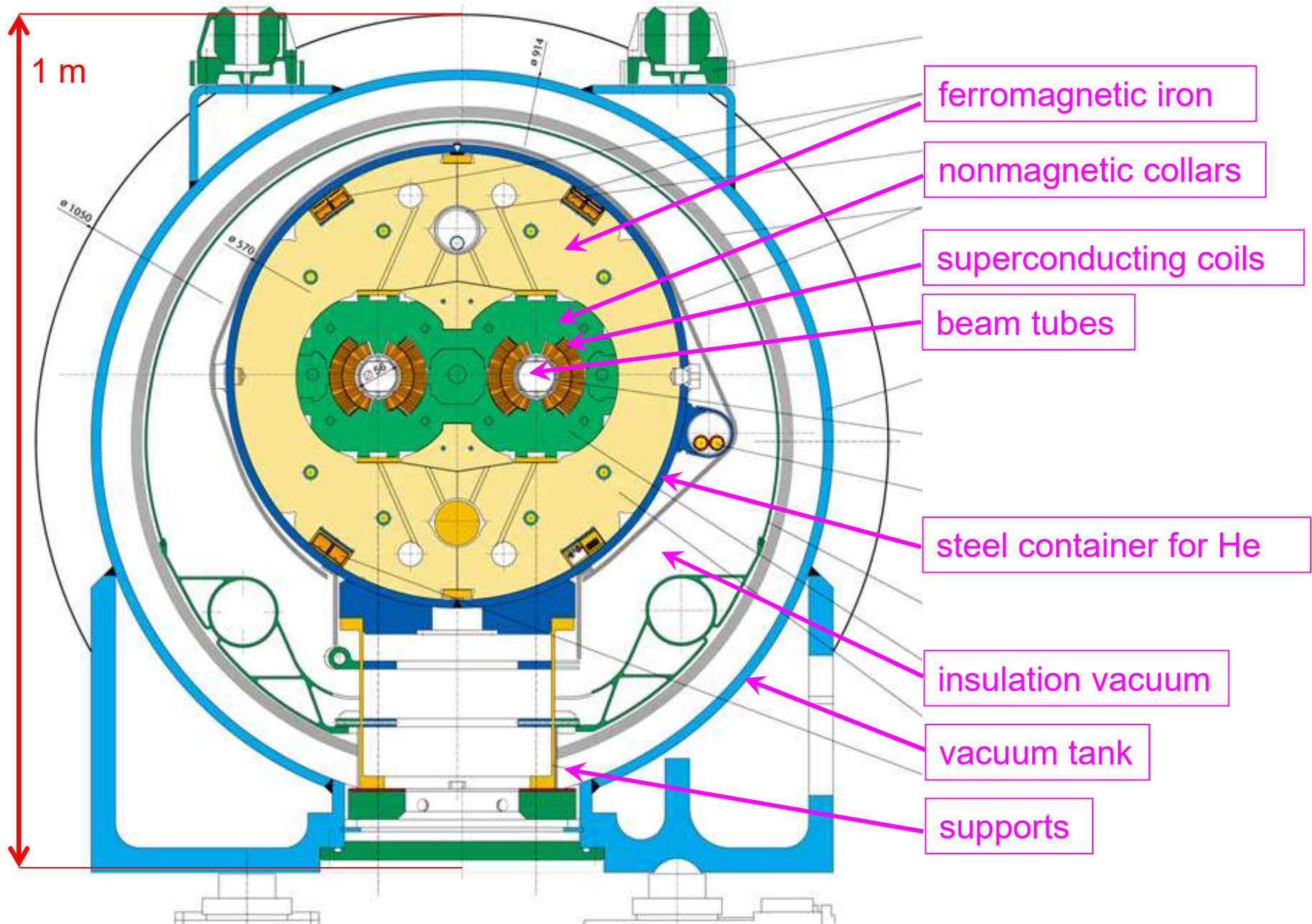
ferromagnetic iron



Computed magnetic flux map



# LHC DIPOLE : STANDARD CROSS-SECTION



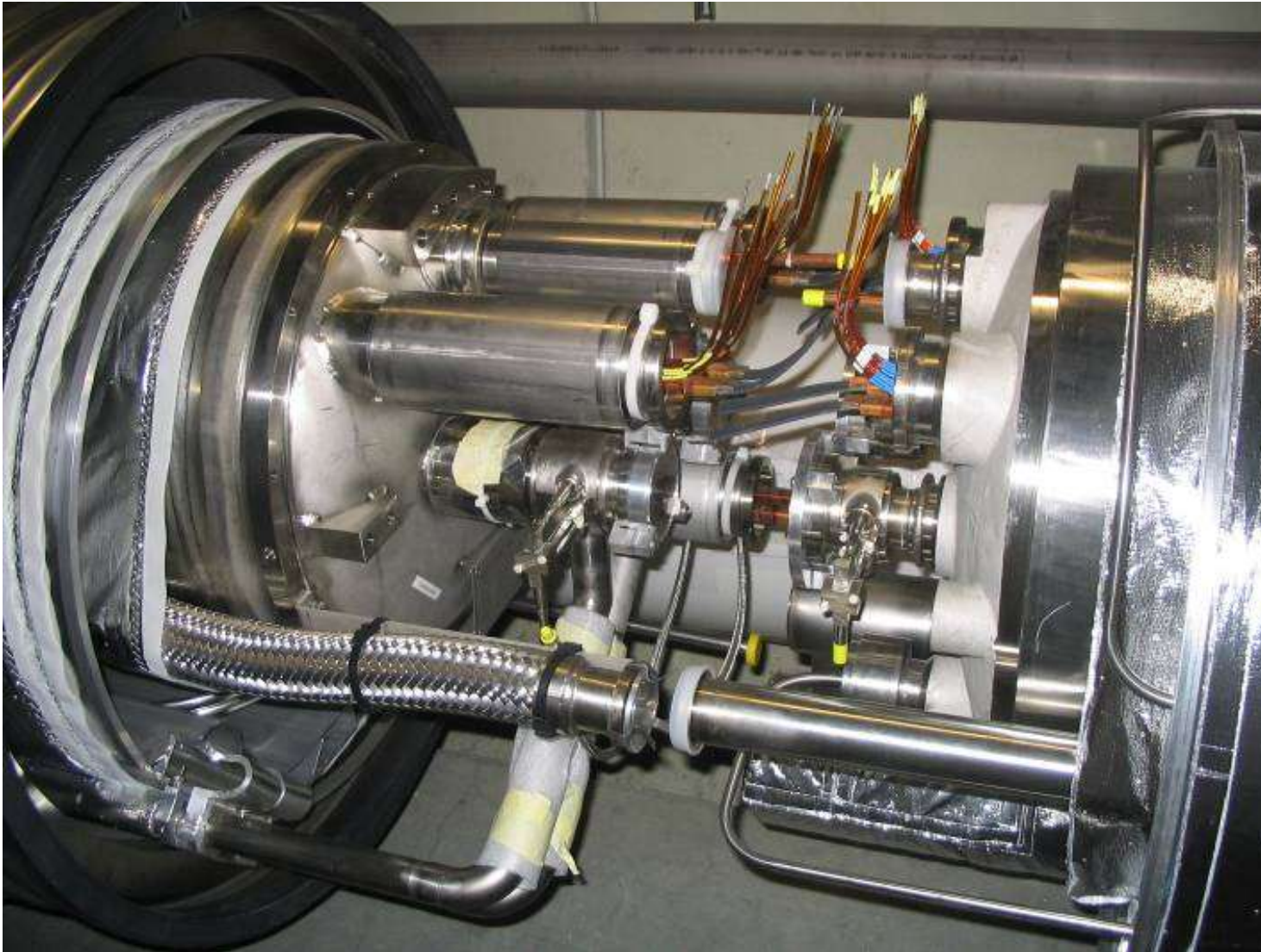
# Superconducting dipole magnets

LHC dipole magnet interconnection:



# Superconducting dipole magnets

LHC dipole magnet interconnection:



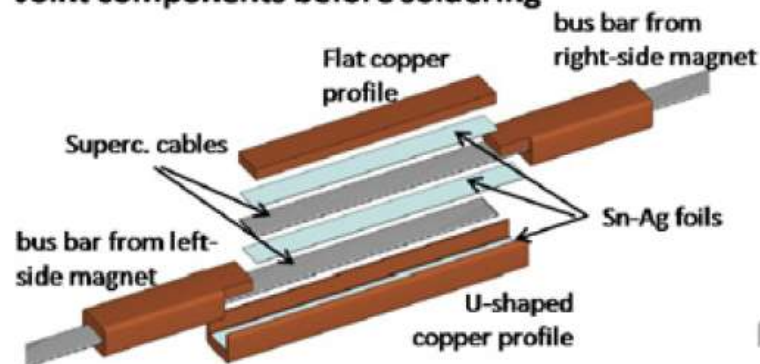


# Electrical joint between superconducting modules

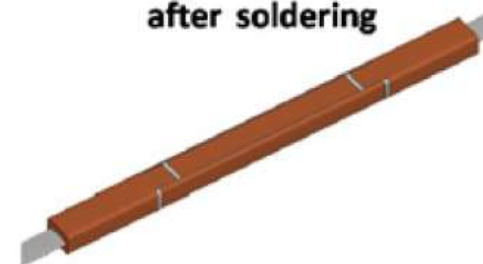
dipole bus bar splice  
(electrical joint)



Joint components before soldering



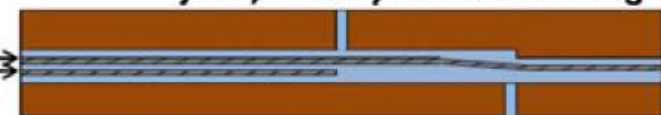
Bus bar well reconstituted after soldering



Cross section of the joint



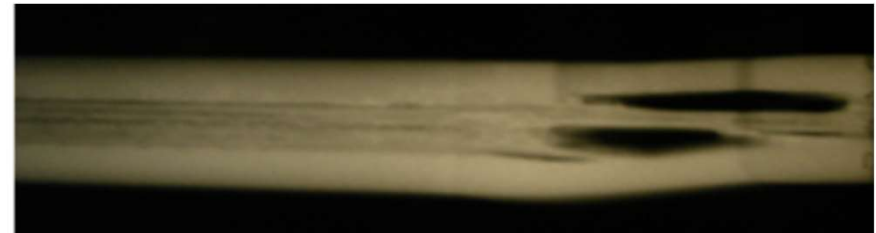
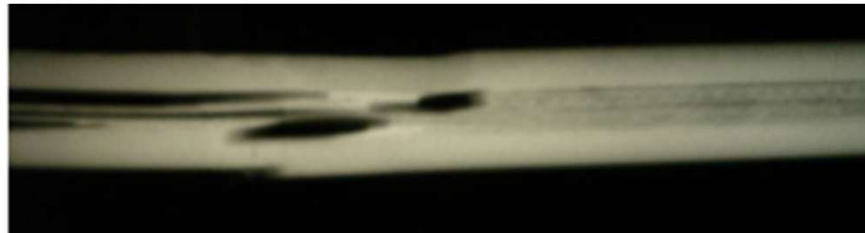
Longitudinal section of the joint, entirely filled with Sn-Ag



## Electrical joint between superconducting modules



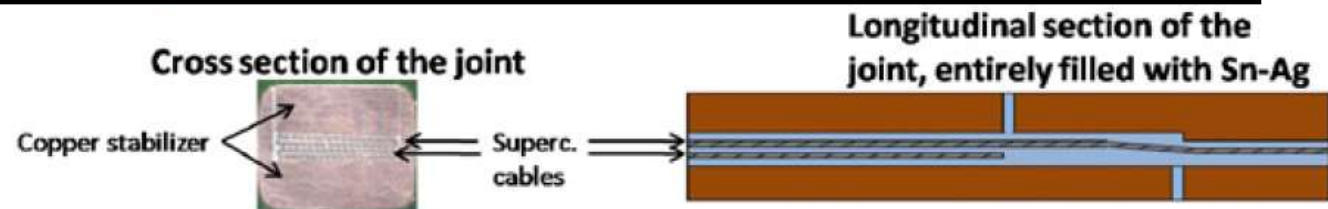
- Resistance measurements and X-ray pictures have shown the presence of many of such defective joints in the machine



## Electrical joint between superconducting modules

September 19, 2008

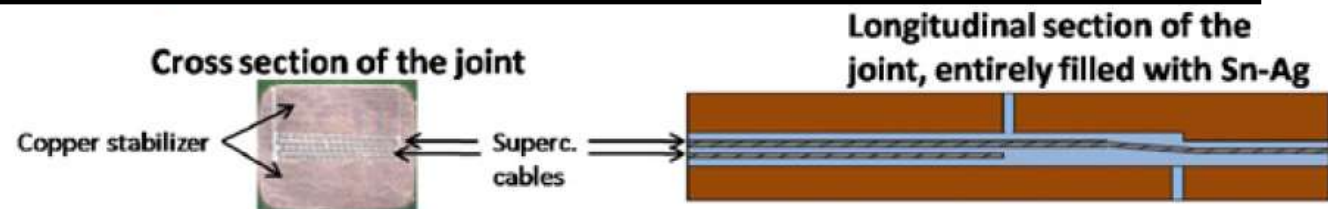
- Ramping the dipole current to 9.3 kA (6.5 T)
- At 8.7 kA, an electrical arc developed in a dipole bus bar splice, which punctured the helium enclosure
- The magnetic energy stored in one dipole string (1 octant) at 8.7kA (6.1 T) is 600 MJ which is equivalent to 140 tonnes of TNT



## Electrical joint between superconducting modules

September 19, 2008

- Ramping the dipole current to 9.3 kA (6.5 T)
- At 8.7 kA, an electrical arc developed in a dipole bus bar splice, which punctured the helium enclosure
- The magnetic energy stored in one dipole string (1 octant) at 8.7kA (6.1 T) is 600 MJ which could heat and melt 900 kg of copper



## Electrical joint between superconducting modules

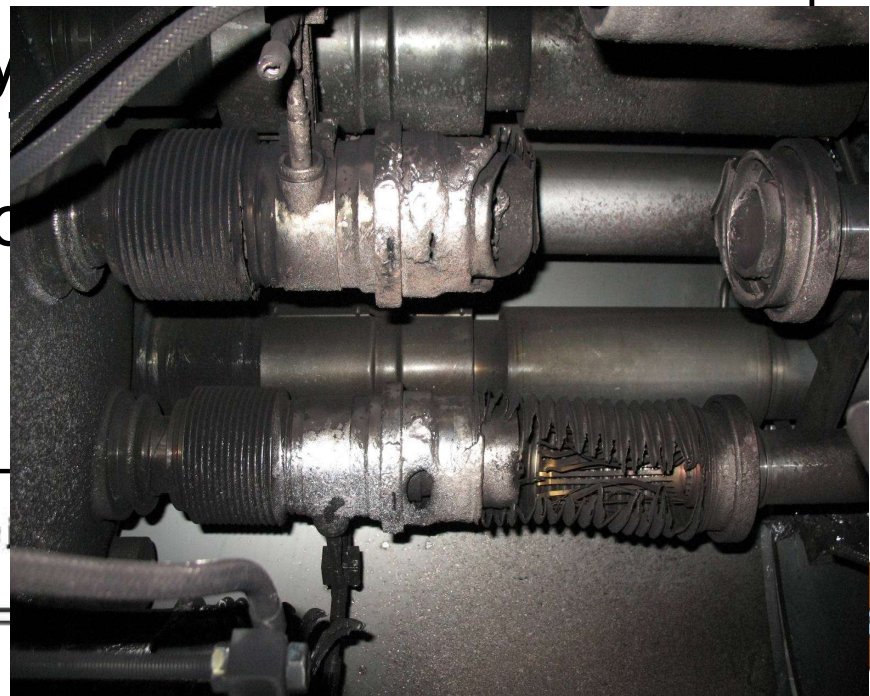
September 19, 2008

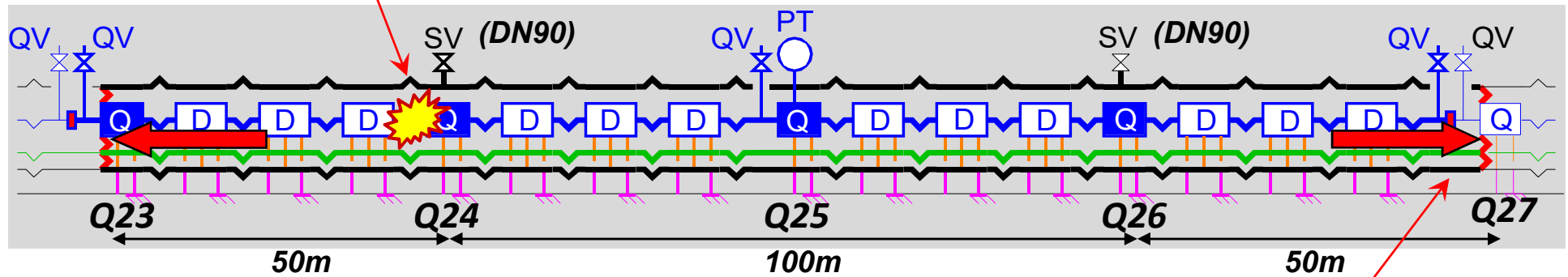
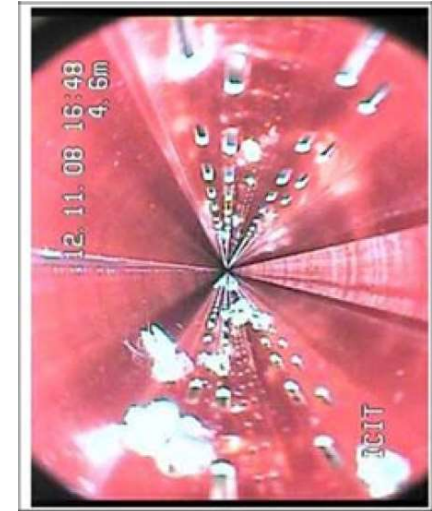
- Ramping the dipole current to 9.3 kA (6.5 T)
- At 8.7 kA, an electrical arc developed in a dipole bus bar splice, which punctured the helium enclosure



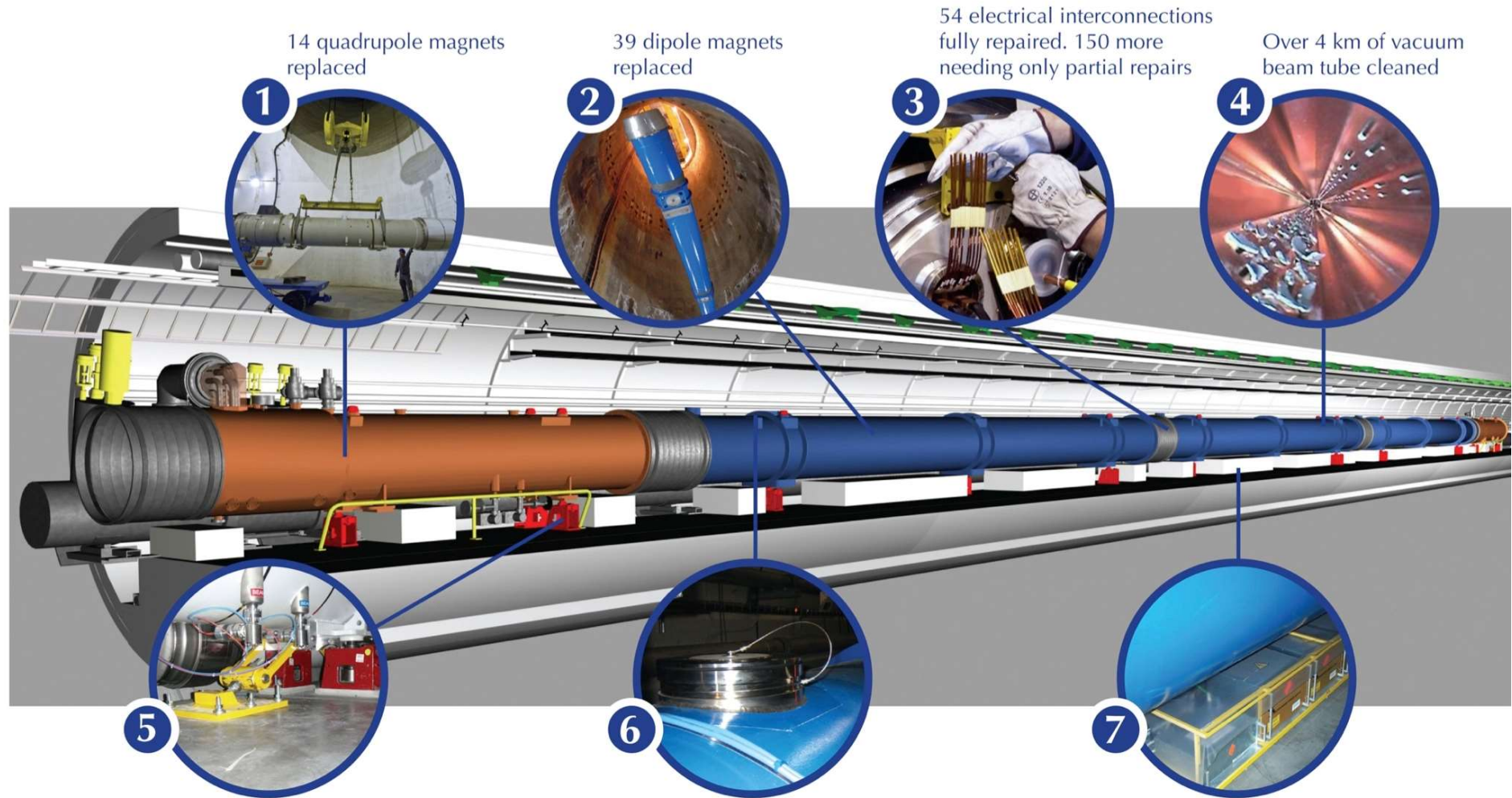
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# The LHC repairs in detail



14 quadrupole magnets replaced

39 dipole magnets replaced

54 electrical interconnections fully repaired. 150 more needing only partial repairs

Over 4 km of vacuum beam tube cleaned

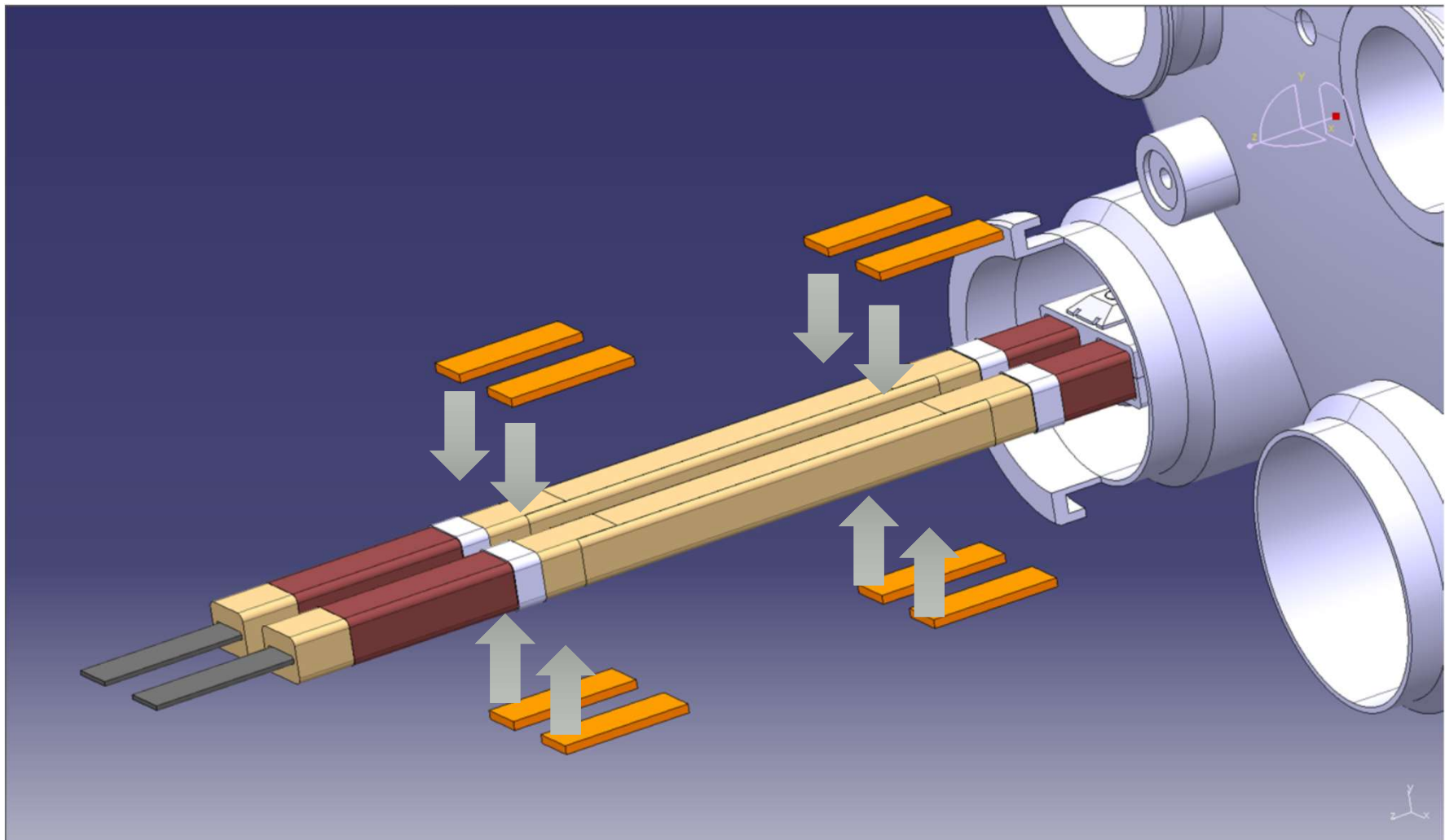
5 A new longitudinal restraining system is being fitted to 50 quadrupole magnets

6 Nearly 900 new helium pressure release ports are being installed around the machine

7 6500 new detectors are being added to the magnet protection system, requiring 250 km of cables to be laid



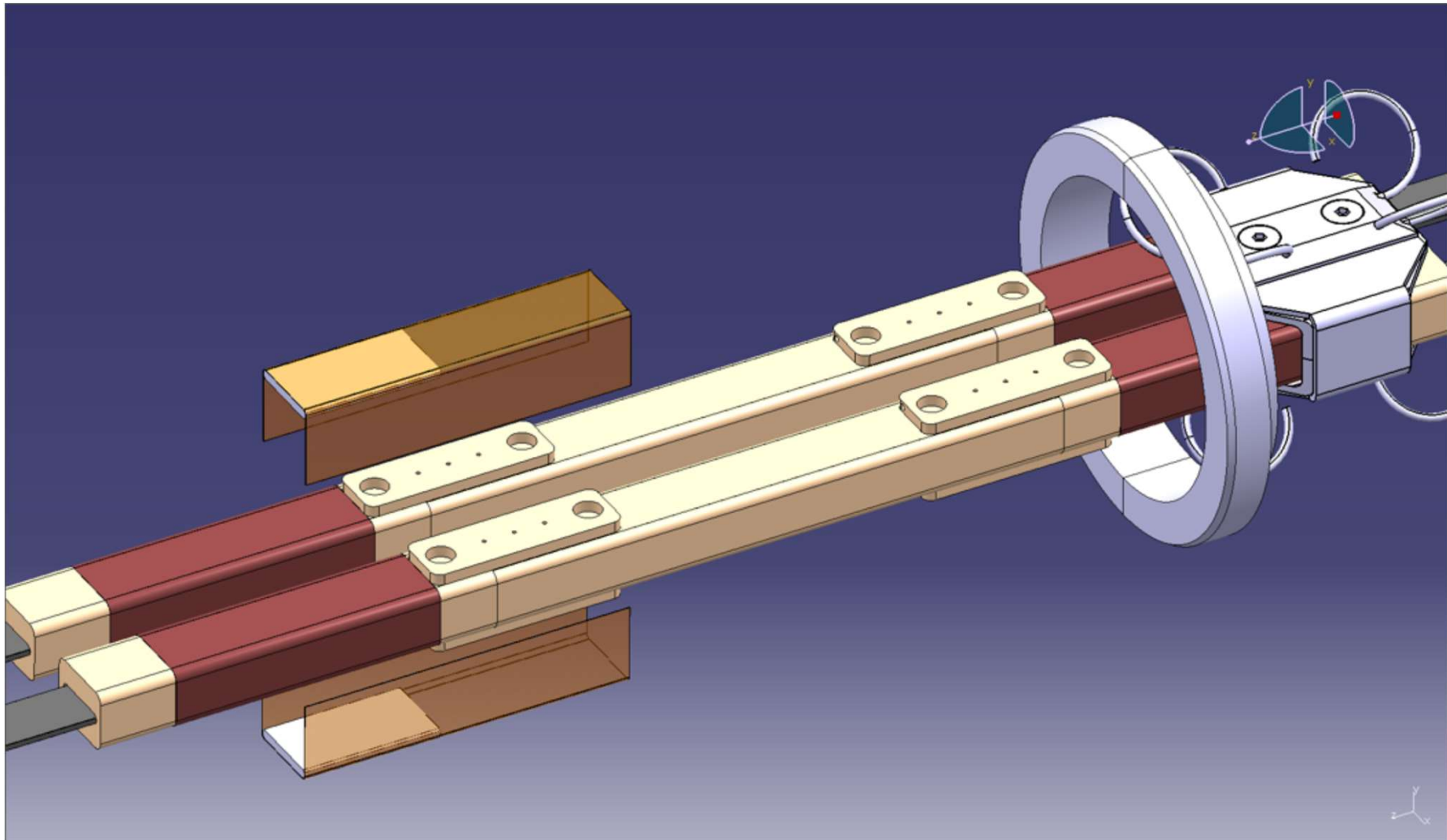
## New electrical joint between superconducting modules



Phase I  
Surfacing of bus bar and installation of redundant shunts by soldering

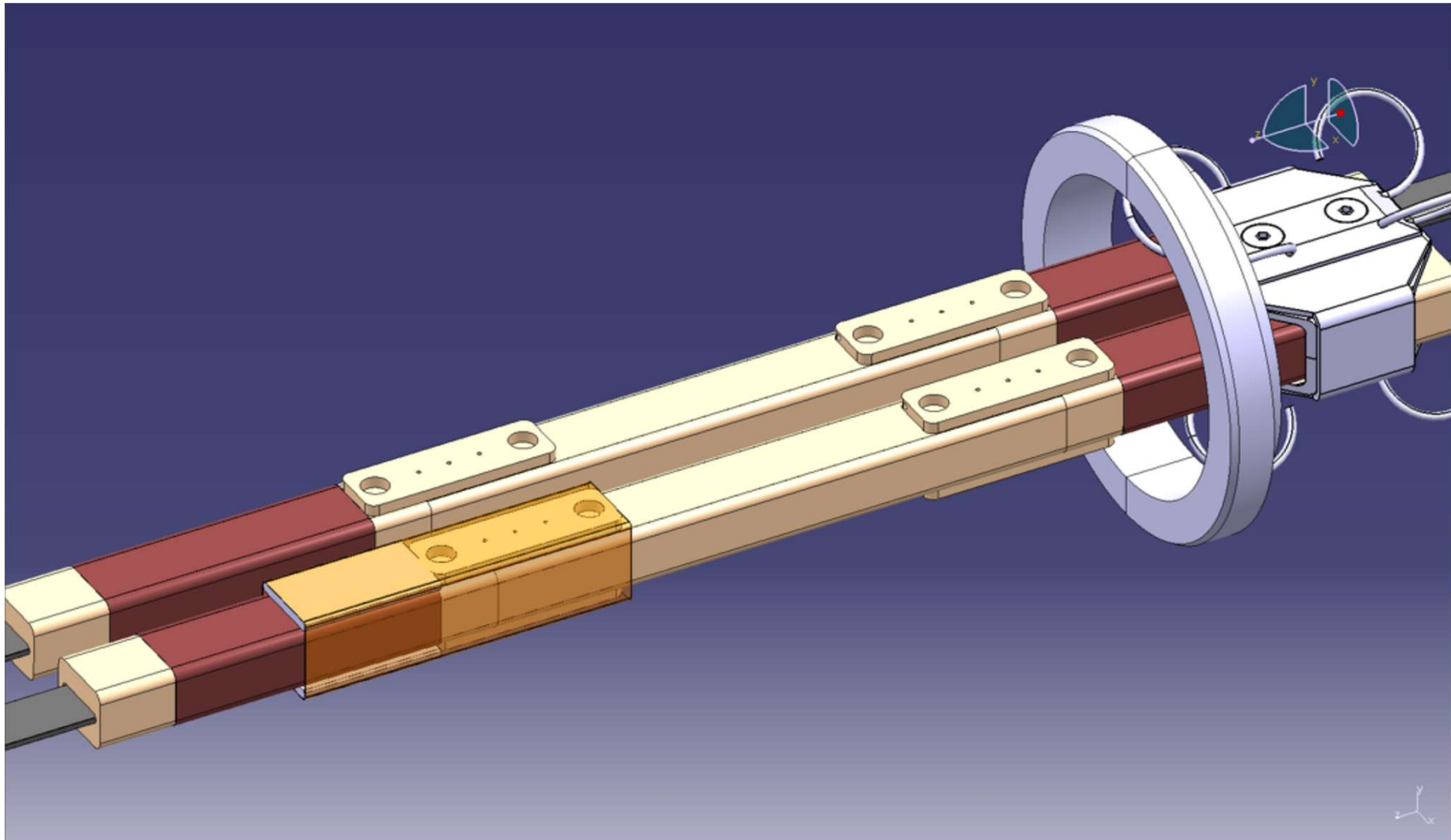


## New electrical joint between superconducting modules



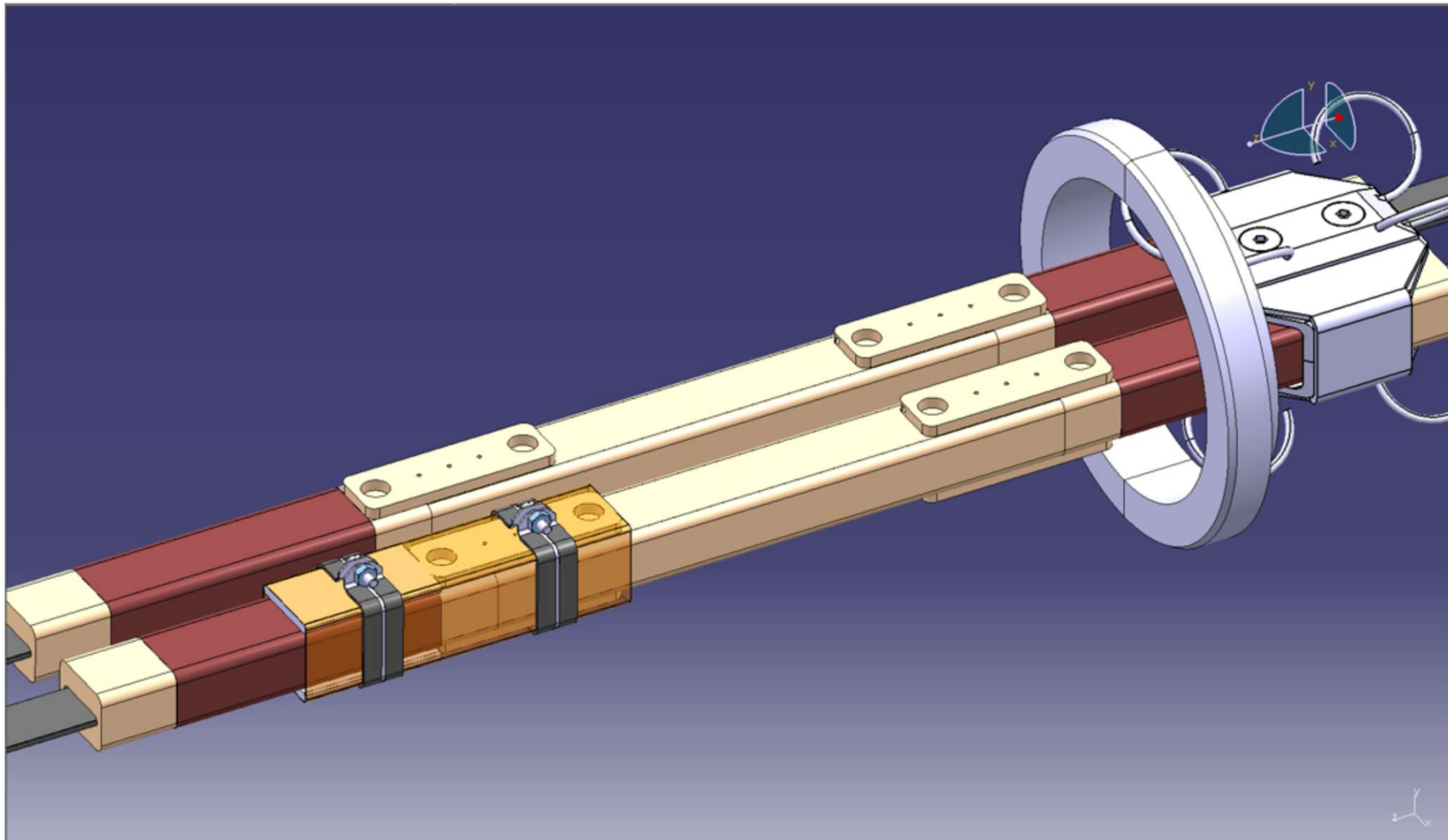
Phase II  
Application of clamp and reinforcement of nearby bus bar insulation

## New electrical joint between superconducting modules



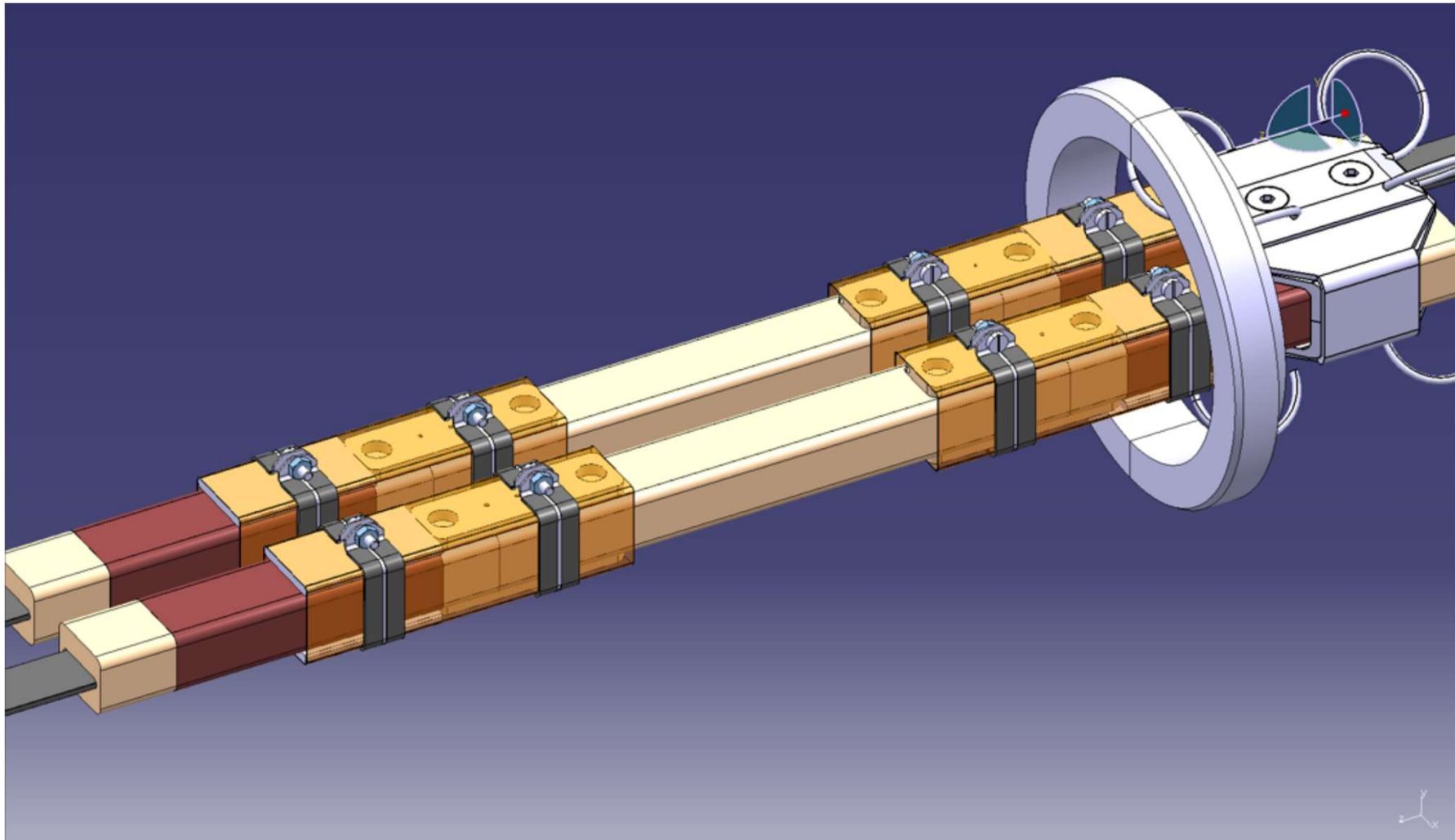
Phase II  
Application of clamp and reinforcement of nearby bus bar insulation

## New electrical joint between superconducting modules



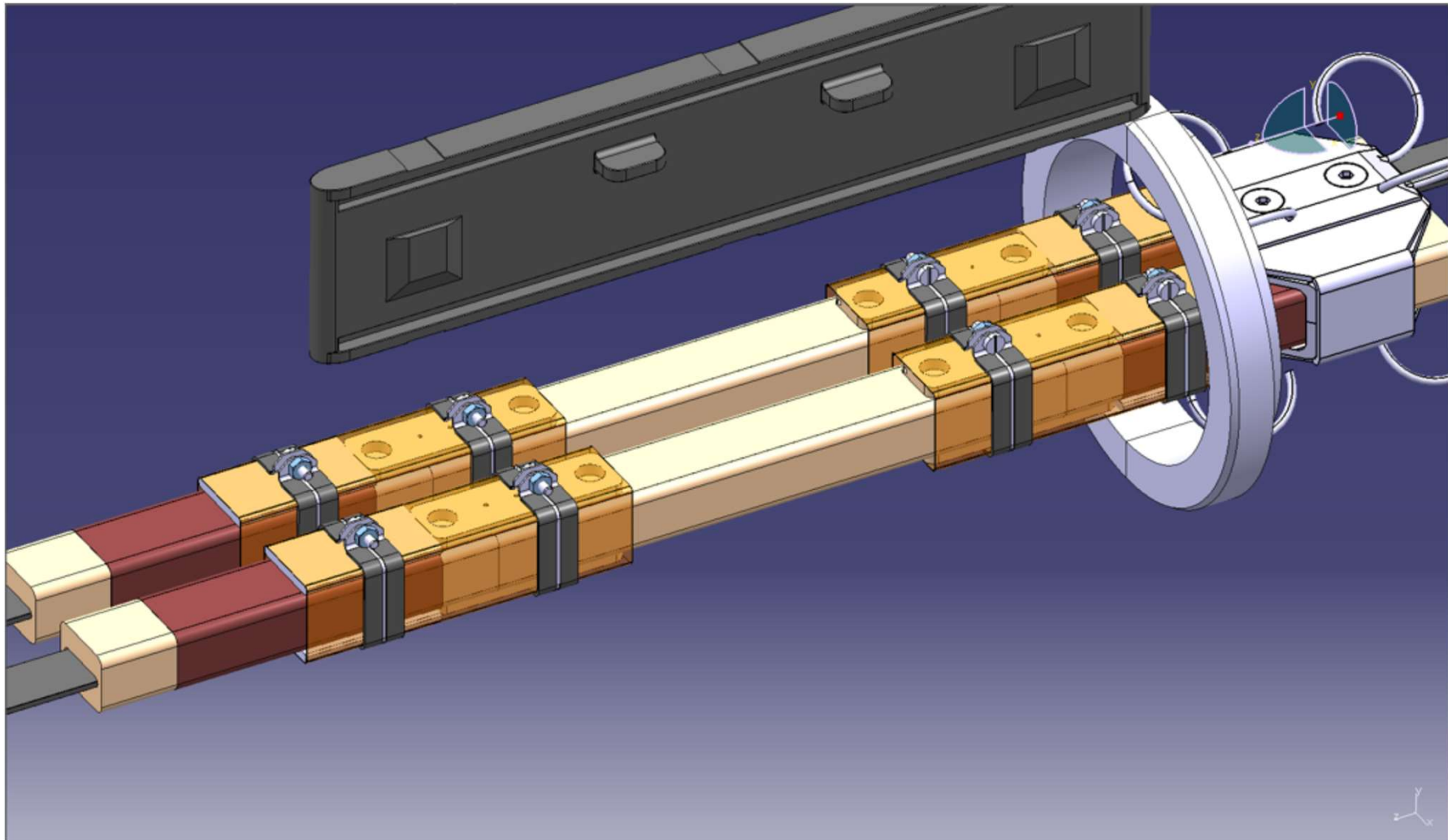
Phase II  
Application of clamp and reinforcement of nearby bus bar insulation

## New electrical joint between superconducting modules



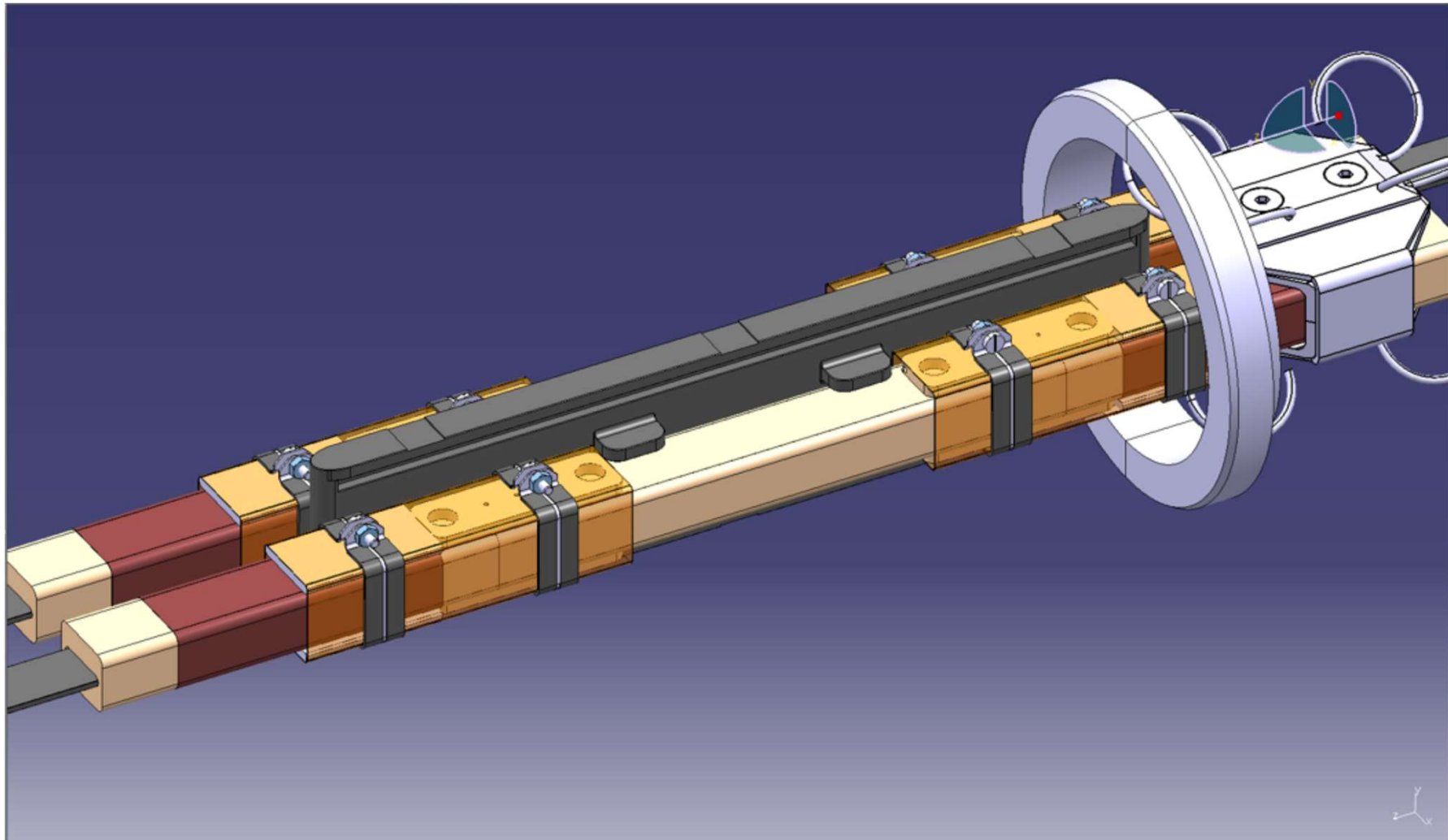
Phase II  
Application of clamp and reinforcement of nearby bus bar insulation

## New electrical joint between superconducting modules



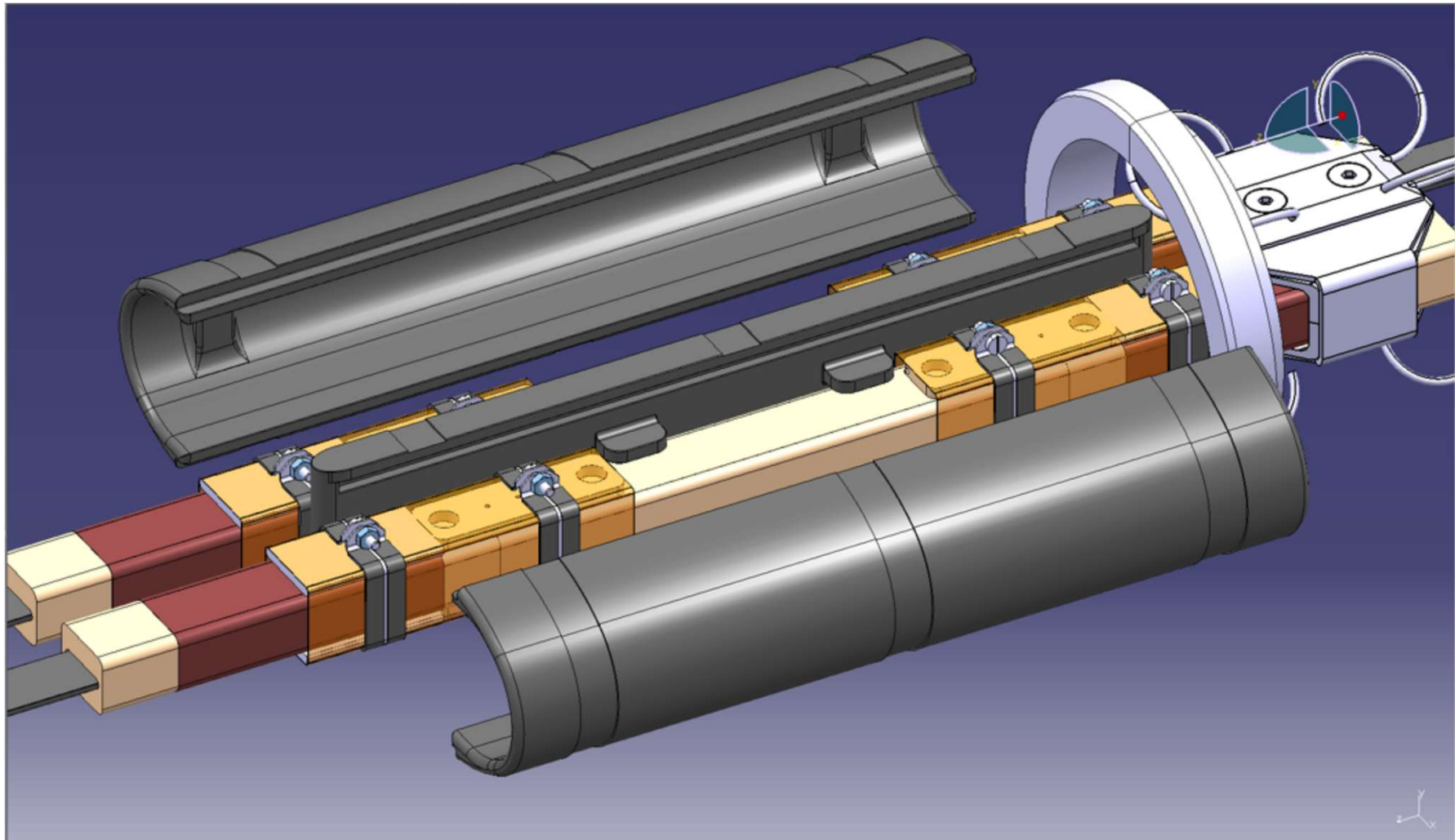
Phase III  
Insulation between bus bar and to ground, Lorentz force clamping

## New electrical joint between superconducting modules



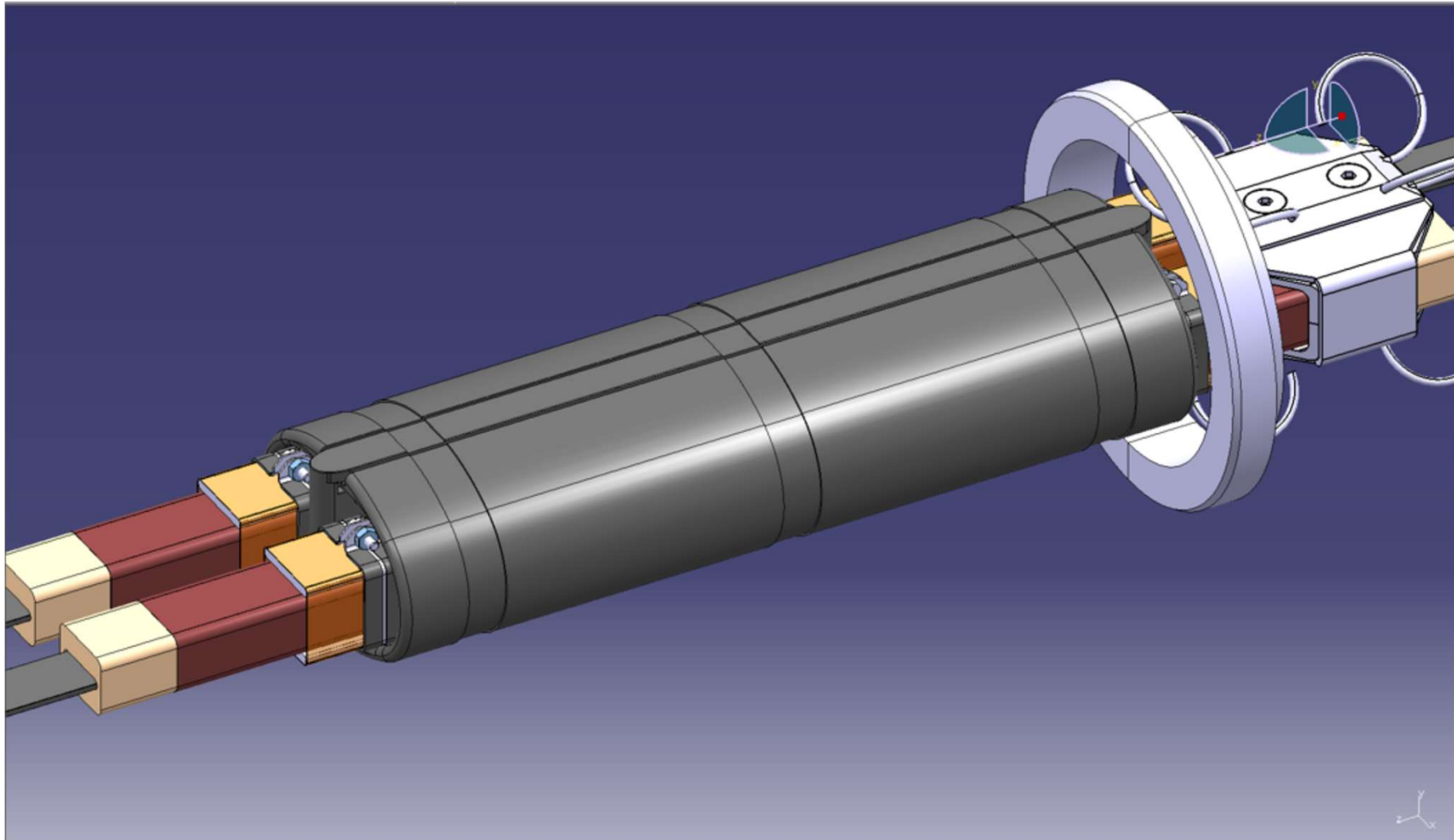
Phase III  
Insulation between bus bar and to ground, Lorentz force clamping

## New electrical joint between superconducting modules



Phase III  
Insulation between bus bar and to ground, Lorentz force clamping

## New electrical joint between superconducting modules

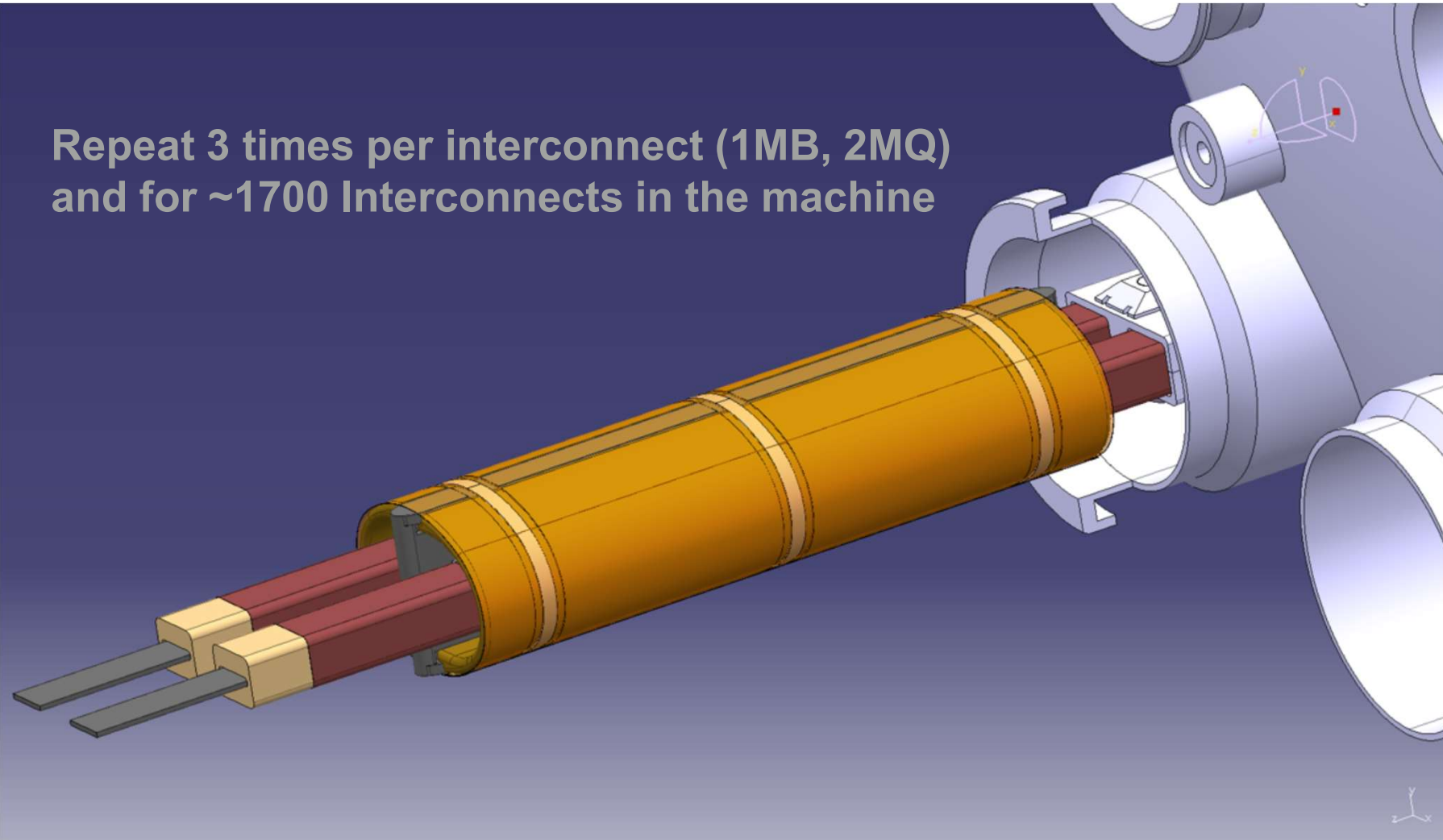


Phase III  
Insulation between bus bar and to ground, Lorentz force clamping



## New electrical joint between superconducting modules

Repeat 3 times per interconnect (1MB, 2MQ)  
and for ~1700 Interconnects in the machine



Phase III  
Insulation between bus bar and to ground, Lorentz force clamping

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# The Nobel Prize in Physics 2013

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**François Englert**

Prize share: 1/2



© Nobel Media AB. Photo: A. Mahmoud

**Peter W. Higgs**

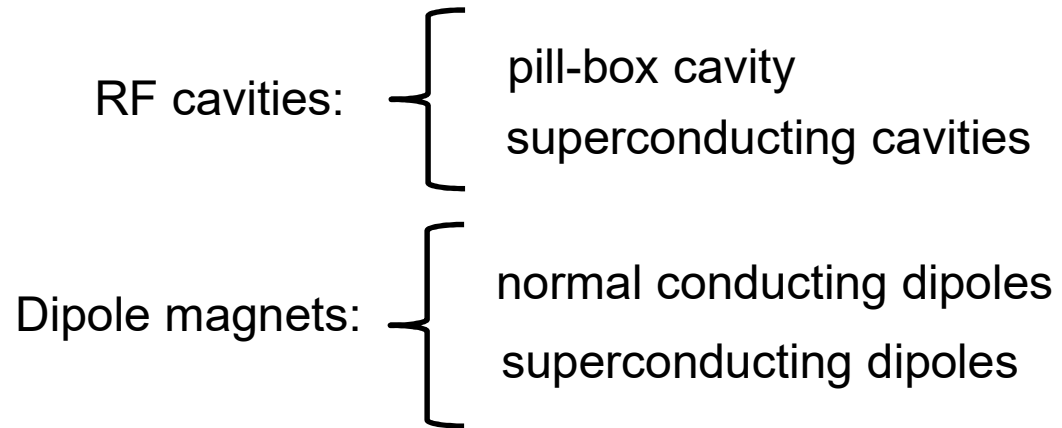
Prize share: 1/2

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The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider."

# Summing-up of this part

Circular accelerators: the synchrotron



„I cannot teach anybody anything,  
I can only make them think.“ (Socrates)

## Contact

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