Introduction to Accelerator Physics

Part 4

Pedro Castro / Accelerator Physics Group (MPY)
Hamburg, 26th July 2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

LHC commissioning

April 2008
Last dipole down
(Total: 1232 dipoles)

September 10, 2008
First beams around

2008 | 2009 | 2010

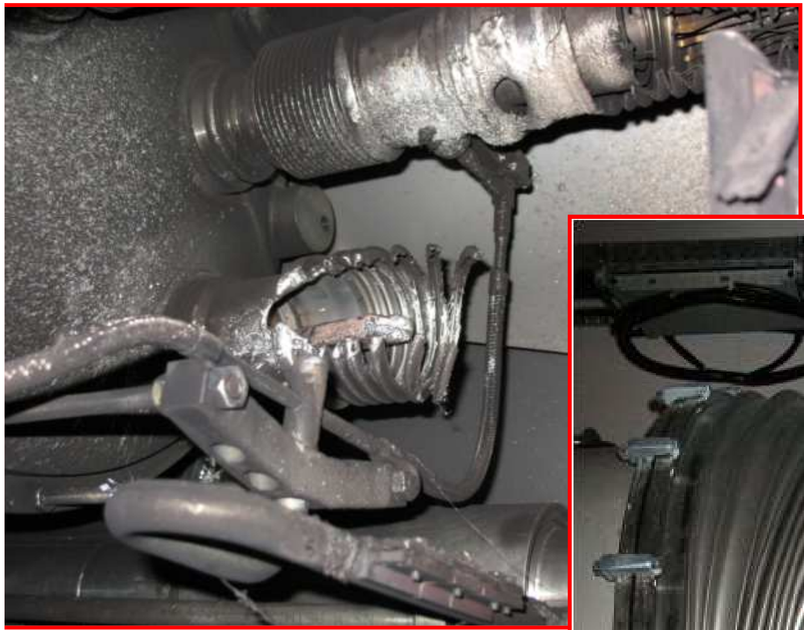
September 30, 2008
First collisions planned …

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

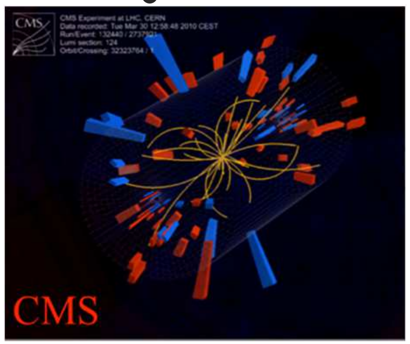
Repair and Consolidation

November 20, 2009
Beam back

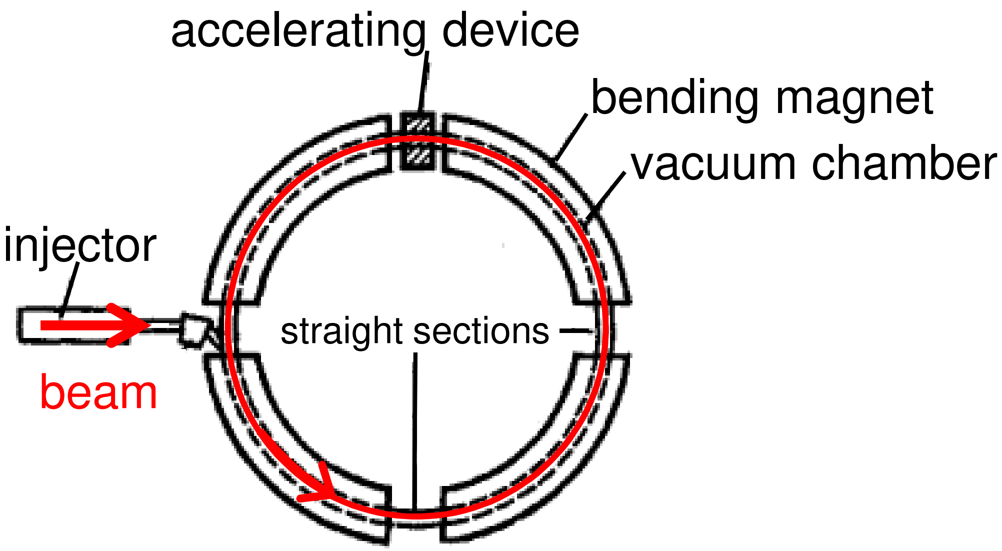
2008 | 2009 | 2010

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

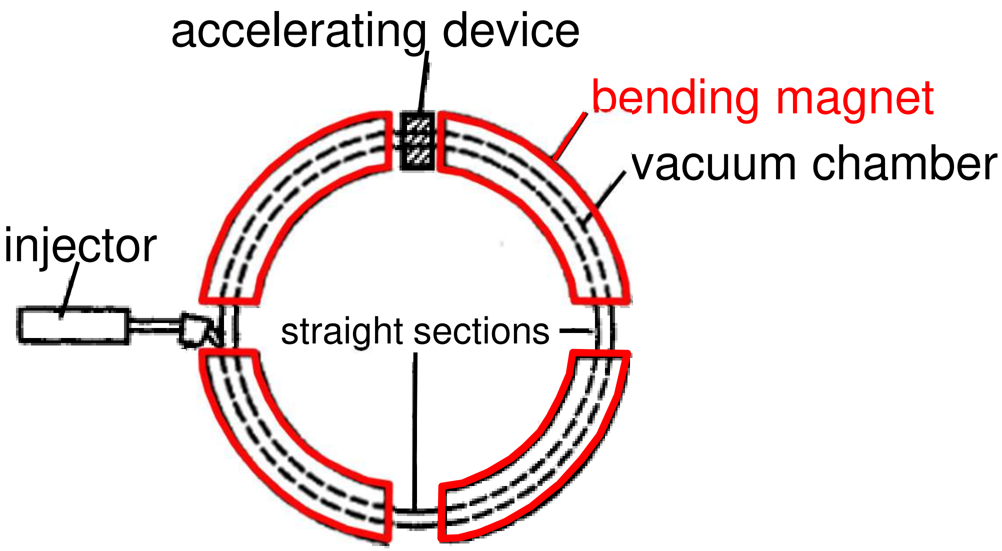
March 30, 2010
First collisions at 3.5 TeV



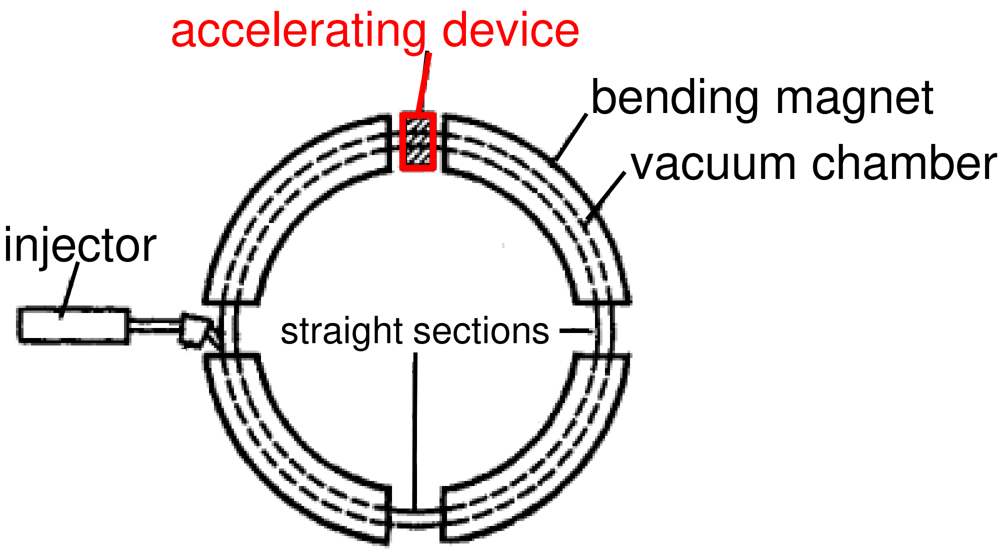
Circular accelerators: the synchrotron



Circular accelerators: the synchrotron

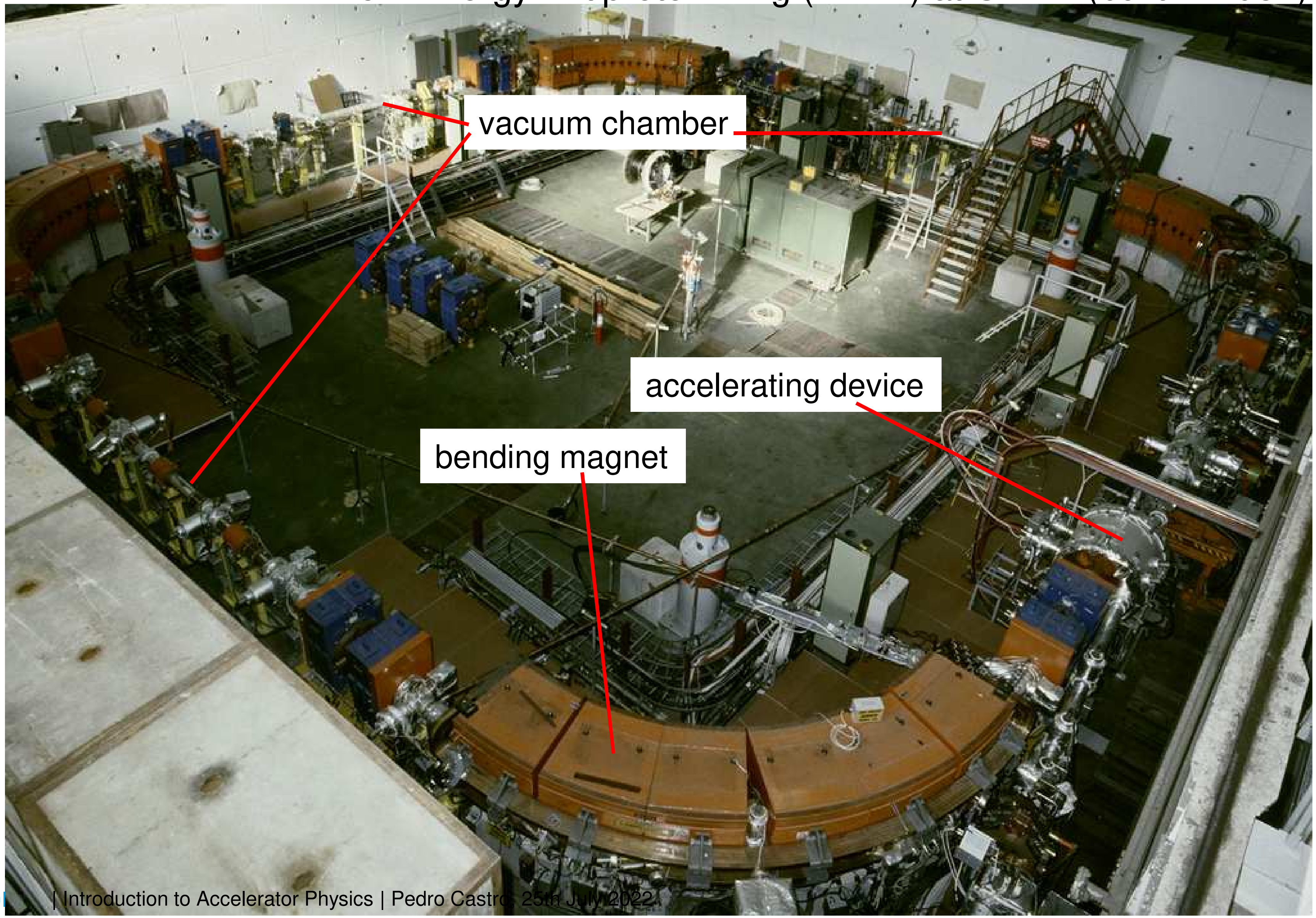


Circular accelerators: the synchrotron

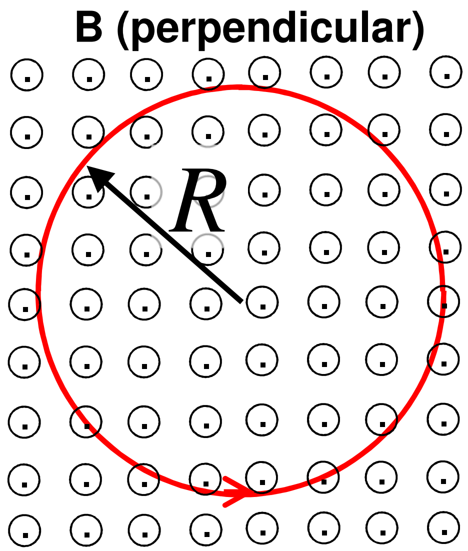


Circular accelerators: the synchrotron

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 — of the particle; magnetic field

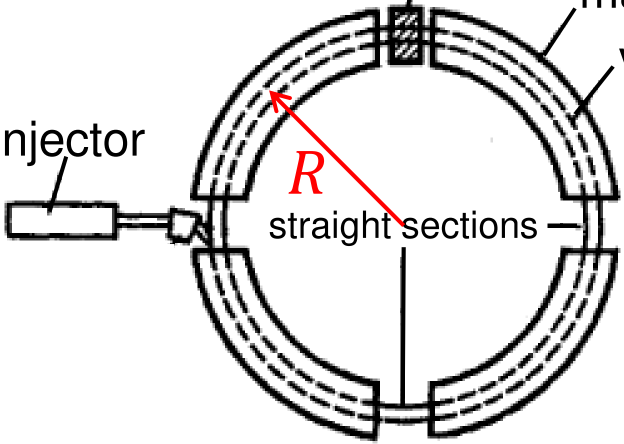
$$\vec{B} \perp \vec{v} \quad \rightarrow \quad F = qvB$$

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

(circular motion)

$$qB = \frac{mv}{R} \quad \rightarrow \quad R = \frac{mv}{qB}$$

Circular accelerators: the synchrotron



$$\vec{B} \perp \vec{v} \quad \rightarrow \quad F = qvB$$

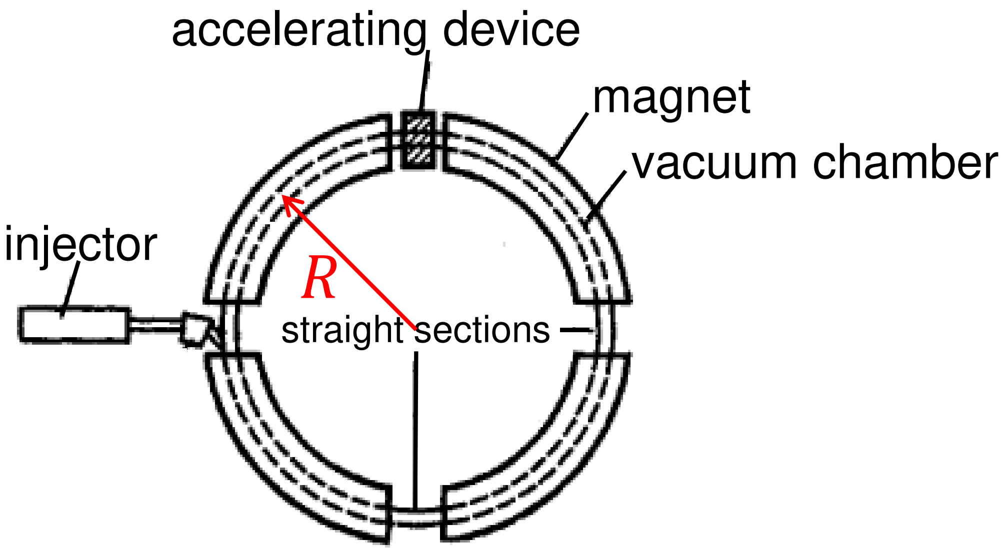
$$\vec{F} \perp \vec{v} \quad \rightarrow \quad F = m\frac{v^2}{R}$$

(circular motion)

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

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

Circular accelerators: the synchrotron



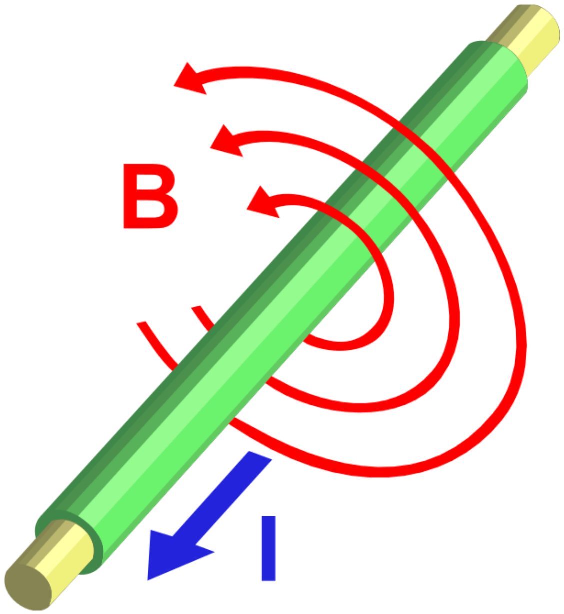
$$\vec{B} \perp \vec{v} \quad \rightarrow \quad F = qvB$$

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

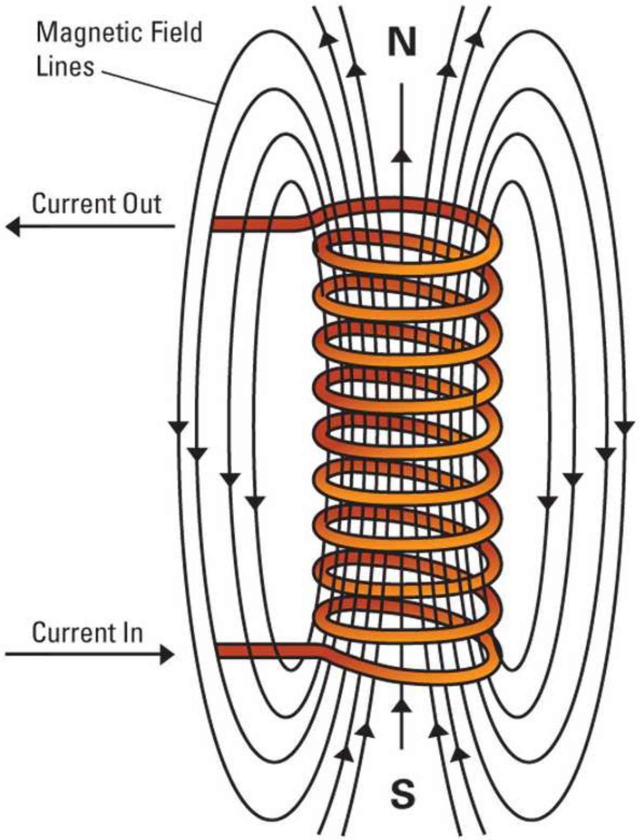
(circular motion)

$$qB = \frac{mv}{R} \rightarrow R = \frac{(mv)_{max}}{qB_{max}} = constant$$

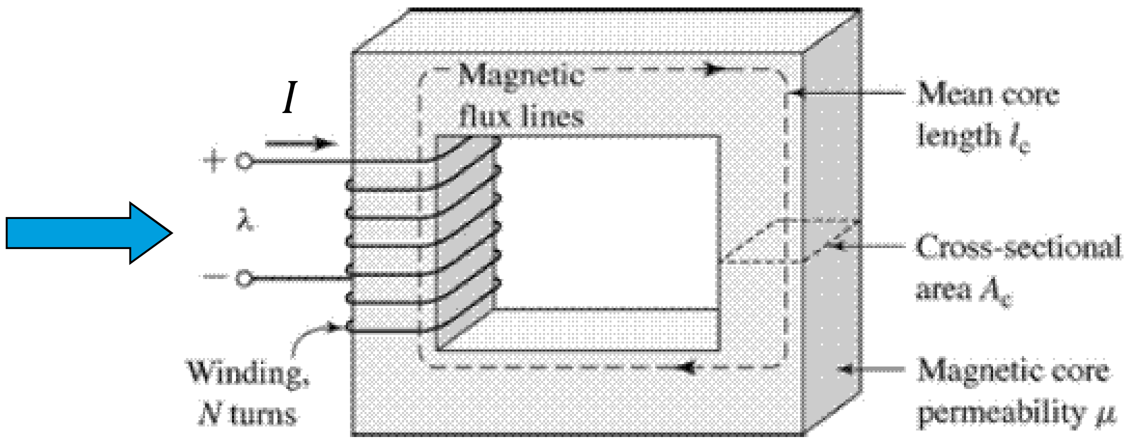
Electromagnet



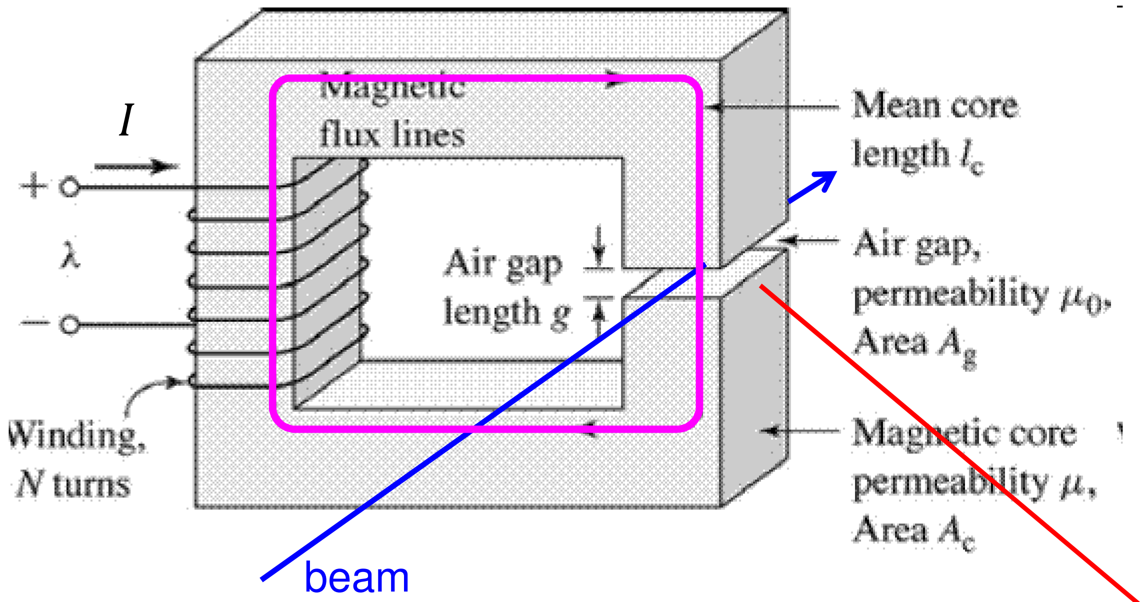
Electromagnet



permeability of iron = 300…10000 larger than air



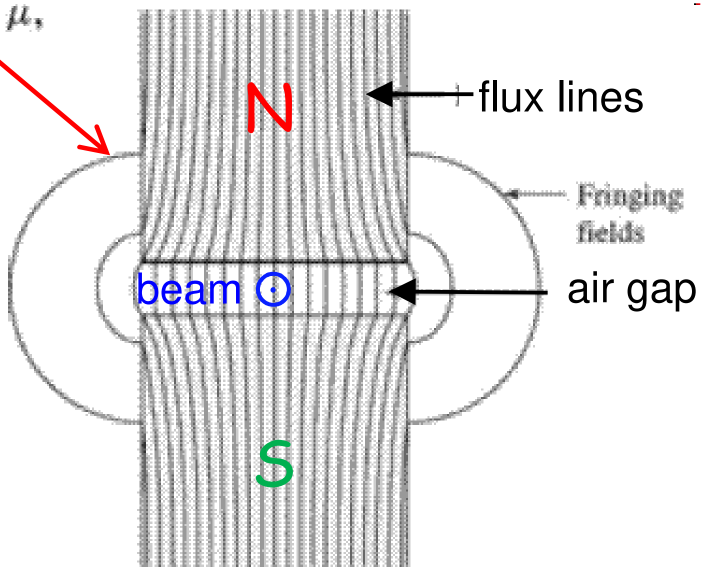
Dipole magnet



$$\int_{gap} \frac{\vec{B}}{\mu_0} \overrightarrow{ds} = \frac{B g}{\mu_0} = N\, I$$

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

gap height



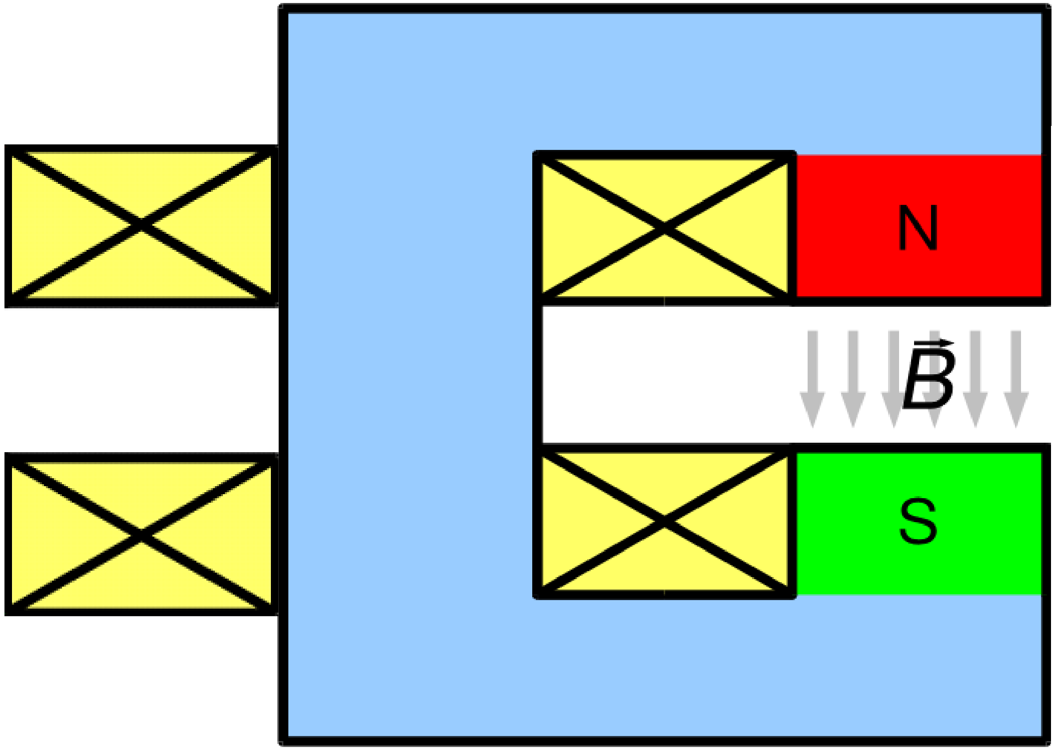
Ampere's law:

$$\oint \vec{H}\, \overrightarrow{ds} = I_{enclosed} = NI$$

$$\oint \vec{H}\, \overrightarrow{ds} = \int_{iron} \vec{H}\, \overrightarrow{ds} + \int_{gap} \vec{H}\, \overrightarrow{ds} = N\, I$$

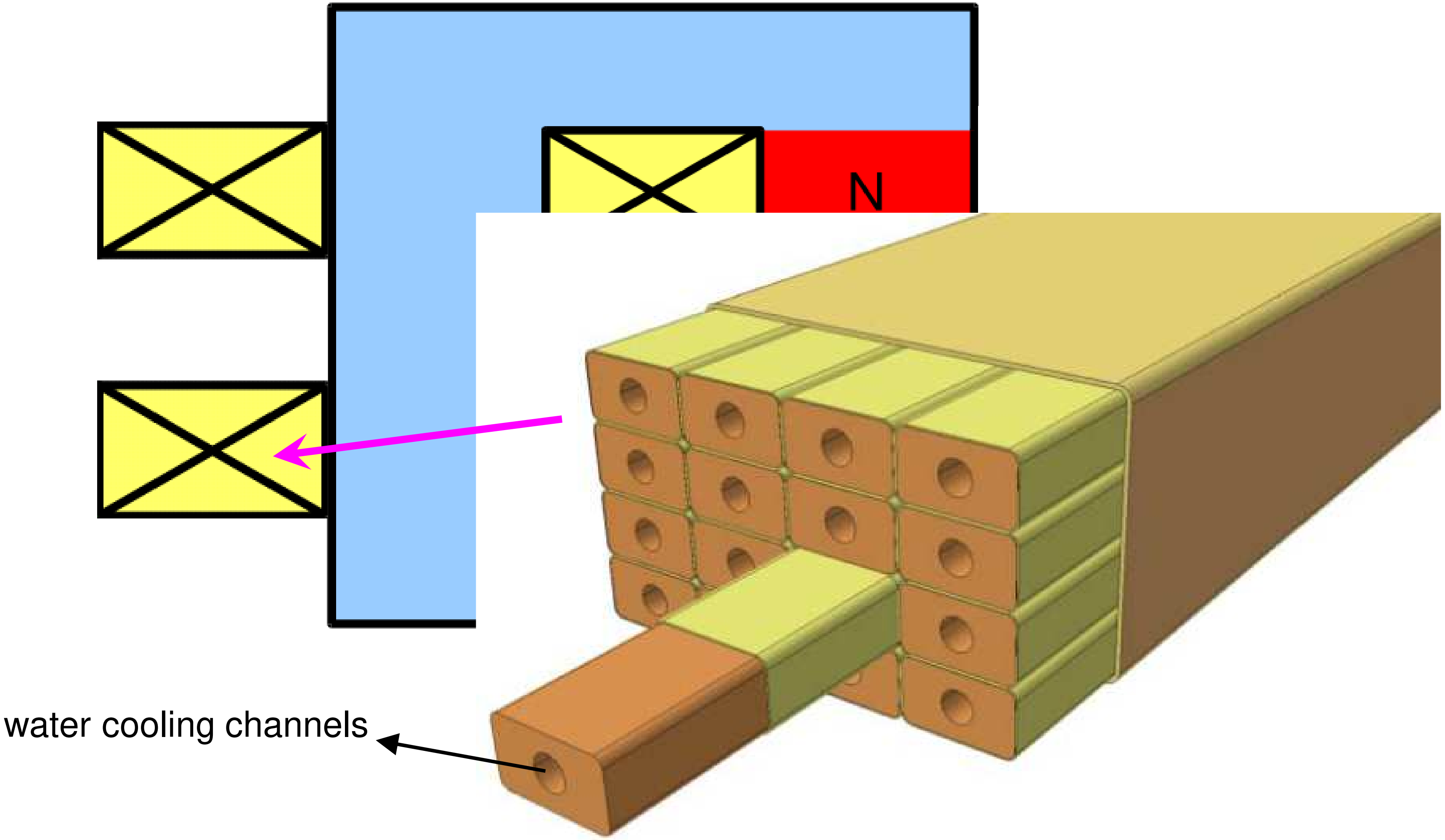
$$\int_{iron} \frac{\vec{B}}{\mu_{iron}} \overrightarrow{ds} + \int_{gap} \frac{\vec{B}}{\mu_0} \overrightarrow{ds} = N\, I$$

Dipole magnet cross section

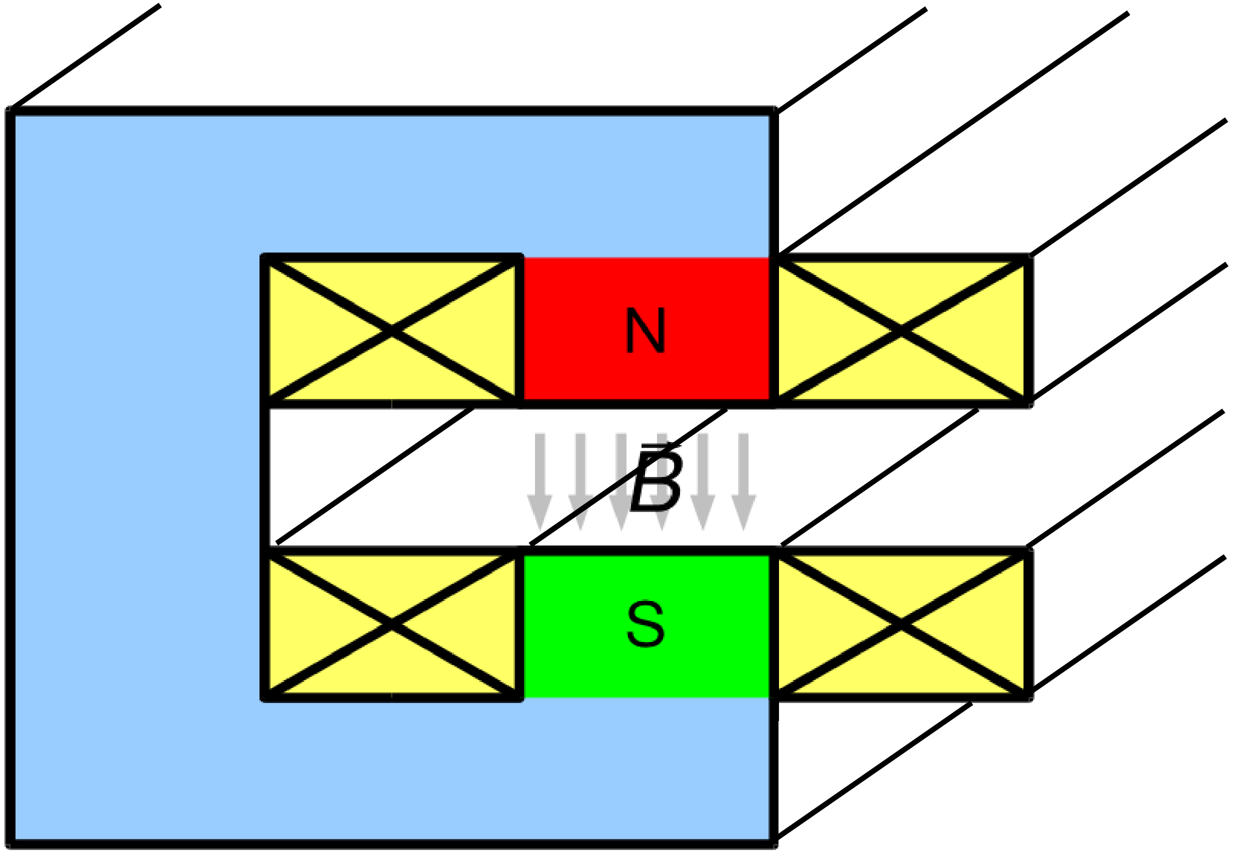


increase B ➔ increase current, but power dissipated $\mathrm{P} = R \cdot I^2$
➔ large conductor cables

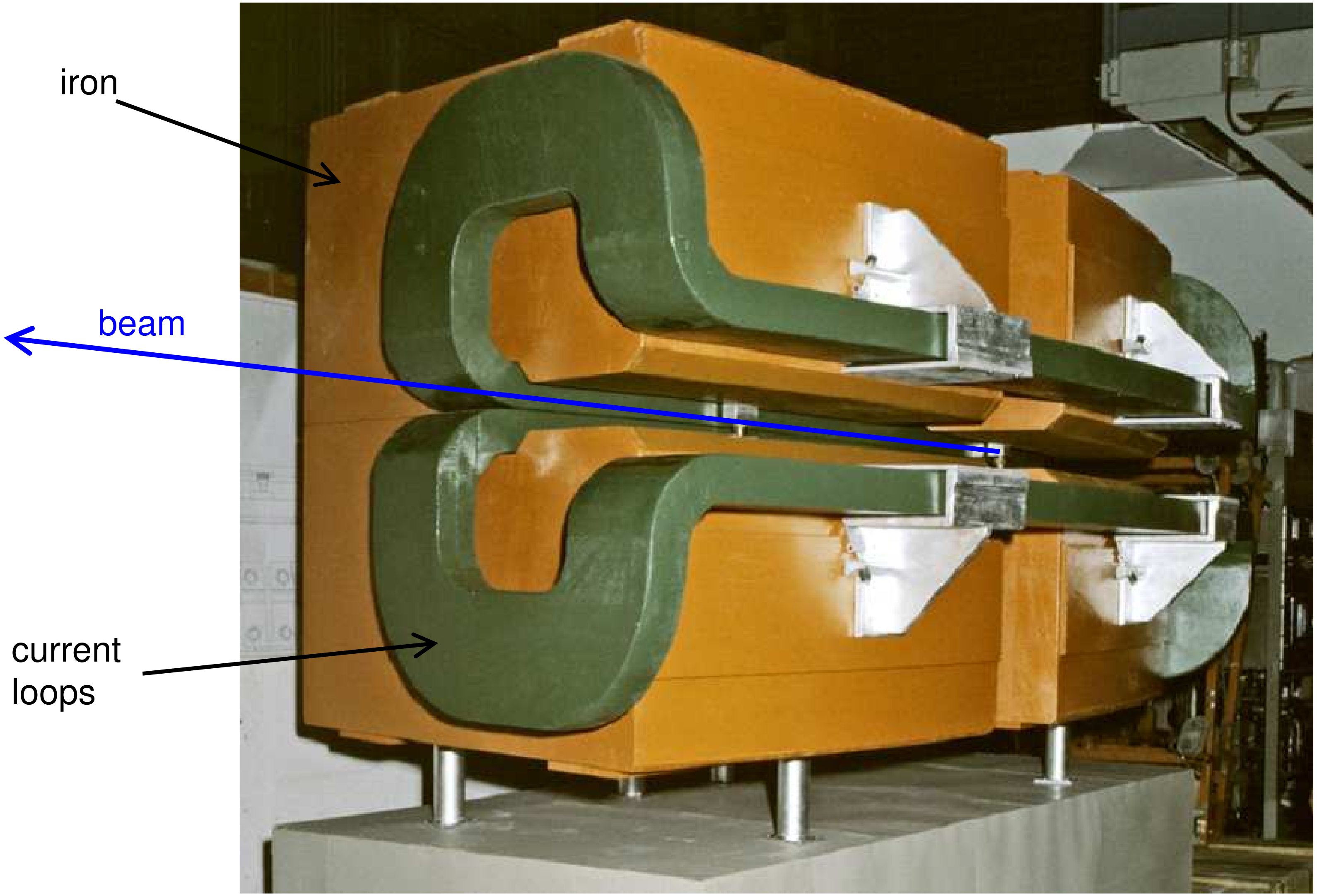
Dipole magnet cross section



Dipole magnet cross section

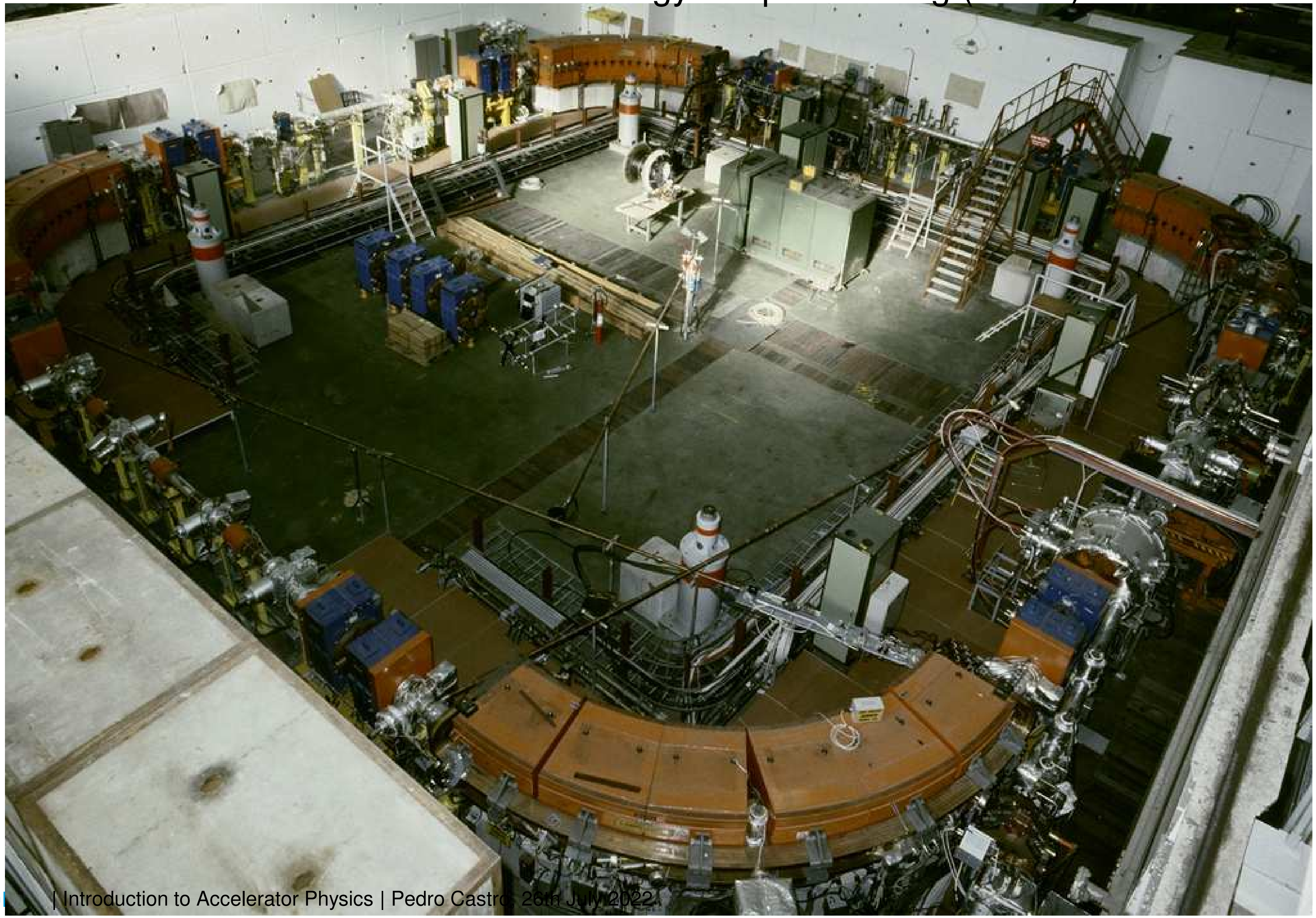


Dipole magnet

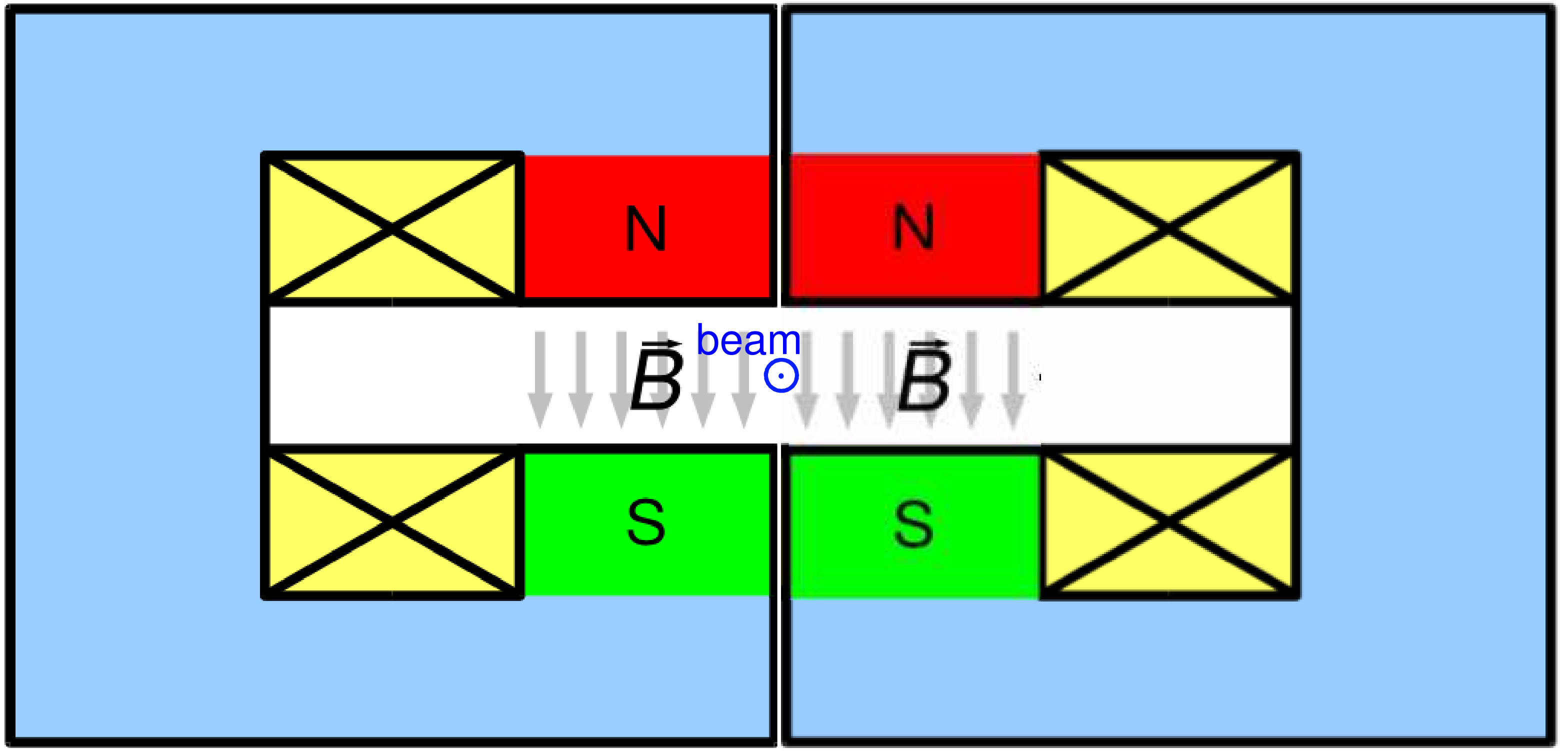


Dipole magnet

Low Energy Antiproton Ring (LEAR) at CERN

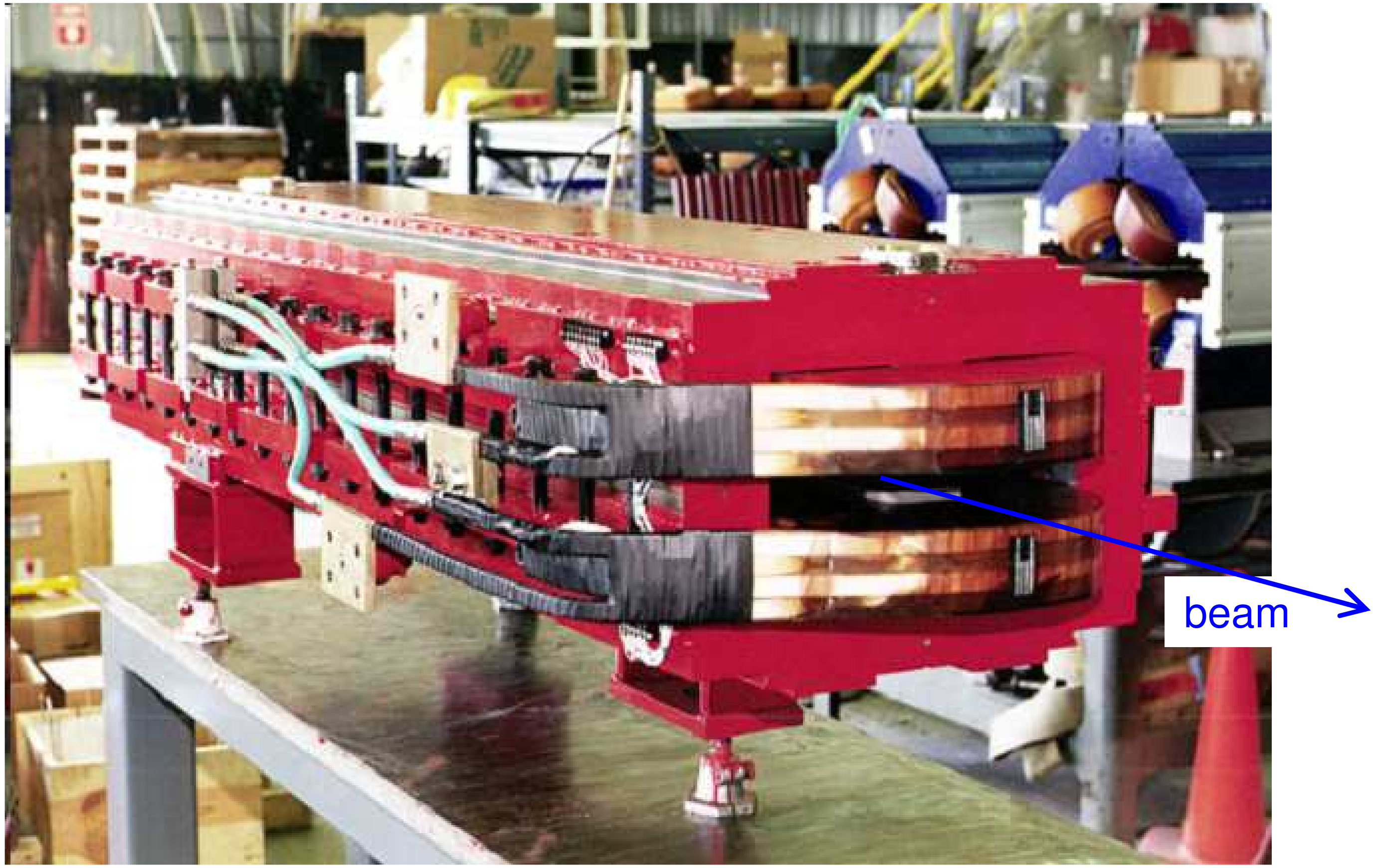


Dipole magnet cross section

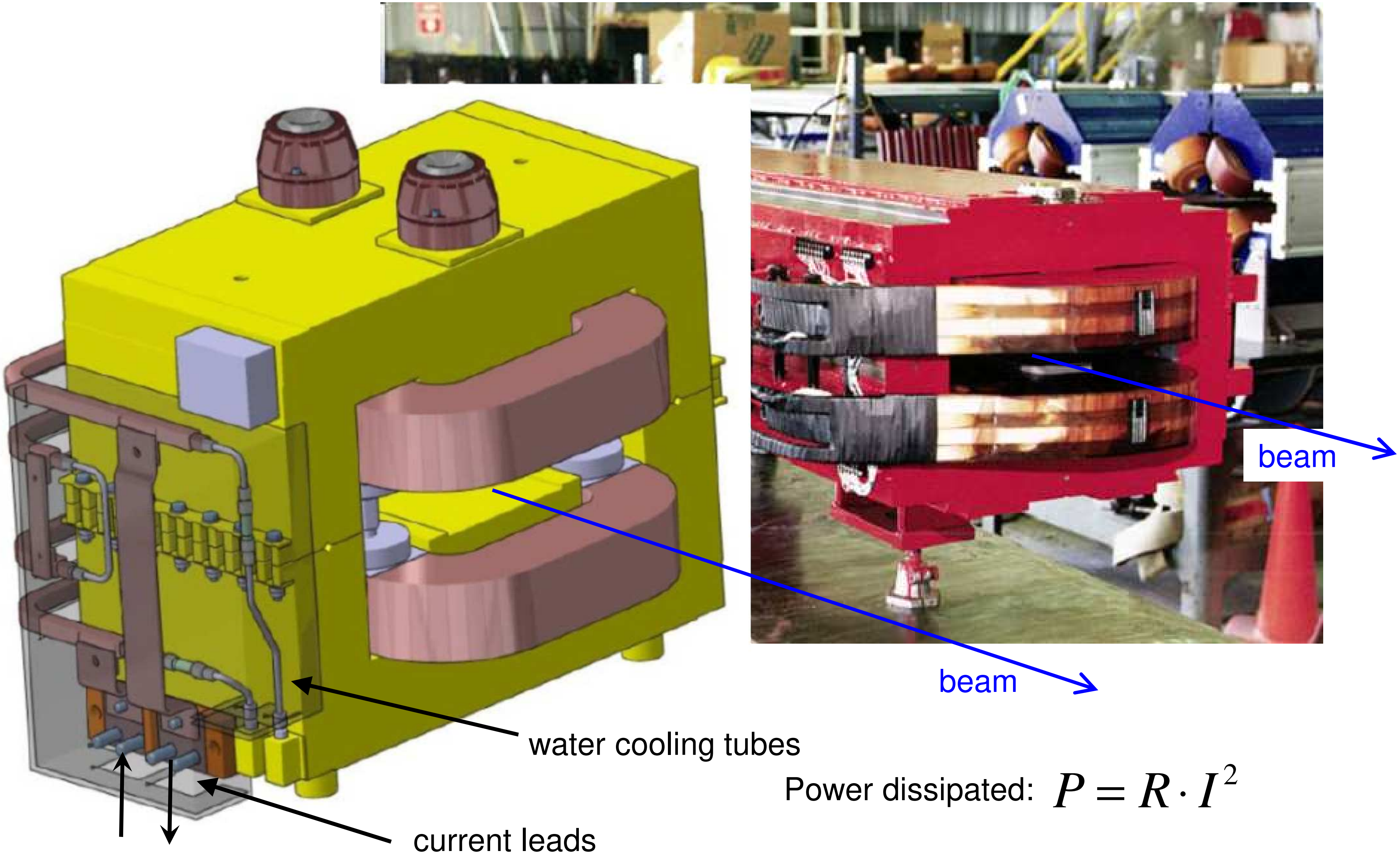


C magnet + C magnet = H magnet

Dipole magnet cross section (another design)

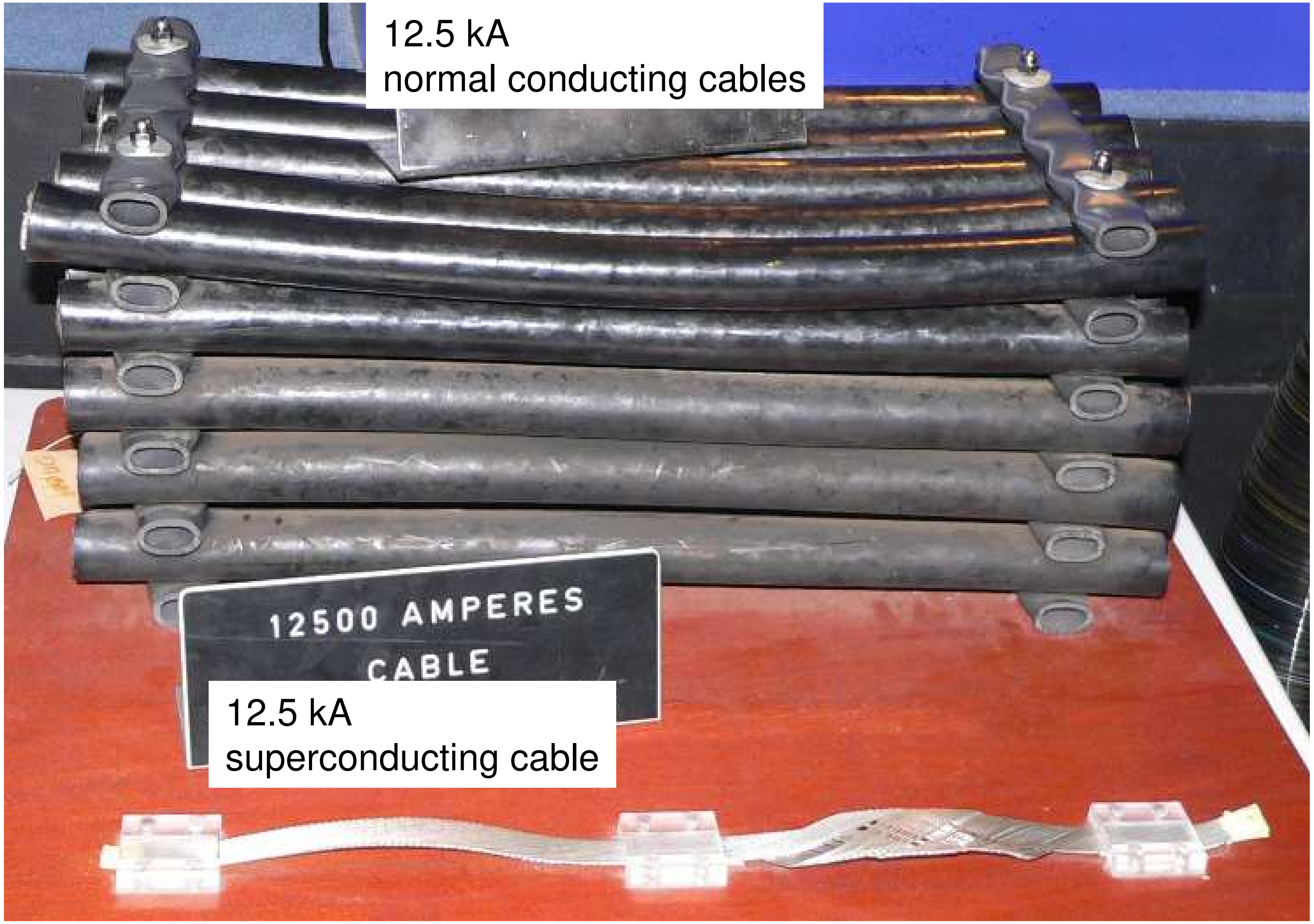


Dipole magnet cross section (another design)



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

Superconductivity

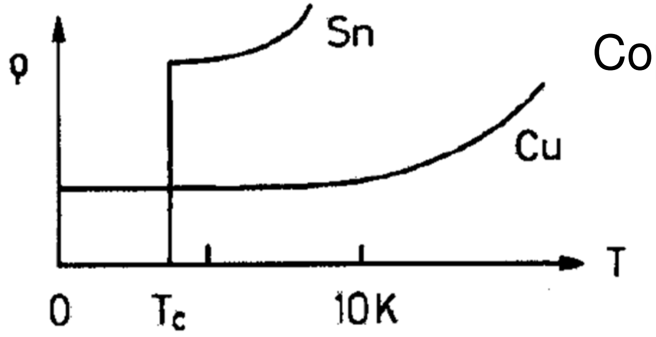


Superconductivity

Tin

resistance

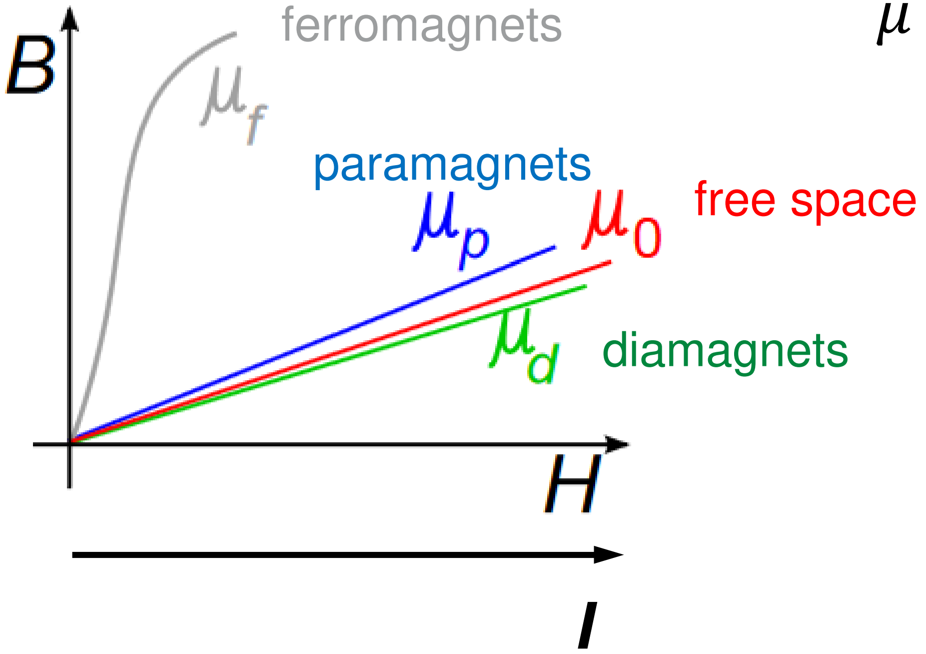
Copper



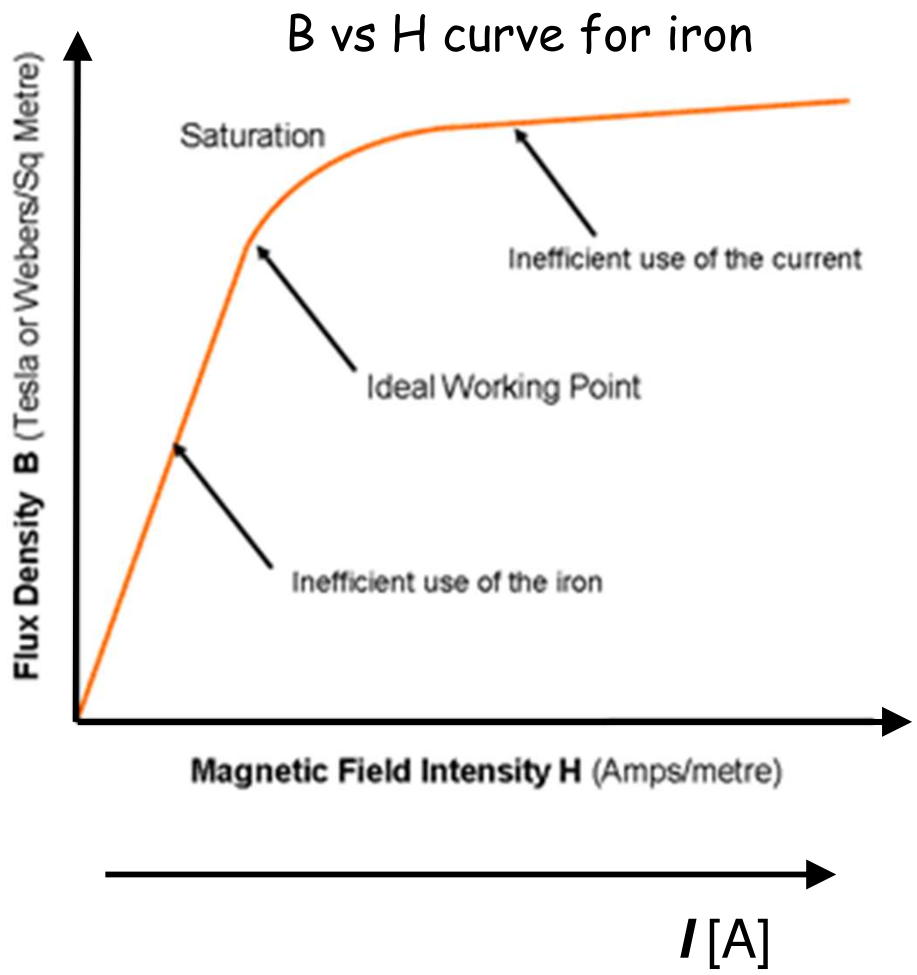
critical temperature (Tc):

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

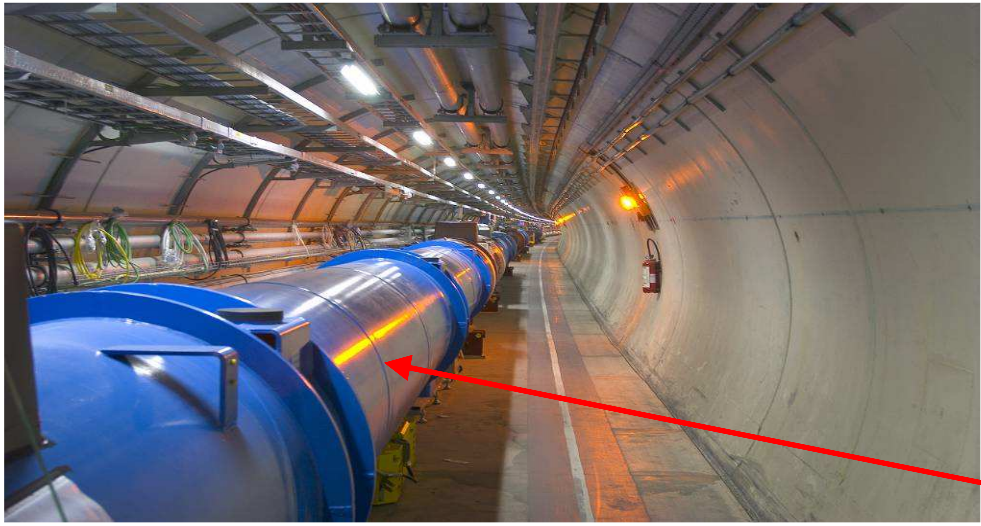
μ : permeability



Saturation of iron: 1.6 – 2 T

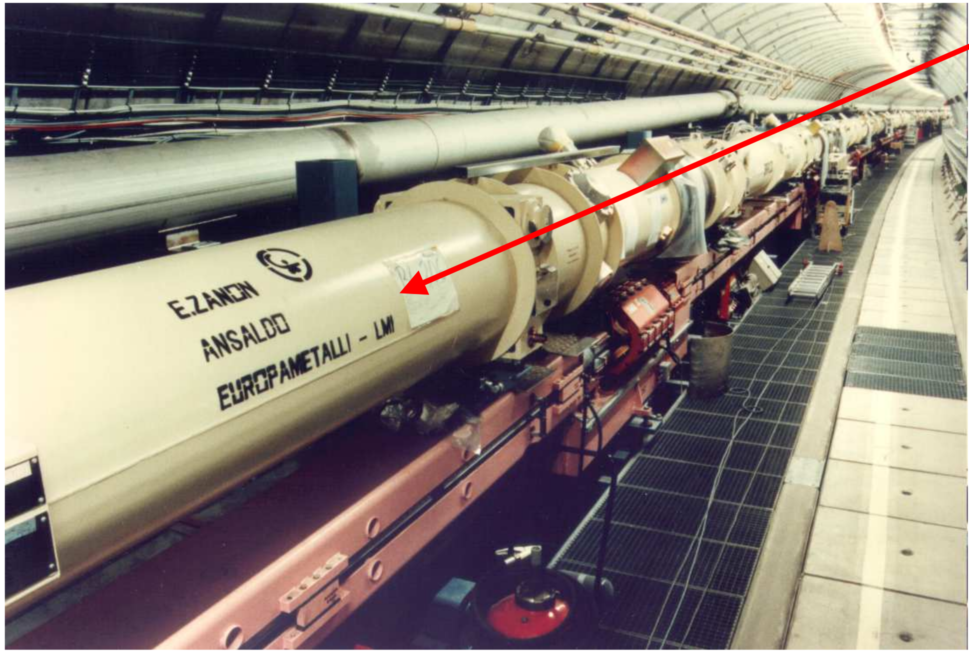


Superconducting dipole magnets



LHC

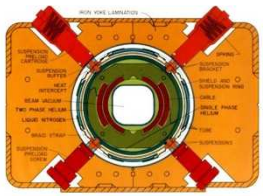
superconducting dipoles

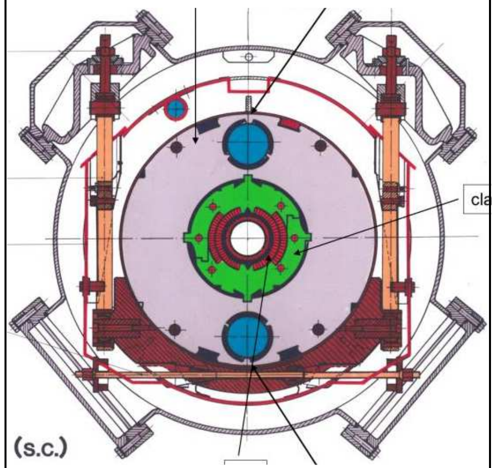


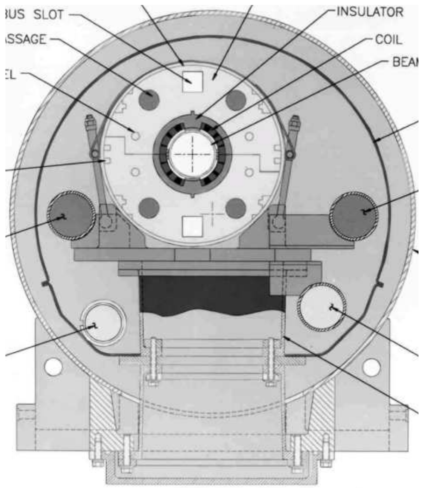
HERA

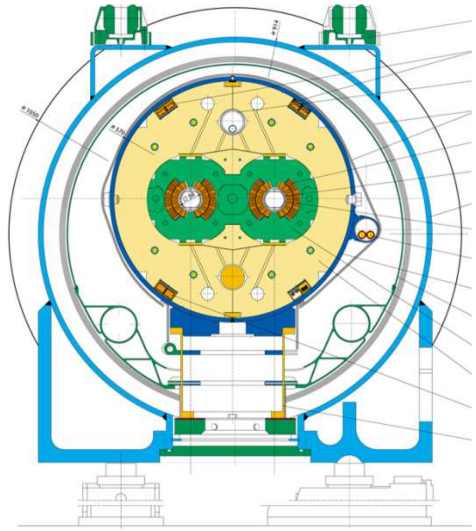
Superconducting dipole magnets: cross section

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	8.3T

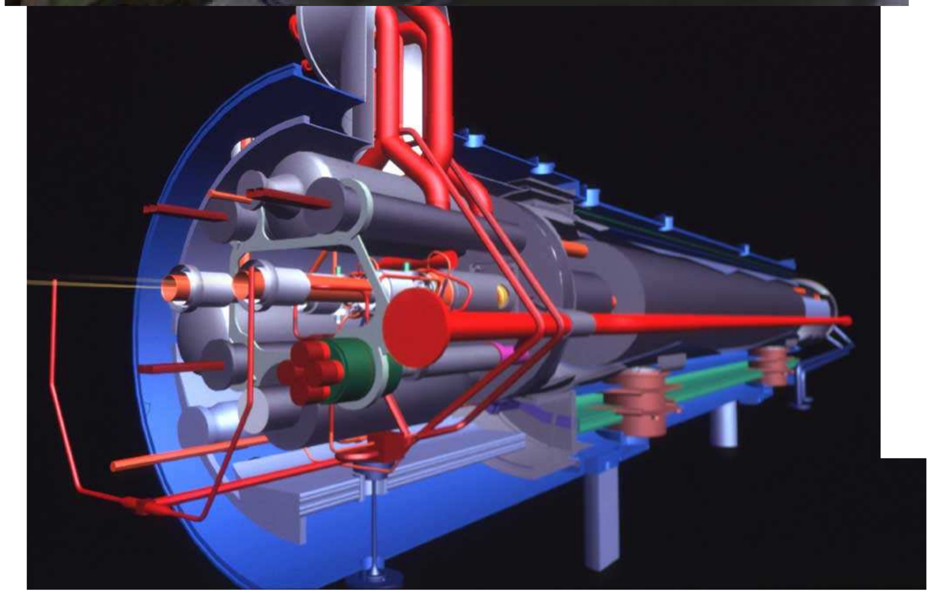


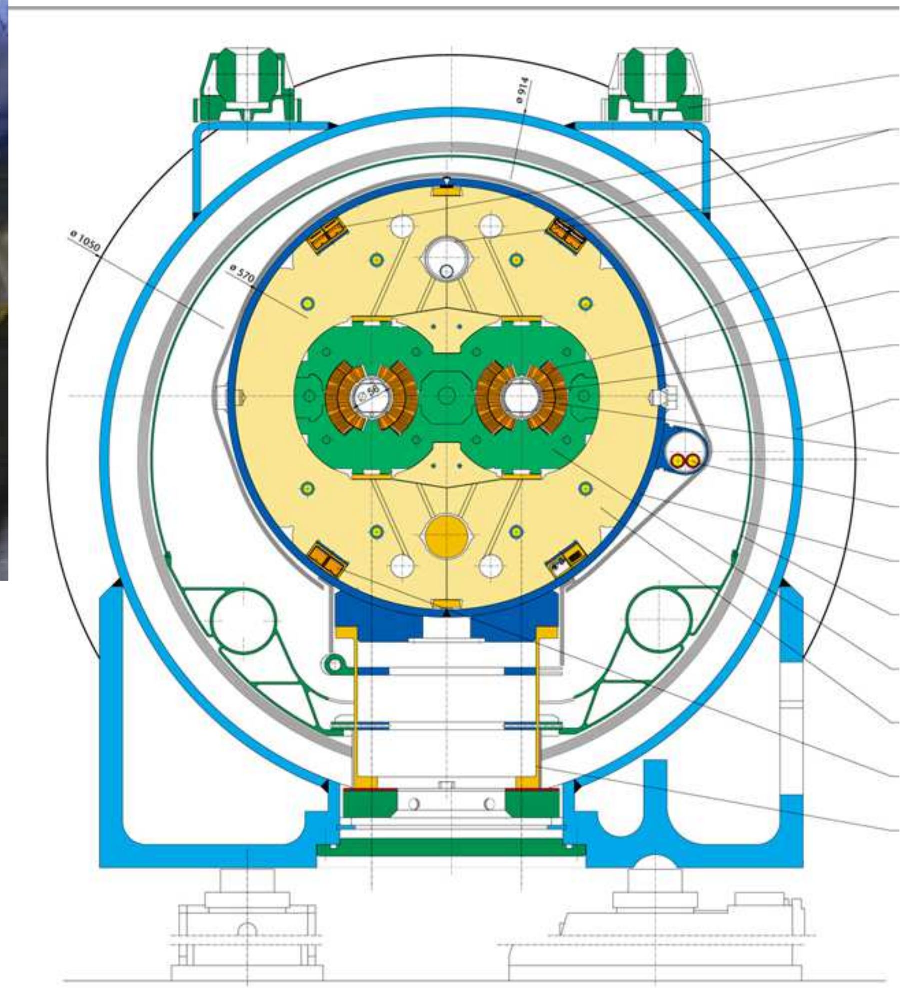






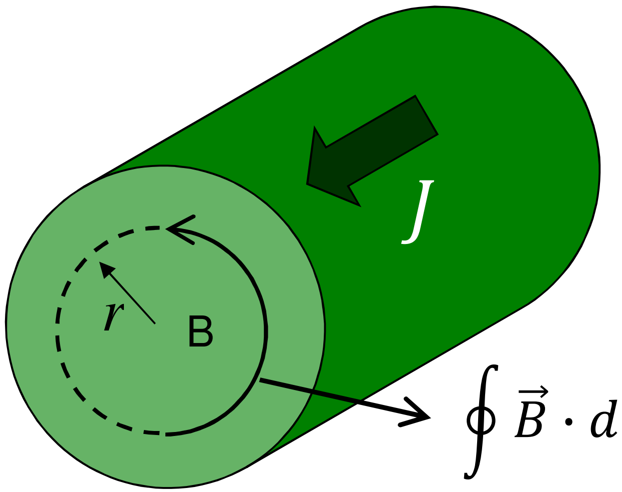
Superconducting dipole magnets





Dipole field inside 1 conductor

J: uniform current density

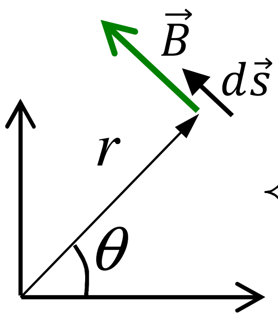


Ampere's law:

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

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

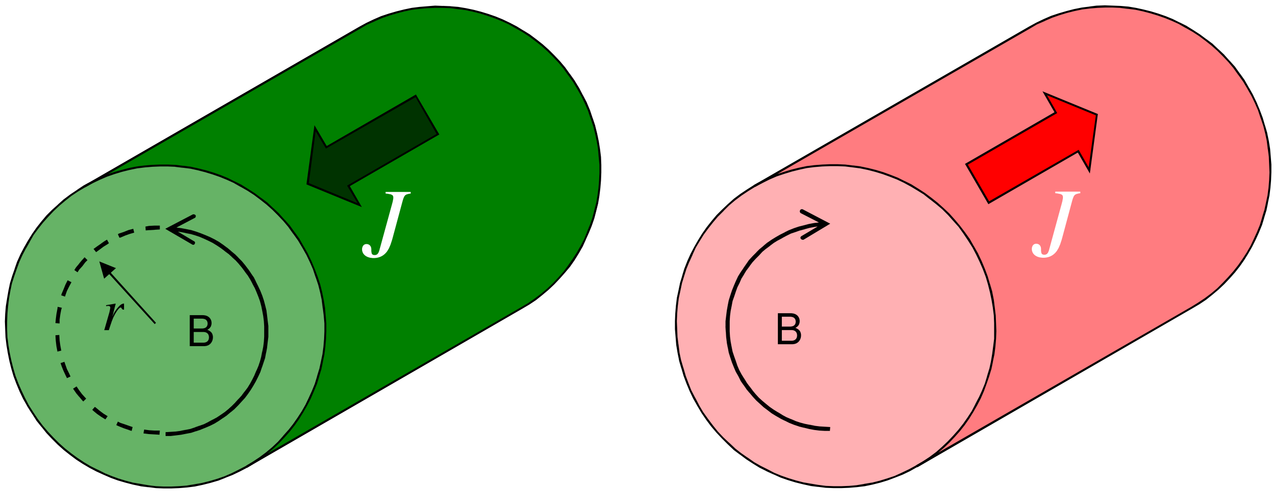
$$B = \frac{\mu_0 J}{2} r$$



$$\begin{cases} B_x = -\dfrac{\mu_0 J}{2} r \sin\theta \\ B_y = \dfrac{\mu_0 J}{2} r \cos\theta \end{cases}$$

Dipole field inside 2 conductors

J = uniform current density

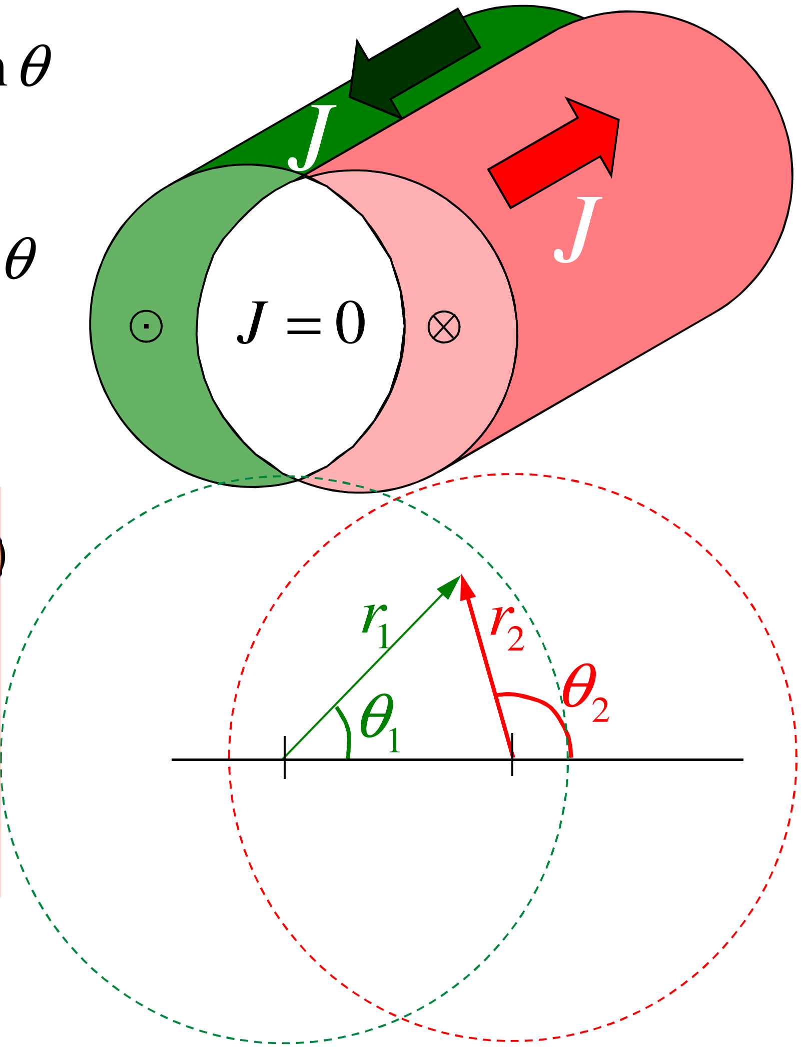


Dipole field inside 2 conductors

$$J = \text{uniform current density}$$

one conductor:

$$\begin{cases} B_x = -\dfrac{\mu_0 J}{2} r \sin\theta \\ B_y = \dfrac{\mu_0 J}{2} r \cos\theta \end{cases}$$



superposition:

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

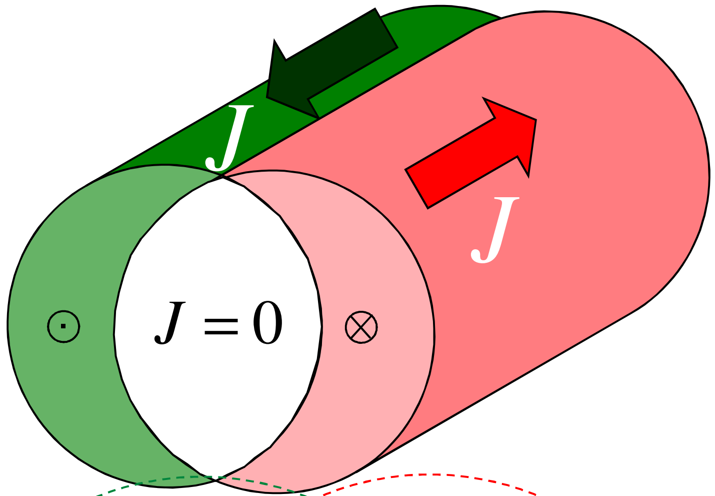
$$B_y = \frac{\mu_0 J}{2}\left(r_1 \cos\theta_1 - r_2 \cos\theta_2\right)$$

Dipole field inside 2 conductors

$J = \text{uniform current density}$

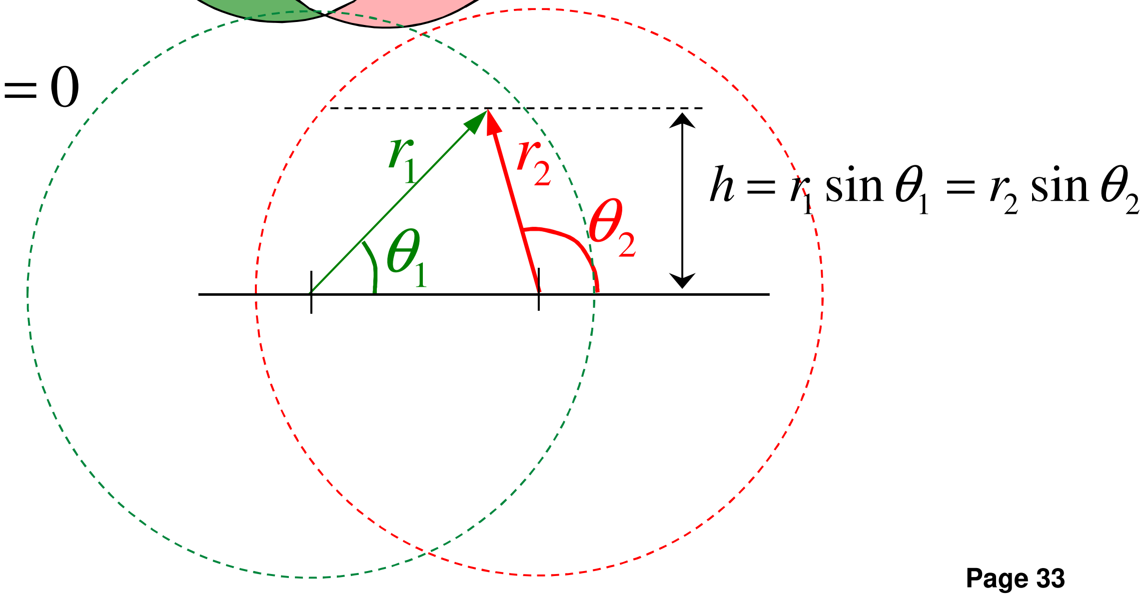
one conductor:

$$\begin{cases} B_x = -\dfrac{\mu_0 J}{2} r \sin\theta \\ B_y = \dfrac{\mu_0 J}{2} r \cos\theta \end{cases}$$



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

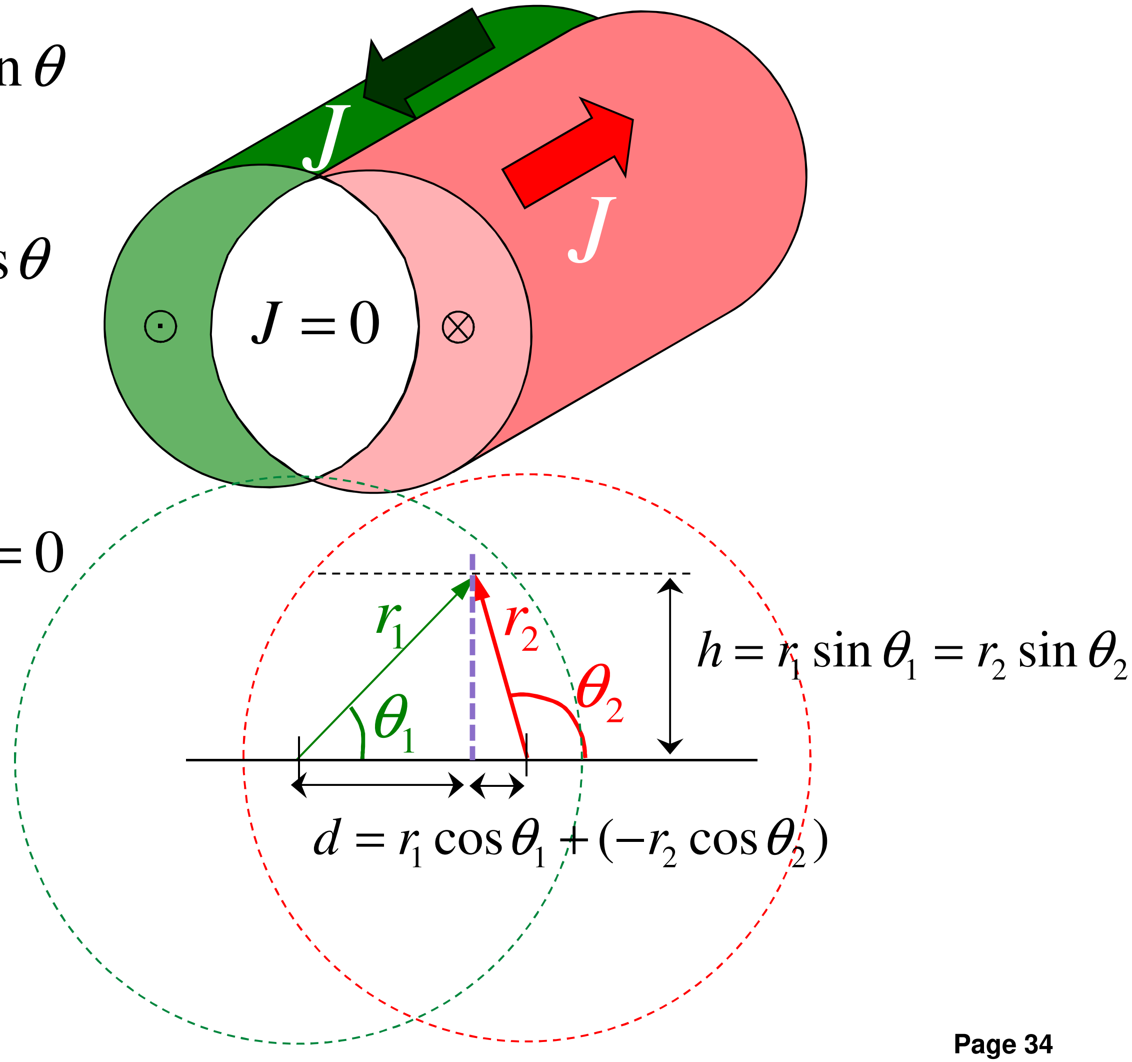
$$B_y = \frac{\mu_0 J}{2}(r_1 \cos\theta_1 - r_2 \cos\theta_2)$$



Dipole field inside 2 conductors

$$J = \text{uniform current density}$$

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



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Dipole field inside 2 conductors

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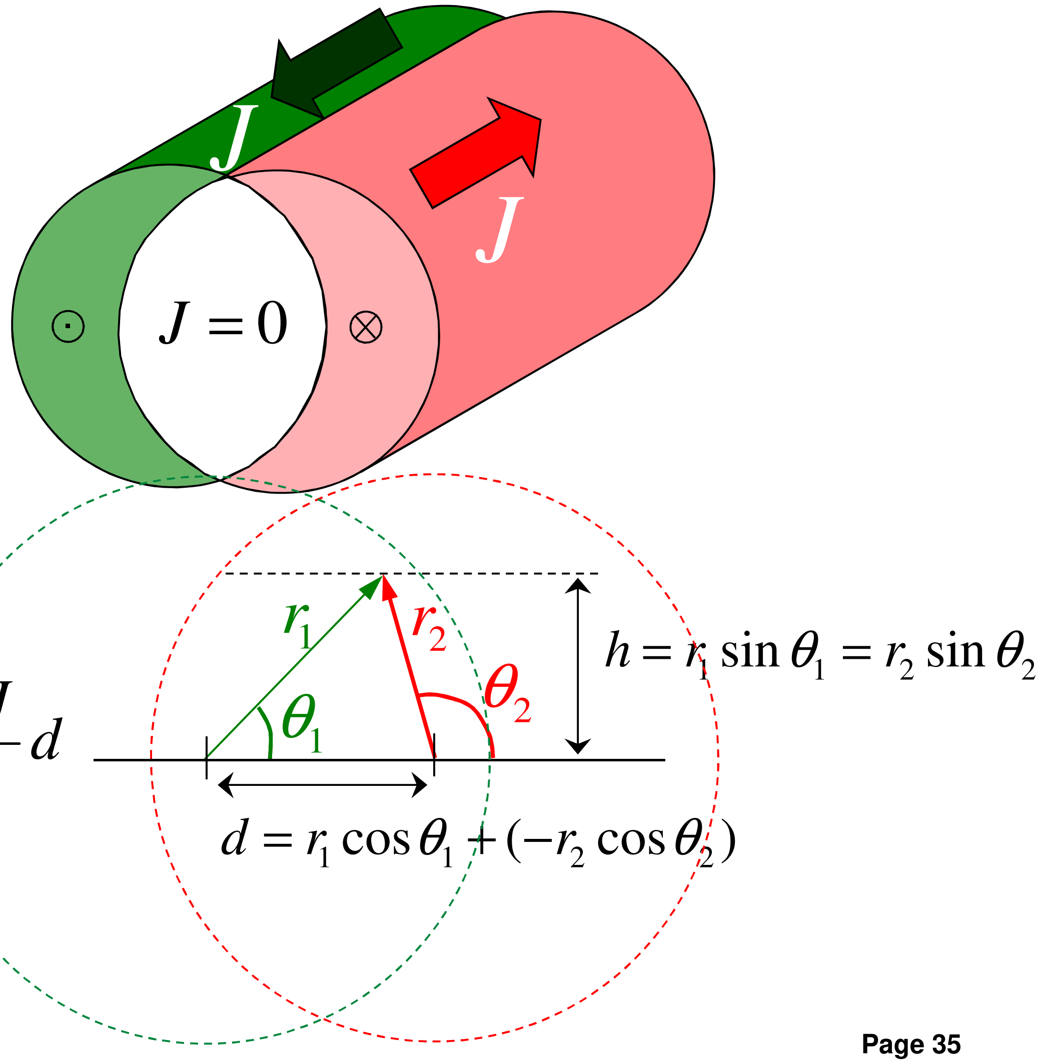

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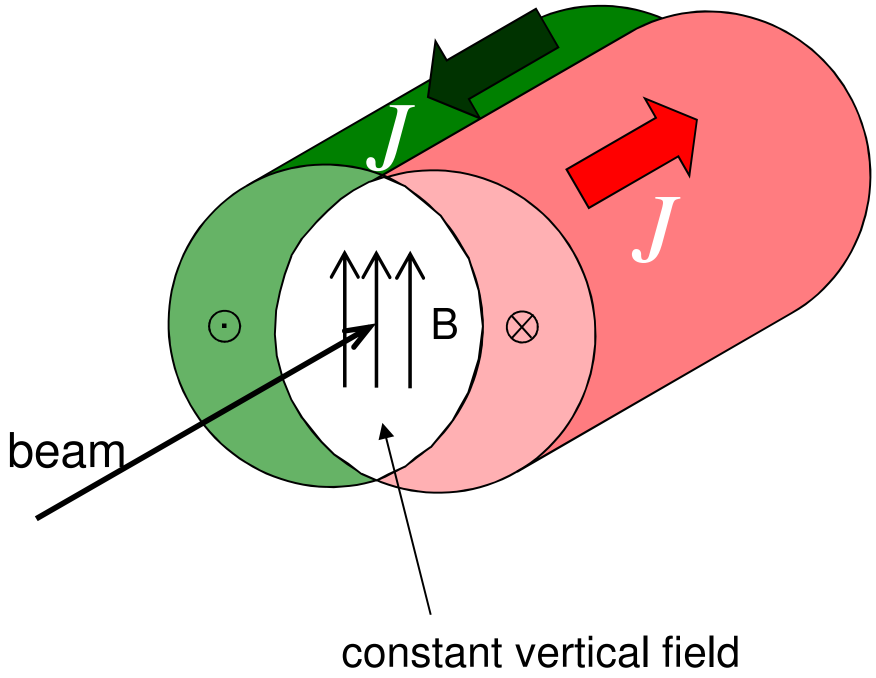
$$B_y = \frac{\mu_0 J}{2}(r_1 \cos\theta_1 - r_2 \cos\theta_2) = \frac{\mu_0 J}{2} d$$

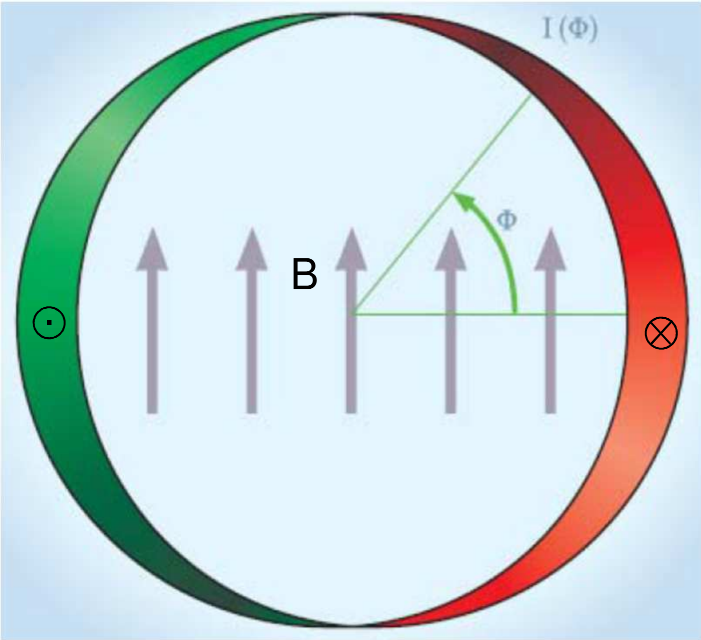
Dipole field inside 2 conductors

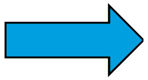
$$J = \text{uniform current density}$$

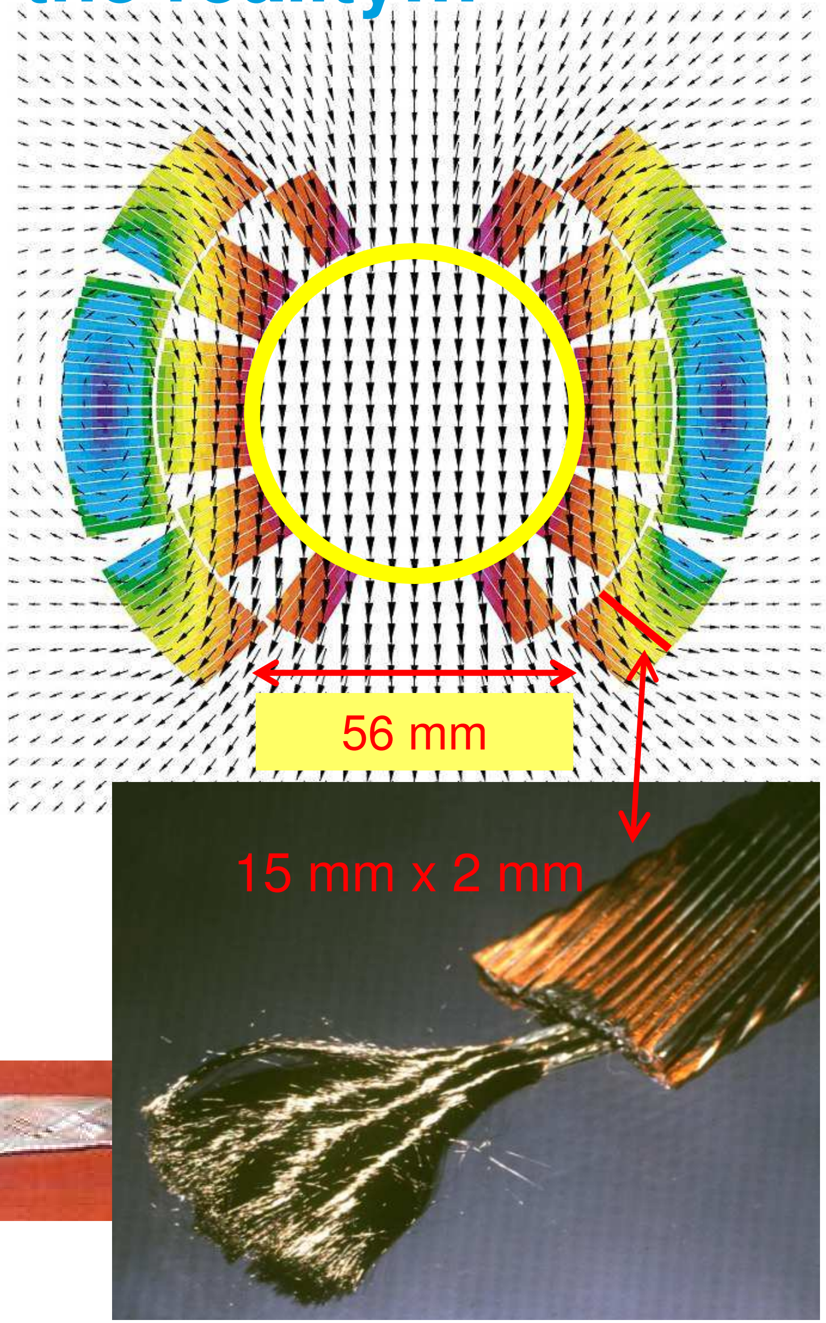


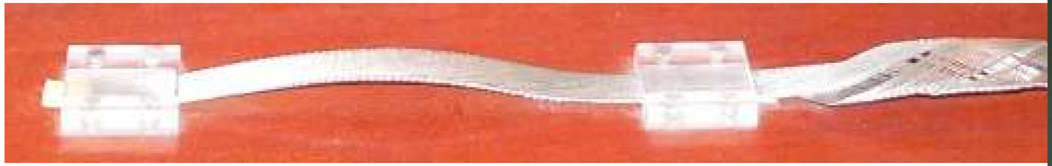
$$B_y = \frac{\mu_0 J}{2} d$$

From the principle … to the reality…

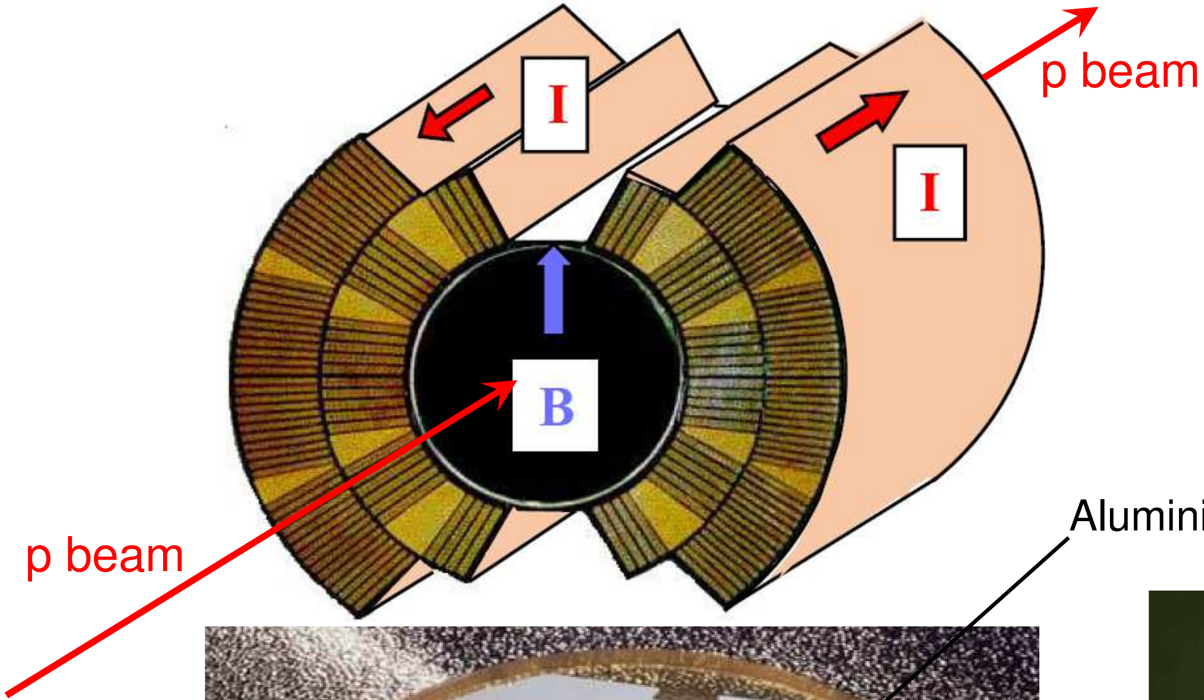


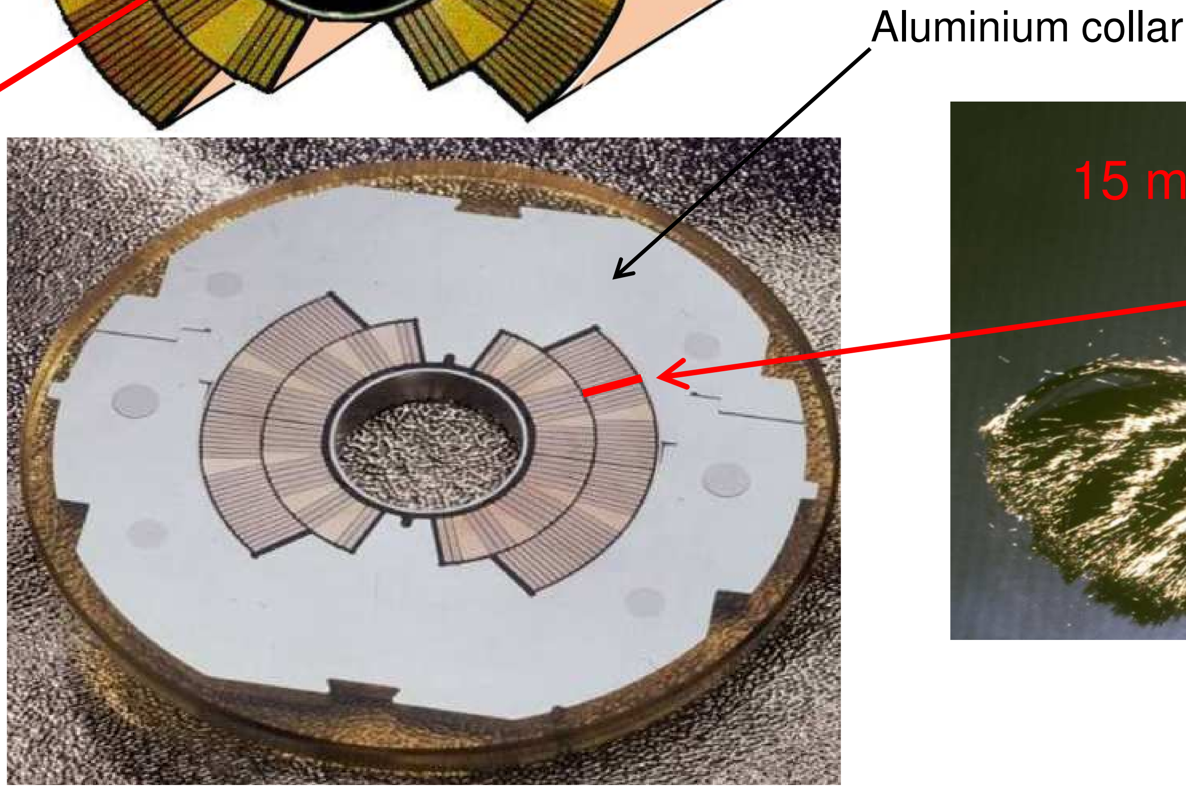


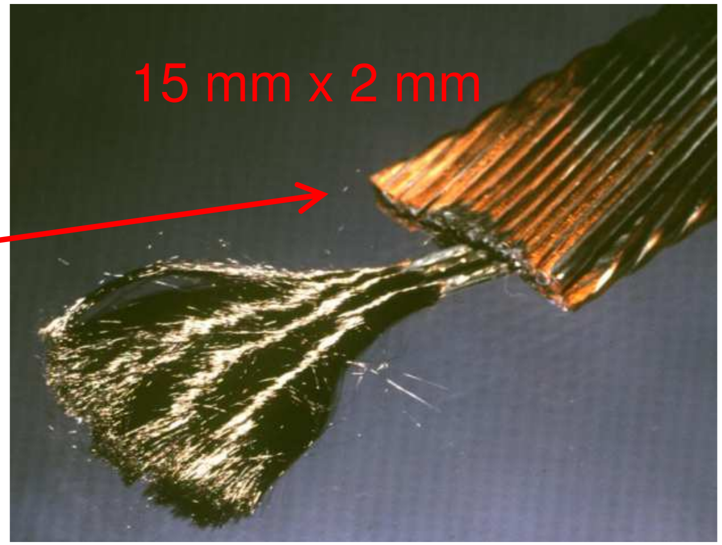




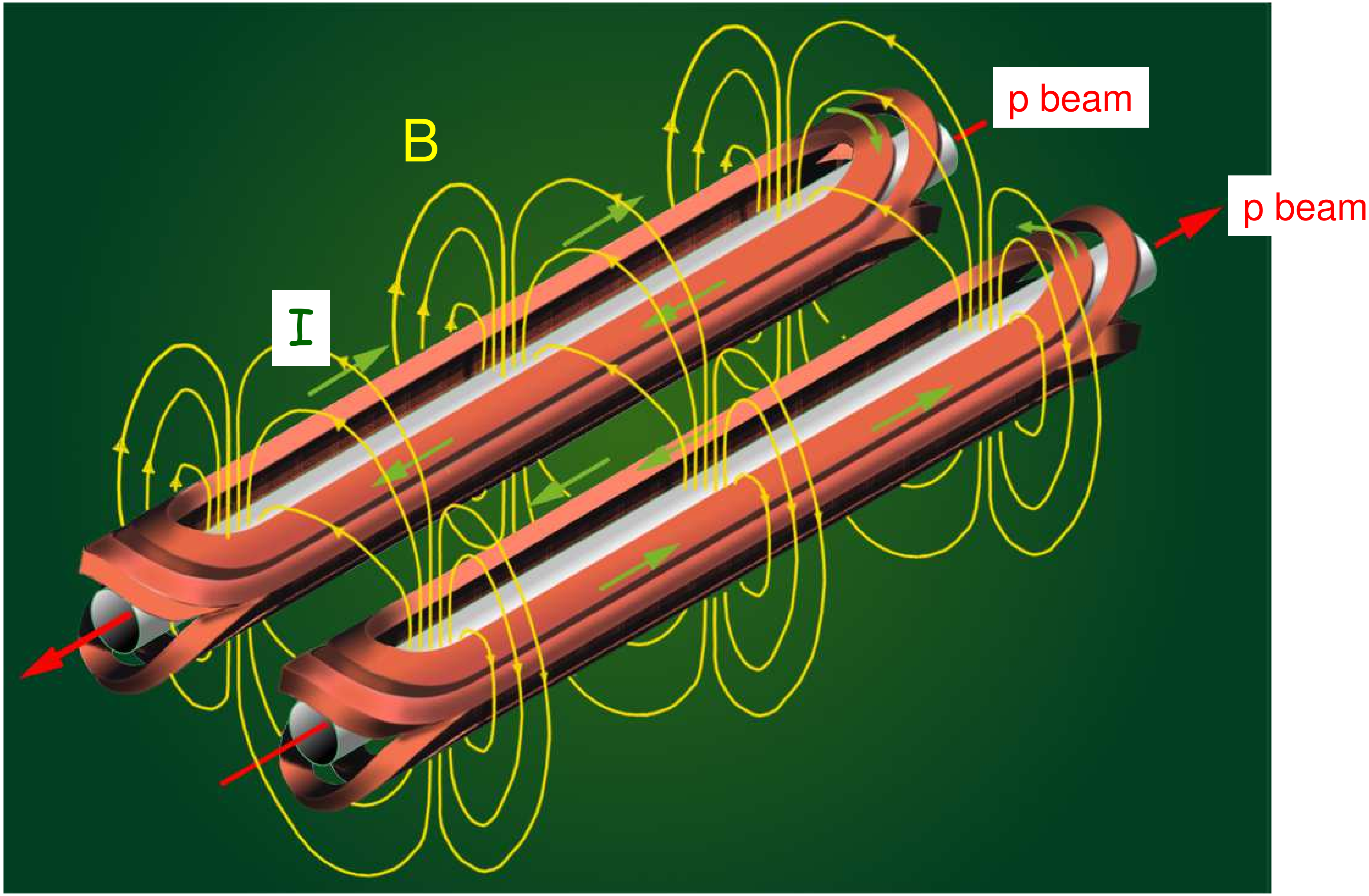
LHC dipole coils in 3D



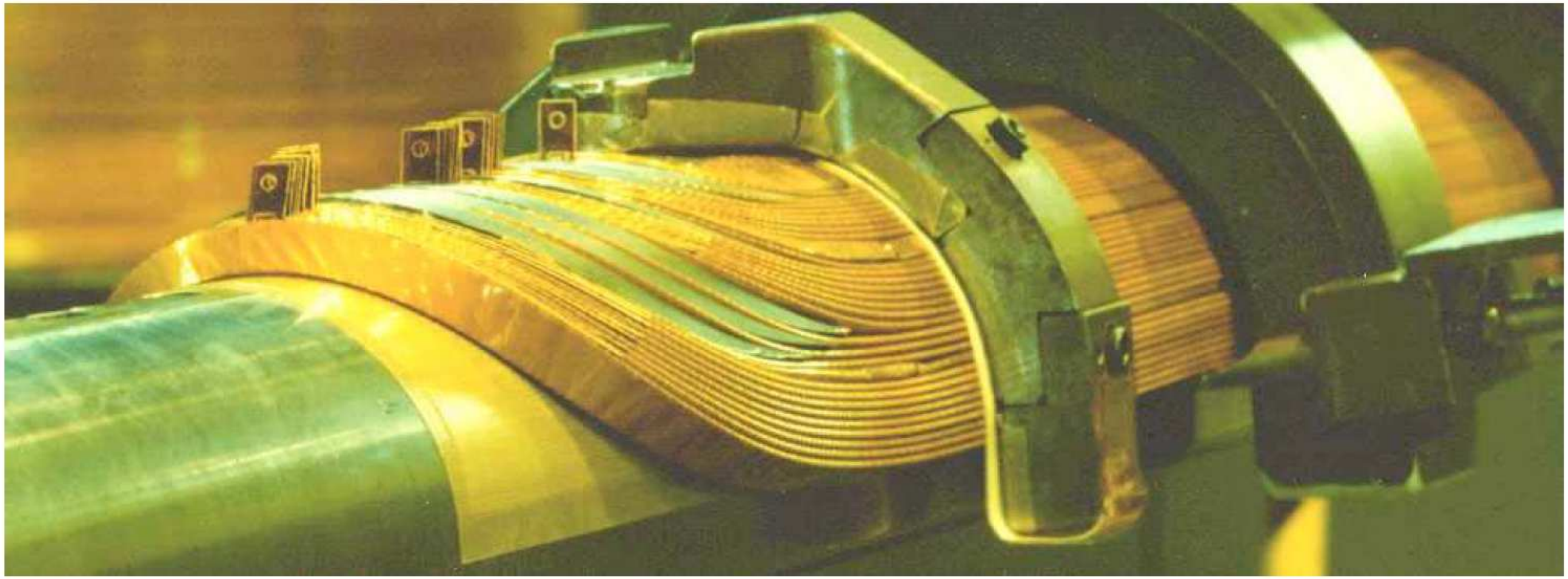


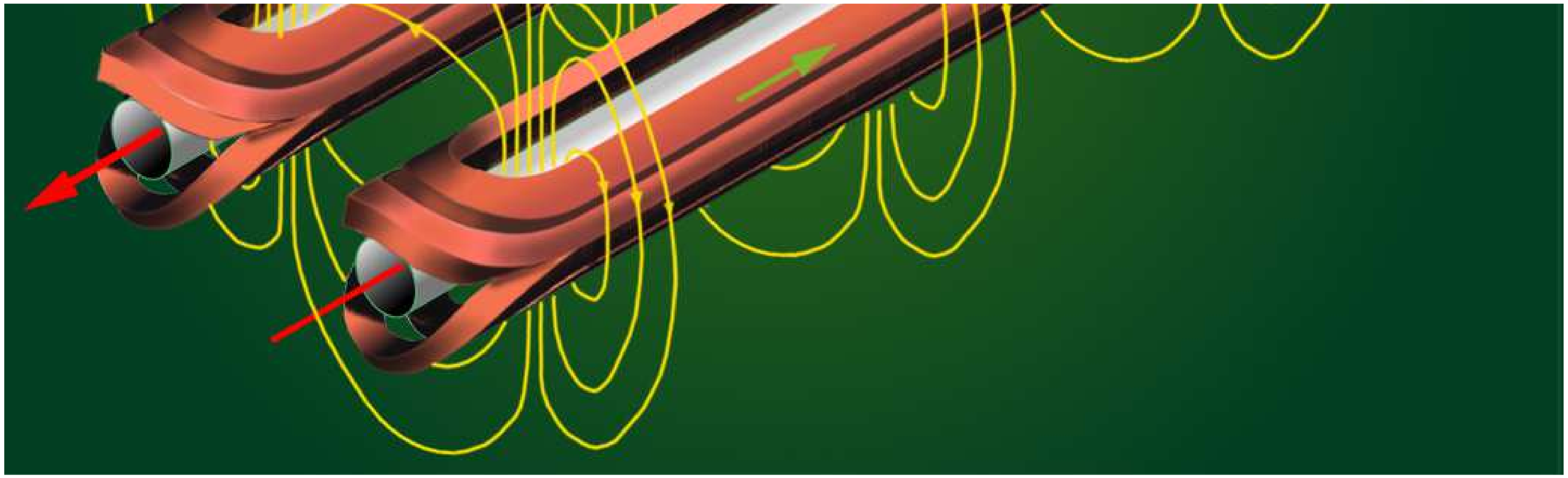


LHC dipole coils in 3D

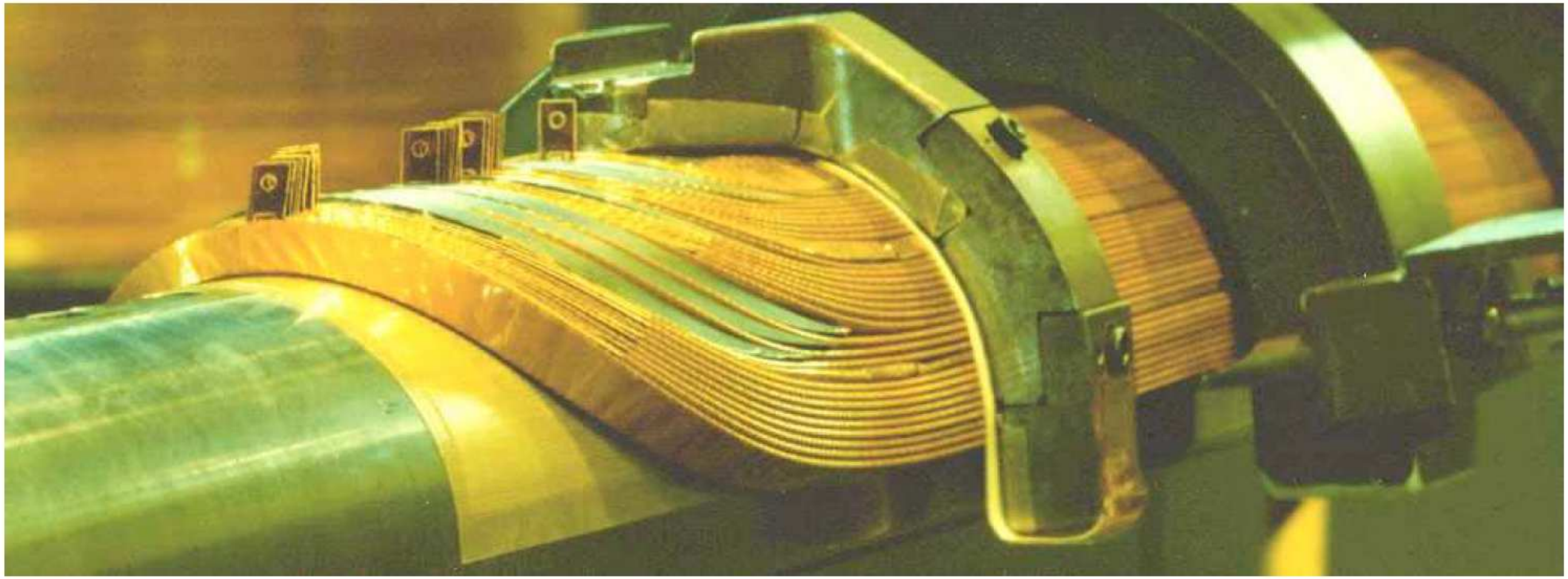


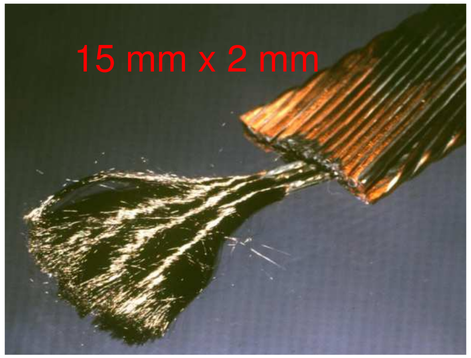
LHC dipole coils in 3D

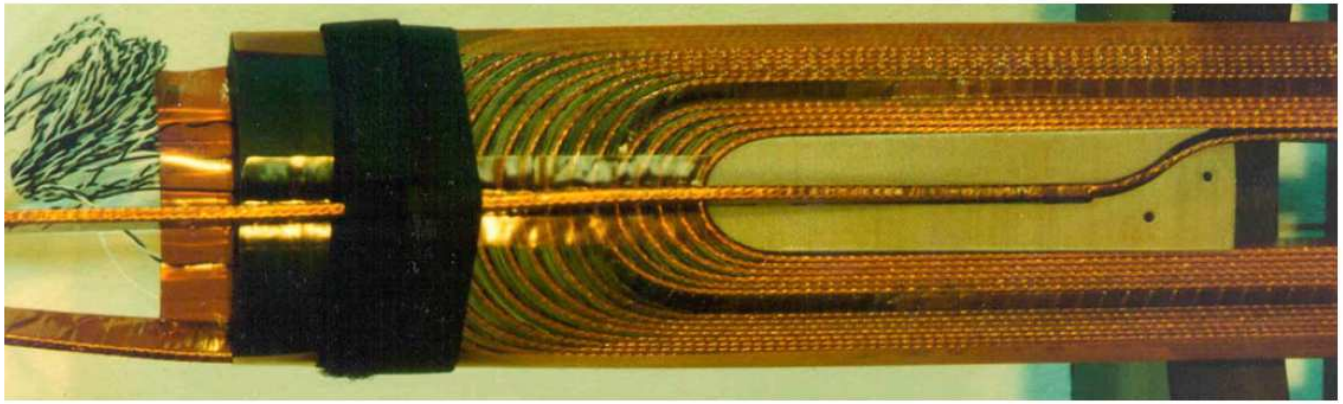




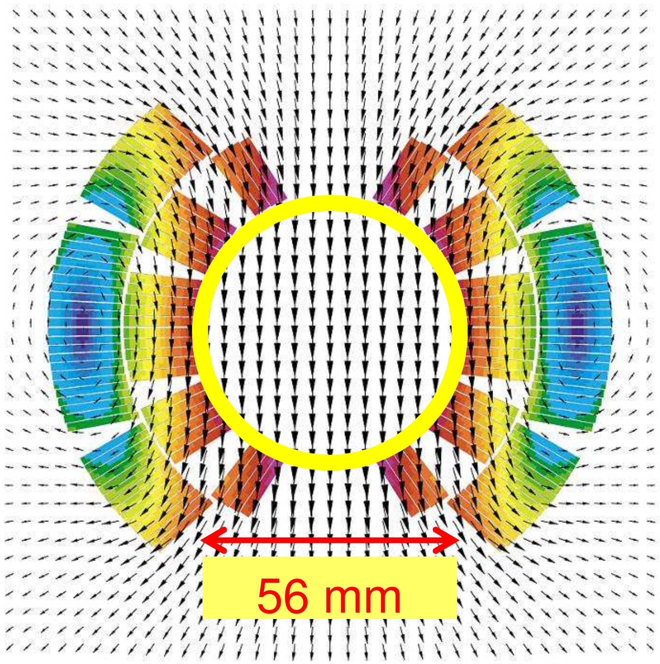
LHC dipole coils in 3D

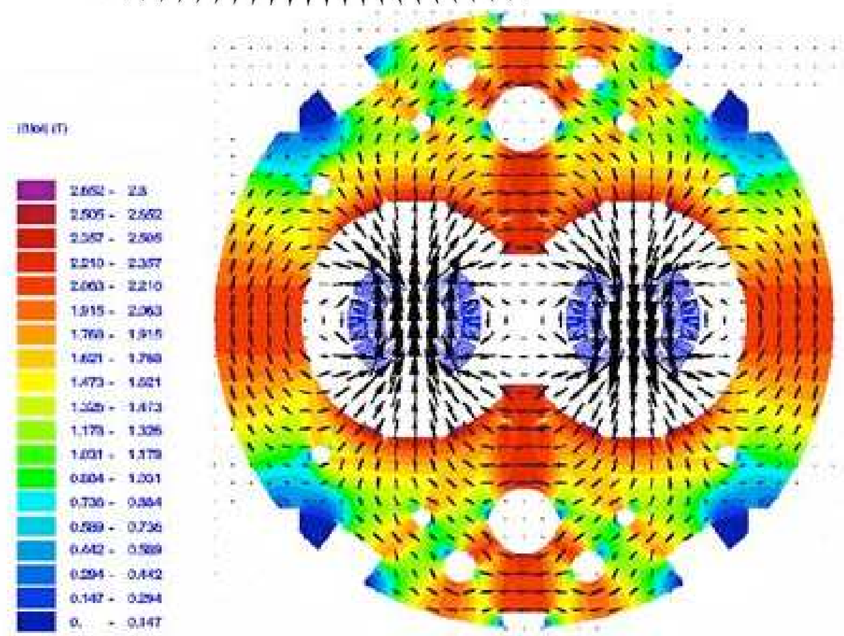


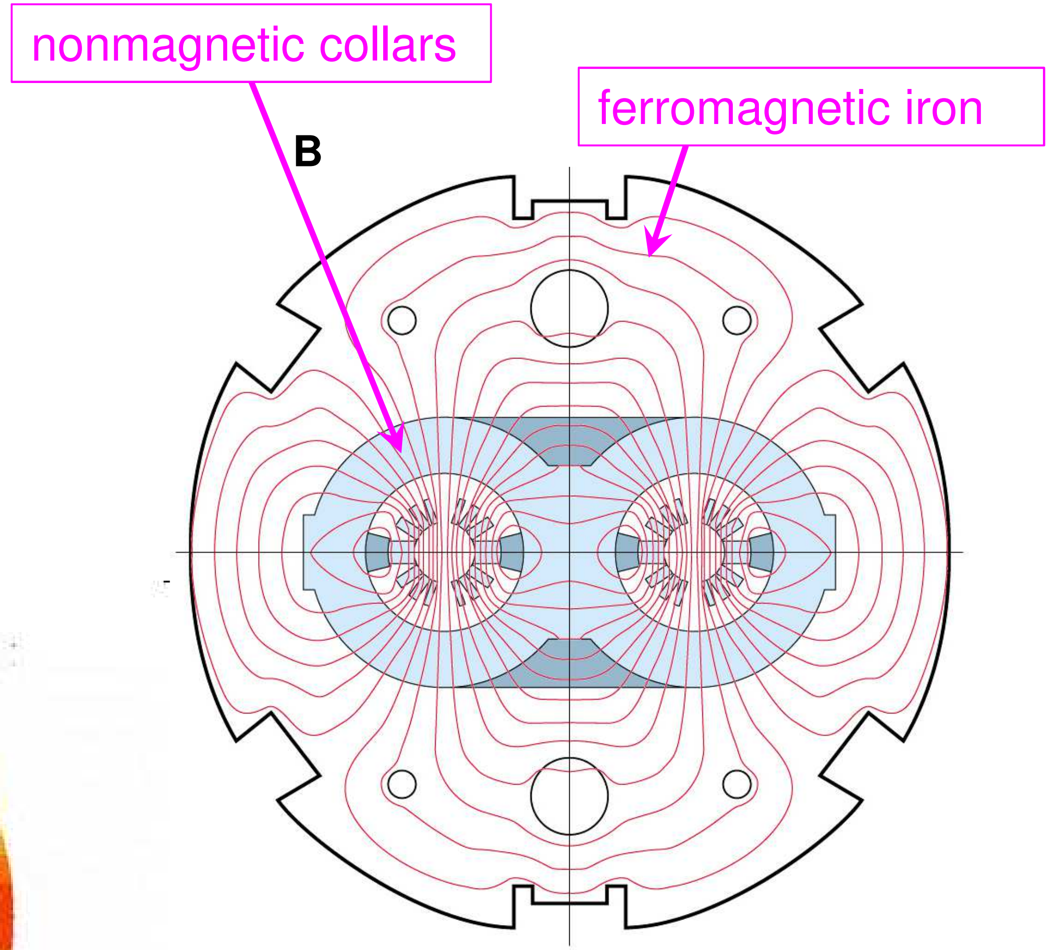




Computed magnetic field

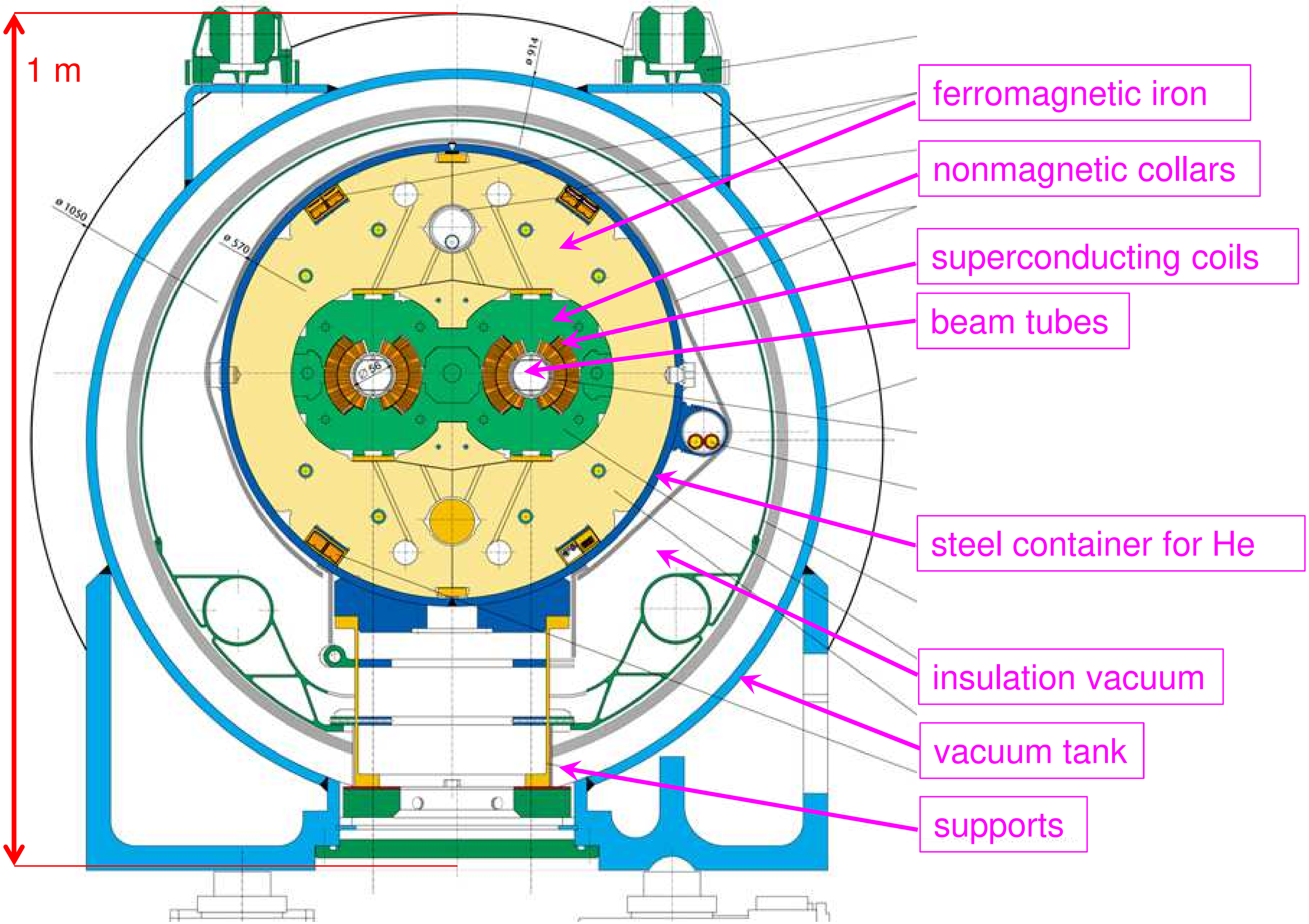






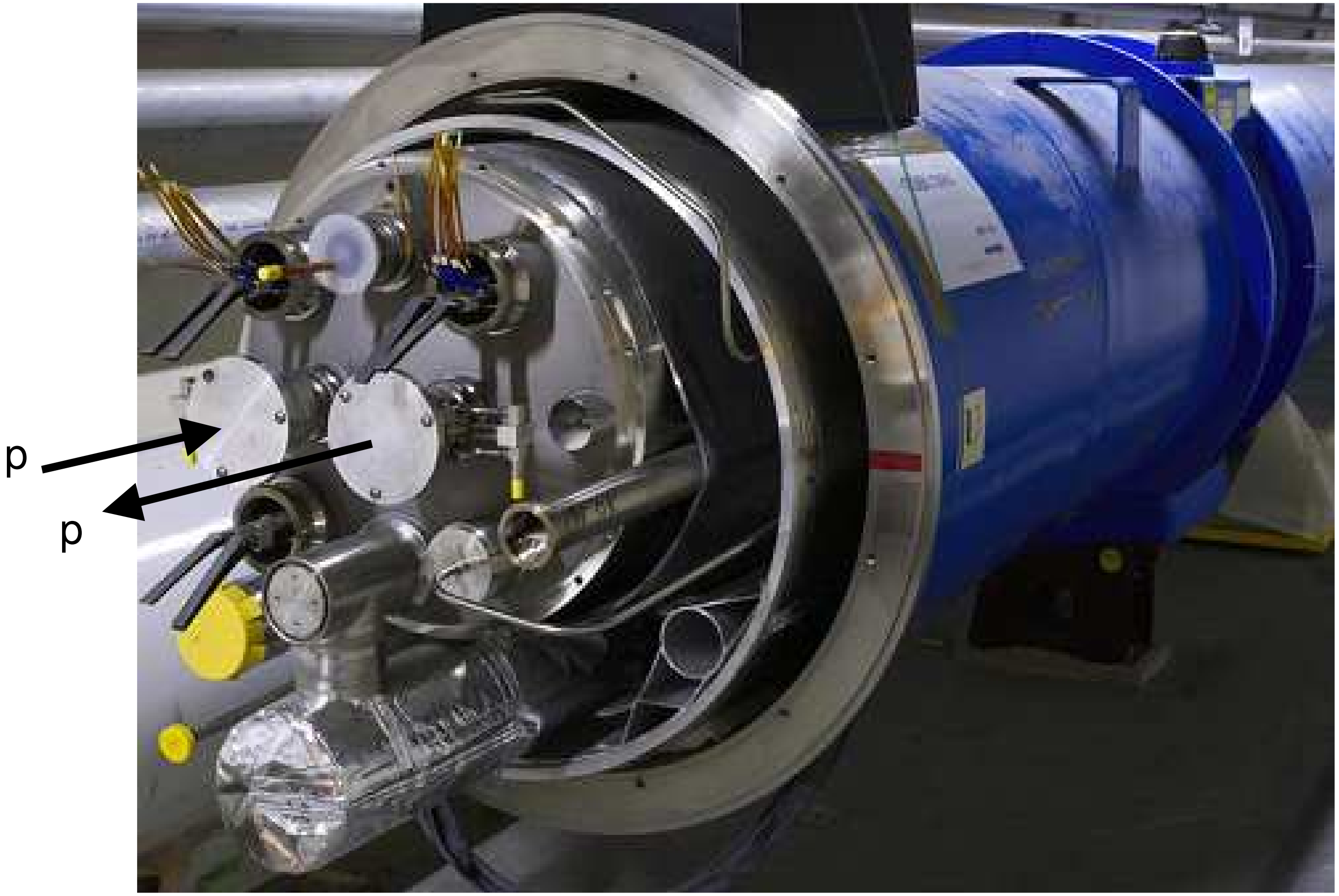
Computed magnetic flux map

LHC DIPOLE : STANDARD CROSS-SECTION



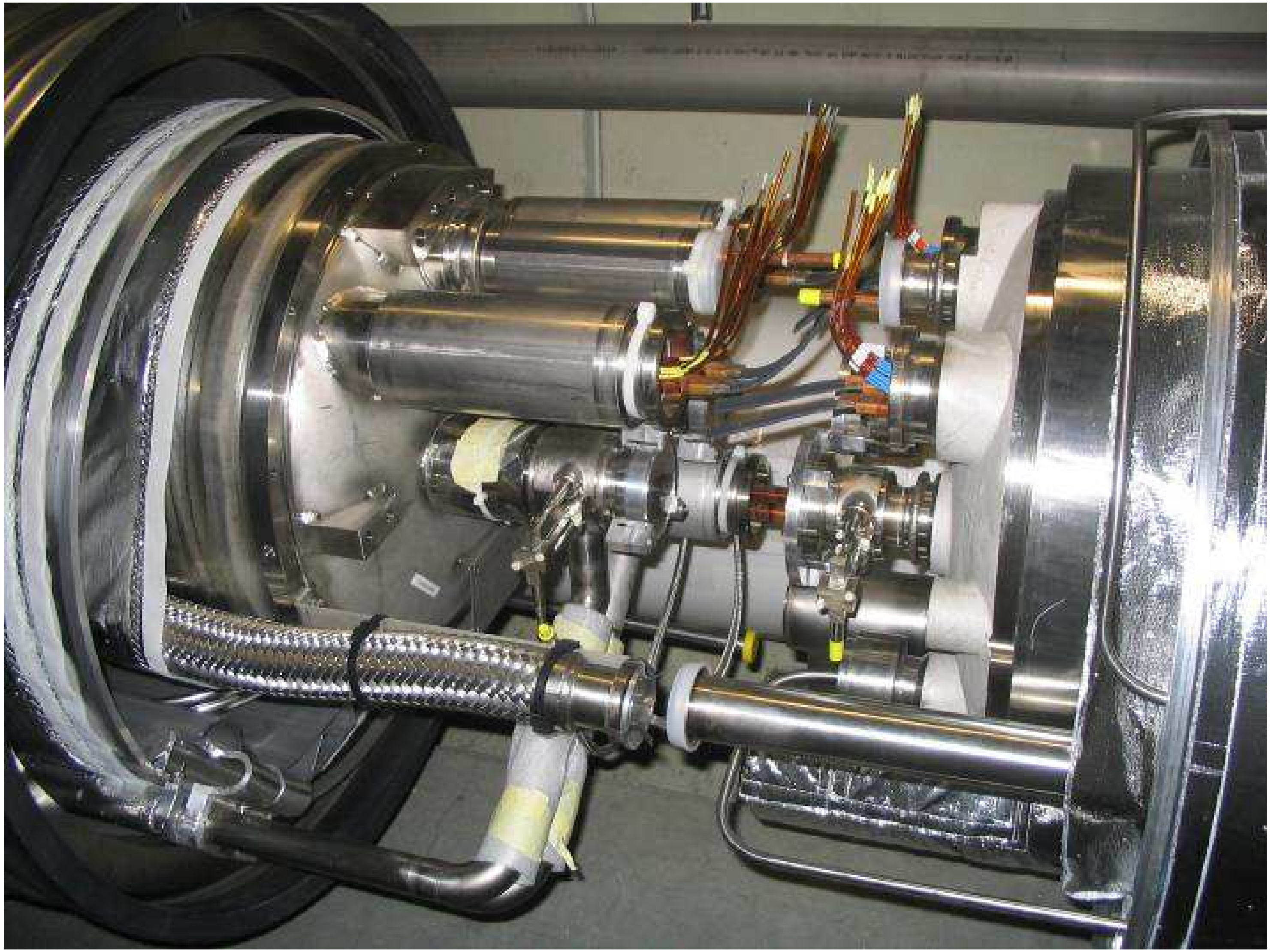
Superconducting dipole magnets

LHC dipole magnet interconnection:



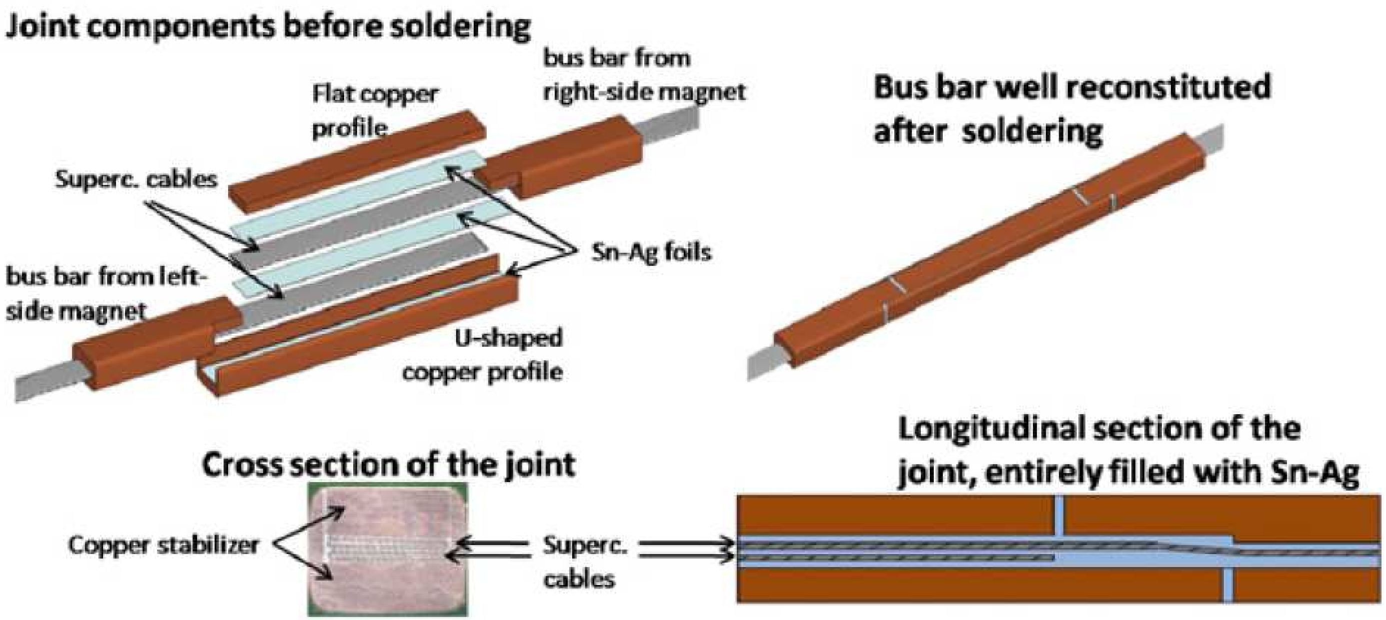
Superconducting dipole magnets

LHC dipole magnet interconnection:



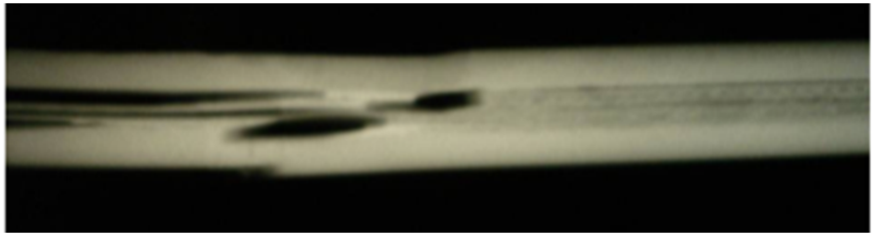
Electrical joint between superconducting modules

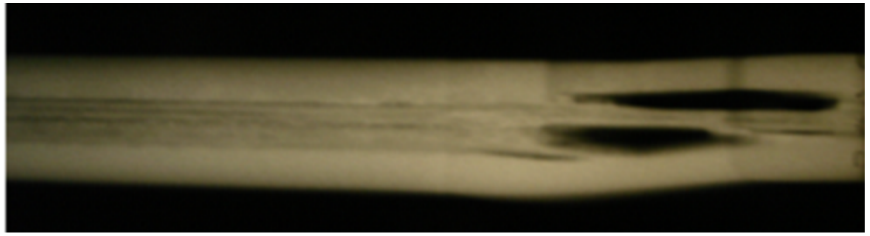
dipole bus bar splice
(electrical joint)



Electrical joint between superconducting modules

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

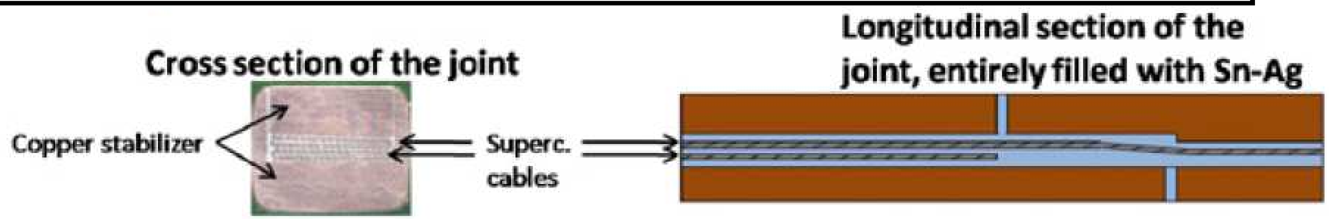




Electrical joint between superconducting modules

September 19, 2008

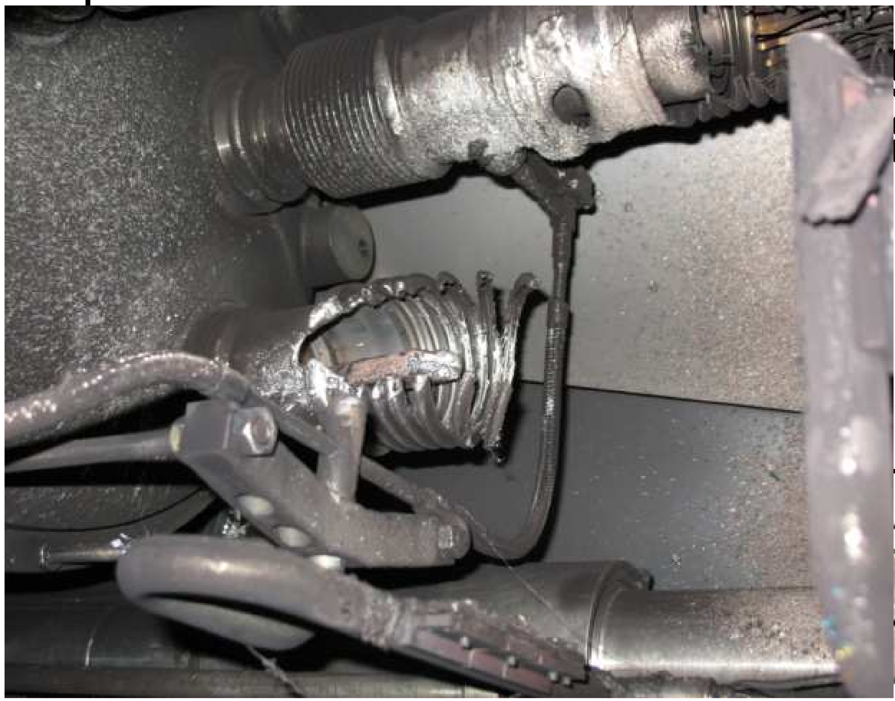
- Ramping the dipole current to 9.3 kA (6.5 T)
- At 8.7 kA, an electrical arc developed in a dipole bus bar splice, which punctured the helium enclosure
- The magnetic energy stored in one dipole string (1 octant) at 8.7kA (6.1 T) is 600 MJ which could heat and melt 900 kg of copper

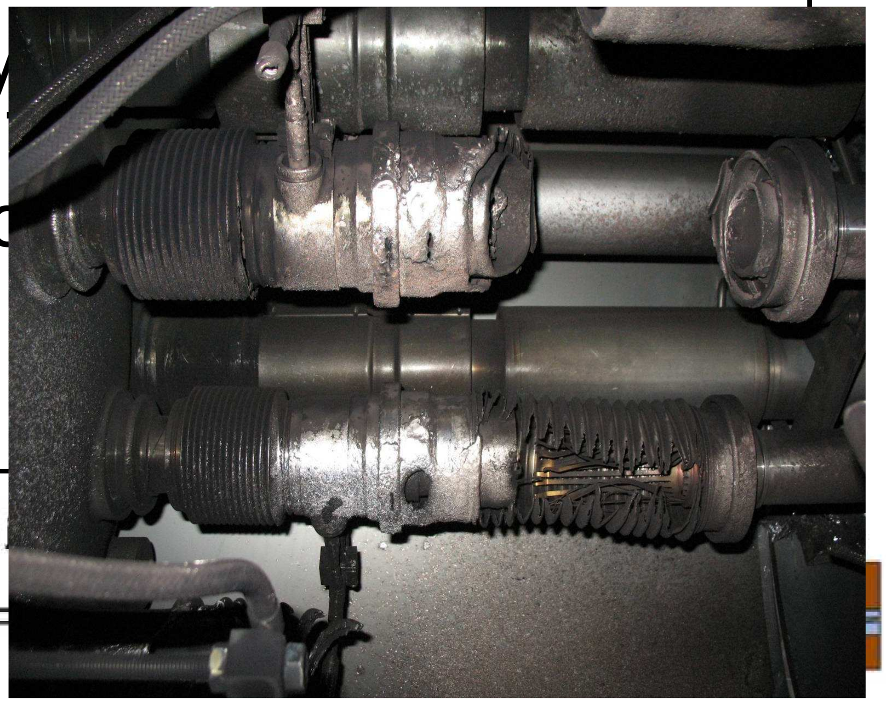


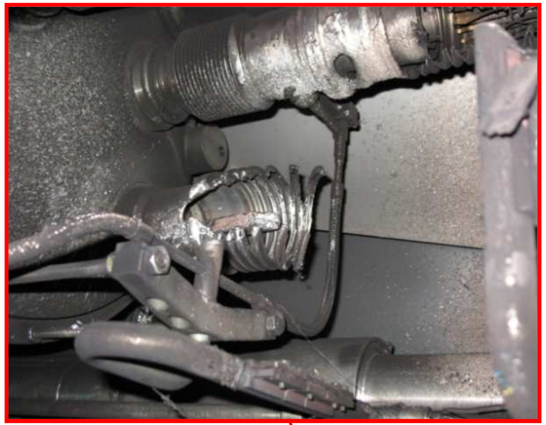
Electrical joint between superconducting modules

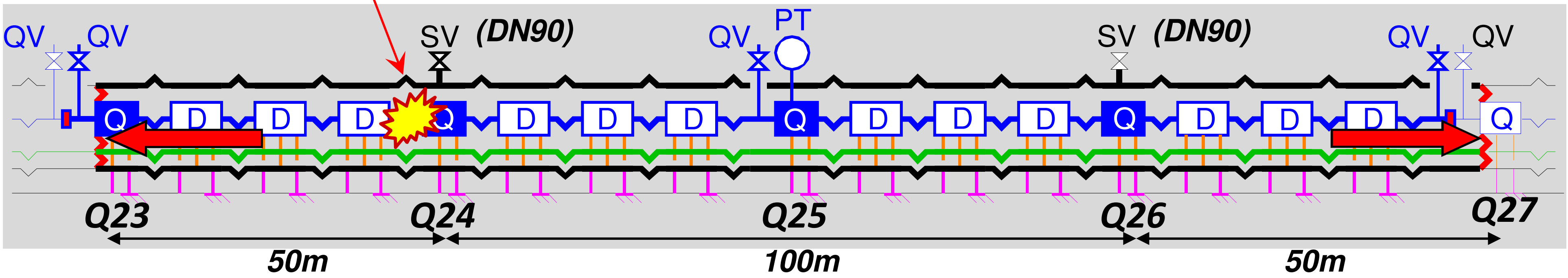
September 19, 2008

- 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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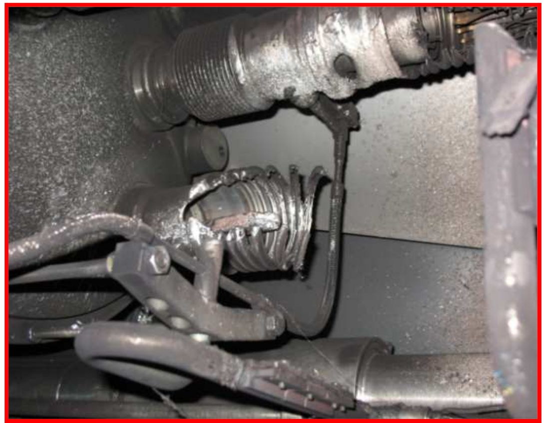

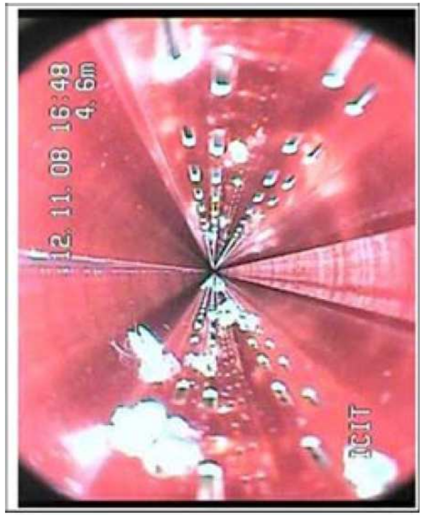
12. 11. 08 16:48
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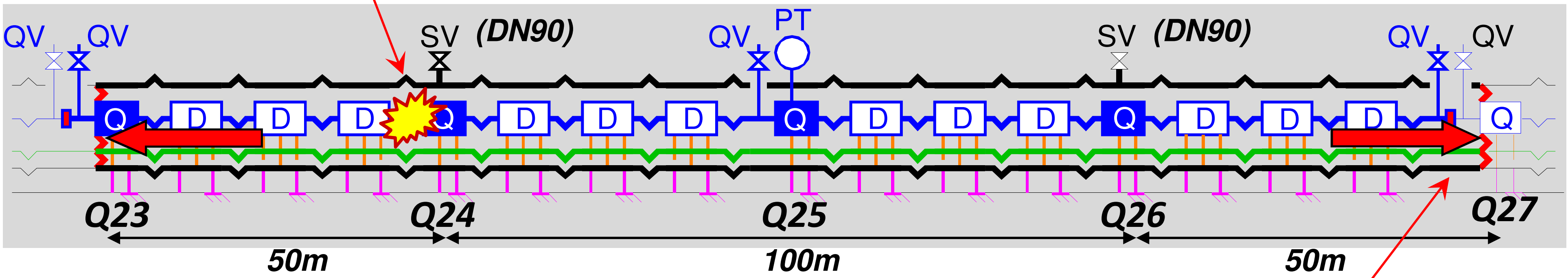
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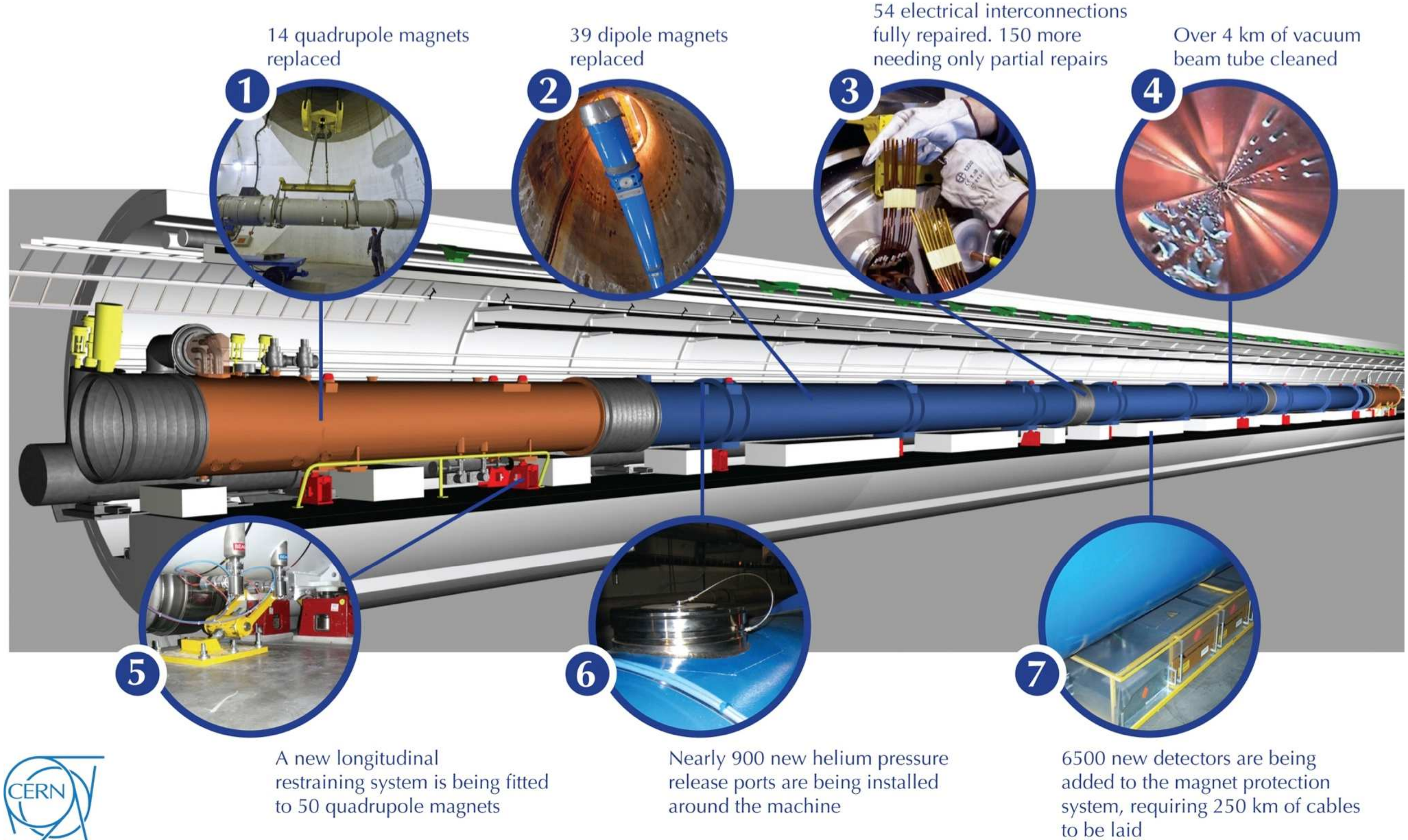
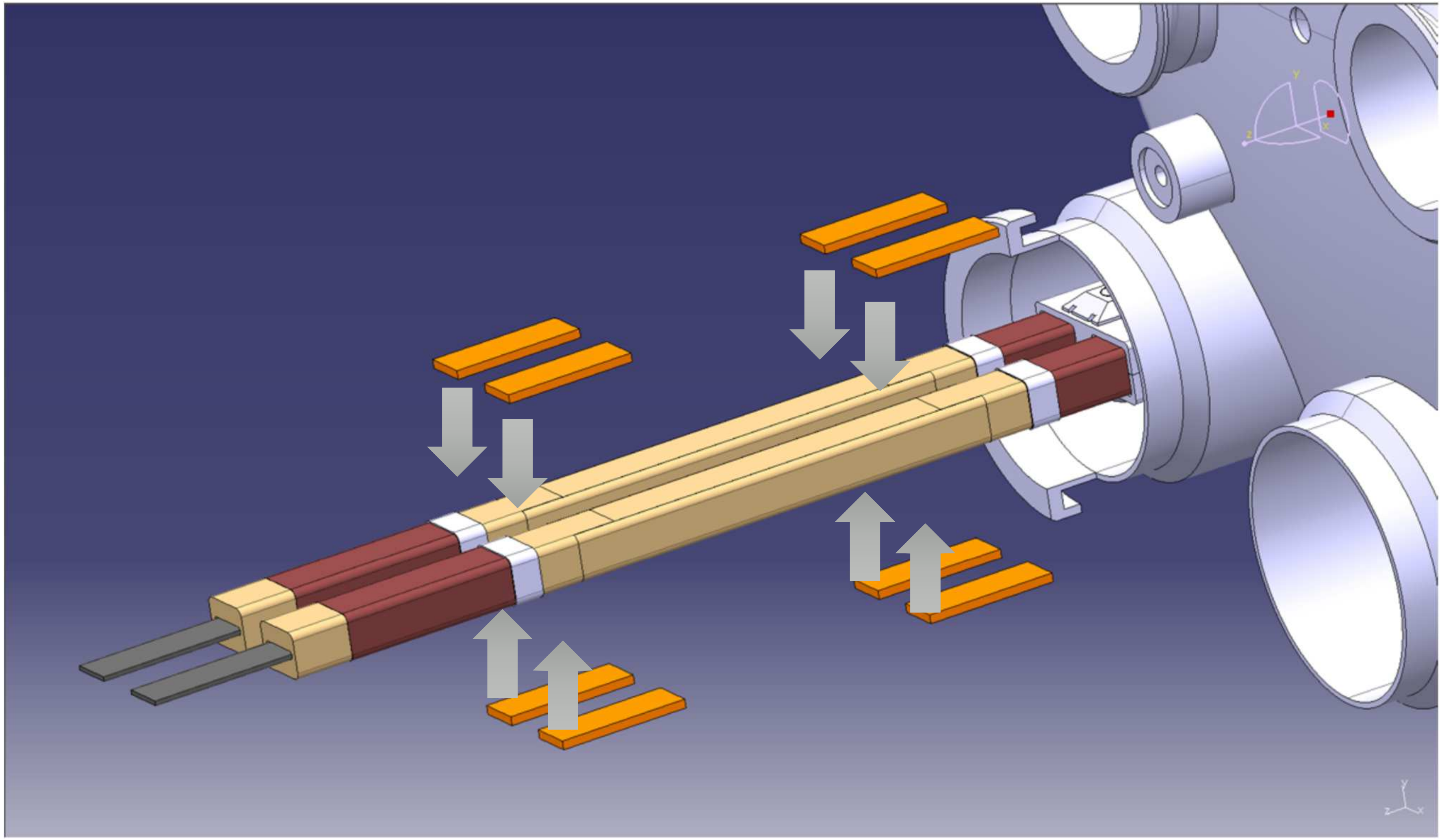
The LHC repairs in detail



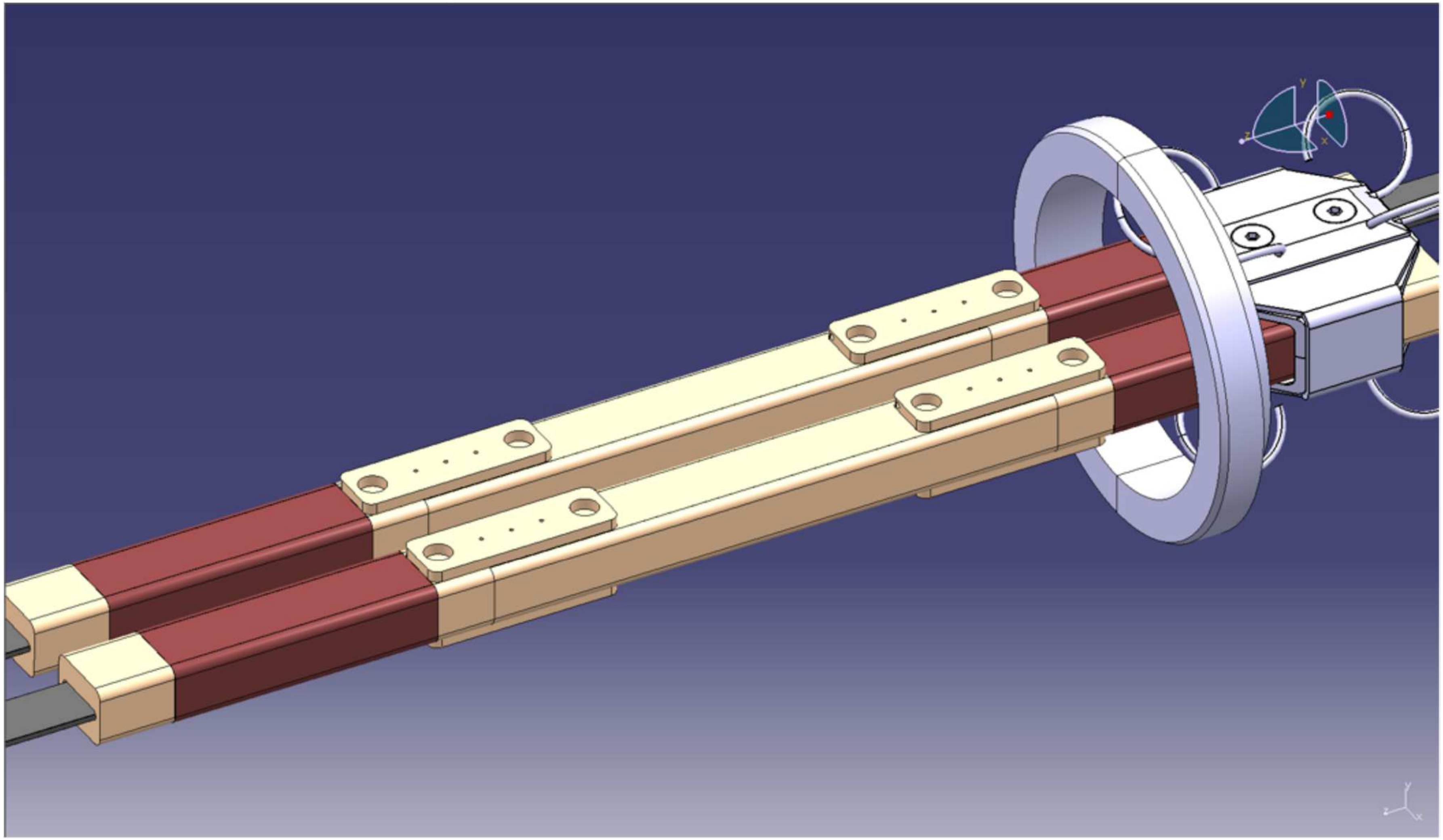
New electrical joint between superconducting modules



Phase I

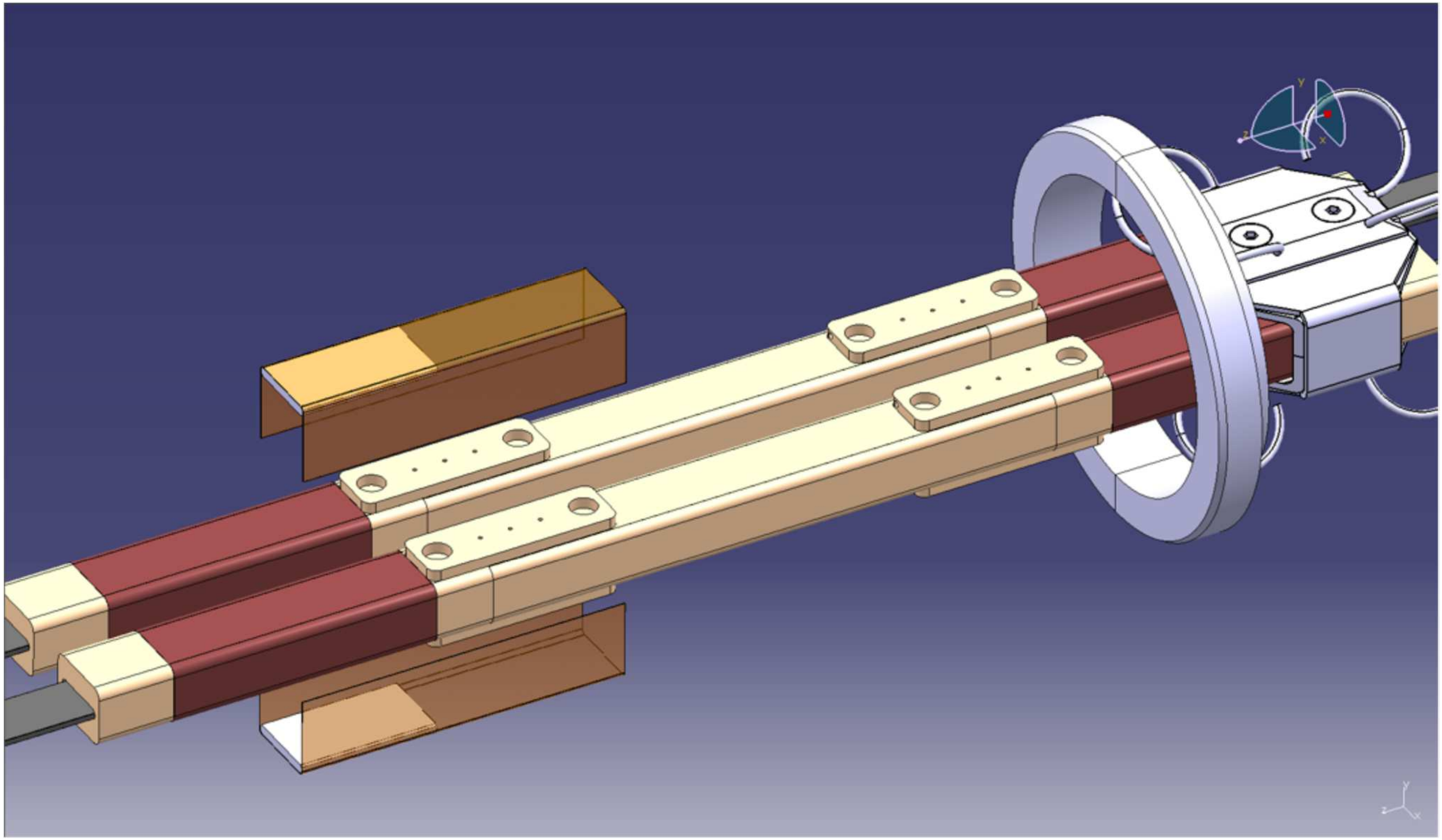
Surfacing of bus bar and installation of redundant shunts by soldering

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
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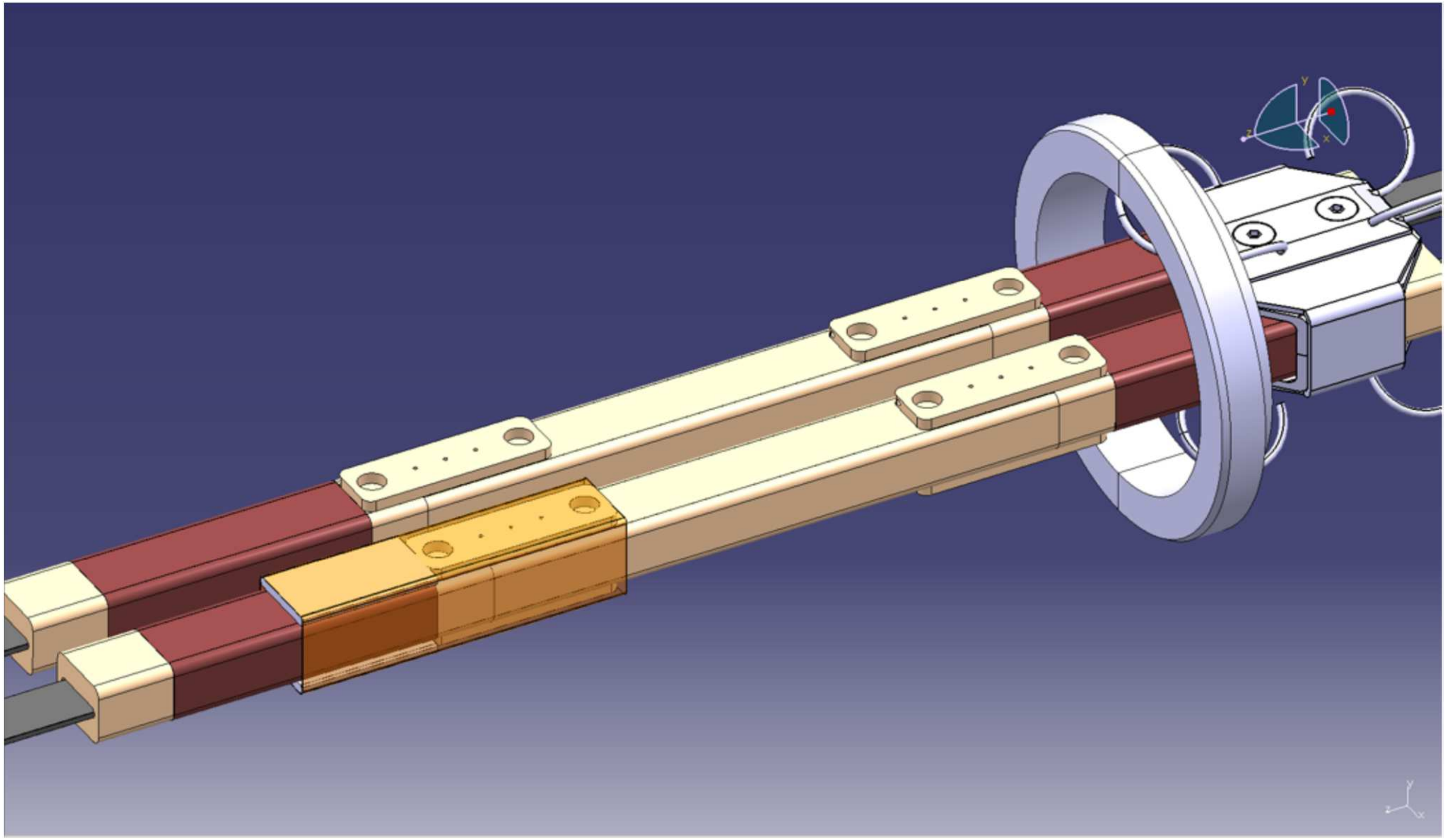
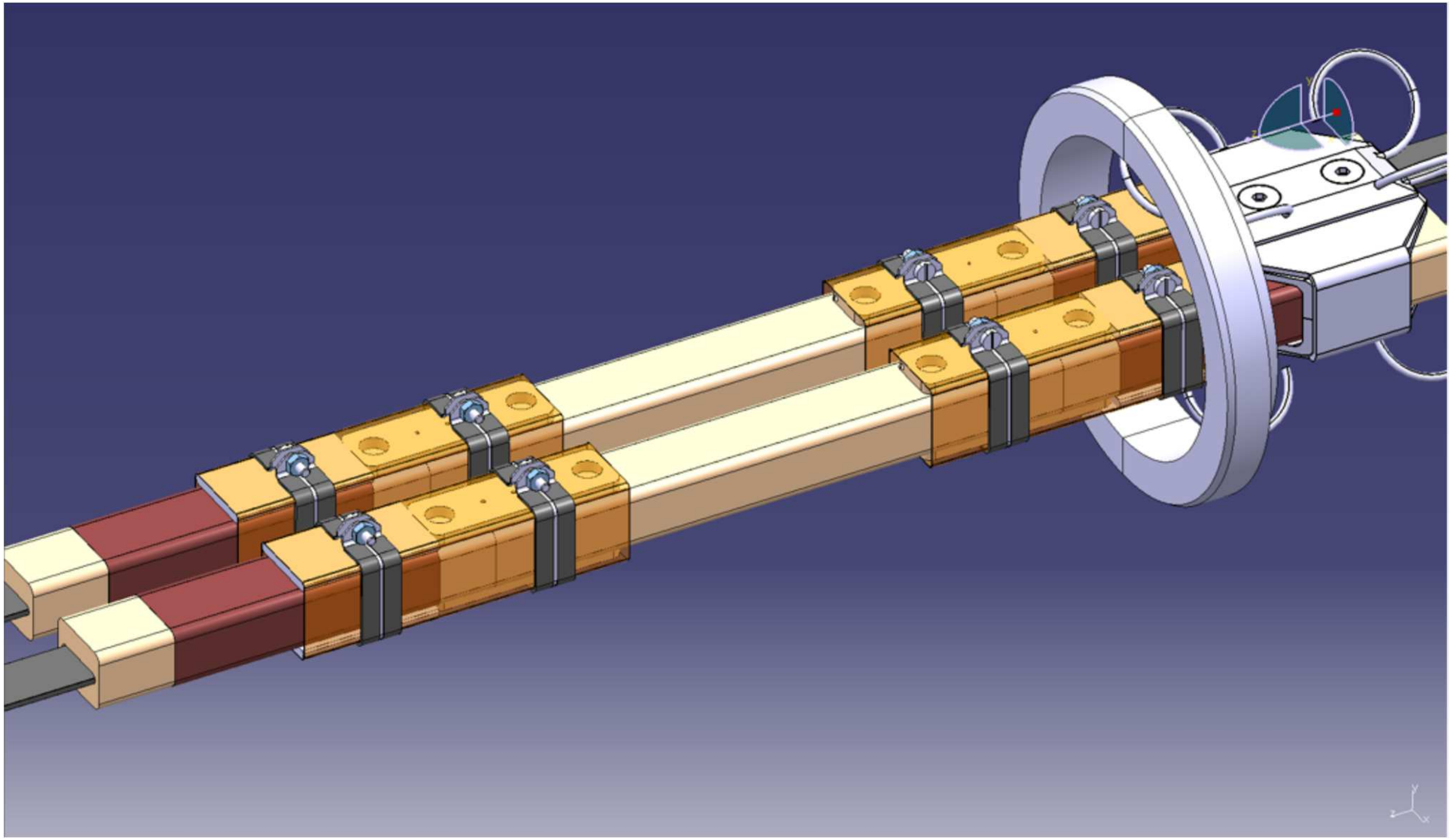
New electrical joint between superconducting modules



Phase II

Application of clamp and reinforcement of nearby bus bar insulation

New electrical joint between superconducting modules



Phase II

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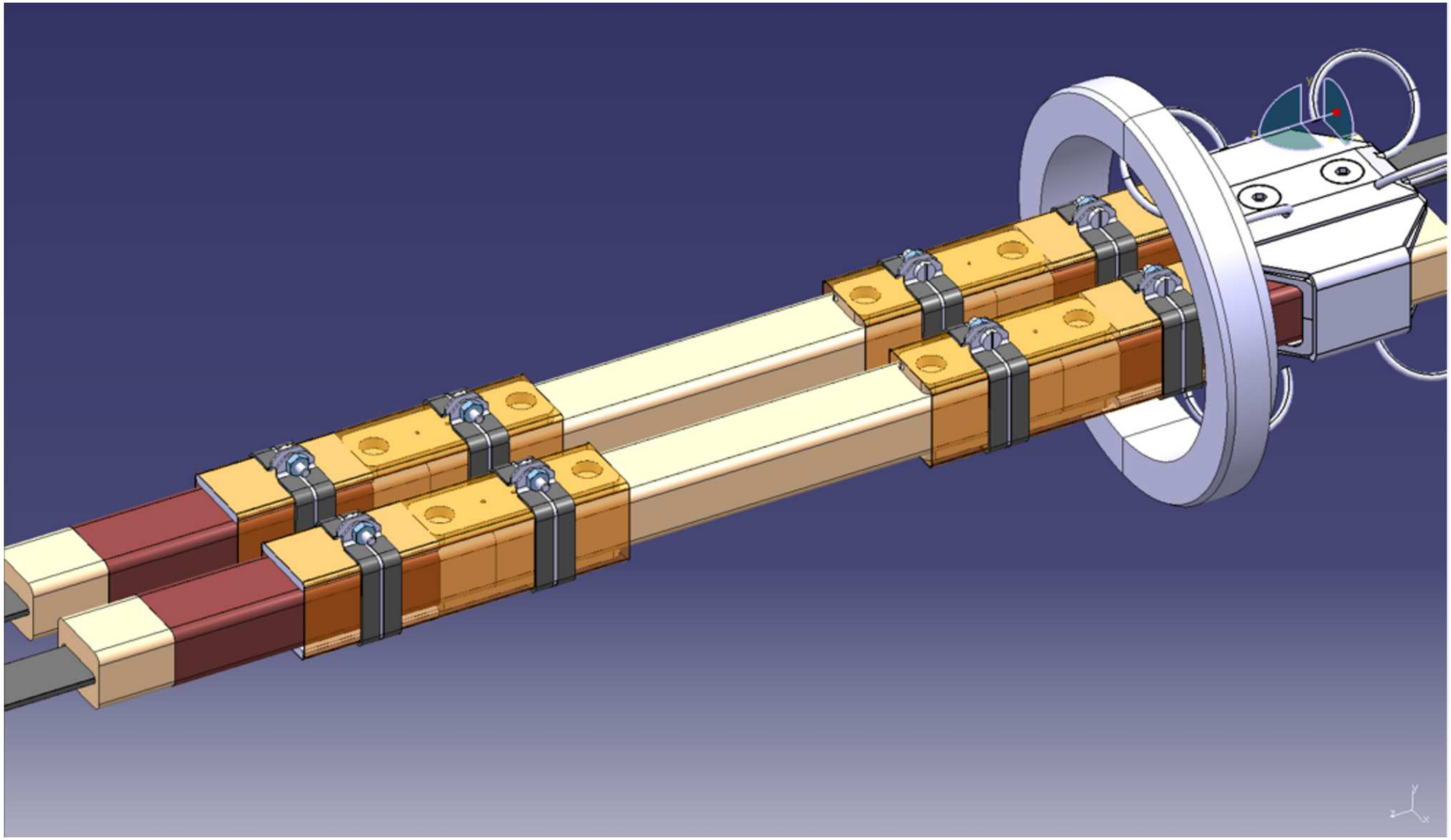
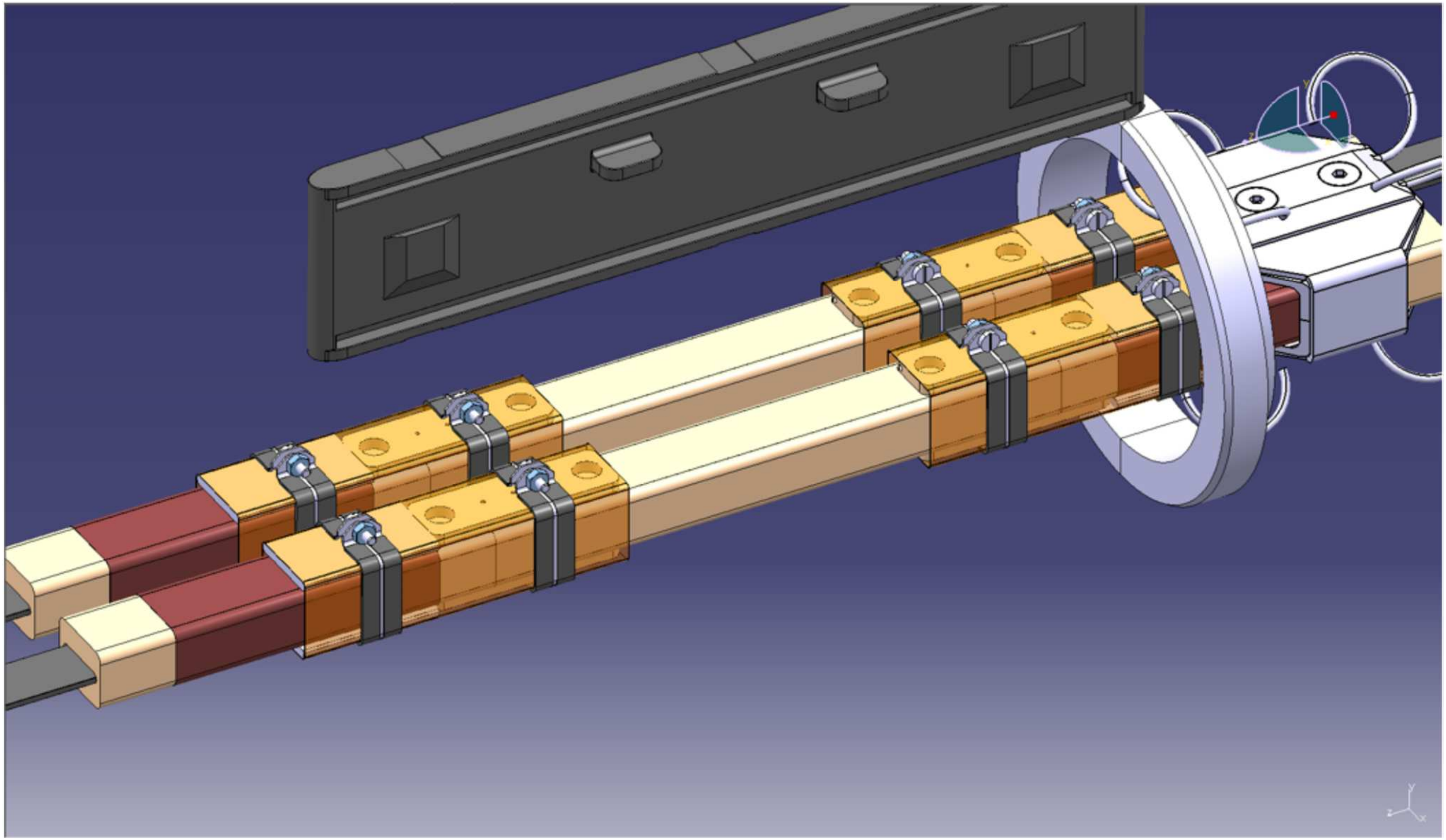
New electrical joint between superconducting modules



Phase III

Insulation between bus bar and to ground, Lorentz force clamping

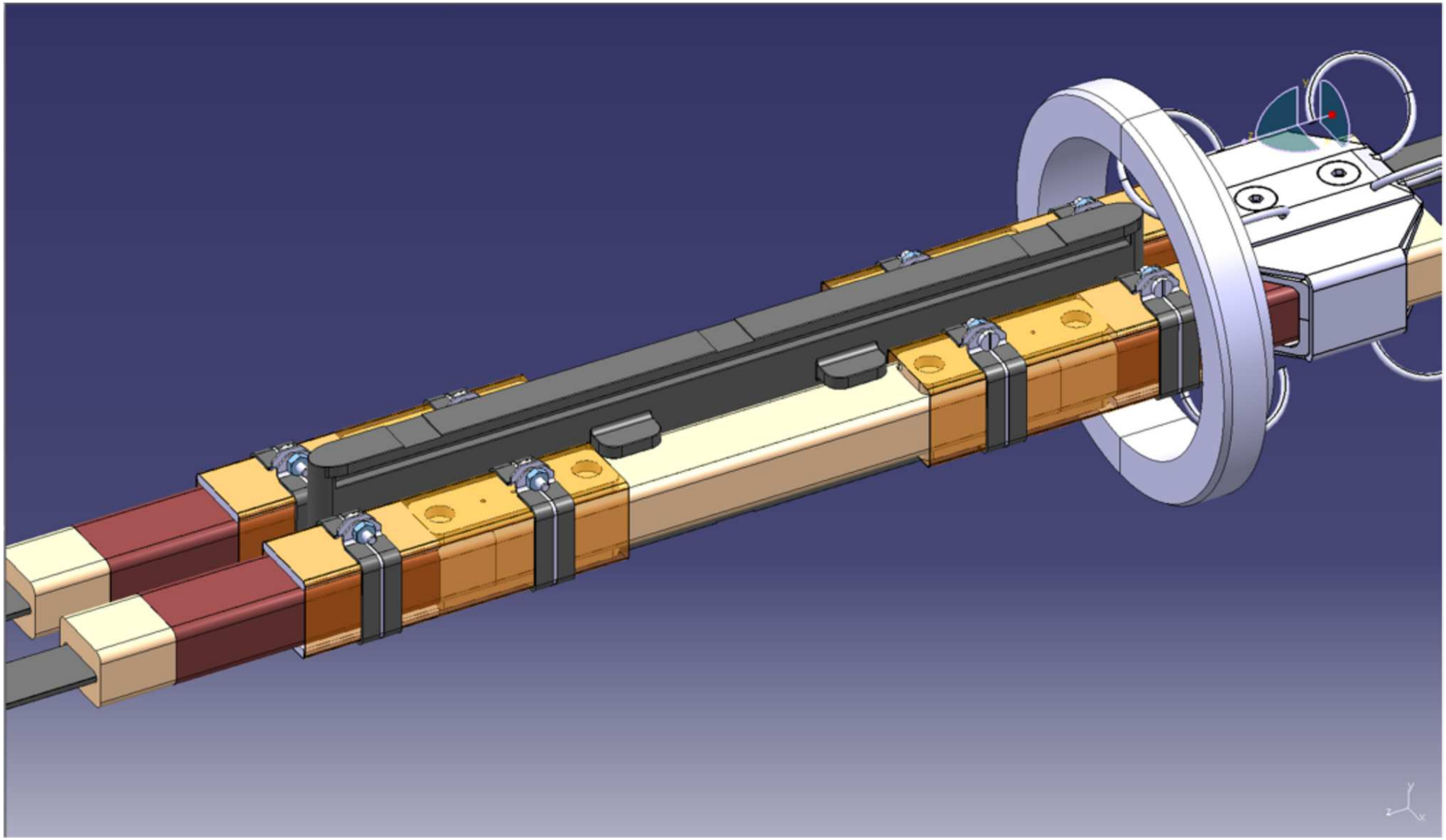
New electrical joint between superconducting modules



Phase III

Insulation between bus bar and to ground, Lorentz force clamping

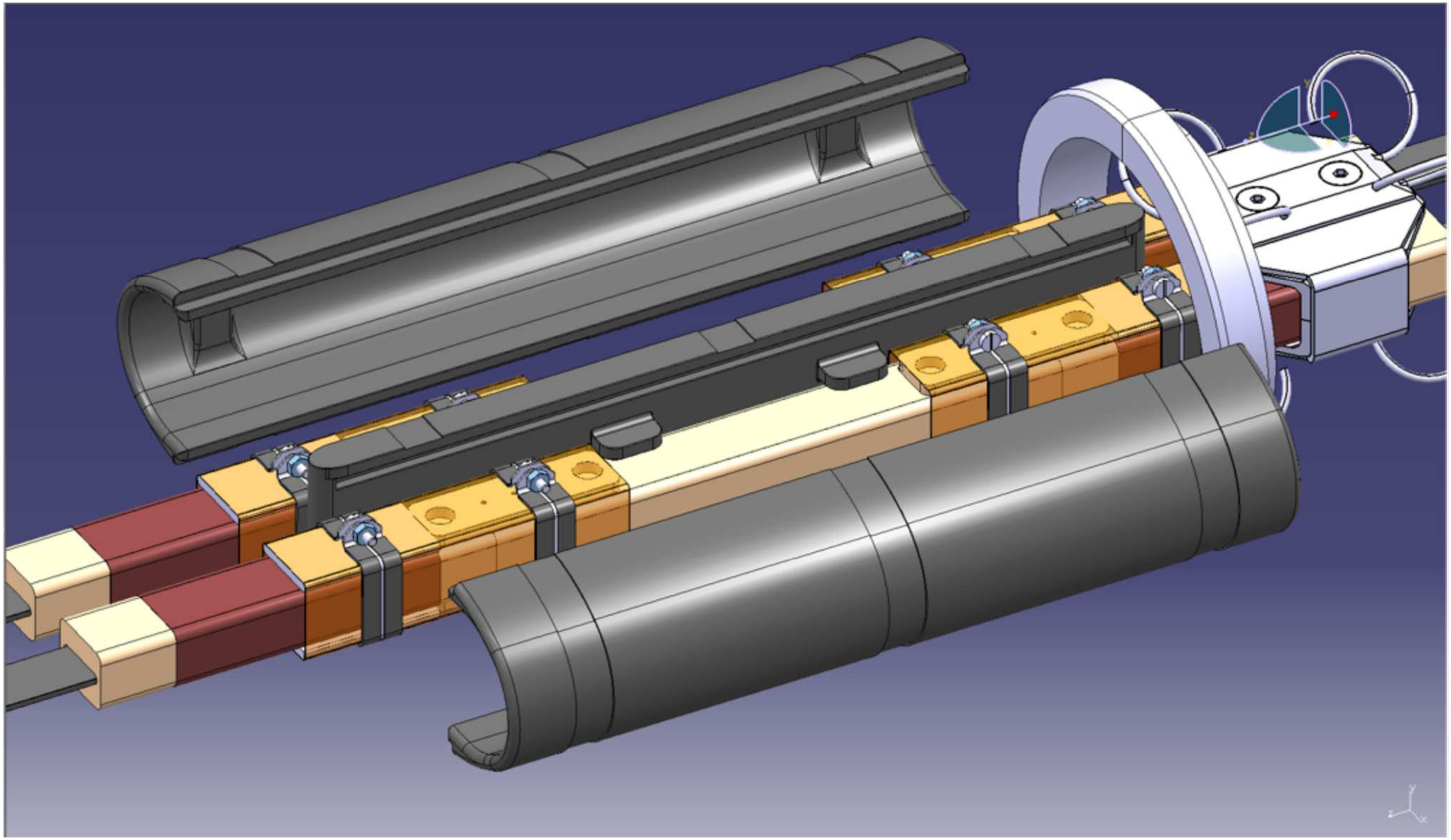
New electrical joint between superconducting modules



Phase III

Insulation between bus bar and to ground, Lorentz force clamping

New electrical joint between superconducting modules



Phase III
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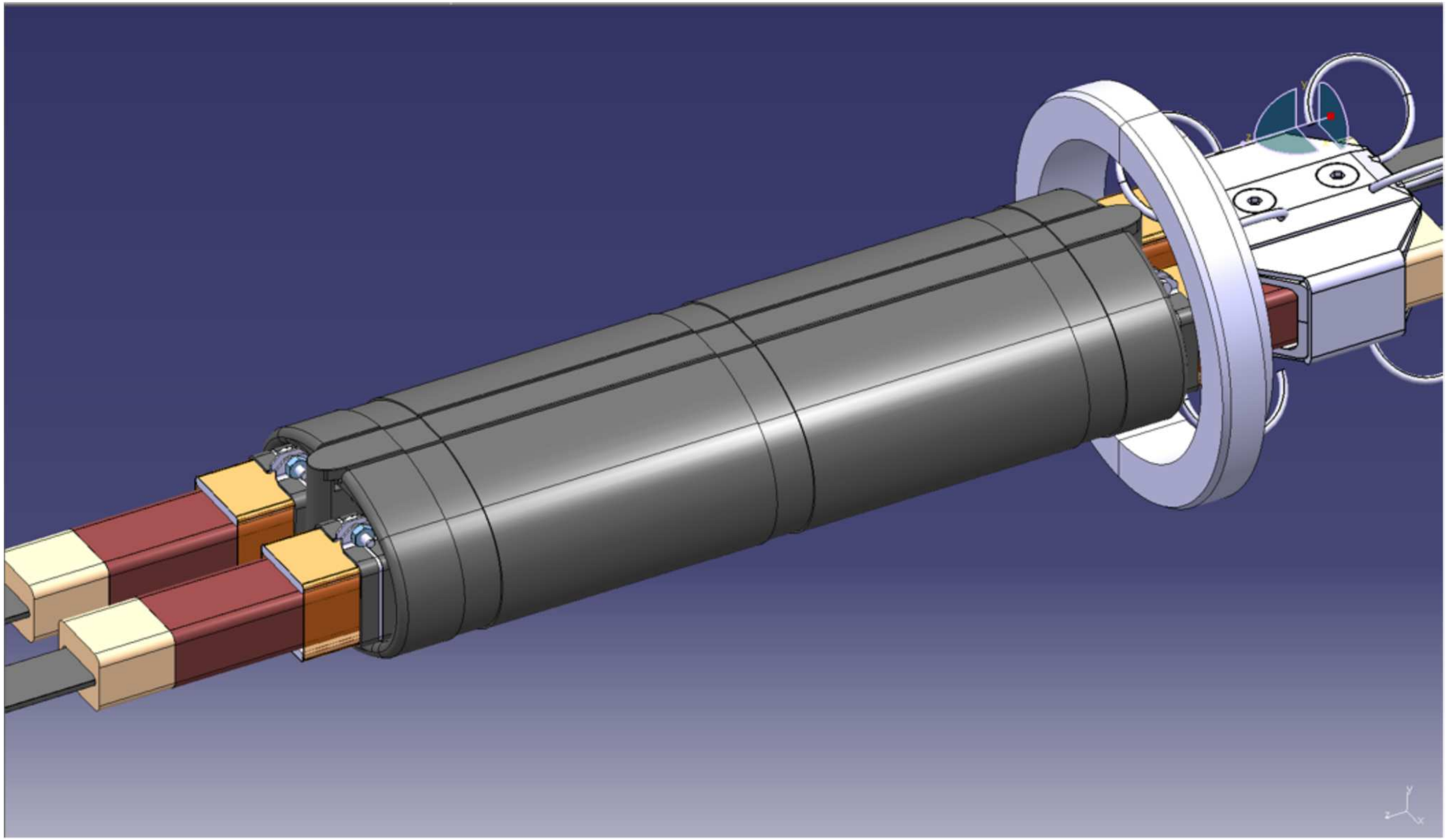
New electrical joint between superconducting modules



Phase III

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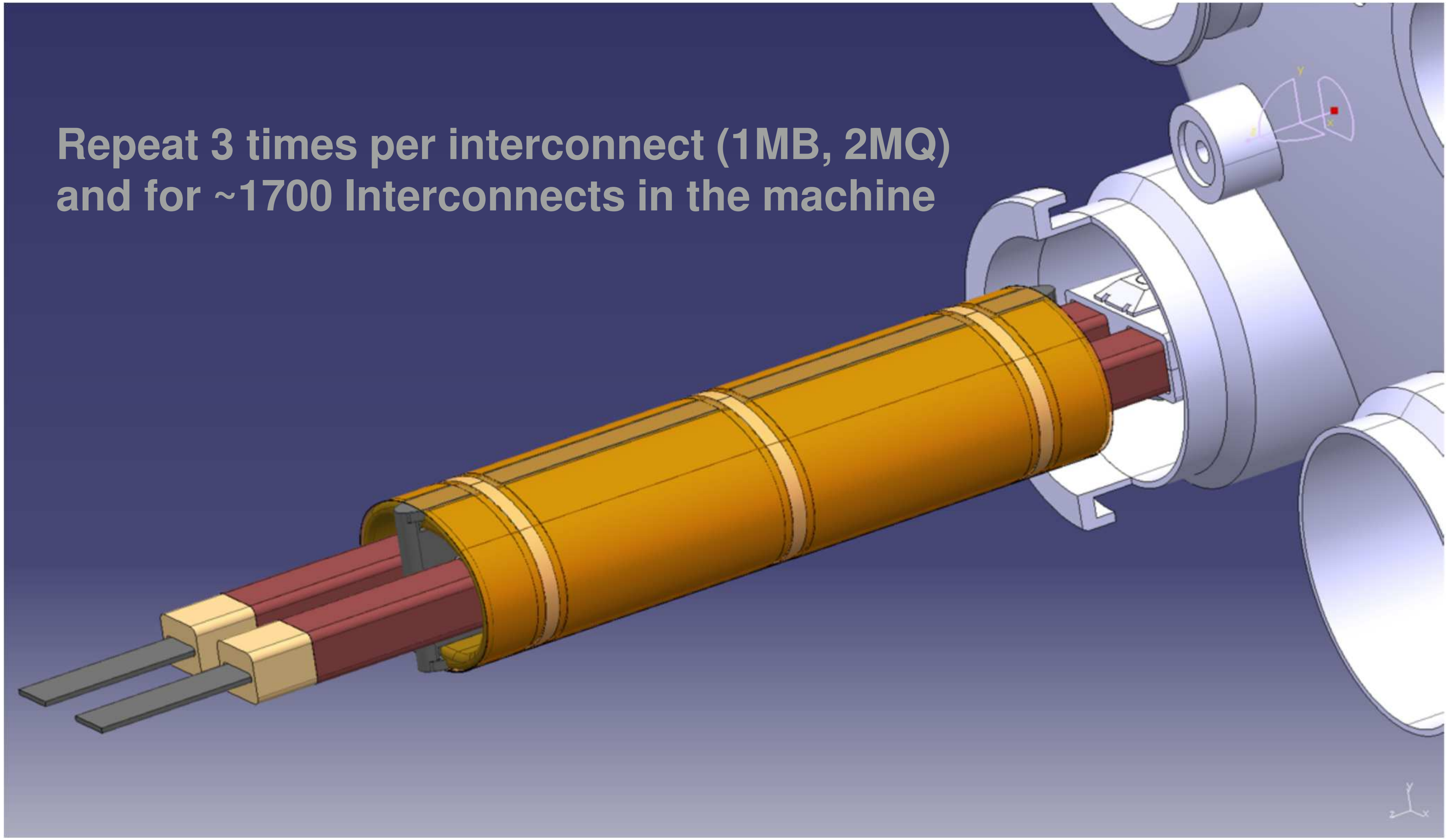
New electrical joint between superconducting modules



Phase III

Insulation between bus bar and to ground, Lorentz force clamping

Summing-up of this part

Circular accelerators: the synchrotron

RF cavities:
- pill-box cavity
- superconducting cavities

Dipole magnets:
- normal conducting dipoles
- superconducting dipoles

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

Contact

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