HiLumi
HL-LHC PROJECT

Impact of the forces due to CLIQ discharges on the MQXF Beam Screen

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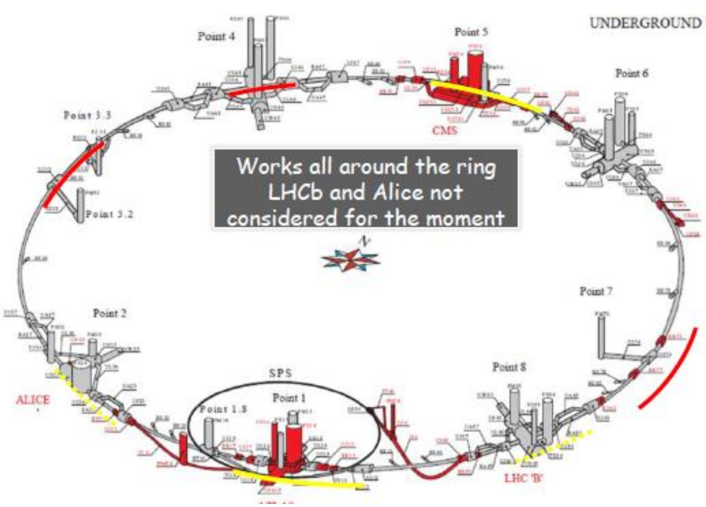
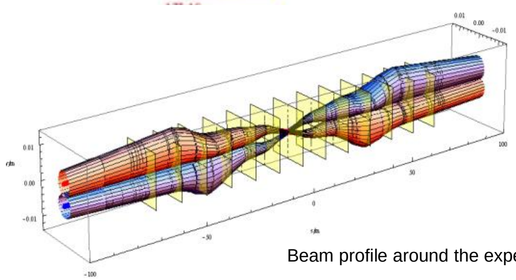
The High Luminosity - LHC Project



- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …



Beam profile around the experiments

→ Smaller beam size at the interaction points.

Major intervention on more than <u>1.2 km</u> of

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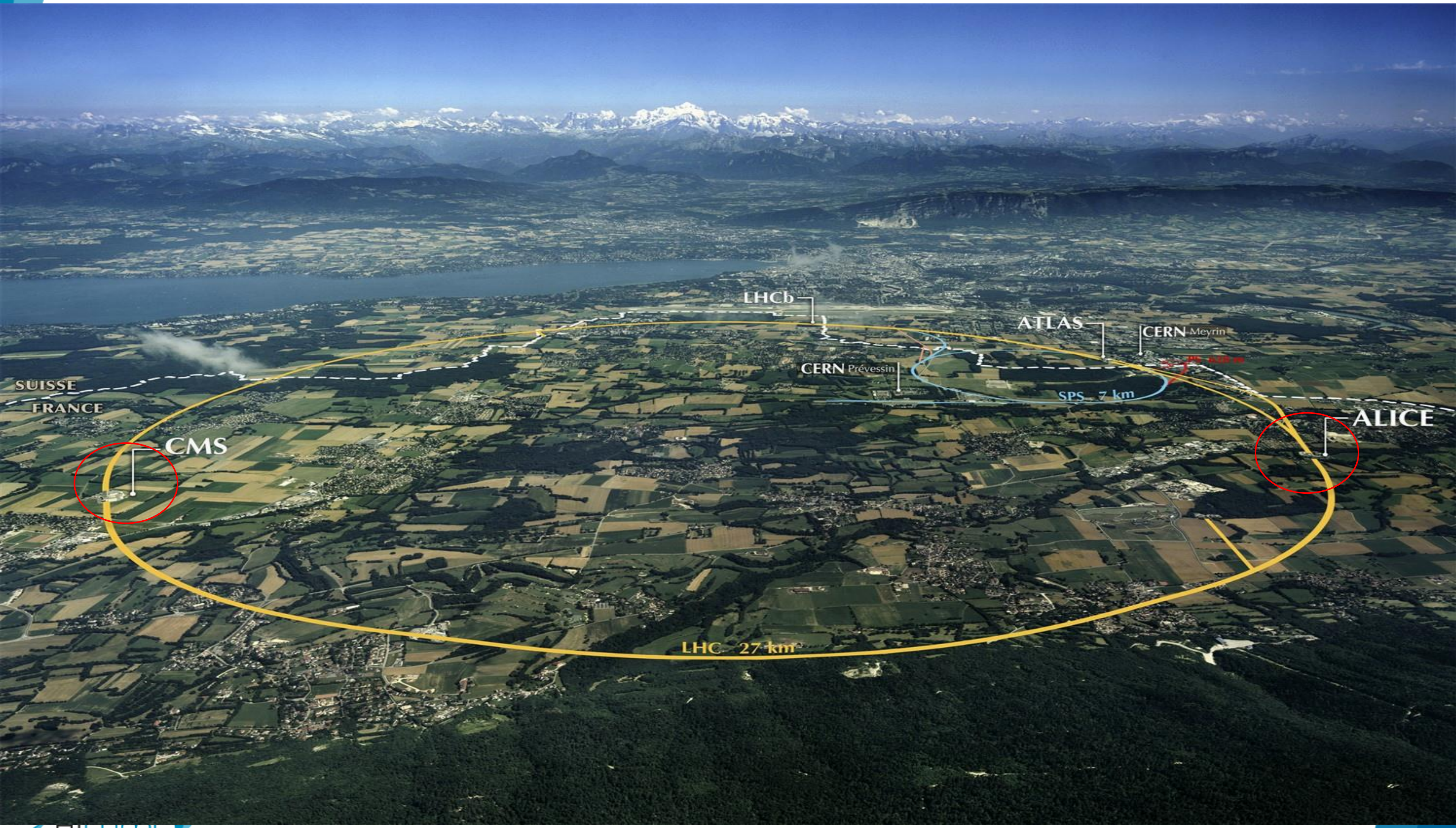
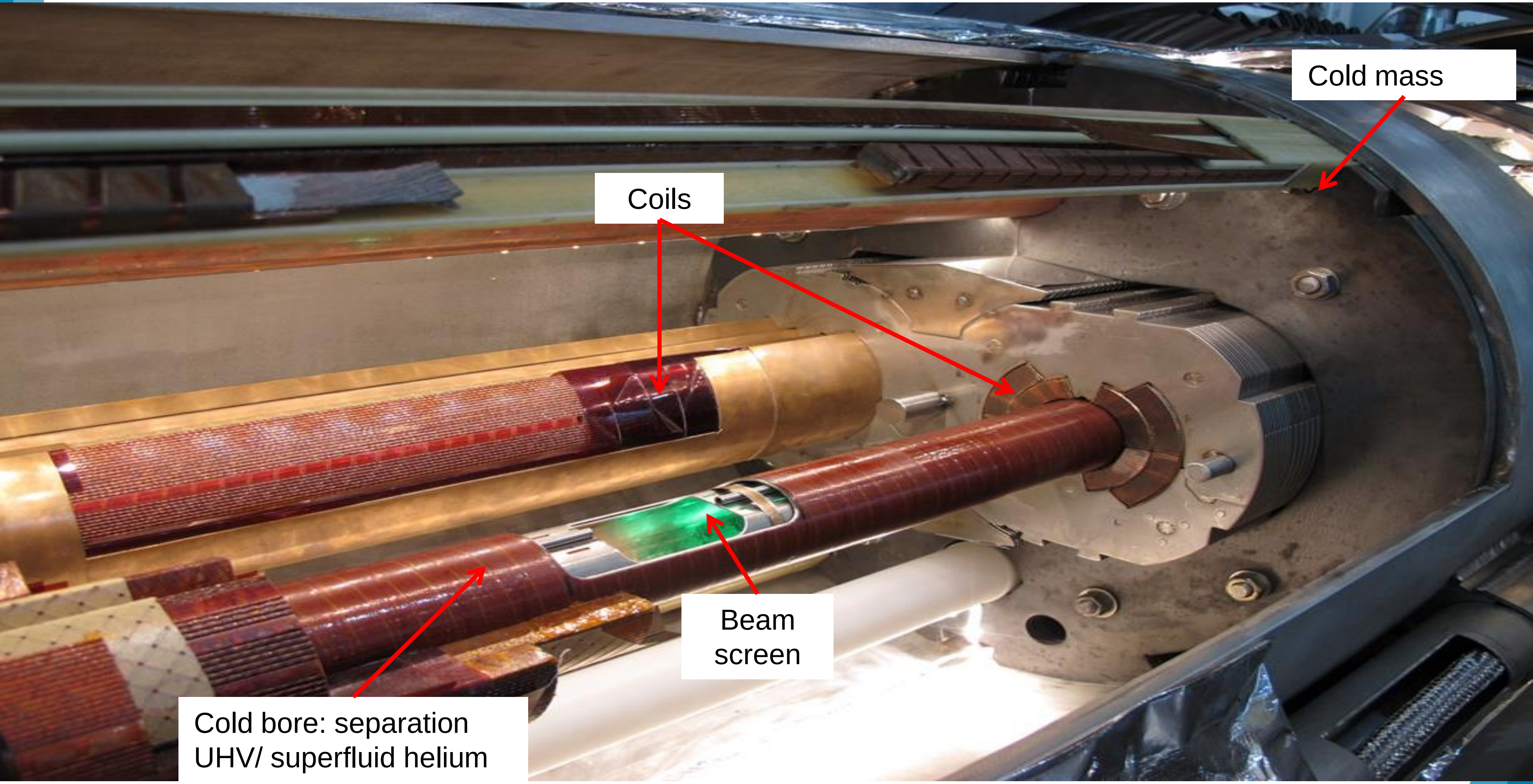
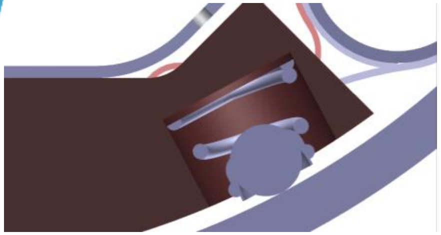
The High Luminosity - LHC Project



LHC ring

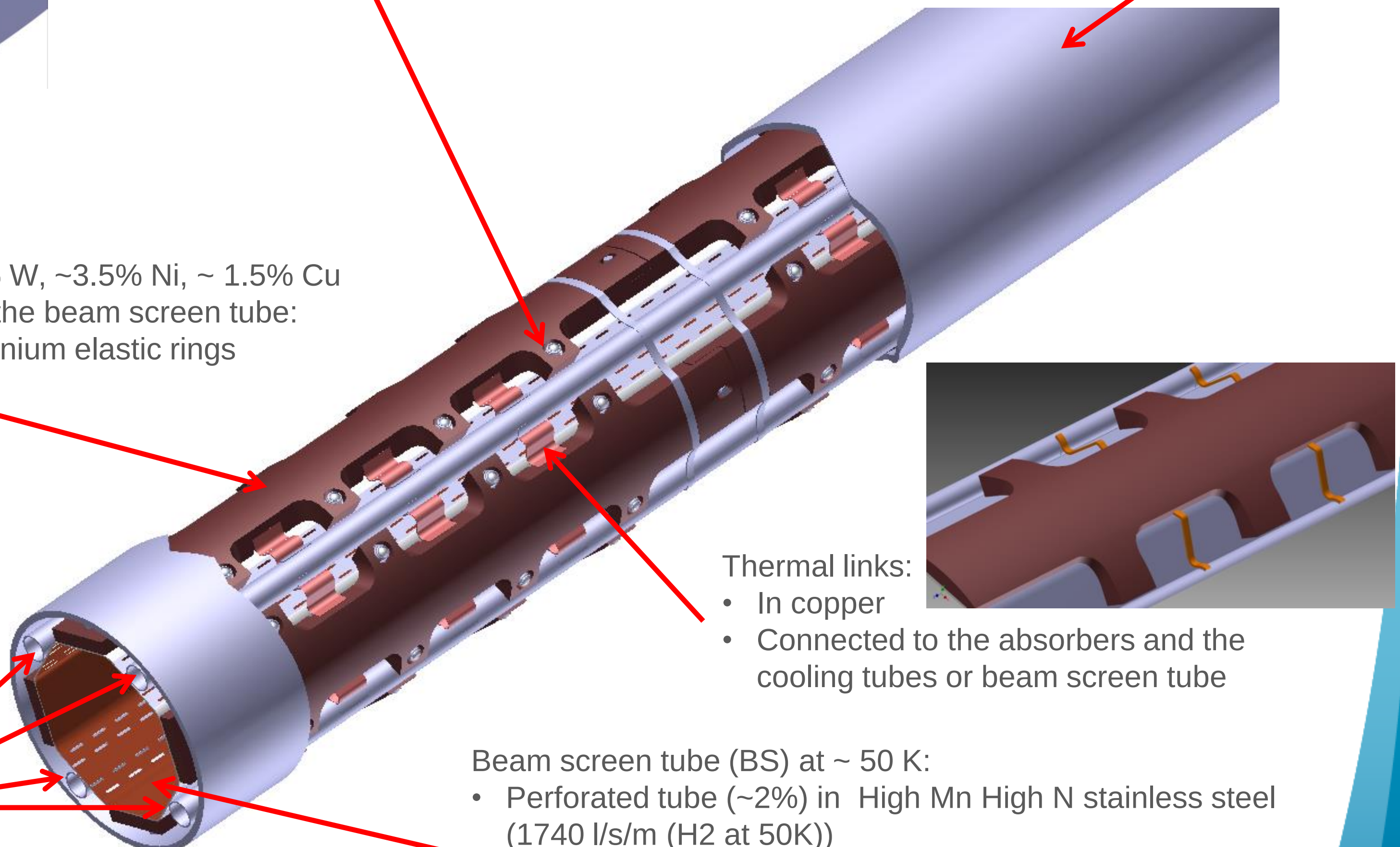

Cold mass
Coils
Beam screen
Cold bore: separation UHV/ superfluid helium

HL-LHC beam screen design



Elastic supporting system:
Low heat leak to the cold bore tube at 1.9K
Ceramic ball with titanium spring

Cold bore (CB) at 1.9 K:
4 mm thick tube in 316LN



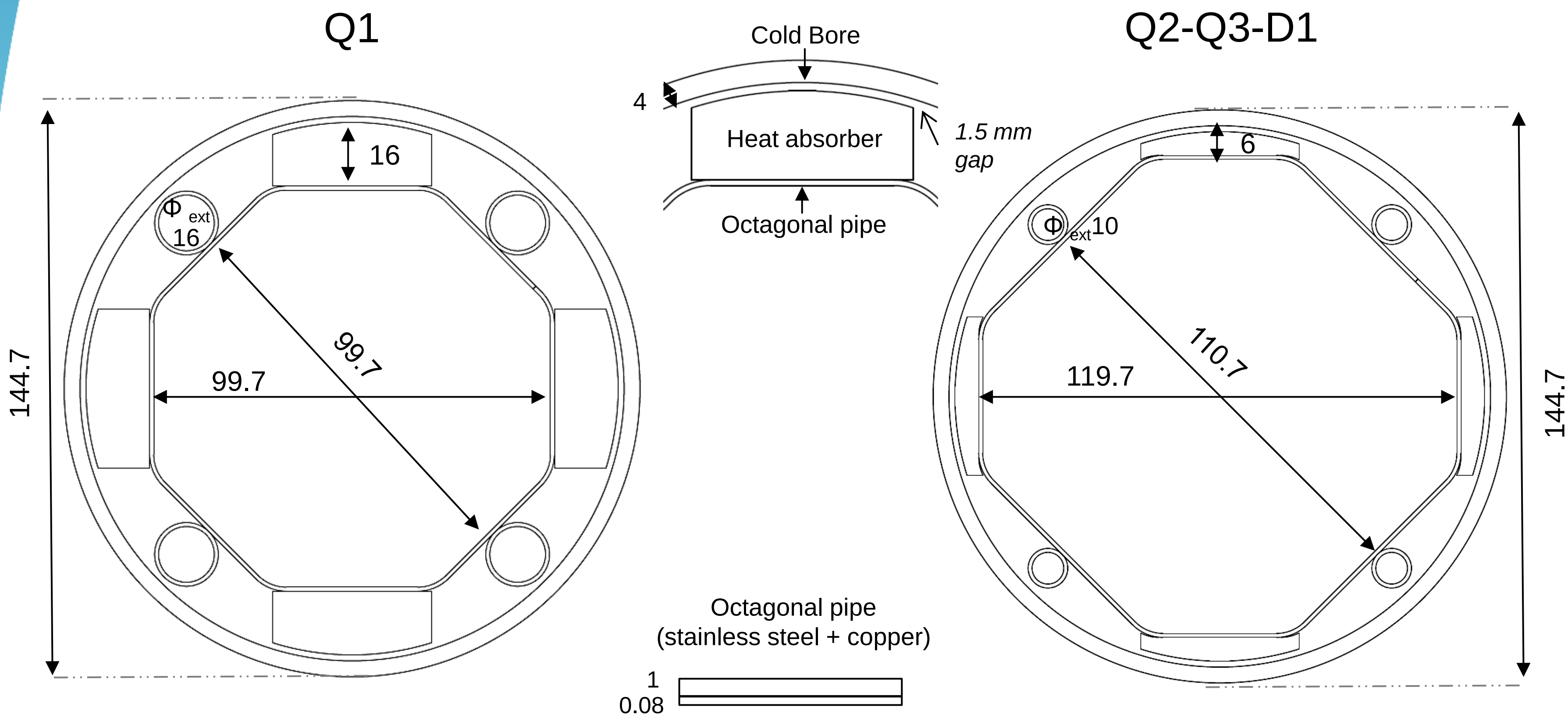
Tungsten alloy blocks:
- Chemical composition: 95% W, ~3.5% Ni, ~ 1.5% Cu
- mechanically connected to the beam screen tube: positioned with pins and titanium elastic rings
- Heat load: 15-25 W/m

Thermal links:
- In copper
- Connected to the absorbers and the cooling tubes or beam screen tube

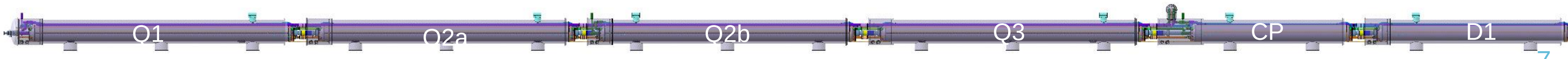
Beam screen tube (BS) at ~ 50 K:
- Perforated tube (~2%) in High Mn High N stainless steel (1740 l/s/m (H2 at 50K))
- Internal copper layer (80 μm) for impedance
- a-C coating (as a baseline) for e- cloud mitigation
- Laser treatments under investigation

Cooling tubes:
- Outer Diameter: 10 or 16 mm
- Laser welded on the beam screen tube

Beam screen dimensions*



*The dimensions are given in mm



Triplet area layout

Conceptual specification

“This component ensures the vacuum performance together with shielding the cold mass from physics debris and screening the cold bore cryogenic system from beam induced heating.

The shielded beam screen has to withstand the Lorentz forces induced by eddy currents during a quench. **50 cycles at high field.** *(13th HL-LHC TC)*

The temperature of the shielded beam screen must be actively controlled in a given temperature range: ***60-80 K.*** *(Temperature window to be confirmed)*

The system must be compatible with impedance performances.

The system must be compatible with the machine aperture.”

Coupling-Loss Induced Quench (CLIQ)
Magnet quench protection scheme

High-field magnets operate at currents as high as 12 kA in superconducting state at 1.9 K.

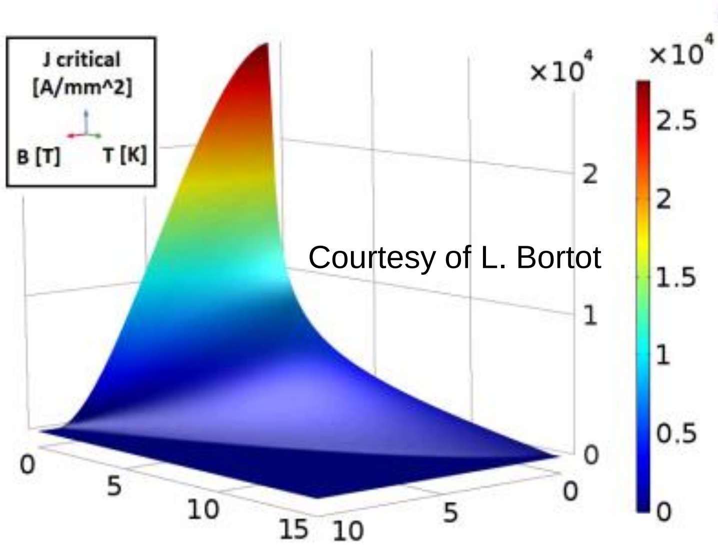
The superconducting state is defined by:

- Critical temperature;
- Electric current density;
- Magnetic field.

The superconducting state can be perturbed for example by:

- Mechanical movements;
- AC losses;
- Beam losses.

Magnet quench: resistive transition of a portion of the magnet



Critical surface for Nb-Ti, showing the maximum allowed current density as function of temperature and magnetic field.

Release of energy = 7 MJ of energy stored in each magnet that can melt more than 10 Kg of copper.

CLIQ protects the magnet by heating up it from the inside in a uniform way.

Mechanical forces during a uniform magnetic field decay

Foucault currents are governed by Maxwell's equation:

$$\mathbf{rot\ E} = -\partial B/\partial t$$

$$\mathbf{j} = \mathbf{E}/\rho$$

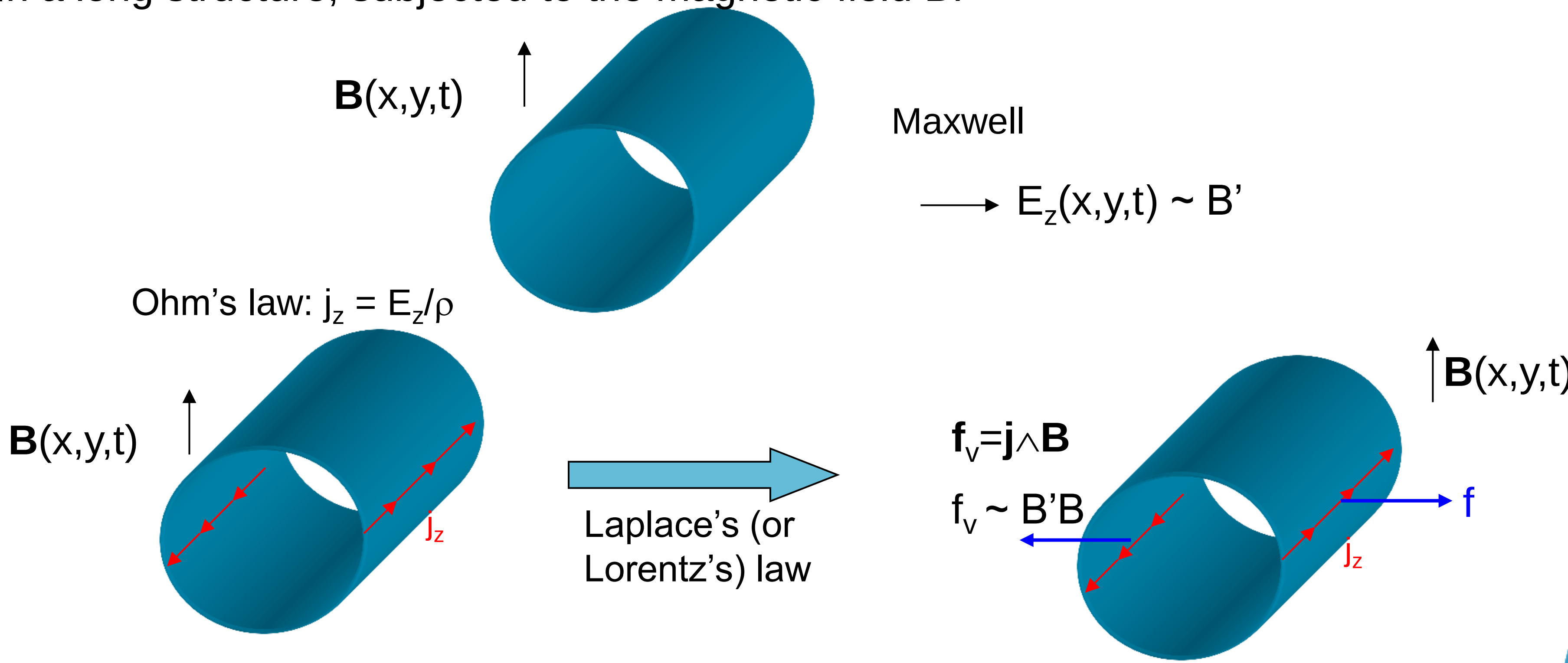
B: magnetic field

E: electric field

j: current density

ρ: electrical resistivity

In a long structure, subjected to the magnetic field B:



Mechanical forces during a uniform magnetic field decay

For a *quadrupole magnetic* field:
$\mathbf{B}$=G.r.((sin(2φ)$\mathbf{e}_r$+ cos(2φ)$\mathbf{e}_\theta$)

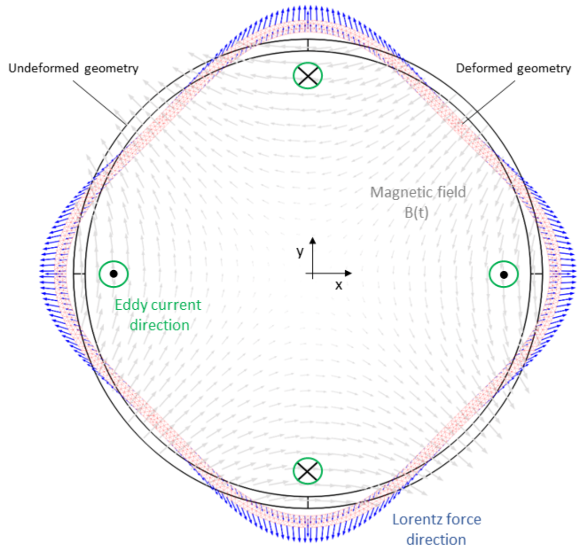
- Electrical field: $\mathbf{E}$ = 1/2.G'.r^2. cos(2φ).$\mathbf{e}_z$
- Current density: j_z = 1/2.G'.r^2. cos(2φ)/ρ
- Specific Lorentz force:

$\mathbf{f}$ = 1/2.G.G'.r^3. cos(2φ)/ρ.(sin(2φ)$\mathbf{e}_\theta$- cos(2φ)$\mathbf{e}_r$)

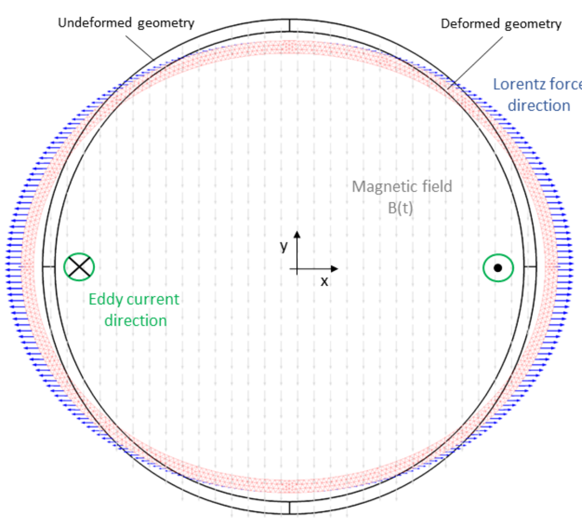
For a *dipole magnetic* field:
$\mathbf{B}$=B.$\mathbf{e}_y$

- Electrical field: $\mathbf{E}$ = B'.x.$\mathbf{e}_z$
- Current density: j_z = B'.x/ρ
- Specific Lorentz force:

$\mathbf{f}$ = -B.B'. x/ρ. $\mathbf{e}_x$



Lorentz force distribution during a quadrupole magnet quench



Lorentz force distribution during a dipole magnet quench

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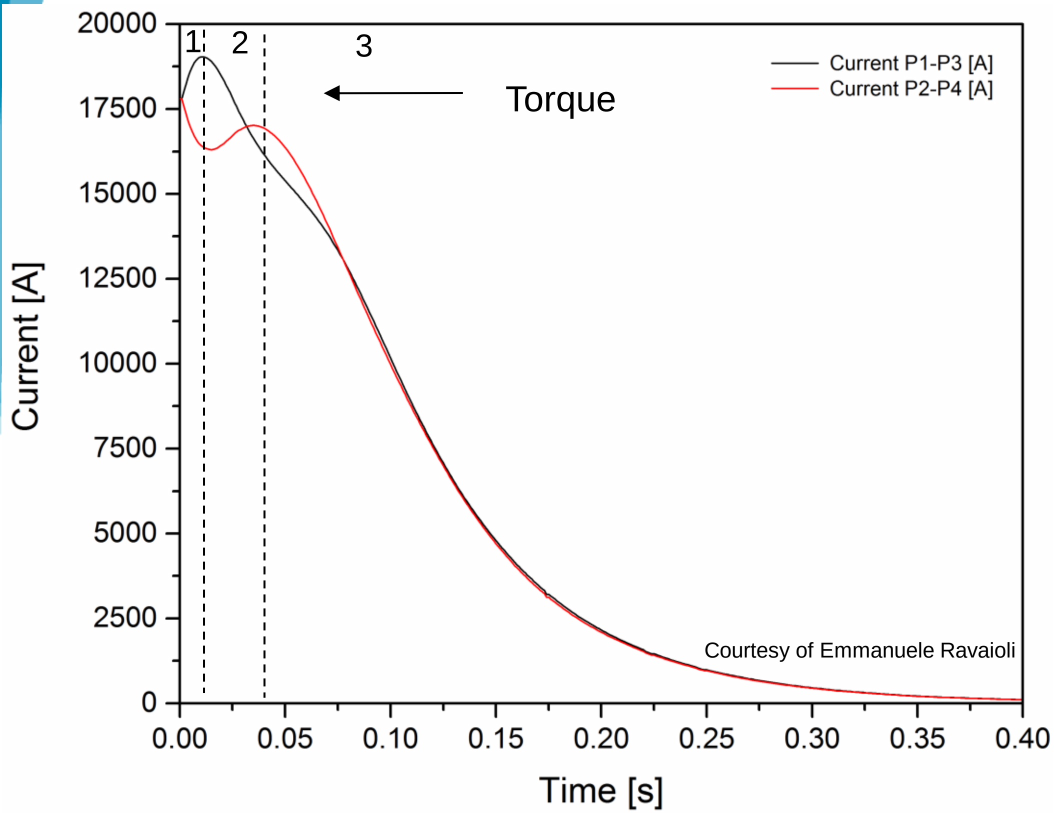
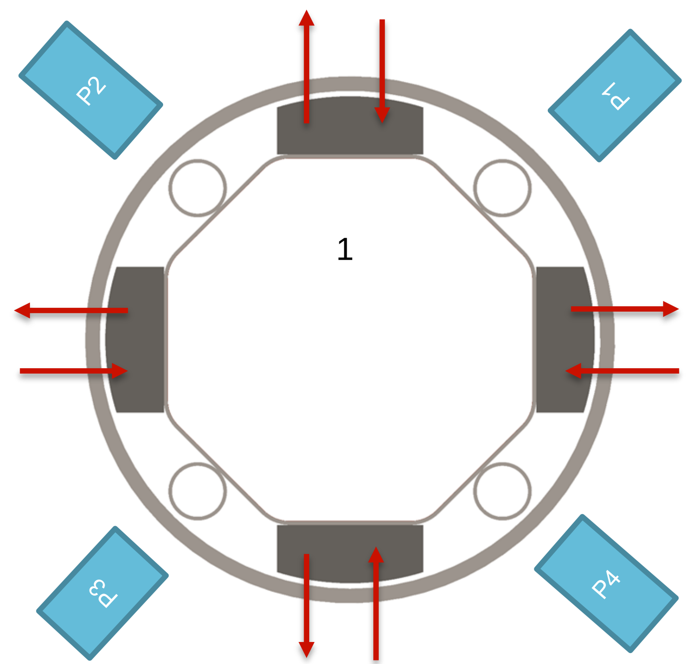
CLIQ currents evolution

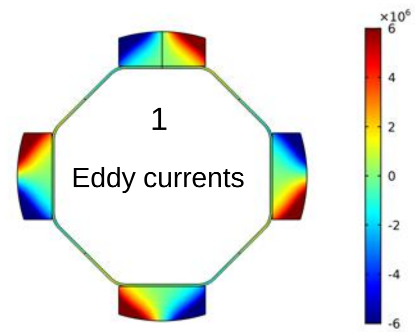
$$\vec{f} \propto \frac{G\dot{G}}{\rho} r^3$$

Ultimate currents_ I_0=17800 A





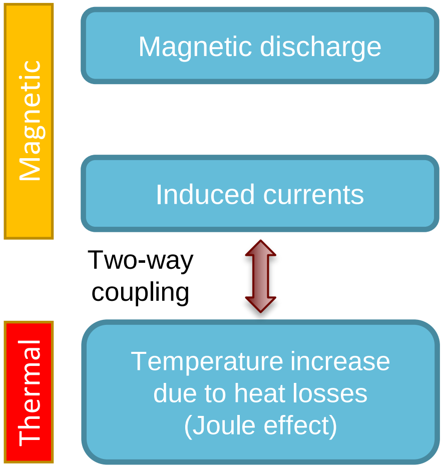
Main direction of the equivalent forces.

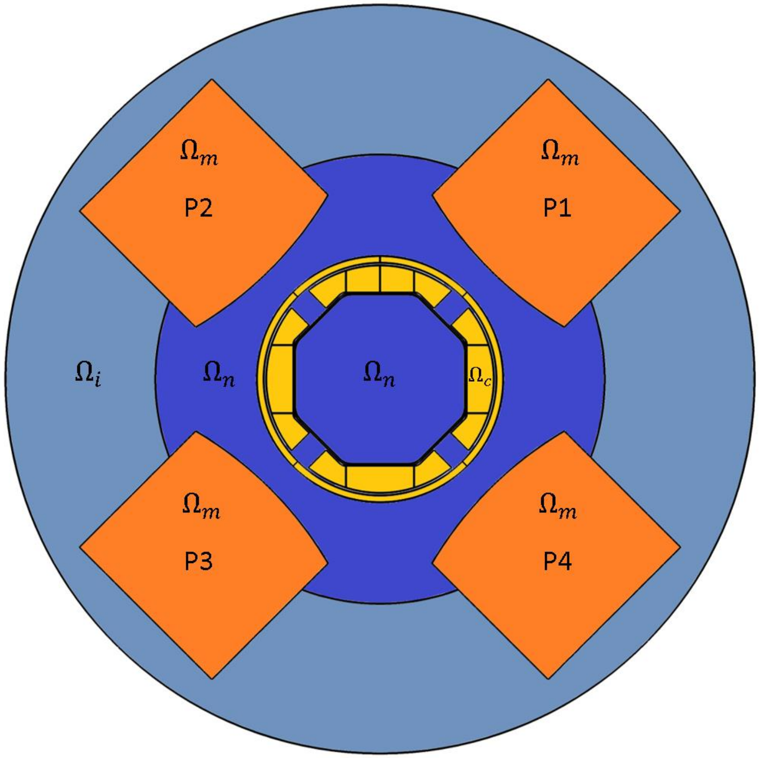


The CLIQ discharge is due to a bank capacitor connected in Parallel to the magnet coil. It introduces a current oscillation and, Therefore, a magnetic field oscillation.

$\dot{G}$ has opposite sign in the first phase of the CLIQ discharge
Therefore, opposite forces are expected in the same compo

Multiphysics model





Ω_m= poles Ω_i =iron domain
Ω_n = non conducting domain Ω_c =conducting domain

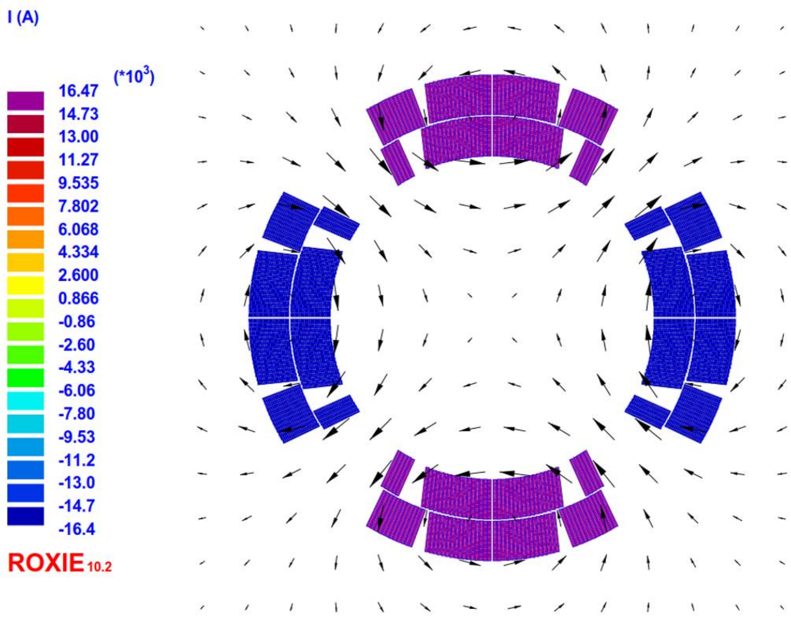
The model accounts for:

- Self-inductance;
- Two-way coupling (magnetic - thermal);

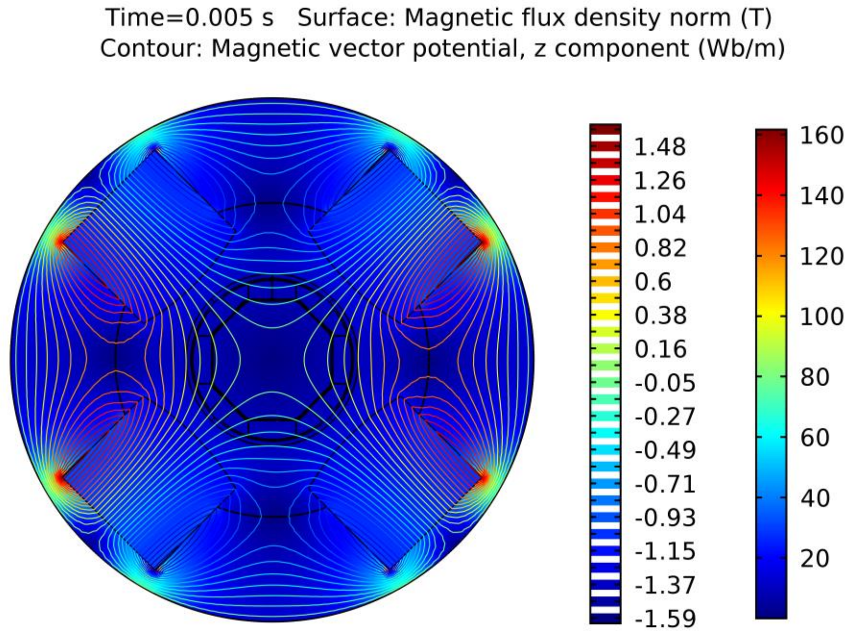
Each Ω_m domain can be controlled in current independently.
From the appropriate current input the quadrupole field can be approximated.

Multiphysics model

The **reduced field formulation** cannot be used as the magnetic field decay is not uniform for each pole. Therefore, the poles need to be taken into account. To this purpoe the coils are conveniently approximated as *permanent magnets* and controlled in current to obtain an arbitrary magnetic field profile. The CLIQ discharge can be then represented.

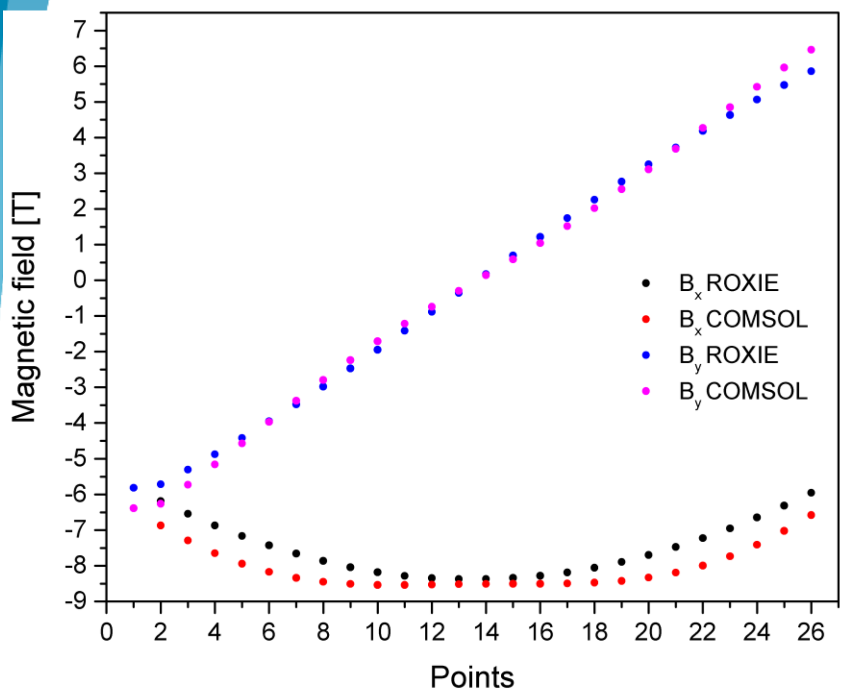


Roxie software used to field quality analysis at CERN. The complex magnet coils need to be considered.

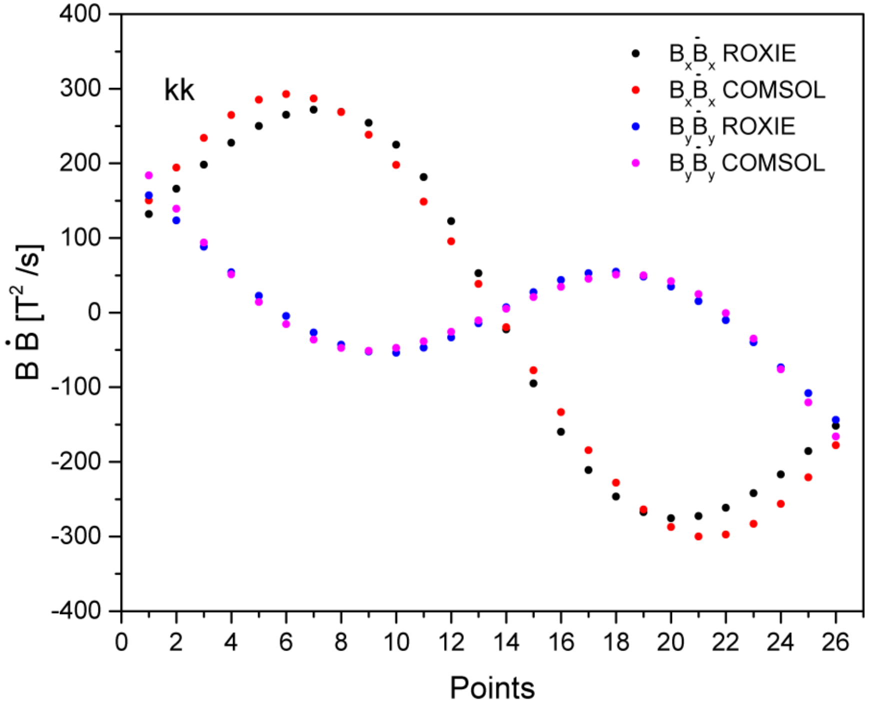


COMSOL model used to approximate the magnetic field generated through four permanent magnets.

Multiphysics model



Comparison of B_x,B_y given for 100 points around a circumference of radius 58.85 mm.



Comparison of B_xB_x_dot and B_yB_y_dot given for 100 points around a circumference of radius 58.85 mm.

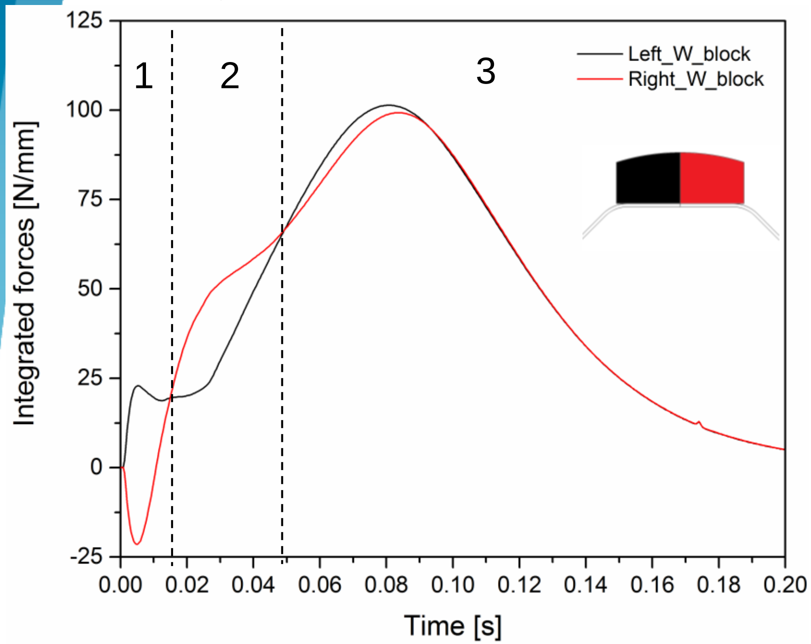
Points	$B_x B'_x1$	$B_yB'_y1$	$B_x B'_x2$	$B_yB'_y2$…
ROXIE	131.9574	157.3413	165.9134	123.4483
COMSOL	150.1908	183.7115	194.387	139.0675

average diff -0.226 %

B_xB_x_dot and B_yB_y_dot are good indicator of the Lorentz forces magnitude

Quench protection scheme including CLIQ

Integrated forces induced in the W block



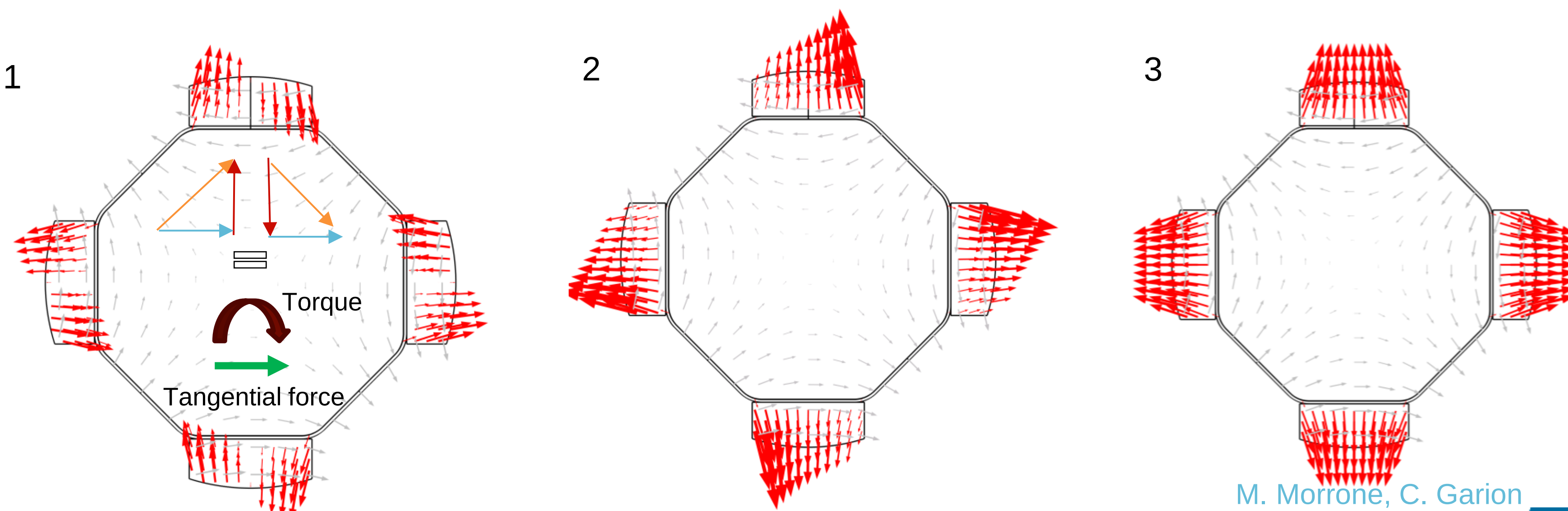
Phase 1: Most critical!!

component	Q1		Q2	
	Torque [N m/W block]	Tangential force [N/W block]	Torque [N m/W block]	Tangential force [N/ W block]
Cold bore	253	3400	253	3400
Heat absorber	280	4200	148.5	2216
Octagonal pipe	81.5	1600	231	3800

Phase 2: Less severe than phase 1

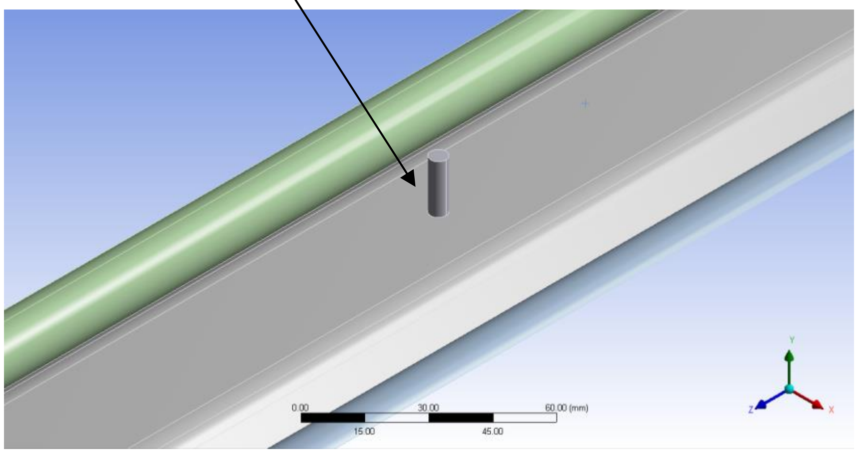
Phase 3: Less severe than without CLIQ

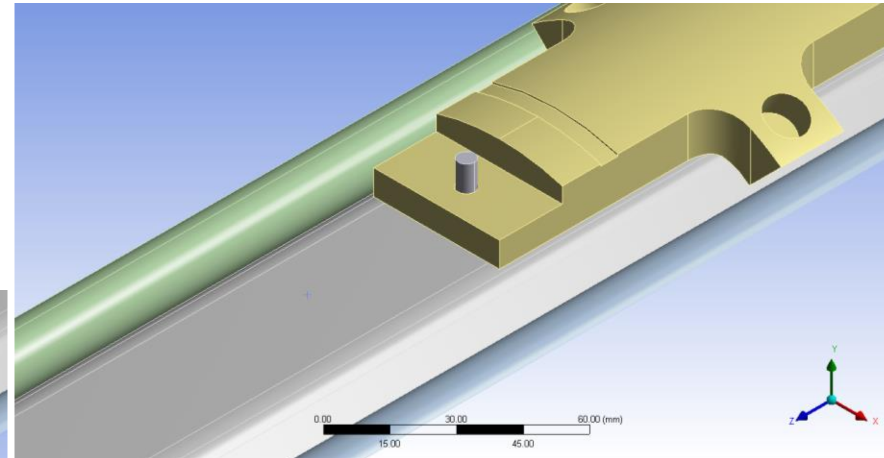
E.g. Fy for the tungsten block: $Q1_{NO\ CLIQ}$ ~233.5 [N/mm] > $Q1_{CLIQ}$ ~200.5 [N/mm]

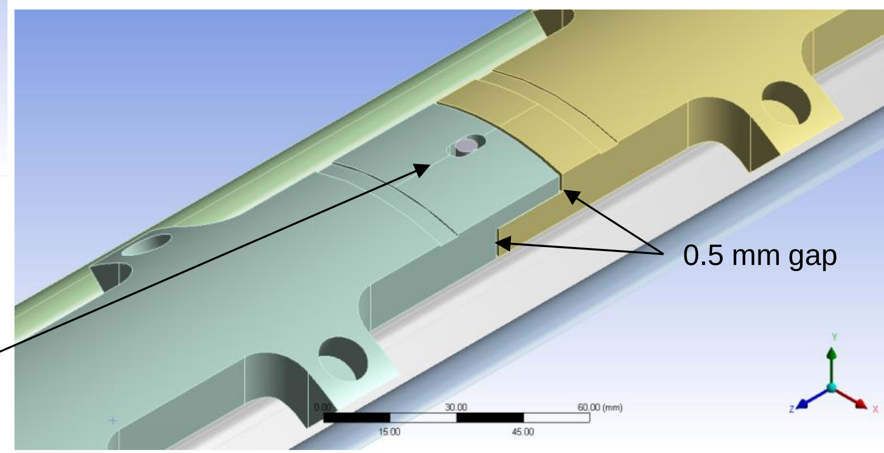


Consequence of the CLIQ discharge on the beam screen design

Pin welded through
Electric Resistance Welding (ERW)

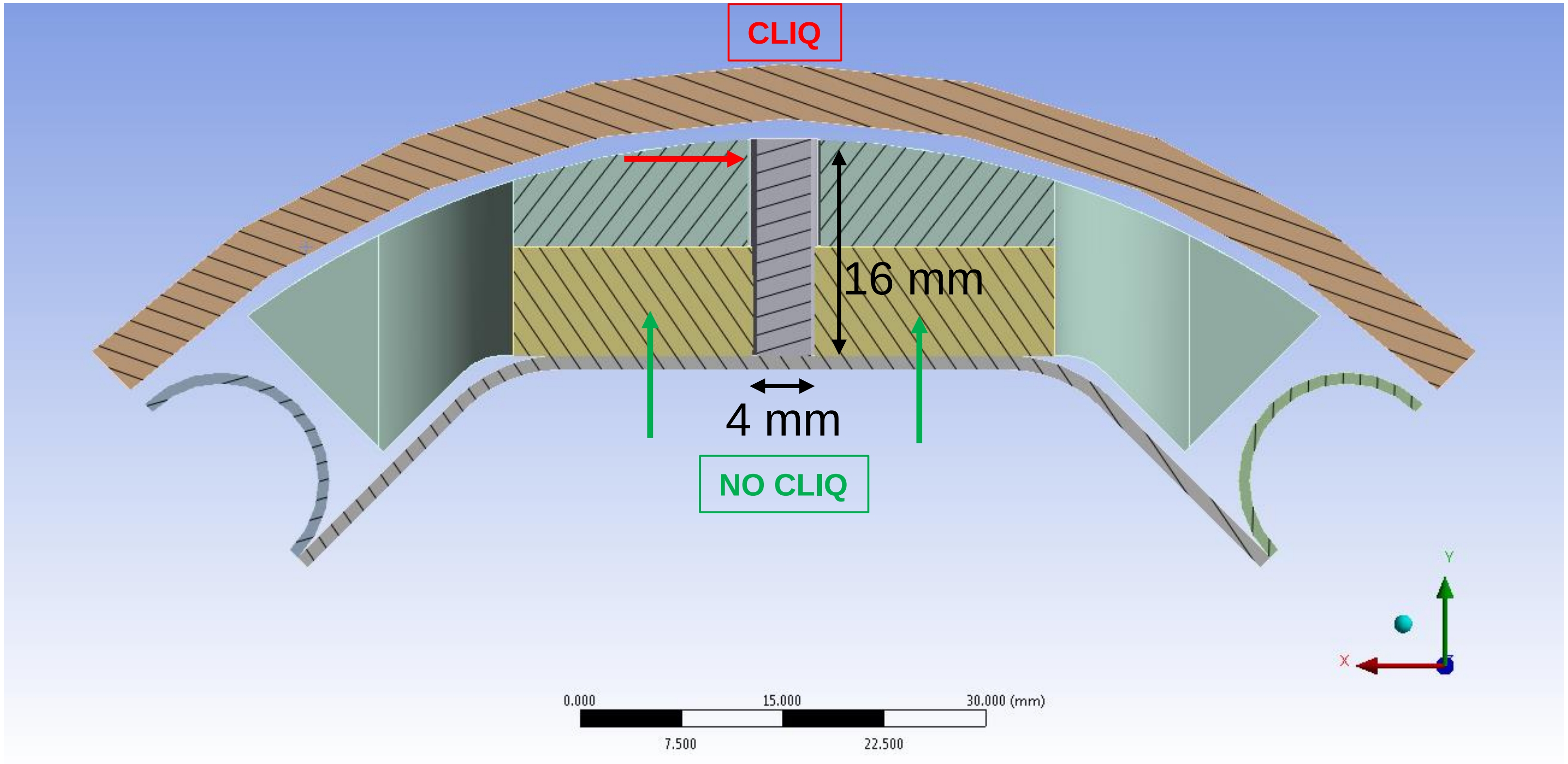






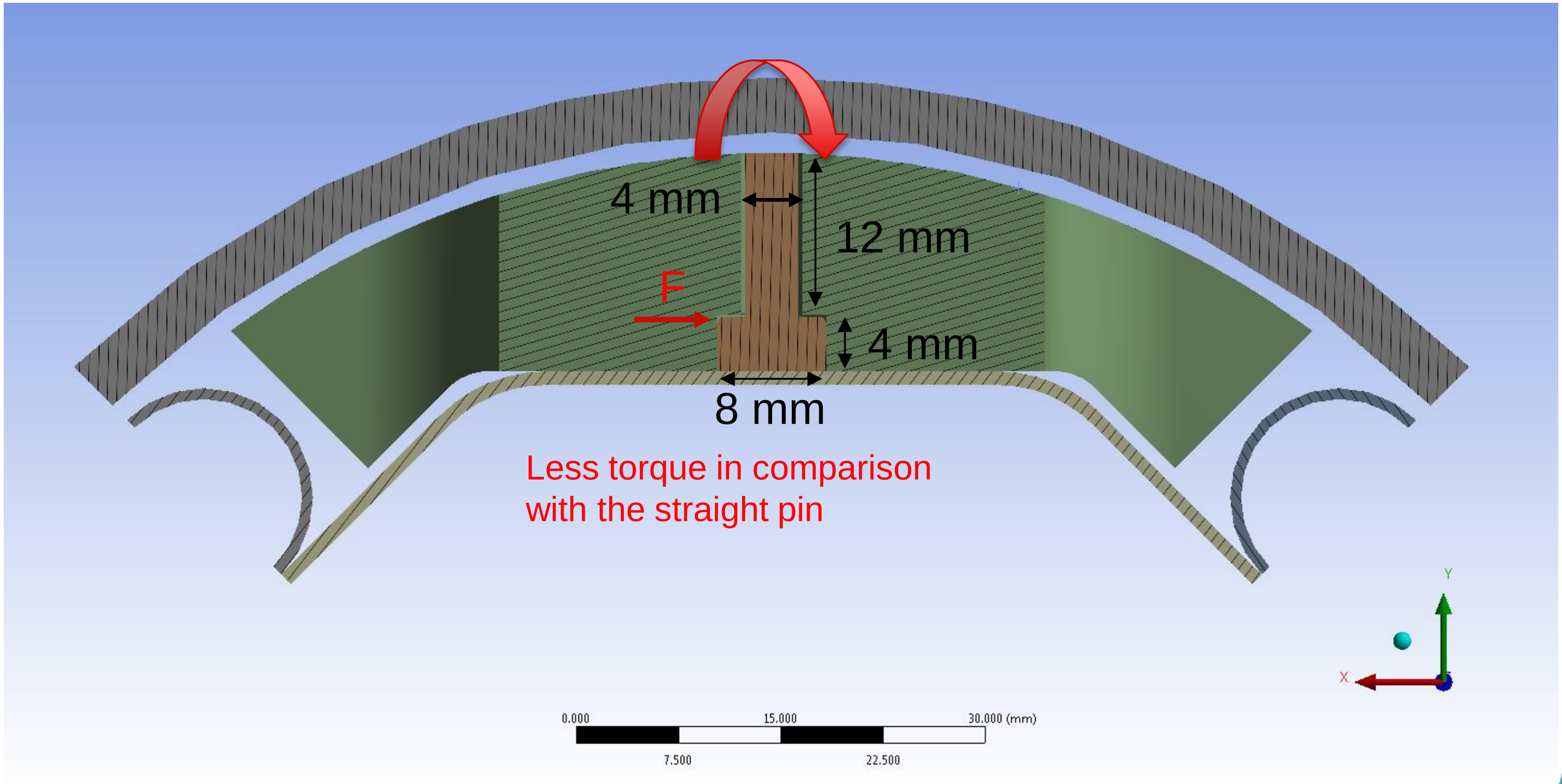
Oval slot to allow different thermal contraction
at the W/ss interface (not welded!!)

Centring of the original beam screen design



Centring of the proposed beam screen design

New pin concept



Conclusions:

- The COMSOL model based on a 2 way coupling between the magneto-thermal physics has allowed to estimate the loads induced by CLIQ;

- The current design of the beam screen does not withstand the effects of the CLIQ discharge without plastic deformations (Magnetic forces exported in an other commercial FEM suite for the mechanical calculations);

- An alternative solution of the beam screen based on new pins and heat absorbers is proposed.

Thank you for you attention