CERN

# Preliminary Design of the HL-LHC Shielded Beam Screen

R. Kersevan, C. Garion, V. Baglin, CERN/TE-VSC

## Outline:

- Why HL-LHC needs a shielded beam screen?
- Functional requirements
- Initial proposal
- Alternative design
  - Concept
  - Design of main elements
    - Elastic ring
    - Thermal link
    - Supporting system
  - Stability w.r.t. internal pressure in the capillaries
  - Tolerances
- Conclusion and next steps

# Why HL-LHC needs a beam screen? (1)

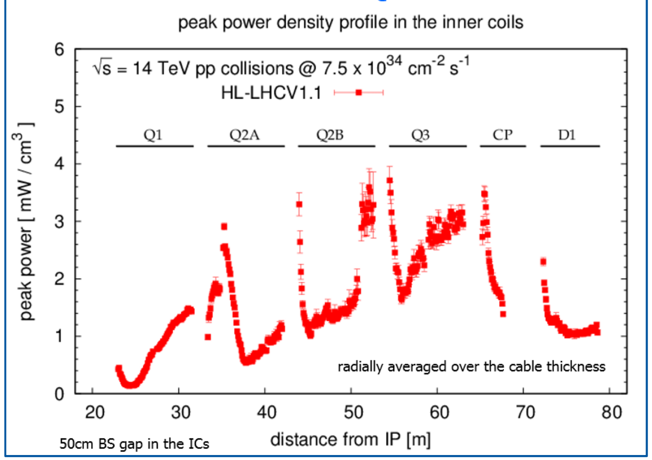
- High-intensity collision debris is channelled by the strong gradient of the inner-triplet magnets in two perpendicular planes (hor. and vert.)
- The calculated energy deposition and coil damage is too high if no absorber is placed in front of the coils
- The absorber must be placed inside of the 2 K magnet cold bore
- A high-Z vacuum-compatible material must be used: Inermet 180 (sintered 95% W)
- The calculated power to dissipate is of the order of 780 W over the whole Q1-D1 area (~ 56 m length), taking into account beam impedance losses (e-cloud will need mitigation!)

## INTEGRAL POWER

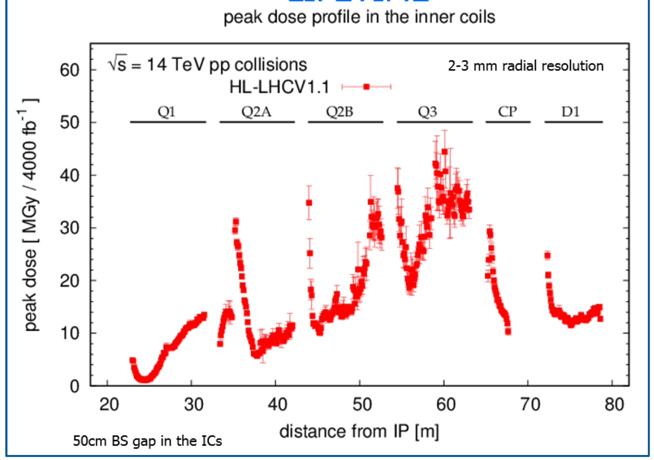
| @ 7.5 $L_0$ | HL-LHCV1.1 | |
|---|---|---|
| **Power [W]** | **Magnet cold mass** | **Beam screen** |
| **Q1A + Q1B** | 140 | 210 |
| **Q2A + corr** | 150 | 90 |
| **Q2B + corr** | 165 | 100 |
| **Q3A + Q3B** | 220 | 105 |
| **CP** | 105 | 90 |
| **D1** | 135 | 80 |
| **Interconnects** | 30 | 110 |
| **Total** | **945** | **780** |

Values for horizontal crossing are about 10% lower

## MARGIN TO QUENCH



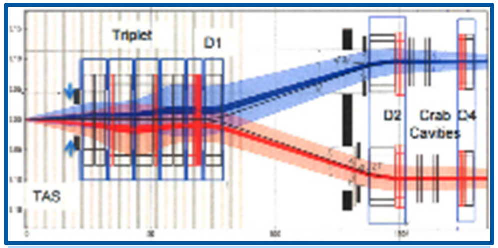

## LIFETIME



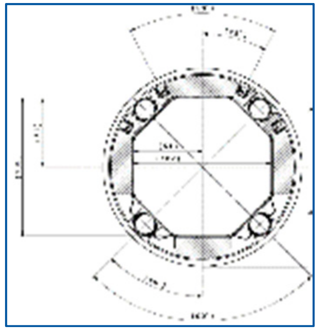

Ref: F. Cerutti, L. Esposito, "Debris Impact in the TAS-Triplet-D1 Region", 4th CERN-LARP Meeting, KEK, Nov 2014

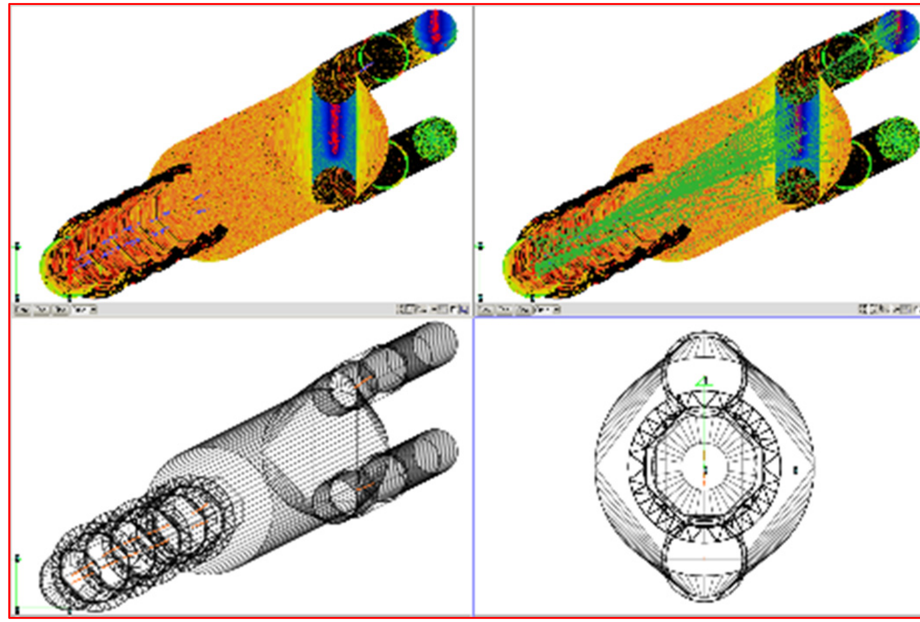
# Why HL-LHC needs a beam screen? (2)

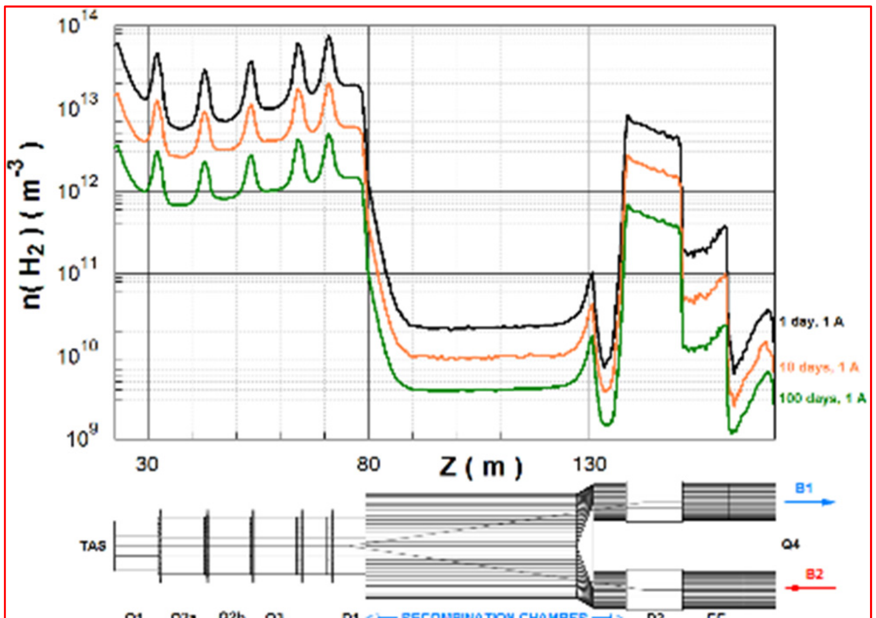
- Synchrotron radiation from the off-axis beams in the triplet and in D1 and D2 will generate local outgassing loads and source of photo-electrons



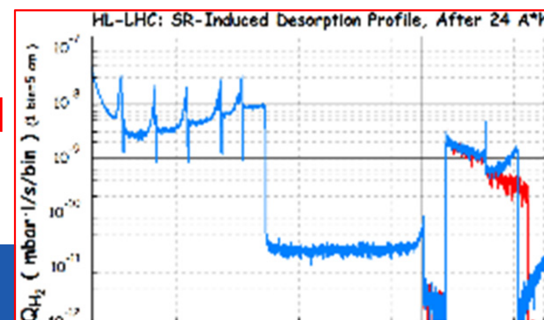

Ref: HL-LHC V1.1 orbits with 12 s enveloped: R. de Maria, CERN








Ref: R. Kersevan, "Synchrotron Radiation Distribution and Related Outgassing and Pressure Profiles for the HL-LHC Final Focus Magnets", paper WEPHA012, this conference



# Functional Requirements of the Beam Screen

Conceptual specification: EDMS 1361079.

*"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?***

*The temperature of the shielded beam screen must be actively controlled in a given temperature range:* ***40-60 K.***

*The system must be compatible with impedance performances.*

*The system must be compatible with the machine aperture."*

# Initial design

Talk R. Kersevan, Kick off meeting HL-LHC, Daresbury Nov. 2013:

- Tungsten blocks, 40 cm long,
- **Soldered** onto the beam screen

Aperture model in HLLHCV1.0:

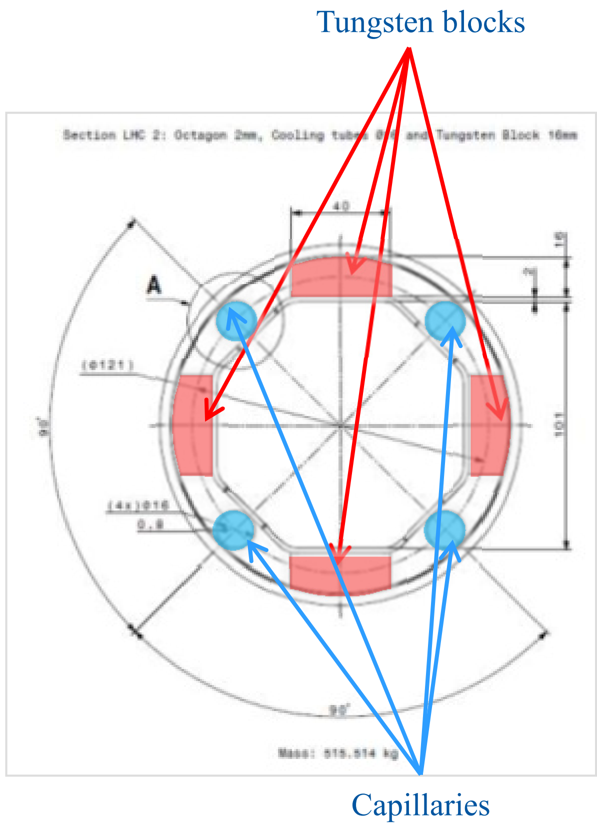
- He (1.5 mm), CB (5 mm) , CB to BS (1.5 mm), BS (2 mm), W (16/6 mm)

→ Aperture: 118/98 mm

<u>Issues:</u>

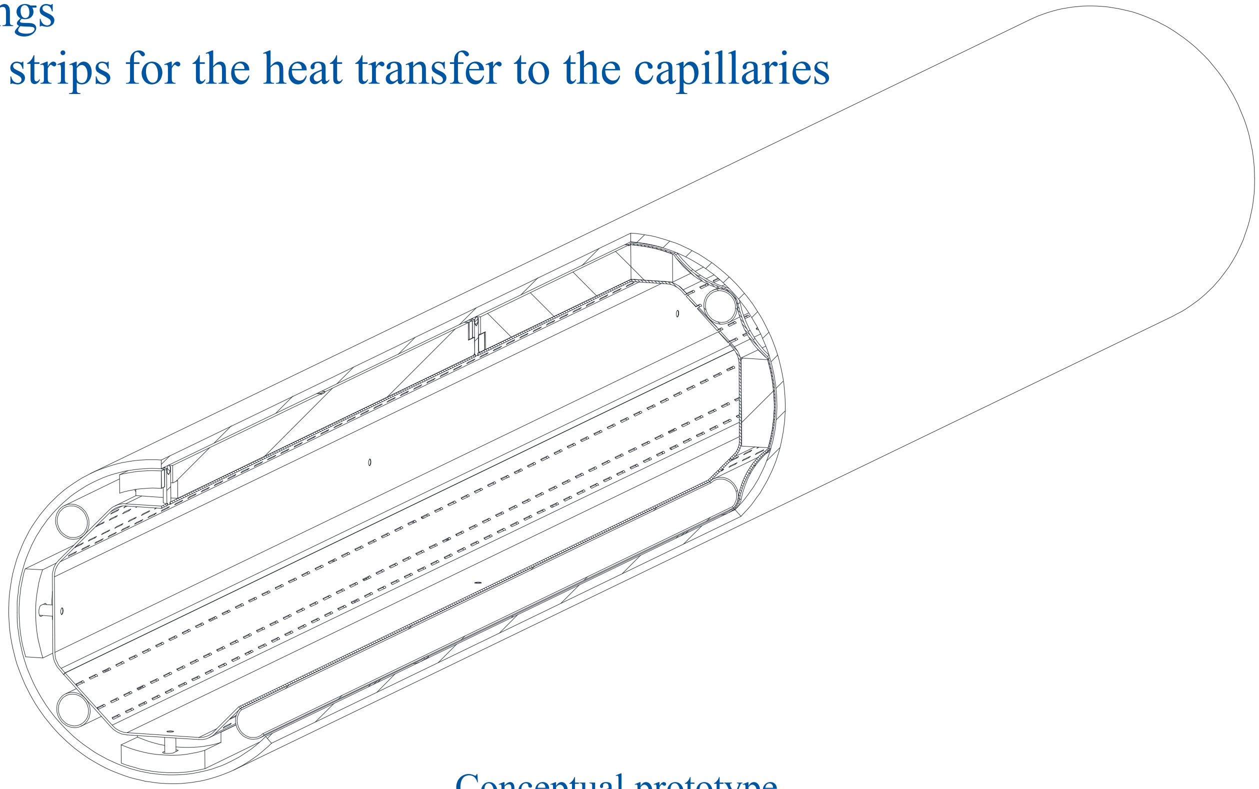
- Soldering of tungsten block
  - ➢ High differential thermal contraction
    - → Feasibility? Intermediate accommodation layer?
    - → Reliability during quenches at cryogenic temperature
  - ➢ Manufacturing
    - → Procedure? 8 m long vacuum furnace?
    - → Risk (1 failed blocks → the whole beam screen out)
    - → Deformations/tolerances after process?
  - ➢ Electrical resistivity of the copper layer?

- Assembly of the long "stiff" beam screen into the cold bore?



# Alternative design - Concept

1. Tungsten block mechanically connected to the beam screen
   - Positioning pins
   - Elastic rings
2. Copper based strips for the heat transfer to the capillaries

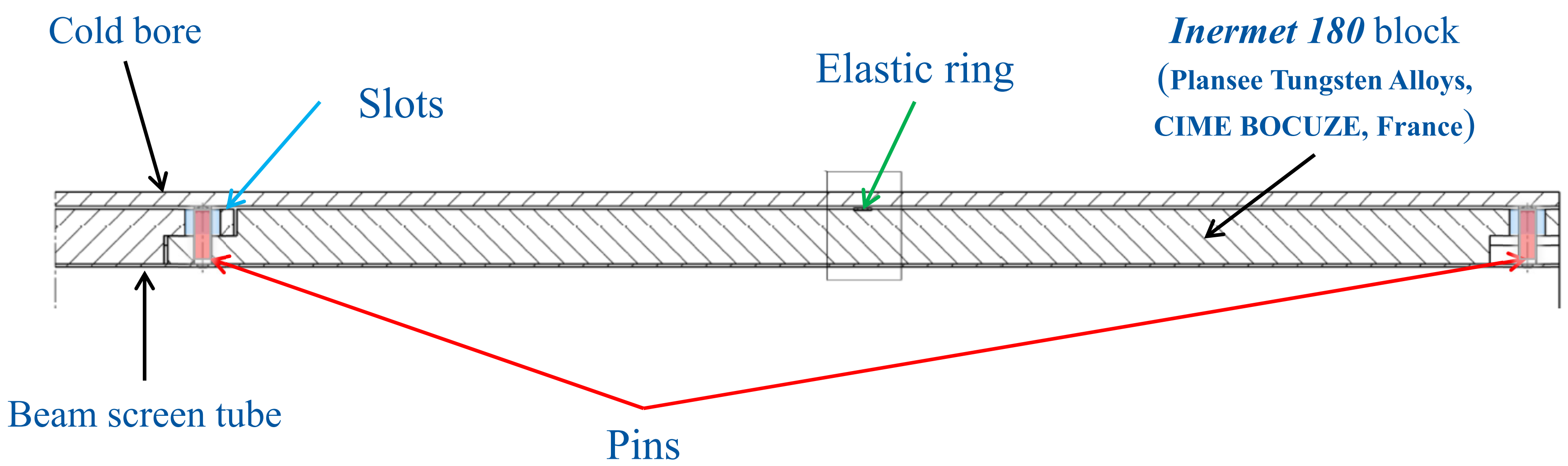


Conceptual prototype

# Alternative design - Positioning

Positioning Pins:

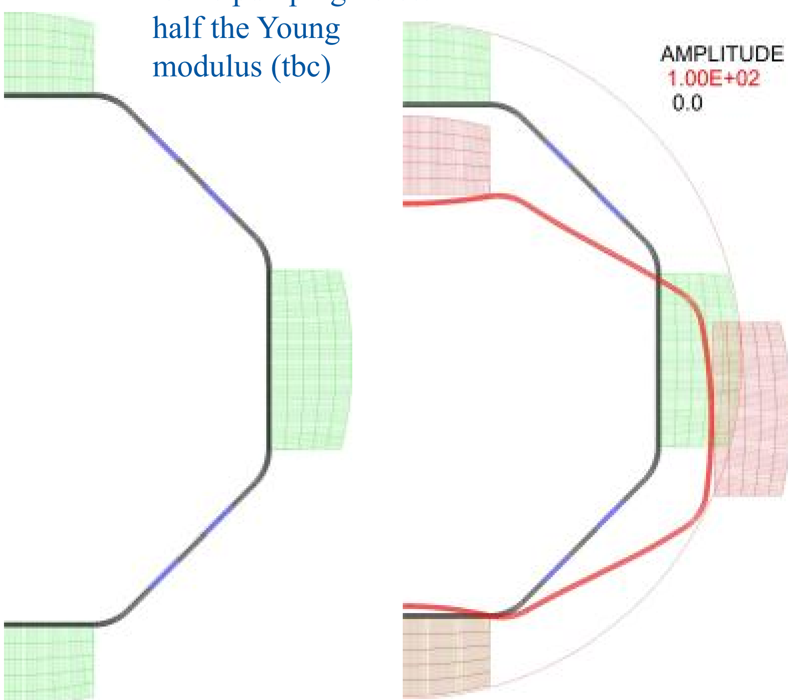
- Pins are positioned and welded to the beam screen
- Inermet blocks are positioned thanks to the pins
    - Dedicated slots are used on one side to allow the differential thermal contraction (W contracts ~ 1/3 w.r.t. stainless steel)
    - An overlap is used to reduce the number of pins
- Blocks are maintained in position with elastic rings



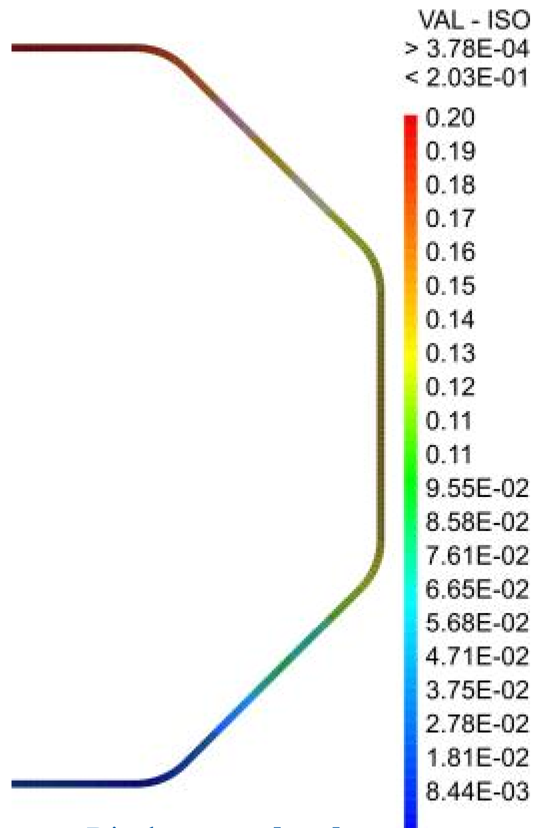
# Alternative design – Gravity effect

Self weight deformation ( 1mm thick BS )
(no contact with cold bore)

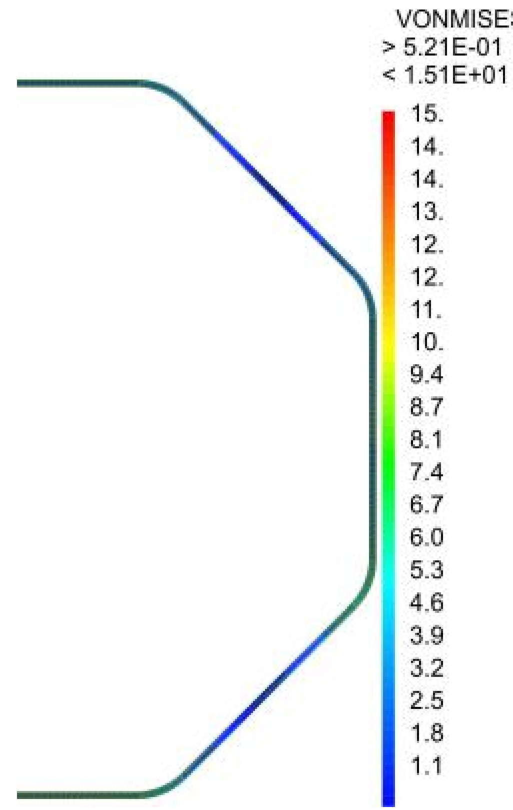
Stiffness reduction due to the pumping holes: half the Young modulus (tbc)




Deformed shape




Displacement [mm]




Von Mises stress [MPa]

**→ Aperture reduction of 0.2 mm due to the gravity ←**

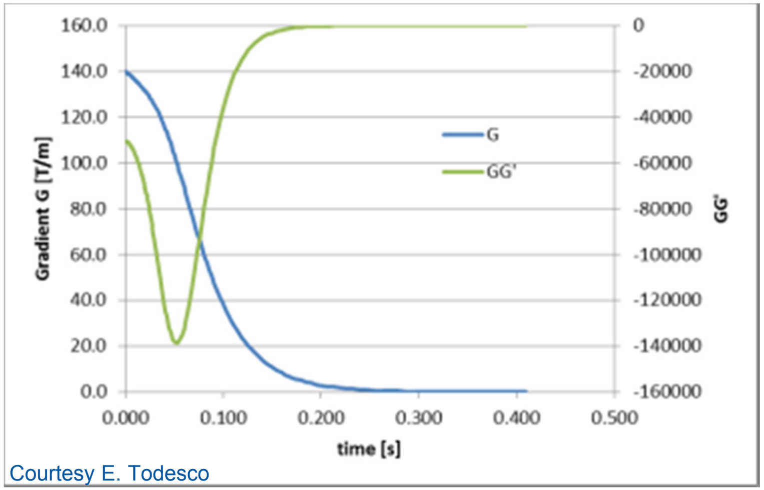
# Alternative design – quench

Lorentz's forces induced by the Foucault's currents during a quench:

Specific force → $\vec{f} \propto \frac{G\dot{G}}{\rho}$ ← Electrical resistivity

Magnetic gradient ($G\dot{G}$)

## Magnetic gradient evolution

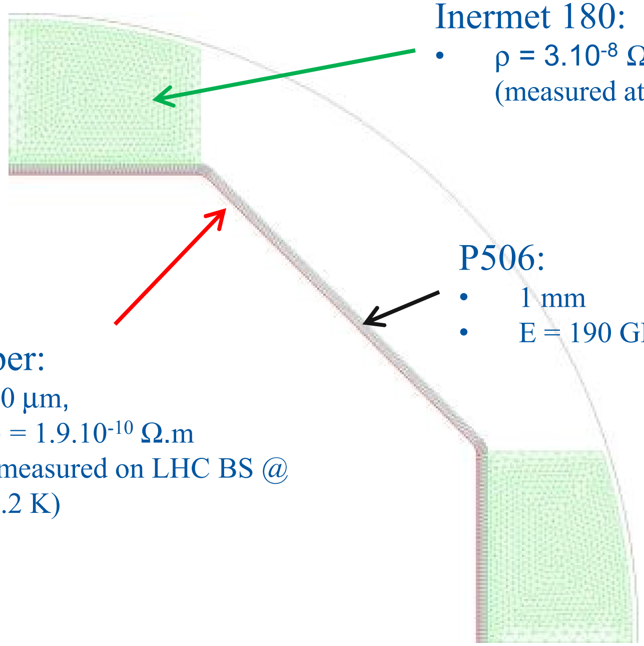



Courtesy E. Todesco

→ Magnetic forces are maximum after 50 ms.

→ Maximum GG' = 140000 $T^2/m^2/s$ (Computed by E. Todesco, CERN)

## Model



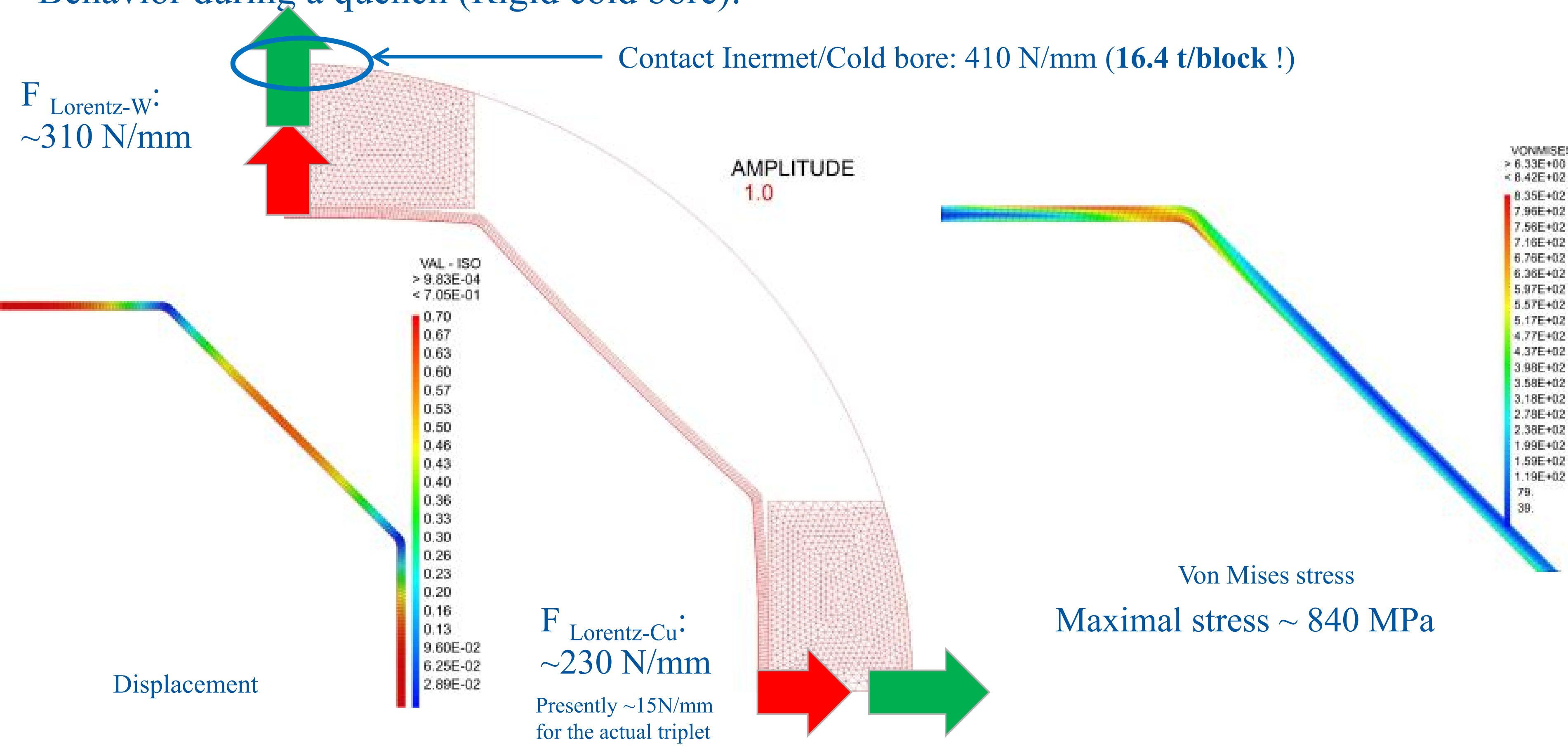
**Inermet 180:**
- $\rho = 3.10^{-8}$ Ω.m @ 50K (measured at cryolab)

**P506:**
- 1 mm
- E = 190 GPa

**Copper:**
- 80 µm,
- $\rho = 1.9.10^{-10}$ Ω.m (measured on LHC BS @ 4.2 K)

# Alternative design – 1st quench model

Behavior during a quench (Rigid cold bore):




Deformations and stresses are limited by the contact between the tungsten blocks and the cold bore.

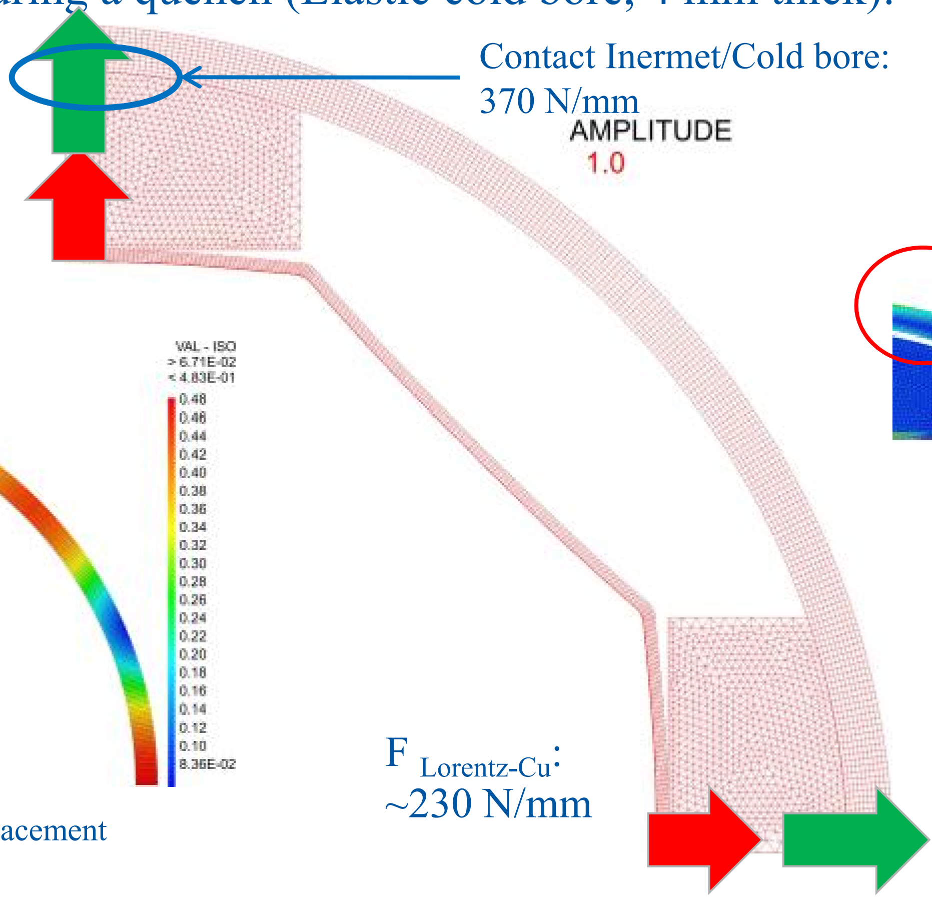
**→ No plastic deformation of the beam screen ←**

# Alternative design – updated quench model

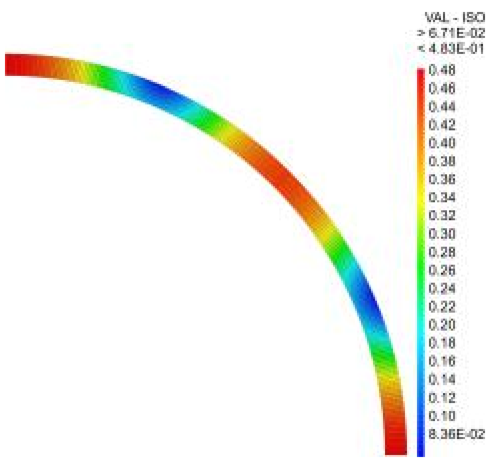
Behavior during a quench (Elastic cold bore, 4 mm thick):

F $_{\text{Lorentz-W}}$: ~310 N/mm

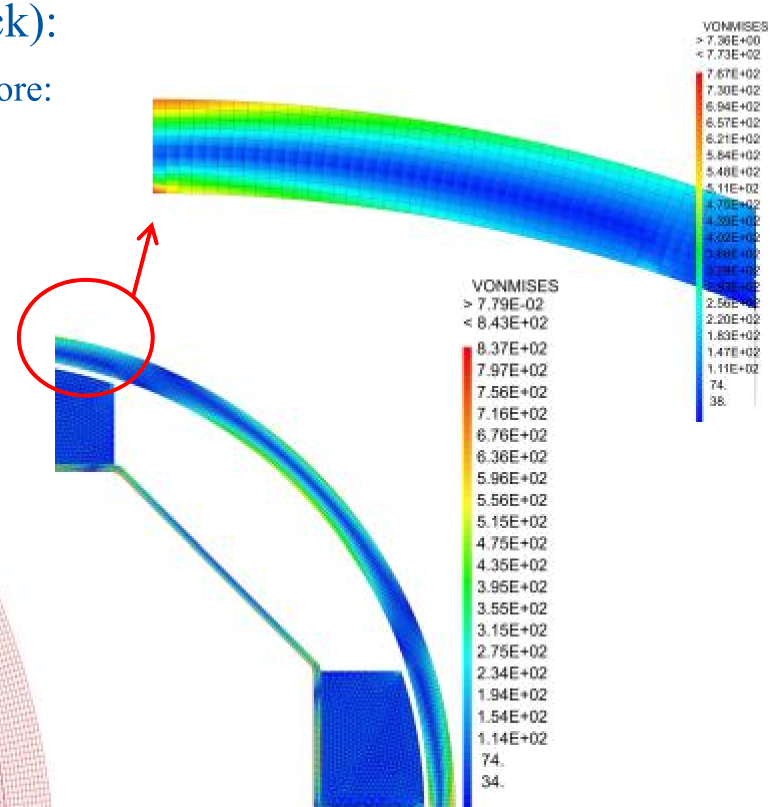
Contact Inermet/Cold bore: 370 N/mm




F $_{\text{Lorentz-Cu}}$: ~230 N/mm




Cold bore displacement




Von Mises stress

Maximal stress ~ 840 MPa in the BS
Maximal stress ~ 650 MPa in the CB

**Stress level and deformation are quite high in the cold bore but no plastic deformation of the cold bore is expected.**

# Alternative design – Elastic ring

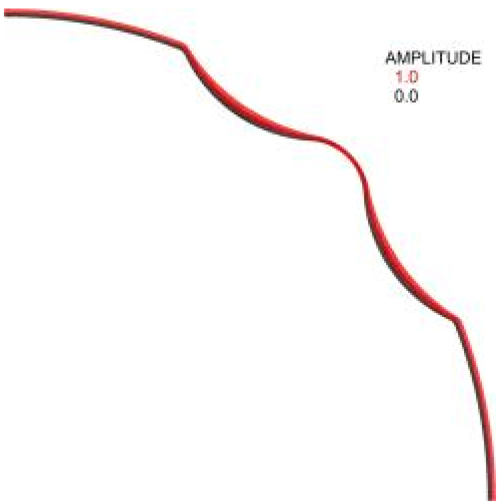
Elastic ring:

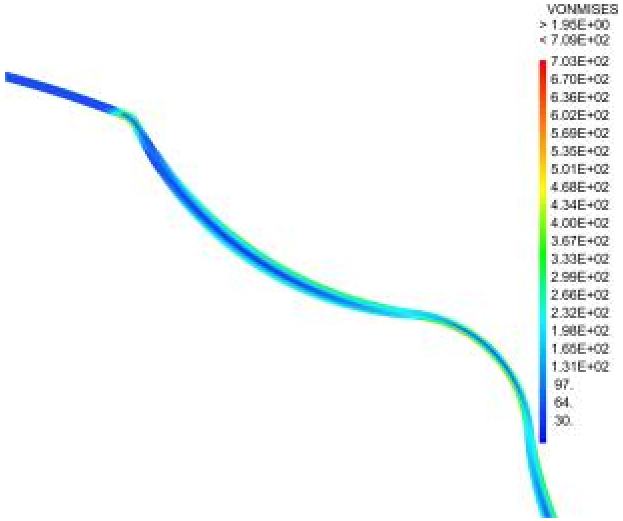
- Material defined to get the maximum elastic energy before plastic deformation:

$$E \propto \sigma_y^2/E$$

→Titanium grade 5

- Pre-stressed during assembly



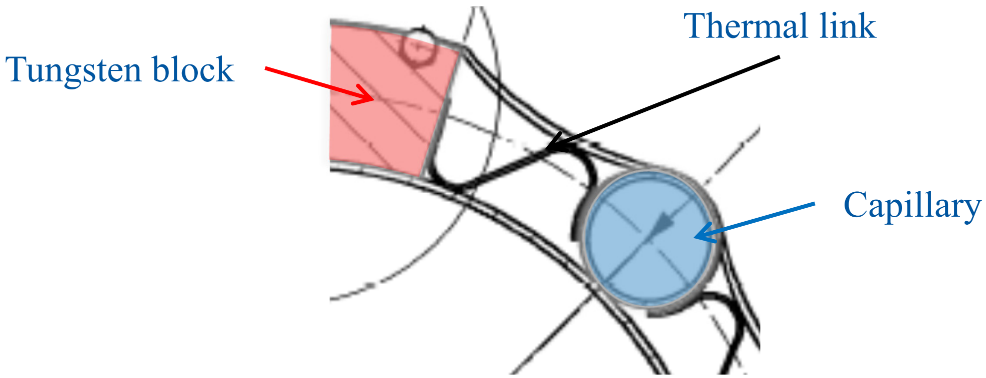



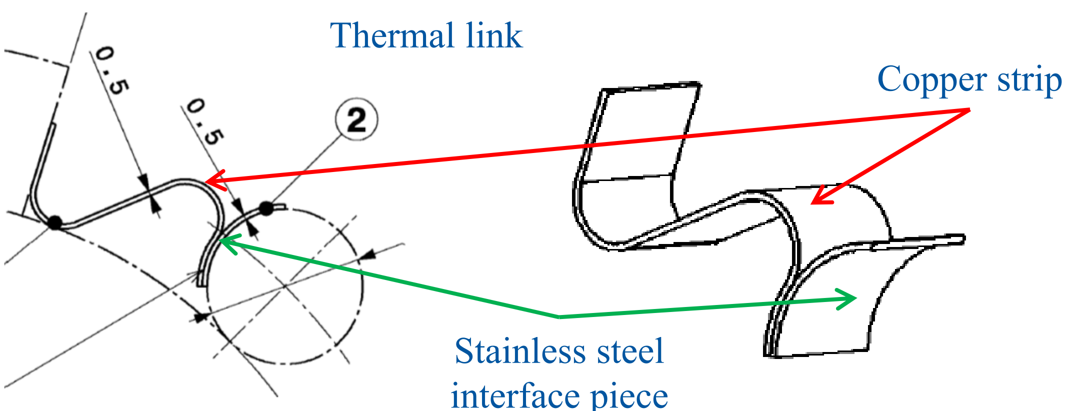

Deformation and stress analysis during a quench (displacement of the W blocks)

# Alternative design – Thermal link

Thermal link:

- High thermal conductivity material needed: copper based.
- Mechanical loads during a quench to be assessed. High strength copper ? CuZr?




Assembly procedure:

1. The stainless steel interface piece is joined to the copper strip
2. The thermal link is brazed (or welded) on the tungsten block
3. The tungsten blocks, equipped with the thermal links, are assembled onto the beam screen shell
4. The stainless steel parts of the thermal links are welded on the capillary

# Alternative design – Thermal link

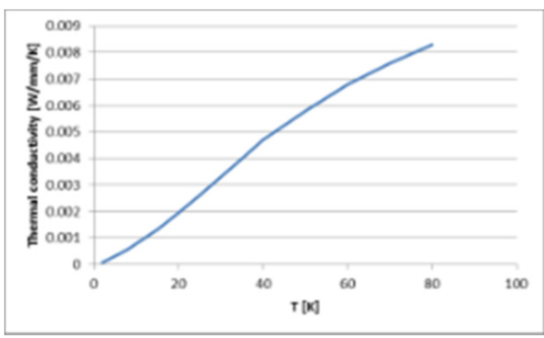
## Thermal link:
- 4 links per W blocks
- 20 mm wide
- 0.5 mm thick

Convection heat transfer coefficient:
150 W.K$^{-1}$.m$^{-2}$
Values in the range 137-365 depending on estimation formulas (Colburn, Dittus-Boelter, Petukhov)

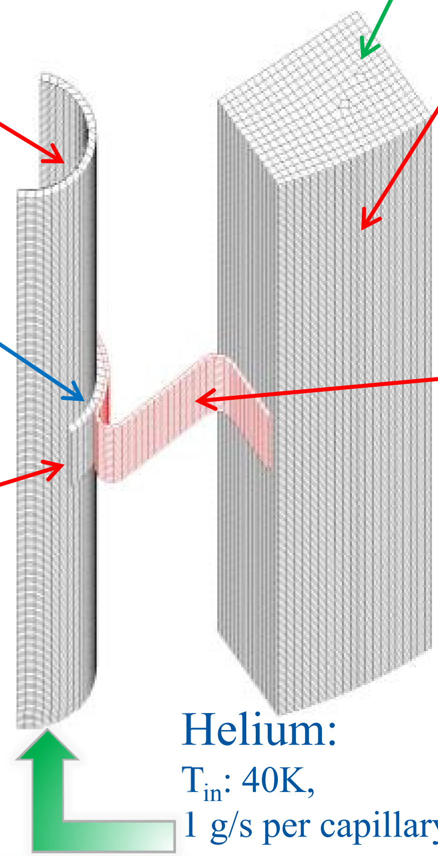
Welds on the 3 external edges

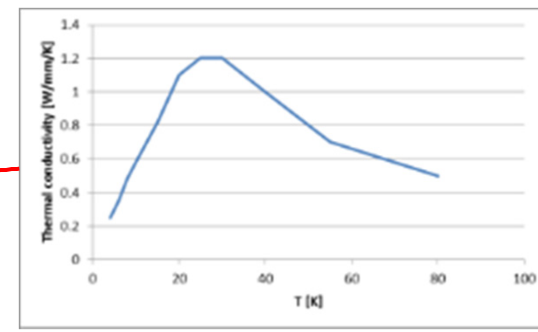
Thermal load: 20W/m (beam screen)

Thermal conductivity: 100 W.m$^{-1}$.K$^{-1}$
(Measurements in preparation with cryolab)




Thermal conductivity of P506



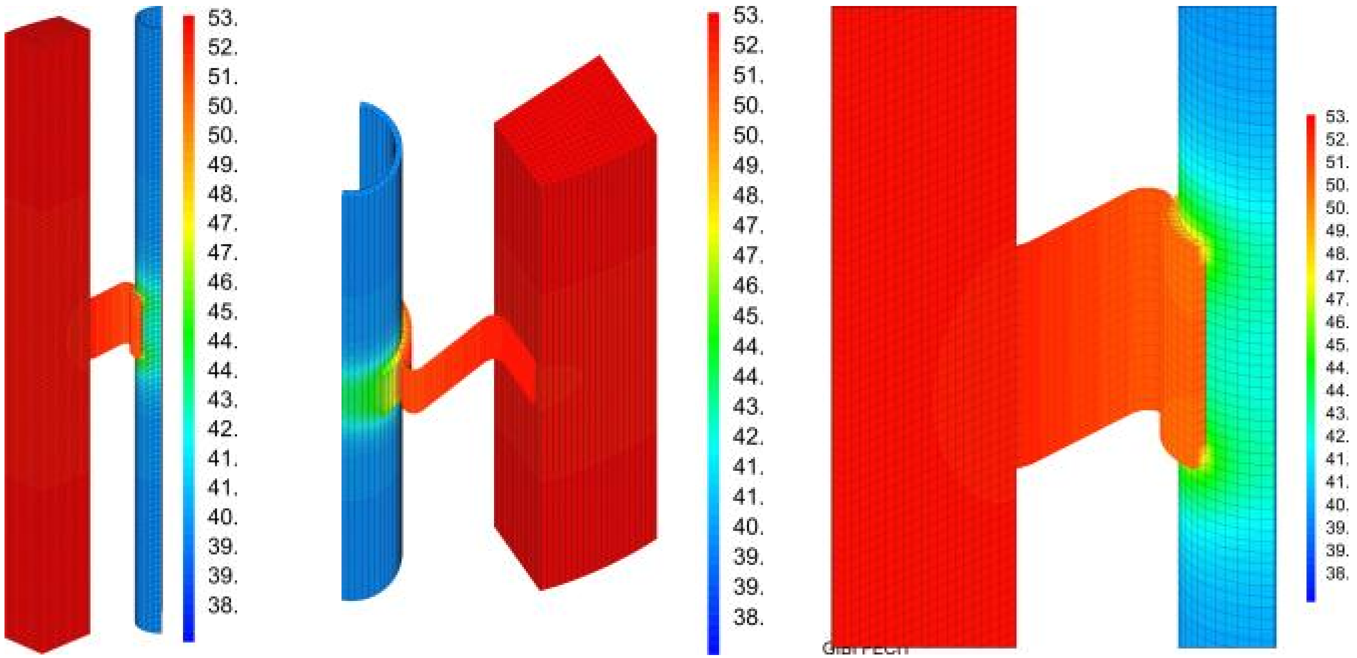



Thermal conductivity of copper

## Helium:
$T_{in}$: 40K,
1 g/s per capillary

# Alternative design – Thermal link

Thermal link: heat transfer



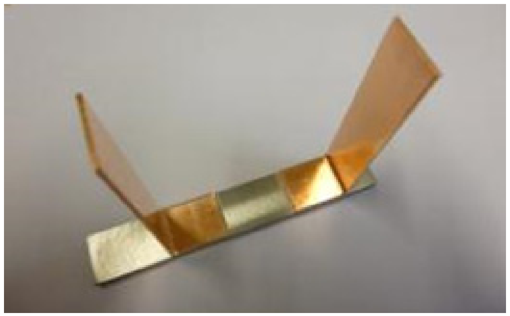

Temperature profiles

→ Temperature gradient between helium and tungsten block: ~ 13K
(Temperature gradient in helium: 0.5 K/m)

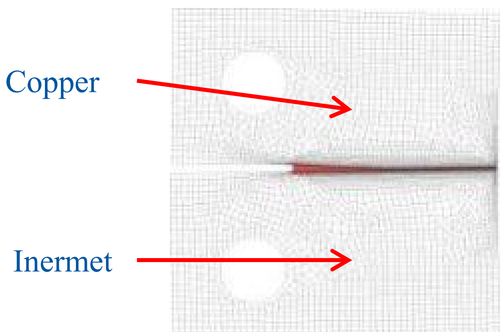
# Alternative design – Thermal link

Mechanical strength of the thermal link and its interface, especially during quench

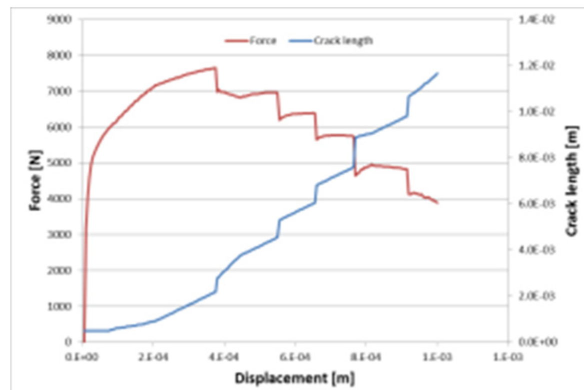
- Brazing Inermet 180 with copper. First tests done: promising



- Toughness assessment : test in preparation, then comparison with simulated crack propagation curve




Bimetallic crack propagation specimen




Typical expected curves

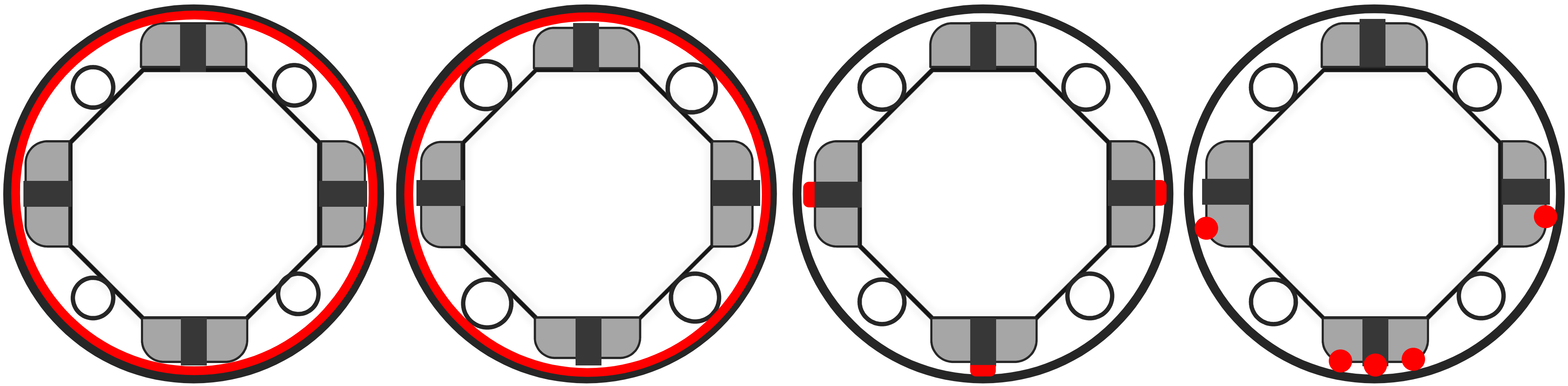
**→ Evaluation of Lorentz's forces during quench to be done ←**

# Supporting system

Thermal aspect: heat load budget: 0.5 W/m.

Different technical solutions have been considered:

**Sliding rings** | **Local contact**



Sliding rings in contact with the tungsten blocks
→ Friction Cold bore/ sliding ring

Sliding rings in contact with the capillaries
→ Friction Cold bore/ sliding ring

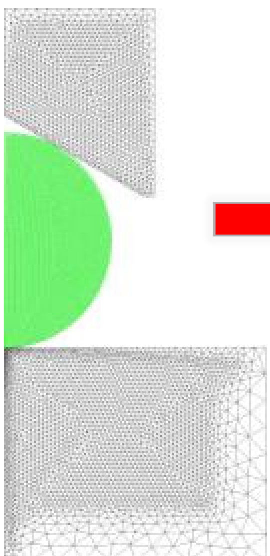
Spherical tips brazed on the pin extremities
→ Friction Cold bore/ tips

Ball inserted in the pins and/or in the tungsten blocks
→ Friction ball/tunsgten
→ Rolling Ball/ cold bore

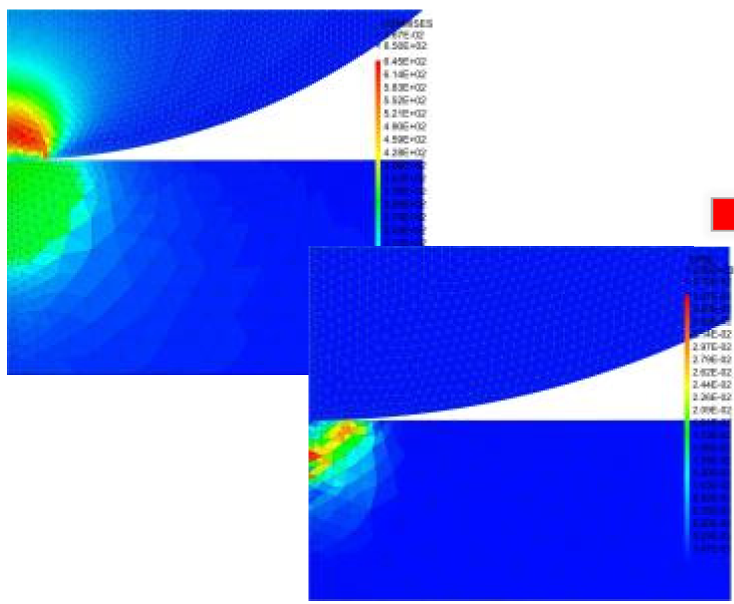
# Supporting system

For each proposal:

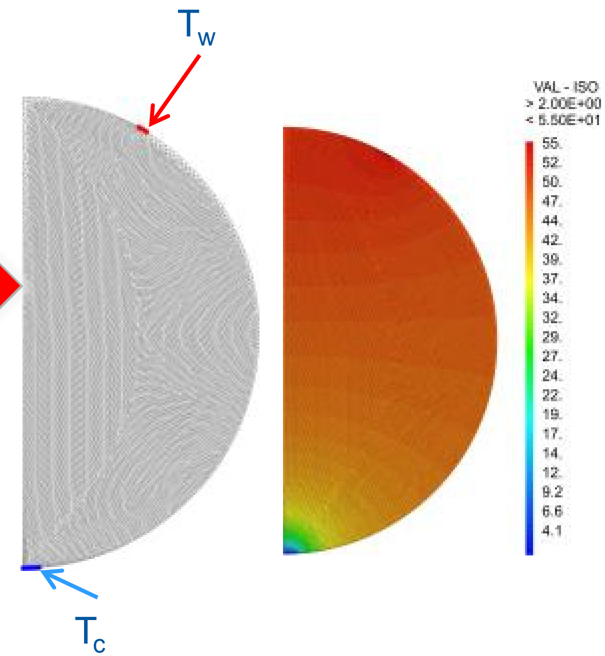
1. Mechanical analysis as a function of number of supports (simplified contact model)
   - ➢ Mechanical stresses under gravity
   - ➢ Contact geometry
2. **Thermal analysis** based on contact surface



Initial model:
- ➢ elastic (plastic) materials
- ➢ contact



Deformation, stresses and plastic strain

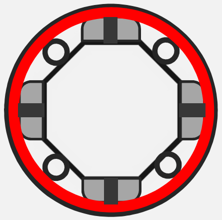
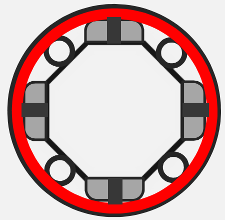
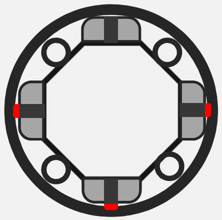
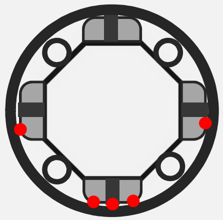



Boundary conditions and temperature field

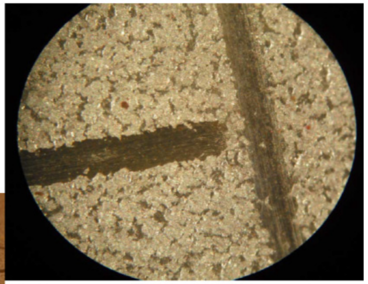
# Supporting system

## Some results:

- Heat load [W/m]

| Number of W blocks (*4) per support | Solution 1 | Solution 2 | Solution 3 | Solution 4 |
|---|---|---|---|---|
| |  |  |  |  |
| **0.25** | - | - | - | 0.25 |
| **1** | 15.6 | >0.52 | 0.58 | 0.1 |
| **2** | 6.7 | >0.36 | 0.38 | 0.06 |
| **3** | 5.9 | >0.28 | 0.3 | 0.05 |
| **4** | 4.6 | >0.24 | >0.24 | 0.04 |
| | **Heat load** | **Stresses** | **Contact stress** | **Promising** |

- Equivalent friction coefficient: ~ 0.15

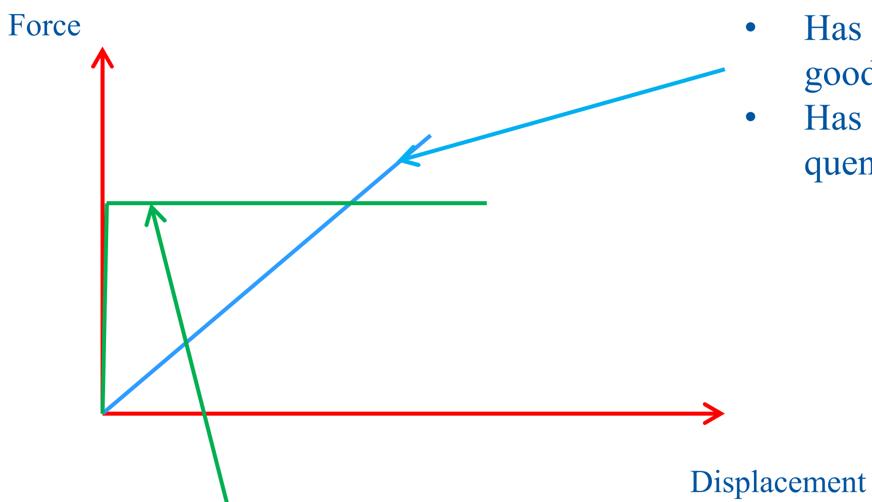


# Supporting system

<u>Other considerations:</u>

Quench force >> gravity forces

→ Some "flexibility" of the support has to be introduced.




Elastic linear:

- Has to be stiff enough to withstand the weight and assure a good positioning
- Has to be soft to not introduce large contact force during quench

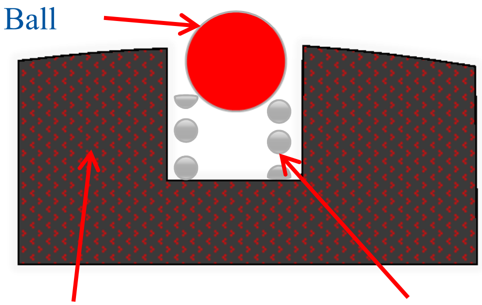
Elastic non-linear:

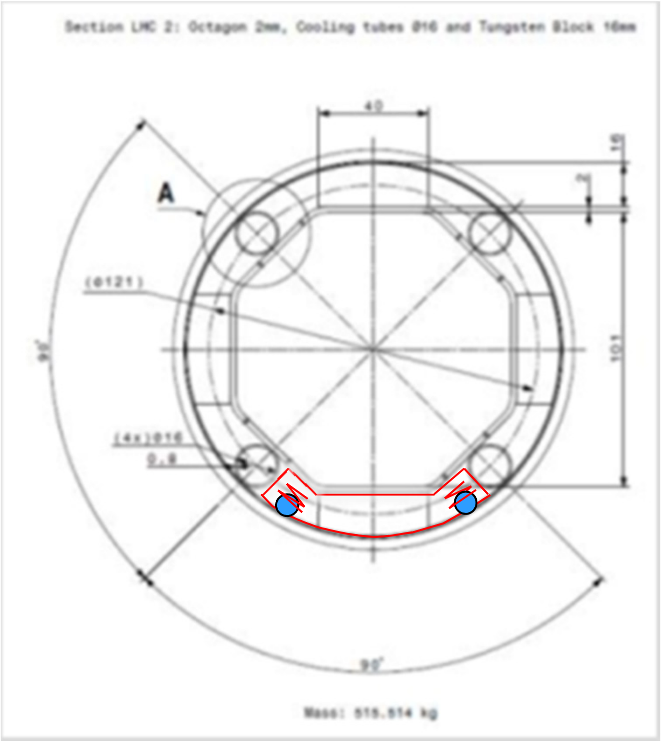
- High stiffness at low force: good positioning; full stroke available for the quench
- Large displacement above a given threshold: limited contact force during quench

# Supporting system

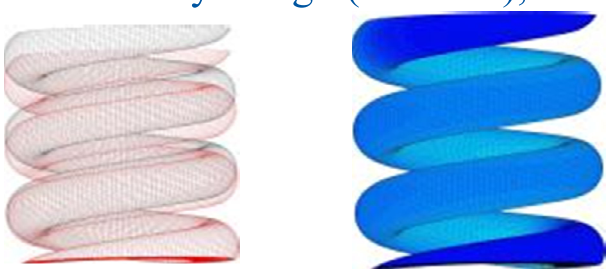
Proposal 1: linear behaviour

Ball with springs




Preliminary design (titanium), to be studied



De = 5 , Dc = 1, h0 = 5 mm:

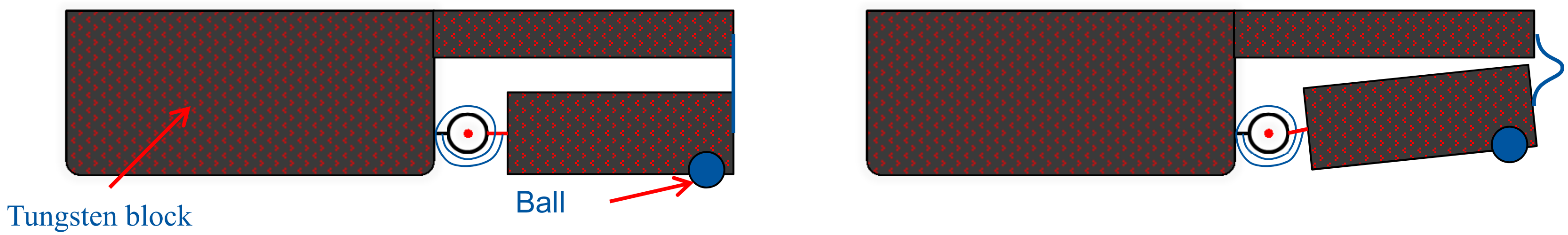
- Stiffness ~ 35 N/mm
- Maxi. compression ~ 2 mm
- Stress ~ 860 Mpa (1 mm compression)

De = 8 , Dc = 1.6, h0 = **7.3 mm**:

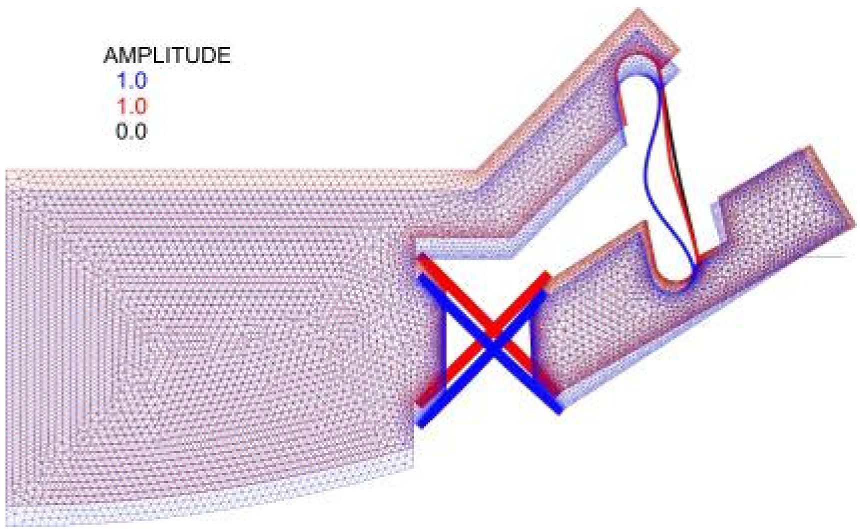
- Stiffness ~ 54 N/mm
- Maxi. compression ~ 2.5 mm
- Stress ~ 580 Mpa (1 mm compression)

# Supporting system

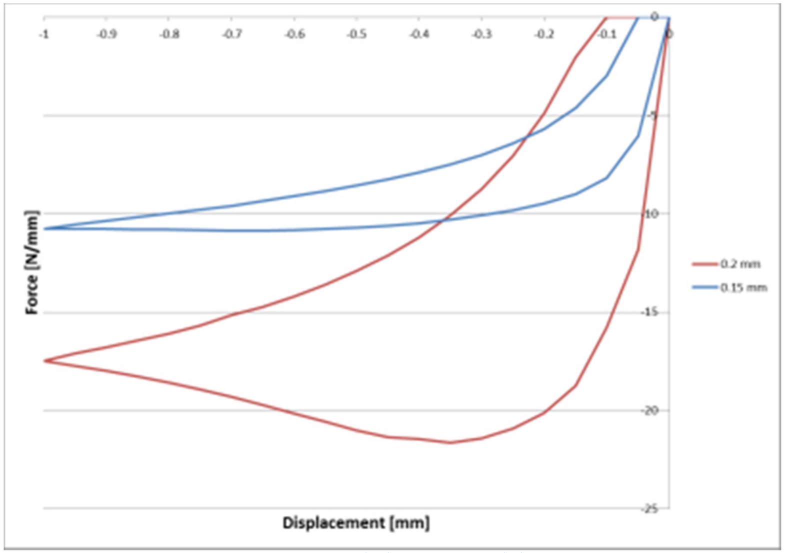
## Proposal 2: non-linear behaviour (Threshold)




Principle: elastic hinge with thin strip that buckles during the quench




Model and deformed shape




Response of the assembly

→ Interesting expected behaviour… but difficult to implement due to space constraints

# Stability of beam screen

Stability under internal pressure in capillaries

Capillary diameter: 16 mm
Moment of inertia ~ $4.5.10^5$ mm$^4$ (Beam screen tube and capillaries)

Depending on the supports:

- Fixed at only one extremity (worst case): Column buckling pressure $P_b$ ~ 40 bars
- Simply supported at the beam screen extremity: $P_b$ ~ 160 bars
- …

**→ Column buckling of the beam screen under internal pressure in the capillaries isn't an issue.**

# Component tolerances

Cold Bore:

Machined long circular tube: (Input from “Manufacture de Forage”, tbc)

- ID : 139 0/+0.1
- Thickness: 4 +/- 0.5
- Straightness: 0.3 mm/m

Tungsten blocks:

- Shape +/- 0.05

Balls:

diameter: +/- 0.0002

Beam screen:

**To be assessed. +/- 1 mm?**

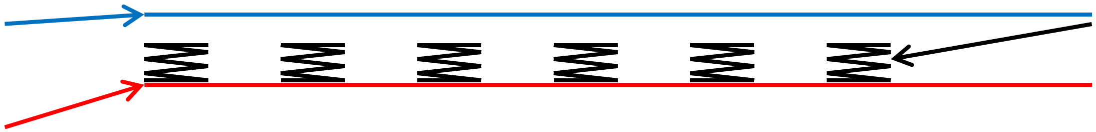
Spring:

+/- 0.1 mm ?

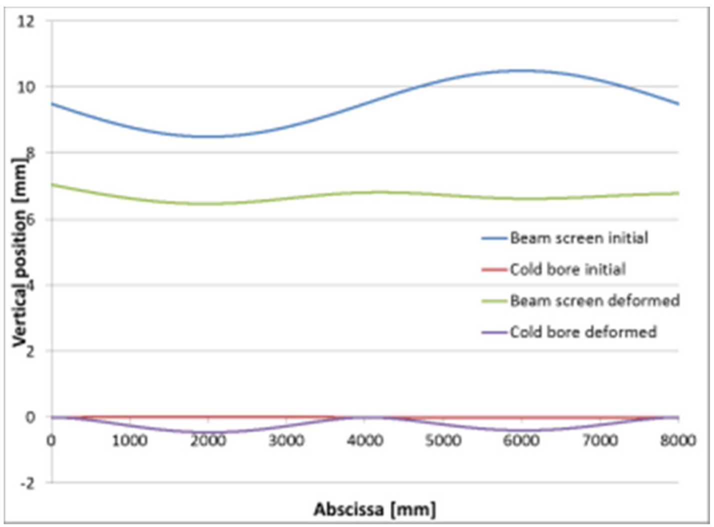
# Assembly tolerances

Beam screen;
- 1 mm thick, I ~ $4.5.10^5$ $mm^4$
- 45 kg/m

Spring:
- 75 N/mm;
- every 10 cm
- Free length 7.5 mm

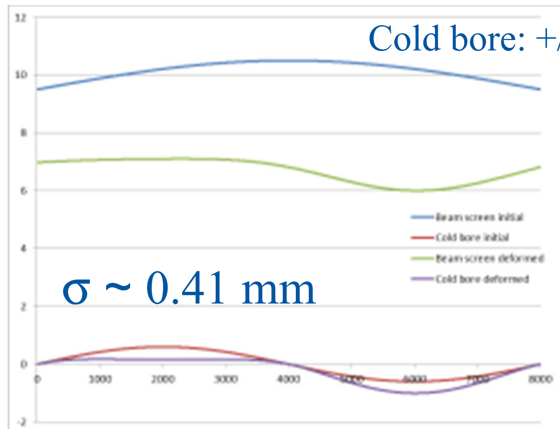


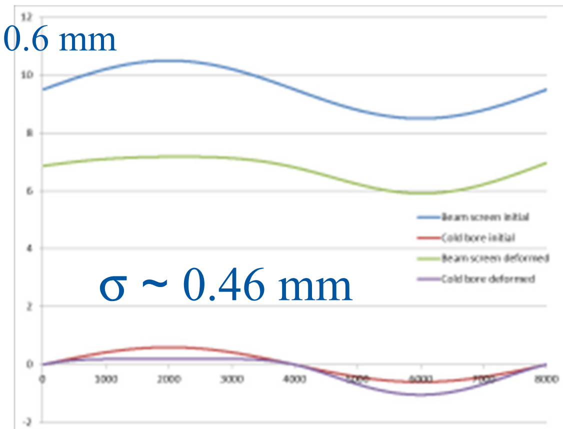
Cold bore;
- OD 147; 4 mm thick
- Clamped at the extremities, simply supported at the middle

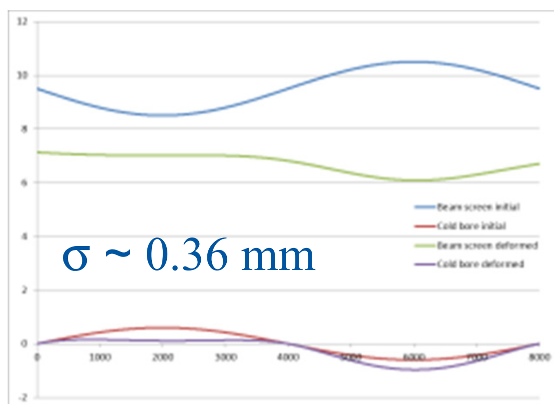


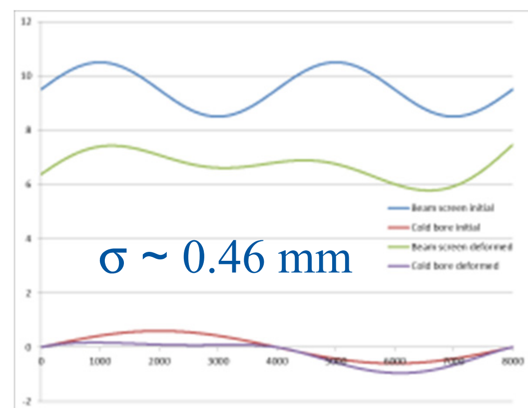

"Perfect" cold bore, +/- 1 mm beam screen: <y> ~ 6.7 mm, σ ~ 0.12 mm

Cold bore: +/- 0.6 mm



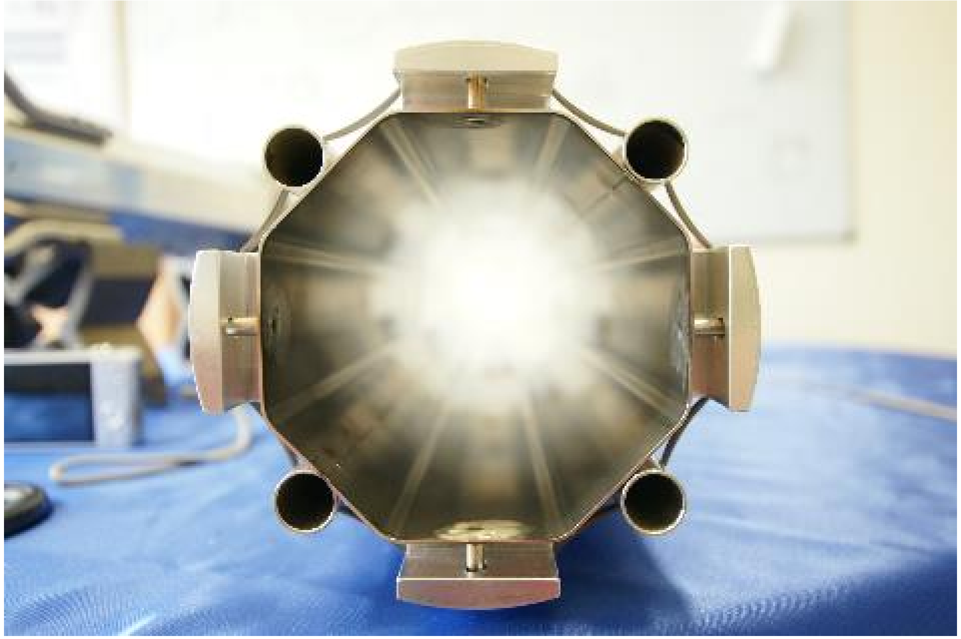



# Prototyping

**April 2015:**
1.2 m long cold bore with Q1-type BS (stainless steel), mock-up W shielding, real Ti springs and $ZrO_2$ balls, 3D printed Ti ring.



# Next steps (1)

Material qualification at low temperature:

- Inermet 180
- $ZrO_2$

Thermal link design:

- Joining techniques of tungsten alloy
- Behaviour during a quench
- Reliability at low temperature

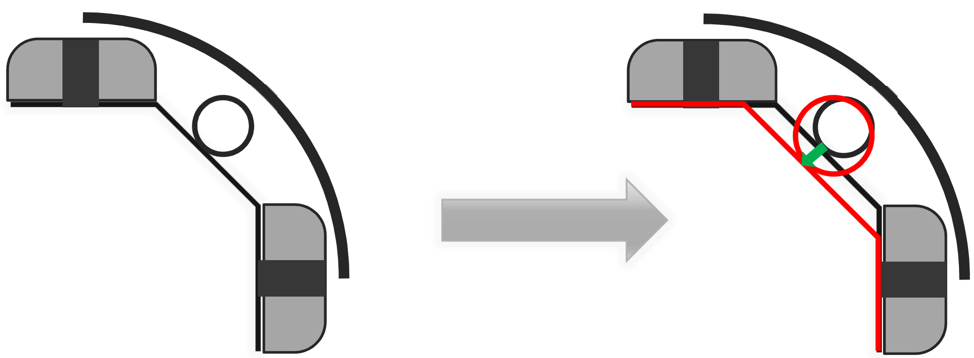
Prototypes for supporting and assembly aspects:

- Procurement started
- Assembly in Autumn 2014

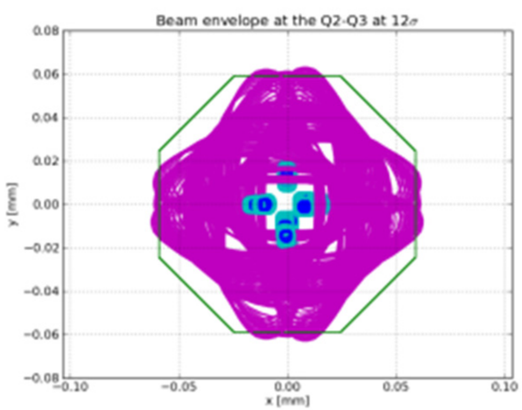
# Next steps (2)

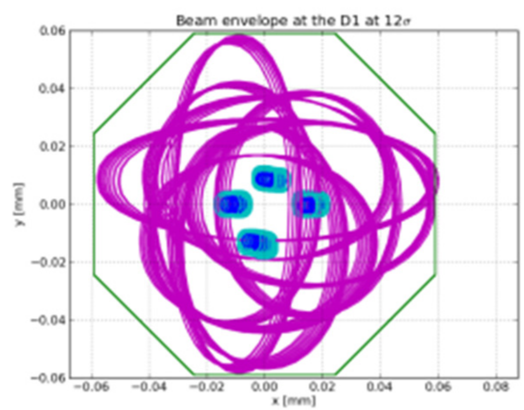
Update the geometry according to last requirements

- Increase of the capillary diameter (8.5 mm OD)



- Same maximal aperture in the vertical and horizontal planes
- Reduction of the aperture in the +/- 45° directions



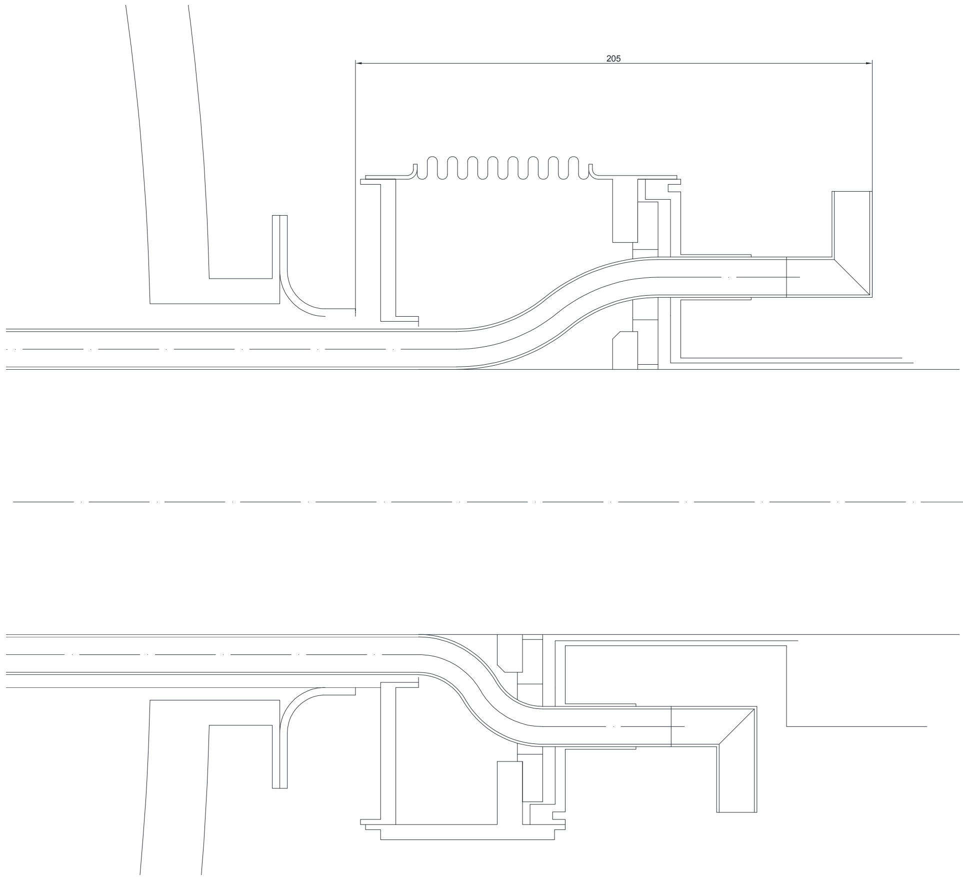

Courtesy Riccardo De Maria, CERN,Technical Meeting on Vacuum for HL-LHC, 5 March 2014

→ No significant beam free aperture reduction is expected

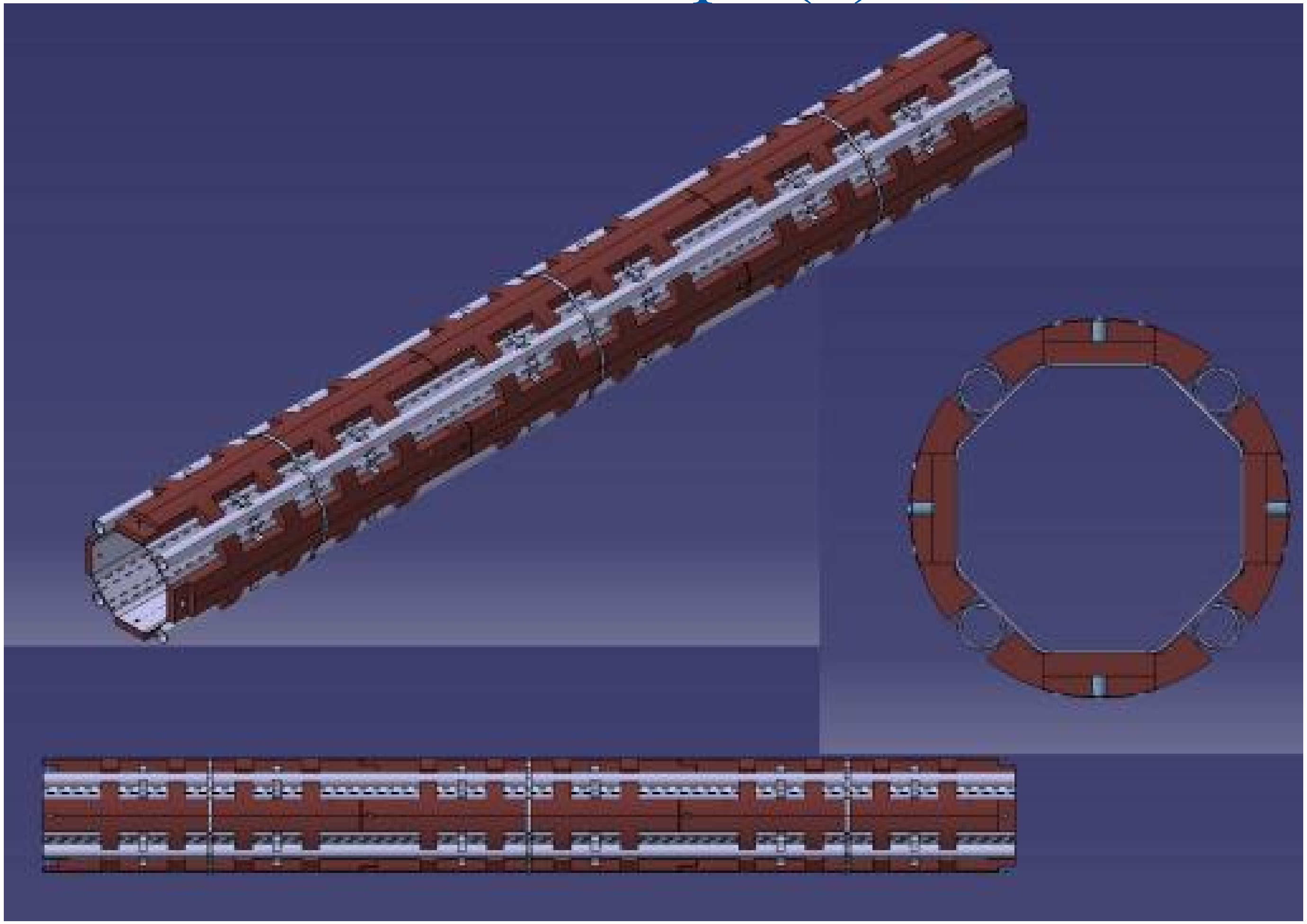
# Next steps (3)

Update the geometry according to last requirements

- Define the beam screen extremities
    - ➢ No weld helium/beam vacuum
    - ➢ Automatic welding
    - ➢ Compact
        - → Study of the interconnections in parallel to optimize the longitudinal space



# Next steps (4)



(for information only, not up to date)

1 short prototype (~1m) with real materials and geometry: Q2 2015

# Summary

A design of the shielded HL-LHC beam screen has been presented. It is based on a mechanical connection between the beam screen tube and the tungsten blocks.

It integrates mechanical and thermal aspects while paying attention to the maximization of the aperture:

- Lorentz forces occurring during a quench are transmitted and absorbed by the cold bore,
- Heat load, absorbed by the tungsten blocks, are transferred to the cooling tubes via copper based thermal links,
- The beam screen is supported by ceramic balls to minimise heat load to the cold masses.
- The possibility to use springs for the supporting system is considered. Dynamic behaviour has to be assessed.
- Tolerances are being considered… but values need to be confirmed with long prototypes.

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