Experimental campaign of the HL-LHC beam screen

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with inputs from: Piotr Gach

WP3 meeting – 18 May 2017

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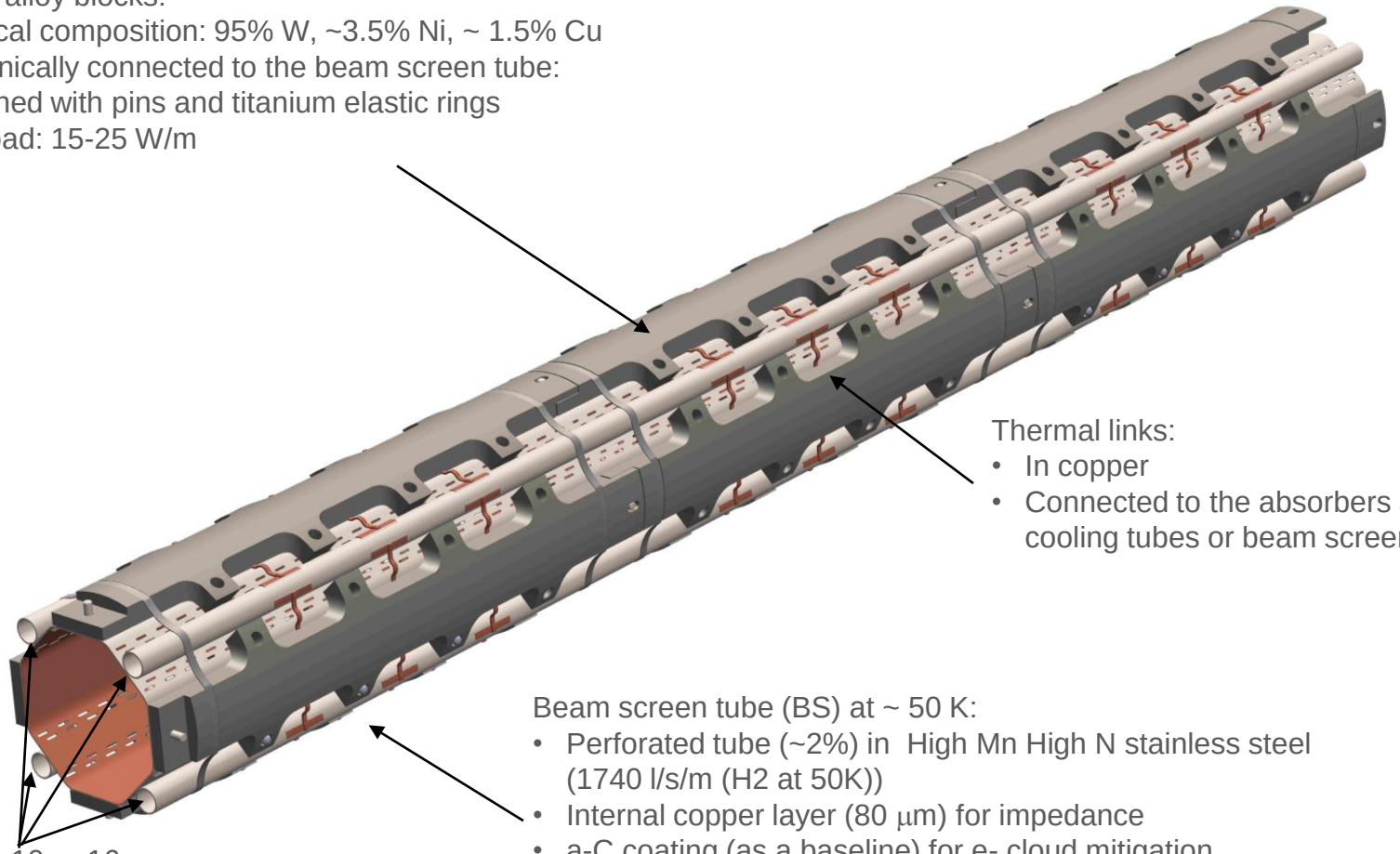
The HL-LHC beam screen *

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



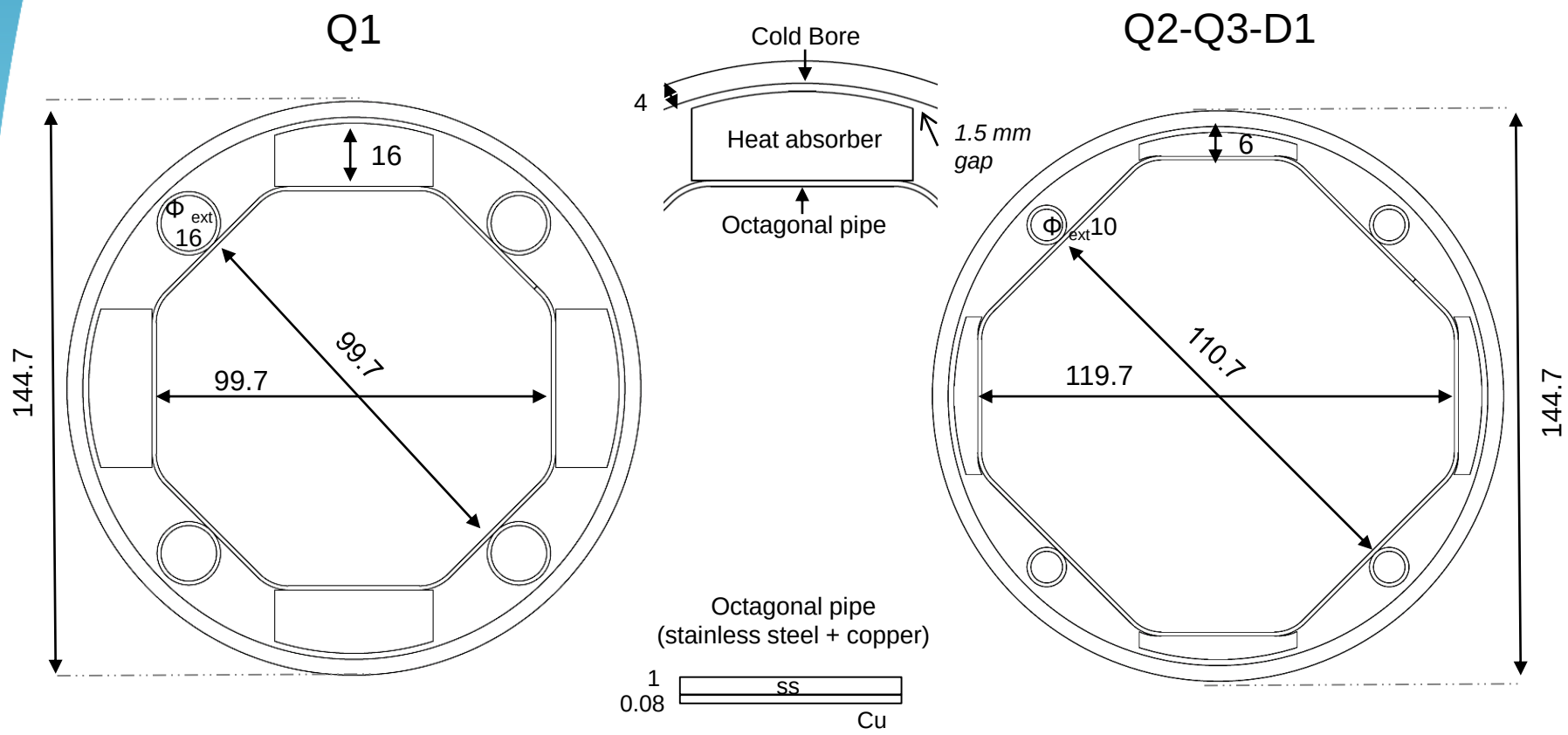
Thermal links:
- In copper
- Connected to the absorbers and the cooling tubes or beam screen tube

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

*Q1 version (W block 16 mm thick)

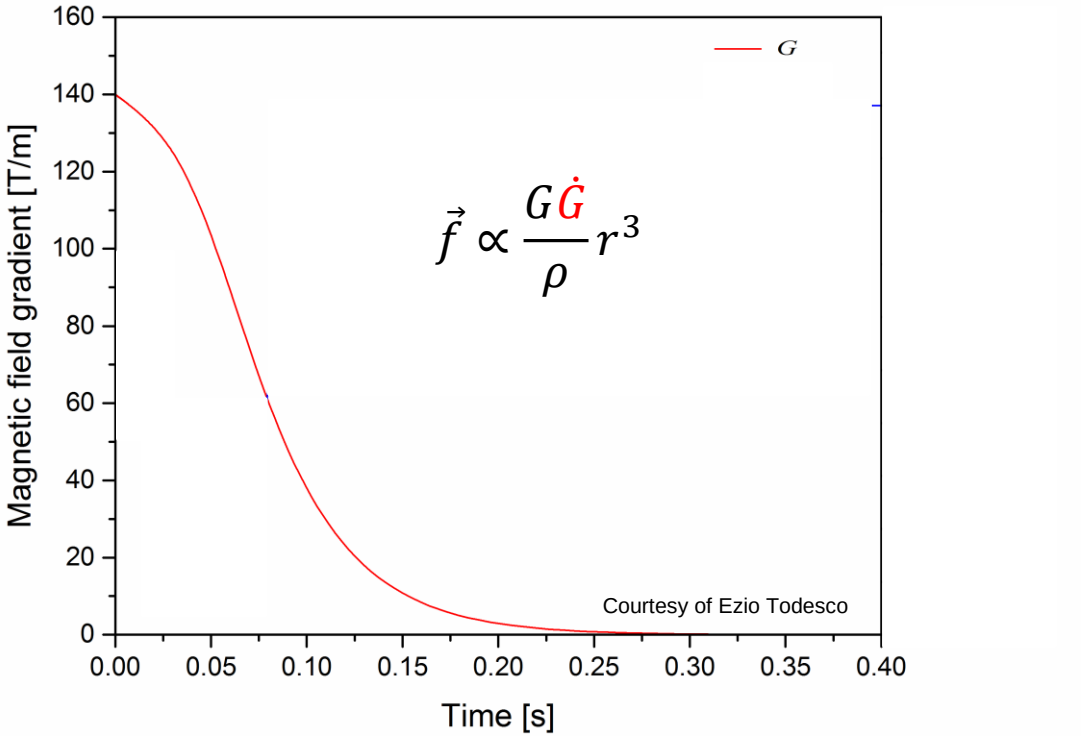
Beam screen dimensions*



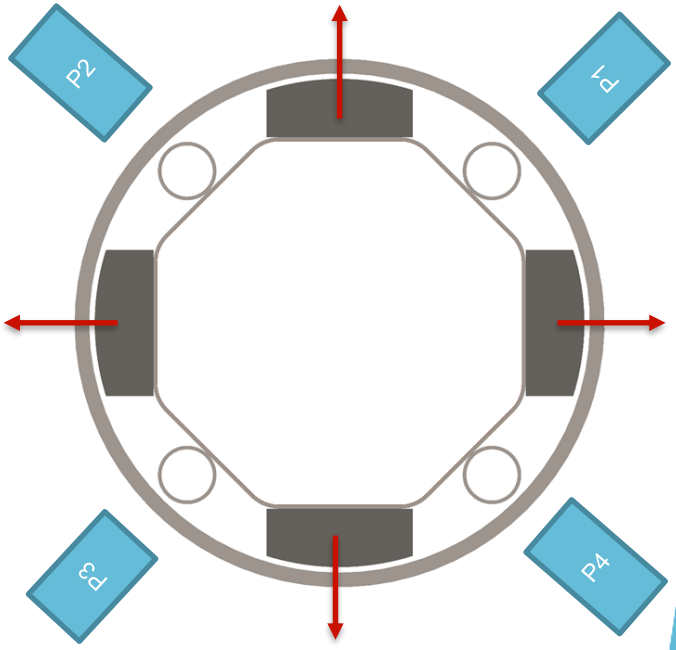
*The dimensions are given in mm

Triplet area layout

Quench protection scheme without CLIQ



F_max _heat absorber
233.46 N/mm

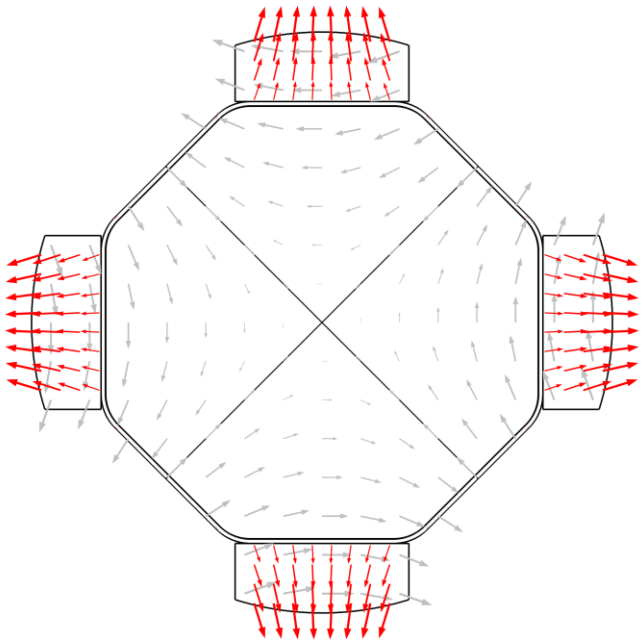


In red the expected forces.

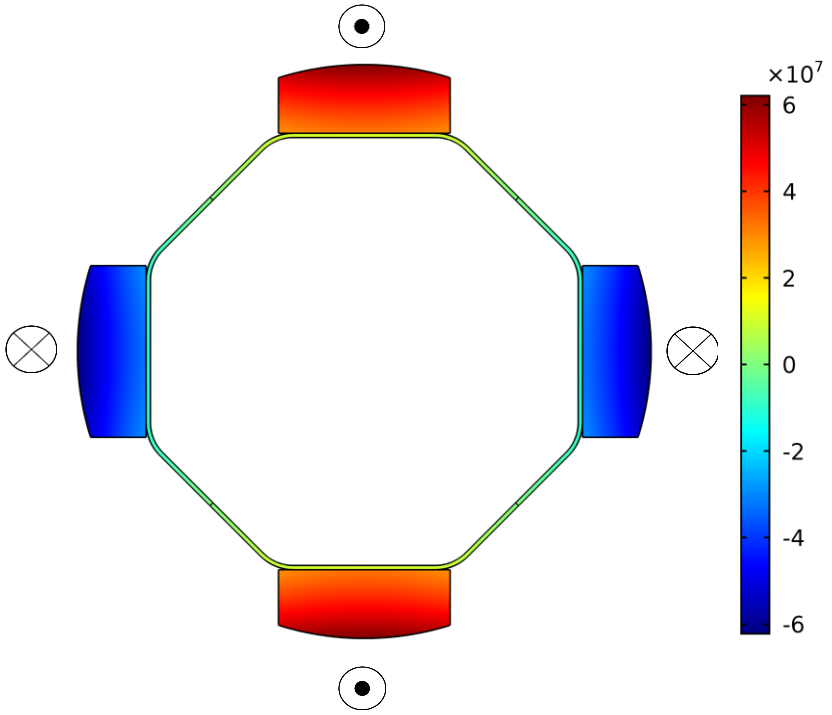
→ Magnet gradient uniform for all the poles.
→ G' always negative!!

Quench protection scheme without CLIQ

Lorentz forces



Eddy currents

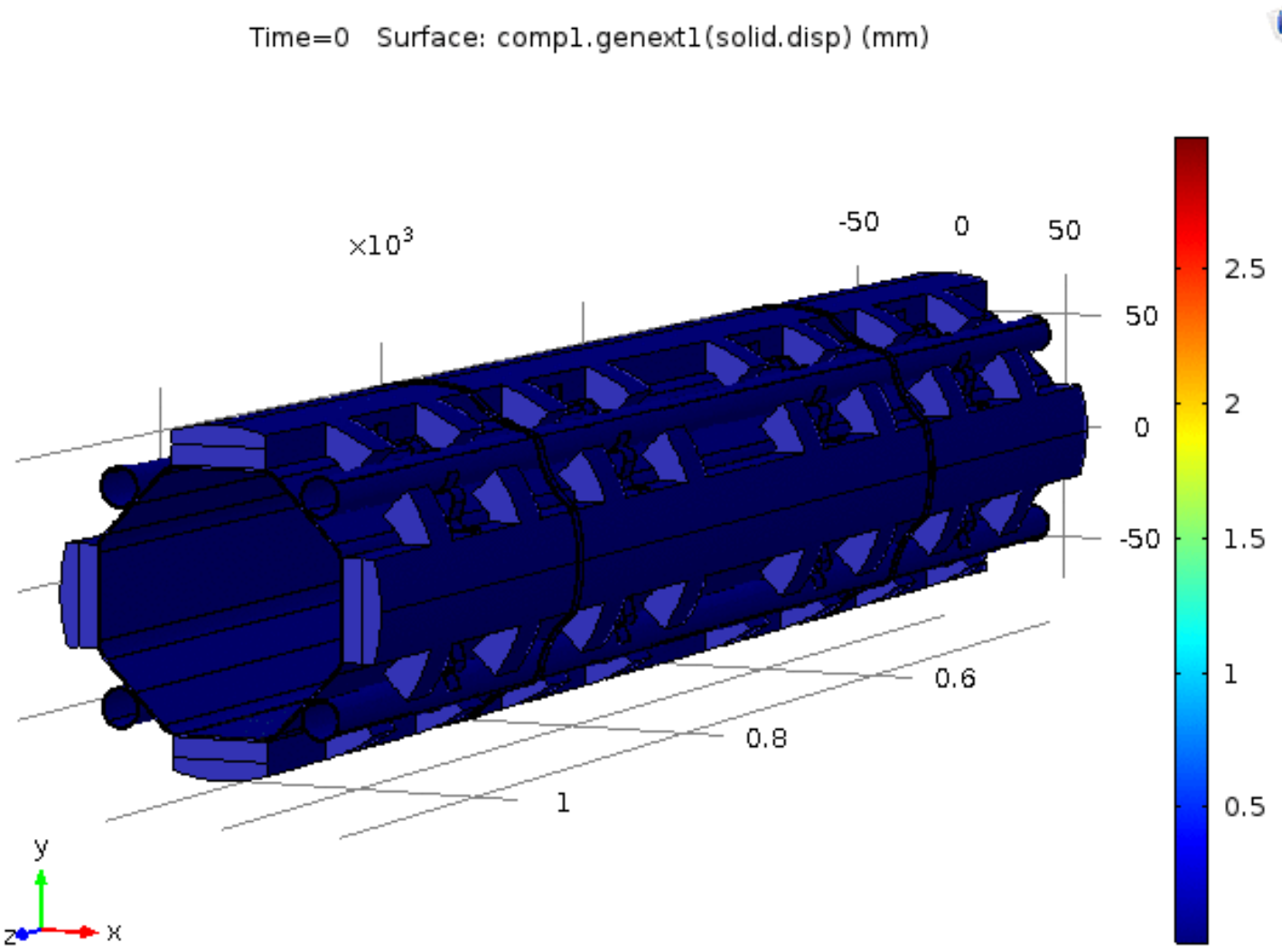


The integrated forces are equal in each quadrant. Therefore, one quadrant is sufficient to describe the behavior of the whole assembly.

Q1_W= 44.8 kA
Q2_W= 18.9 kA

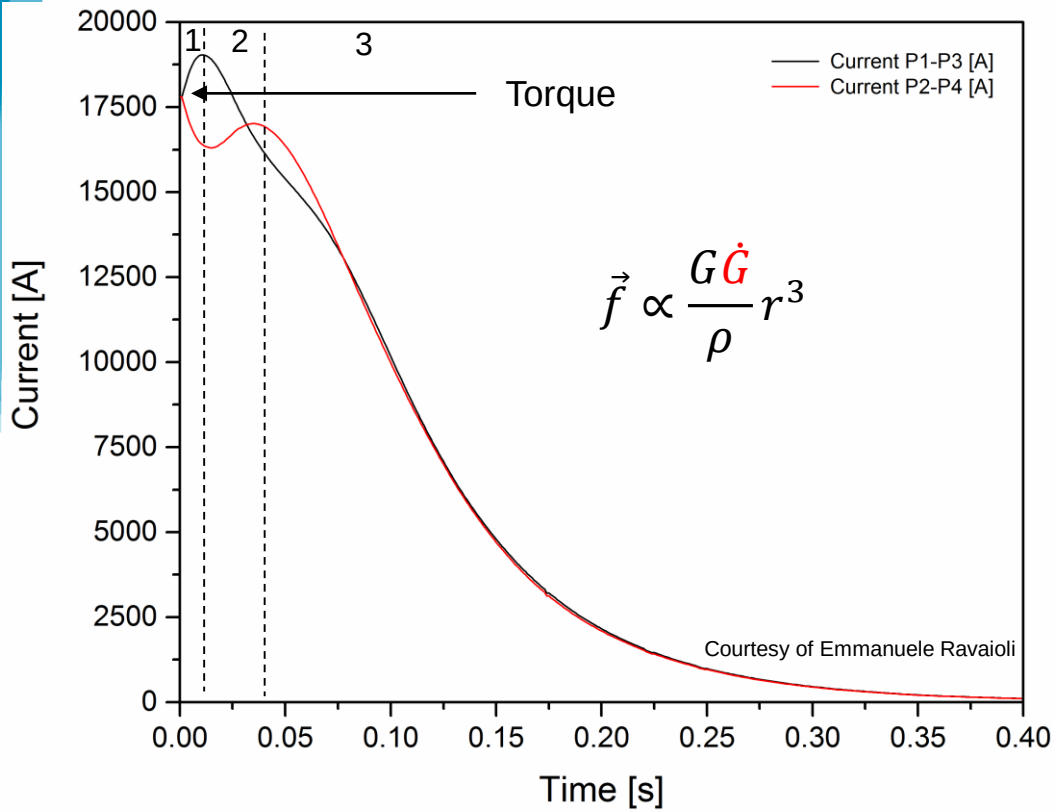
Q1_Cu= 7.3 kA
Q2_Cu= 9.5kA

Quench protection scheme without CLIQ

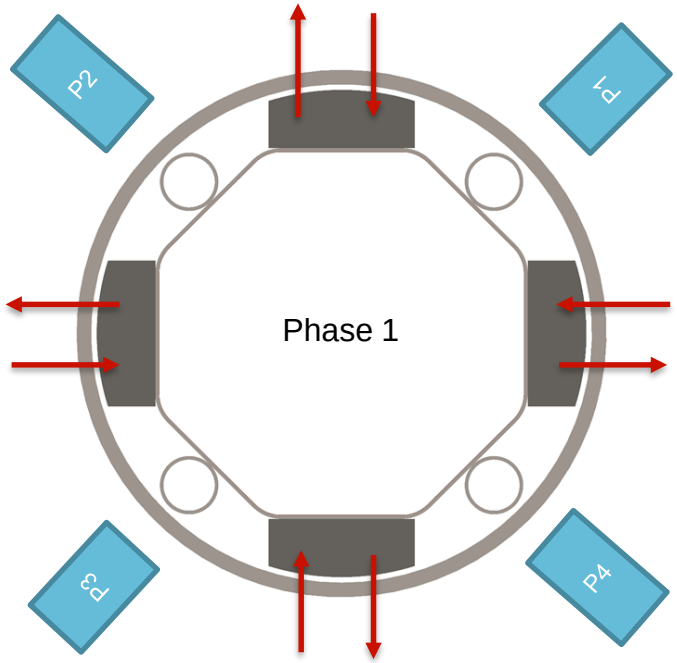


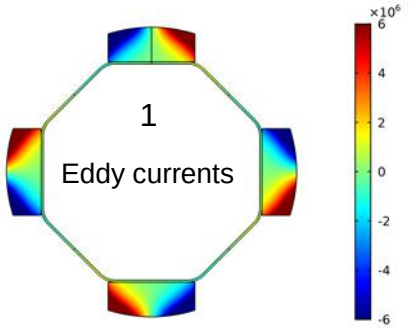
Quench protection scheme including CLIQ

Ultimate currents_ I_0=17800 A



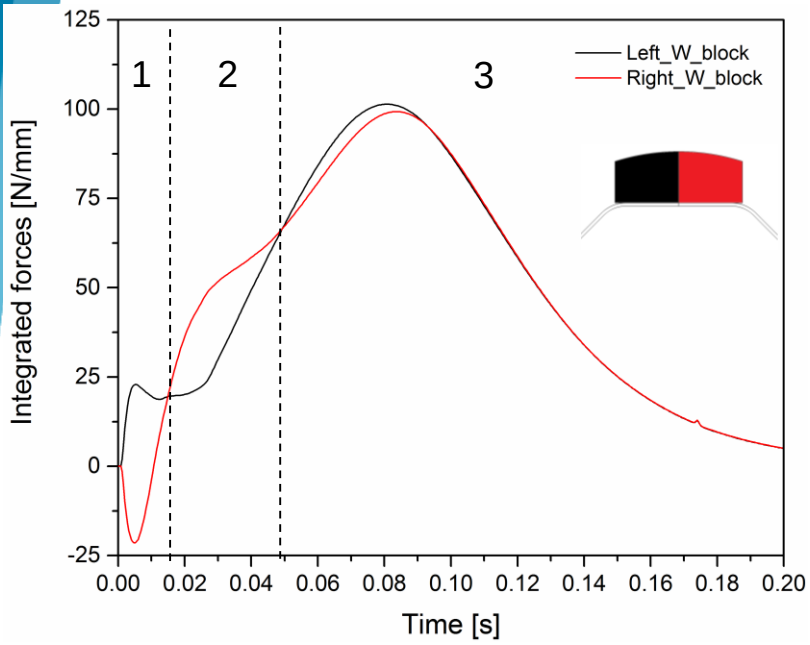
→ Magnet gradient NOT uniform for the poles.
→ G' negative for pole 2/4 and positive for pole 1/3.!!





Quench protection scheme including CLIQ

Integrated forces induced in the W block



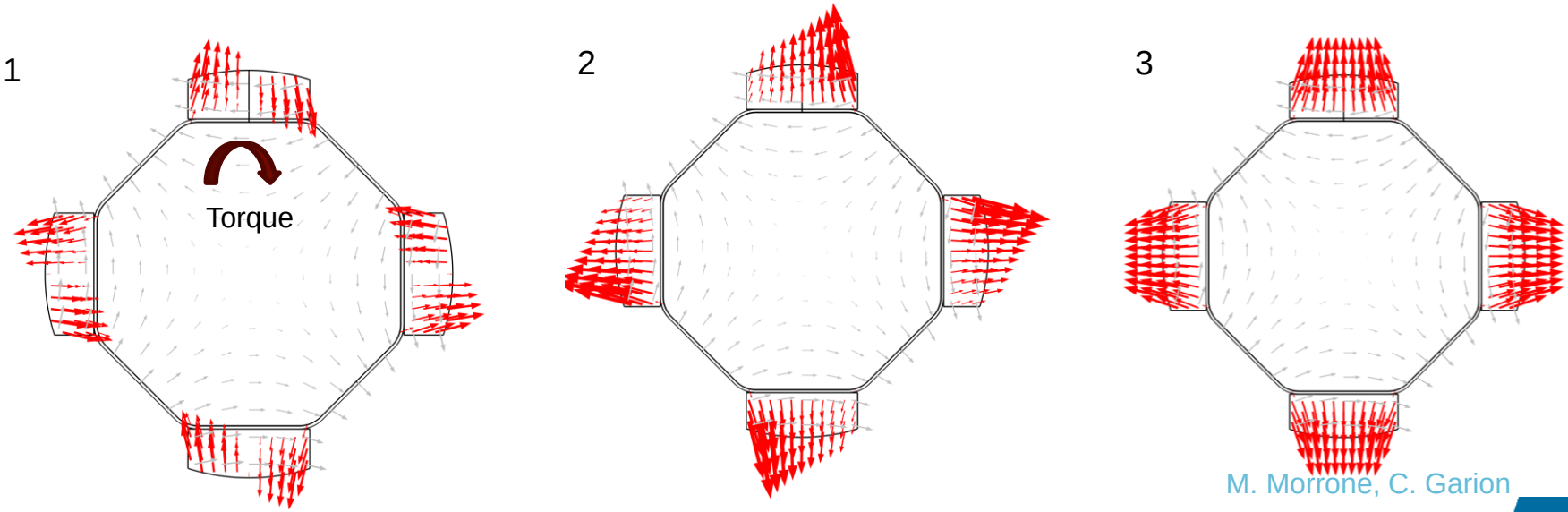
Phase 1: Most critical!!

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

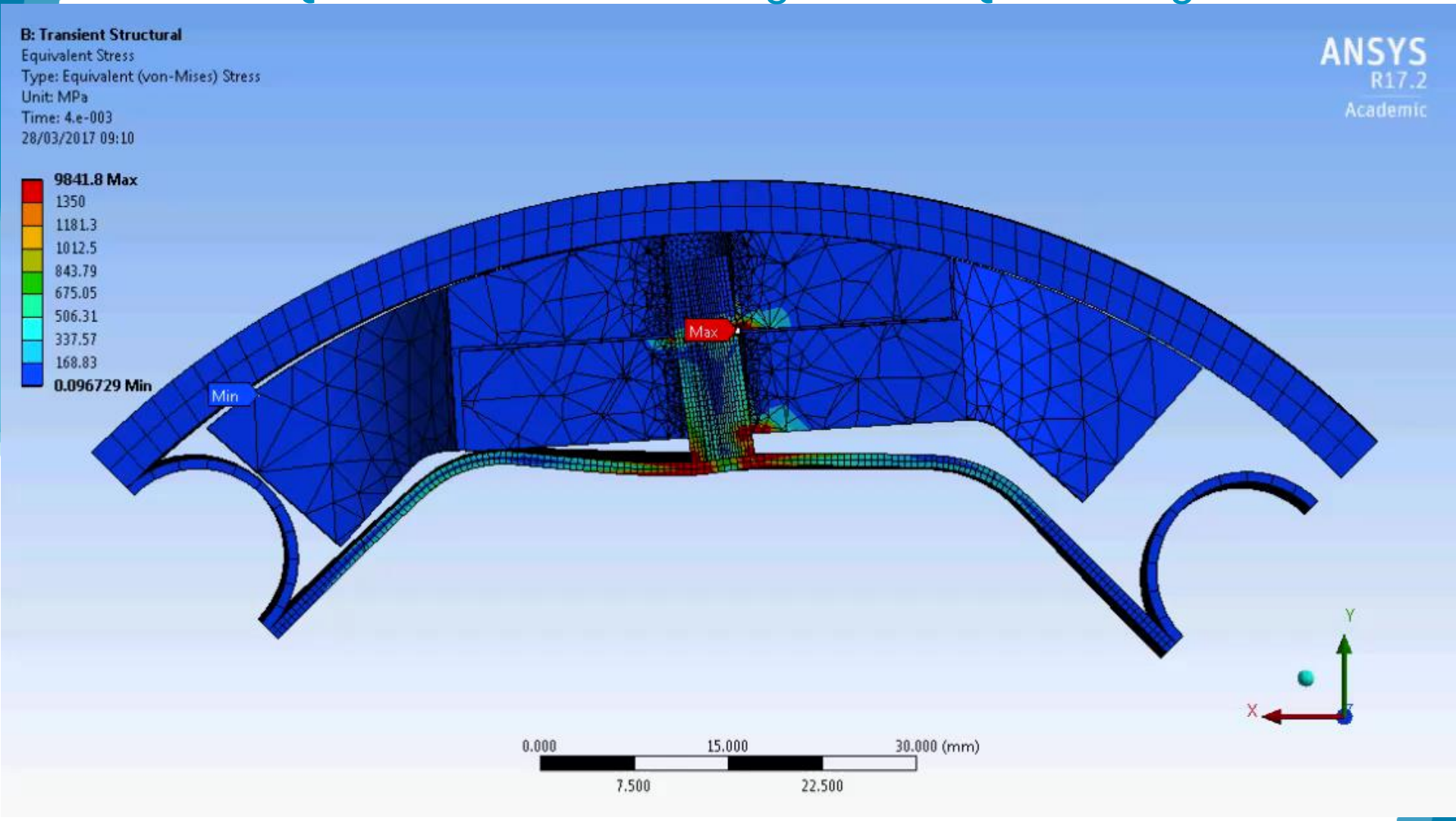
Phase 2: Less severe than phase 1

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]



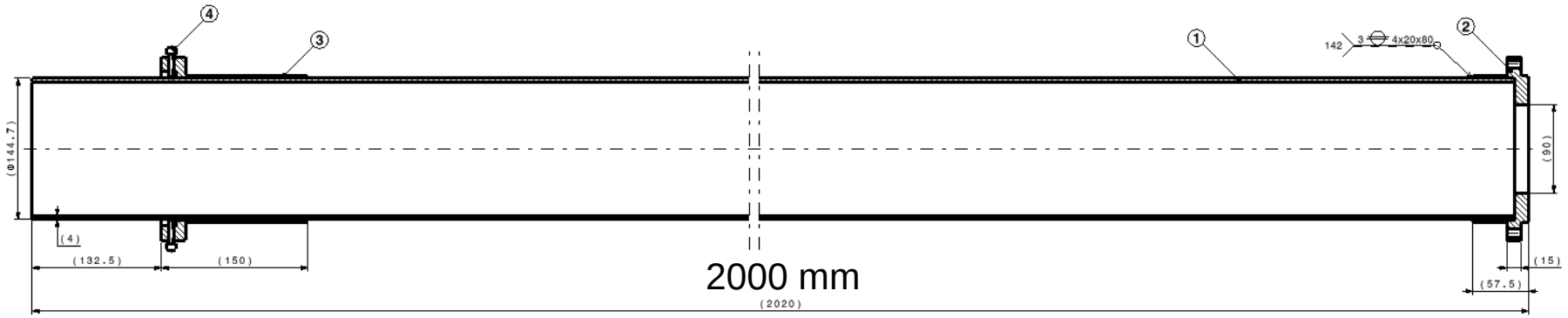
Q1 beam screen during the CLIQ discharge



Aim of the test

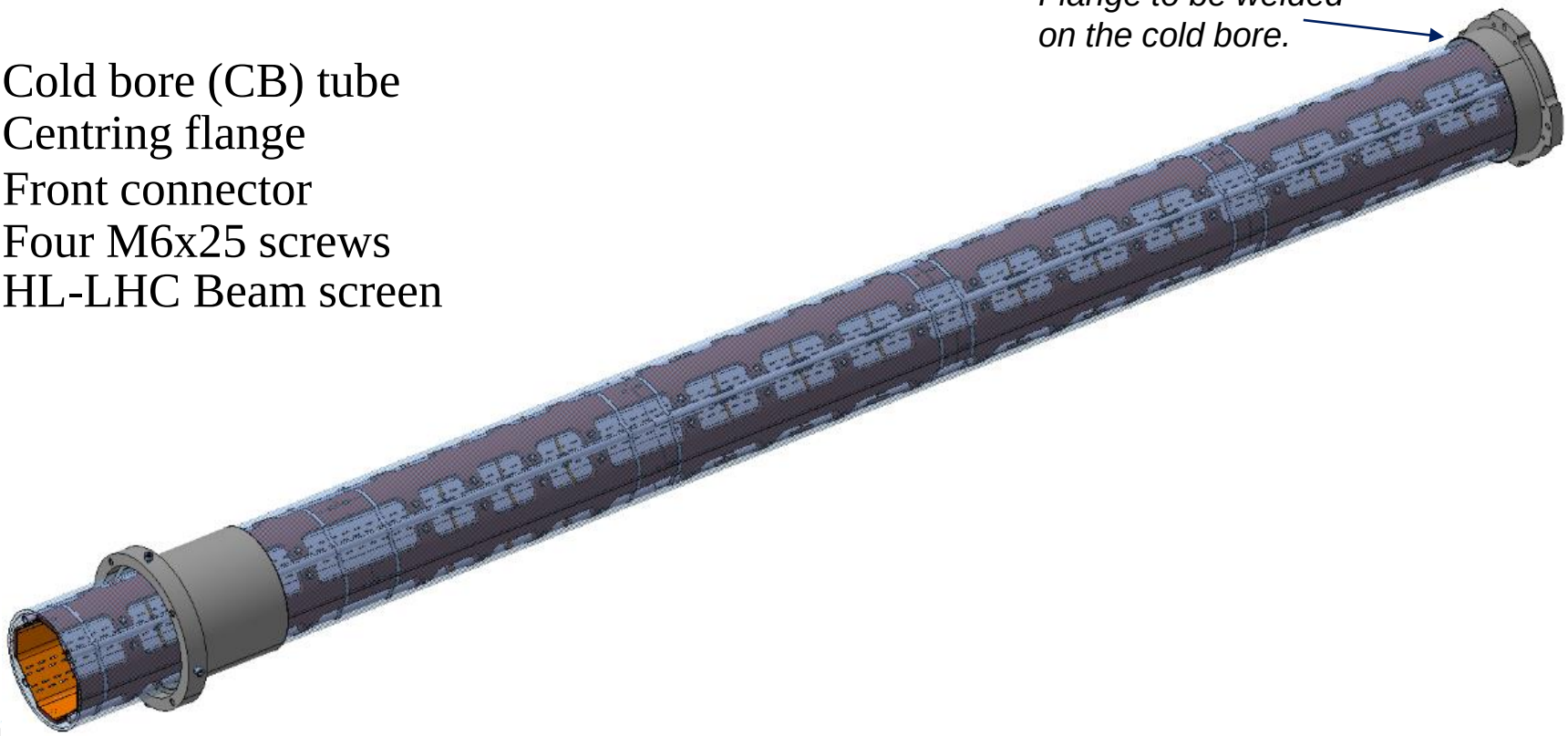
Validation of the proposed beam screen design, compatible with the CLIQ system, during a magnet quench.

Quench test setup



Flange to be welded on the cold bore.

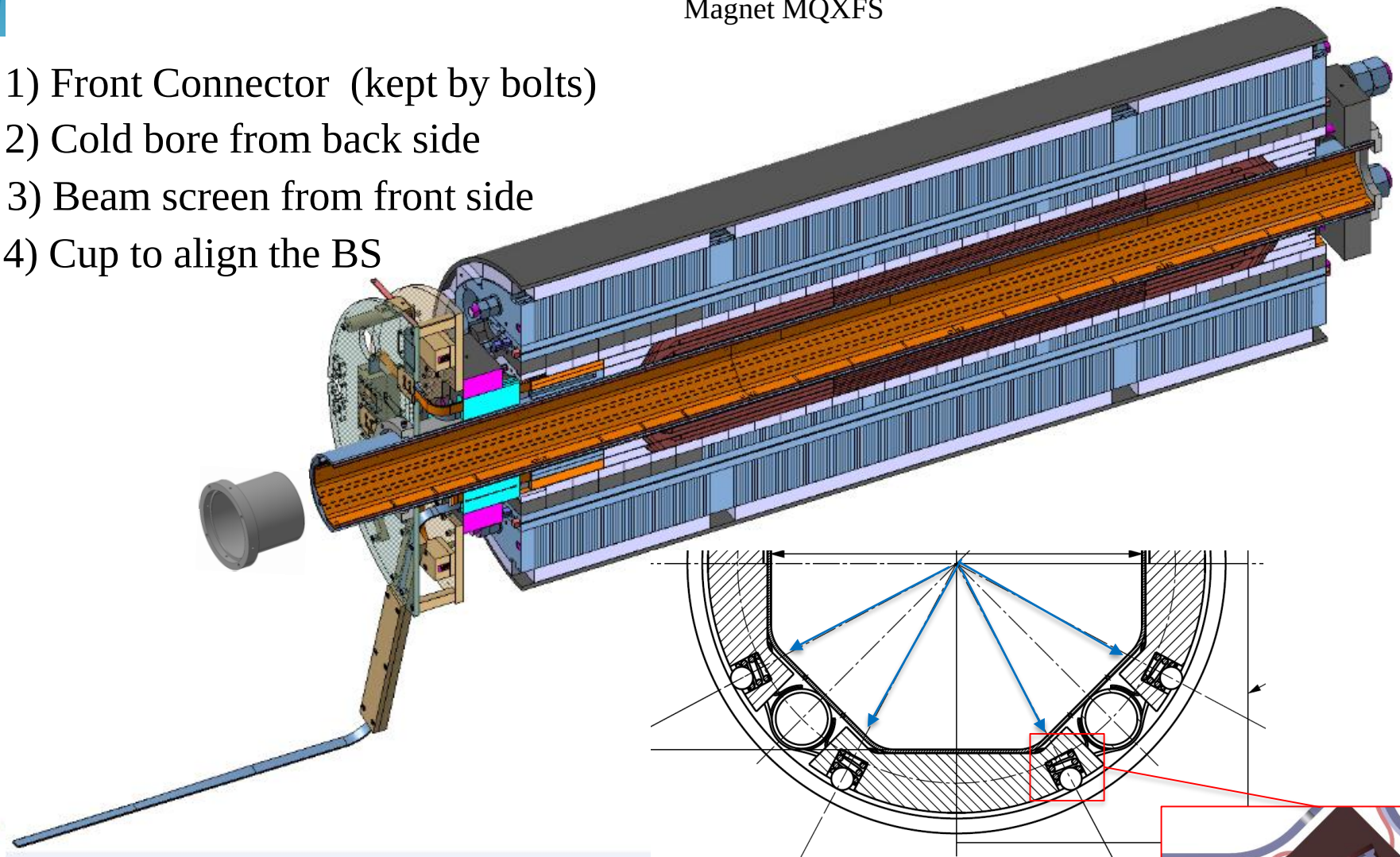
1 Cold bore (CB) tube
2 Centring flange
3 Front connector
4 Four M6x25 screws
5 HL-LHC Beam screen

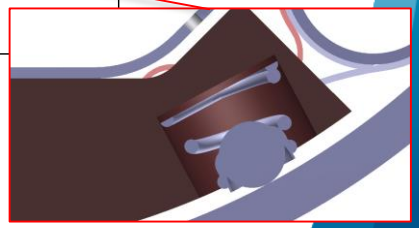


Quench test setup

Magnet MQXFS

1) Front Connector (kept by bolts)
2) Cold bore from back side
3) Beam screen from front side
4) Cup to align the BS

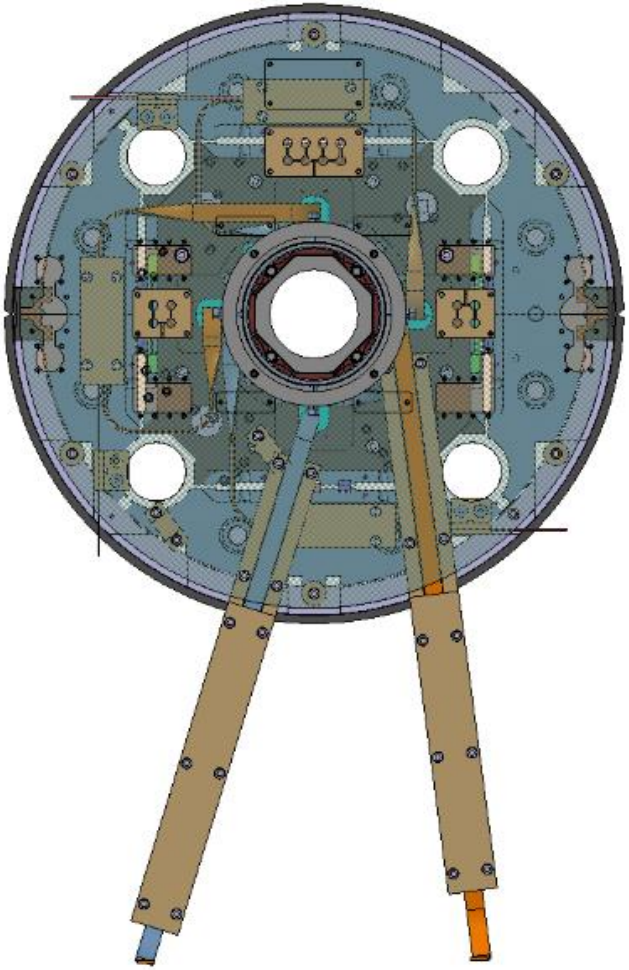




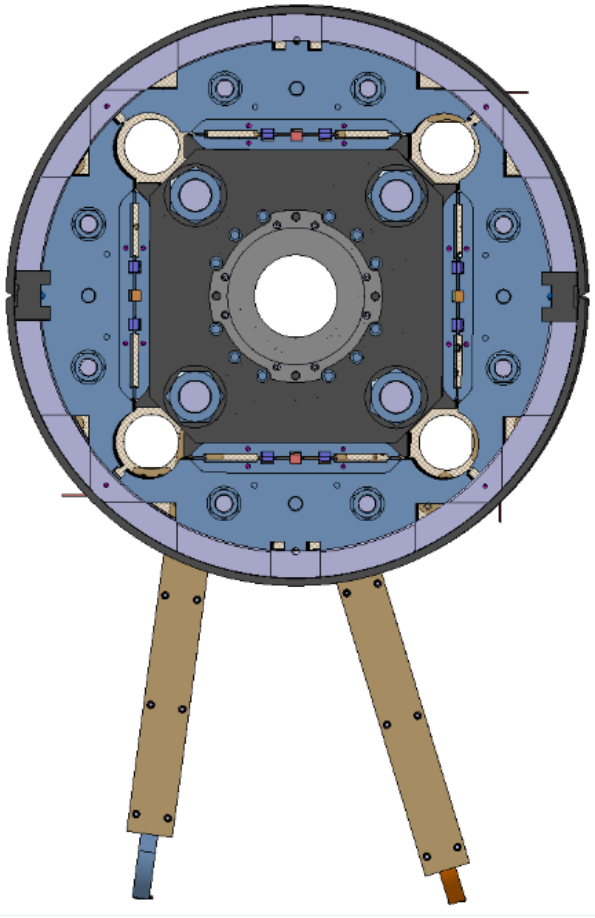
Supporting system
(spring+ceramic ball)

*In collaboration with Nicolas Bourcey and Juan Carlos Perez

Quench test setup



Front view

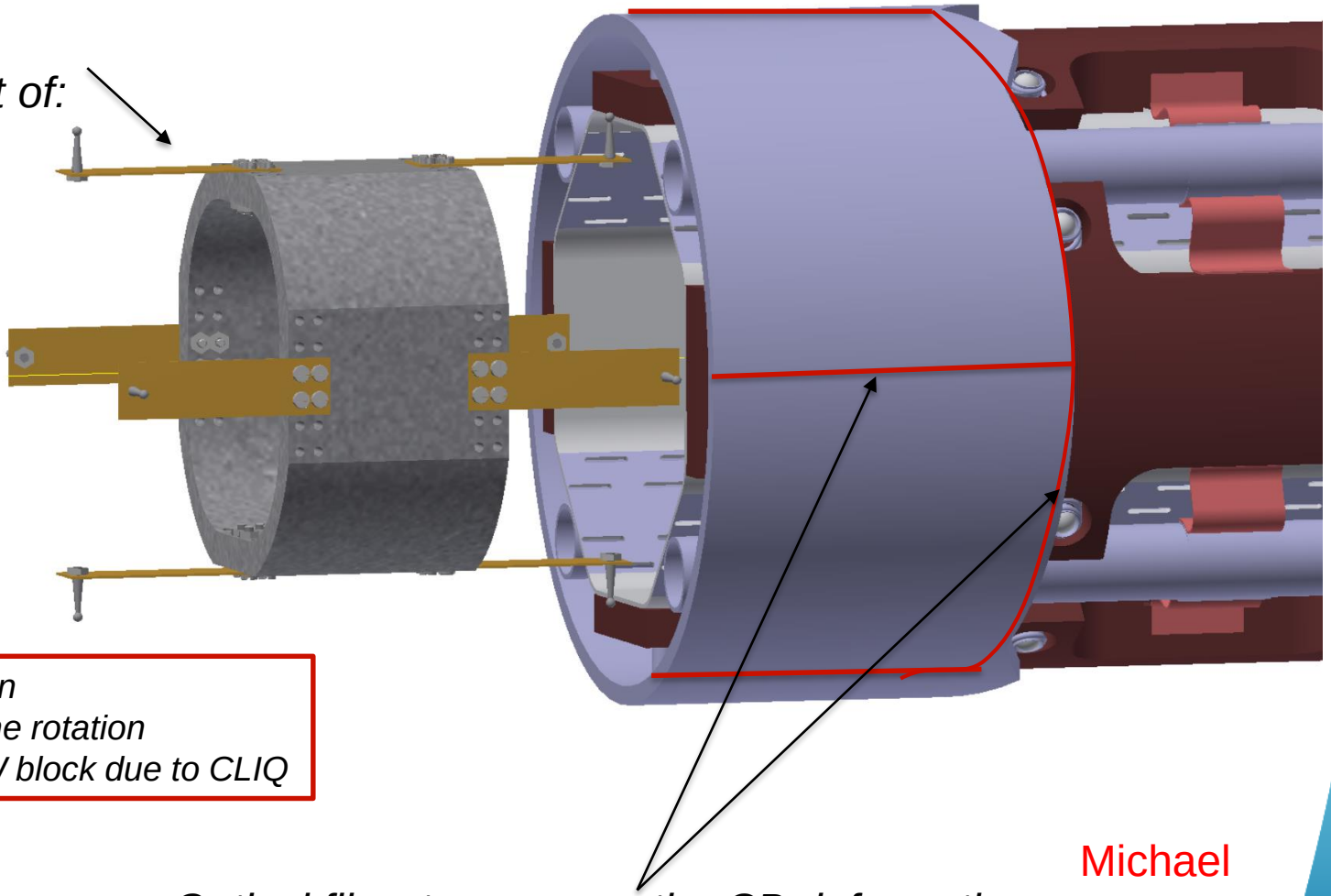


Rear view

Instrumented beam screen

Tool to measure the displacement of:

- *Beam screen,*
- *W blocks.*

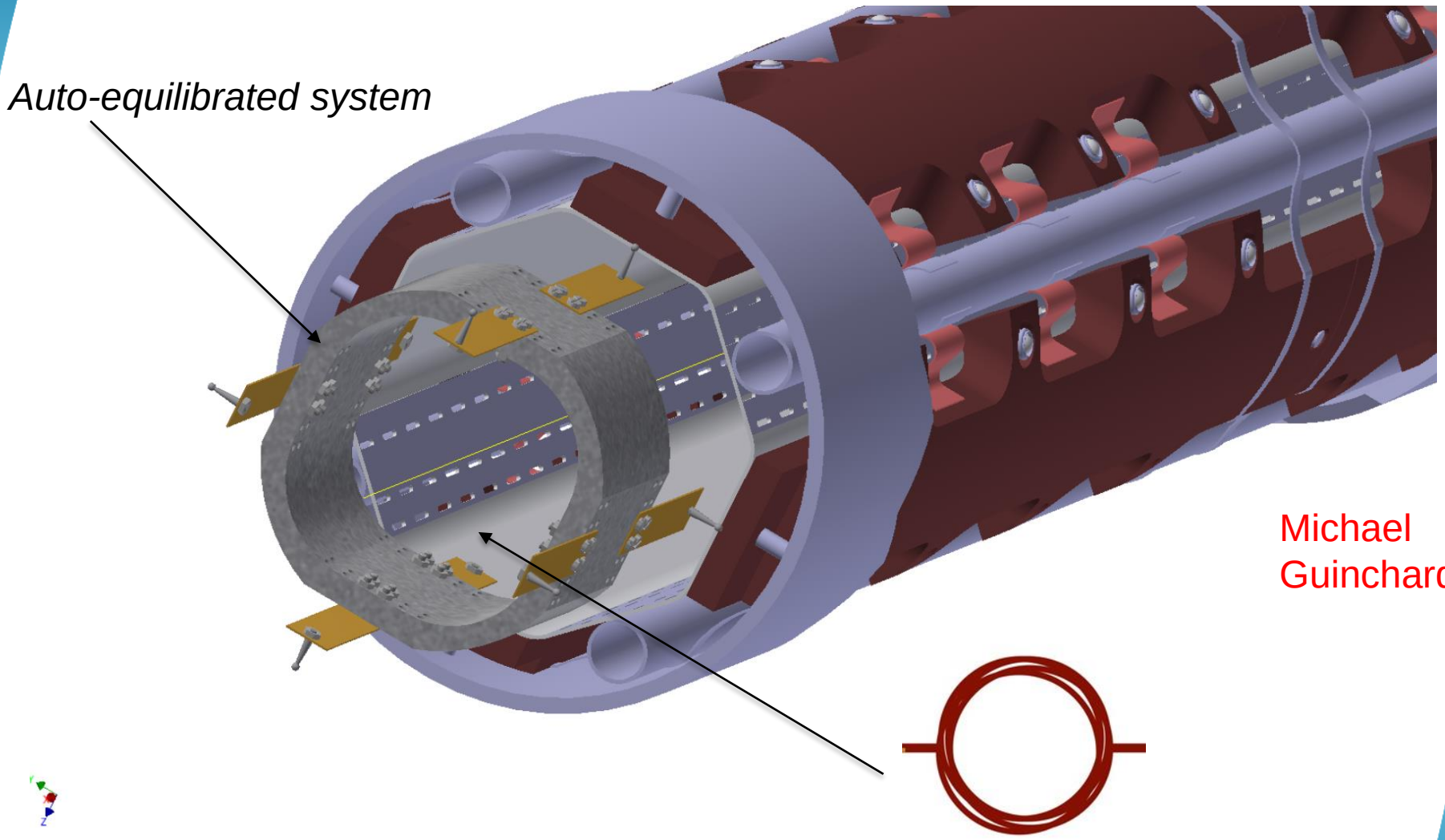


The same principle can be used to measure the rotation of the beam screen/W block due to CLIQ

Optical fibre to measure the CB deformation (longitudinal+azimuthal)

Michael Guinchard

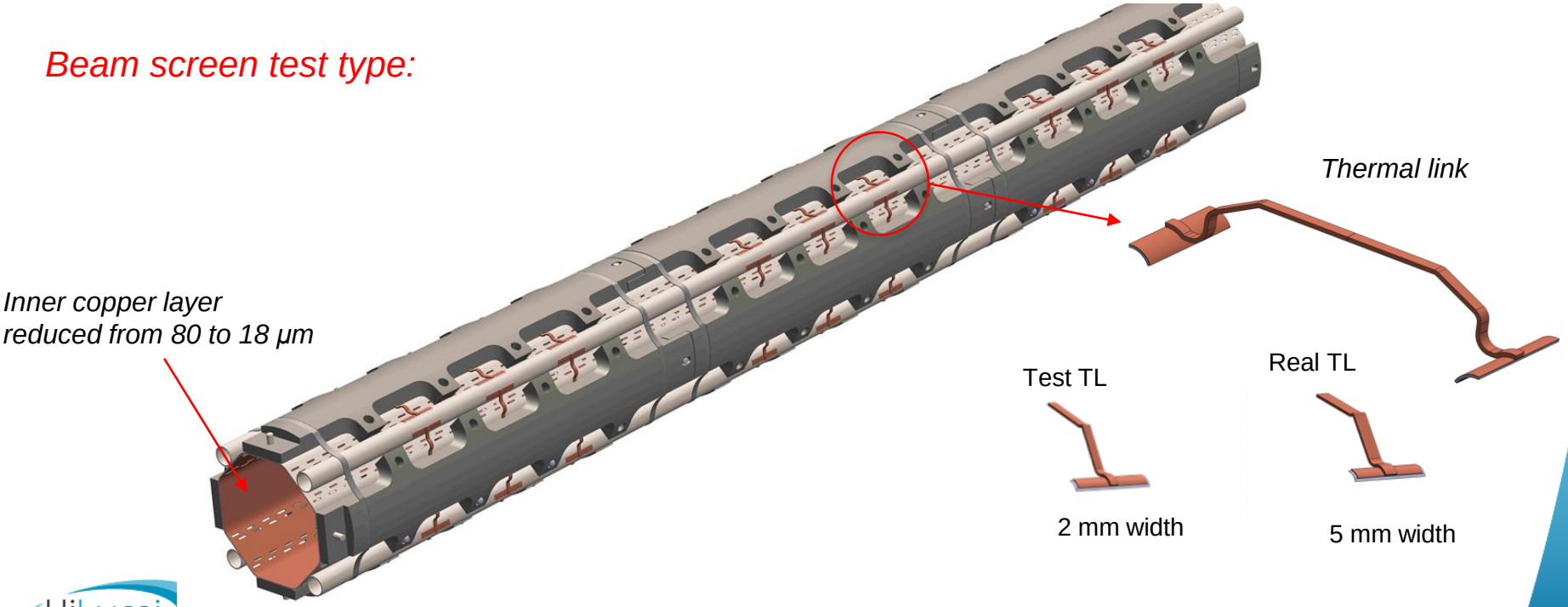
Instrumented beam screen



Test conditions

- *Temperature: 1.9 K (significant change of the electrical resistivity for Cu*);*
- *BS immersed in the helium bath (damping of the dynamic response);*
- *Magnetic field decay representative of the HL-LHC conditions, including the CLIQ system;*
- *Vertical position of the beam screen.*

Beam screen test type:



*this applies only to Cu components as for the other materials the electrical resistivity is constant between 1.9 - 80 K.

Experimental campaign proposal

Beam screens to be tested:	*Magnet:*	*Date:*
-Q1_v1 (W block 16 mm thick);	MQXFS+CLIQ;	Mid-July 2017 ?
-Q2_v1 (W block 6 mm thick);	MQXFS+CLIQ;	October 2017 ?
-D1_v1 (W block 6 mm thick).	KEK	Beginning of 2018 ?

In case of any modifications:

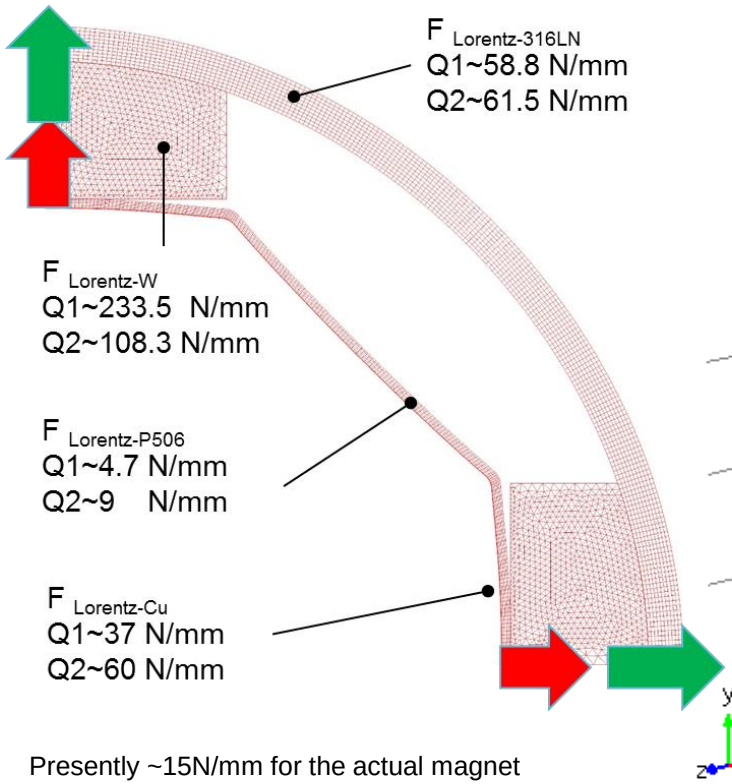
-Q1_v*2* (W block 16 mm thick);	MQXFS+CLIQ;	2018
-Q2_v*2* (W block 6 mm thick);	MQXFS+CLIQ;	2018
-D1_v*2* (W block 6 mm thick).	KEK	2018

Thank you for your attention

SPARES

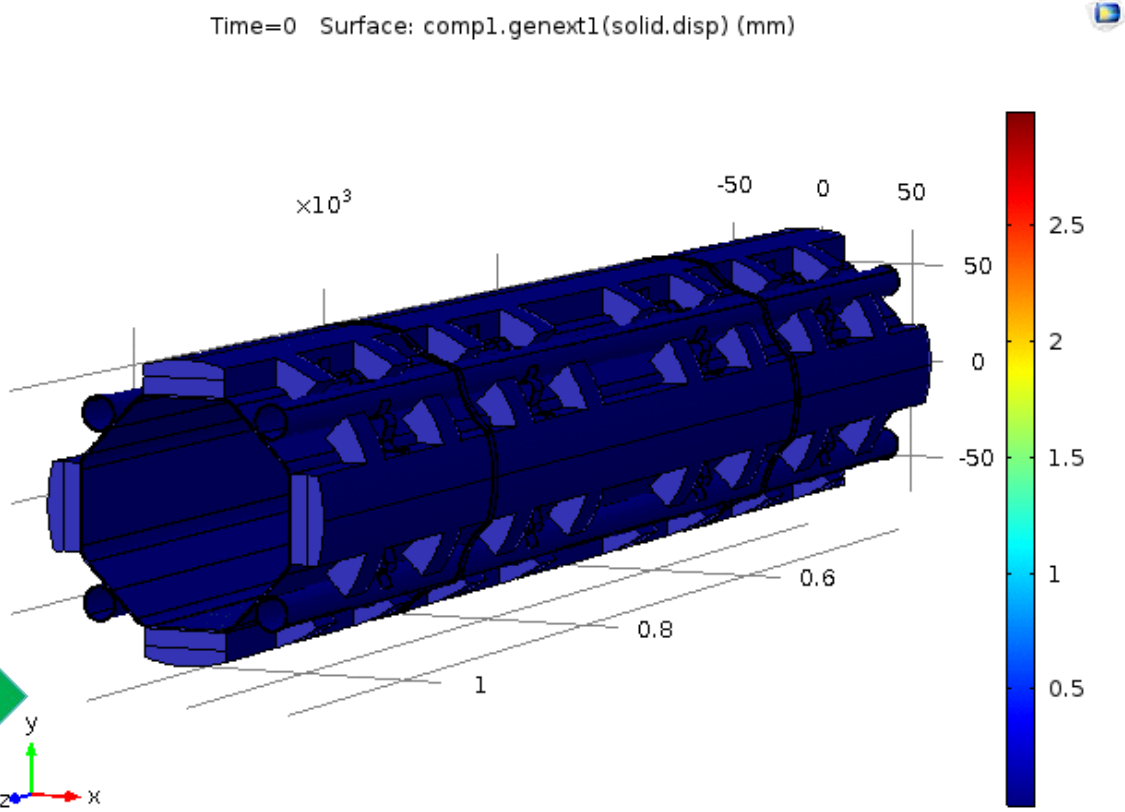
Quench protection scheme without CLIQ

Highest Lorentz forces induced by Foucault currents per quadrant:



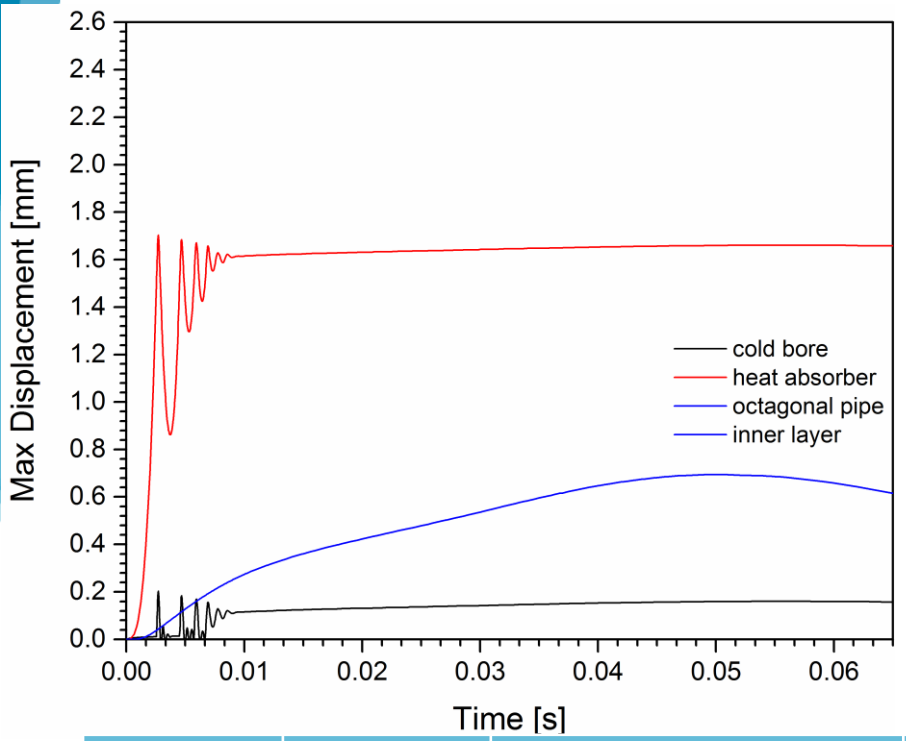
Presently ~15N/mm for the actual magnet

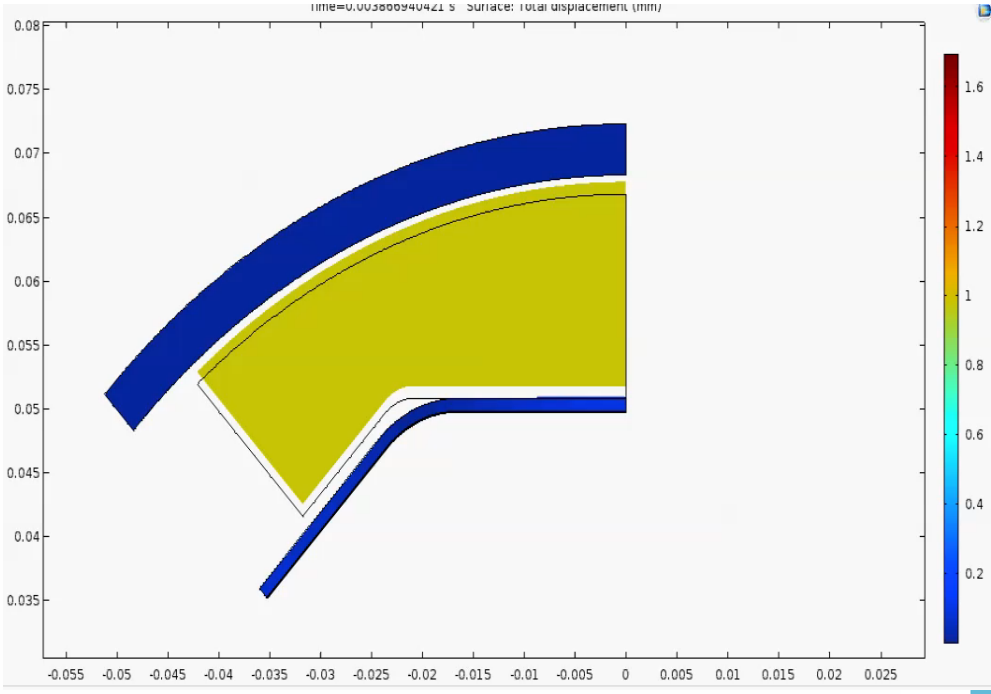
Beam screen displacement during a magnet quench:



For illustrative purposes only!! W blocks are not welded but posed on the octagonal pipe.

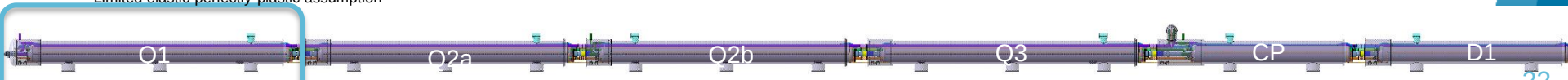
Q1
Quench protection scheme not including CLIQ



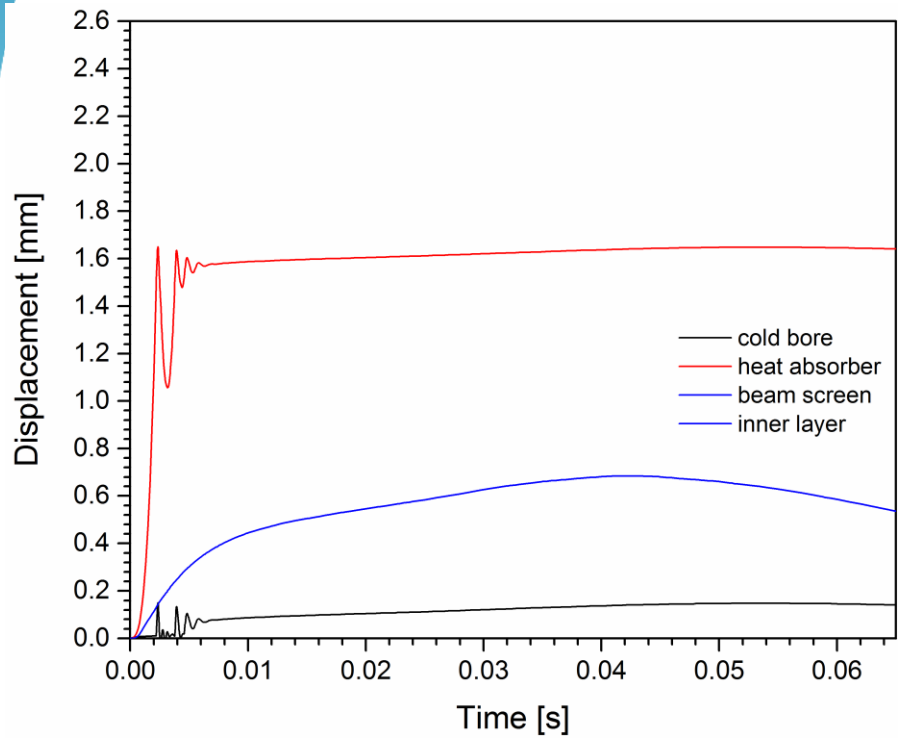


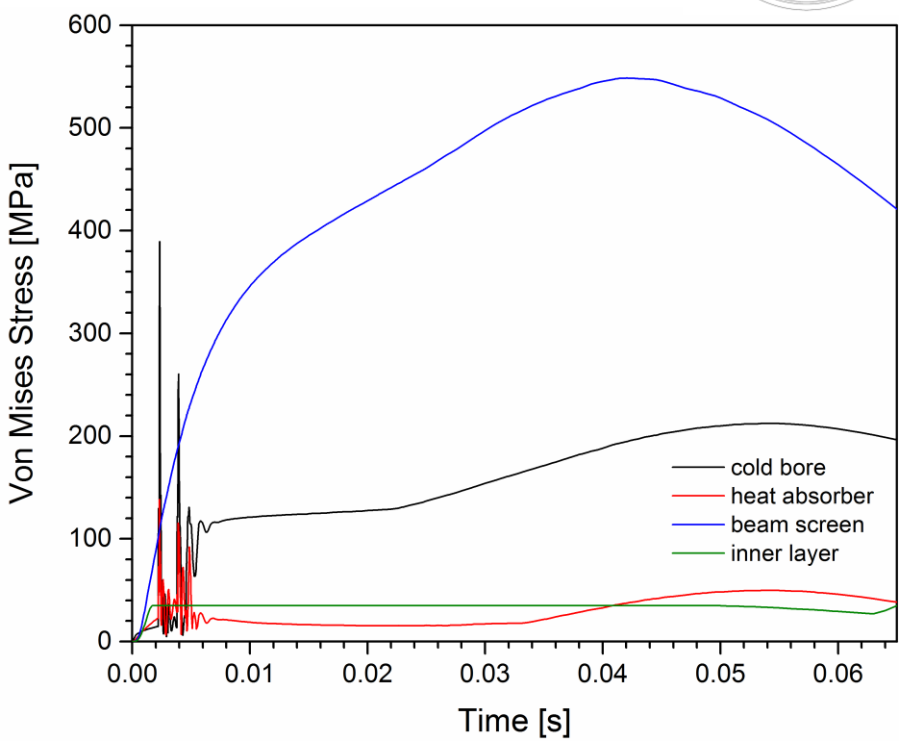
Component	Material	Tensile strength [MPa]	Max VM stress [MPa]	Max displacement [mm]
Cold Bore	Ss 316 LN	860 (at 4 K)	524	0.20
Absorber	Inermet	1284 (at 77K)	25	1.70
Octagon	Ss P506	1350 (at 50 K)	469	0.69
Inner layer	Copper	35 (at 50 K)	35	0.69

* Limited elastic-perfectly plastic assumption



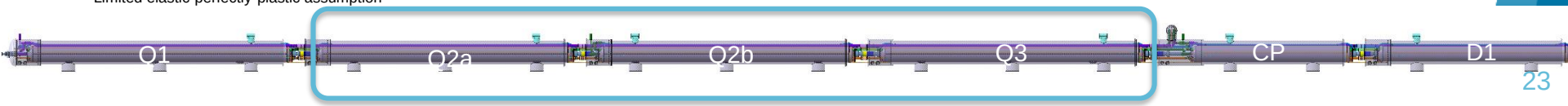
Q2-Q3
Quench protection scheme not including CLIQ



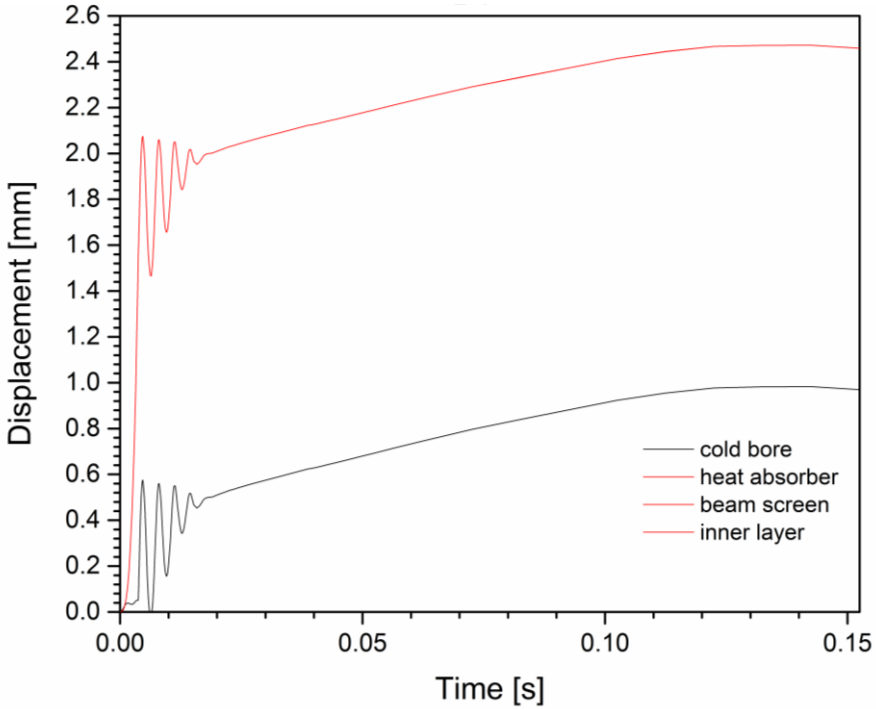


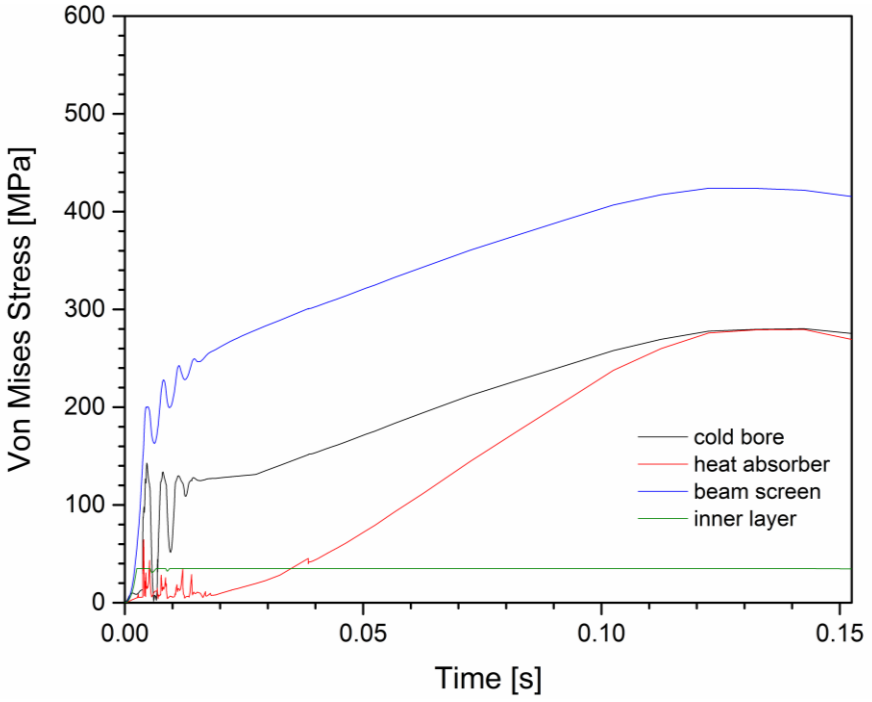
Component	Material	Tensile strength [MPa]	Max VM stress [MPa]	Max displacement [mm]
Cold Bore	Ss 316 LN	860 (at 4 K)	389.45	0.15
Absorber	Inermet	1284 (at 77K)	138.34	1.65
Octagon	Ss P506	1350 (at 50 K)	548.49	0.68
Inner layer	Copper	35 (at 50 K)	35	0.68

* Limited elastic-perfectly plastic assumption



D1
Quench protection scheme not including CLIQ



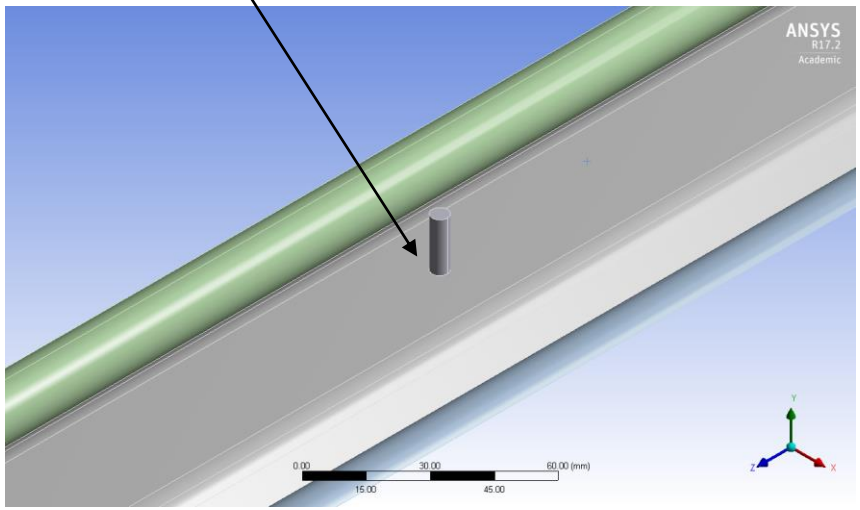


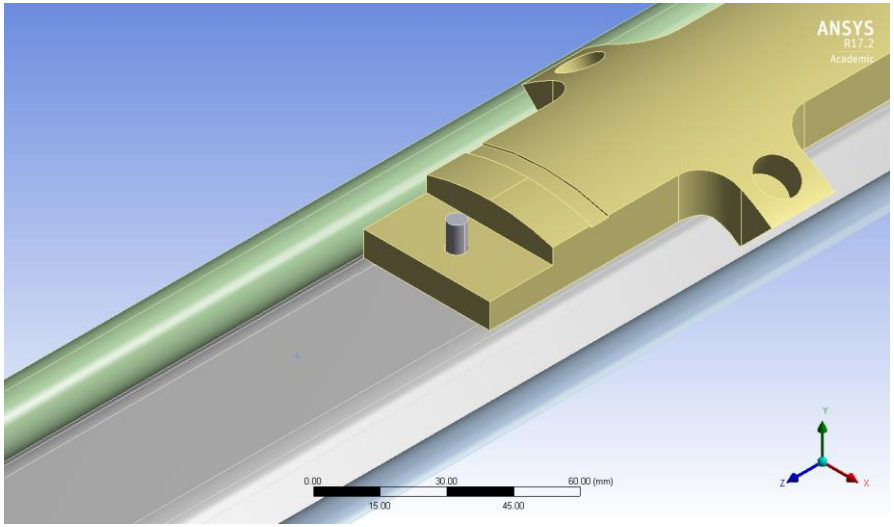
Component	Material	Tensile strength [MPa]	Max VM stress [MPa]	Max displacement [mm]
Cold Bore	Ss 316 LN	860 (at 4 K)	280.23	0.98
Absorber	Inermet	1284 (at 77K)	279.51	2.47
Octagon	Ss P506	1350 (at 50 K)	423.92	2.47
Inner layer	Copper	35 (at 50 K)	35.02*	2.47

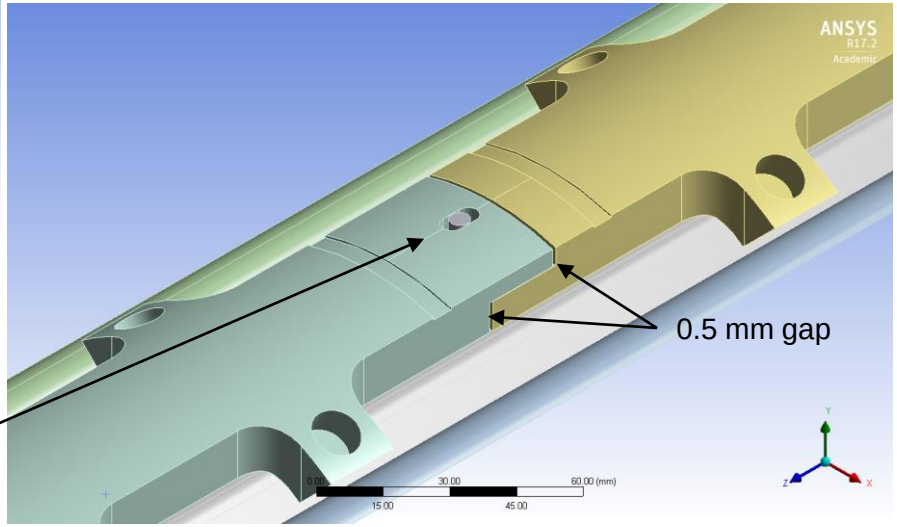
* Limited elastic-perfectly plastic assumption

Details of the original beam screen design (without CLIQ)

Pin welded through
Electric Resistance Welding (ERW)



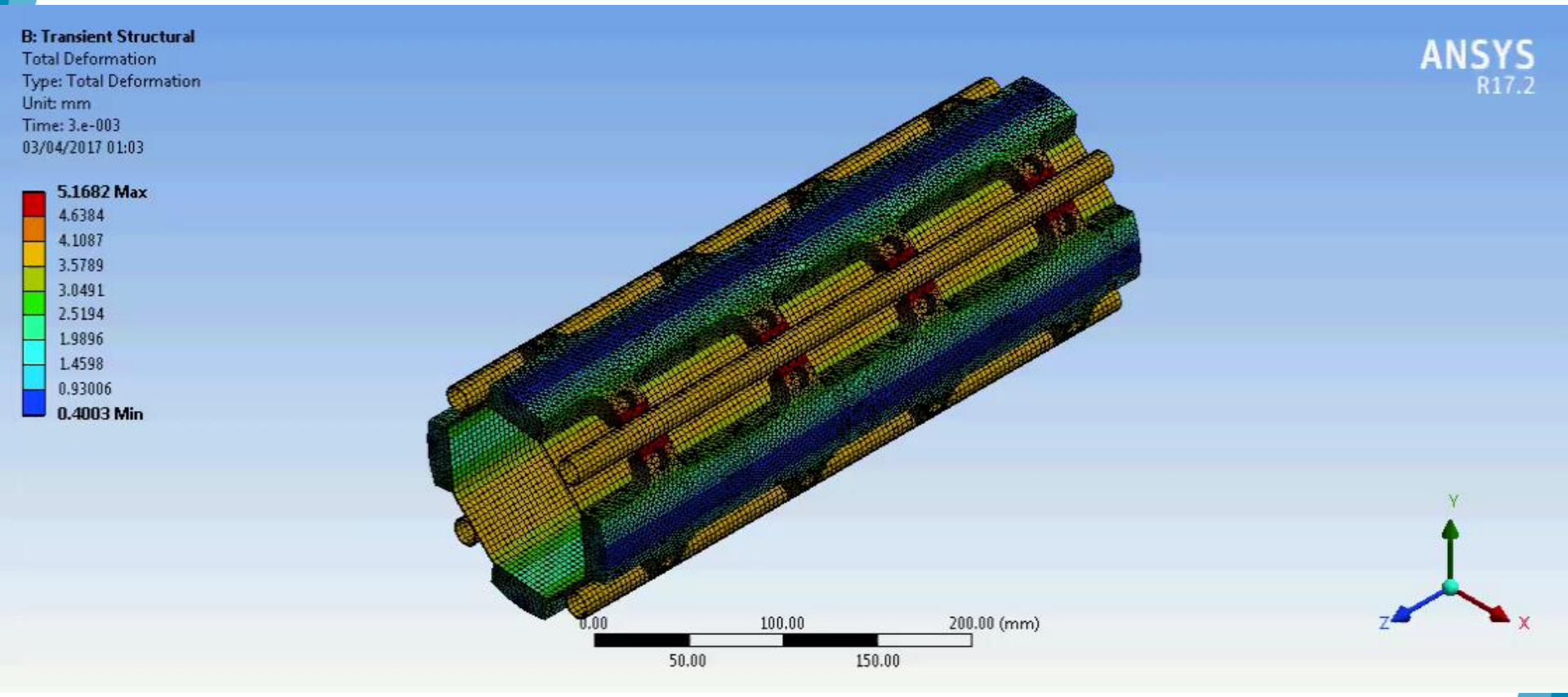




0.5 mm gap

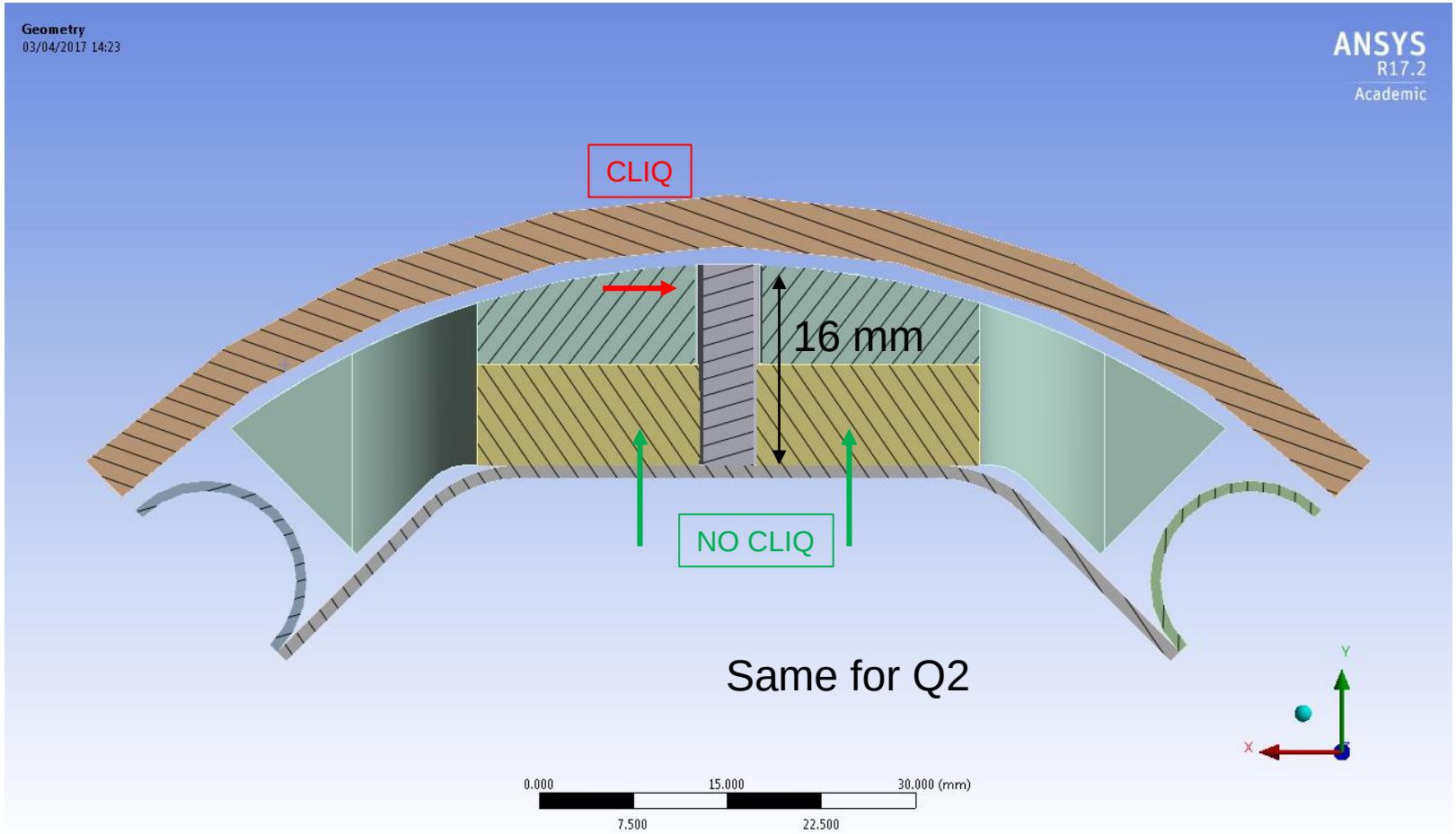
Oval slot to allow different thermal contraction
at the W/ss interface (not welded!!)

Quench protection scheme including CLIQ

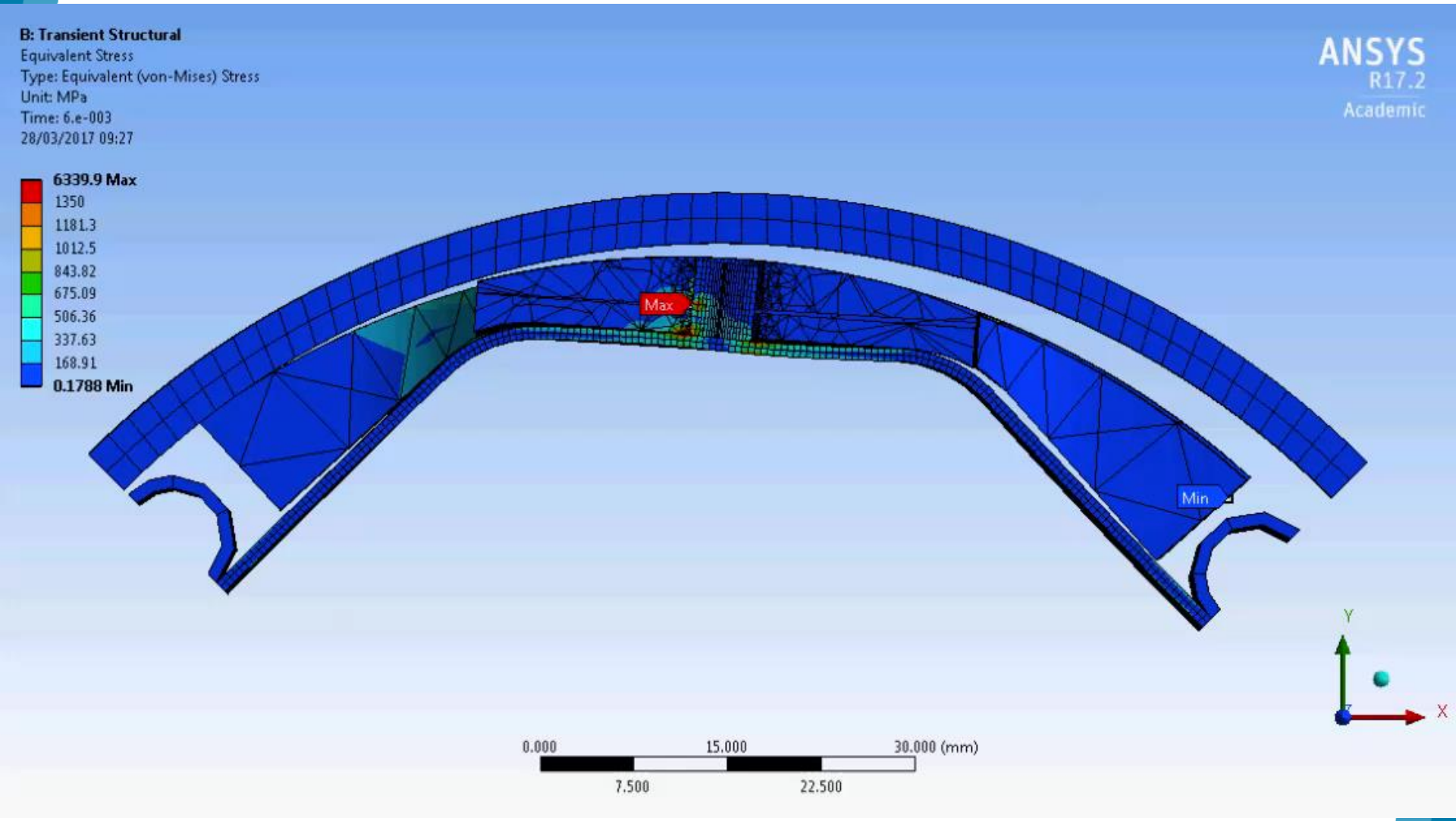


For illustrative purposes only!! W blocks are not welded but posed on the octagonal pipe.

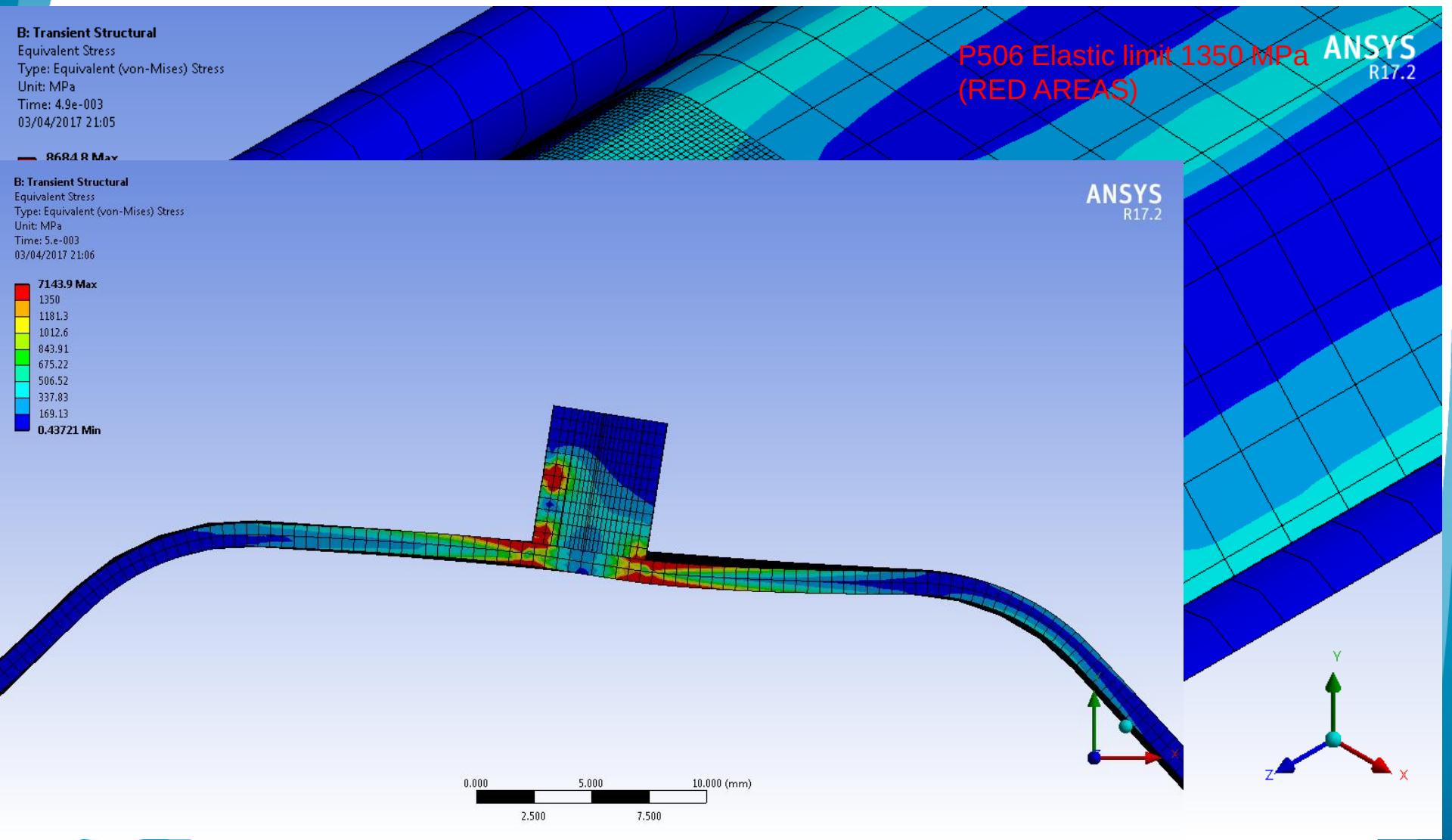
Details of the original beam screen design



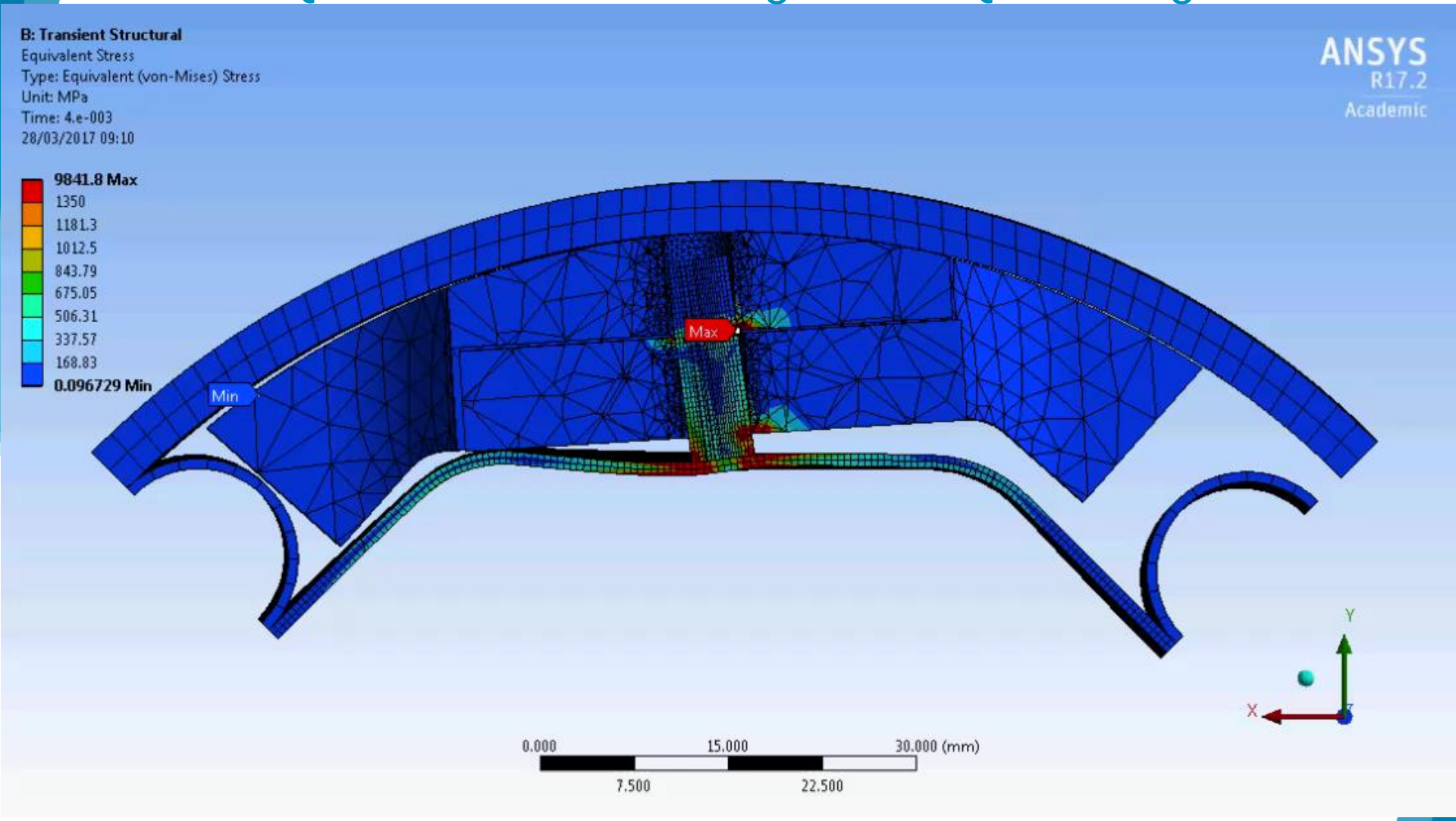
Q2 beam screen during the CLIQ discharge



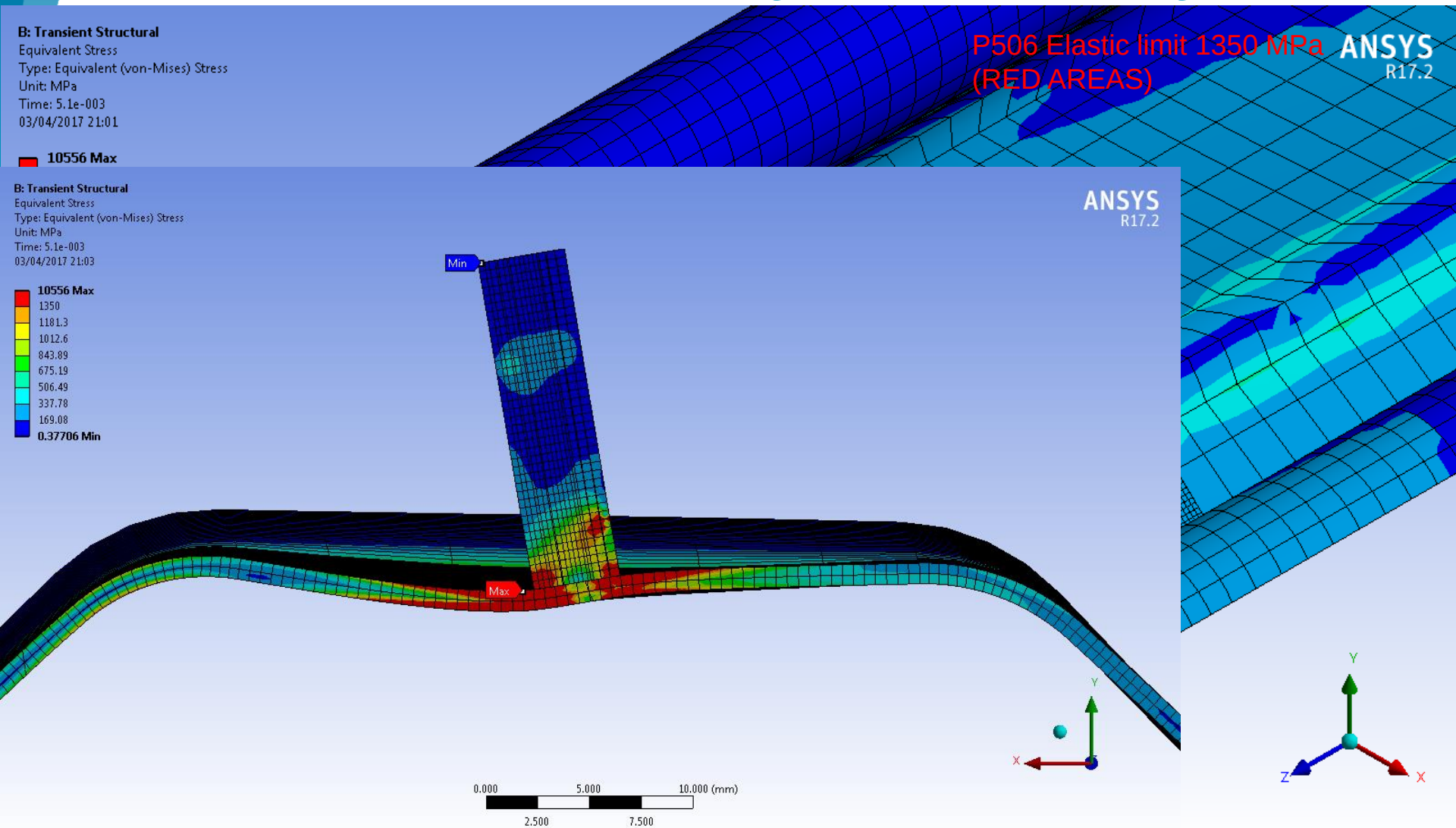
Q2 beam screen during the CLIQ discharge



Q1 beam screen during the CLIQ discharge



Q1 beam screen during the CLIQ discharge

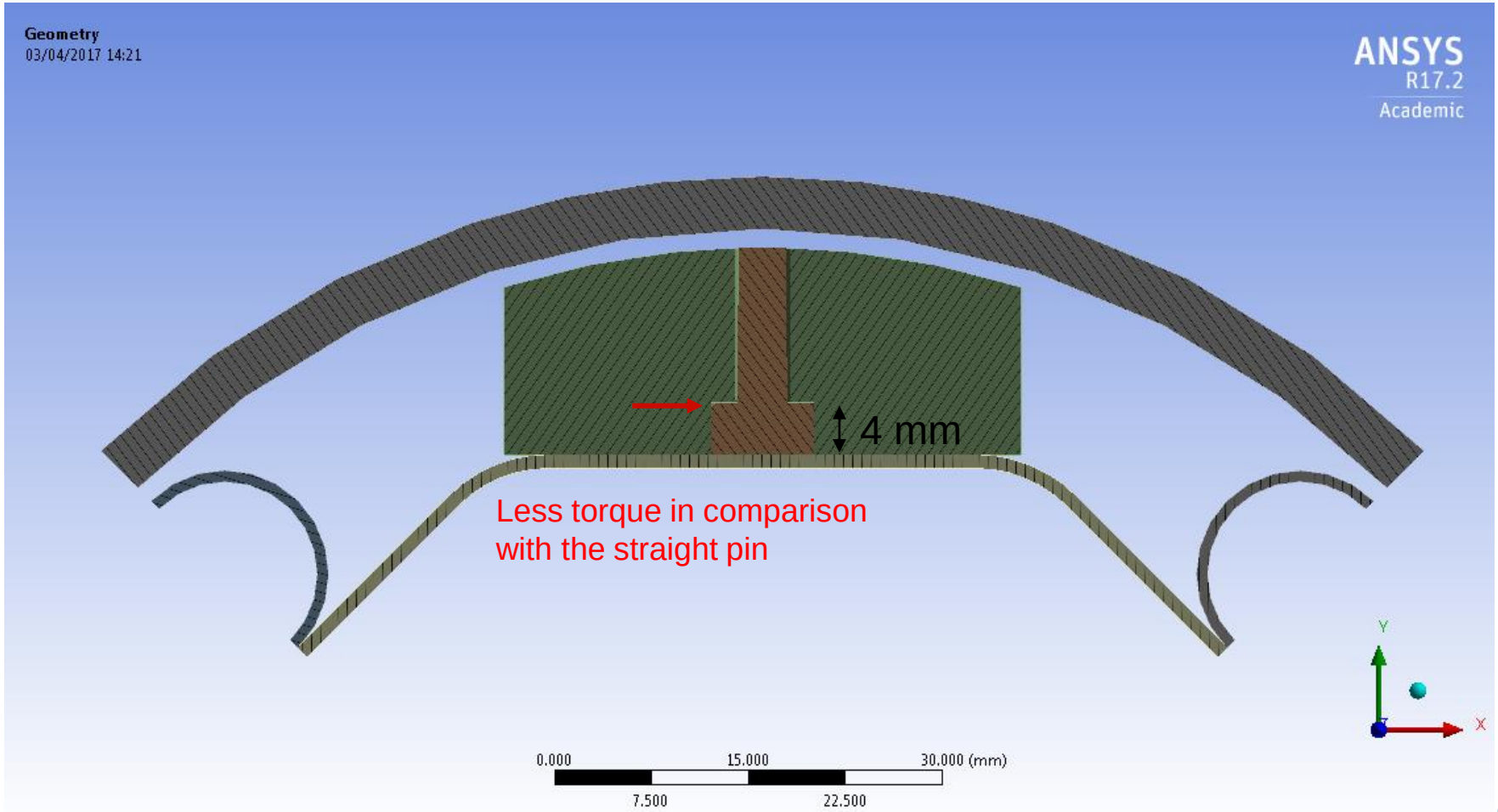


The original design of the beam screen does not withstand the effects of the CLIQ discharge without plastic deformations.

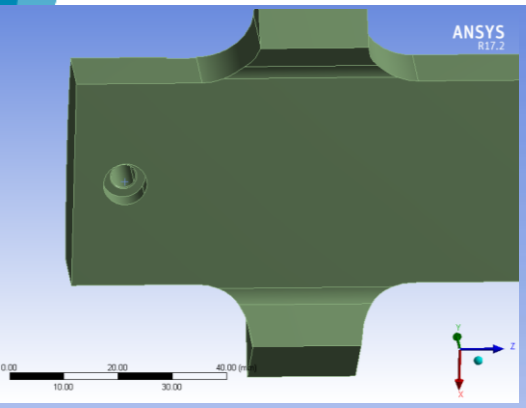
Therefore…

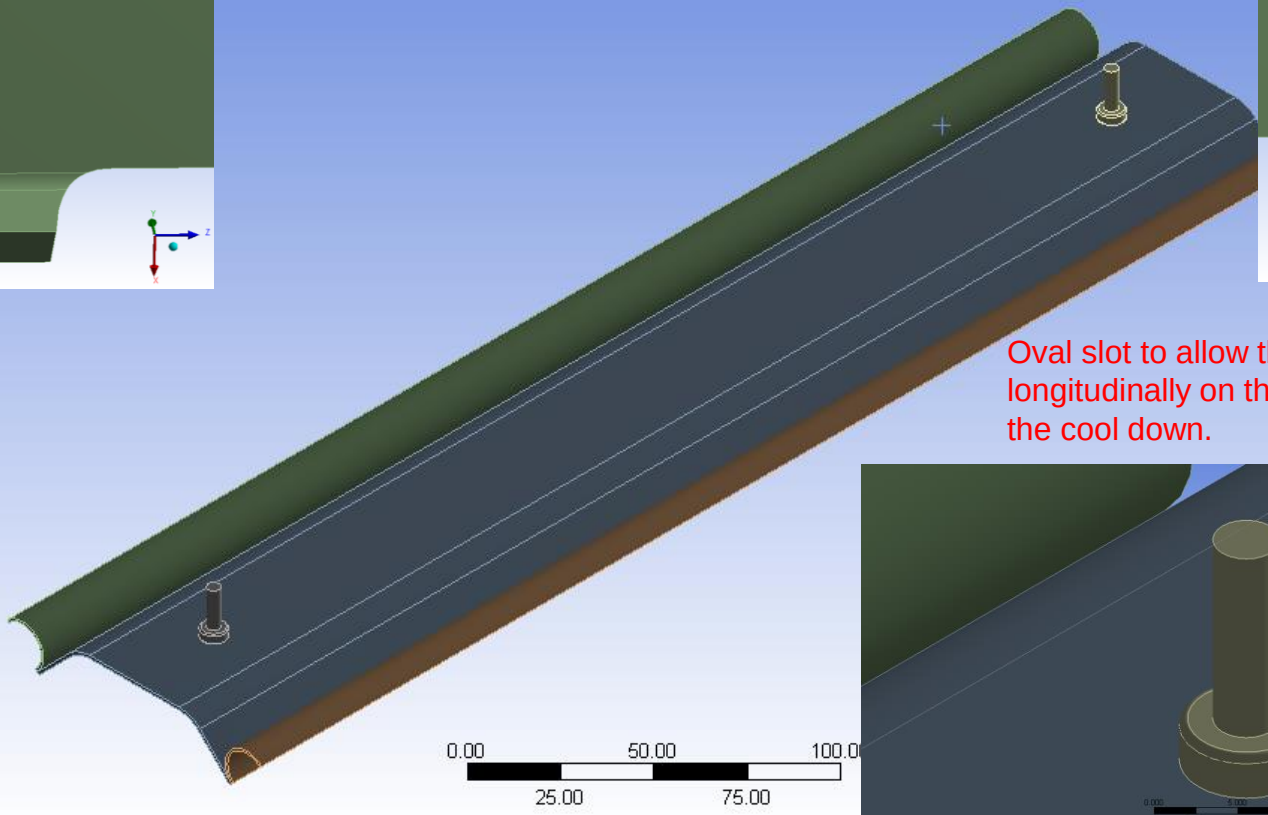
Details of the proposed beam screen design

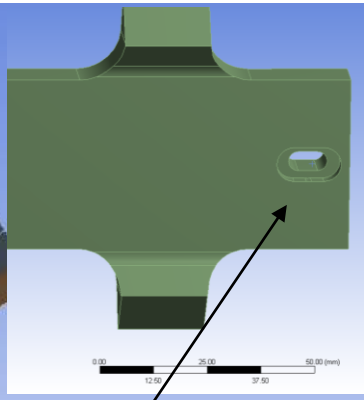
New pin concept



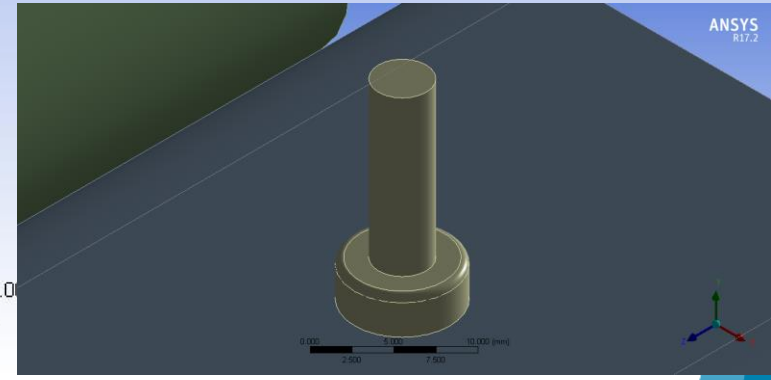
Details of the proposed beam screen design



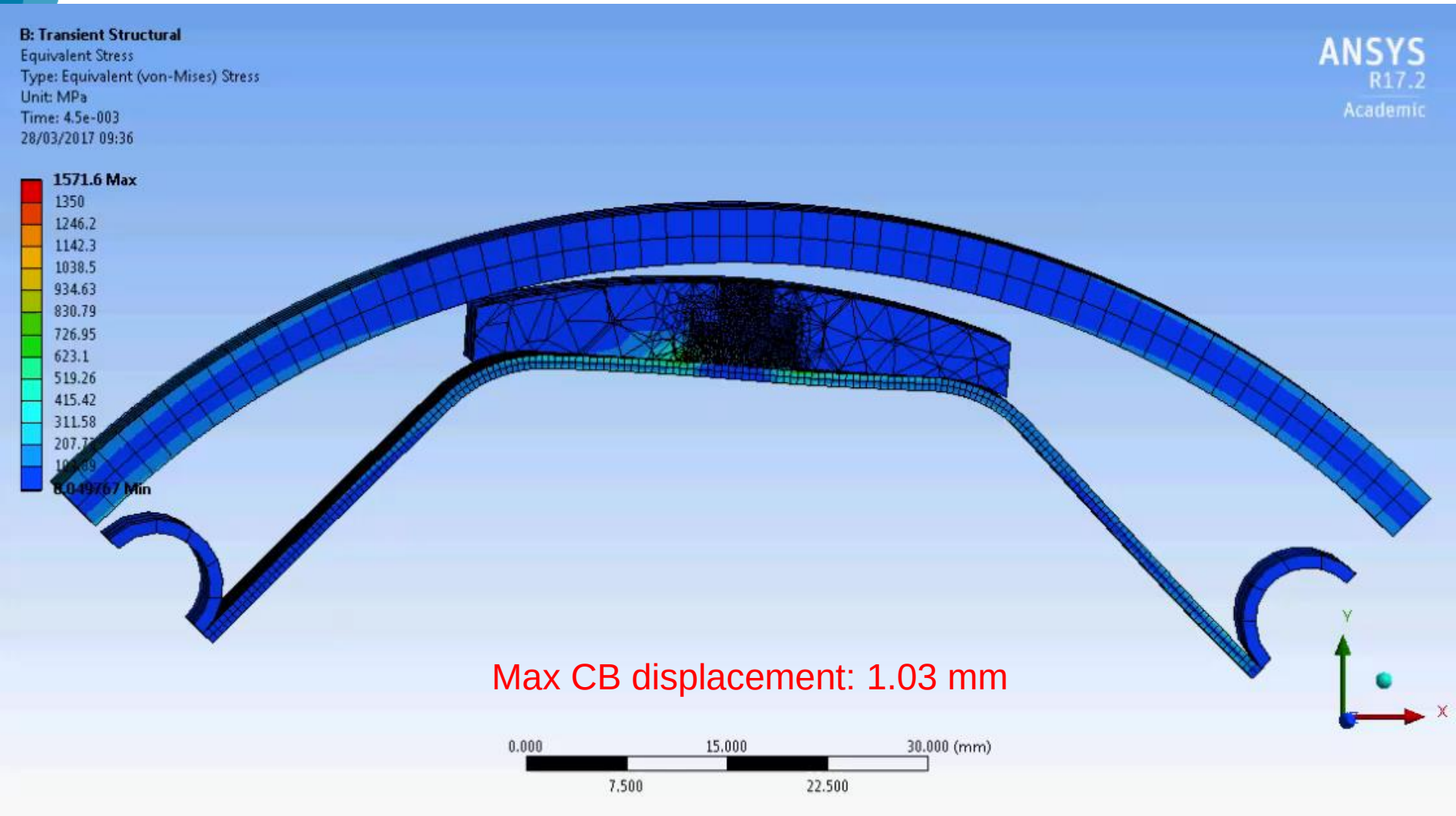




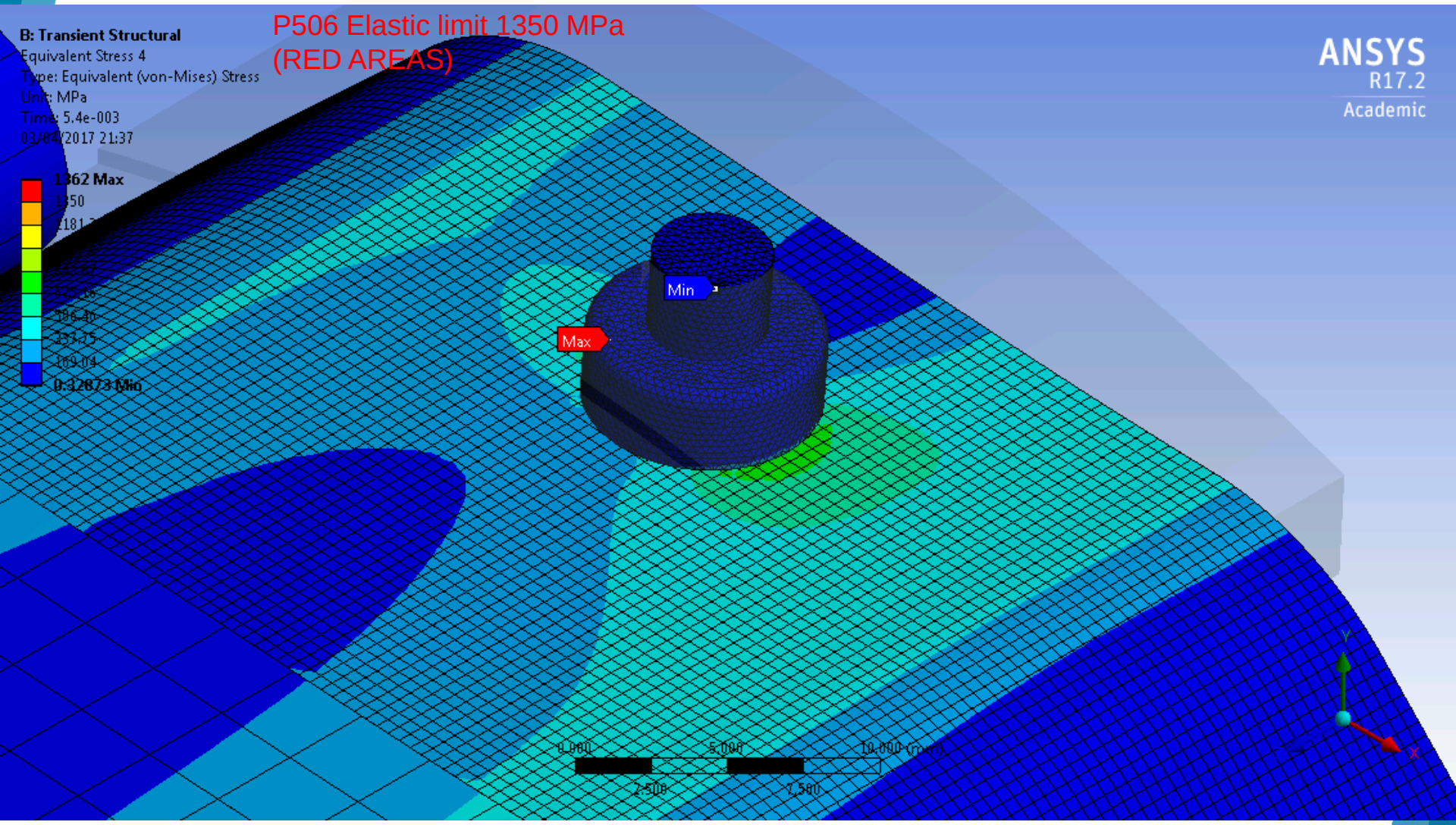
Oval slot to allow the heat absorber to slide longitudinally on the beam screen during the cool down.



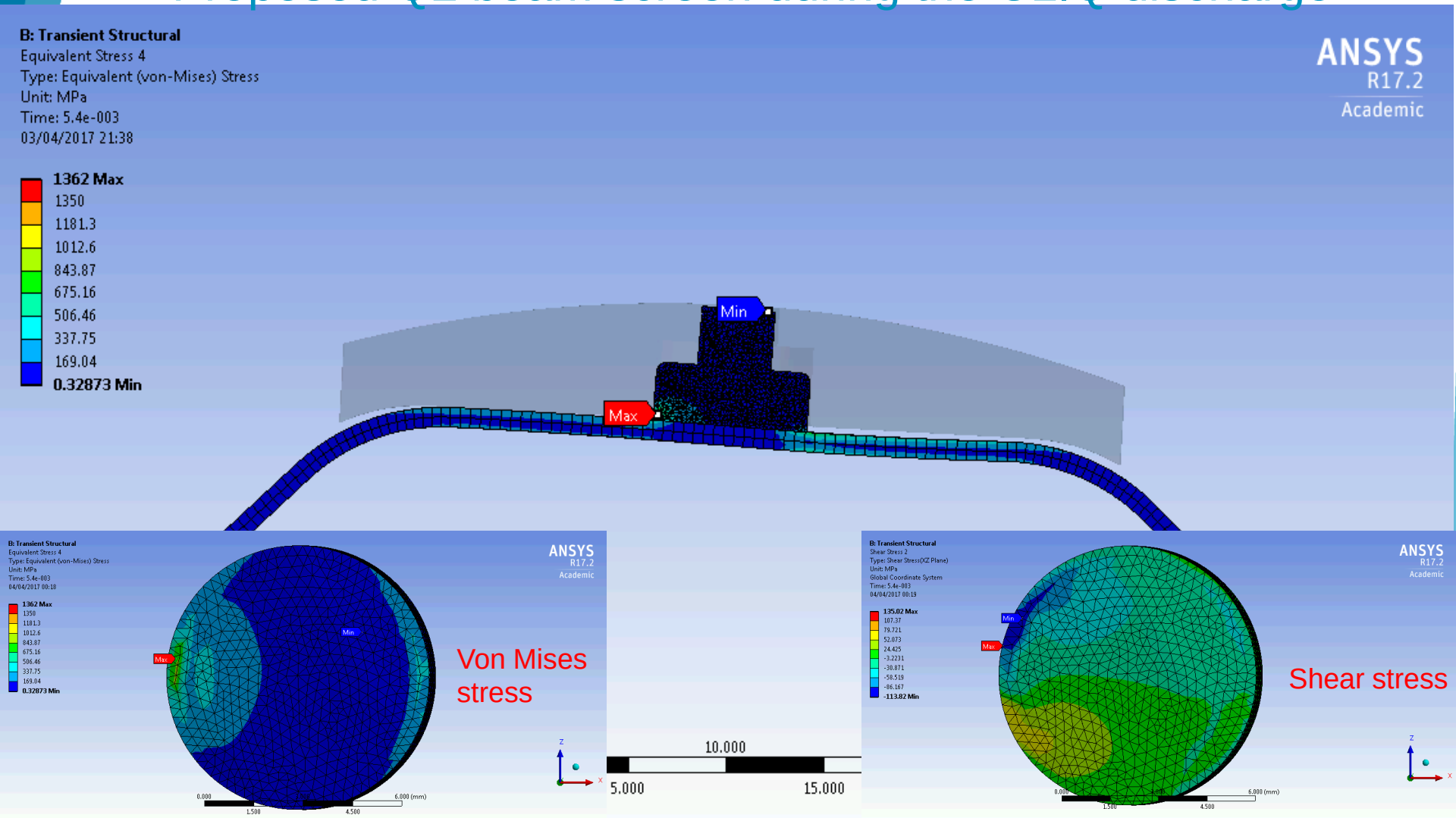
Proposed Q2 beam screen during the CLIQ discharge



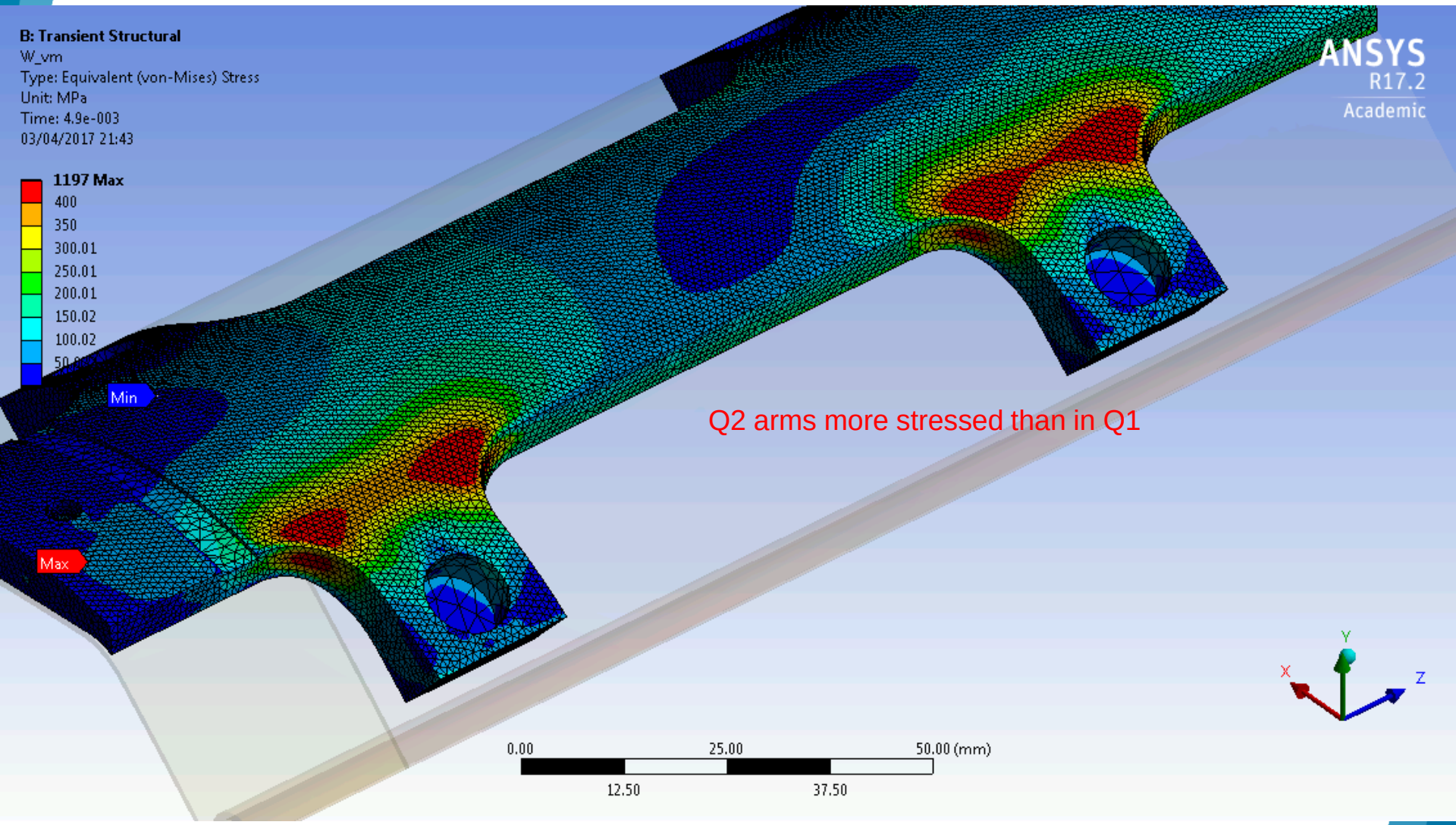
Proposed Q2 beam screen during the CLIQ discharge



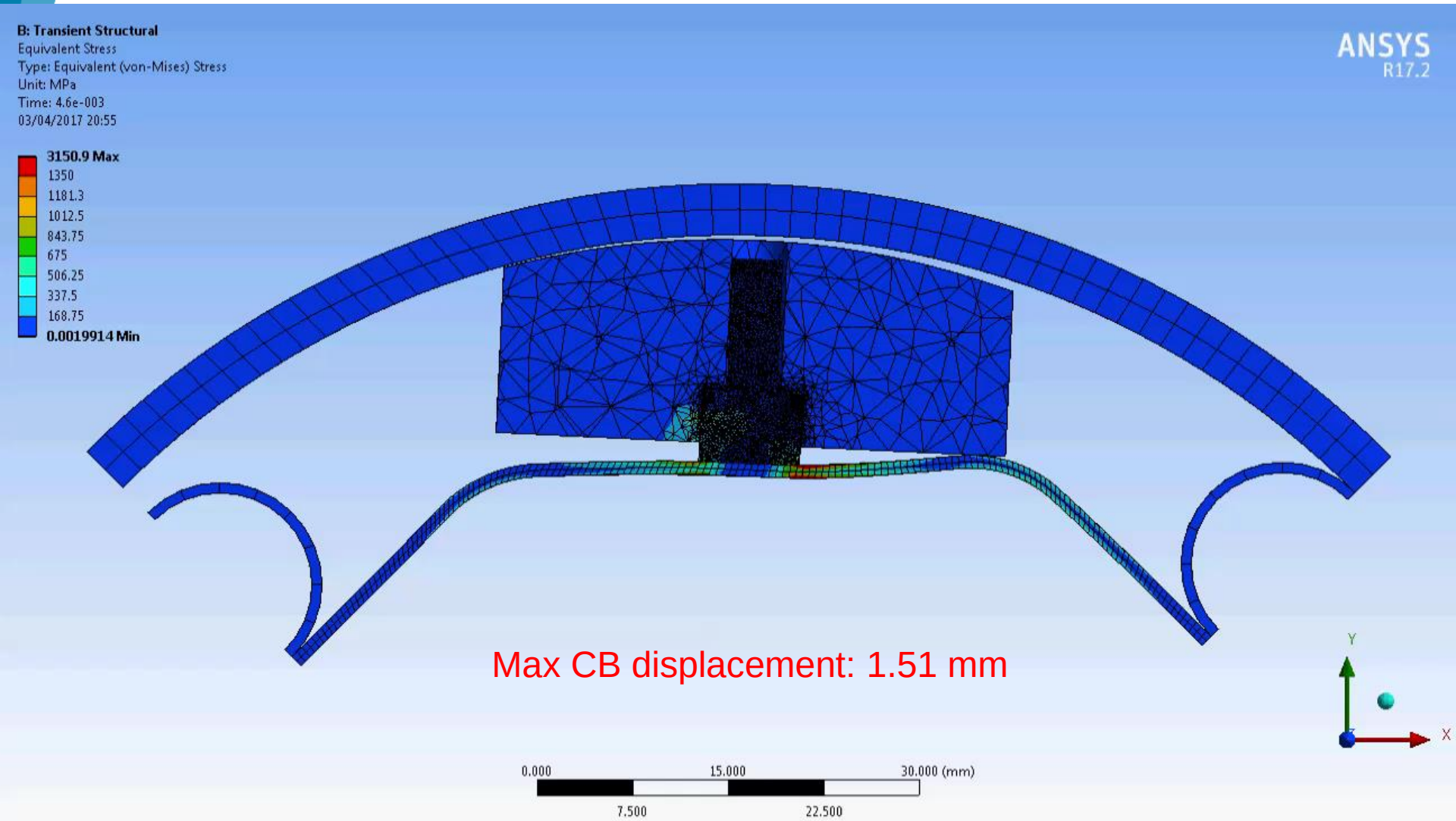
Proposed Q2 beam screen during the CLIQ discharge



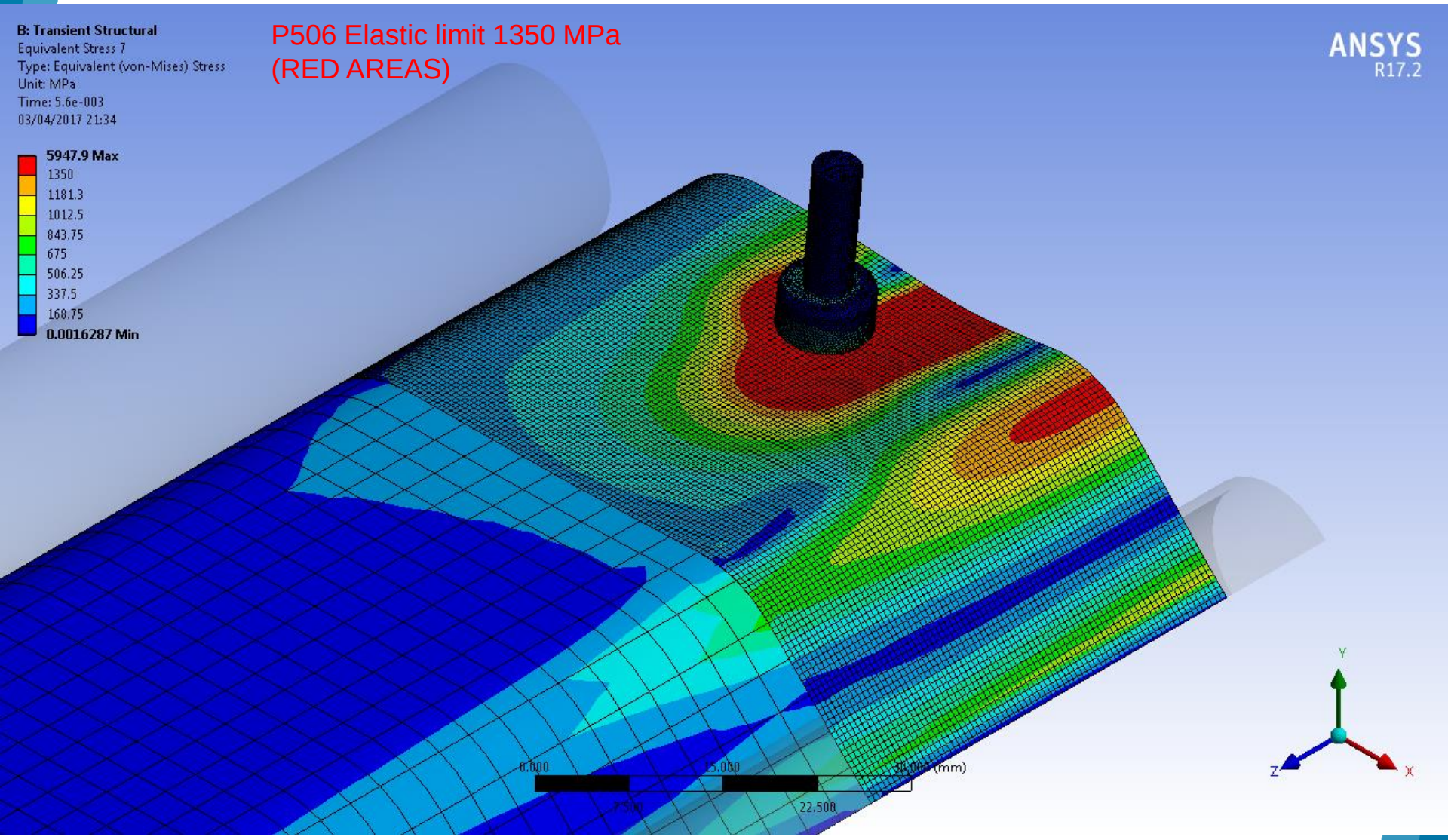
Proposed Q2 beam screen during the CLIQ discharge



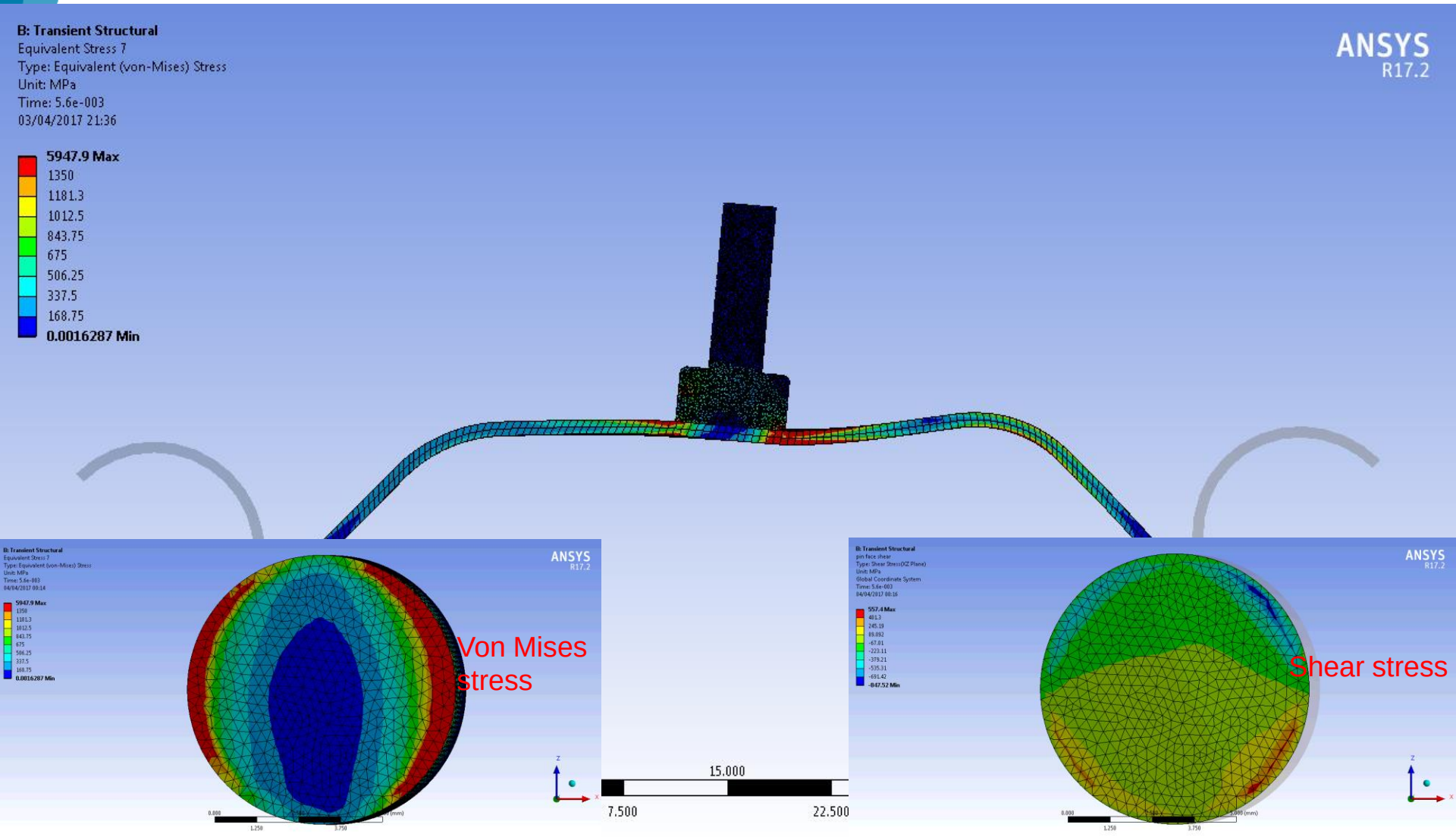
Proposed Q1 beam screen during the CLIQ discharge



Proposed Q1 beam screen during the CLIQ discharge_v1



Proposed Q1 beam screen during the CLIQ discharge_v1



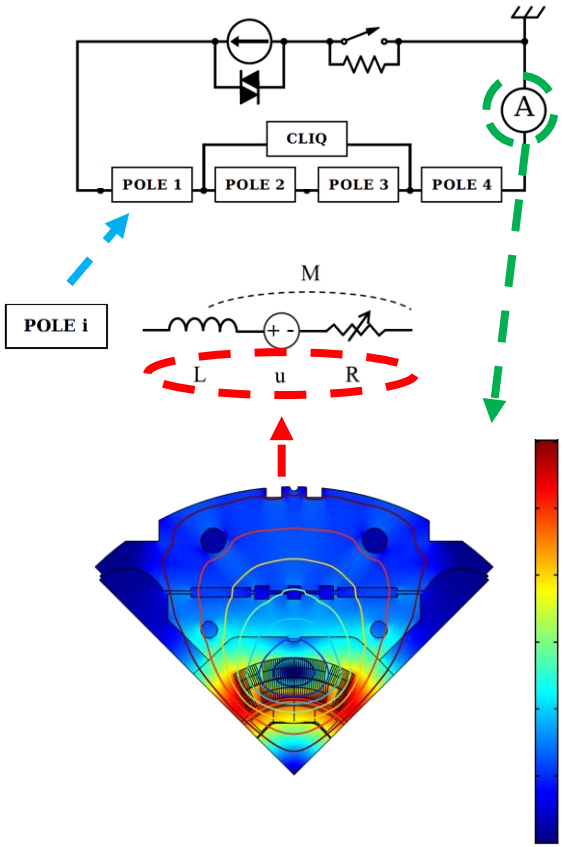
Multiphysics model 2

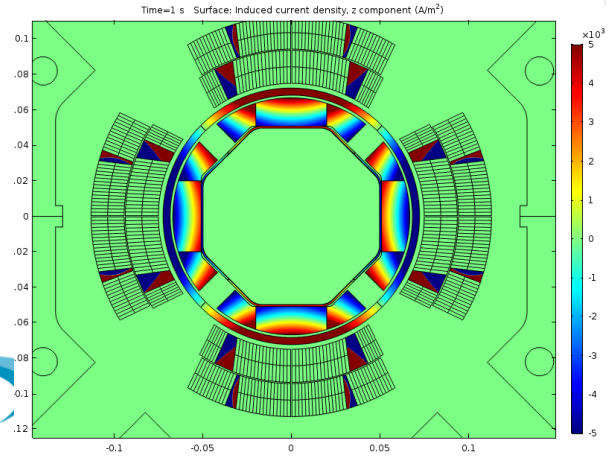
FEM governing equations

Magnetic Vector Potential + Thermal Balance Equation

The model accounts for

1. **Saturation** $\bar{B}(\bar{H})$
2. **Magneto-thermal properties** $C_p(T,B,..)$ $k(T,B,..)$
3. **Coil electrodynamics (equivalent $\bar{M}$)** IFCC ISCC
4. **Quench transition** Q_{Joule}
5. **Eddy currents in conductive domains** J_{Eddy}
6. **CLIQ (Co-simulation)** CLIQ



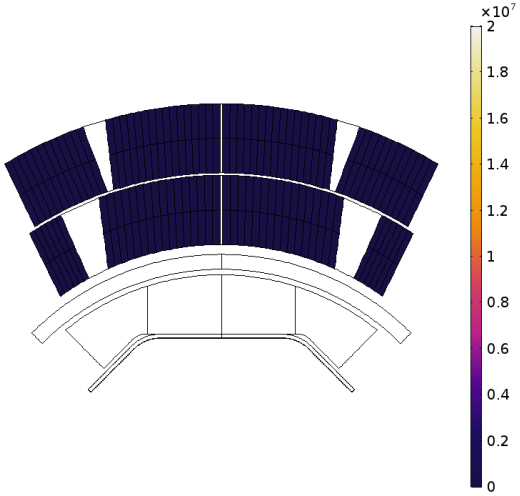


Courtesy of Lorenzo Bortot

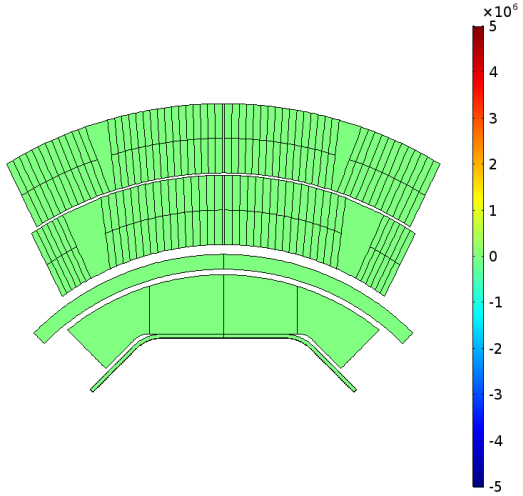
Assumptions:

CLIQ unit (40 mF, 600V) discharge in Q1 magnet, [0-30] ms

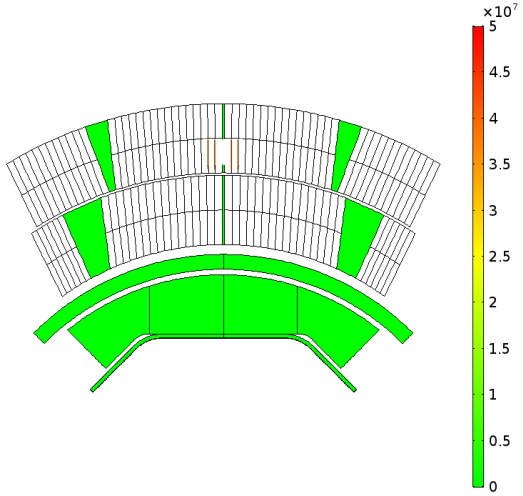
Coupling-currents losses [W/m^3]



Eddy currents [A/m^2]



Lorentz forces [N/m^3]



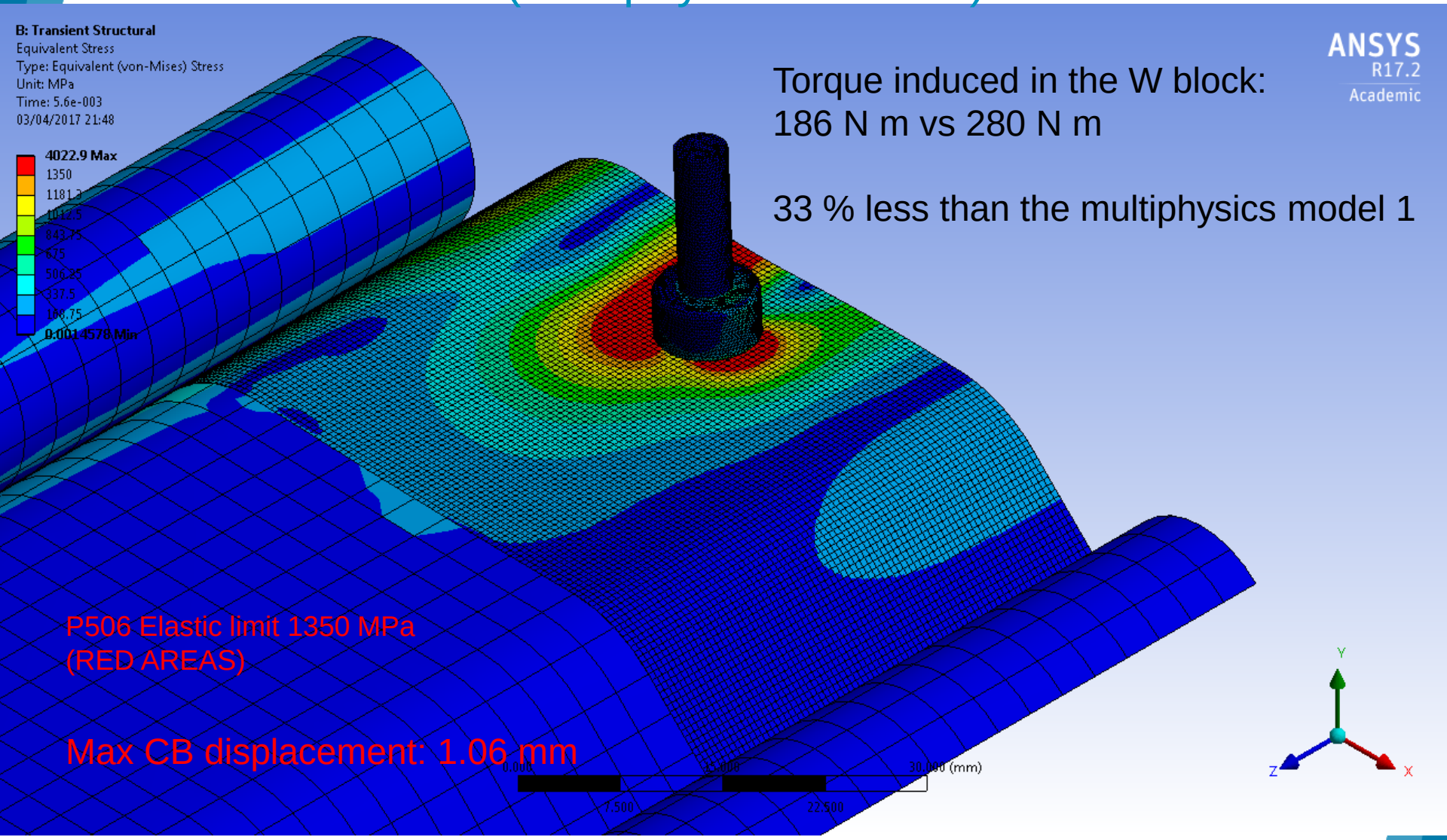
Benchmark

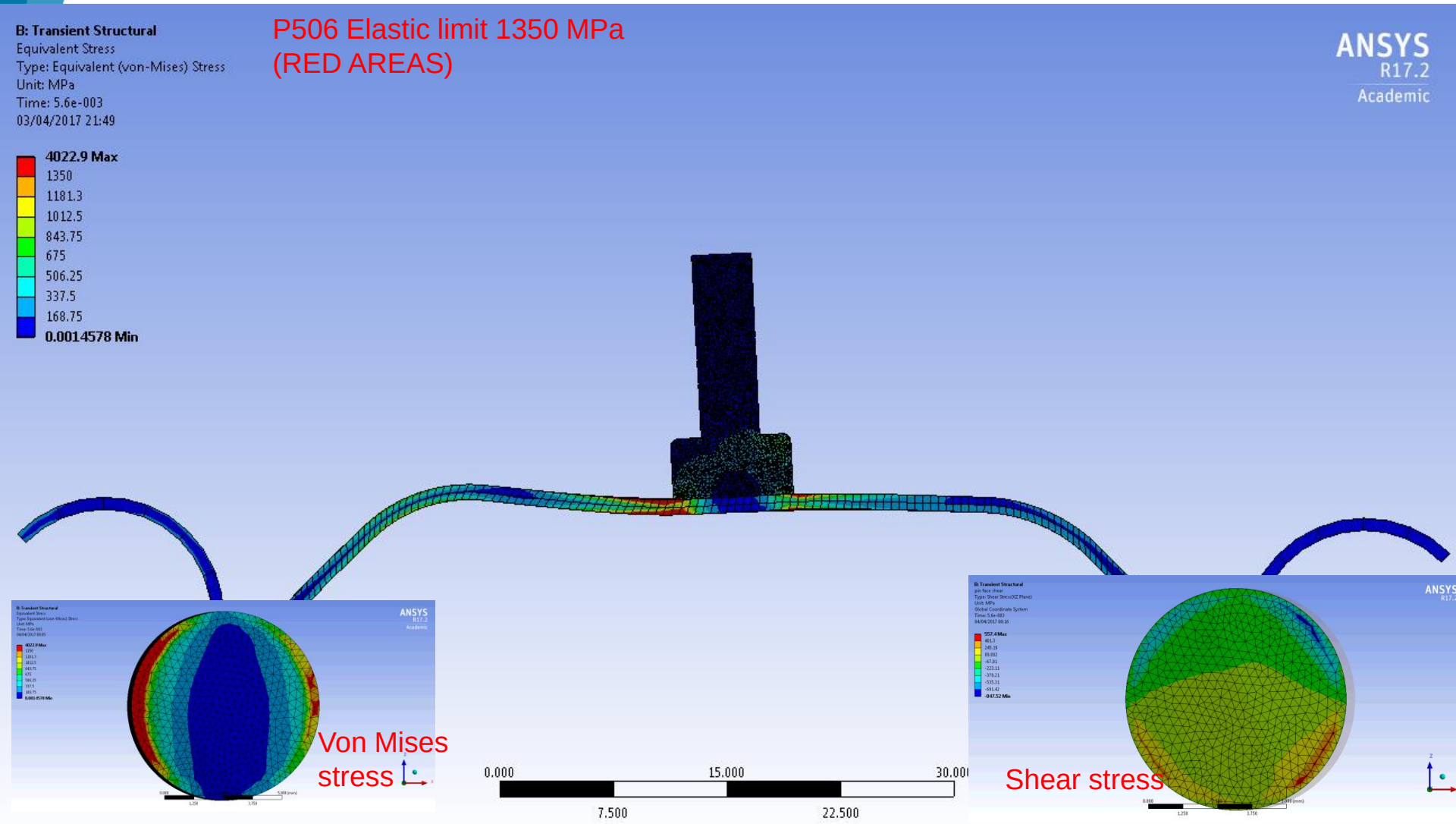
The arm of the force developing the torque according to:

multiphysics model 1→ 15.76 mm;
multiphysics model 2→ 15.72 mm.

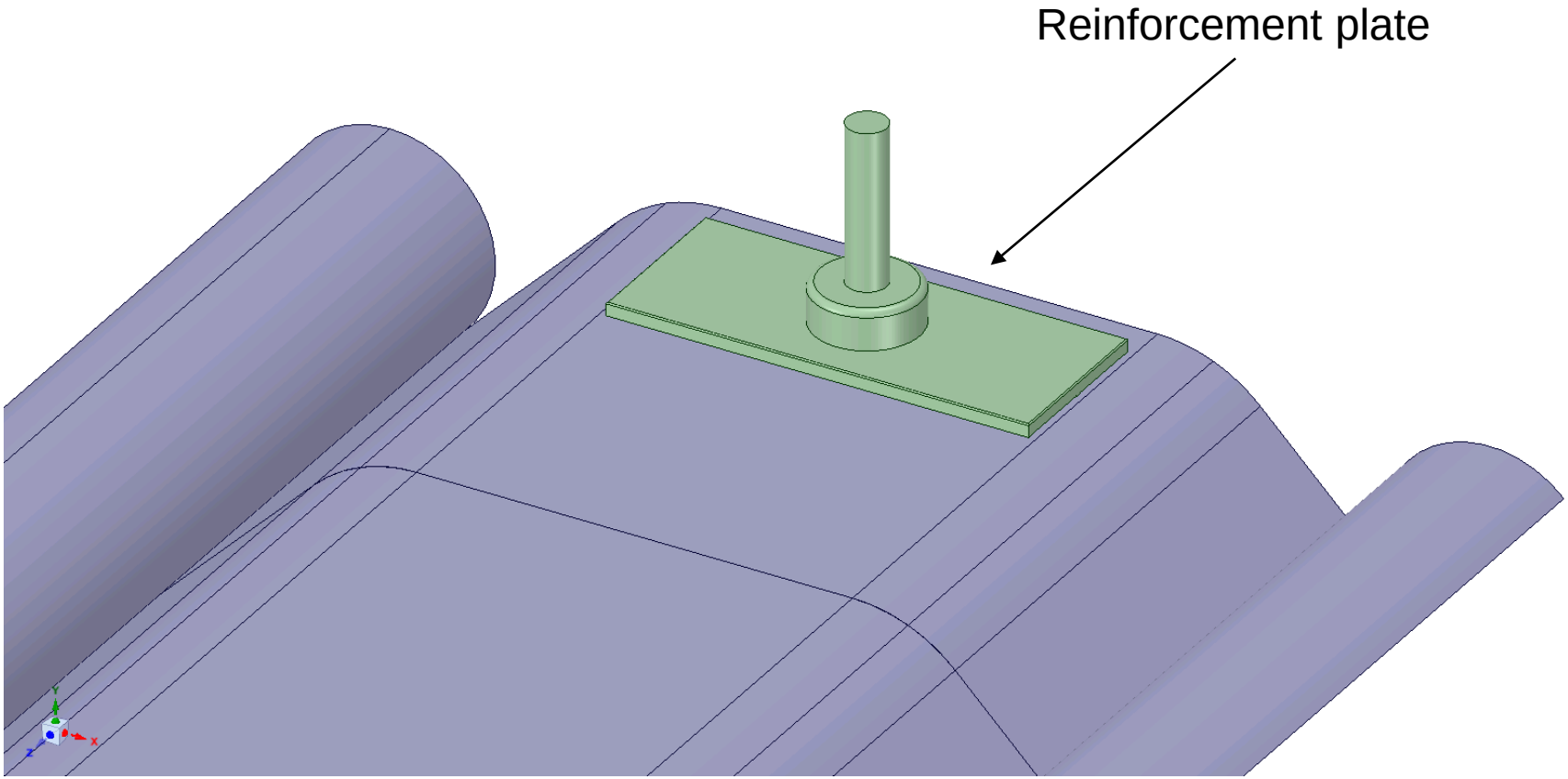
Courtesy of Lorenzo Bortot

Proposed Q1 beam screen during the CLIQ discharge (multiphysics model 2)

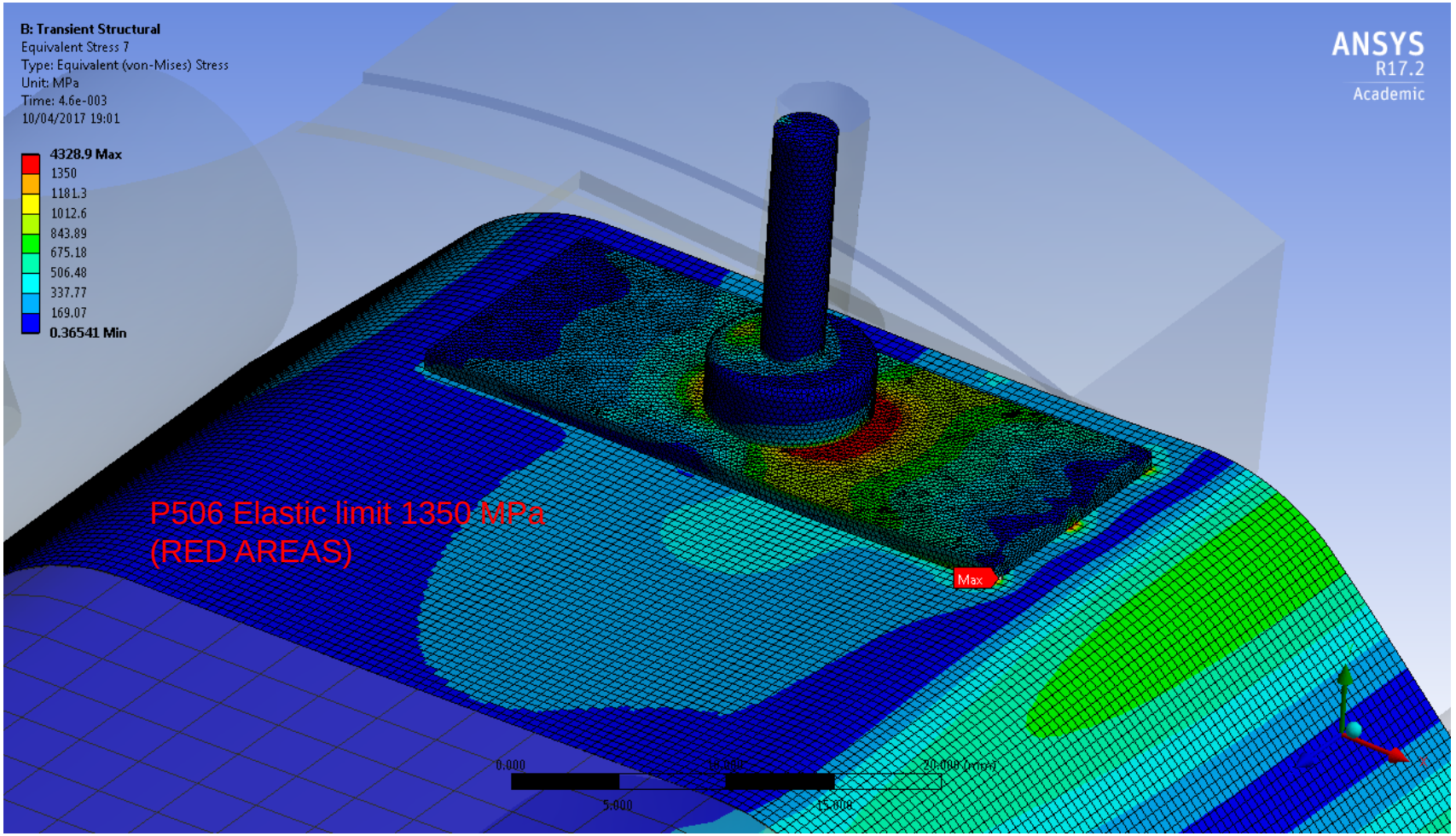



B: Transient Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 5.6e-003
03/04/2017 21:49
4022.9 Max
1350
1181.3
1012.5
843.75
675
506.25
337.5
168.75
0.0014578 Min
P506 Elastic limit 1350 MPa
(RED AREAS)
ANSYS
R17.2
Academic
Von Mises
stress
0.000
15.000
30.000
7.500
22.500
Shear stress

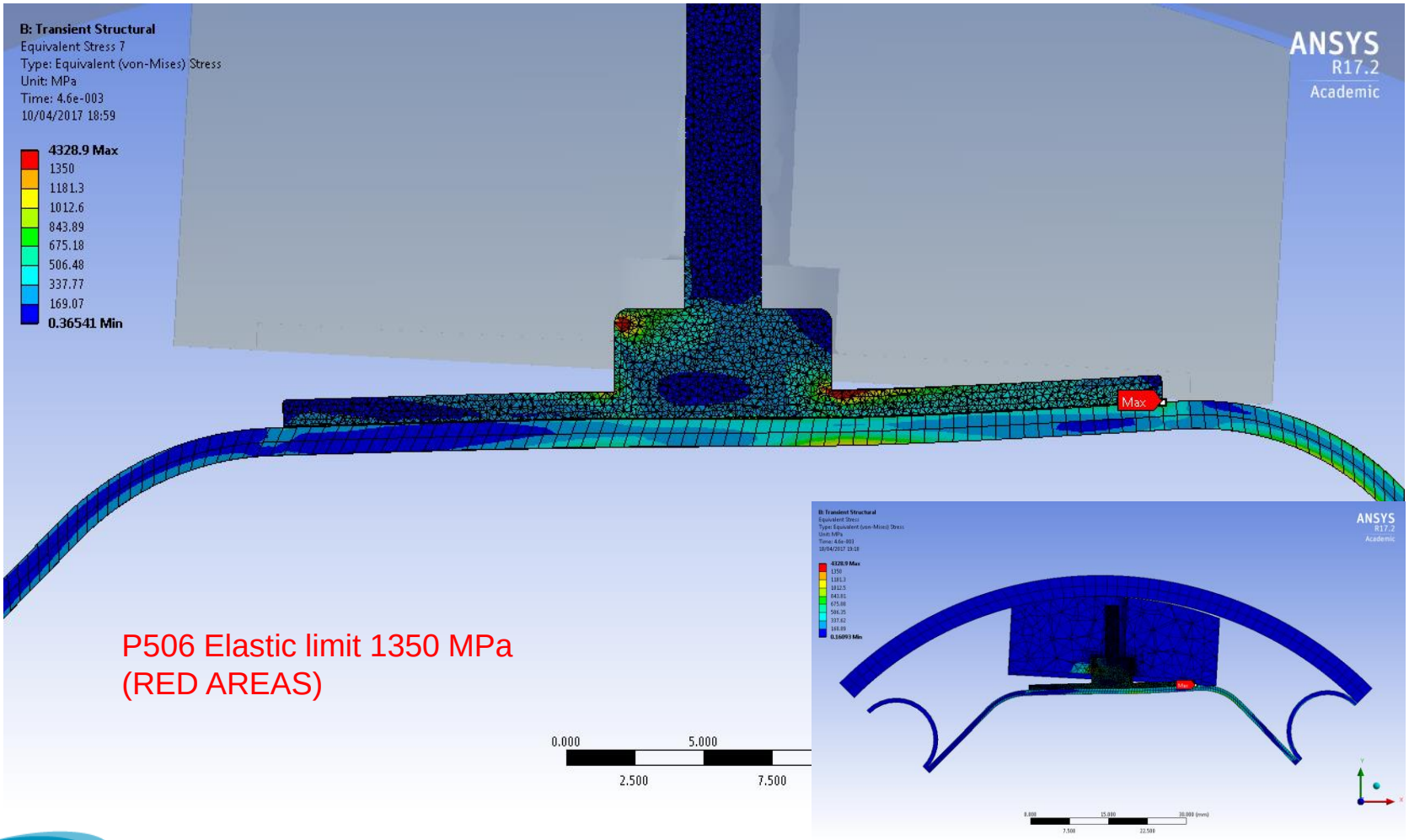
Proposed Q1 beam screen during the CLIQ discharge_v2



Proposed Q1 beam screen during the CLIQ discharge_v2

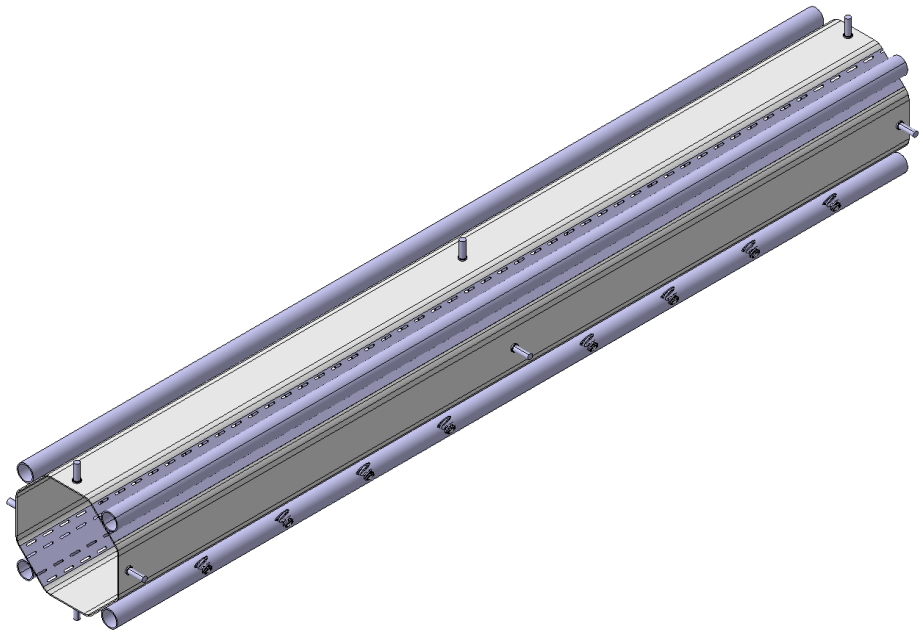


Proposed Q1 beam screen during the CLIQ discharge_v2

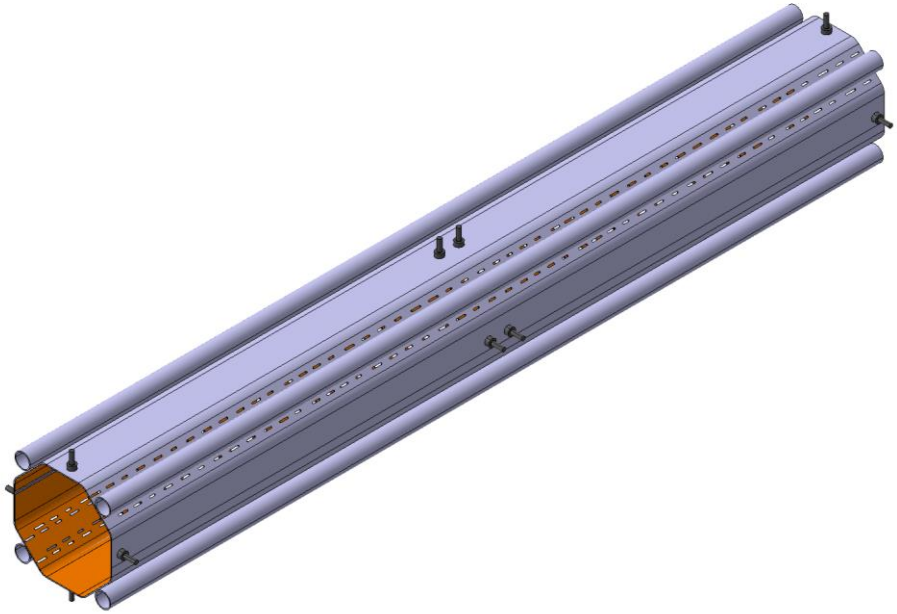


Comparison

NO CLIQ

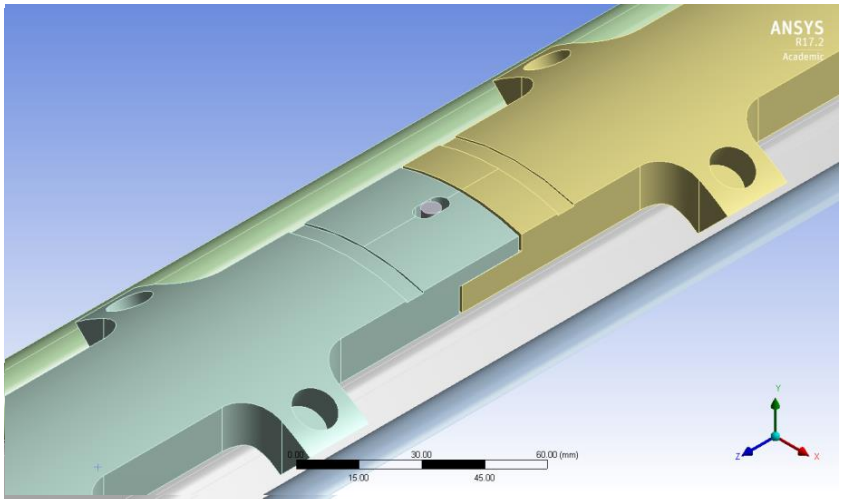


WITH CLIQ

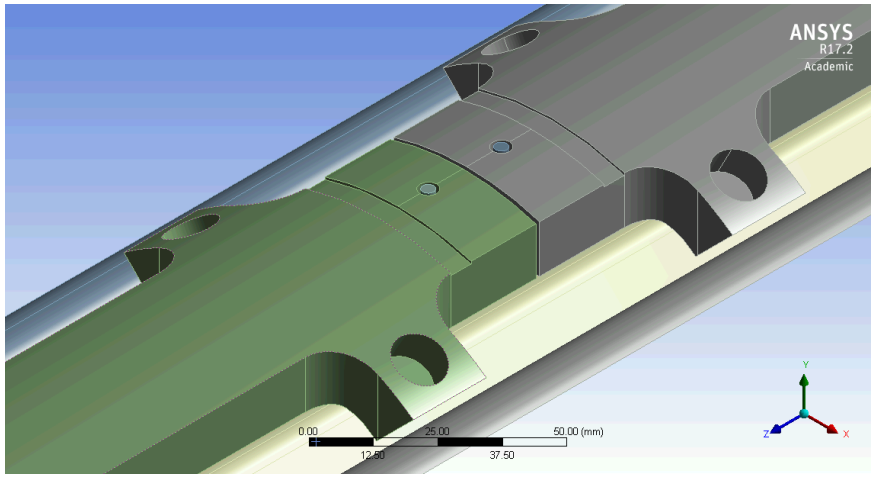


Comparison

NO CLIQ

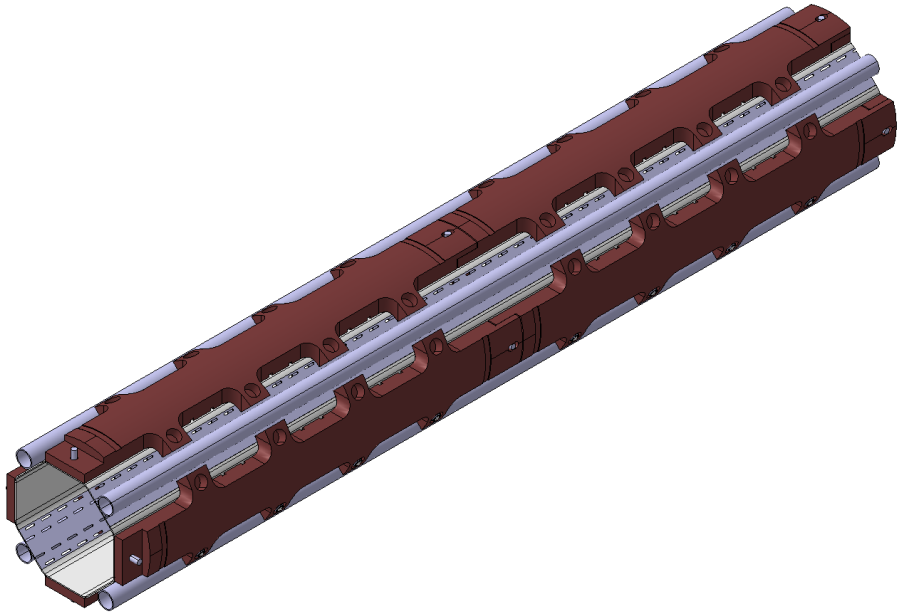


WITH CLIQ

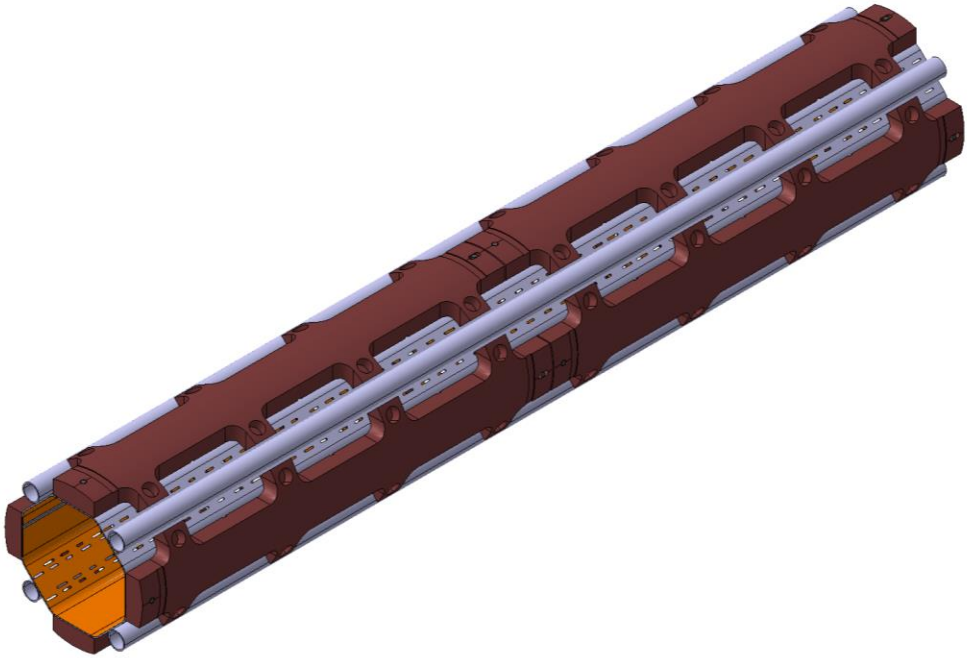


Comparison

NO CLIQ



WITH CLIQ



Comparison

No CLIQ

component	material	Elastic limit	Q1			Q2			D1		
			$F_{y\,max}$ [N/mm] -per quadrant-	σ_{max} [MPa]	δ_{max} [mm]	$F_{y\,max}$ [N/mm] -per quadrant-	σ_{max} [MPa]	δ_{max} [mm]	$F_{y\,max}$ [N/mm] -per half-	σ_{max} [MPa]	δ_{max} [mm]
Cold bore	Ss 316 LN	860 MPa (at 4 K)	58.77	523.56	0.202	61.47	389.45	0.150	30.56	280.23	0.983
Heat absorber	Inermet	1284 (at 77K)	233.46	61.19	1.703	108.27	138.34	1.650	27.94	279.51	2.472
Octagonal pipe	Ss P506	1350 Mpa (at 50 K)	4.71	469.09	0.694	9.06	548.49	0.684	5.7	423.92	2.472
Cu layer	Copper OFE	35 MPa (at 50 K)	36.99	35*	0.694	59.39	35*	0.684	48.42	35*	2.472

CLIQ phase 1

component	material	Elastic limit	Q1			Q2			Q1 (Em dynamics)		
			$F_{y\,max}$ [N/mm] -per eight-	σ_{max} [MPa]	δ_{max} [mm]	$F_{y\,max}$ [N/mm] -per eight-	σ_{max} [MPa]	δ_{max} [mm]	$F_{y\,max}$ [N/mm] -per eight-	σ_{max} [MPa]	δ_{max} [mm]
Cold bore	Ss 316 LN	860 MPa (at 4 K)	12.3	624.19	1.51	12.3	282	1.03	8.3	445	1.06
Heat absorber	Inermet	1284 (at 77K)	22	**> 1284***	-	11.3	505	-	16	1100	-
Octagonal pipe+ Cu layer	Ss P506	1350 MPa (at 50 K)	5.3	**> 1350***	-	14	950	-	3.8	**> 1350***	-
Pin	Ss P506	1350 MPa (at 50 K)	-	**> 1350***	-	-	650	-	-	**> 1350***	-

* local