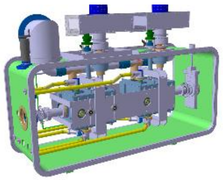
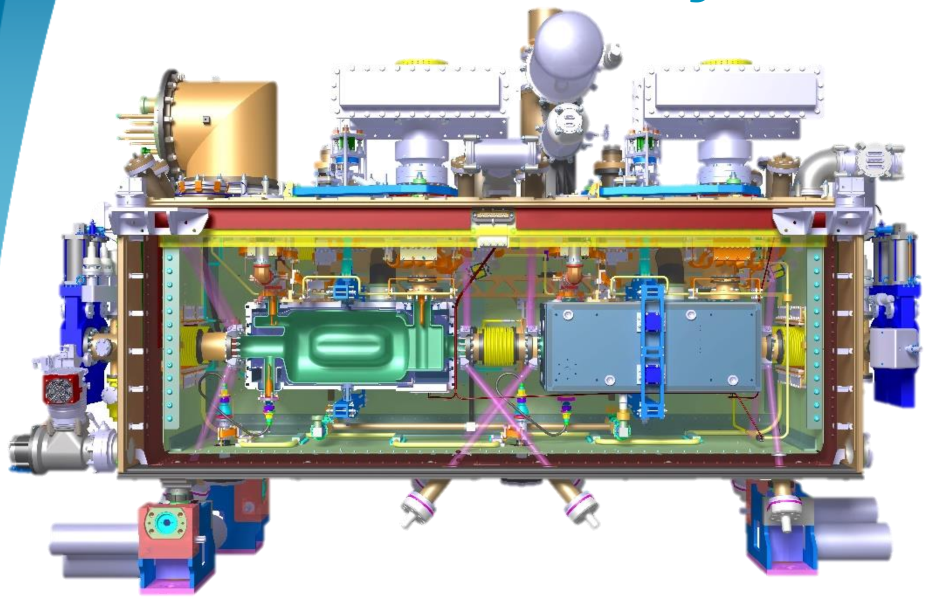
WP4-Series cryomodules design

13th HL-LHC Collaboration Meeting, CERN – 25-28 September 2023

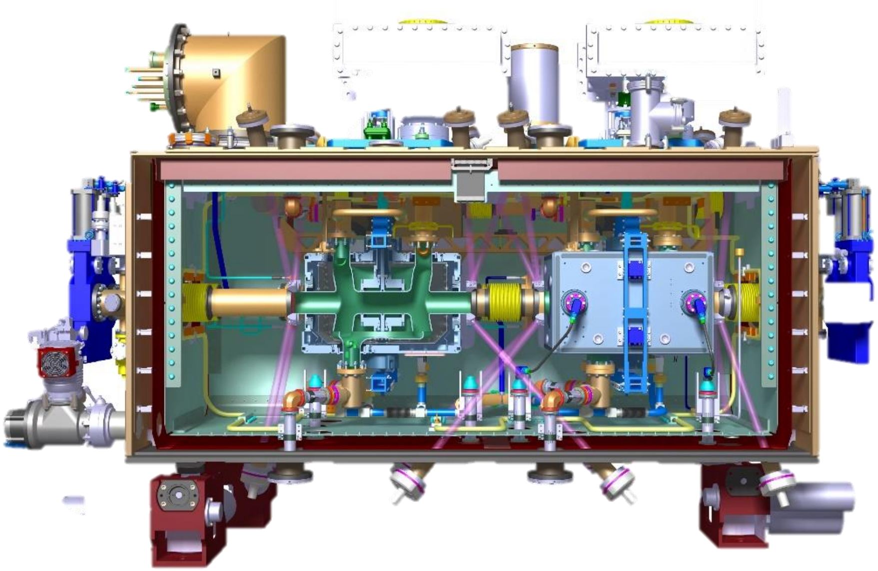
Teddy Capelli on behalf of the WP4 collaboration

LHC Cryomodules overview





- RFD Cryomodule
  - Overall dimensions (L/l/h): 3350/950/1900mm
  - Mass : ~4400kg
  - Cavities : RadioFrequency Dipole
  - HOM filters : 4 pces (2 per cavity)
  - Pick Up Antenna : 2 pces (1 per cavity)
  - Position of installation : Point 1 (Before and after ATLAS)

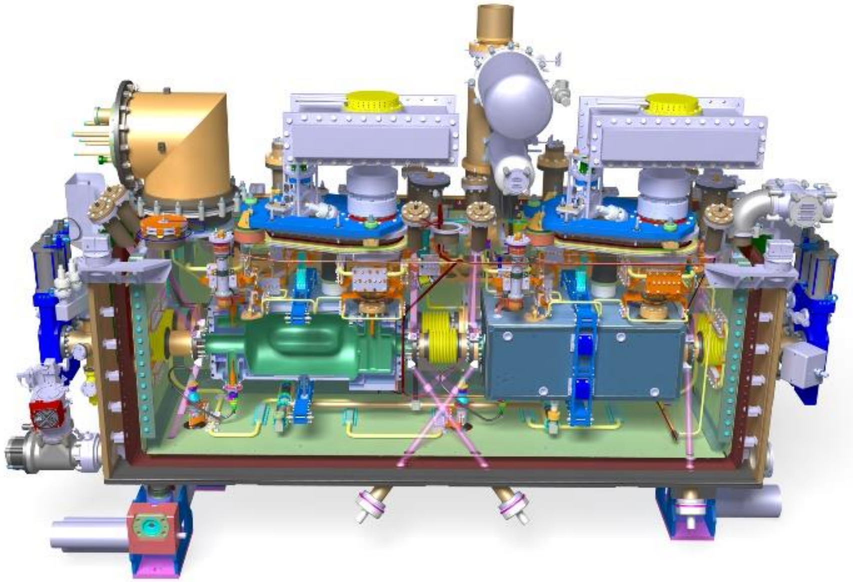


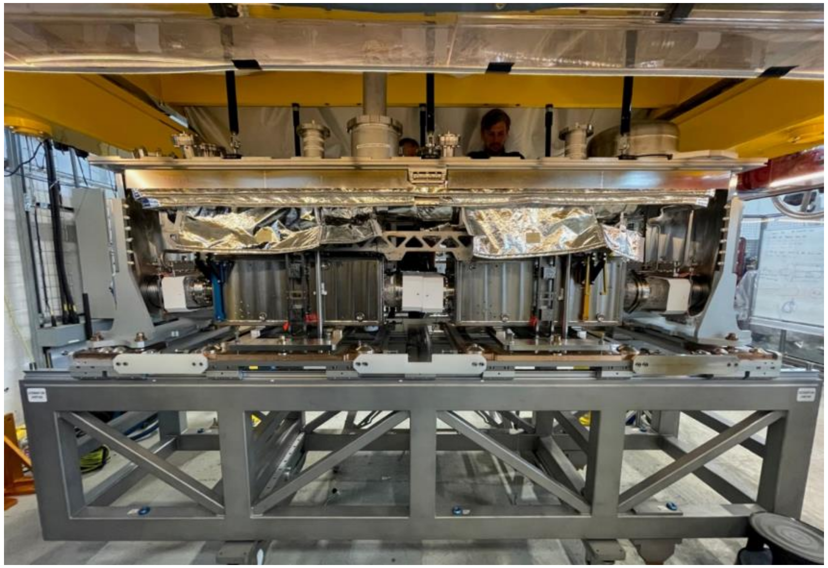
- DQW Cryomodule
  - Overall dimensions (L/l/h): 3120/1000/1800mm
  - Mass : ~4300kg
  - Cavities : Double Quarter Wave
  - HOM filters : 8 pces (4 per cavity)
  - Pick Up Antenna : 2 pces (1 per cavity)
  - Position of installation : Point 5 (Before and after CMS)

Overview of cryomodule design updates

- Detailed design and simulation for DQW/LHC cryomodule
- New input imposing a modification of the design of both DQW and RFD cryomodules
- Optimisation of the design integrating the feedback from RFD cryomodule
  - Feedback provided by STFC on RFD assembly :
    - Clean room
    - String assembly
    - MLI design and installation

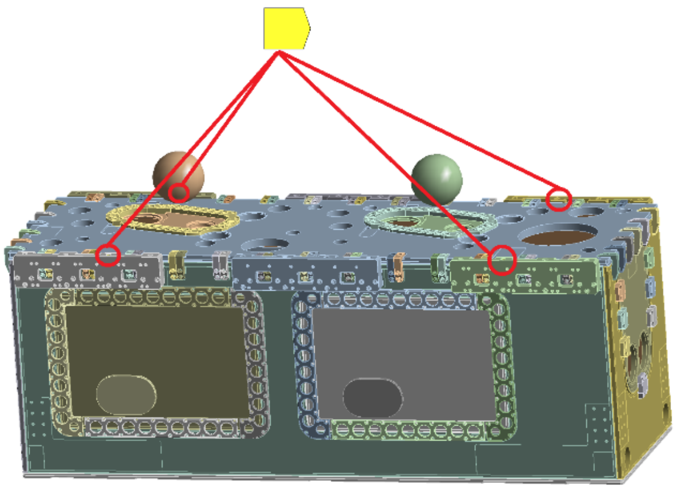
see presentations of N.Templeton & E.Jordan

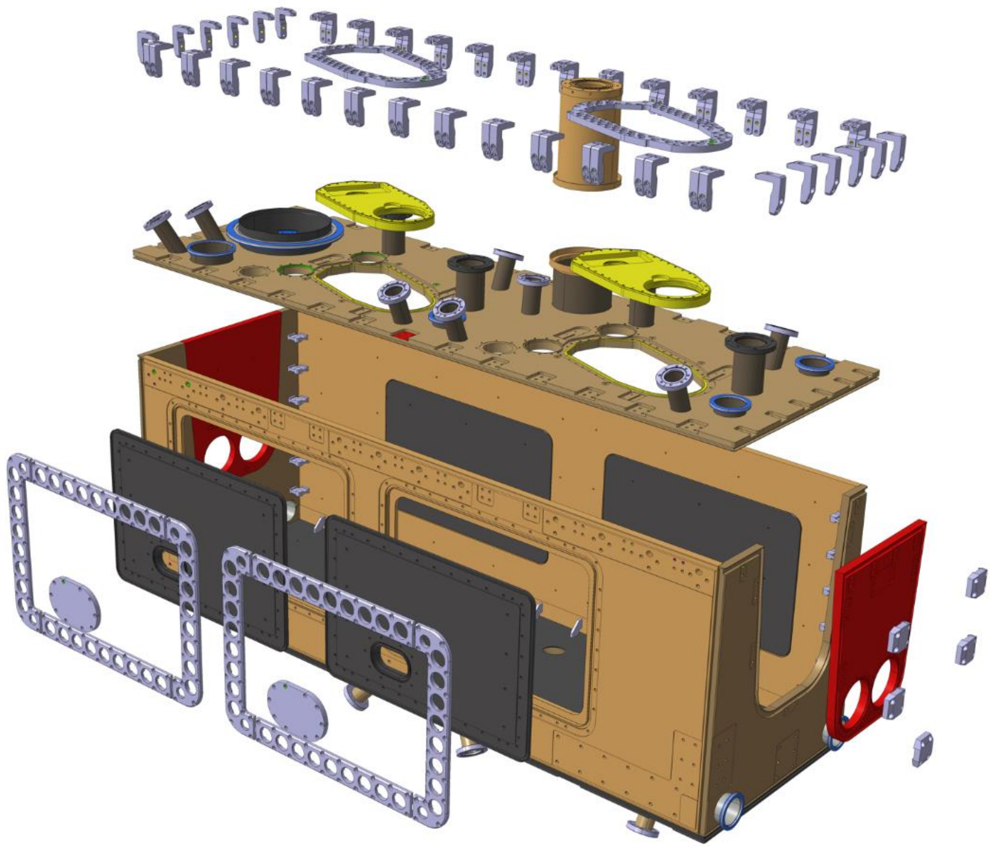




OVC updates and simulations

- Design optimization for mechanical performances and new interfaces needed for LHC
- Simulations :
  - Operation and transport load cases check
  - Overall buckling check
  - Bolted and welded joints checks

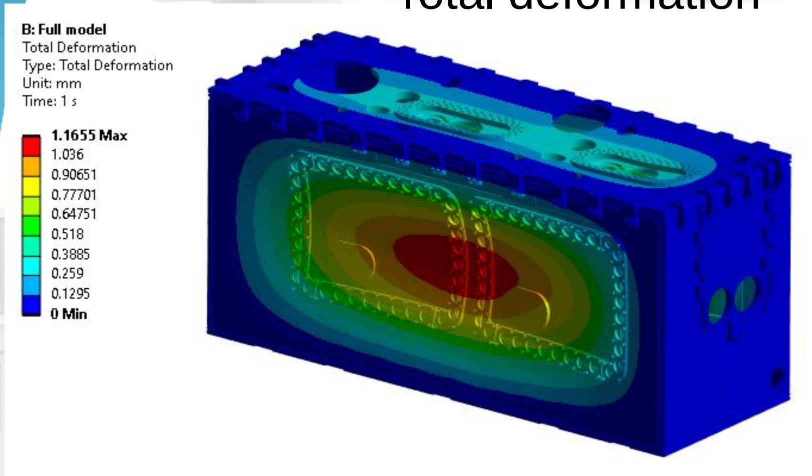




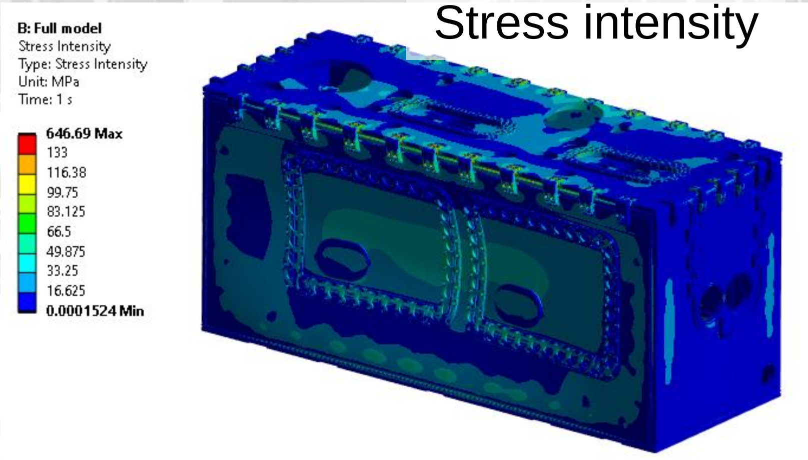
DQW OVC simulations

- Load case : Normal operation
- Vacuum inside / Atmospheric pressure outside
- The overall deformation impact cavity alignment

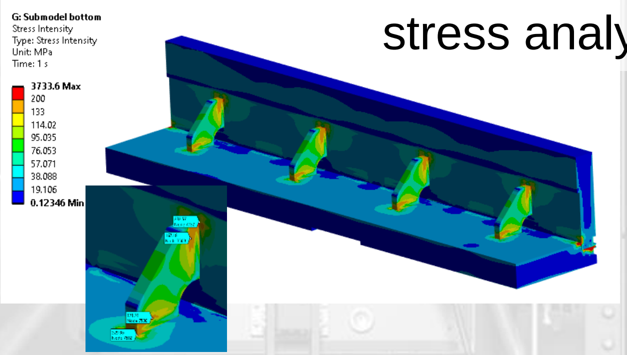
Total deformation

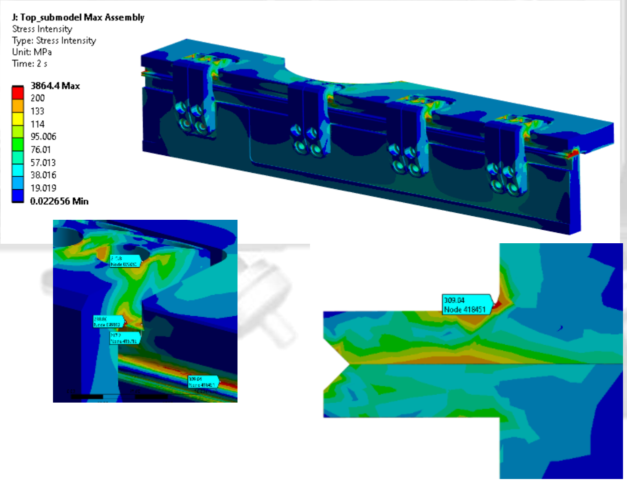


Stress intensity



Sub modelling for stress analysis

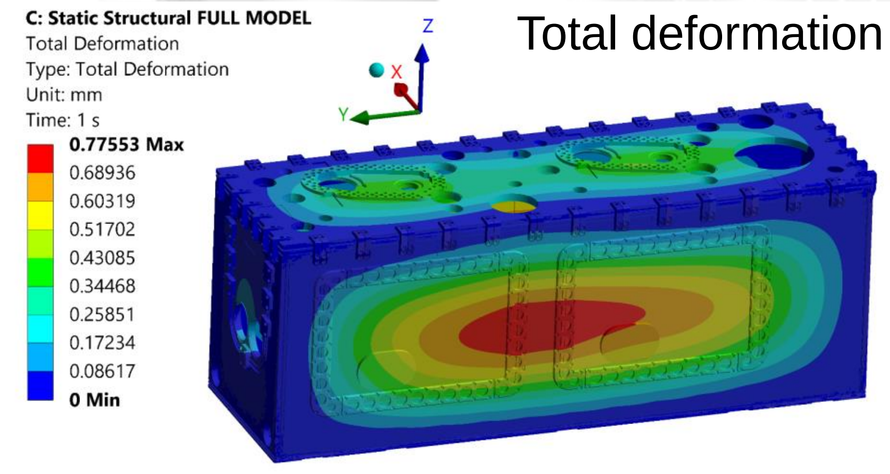




OVC strength assessment :
See EDMS 2920955 - DQW vacuum vessel strength assessment
Courtesy T. Hernandez – E.Cano Pleite

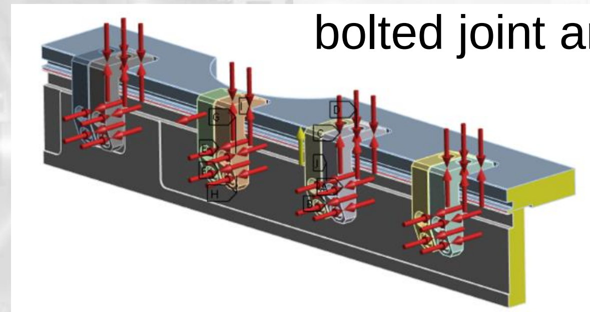
RFD OVC simulations

Total deformation

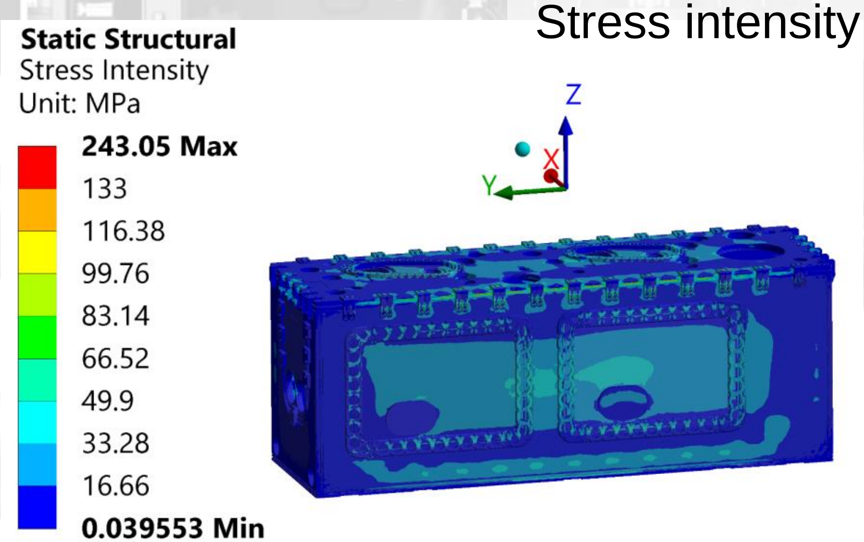


- Load case : Normal operation
- Vacuum inside / Atmospheric pressure outside
- The overall deformation impact cavity alignment

Sub modelling for bolted joint analysis



Stress intensity



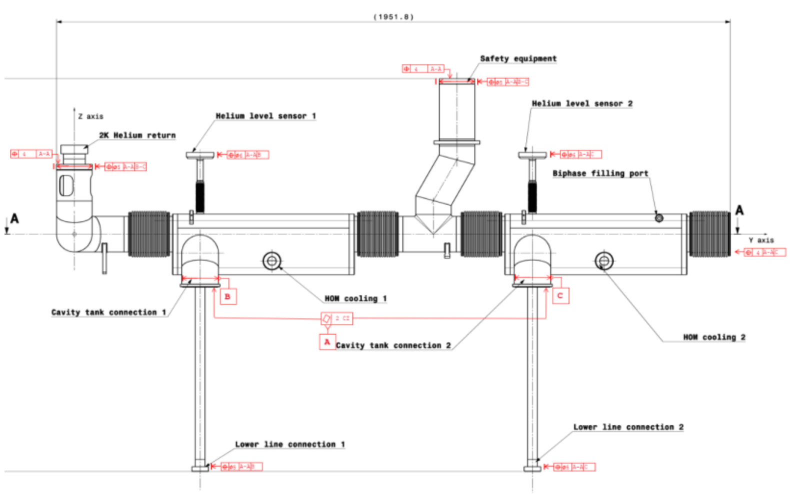
Worst bolt (combination of maximum axial, bending, shear, torsional)

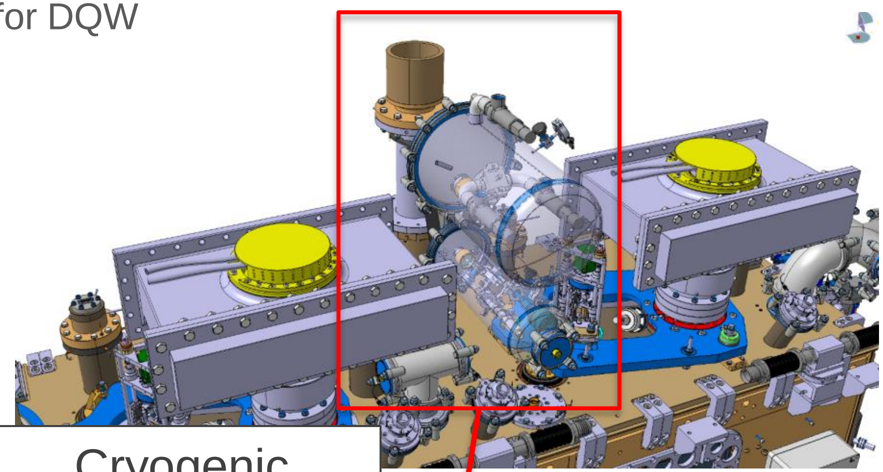
Conditions	Preload [N]	Axial Force [N]	Bending moment [N·mm]	Torsional moment [N·mm]	Shear force [N]	Safety factor
Frictional	22600	22719	9250.7	512.3	2016.8	1.3

OVC strength assessment :
See EDMS 2272855 - RFD vacuum vessel strength assessment
Courtesy T. Hernandez – E.Cano Pleite

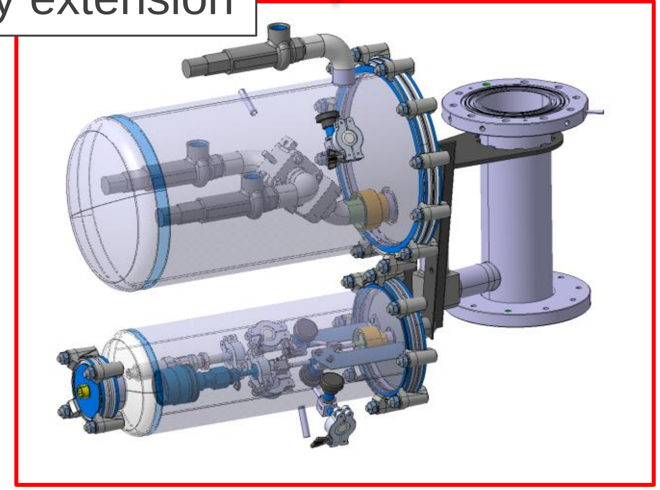
Cryogenic for series cryomodules

- Design and drawing for manufacturing for DQW cryogenic lines
- Detailed study of the cryogenic extension for LHC
- Definition and integration of cryogenic instrumentation for DQW cryomodule
- Update RFD drawing with feedback from RFD/SPS
  - Minor geometry changes
  - Material specification update



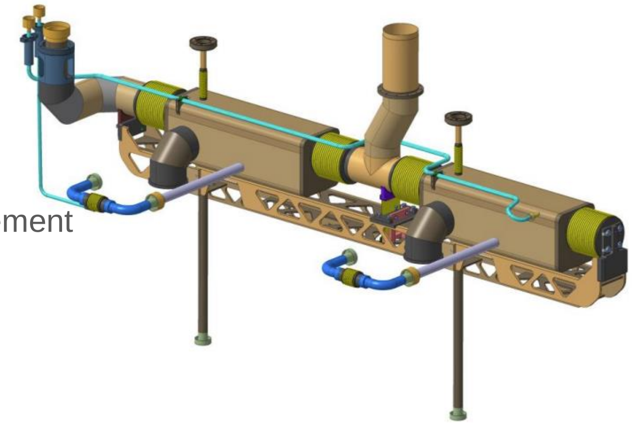


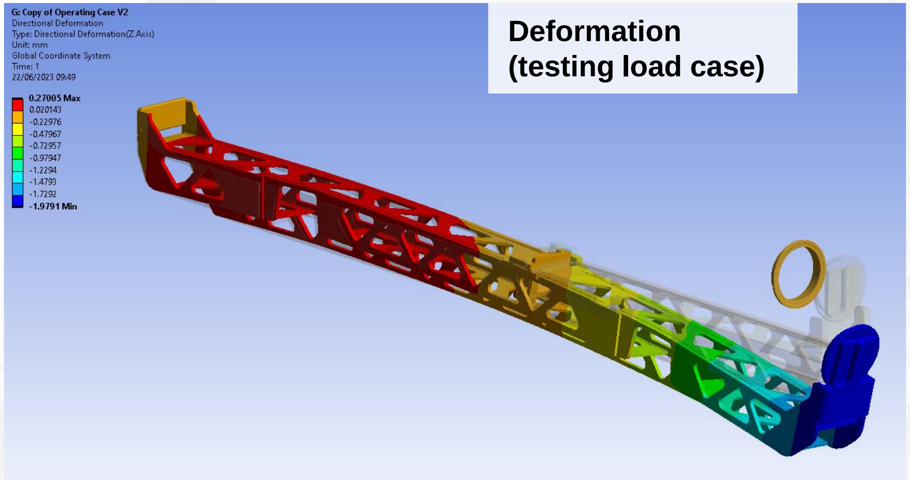
Cryogenic Safety extension



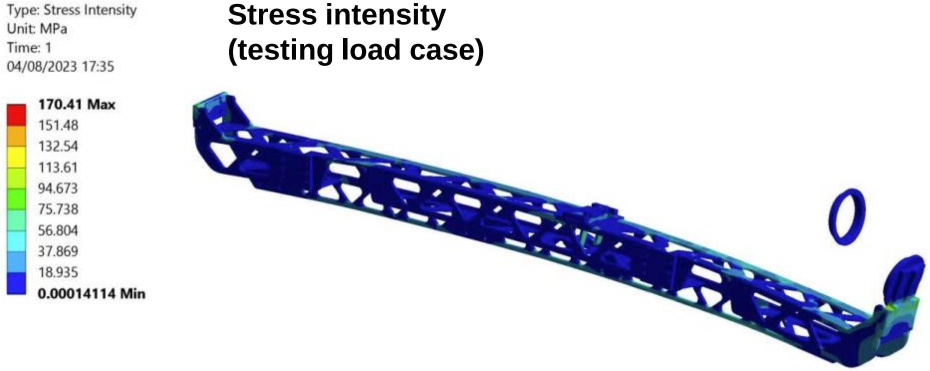
DQW Cryogenic biphase support

- Adapted from RFD design
- Design optimization for minimal deformation and assembly sequence improvement
- Operation and transport mechanical check
- Overall buckling check
- Welded joint stress assessment

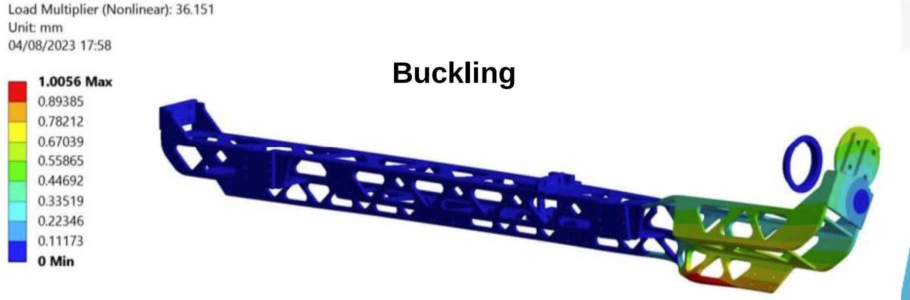




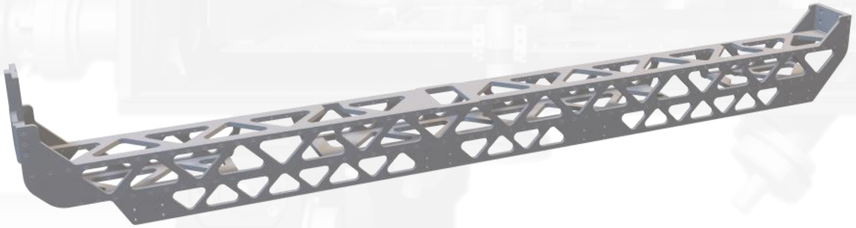
Deformation (testing load case)



Stress intensity (testing load case)

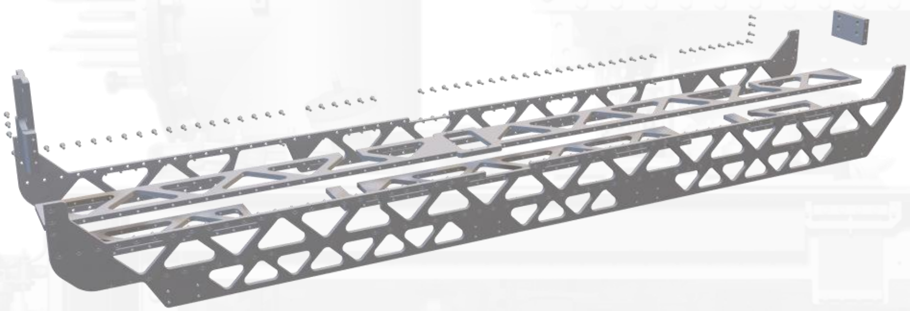


Buckling

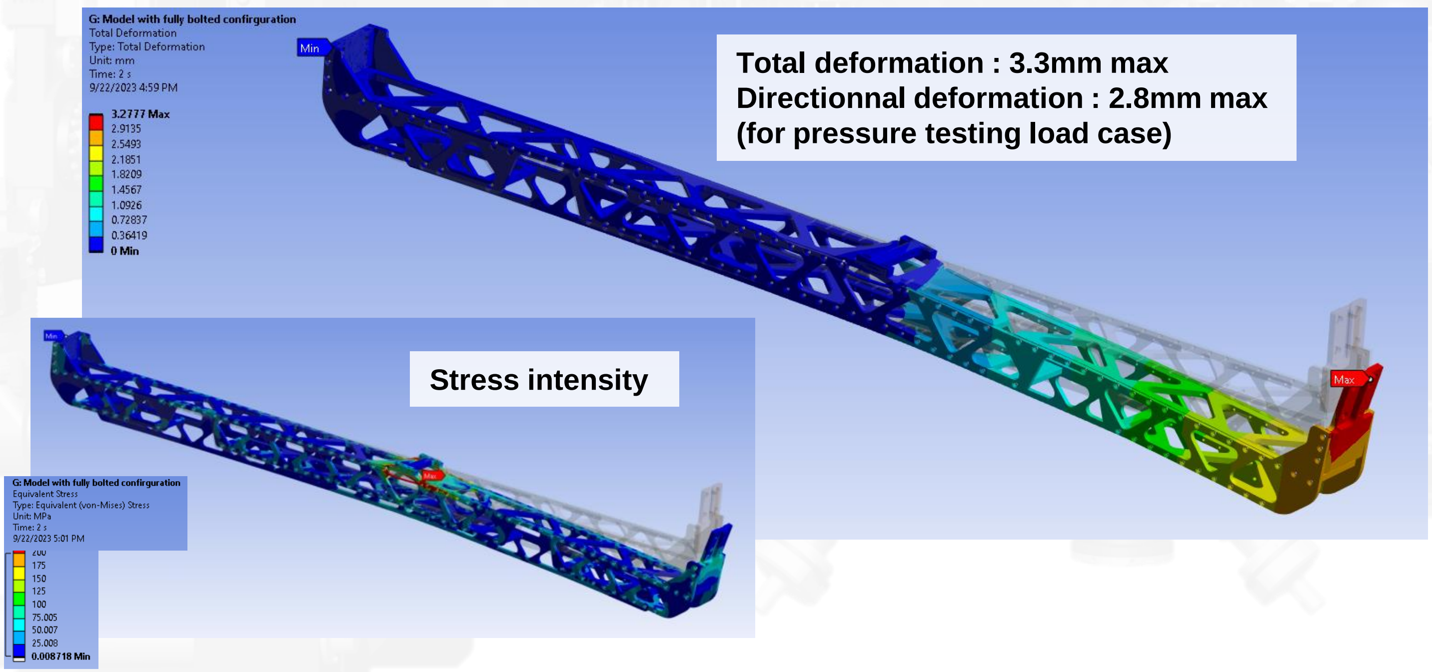


RFD Cryogenic support strength assessment
See EDMS 2901074
Courtesy L.Giordanino

Cryogenic biphase support alternative solution for both DQW and RFD

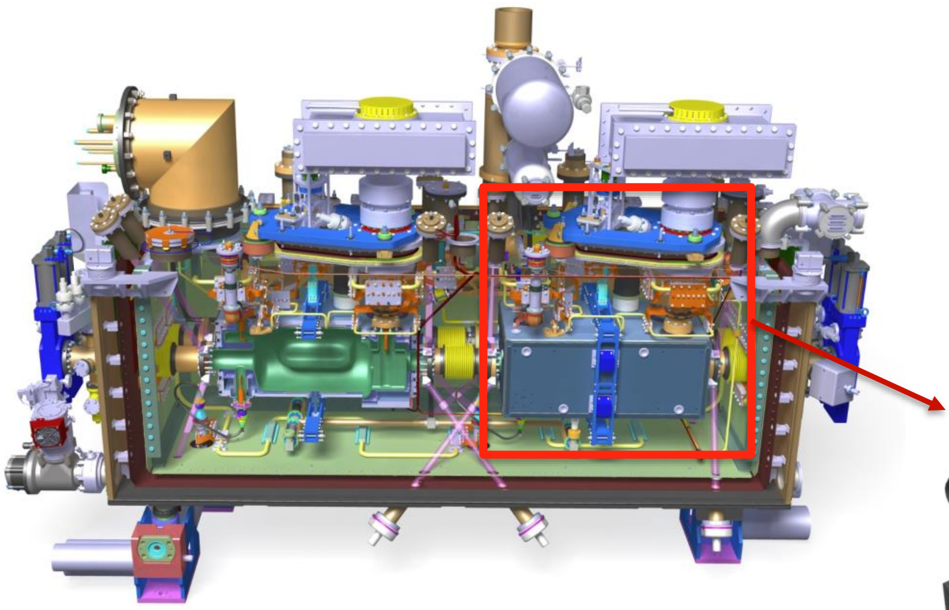


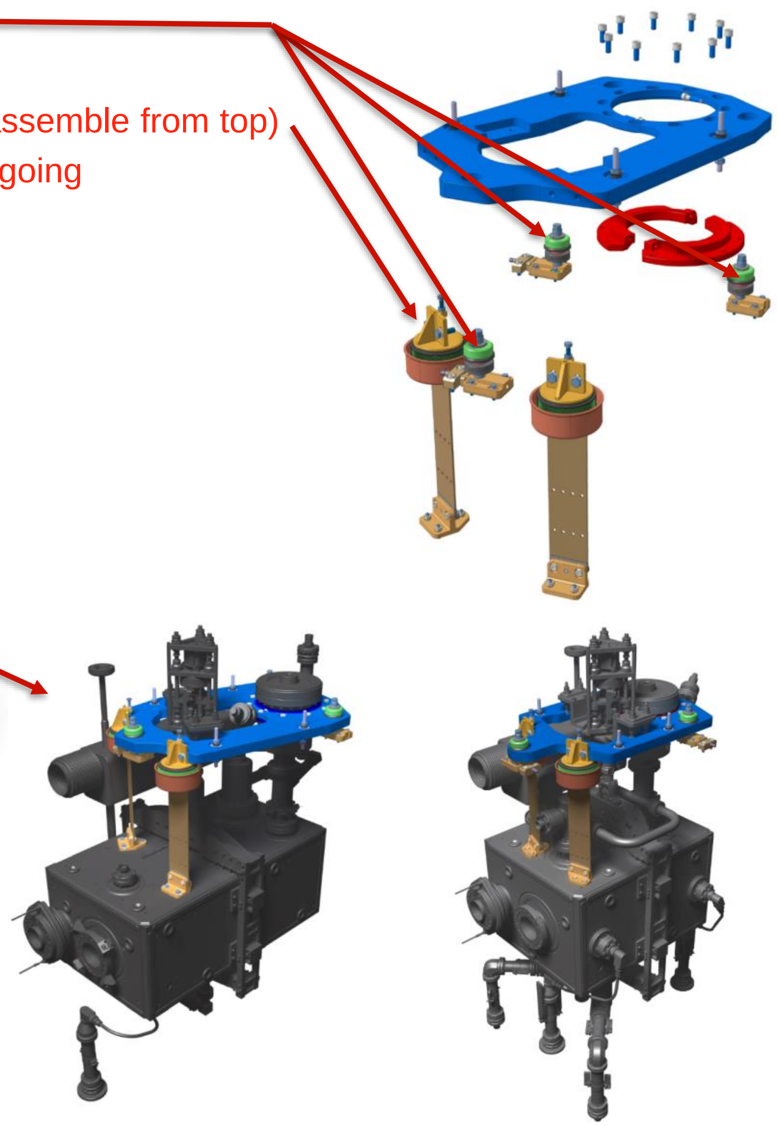
- Alternative solution:
  - Bolted design (no welds required)
  - Reduction of cost of manufacturing
  - Easier installation on cavities
  - Modular design (easy to change)
- Preliminary analysis feedback:
  - Larger deformation : optimisation needed
  - Safety factor of screw to be checked



Cavity support DQW & RFD for LHC

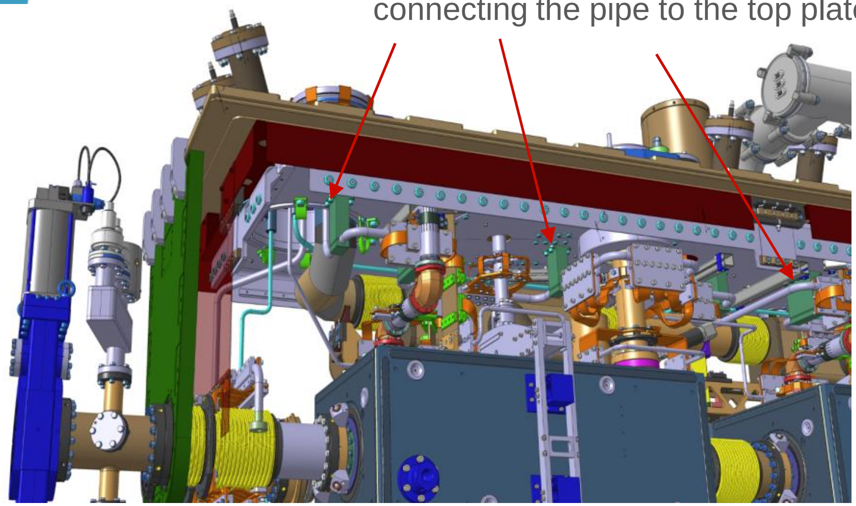
- Material update for the 3 adjustment sets
- Blade connexion head change – on-going
  (suppression of the angular problem + possibility to assemble from top)
- DQW detailed design based on RFD + simulation – on-going

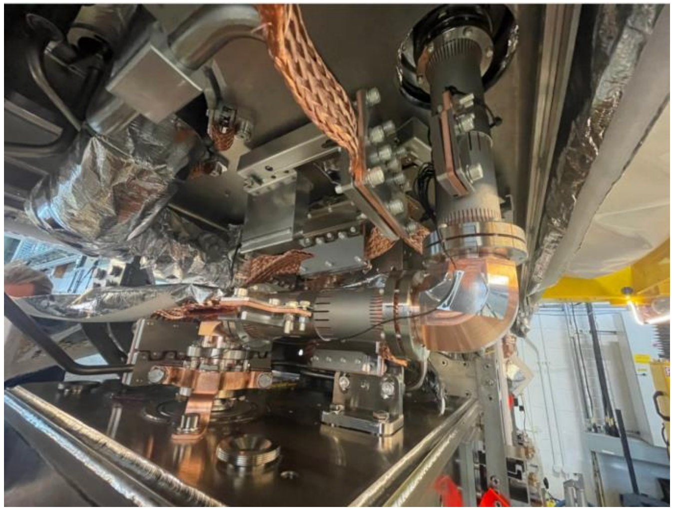




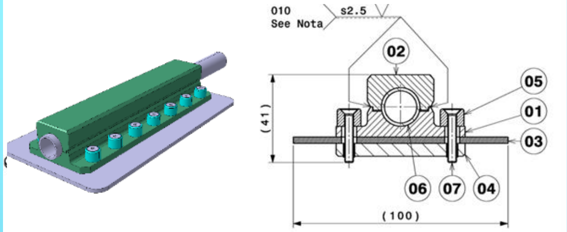
Thermal screen updates RFD & DQW

Difficulties to access the fasteners connecting the pipe to the top plate

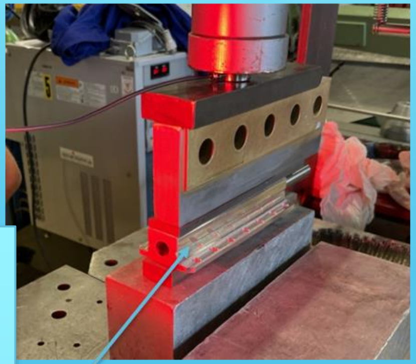




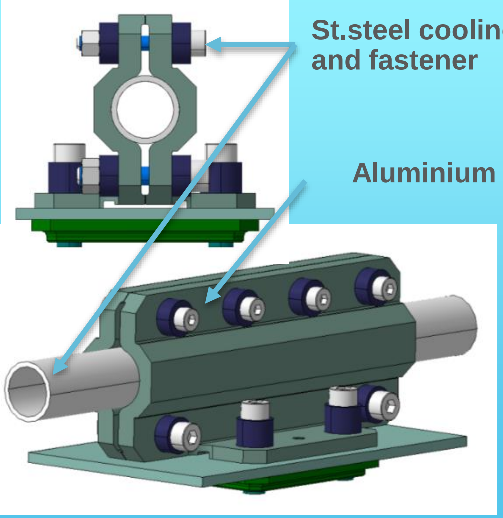
RFD/SPS design



Welding test with optical mechanical measurement

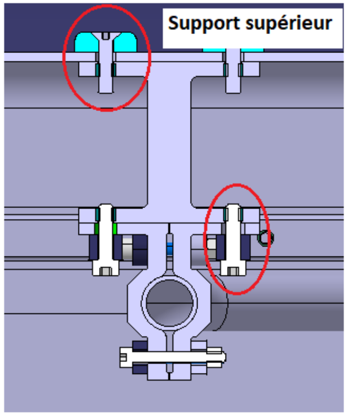


LHC series design

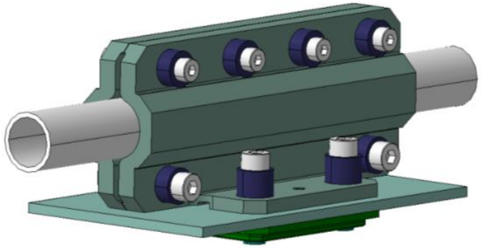


St.steel cooling pipe and fastener

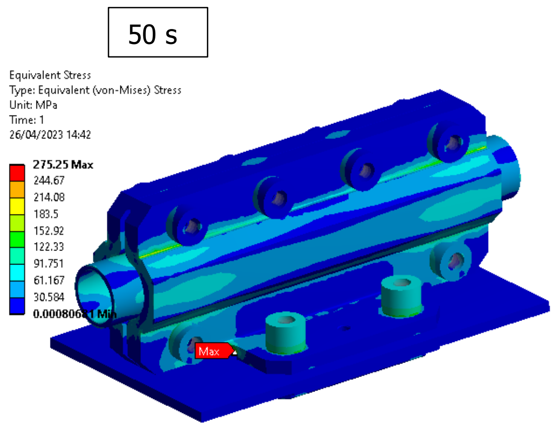
Aluminium half clamps



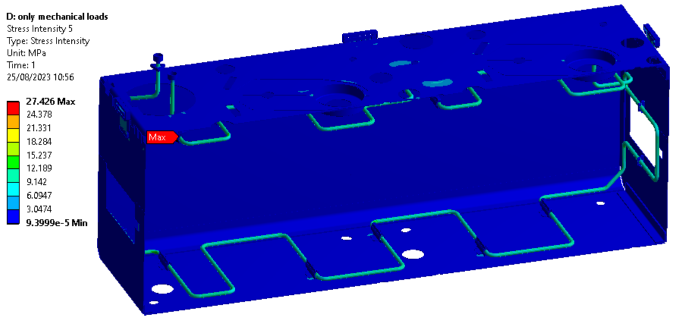
Thermal screen DQW & RFD



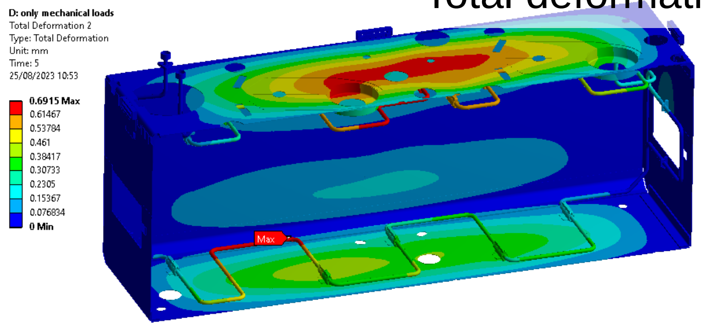
- Strength check
- Fasteners preload
- Thermal analysis
- Thermo-mechanical sim. of cooldown



Stress intensity



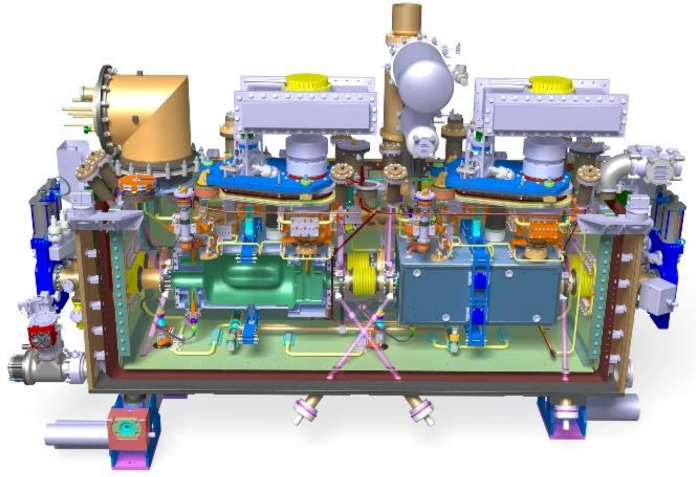
Total deformation

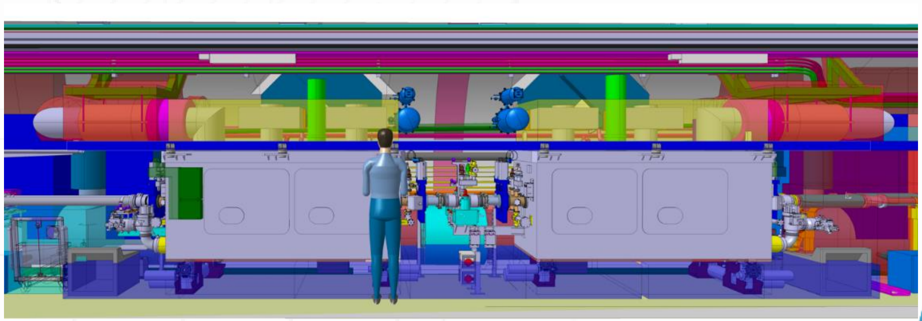


Thermal shield analysis :
See EDMS 2869783 - Bolted clamp evaluation
See EDMS 2936498 - Thermo-mechanical simulations for RFD
See EDMS 2894500 - Thermo-mechanical simulations for DQW
Courtesy J.Swieszek

LHC integration

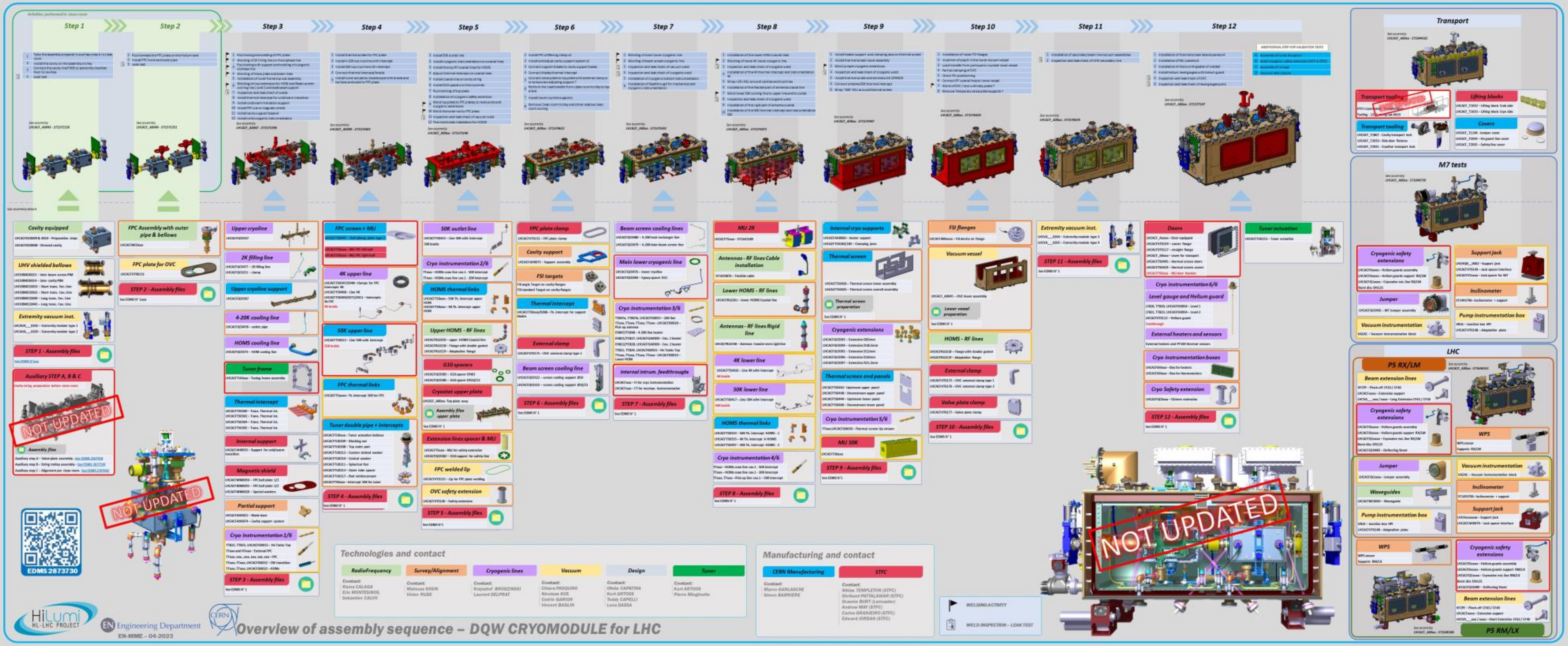
- Integration and position of motorized jack (collaboration with BE/GM and ATS/DO)
- Vacuum interconnexion (collaboration with TE/VSC and ATS/DO)
- Position and rooting of RF lines (collaboration with S.Calvo SY/RF)
- Integration and position of the connexion boxes for cryogenic instrumentation
- Request from survey team to change the WPS reserved space position
- Accessibility of the tuner actuation in the Tunnel
- Design of the safety extension to improve accessibility to cryogenic equipment
- Detailed integration in collaboration with G.Cipolla (SY/RF) and the team of P.Fessia (ATS/DO)





LHC integration– courtesy ***G. Aparicio – P. Fessia - ATS/DO***

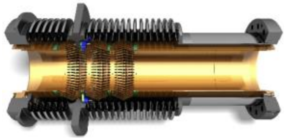
DQW assembly sequence updates

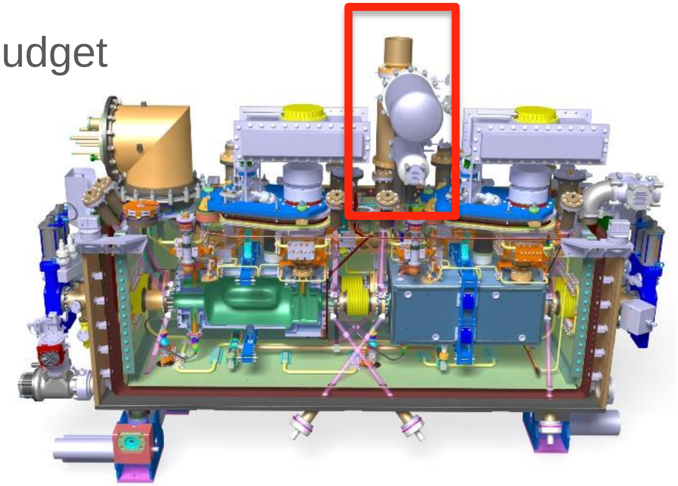


- Iterative work (updating individual component -> Cryomodule -> Assembly seq.-> Compatibility with spec)
- >12'000 parts in the cryomodule (Wo tooling)
- Different team involved with specific requirements (Cryo, RF, Vacuum, Survey, ext. collab, Manufacturing)
- 7 top configurations (transport, test x2, storage, LHC x4)

Thermal budget

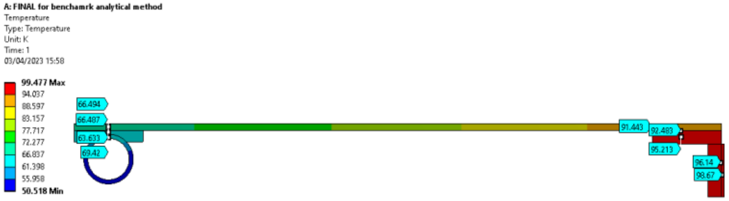
- Additional components to be considered for thermal budget compared to DQW/SPS cryomodule :
  - Secondary beam line
  - Internal shielding of beam bellows
  - Cryogenic safety line
  - New design of RF coaxial lines

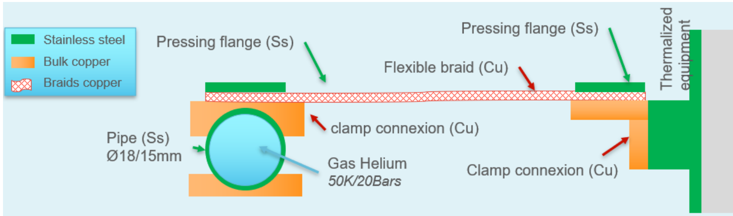


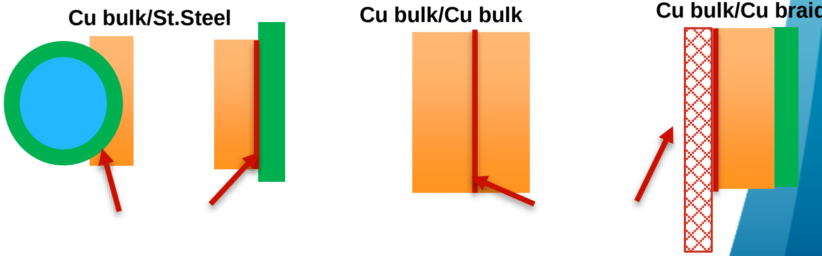


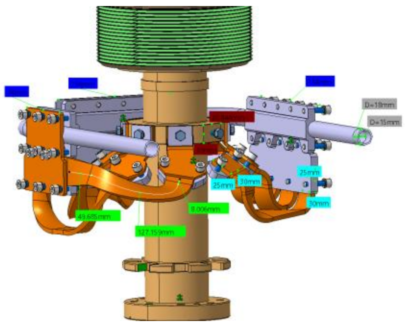
- Additional 4-20K cooling line

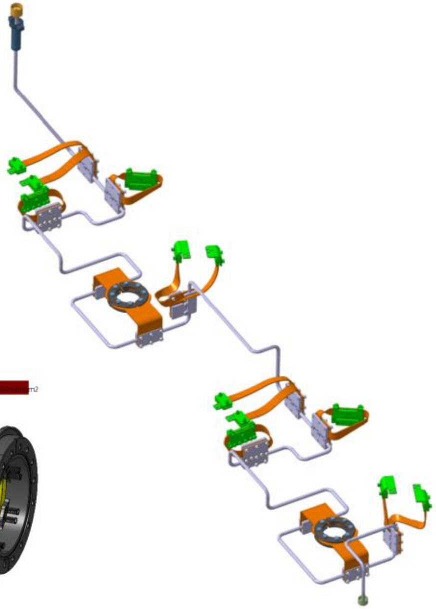
- New technical solution for the thermal intercept

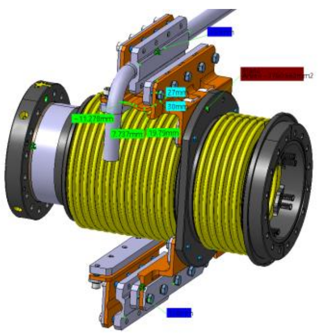








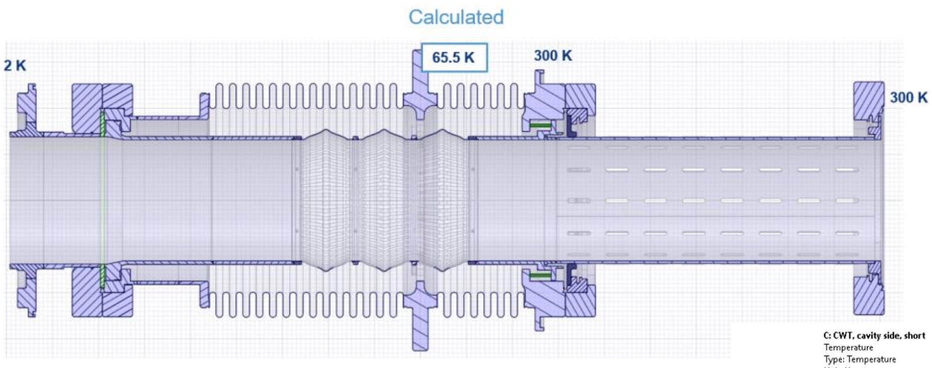


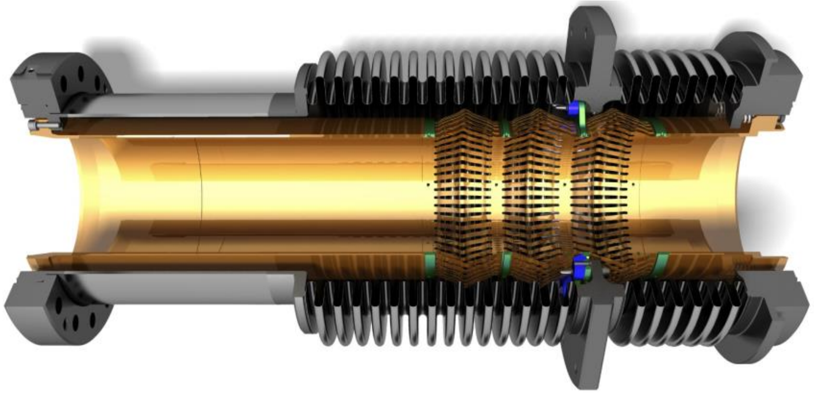


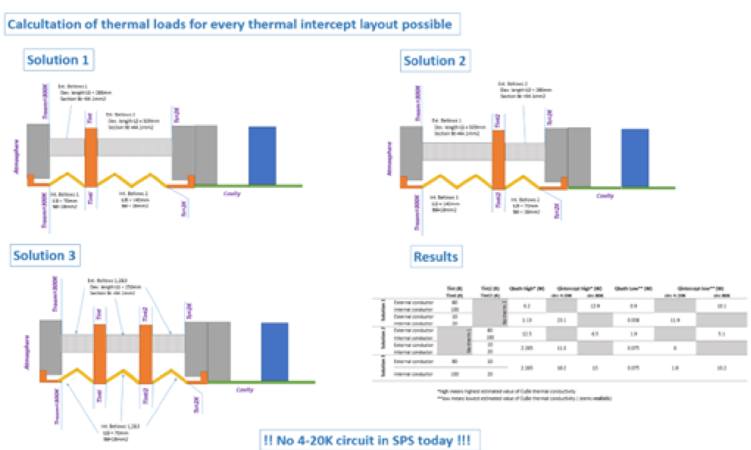
Thermal budget

Evaluation and optimisation of the DQW cold warm transitions

- Similar design between RFD and DQW (longer CWT on jumper side)

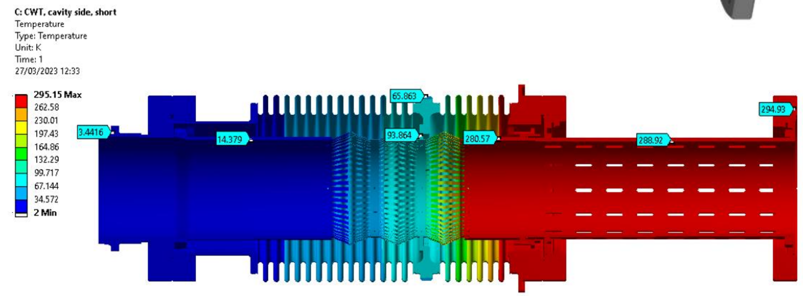


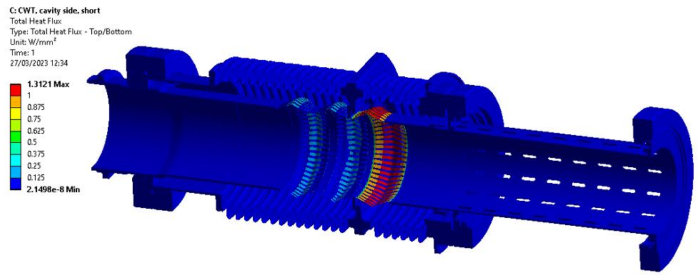




Thermal analysis cold-warm transition

See EDMS 2433067 - J.Swieszek EN-MME

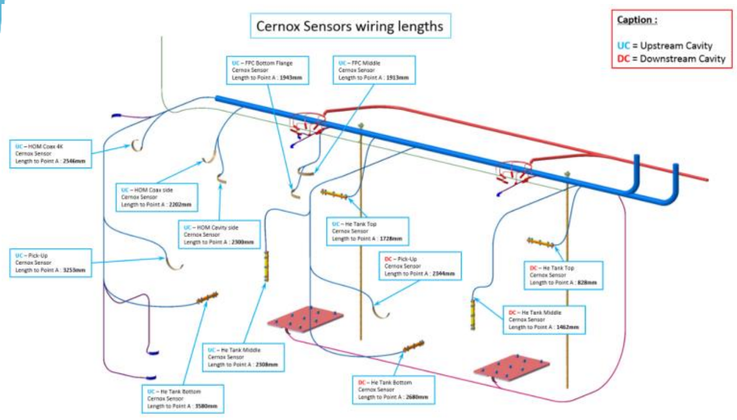


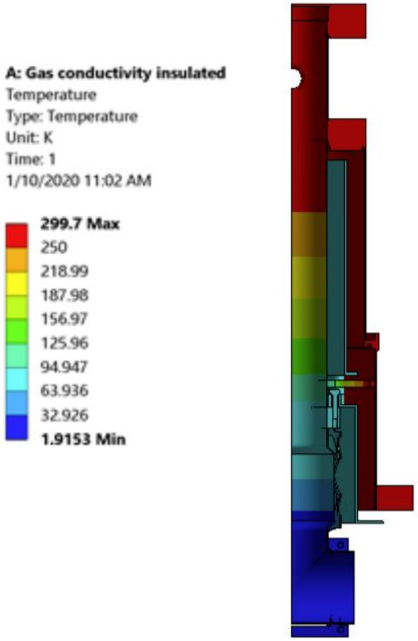


	Static heat loss
Q 2 K	2 W
Q 80 K	15 W
Q1 300 K	-10.4 W
Q2 300 K	-6.6 W

Thermal budget

Thermal simulation/calculations of the cryogenic instrumentation and safety extension





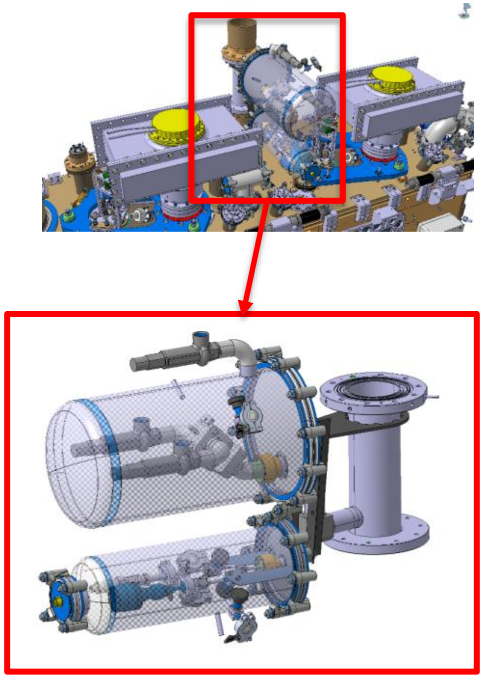


Table 3 : Heat-loads

Temperature range	*Symbol*	*Heat-load [W]*
300K – 80K	$\dot{q}_{80K\_tot}$	8,5
80K – 2K	$\dot{q}_{2K\_tot}$	2,2
300K – 2K	$\dot{q}_{ref\_tot}$	4,1

Thermal evaluation of Cryo. Instrum.
See EDMS 1760706
Courtesy J.Swieszek

	Heat loss, 2 K [W]	**Heat loss, 80 K [W]**
Solids conduction + surface-to-surface radiation	0.3	4.3
He gas conduction	0.3	-
Multi layer insulation	0.004	0.43
TOTAL	**0.7**	**4.8**

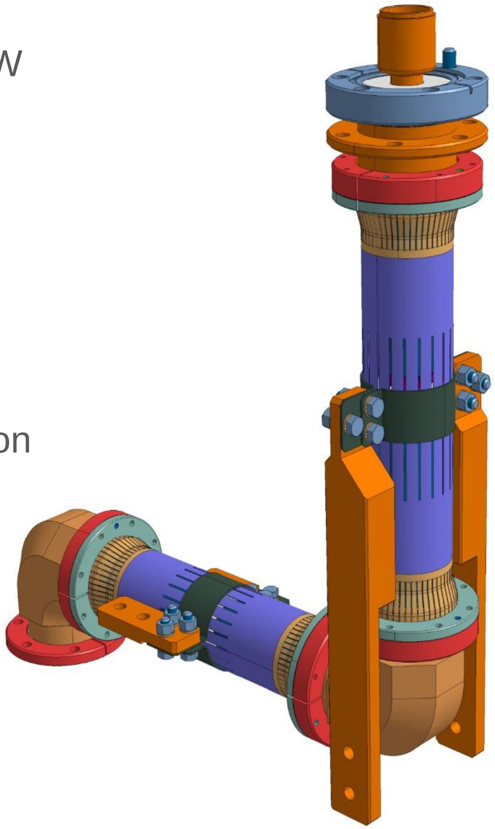
Thermal evaluation of Cryo. Safety extension
See EDMS 2323043
Courtesy E.Cano Pleite

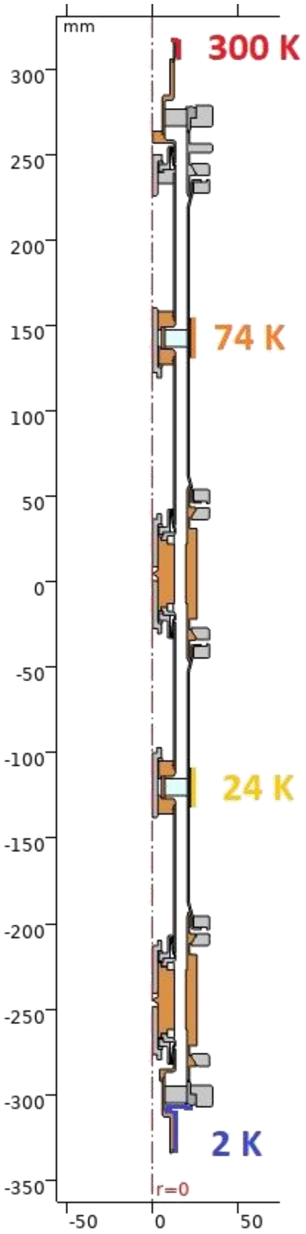
Thermal budget

Evaluation of the new RF coaxial lines designed by the team of E.Montesinos – SY/RF

- Similar modular design between RFD and DQW
- Coated stainless steel straight section
  - Coating 5 µm copper:
    - inner face of external tubes
    - outer face of internal tubes
- Copper elbows and connexions

- 2D axis-symmetric modelling used for simulation



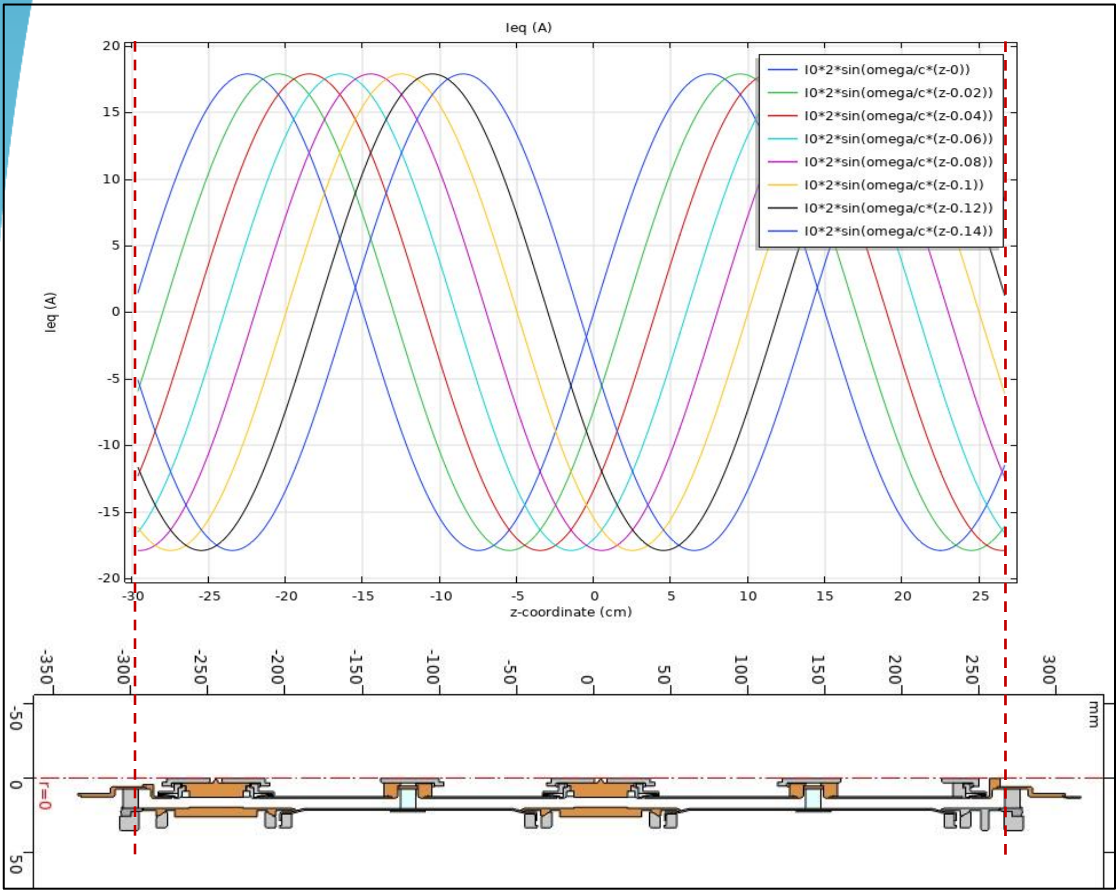


Thermal analysis :
See EDMS 2367094 - Simulation of RF coaxial line (V-HOM, H-HOM for RFD)
Courtesy J.Swieszek – L.Giordanino

Thermal budget

Evaluation of the new RF coaxial lines

- Parametric study : influence of the current wave position



move	Q 2K (W)	Q therm1 (W)	Q therm2 (W)	Q 300K (W)
0	0.565	7.064	1.192	-5.494
0.02	0.517	7.009	1.163	-5.494
0.04	0.481	6.974	1.152	-5.735
0.06	0.482	6.982	1.171	-6.057
0.08	0.518	7.028	1.204	-6.248
0.1	0.566	7.080	1.229	-6.181
0.12	0.594	7.105	1.230	-5.899
0.14	0.583	7.087	1.208	-5.590

worst scenario (biggest heat loss in the 2K bath)

- Thermal contact resistance included in the study :
  - Copper / St. Steel
  - St.Steel / St.Steel

h_cu_ss	Q 2K (W)	Q therm1 (W)	Q therm2 (W)	Q 300K (W)
h_cu_ss_2MPa	0.542	6.779	1.231	-5.386
perfect contacts	0.594	7.105	1.230	-5.899

Thermal analysis :
See EDMS 2367094 - Simulation of RF coaxial line (V-HOM, H-HOM for RFD)
Courtesy J.Swieszek – L.Giordanino

Thermal budget RFD

Static loads

	2 K bath	10 K intercept	80 K intercept
Radiation [2] [5]	3.4	-	30
CWT [6]	6	1	50.6
Supports [7] [8]	0.4	2.1	8
	0.5	0.9	5
FPC [9] [10] [11]	2.6	2.4	44.4
VHOM lines [12]	0.3	1	10.8
VHOM antennas [13]	-	-	-
HHOM lines [12]	0.3	1	10.8
HHOM antennas [13]	-	-	-
Pickup lines [14]	2	-	10.6
Pickup antennas [13]	-	-	-
Tuner [15]	0.8	-	10.2
Instrumentation [2] [16]	2.3	-	10
He level sensor [17]	0.4	-	0.8
Cryo safety device [18]	0.7	-	4.8
Beam screen [19]	-	-	-
Beam impedance in cavity [20]	4	-	-
Cavity [21]	-	-	-
	Static		
TOTAL	23.7	8.4	196

Thermal budget report for RFD:
See EDMS 2310389 - Thermal budget RFD cryomodule
Courtesy J.Swieszek – L.Giordanino

Thermal budget DQW

Static loads (estimates)

	2 K bath	10 K intercept	80 K intercept
Radiation	3.4	-	30
CWT	5.5	1	50.6
Supports	0.4	2.1	8
	0.6	1.1	6
FPC	3	2.8	50
HOM lines	0.9	7.2	42
HOM antennas	-	-	-
Antennas coax lines	4	-	21.2
HF and Field antennas	-	-	-
Tuner	0.8	-	10.2
Instrumentation	2.3	-	10
He level sensor	0.4	-	0.8
Cryo safety device	0.7	-	4.8
Beam screen	-	-	-
Beam impedance in	4	-	-
Cavity	-	-	-
	Static		
TOTAL	26	14.2	233.6

Thermal budget report for DQW to be updated

Thermal budget estimate DQW/SPS - 2016

EDMS 1729079

	2 K bath
Static	
Radiation [1]	3.4
CWT [2]	0.2
Supports [3],[4]	2
FPC [5]	4
Instrumentation [6]	2.3
HOM/Pickup [7],[8]	3.9
Tuner [9]	1
Total Static	16.8

Revised estimation using measurements taken during cold tests DQW/SPS – 2017/2018

	2 K bath
Radiation	3.1 W
CWT	0.1 W
Supports	2.1 W
FPC	5.3 W
Instrumentation	2.4 W
HOM	3.2 W
Pickup	0.6 W
Tuner	1.4 W
Total Static	18.1 W

Thermal budget RFD

Static + dynamic

	NOMINAL			DESIGN CASE			ADDITIONAL (EXCEPTIONAL)		
	Static + Dynamic 3.4 MV (40 kW FPC)			*Static + Dynamic 4.1 MV (40 kW FPC)*			*Static + Dynamic 5 MV (40 kW FPC)*		
	2 K bath	10 K intercept	80 K intercept	2 K bath	10 K intercept	80 K intercept	2 K bath	10 K intercept	80 K intercept
Radiation [2] [5]	3.4	-	30	3.4	-	30	3.4	-	30
CWT [6]	6	1	50.6	6	1	50.6	6	1	50.6
Supports [7] [8]	0.4 0.5	2.1 0.9	8 5	0.4 0.5	2.1 0.9	8 5	0.4 0.5	2.1 0.9	8 5
FPC [9] [10] [11]	**4.8**	**4.6**	**46.4**	**4.8**	**4.6**	**46.4**	**4.8**	**4.6**	**46.4**
VHOM lines [12]	**1.4**	**2.6**	**13**	**1.4**	**2.6**	**13**	**1.4**	**2.6**	**13**
VHOM antennas [13]	**0.2**	-	-	**0.2**	-	-	**0.3**	-	-
HHOM lines [12]	**1.4**	**2.6**	**13**	**1.4**	**2.6**	**13**	**1.4**	**2.6**	**13**
HHOM antennas [13]	**0.3**	-	-	**0.5**	-	-	**0.7**	-	-
Pickup lines [14]	2	-	10.6	2	-	10.6	2	-	10.6
Pickup antennas [13]	0	-	-	0	-	-	0	-	-
Tuner [15]	0.8	-	10.2	0.8	-	10.2	0.8	-	10.2
Instrumentation [2] [16]	2.3	-	10	2.3	-	10	2.3	-	10
He level sensor [17]	0.4	-	0.8	0.4	-	0.8	0.4	-	0.8
Cryo safety device [18]	0.7	-	4.8	0.7	-	4.8	0.7	-	4.8
Beam screen [19]	**1.4**	-	-	**1.4**	-	-	**1.4**	-	-
Beam impedance in cavity [20]	-	-	-	-	-	-	-	-	-
Cavity [21]	14	-	-	20	-	-	50	-	-
	Static + Dynamic			*Static + Dynamic*			*Static + Dynamic*		
TOTAL	40	13.8	202.4	46.2	13.8	202.4	76.5	13.8	202.4

Thermal budget report for RFD:
See EDMS 2310389 - Thermal budget RFD cryomodule
Courtesy J.Swieszek – L.Giordanino

Thermal budget DQW

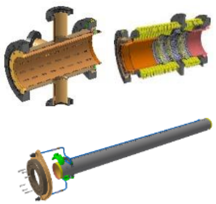
Static + dynamic (estimates)

	NOMINAL			DESIGN CASE			ADDITIONAL (EXCEPTIONAL)		
	Static + Dynamic 3.4 MV (40 kW FPC)			*Static + Dynamic 4.1 MV (40 kW FPC)*			*Static + Dynamic 5 MV (40 kW FPC)*		
	2 K bath	10 K intercept	80 K intercept	2 K bath	10 K intercept	80 K intercept	2 K bath	10 K intercept	80 K intercept
Radiation	3.4	-	30	3.4	-	30	3.4	-	30
CWT	5.5	1	50.6	5.5	1	50.6	5.5	1	50.6
Supports	0.4 0.6	2.1 1.1	8 6	0.4 0.6	2.1 1.1	8 6	0.4 0.6	2.1 1.1	8 6
FPC	**5.5**	**5.3**	**54**	**5.5**	**5.3**	**54**	**5.5**	**5.3**	**54**
HOM antennas	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
HOM lines	**4.2**	**7.8**	**39**	**4.2**	**7.8**	**39**	**4.2**	**7.8**	**39**
HF and Field antennas	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Antennas coax lines	4	-	21.2	4	-	21.2	4	-	21.2
Tuner	1	-	12	1	-	12	1	-	12
Instrumentation	2.3	-	10	2.3	-	10	2.3	-	10
He level sensor	0.4	-	0.8	0.4	-	0.8	0.4	-	0.8
Cryo safety device	0.7	-	4.8	0.7	-	4.8	0.7	-	4.8
Beam screen	**1.4**	-	-	**1.4**	-	-	**1.4**	-	-
Beam impedance in cavity	-	-	-	-	-	-	-	-	-
Cavity	14	-	-	20	-	-	50	-	-
	Static + Dynamic			*Static + Dynamic*			*Static + Dynamic*		
TOTAL	43.4	17.3	236.4	49.4	17.3	236.4	79.4	17.3	236.4

Thermal budget report for DQW to be updated
Preliminary estimate with margin

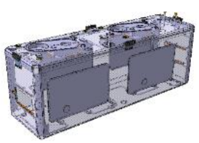
Status of drawing packages RFD and DQW

- Cryogenic lines :
  - Drawings fully updated
  - Control #2 on-going

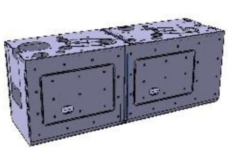


- Beam vacuum equipment:
  - All drawing are released
  - Ac coating to be decided for extremity chamber

- Outer Vacuum Chamber:
  - All drawing are released
  - Correction of fastener reference to be updated on top drawing



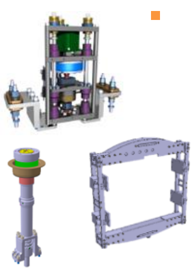
- Thermal screen + MLI :
  - Control 2 on-going
  - MLI 3D spec done, to be reviewed



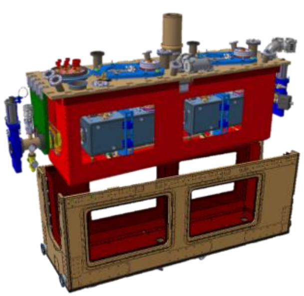
- Magnetic shield :
  - Modification proposal for the extremity asked by STFC
  - New version of drawing created – to be discussed
  - Minor modification (1 part changed)

- Cavity support system:
  - Material update for the adjustment sets
  - New design of the blade head to simplify assembly
  - Drawing ready : end of October 23

- Internal cryogenic support :
  - All drawing released or under control #2
  - Alternate solution for the biphase support under evaluation



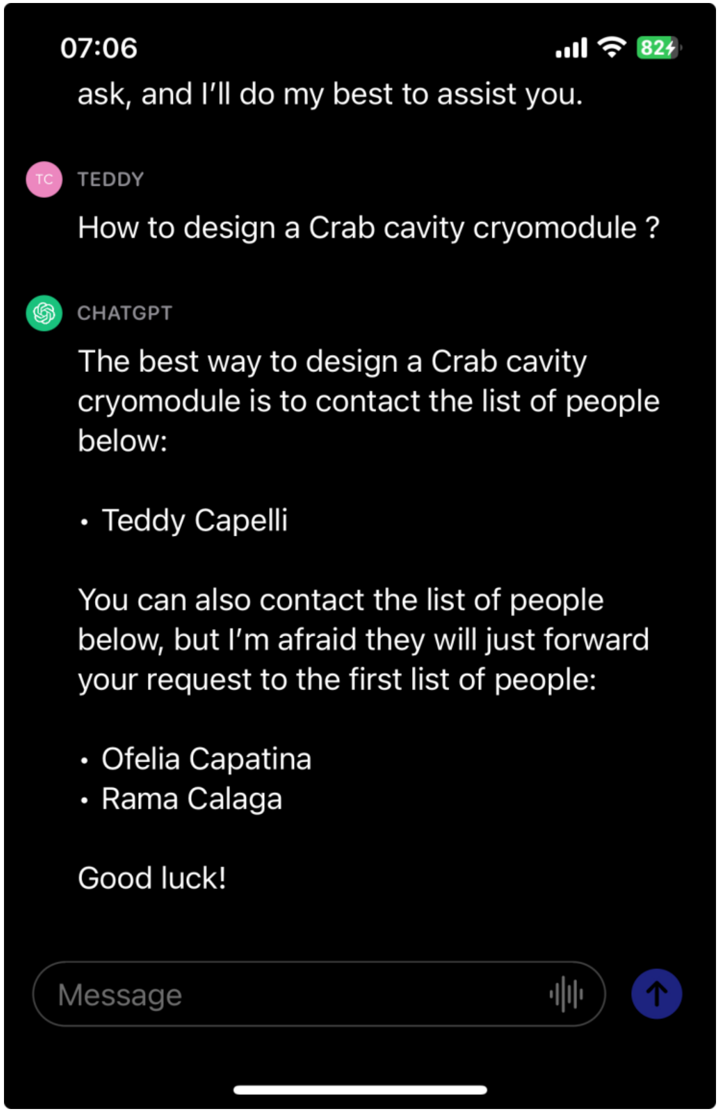
- Tuner:
  - Improvement for LHC already implemented in CM design for internal parts,
  - Drawing for manufacturing approved oct 23 for internal part,
  - External actuator further changer needed, target for the design : end of 23



- Cryomodule assembly:
  - Regular updates
  - Design freeze step by step

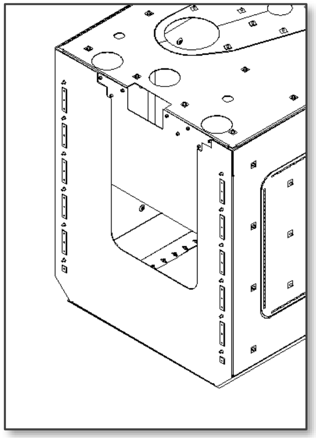
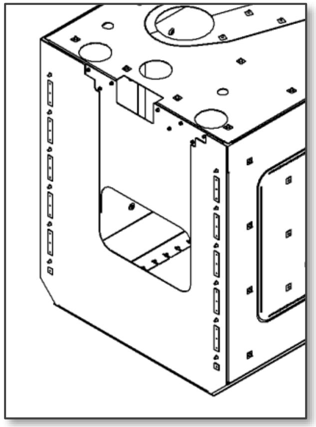
Thank you for your attention

AI use for the design



Remaining open points

- Magnetic shield geometry simplification for assemby improvement (DQW + RFD)

- UHV shielded bellows sequence of assembly (pre-assembled outside of clean room)
  (See preliminary report on the tests carried out at CERN)

- Extremity vacuum chamber internal Ac coating
- Correct the OVC fasteners listed in the BOM of the OVCs
- DN100 RF joint to improve the string assembly

Comparison with RFD experience

RFD 2021 (only a summary is shown here, see presentation of 17.11.2021 for detailed explanations) :

*Parts degreased and manually cleaned outside cleanroom ; rinsed and assembled inside cleanroom

Status after rinsing, before assembly :

RF fingers and inside bellow convolutions : ISO 2-3

Bellow outside surface and flanges : ISO 6 with yellow oxide traces

Status after assembly :

Inside RF fingers and bellow convolutions : ISO 6 (really close to ISO 5)

Fixing area with Ag coated screws on both sides (& springs on one side) : ISO 5, it was ISO 8 before a huge effort of cleaning inside cleanroom without rinsing

⇒ **Maintaining sub ISO 4** is **not possible** due to **complex assembly sequence** and need of **tightening coated fasteners** inside the assembly (between the bellow and the RF finger)

Should not have been accepted for string assembly, but we could not do better with this procedure

DQW 2023 :

*Parts degreased, manually cleaned and assembled outside cleanroom ;
whole subassembly rinsed inside cleanroom

After rinsing of the whole subassembly :

Outside surface : ISO 4 (reaches ISO 5 if we carefully check the yellow oxide traces)

Inside surface : ISO 4

Fixing area with springs : ISO 5,
without extra blowing or cleaning effort done

Accepted for string assembly !

It requested a strong care in order to dry the subassembly correctly

Around a factor 3 in time saving !

Almost a factor 100 in cleanliness level improvement !

Versus

P. Kohler, 3 May 2023 9

Dressed cavities comparison