WP4-Series cryomodules design

14th HL-LHC Collaboration Meeting, CERN – 7-10 October 2024

Teddy Capelli on behalf of the WP4 collaboration

Status of drawing packages RFD & DQW – Series

- Status of drawing folders for cryomodule **internal** components :

	Status
OVC & internal support	✓
Cryogenic lines, jumper, and cryogenic supports	✓
Thermal screen, MLI blankets 2K/50K, thermal intercept	✓
RF coaxial lines, FPC, FPC outer pipe	✓
UHV vacuum equipment	✓
Magnetic shield	✓
Mechanical and cryogenic instrumentation	× (Q4 2024)

Extracted from EDMS Docs 2730814 & 2801330

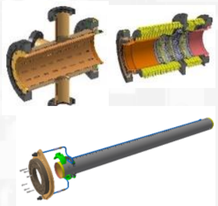
- Status drawing folders for cryomodule **external** components :

	Status
Cryogenic safety extension* *Only needed for LHC*	× (Q1 2025)
Tuner actuation*	× (TBD Kurt)
FSI heads	✓
Rooting of cable for LHC integration (2 configurations)	✓
Mechanical and cryogenic instrumentation *Only needed at CERN*	× (Q4 2024)
Drawing & BOM for STEP of assembly – Step 1->5	✓
Drawing & BOM for STEP of assembly – Step 6->12	× (Q1 2025)

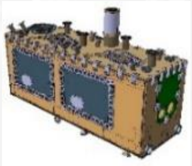
** Improvement of the original design*

Summary of drawing status

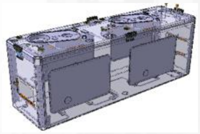
- Cryogenic lines :
  - All drawing are released



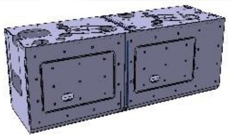
- Beam vacuum equipment:
  - All drawing are released



- Outer Vacuum Chamber:
  - All drawing are released

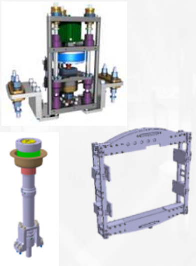


- Thermal screen, thermal intercept & Multi Layer Insulation :
  - All drawing are released

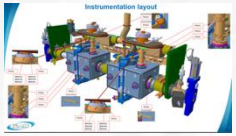


- Magnetic shield :
  - All drawing are released

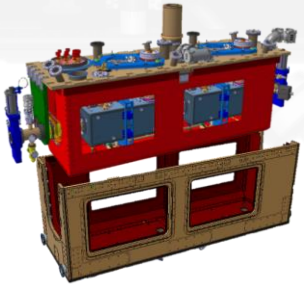
- Cavity support system:
  - All drawing are released
- Internal cryogenic support :
  - All drawing released



- Tuner:
  - Improvement for external actuation
  - Internal component released
  - See presentation K.Artoos

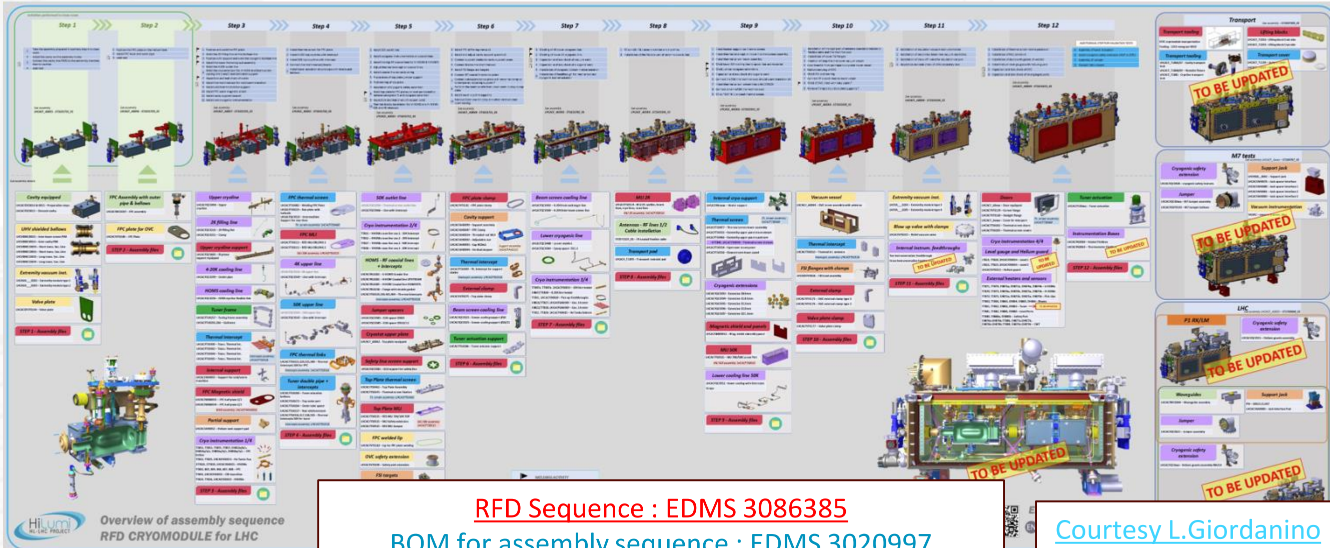


- Cryogenic instrumentations:
  - Design done and doc. Under review



- Cryomodule assembly:
  - Iterative updates
  - Design freeze step by step
  - Step 1-6 done
  - Step 7-12 **on-going**

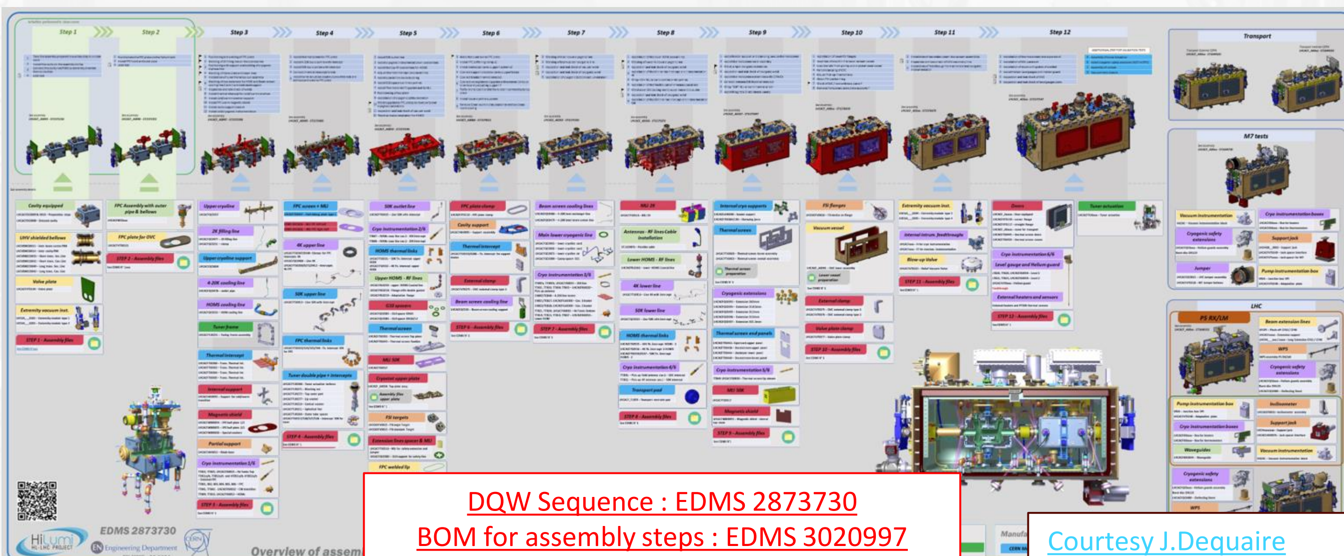
Assembly sequence updates



RFD Sequence : EDMS 3086385
BOM for assembly sequence : EDMS 3020997

Courtesy L.Giordanino

- 11500 components to be assembled (~950 2D drawings, 3500 3D part models not including tooling)

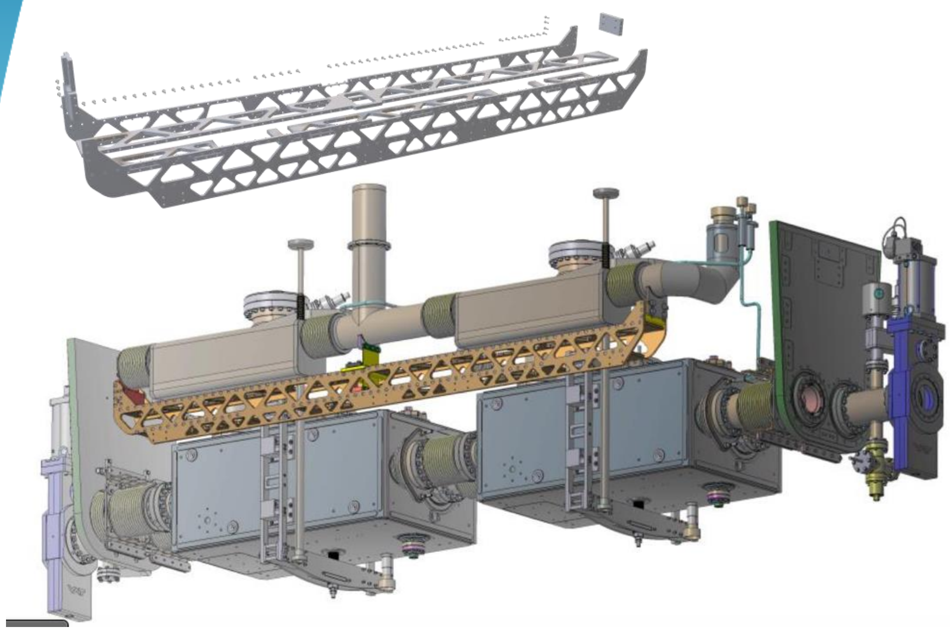


DQW Sequence : EDMS 2873730
BOM for assembly steps : EDMS 3020997

Courtesy J.Dequaire

Cryogenic biphase support bolted design

Design released ✓



- Manufacturing advantages:
  - Bolted design (no welds required)
  - Reduction of cost of manufacturing
  - Modular design
- Assembly advantages:
  - Easier installation on cavities
  - Free space for biphase welding

DQW Cryogenic support strength assessment
EDMS 3075772
Courtesy L.Giordanino

RFD Cryogenic support strength assessment
EDMS 3063725
Courtesy L.Giordanino

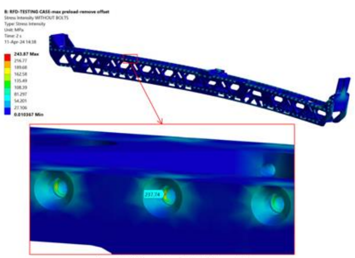
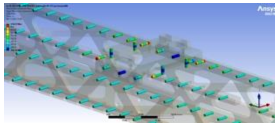


Figure 12: Stress intensity in testing condition

Stress and Buckling analysis
Maximum stress : stress below limit defined by EN13445-3 for each operating condition
Load multiplier of buckling : >40 for both design

Bolt stress
Minimum safety factor for both DQW and RFD design : 1.3 for M5 and 1.9 for M6 fasteners

Fastener A80 – not mandatory everywhere but safer to standardize in order to avoid mistake during assembly



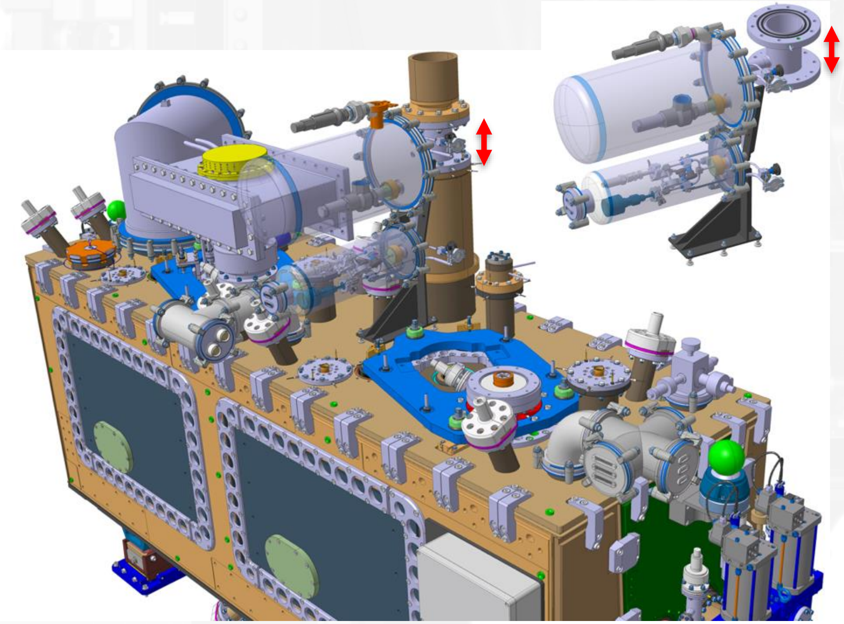
Total maximum deformation : 1.9mm (DQW) / 2.7mm (RFD)
Directional deformation : 1.6mm (DQW) / 2.4mm (RFD) – target 3mm max
(for pressure testing load case)

Cryogenic safety extension for series cryomodules

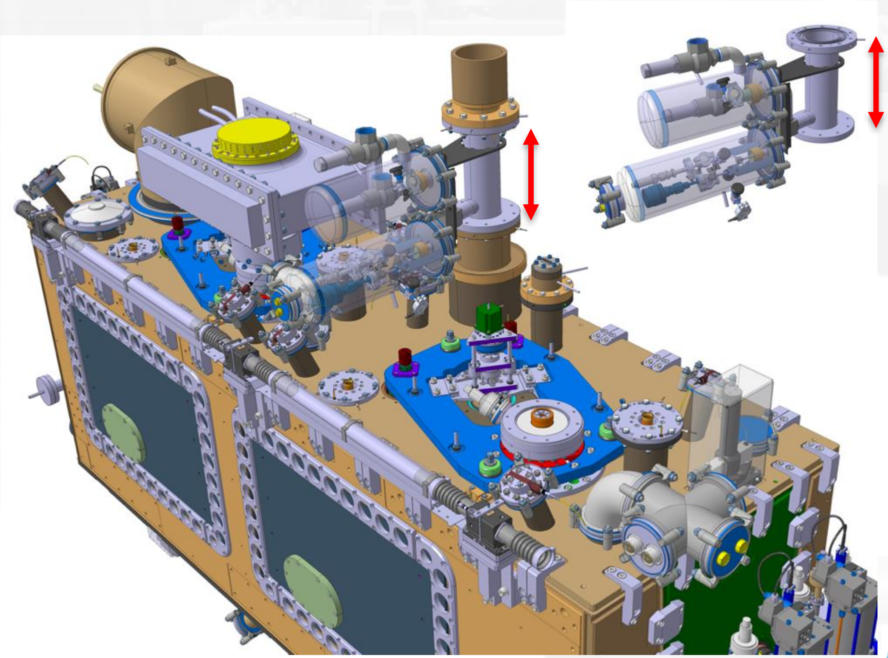
Design under review
Only needed for LHC

- Detailed study of the cryogenic extension for LHC - with new input from CRG expert
  - Change of design to protect burst from thermal cycles
  - Change the layout of safety valve (under review with TE-CRG)
- Definition and integration for the LHC 0 and 180° orientation

SPS version

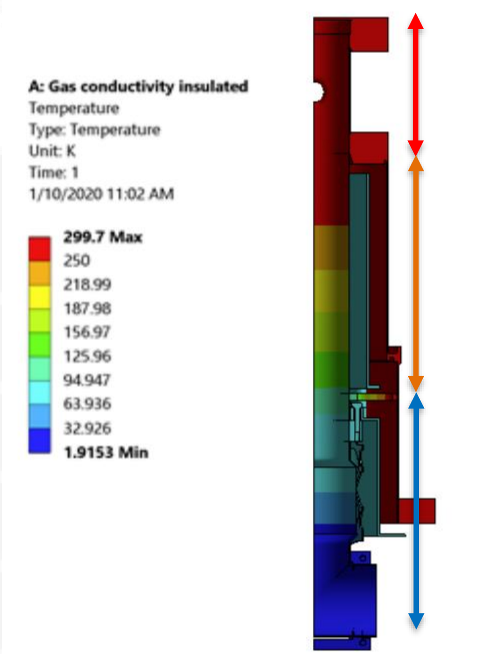


LHC version



Safety extension thermal sim.

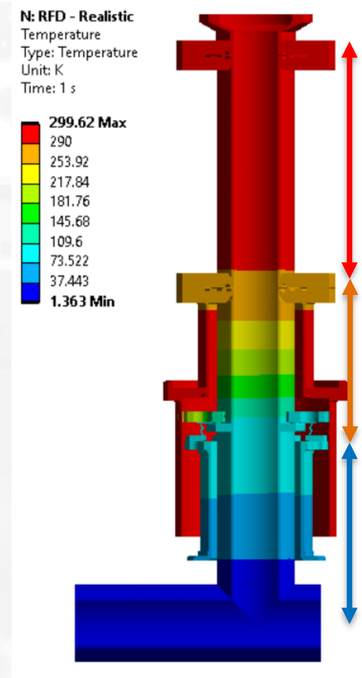
RFD / SPS design



	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 (SPS)
See EDMS 2323043
Courtesy E.Cano Pleite

LHC design



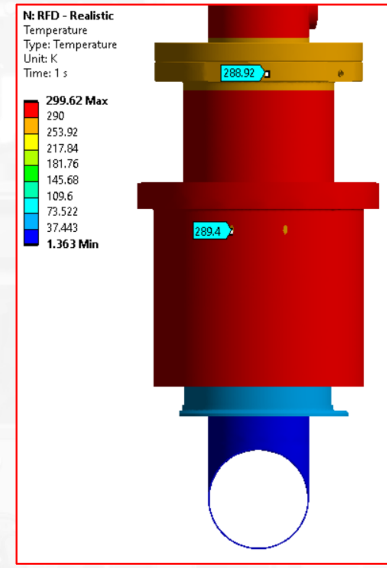


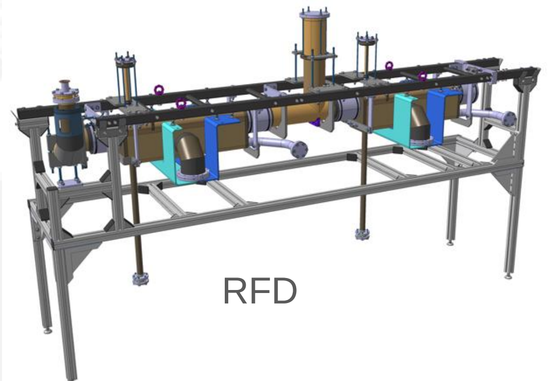
Table 2. Summary of the heat loss contributions for RFD safety device.

	Heat loss, 2 K [W]	Heat loss, 70 K [W]
Solids conduction + surface-to-surface radiation	1.48	7.23
He gas conduction	0.57	-
Multi-layer insulation	0.002	0.125
TOTAL	**2.1**	**7.4**

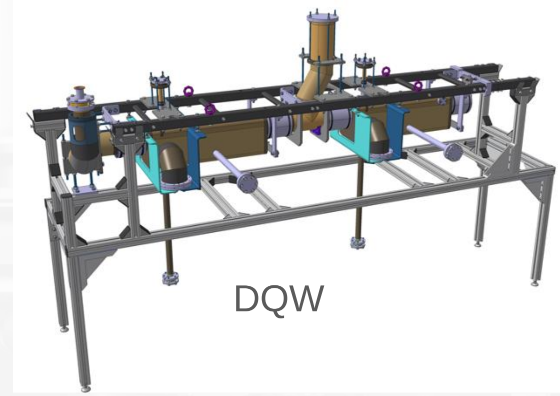
Cryogenic safety extension optimization (LHC) :
DQW : EDMS 3024965
RFD : EDMS 3024966
Courtesy E.Cano Pleite

Cryoline stress assessment and pressure test tooling

Design released ✓



RFD Cryogenic lines stress assessment: EDMS 2477175
Courtesy T.GUILLEN HERNANDEZ – L. DASSA
document update on-going (design is really close to SPS's)



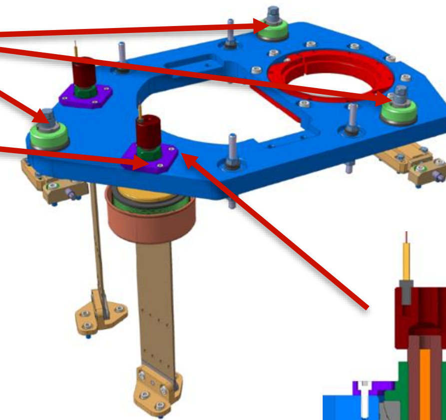
DQW Cryogenic lines stress assessment: EDMS 3000051
Courtesy J.SWIESZEK

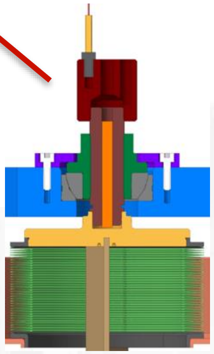
- Design of a test bench for pressure test representing cryomodule config.
- Design of several other tooling for lower lines and 4-20K lines
- Analysis performed according to the Annex B of the EN 13445-3 "Design by analysis - Method based on Direct Route", the testing condition for the Bi-phase line has been separately evaluated (see the full report)
  - All the criteria from standard have been satisfied and the results are fully acceptable

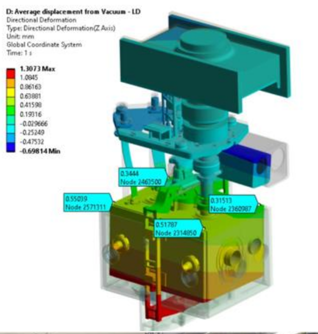
Cavity support DQW & RFD for LHC

Design released ✓

- Material update for the 3 adjustment sets
- Blade connexion head change
- Improvement of assembly on CM



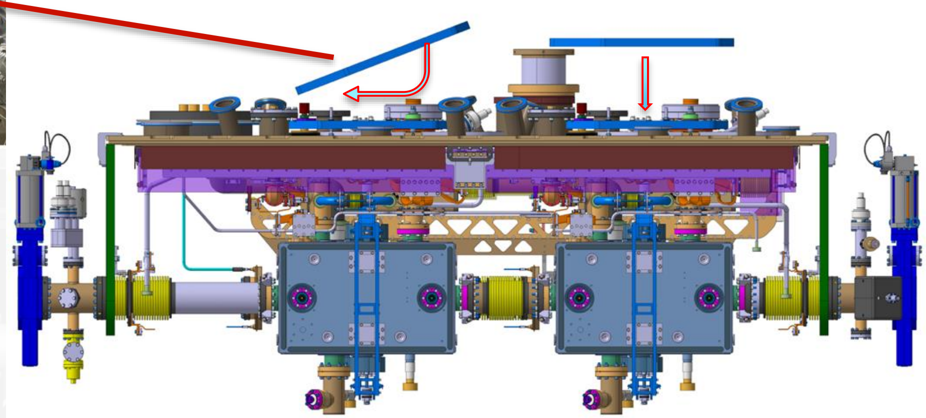


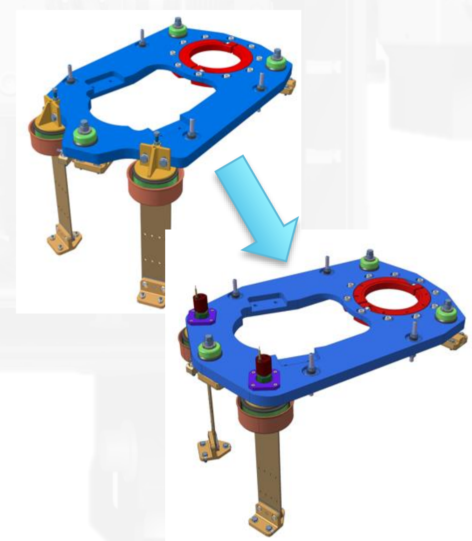


- Cavity support simulation results are acceptable
  - Both report done by E. Cano-Pleite
  - to be uploaded on EDMS
  - Anticipation of displacement for alignment of cavities
  - No significant change in stress WRT previous design

Previous design (SPS)

New design (LHC)

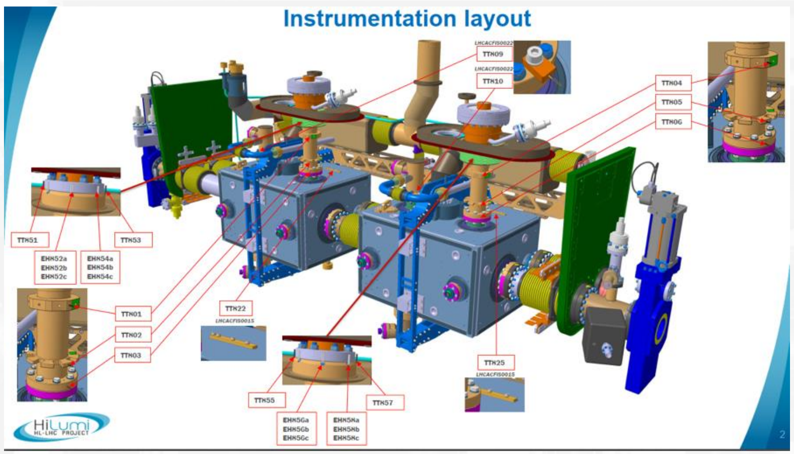


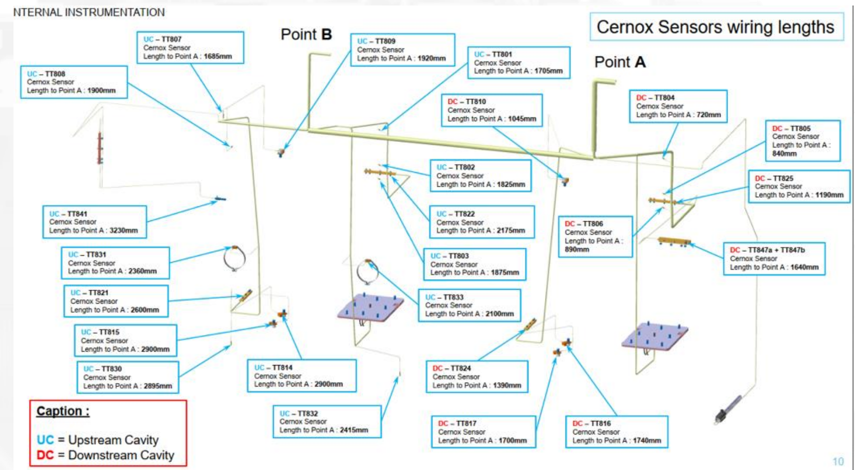


Cryogenic instrumentation

Design released ✓
List under review
Waiting for CRG validation

- RFD cryogenic instrumentation : https://edms.cern.ch/project/CERN-0000181755
  - https://edms.cern.ch/document/3161276
- DQW cryogenic instrumentation : https://edms.cern.ch/project/CERN-0000181671
  - https://edms.cern.ch/document/3167444





	A	D	E	H	K	L	M	N	O	P	Q	R	S	T	U	V	
1	Engineer / Cont	Assen	Assembly Step	Zon	Production	Component Cl	Component type	Component detail	Tag	Functional Descript	Quar	Responsib	Smarteam number		Physical	Measurement range (from P.Eng)	
2	Cryomodule RFD Series "Standard Plus"																
3	L. Delprat	Cavity 1	STEP 12	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR15c M6-10 screwed	TT871	VHOM	1	TRIUMF	ST1570474_01	M6x10 holder PT100	K	300 K	
4	L. Delprat	Cavity 1	STEP 12	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR15c M6-10 screwed	TT870	HHOM	1	TRIUMF	ST1570474_01	M6x10 holder PT100	K	300 K	
5	L. Delprat	Cavity 1	STEP 12	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR15c M6-10 screwed	TT872	Pick-up Antenna	1	TRIUMF	ST1570474_01	M6x10 holder PT100	K	300 K	
6	L. Delprat	Cavity 1	STEP 12	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR15c M6-10 screwed	TT863	Left Blade	1	TRIUMF	ST1570474_01	M6x10 holder PT100	K	300 K	
7	L. Delprat	Cavity 1	STEP 3	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR7c	TT851	FPC	1	CERN	ST1416942_01	PT100 temperature sensor	K	300 K	demander a Laurent si
8	L. Delprat	Cavity 1	STEP 3	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR7c	TT853	FPC	1	CERN	ST1416942_01	PT100 temperature sensor	K	300 K	demander a Laurent si
9	L. Delprat	Cavity 1	STEP 12	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR15c M6-10 screwed	TT881	Level Port	1	TRIUMF	ST1570474_01	M6x10 holder PT100	K	300 K	
10	L. Delprat	Cavity 1	STEP 12	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 integrated to the EH876a/b flexible collar.	TT886	CWT crab line	1	CERN	ST1580722_01	Flexible collar heaters with PT100 450x10	K	300 K	
11	L. Delprat	Cavity 1	STEP 9	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR7c mounted on long block	TT840	CWT crab line	1	TRIUMF	ST1545653_01	CRYOGENIC THERMOMETER - LONG (PT100)	K	50 K	
12	L. Delprat	Cavity 1	STEP 12	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR7c inserted or M5 screwed (tbc with Kurt).	TT861	Tuner	1				K	300 K	
13	L. Delprat	Cavity 2	STEP 12	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR15c M6-10 screwed	TT874	VHOM	1	TRIUMF	ST1570474_01	M6x10 holder PT100	K	300 K	
14	L. Delprat	Cavity 2	STEP 12	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR15c M6-10 screwed	TT873	HHOM	1	TRIUMF	ST1570474_01	M6x10 holder PT100	K	300 K	
15	L. Delprat	Cavity 2	STEP 12	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR15c M6-10 screwed	TT875	Pick-up Antenna	1	TRIUMF	ST1570474_01	M6x10 holder PT100	K	300 K	
16	L. Delprat	Cavity 2	STEP 12	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR15c M6-10 screwed	TT866	Right Blade	1	TRIUMF	ST1570474_01	M6x10 holder PT100	K	300 K	
17	L. Delprat	Cavity 2	STEP 3	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR7c	TT855	FPC	1	CERN	ST1416942_01	PT100 temperature sensor	K	300 K	demander a Laurent si
18	L. Delprat	Cavity 2	STEP 3	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR7c	TT857	FPC	1	CERN	ST1416942_01	PT100 temperature sensor	K	300 K	demander a Laurent si
19	L. Delprat	Cavity 2	STEP 12	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR15c M6-10 screwed	TT882	Level Port	1	TRIUMF	ST1570474_01	M6x10 holder PT100	K	300 K	
20	L. Delprat	Cavity 2	STEP 12	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 integrated to the EH878a/b flexible collar.	TT888	CWT crab line	1	CERN	ST1580722_01	Flexible collar heaters with PT100 450x10	K	300 K	
21	L. Delprat	Cavity 2	STEP 12	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR7c inserted or M5 screwed (tbc with Kurt).	TT862	Tuner	1				K	300 K	
22	L. Delprat	N/A	STEP 12	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR15c M6-10 screwed	TT880	Safety Port	1	TRIUMF	ST1570474_01	M6x10 holder PT100	K	300 K	
23	L. Delprat	N/A	P1	IP1	Series "Standard Plus"	Thermometry	PT100	PT100 TR15c M6-10 screwed	TT883	Safety Port	1	TRIUMF	ST1570474_01	M6x10 holder PT100	K	300 K	
24	L. Delprat	Cavity 1	STEP 5	IP1	Series "Standard Plus"	Thermometry	Cernox	CX-AA canister	TT817	VHOM	1	CERN	ST0467999_01	Resistance Temperature Sensor Cernox CX-AA	K	1.5-300 K	
25	L. Delprat	Cavity 1	STEP 5	IP1	Series "Standard Plus"	Thermometry	Cernox	CX-AA canister	TT818	VHOM	1	CERN	ST0467999_01	Resistance Temperature Sensor Cernox CX-AA	K	1.5-300 K	
26	L. Delprat	Cavity 1	STEP 3	IP1	Series "Standard Plus"	Thermometry	Cernox	CX-AA canister	1TT819	VHOM	1	CERN	ST0467999_01 (dans LHCACFIS0025)	Resistance Temperature Sensor Cernox CX-AA	K	1.5-300 K	
27	L. Delprat	Cavity 1	STEP 5	IP1	Series "Standard Plus"	Thermometry	Cernox	CX-AA canister	TT811	HHOM	1	CERN	ST0467999_01	Resistance Temperature Sensor Cernox CX-AA	K	1.5-300 K	
28	L. Delprat	Cavity 1	STEP 5	IP1	Series "Standard Plus"	Thermometry	Cernox	CX-AA canister	TT812	HHOM	1	CERN	ST0467999_01	Resistance Temperature Sensor Cernox CX-AA	K	1.5-300 K	
29	L. Delprat	Cavity 1	STEP 3	IP1	Series "Standard Plus"	Thermometry	Cernox	CX-AA canister	TT814	HHOM	1	CERN	ST0467999_01 (dans LHCACFIS0022)	Resistance Temperature Sensor Cernox CX-AA	K	1.5-300 K	

Other design activities

- Modification of material requirements
  - Lower grades requirement on some components
  - Change of material for a better coherence between drawing packages

Component	Material spec
Jumper support (LHCACFQC0310)	Cryoline spec EDMS 2093032
4-20k cooling line support LHCACFQC0519	Cryoline spec EDMS 2093032
Thermal screen ancillaries for thermal screen LHCACFTS0460 + LHCACFTS0425	Thermal screen spec EDMS 2101922+ only for plate: spec EDMS 790774 (1002)
Cavity support system LHCACFAH0095 & 0101	Vac vessel spec EDMS 2101924 + Cryoline spec EDMS 2093032 Fasteners in Stainless steel whenever possible
Jumper for LHC LHCACFQC0621	No UK or Triumf production / CERN spec ONLY for internal use: EDMS 3055177
CWT Supports (LHCACFAH0055)	Vac vessel spec EDMS 2101924

- Follow up NCRs & change request coming from the collaboration
- Design of tooling for repairs & assembly
- Check report from suppliers & collaboration (metrology, material properties, ISO GPS drawing checks…)
- Follow up test and get feedback for potential improvement for series

Cold test – static heat load @2K measurement

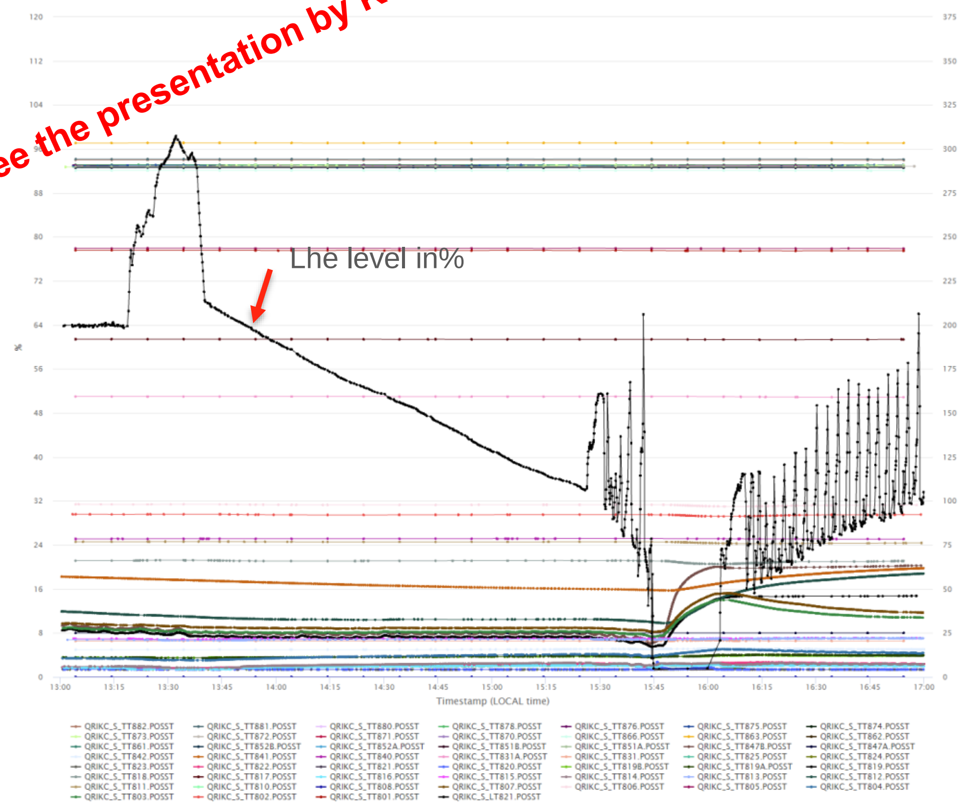
- The static heat load at cold can be evaluated by stopping the liquid helium supply when all the temperatures are stabilized and checking the variation of the level in the cavities (the 4-20K and 50K thermalization line are kept in circulation)
- In our case the level was at 68% when the 2K liquid helium supply was stopped and went down to 34% 105min later

- These measurement gives us :

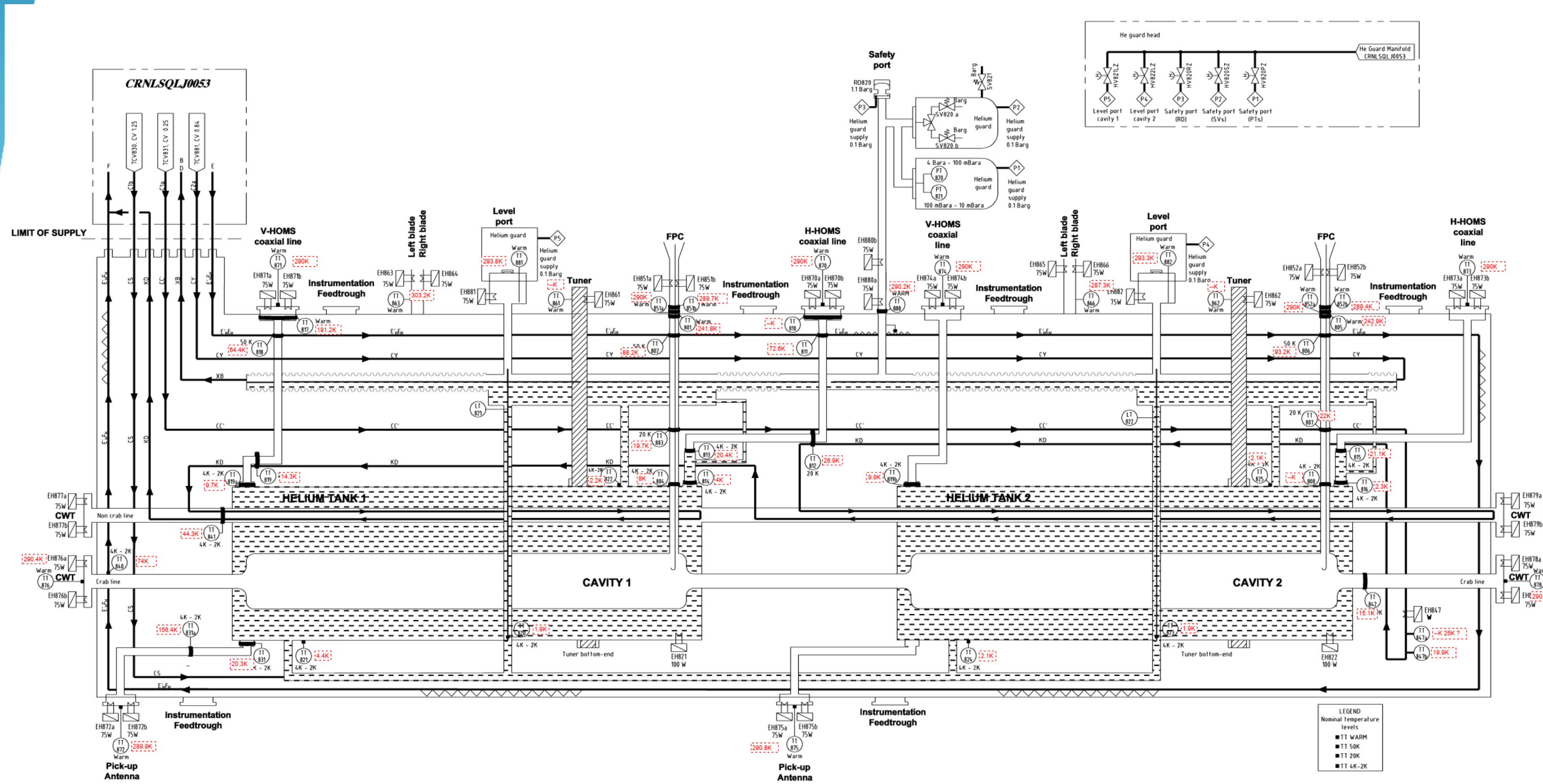
- 68 to 34% : ~52.5L
- Time : 105min
- Load on 2K : ~21W
- Load estimated : 23.7W

(See EDMS 2310389)

See the presentation by K. Turaj



SM18 – M7 test T° measurement feedback

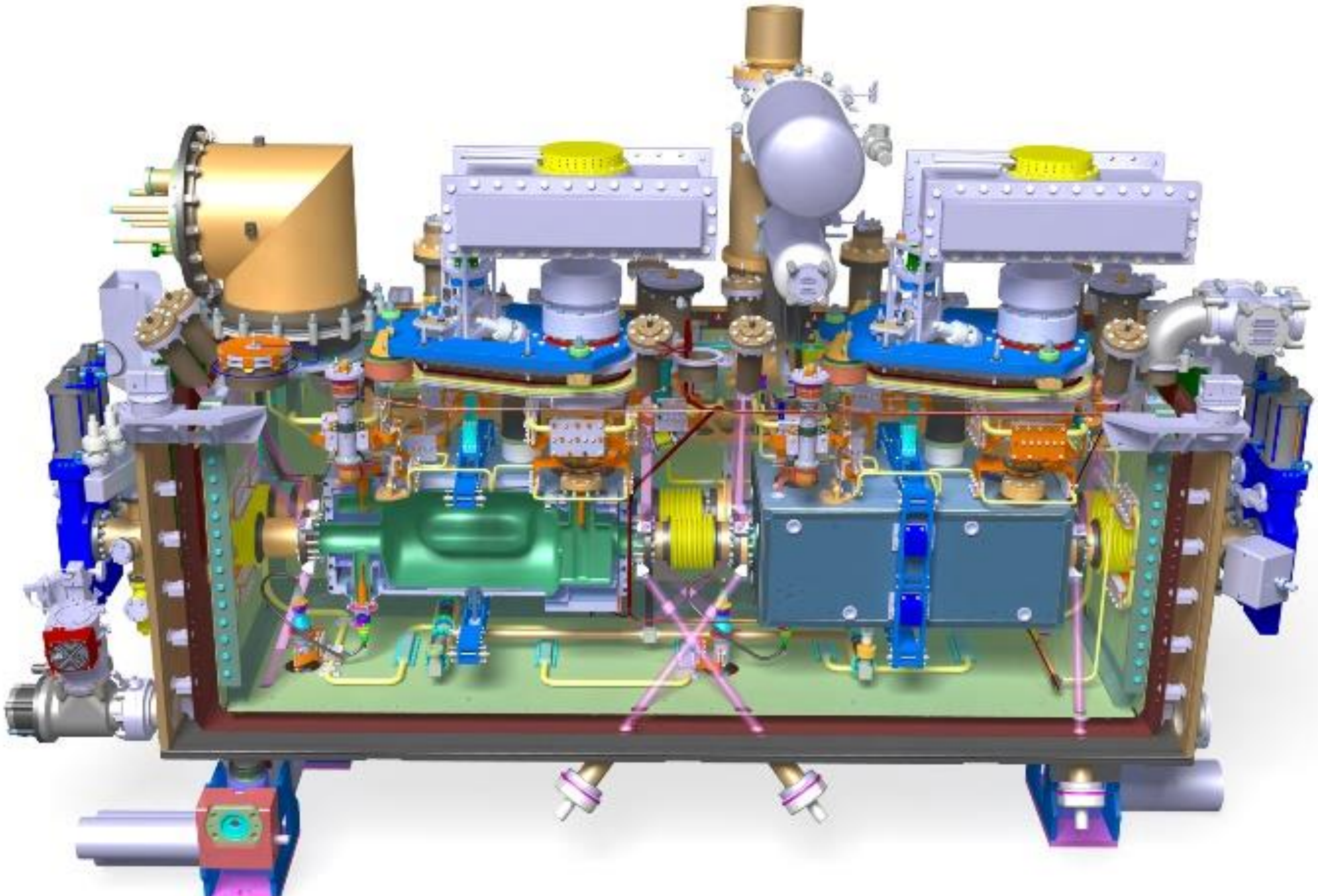


- Good matching of the temp measured WRT simulation
- Robustness of the simulation performed -> validation of design for LHC CMs

Conclusions

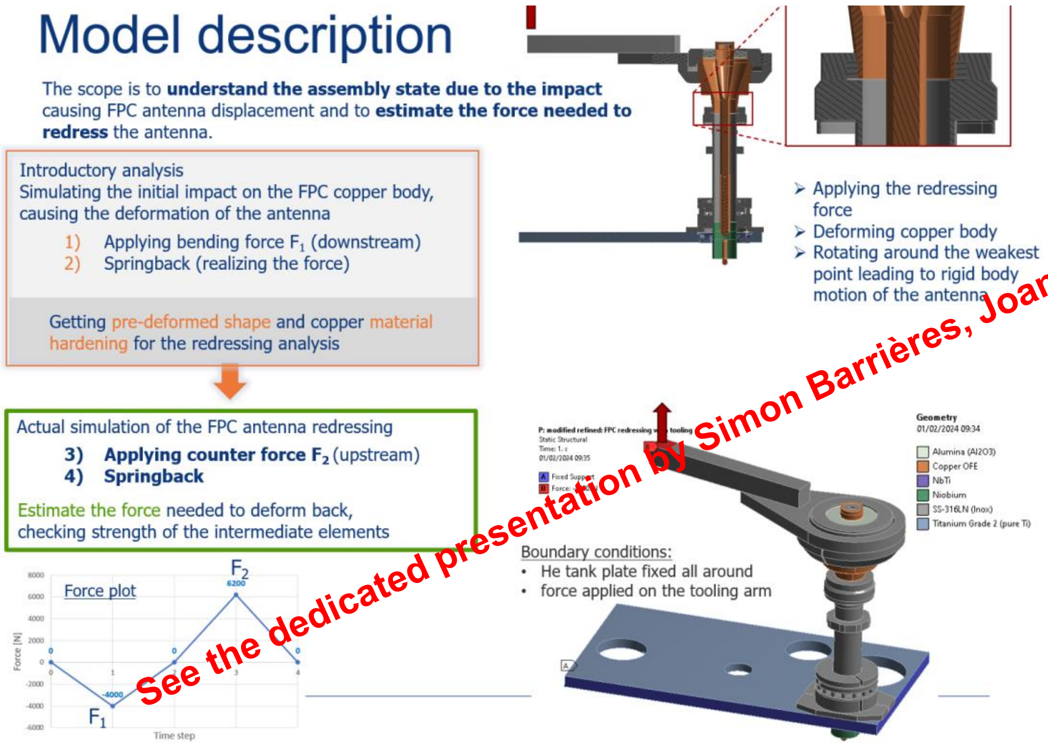
- Engineering activities both cryomodules enter final phase
  - Assembly BOMs & steps 6-12 -> adaptation for STFC and Triumf
  - Follow up manufacturing and evaluation impact of CRs and NCRs
  - Definition of missing design for LHC integration (cable rooting, transport, interfaces with surrounding equipment)
- Preparation of CERN cryomodule assembly procedures
  - Step 1-3 done – further steps are on-going
- Update thermal budget evaluation for both cryomodule

Thank you for your attention

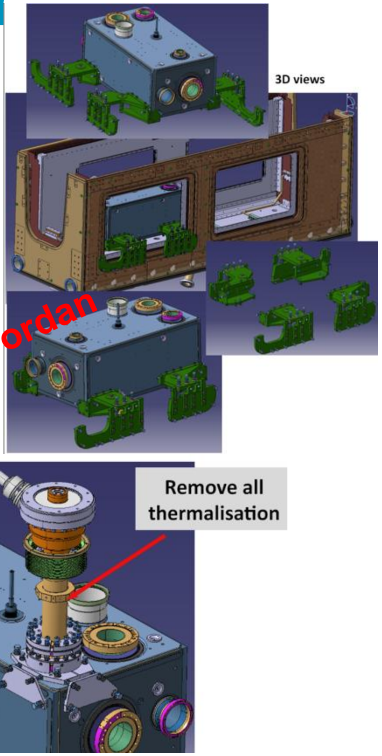


Design and Sim. Activities for FPC repair

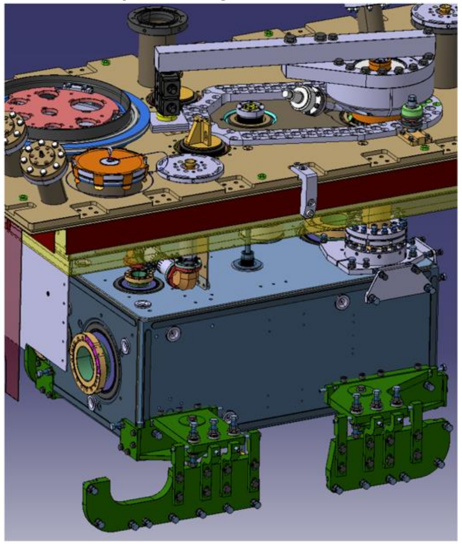
- Mechanical simulation : EDMS 2977959 – J.SWIESZEK
- Tooling design to repair both cavities : EDMS 2977959 – P.MINGINETTE



courtesy J.SWIESZEK



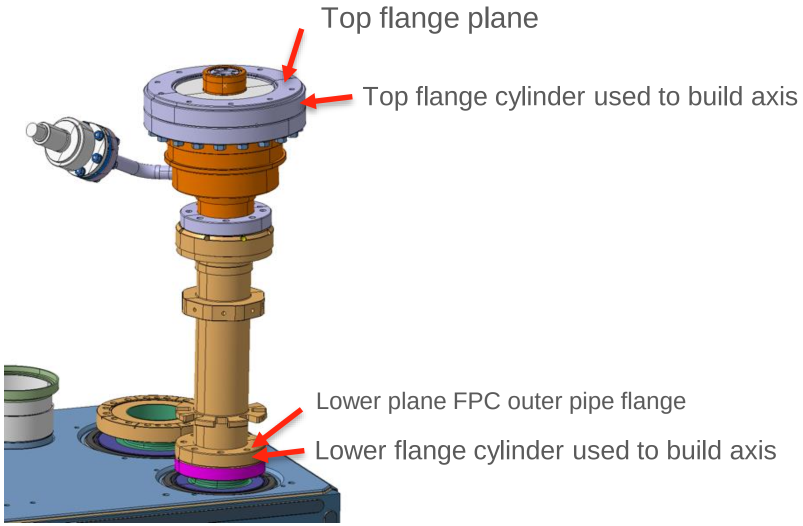
courtesy P.Minginette



The calculation and the design were iterative and includes the inputs from S.Barrière, L.Prever Loiri and SY/RF (S.Calvo, E.Montesinos)

Virtual evaluation of deformation
FSI Measures – V.Rude

- A measure of both the top FPC flange and the lower FPC outer pipe flange (Plane + axis for both) show a deviation as described on the sketches bellow :



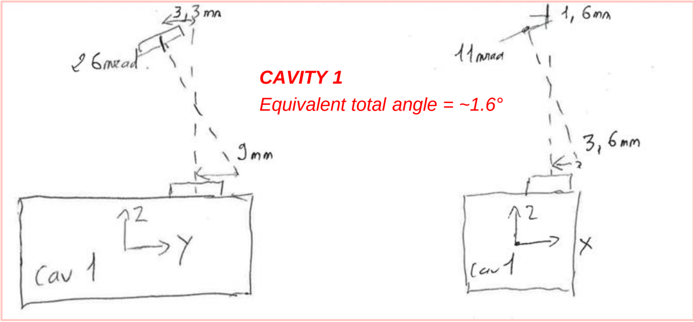


Fig .5 *Measured using laser tracker – courtesy V.Rude*

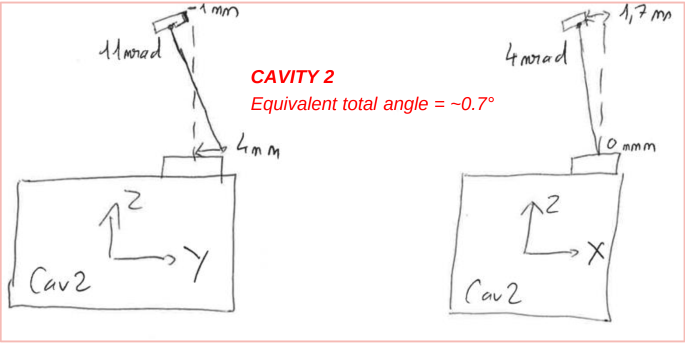
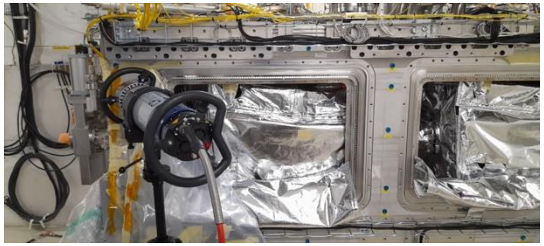


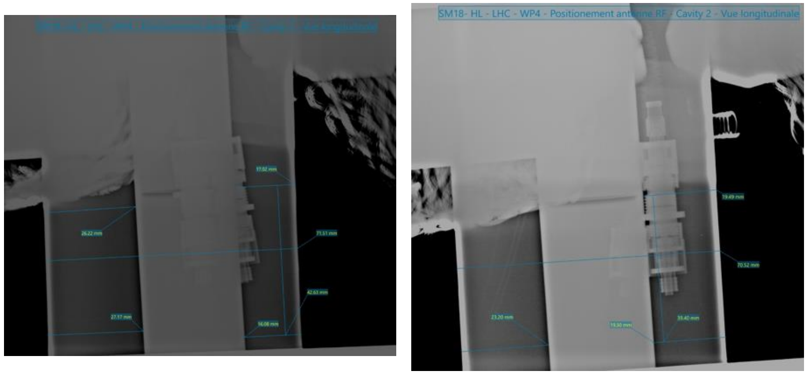
Fig .6 *Measured using laser tracker – courtesy V.Rude*

Virtual evaluation of deformation Radiographic measures – A.Porret

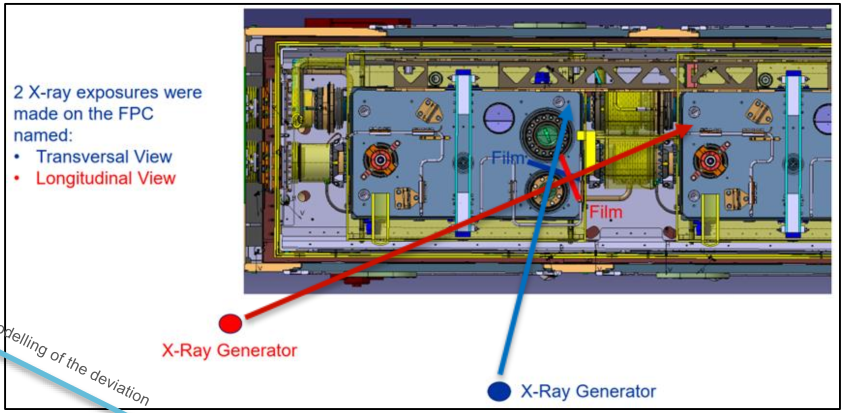
- X-ray confirms our preliminary observations :
  - The hook isn't bended
  - The deviation starts from the top



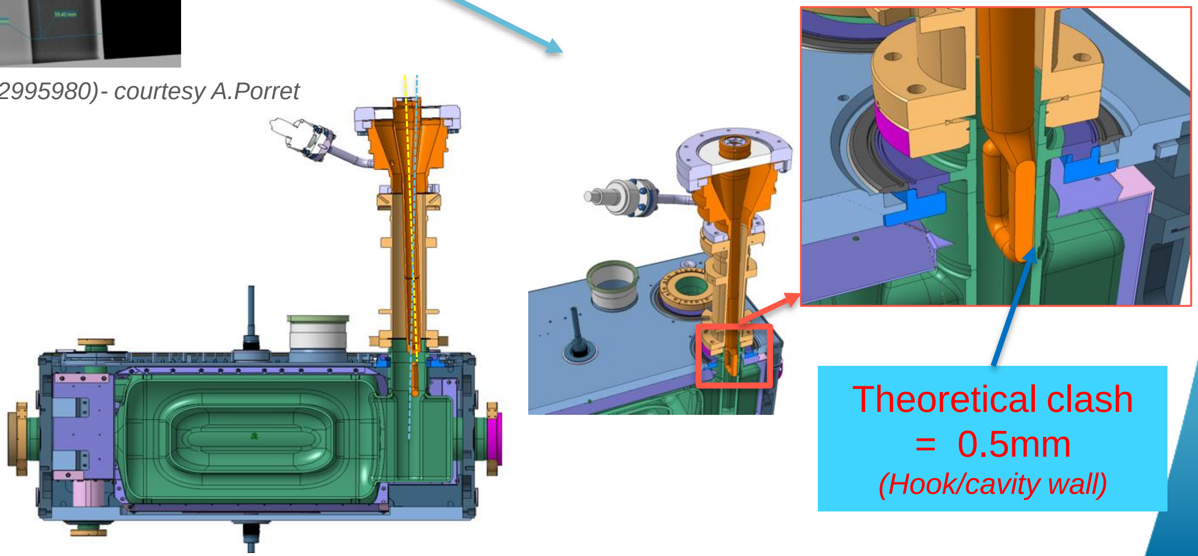
Set up preview - courtesy A.Porret



Result of radiographic measure (see full results in EDMS 2995980)- courtesy A.Porret



3D modelling of the deviation



Bonus : Test of material for clean room tooling

Machining

Non-anodized Aluminum

Additive manufacturing

Accura25 (Polycarbonate)

PLA (Polylactic acid)

- Cost of manufacturing :
  - the Accura cost of manufacturing is 2 times the cost of the PLA
  - Aluminium parts costs 4 times the PLA part

Results

	0,3µm	0,5µm	1µm	5µm	ISO
Aluminum	0	0	0	0	1
Accura25	211	194	158	17	5
PLA	2818	741	194	0	5

Extracted from report EDMS 3141216
(courtesy Micaela Battista – Nuria Valverde)

Figure 1. ISO 14644-1 Cleanroom Classifications

Class	Maximum Particles/m³					
	≥0.1 µm	≥0.2 µm	≥0.3 µm	≥0.5 µm	≥1 µm	≥5 µm
ISO 1	10	-	-	-	-	-
ISO 2	100	24	10	-	-	-
ISO 3	1,000	237	102	35	-	-
ISO 4	10,000	2,370	1,020	352	83	-
ISO 5	100,000	23,700	10,200	3,520	832	-
ISO 6	1,000,000	237,00	102,000	35,200	8,320	293
ISO 7	-	-	-	352,000	83,200	2,930
ISO 8	-	-	-	3,520,000	832,000	29,300
ISO 9	-	-	-	35,200,000	8,320,000	293,000

Discussion about the possibility to use Accura if the part is not close to the working area
(i.e. : close to open SRF/UHV volume)

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

Alignment / Survey activities during CM build

#	Task Name
0	CM2
1	**Step Aux.A - Pre-Cleanroom**
4	Alignment of components on the trolley
6	**Step1 - Cleanroom String Assembly**
22	**Step Aux.F Top Plate Equipped**
23	Attach fiducials to Top Plate
24	Install FSI heads
25	Fiducialization of top plate
33	**Step Aux.*G* Lower OVC**
34	Attach fiducials to lower OVC
35	Install FSI heads
36	Fiducialization of lower OVC
38	**Step3 BiPhase & Tuner Frame Assy & FPC Plate Weld**
40	Alignment of FPC plate
60	**Step 5 Top Plate Assy & Interfaces**
64	Alignment of top plate WRT string
72	**Step 6 Load Transfer**
76	Install FSI targets on cavity flanges
98	**Step 10 Lower OVC Integration**
101	Alignment between lower vessel and top assembly
105	Check alignment of cavities -->Model for the movement of the cavities caused by vacuum and cooling
	Installation FSI system + Optcal fibers
	Measurement of the cryomodule + FSI Heads at ambient pressure
	Intercomparison FSI versus laser tracker
106	**Step 11 OVC Welding & CM Ancillaries**
118	**CM2 Acceptance Tests**
119	Pressure Tests
	Measurement of the cryomodule + FSI Heads under vacuum
120	Cold Cycling + Tuner Check
	Measurement of the cryomodule + FSI Heads at cold