Design of beam lines inside 11T dipoles and TCLD collimators cryostats

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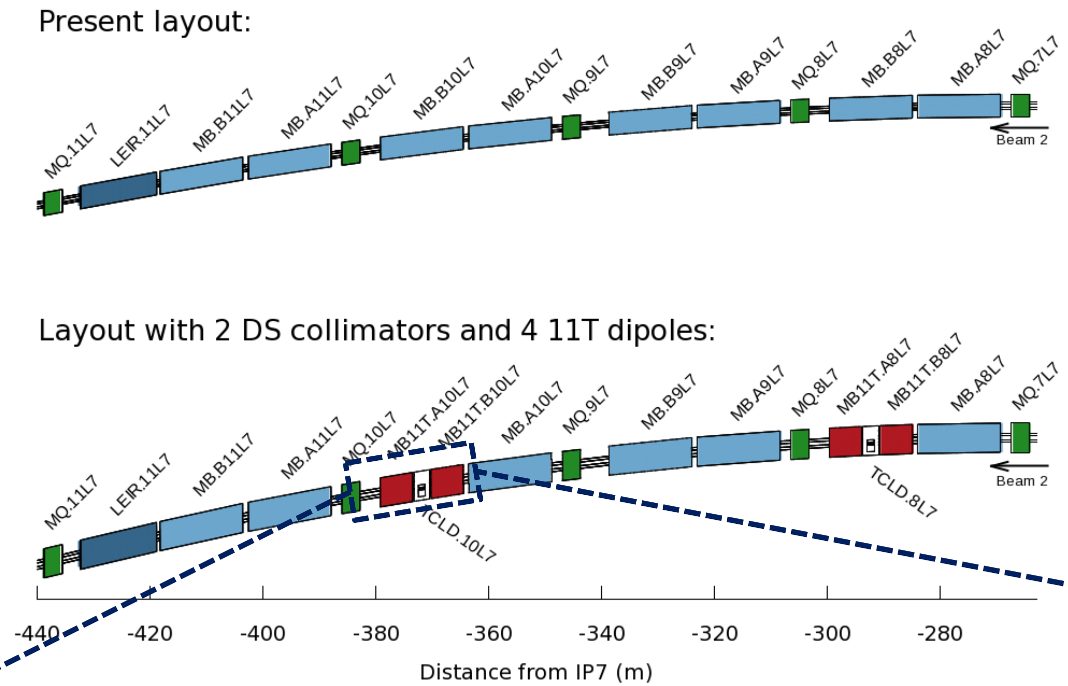
V. Baglin, G. Bregliozzi, E. Page, J. Finelle, N. Zelko.

TE-VSC Seminar
Friday, 10th June 2016
CERN

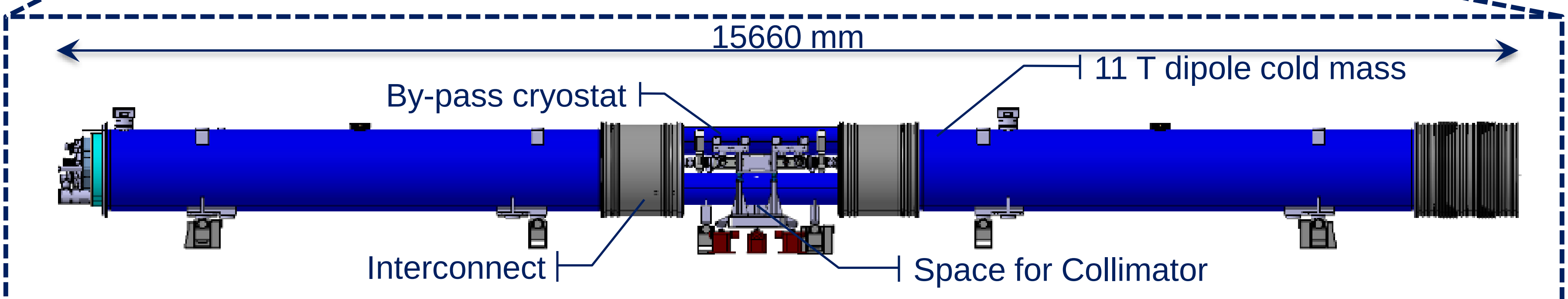
Outline

1. Project guideline and status
2. Design of critical components
3. Instrumentation, integration and quality
4. Conclusion

Integration baseline



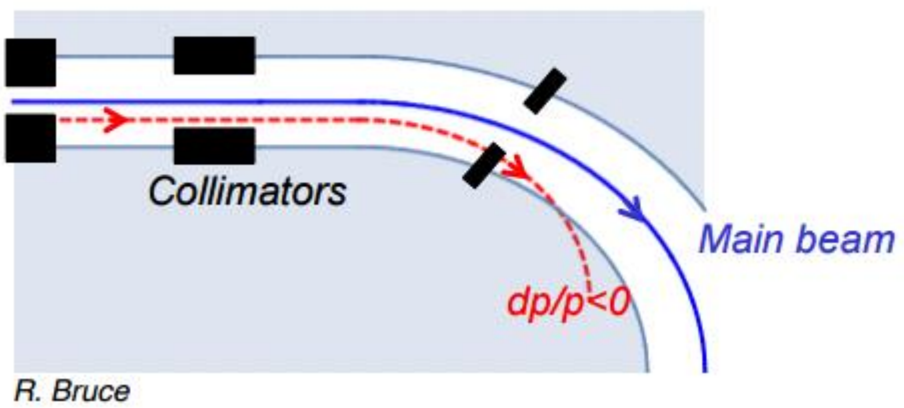
<u>Aim</u>**:** Replace a main dipole (or a connection cryostat) by 2 11T dipoles (or 2 connection cryostats) and 1 TCLD collimator at several places in IR7 and IR2.



F. Savary, Introduction and New 11T Plan in HL-LHC, 6th April 2016

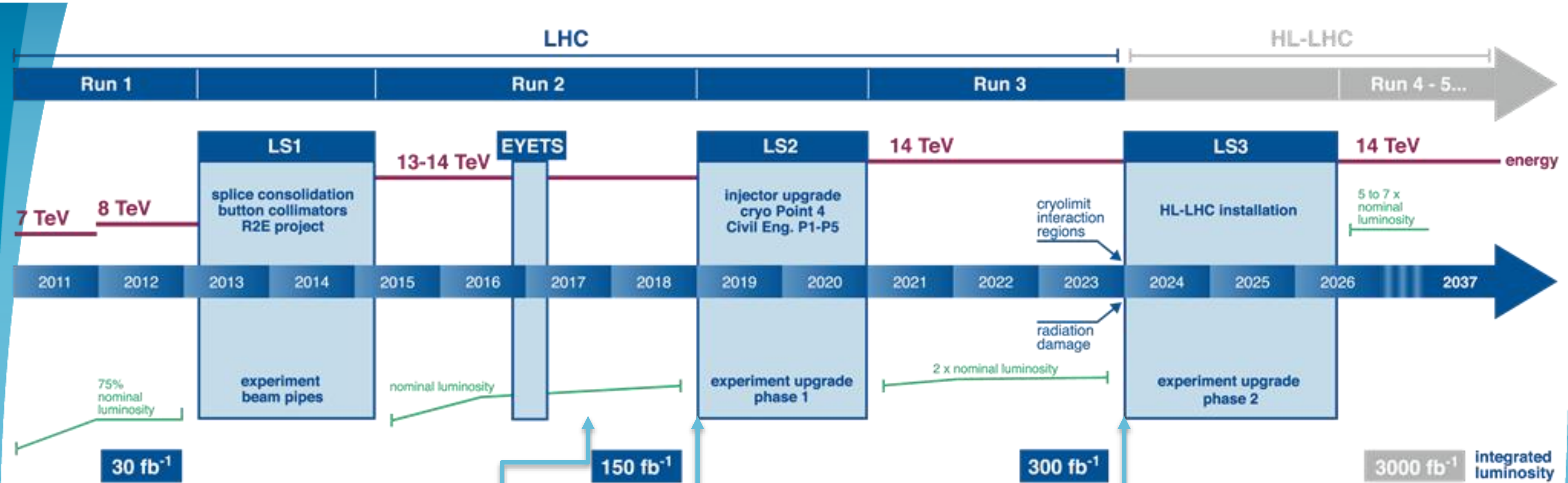
Goals

- Create space in the DS regions of the LHC to install TCLD collimators (Target Collimator Long Dispersion suppressor)
- These collimators will be installed to clean particles that start deviating downstream of LSS collimators in order to protect exposed magnets.
- The pair of 11T dipoles will produce the same integrated field than a main dipole (119 T.m)



Needs and timeline

For more details F. Savary, HL-LHC integration meeting, https://indico.cern.ch/event/502026/



- 1 Bypass cryostat prototype

- P2: 4 Connections cryostats + 2 bypass cryostat
- IP7: 4 11T dipoles + 2 bypass cryostat
- 1 11T dipole spare unit*
- 1 prototype RRP

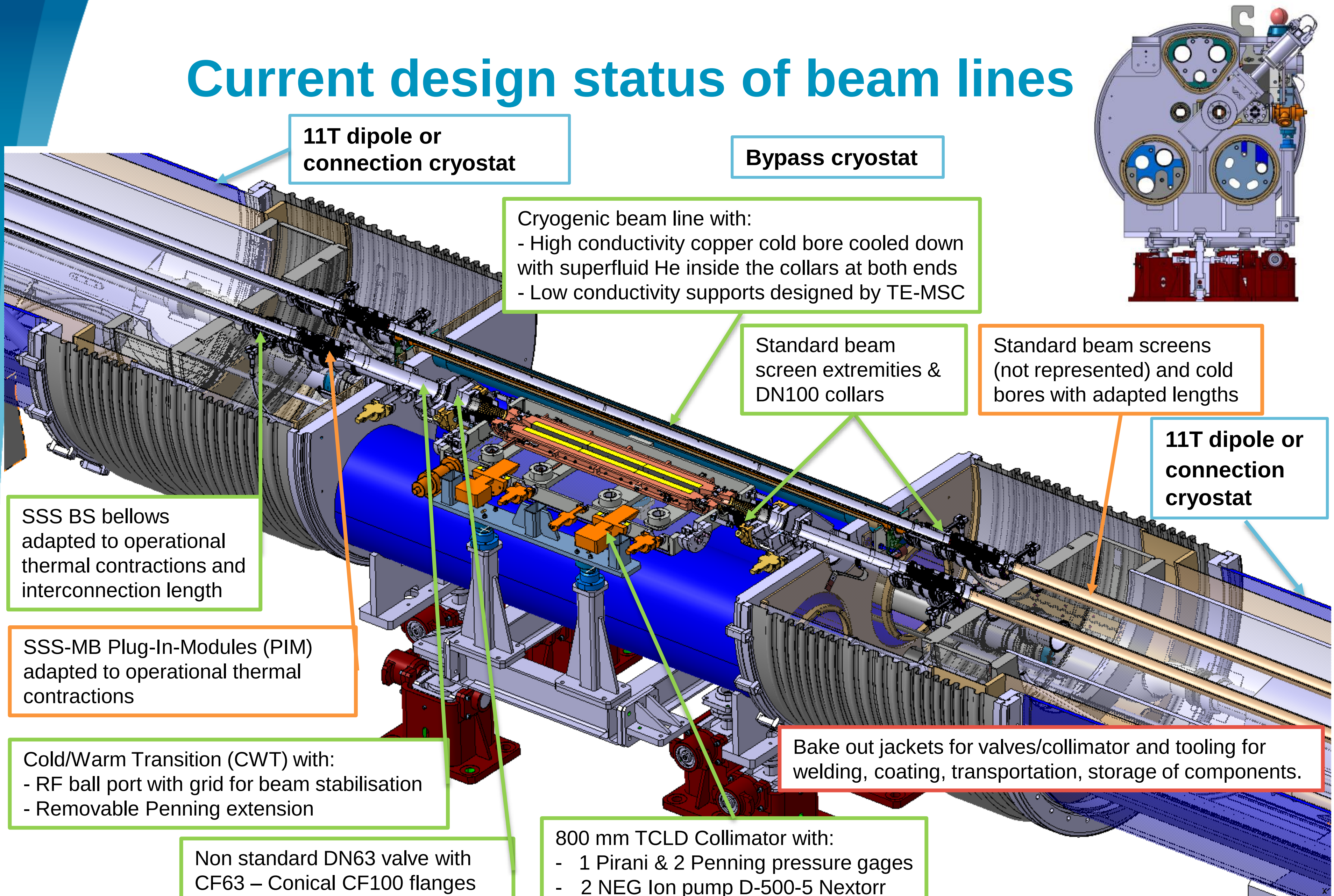
- IP7: 4 11T dipoles + 2 bypass cryostat
- 1 11T dipole spare unit*
- 1 prototype PIT

Quantities to be confirmed
*The prototypes can be used as spare

TE-VSC aim: not to be the limiting element i.e we need to have assembled the bypass cryostat by the end of 2017 and the first dipole before LS2 (end 2018) and have the components ready to install in the other units (fully tested and controlled).

Note: The beam screen facility won’t be ready before mid-2017

Current design status of beam lines



ST0660382 – Christophe Mucher

Finished — On going — Not started

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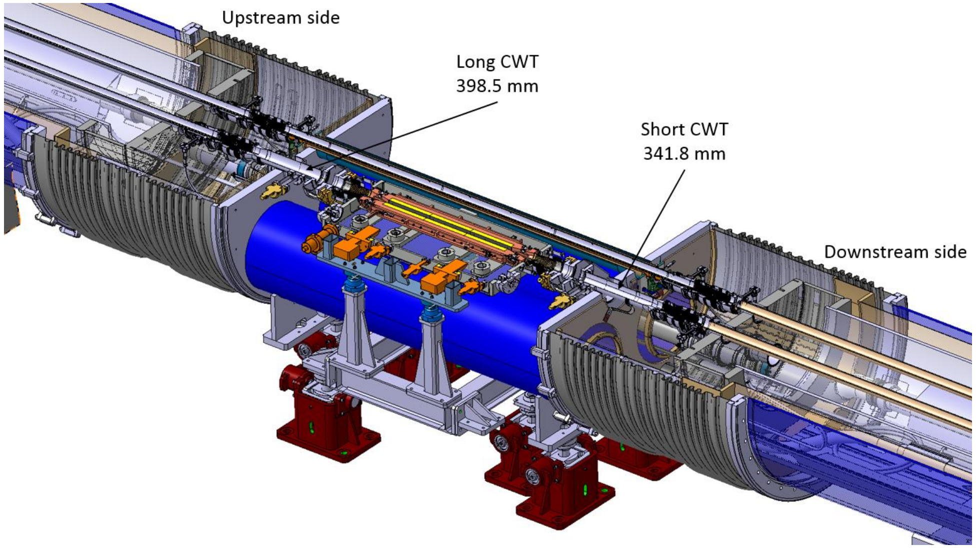
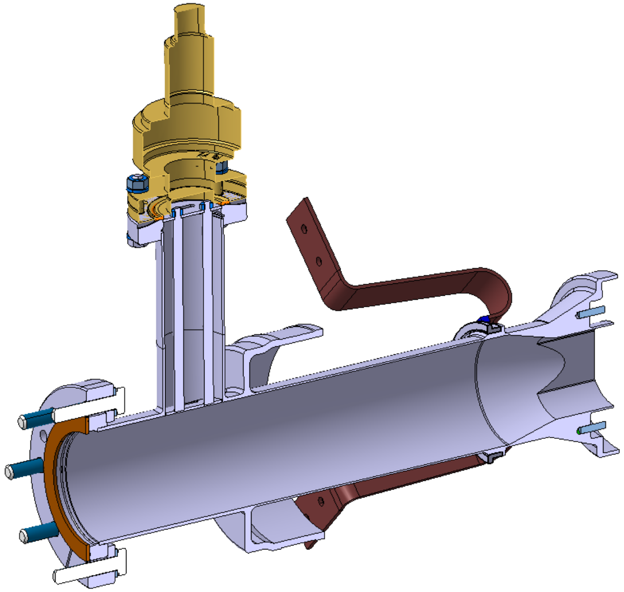
Cold-Warm Transition (CWT) - Requirements

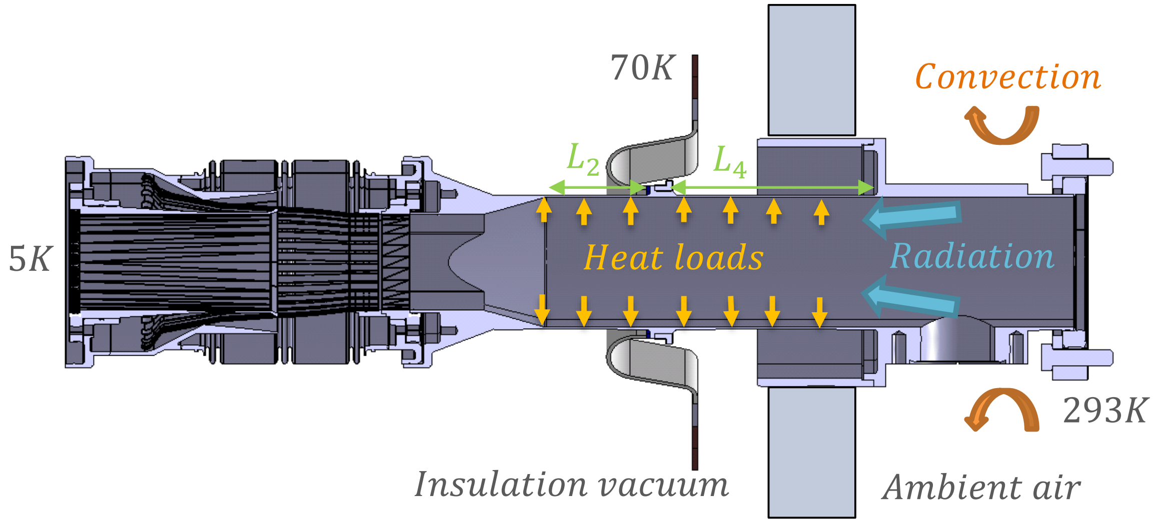




- **Ensure the connection between the cryogenic beam line and the room temperature region (collimator) while respecting different requirements:**
  - ✓ Ultra-high vacuum → no leak rather than $10^{-11}\ Pa.m^3.s^{-1}$ ($10^{-10}\ mbar.l.s^{-1}$))
  - ✓ Pressure measurement, interlock as close as possible to the valve → Penning on RF ball port
  - ✓ Alignment, position, orientation, length with reduced interconnection and aperture Ø63 mm
  - ✓ Beam stability → good electrical conductance and continuity to respectively minimise the transverse impedance and ensure the continuity of the image current
  - ✓ Limit the thermal leak reaching the cold part, the heat load to the beam screen has to be below 2.5 W (*EDMS n°351092, I. Collins, B. Jenninger, J.K Refolio, 2002)*
  - ✓ Avoid solid and liquid condensation in the room temperature area

CWT - Finite element model

- Static heat loads:
  - Actively cooled beam screen (Between 5 K and 20 K)
  - Actively cooled thermal shield (Around 60 K → 70 K at the braids end)
  - Vacuum vessel at room temperature (293 K) representing the convection on the cryostats
  - Convection on the part in contact with the air (1 W/m².K)
  - Heat load from image current, electron cloud and SR respectively 522, 4264 and 310 mW/m *(p.170 The HL LHC, Oliver Bruning and Lucio Rossi)*
  - Thermal radiation from the room temperature chamber to cryogenic equipment

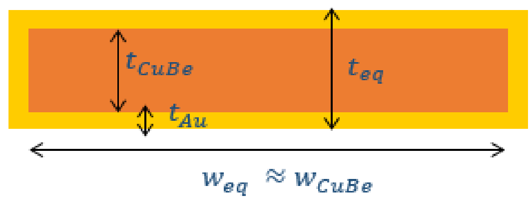


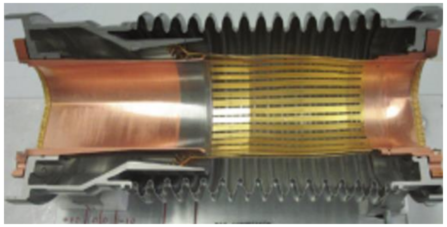
Use of equivalent material for PIM RF fingers

Use of thin layer to represent the copper coating inside the CWT drift tubes

Where to position the heat interception (70K) ?

CWT - Material properties

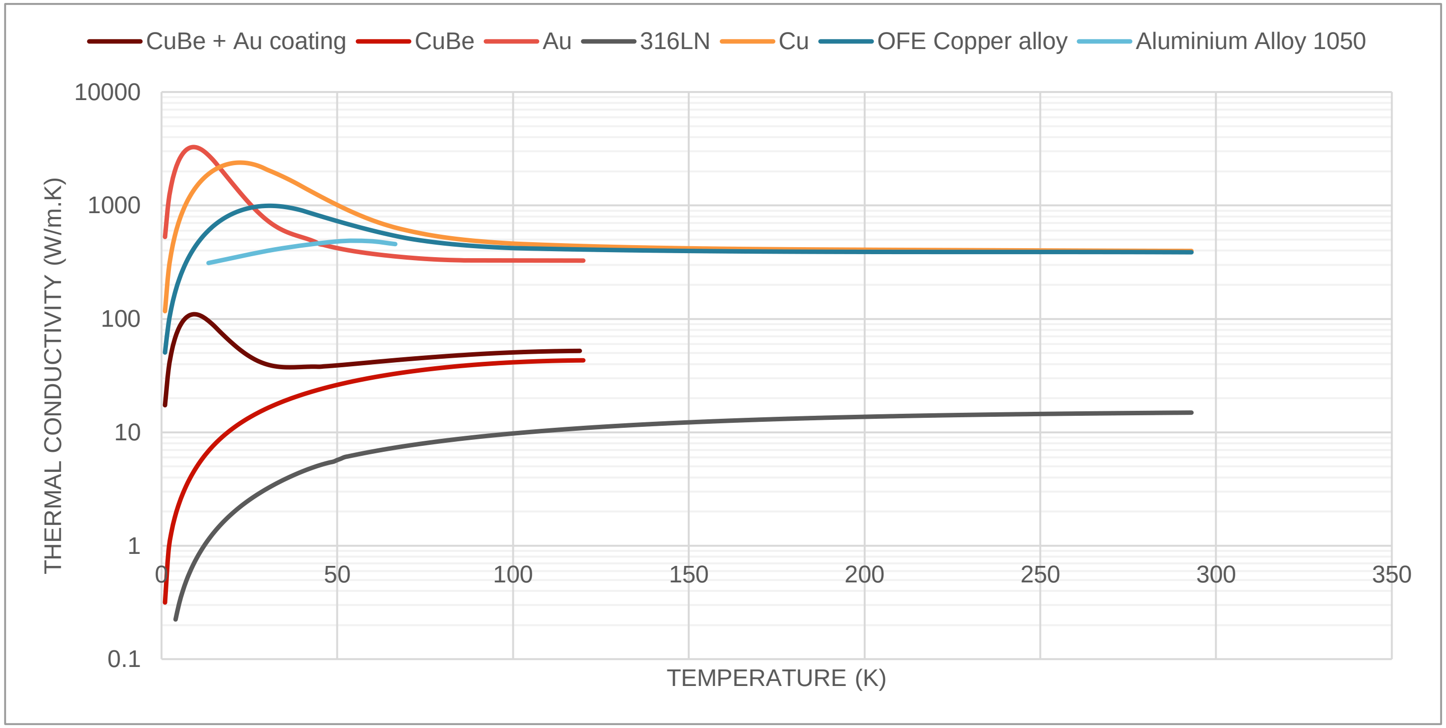




Equivalent CuBe RF finger with 5 μm Au coating:

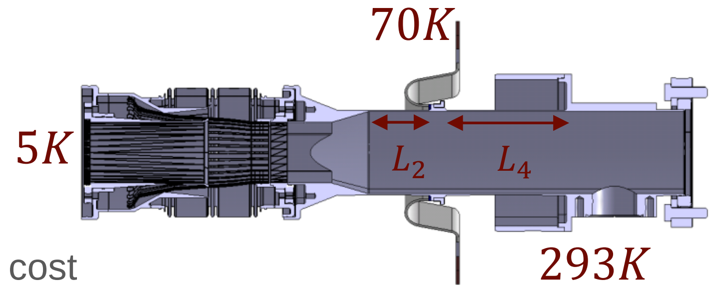
$$\int \lambda_{eq} dT \approx \frac{t_{CuBe}}{t_{CuBe} + 2t_{Au}} \int \lambda_{CuBe} dT + \frac{2t_{Au}}{t_{CuBe} + 2t_{Au}} \int \lambda_{Au} dT$$

λ: Thermal conductivity (W/(m.K))
t: Thickness (m)
T: Temperature (K)



Data from MPDB database

CWT - Thermal performance



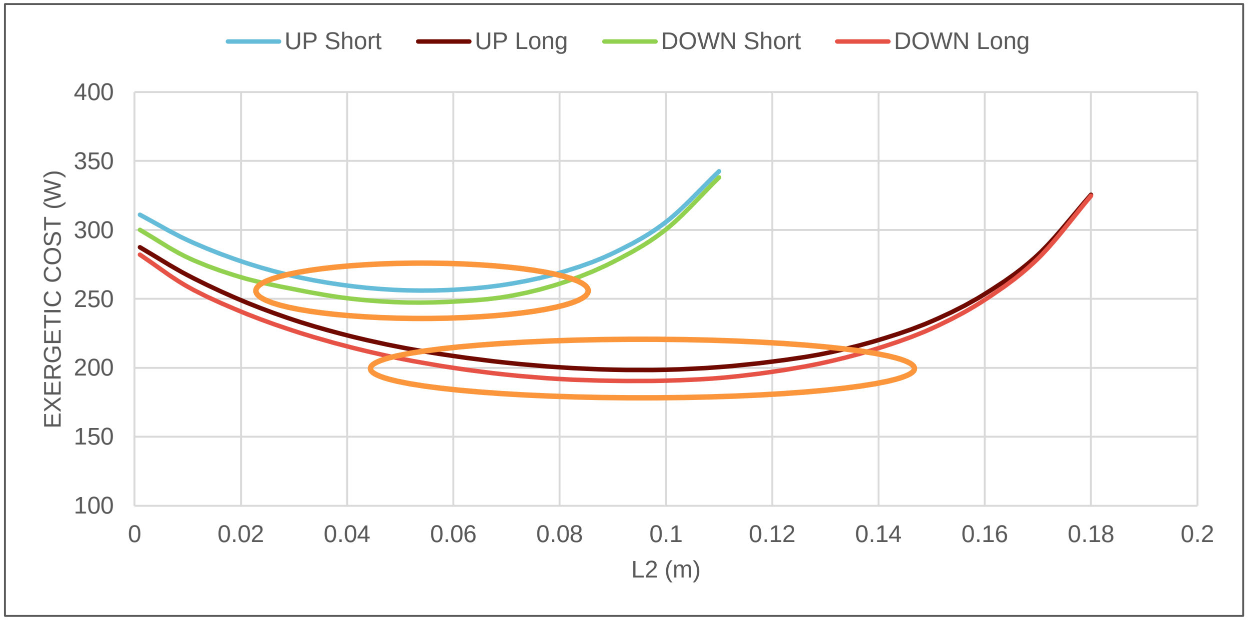
- Weighting function of low-temperature refrigeration exergetic cost

$$Q_{tot} = Q_{5K} * 125 + Q_{70K} * 16$$

(Advances in Cryogenic Engineering, Volume 43, Peter Kittel)

Where Q_{5K} and Q_{70K} represent the heat loads at the temperature levels indicated in Watts.

- The minimum of exergetic cost corresponds to the best position for the heat interception (70K) to minimise the refrigeration cost.



Best configuration in terms of thermal performance

CWT - Condensation

Convection FE simulation on the entire model:

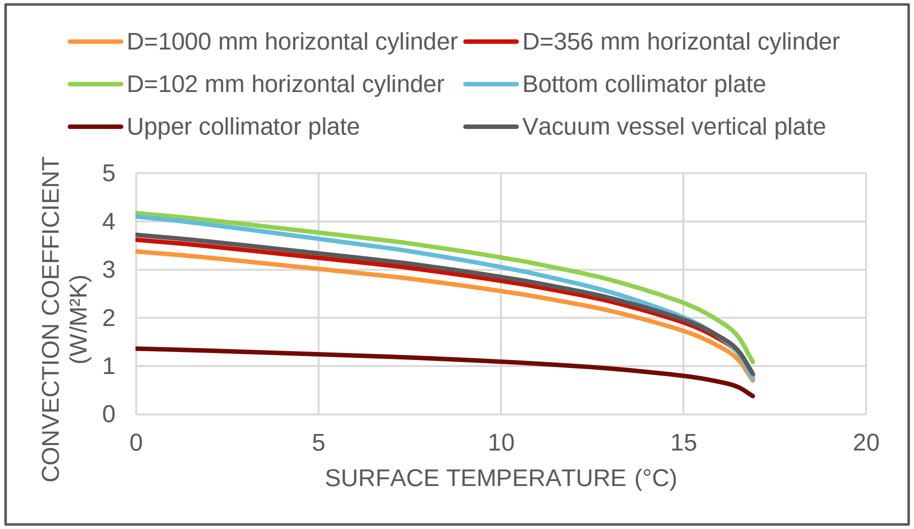
- The convection coefficient has been set to an average value of 2 W/(m.K) assuming a small delta of temperature between the vacuum vessels and the air inside the LHC (around 17°C)
- Churchill and Chu correlation and W. H. McAdams equations have been used to define the convection coefficient of each part in contact with the ambient air.

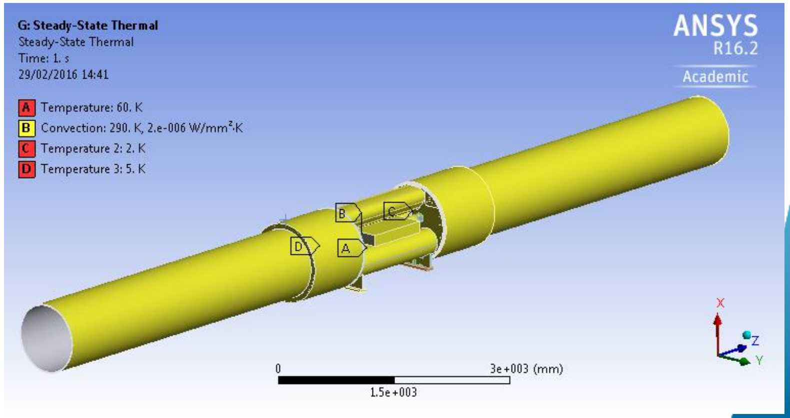
Analytical models used to calculate convection coefficients

Horizontal cylinder	$h = \frac{\lambda}{D}\left(0{,}6 + \frac{0{,}387 {Ra_D}^{1/6}}{\left(1+\left(0{,}559/P_r\right)^{9/16}\right)^{8/27}}\right)^2$
Vertical plate	$h = \frac{\lambda}{L}\left(0{,}825 + \frac{0{,}387 {Ra_D}^{1/6}}{\left(1+\left(0{,}492/P_r\right)^{9/16}\right)^{8/27}}\right)^2$
Horizontal plate cold surface facing down	$h = \frac{\lambda 0{,}27 {Ra_L}^{1/4}}{L}$
Horizontal plate cold surface facing up	$h = \frac{\lambda 0{,}14 {Ra_L}^{1/3}}{L}$

Where:

h Convection coefficient $(\mathrm{W/(m^2.K)})$
λ Thermal conductivity $(\mathrm{W/(m.K)})$
D, L Characteristic dimension
Ra, P_r Rayleigh, Prank numbers

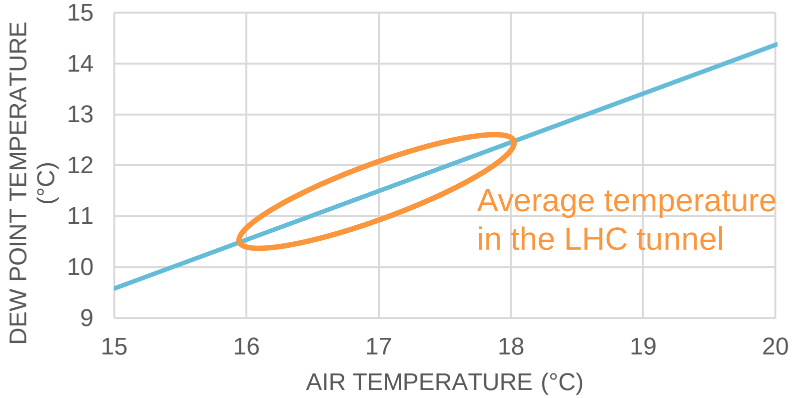




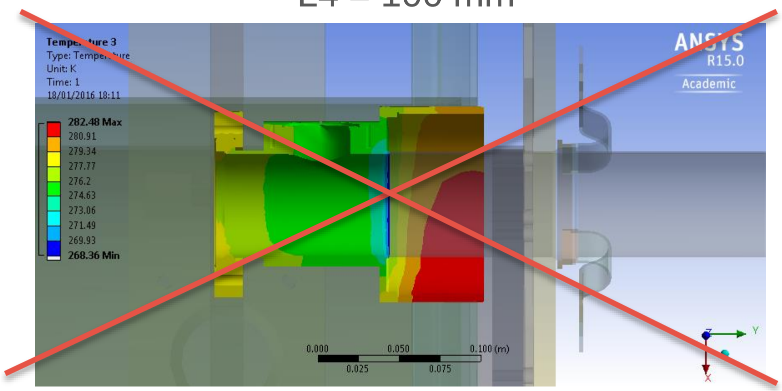
CWT - Condensation

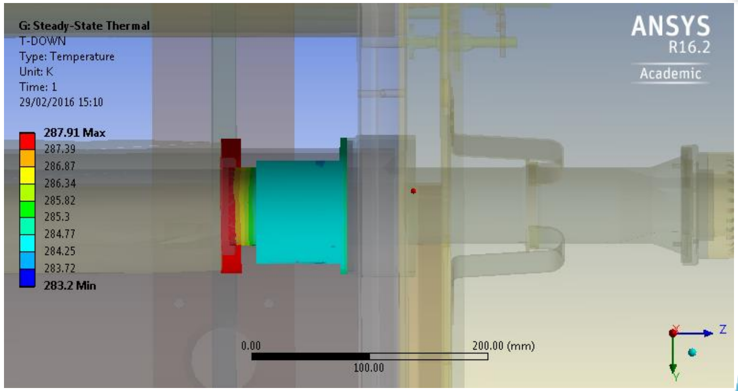
- Temperature on the part in contact with ambient air

Dew point temperature as a function of the ambient air temperature for 70% of humidity.



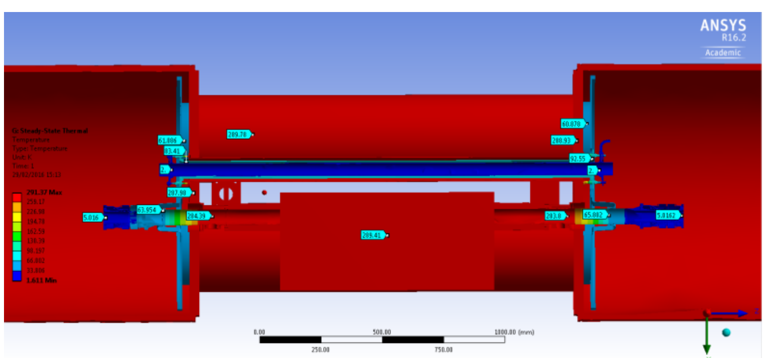
L4 = 100 mm





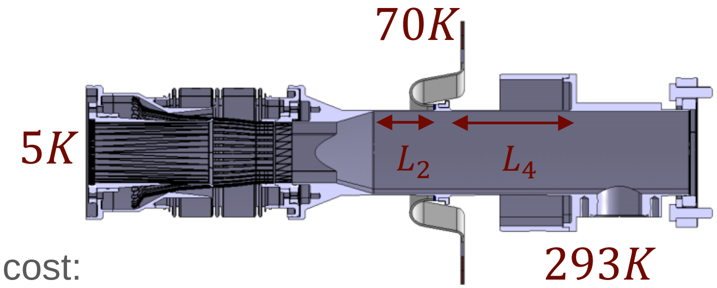
L4 = 148 mm

Temperature repartition on cryostats and beam lines



We might observe a bit of condensation but very locally together with low temperature of high humidity rate.

CWT - Thermal performance



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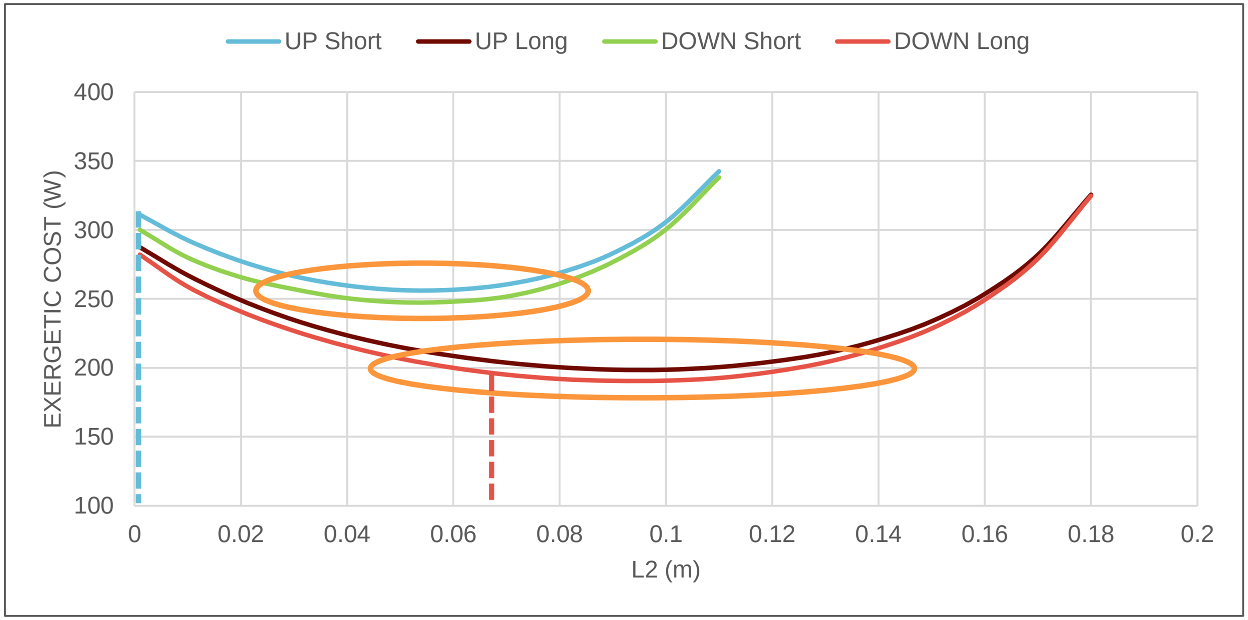


Best configuration in terms of thermal performance

CWT - Radiation

Net radiation analytical model:

$$Q_{1\to2} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\epsilon_1}{A_1\epsilon_1} + \frac{1}{A_1 F_{A1\to A2}} + \frac{1-\epsilon_2}{A_2\epsilon_2}}$$

Where:

$Q_{1\to2}$ Net radiation (W)

ϵ_1 Emissivity

T Temperature (K)

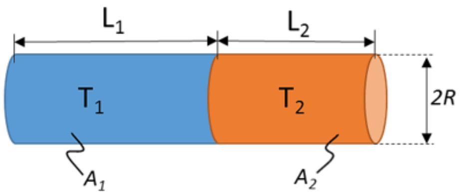
A_2 Surface area (m^2)

σ Boltzmann constant ($\mathrm{W.m^{-2}.K^{-4}}$)

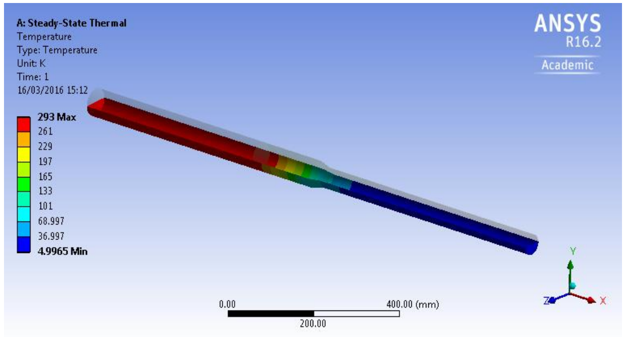
$F_{A1\to A2}$ View factor

With a view factor analytical model:

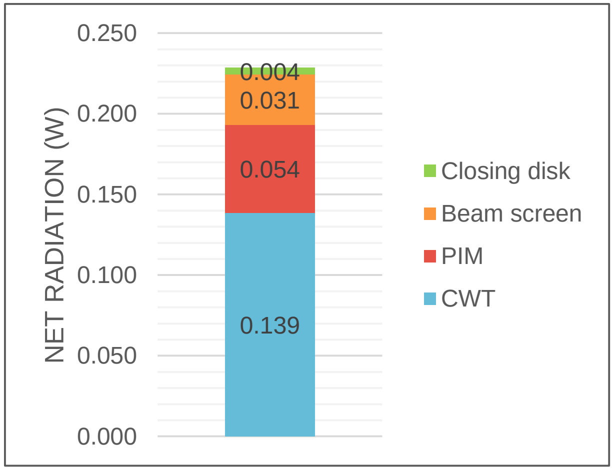
$$F_{1\to2} = \frac{L_2}{2R} + \frac{1}{4}\left[\sqrt{4+\frac{L_1^2}{R^2}} + \frac{L_2}{L_1}\sqrt{4+\frac{L_2^2}{R^2}} - \left(\frac{L_1+L_2}{L_1}\right)\sqrt{4+\left(\frac{L_1+L_2}{R}\right)^2}\right]$$



Little influence of the radiation for this aperture



CWT radiation model settled as surface to surface with 0.05 surface emissivity (copper coating)

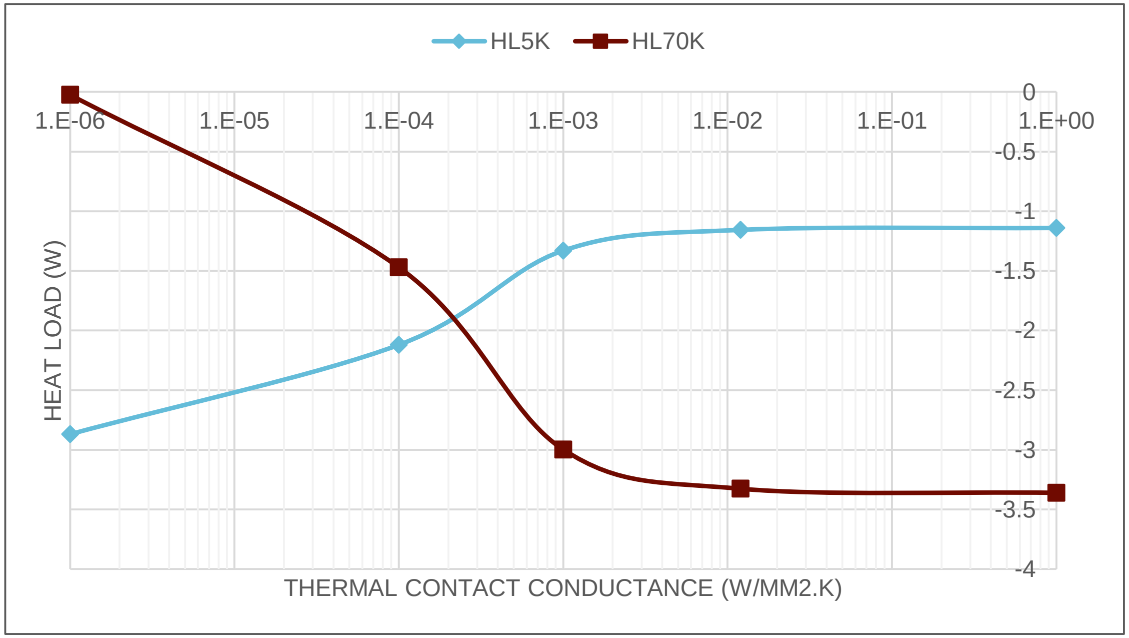


Heat loads due to radiation reaching each parts

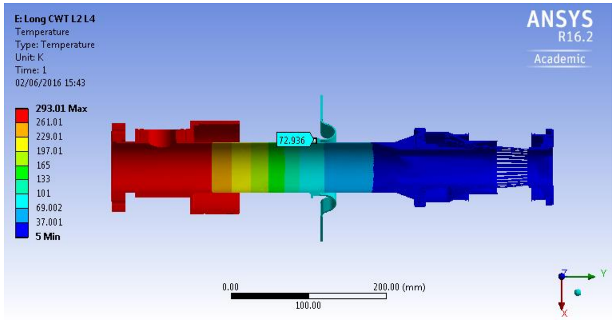
More details in the note, EDMS 1610910, Thermal radiation simulation guidelines for cylindrical enclosures, M.Sitko, Q. Deliege

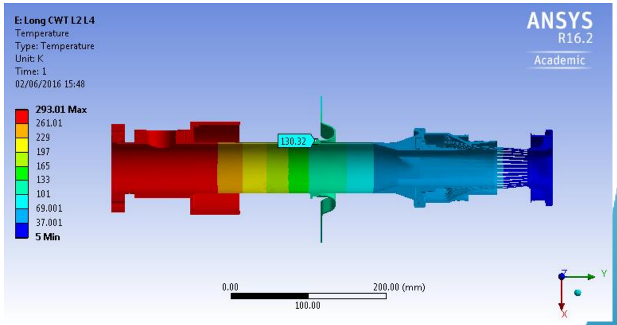
CWT - Braids

- TE-MSC made the request to stop welding the bonded bi-material Al/Cu to the thermal shield in order not to warm up the flammable M.L.I. → use of riveted nuts + bolts
- It has to be verified that the thermal contact conductance (TCC) remains over $1.10^{-3}\ W/(\mathrm{mm}^2.K)$ to avoid to much heat load on the 5K level. Use of thermal grease or ductile material ?



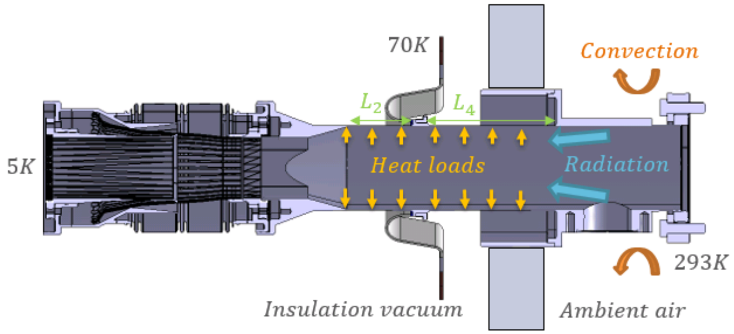
Perfect TCC





$\mathrm{TCC} = 1.10^{-3}\ W/(mm^2.K)$

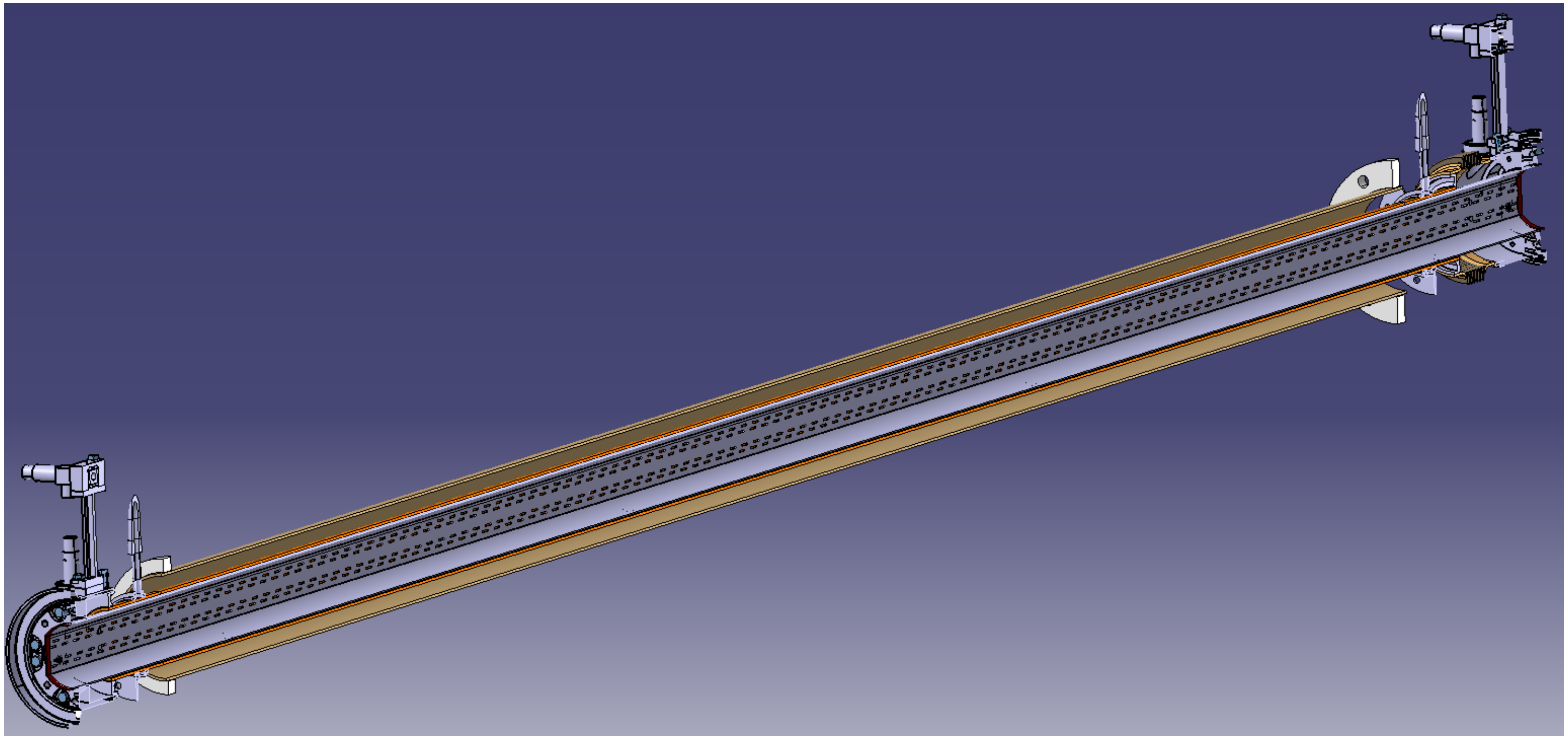
CWT - Conclusion



CWT drift tube total length (mm)	Short 148 mm	Long 214 mm	Average on both CWTs
PIM position	Upstream	Downstream	
Exergetic costs (W)	324 W	210 W	267 W
L2 (mm)	0 mm	66 mm	-
L4 (mm)	148 mm	148 mm	-
Heat load 5K including radiation (W)	2,30 W	1,23 W	1,68 W
Heat load 70K including radiation (W)	2,30 W	3,49 W	2,90 W

- Not the best configuration for thermal performances but would avoid liquid and solid condensation.
- The TCCs were considered as perfect in the different simulations. It would be interesting to carry out precise study on TCC, especially on the PIM that contributes a lot to reduce the heat load to the beam screen.

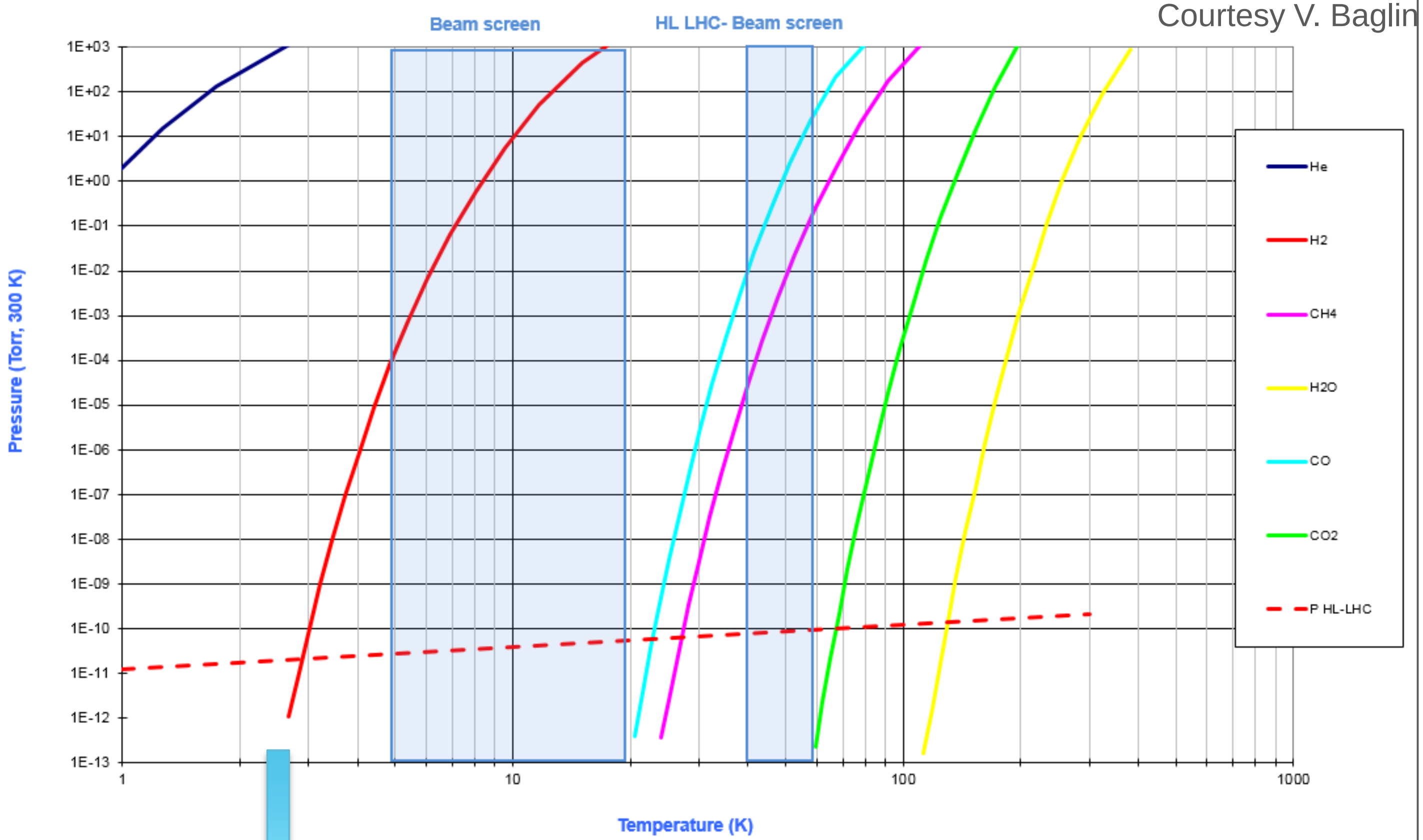
Cryogenic line design



Cryogenic line design

Saturated vapour pressure from Honig and Hook (1960)

Courtesy V. Baglin

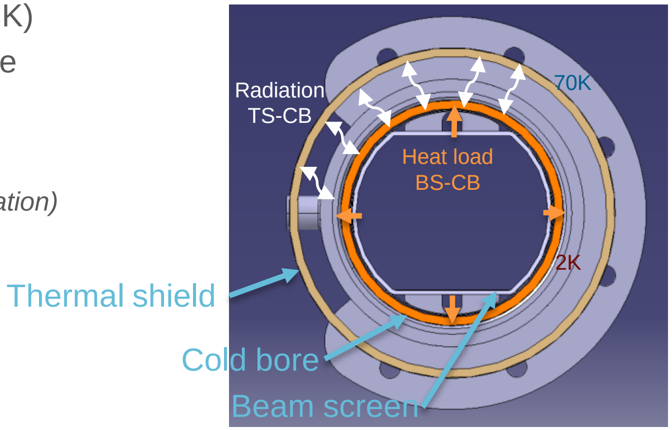


The cold bore temperature should remain < 2.7 K, where H2 saturated vapour pressure > HL-LHC beam vacuum baseline

Cryogenic line – First FE approach

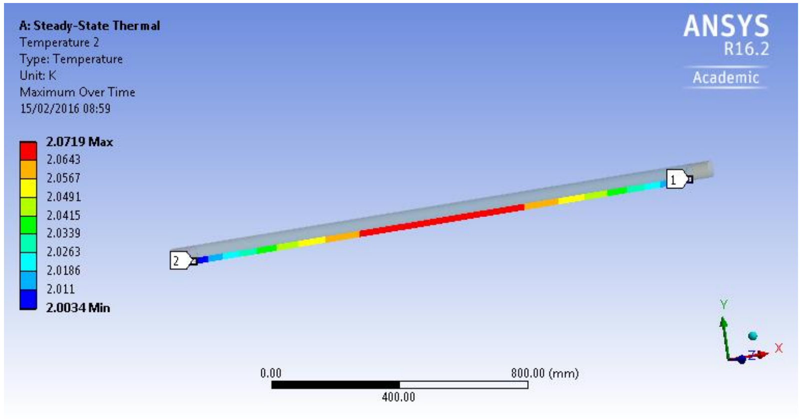
Load conditions

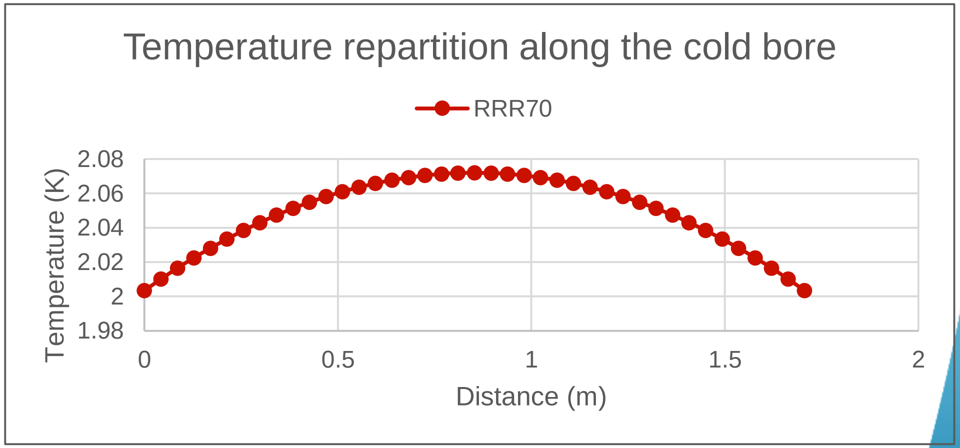
- Thermal shield temperature: 70 K (conservative, usually 55-70 K)
- He cooling rings temperature: 2 K on both sides of the cold bore
- Perfect radiation: thermal shield → cold bore
- Heat load: 0.009 W beam screen → cold bore *(Edms n°350448)*
- Heat load: 0.035 W per support → cold bore *(Ján Hrivňák presentation)*



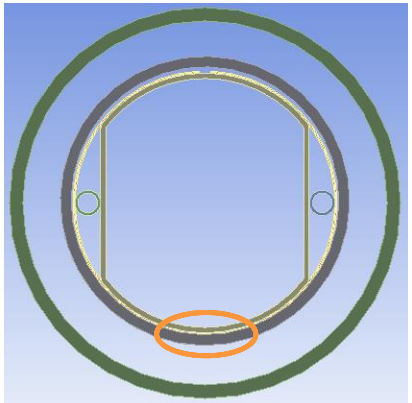
Materials

- SS 316 LN: He cooling rings – welding nozzles
- Al 1050: Thermal shield
- Cu OFE RRR 70: Cold bore 170 W/(K.m) at 2 K



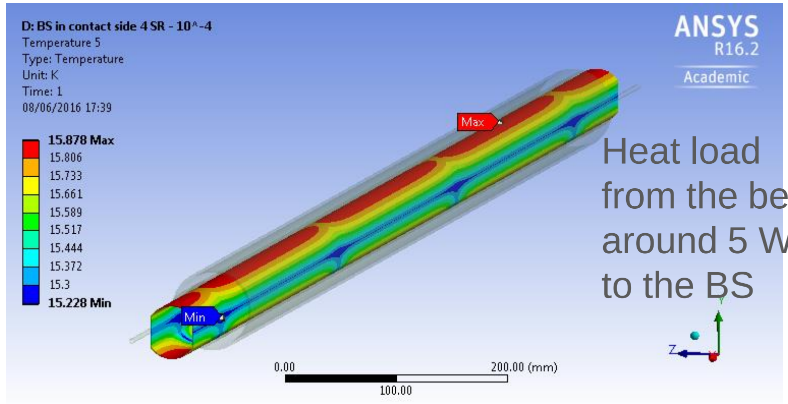


Cryogenic line – Second FE approach

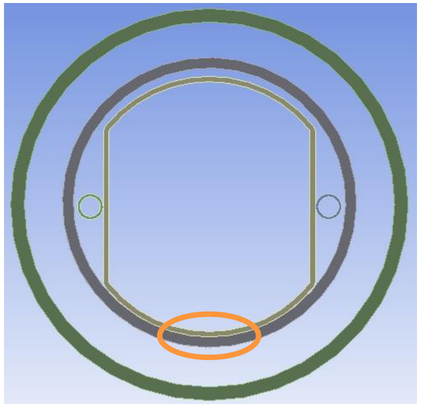


Homogenous contact between 4 sliding rings and the CB on the entire length

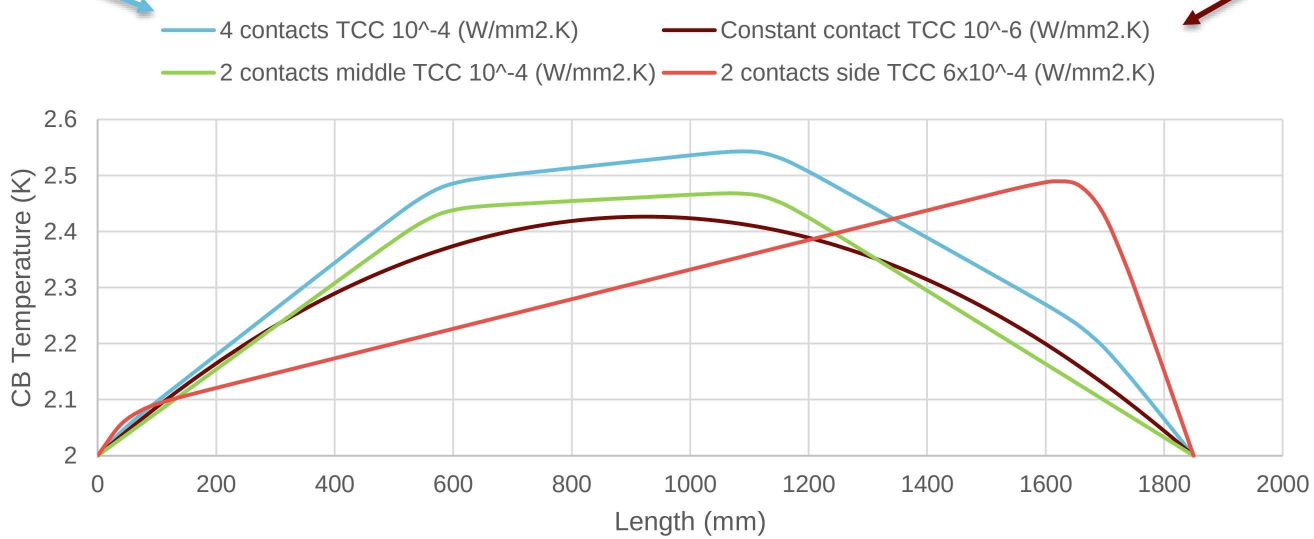
Contact on the side, where the BS temperature is the highest.



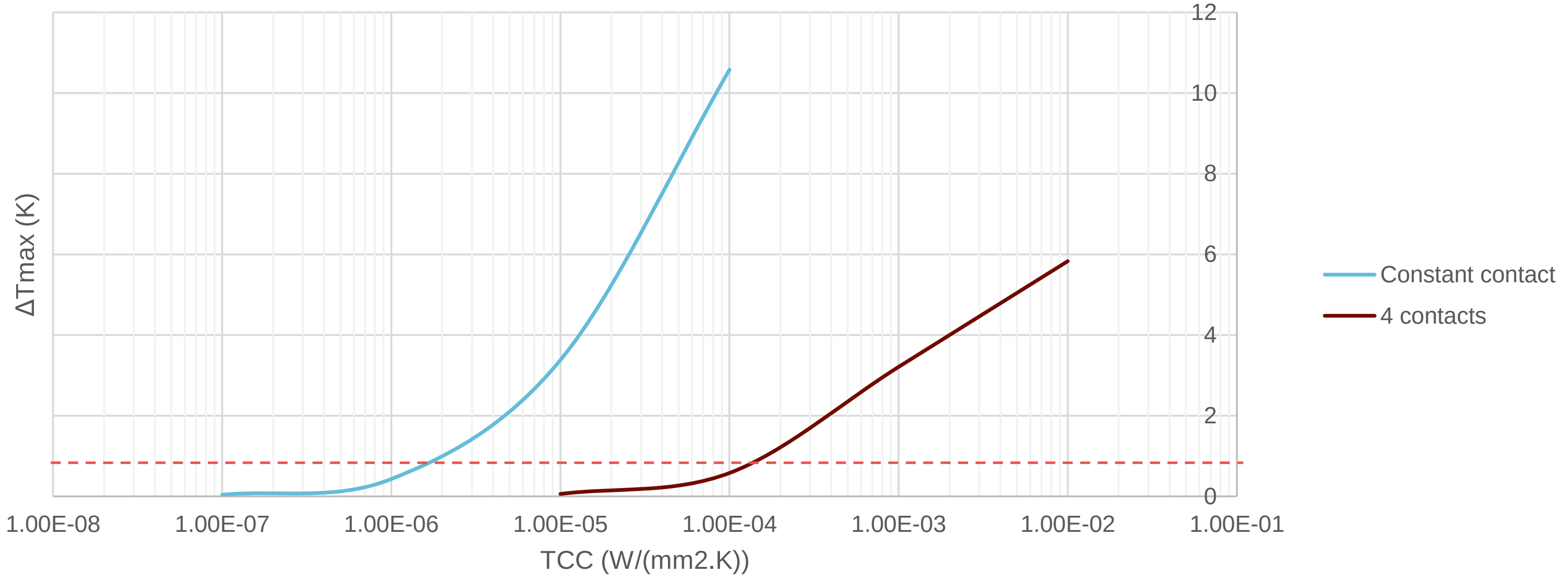
Heat load from the beam around 5 W/m to the BS



No sliding ring, constant contact between the BS and the CB on the entire length

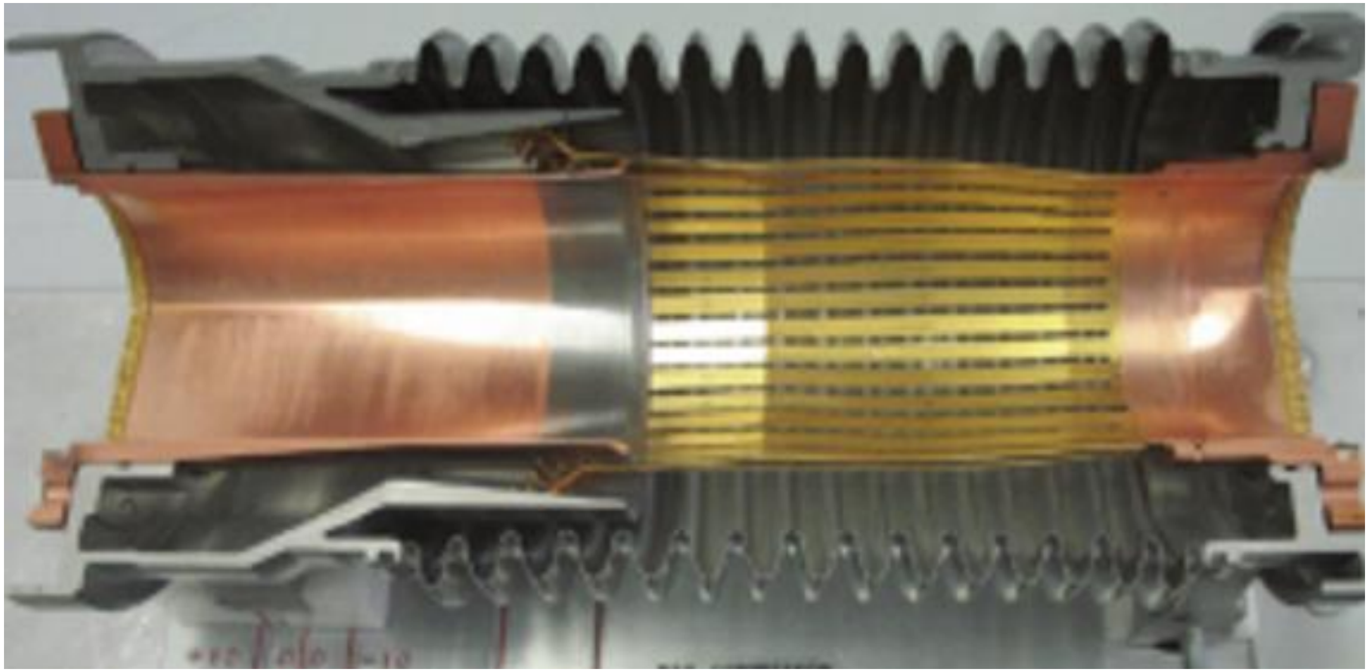


Cryogenic line – Second FE approach



- 2 solutions to remain below the 2.7 K requirement:
  - Centre the BS with or without sliding rings and ensure a TCC below $3.10^{-3}\ W/K$
  - Be sure to avoid any contact between the cold bore and the beam screen by controlling the BS and CB straightness and ensuring the mounting gaps.
- Straightness analysis is ongoing at the metrology laboratory
- $Q_{CB} = Q_{TS\_rad} + \underbrace{Q_{CB\_supports} + Q_{BS}}_{\text{Not settled yet}}$

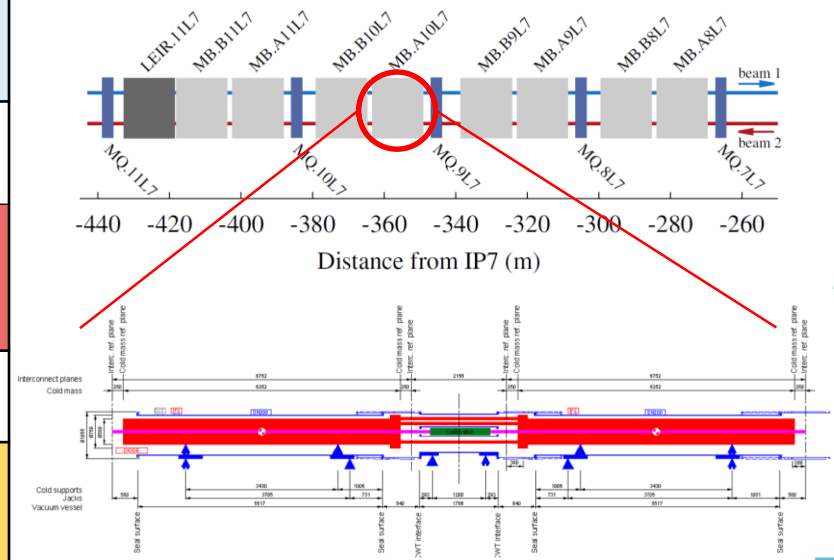
Plug-in-Module design (PIM)



Plug-in-Module design (PIM)

- Forecasted PIM displacement while replacing a MB.A10:

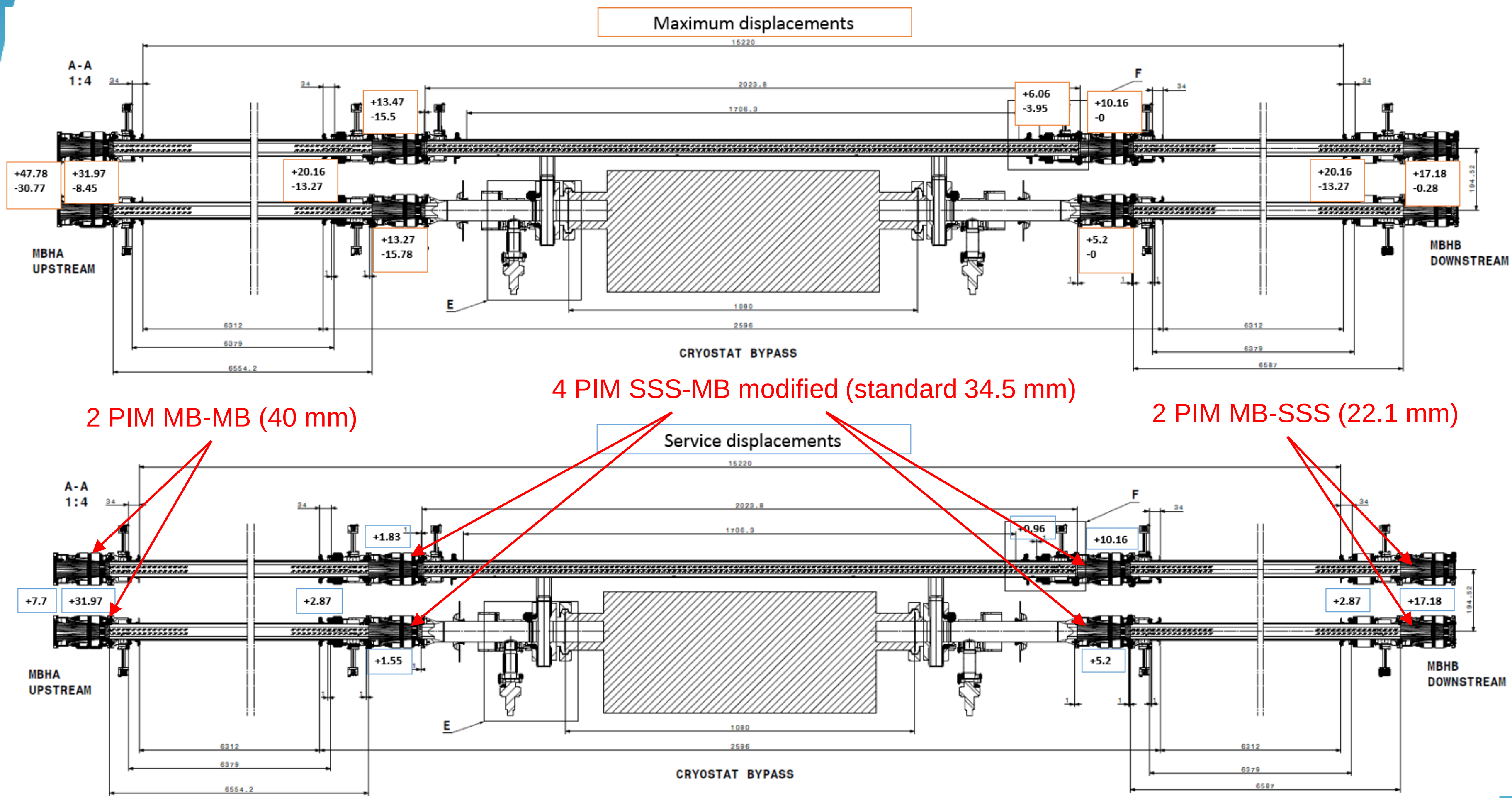
Maximum differential displacement (mm)	Temperature conditions	PIM MBHA UP	PIM UP (Cryo line)	PIM UP (RT line)	PIM DOWN (Cryo line)	PIM DOWN (RT line)	PIM MBHB DOWN
Cool down	CM1 at 150K BS at 293K CM2 at 293K	-5.93	-11.09	-11.09	3.63	3.63	-0.19
	Normal Operation CM1 at 1.8K 5K<BS<20K CM2 at 1.8K	**31.97**	**1.83**	**1.55**	**10.16**	**5.2**	**17.18**
Warm up	CM1 at 293K BS at 150K CM2 at 150K	30.83	13.47	13.27	3.8	0.01	13.3
Exeptional Service Conditions	Line C' valve leaks during short intervention CM1<50K BS at 293K CM2<50K	-8.45	-15.5	-15.78	4.89	5.15	-0.28
	Line C' valve leaks at a beginning of a cool down: CM1 at 293K BS at 150K CM2 at 293K	30.83	13.28	13.27	3.99	0.01	13.3



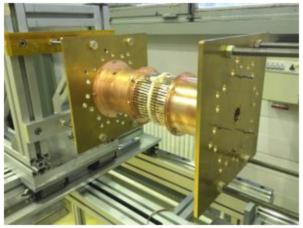
At each interconnection the PIM expansion – compression is lower than the standard PIM installed in the LHC.

Problem for the image current continuity

Plug-in-Module design (PIM)



Try to find the best configuration with standard PIM to ensure a good electrical contact. It will be measured on the test bench



HiLumi HL-LHC PROJECT

CERN

Q. Deliege

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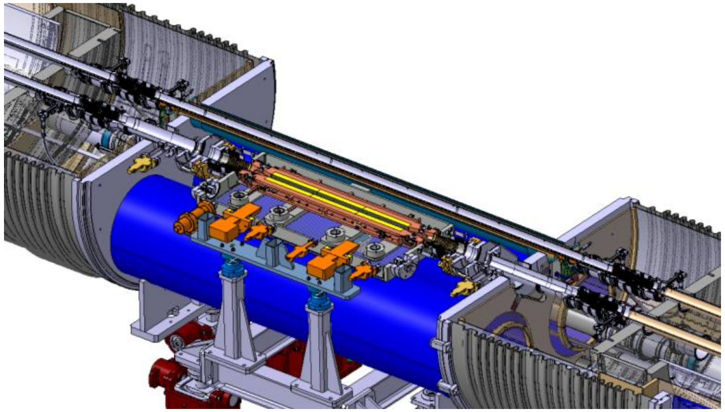
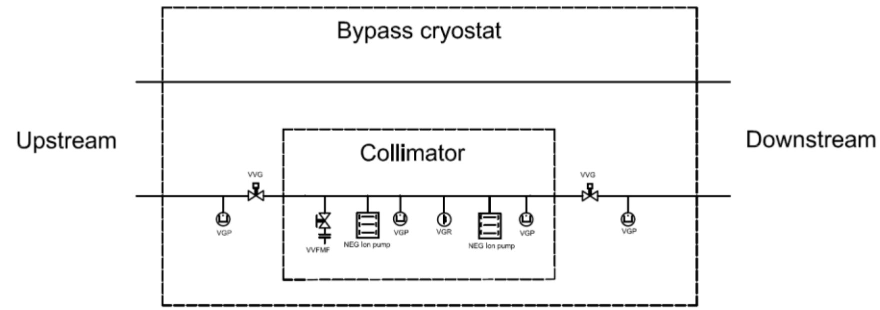
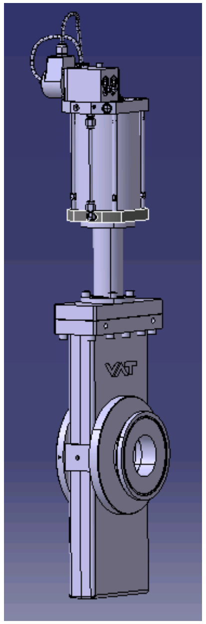
TCLD and bypass instrumentation



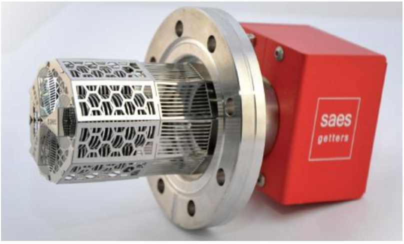


Vacuum performance with real collimators to be assessed (pumping speed of NEG cartridges, outgassing of materials)



All metal interlock gate valve VVG with integrated seal

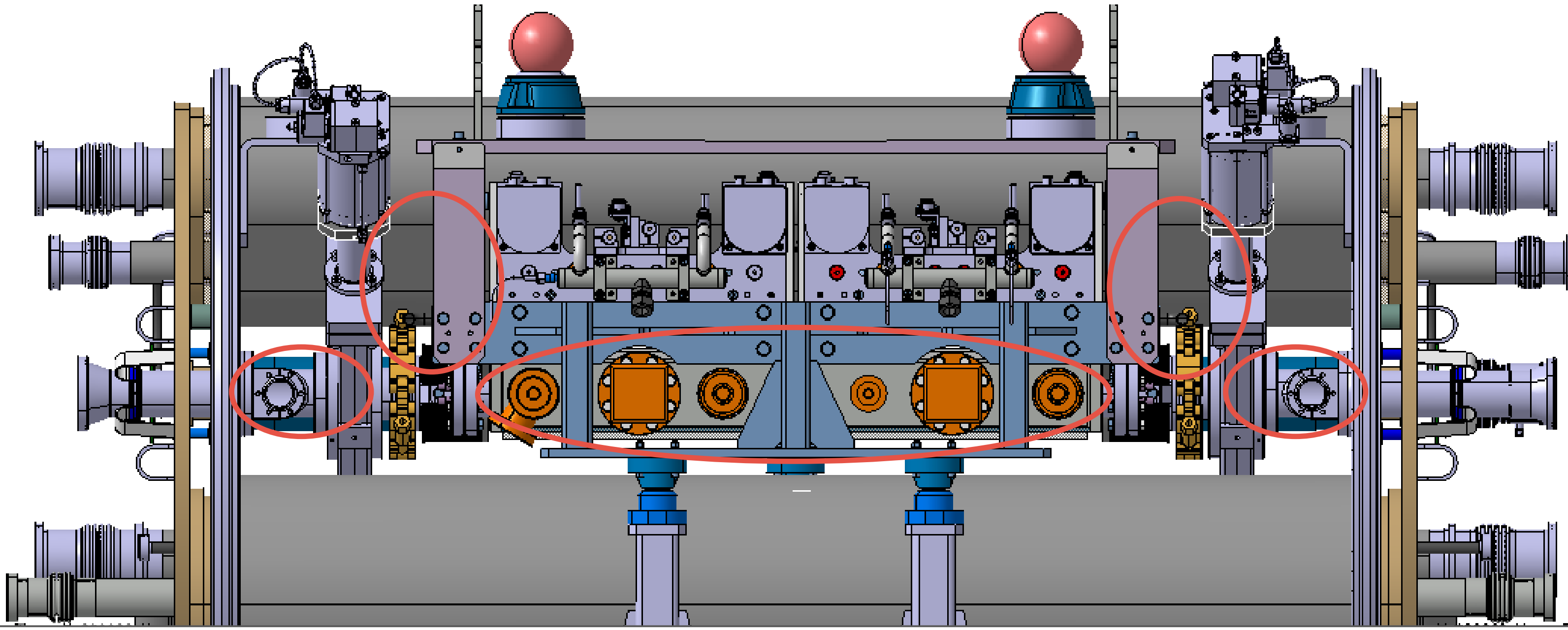
All metal angle valve VVFMF for mobile pumping group



NEG Ion pump D-500-5 Nextorr (increases pumping efficiency for H_2 and CH_4)

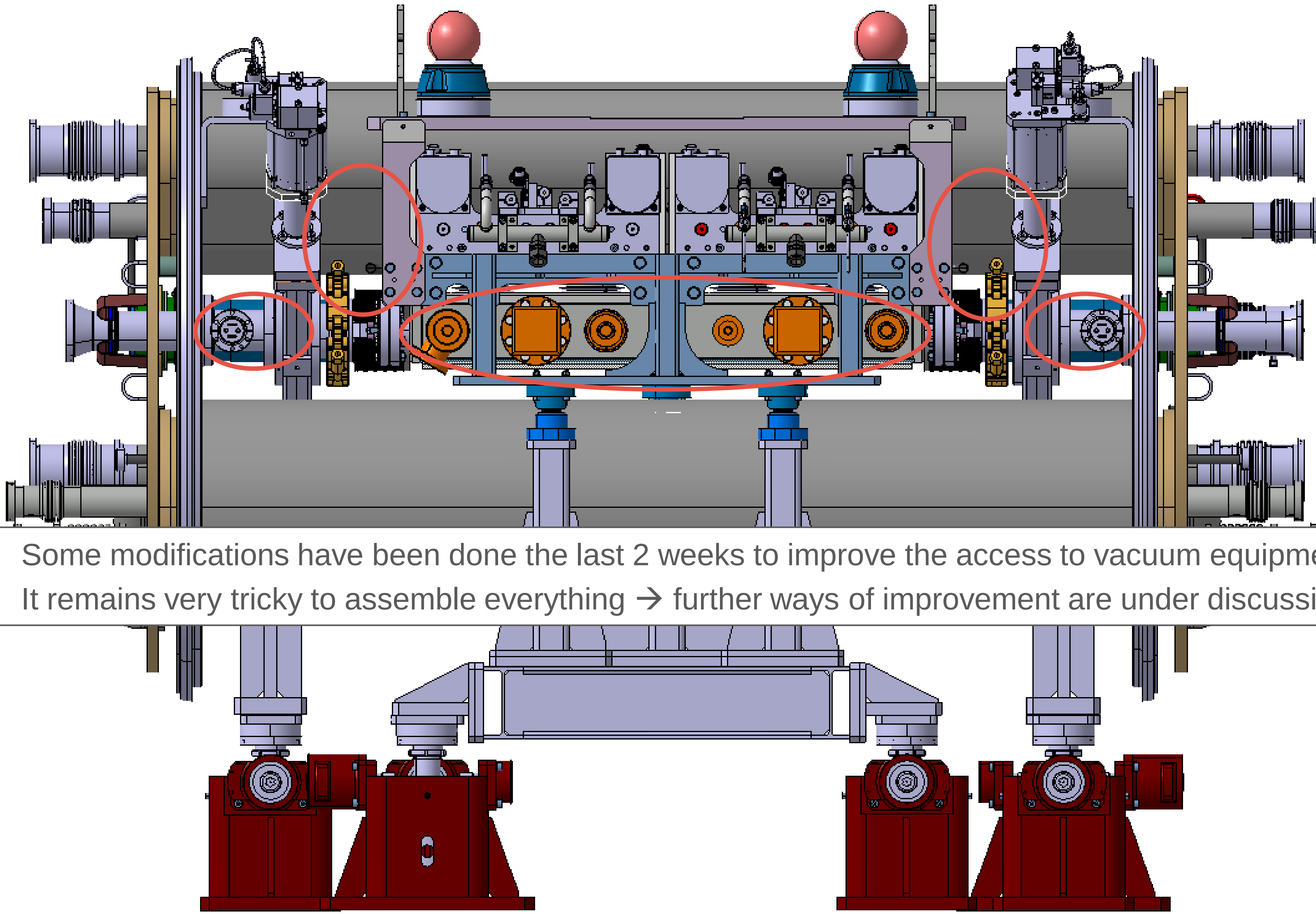
Pressure gauge Pirani and Penning VGR/VGP

Integration and assembly



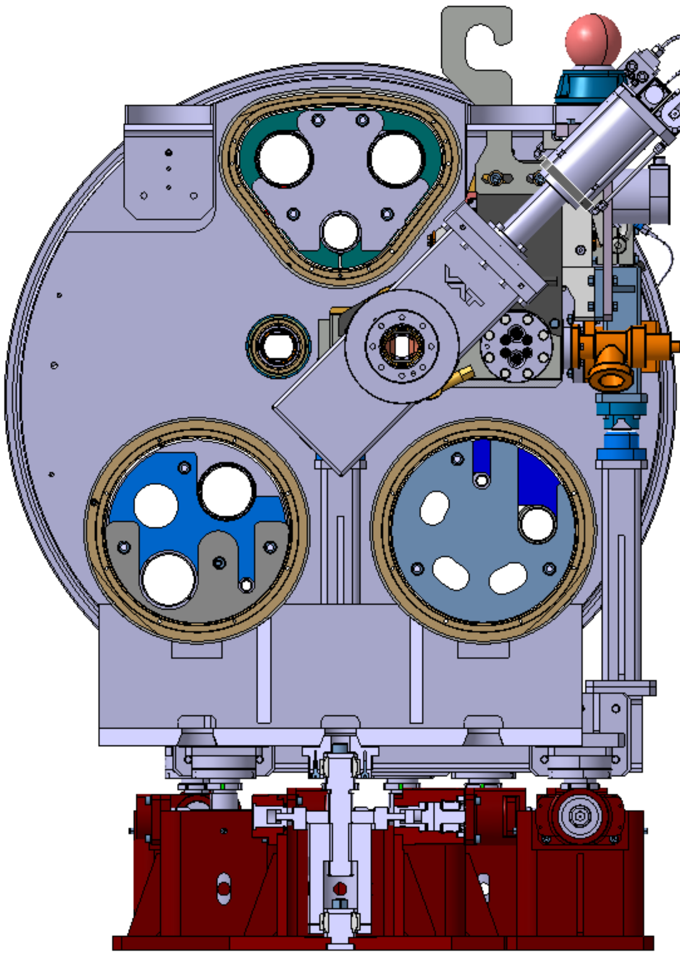
- Room to mount the CWT on the valve and the Penning gauge
- Room to mount the quick flanges and access the BPM flanges and collimator bellows
- Room to assemble the vacuum instrumentation on the collimator
- Room to bake out jackets

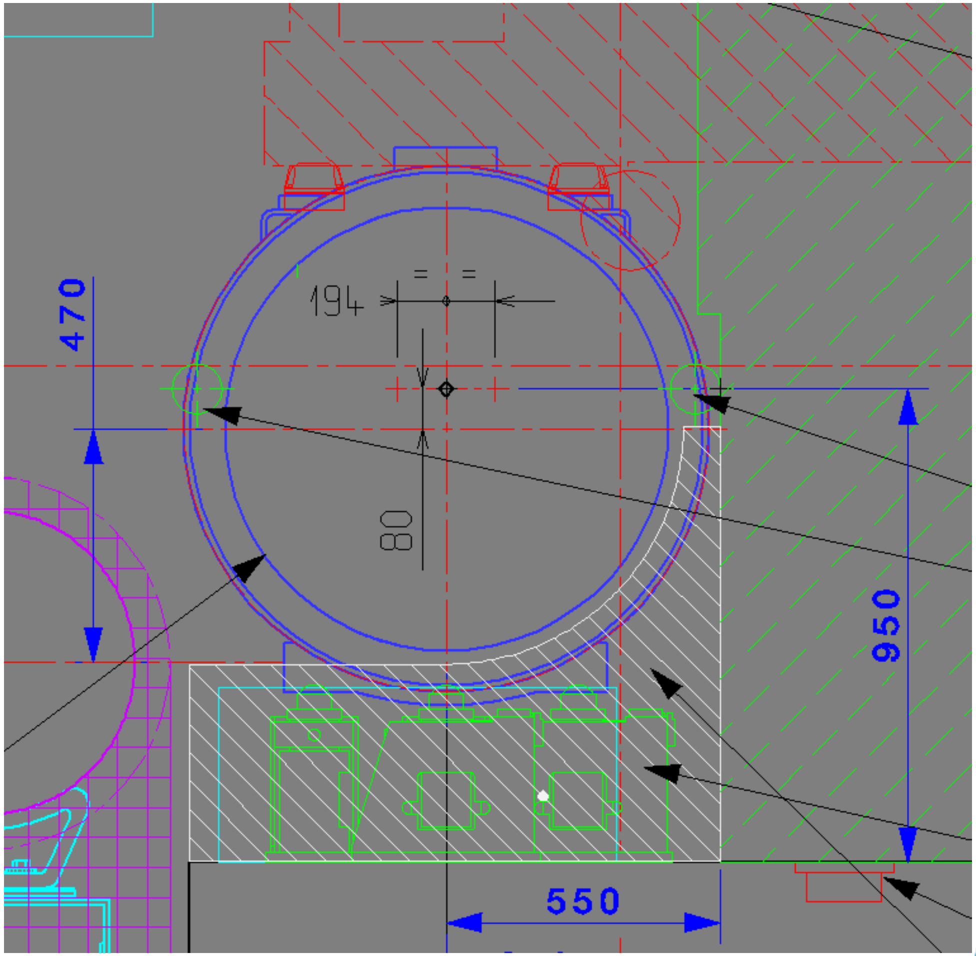
Integration and assembly



- Some modifications have been done the last 2 weeks to improve the access to vacuum equipment.
- It remains very tricky to assemble everything → further ways of improvement are under discussions

Integration and assembly

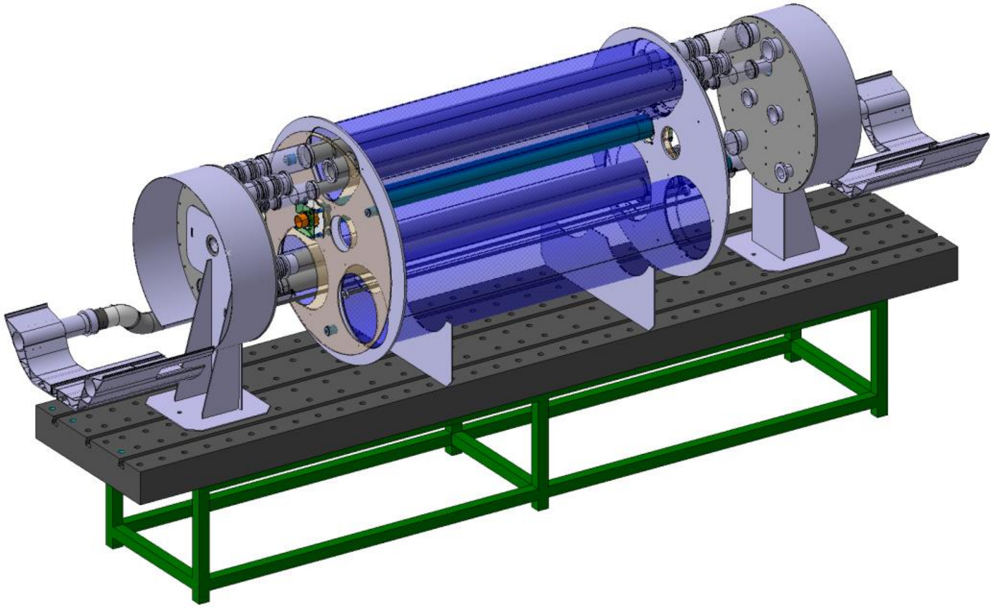




Any possible interference with survey, cryogenic equipment and transport have to be avoided

Bypass cryostat mockup (SMI2)

- The prototypes of vacuum beam lines will be manufacture in the next months.
- A bypass cryostat prototype is used for integration issues in SMI2.



Quality assurance – quality control

- Conceptual specifications:
  - From WP5 (collimation): EDMS n°1366517 and 1366519
  - From WP11 (11T)
  - From WP12 (Vacuum): EDMS n°1361087
- Functional specifications (To be written)
- Technical/engineering specifications (To be written)
- Engineering documents and technical notes for main components (In progress for CWT, PIM and cryogenic line)
- CDD equipment codes discussed with naming convention responsible:
  - LHCVSSB_ for beam screen components
  - LHCVCC__ for cold bore
  - LHCVSTB_ for cold/warm transitions
  - Integration drawings code to be defined
- Drawing labels defined by LHC standards (EDMS n°1585240 and 1221536)
- Manufacturing Inspection Plan (MIP) listing each manufacturing and quality control steps will be defined according to HL-LHC project management recommendations, UHV requirements and 11T project documentation management LHC-LBH-QA-0005. It will contain visual inspections, metrology control, welding inspections, pressure and leak tests results…
- Assembly procedure establishment in collaboration with TE-MSC
- Material procurement according to UHV requirements
- Leak tests will be carried out after each manufacturing step

More details concerning HL-LHC project management recommandations in I. Bejar Alonso's presentation, from PDR to TDR, October 2015

Conclusions

- The design of beam lines inside 11T dipoles and TCLD collimators cryostats is still in progress.
- A careful theoretical study on Thermal Contact Conductance together with an experimental study would be very interesting to carry out.
- Electrical measurements on Plug-In-Modules will be done during the following weeks.
- Prototypes of Cold-Warm Transitions and the cryogenic temperature beam line will be manufactured.
- Functional and technical specifications have to be written as well as technical notes on specifically designed equipment.

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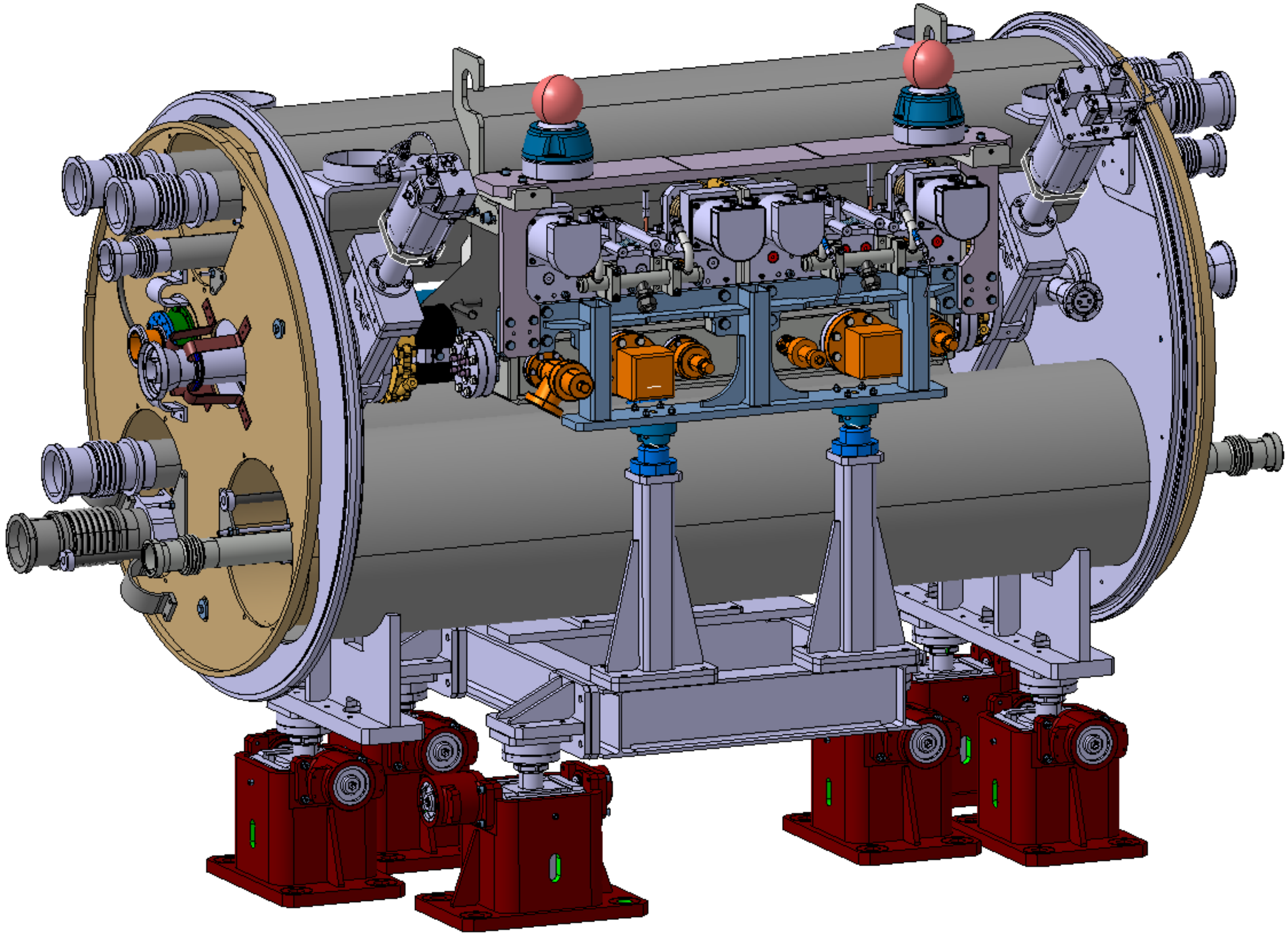
Thank you for your participation !

Integration and assembly



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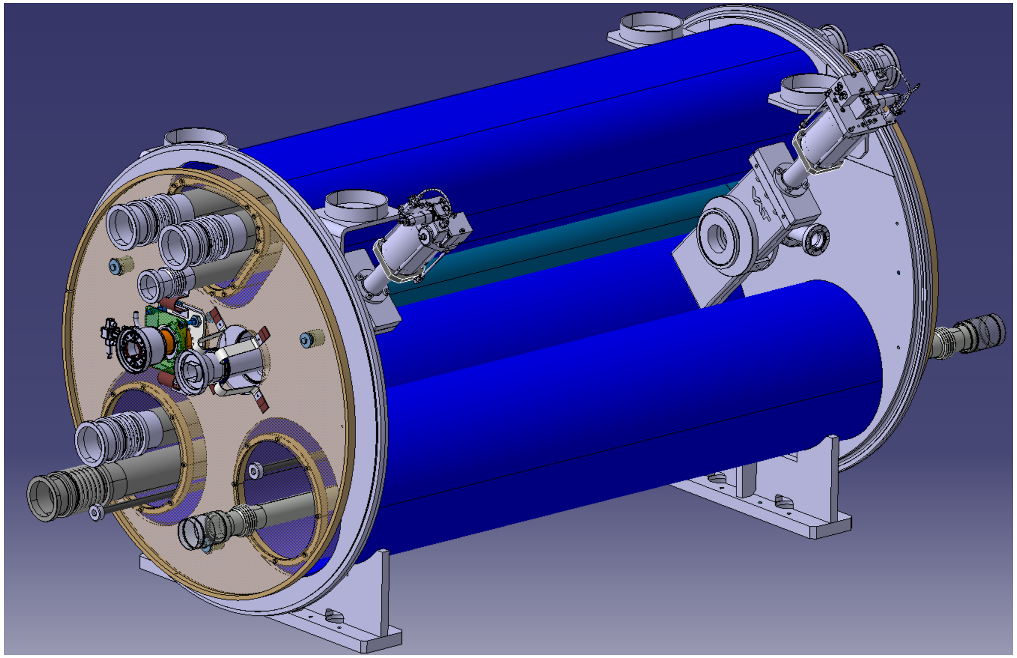
Q. Deliege

Assembly procedure - On the surface



Note: protection tooling for transportation and storage is not represented

- Bypass cryostat with beam lines **aligned in the cryostat by surveyors** and:
  - Cold/warm transitions (CWT) welded on the vacuum vessel
  - Valves screwed to CWTs with bake out jackets (To be checked with integration)
  - Penning gauges installed
  - Cold line equipped with beam screen, cooling tubes, cooling tube exits
  - Superfluid Helium cooling collars welded to hoses
  - Cold line supports assembled
- Leak tests and pressure tests have to be carried out before sending the cryostat into the tunnel.

Assembly procedure - In the tunnel

1. Final alignment of the bypass cryostat with 11T dipoles or connection cryostats
2. Welding of interconnections (PIM for beam lines)
3. Welding of the hoses carrying the He flow to the beam screens cooling tubes
4. Collimator installation and beam line closure
5. Mounting of collars on DN100 conical flanges linking the valves and the collimator bellows.
6. Set up and control of the beam vacuum instrumentation
7. Commissioning of room temperature and cryogenic temperature vacuum sectors

<u>Note</u>: The bellows have to be protected up to the closure of the interconnection

List of beam lines components

Beam line assembly list

Components list

Sub-components example: Common components for the two CWTs

CDD reference	Definition	ST reference	Quantity / bypass	Quantity / MBHA & MBHB or 2 connection cryostats
LHCVSSB_	Warm upstream line		1	
LHCVSSB_	Warm downstream line		1	
LHCVSSB_	Cryogenic line		1	
LHCVSSB_	MBHA V2	ST0721080		1
LHCVSSB_	MBHA V1	ST0721087		1
LHCVSSB_	MBHB V2	ST0721090		1
LHCVSSB_	MBHB V1	ST0721093		1
LHCVSSB_	Cold line assembly	ST0670736	1	
LHCVSSB_	Short copper cold bore ass. Up	ST0745721	1	
LHCVSSB_	Short copper cold bore ass. down	ST0745729	1	
LHCVBMB_0002	PIM	ST0152888	4	4
	VAT valve with conical DN100 flange	ST0668056	2	
	Tensioning chain - CF 100 conical	ST0672539	2	
LHCVSSB_0098	Embout a souder male upstream	ST0677099		4
LHCLMQ_S0044	Quadrupole welding flare V line	ST0721803		8
LHCVCC__0007	Cold bore Ø50/53mm for 11T dipole	ST0695795		4
LHCVSSB_0097	Embout a souder male downstream	ST0674129		4
LHCVSSB_0200	Helium cooling collar	ST0692830	2	
LHCVSSB_0196	Manchon cold bore cuivre Ø50/54	ST0670761	2	
LHCVSSB_0194	Embout a souder male upstream ID54	ST0712272	1	
LHCVSSB_0193	Embout a souder male downstream ID54	ST0712266	1	
LHCVCC__0006	Cold bore cuivre Ø50/54	ST0676026	1	
LHCVSTB_	Short CWT cryostat BP coll. Ass.	ST0672337	1	
LHCVSTB_	Long CWT cryostat BP coll. Ass.	ST0717357	1	
LHCVSSB_0162	S/E Female cooling tube exit		1	4
LHCVSSB_0161	S/E Male cooling tube exit		1	4
LHCVSSB_	Ass. Beam screen BP cryostat V1	ST0720086	1	
LHCVSSB_	Assembly beam screen 11T			4
LHCVSSB_0192	Ass. short beam screen bellow	ST0728371	1	2
LHCVSSBA0017	Beam screen bellow Scodock B0102800	ST0305551		2
	Penning gauge		4	
	Pirani gauge		1	
	VVFMF valve for mobile pumping group		1	
	INEG ion pump D-500-5 Nextorr		2	
Cold-warm transitions				
LHCVSTB_0005	Short CWT cryostat bypass coll.	ST0704675	1	
LHCVSTB_0006	Long CWT cryostat bypass coll.	ST0717362	1	
LHCVSSB_0153	Brazing ring CB51 Q1	ST0326195	2	
LHCVST__	Braid Cold/warm transition ASS.	ST0740410	8	
LHCVST__	Copper braid	ST0740413	8	
LHCVSSB_0155	Braid end part 1	ST0326281	8	
LHCVSSB_0158	Braid end part 2	ST0326299	8	
LHCVSSB_0159	Bimettalic plate for Q1	ST0326300	8	
STDVFUHV0006	V0172305MQ CWT CB53 FOR Q1	ST0026422	2	
LHCVSSB_0188	DN63 Flange CWT extremity	ST0393796	2	
SCEM : 47.62.83.112.5	HEX HD SCREW M8X30 UHV FLANGE	ST0425234	16	
LHCVST__0070	Ass. Penning extension	ST0745812	2	
LHCVST__	Grid for RF ball port	ST0711134	2	
LHCVST__	Grid support for RF ball port	ST0745794	2	
LHCVST__0067	UHV CF flange DN40 with collar	ST0695165	2	
LHCVST__	Penning extension tube	ST0711136	2	
LHCVST__0068	UHV CF flange DN40 grid support	ST0684816	2	
SCEM : 47.62.83.012.8	HEX HD SCREW M6X25 UHV FLANGE	ST0392802	12	
ISO 2338_4x16-A1	Parallel pin unhardened 4x16	ISO 2338_4x16	4	
SCEM : 47.62.83.014.6	HEX HD SCREW M6X35 UHV FLANGE	ST0465606	12	

- List 90% complete containing all beam lines assemblies, components and sub-components. PIM and beam screen sub-components will be added when designed.
- 80% of 2D drawings by the end of April. It will remain PIM, beam screens and assembly drawings.
- Spare of vacuum components are not included in this table.
- If available, the standard components will be taken from stocks. A list of components in stock is in progress.