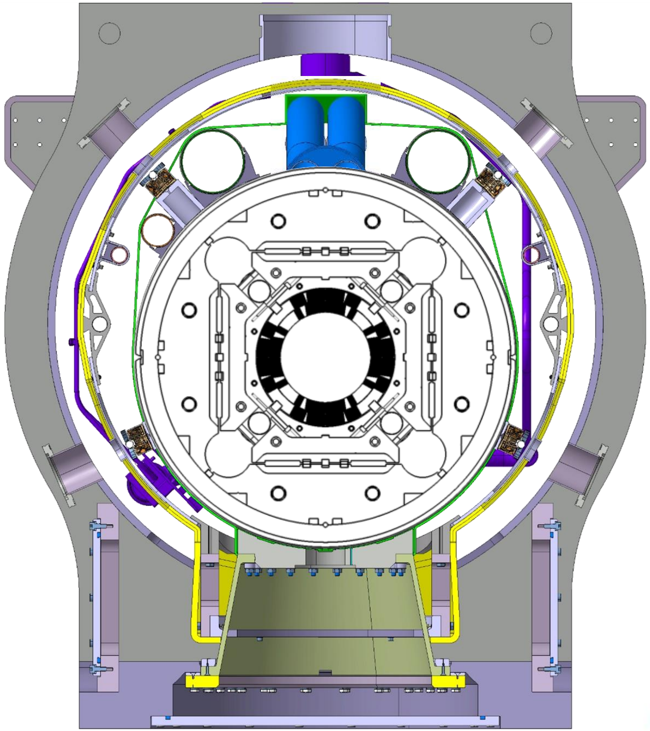
HiLumi
HL-LHC PROJECT

Cryostat design and fabrication

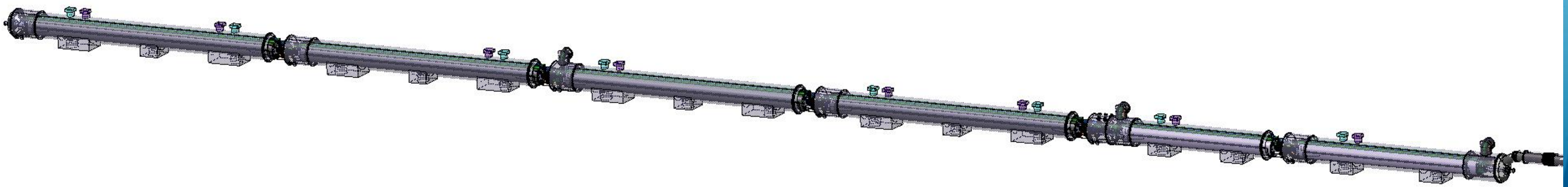


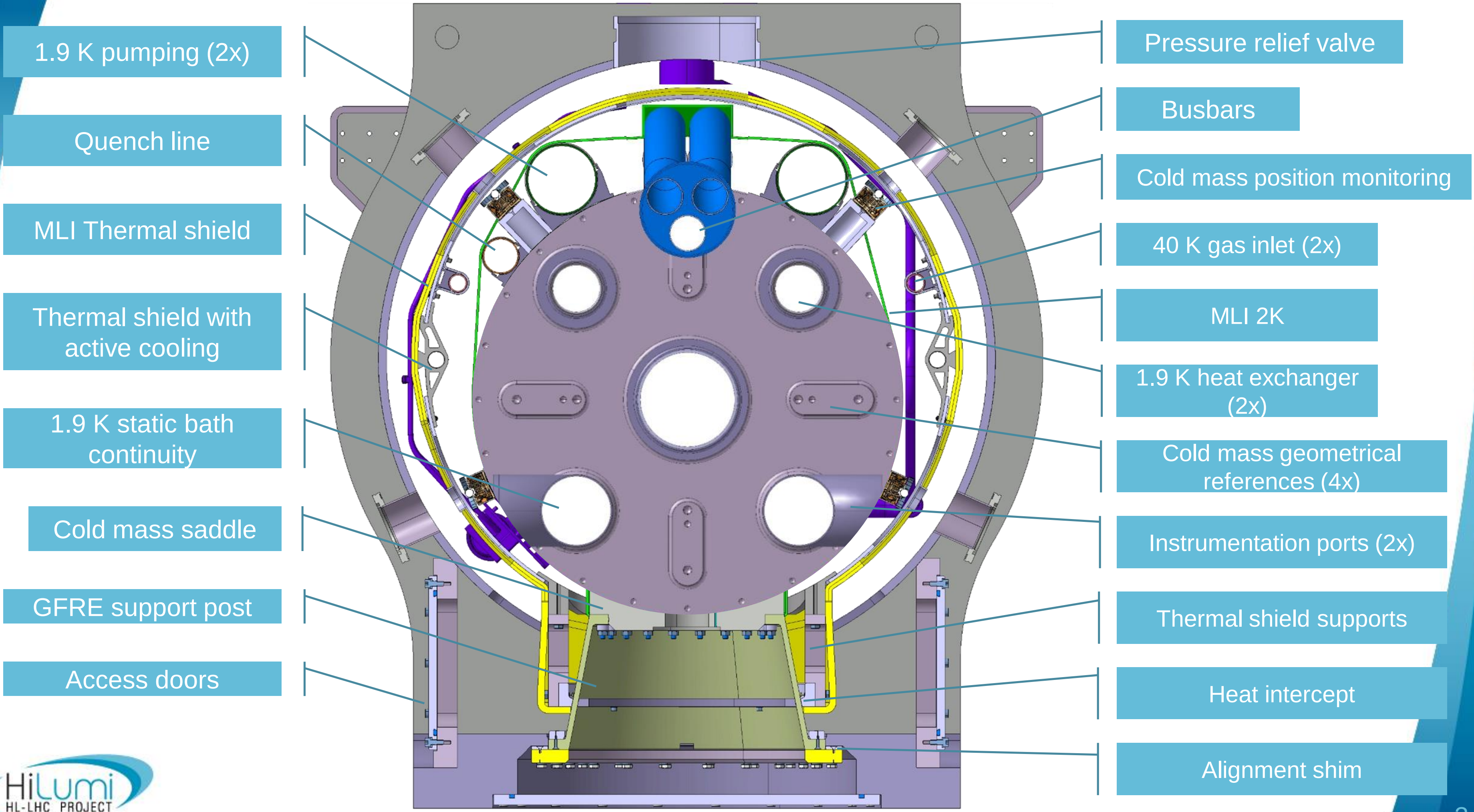
D. Ramos,V. Parma, A. Vande Craen, G. Barlow, C. Eymin, L. Williams, M. Struik, Y. Leclercq, O. Riu, F. Micolon, P. Moyret, A. Bouzoud, E. Chaudet, H. Prin, F. Pasdeloup, H. Prin

9th HL-LHC Collaboration Meeting, 14-16 October 2019

Outline

- Recent design developments
  - Independent inlets for beamscreen and thermal shield (additional 40 K supply line)
  - CLIQ, K-mod and instrumentation feedthroughs
  - Expansion joints and interconnects design
  - Technical service modules: Phase separator with passive He boiling; thermal shield; vacuum vessel; MLI; LD to cold mass connection
- Procurement/fabrication
  - Vacuum vessel
  - Thermal shield
  - Cold supports
  - Multi layer insulation (MLI)
  - Tooling
  - Service modules
  - Tooling





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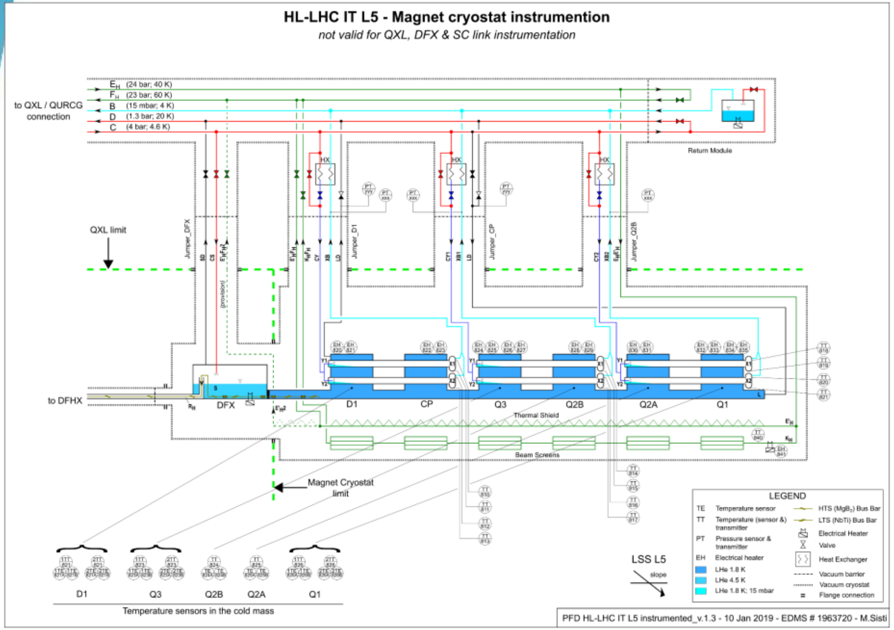
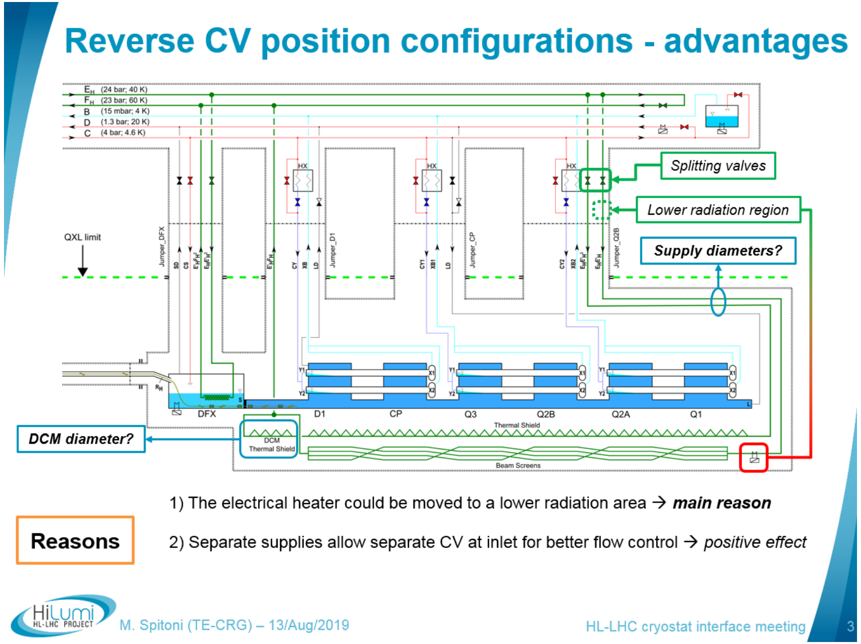
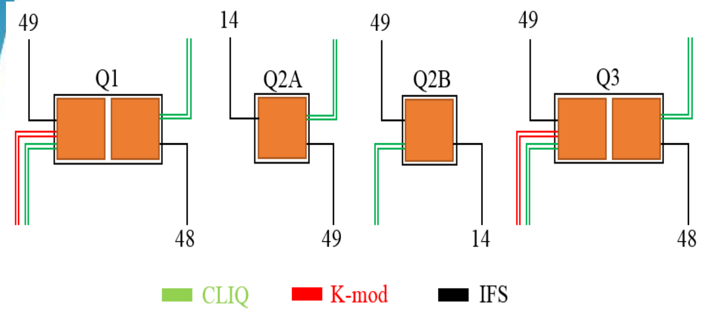
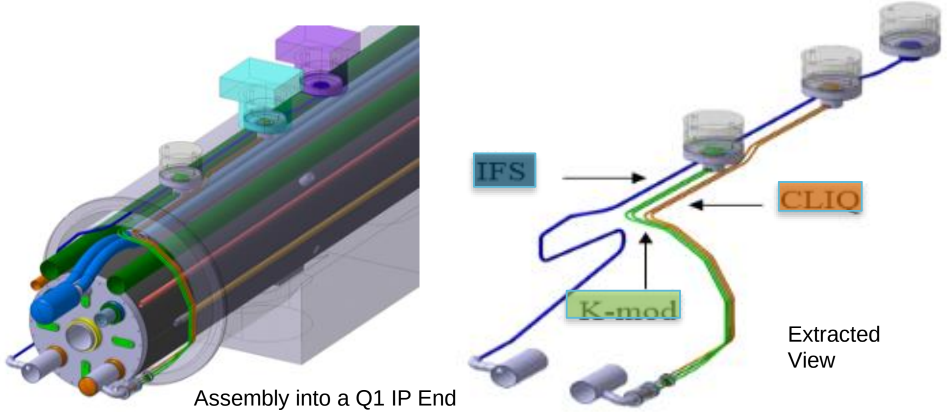
Additional 40 K supply line





IFS, CLIQ and K-MOD Current Feeders for HL-LHC Triplets





Assembly into a Q1 IP End

IFS	#Wires	Cond. x-section OHFC Copper	L tube	L cond.	Tube Dia	#Tubes	Cold Connection	Branch Resistance
1	~50	~20 mm2	~4m	~4.4 m	14/12 mm	1	No	
2	14	~2 mm2	~3m	~3.4 m	8/6 mm	1	No	
K-mod								
1	2	2x10 mm2	1.7m	~2 m	8/6 mm	2	Yes	
CLIQ								
1	2	2x6.7 mm2	2.45m	~2.9 m	8/6 mm	2	Yes	2.5 mΩ
2	2	2x10 mm2	2.45m	~2.9 m	8/6 mm	2	Yes	1.5 mΩ

Calculated Thermal Performance

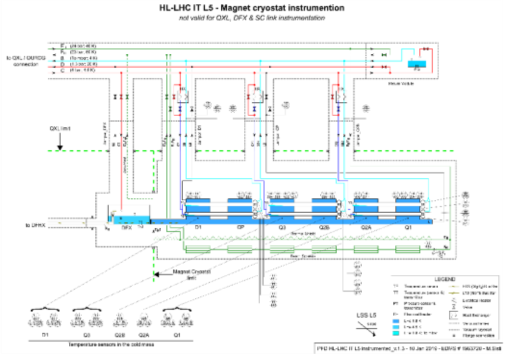
Feeder	Qty feeders Q1 or Q3	Qty feeders Q2A or Q2B	Heat/feeder [W]
IFS 50	2	1	0.88
IFS 14	0	1	0.16
CLIQ	4	2	0.68
K-mod	2	0	0.94

Total Q1 or Q3 [W]	6.35
Total Q2A or Q2B [W]	2.4
Total/triplet [W]	17.5

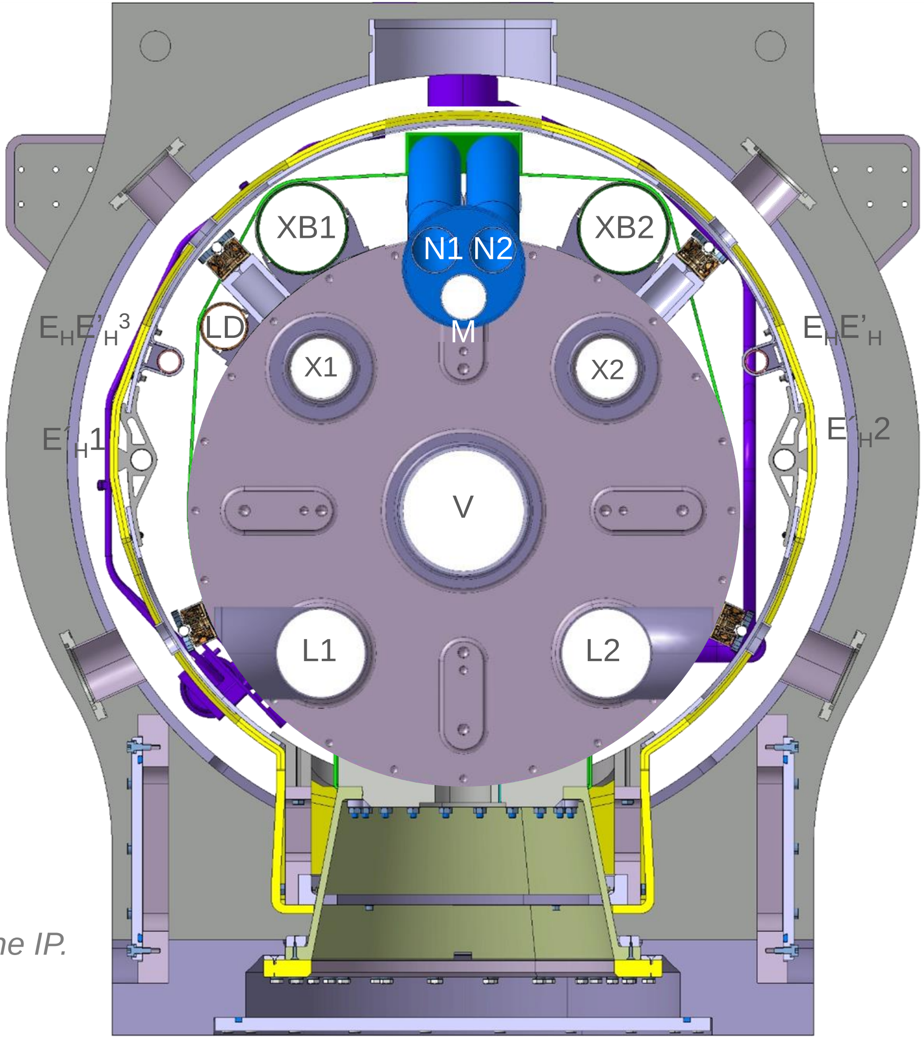
The **functional design and thermo-electrical optimization**, together with the integration (position and assembly sequence) of the IFS, CLIQ and K-mod systems into their respective cryo-magnets has been **completed**. Experimental **performance validation** on representative feeders of the K-mod type will be carried out in autumn 2019. The design of the HL-LHC triplet IFS, CLIQ and K-mod feeders is now moving from the conceptual to a **detail phase**. First prototype units for assembly to HL-LHC triplets will be available in the **first half of 2020**.

Naming convention for interconnect lines

According to edms [1963720](1963720)



As seen from the interaction point.
Applicable to both left and right of the IP.



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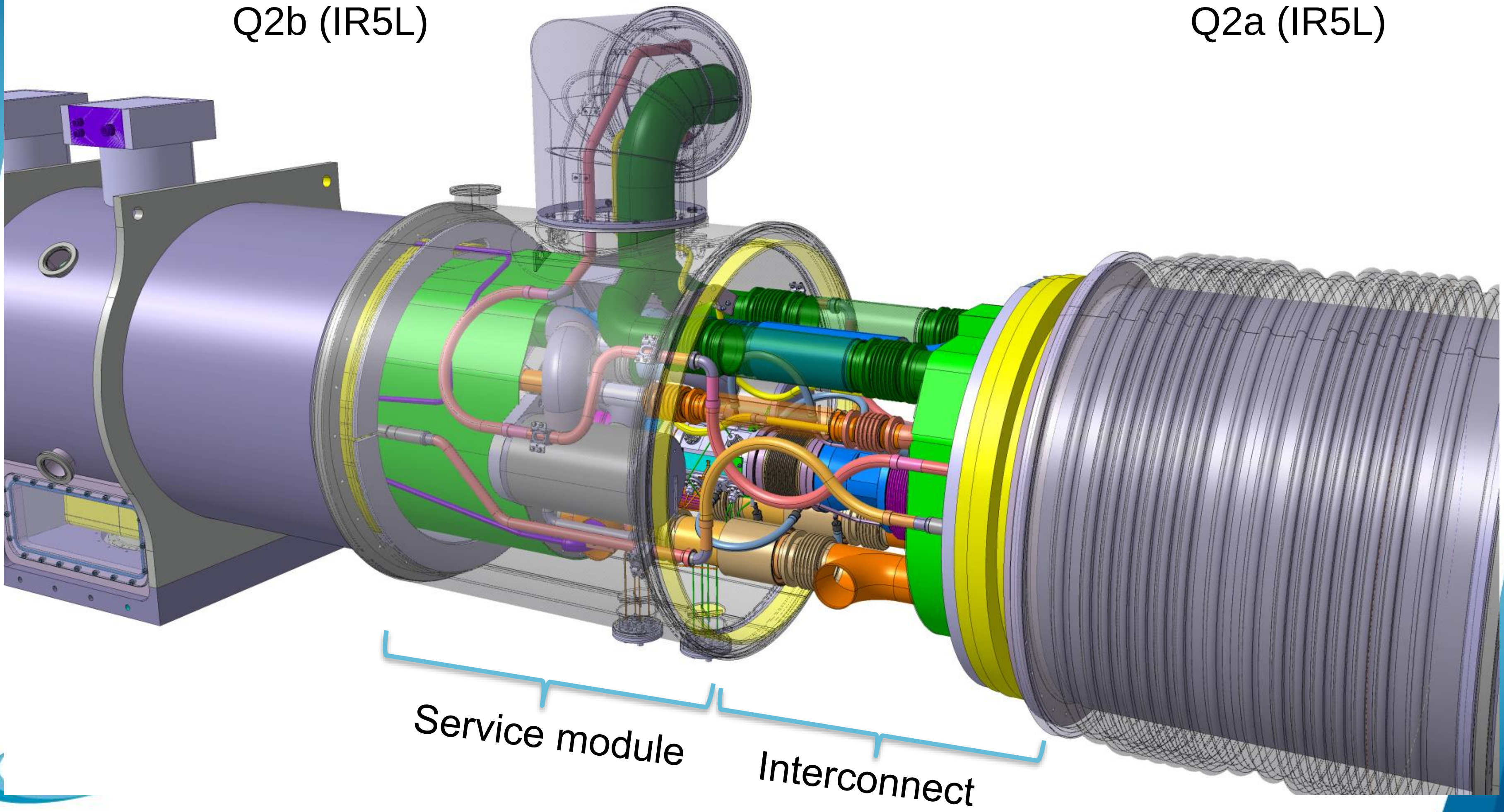
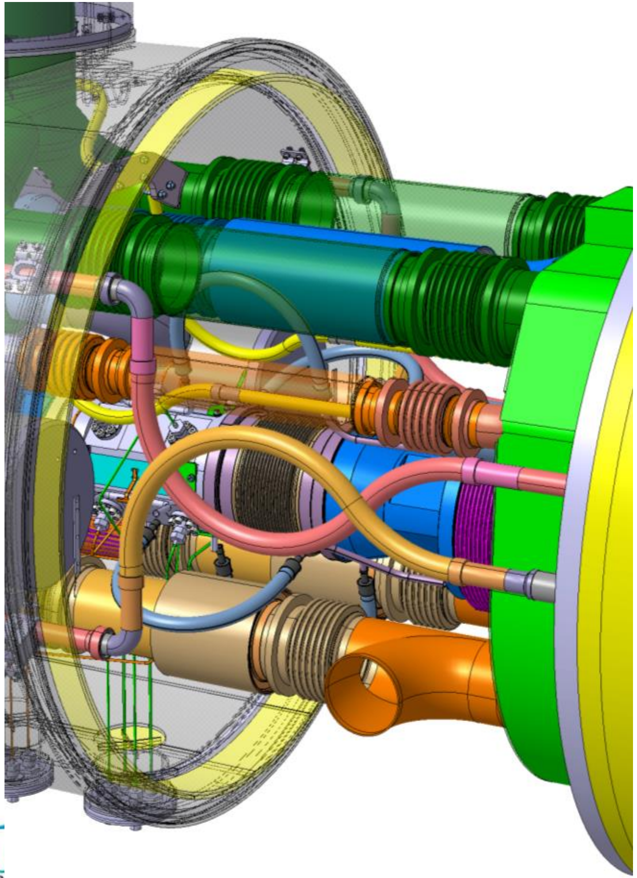
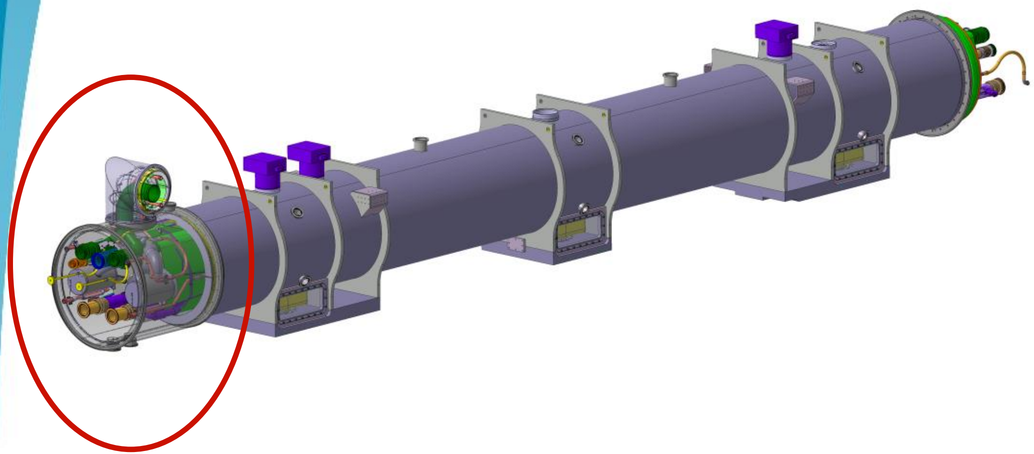

Q2b (IR5L)
Q2a (IR5L)
Service module
Interconnect

Piping interconnects and expansion joints



- **Universal expansion joints** for larger diameter pipes; flexible hoses for smaller diameters: low transverse interconnect forces
- Bellows assembled on the surface. **Sliding sleeve** welded in the tunnel between two bellows to form an universal expansion joint.
- **Thermal shield** interconnect follows the LHC arc baseline design using **bolted joints** for quick opening and closure
- MLI on 2K surfaces **individually applied on each pipe** enclosing liquid helium, in the form of a 10 layer blanket. Gas tubing and phase separators without MLI. MLI for the thermal shield applied in the form of two blankets of 15 layers each.
- Piping layout has been optimised for maximum free **annular space for welding and cutting** of the sleeves. **Standard LHC sleeve** diameters have been used when possible to minimise new tooling.
- Vacuum **vessel thin wall sleeve is of standard LHC design**

Technical service modules



- Location specific
- Vacuum **vessel extension** with connections to cryo supply line, insulation vacuum instrumentation, beam instrumentation ports, beam vacuum pumping ports, etc.
- **Enlarged diameter** to enclose phase separators and large diameter pumping lines
- Of **variable complexity** depending on cryo requirements at given location

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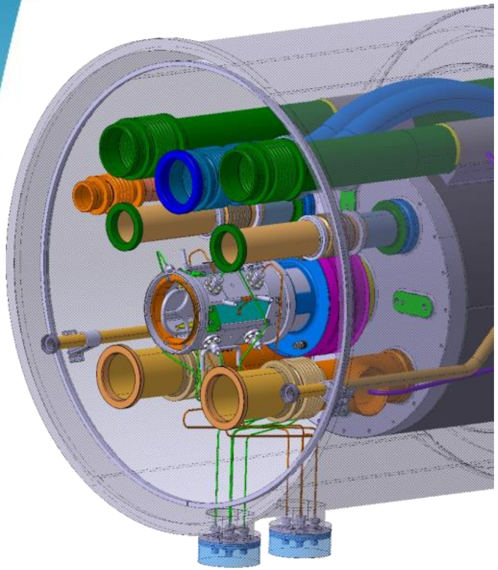
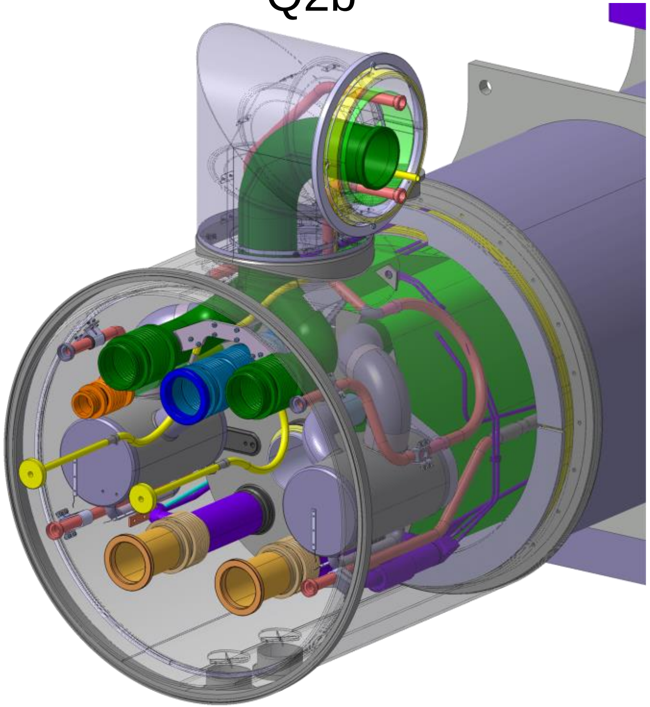
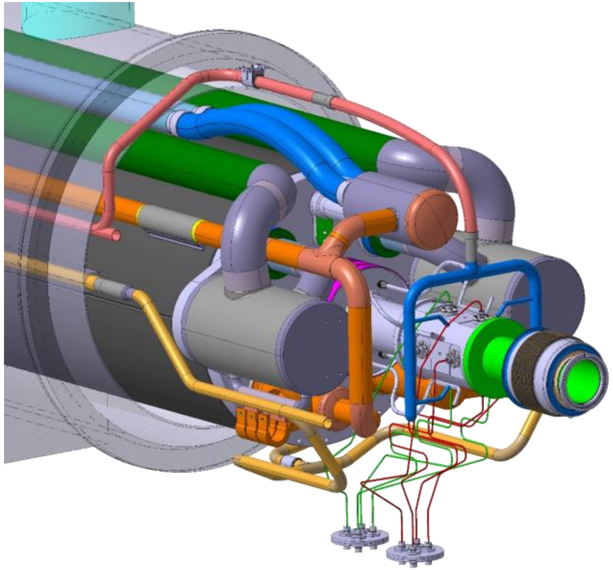
Q3
(similar to Q2a)



Q2b



Q1



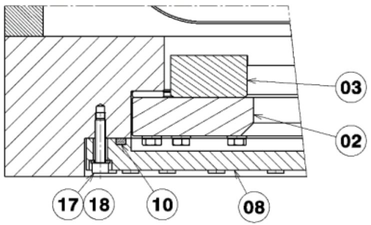
- Recent work:
  - Pipe routing and supporting
  - Interfaces with cold masses
  - Thermal shield and MLI design
  - LD to cold mass connection

- Beamscreen cooling pipes (TE-VSC)
- BPM cooling pipes and cable routing (BE-BI)
- Cold to warm transition integration (TE-VSC)
- Vacuum vessel
- Integration of instrumentation feedthroughs

Vacuum vessels

- Low carbon fine grain steel for pressure applications (P355NL2), impact tested 50 ºC. Stainless steel flanges.
- Manufacturing and inspection requirements aligned with **European pressure regulations.**
- **Precise machining** of support post interfaces and end flanges.
- **2 units available**: 1 for Q1/3; 1 for Q2a/b
- Contract F729/TE (MS/IT-4380) for 38 vacuum vessels
  - Production readiness review https://indico.cern.ch/event/781195 edms https://edms.cern.ch/document/2067765
  - Specification, tender form and drawings: https://edms.cern.ch/document/1836801
  - Build to print supply
  - Pre-series delivery of 2 units: Feb 2020
  - Series delivery: from May 2020 to Jun 2022

Quantity	Type	Code	Drawing	Length
2 pre-series	Q2A/Q2B	QQXF_SA/B	LHCQQXFB0001	9030 mm
9	Q2A/Q2B	QQXF_SA/B	LHCQQXFB0001	9030 mm
10	Q1/Q3	QQXF_SC	LHCQQXFA0001	9345 mm
5	CP	QCXF_S	LHCQCXF_0001	5399 mm
5	D1	QBXF_S	LHCQBXF_0001	6460 mm
6	D2	QBRD_S	LHCQBRD_0001	12360 mm
1	D2 proto	QBRD_S	LHCQBRDP0001	12360 mm



Seals: baseline is elastomer o-rings but flanges designed compatible with metal helicoflex

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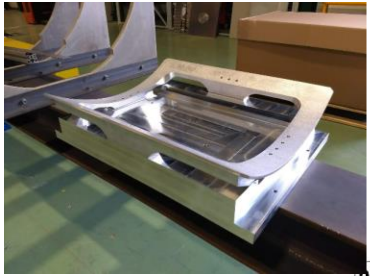
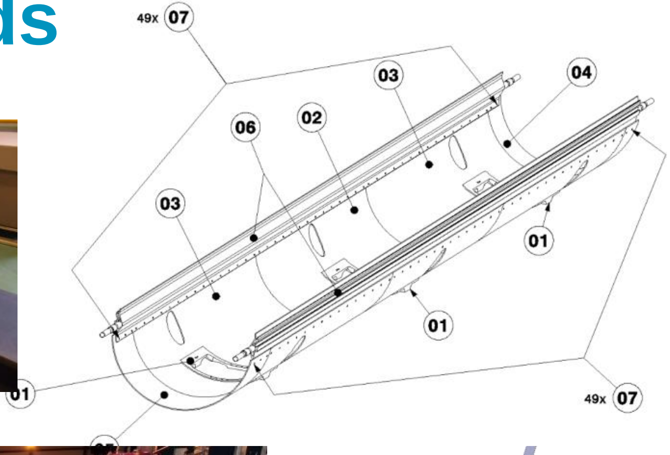
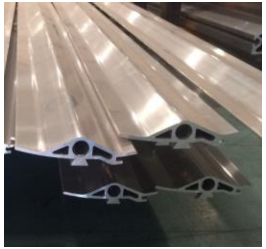
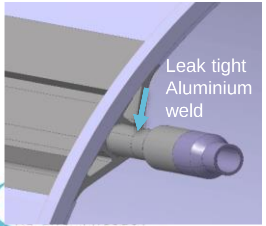
Thermal shields

- Actively cooled shield with two parallel cooling channels to **prevent deformation** during cooldown/warm-up
- Aluminium cylindrical shell with **extruded cooling channels**
- **Bottom half** pre-assembled in dedicated jig
- Aluminium to stainless steel **transitions**
- Cold mass lowered onto bottom half and upper shells welded on top
- Inserted into vacuum vessel together with the cold mass
- **Bending/rolling tests on-going** to achieve dimensional accuracy. Various alloys and thicknesses being tested with FEA therma and structural analysis in parallel
- Assembly at CERN due to **critical Al/Al weld**





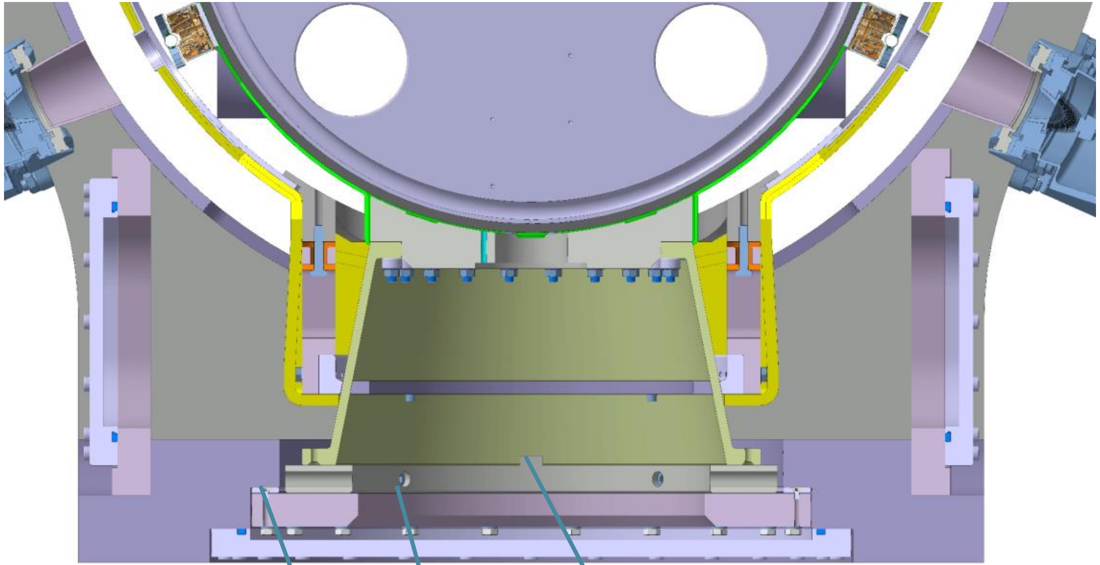




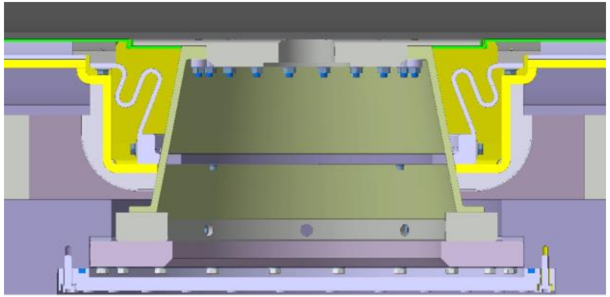
- Machines extrusions available
- Welding qualifications and assembly tests on-going
- Prototype saddles and support ancilliaries available
- Assembly jig is ready
- Sheet rolling tests on-going

Support posts design

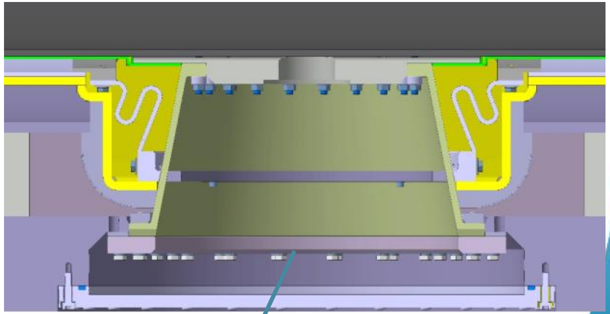
Sliding support (transv. section)



Sliding support (longi. section)



Fixed support



Support posts production

- Glass fibre reinforced epoxy (GFRE). Manufacturing by prepreg lamination and autoclave curing
- Max **1% void content**. Fibre volume fraction between 40% and 50% within a margin of +/-2%. **Tested per material batch and delivery batch**.
- Glued aluminium heat intercept ring.
- All parts are **ultrasonic tested**, load tested and geometrical checked
- **Thickness minimised** given 4 load cases: 5.3 mm
- Material testing at 80K on-going in EN mechanical lab
- Manufacturing of **140 units** in industry as per IT-4376
  - Technical specification, drawings and tender documents: https://edms.cern.ch/document/1889234
  - 10 unit pre-series delivered and accepted
  - Series production on-going

	Load case 1: Cryostat handling and testing conditions	Load case 2: Operational conditions	Load case 3: Compression load test	Load case 4: Transverse shear load test
Vertical compression load (kN)	205	142	250	-
Transverse shear load (kN)	135	125	-	165
Temperature	290 K uniform	1.9 K at top flange 70 K at heat intercept 290 K at bottom flange	290 K uniform	290 K uniform

See load case analysis in https://edms.cern.ch/document/1868420

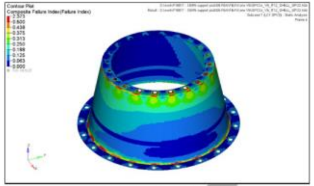
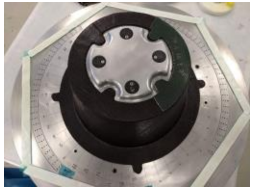


Figure 21 – Failure index – I




Thermal shocks in LN2: no damage found


Load test rig

Multi-layer insulation (MLI)

- Layout and specifications identical to LHC: **Two blankets of 15 layers** each at 60-80K level; **one blanket of 10 layers at 2 K** level
- Blankets for first Q1/3 and Q2a/b in stock.
- **Market survey** done for series production including standard section, service modules, end covers and jumpers (MS-4512 https://edms.cern.ch/document/2102694)
- Preparation for **invitation to tender on-going**; to be released end of the month. Supplier makes detail design based on CAD 3D models of the cryostat assembly
- Purchase order planned for end of the year. Delivery of pre-series mid 2020 and series production over 1 year.

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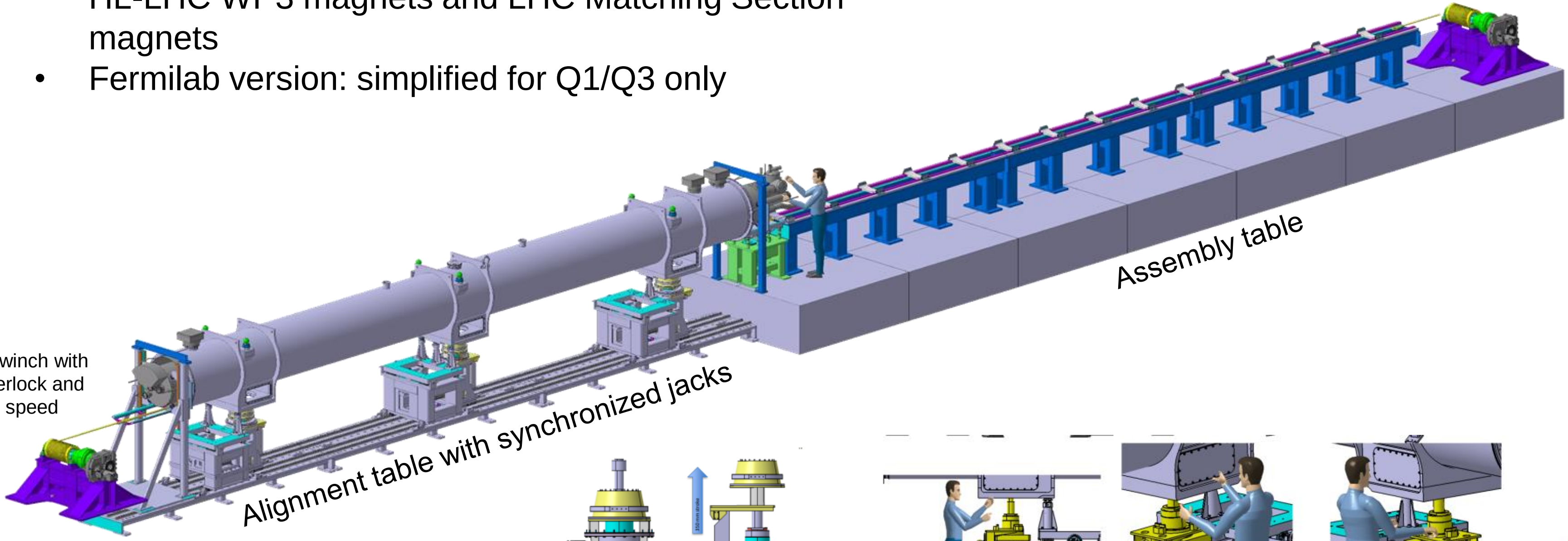
Assembly tooling

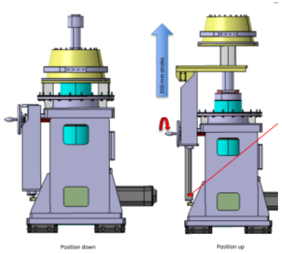
- **Turnkey contract** including design, fabrication, installation and commissioning on site:
  - One **multi-purpose tooling for CERN** to cover all HL-LHC assemblies plus repairs of LHC Matching Section cryo-magnets
  - One tooling installed in **Fermilab for assembly of Q1/3** standard section cryostats
- Specification (MS/IT-4352): https://edms.cern.ch/document/1855811
- Contract awarded to ZTS in March 2018 but **terminated in May 2019** due to insolvency of the firm
- New contract with second bidder APPLUS for the same scope of supply and kick-off meeting in June 2019:
  - **Conceptual design review: 22-23/10/2019**
  - Final design review: 21/11/2019
  - Manfacturing: Nov/2019 to Mar/2020
  - Installed at Fermilab: 1/6/2020
  - Installed at CERN: 17/6/2020

https://edms.cern.ch/document/2173537/1

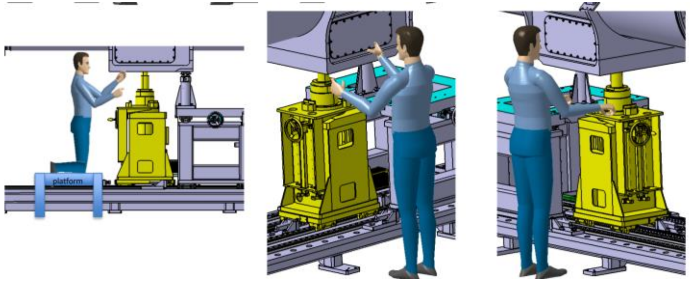
- CERN version: versatile tooling compatible with all HL-LHC WP3 magnets and LHC Matching Section magnets
- Fermilab version: simplified for Q1/Q3 only



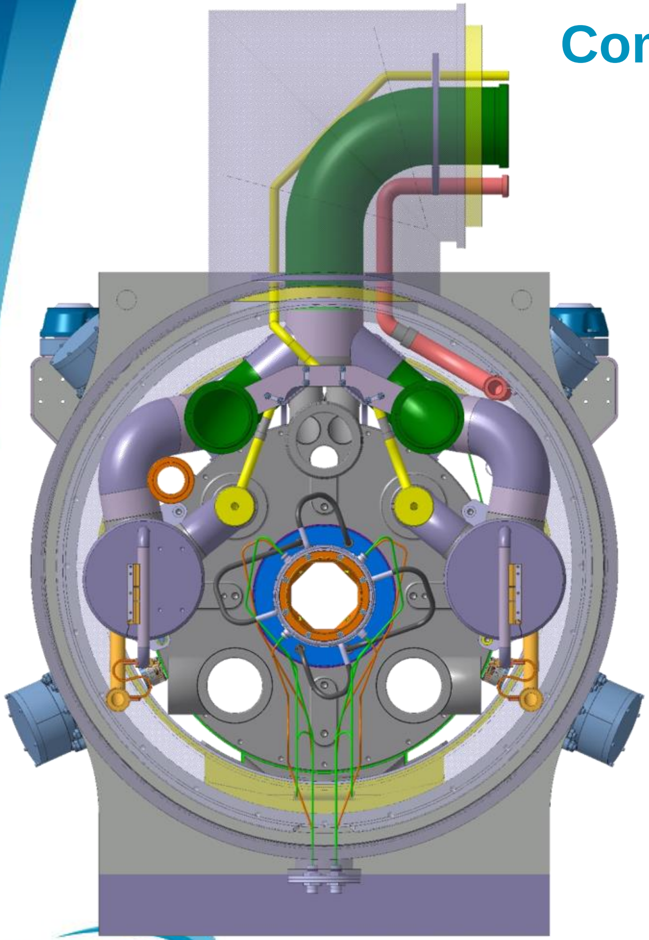
Double winch with
load interlock and
variable speed



Support lifting jack



Ergonomy studies

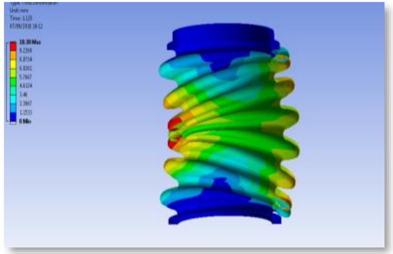


Components for technical service modules

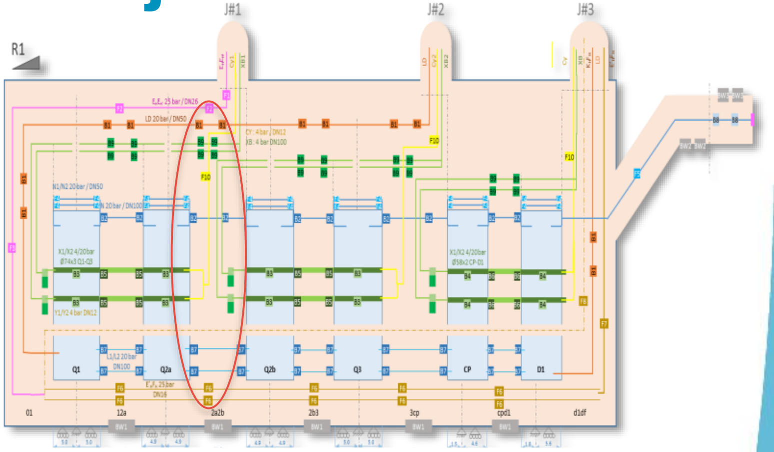
- Vacuum vessel extensions
  - **Market survey** on-going for procurement contract including the vacuum vessels, jumper elbows and dome ends (MS/IT-4556)
  - Detailed drawings for invitation to tender on-going
  - Purchase order by end of 2019; Pre-series delivery Jun 2020.
- Thermal shields
  - **Detailed design** on-going taking into account **integration** of BPM cables, pumping ports, instrumentation feedthroughs, etc
- Phase separators and pumping manifolds
  - **Passive helium boiling** by conduction from thermal shield circuit and liquid detection using thermometers
  - Integration of thermometers and thermalisation straps being studied together with TE-CRG
  - Manufacturing at CERN (EN-MME): tooling under preparation. First prototypes before end of the year.

Interconnect expansion joints

- Design complete
- Tender closed and technical visits on-going. Adjudication in less than one month.

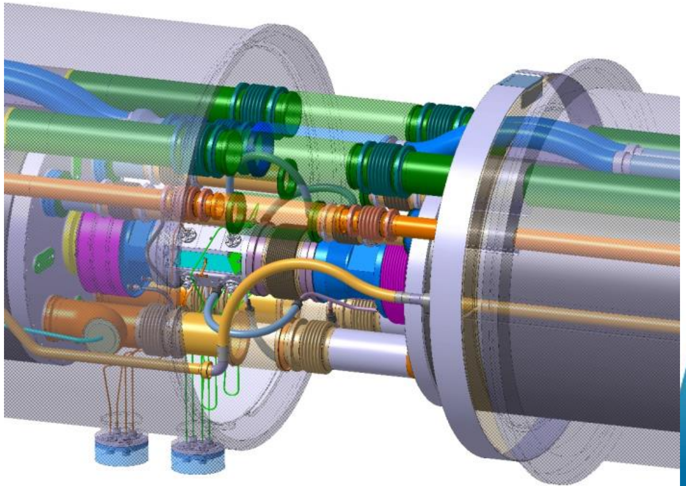


IR5Left bellows and fixed point layout



Delivery plan:

Ref.	Expansion joint reference	Drawing reference	Quantity		
			Pre-series	Series #1	Series #2
A-1	Formed bellows internal line X - LQXF	LHCLMQXF_S0014	2	10	28
A-2	Formed bellows internal line X - CP-D1	LHCLMCXF_S0010	2	5	13
B-1	Formed bellows line LD	LHCQ_XFC0012	5	12	46
B-2	Formed bellows line L1/L2	LHCLMQXF_S0016	5	29	101
B-3	Formed bellows line XB	LHCQ_XFC0011	5	33	54
B-4	Formed bellows external line X - LQXF	LHCLMQXF_S0015	5	17	60
B-5	Formed bellows external line X - CP-D1	LHCLMCXF_S0014	5	5	22
C-1	Universal expansion joint line M	LHCLMQXF_S0018	5	5	26
		Total	**34**	**116**	**350**
		Expected delivery	**March 2020**	**July 2020**	**Nov. 2020**



Design parameters	
Pressure	Int: 25 bar / Ext: 20 bar
Stroke	Up to 34 mm
Internal diameter	40 to 120 mm
Temperature	1.9K to 350K

Supply requirements
Standards: EN14917 / EN13445 / PED
Nb of bellows: 5L x90 / 5R x80
HL-LHC QA requirements
CE certification

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Conclusion

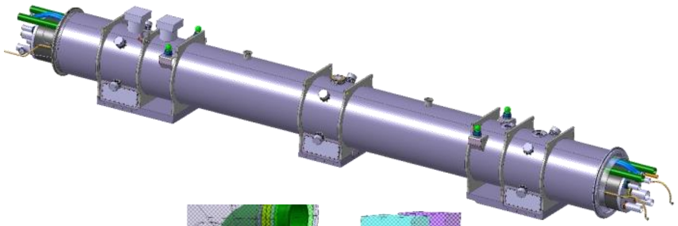
- The **design of long lead items is finished** and procurement/manufacturing is on-going
- Main cryostat components required for the **cold test of first Q1/3 and Q2 are available** and remainder will be available soon
- New contract for main **assembly tooling** is in place with planned delivery for **June 2020**
- Integration in the **service module and interconnect zone** is close to finish, including beam vacuum, beam instrumentation, magnet instrumentation, cryo instrumentation
- A complete **manufacturing/procurement plan** is in place for availability of components and tooling in-line with magnet production

Thank you

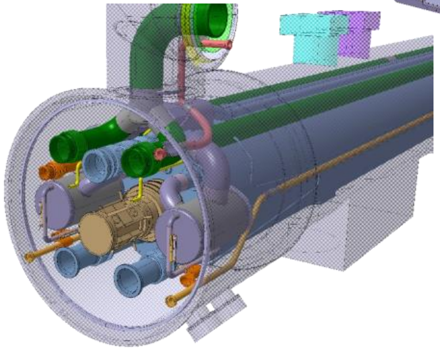
Additional slides

Cryostat assembly in 2 or 3 phases

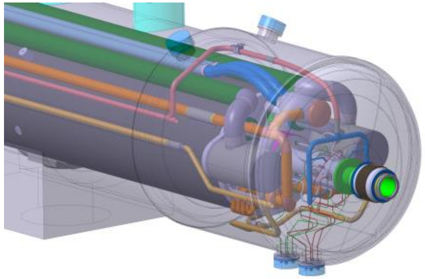
- Phase 1: the standard section
  (Q1 and Q3 are identical at this stage)



- Phase 2: the service module



- Phase 3: end cover (Q1)



Assembly workflow for QXF cryostats

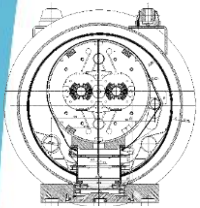
		Q1	Q2a	Q2b	Q3
Phase 1	Standard section w/ test bench interfaces	US	CERN	CERN	US
	Horizontal cold test	US	CERN	CERN	US
Phase 2	Service module	CERN	CERN	CERN	CERN
Phase 3	“Fiducialization”	CERN	CERN	CERN	CERN
	Beamscreen and BPM	CERN	CERN	CERN	CERN
	Cold to warm transition	CERN	-	-	-
	End cover	CERN	-	-	-

With weld NDT, leak tests, pressure tests, metrological/alignment checks throughout the assembly workflow

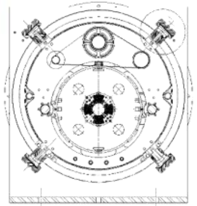
Concept (2106)

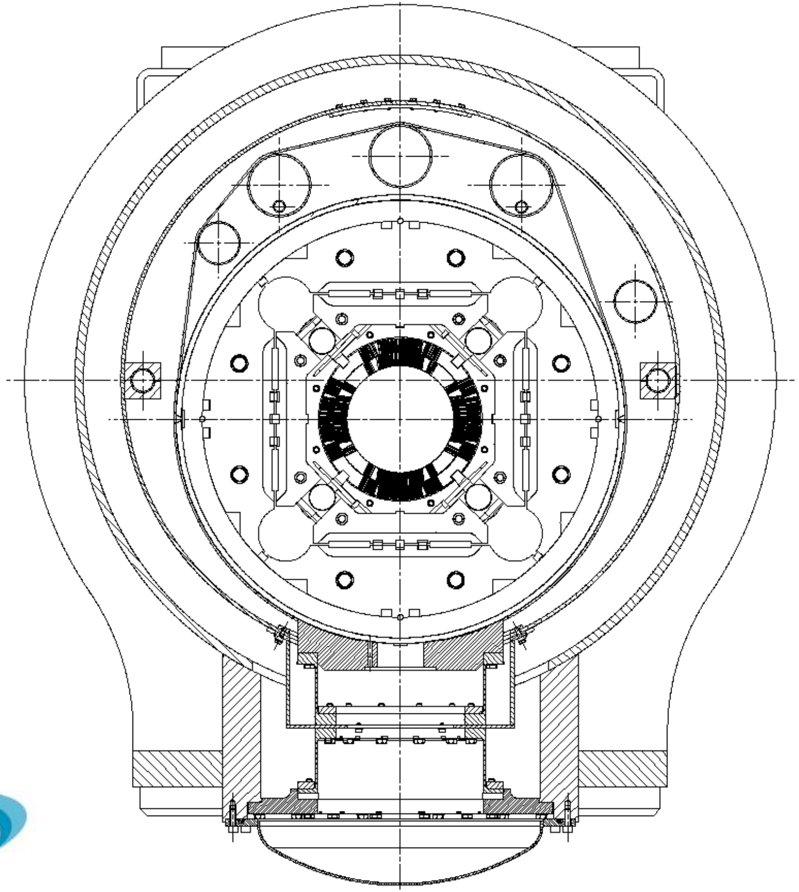
Present Design

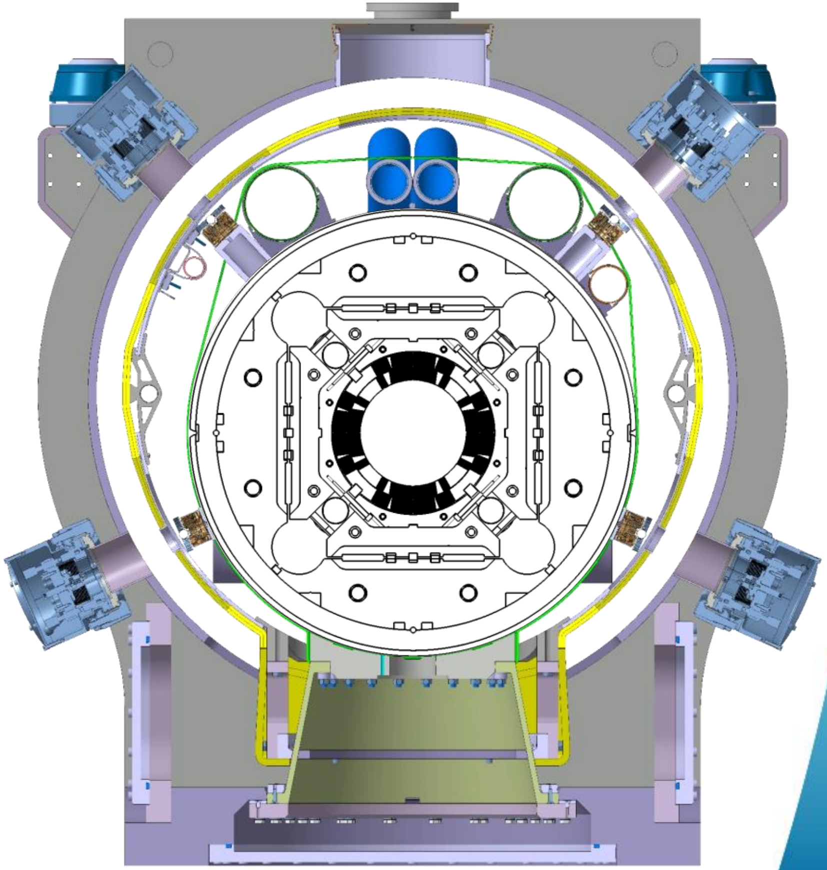
LHC Arc



LHC Triplet

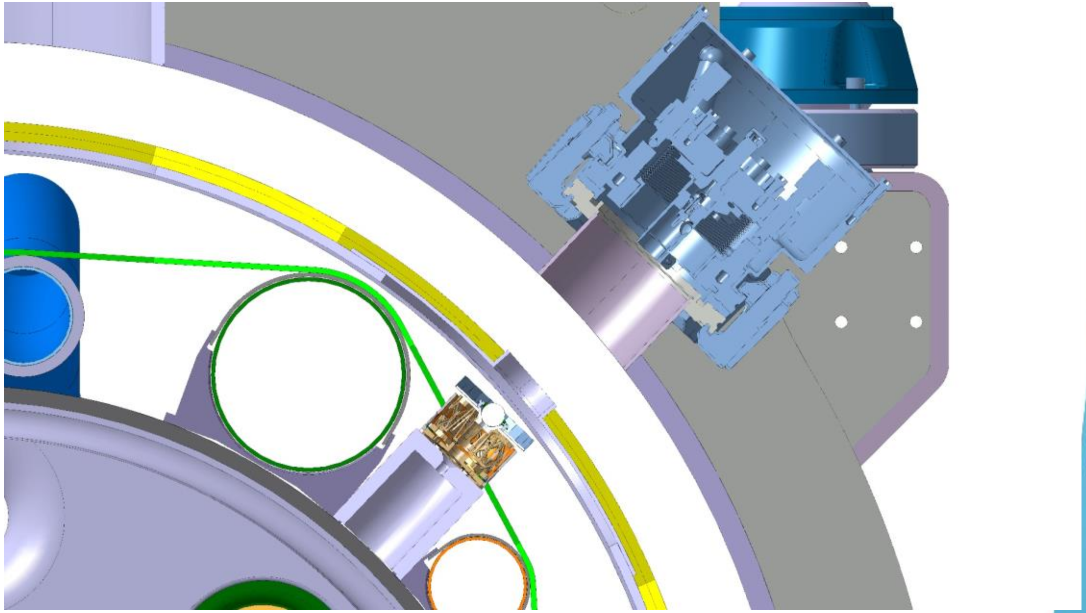






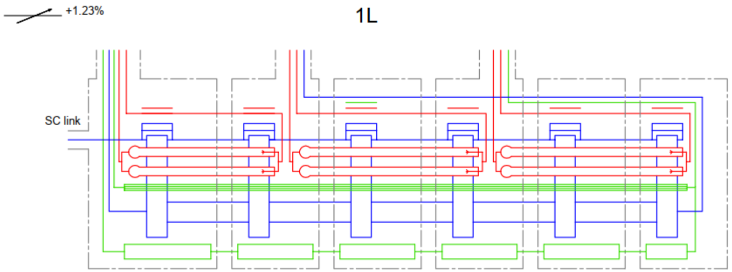
Alignment

- Cold mass position monitoring integration (FSI) is finished
- Geometrical acceptance https://edms.cern.ch/document/2135082
- Loads on alignment jacks

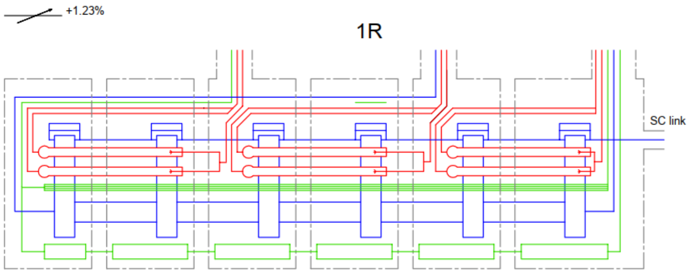


	Radial jack	Logitudinal jack	Vertical jack	*Longitudinal anchor*
Longitudinal load Fy [kN]	0	27	0	*LHC-HQF-ES-0001*
Radial load Fx [kN]	12	0	0	*0*
Vertical load Fz [kN]	162	162	162	*0*

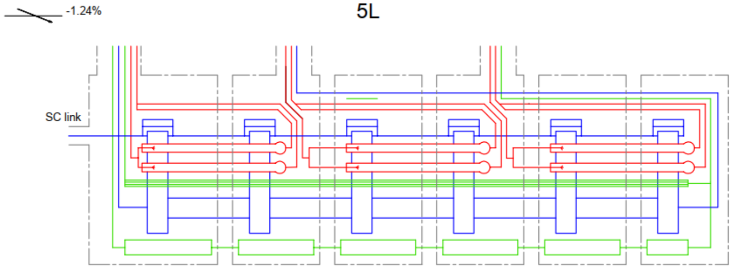
Cryostat assembly types



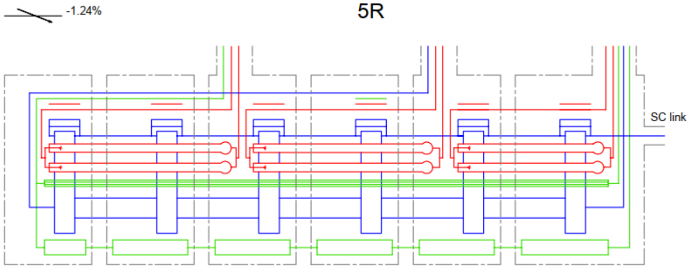
	D1	CP	Q3	Q2B	Q2A	Q1
Phase I (Standard section)	QBXF_S	QCXF_S	QQXF_SC	QQXF_SB	QQXF_SA	QQXF_SC
Phase II (Tech service module)	QBXFA	QCXFA	QQXFB	QQXFH	QQXFC	QQXFA
Phase III (Beam vacuum, end closures)	LBXFA	LCXFA	LQXFB	LQXFH	LQXFC	LQXFA



Q1	Q2A	Q2B	Q3	CP	D1
QQXF_SC	QQXF_SA	QQXF_SB	QQXF_SC	QCXF_S	QBXF_S
QQXFE	QQXFG	QQXFI	QQXFF	QCXFB	QBXFB
LQXFE	LQXFG	LQXFI	LQXFF	LCXFB	LBXFB



	D1	CP	Q3	Q2B	Q2A	Q1
Phase I (Standard section)	QBXF_S	QCXF_S	QQXF_SC	QQXF_SB	QQXF_SA	QQXF_SC
Phase II (Tech service module)	QBXFC	QCXFC	QQXFF	QQXFJ	QQXFG	QQXFE
Phase III (Beam vacuum, end closures)	LBXFC	LCXFC	LQXFF	LQXFJ	LQXFG	LQXFE



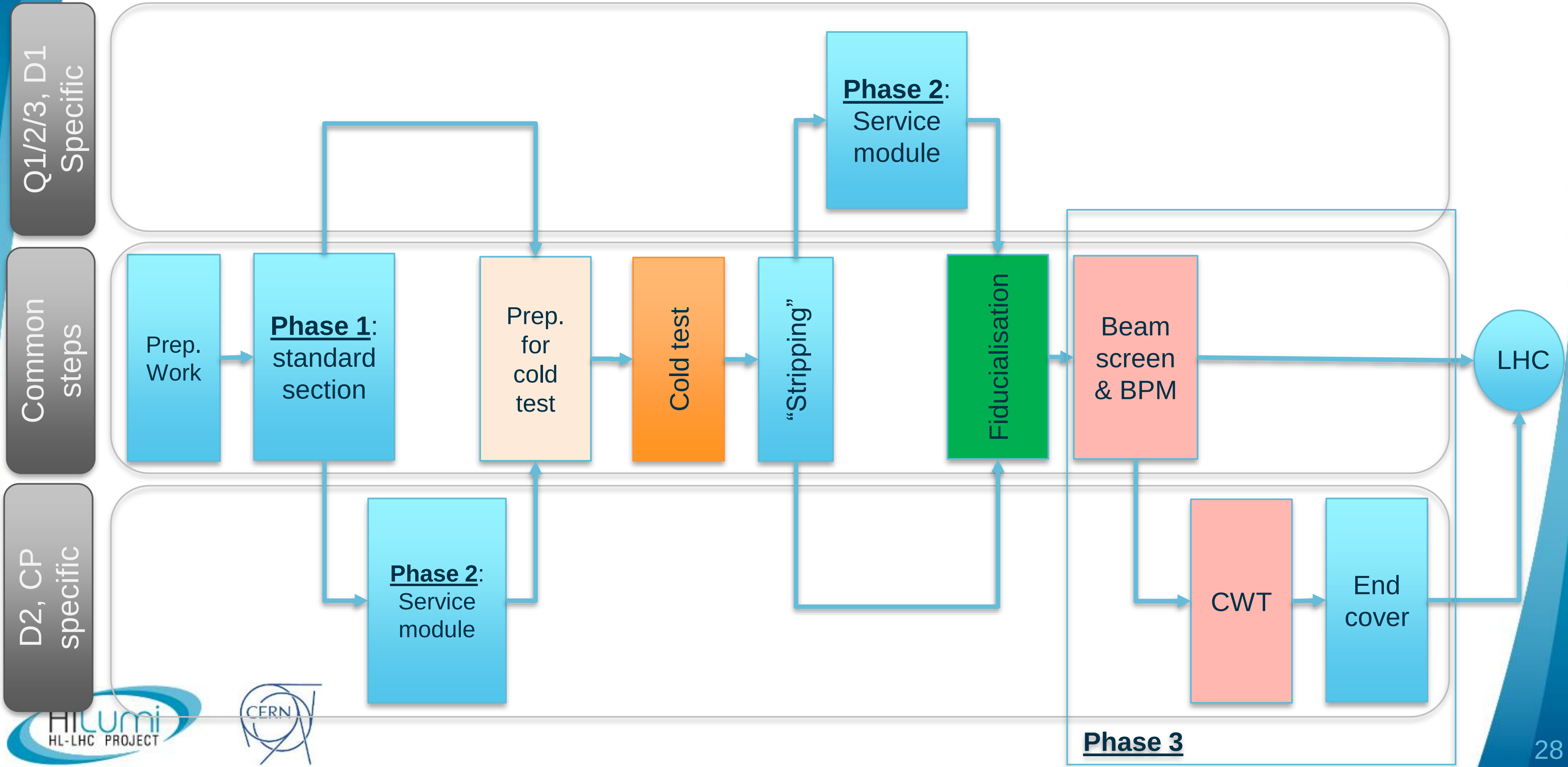
Q1	Q2A	Q2B	Q3	CP	D1
QQXF_SC	QQXF_SA	QQXF_SB	QQXF_SC	QCXF_S	QBXF_S
QQXFA	QQXFC	QQXFD	QQXFB	QCXFD	QBXFD
LQXFA	LQXFC	LQXFD	LQXFB	LCXFD	LBXFD

He II saturated
He II pressurized
60-80 K

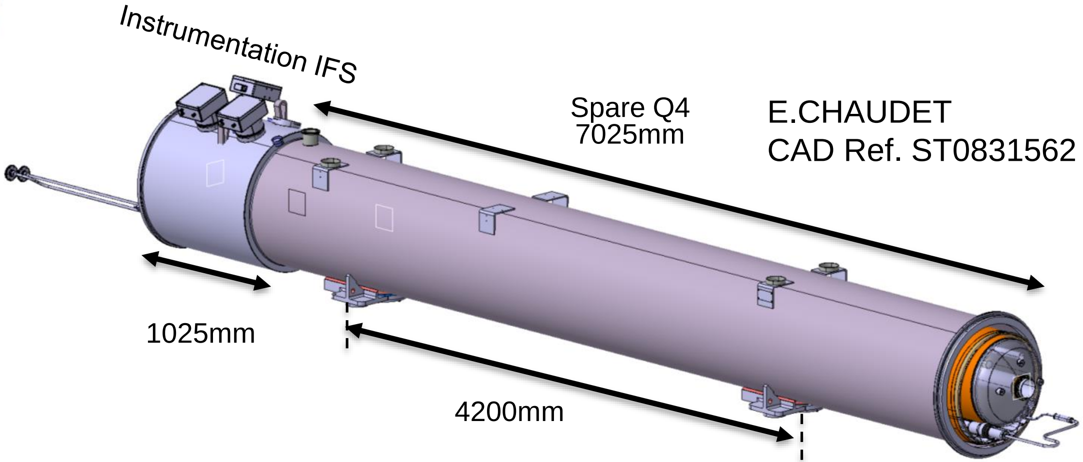
PIPING DIAGRAM AND TYPES OF ASSEMBLIES FOR THE HL-LHC INSERTION REGION CONTINUOUS CRYOSTAT Q1 TO D1		
EDMS No.: 1964233	Version: 2.0	Date: 2019-03-05
Prepared by: D. Ramos	Approved by: Cryostat Interface WG	

HiLumi HL-LHC PROJECT

Simplified workflow



Temporary test cryostat for 8.1m long MQXFB cold mass

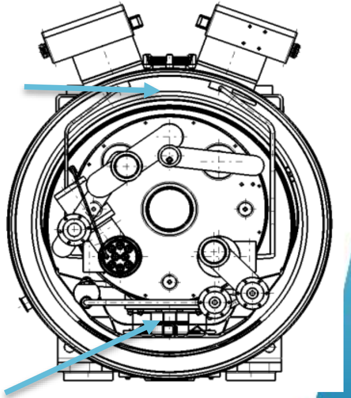


E.CHAUDET
CAD Ref. ST0831562

Custom made GFRE support posts in collaboration with **EP-DT**

- To avoid making a dedicated vacuum vessel we plan to reuse a Q4 vacuum vessel (LHC stock)
- But (almost) everything else is non-standard: Vacuum vessel extension (cryostat length & instrumentation); Bottom tray; Thermal shield
- The MQXF bigger diameter calls for the design of dedicated cold foot to limit the total height (limited by cryostating procedure).
- New cold foot proto have been manufactured in-house (EP/composite lab) from prepreg glass fibers.

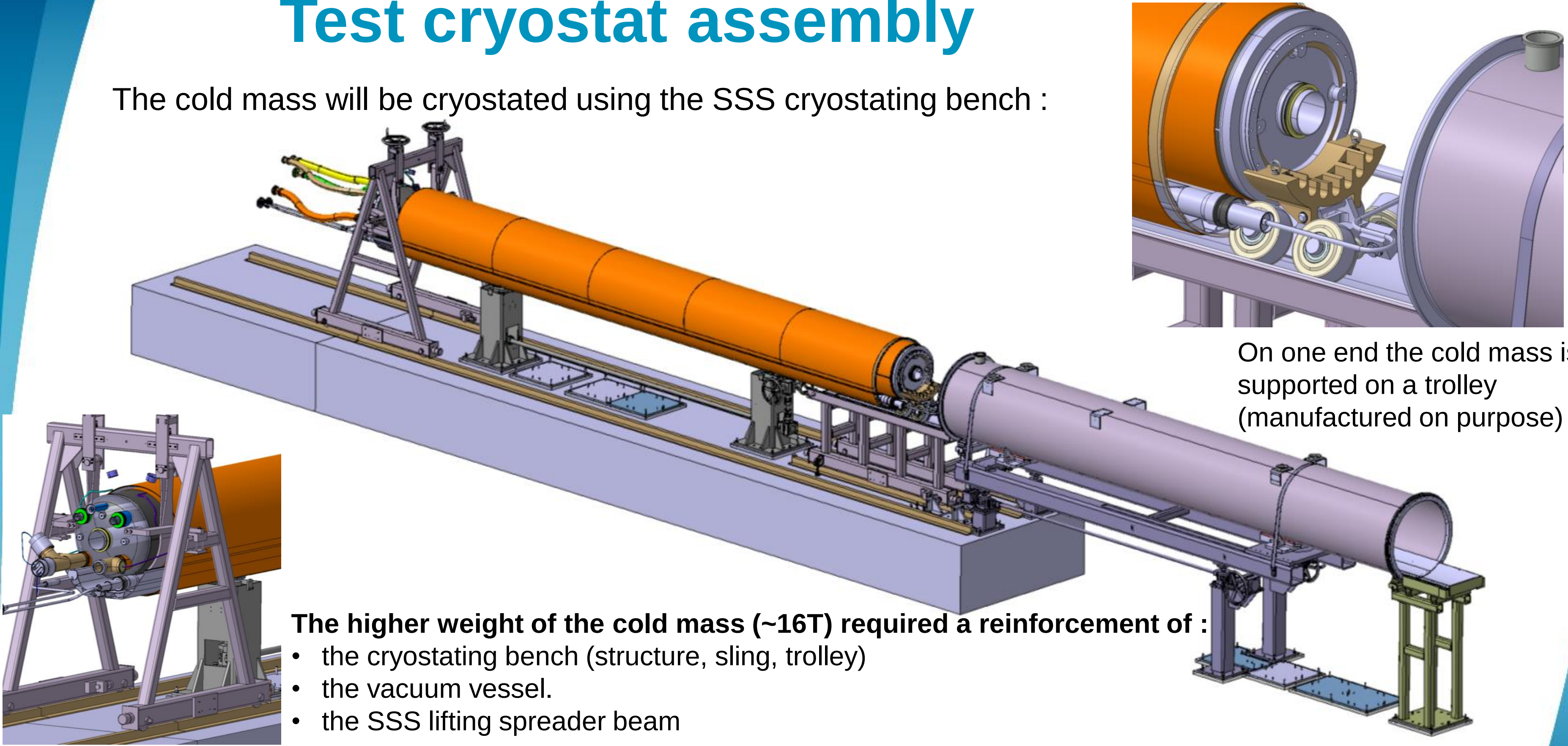
Space required for the cryostating procedure (must stay clear)



Reduced foot height to fit the CM in the Th. Shield
(-60mm vs LHC foot)

Test cryostat assembly

The cold mass will be cryostated using the SSS cryostating bench :



On one end the cold mass is supported on a trolley (manufactured on purpose)

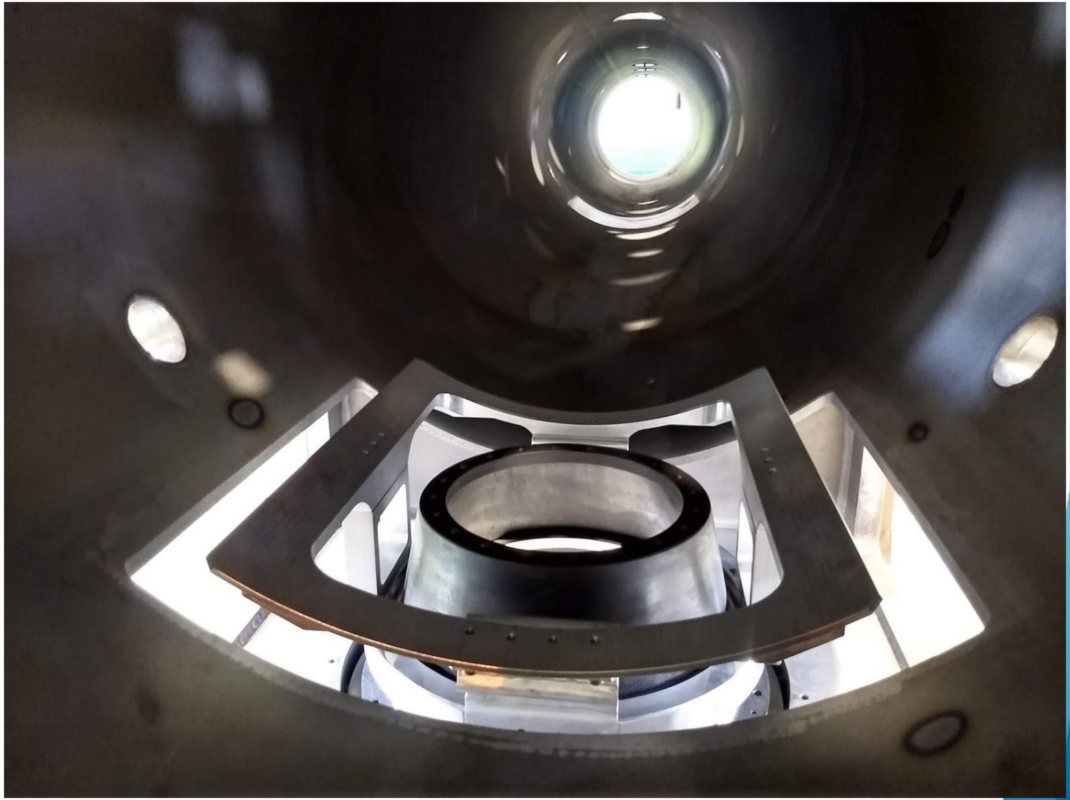
The higher weight of the cold mass (~16T) required a reinforcement of :

- the cryostating bench (structure, sling, trolley)
- the vacuum vessel.
- the SSS lifting spreader beam

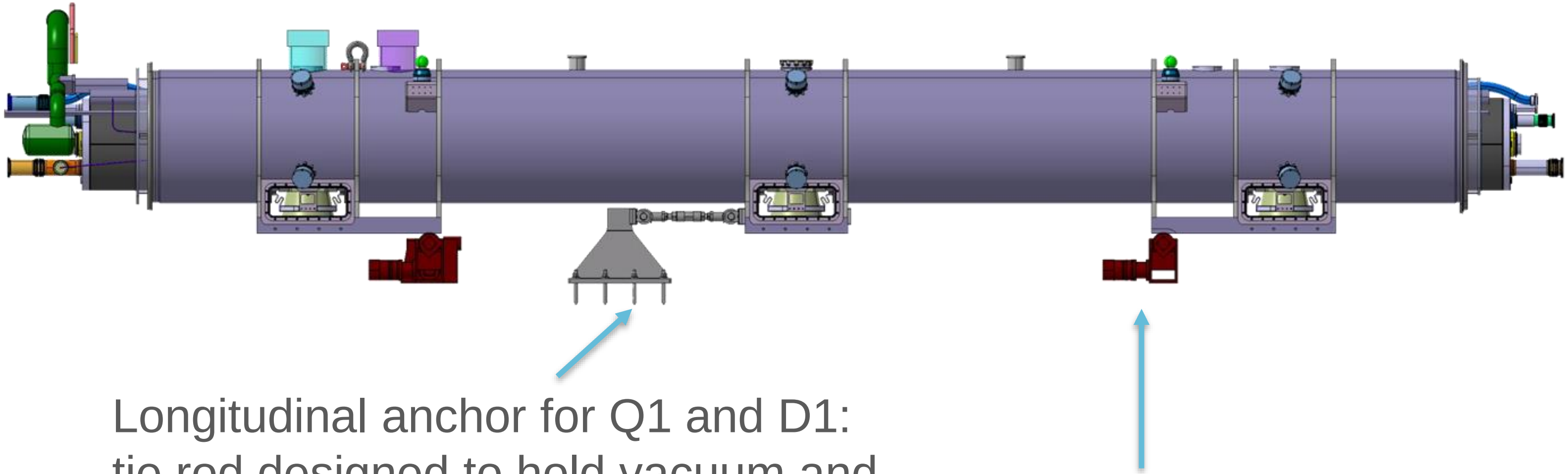
More details here:
https://indico.cern.ch/event/785918/

Cryostating bench resistance review (report)
Vacuum vessel resistance review (report)

Support post and thermal shield saddle in vacuum vessel



Longitudinal anchor for Q1 and D1



Longitudinal anchor for Q1 and D1: tie rod designed to hold vacuum and quench loads (longitudinal)

Alignment jacks on three points (isostatic) with remote actuation

HiLumi HL-LHC PROJECT

Preparation activities

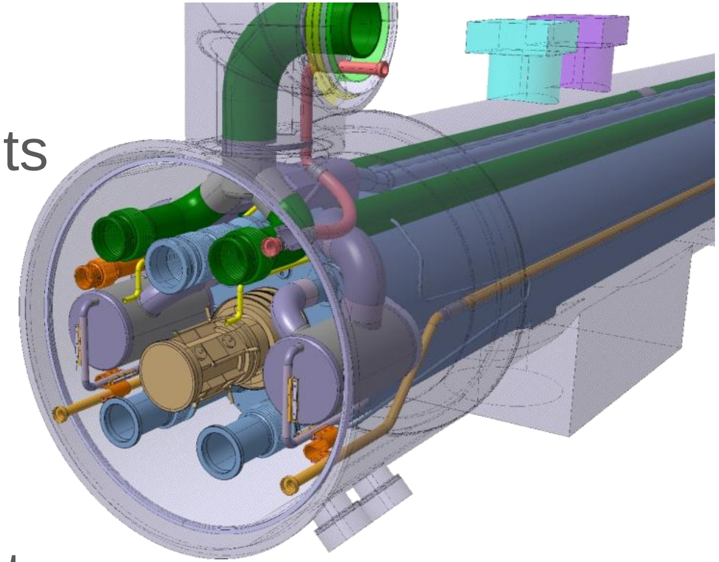
- Vacuum vessel and support posts (see edms 2135082 LHC-LM-ES-0001)
  - Check alignment of cold mass interface on support posts inside the vacuum vessel
  - Adjust shim height and horizontal alignment if required
- Thermal shield bottom half
  - Welding and pressure+leak testing of aluminium to stainless steel transitions
  - Assembly and welding of shells to extrusions
- Cold mass
  - Cold mass equipped with *feedthroughs* and auxiliary busbar lines
  - Extra length on piping extremities
  - Pressure tested, leak checked and electrically tested

Phase 1: Standard section assembly

- Setup vacuum vessel and rails on cryostating tooling
- Place thermal shield bottom half on cryostating sledges (on the assy table) and 2K blanket inside
- Position cold mass over sledges
- Install cryogenic piping
- Wrap 2K blanket on cold mass
- Assemble thermal shield
- Wrap 70K blankets on thermal shield
- Move cold mass inside vacuum vessel
- Remove rails and sledges.
- Install support posts (preliminary draft in edms 2175663)
- Check cold mass alignement inside vacuum vessel along cold bore length
- Weld, connect and electrically check feedthroughs
- Q2: shipping to cold test; D2: Start phase 2

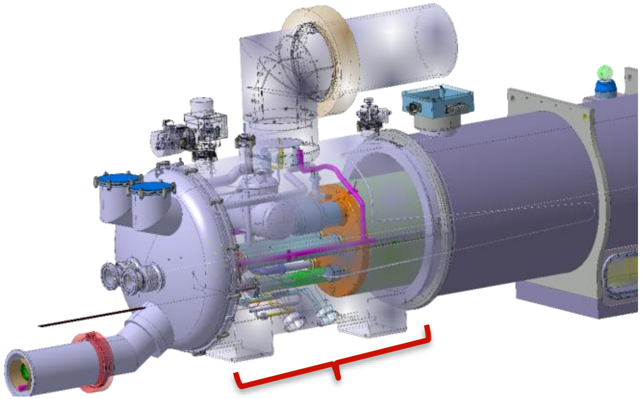
Phase 2: Q2 service module assembly

- Stripping after cold test
- Phase separators
- Pipe extremities and expansion joints
- Thermal shield
- MLI
- Vacuum vessel
- Jumper
- Pressure test
- Removal of pressure test equipment
- Dimensional check of interfaces
- Shipping to TE-VSC for beamscreen and BPM



Phase 2: D2 service module assembly

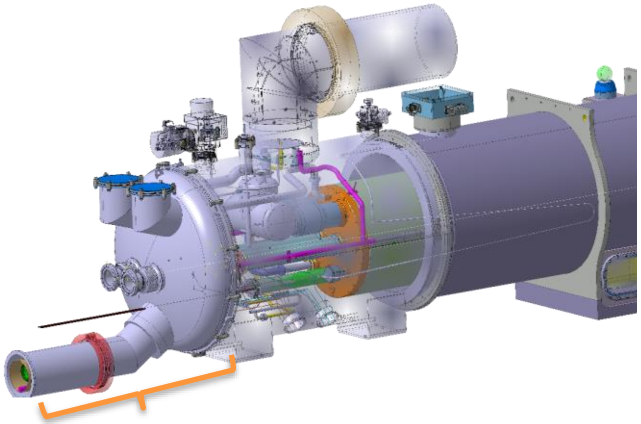
- Heat exchanger (to be decided if part of cold mass assembly or cryostating activity)
- Pipe connections
- Thermal shield
- Vacuum vessel
- Jumper
- Pressure test
- Shipping to cold test



- Stripping
- Fiducialization
- Shipping to TE-VSC for beamscreen BPM and CWT

Phase 3: D2 end covers

- Connection to SC link
- Thermal shield end covers
- MLI
- Vacuum vessel end covers



Response to random base excitation

Complete presentation can available here: https://indico.cern.ch/event/742082/contributions/3085159/

Random excitation: at a given frequency the **amplitude** of the excitation constantly changes, but its **average** value tends to remain relatively constant. It follows a Gaussian distribution.

This gives the ability to characterise a random excitation as a statistical process: **Power Spectral Density** plots (units mm^2/Hz for displacement, mm/s^2/Hz for acceletation, N^2/Hz for force).

Frequency Response Function: Can be obtained from a finite element model of the cryo-assembly through a modal analysis followed by a harmonic analysis.

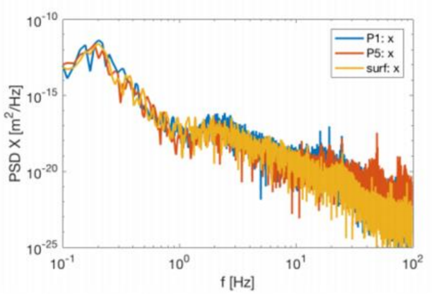
Response of the system to a single input:

$$RPSD(\omega) = |H(\omega)|^2 . PSD(\omega)$$

Spectral density response

Spectral density input

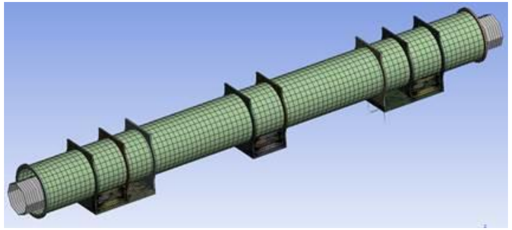
$$RMS = \sqrt{\int_0^\infty RPSD(\omega) d(\omega)}$$



$$H(\omega) = A(\omega) - iB(\omega)$$

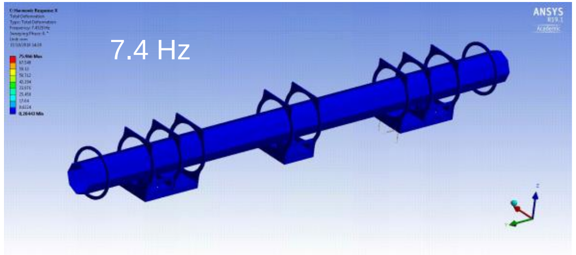
$$|H(\omega)| = \sqrt{A^2 + B^2} = \frac{a_{out}}{a_{in}}$$

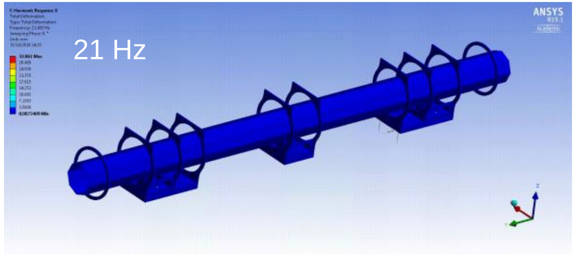
$$\frac{\mathrm{Im}[H(\omega)]}{\mathrm{Re}[H(\omega)]} = \frac{B}{A} = \tan\phi$$

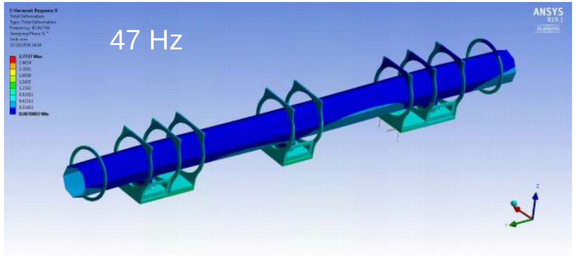


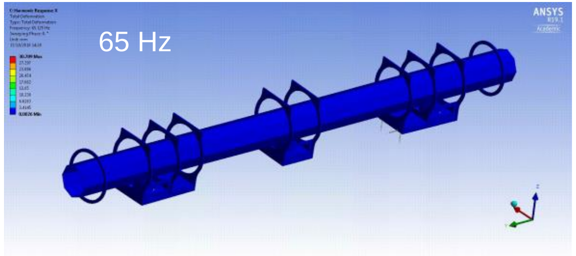
FE model of HL-LHC Q2 cryoassembly. Jacks modelled as springs (not visible).

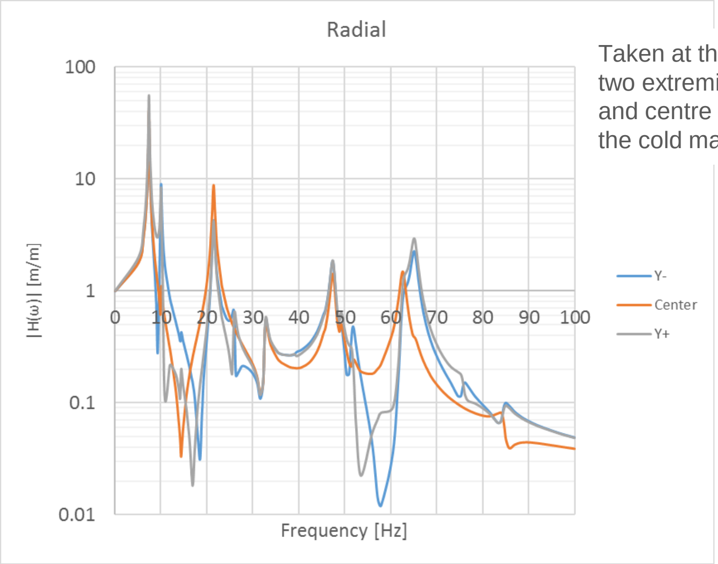
HL-LHC Frequency Response Function: Radial





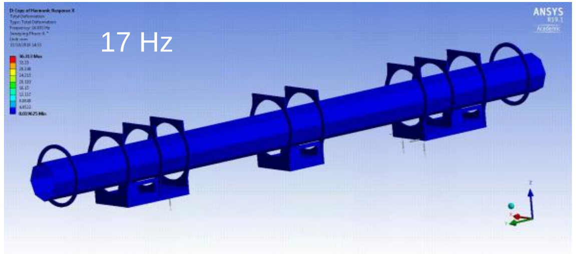


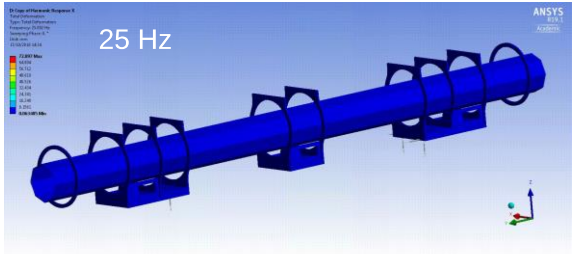


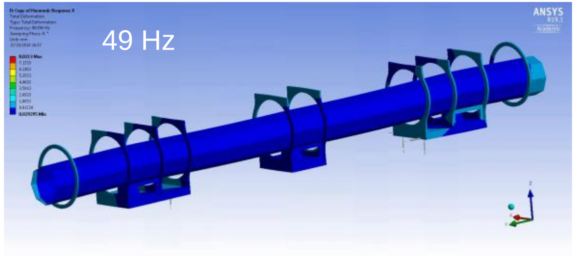


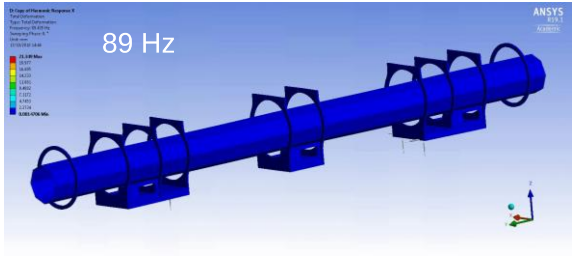
Assuming 1% overal damping ratio. NOTE: Amplification at ressonance ponts are highly dependent on damping: measurements on real cryo-assemblies are necessary.

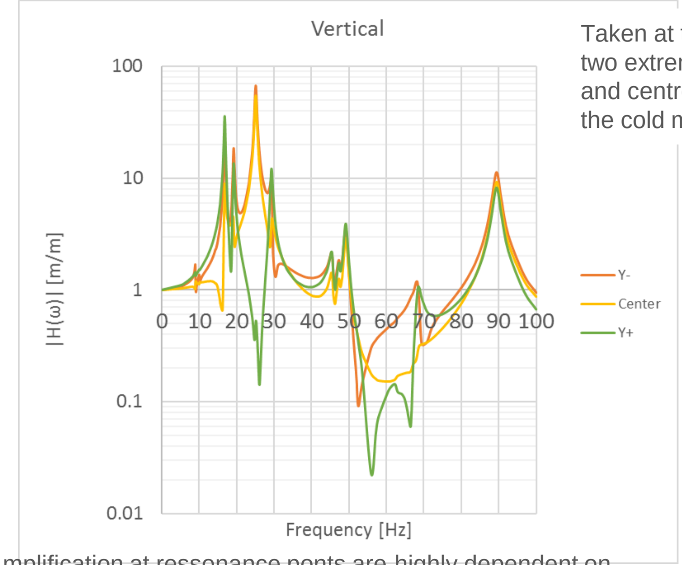
HL-LHC Frequency Response Function: Vertical







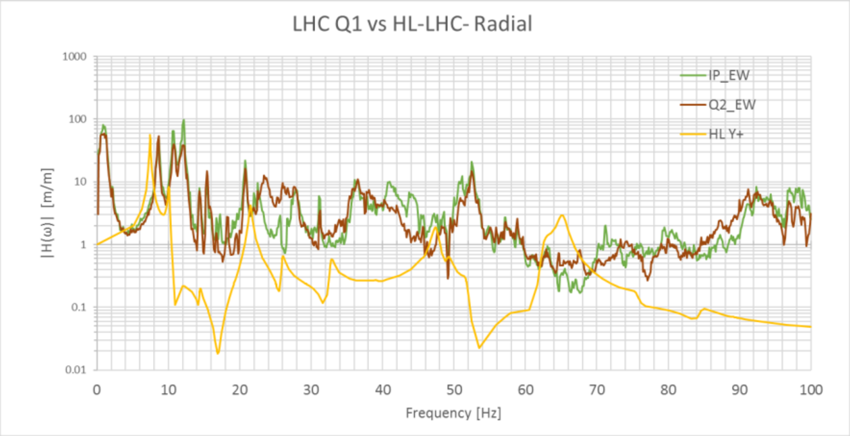


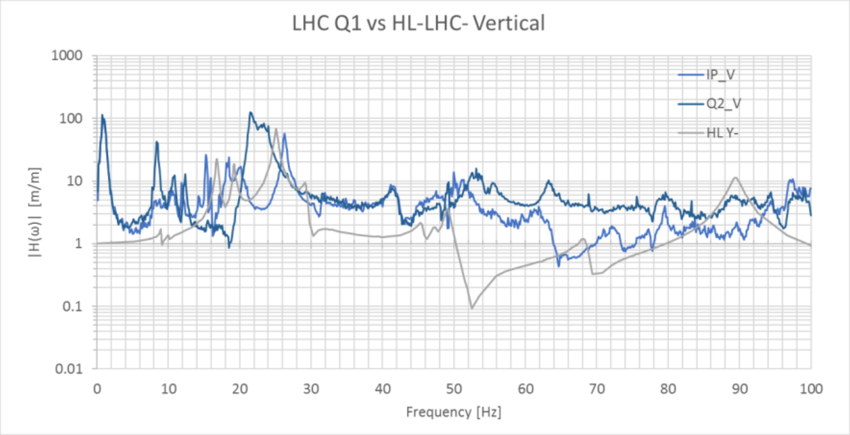


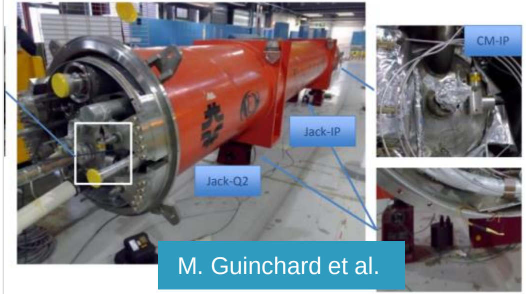
Taken at the two extremities and centre of the cold mass

Assuming 1% overal damping ratio. NOTE: Amplification at ressonance ponts are highly dependent on damping: measurements on real cryo-assemblies are necessary.

Comparison with measurements on LHC Q1







- Comparable resonant frequencies despite substantially different structure
- Significant difference observed on attenuation frequencies for radial excitation
- On-going work on a model of LHC Q1 cryoassembly will give us a better understanding of the differences between LHC and HL-LHC

Interconnect opening