Hi Lumi LHC
Crab Cavity Cryomodules

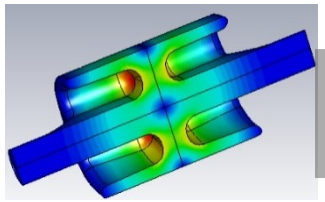
Niklas Templeton

STFC Daresbury Laboratory

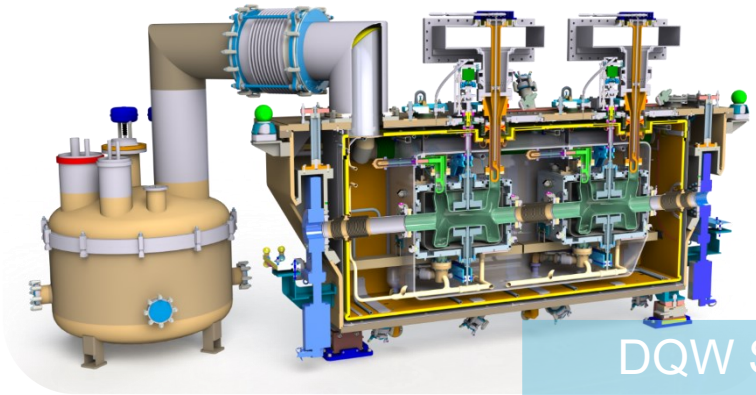
UK Crab Cavity Cryomodules WP Lead

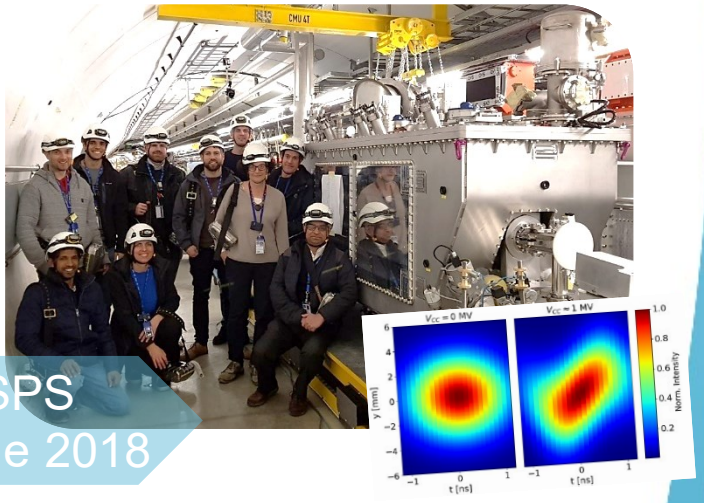
Crab Cavity Cryomodules for Hi Lumi LHC

- Hi Lumi LHC Crab Cavities
- Crabs Collaboration
- Design Features & Innovations
- RFD SPS Prototype Cryomodule Build
- UK Lessons Learnt (so far)

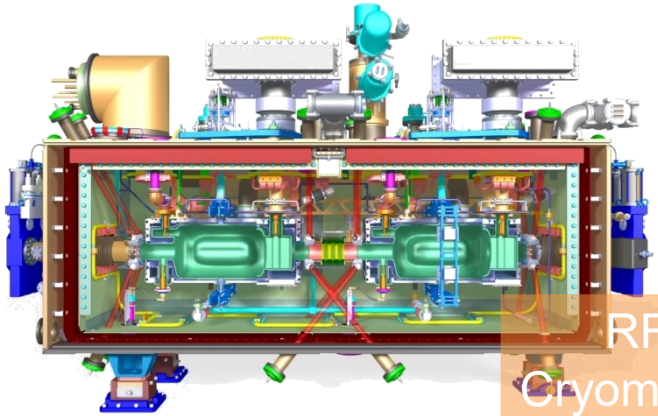


UK 4-Rod Cavity Prototype 2012





DQW SPS Cryomodule 2018



RFD SPS Cryomodule 2023

Hi Lumi LHC Crab Cavities

To **maximise discovery potential of LHC** by increasing rate of collisions

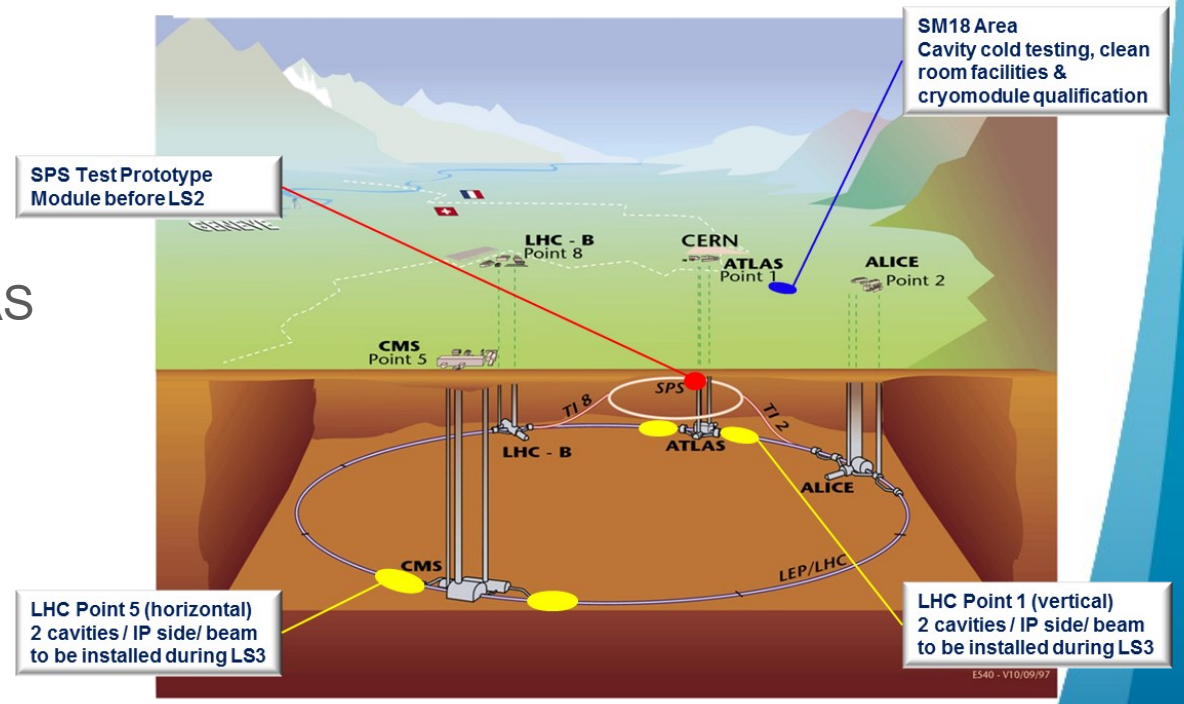
- 400 MHz crab cavities to **mimic head on collision**
- 4 cavities installed either side of Interaction Points

Double Quarter Wave (**DQW**) – vert. crabbing at CMS
- RF design by BNL & CERN
- Supplied by CERN & R.I.

Radio Frequency Dipole (**RFD**) – horiz. crabbing at ATLAS
- RF design by ODU
- Supplied by US-AUP & Zanon

Bunches colliding without crab crossing (left) & with the crab crossing (right)

DQW & RFD Crab Cavities



HiLumi HL-LHC PROJECT

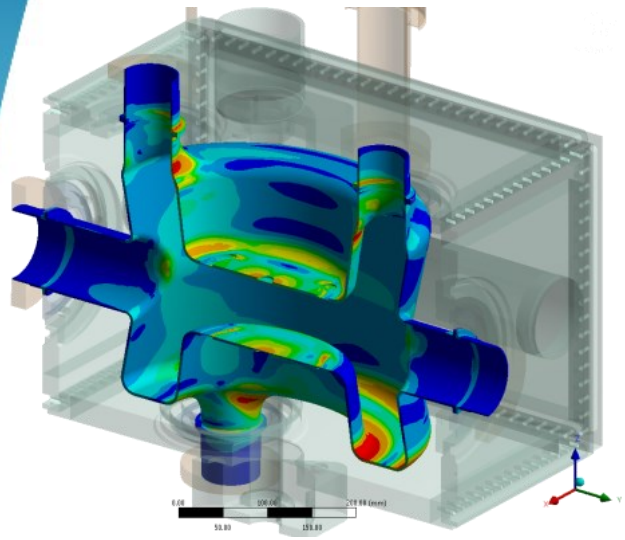
UKRI Science and Technology Facilities Council

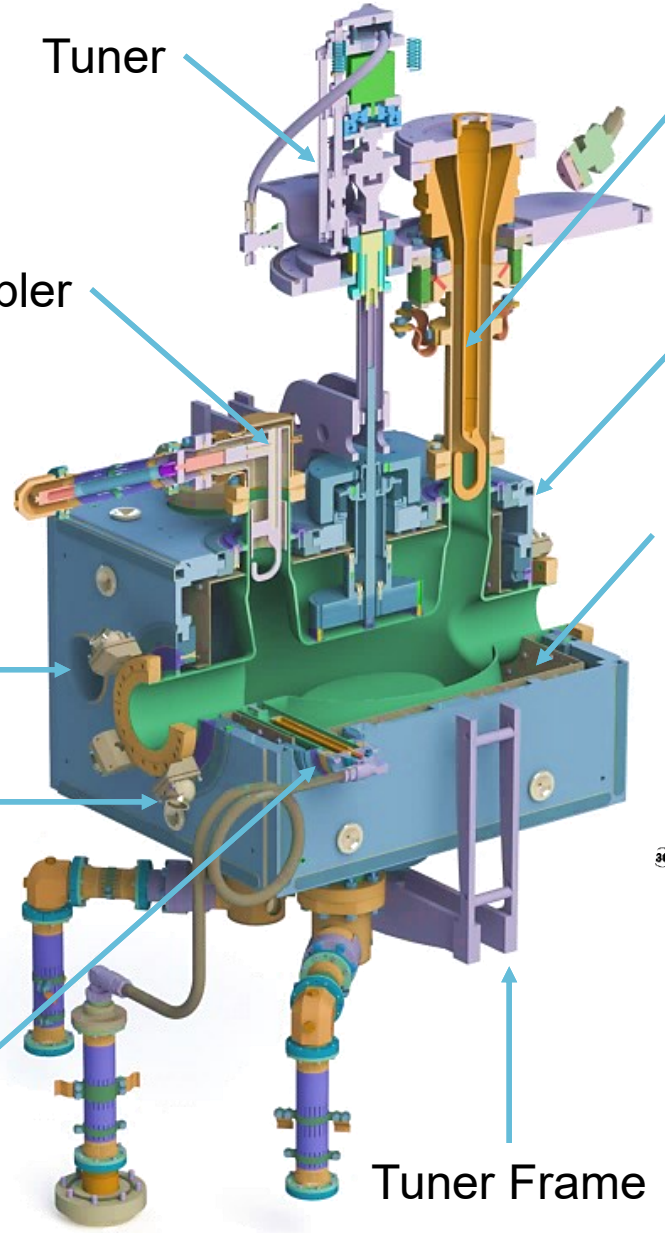
Thanks to Rama Calaga

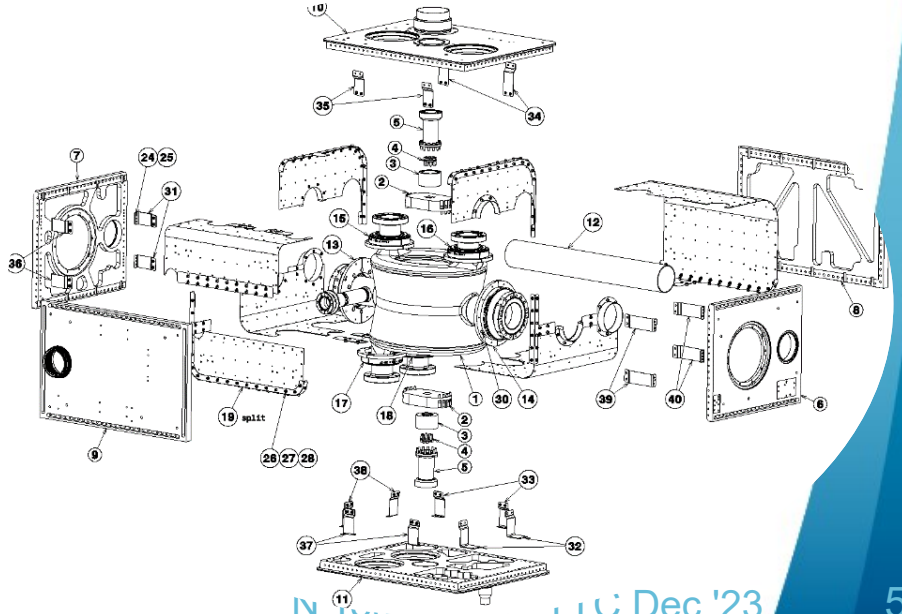
HL-LHC Crab Cavity Collaboration

5 DQW cryomodules	5 RFD cryomodules	20 RF Systems
• Cavities + processing + helium vessels by Research Instruments (**DE**) & **CERN** • Cold magnetic shields by **UK** • HOM couplers + antennas by **CERN** • 4 CM by **UK** (STFC) & 1 CM at **CERN** with some components from **CERN** • All cavities & CM cold validation tests at **CERN** (and a back up at Uppsala-Sweden)	• Bare cavities by Zanon (**IT**) under **US-AUP** • Processing + cold magnetic shield + helium vessel + HOM couplers + antennas + cold tests by **US-AUP** • 5 CM by **TRIUMF-Canada** with some components by **CERN** • CM cold validation tests at **CERN**	• High power amplifiers (IOT) **CERN-KEKB** • High power RF lines, circulators, loads by **CERN-KEKB** • μTCA platform for LLRF by CERN

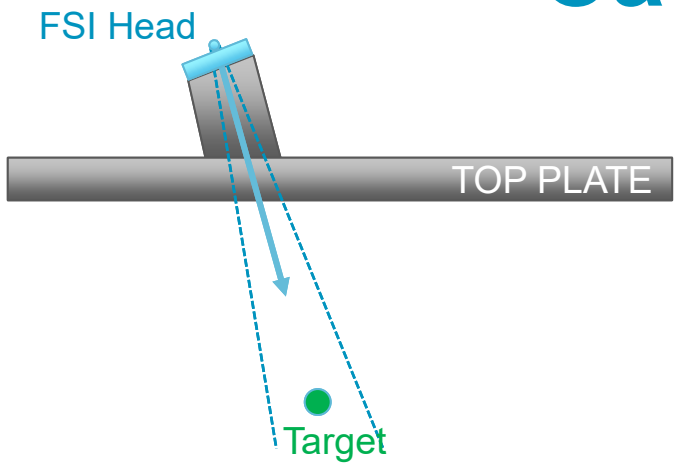
Dressed Cavity Equipped



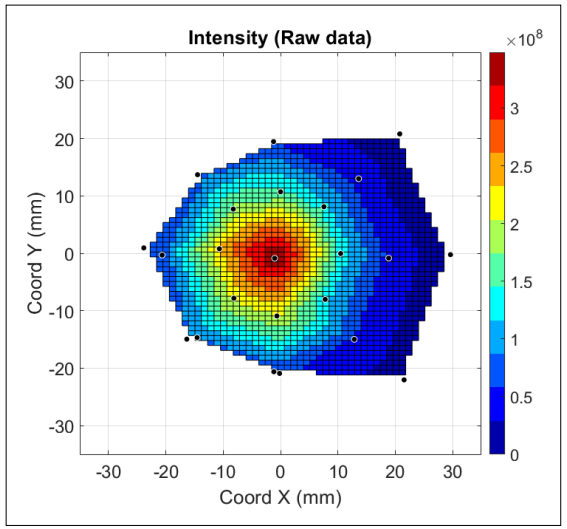


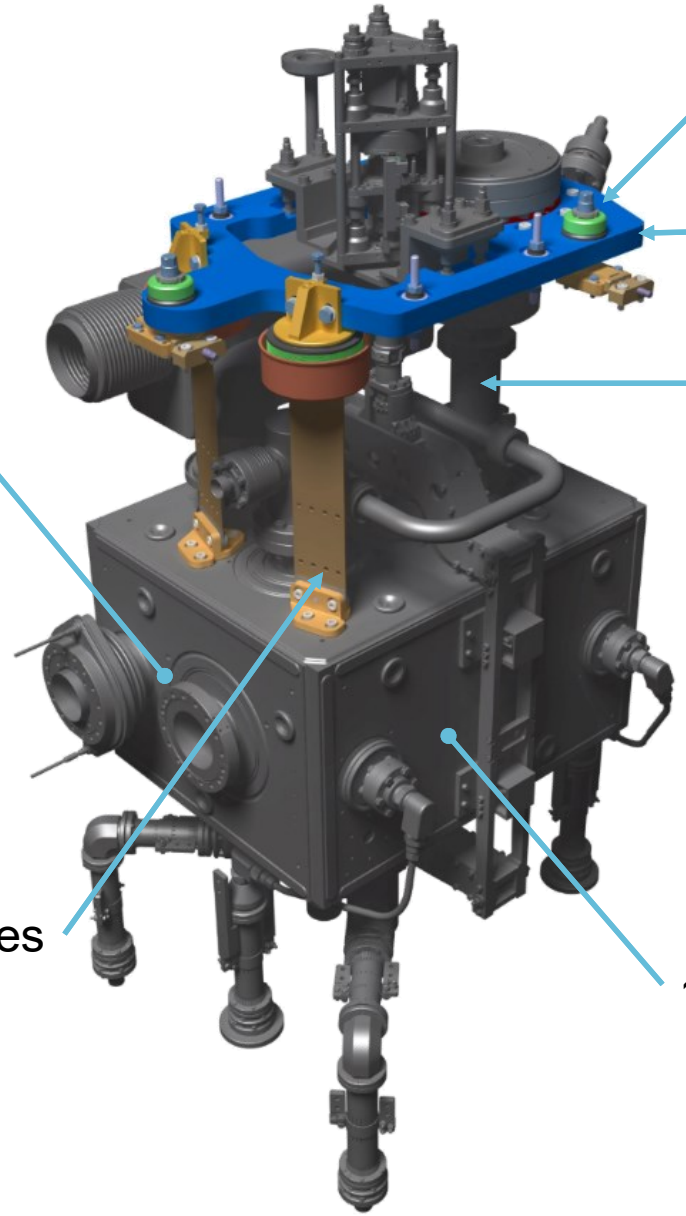


Cavity Support System



FSI Position Monitoring





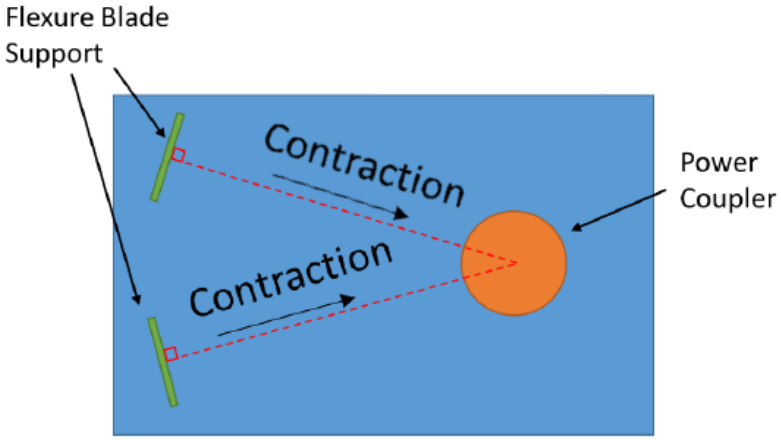
5-Point Kinematic Adjustment

Common Support Plate

FPC Fixed Point

Flexure Blades

~200kg Offset Mass



HiLumi HL-LHC PROJECT

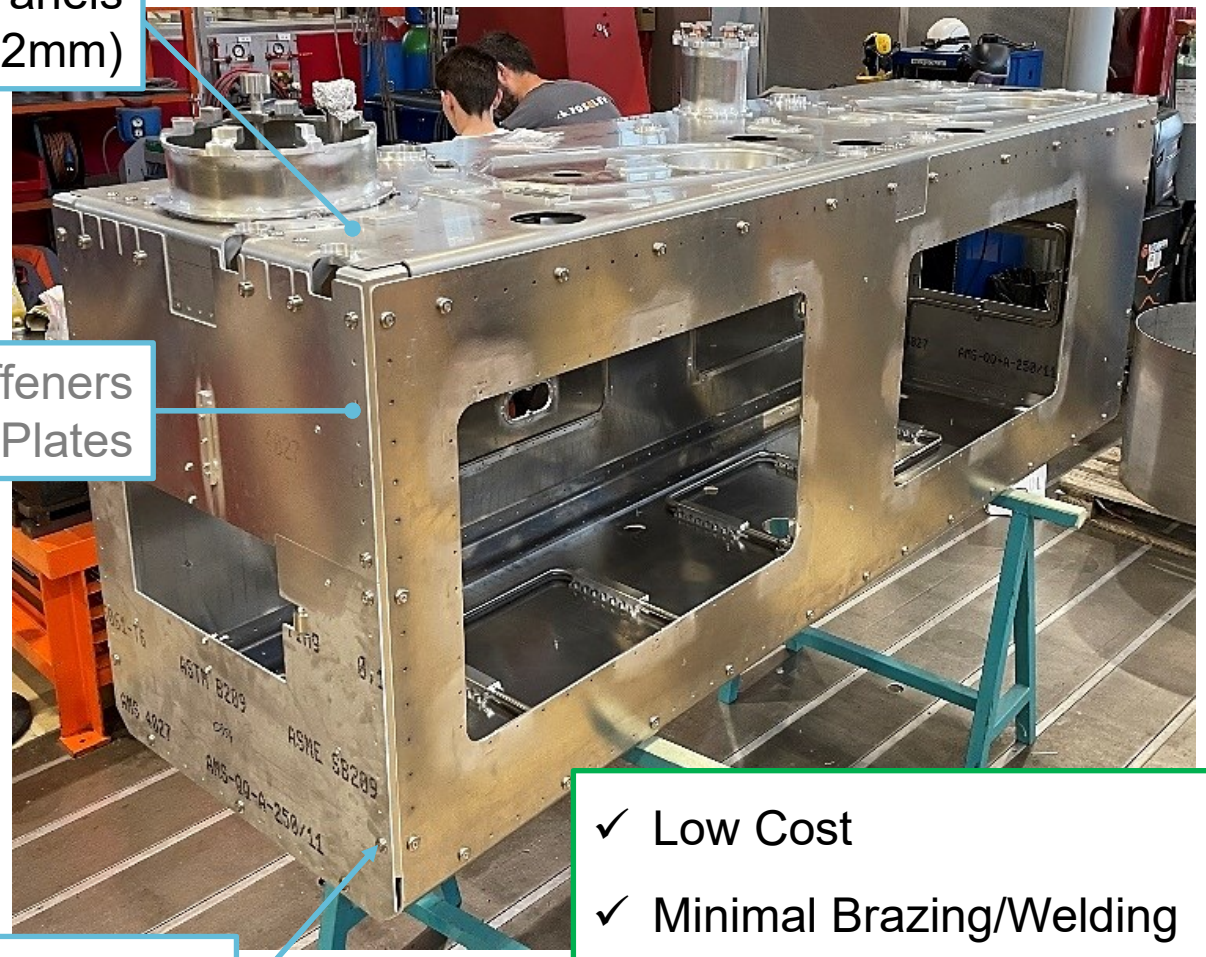
Science and Technology Facilities Council

Thermal Screen

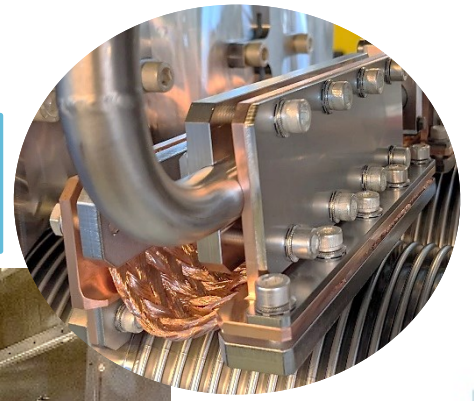
Al6061 Panels (t=2mm)

Al Stiffeners & Nut Plates

Ti Compensation Washers

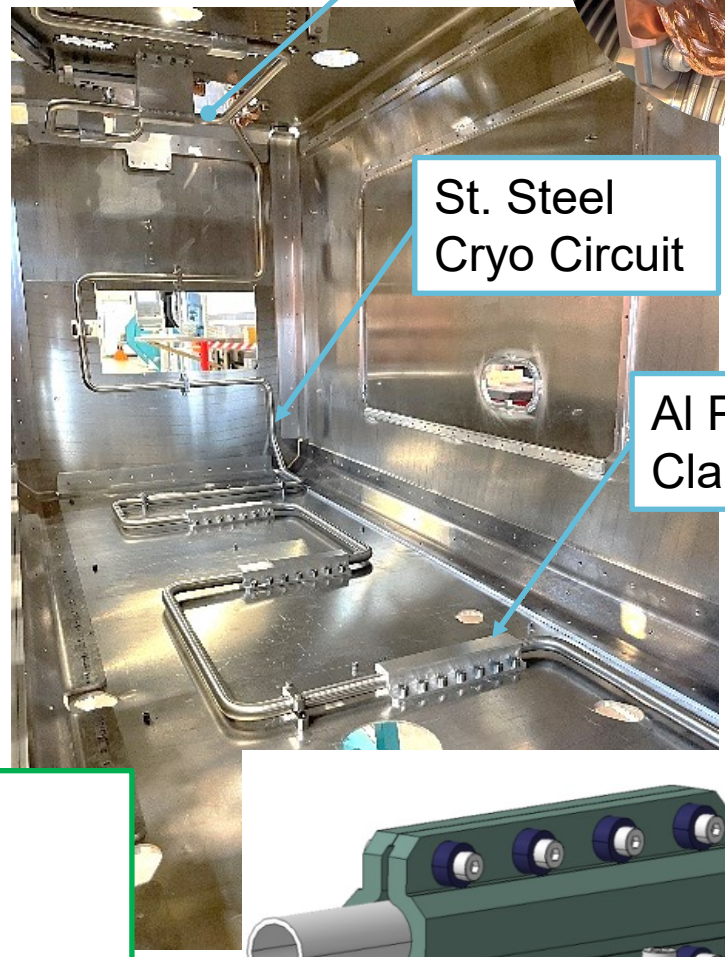


Cu Braids - **Direct to Pipes**



St. Steel Cryo Circuit

Al Pipe-Panel Clamps



- ✓ Low Cost
- ✓ Minimal Brazing/Welding
- ✓ Ease of Assembly
- ✓ Thermal Performance Validated

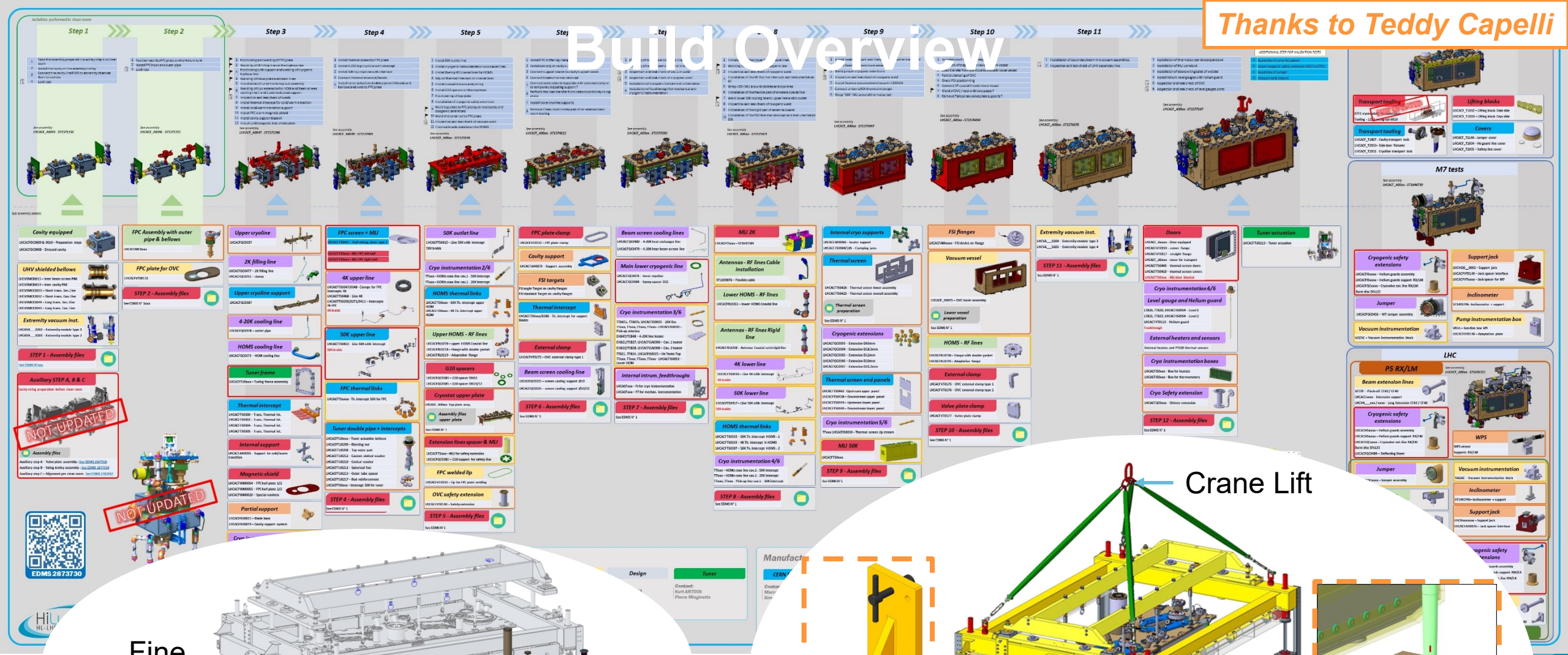
Series Pipe-Panel Clamps

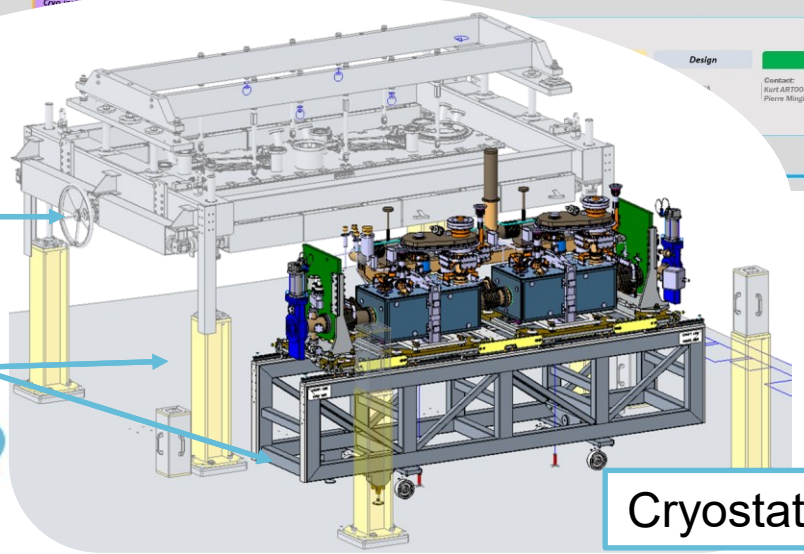
HL-LHC PROJECT

Science and Technology Facilities Council

Build Overview

Thanks to Teddy Capelli

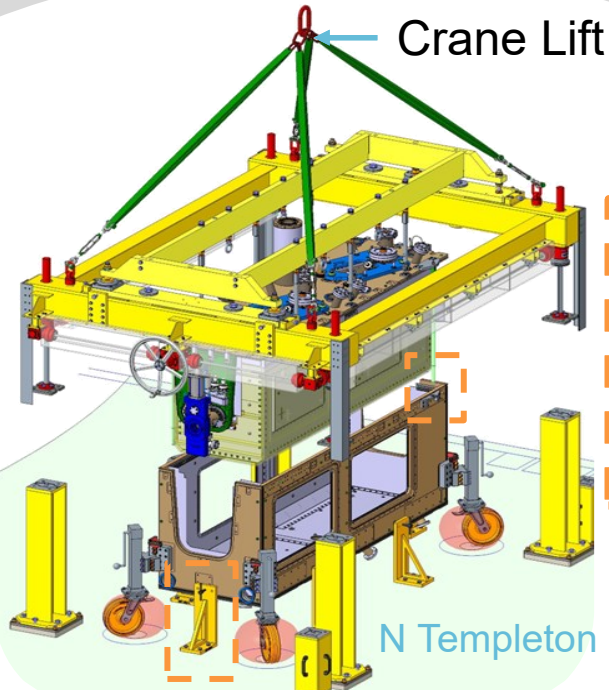




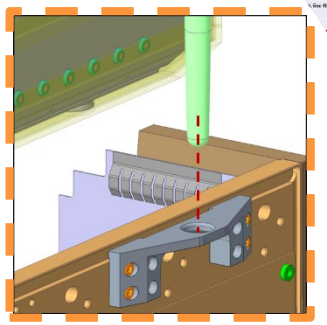
Fine Adjustment

2 Bays

Pushers



Crane Lift

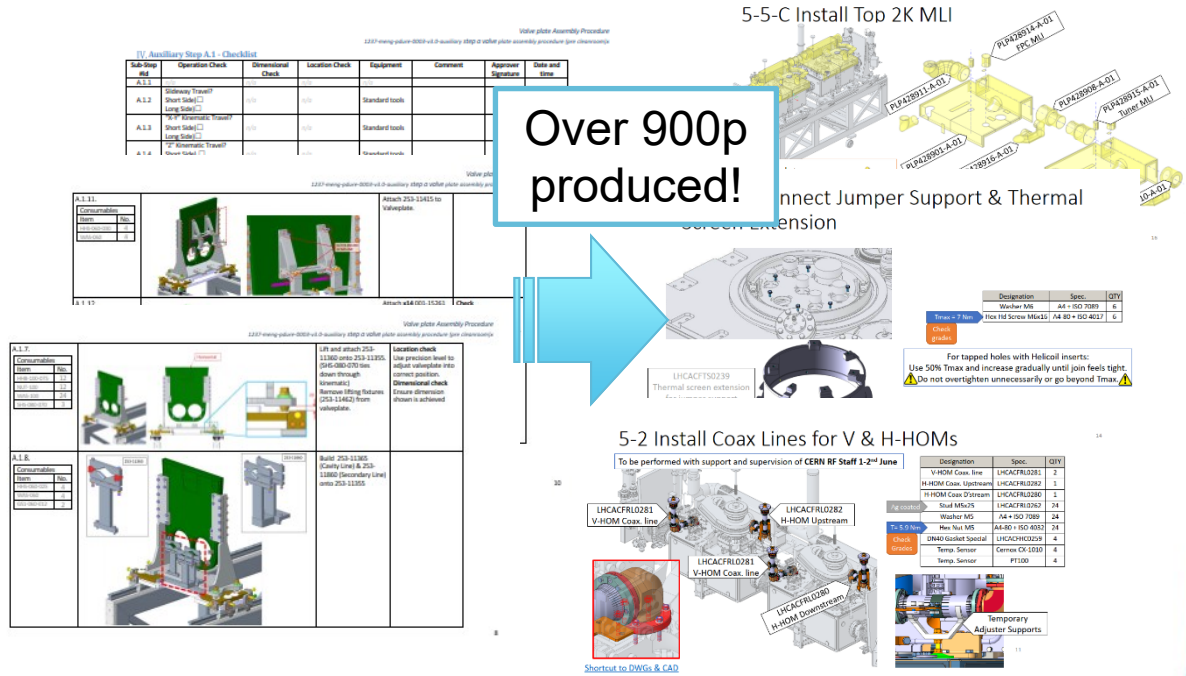


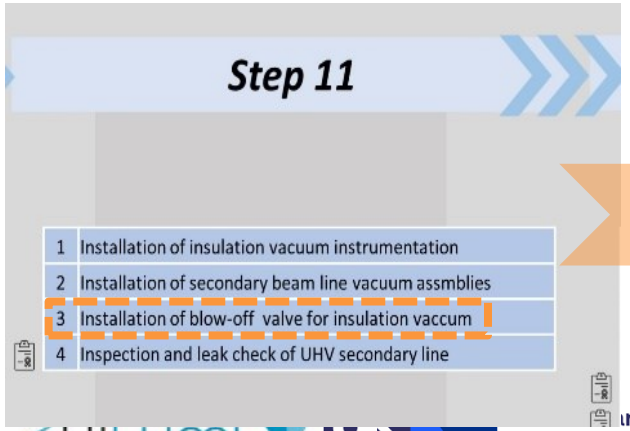
Guide Rods

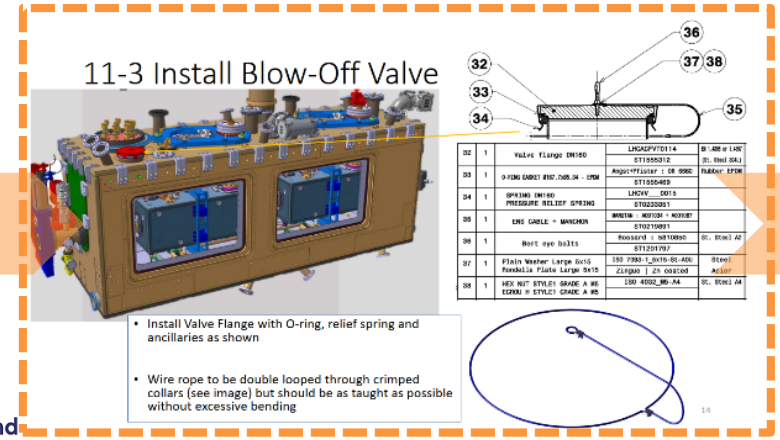
Cryostating Infrastructure

Detailed Build Procedures

- Poster logic + tooling & infrastructure
- Part of Traveller (QA)
- Troubleshoots & de-risk build
- Captures critical requirements, torques & sign-off
- ‘BOM kits’ pre-prepared by sub-step







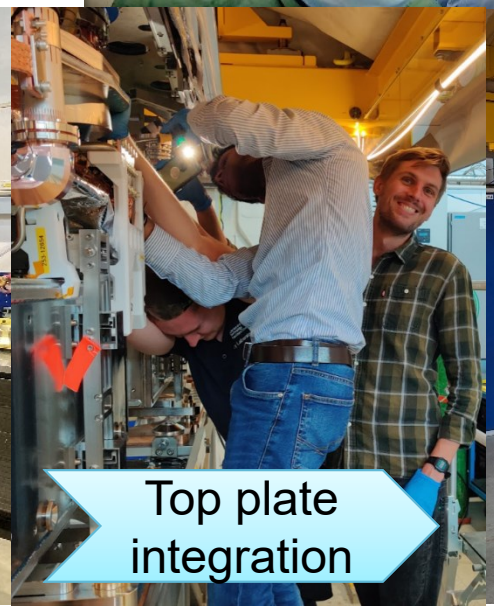
RFD Highlights (1/2)

Cavity string pre-cleanroom

Cleanroom assembly

First Welds

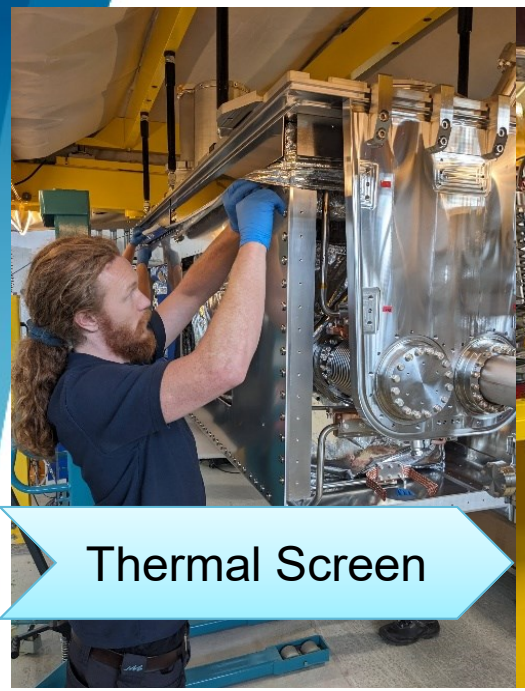
Upper cryo install



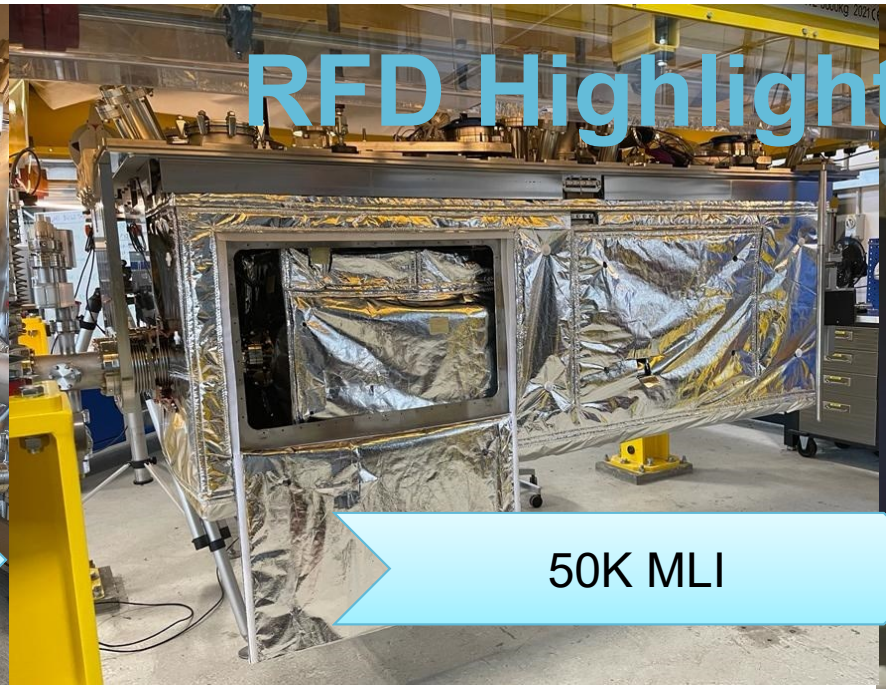
Top plate integration

Load Transfer Complete

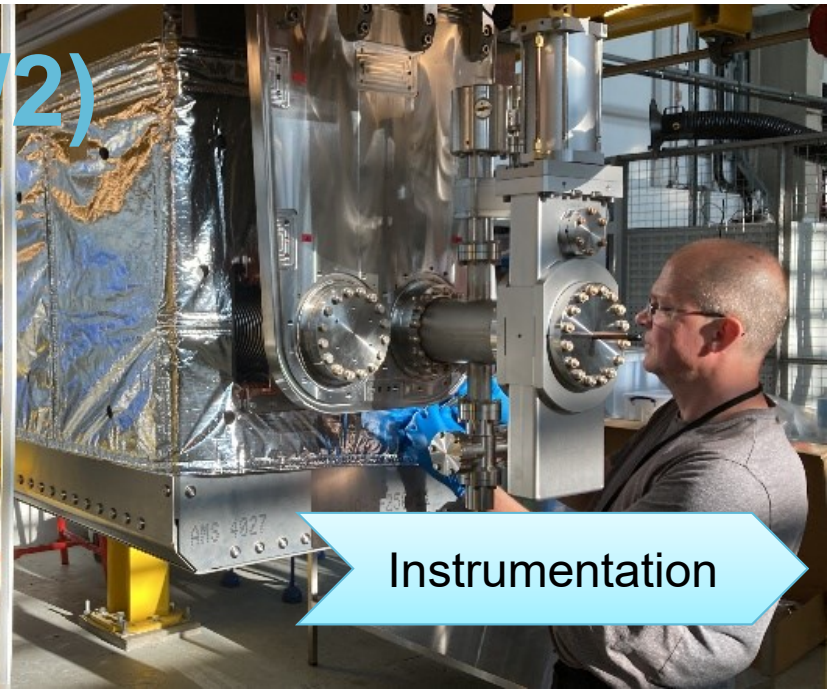
RFD Highlights (2/2)



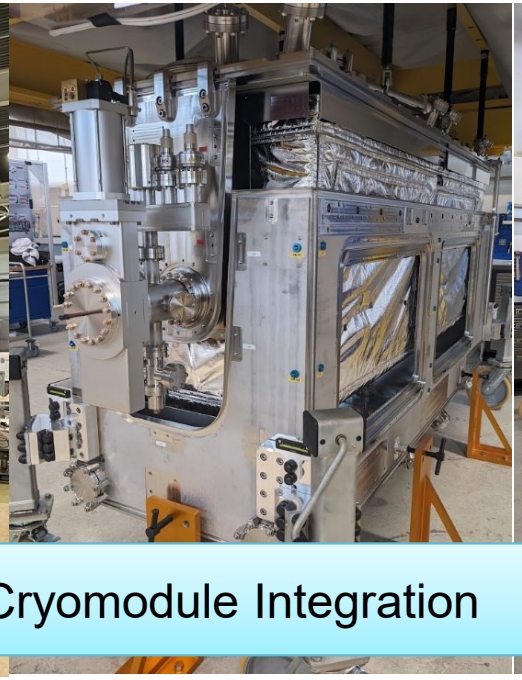
Thermal Screen



50K MLI



Instrumentation



Lower Cryomodule Integration

Shipping

RFD *Low*lights…

4 Lessons Learnt

…with memorable titles

> *"Learn from the mistakes of others. You can't live long enough to make them all yourself." – Eleanor Roosevelt*

Protect Ya Bellows

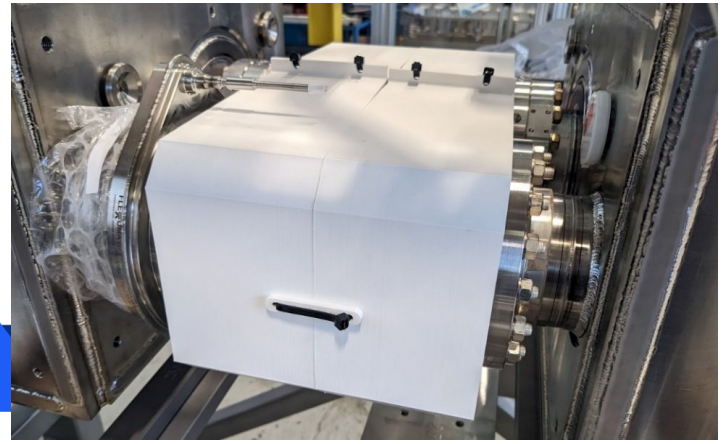
Issue: hydroform **bellows dent** pre-cleanroom

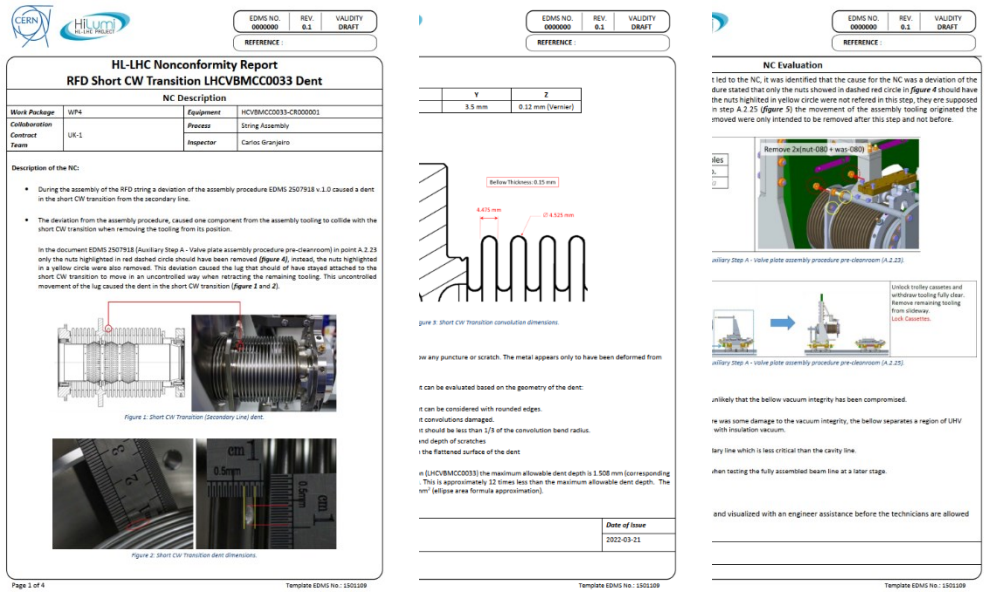
Impact: minor (thankfully)

Root cause: assembly procedure execution error

Mitigations:

- **Better comms** between engineers & technicians
  - Procedure roll-out & sign-off
  - More technical oversight
  - Many phone calls
- **Additional bellows protection** installed





HL-LHC Nonconformity Report
RFD Short CW Transition LHCVBMCC0033 Dent

NC Description

NC Evaluation

Take On M.E. (Multi-complex Engineering)

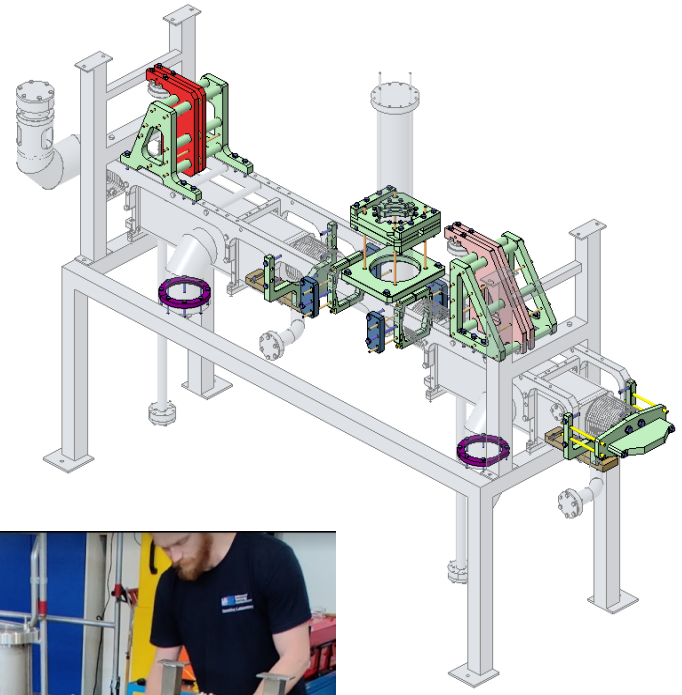
Issue: **Re-design** of test rig & **re-qualification** of Bi Phase line

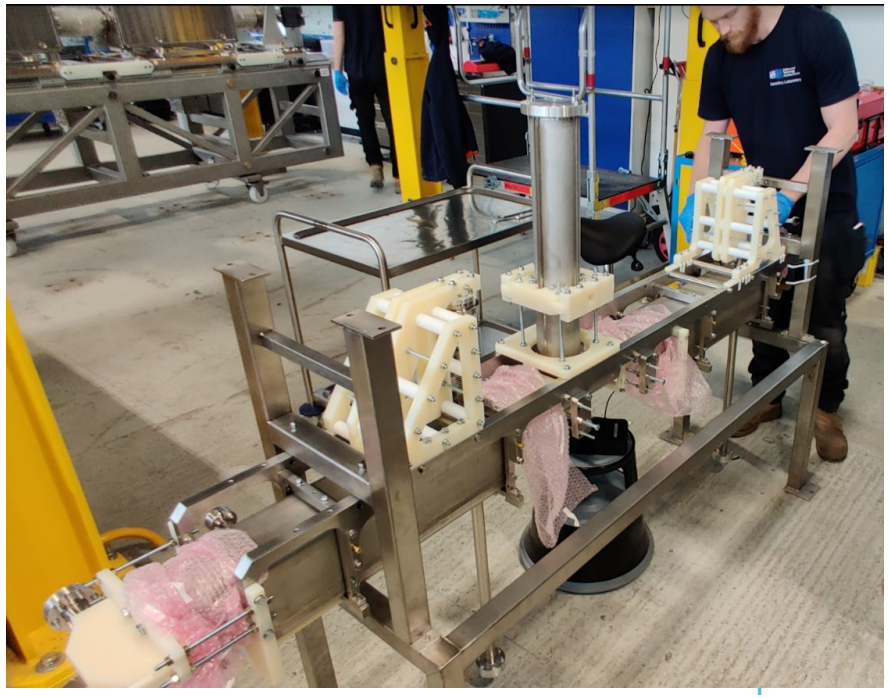
Impact: **Many months delay** to manage QA & resolve NCs

Root Cause: Poor supplier QA

Mitigations: developed & brought in-house:

- **Welding & weld engineering**
- **Steel procurement**
- **Design of weld-test-transport jigs**





Respect Yo QMS (Quality Management System)

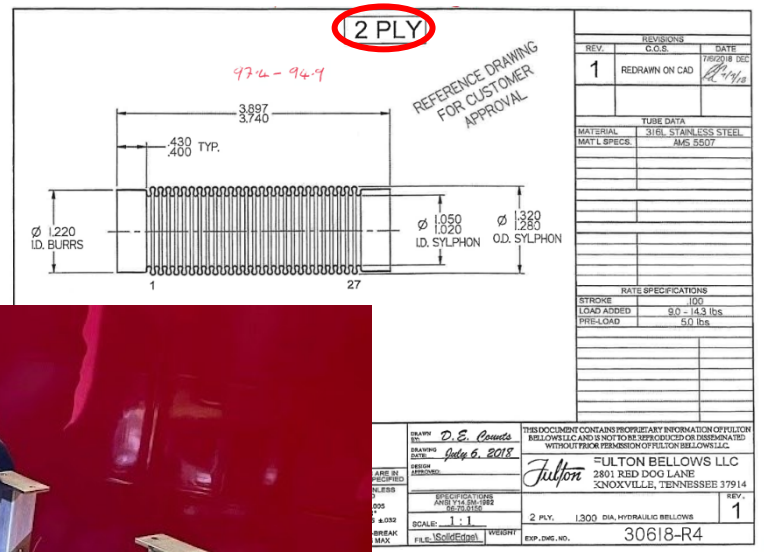
Issue: removal & replacement of **NC bellows sub-assembly** after delivery

Impact: Many weeks to fabricate, re-work & re-qualify

Root Cause: QA **processes not followed**

Mitigations:

- Improved **quality training & refreshers**
- More QA oversight
- **Local instructions** to remove QMS barriers



Mo Checks – Less Problems

Issue: **damage** to power couplers **discovered at CERN**

Root cause **analysis & resolution: on-going**

Hypothesis: complex load transfer issue

Mitigations:

- Tooling design improvements
- **More** intermediate **test & checks**
  - ISO4 glovebox for beamline tests
  - Fundamental power coupler checks

BUILD CHECK & TEST (HOLD) POINTS

Step #	Activity	Alignment	RF	Leak Test	Other
0	Cavity string pre-assembly	Y			
1	ISO4 string assembly		Y	Beamline	
2	FPC assembly		Y	Beamline	
3	Bi Phase welding			Welds	
4	Tuner & thermal links				
5	Top plate integration	Y	Y	Welds	
6	Top plate load transfer	Y	Y		
7	Lower cryolines & instr'n			Welds	Instr'n
8	2K MLI				
9	Thermal Screen & 50K MLI			Welds	
10	Cryomodule load transfer	Y	Y		
11	Vacuum equipment			2ndline	
12	Cryomodule doors				
13	Outgoing acceptance	Y	Y	Insu-vac, Beamlines	Pressure, LN2, Instr'n
14	Transport tooling & frame				Shockloggers

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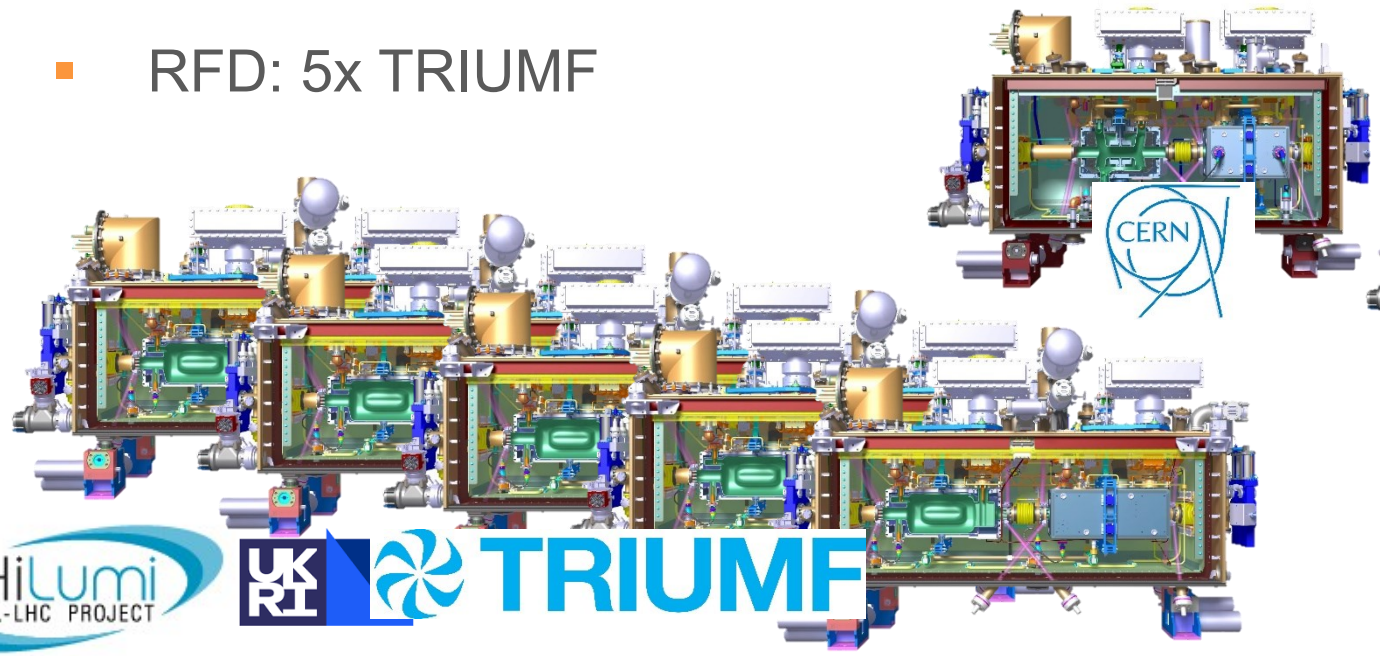
Hi Lumi Crab Cavity Cryomodules

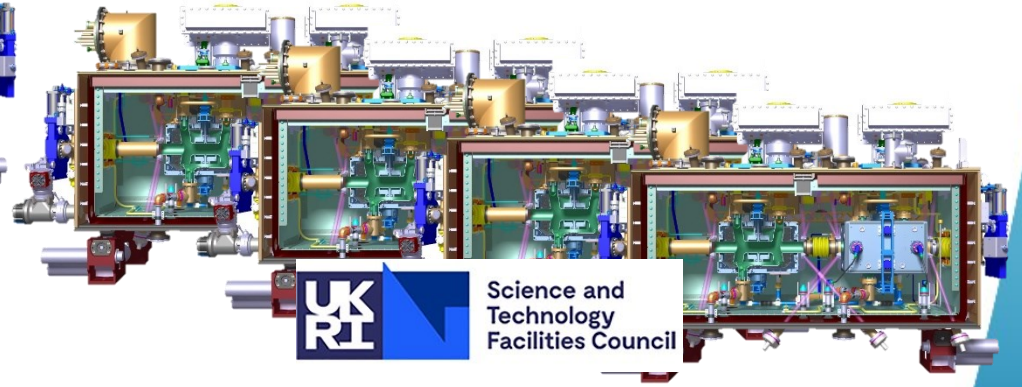
RFD SPS Cryomodule delivered Oct ’23 with many challenges & obstacles overcome!

- >10k components (5k unique)
  - >900 procedure pages
  - 56 CM welds (24 types)

Next: series LHC Cryomodules:

- DQW: 1x CERN + 4x STFC
- RFD: 5x TRIUMF





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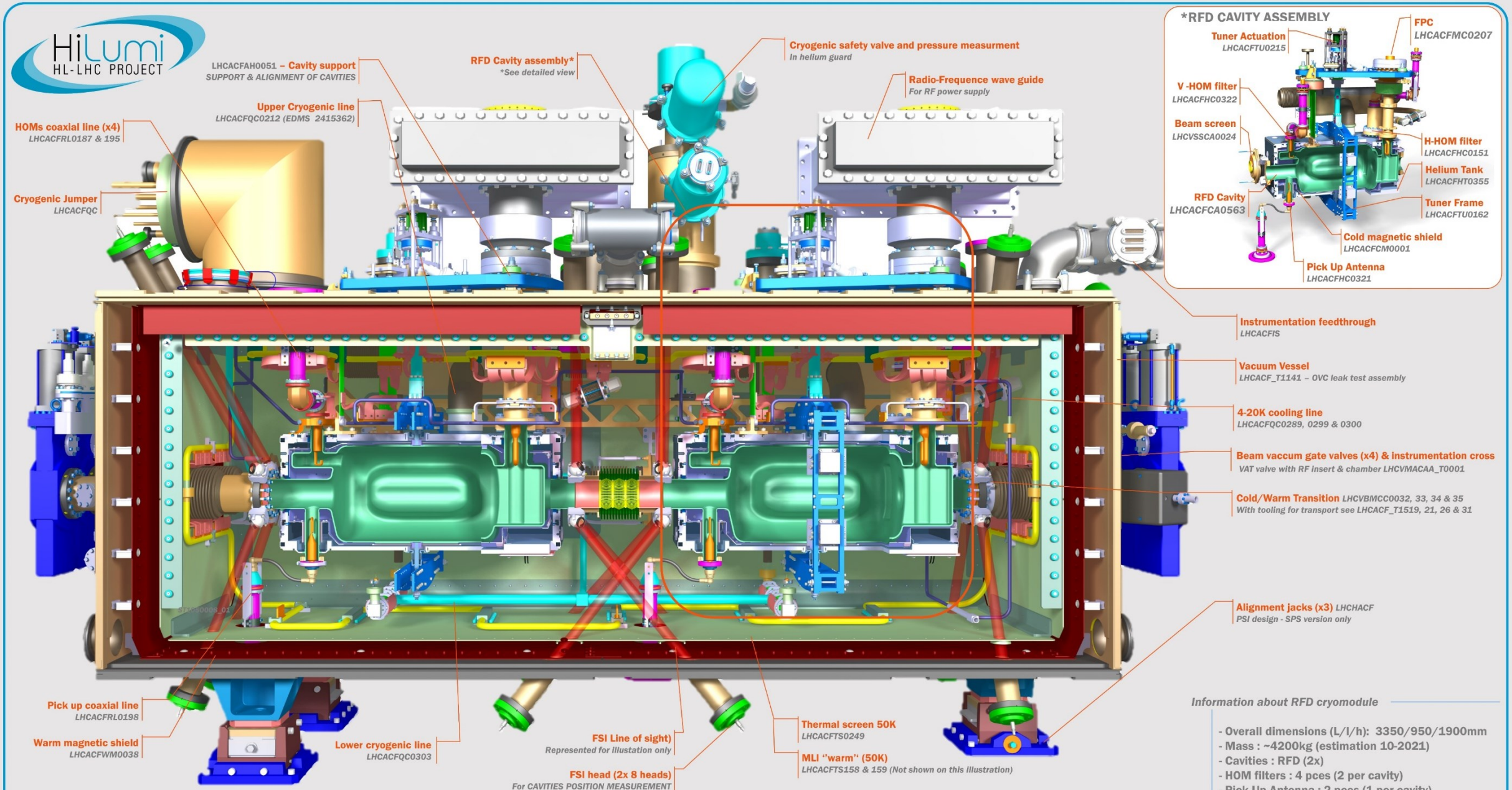
UKRI TRIUMF


Science and Technology Facilities Council
CERN
Lancaster University
The Cockcroft Institute of Accelerator Science and Technology
OLD DOMINION UNIVERSITY
HiLumi HL-LHC PROJECT
Science and Technology Facilities Council
Thanks!
Questions?
Thanks to all Hi Lumi Crabs collaborators for their contributions


HiLumi
HL-LHC PROJECT
LHCACFAH0051 – Cavity support
SUPPORT & ALIGNMENT OF CAVITIES
RFD Cavity assembly*
*See detailed view
Cryogenic safety valve and pressure measurment
In helium guard
Radio-Frequence wave guide
For RF power supply
Upper Cryogenic line
LHCACFQC0212 (EDMS 2415362)
HOMs coaxial line (x4)
LHCACFRL0187 & 195
Cryogenic Jumper
LHCACFQC
*RFD CAVITY ASSEMBLY
Tuner Actuation
LHCACFTU0215
FPC
LHCACFMC0207
V -HOM filter
LHCACFHC0322
Beam screen
LHCVSSCA0024
H-HOM filter
LHCACFHC0151
Helium Tank
LHCACFHT0355
RFD Cavity
LHCACFCA0563
Tuner Frame
LHCACFTU0162
Cold magnetic shield
LHCACFCM0001
Pick Up Antenna
LHCACFHC0321
Instrumentation feedthrough
LHCACFIS
Vacuum Vessel
LHCACF_T1141 – OVC leak test assembly
4-20K cooling line
LHCACFQC0289, 0299 & 0300
Beam vaccum gate valves (x4) & instrumentation cross
VAT valve with RF insert & chamber LHCVMACAA_T0001
Cold/Warm Transition LHCVBMCC0032, 33, 34 & 35
With tooling for transport see LHCACF_T1519, 21, 26 & 31
Alignment jacks (x3) LHCHACF
PSI design - SPS version only
Pick up coaxial line
LHCACFRL0198
Warm magnetic shield
LHCACFWM0038
Lower cryogenic line
LHCACFQC0303
FSI Line of sight)
Represented for illustation only
FSI head (2x 8 heads)
For CAVITIES POSITION MEASUREMENT
Thermal screen 50K
LHCACFTS0249
MLI "warm" (50K)
LHCACFTS158 & 159 (Not shown on this illustration)
Information about RFD cryomodule
- Overall dimensions (L/l/h): 3350/950/1900mm
- Mass : ~4200kg (estimation 10-2021)
- Cavities : RFD (2x)
- HOM filters : 4 pces (2 per cavity)
- Pick Up Antenna : 2 pces (1 per cavity)
- Tuner : 2 unit (1 per cavity)
- RF Gate valves : 4 pces
- FSI Heads : 16 ports (8 per cavity)
CERN
HL-LHC-WP04—CRAB CAVITIES RFD CRYOMODULE FOR SPS TESTS
Poster by Teddy Capelli
EN Engineering Department

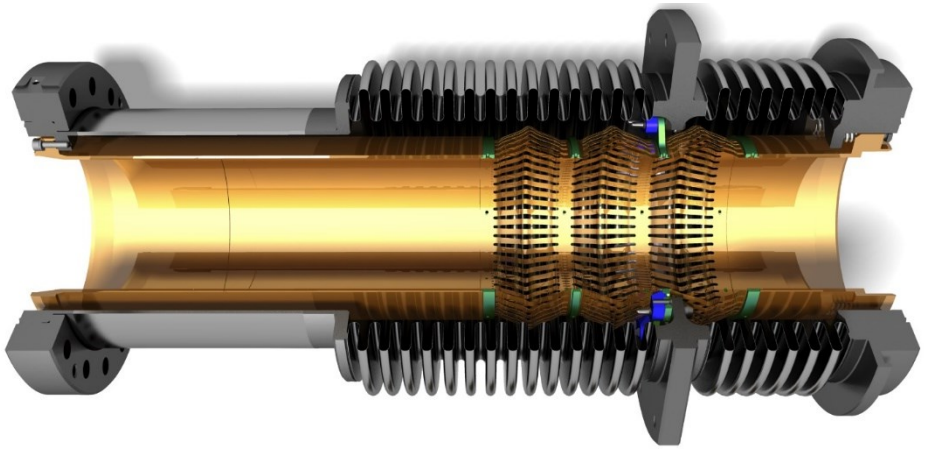
RFD Thermal Budget

Static + Dynamic 4.1 MV (40 kW FPC)			
Source	**2 K**	**10 K**	**80 K**
Radiation	3.4	-	30.0
CWT	6.0	1.0	50.6
Supports Cav1	0.4	2.1	8.0
Supports Cav2	0.5	0.9	5.0
FPC	4.8	4.6	46.4
VHOM lines	1.4	2.6	13.0
VHOM antennas	0.2	-	-
HHOM lines	1.4	2.6	13.0
HHOM antennas	0.5	-	-
Pickup lines	2.0	-	10.6
Pickup antennas	0.0	-	-
Tuner	0.8	-	10.2
Instrumentation	2.3	-	10.0
He level sensor	0.4	-	0.8
Cryo safety device	0.7	-	4.8
Beam screen	1.4	-	-
Beam impedance	-	-	-
Cavity	20.0	-	-
	46.2	**13.8**	**202.4**

Thermal budget report for RFD

See EDMS 2310389 - Thermal budget RFD cryomodule

Courtesy J.Swieszek – L.Giordanino

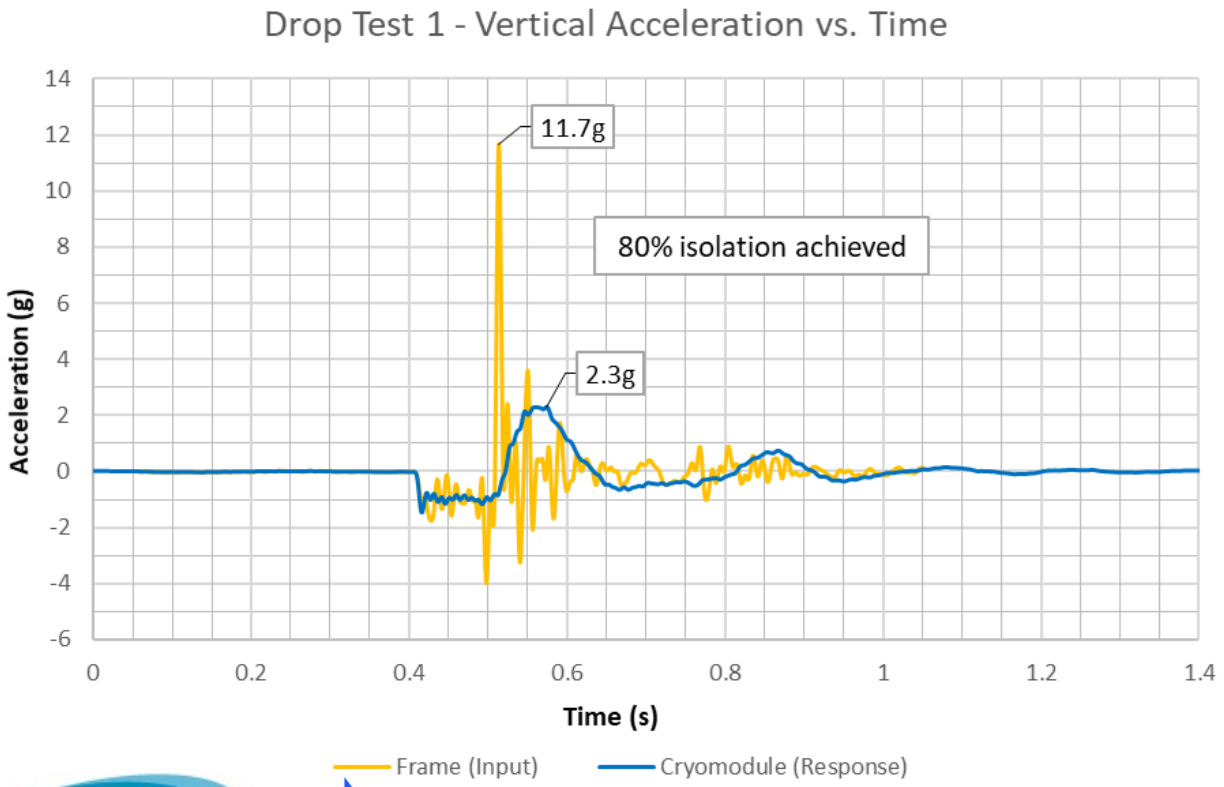


Thermal analysis cold-warm transition

See EDMS 2433067 - J.Swieszek EN-MME

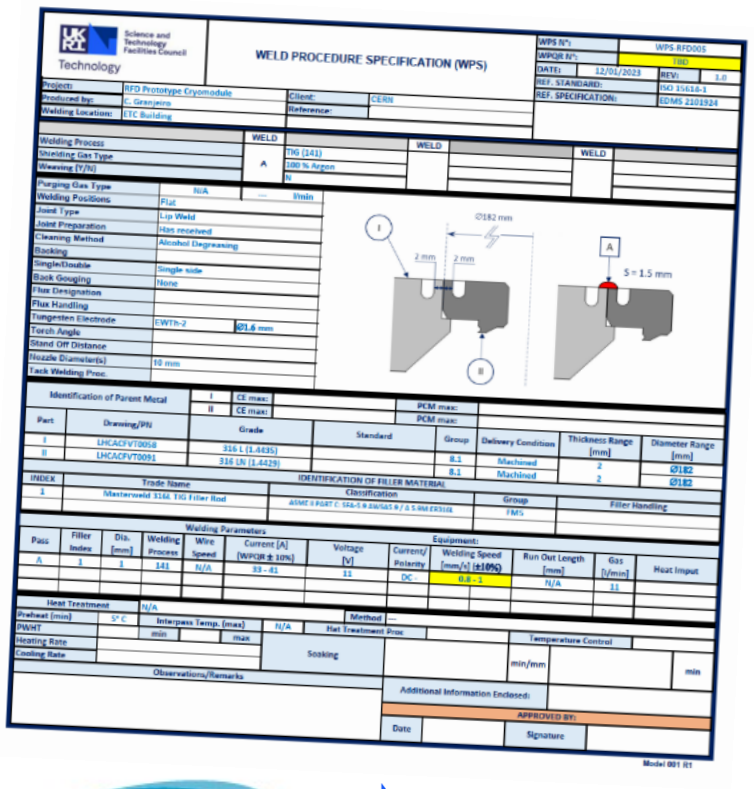
Transport Frame Design & Test

- 38mm drop test performed with a dummy CM
- ~80% shock isolation



Welding Developments at Daresbury

- Weld Procedure Specifications
- Sample qualification: dye & macroscopic



WELD PROCEDURE SPECIFICATION (WPS)

Science and Technology Facilities Council

WPS N°:	WPS-RFD005
WPQR N°:	TBD
DATE:	12/01/2023
REV:	1.0
REF. STANDARD:	ISO 15614-1
REF. SPECIFICATION:	EDMS 2101924
Project:	RFD Prototype Cryomodule
Produced by:	C. Granjeiro
Welding Location:	ETC Building
Client:	CERN
Reference:	

	WELD	WELD	WELD
Welding Process	TIG (141)		
Shielding Gas Type	100 % Argon		
Weaving (Y/N)	N		
Purging Gas Type	N/A	—	l/min
Welding Positions	Flat		
Joint Type	Lip Weld		
Joint Preparation	Has received		
Cleaning Method	Alcohol Degreasing		
Backing			
Single/Double	Single side		
Back Gouging	None		
Flux Designation			
Flux Handling			
Tungsten Electrode	CWTh-2	Ø1.6 mm	
Torch Angle			
Stand Off Distance			
Nozzle Diameter(s)	10 mm		
Tack Welding Proc.			

Identification of Parent Metal — I CE max: — II CE max: — PCM max: — PCM max:

Part	Drawing/PN	Grade	Standard	Group	Delivery Condition	Thickness Range [mm]	Diameter Range [mm]
I	LHCACFVT0058	316 L (1.4435)		8.1	Machined	2	Ø182
II	LHCACFVT0091	316 LN (1.4429)		8.1	Machined	2	Ø182

INDEX	Trade Name	Classification	Group	Filler Handling
1	Masterweld 316L TIG Filler Rod		FM5	

Welding Parameters — Equipment:

Pass	Filler Index	Dia. [mm]	Welding Process	Wire Speed	Current [A] (WPQR ± 10%)	Voltage [V]	Current/ Polarity	Welding Speed [mm/s] (±10%)	Run Out Length [mm]	Gas [l/min]	Heat Input
A	1	1	141	N/A	33 - 41	11	DC	0.8 - 1	N/A	11	

Heat Treatment	N/A						
Preheat (min)	5° C	Interpass Temp. (max)	N/A	Method	–		
PWHT		min	max	Hot Treatment Proc.		Temperature Control	
Heating Rate				Soaking		min/mm	min
Cooling Rate							

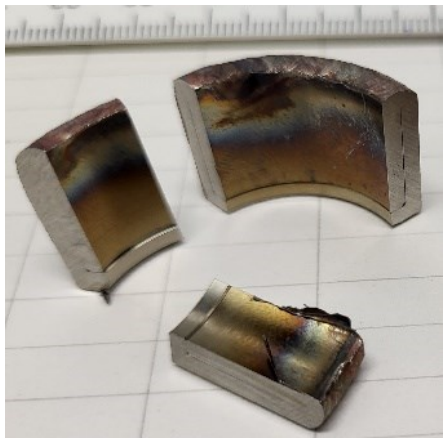
Observations/Remarks

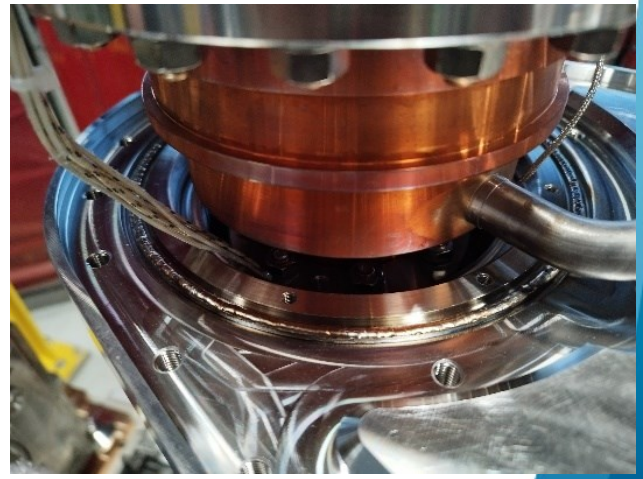
Additional Information Enclosed:

APPROVED BY:

Date | Signature

Model 001 R1





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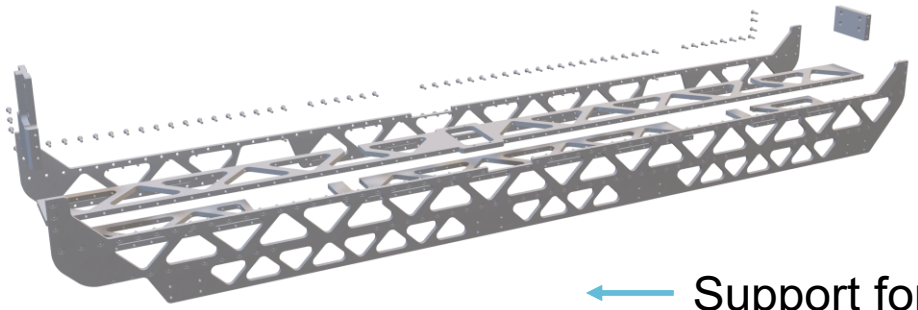
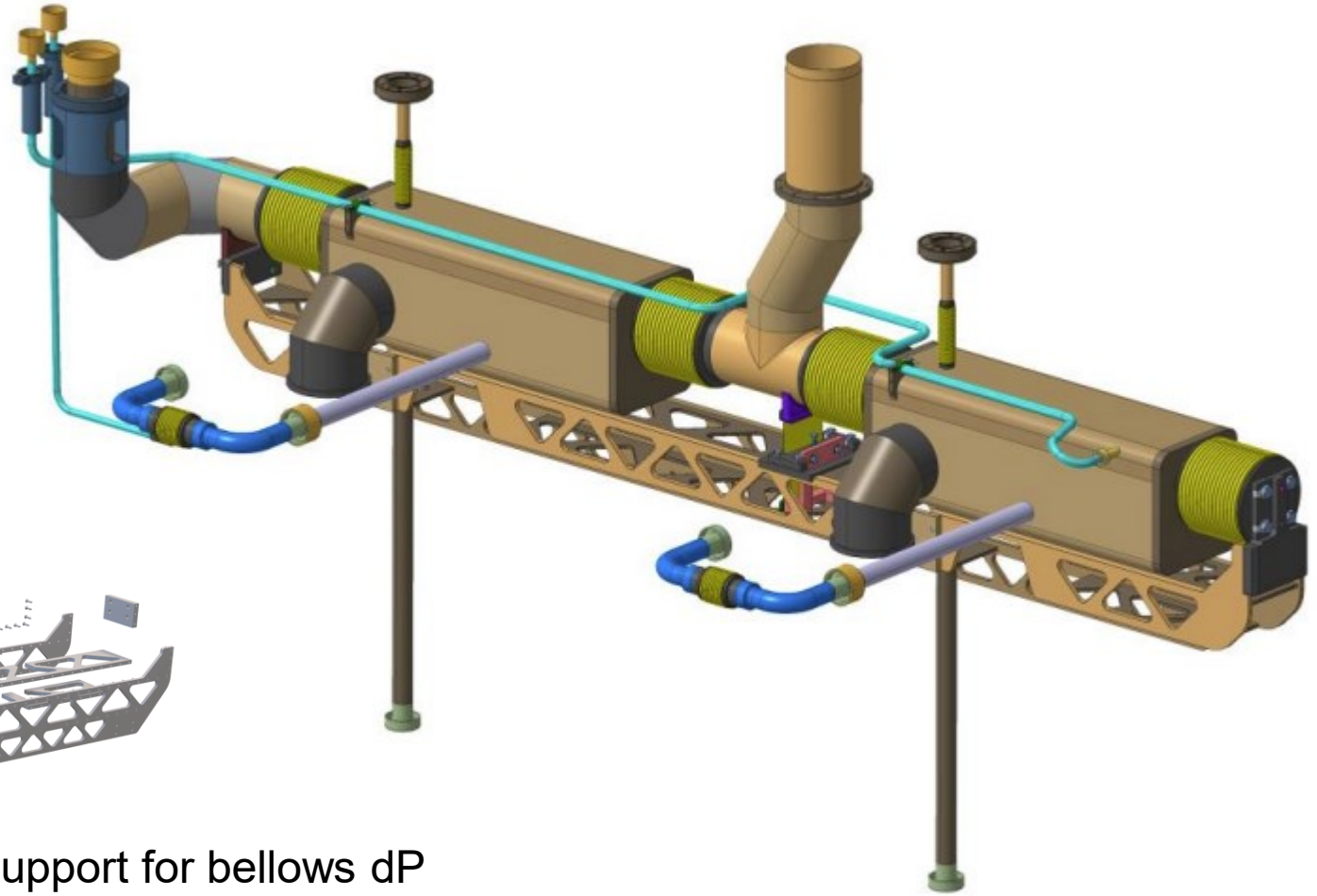
Upper (Bi Phase) Cryoline





← Support for bellows dP