

Hi Lumi LHC Crab Cavity Cryomodules

Niklas Templeton

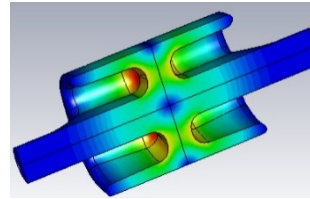
STFC Daresbury Laboratory

UK Crab Cavity Cryomodules WP Lead

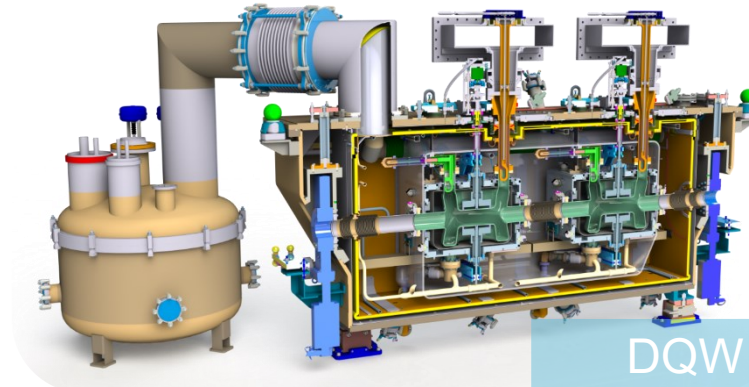


Crab Cavity Cryomodules for Hi Lumi LHC

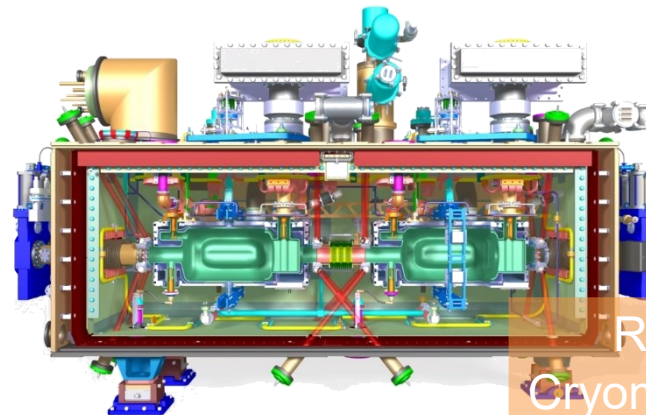
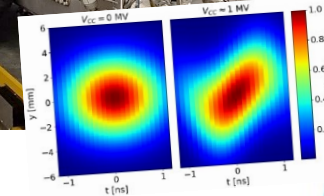
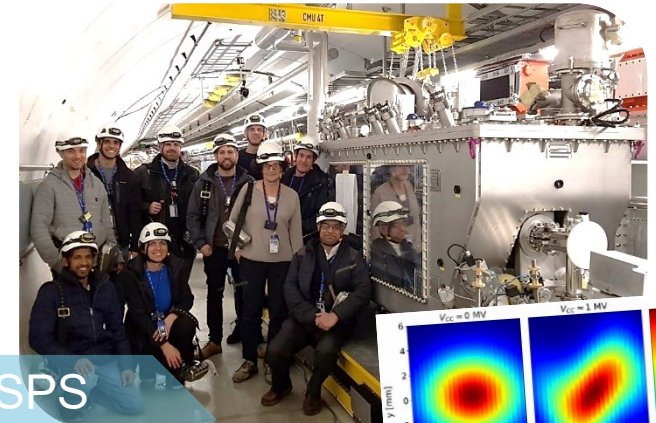
- Hi Lumi LHC Crab Cavities
- Crabs Collaboration
- Design Features & Innovations
- RFD SPS Prototype Cryomodule Build
- UK Lessons Learnt (so far)



UK 4-Rod Cavity
Prototype 2012



DQW SPS
Cryomodule 2018



RFD SPS
Cryomodule 2023



Templeton - TTC Dec '23

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

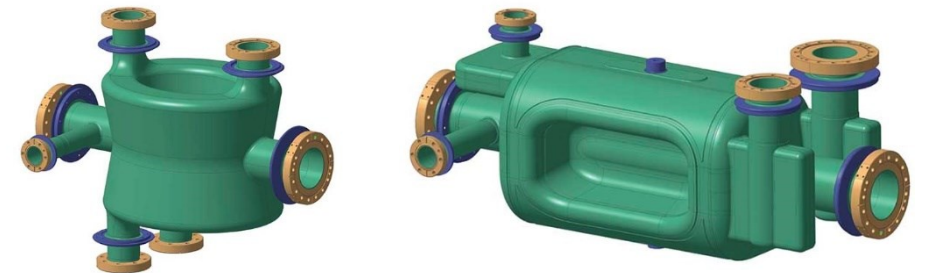
- RF design by BNL & CERN
- Supplied by CERN & R.I.

Radio Frequency Dipole (**RFD**) – horiz. crabbing at ATLAS

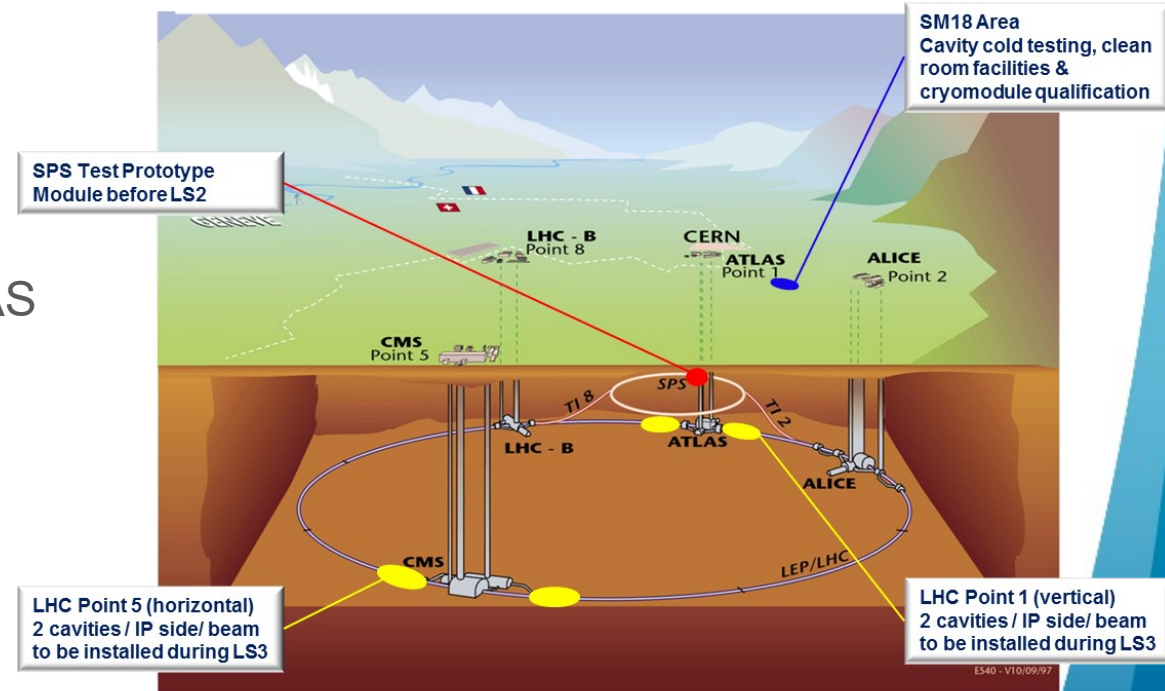
- RF design by ODU
- Supplied by US-AUP & Zanon



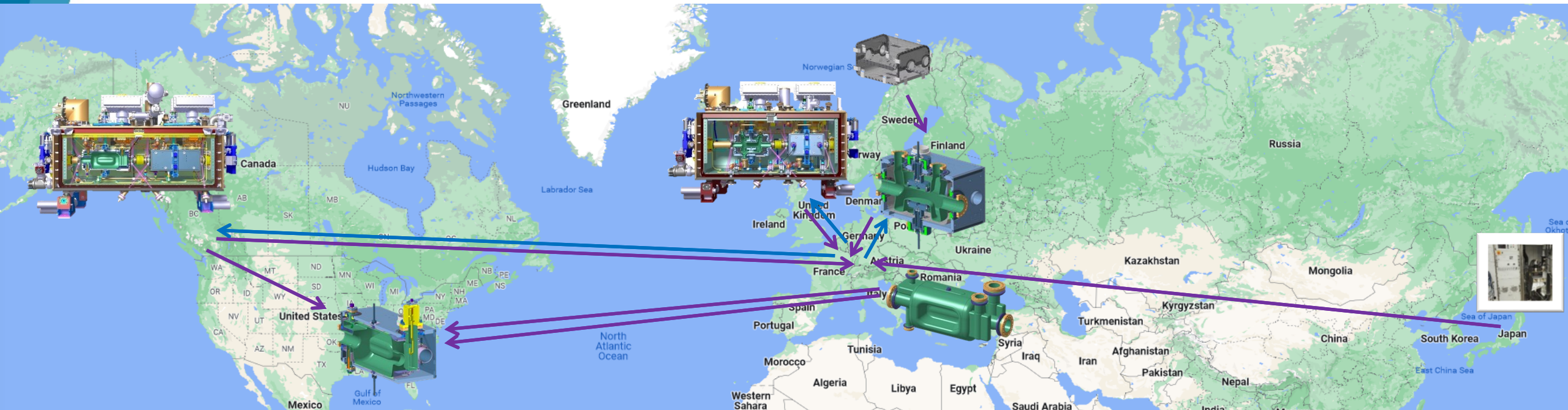
Bunches colliding without crab crossing (left) & with the crab crossing (right)



DQW & RFD Crab Cavities



HL-LHC Crab Cavity Collaboration



5 DQW cryomodules

- 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)

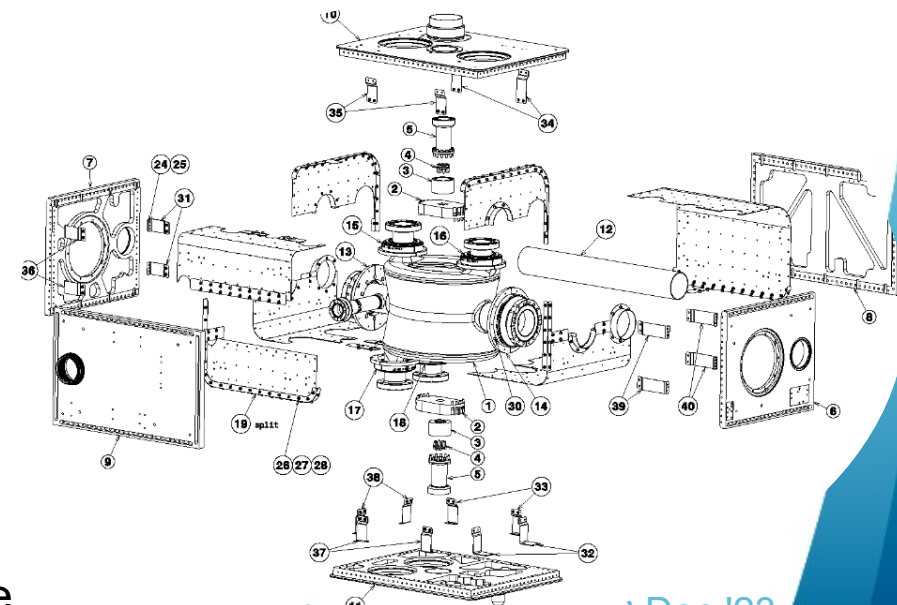
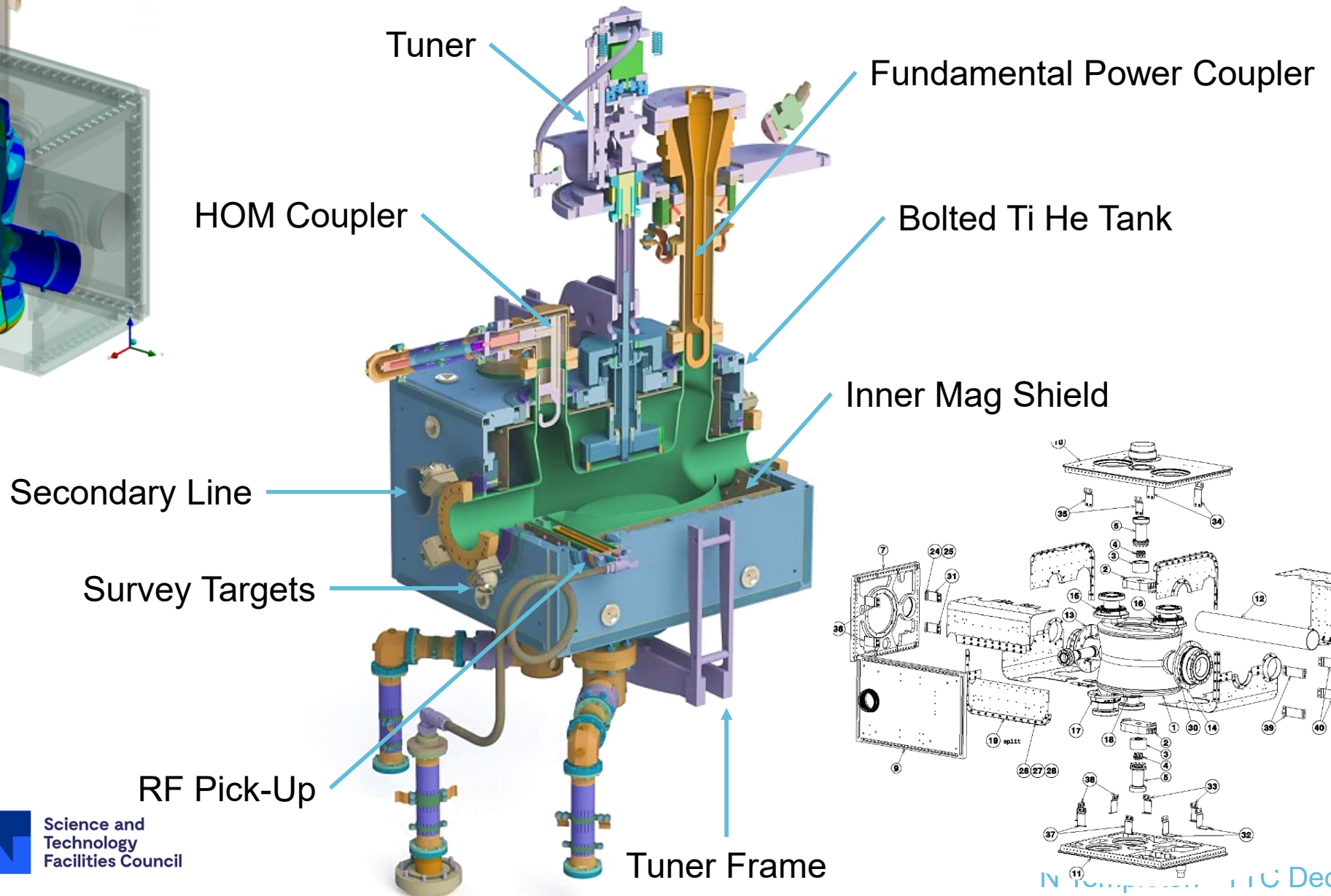
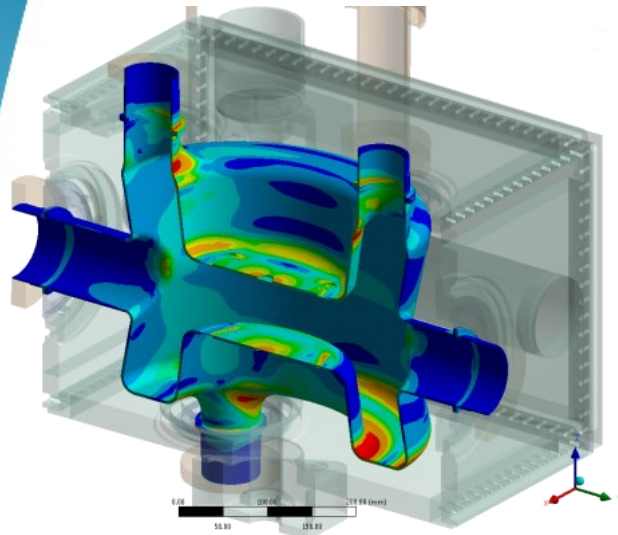
5 RFD cryomodules

- 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**

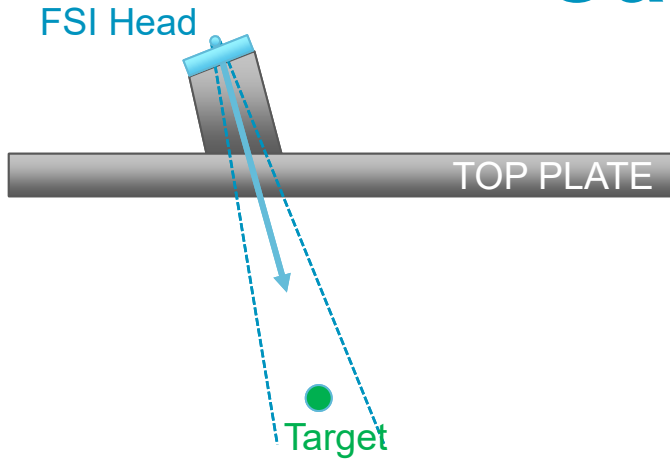
20 RF Systems

- High power amplifiers (IOT) **CERN-KEKB**
- High power RF lines, circulators, loads by **CERN-KEKB**
- μ TCA platform for LLRF by CERN

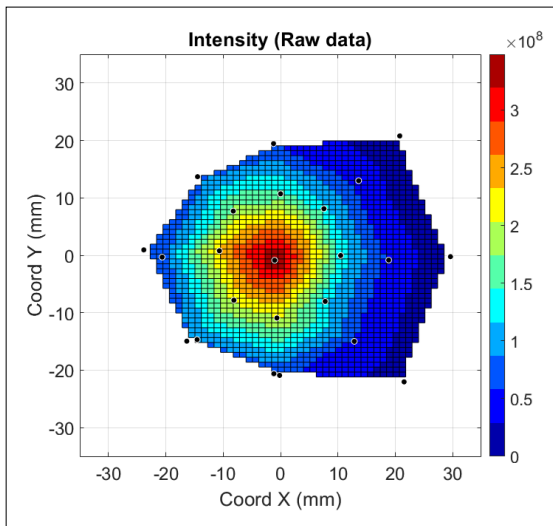
Dressed Cavity Equipped



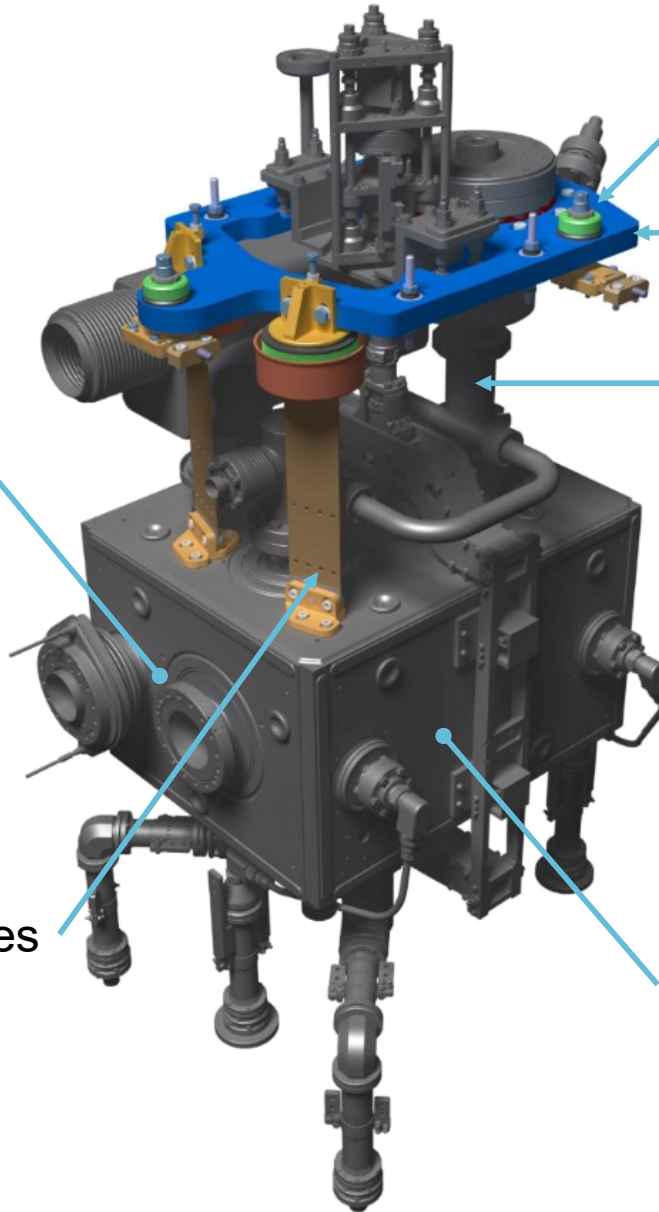
Cavity Support System



FSI Position Monitoring



Flexure Blades

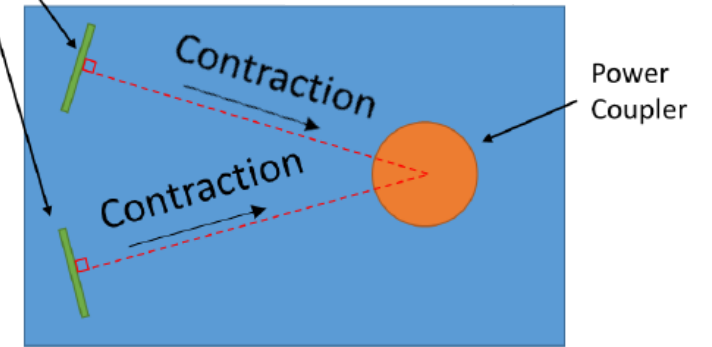


5-Point Kinematic Adjustment

Common Support Plate

FPC Fixed Point

Flexure Blade Support



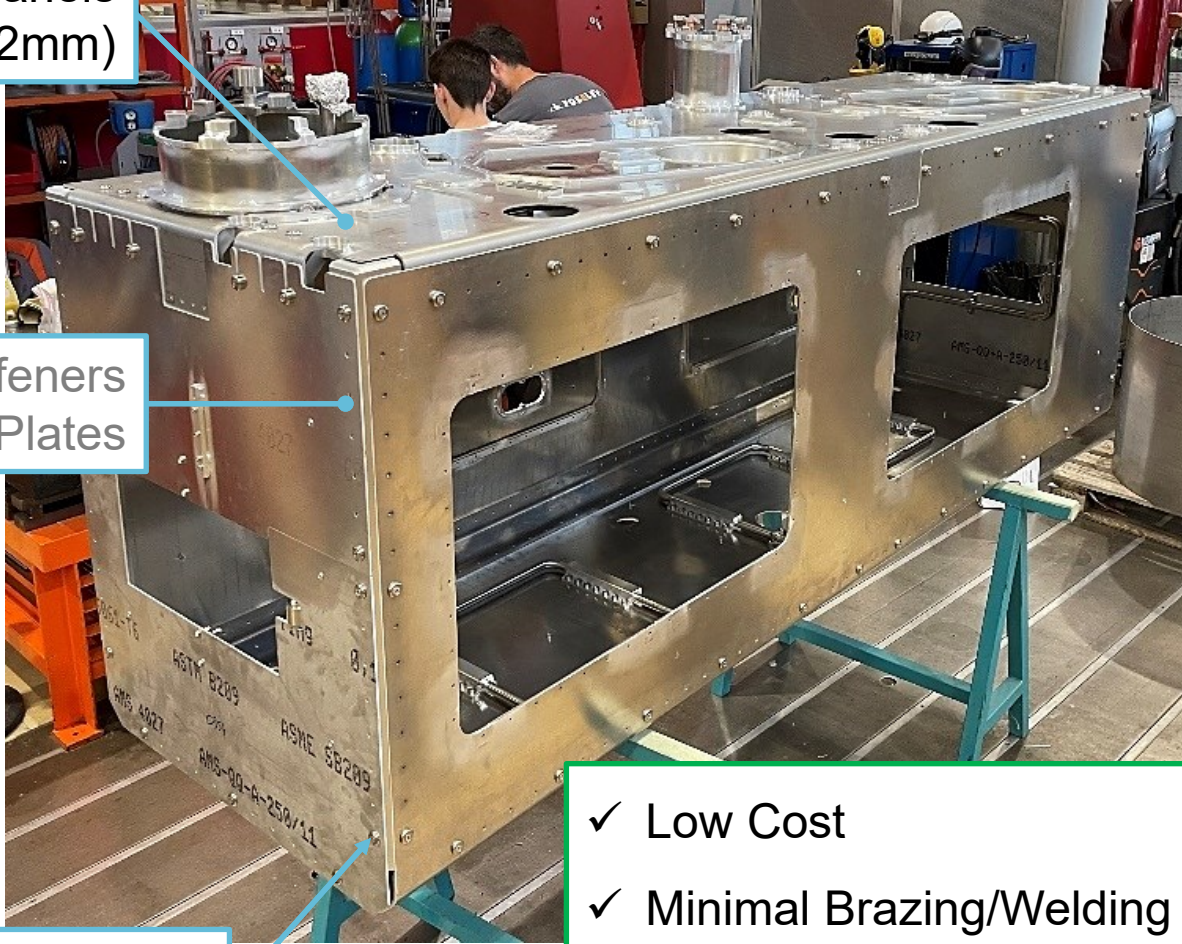
~200kg Offset Mass

Thermal Screen

Al6061 Panels
(t=2mm)

Al Stiffeners
& Nut Plates

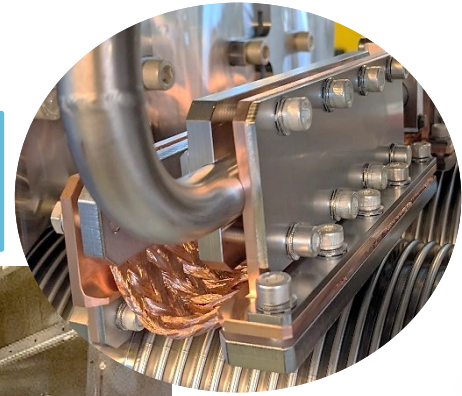
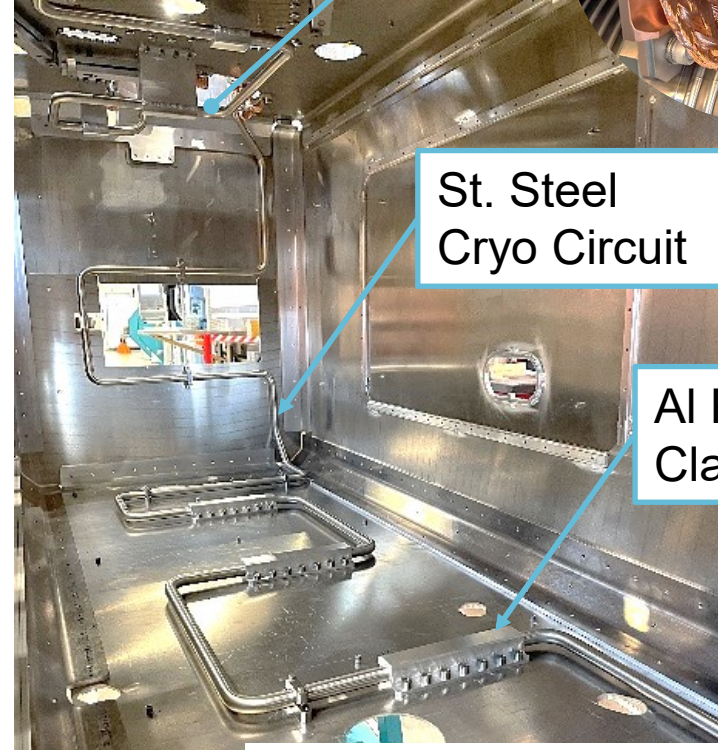
Ti Compensation
Washers



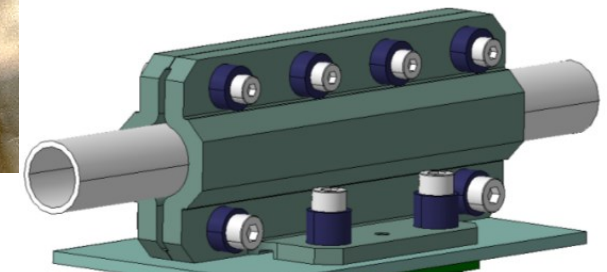
Cu Braids -
Direct to Pipes

St. Steel
Cryo Circuit

Al Pipe-Panel
Clamps

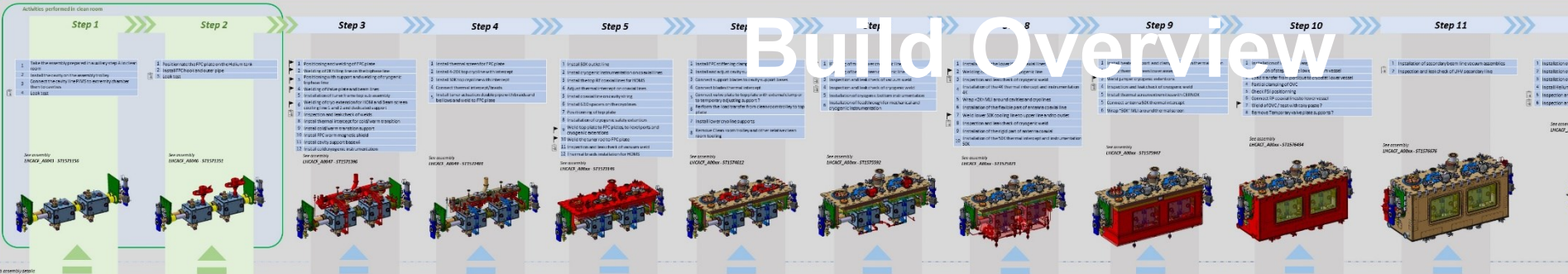


- ✓ Low Cost
- ✓ Minimal Brazing/Welding
- ✓ Ease of Assembly
- ✓ Thermal Performance Validated



Series Pipe-Panel Clamps

Build Overview



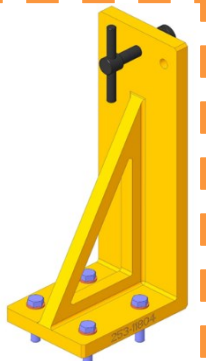
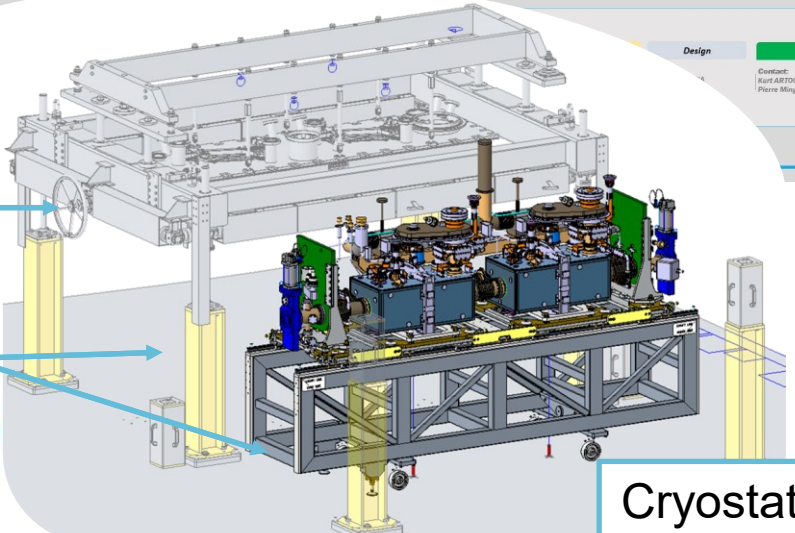
Cavity equipped UHCAT0008 & 0009 - Passivation slots UHCAT0008 - Cooled cavity	FPC Assembly with outer pipe & bellows UHCAT0007	Upper cryostat UHCAT0007	2K filling line UHCAT0007 - 2K filling line UHCAT0007 - 2K filling line	Upper cryostat support UHCAT0008	4-20K cooling line UHCAT0008	HOMS cooling line UHCAT0007 - HOMS cooling line	Tuner frame UHCAT0008 - Tuner frame assembly	Thermal intercept UHCAT0008 - Thermal IC UHCAT0008 - Thermal IC UHCAT0008 - Thermal IC UHCAT0008 - Thermal IC	Internal support UHCAT0007 - Support for cav/cav UHCAT0008	Magnetic shield UHCAT0008 - FPC/flat plate SOK UHCAT0008 - FPC/flat plate SOK UHCAT0008 - SOK/valves	Partial support UHCAT0007 - Base line UHCAT0008 - Cavity support system
UHV shielded bellows UHCAT0008 - 2mm beam screen PMS UHCAT0008 - 2mm beam screen PMS UHCAT0008 - 2mm beam screen PMS UHCAT0008 - 2mm beam screen PMS UHCAT0008 - 2mm beam screen PMS	FPC plate for OVC UHCAT0007	4K upper line UHCAT0008 - 4K upper line UHCAT0008 - 4K upper line	4-20K cooling line UHCAT0008	HOMS upper line UHCAT0008 - HOMS upper line UHCAT0008 - HOMS upper line	G10 spacers UHCAT0008 - G10 spacer UHCAT0008 - G10 spacer	Cryostat support plate UHCAT0008 - Cryostat support plate UHCAT0008 - Cryostat support plate	Extension lines spacer & MU UHCAT0008 - Extension lines spacer UHCAT0008 - MU	FPC welded lip UHCAT0008 - FPC welded lip UHCAT0008 - FPC welded lip	OVC safety extension UHCAT0008 - OVC safety extension UHCAT0008 - OVC safety extension	Assembly files UHCAT0007 - Assembly files UHCAT0008 - Assembly files	Assembly files UHCAT0007 - Assembly files UHCAT0008 - Assembly files

Transport tooling UHCAT_1001 - Transport tooling UHCAT_1002 - Transport tooling	Lifting blocks UHCAT_1003 - Lifting blocks UHCAT_1004 - Lifting blocks	Covers UHCAT_1005 - Covers UHCAT_1006 - Covers
M7 tests UHCAT_1007 - M7 tests UHCAT_1008 - M7 tests	Cryogenic safety extensions UHCAT_1009 - Cryogenic safety extensions UHCAT_1010 - Cryogenic safety extensions	Support jack UHCAT_1011 - Support jack UHCAT_1012 - Support jack
Inclinometer UHCAT_1013 - Inclinometer UHCAT_1014 - Inclinometer	Pump instrumentation box UHCAT_1015 - Pump instrumentation box UHCAT_1016 - Pump instrumentation box	LHC UHCAT_1017 - LHC UHCAT_1018 - LHC
PS RX/LM UHCAT_1019 - PS RX/LM UHCAT_1020 - PS RX/LM	Beam extension lines UHCAT_1021 - Beam extension lines UHCAT_1022 - Beam extension lines	WPS UHCAT_1023 - WPS UHCAT_1024 - WPS
Cryogenic safety extensions UHCAT_1025 - Cryogenic safety extensions UHCAT_1026 - Cryogenic safety extensions	Jumpers UHCAT_1027 - Jumpers UHCAT_1028 - Jumpers	Vacuum instrumentation UHCAT_1029 - Vacuum instrumentation UHCAT_1030 - Vacuum instrumentation
Inclinometer UHCAT_1031 - Inclinometer UHCAT_1032 - Inclinometer	Support jack UHCAT_1033 - Support jack UHCAT_1034 - Support jack	Cryogenic safety extensions UHCAT_1035 - Cryogenic safety extensions UHCAT_1036 - Cryogenic safety extensions

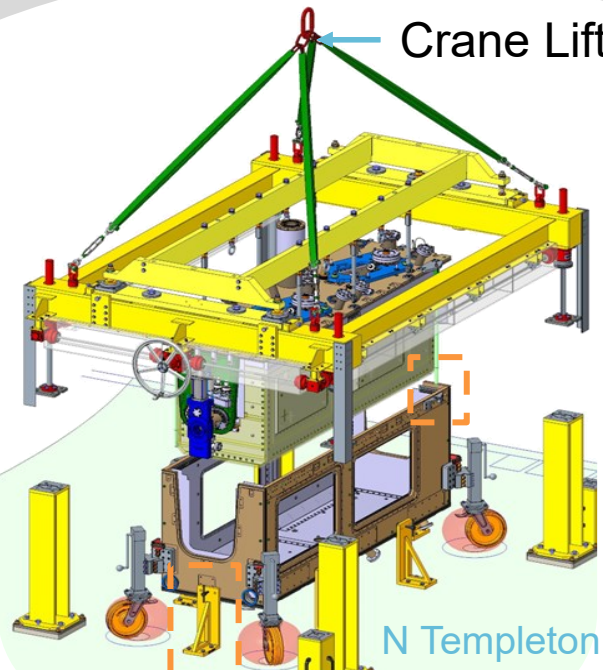


Fine Adjustment

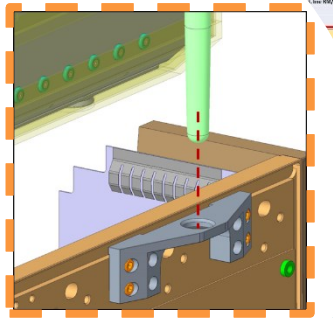
2 Bays



Pushers



Crane Lift



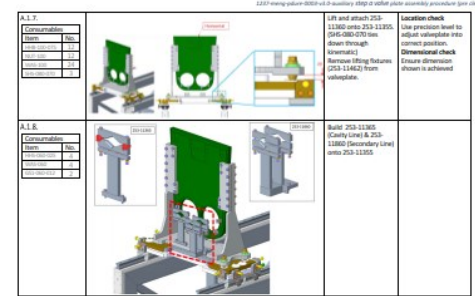
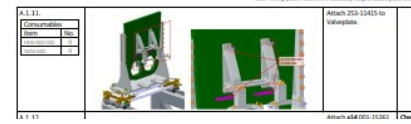
Guide Rods

Detailed Build Procedures

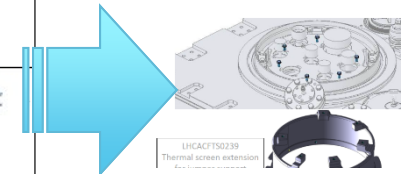
- Poster logic + tooling & infrastructure
- Part of Traveller (QA)
- Troubleshoots & de-risk build
- Captures critical requirements, torques & sign-off
- 'BOM kits' pre-prepared by sub-step

IV. Auxiliary Step A.1 - Checklist

Sub-Step Ref	Operation Check	Dimensional Check	Location Check	Equipment	Comments	Approver Signature	Date and Time
A.1.1	Geometry Transfer Short Side <input type="checkbox"/> Long Side <input type="checkbox"/>	OK	OK	Standard tools			
A.1.2	V-F Flange Transfer Short Side <input type="checkbox"/> Long Side <input type="checkbox"/>	OK	OK	Standard tools			
A.1.3	V-F Flange Transfer Short Side <input type="checkbox"/> Long Side <input type="checkbox"/>	OK	OK	Standard tools			
A.1.4	V-F Flange Transfer Short Side <input type="checkbox"/> Long Side <input type="checkbox"/>	OK	OK	Standard tools			



Over 900p produced!



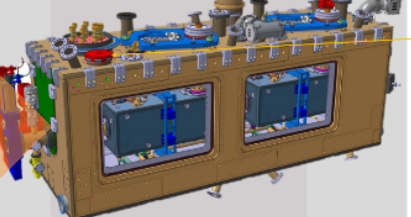
5-2 Install Coax Lines for V & H-HOMs

To be performed with support and supervision of CERN RF Staff 1-2nd June

Designation	Spec.	QTY
V-HOM Coax line	LHCACFRLO281	2
H-HOM Coax Upstream	LHCACFRLO282	1
H-HOM Coax Downstream	LHCACFRLO283	1
Washer MS	A4 + ISO 7089	24
Hex Nut MS	A4-80 + ISO 4032	24
Temp. Sensor	LHCACFRLO284	4
Temp. Sensor	Demco CX 1010	4
Temp. Sensor	PT100	4

Step 11

11-3 Install Blow-Off Valve



32	Valve Flange EN10	LHCACFRLO114	Ø 148 x L=67	Ø 148 x L=67
33	O-RING EN10 Ø10.7x16.4 - EN	ST1550312	Ø10.7x16.4	Ø10.7x16.4
34	SPRING EN10 PRESSURE RELIEF SPRING	LHCACFRLO115		
35	WASHER - MANCHON	ST0202081		
36	HEX NUT	ST0202091		
37	HEX NUT	ST0202091		
38	HEX NUT	ST0202091		

- Install Valve Flange with O-ring, relief spring and ancillaries as shown
- Wire rope to be double looped through crimped collars (see image) but should be as taught as possible without excessive bending



RFD Highlights (1/2)

Cavity string pre-cleanroom



Cleanroom assembly



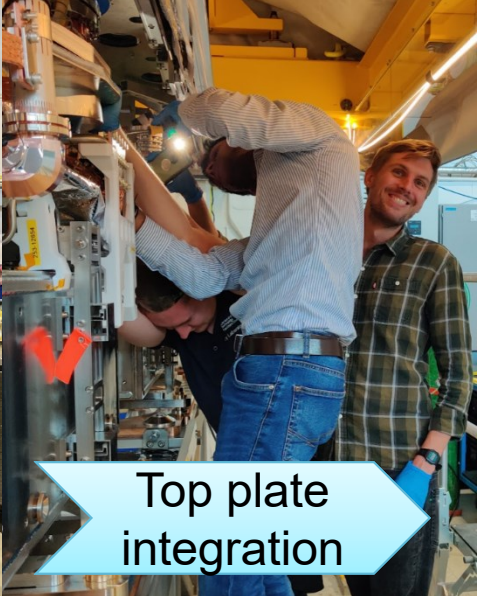
First Welds



Upper cryo install



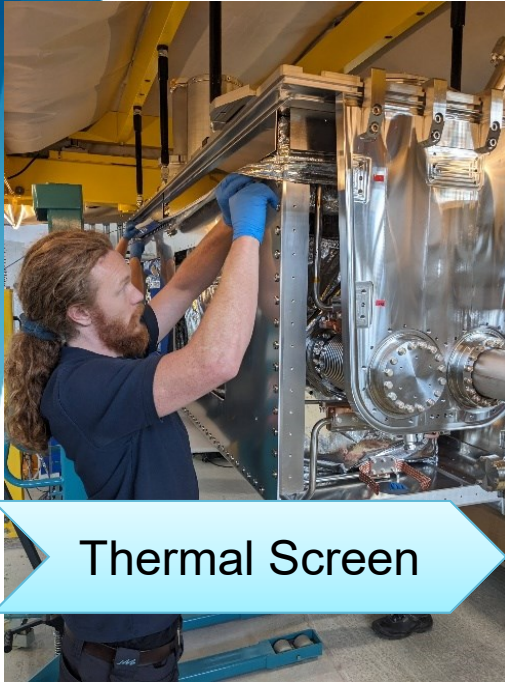
Top plate integration



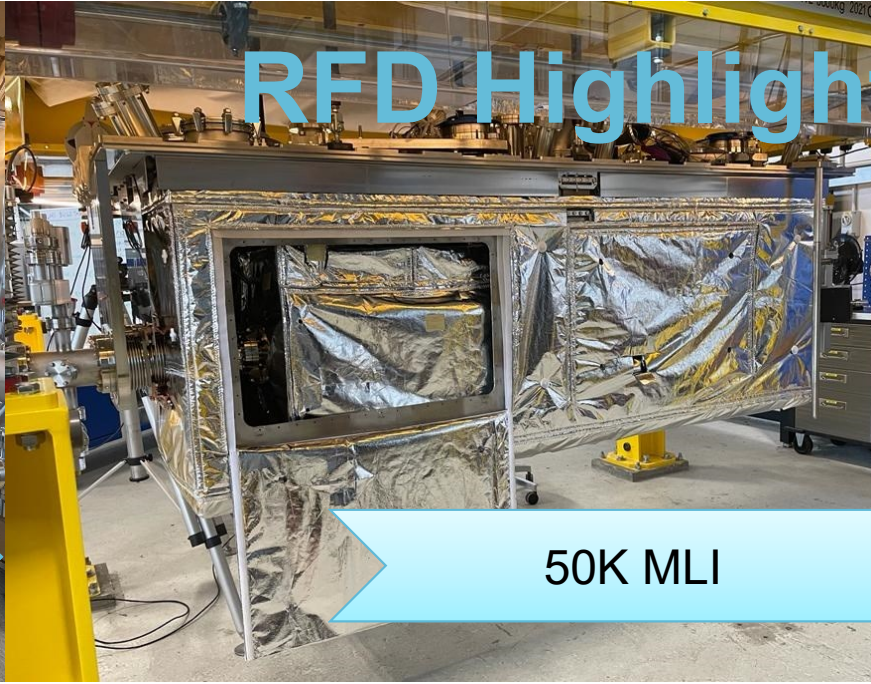
Load Transfer Complete



RFD Highlights (2/2)



Thermal Screen



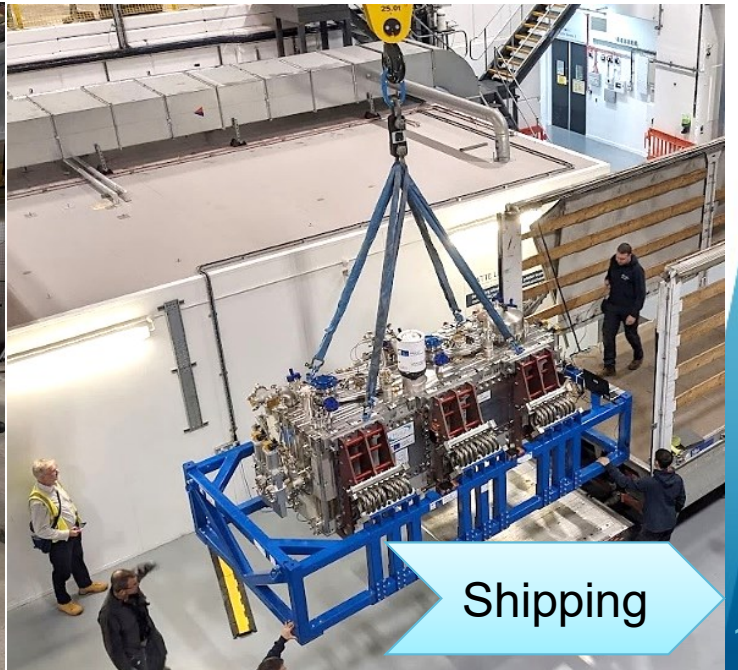
50K MLI



Instrumentation



Lower Cryomodule Integration



Shipping

RFD *Lowlights*...

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

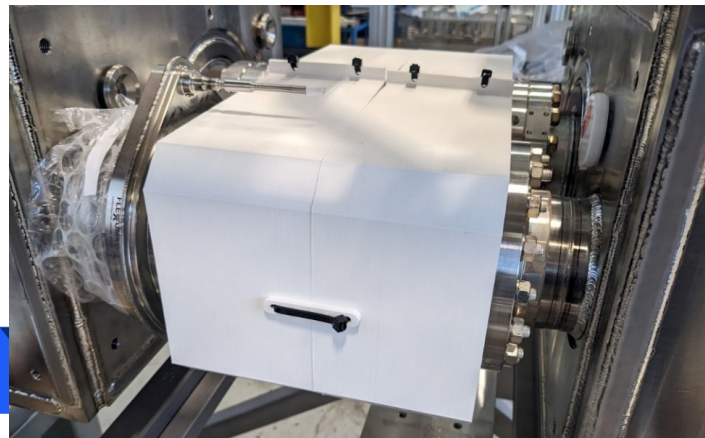
Issue: hydroform **bellows dent** pre-cleanroom

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 LHC/BMCC0033 Dent

NC Description	
Work Package	W4
Equipment	HCVBMCC0033-CR00001
Consideration	Process
Contract	UK-1
Team	Inspector: Carlos Granjero

Description of the NC:

- During the assembly of the RFD using a deviation of the assembly procedure EDM5 2507918 v-1.0 caused a dent in the short CW transition from the secondary line.
- The deviation from the assembly procedure, caused one component from the assembly tooling to collide with the short CW transition when removing the tooling from its position.

In the document EDM5 2507918 (Auxiliary Step 4 - Valve plate assembly procedure pre-cleanroom) in point A.2.2.3 only the nuts highlighted in red dashed circle should have been removed (Figure 4), instead, the nuts highlighted in a yellow circle were also removed. This deviation caused the lig that should of have stayed attached to the short CW transition to move in an uncontrolled way when retracting the remaining tooling. This uncontrolled movement of the lig caused the dent in the short CW transition (Figure 2 and 3).

Page 2 of 4 Template EDM5 No.: 150109

Y	Z
5.5 mm	0.12 mm (2times)

page 3: Short CW Transition consultation dimensions.

no any puncture or scratch. The metal appears only to have been deformed from

it can be evaluated based on the geometry of the dent:

- it can be considered with rounded edges.
- it convolutions damaged.
- it should be less than 1/3 of the convolution bend radius.
- and depth of scratches
- the flattened surface of the dent

at [LHC/BMCC0033] the maximum allowable dent depth is 1.508 mm (corresponding to this is approximately 12 times less than the maximum allowable dent depth. The 'm' (elliptic area formula approximation).

Date of issue: 2022-03-21

Page 3 of 4 Template EDM5 No.: 150109

NC Evaluation

1) tied to the NC, it was identified that the cause for the NC was a deviation of the procedure stated that only the nuts showed in dashed red circle in figure 4 should have the nuts highlighted in yellow circle were not referred in this step, they are supposed in step A.2.2.5 (figure 5) the movement of the assembly tooling originated the moved were only intended to be removed after this step and not before.

unlock tooling casetes and withdraw tooling fully clear. Remove remaining tooling from gateway. Lock Casetes.

unlikely that the below vacuum integrity has been compromised.

it was some damage to the vacuum integrity, the bellows separates a region of LHV with insulation vacuum.

very low which is less critical than the cavity line.

when testing the fully assembled beam line at a later stage

and visualized with an engineer assistance before the technicians are allowed

Page 4 of 4 Template EDM5 No.: 150109

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

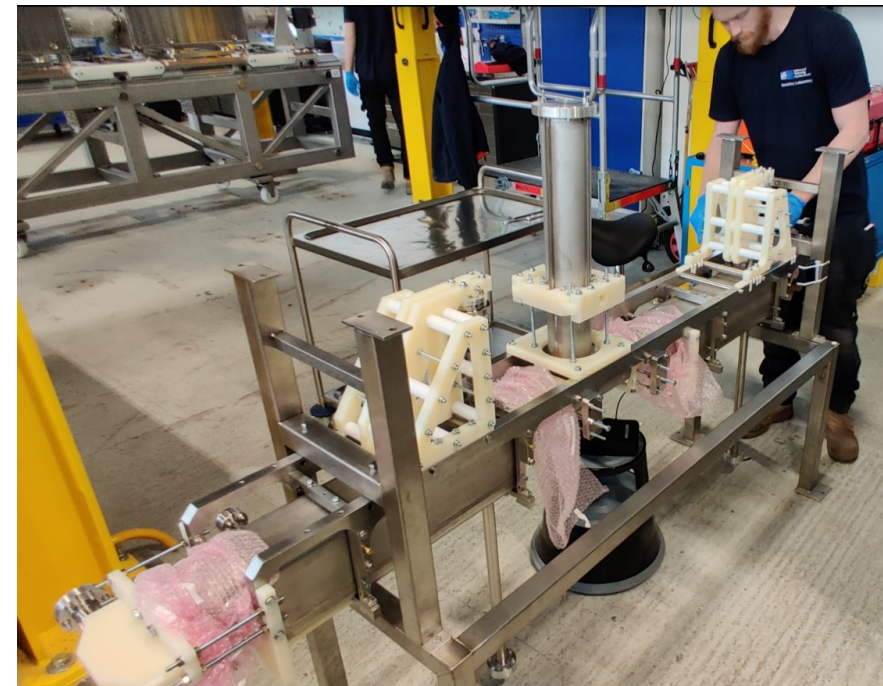
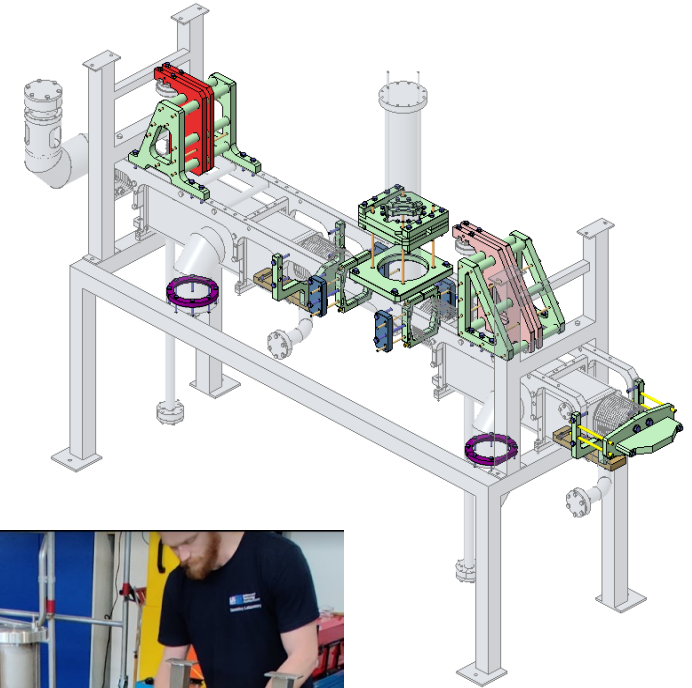
Issue: **Re-design** of test rig & **re-qualification** of Bi Phase line

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)

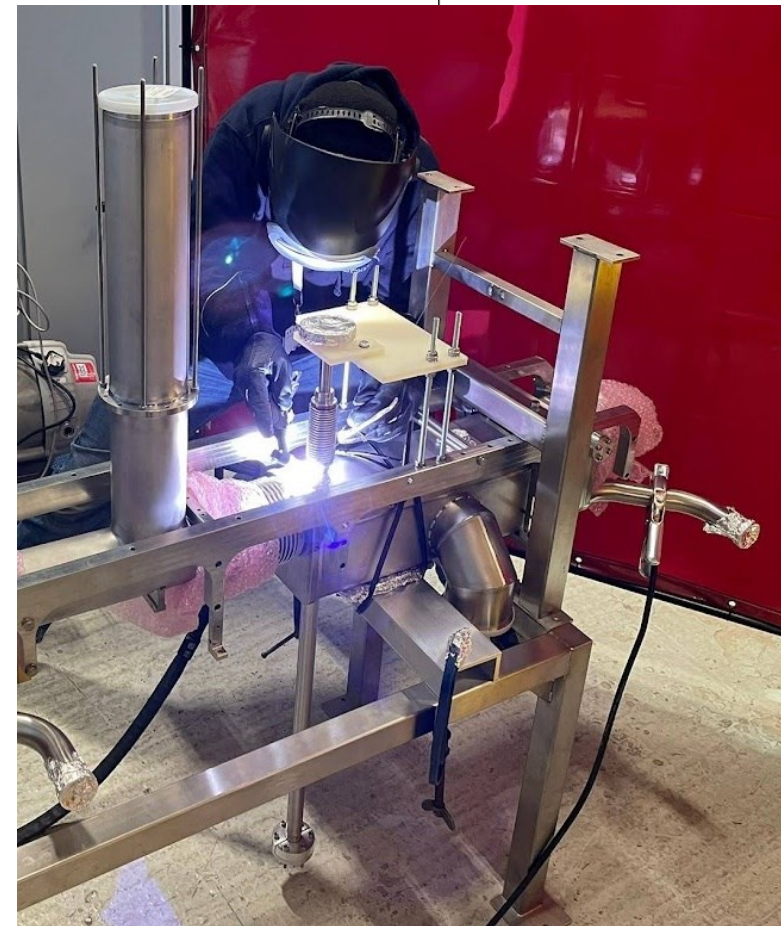
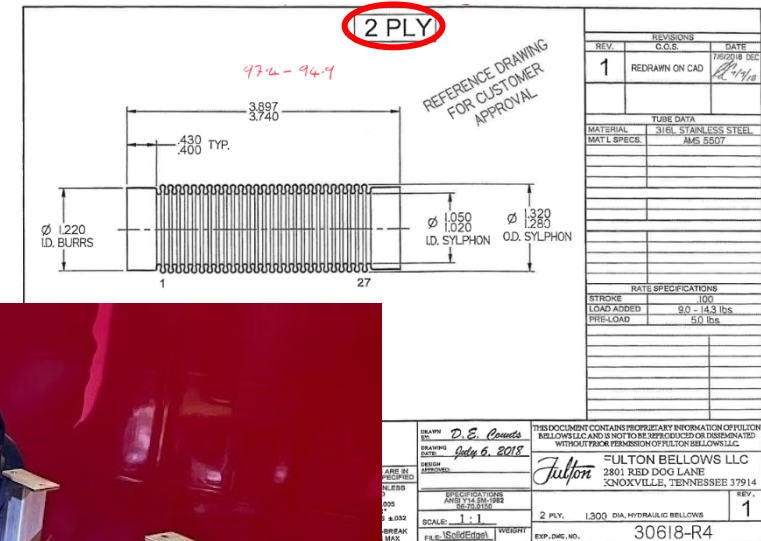
Issue: removal & replacement of **NC bellows sub-assembly** after delivery

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

Hi Lumi Crab Cavity Cryomodules

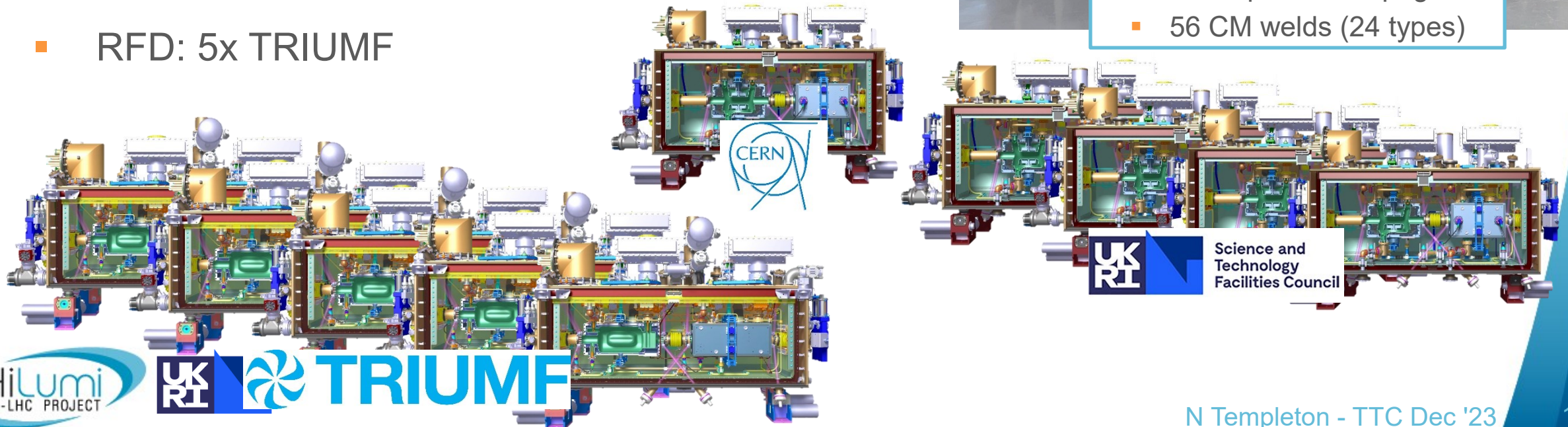
RFD SPS Cryomodule delivered Oct '23 with many challenges & obstacles overcome!

Next: series LHC Cryomodules:

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



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

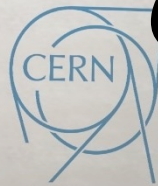


Lancaster
University



The Cockcroft Institute
of Accelerator Science and Technology

OLD DOMINION
UNIVERSITY



Science and
Technology
Facilities Council

Thanks!

Questions?

**Thanks to all Hi Lumi Crabs
collaborators for their contributions**

HOMs coaxial line (x4)
LHCACFRL0187 & 195

LHCACFAH0051 - Cavity support
SUPPORT & ALIGNMENT OF CAVITIES

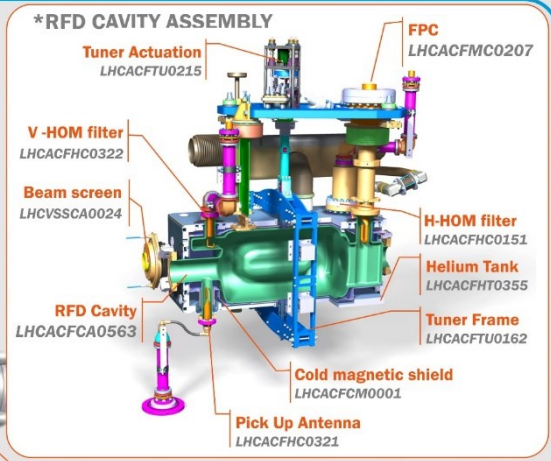
Upper Cryogenic line
LHCACFQC0212 (EDMS 2415362)

Cryogenic Jumper
LHCACFQC

RFD Cavity assembly*
*See detailed view

Cryogenic safety valve and pressure measurement
In helium guard

Radio-Frequency wave guide
For RF power supply



Instrumentation feedthrough
LHCACFIS

Vacuum Vessel
LHCACF_T1141 - OVC leak test assembly

4-20K cooling line
LHCACFQC0289, 0299 & 0300

Beam vacuum 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) LHCACF
PSI design - SPS version only

Pick up coaxial line
LHCACFRL0198

Warm magnetic shield
LHCACFWM0038

Lower cryogenic line
LHCACFQC0303

FSI Line of sight
Represented for illustration only

FSI head (2x 8 heads)
For CAVITIES POSITION MEASUREMENT

Thermal screen 50K
LHCACFTS0249

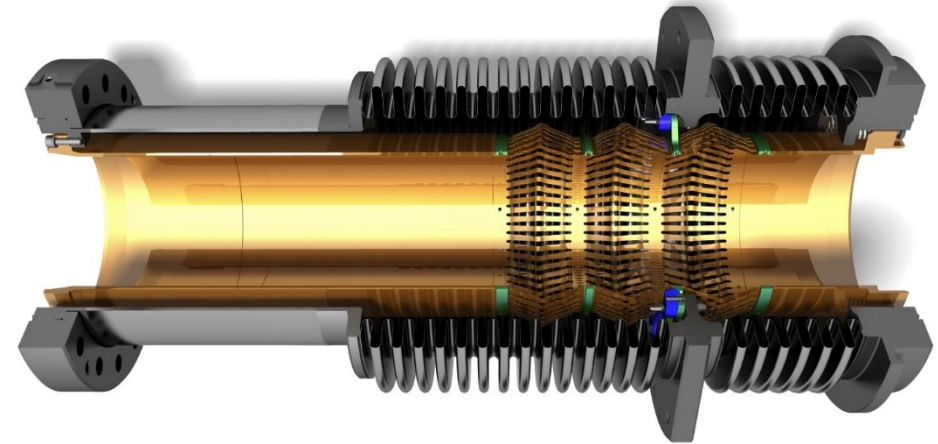
MLI "warm" (50K)
LHCACFTS158 & 159 (Not shown on this illustration)

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)

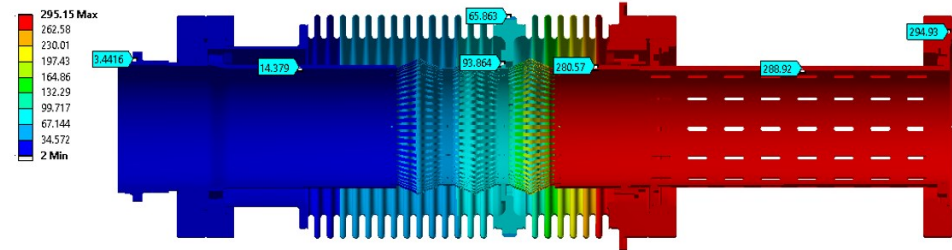
RFD Thermal Budget

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 analysis cold-warm transition
See EDMS 2433067 - J.Swieszek EN-MME

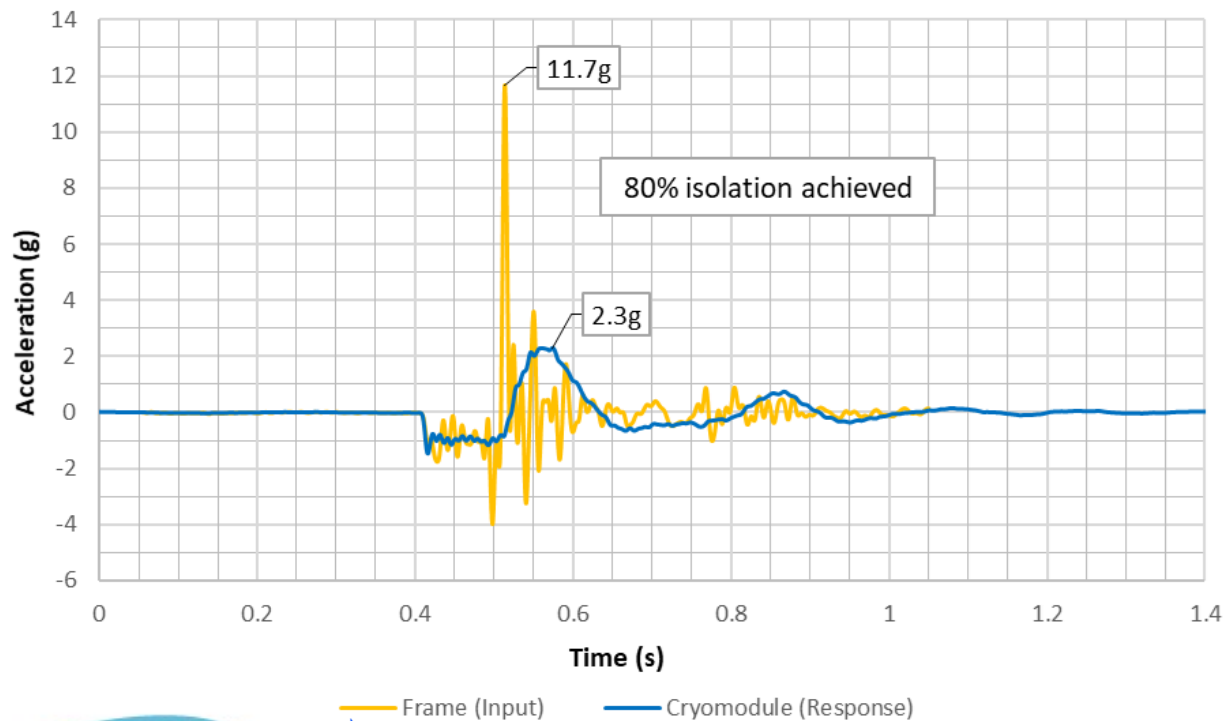
C: CWT, cavity side, short
Temperature
Type: Temperature
Unit: K
Time: 1
27/03/2023 12:33



Transport Frame Design & Test

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

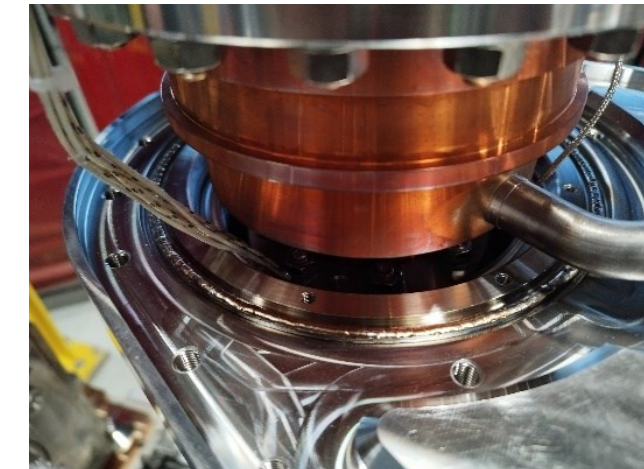
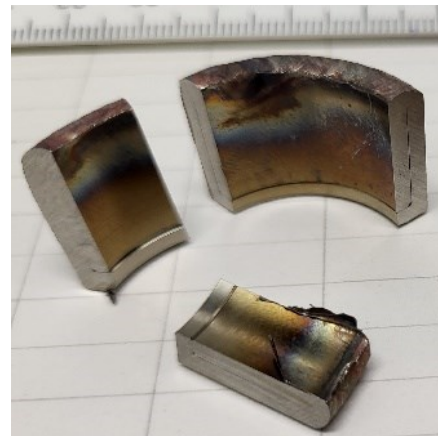
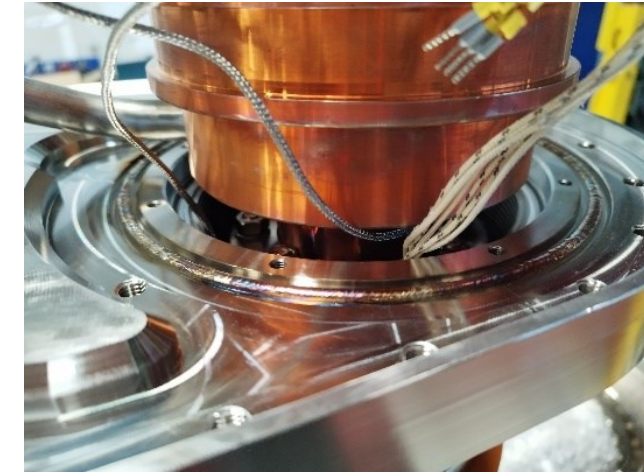
Drop Test 1 - Vertical Acceleration vs. Time



Welding Developments at Daresbury

- Weld Procedure Specifications
- Sample qualification: dye & macroscopic

UKRI Science and Technology Facilities Council		WELD PROCEDURE SPECIFICATION (WPS)		WPS NO.	WPS RTD006																																										
Project:	RFD Prototype Cryomodule	Clinic:	CEM	DATE:	12/01/2023																																										
Authorised by:	E. Garsane	Reference:		REV:	1.0																																										
Welding Location:	TTC Building	REF. STANDARD:	ISO 15614-1	REF. SPECIFICATION:	EDMS 1203324																																										
Welding Process:	TIG (G4)	WELD:		WELD:																																											
Shielding Gas Type:	100% Argon	WELD:		WELD:																																											
Shielding Gas Flow:		WELD:		WELD:																																											
Purging Gas Type:	N/A	WELD:		WELD:																																											
Welding Position:	Flat	WELD:		WELD:																																											
Joint Type:	Lip Weld	WELD:		WELD:																																											
Joint Preparation:	Hot finished	WELD:		WELD:																																											
Cleaning Method:	Alcohol Degreasing	WELD:		WELD:																																											
Blanketing:		WELD:		WELD:																																											
Single Bevel:	Single side	WELD:		WELD:																																											
Bevel Grooving:	None	WELD:		WELD:																																											
Flux Designation:		WELD:		WELD:																																											
Flux Handling:		WELD:		WELD:																																											
Tungsten Electrode:	CW18-2	WELD:		WELD:																																											
Tip Length:	Ø1.6 mm	WELD:		WELD:																																											
Shield Off Distance:		WELD:		WELD:																																											
Nozzle Diameter(s):	10 mm	WELD:		WELD:																																											
Back Welding Proc:		WELD:		WELD:																																											
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Upper (Bi Phase) Cryoline

