Cold Testing and HOM Coupler Qualification for HL-LHC Crab Cavity Systems

Amelia Edwards on behalf of HL-LHC WP4

International Workshop on Higher Order Modes in Superconducting Cavities

DESY, Hamburg, Oct 6 – 8, 2025

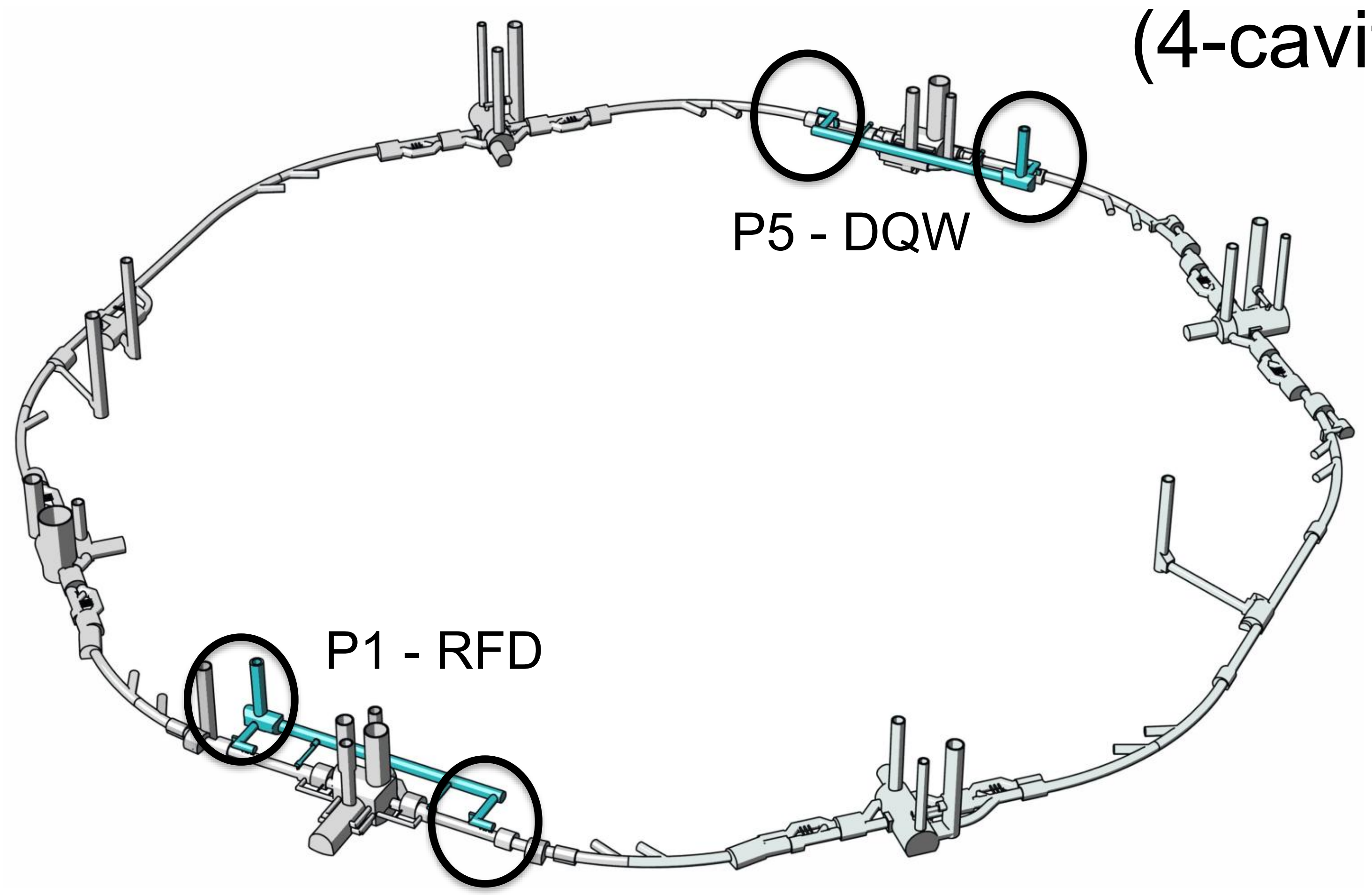
Outline

- Introduction to the project
- HOM Measurements at 2K
- Results& Status
    - DQW Cavities
    - RFD Cavities
- 25Ω RF Lines Qualification

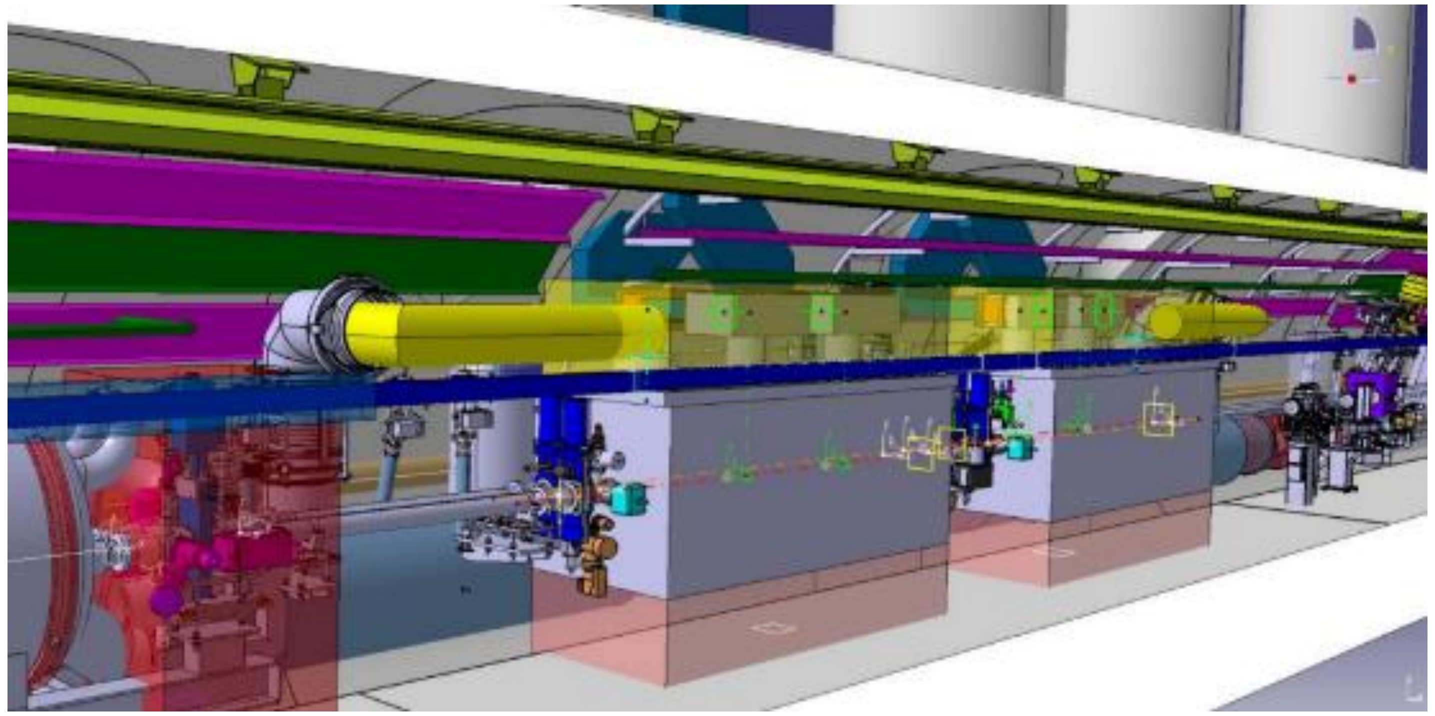
Part 1: Introduction to the Crab Cavities for HL-LHC

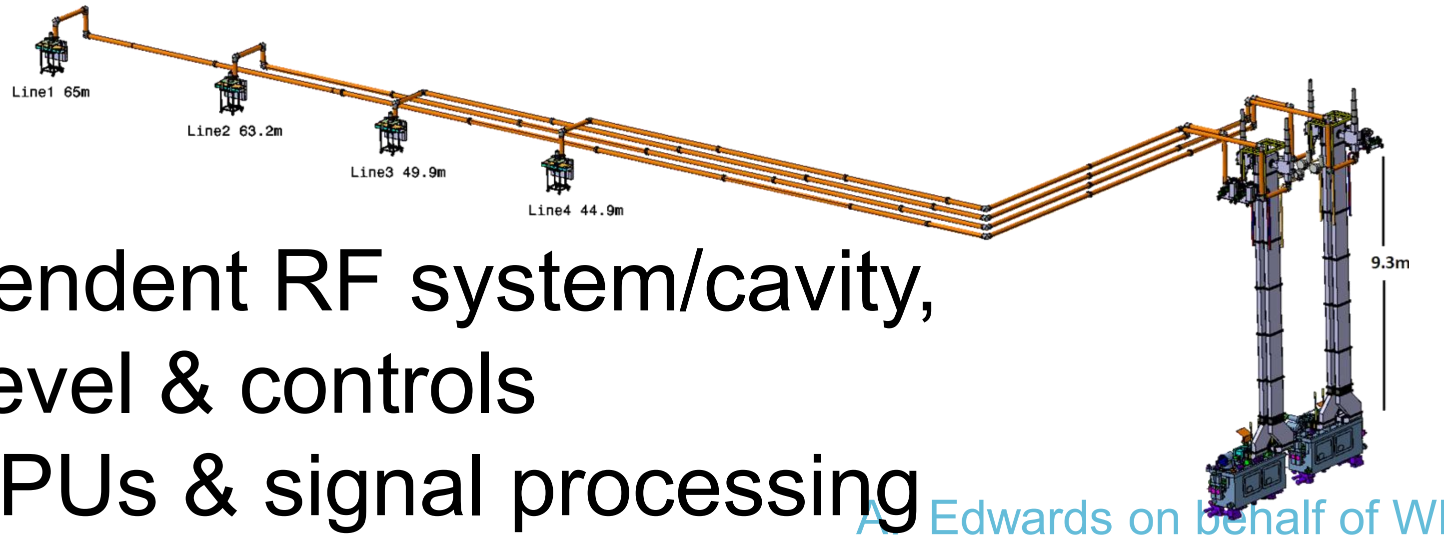
HL-LHC Crab Cavities

- 16 SC compact RF deflectors (ATLAS + CMS) & RF system to partially compensate the geometric x-angle and maximize the luminous region



One IP side
(4-cavities in 2-CM)

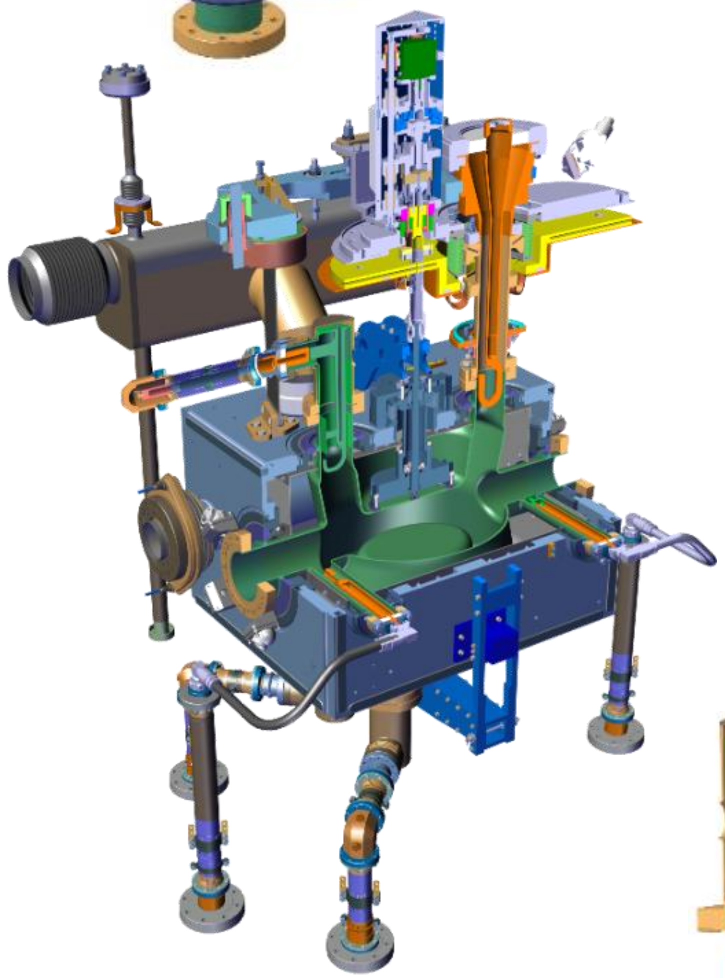


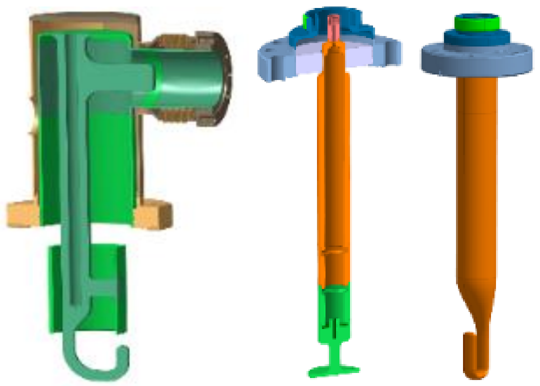


Independent RF system/cavity,
Low-level & controls
4 CC-PUs & signal processing

HL-LHC Cavity Geometries

Double Quarter Wave (DQW) cavity
– to be used in Point 5 (CMS), vertical





Bulk Nb Cavities

$$f_0 = 400.79 \text{ MHz}$$

$$\mathrm{V_T} = 3.4 \text{ MV/cavity*}$$

$$(\mathrm{E_p}, \mathrm{B_p} < 40 \text{ MV/m}, 70 \text{ mT})$$

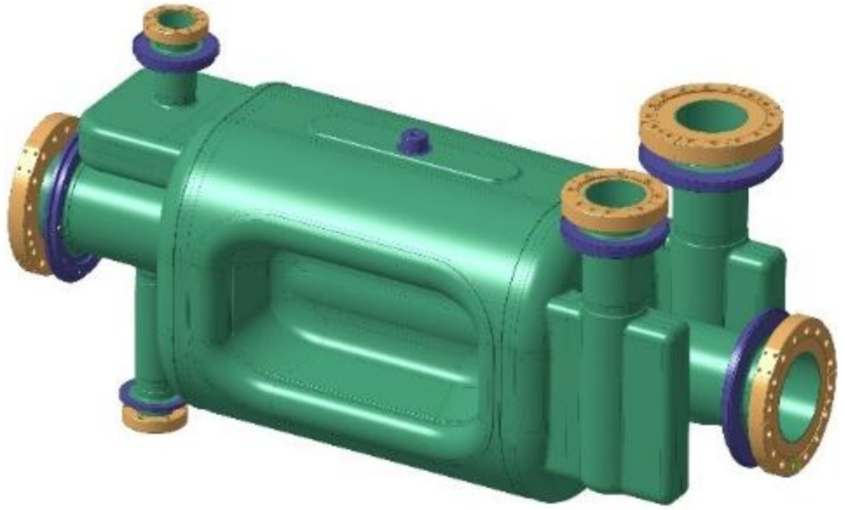
$$\text{Beam aperture} = 84 \text{ mm}$$

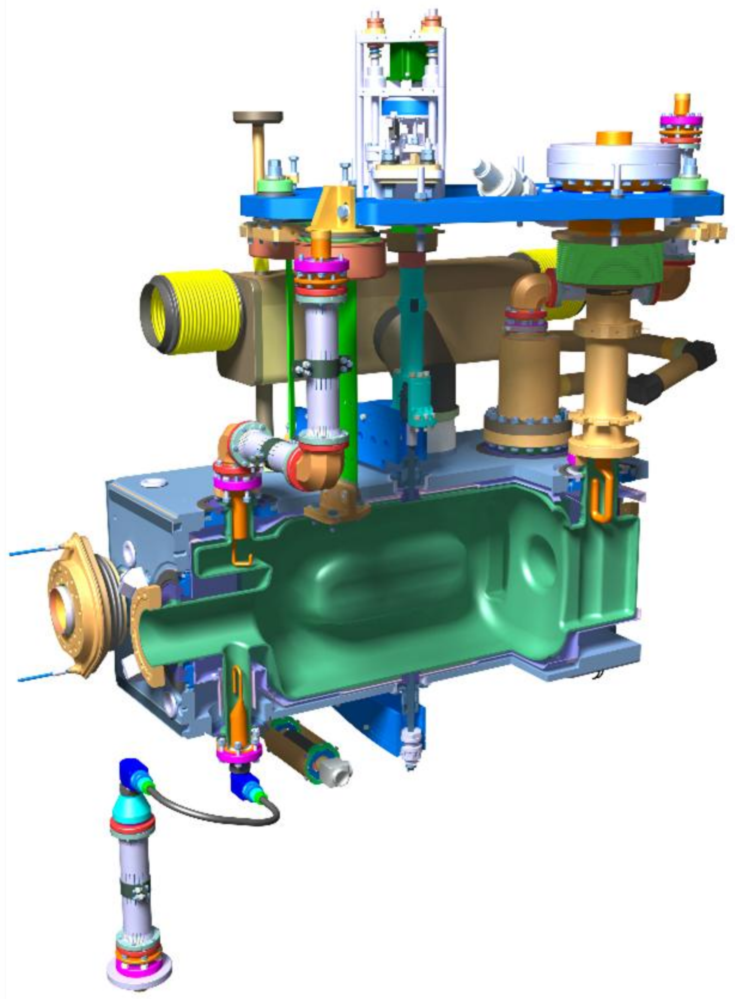
$$\text{RF power} = 40 \text{ kW-CW}$$

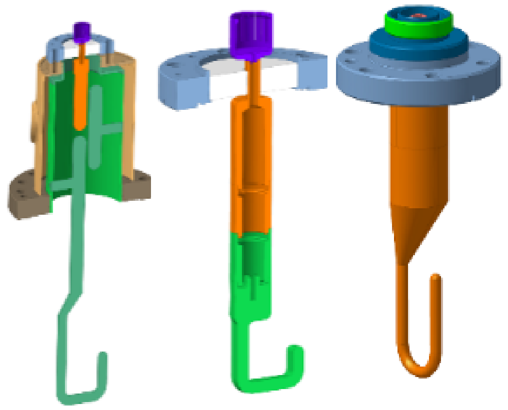
$$\text{Operating Temp} = 2 \text{ K}$$

Limits of 1 MΩ/m/cavity for transverse impedances was imposed and 200 kΩ/cavity for longitudinal modes

Radio Frequency Dipole (RFD) cavity
– to be used in Point 1 (ATLAS), horizontal



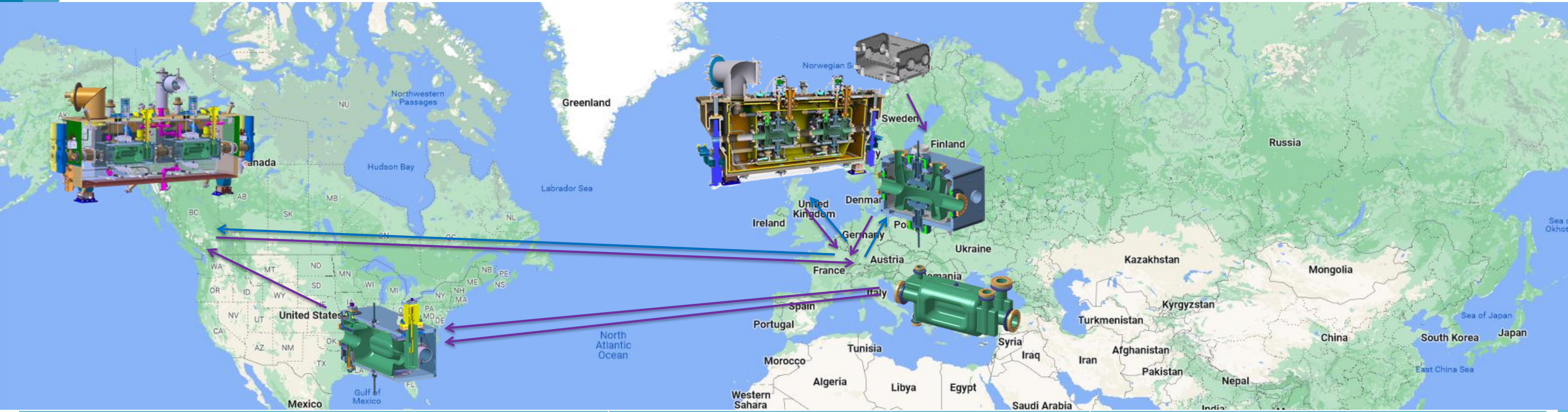




*Engineering spec: 4.1 MV dressed for 20% margin

HL-LHC PROJECT

HL-LHC Crab Cavities



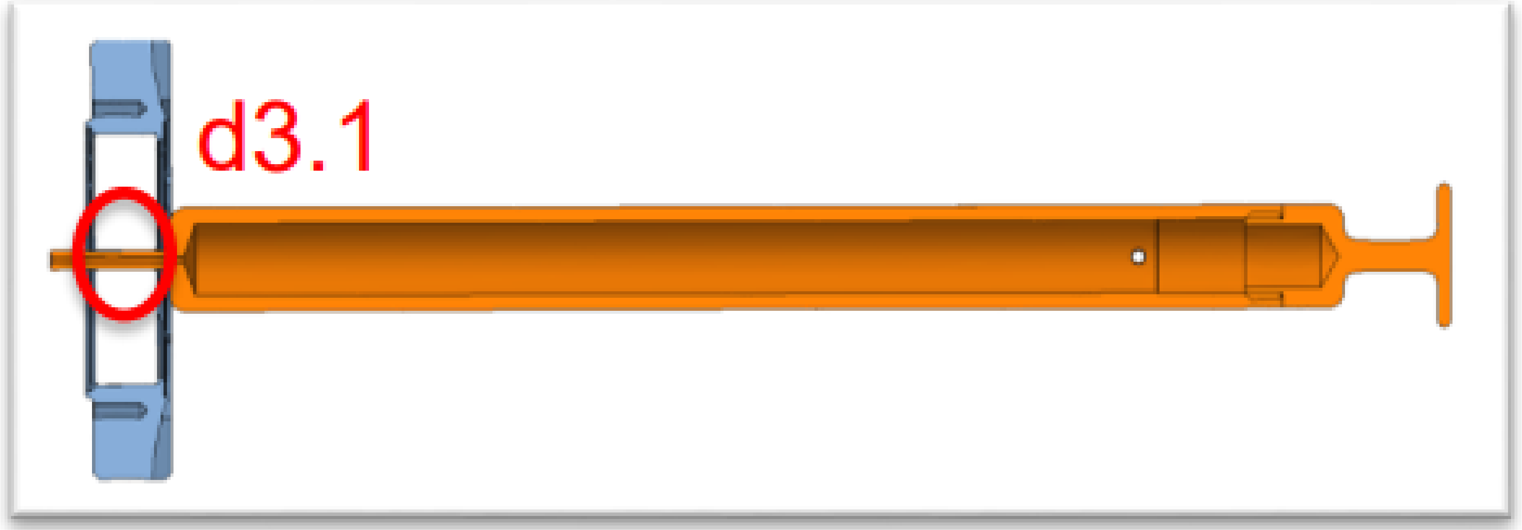
5 DQW cryomodules	5 RFD cryomodules	20 IOT RF Systems
• Cavities + processing + helium vessels by Research Instruments (**DE**) & **CERN** • Cold magnetic shields by **UK** • HOM couplers + antennas by **CERN** • 4 CM by **UK** (STFC) & 1 CM at **CERN** with some components from **CERN** • All cavities & 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** • High power RF lines, circulators, loads by **CERN** (exploring new frontiers) • μTCA platform for LLRF by CERN

Part 2: HOM Measurements & Impedance Calculations

Vertical Cold Test Set-up in CERN SM18

- Test temperature: 2K
- Sensors used during the tests:
  - Temperature sensors: CERNOX
  - 3 single-axis magnetic flux probes
  - Radiation monitors (different position depends on the cryostat)
- Cryostats are equipped with magnetic field compensation coils - set at ~0.5μT (BC) – *NOT USED FOR DRESSED CAVITIES*
- JC and DC tested fully immersed in the LHe bath
- Cavity vacuum actively pumped by turbo and ion pump, then only cryo-pumping

HOM Couplers & Field Antennas feedthroughs



Ideal design D39.7/d3.1 ; $Z_{ceramic} = 50\ \Omega$

$$Z_{ceramic} = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{D}{d}\right) \; ; \; Z_{ceramic} \sim 20 \ln\left(\frac{D}{d}\right)$$

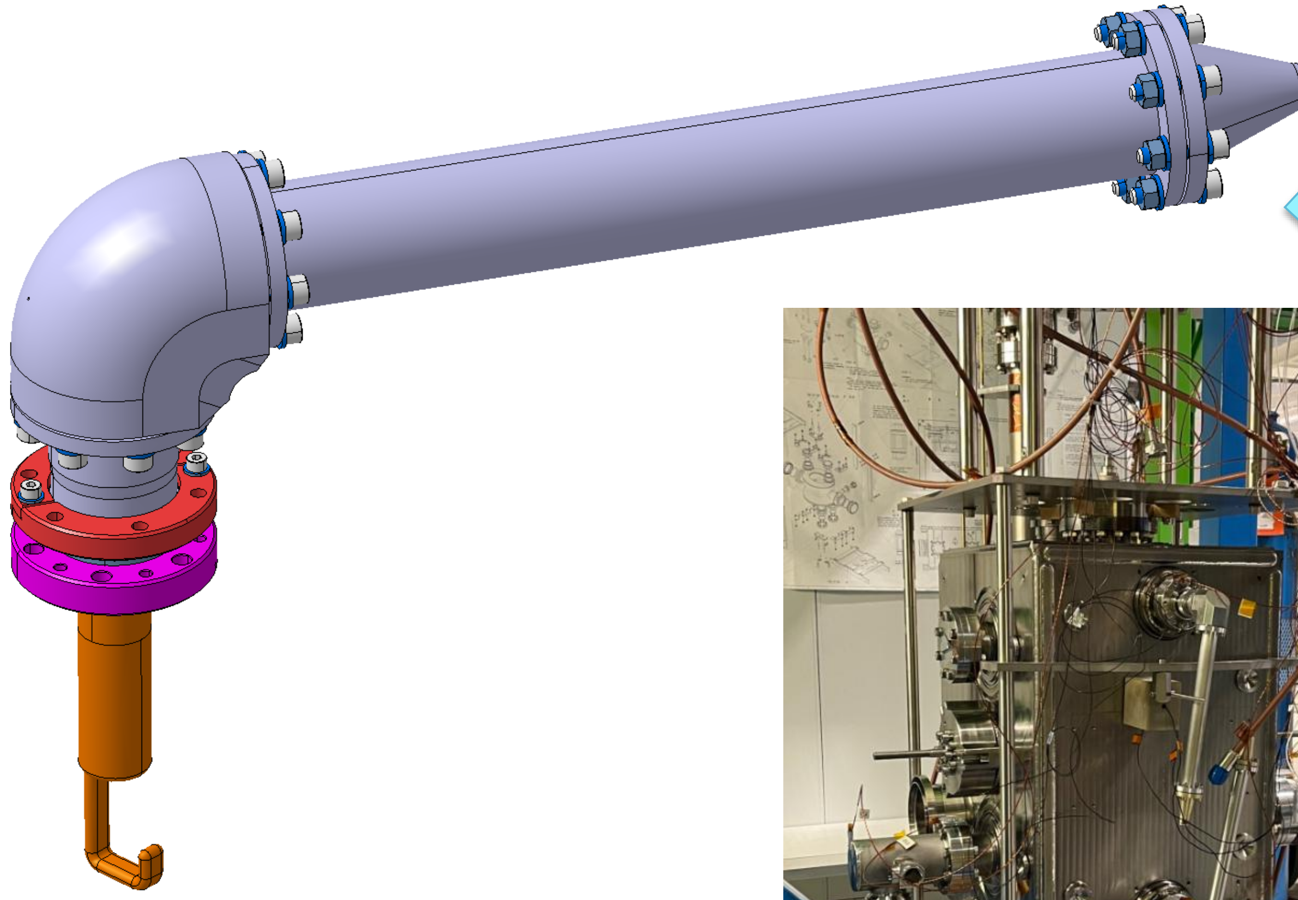
In order to make it much more robust, Rama had the clever idea to propose 25 Ω

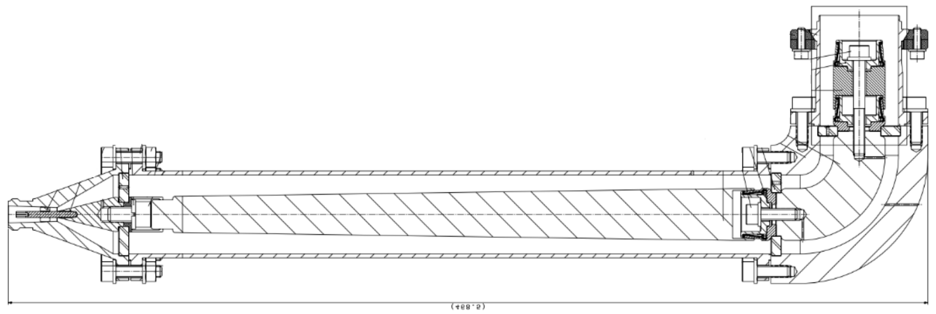
Crab design D40/d14 ; $Z_{feedthrough} = 25\ \Omega$

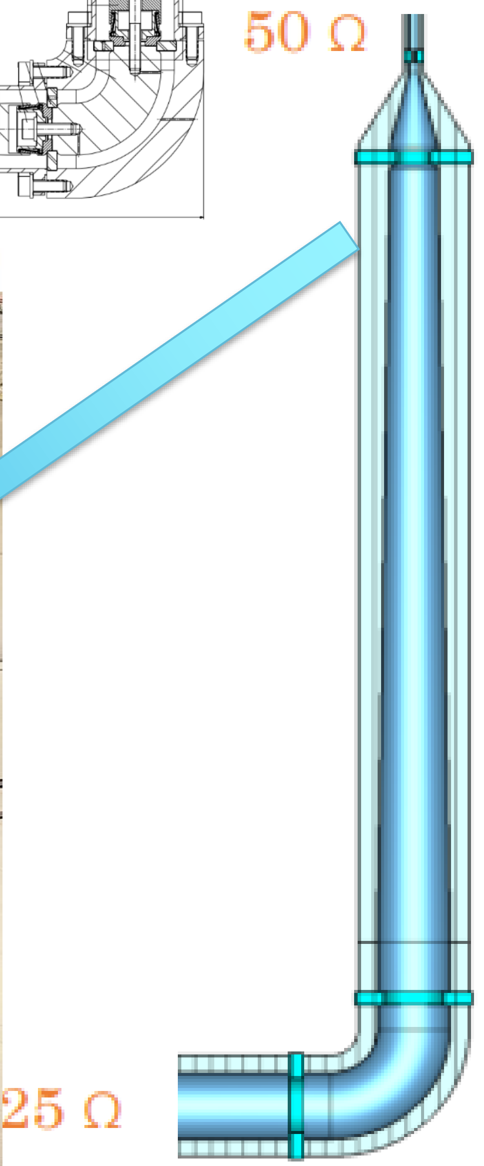
Slide courtesy of E. Montesino

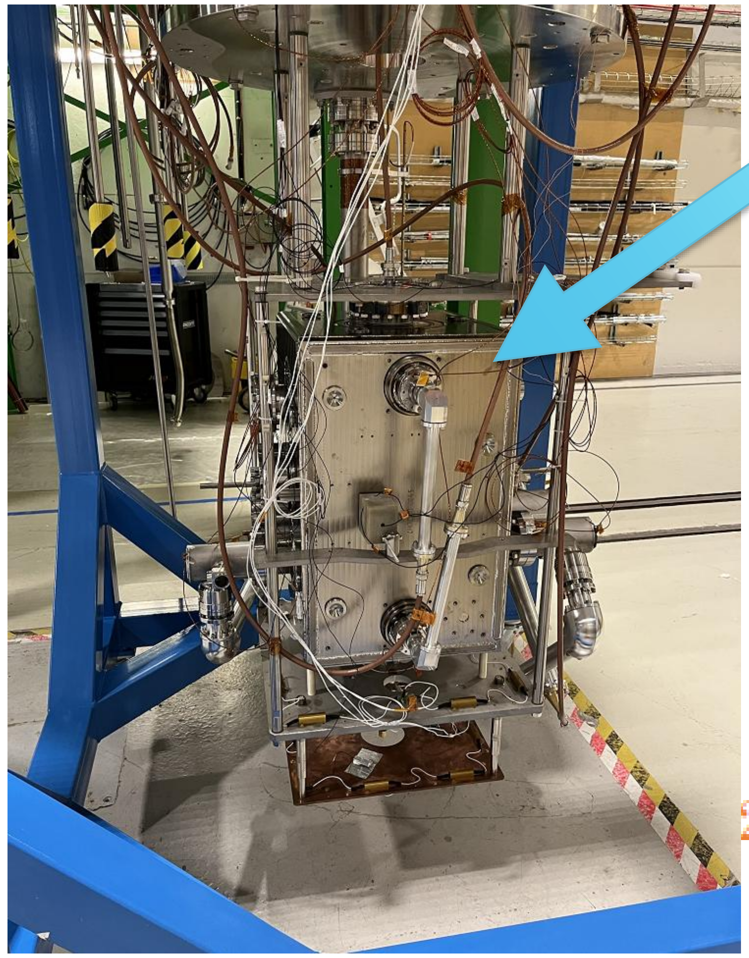
25 Ω to 50 Ω Adapters for HOMs

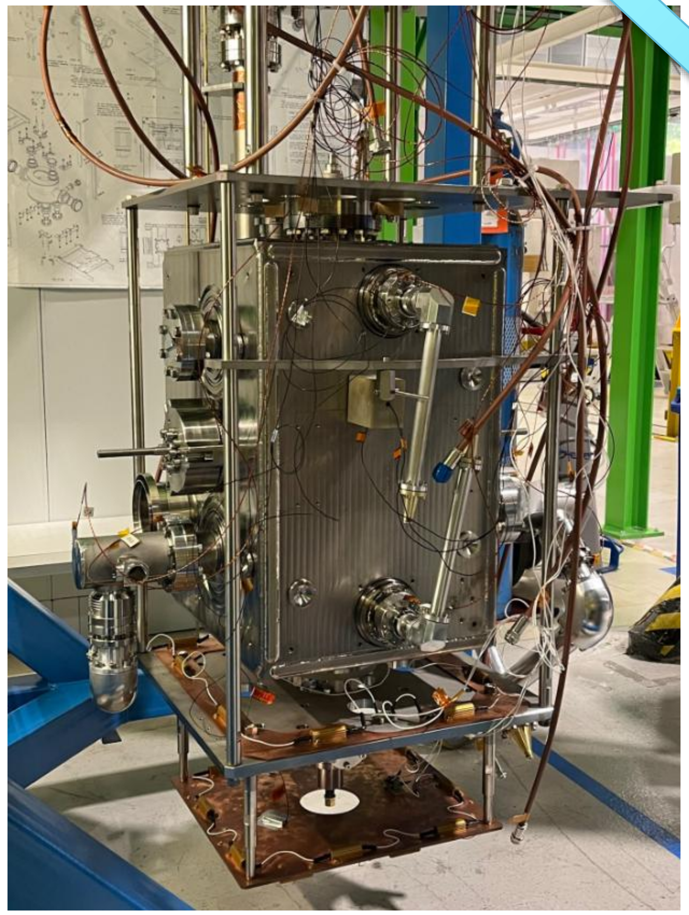
- 25 to 50 Ω adapters designed to qualify the HOM couplers and antennas before and after installation onto the cavity.
- Verified before cold test by TDR measurement and s-parameter measurement

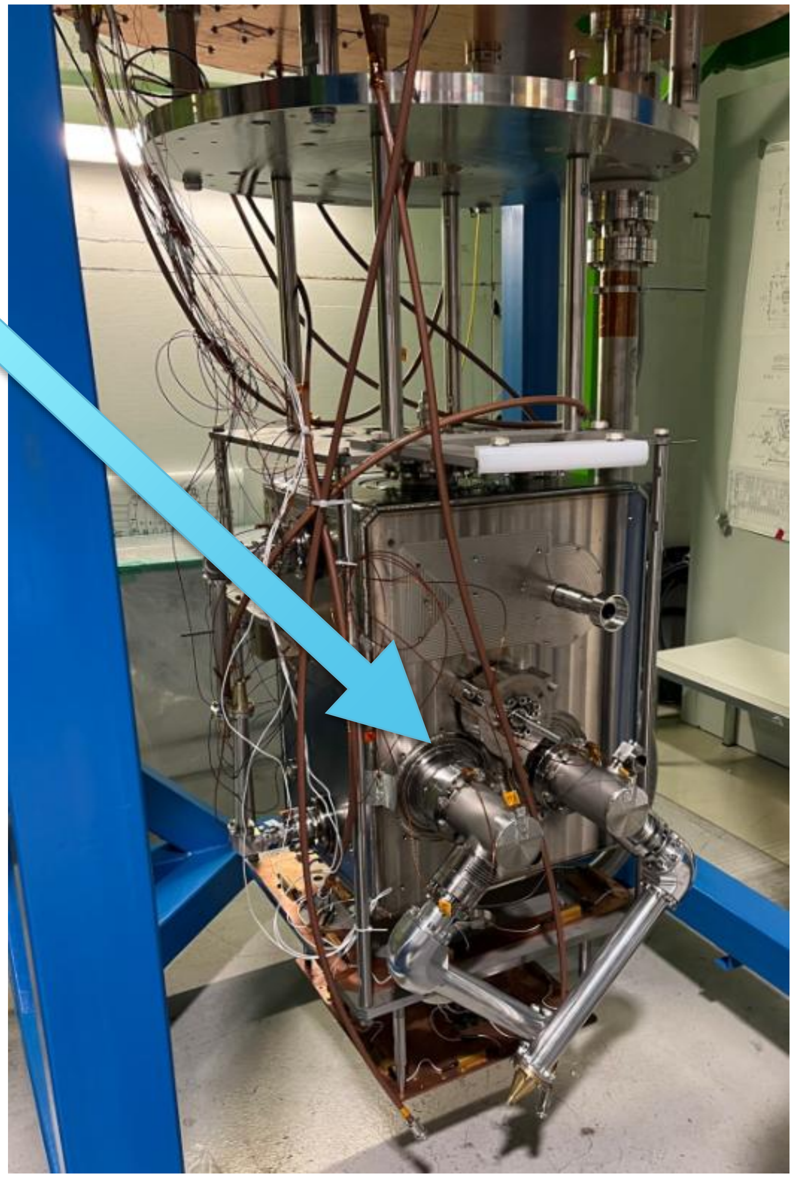


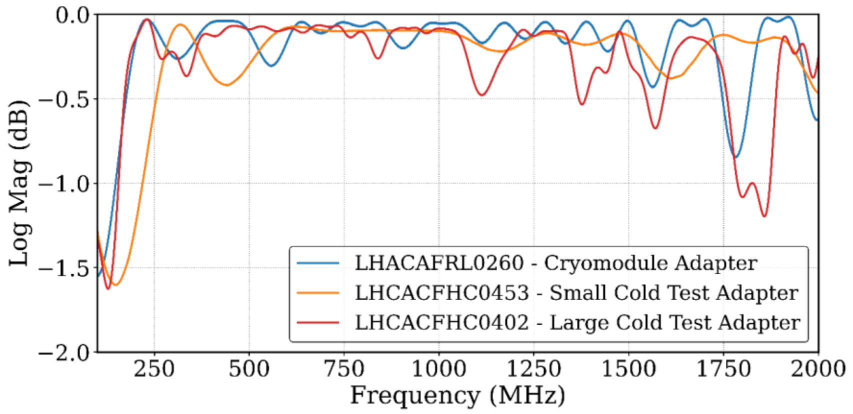






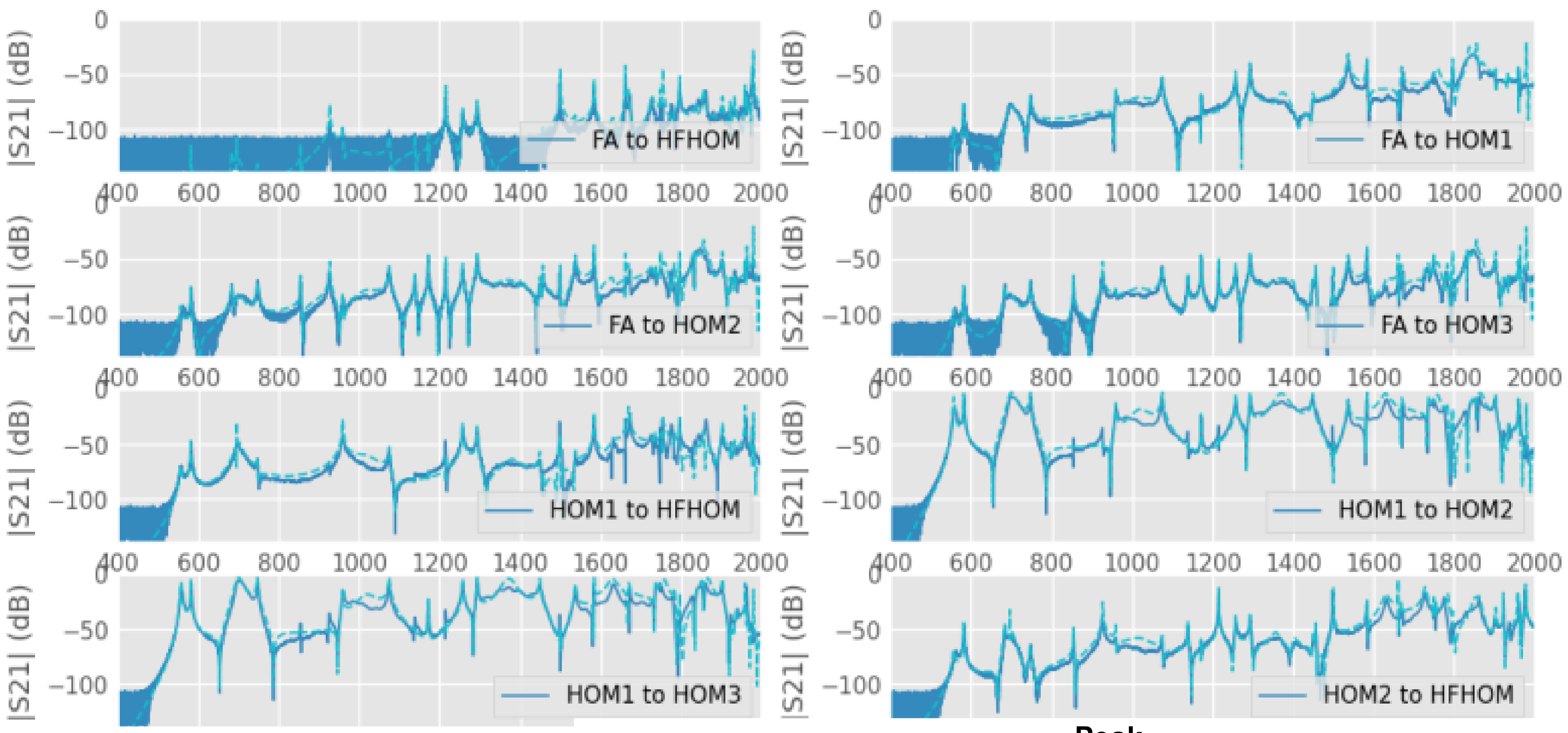


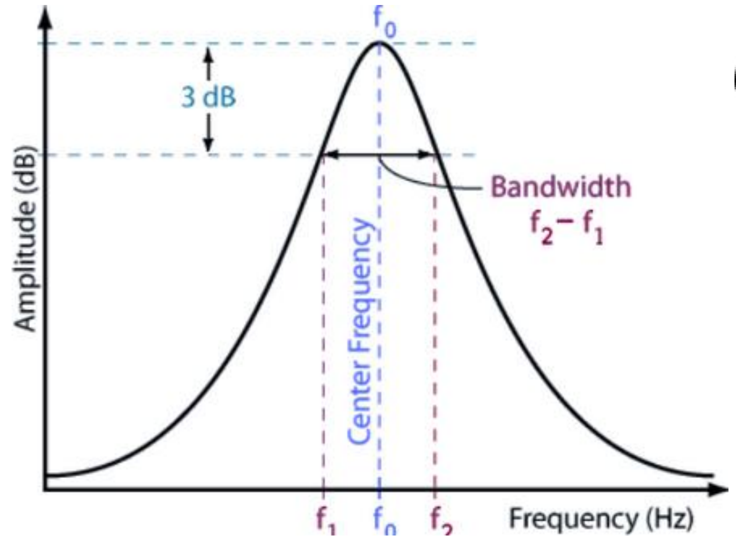




Obtaining 2K HOM Measurements

- High resolutions (>100,001 points, several spans) measured at 2K during cold test
- All port combinations are measured, for DQW this is produced 10 combinations
- Not all HOMs couple strongly to all ports so some results can be easily discounted
- From remaining values, the highest impedance is selected as a ‘worse case’ scenario
- Z in three planes (horizontal, vertical & longitudinal) are computed from simulated R/Q values



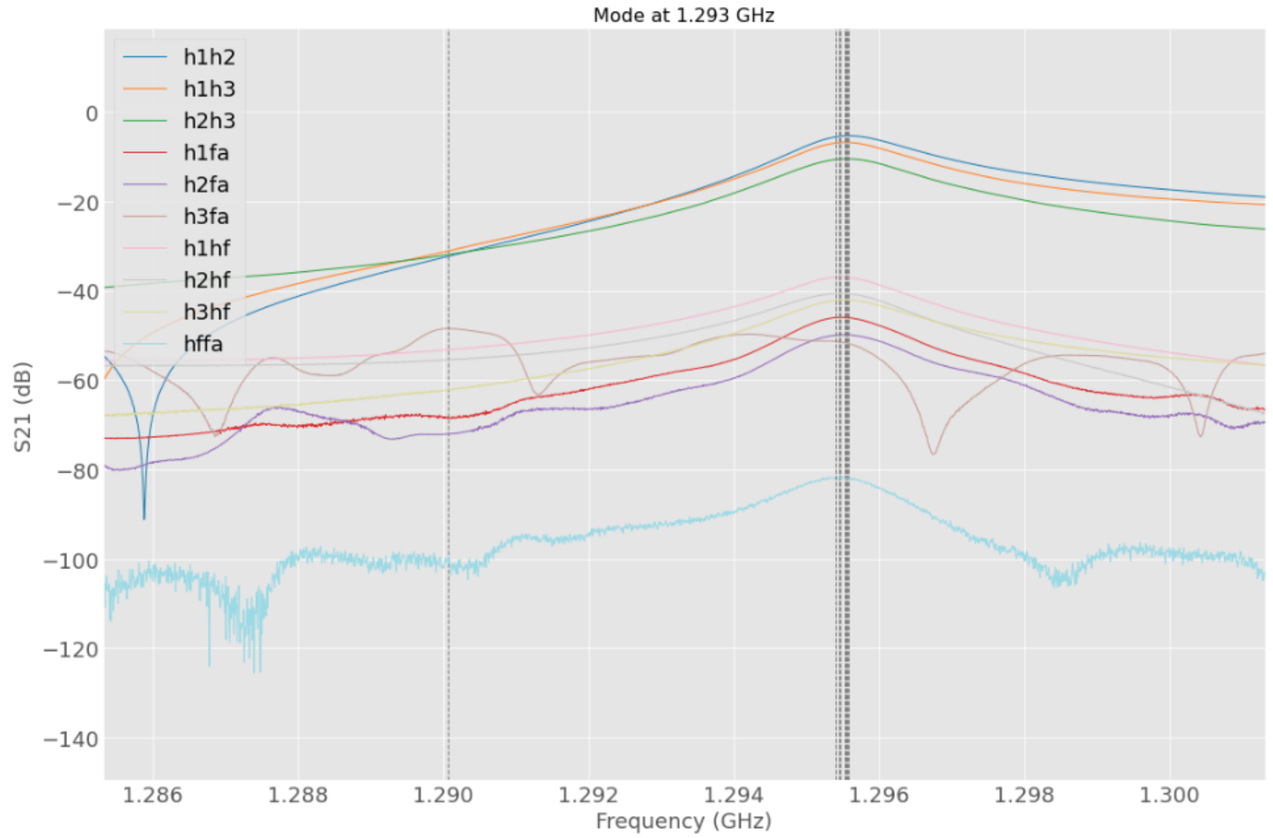


$$Q_l = \frac{f_0}{BW_{3dB}}$$

$$Q_e \approx Q_l$$

$$R_z = (R/Q)_z \cdot Q_{ext}$$

$$R_{\perp(x,y)} = (R/Q)_{\perp(x,y)} \cdot Q_{ext} \cdot \frac{\omega}{c}$$



Network	Mode (GHz)	Peak Frequency (GHz)	Bandwidth (MHz)	Q Factor
h1h2	1.293	1.296	1.556	833
h1h3	1.293	1.296	1.509	858
h2h3	1.293	1.296	1.618	801
h1fa	1.293	1.295	1.333	972
h2fa	1.293	1.296	1.427	908
h3fa	1.293	1.290	5.870	220
h1hf	1.293	1.295	1.502	862
h2hf	1.293	1.295	1.612	804
h3hf	1.293	1.296	1.611	804
hffa	1.293	1.295	1.312	988

HOMs for DQW & RFD: Simulated Values

- Joining a mature project, long time since design stage!
- Critical HOMs identified during design stages for both cavity types (DQW & RFD)
- CST used for DQW (J. Mitchell, 2021) & AECP3 used for RFD (Z. Li, US-AUP Collaboration, 2019)
- HOMs flagged for several reasons: high power, high impedance or proximity to bunch spacing harmonics

$$\left(\frac{r}{Q}\right)_{\parallel} = \frac{V_{\parallel}^2}{2\omega U}, \qquad R_{\parallel} = \left(\frac{r}{Q}\right)_{\parallel} Q_l$$

$$\left(\frac{r}{Q}\right)_{\perp} = \frac{1}{2\omega U}\left(\frac{c}{\omega}\left|\frac{dV_{\parallel}}{dr}\right|\right)^2, \qquad R_{\perp} = \frac{\omega}{c}\left(\frac{r}{Q}\right)_{\perp} Q_l.$$

RFD (dressed)

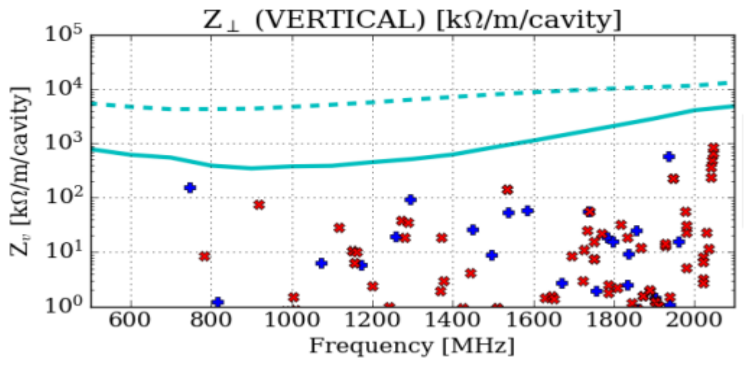
File provided by Z. Li (SLAC): ImpedanceTable_RFDwFT_20191118_Zenghai.csv (19/11/2019)
EDMS 2009911 [1], model at 2K, windows with ε_r = 9.6

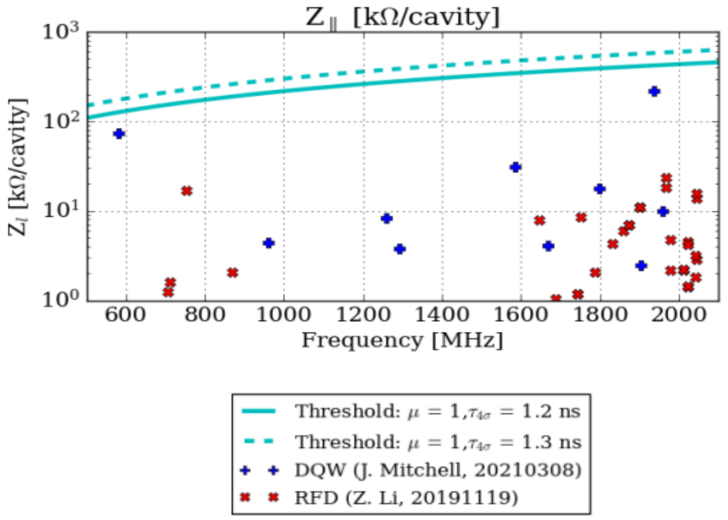
f [MHz]	Qe	$R_{\perp v}$ [kΩ/m]	$R_{\perp h}$ [kΩ/m]	$R_{\parallel}$ [kΩ]	Notes
635	1121	0	**573**	0	
752	192	0	0	**17**	High power mode.
1322	2974	0	**625**	0	Mode over transverse threshold.
1470	38208	0	**348**	0	
1629	10404	1	**758**	0	
1646	10742	2	**63**	**8**	Close to bunch spacing harmonic.
1726	39216	11	**355**	0	
1808	7574	2	**389**	0	

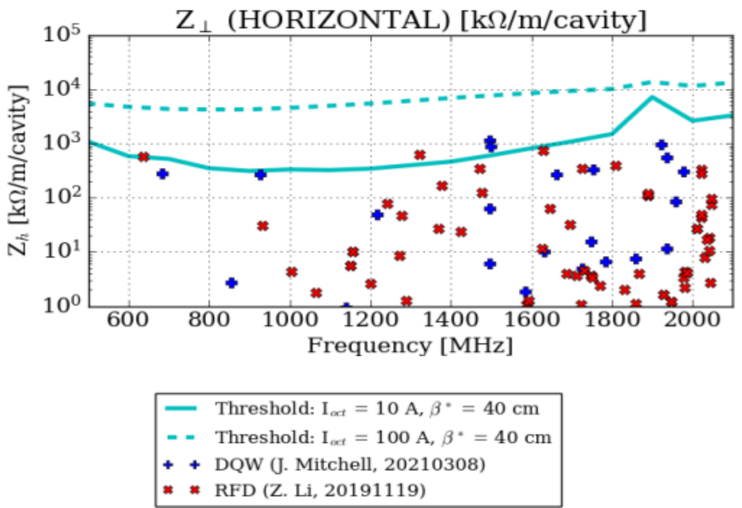
DQW (dressed)

File provided by J. Mitchell (CERN): DQW_LHC_2K_Z-Table_20210308.csv (08/03/2021)
EDMS 1347072 [2], model at 2K, windows with ε_r = 9.6.

f [MHz]	Qe	$R_{\perp v}$ [kΩ/m]	$R_{\perp h}$ [kΩ/m]	$R_{\parallel}$ [kΩ]	Notes
582	1365	1	0	**73**	High power mode. Frequency is > 10 MHz from nearest bunch spacing harmonic.
683	580	0	**276**	0	
748	522	**156**	0	0	
927	845	0	**266**	0	
959	480	1	0	**4**	High power mode.
1496	2126828	0	**1137**	0	Mode over transverse threshold.
1500	17581	0	**874**	0	Damped by HF-HOMC. Mode over transverse threshold.
1584	3863	**57**	2	**31**	
1661	18343	0	**268**	0	Many modes near to this frequency.
1754	3791	0	**331**	0	Damped by HF-HOMC.
1922	24305	0	**953**	0	



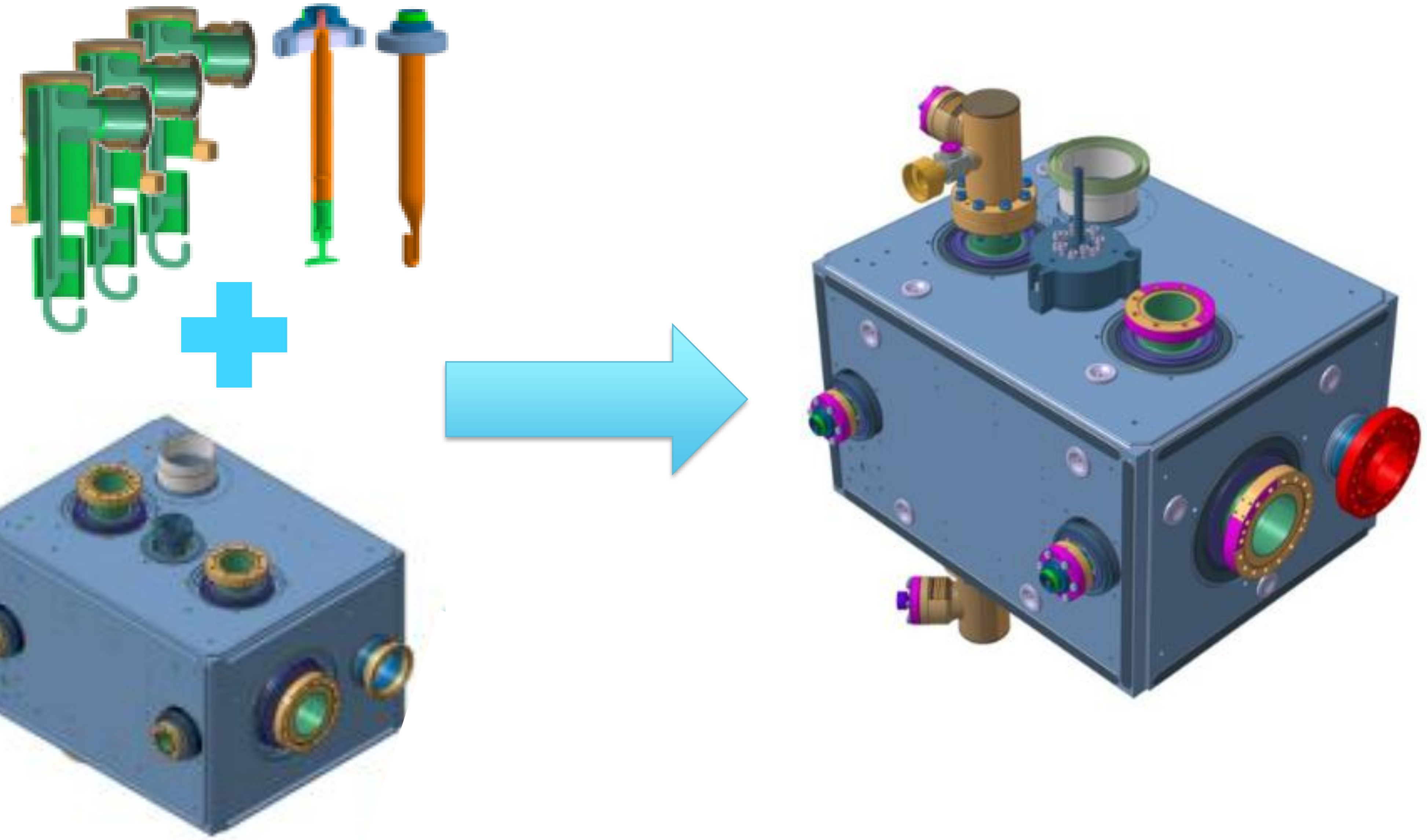




Limits of 1 MΩ/m/cavity for transverse impedances was imposed and 200 kΩ/cavity for longitudinal modes

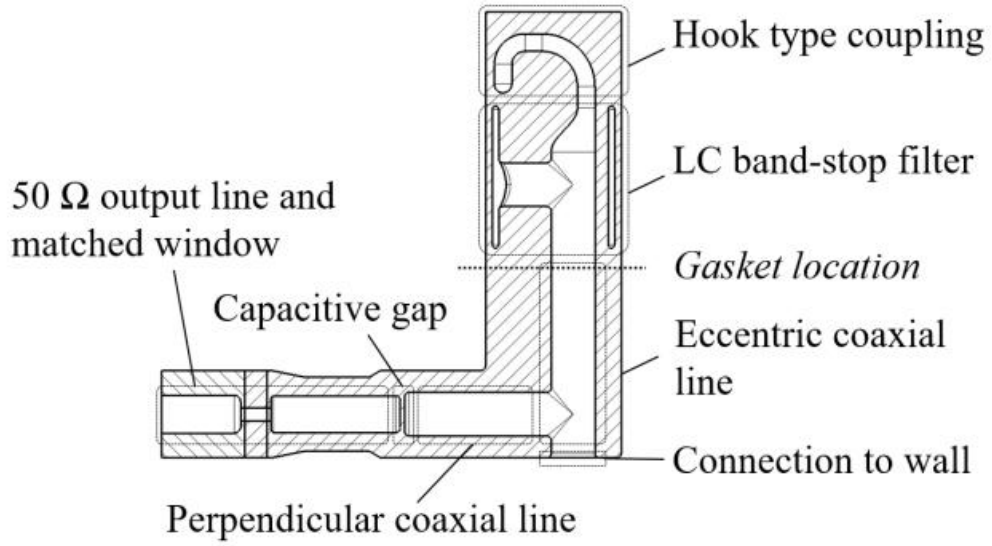
Part 3: Measured Results from DQW Crab Cavities

Dressed Cavity



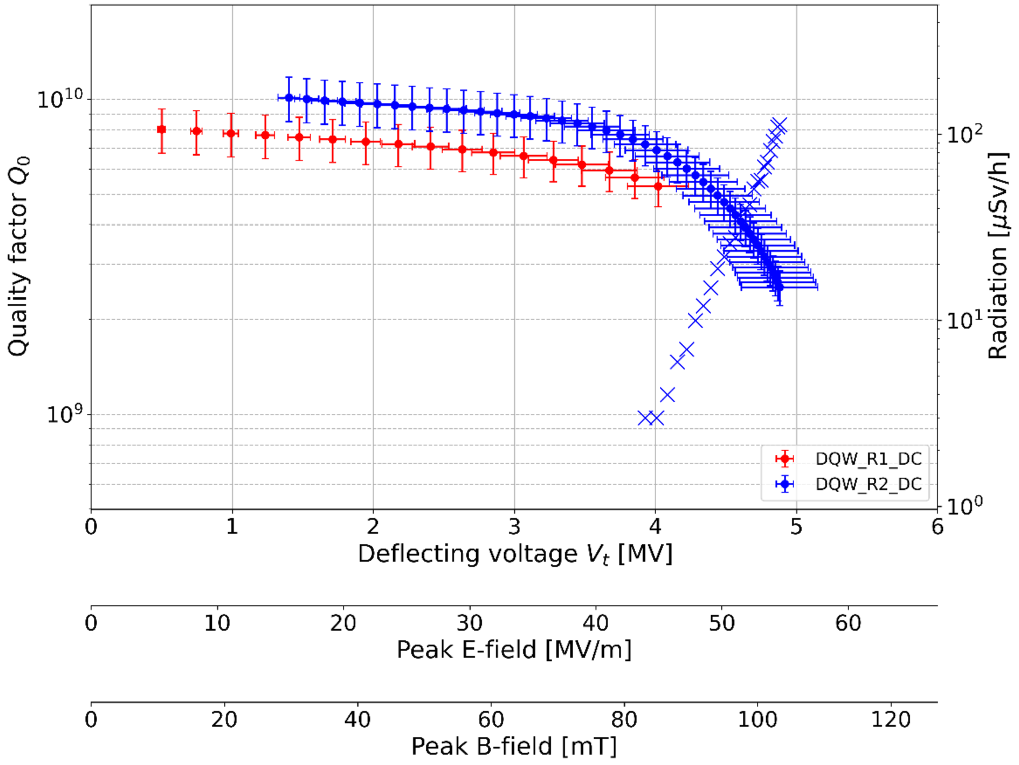
Status of DQW Crab Cavities at CERN

- Four DQW cavities qualified with all couplers installed
- HOM couplers produced at CERN
- Two cavities produced by Research Instruments (DE) and two produced at CERN
- Cavity contains x3 Nb HOM couplers, x1 HF-HOM & 1 FA
- HF-HOM added to specifically damp the mode at 1754MHz
- No test box available for DQW HOM couplers
- The cavity is the test box!
- **Presence of so many couplers perturbed standard measurements of Voltage & Q0**

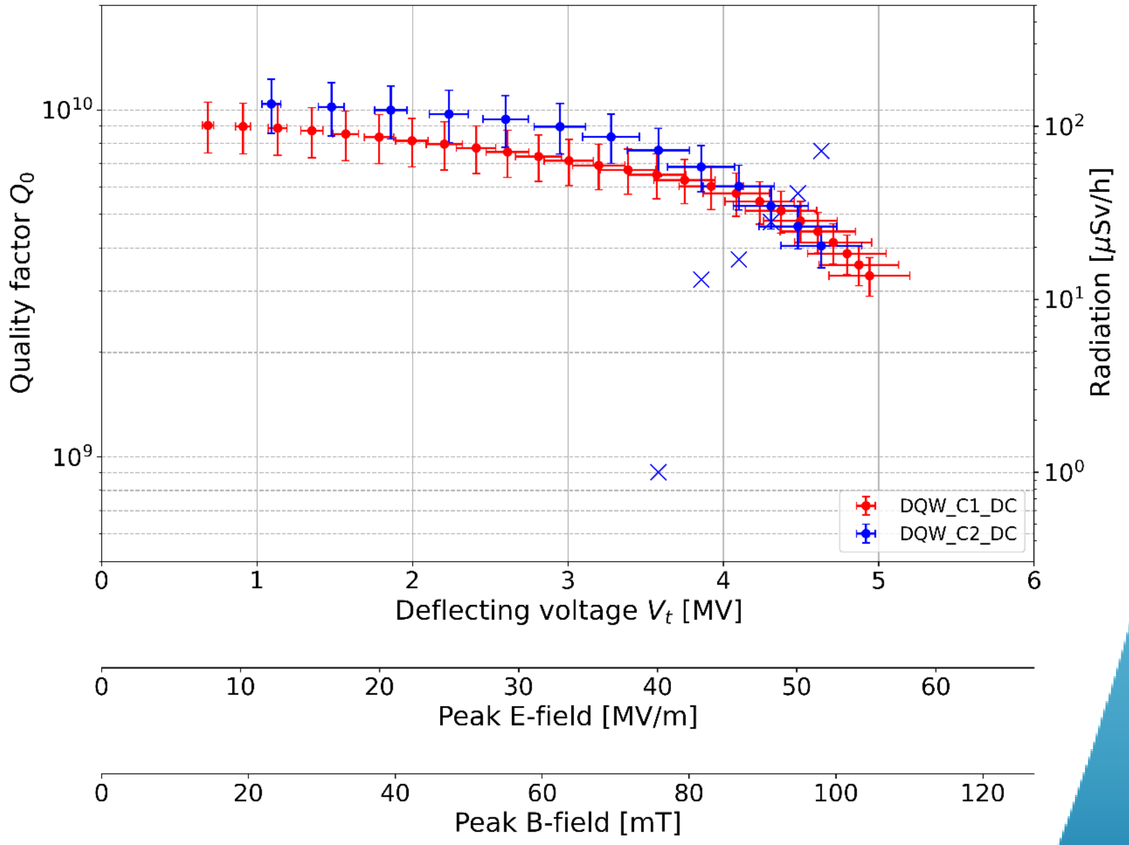


HL-LHC DQW HOM Coupler

RI DQW1 & DQW2

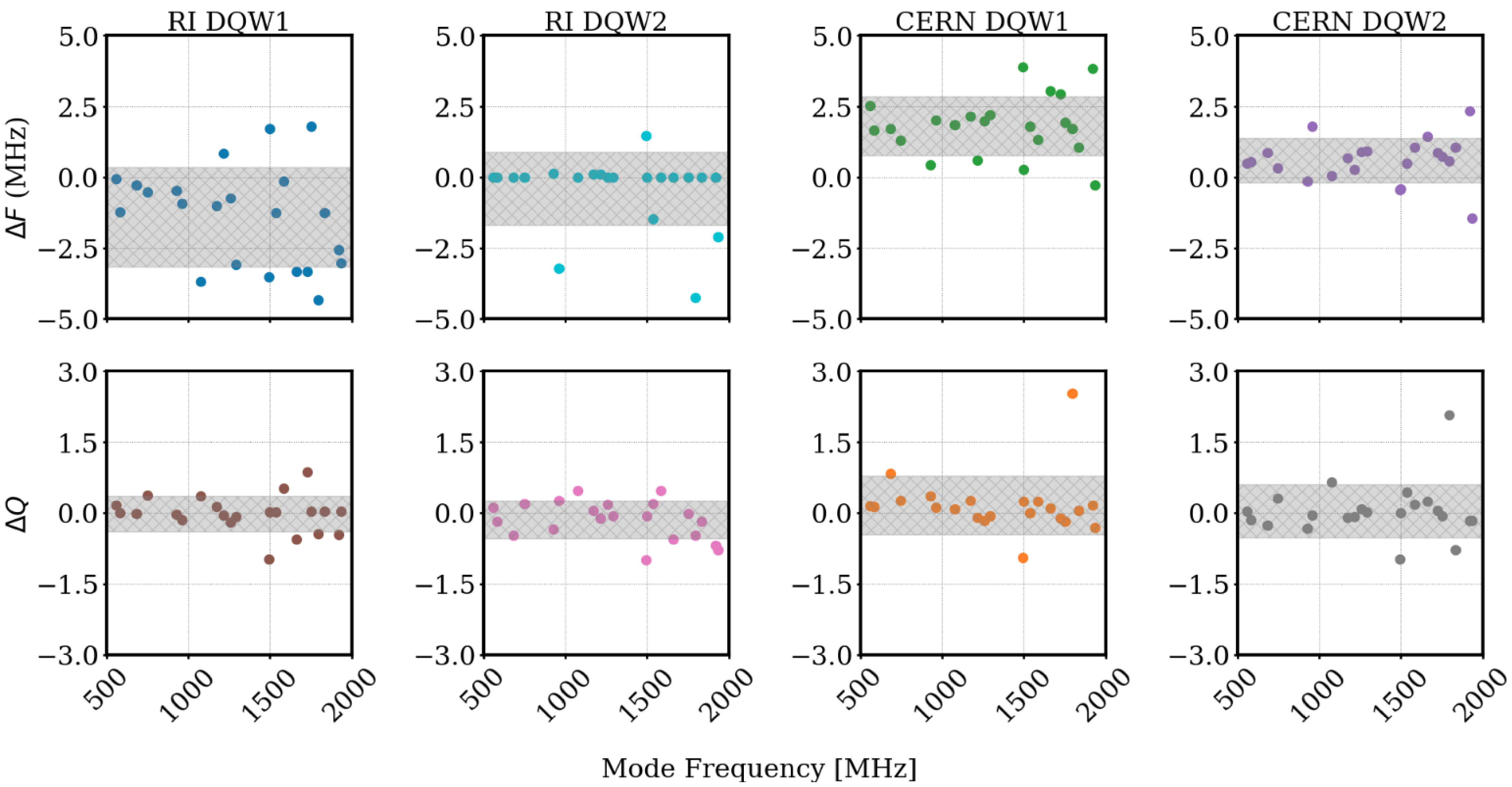


CERN DQW1 & DQW2



DQW Series Cavities
Frequency & Q deviation from Simulation

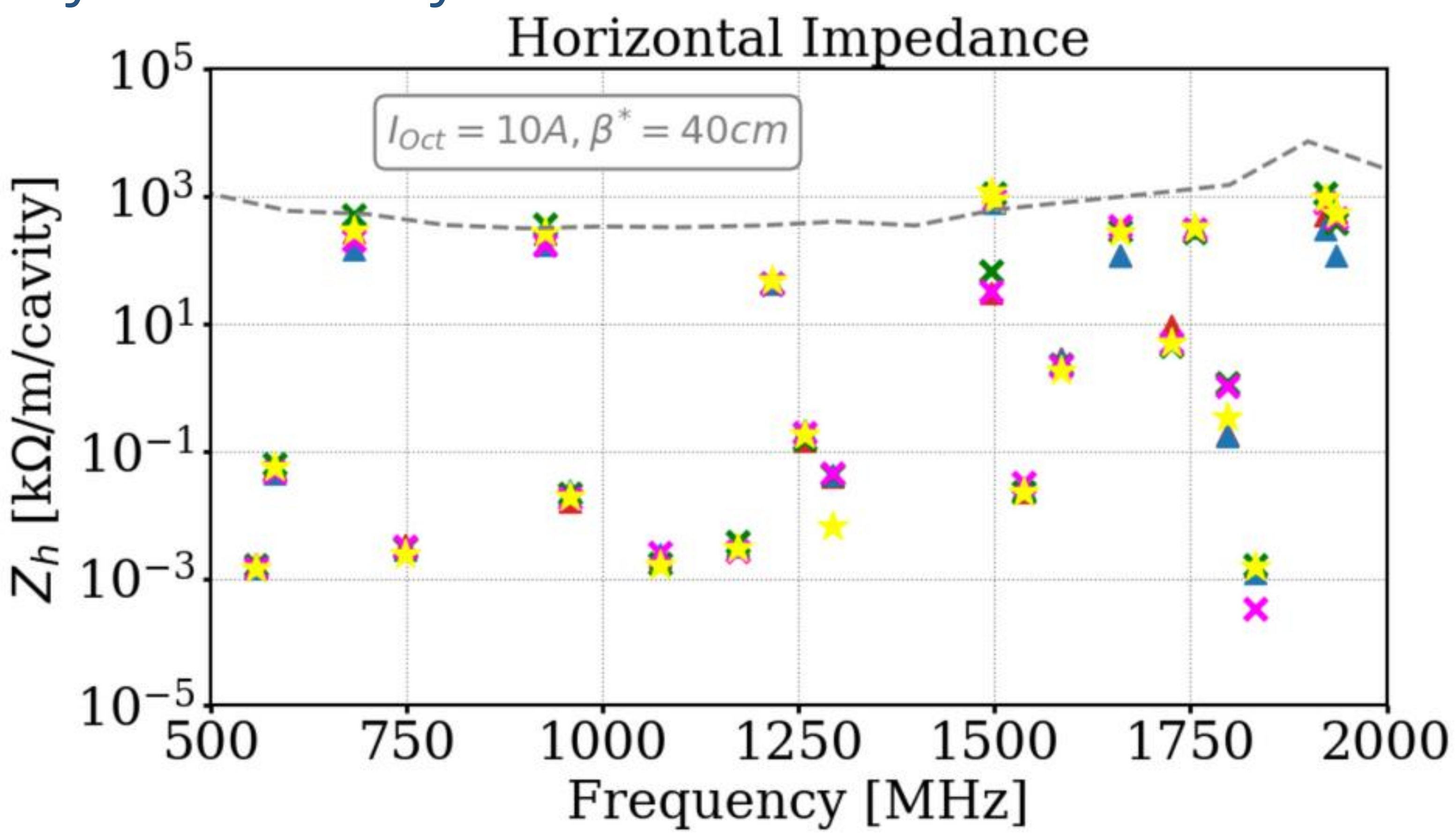
- Comparison with simulated values from CST simulations: EDMS 1347072
- Measured differences in frequency and quality factor w.r.t simulated values

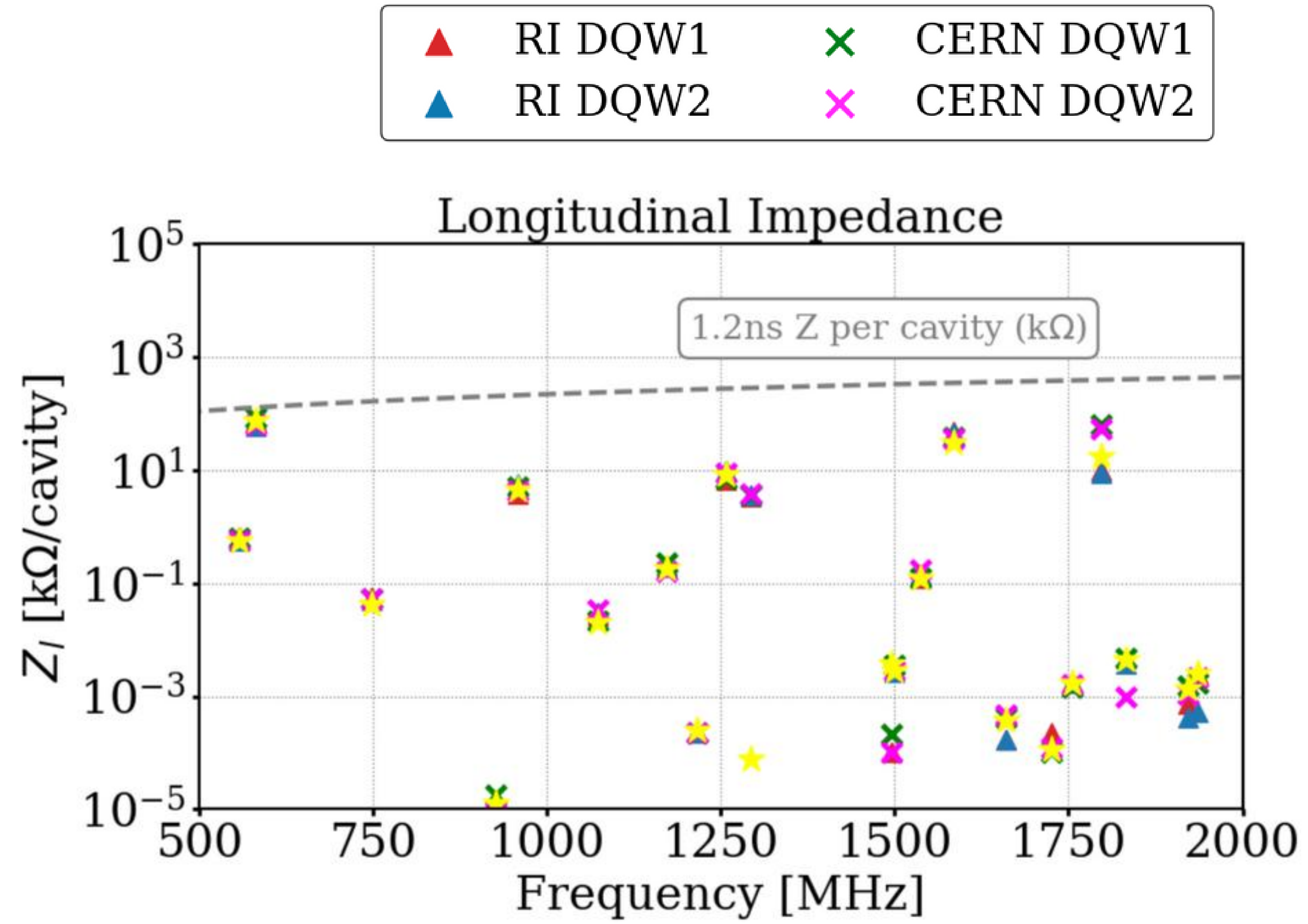


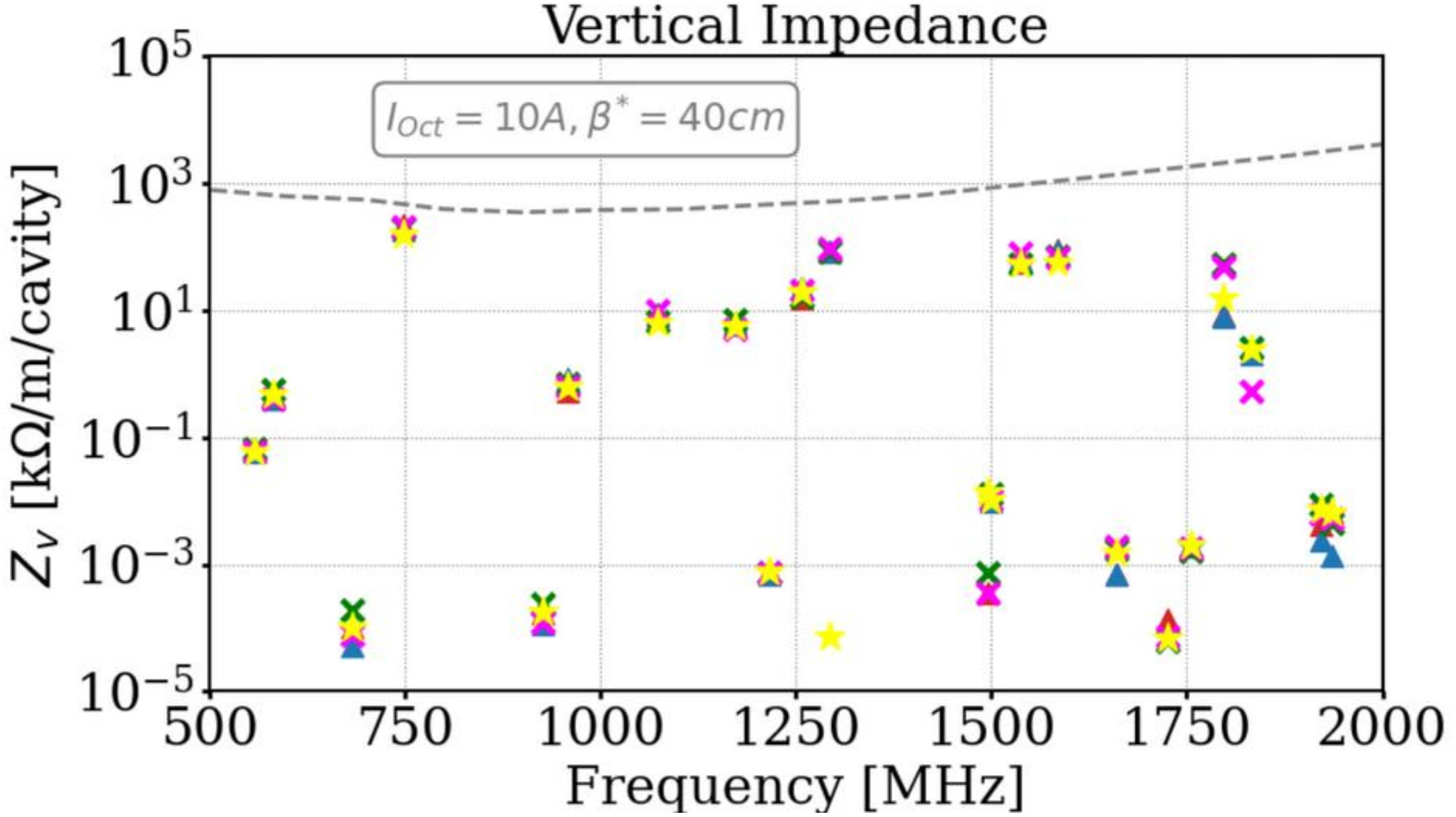
	Freq (kHz)	Q
RI 1	-1.4 ± 1.76	-0.02 ± 0.38
RI 2	-0.4 ± 1.29	-0.14 ± 0.4
CERN 1	-1.8 ± 1.05	-0.17 ± 0.62
CERN 2	-0.6 ± 0.79	-0.04 ± 0.57

DQW Series Cavities Measured Impedance at 2K

- So far measurements for x4 series cavities are consistent!
- Final impedance values have been provided for beam dynamics analysis



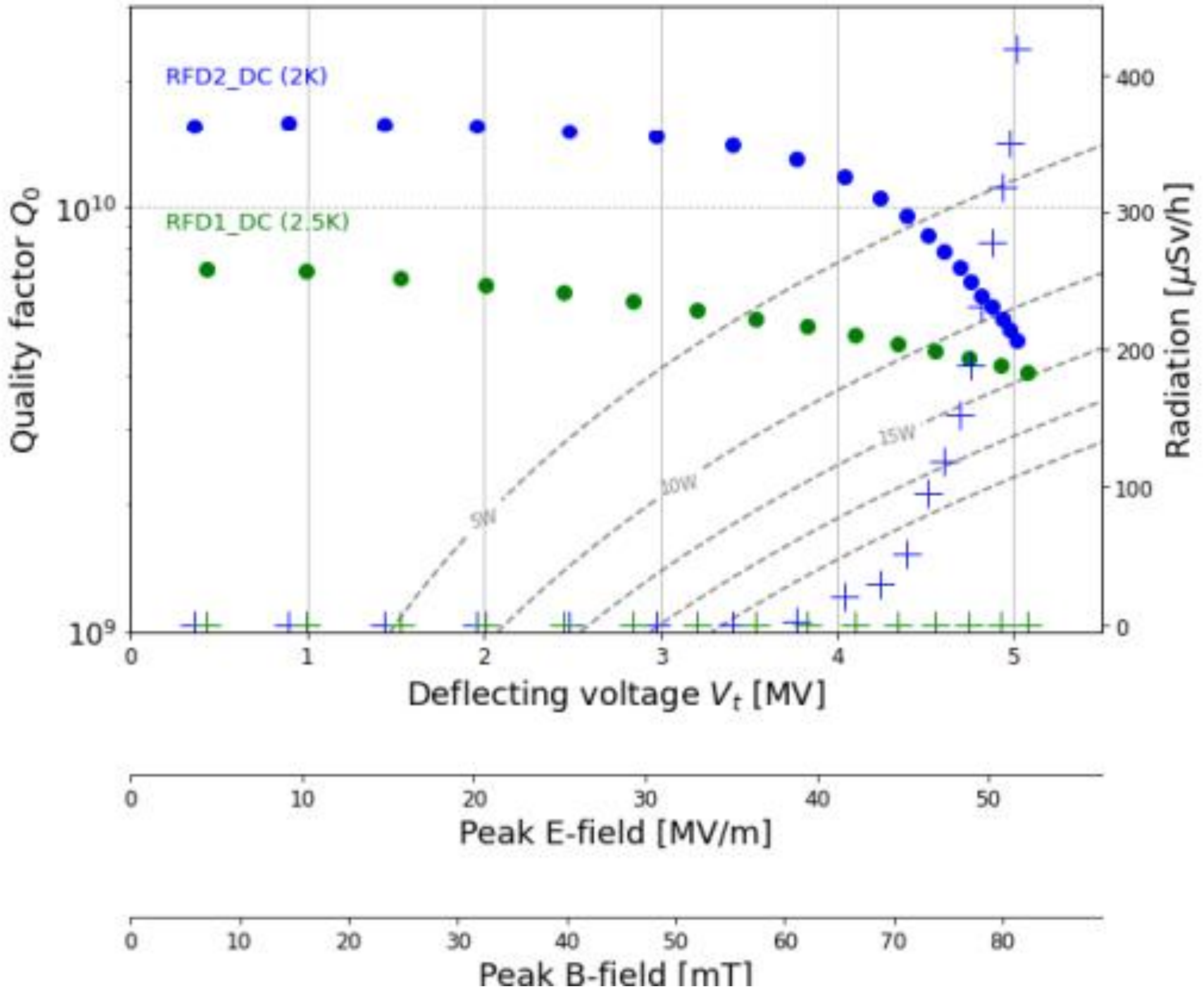




Part 4: Measured Results from RFD Crab Cavities

RFD Cavities – Dressed Cavity Qualification

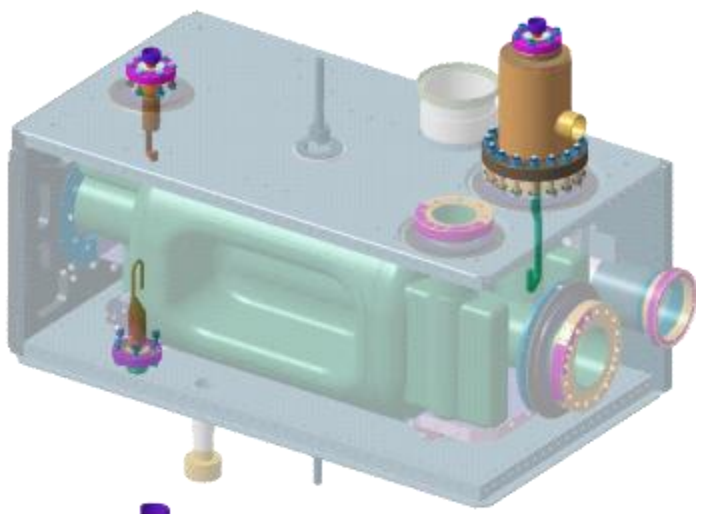
- Test purposely stopped at 5MV; no quench observed
- **RFD1:** measured at 2.5K with active pumping due to the leak
  - Due to the leak, the leaky flange was tightened at warm
  - Radiation not observed → 3xHPR
  - Stable results also after the thermal cycle (~20K)
  - Surface resistance: ~14nΩ→ R_{BCS} ~2nΩ @2K and ~9nΩ @2.5K (ΔR_{BCS} ~7nΩ) → R_{res} ~7nΩ
- **RFD2:**
  - Residual resistance ~6.5nΩ

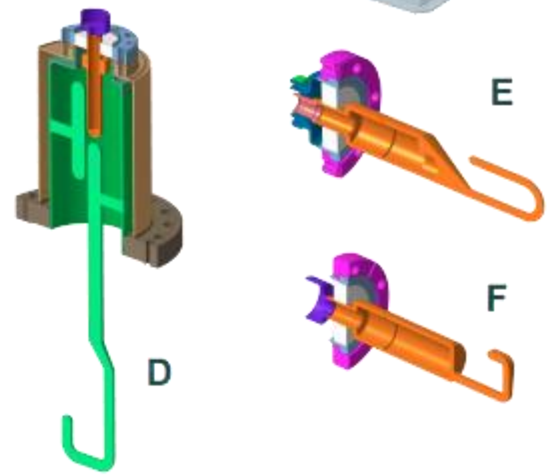


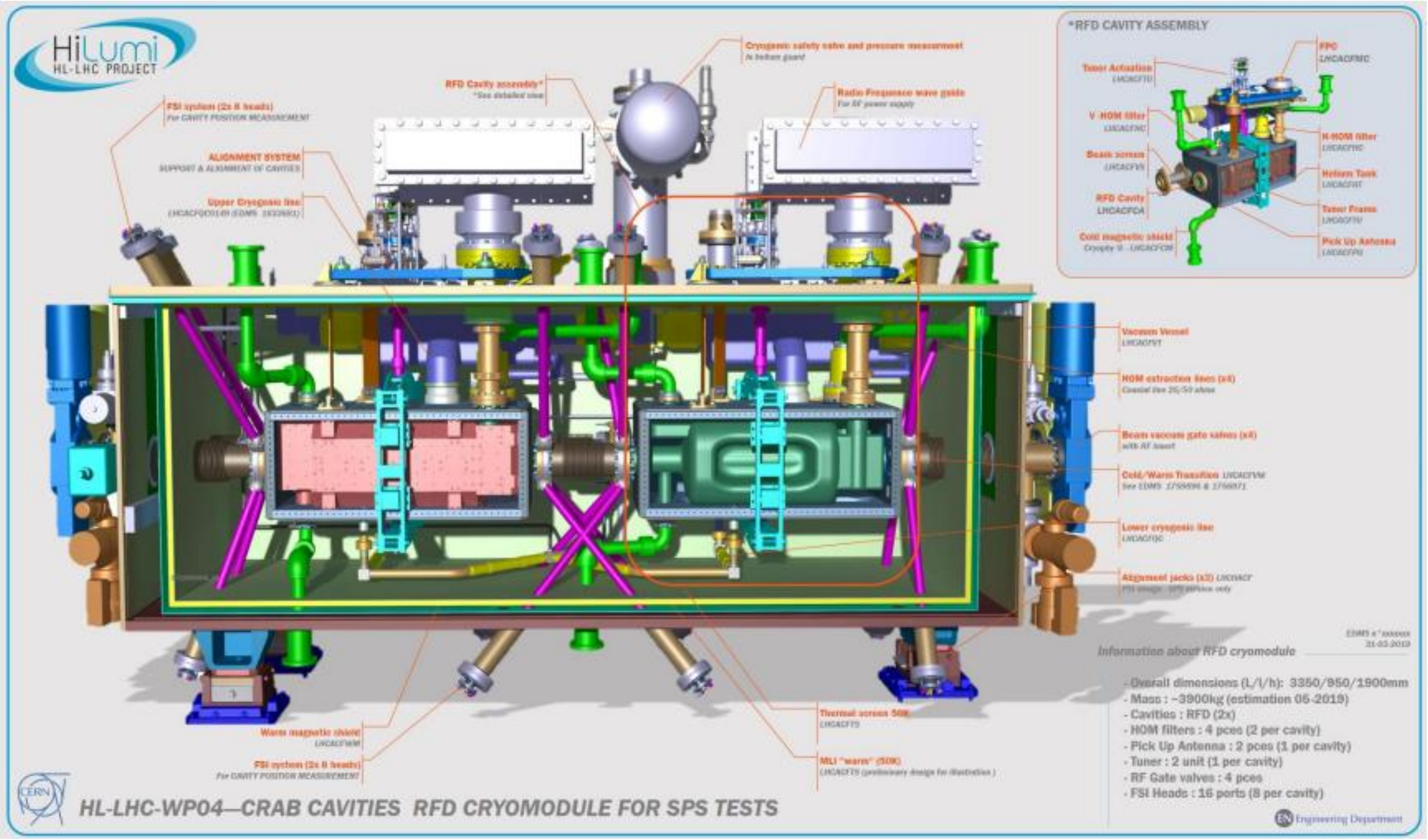
Slide courtesy of K. Turaj

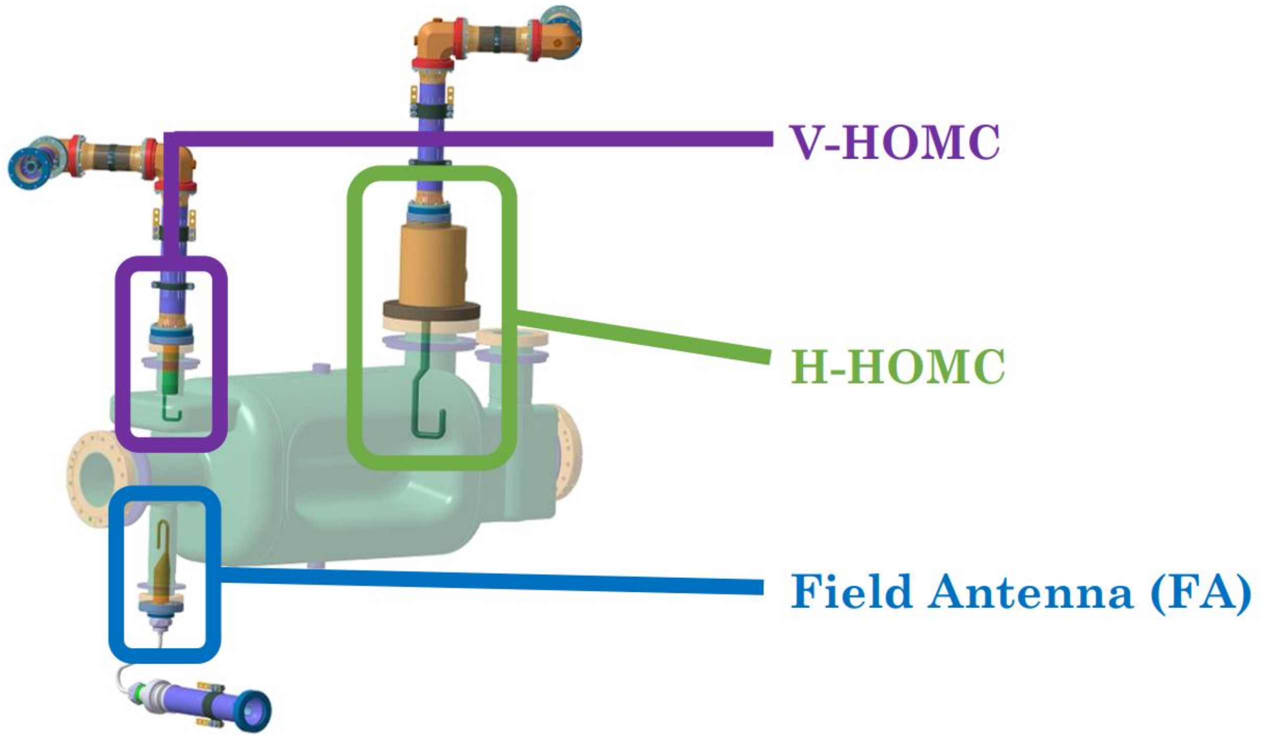
Current Status of RFD Cavities at CERN

- Main RFD contract is handled by the US collaboration (not covered here)
- Dressed cavities integrated into a prototype cryomodule by STFC Daresbury Laboratory (UK)
- Cryomodule shipped to CERN for testing at 2K in horizontal test bunker M7



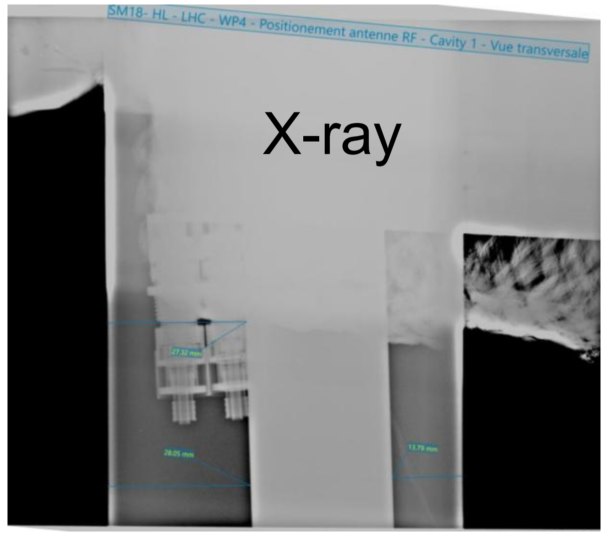


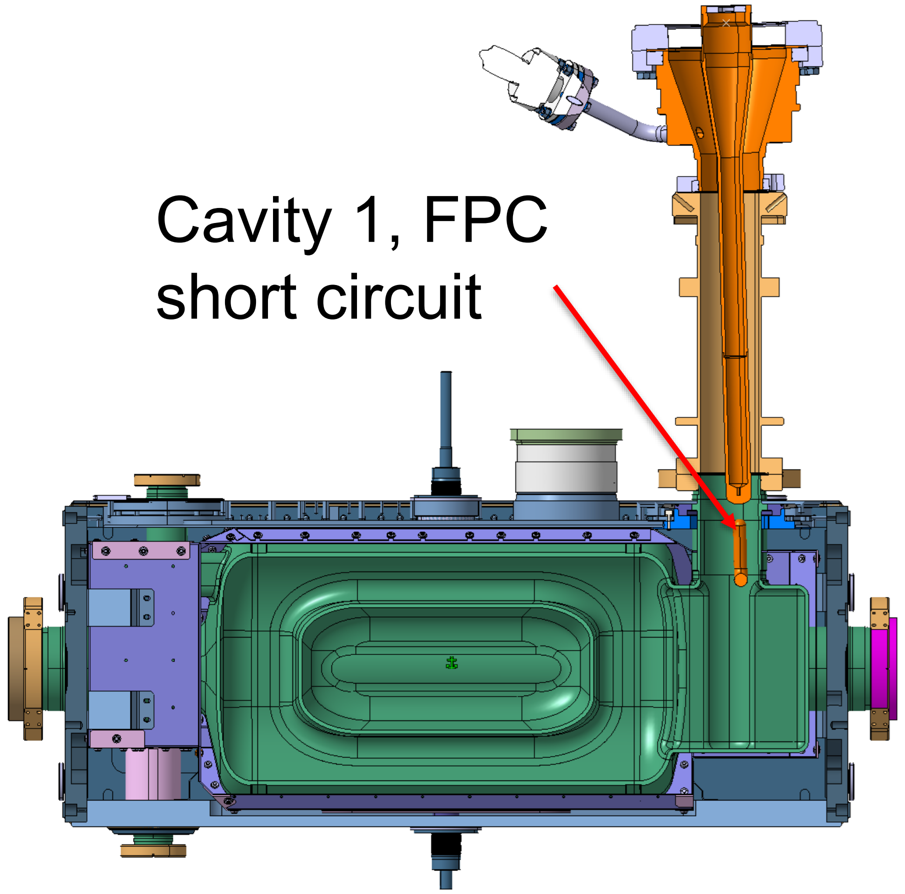




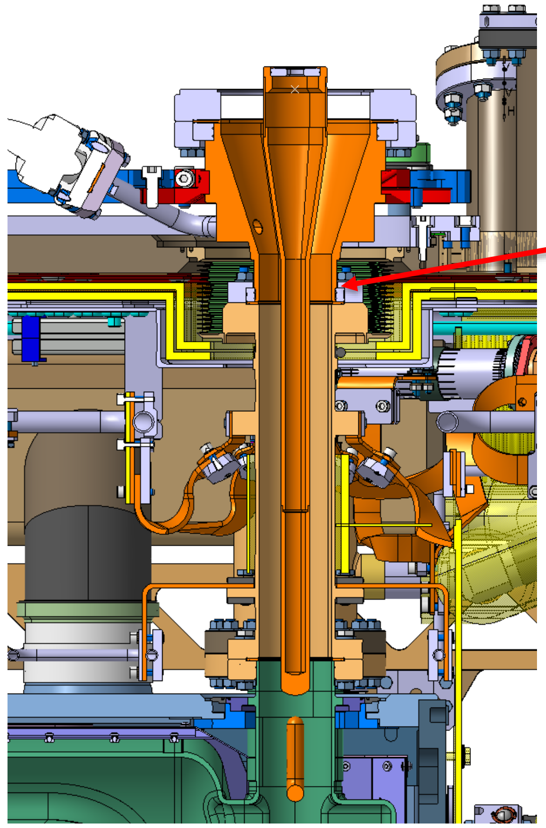
Outcomes

- **2 critical NCRs** postponing the installation at SPS (YETS 24-25).
  - Tilt of the FPC on CAV 1 – short circuit.
  - Tilt & Vacuum leak on the FPC of CAV 2.





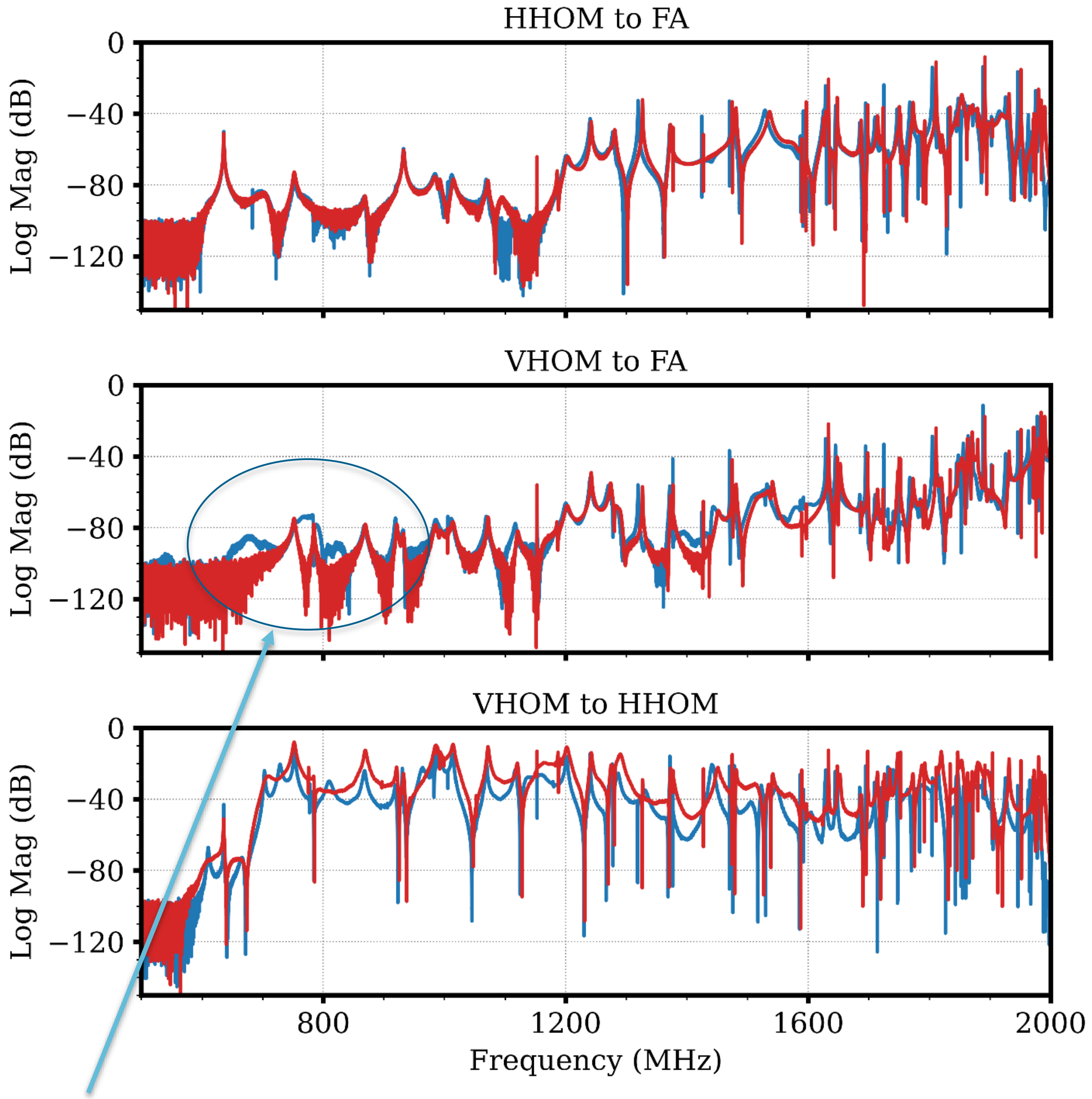
NCR: EDMS 2995980



NCR: EDMS 2995891

RFD Cryomodule Testing at CERN

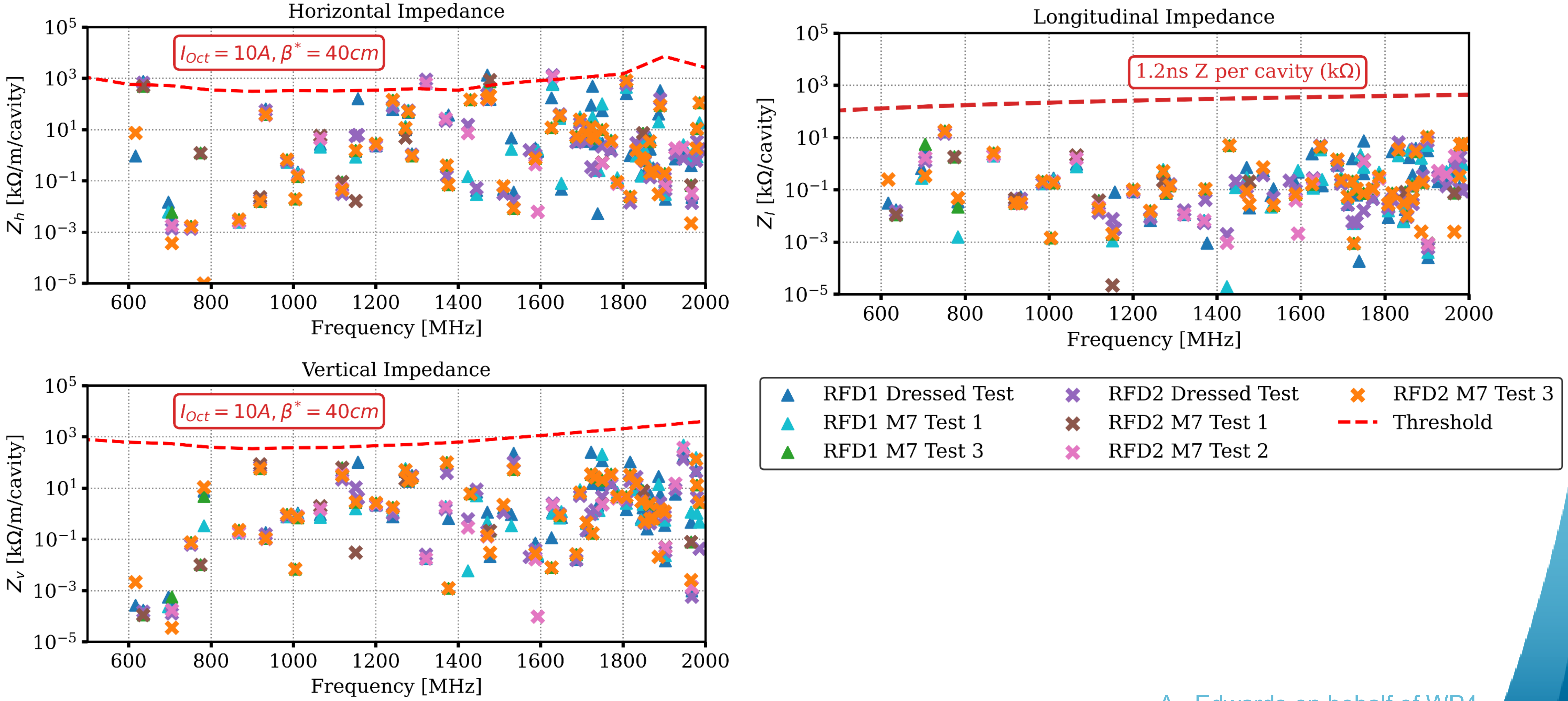
- 2K COOLDOWN 1 – Nov/Dec 2023
  - Check of cryomodule integrity
- 2K COOLDOWN 2 – March/April 2024
  - After repair of leak on RFD2
  - RFD2 conditioned
- 2K COOLDOWN 3 – August/Nov 2024
  - After FPC angle repair on RFD1
  - Both cavities conditioned
- Installation SPS – Dec 2024



Broadband features due to NCR on FPC

2K HOM Measurements on RFD Cryomodule

- Due to repeated cold test the HOMs could be measured several times
- Compared with results from dressed cavity tests



Impedance at 2K of RFD1 & RFD2

- Looking into behavior of critical modes for RFD
- Measurements taken through the series of cryomodule tests and tracked
- Large spread in Q for RFD1, thought to be due to invasive repair work
- Also, the same limitation placed onto fundamental power leakage through HOM couplers (same for DQW & RFD(

RFD (dressed)

File provided by Z. Li (SLAC): ImpedanceTable_RFDwFT_20191118_Zenghai.csv (19/11/2019)

EDMS 2009911 [1], model at 2K, windows with ε_r = 9.6

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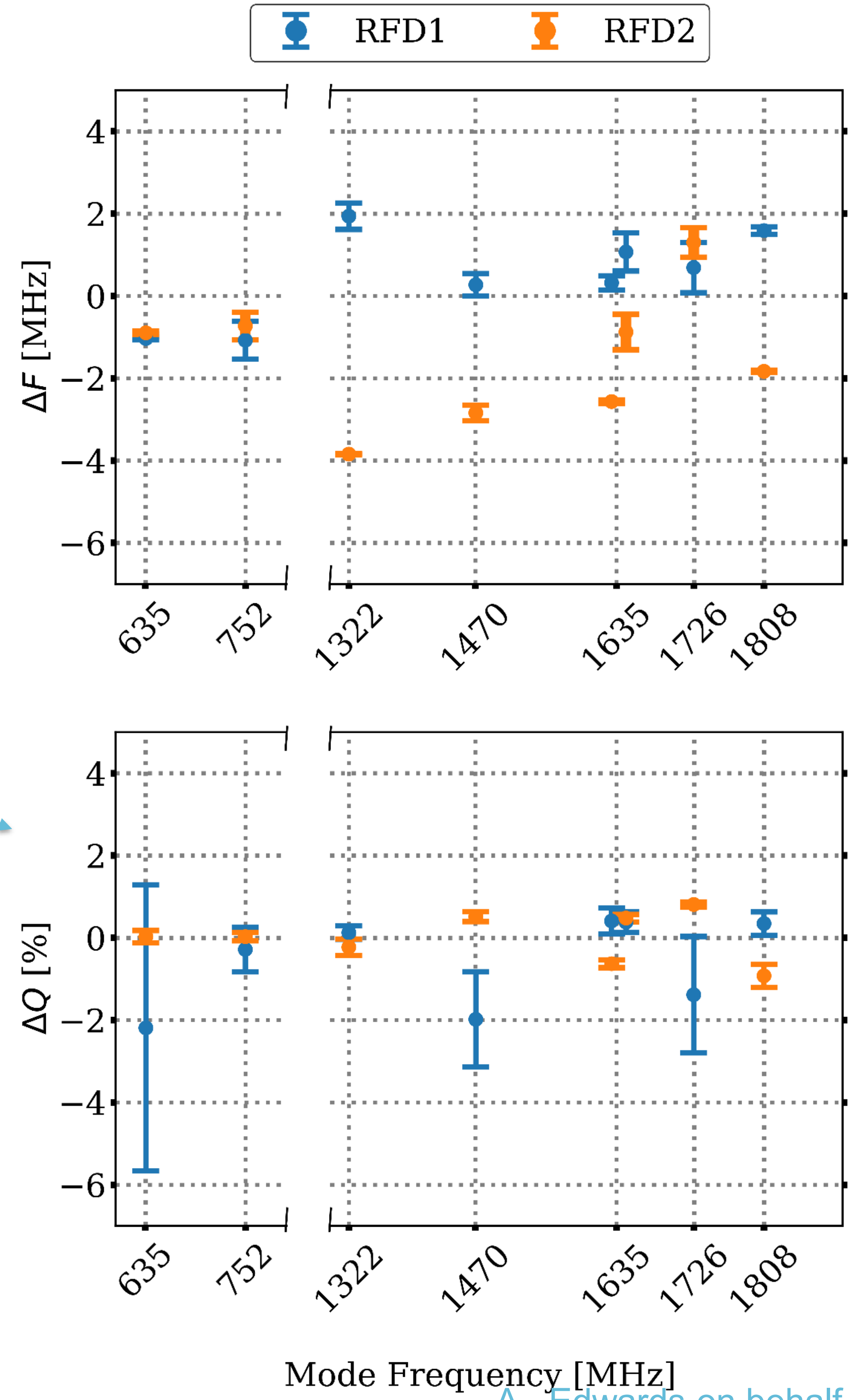
1726	39216	11	**355**	0	
1808	7574	2	**389**	0	

$$P\ (400 \pm\ 0.15\ \text{MHz, VT} = 4.1\ \text{MV})\ \leq 6.7\ \text{W}$$



SPS-prototypes Cryomodules

- DQW: 2018-2023 operation, Removed in 2023/24 YETS
- RFD: Installed in the SPS in YETS 2024-25

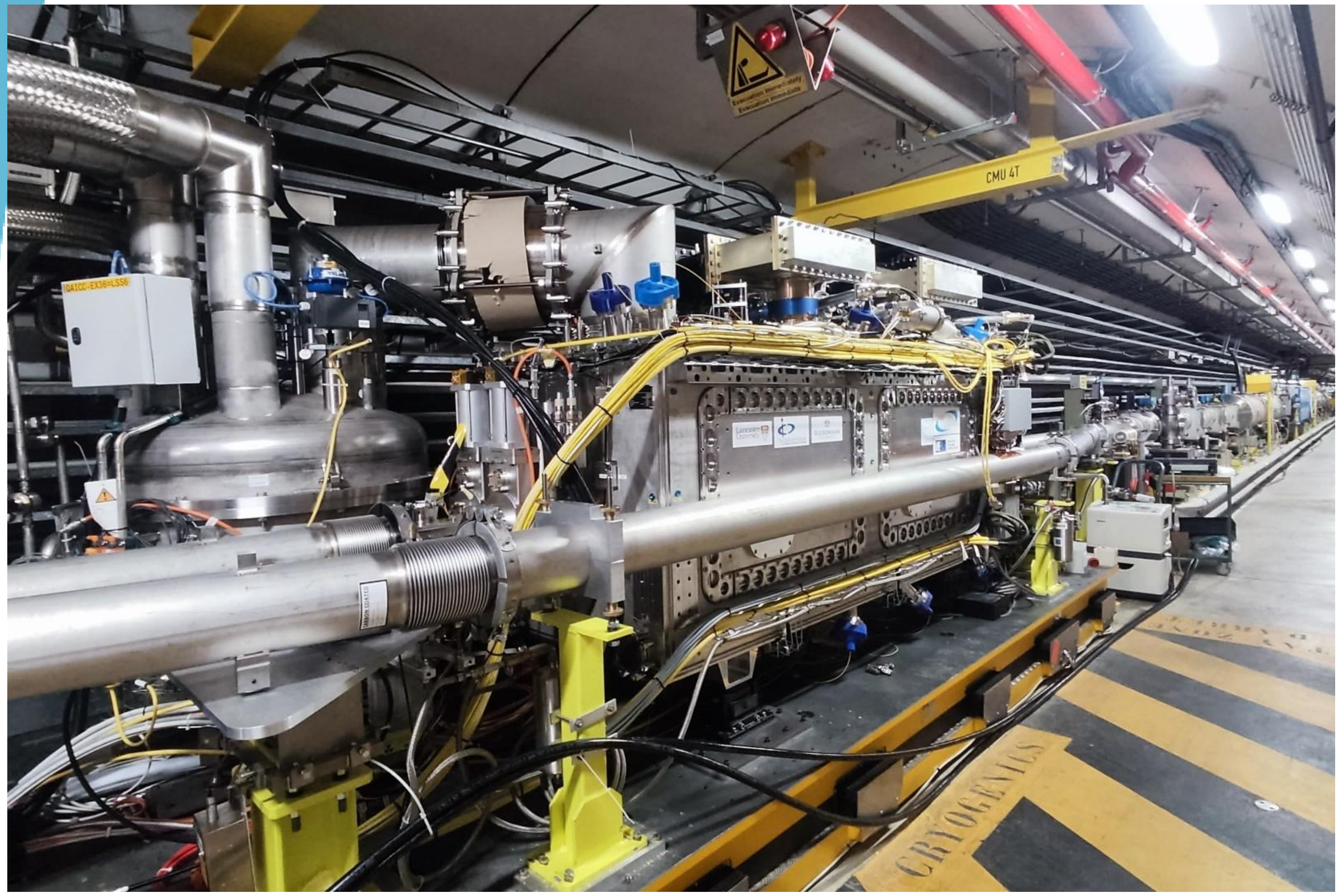
SM18 to SPS-BA6

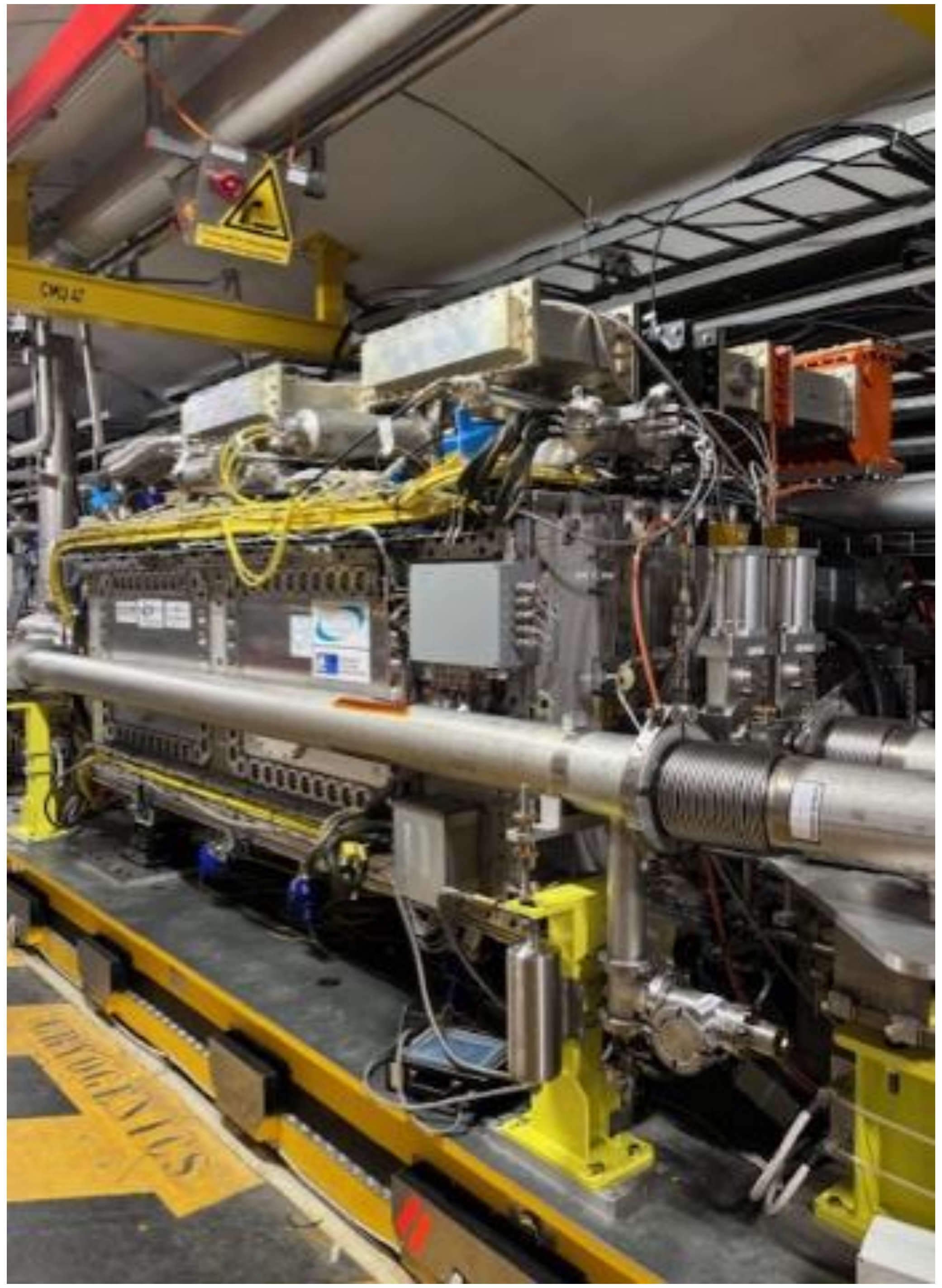
Entering SPS-BA6

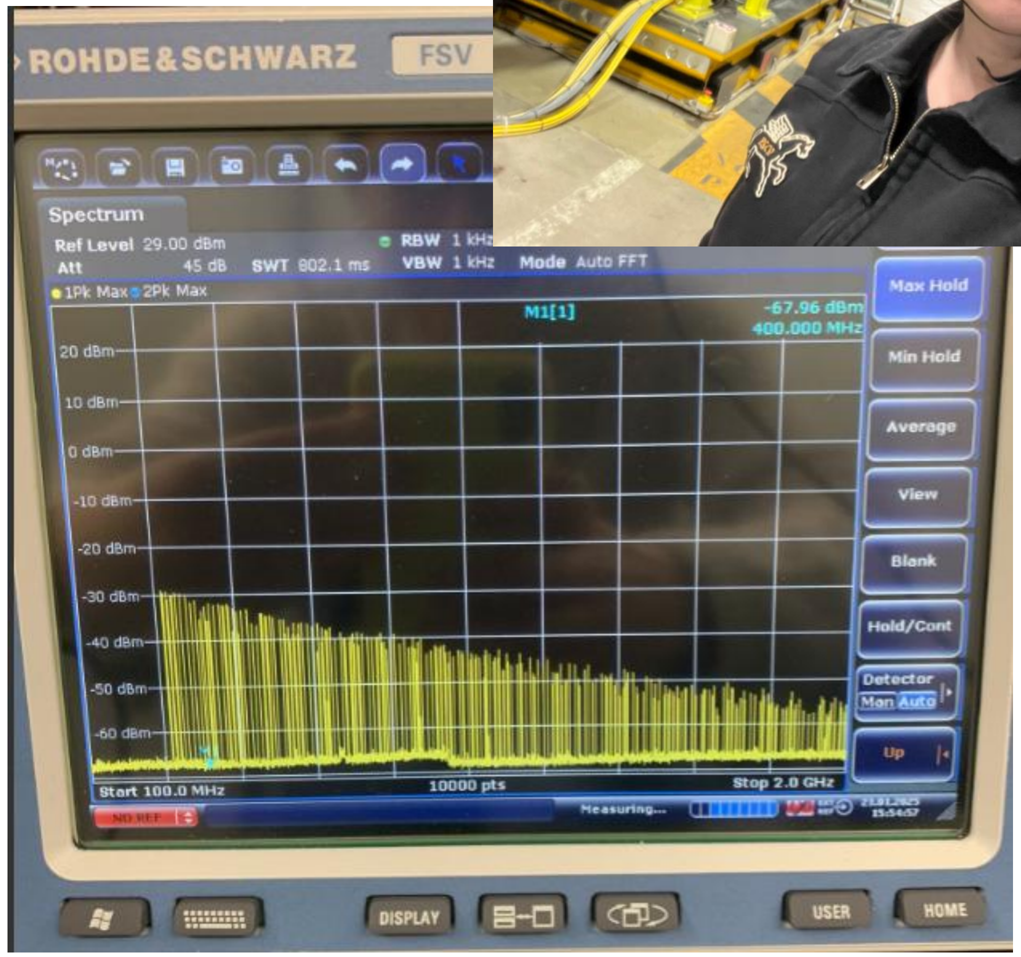
Installed on the table

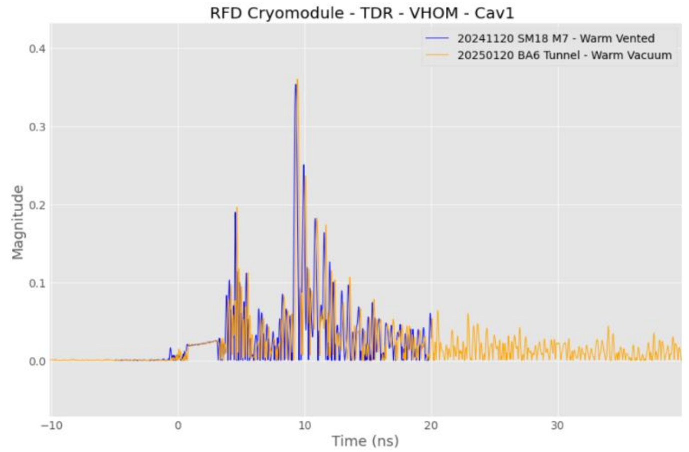
RFD Cryomodule installation into SPS

- After leaving SM18 horizontal test bunker the cryomodule was installed into the SPS during the maintenance period of 23/24









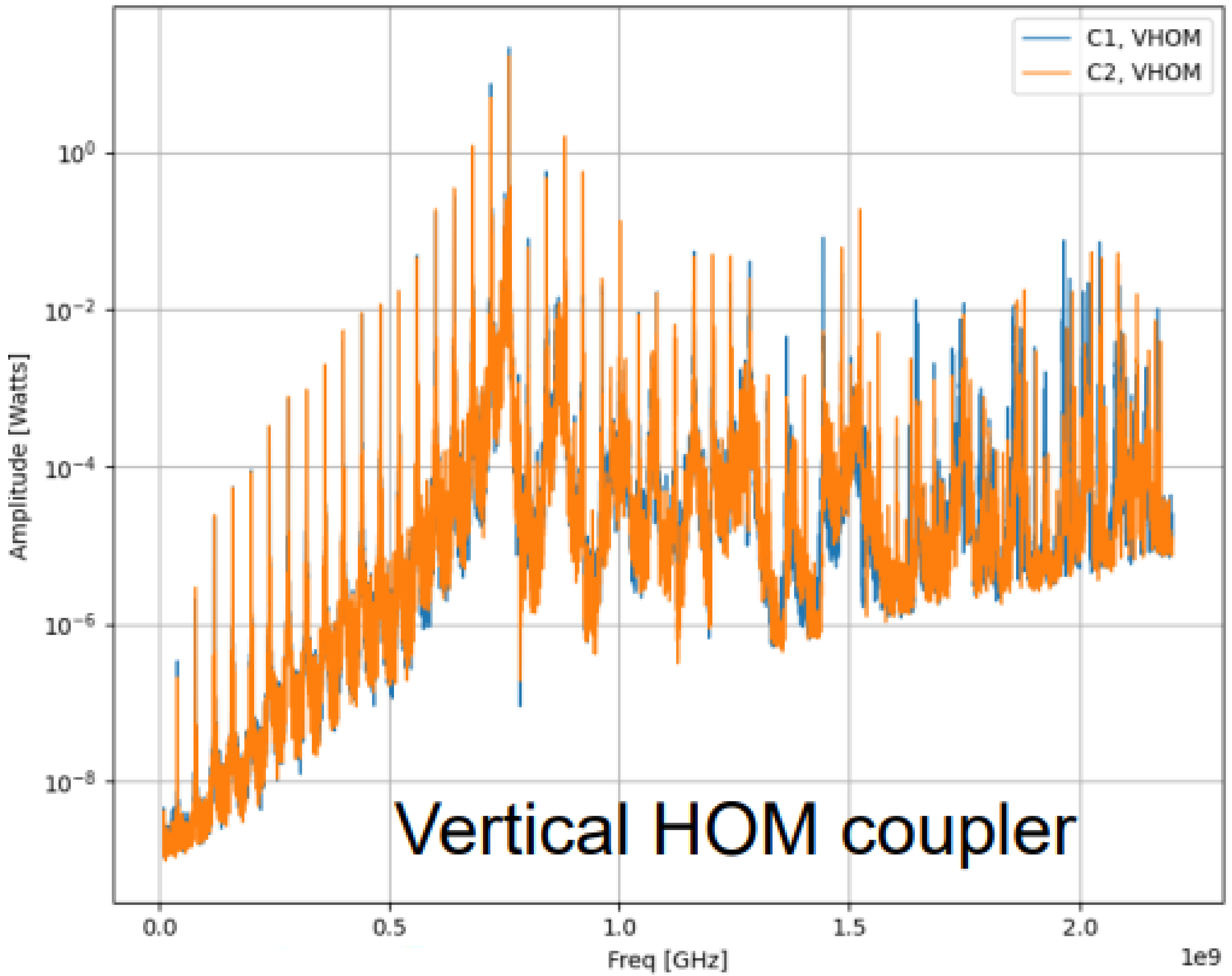
Cable	Description	Attenuation at 400MHz [dB] {+-0.005dB}
3602833	FWD-CC1	-4.57
3602834	ANT-CC1	-4.64
3602836	REV-CC1	-11.88
3602837	HOM3-CC1	-11.98
3602838	HOM1-CC1	-11.96
3602839	HOM2-CC1	-12.11
3602840	FWD-CC2	-4.53
3602841	ANT-CC2	-4.66
3602843	REV-CC2	-11.91
3602844	HOM3-CC2	-12.06
3602845	HOM1-CC2	-12.02
3602846	HOM2-CC2	-12.10

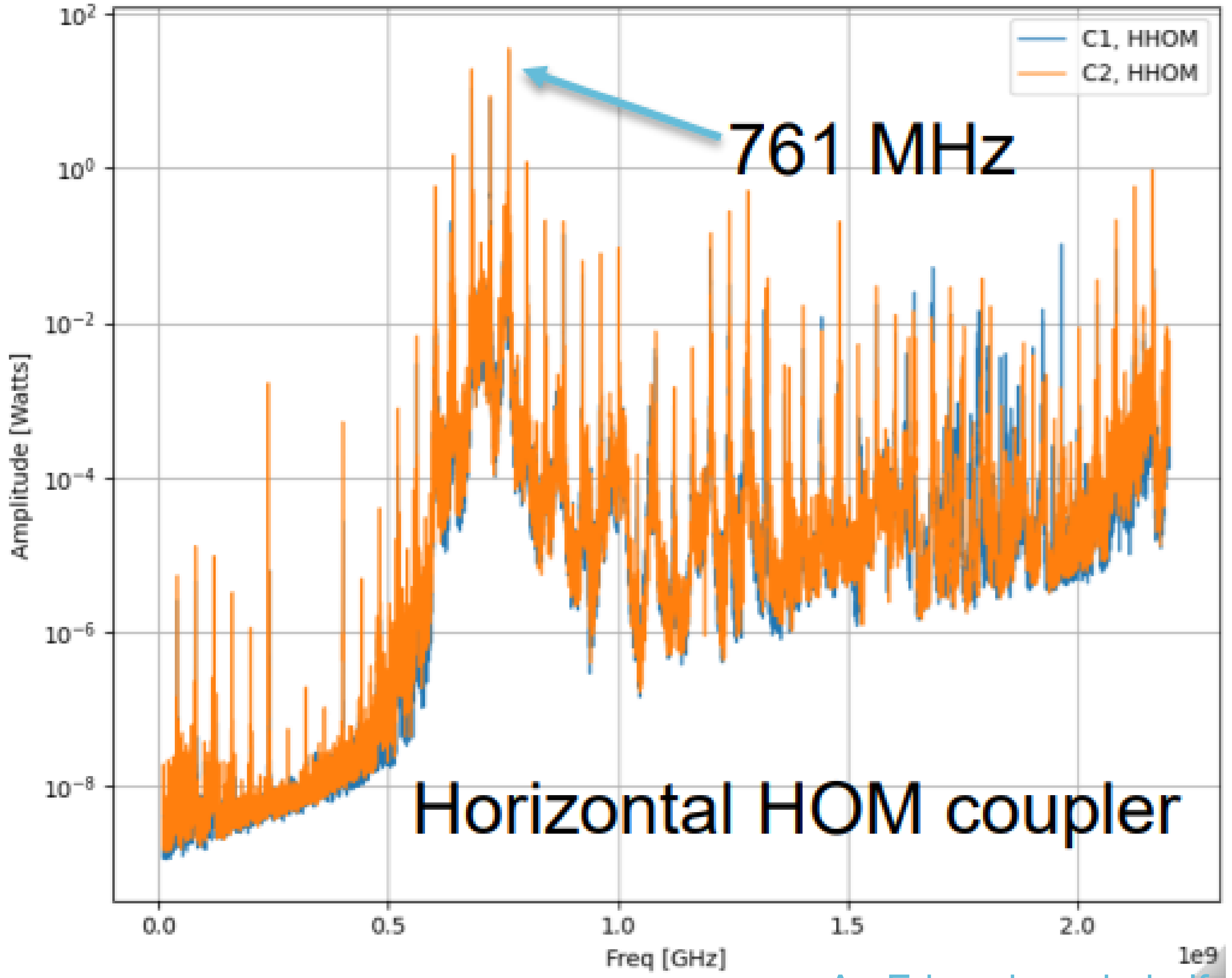
HiLumi HL-LHC PROJECT

Preliminary Results from SPS!

HOMs (450 GeV, 72b x 2batches)

- Highest impedance mode at 761 MHz as expected.
  Measured power 32 & 35 W in C1 & C2 (expected < 40 W).





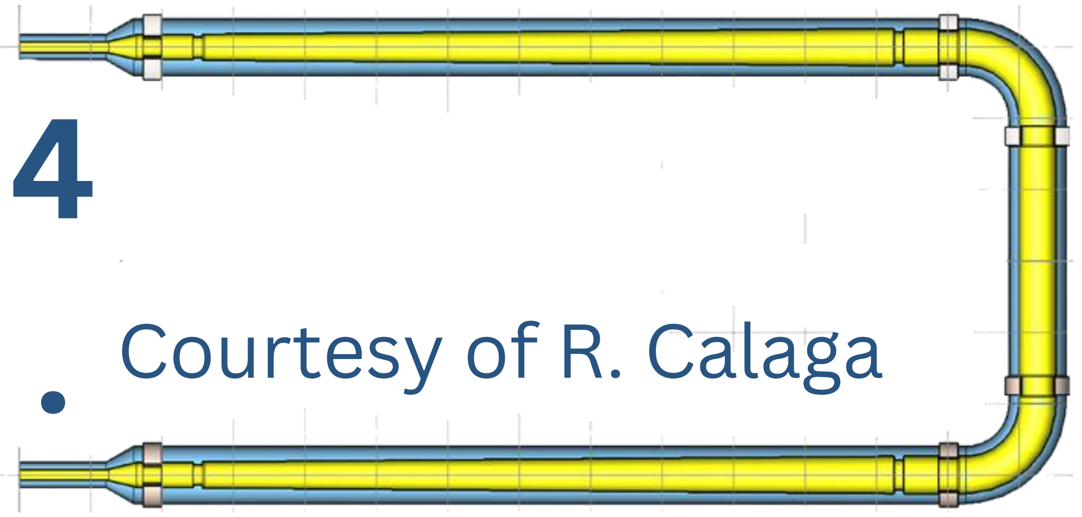
Slide courtesy of R. Calaga

Part 5: Qualification of RF Ancillaries: Impedance Adapters & RF Lines

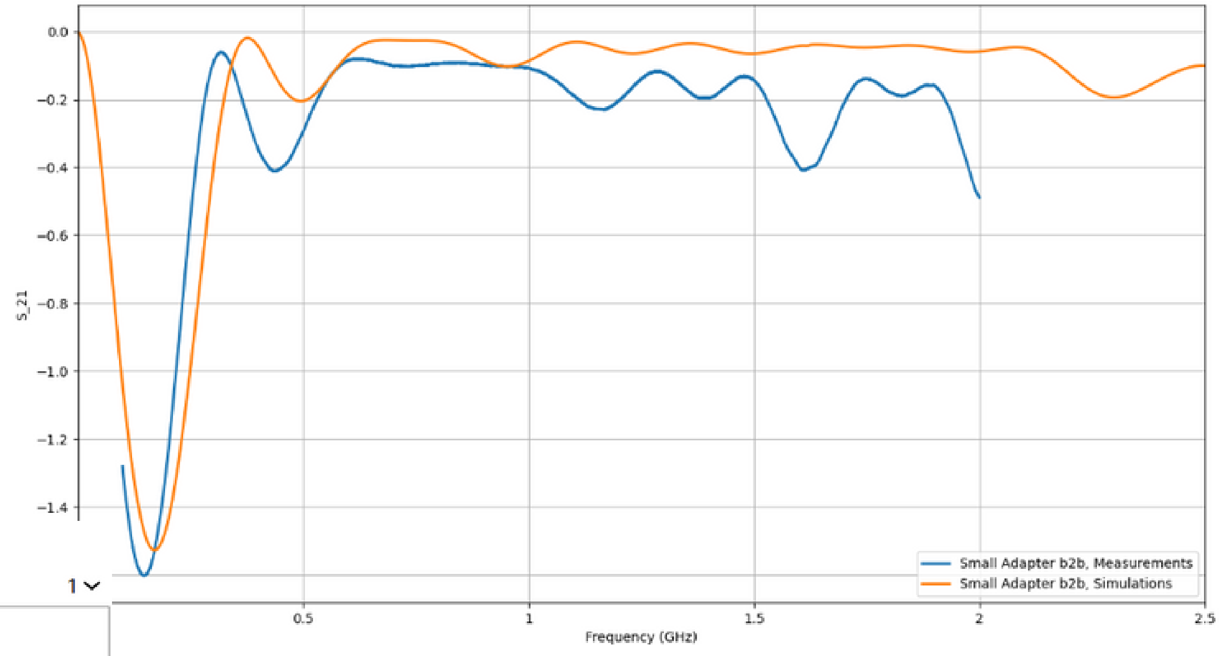
Part 2 - Qualification RF Lines Summary

1. **S21 transmission measurements taken 'back-to-back' is found to be most robust & reliable measurement**
2. TDR and gated TDR attempted
3. Z11 & Z22 measurements also developed
4. Simulations developed from drawings
5. Issues corrected with flex cable & 'cone' in small cold test adapter

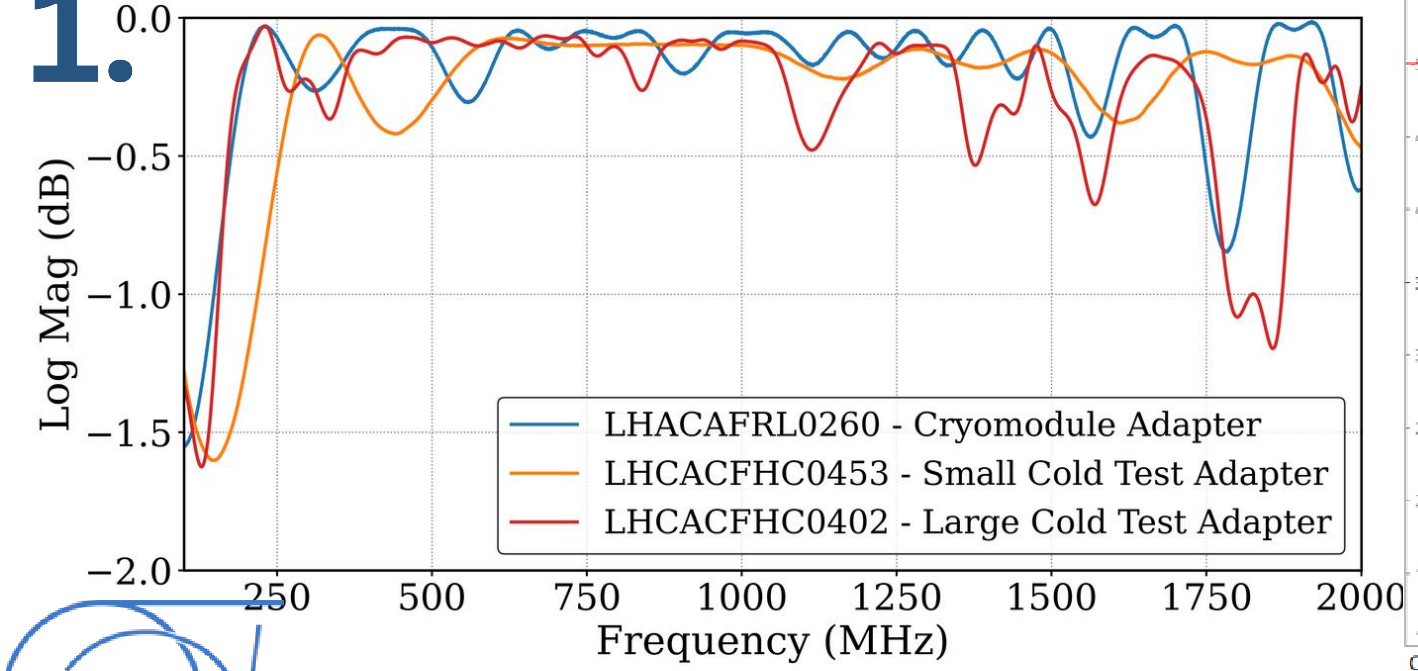
4.



Courtesy of R. Calaga



1.



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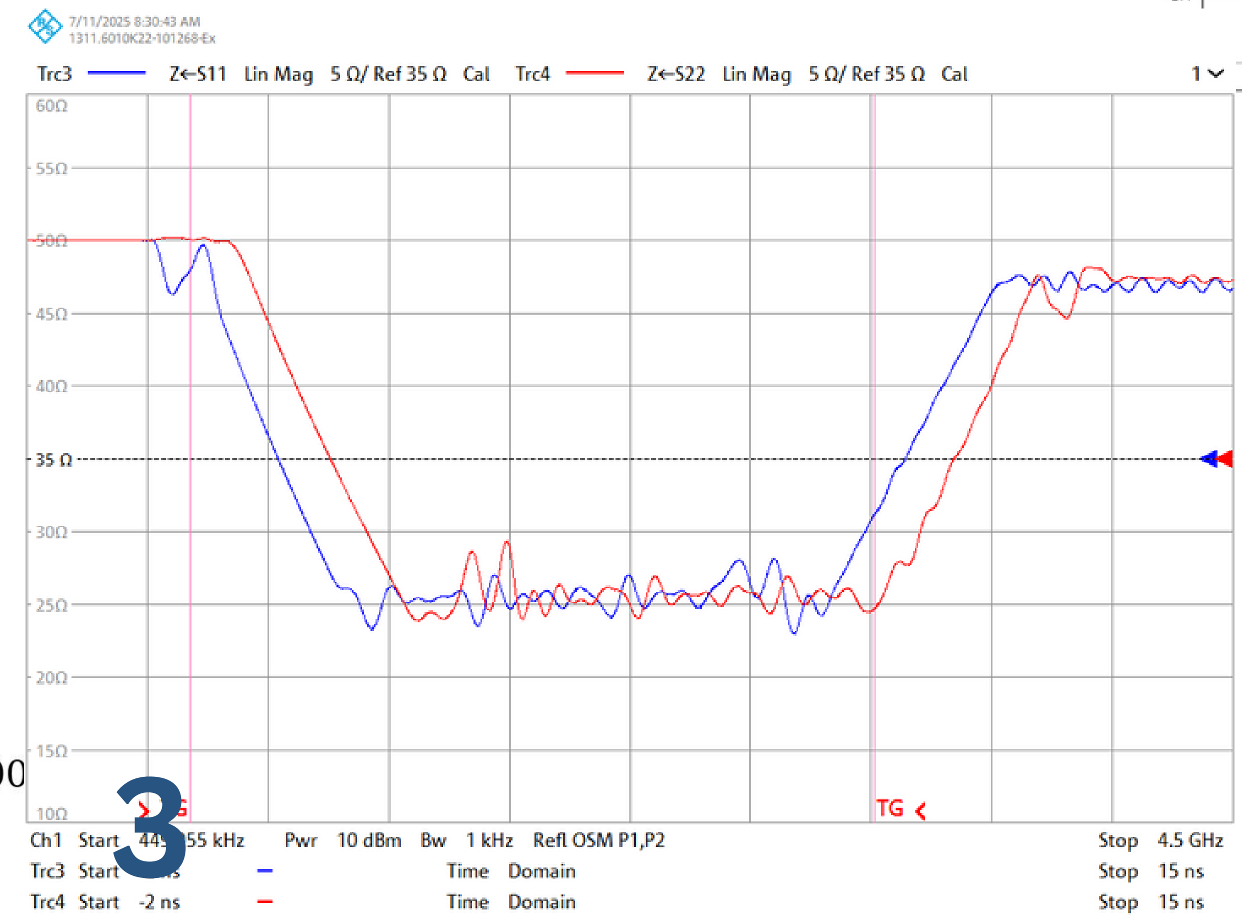

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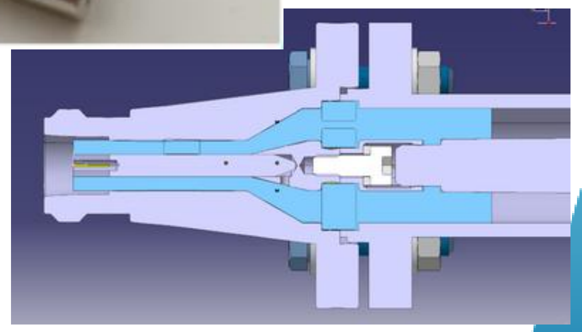
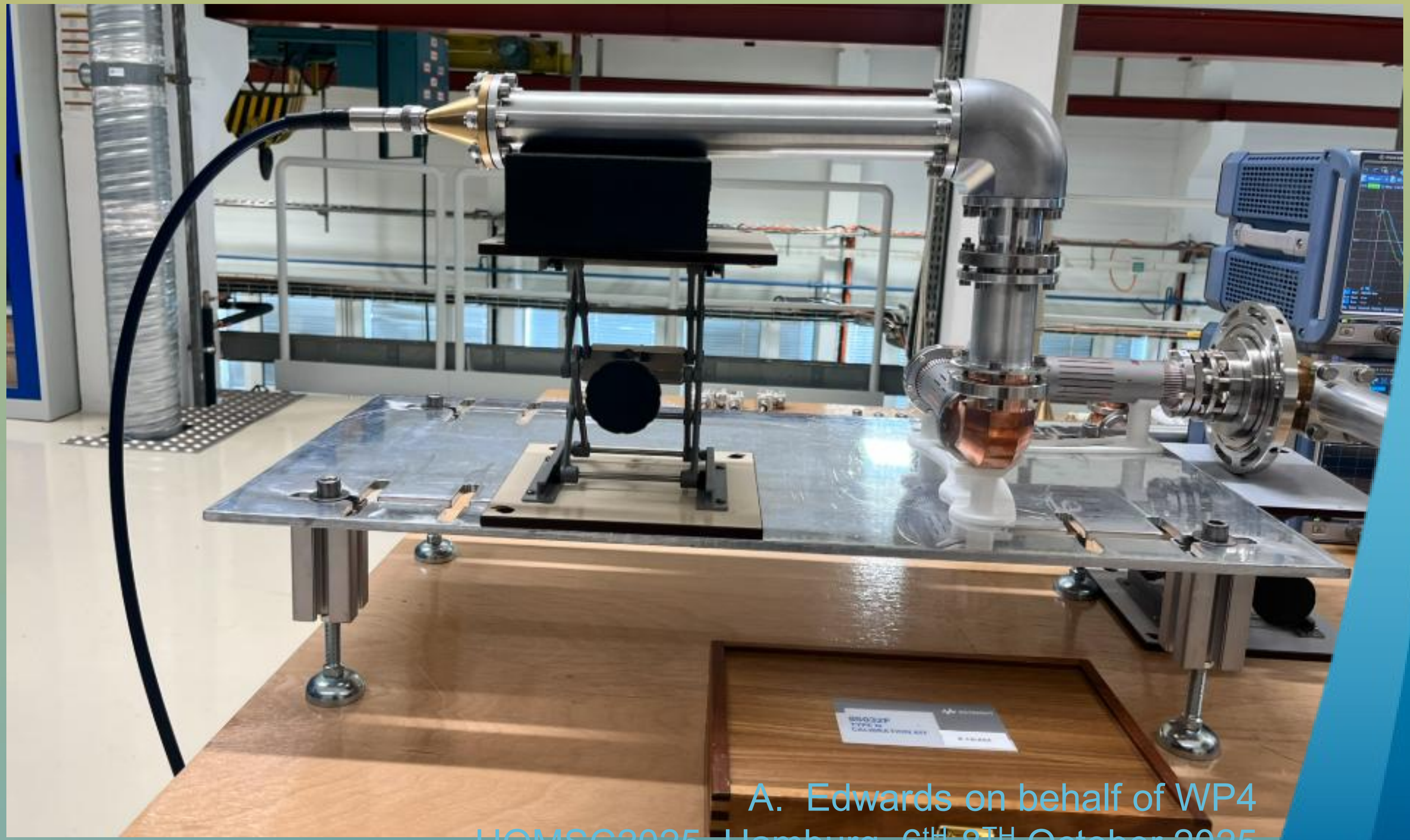


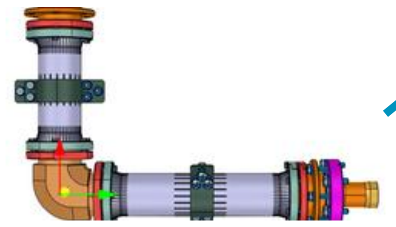
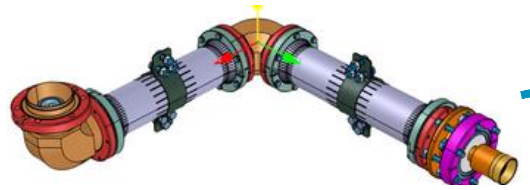
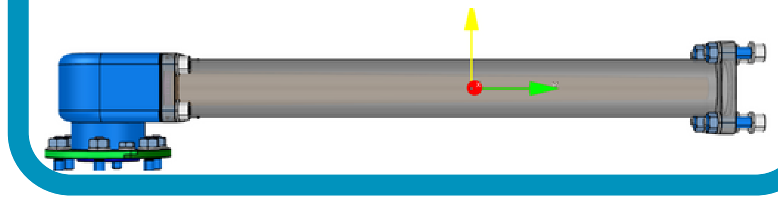
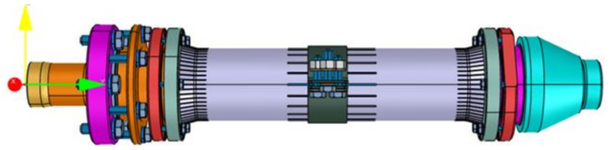
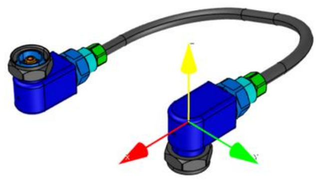
Part 2 - Qualification RF Lines
Internal RF Lines - DQW Cryomodule

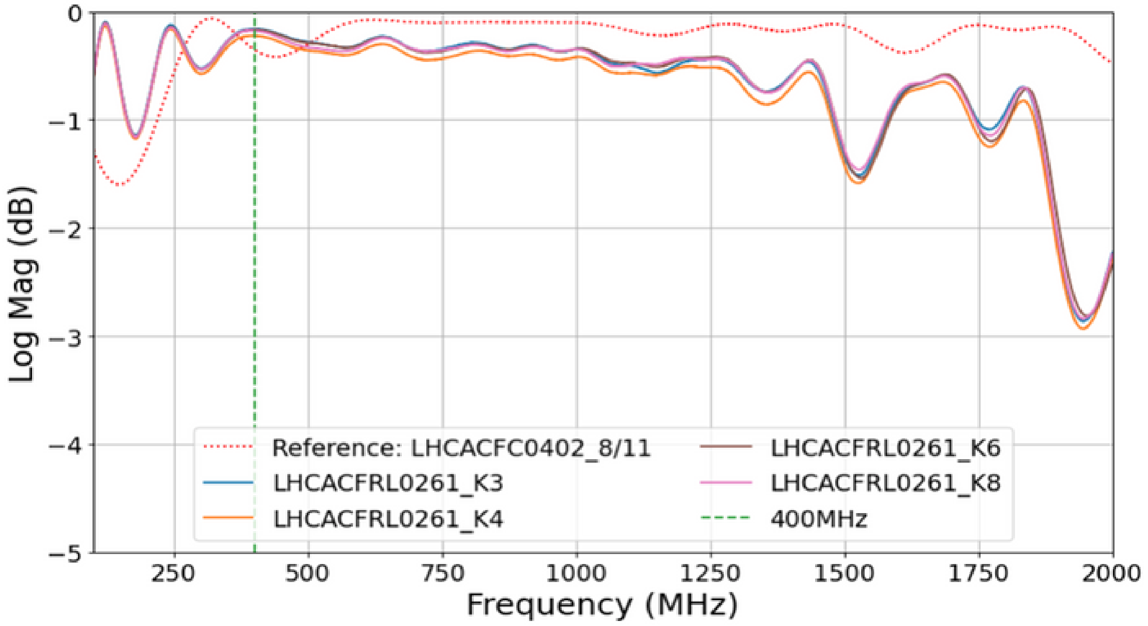
S21 of two small adapters ‘back-to-back’ is always used as reference

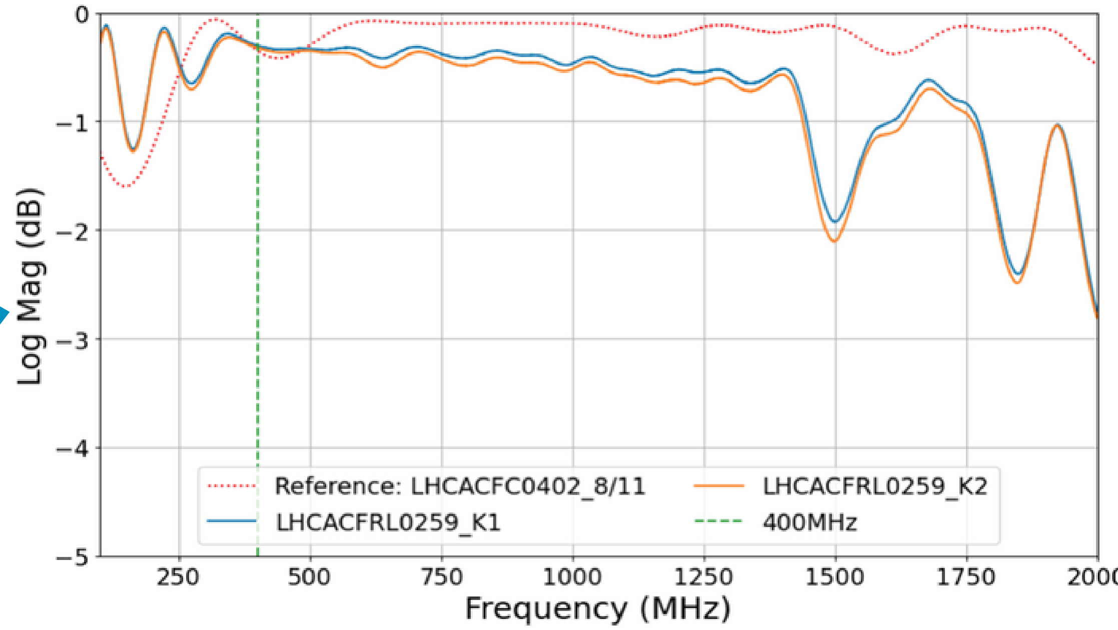


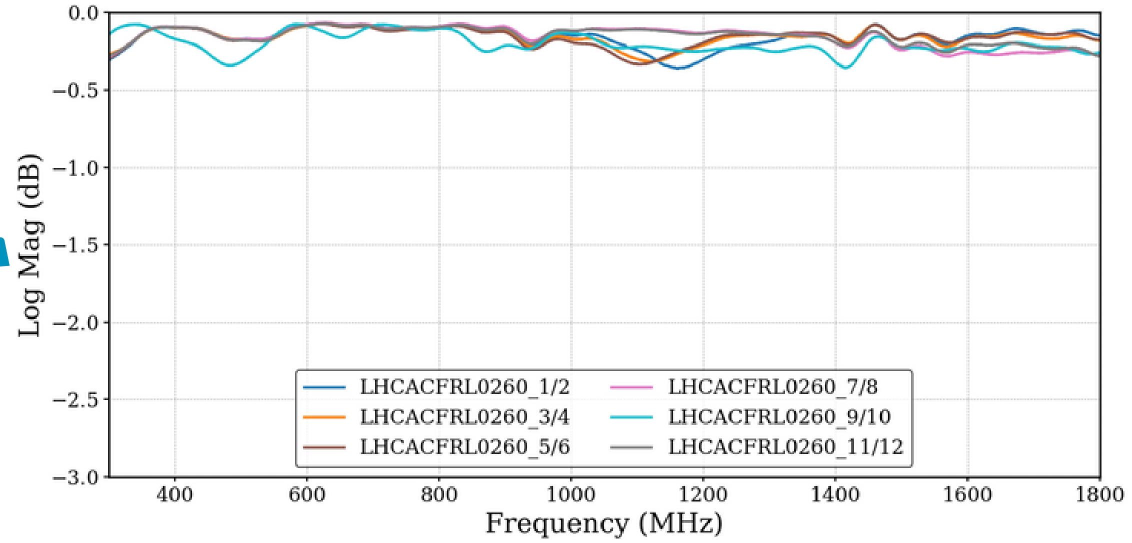
Part 2 - Qualification RF Lines

Internal RF Lines - DQW Cryomodule

CDD	Quantity	
LHCACFRL0261	x4	
LHCACFRL0259	x2	
LCHACFRL0260	x10	
LHCACFRL0258	x4	
LHCACFRL0284	x4	







SUMMARY

- HOM couplers for crab cavities for HL-LHC well into production stage and being integrated into cavities and cryomodules
- DQW:
  - First four series cavities HOM behavior is expected from simulation and consistent between cavities
  - Without test box for these couplers the cold test was first opportunity for validation
  - Impedances computed and forwarded for analysis
- RFD:
  - Two cavities equipped with HOM couplers, integrated into cryomodule and currently in SPS
  - HOM couplers also behaving as predicted for this cavity design
- 25Ω Ancillaries chosen for robustness & qualification is underway

CERN

Thankyou!

This is the work of many colleagues across many departments inside CERN and from our other collaborators in US-AUP, HL-UK and STFC-UK