HL-LHC Crab Cavities, Recent Progress

R. Calaga on behalf of HL-LHC WP4 & Collaborations
CERN

- DQW-SPS operation
- RF Dipole module for SPS tests
- Status of series production including collaborations

14 September 2022

HL-LHC Crab Cavity System

HL-LHC will squeeze the IP beam sizes further to increase integrated luminosity reach by factor 10. This necessitates a doubling of crossing angle to minimize the effect of long-range beam-beam.

The crossing angle implies a reduction in peak & integrated luminosity

Using superconducting compact RF crab cavities (ATLAS-H + CMS-V) geometric angle is compensated to recover up to 70% of the lost peak Luminosity

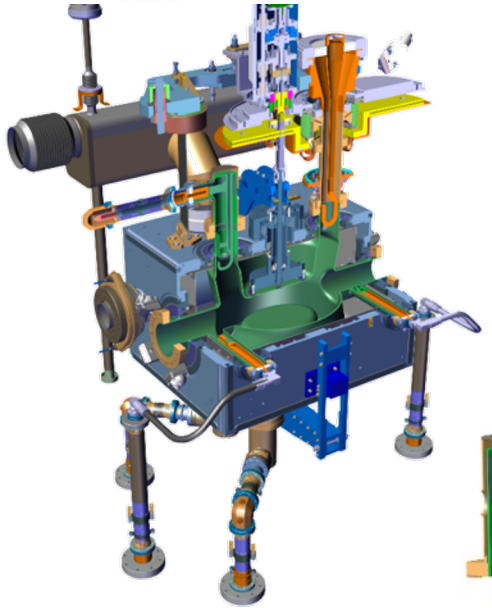
$$\Phi = \frac{\sigma_z}{\sigma_x}\left(\frac{\theta_c}{2}\right)$$

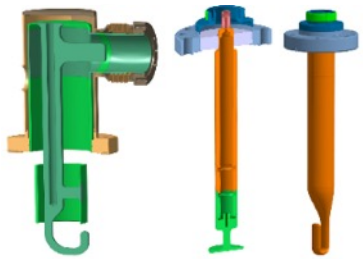
$9\ cm$

$\sim 8 - 9\ \mu m$

HL-LHC Cavity Geometries

Double Quarter Wave





$$f_0 = 400\ \text{MHz}$$

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

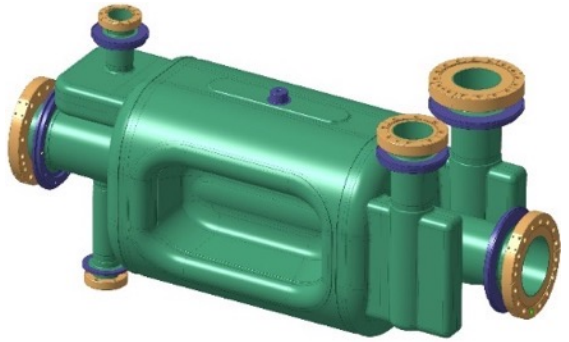
$$(E_p, B_p < 40\ \text{MV/m}, 70\ \text{mT})$$

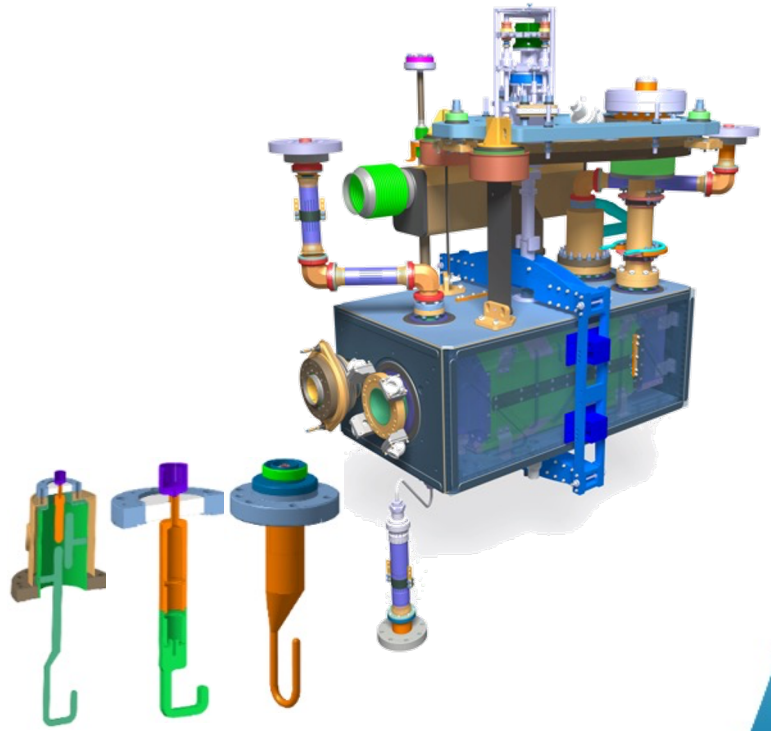
$$\text{Beam aperture} = 84\ \text{mm}$$

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

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

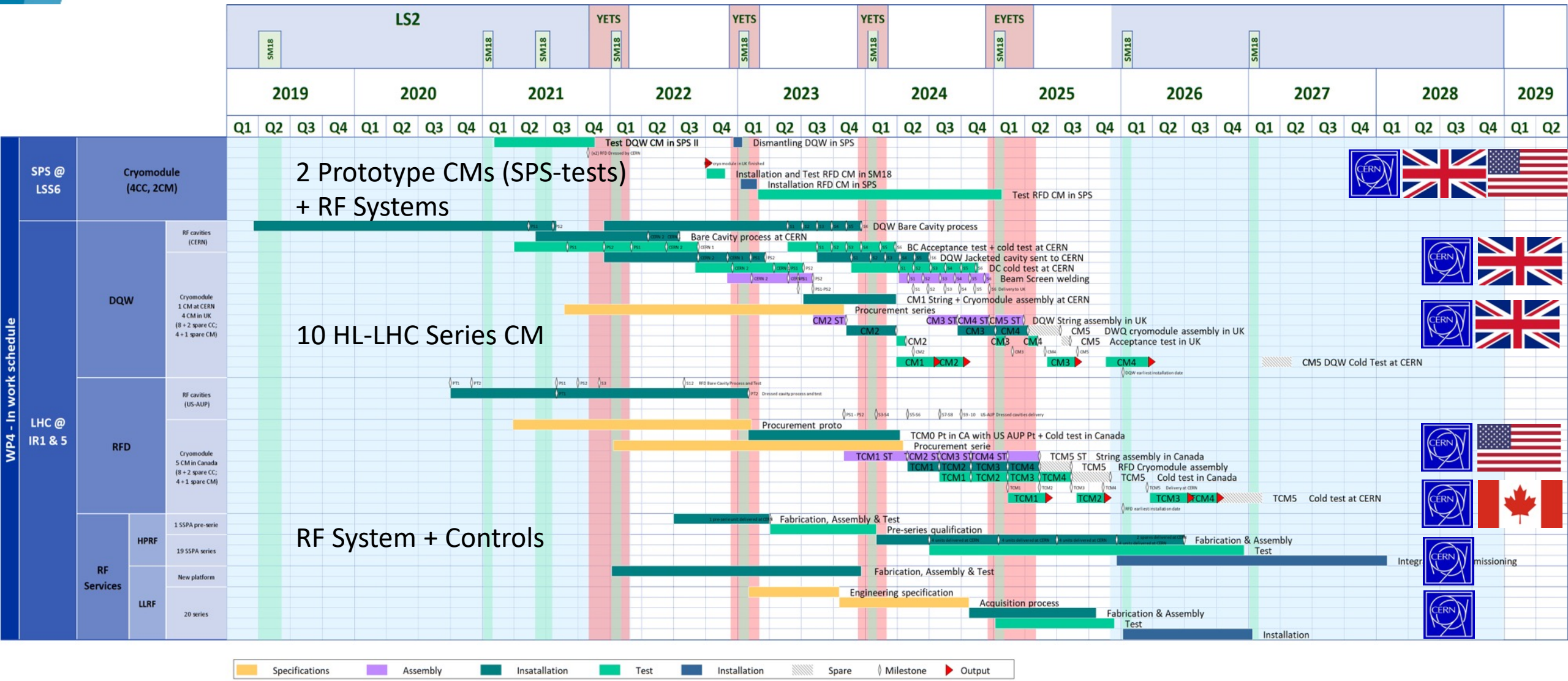
RF Dipole





*Engineering spec: 4.1 MV dressed for 20% margin

Masterplan of WP4



Timeline, Crab Cavities

High Power RF system not shown below

2018	2019	2020	2021	2022	2023	2024	2025	2026	2027

DQW CM SPS-tests

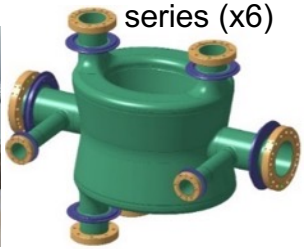
RFD CM SPS-tests

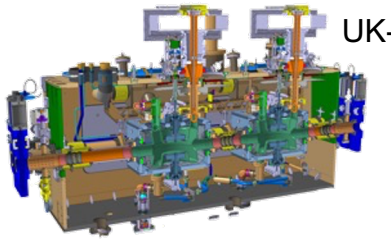
USAUP-RFD proto (x2)

RI-DQW pre-series (x2)

CERN-DQW series (x2)

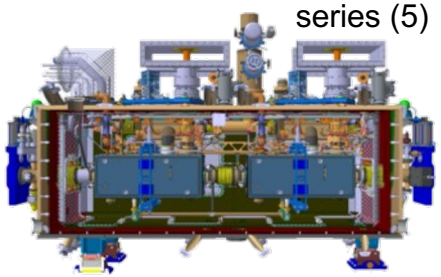
RI-DQW series (x6)





UK-CERN DQW CMs series (4 + 1)

Canada-CERN RFD CMs series (5)

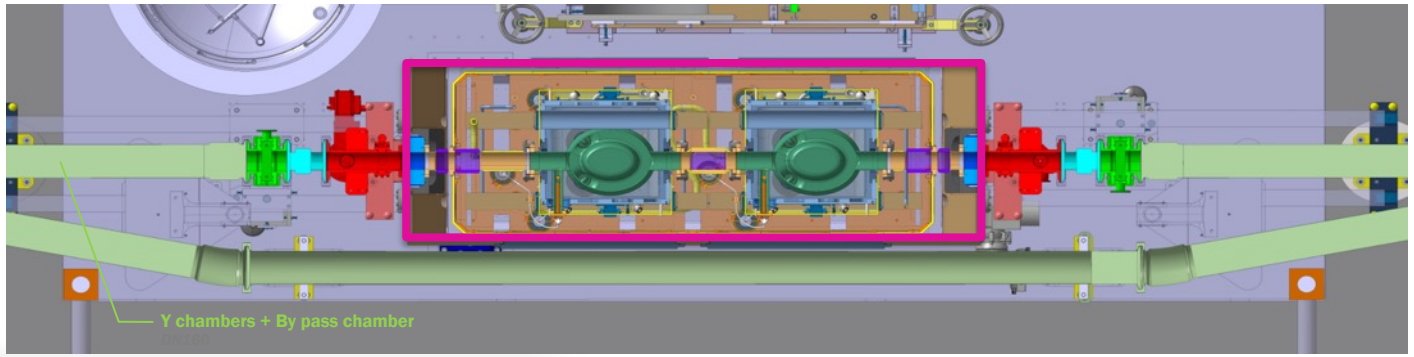


USAUP-RFD pre-series (2)

USAUP-RFD series (10)

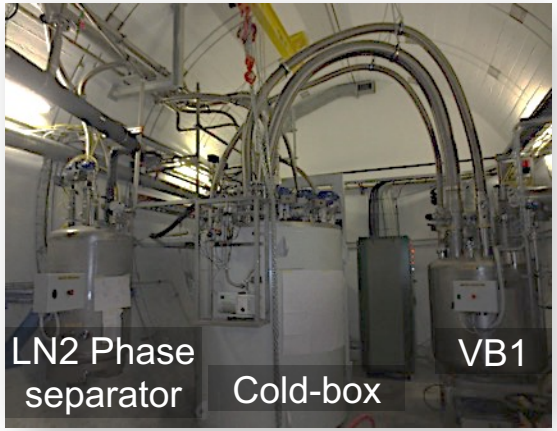
SPS as test bench for crab cavities

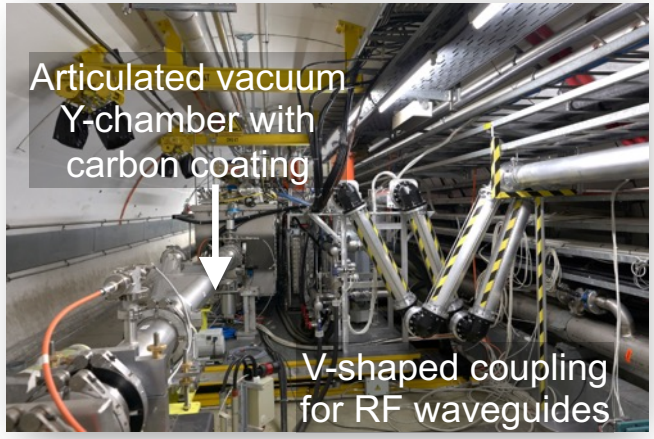
- Goal: Install 2-cavity cryomodule in the **SPS-LSS6** as a demonstrator with Hadron beams (2018)



SPS-test Installation

Massive installation of a new RF & Cryo plant in BA6 in parallel to the cryomodule into the beam line



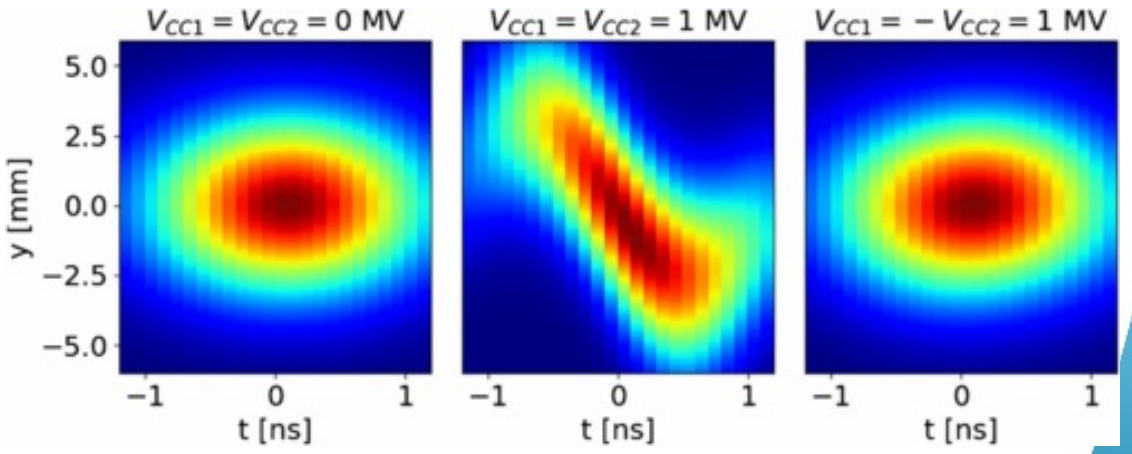


First Demonstration with Hadron

First injection – 12:55, May 23, 2018
Cavity 1 only

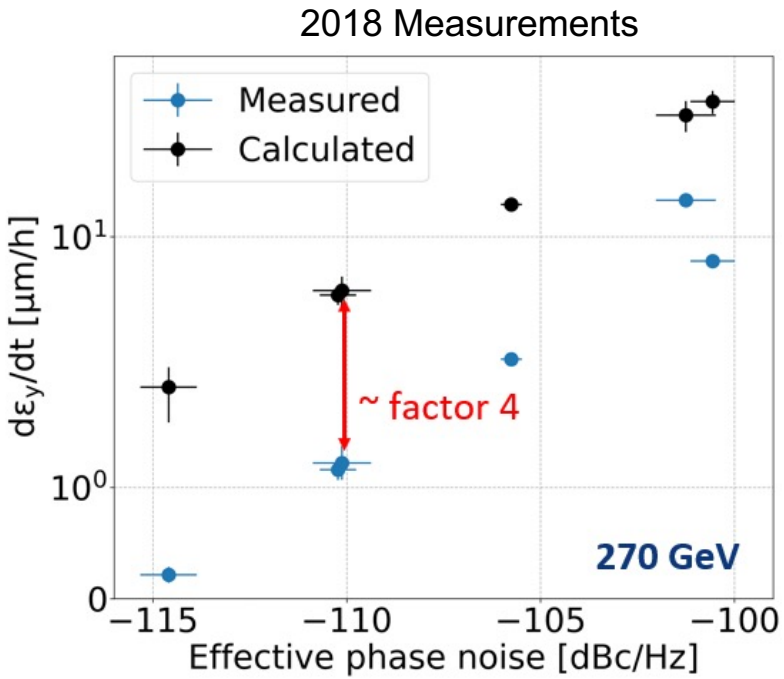
Single bunch
$0.2 - 0.8 \times 10^{11}$ p/b

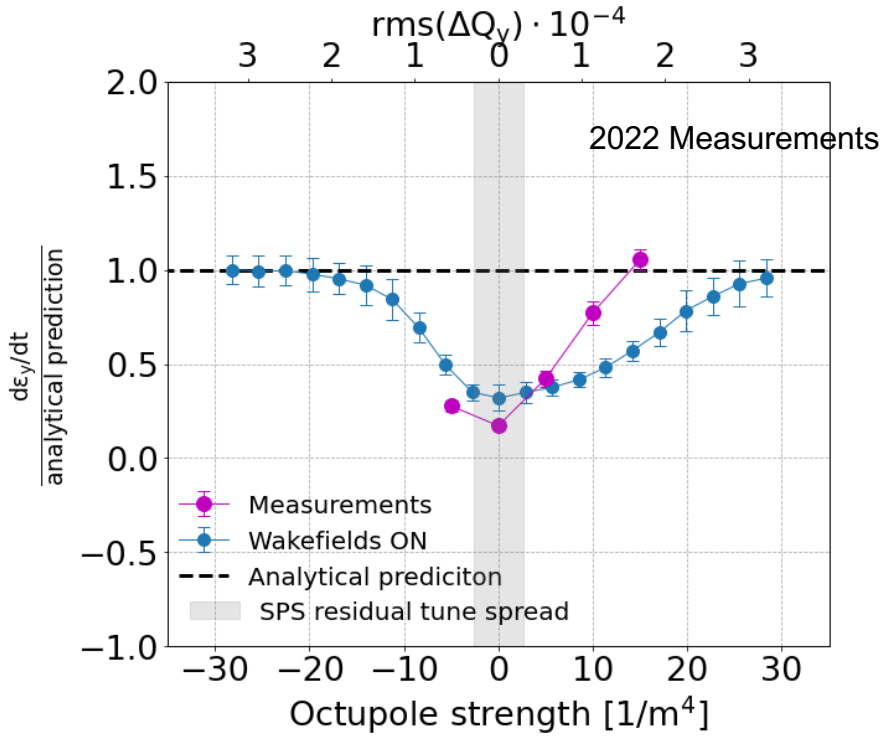
Several experiments with proton beams were performed since 2018 to understand the performance and operational aspects. Experiments continue to date



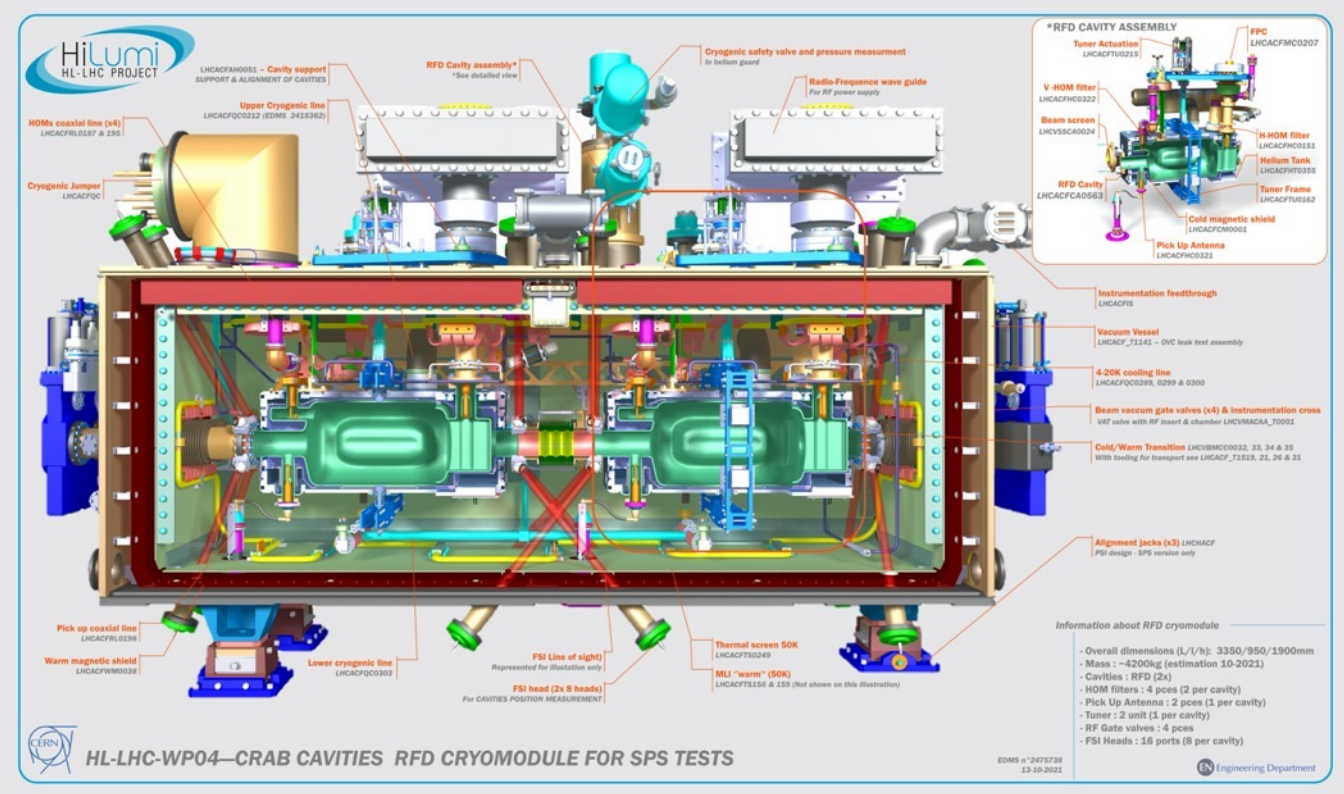
Proton Emittance Growth with RF noise

- HL-LHC we need to be below $0.05\ \mu m/h$ for RF induced growth
  - SPS a good test bench but natural emittance growth $\sim 0.5\ \mu/hr$
- Measured growth smaller by x4 than predicted (2018 & 2022)
- Suppression of emittance growth due SPS machine impedance confirmed !!



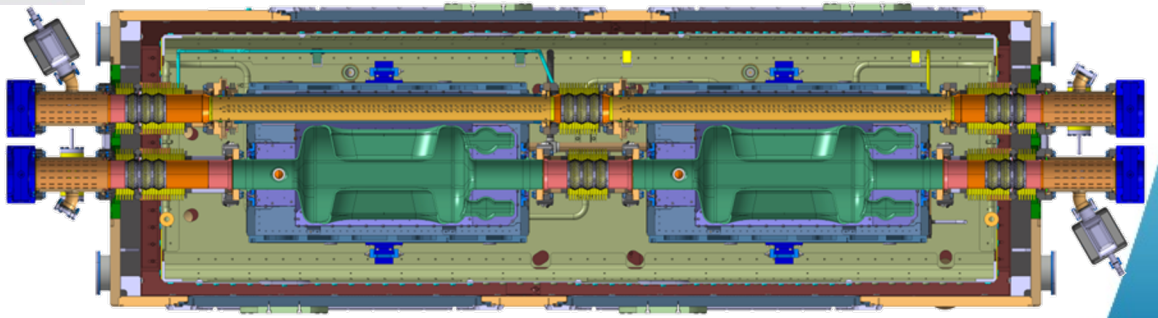


Next step: RF Dipole in SPS (CERN+UK)

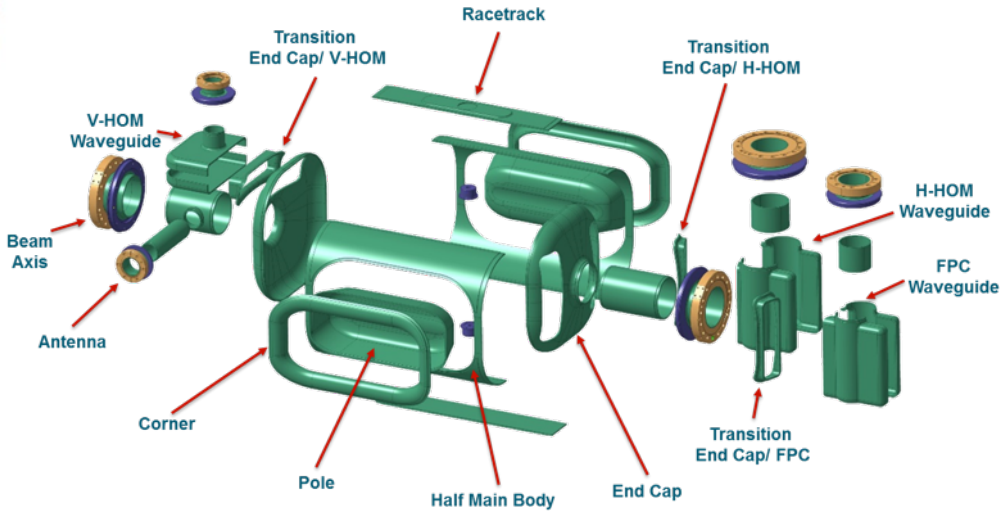


RFD module (horizontal crabbing) for SPS-tests, also fully compatible with HL-LHC

Installation foreseen in 2023-24 YETS



Cavity Fabrication at CERN



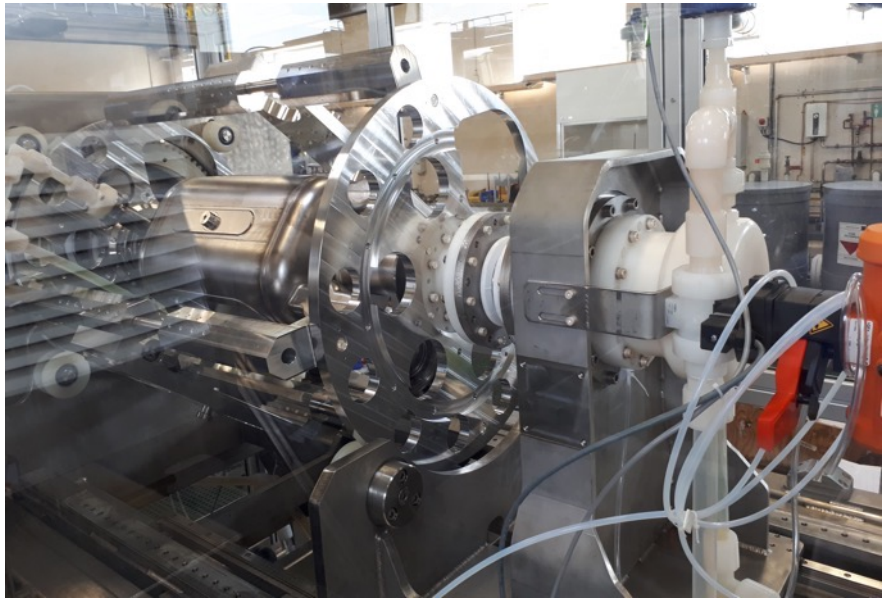
Sub Assemblies

RFD2 Welded

Final weld freq shift

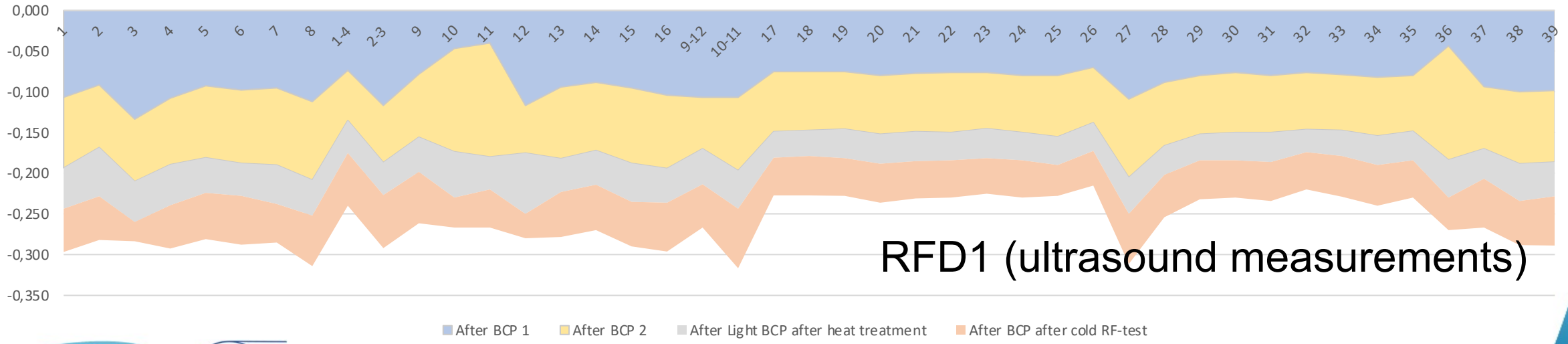
Δf [kHz]	RFD1	RFD2
Expected	+150	+150
Measured	-414	-470

Rotational Chemical Etching of RF Surface



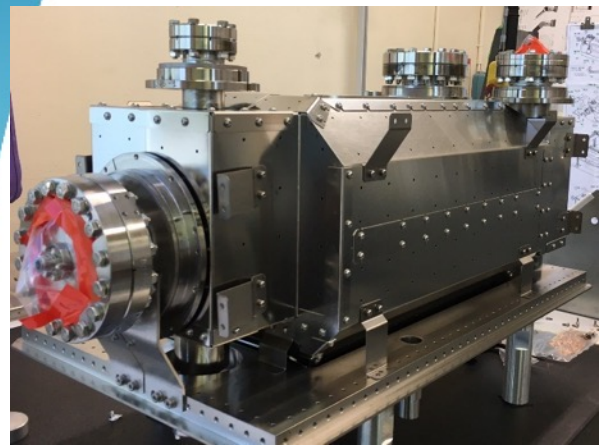
Etching ~250 μm + HT

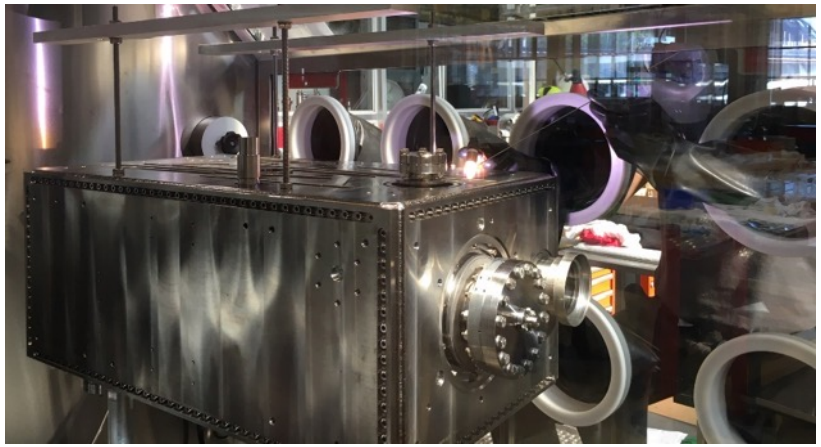
Δf [kHz]	RFD1	RFD2
Expected	-66	-66
Measured	+124	+136

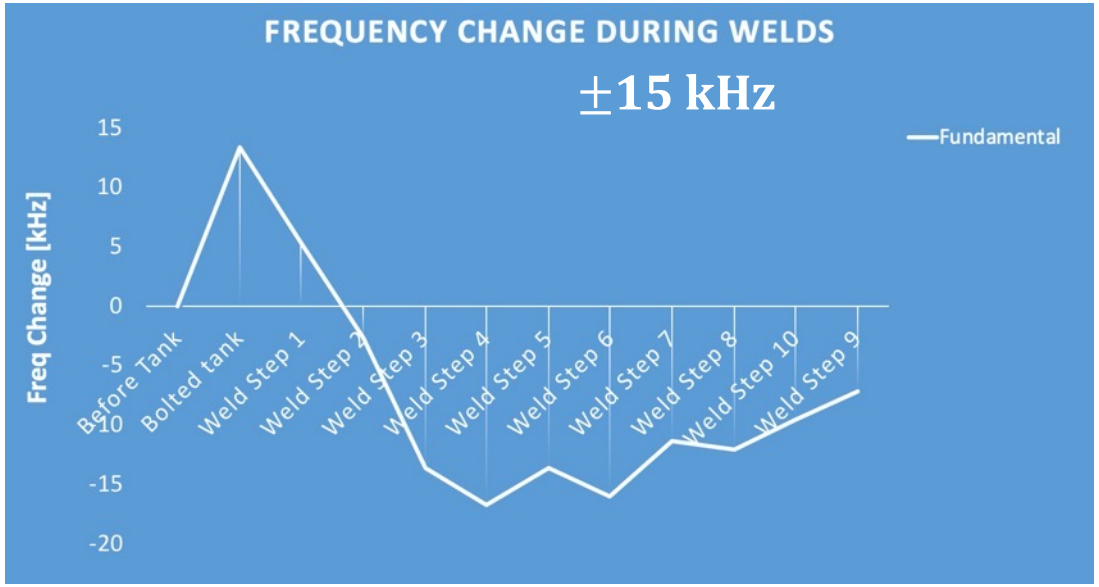


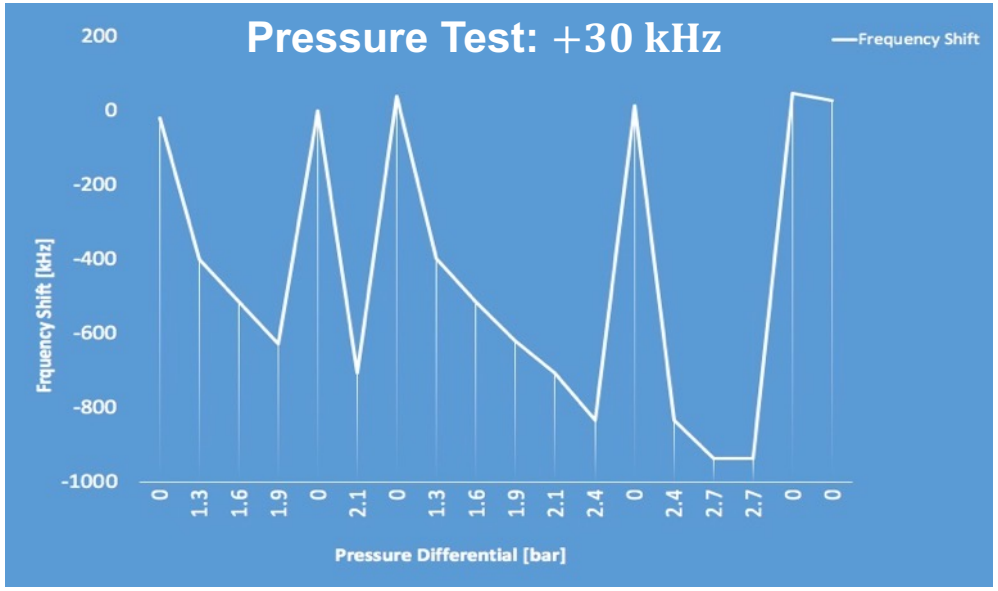
RFD1 (ultrasound measurements)

RFD cavity jacketing assembly

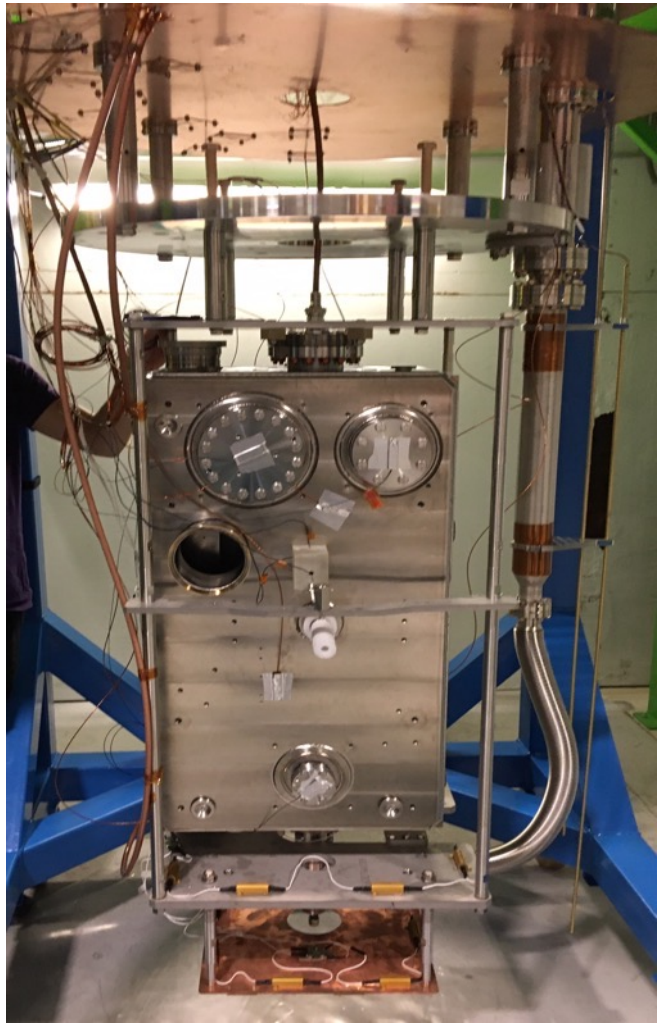


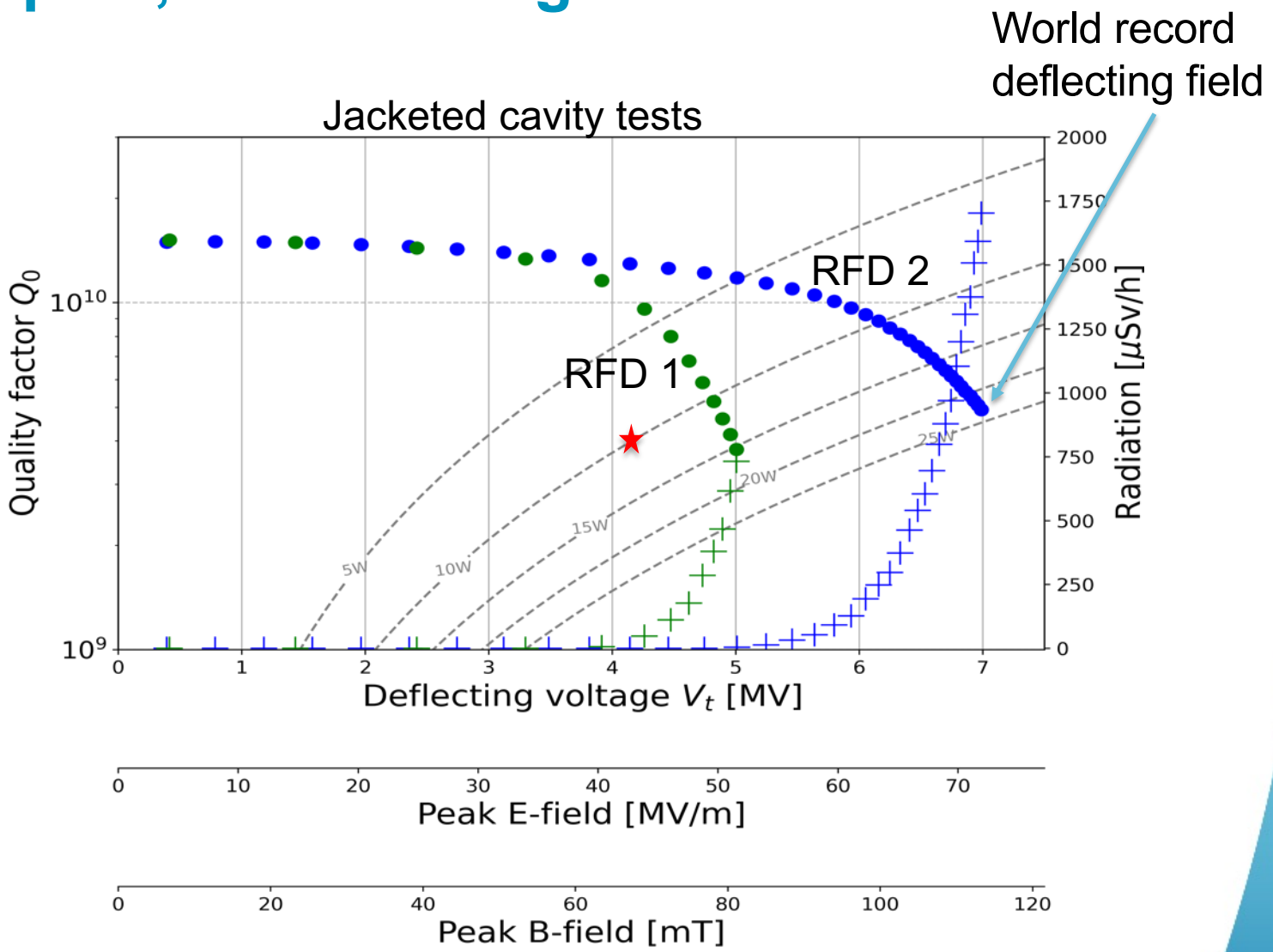






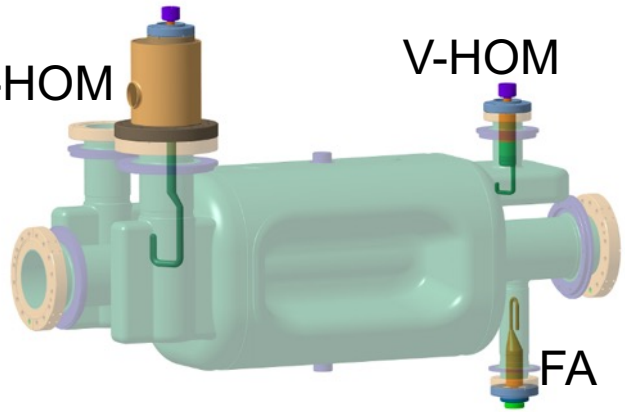
RF Dipole, Cold Testing



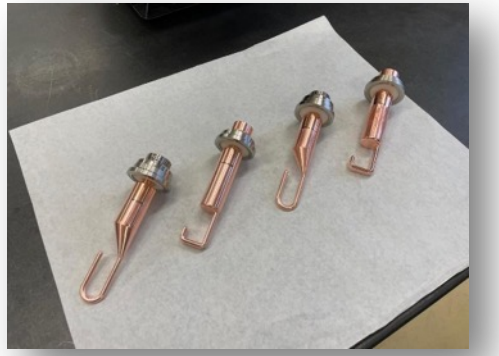


Note: Cavity 1 underwent a 2nd light etching ($\sim 30\mu m$) to recover performance

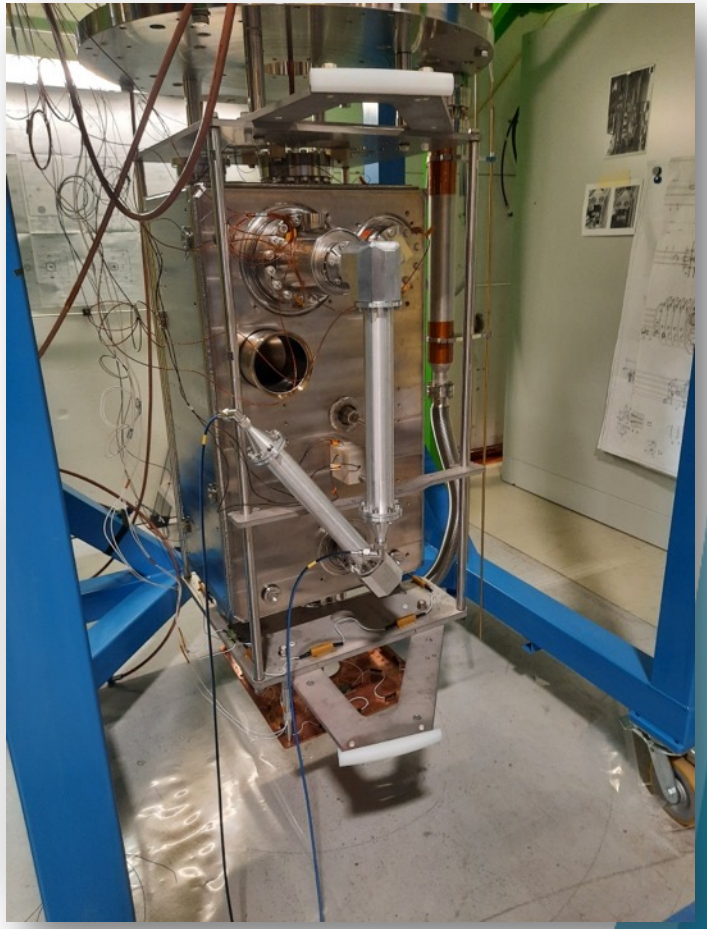
RF Dipole, HOM Couplers



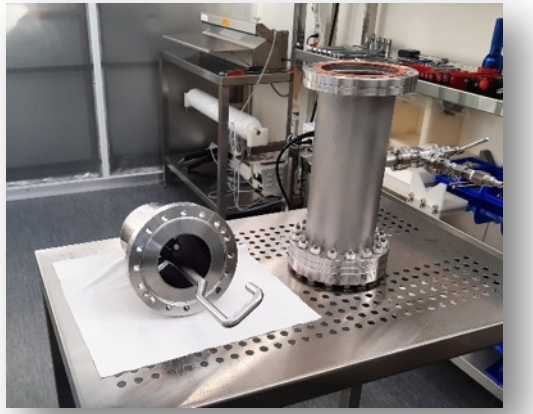
V-HOM & Field Antenna



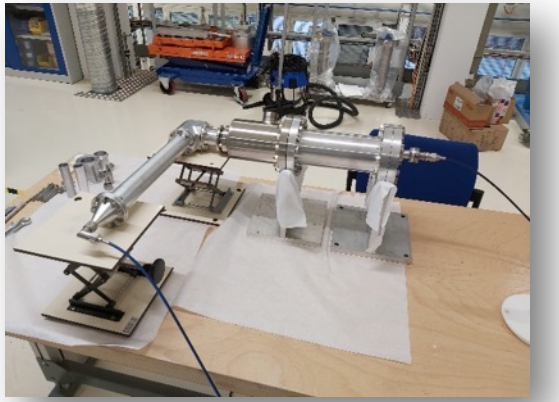
Full Dressed Cavity, 2K test



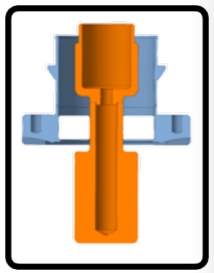
H-HOM, bulk Nb



HOM test-box qualification



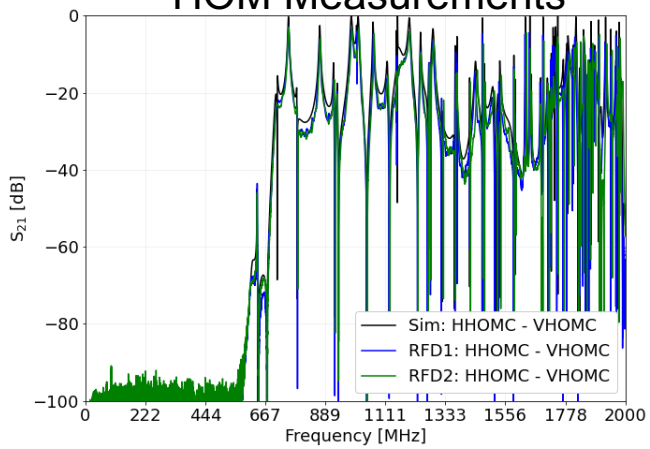
RF feedthrough, 25 Ω
High power

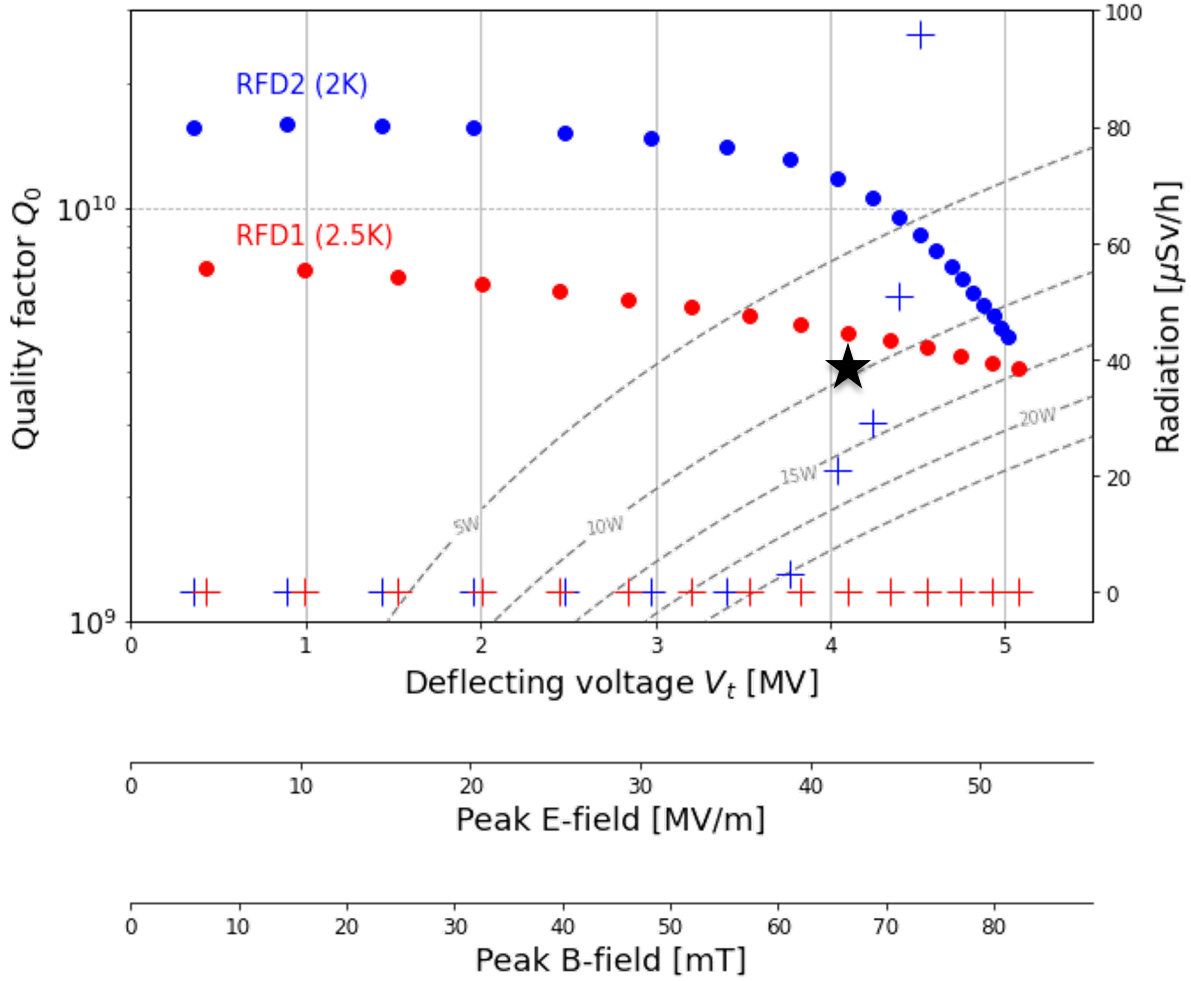


RFD Dressed Cavity with HOMs

CERN-RFD2

HOM Measurements



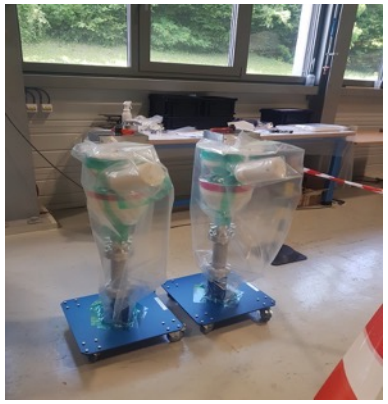


RFD Dressed Cavities to UK

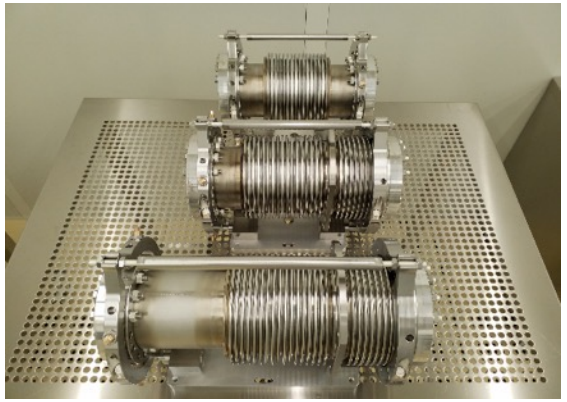
Preparations after the dressed cavity validation for beam vacuum, secondary line and ancillary equipment. Due to proximity of the secondary beam line, assembly of it inside He-tank

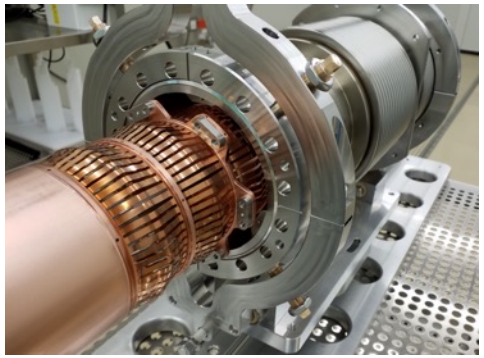
RFD2 dressed cavity & beam screen assembly

RFD Power couplers

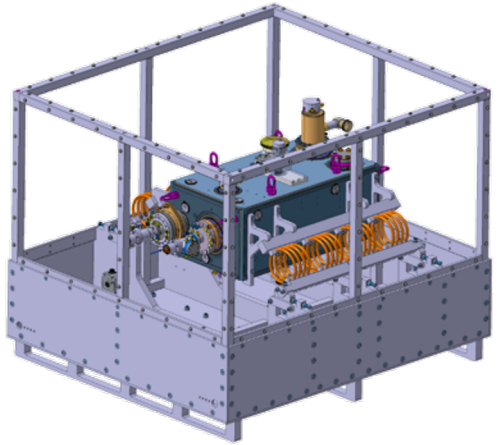


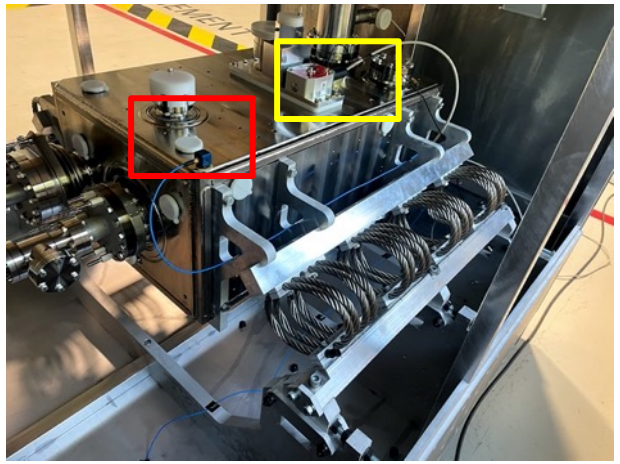
Plug-in-module assembly
Cavity line

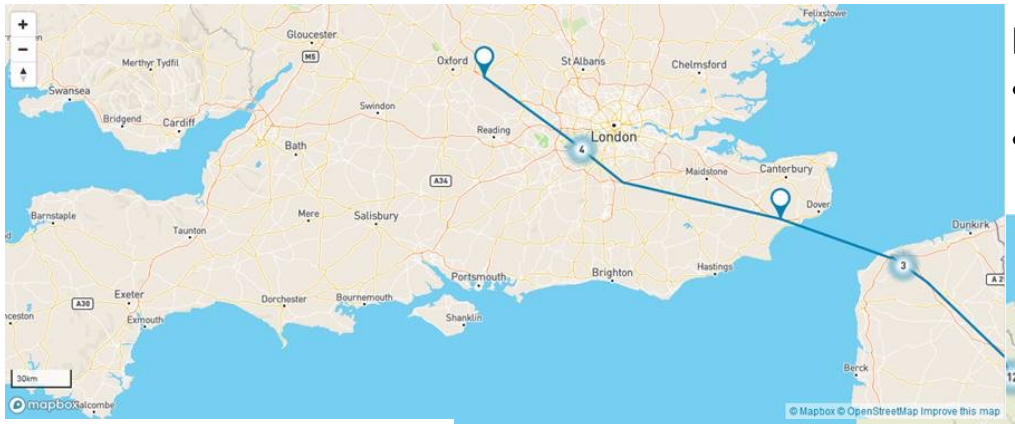




Transport to UK-STFC







Live acquisition of shocks and vibration during transport

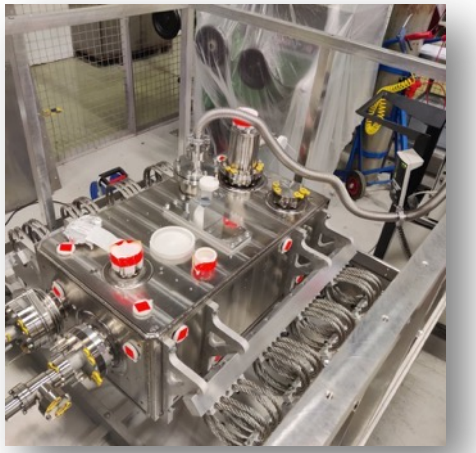
- Shocklog: online with GPS tracking, shock detection, tilt & roll
- Accelerometers : continuous monitoring, for vibrational spectrum check

Transport of the two cavities performed successfully

RFD Cryomodule: UK & CERN joint effort

- Dressed RFD cavities and vacuum components assembly received without incidents and successfully integrated into the clean room for string assembly
- FPCs and all string assembly components installed successfully this summer

Reception tests

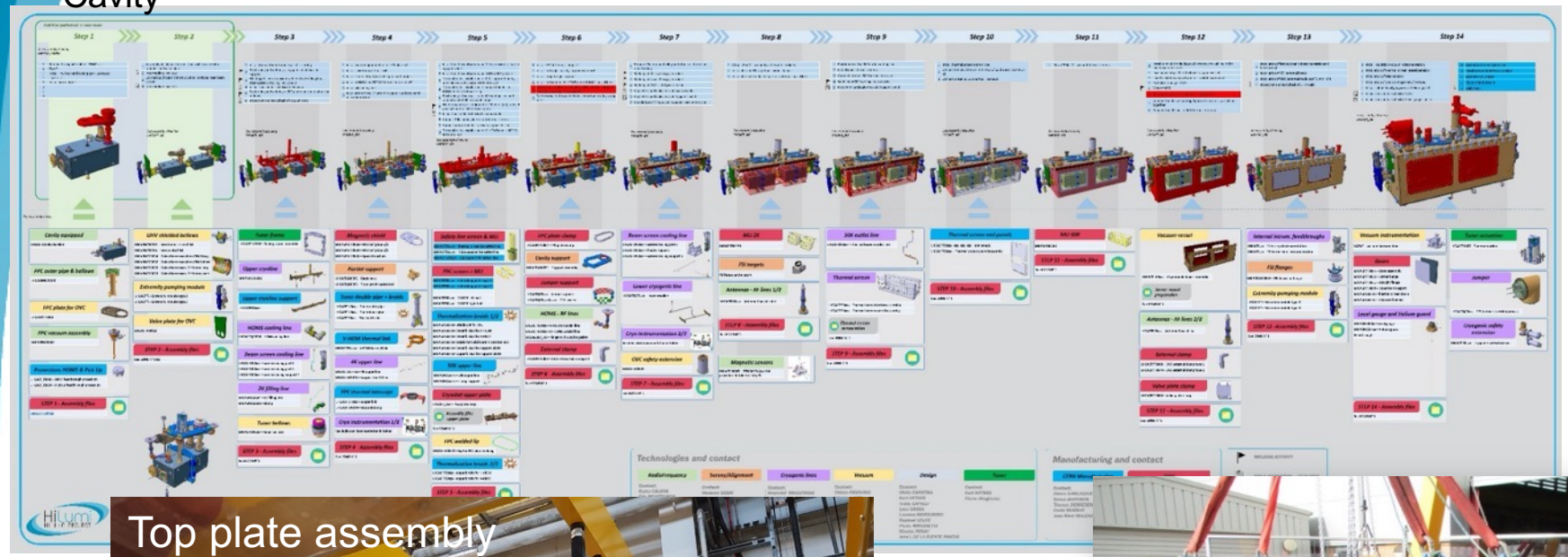


String Prep, Precision Trolley

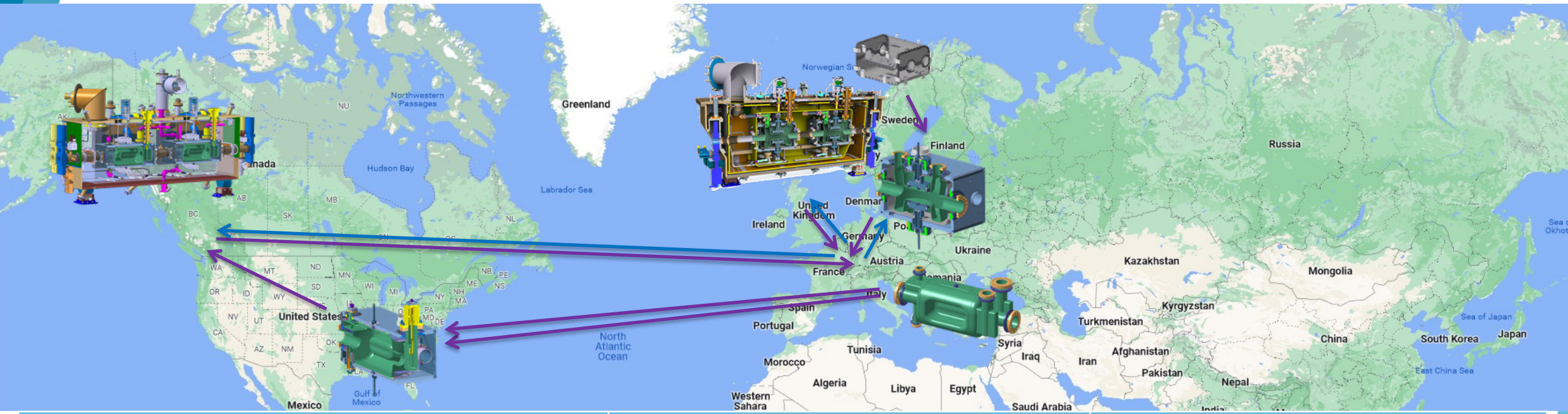
Beam vacuum connections, ISO4

RF Dipole Cryostating in the UK

Dressed Cavity | String Assembly | Cryostating | Q4 2022



HL-LHC Crab Cavity Series

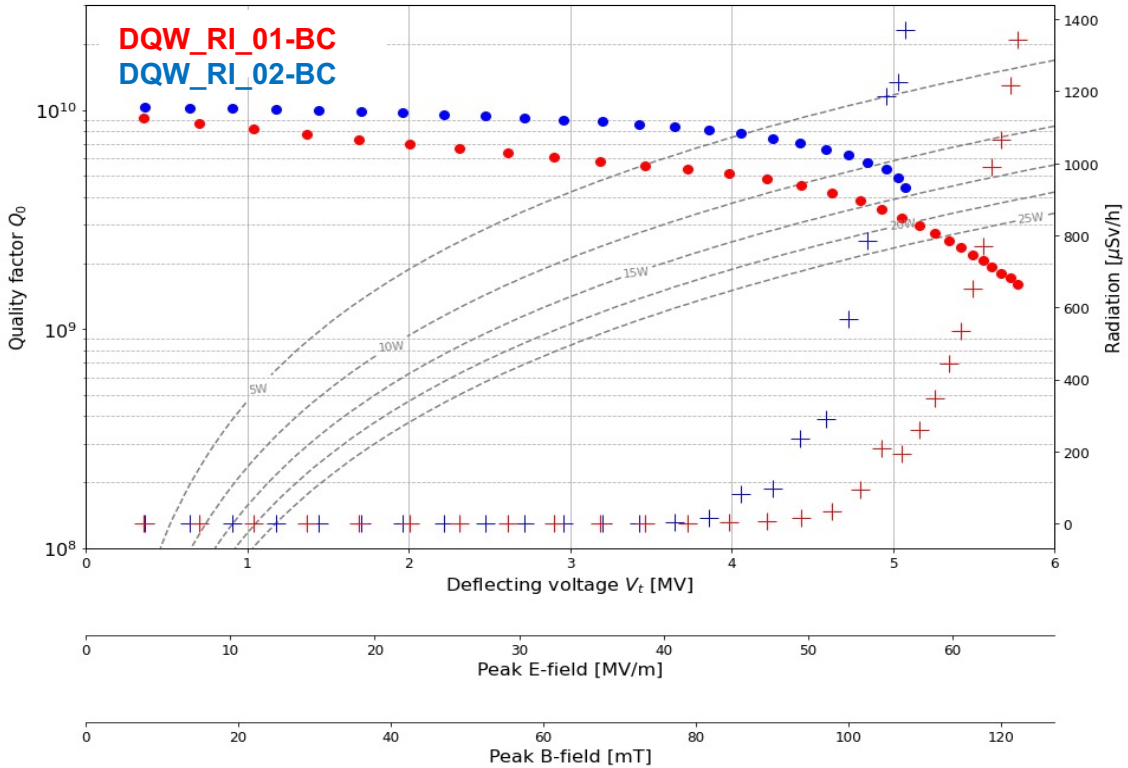


5 DQW cryomodules	5 RFD cryomodules	20 IOT RF Systems
• Cavities + processing + helium vessels by Research Instruments (**DE**) & **CERN** • Cold magnetic shields by **UK** • HOM couplers + antennas by **CERN** • 4 CM by **UK** (STFC) & 1 CM at **CERN** with some components from **CERN** • All cavities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

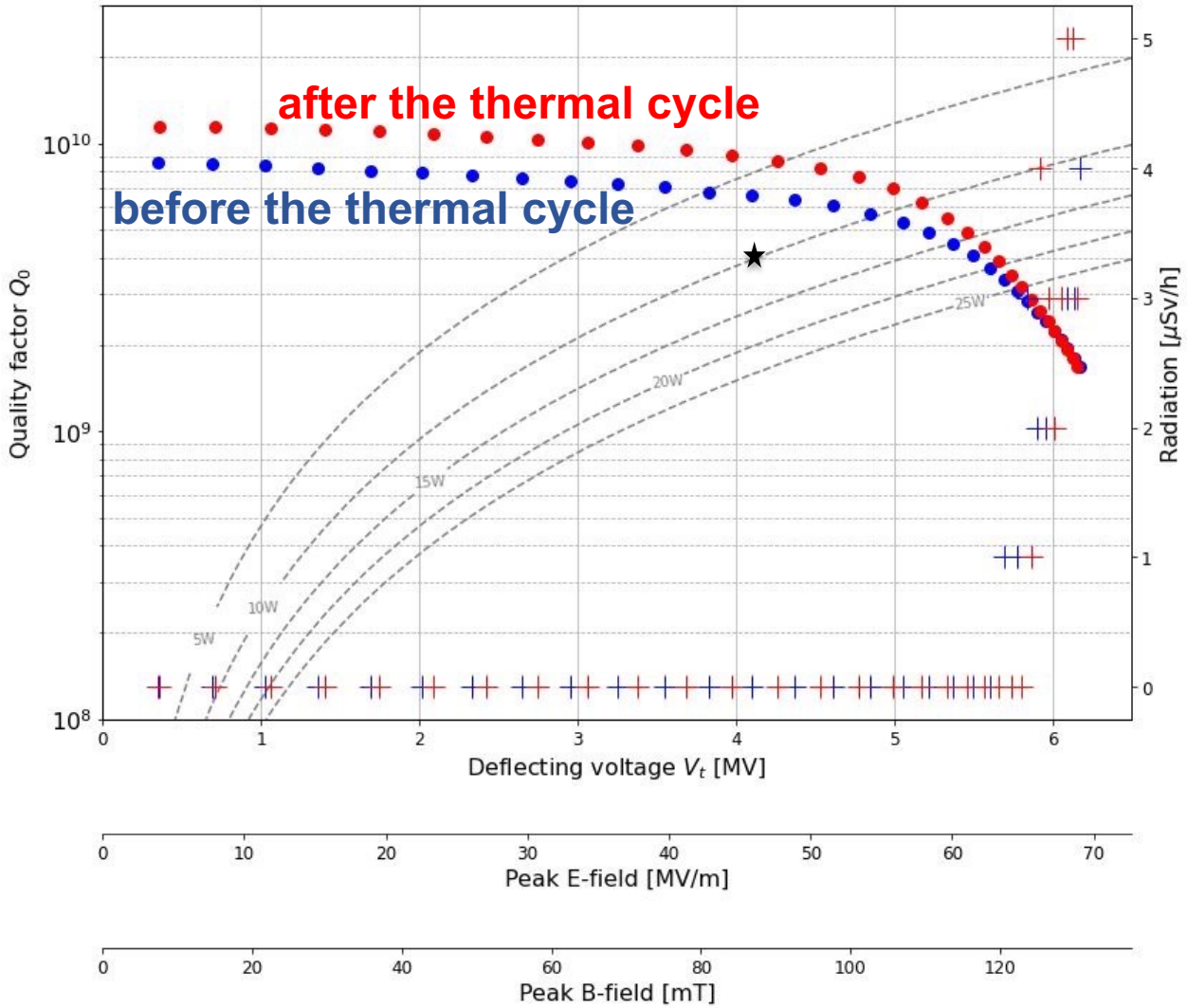
CERN DQW-Series with Industry

- Successful manufacturing of 2 pre-series cavities with industry (RI) with 1-cavity reaching excellent results. 2nd cavity retreated and to be tested
- Due to delays accumulated in industry (COVID + others), CERN building 2-series cavities to recover schedule. 6-series launched with industry

DQW-RI



DQW2-CERN Series, Cold Test

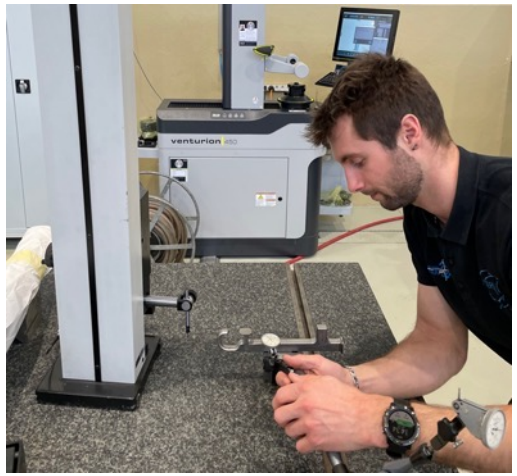


DQW1-CERN series under preparation for cold test

CERN-DQW Series, He-tank & Couplers

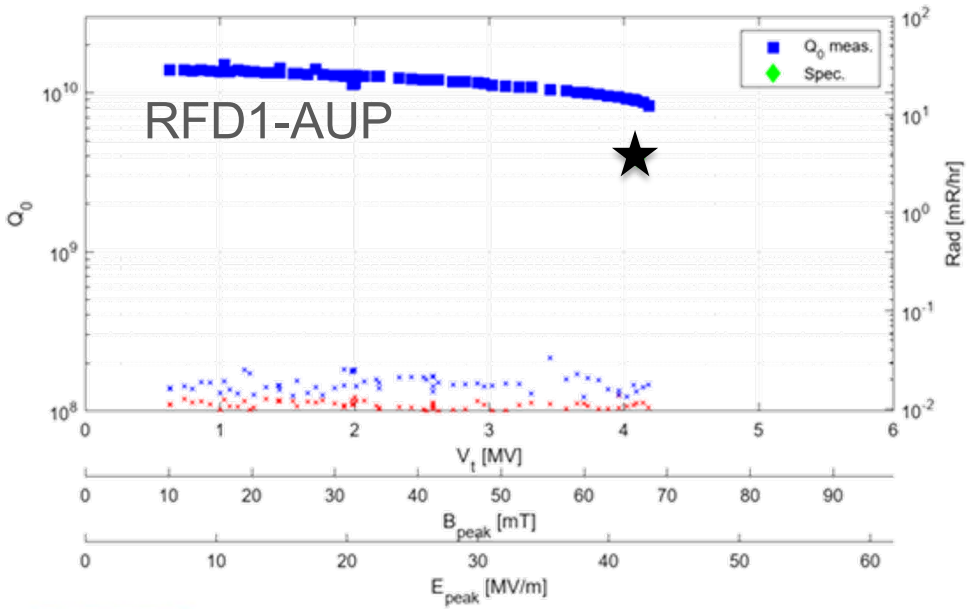
Blank assembly completed, cavity He jacketing started

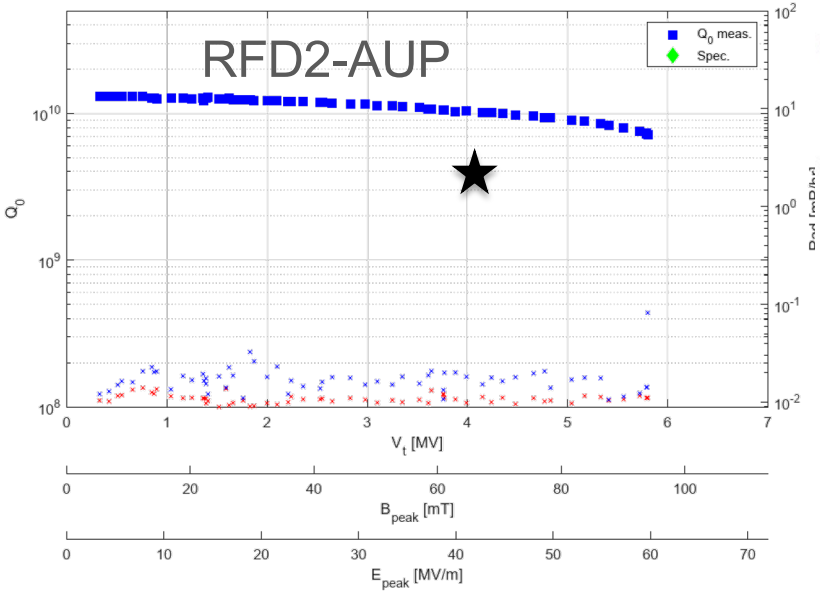
HOM couplers & Antenna's Machining



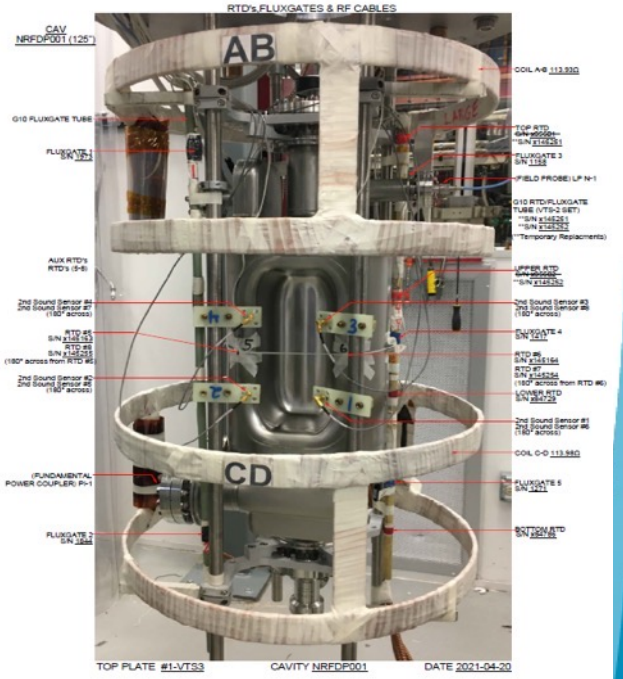
RFD Series (US-AUP & Canada)

- US-AUP will provide 10 fully dressed RFD cavities which will be cryostated at TRIUMF (in-kind)
- Successful completion of industrial RFD prototypes (Zanon) & tested them beyond specification



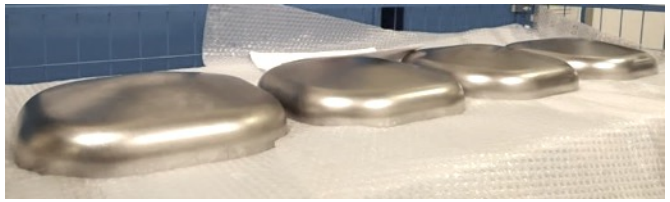


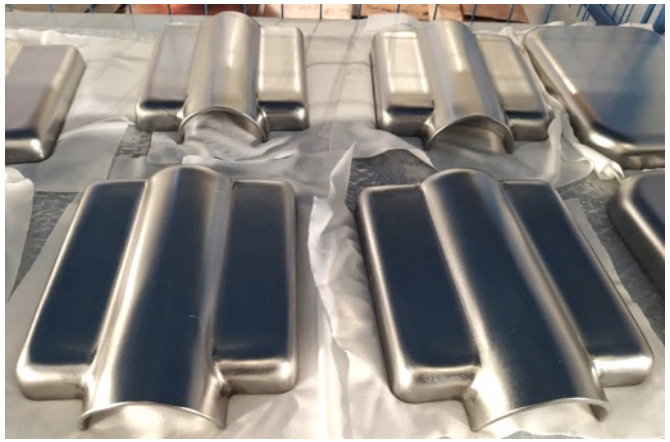
Vertical test stand
FNAL



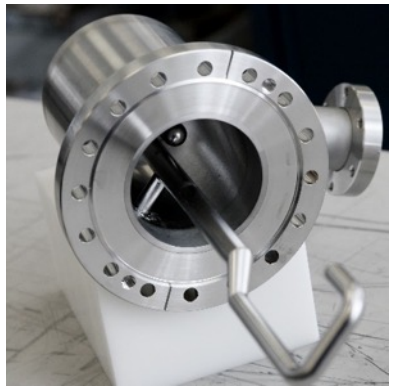
US-AUP Pre-Series

Two pre-series fabrication launched at industry (Zanon) with very good progress.





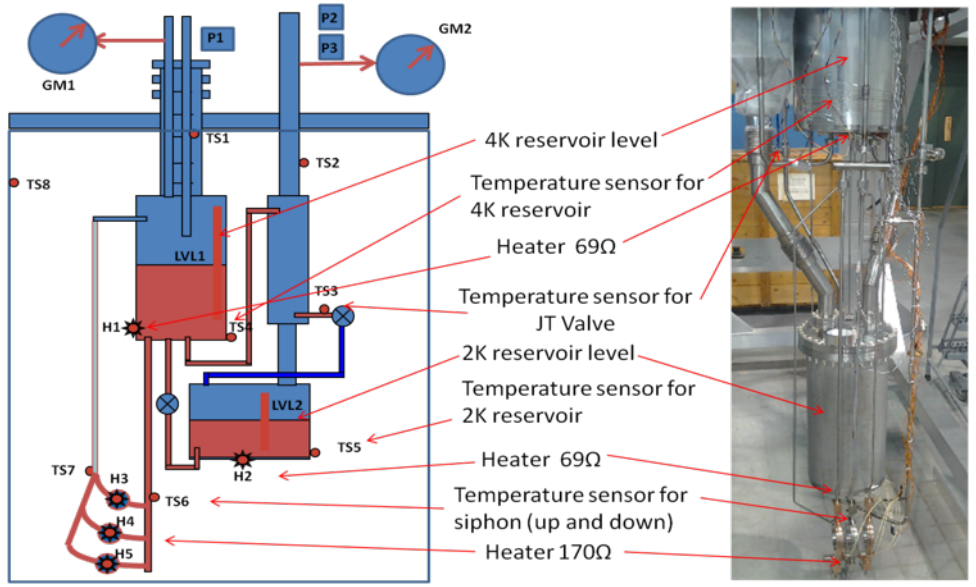
First set of prototypes for HOMs fabricated by Jlab. Cold tests validation ongoing with the two prototypes

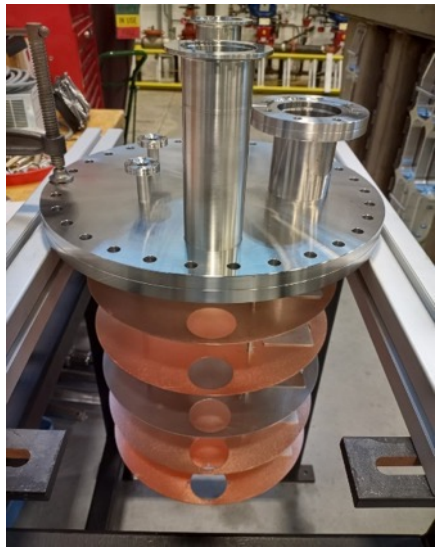


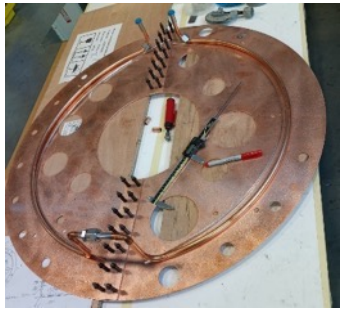
TRIUMF-Canada Activities

- Vertical test infrastructure upgrade for testing dressed cavities from US-AUP at TRIUMF before cryostating

- TCM0 prototype cryomodule foreseen with US-AUP built RFD prototype cavities







HiLumi HL-LHC PROJECT

CERN

Thank you