HL-LHC Crab Cavities

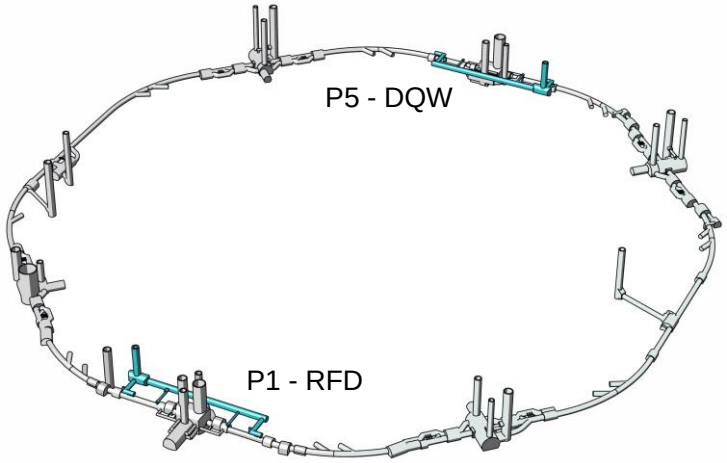
R. Calaga on behalf of HL-LHC WP4 & Collaborations

Acknowledgements: WP2, WP12, WP13, WP19…

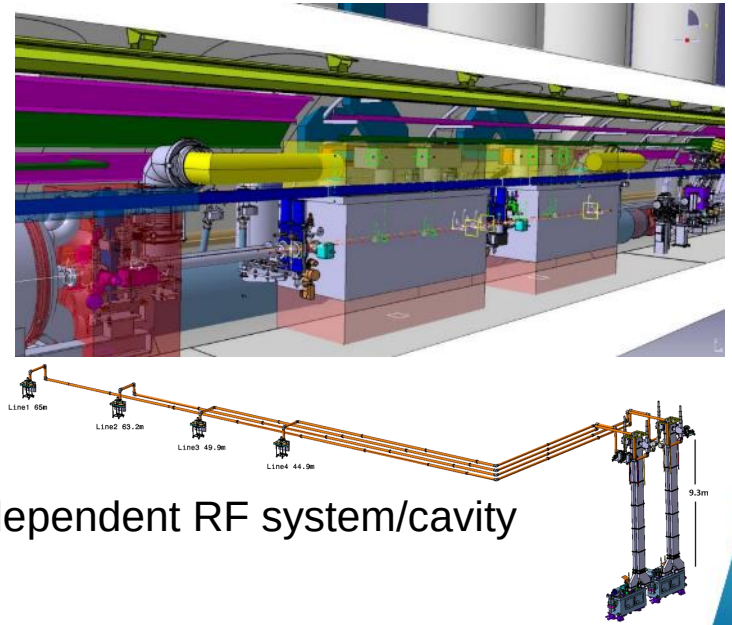
ICHEP 2024, Prague

HL-LHC Crab Cavities

- 16 Superconducting compact RF deflectors (ATLAS + CMS) to partially compensate the geometric angle of $\sim 600\ \mu\mathrm{rad}$ and maximize the luminous region



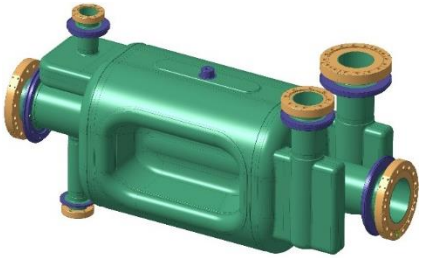
One IP side
(4-cavities)



Independent RF system/cavity

Two Cavity Geometries

RF Dipole (ATLAS)



$f_0 = 400$ MHz

$V_T = 3.4$ MV/cavity

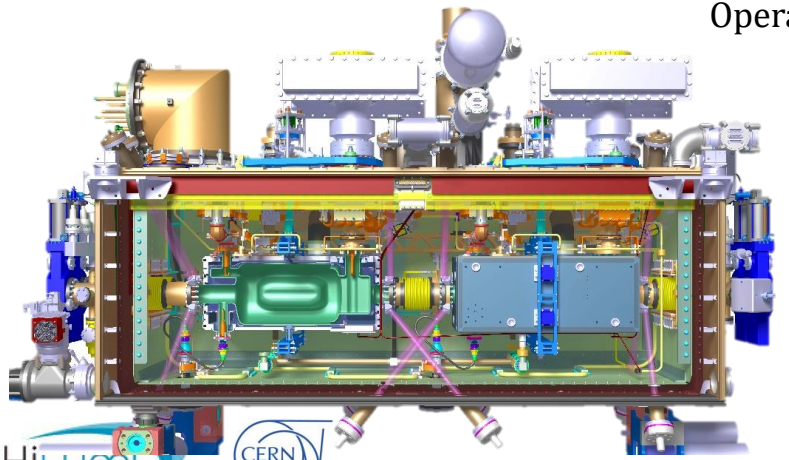
$(E_p, B_p < 40$ MV/m, 70 mT)

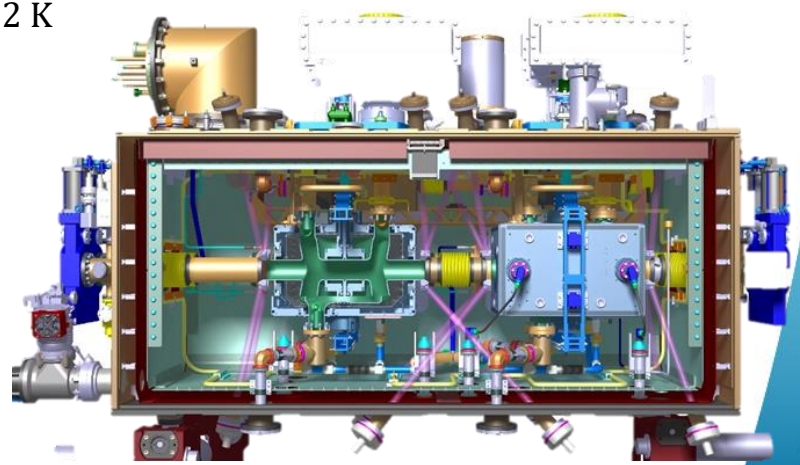
Beam aperture $= 84$ mm

RF Power, Max $= 40$ kW-CW

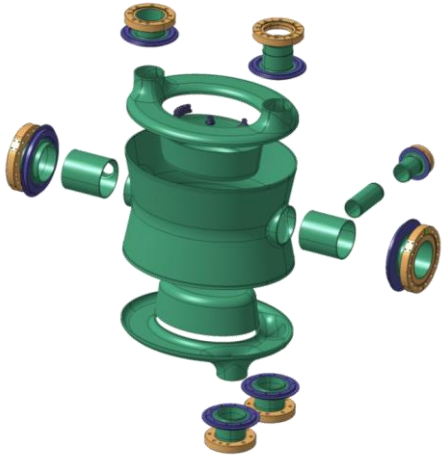
Operating Temp $= 2$ K

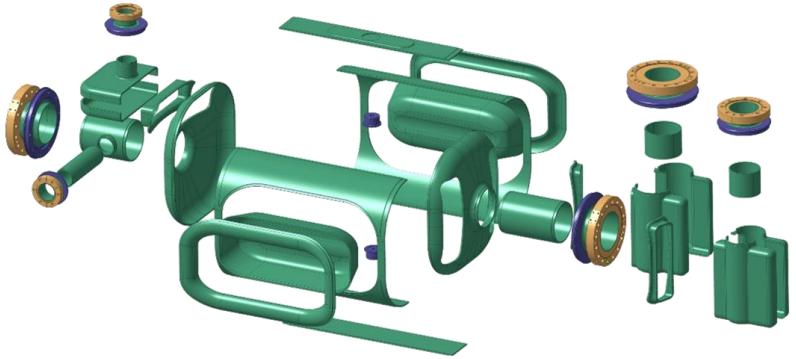
Double Quarter Wave (CMS)





Cavity Manufacturing challenge



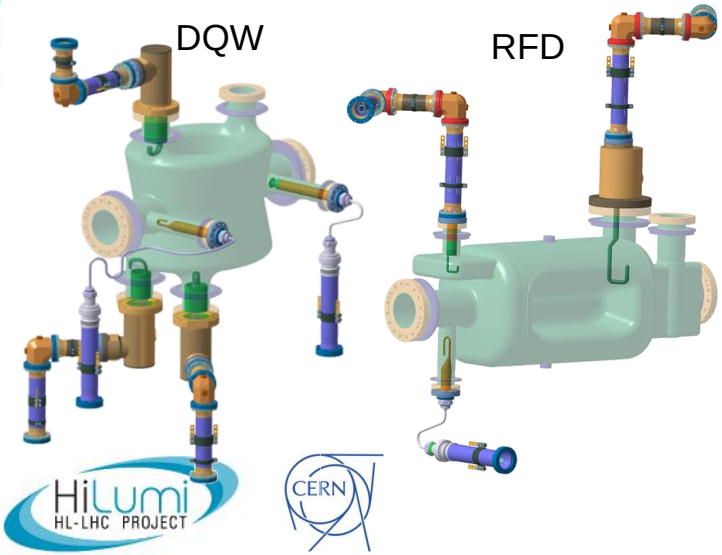


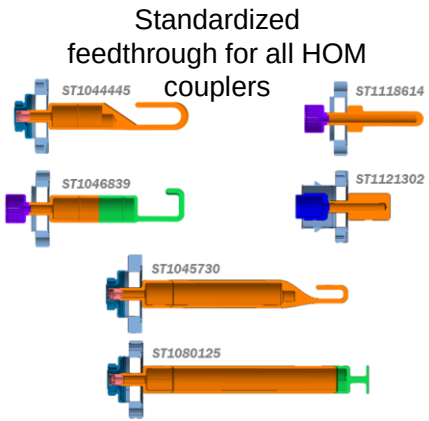
Cavities made of high purity bulk Niobium (superconductor) to sustain surface fields in excess of 50 MV/m & 100 mT

Very complex shaping, welding (30+) & assembly process to reach high final shape

RF Couplers (Input, HOM)

- A 40 kW-CW fundamental power coupler feeds RF power
- 4-HOM couplers in the DQW and 2 HOM couplers in the RFD are used to achieve the strong damping required for HL-LHC





SPS-tests of Crab Cavities

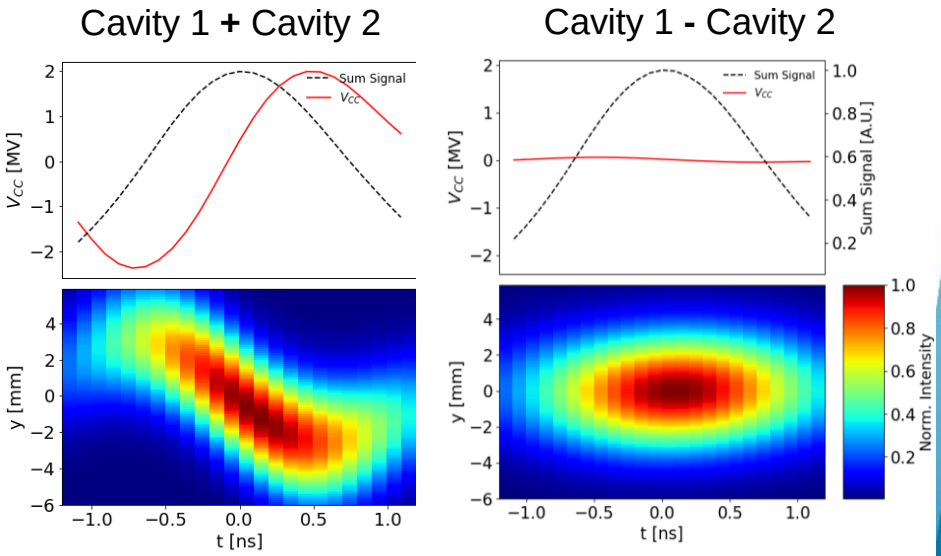
- Purpose: Test one module of each type (DQW & RFD) with protons, pre-requiste before HL-LHC installation

- DQW module was installed in 2018 and 5 yrs of successful operationwith several important experiments & lessons learned which are vital for HL-LHC operation

- De-installation in 2023/24 shutdown to make space for RFD module

SPS tests, DQW Module

- 2018 installation in a special movable bypass to carry out dedicated experiments with protons

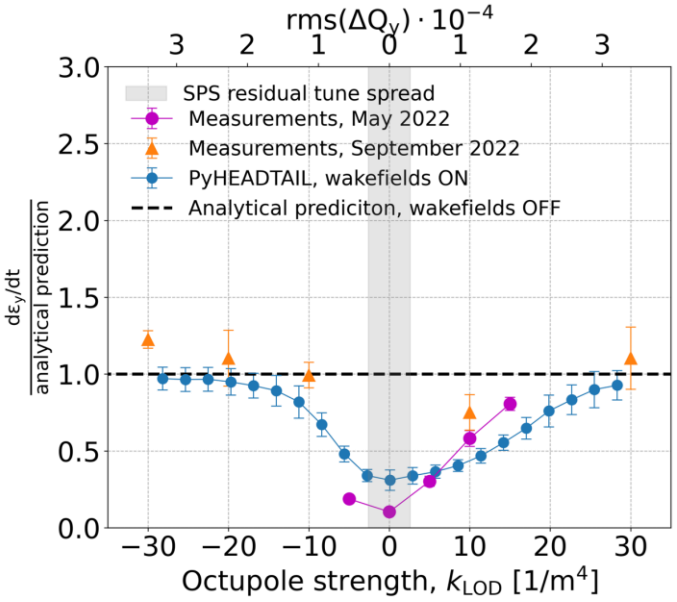


Measurement with head-tail monitor

(PRST-AB – 2021)

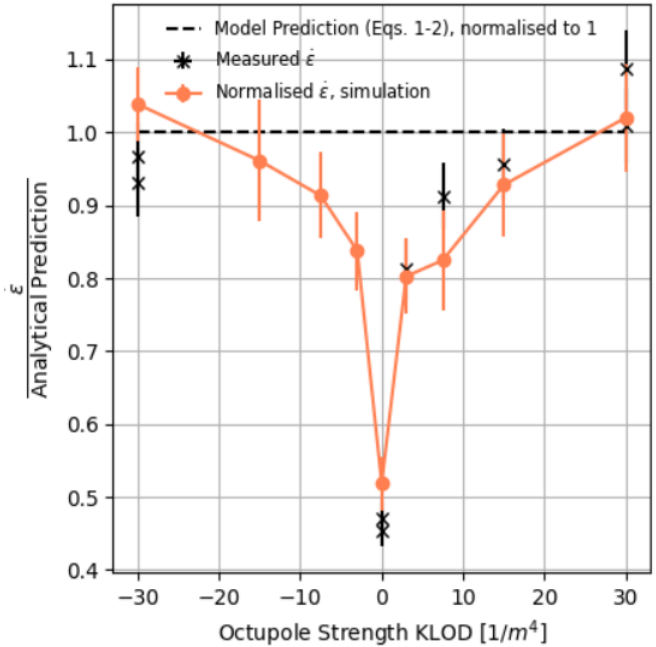
Emittance Growth (Phase & Amplitude Noise)

2022 (RF phase noise)



(N. Triantafyllou, Ph.D. thesis)

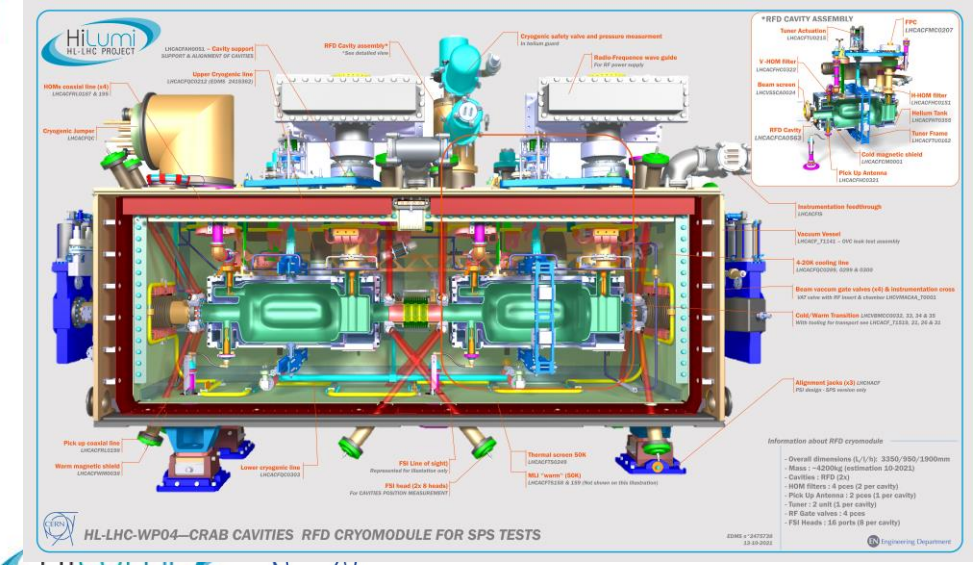
2023 (RF amp noise)



(A. Fornara et al. IPAC 2024)

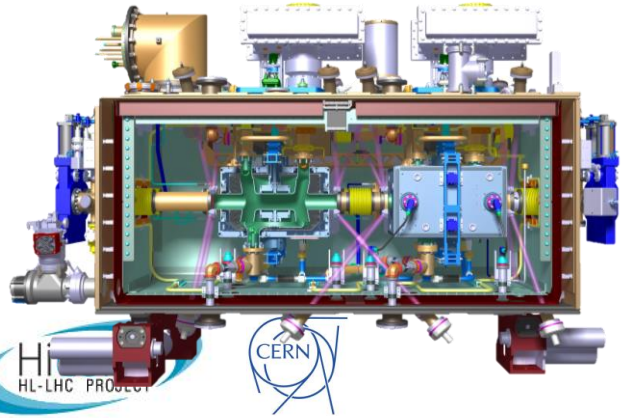
RF Dipole for SPS-tests

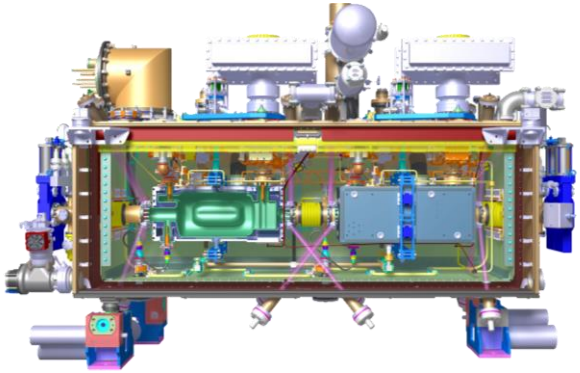
- The second type (RF Dipole) was jointly built by CERN & UK-STFC, completed Oct 2023
- Extensive testing including a repair in two couplers is underway before installation into the SPS this December 2024



Series Production

5 DQW cryomodules (Europe)	5 RFD cryomodules (North America)	20 RF Systems (Asia, CERN)
• 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)	• Jacketed cavities by Zanon (**IT**) under **US-AUP** • Cold magnetic shield + 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** • LLRF by CERN (μTCA platform)





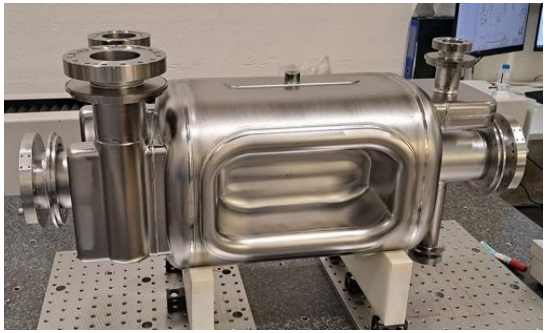
DQW Series Cavities

- Series cavities 8 built by industry (Research Instr.) & 2 by CERN
- 4 cavities completed two fully qualified with HOMs, two under final testing
- Remaining six cavities are in final stages of welding and followed up by RF testing
- The cavities once validated are cryostated jointly with UK-STFC under a collaboration agreement

Series DQW cavities

RF Dipole Series Cavities

- RF Dipole series cavities & some RF ancillaries are in-kind contribution from the US under AUP-program
- 2 pre-series cavities completed in industry (Zanon) and being tested, the remaining 8 cavities progressing well
- The cavities once validated are are cryostated in Canada under a collaboration agreement between CERN & TRIUMF (in-kind)

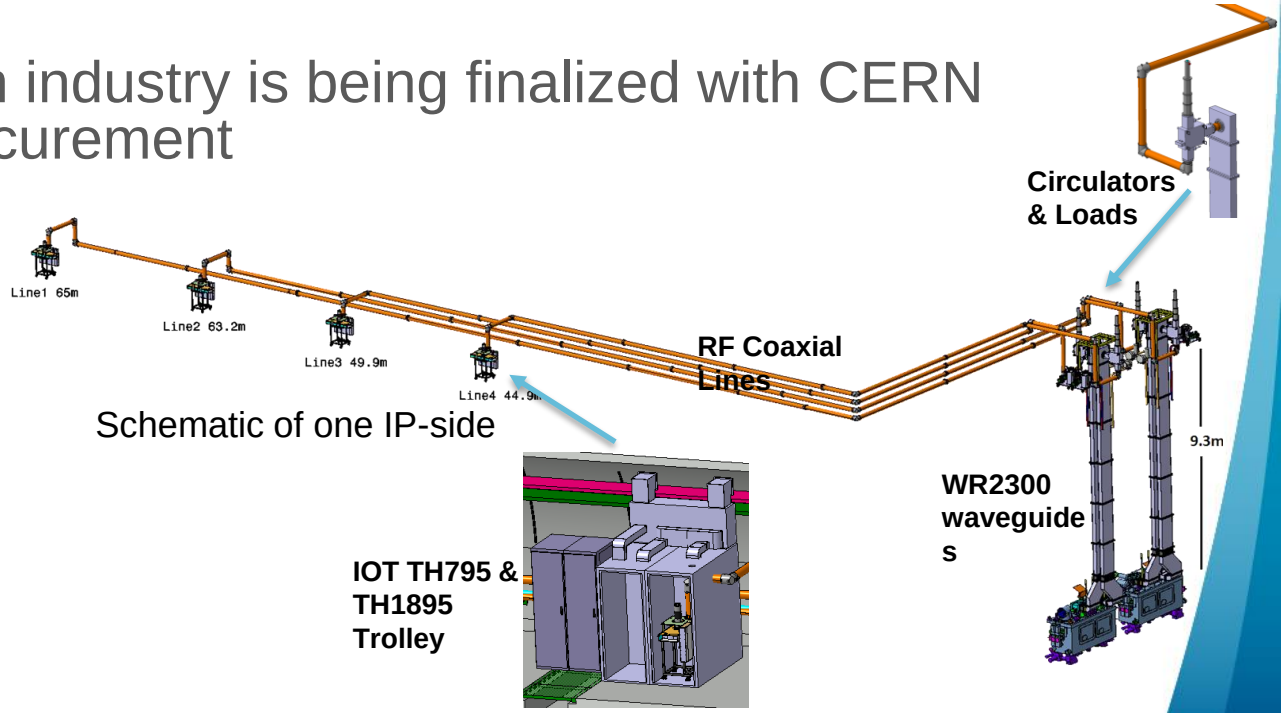


Series cavity sub-assemblies

High Power RF (Amplifiers & Lines)

- In 2023, KEK & CERN finalized a proposal for a Japanese in kind contribution for HPRF & RF lines

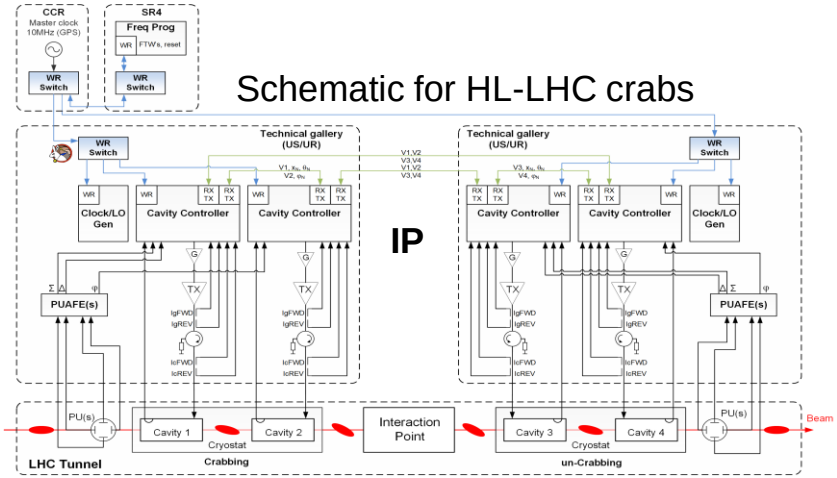
- The contract with industry is being finalized with CERN following the procurement



Schematic of one IP-side

Low Level RF developments

- New μTCA platform (following LIU-SPS upgrade), RF over White-Rabbit (including upgrade of LHC Beam Control)
- Cavity controllers, beam control and interlock systems to designed and produced in house
- 4 Faraday cages & infrastructure (purchased in industry)



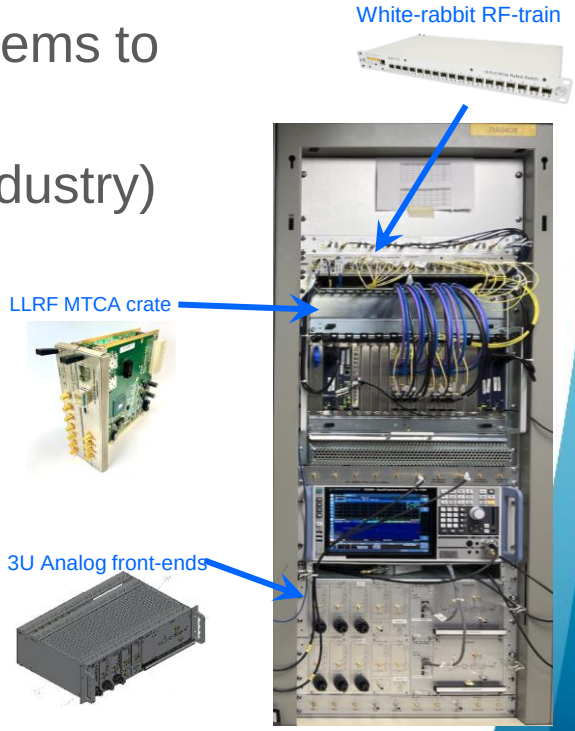


Fig – SPS 200MHz LLRF MicroTCA crate and analog front-end

Final Comments

- The HL-LHC crab cavity project is a multinational effort which resulted in several key technologies to meet the stringent requirements for HL-LHC
  - The SPS tests with protons helped understand some vital beam physics aspects & how to efficiently operate high field CCs in the CERN accelerator chain
  - Series production for HL-LHC is in full swing and expected to finish in 3 years followed by installation in the interaction regions

- The HL-LHC developments opened the door to very high field deflecting/crab cavities which are now an essential technology for many future accelerators (colliders, light sources, etc..)

More details: https://indico.cern.ch/event/1280057/

Timeline

High Power RF system not shown

2018-2022	2023	2024	2025	2026	2027	2028

DQW CM SPS-tests

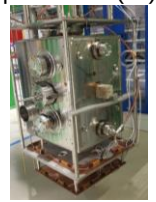
RFD CM SPS-tests

2 prototype cryomodules
for beam tests (DQW & RFD)

5 DQW + 5 RFD
Series modules

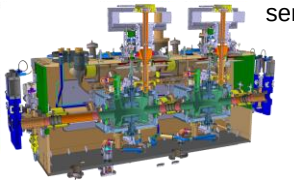
CERN-DQW
series (x2)

RI-DQW
pre-series (x2)



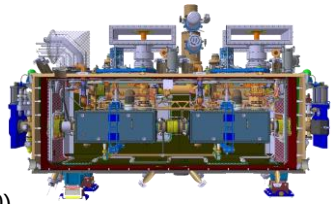
RI-DQW
series (x6)

UK-CERN DQW CMs
series (4 + 1)



USAUP-RFD
pre-series (2)

USAUP-RFD series (10)

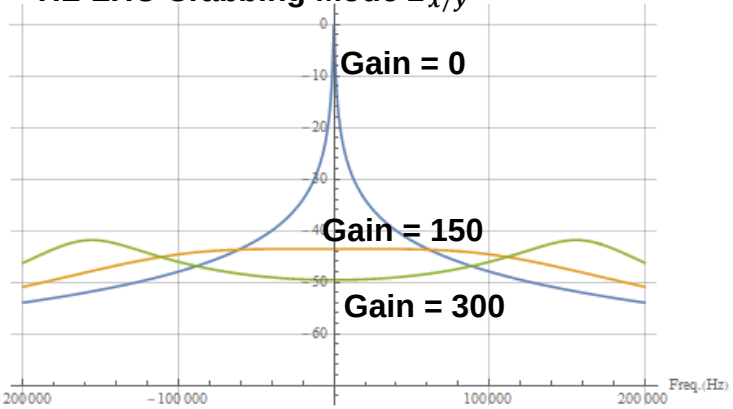


Canada-CERN RFD CMs
series (5)

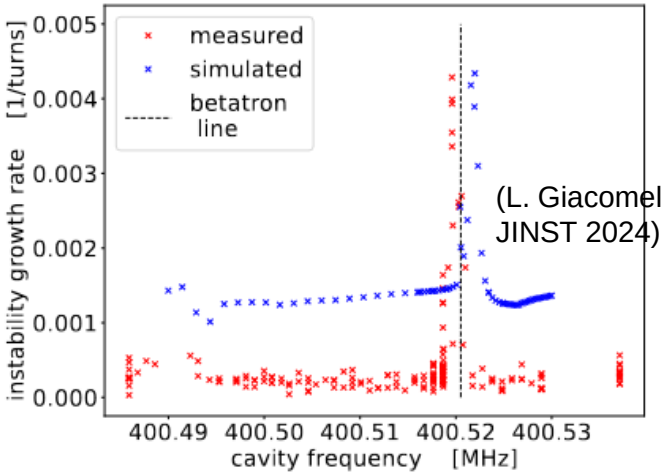
Impedance & Mitigation

- The large impedance at the fundamental mode and HOMs are a concern for transverse stability
  - To reduce the impedance, a direct RF feedback with a gain of 150 and a β-comb filter to gain an additional x10 will be used
  - Several HOM couplers are used for very strong damping to stay within impedance budget
- Experiments in the SPS were valuable to understand the impact and benchmark projections for HL-LHC

HL-LHC Crabbing Mode $Z_{x/y}$



SPS Measurements



(L. Giacomel et al. JINST 2024)

HOM Measurements

- Impedance measurements at 2K on the cryomodule to confirm to be within specification
- Measurements are cross checked at different stages between vertical tests & after cryostating w.r.t the specified impedance budget from beam dynamics requirements