LHC Crab Cavities, WP4

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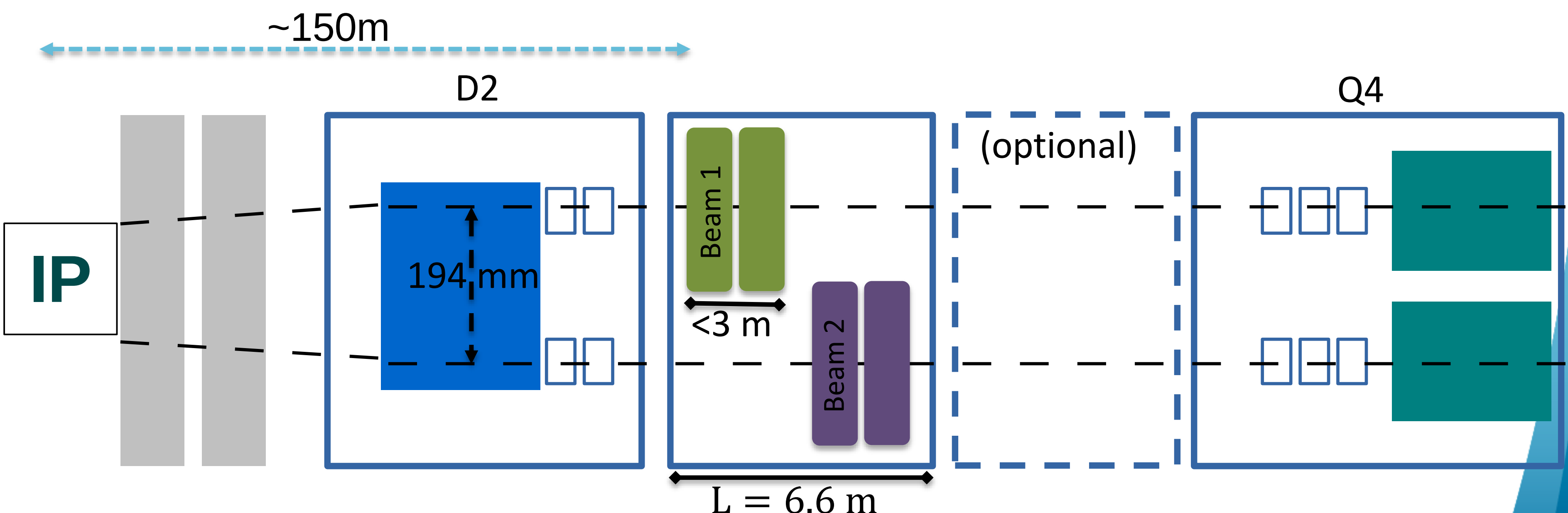
Ack: CERN (BE-RF, EN-MME, TE-VSC), UK-STFC, USLARP

LHC Crab Cavities

16 Superconducting compact RF deflectors (at two experiments) to partially compensate the geometric angle of 590 μrad. Allows to recuperate up to 70% of unused peak luminosity

Voltage $= 3.4$ MV /cavity , Frequency $= 400.79$ MHz
RF power source $= 80$ kW, Cavity tuning $= \pm 100$ kHz
Operating temperature $=$ 2.0 K



Overall WP4 Planning

SPS prototype beam tests

preparation — SPS Test (CM1)

SPS Test (CM2)

2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026

EYETS, YETS

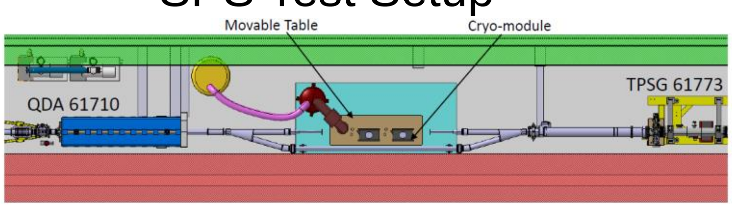
Run 2 | LS2 | Run 3 | LS3 | Run 4

LHC pre-series

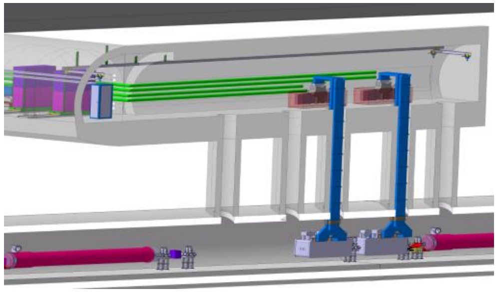
(2 Industrial Dressed Cavities)

LHC series production & Installation (8 CMs)

SPS Test Setup



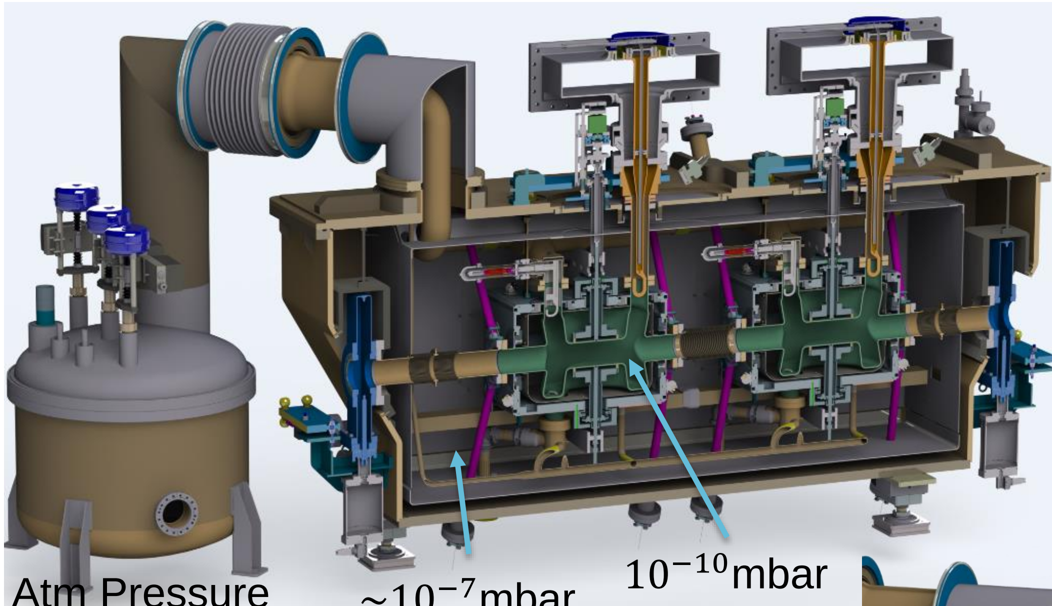
LHC Installation



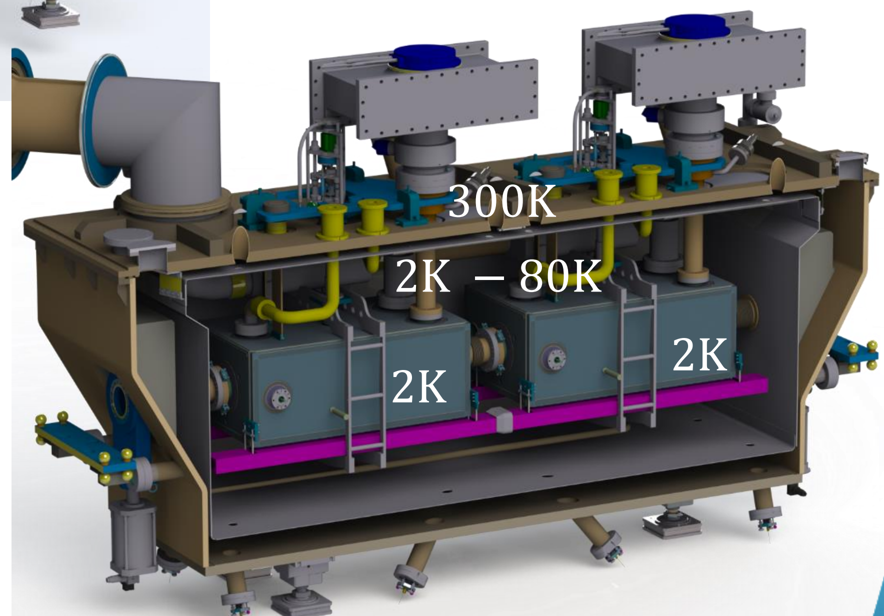
Cavity & CM Production Strategy

- CERN will produce the Technical Specifications based on the SPS experience
- During Pre-Series phase, we plan to launch market survey (2017) to first qualify industry to build 1 dressed cavity of each type, with the option for series
- The Series production of $10 + 10$ dressed cavities and cryomodule components with qualified companies. String assembly and cryostating foreseen at CERN

Prototype Cryomodules

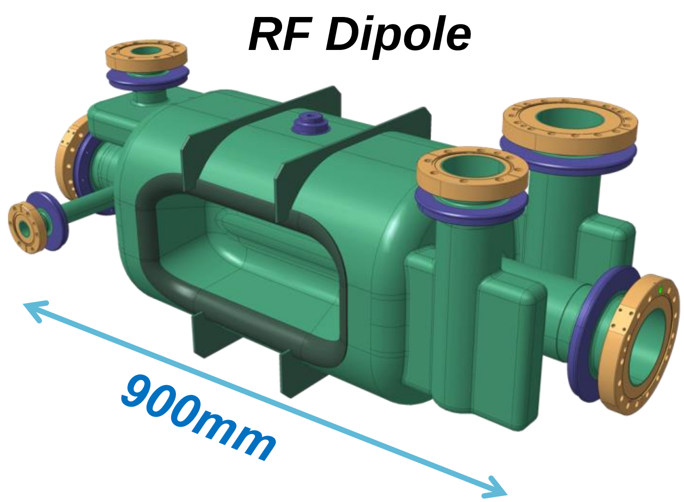


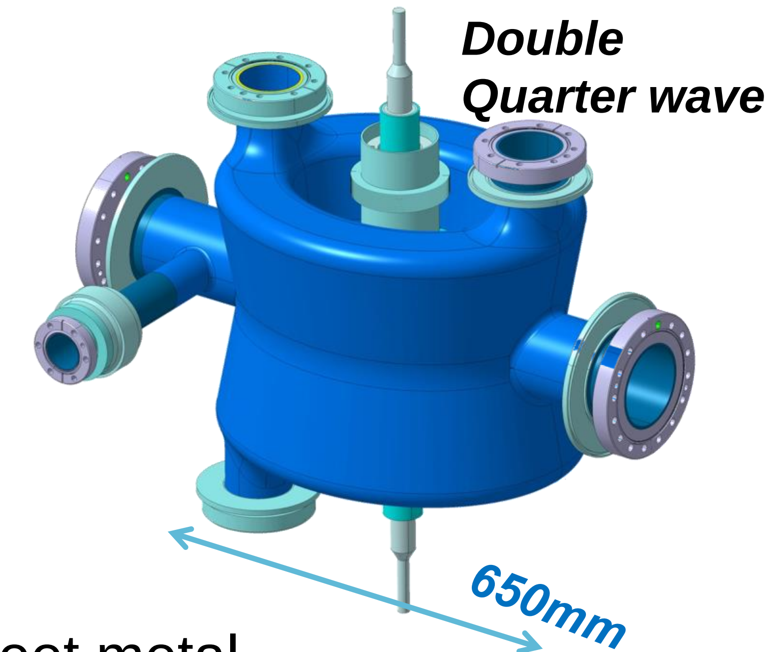
Vertical crossing for ATLAS experiments



Horizontal crossing for CMS experiment

Bottom-Up View: Cavities





Niobium cavities made from 4mm sheet metal
Dipolar symmetry with complex interfaces

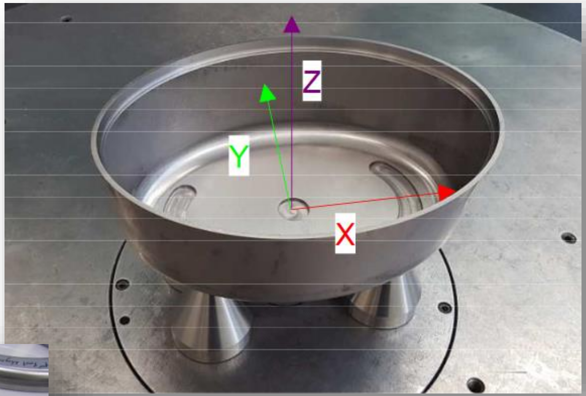
Technologies required:

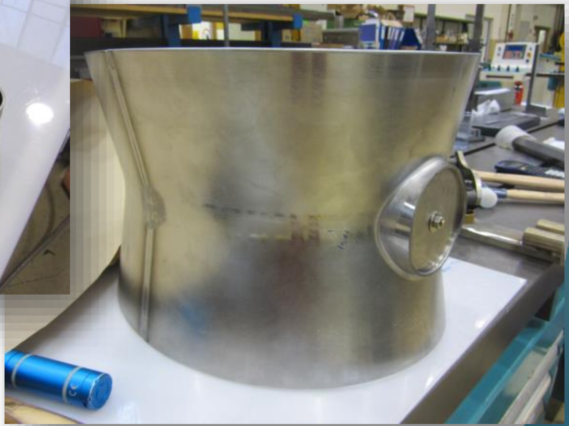
- **Forming** of $3-4$ mm-thick high RRR Niobium sheets
  - Non-axisym. shapes, high aspect ratios, profile tolerance of < 0.5mm
- **EB-welding**: Nb/Nb & Nb/NbTi subject to stringent tolerances < 0.3mm
- **Brazing** (/other) of Nb to S.Steel

Cavity Manufacturing R&D

Early Prototypes (US)

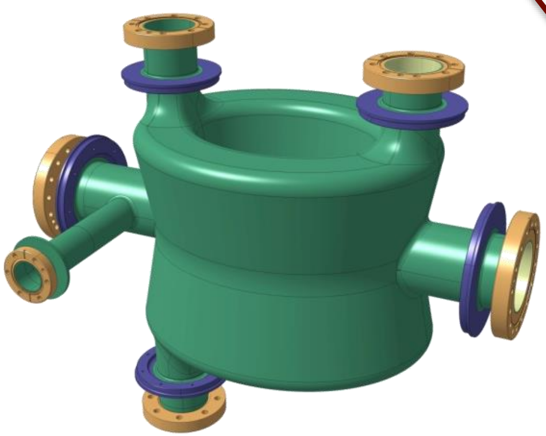
CERN Cavity production for beam tests
(Established manufacturing procedures)

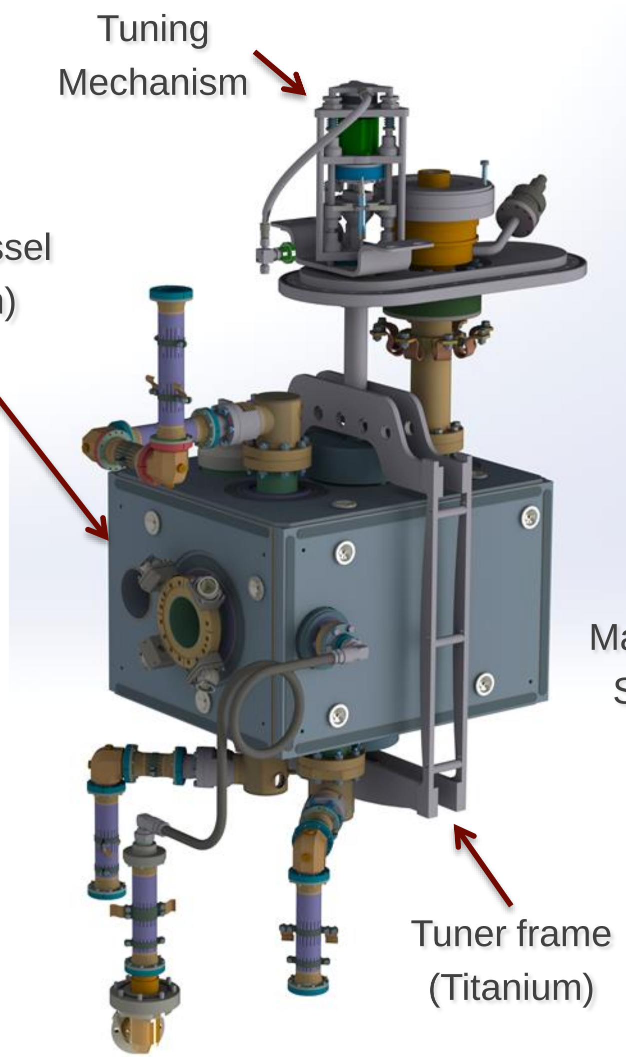


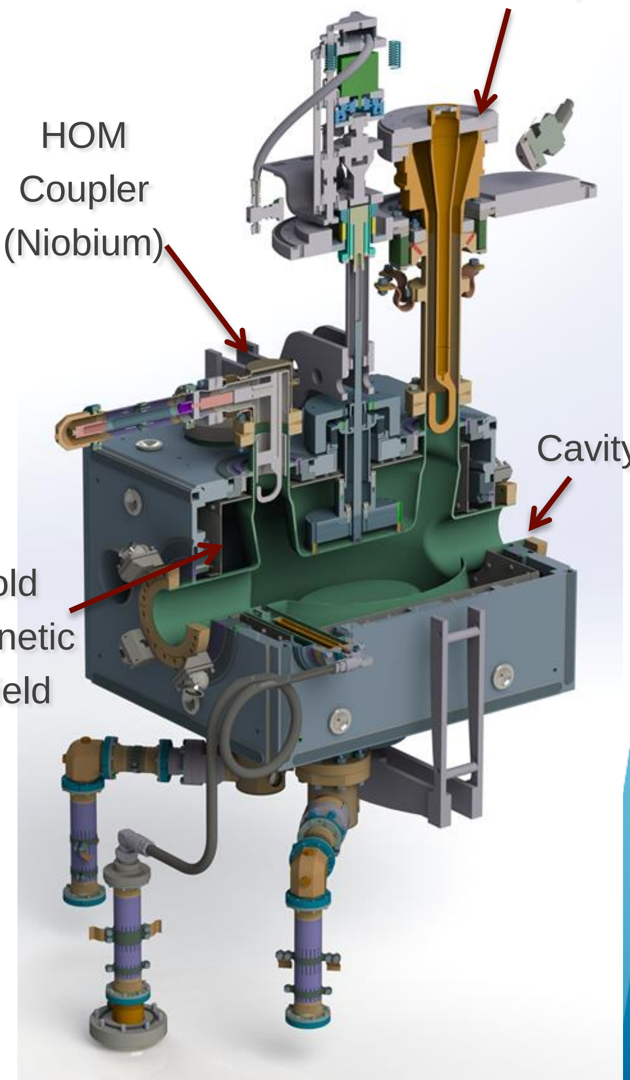


Dressed Cavities (~ 2K volume)

Bare DQW cavity





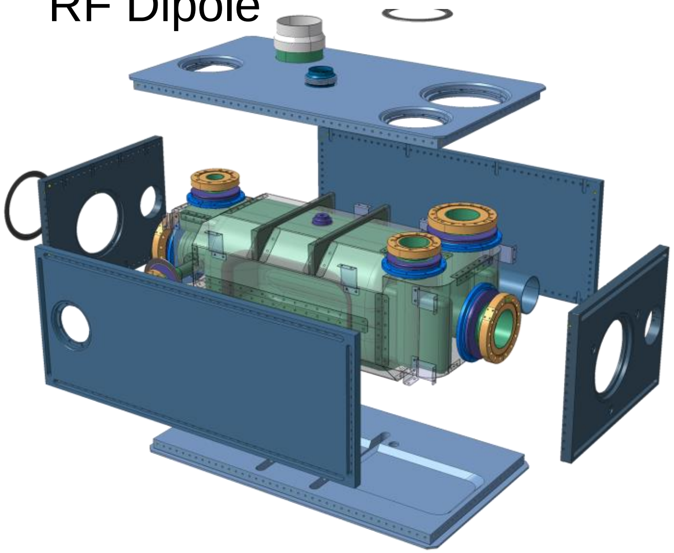


Ti He Vessel & Assembly

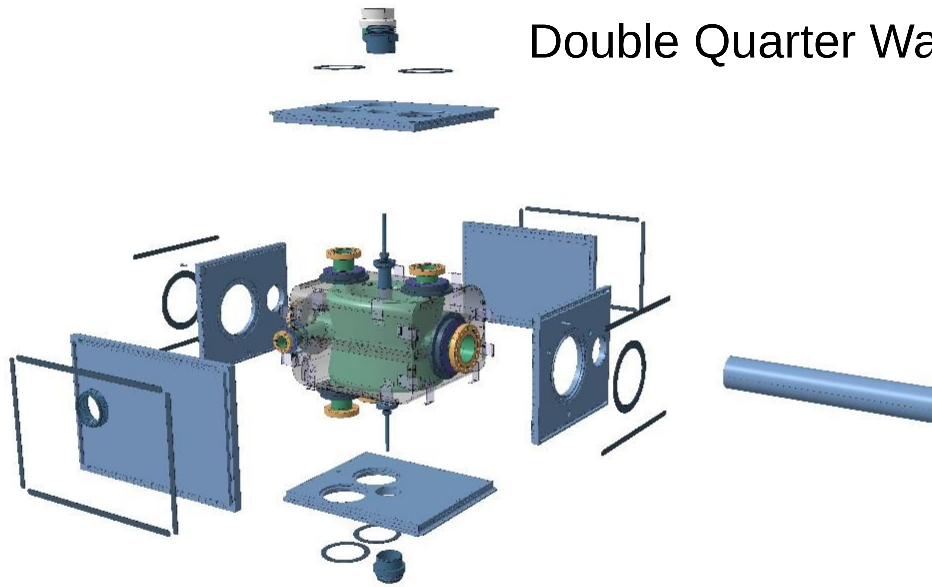
Unique bolted/welded concept for structural integrity & minimal stress to cavity

- **Machining** (Titanium Gr.2)
- **Assembly** + **Titanium TIG welding**
- Supply of **screws** (Ti Gr.5) ~250/vessel
- Supply of interconnection bellows

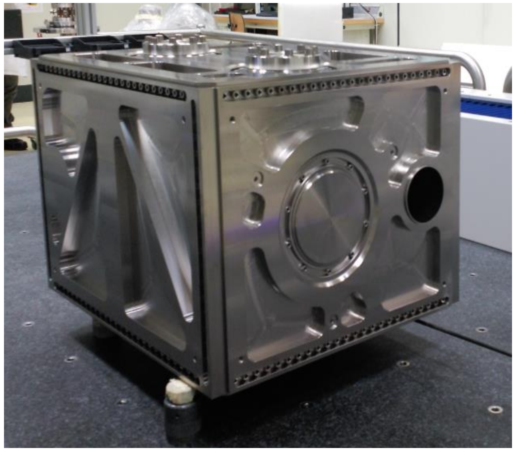
RF Dipole



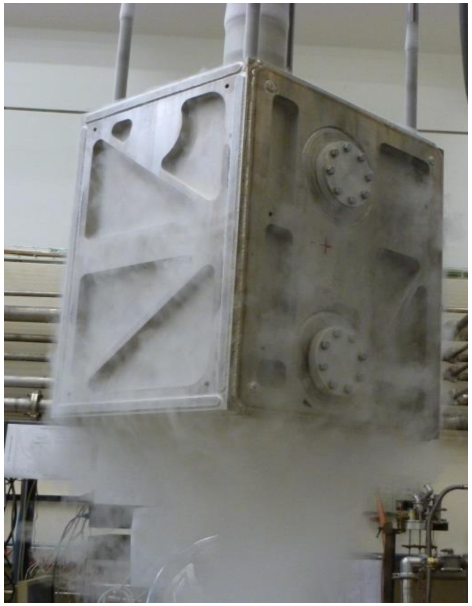
Double Quarter Wave



Prototype He Vessel, Manufacturing R&D



Pressure tests (2.6 bar)

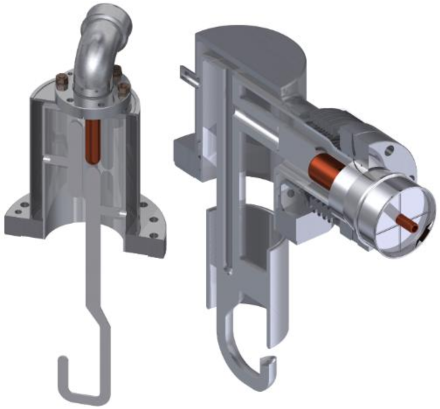


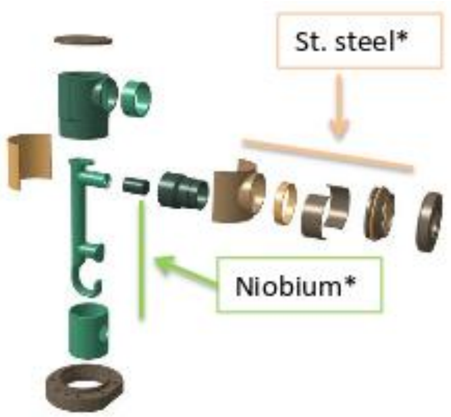
The vacuum levels remained at $\leq 10^{-9}$ mbar (5 thermal cycles)

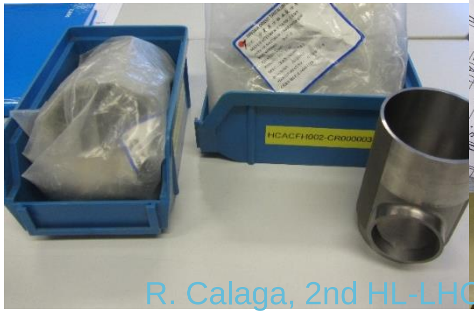
HOM Couplers

One of the several complex pieces
High RRR bulk RRR machined with very tight tolerances (very good results on prototypes)

Series production will require 55+ units

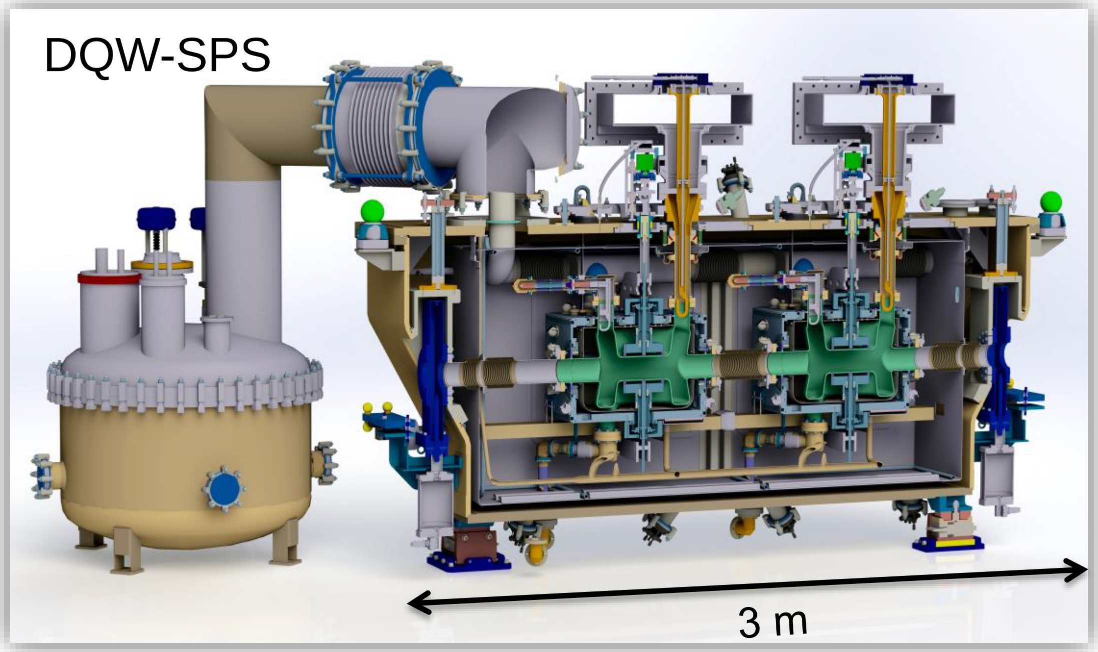






Cryomodule

Manufacturing of Cryomodule components and Auxiliary systems



Sheet metal working of vessel (precision interfaces)

Cryo Line (welds tight at 2K)

Ti-S.Steel direct transitions (also @ 2K)

St. steel Bellows

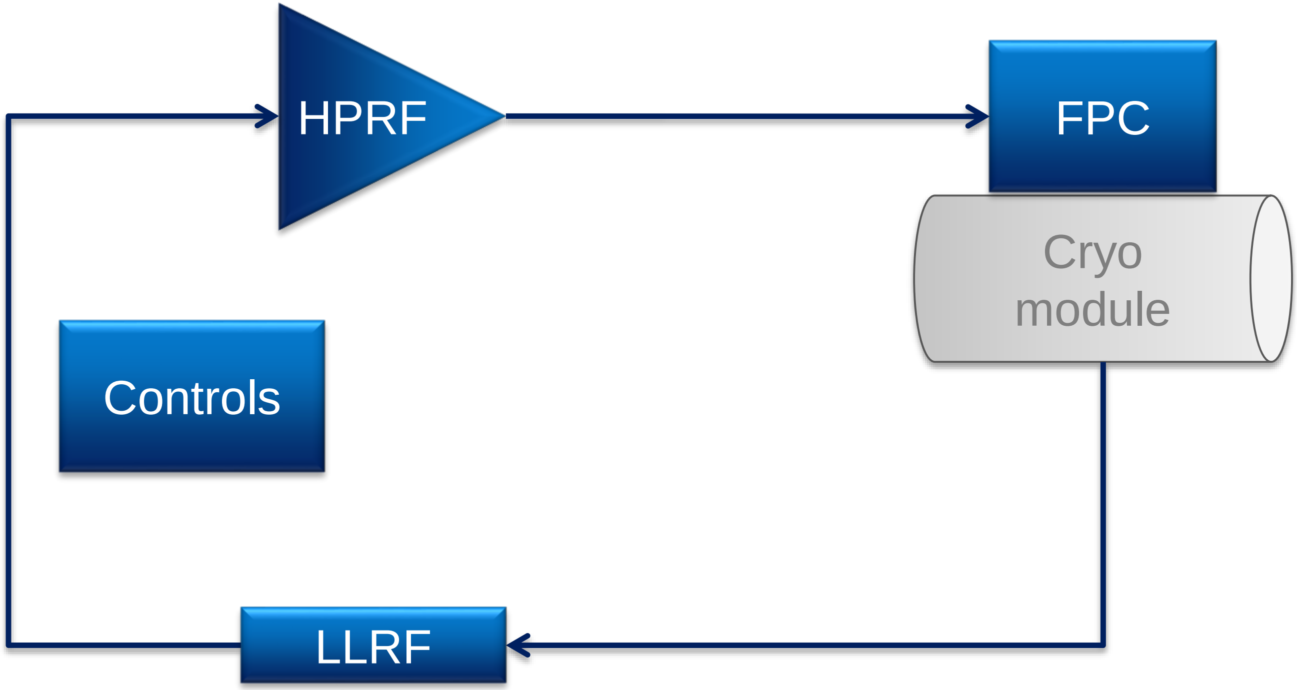
Thermal shielding with Helium cooling, MLI

Alignment & support system

Supply of raw Material: Nb, NbTi, Magn. Shielding, St. Steel, Titanium

RF System

HPRF : High Power RF station (including all power supplies)
FPC : Fundamental Power Coupler
LLRF : RF feedbacks
Controls: All controls systems related to HPRF & LLRF



High Power RF System

- Baseline Option: IOT power stations
  - 80 kW for up to hundreds of ms, 40 kW CW
  - 400 MHz, Input power < 1 mW, BW_{-1dB} 8 MHz
  - 400 VAC from the grid
  - Wall plug efficiency > 55%
- Alternative option to be studied
  - SSPA with same Technical Specification
  - Final cost cheaper than IOT option

Schematic of the RF layout, Underground

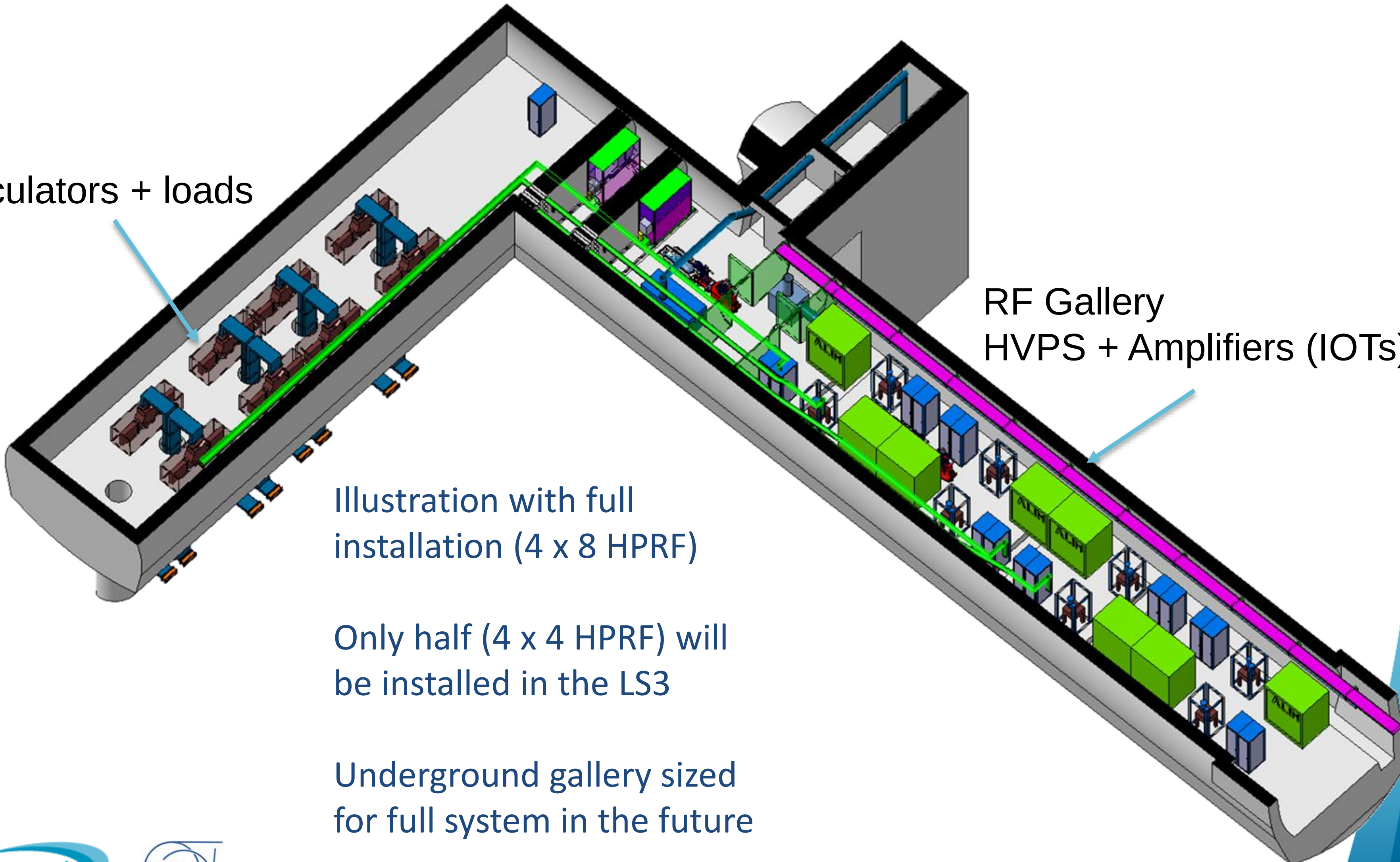


Illustration with full installation (4 x 8 HPRF)

Only half (4 x 4 HPRF) will be installed in the LS3

Underground gallery sized for full system in the future

LHC RF power stations (2019-2022)

- Acquisition Strategy
  - CERN will produce Technical Specification including outcome of the SPS tests
  - 16 entire integrated systems with single supplier
  - Sub contracting of non-strategical sub-assemblies
  - Possibility to directly buy some sub-assemblies to sub-contractor (IOT tube and trolley for example)
  - Market Survey to qualify companies, invitation to Tender to qualified companies

Low Level RF & Slow Controls

- LLRF allows for precise regulation of the cavity field
  - Keep cavity field in phase with bunch centre, alignment of the various cavities (counter-phasing) & reduction of cavity impedance at f_0
  - Fast field regulation following a cavity trip, minimize RF noise induced transverse emittance growth

- Slow controls provide a standard infrastructure to operate the RF power system & interface to external systems (cryo, vacuum, access, etc..)
  - Provide fast interlocks for protection
  - Implement the switch ON/OFF procedures for the RF power plant
  - Implement the local and Remote software interface for operation and for RF experts
  - Expose all relevant data to the CERN standard data acquisition, logging and alarms services

Final Comments

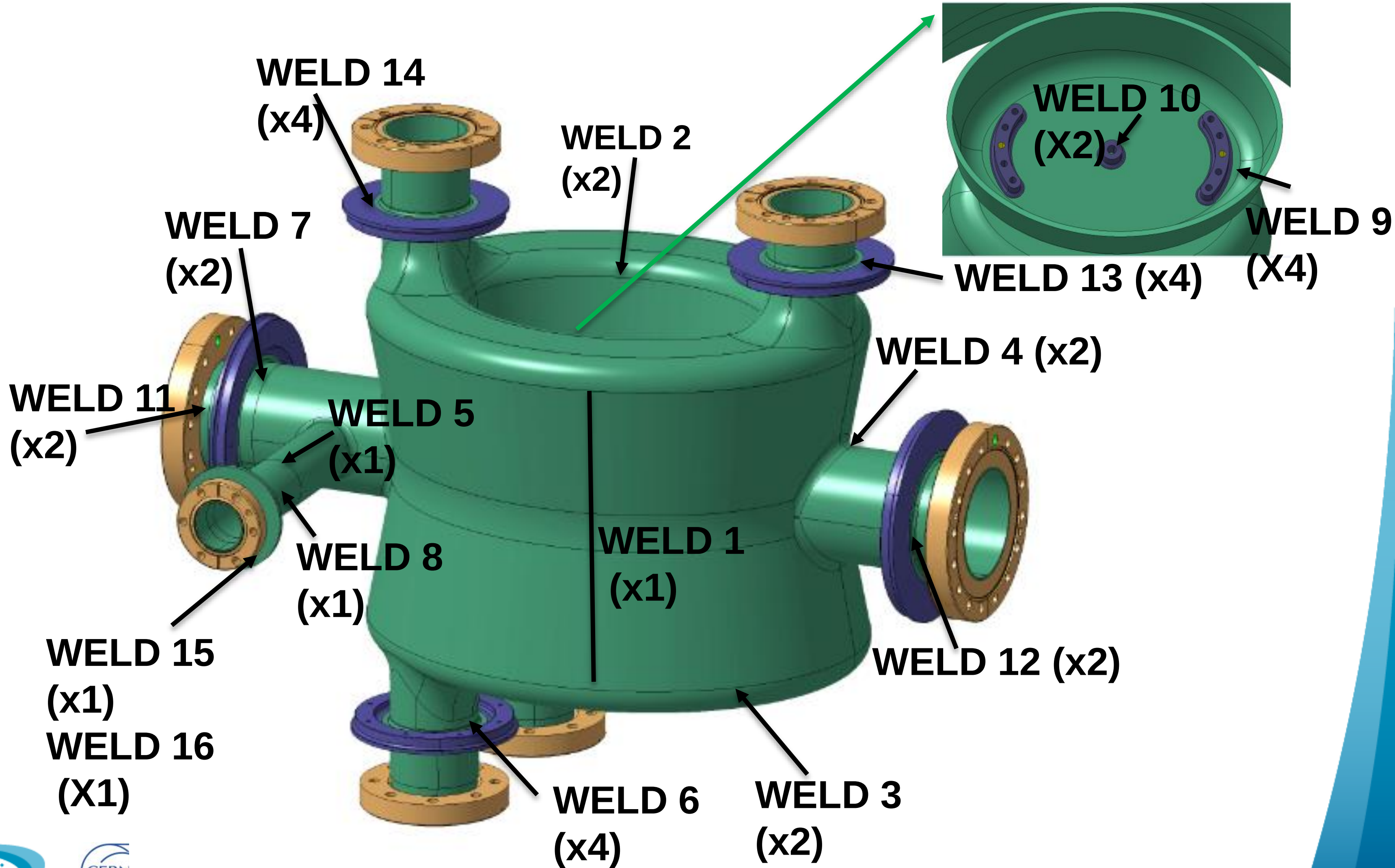
- LHC Crab Cavity system will be one of the most complex systems in the HL-LHC with several state of the art developments that are ongoing presently for technology validation in the SPS

- We are preparing for a progressive & significant involvement of industry in the coming years to industrialize the production of 8 Cryomodules and associated RF system hardware.

Thank you for your attention

Weld Map, DQW

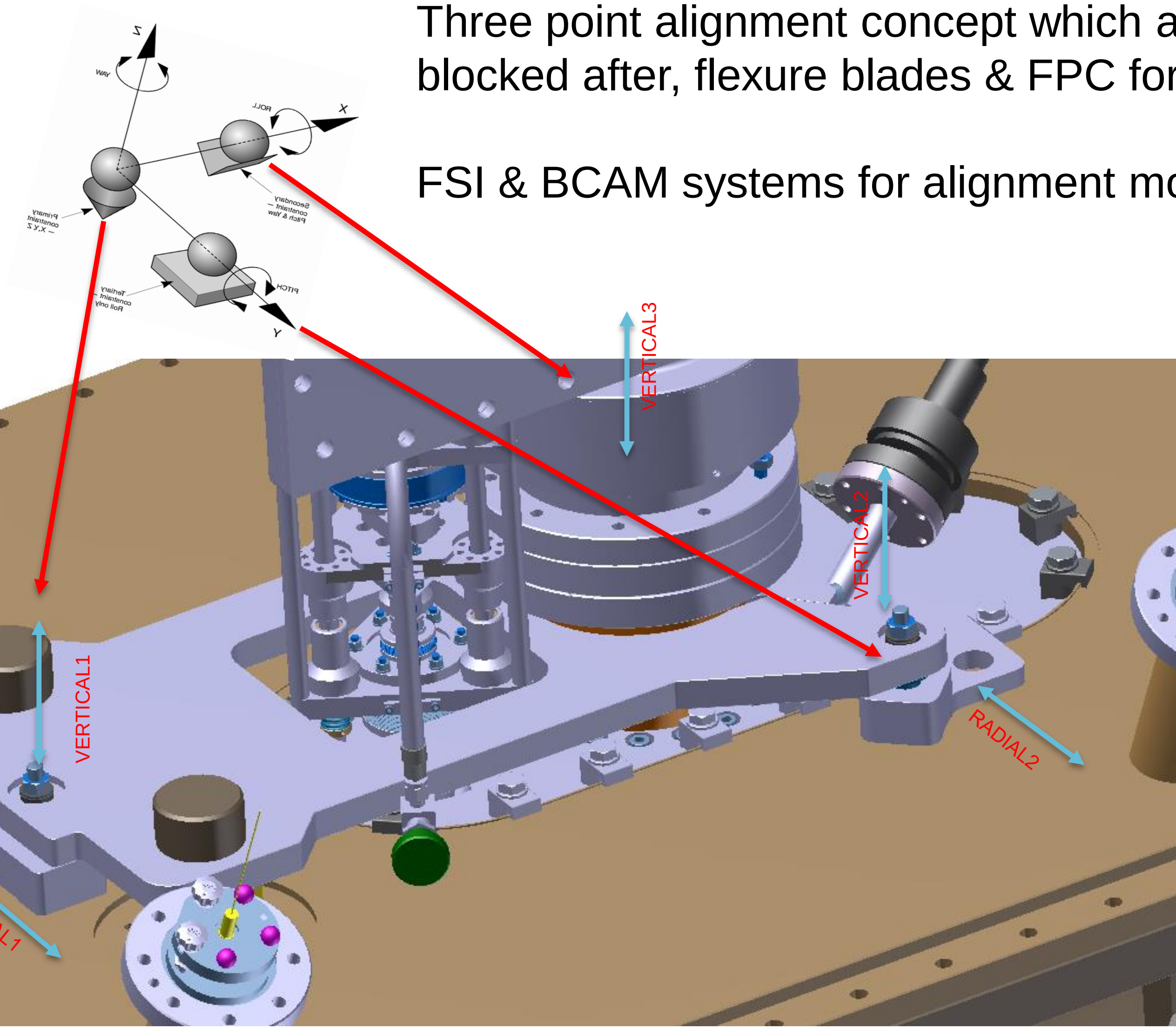
16 complex welds to qualify & perform (with tight tolerances)



Cavity Supports & Alignment

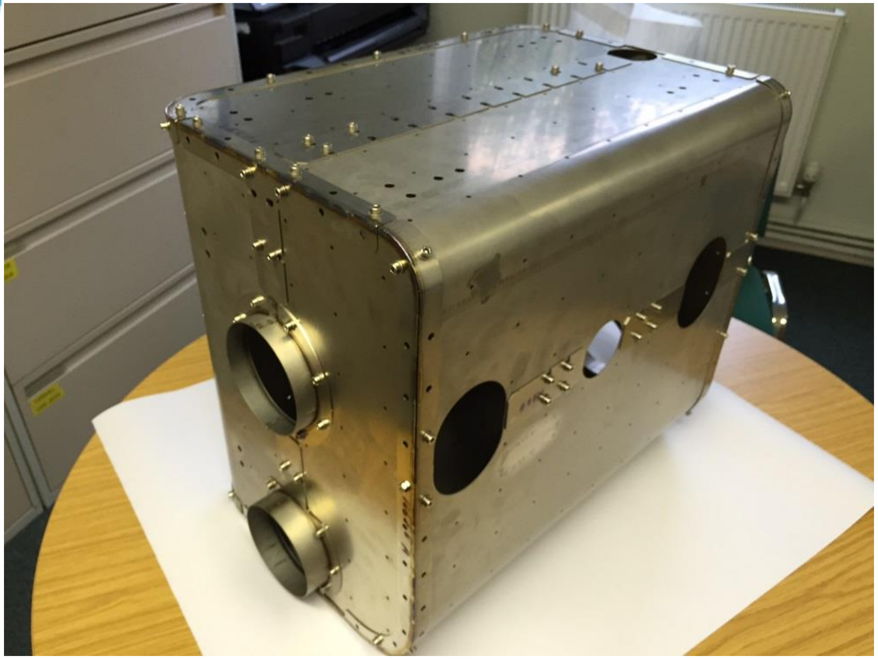
Three point alignment concept which are blocked after, flexure blades & FPC for support

FSI & BCAM systems for alignment monitoring

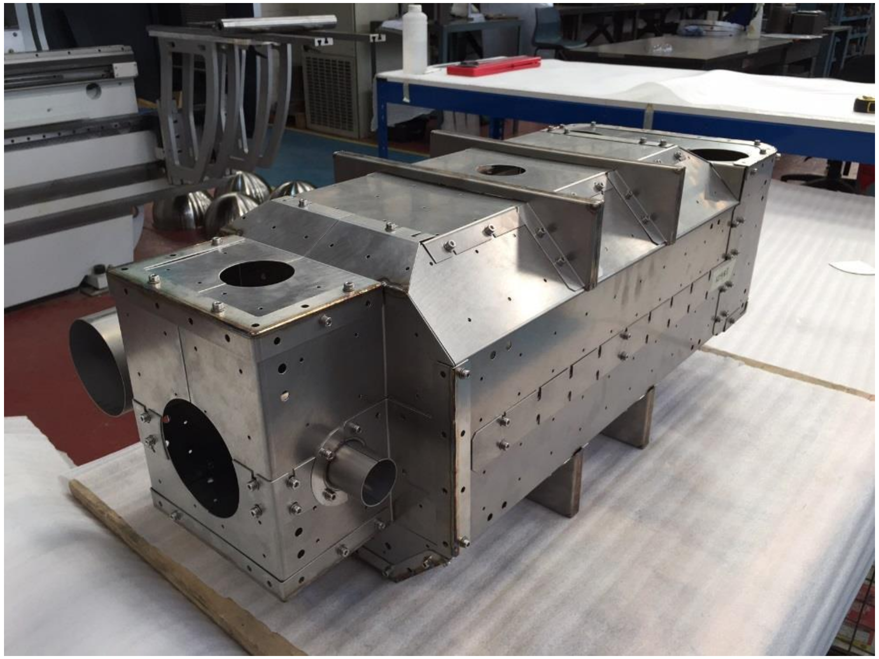


2K Internal Magnetic Shields

Double QW

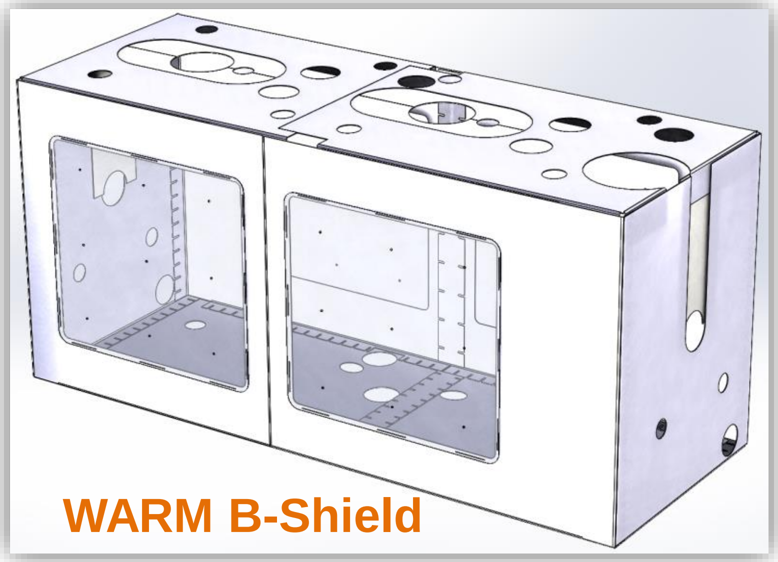


RF Dipole



Internal magnetic shields integrated by STFC-UK industry. 1 mm Cryophy, annealed after shaping, supported by Ti brackets

Shielding: Design for SPS Prototype



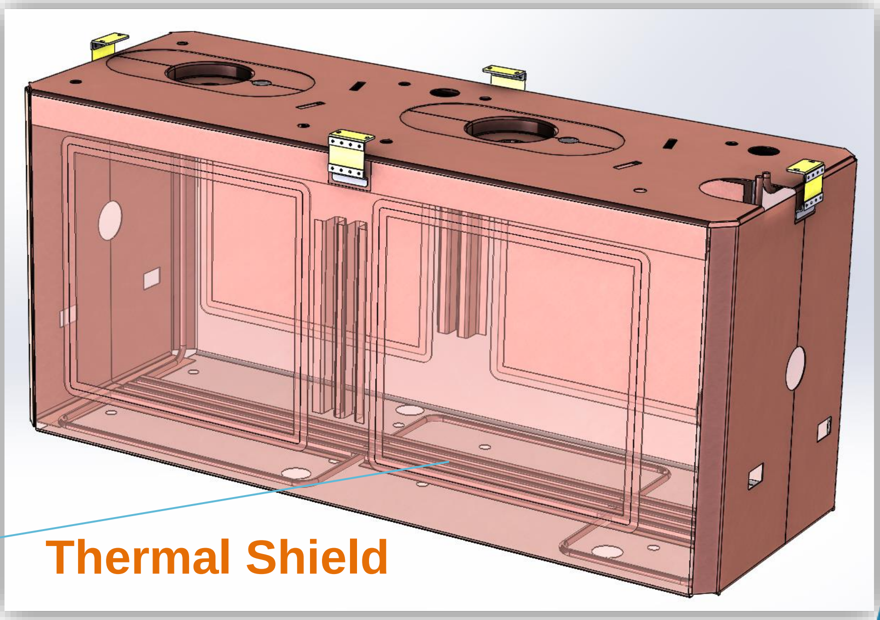
Magnetic Shielding alloy (cryophy, μ-metal):

Forming + **assembly**

Annealing treatment

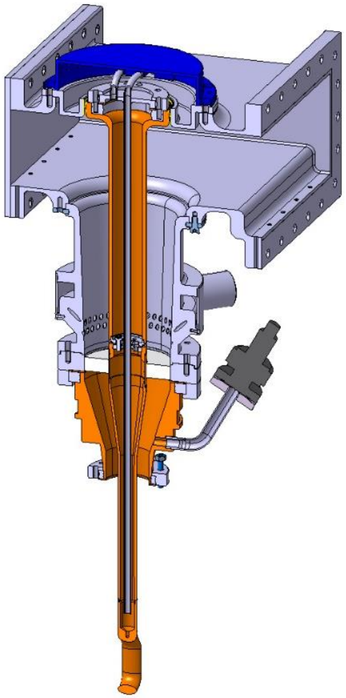
Copper alloy: **Forming** + **assembly**

Copper plates, Copper pipeline brazed on the plates



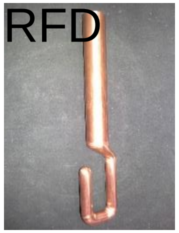
Helium cold gases

Power Coupler Manufacturing R&D

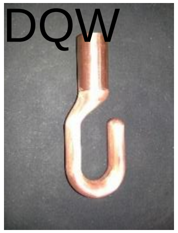


2+2 Couplers fabricated for SPS tests

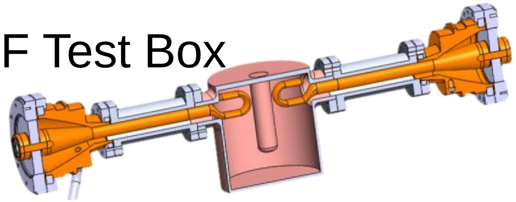
RFD

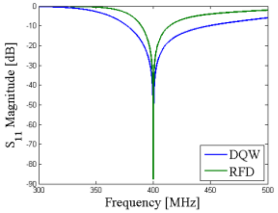


DQW



RF Test Box

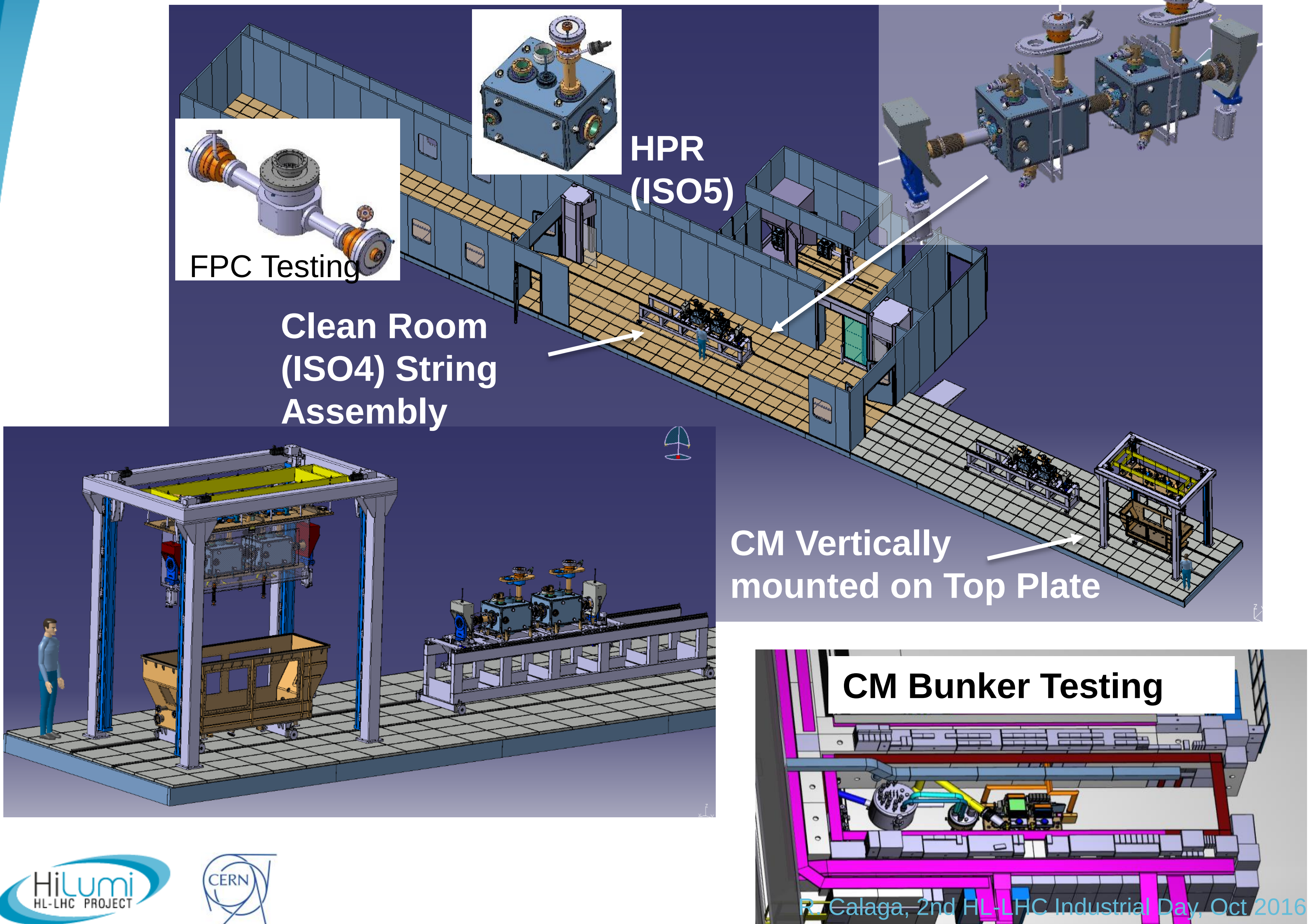




Coaxial-type 50Ω single window coupler
Standardized for both cavities (LHC: 16 + 8 spares)

For the LHC: Raw materials, machining, vacuum brazing & high power conditioning

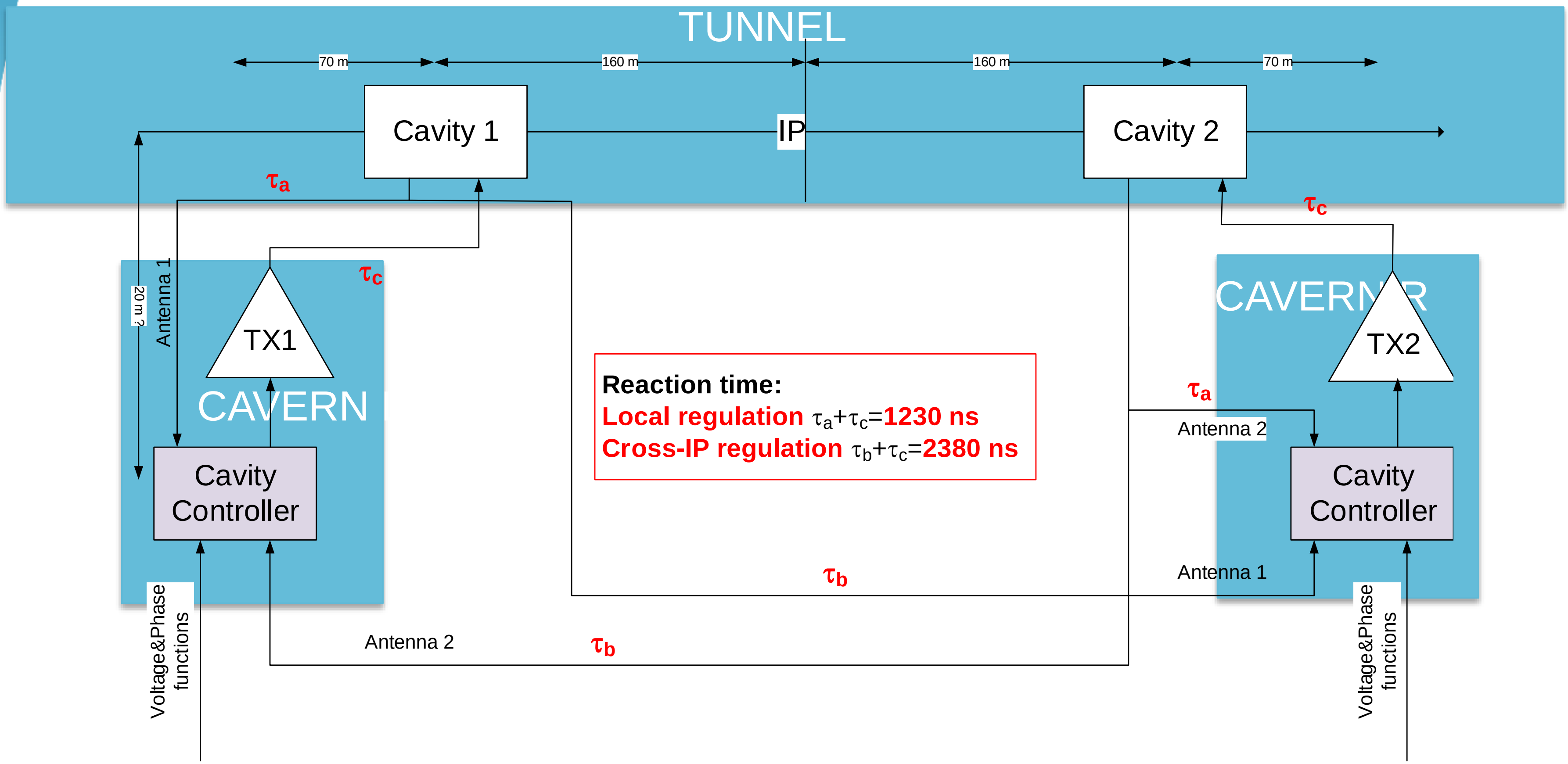
Tooling, Assembly & Testing



R&D for compact SSPA (2017-2018)

- Purchasing strategy, options under study
  - Buy the entire integrated system
  - Buy the system with several contracts
    - RF blocks
    - Combining system
    - Power supplies
    - Controls
  - Mix between CERN internal development and contracts to companies

LLRF Layout for LHC



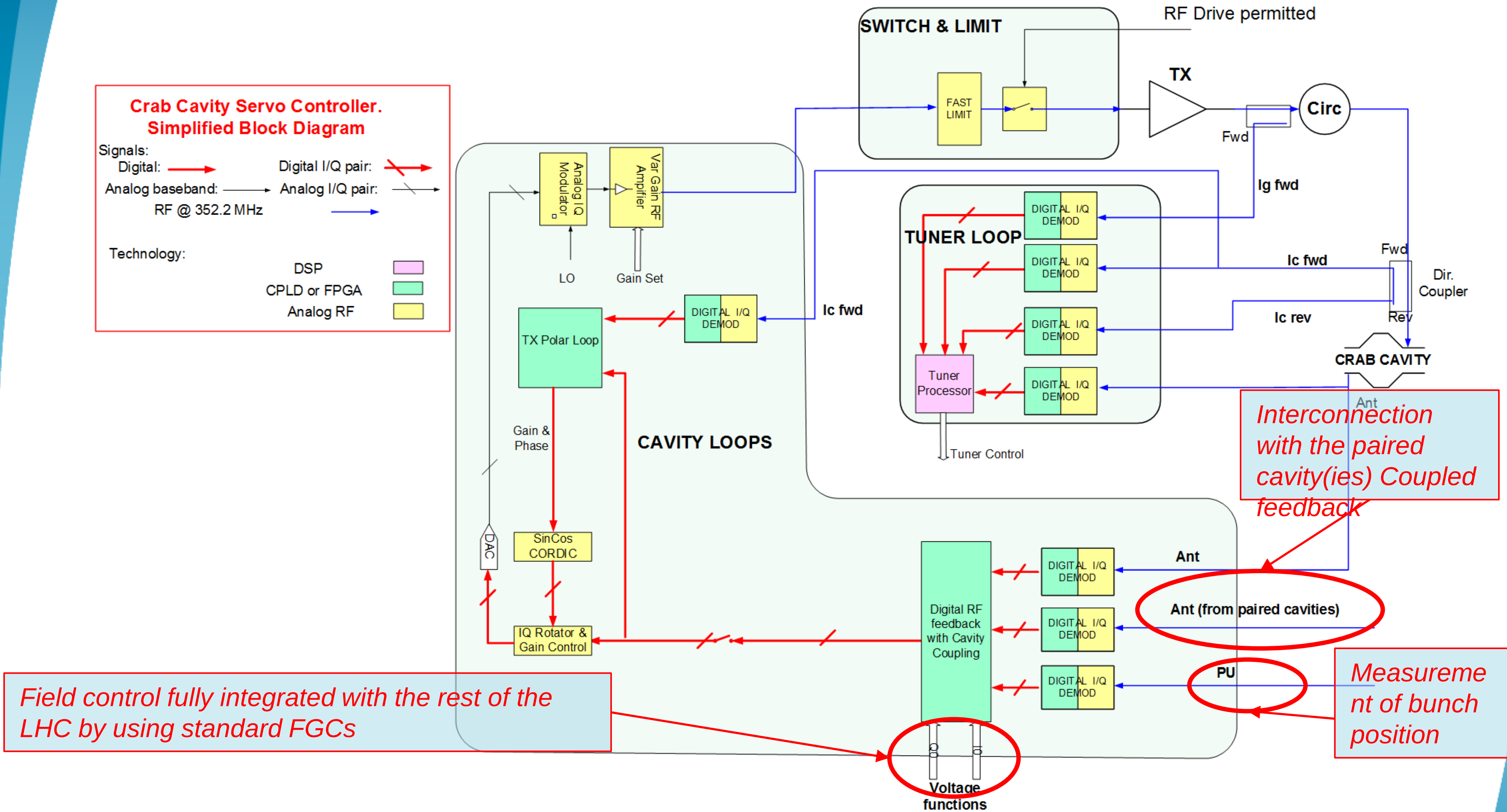
RR cavern architecture:

τ_a is the delay of the local antenna signal (20+70) x 3.7 ns = 333 ns rounded to **370 ns**

τ_b is the delay of the opposite antenna signal (320+70+20) x 3.7 ns = 1517 ns rounded to **1520 ns**

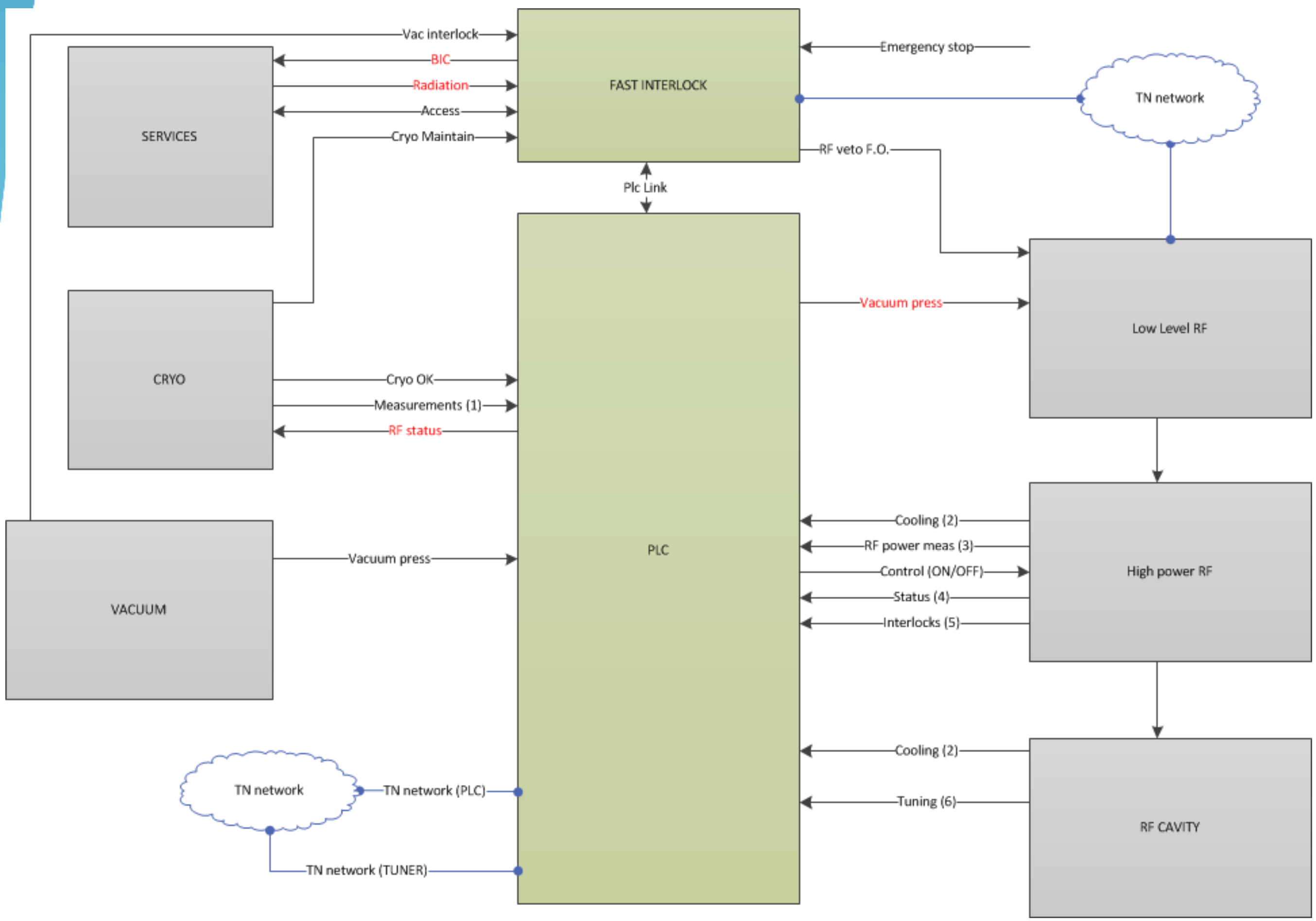
τ_c is the drive path delay, including LLRF, TX, circulator and coax = 300 ns + 100 ns + 50 ns + (20+70) x 3.7 ns = 783 ns rounded to **860 ns**

Low Level, System Architecture



Version: 20150303

Slow Controls, System architecture



One PLC to control 2-cavities in a CM

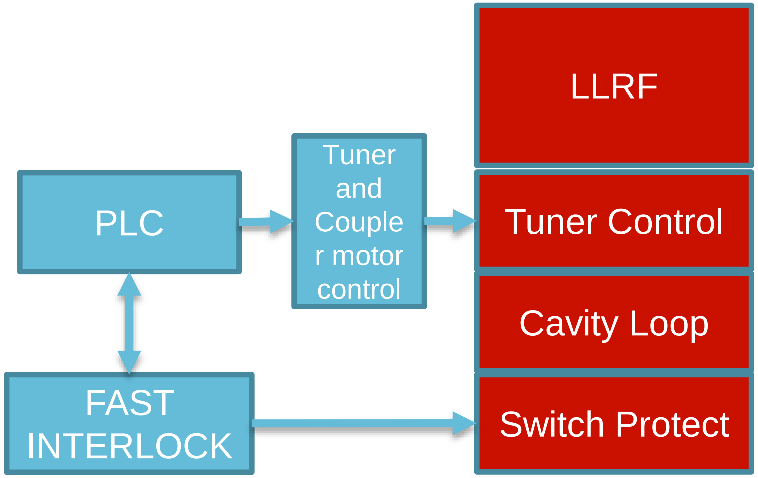
Standard RF controls PLC and hardware components used in LINAC4 and SPS

Expected PLC cycle time **2ms**
Expected Fast Interlock cycle time **15us**

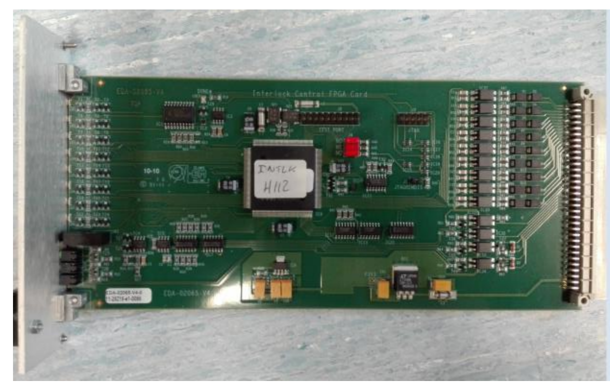
Interlocks

In the RF systems some signals must be controlled with a reaction time faster than a conventional automation device can do, i.e. 15usec

For this we have CERN made FPGA based interlock controllers.
The required number of cards are grouped in a chassis to realize the interlock function



An example of interlock system for LINAC 4



An example of interlock module

SPS Movable Table

In the SPS tests, a movable table along with a mechanical bypass will allow to bring the two-cavity module in and out of the beam

Involves a horizontal movement of 0.51 m &
Active Alignment @ SPS Test: motorized & remotely-controlled