Crab Cavity and Cryomodule Development for HL-LHC

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SRF 2015

17th International Conference on RF Superconductivity

Whistler, BC, Canada – *18 September, 2015*

International Collaboration

The Cockcroft Institute
of Accelerator Science and Technology

CERN

High Luminosity LHC

LARP

Science & Technology Facilities Council

Outline

- Context
- Cryomodule components
- Heat balance
- Summary

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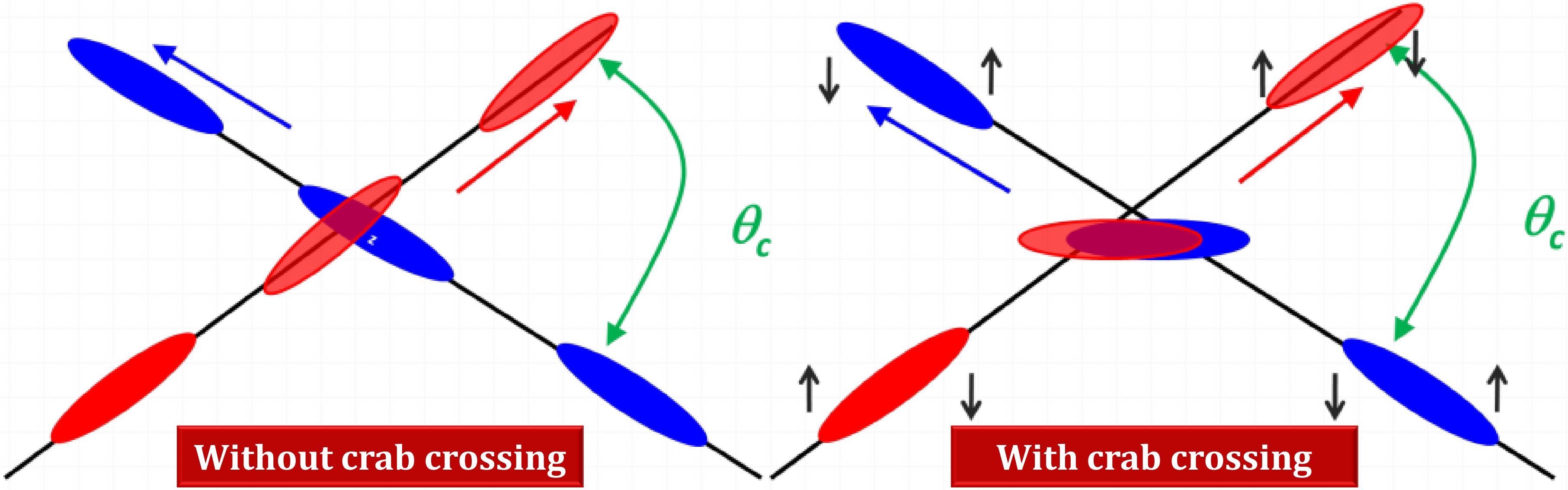
Context

- **Particle accelerators (LHC)**: goal is the study of collisions between two particle beams
- The higher the number of collisions in the unit of time **(luminosity)**, the larger the number of data acquired and studied
- $\theta_c > 0 \rightarrow$ **reduction in luminosity** compared to head-on collisions



- Crab crossing: **rotation of the colliding bunches** at the interaction point until $\boldsymbol{\theta_c = 0}$
- Two RF design : **Double Quarter Wave (DQW) and RF Dipole (RFD)**

RF superconductive crab cavities are a key upgrade in the frame of the HL-LHC project, aiming at increasing the LHC luminosity by a factor 10!

Context

- **Particle accelerators (LHC)**: goal is the study of collisions between two particle beams
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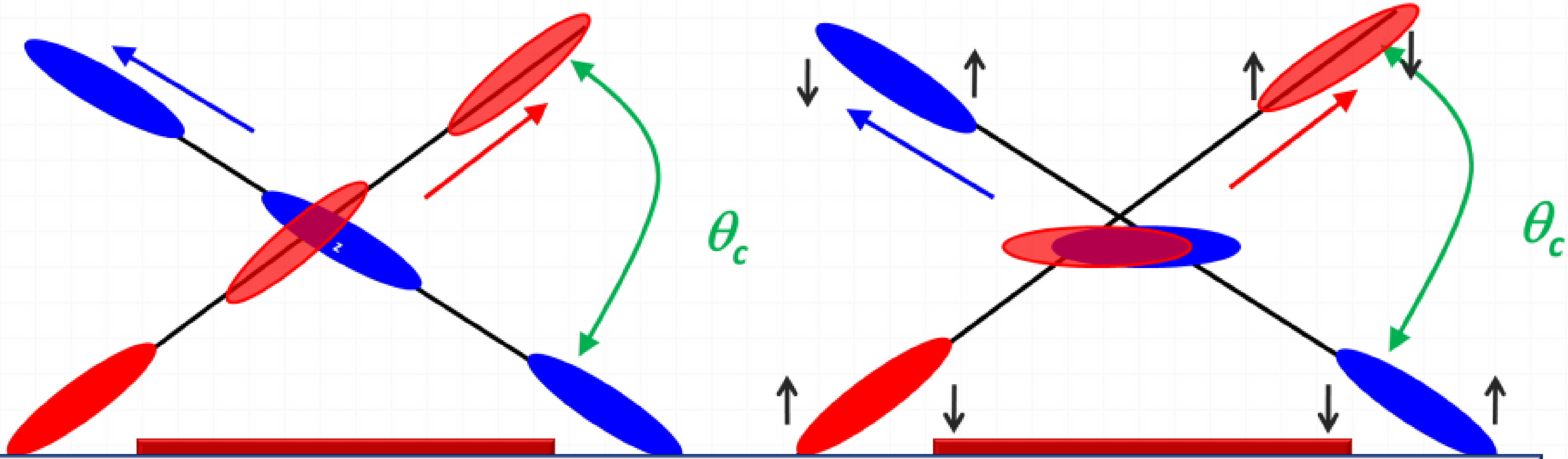


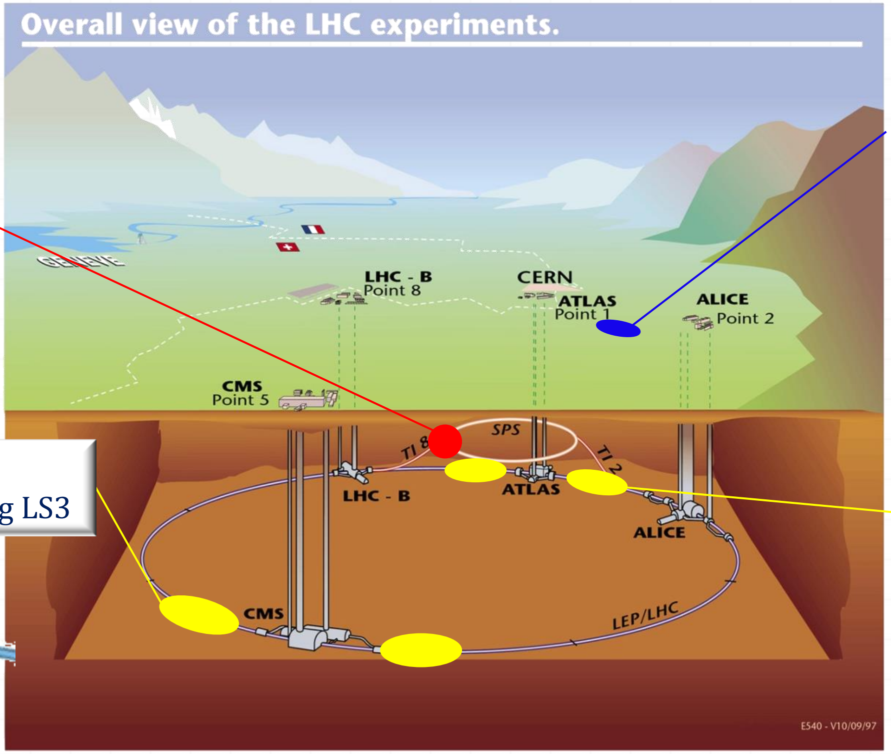
- J. Delayen, "Review of SRF Deflecting Cavity Development", **THAA01**
- S. U. De Silva, "Electromagnetic Design of 400 MHz RF-Dipole Crabbing Cavity for LHC High Luminosity Upgrade", THPB053

RF superconductive crab cavities are a key upgrade in the frame of the HL-LHC project, aiming at increasing the LHC luminosity by a factor 10!

Context

- Crab cavities: **never adopted in hadron colliders**
- **Testing in the SPS** is necessary before installation in the LHC

2013-14	2015-16	2017-18	2019-24	2024-25
Cavity Testing & Prototype Cryomodule	SPS Cryomodule Fabrication	SPS Tests & LHC Pre-Series Module	LHC Cryomodule Construction & Testing	LHC Installation



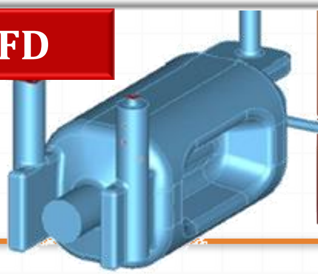
SPS: cryomodule testing before LHC installation

SM18 area: cold test of cryomodules prior tunnel installation

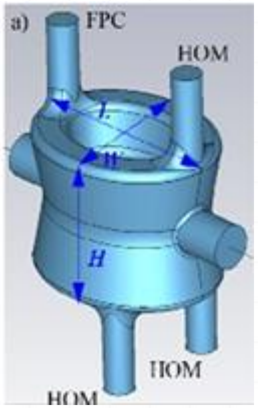
LHC Point 5 (horizontal crabbing): installation during LS3

LHC Point 1 (vertical crabbing): installation during LS3

RFD



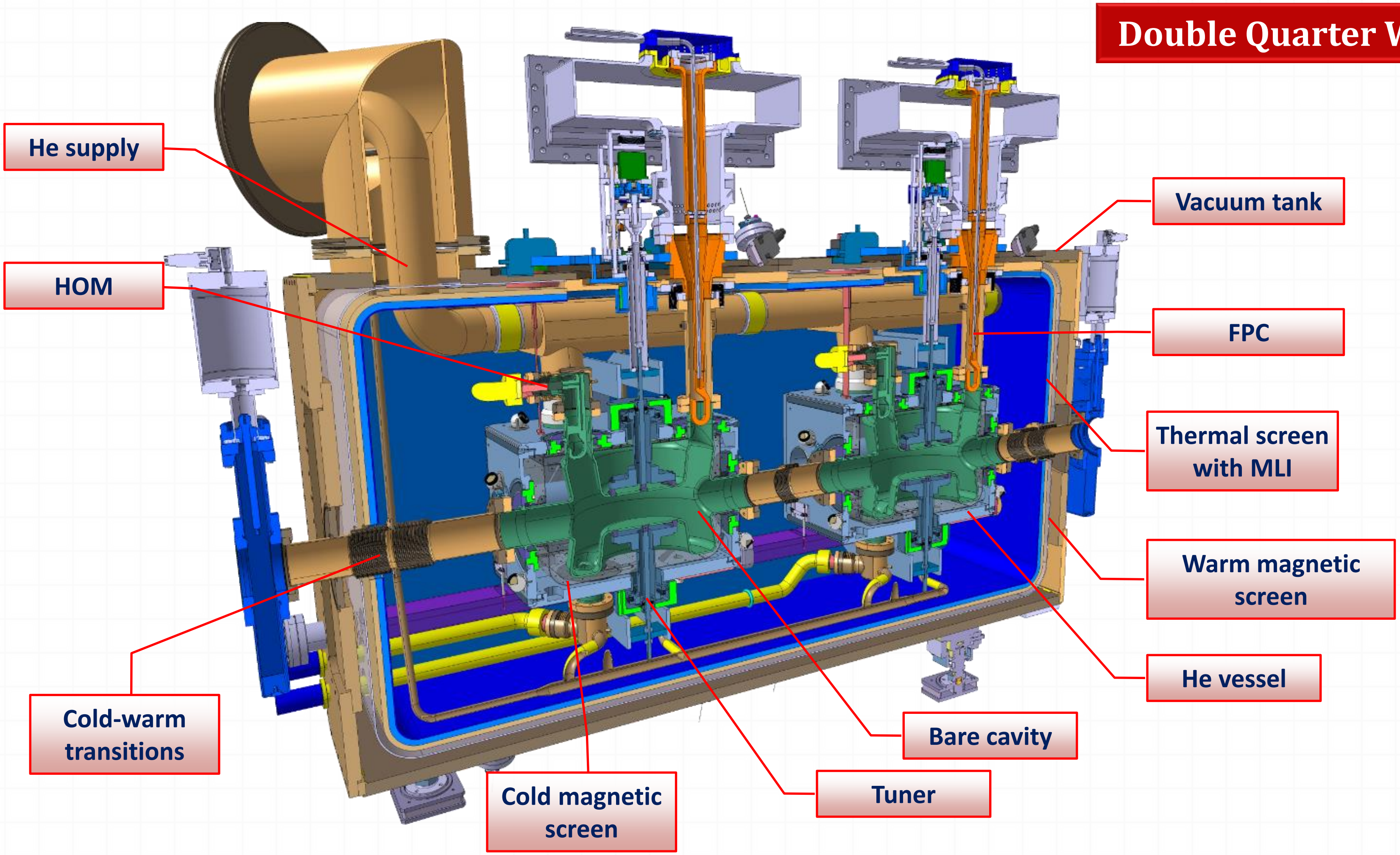
DQW



Cryomodule

- Design of the cryomodule **well advanced**
- **Common effort between CERN, UK and US-Larp**

Double Quarter Wave



Cryomodule

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17th International Conference on RF Superconductivity
Whistler Conference Centre
September 13-18 2015

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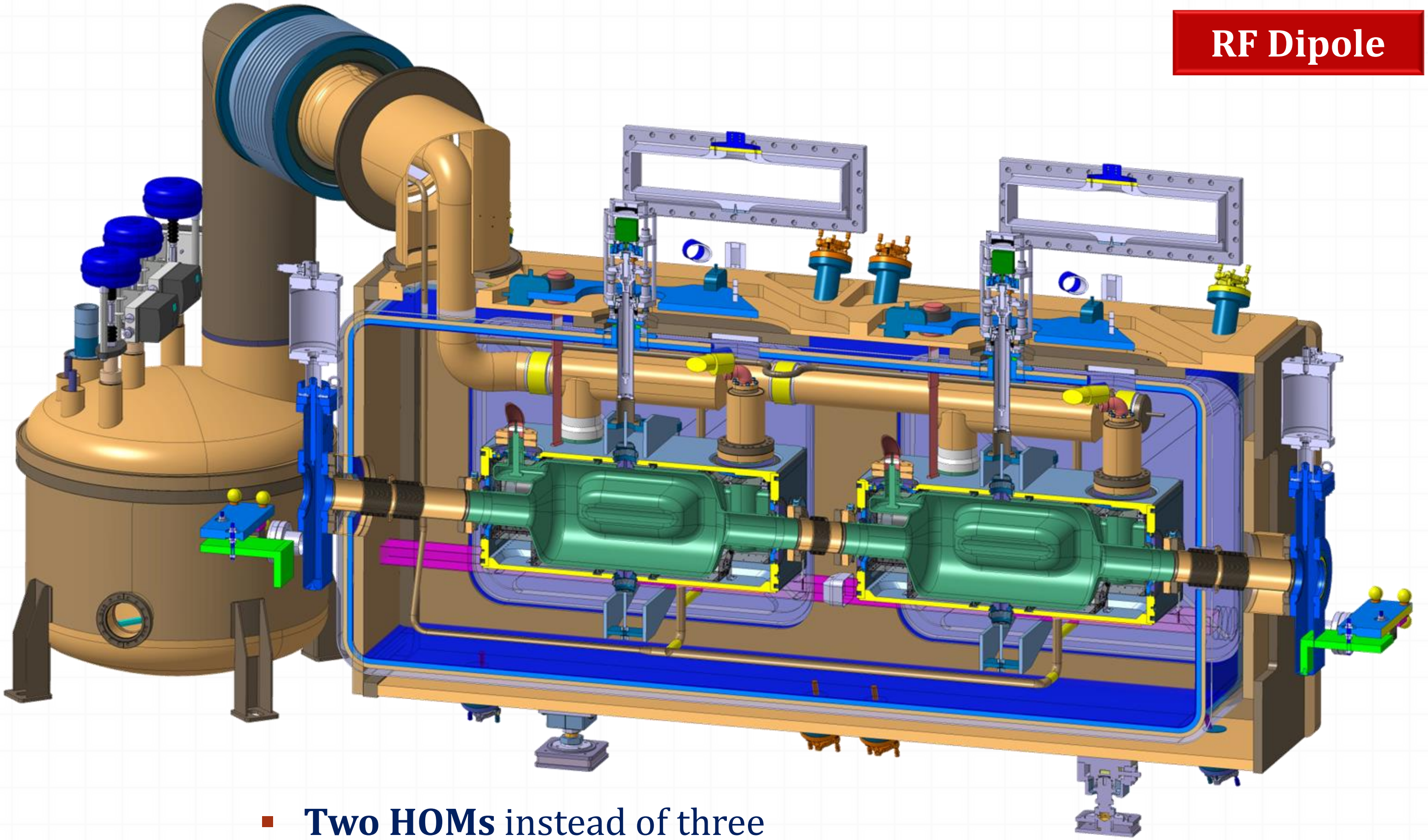
RF Dipole



- **Two HOMs** instead of three
- **Maximum compatibility** of the two designs!

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- Heat balance
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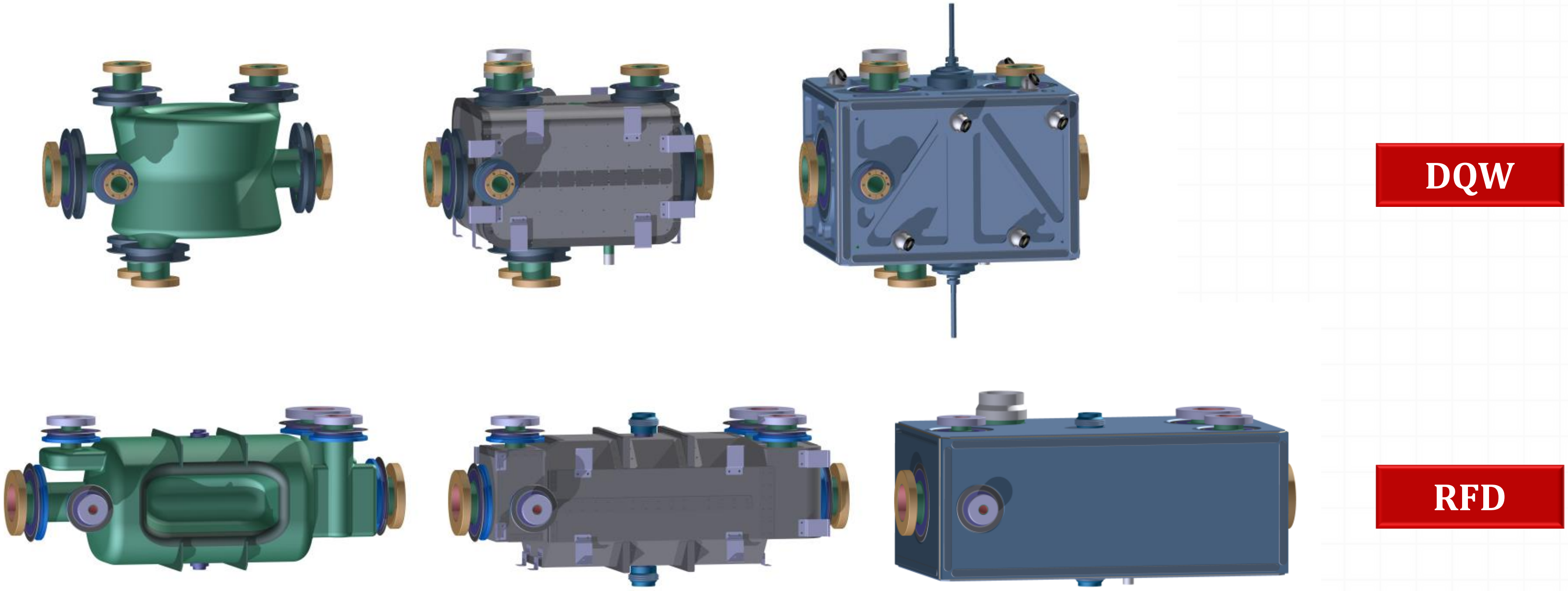
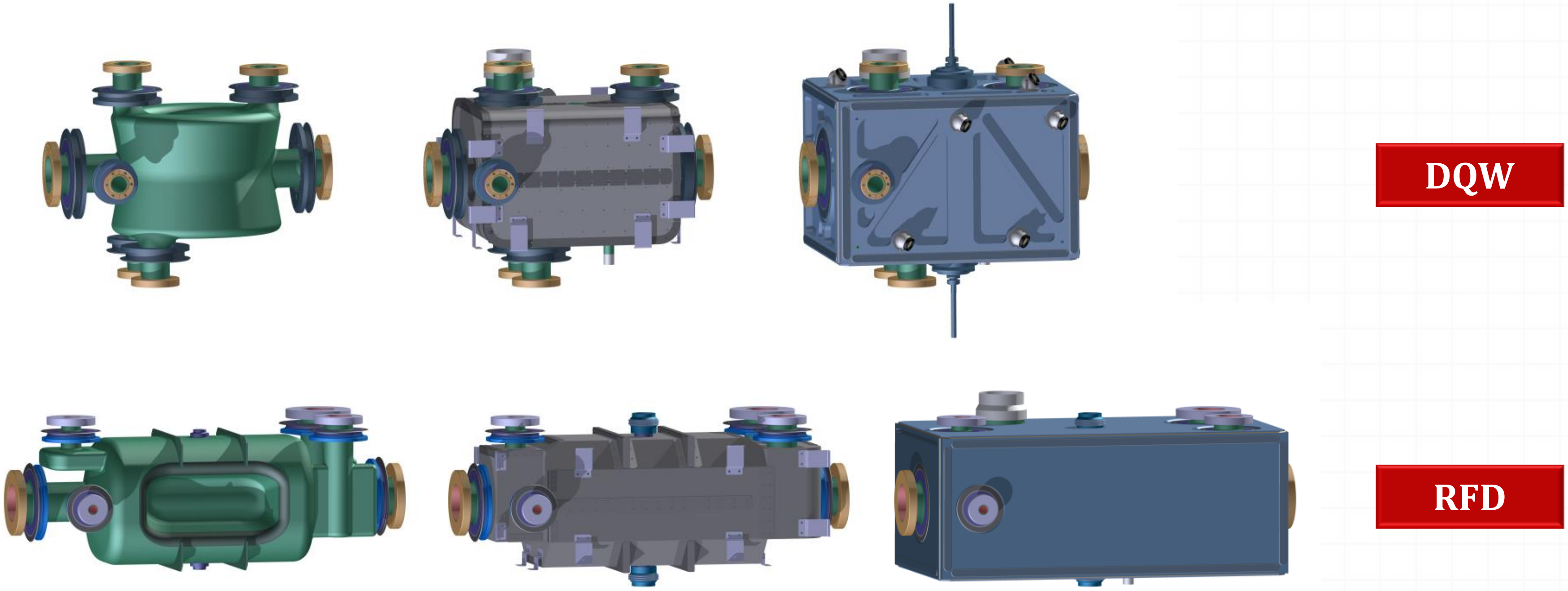
Dressed Cavity



- RF design: **successfully completed**
- PoP RF tested with results **above the specification**
- **Superfluid He at 2 K** (RF performance, microphonics, machine protection)
- **Dressed cavity** = cavity + cold magnetic shield + helium tank + tuning + couplers

Dressed Cavity



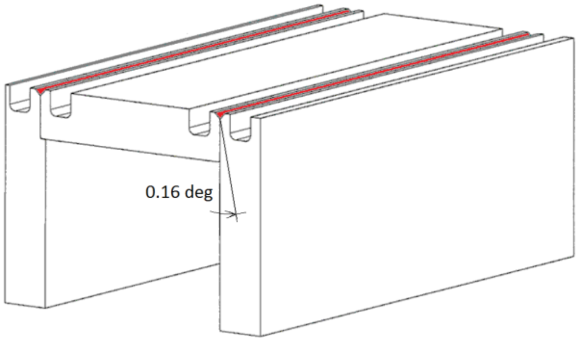
- M. Navarro, R. Calaga, “Bead-Pull Measurements of the Main Deflecting Mode of the Double-Quarter-Wave Cavity for the HL-LHC”, THPB019
- K. G. Hernandez, “Performance Evaluation of HL-LHC Crab Cavity Prototypes in a CERN Vertical Test Cryostat”, THPB050
- C. Zanoni, “Design of Dressed Crab Cavities for the High Luminosity LHC Upgrade”, THPB070

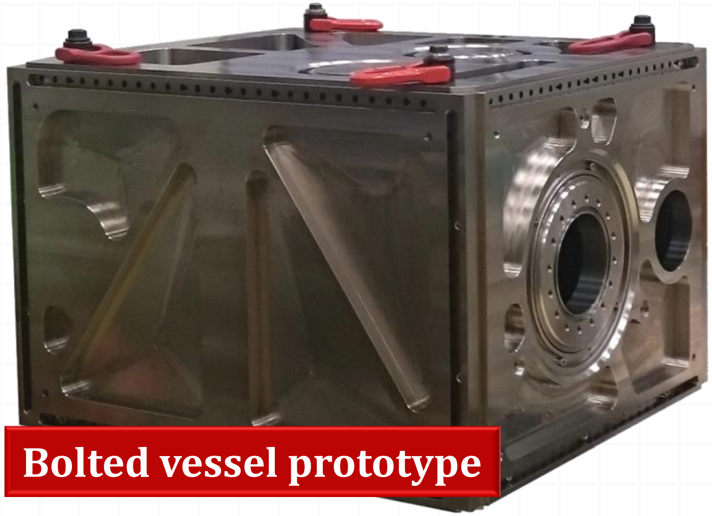
Helium tank

- Functions:
  1. **He container**
  2. **Cavity stiffener** (cavities are only 4 mm thick!)

Deformation of the tank is transferred to the cavity. Estimation (test) of ~**1 mm deformation at interface if tank is fully welded**.

Design approach: **bolted tank** with superficial welds for leak tightness





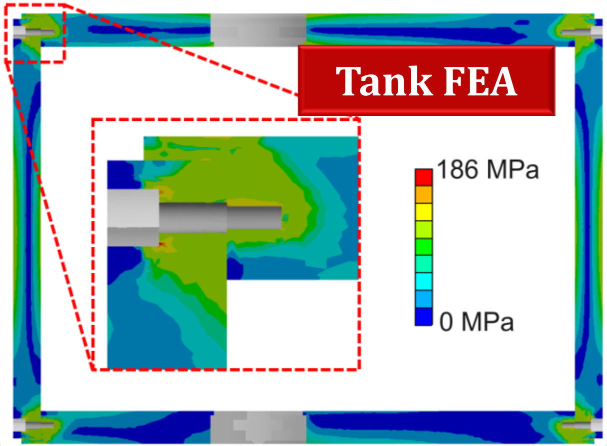
Bolted vessel prototype

- Max loads:
  1. Gravity
  2. 1.8 bara of pressure (during cool down)
  3. 4.4 kN bolt preload
  4. Pretuning, only for DQW (about 0.11 mm displacement at the cavity interface)

Titanium tank and bolts (M6) to minimize the thermal stresses during contraction

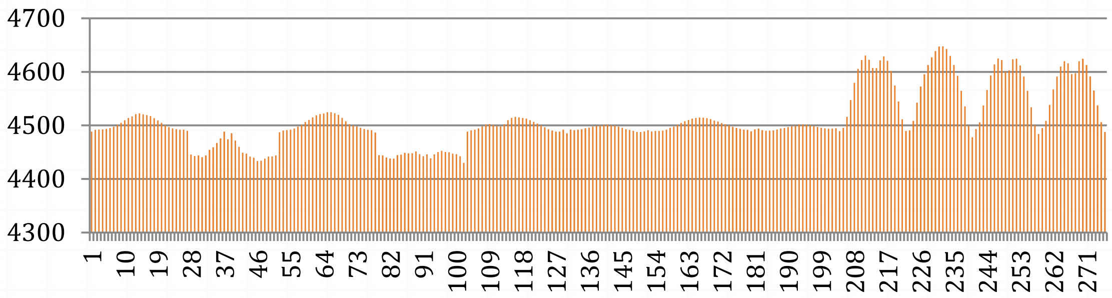
Mechanical Performance

Equivalent stress on cavity



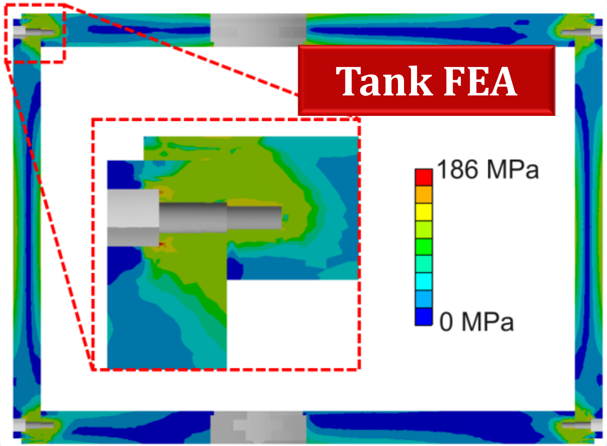
Tank FEA

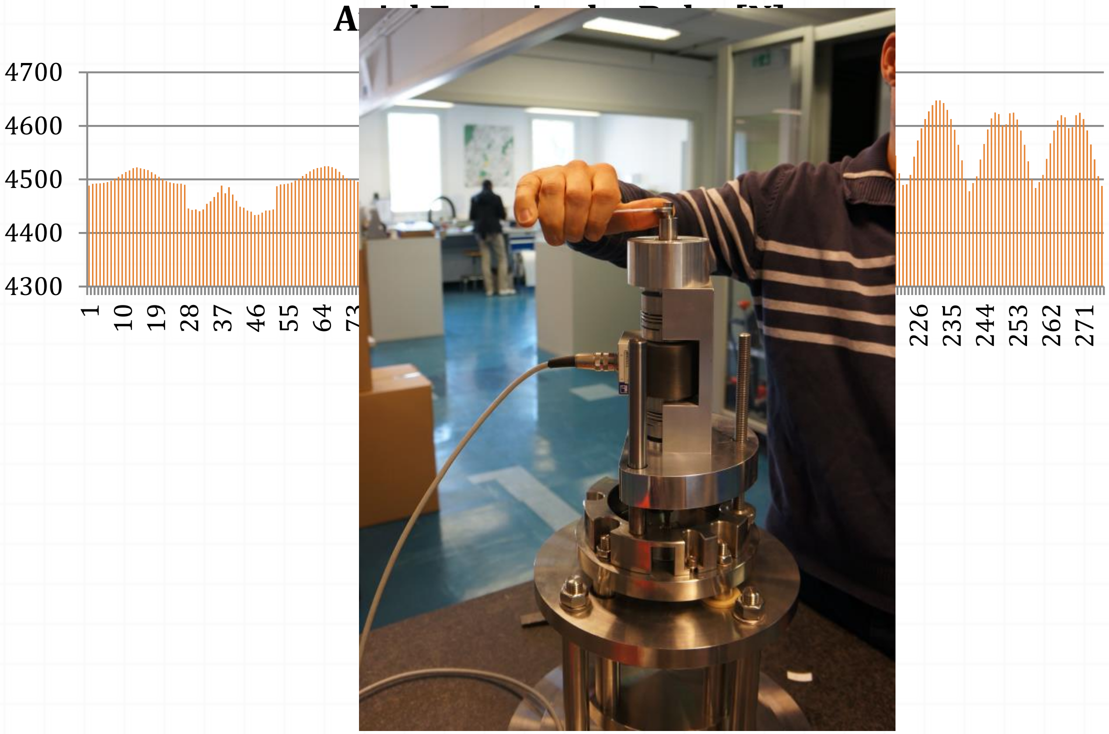
Axial Force in the Bolts [N]



- **Stress in tank, bolts, welds and cavity all acceptable** (cavities require stress linearization)
- **Welding procedure and main loads to be tested with a prototype**
- Minimum tightening torque of the screws **experimentally evaluated**

Mechanical Performance





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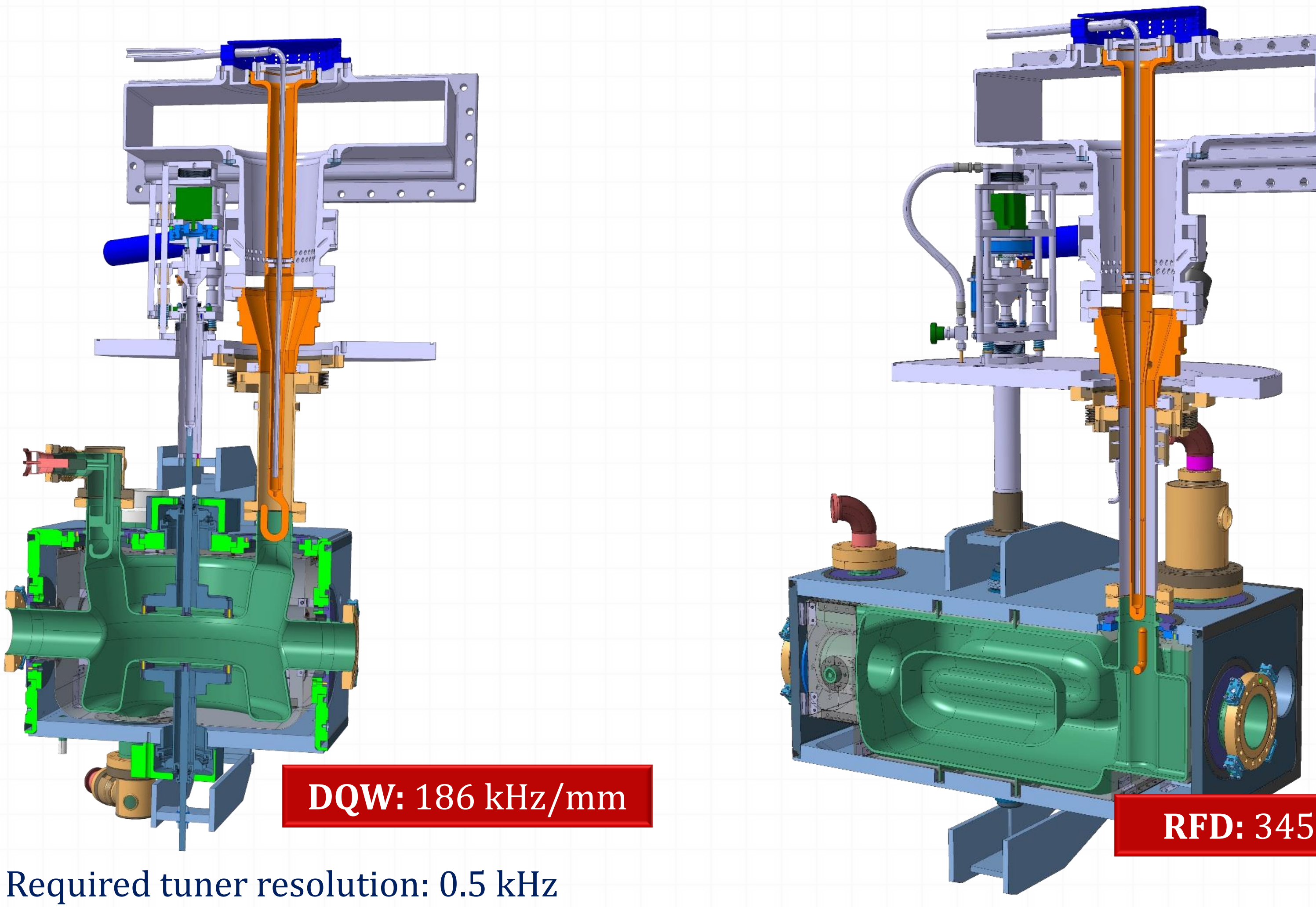
Tuning System

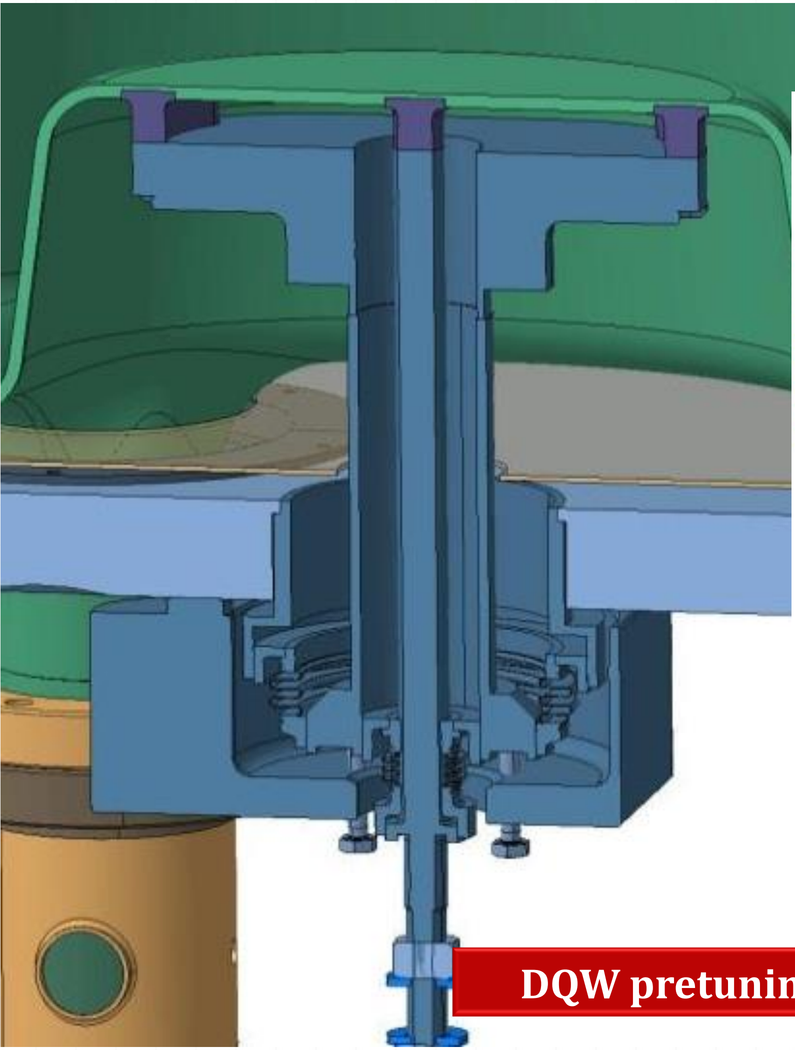


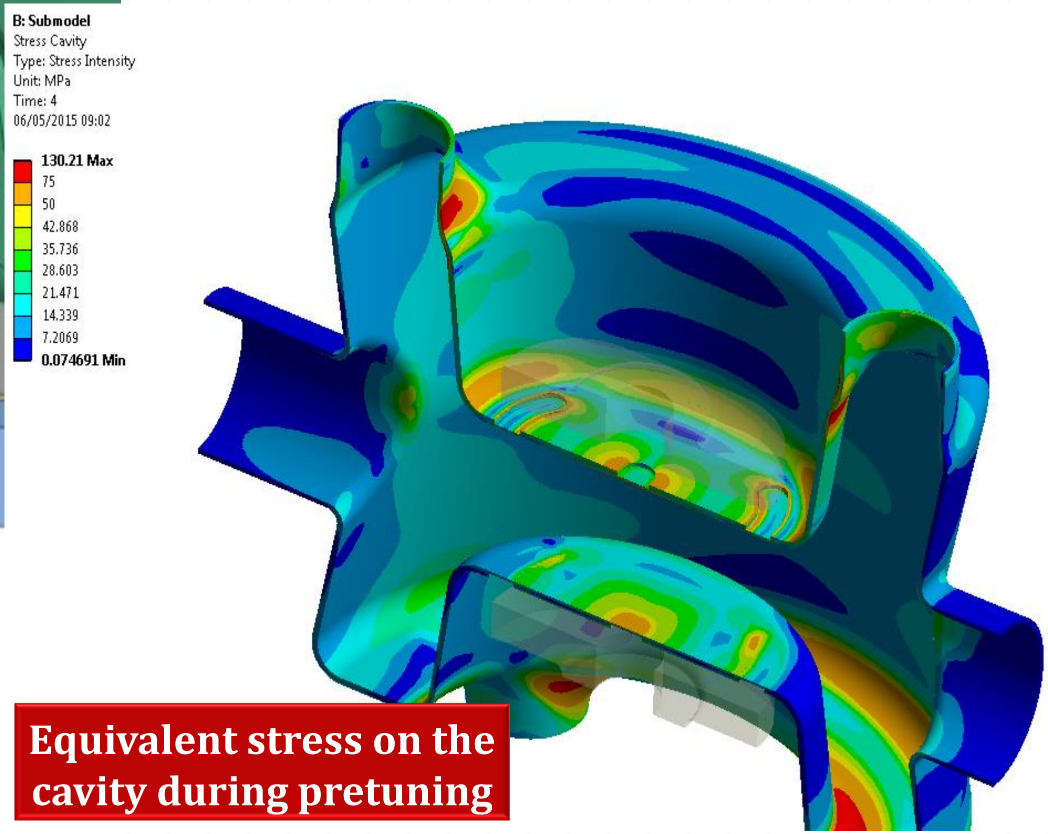
DQW: 186 kHz/mm

RFD: 345 kHz/mm

- Required tuner resolution: 0.5 kHz
- **Fine tuning range:** ±0.31 MHz (DQW), ±0.98 MHz (RFD) → **coarse pretuning added to DQW**
- Coarse tuning sensitivity ~ **0.8 MHz/mm**

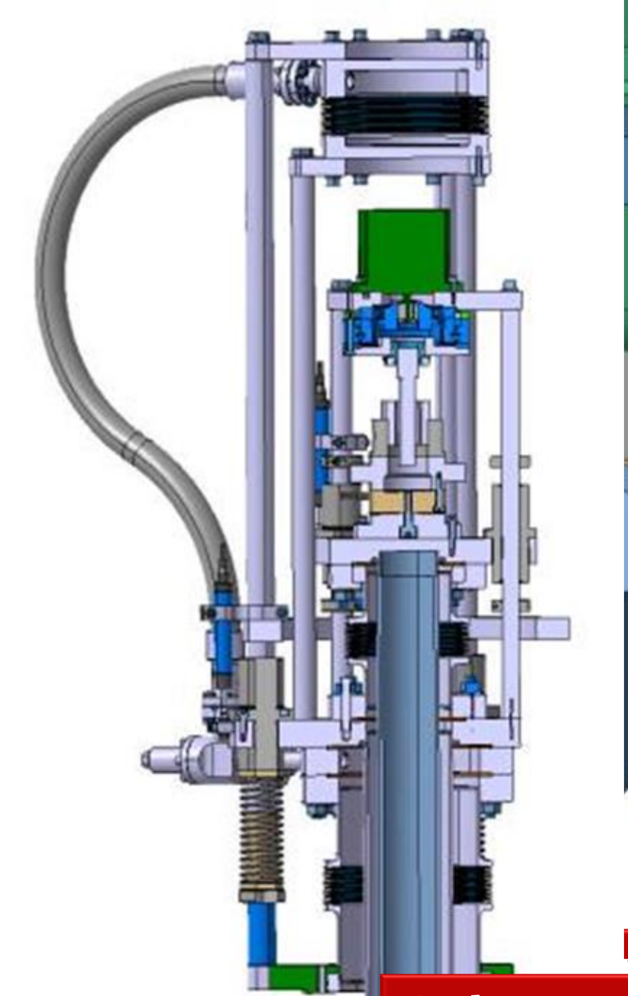
Tuning System

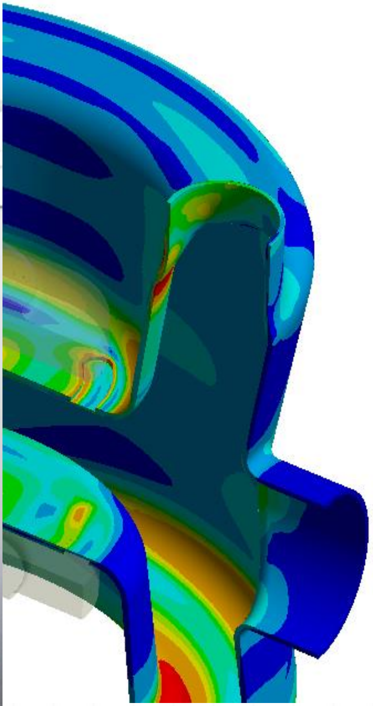

DQW pretuning



Equivalent stress on the cavity during pretuning

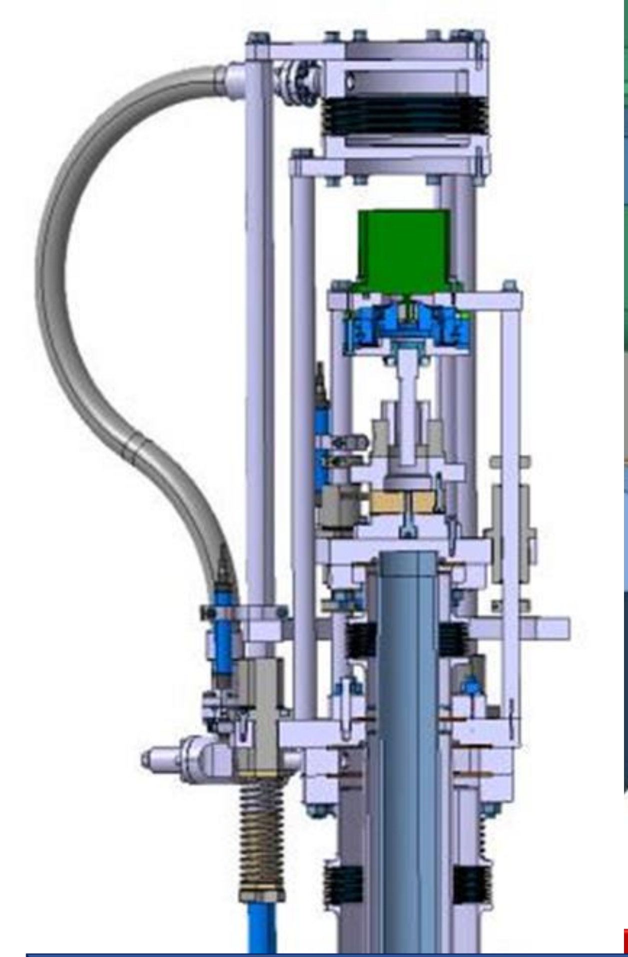
Tuning System

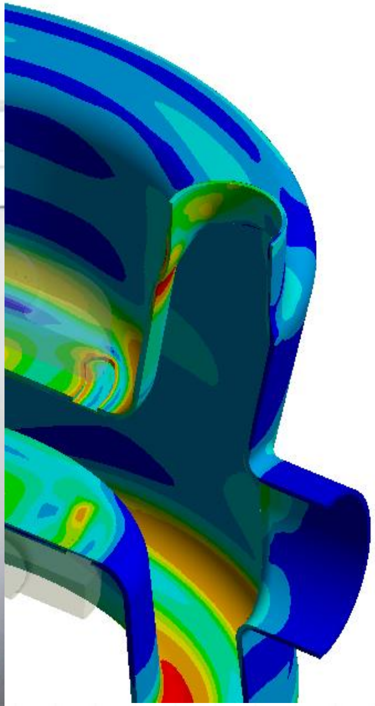




Crab prototype tuner actuator
First tests 0.5 µm precision

Tuning System

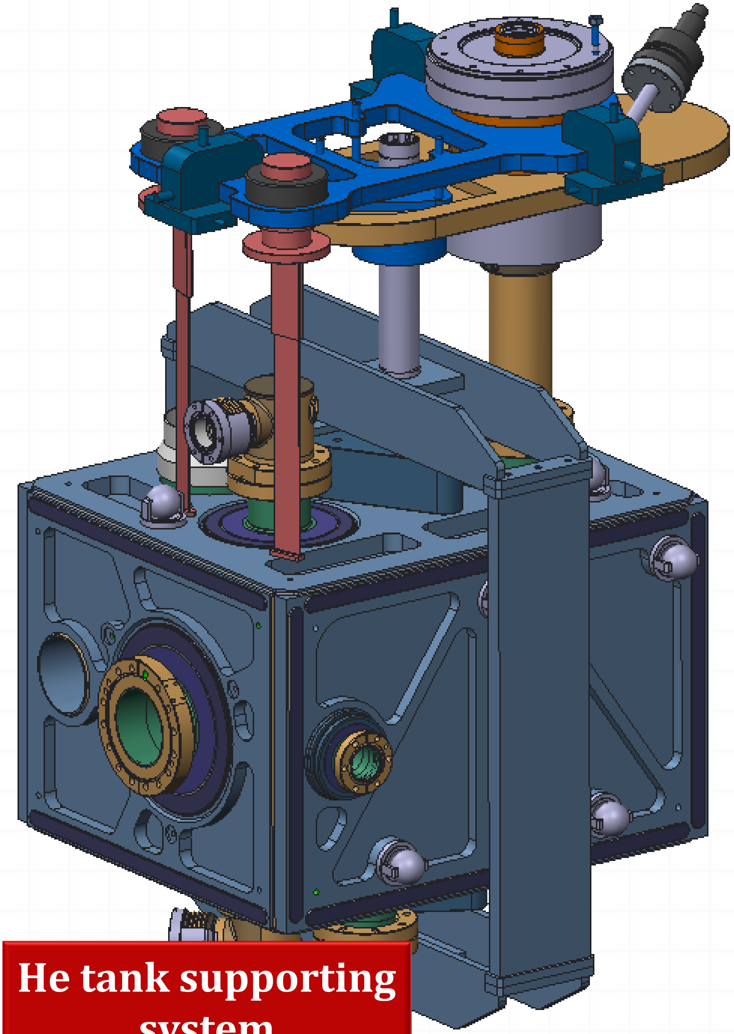




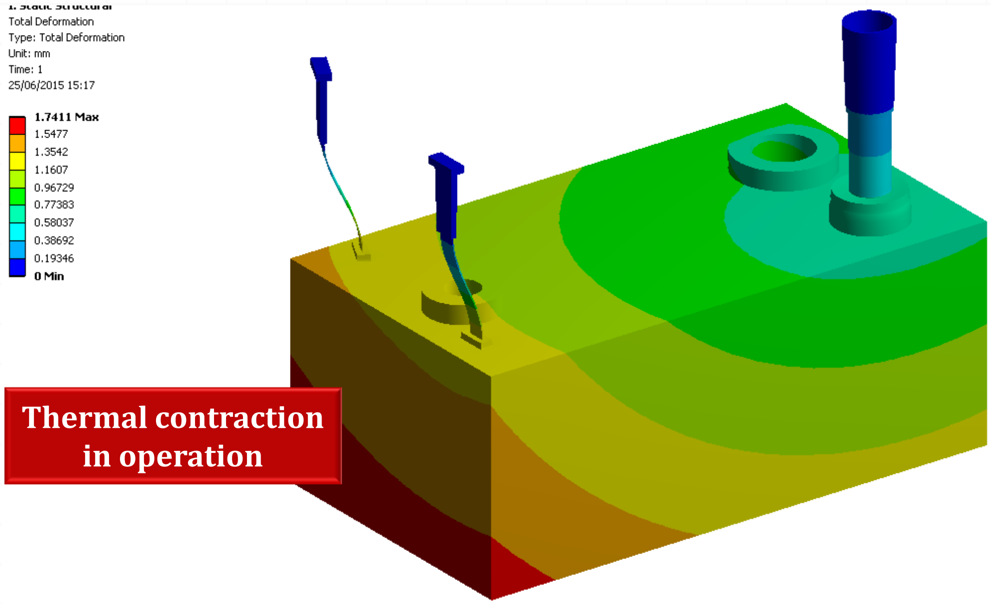
- K. Artoos, “Development of SRF Cavity Tuners for CERN”, THPB060
- S. Verdù, “Lorentz Detuning for a Double-Quarter Wave Cavity”, THPB051

Alignment and Support System

- Dressed cavities are **supported by the FPC and 2 blades supports**
- FPC and blades connected to a plate outside the cryomodule
- Attitude and position of the plate are actuated **through 3 isostatic constraints**
- **Minimisation of thermal stresses and increase of the 1^{st} mechanical mode**



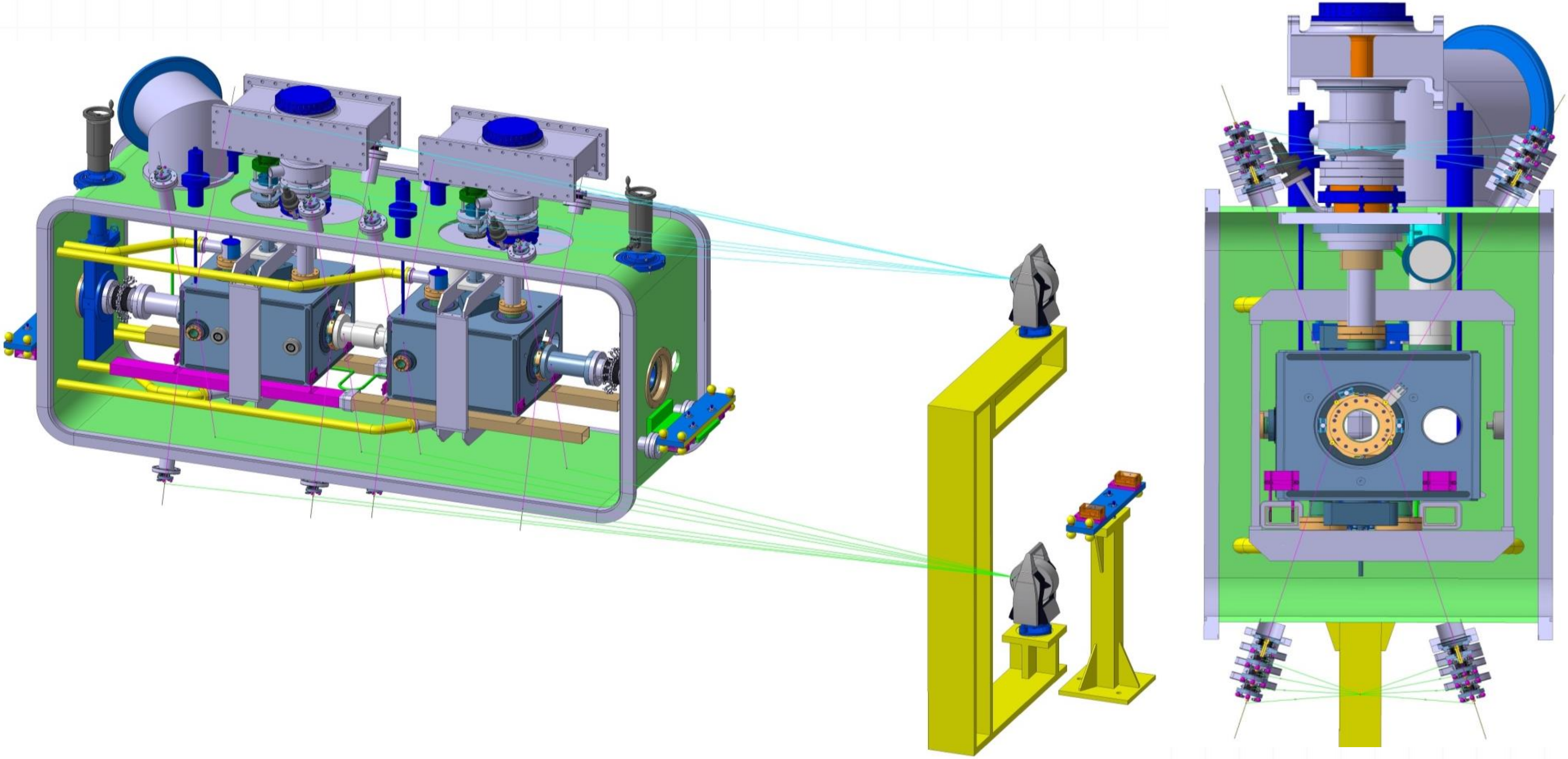
He tank supporting system



Thermal contraction in operation

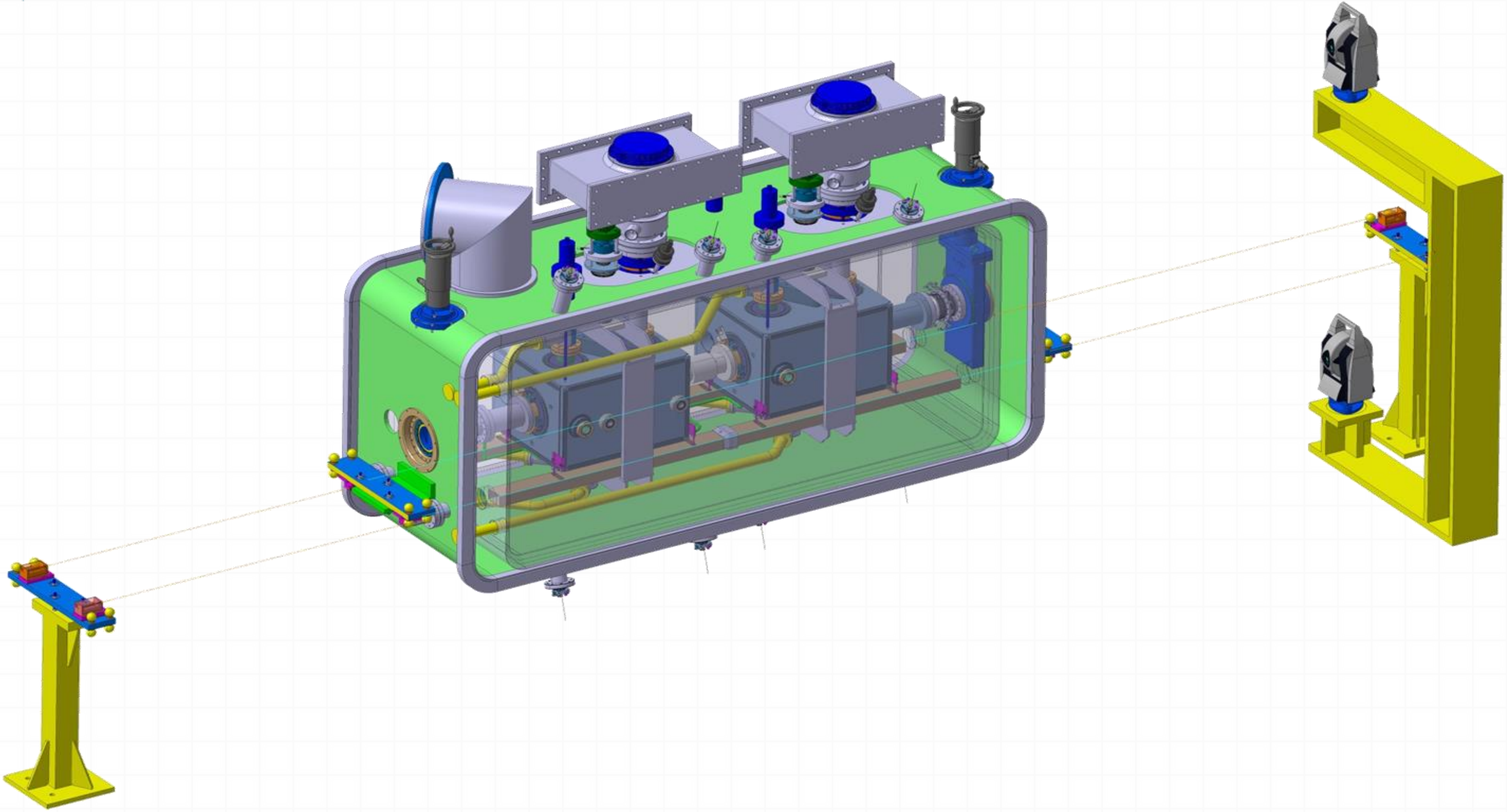
Alignment Monitoring System: FSI*

*Frequency Scanning Interferometry



Alignment Monitoring System: BCAM*

*Brandeis CCD Angle Monitor



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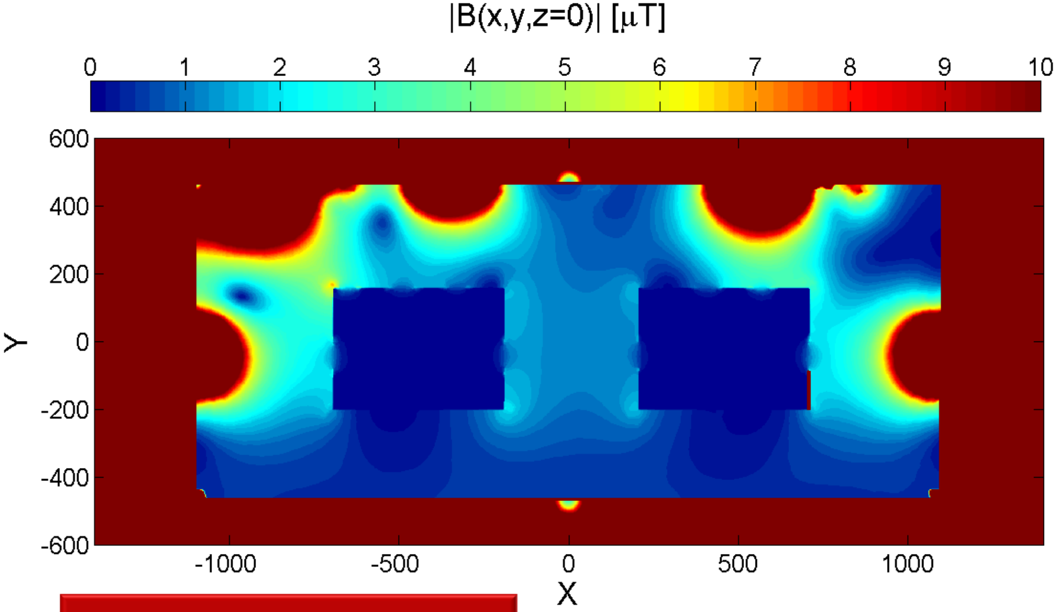
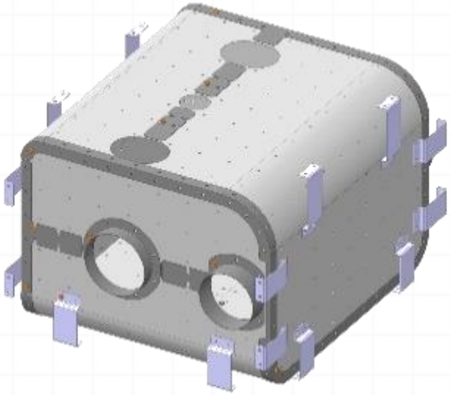
Magnetic Shielding

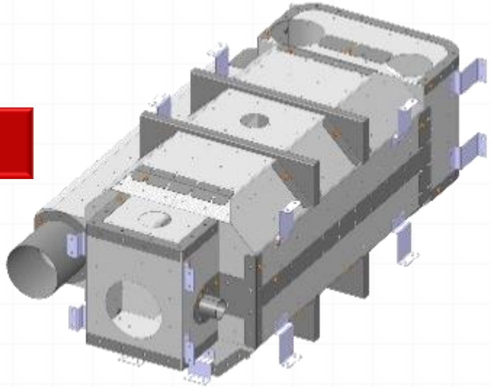


Magnetic field for external 200 μT

DQW

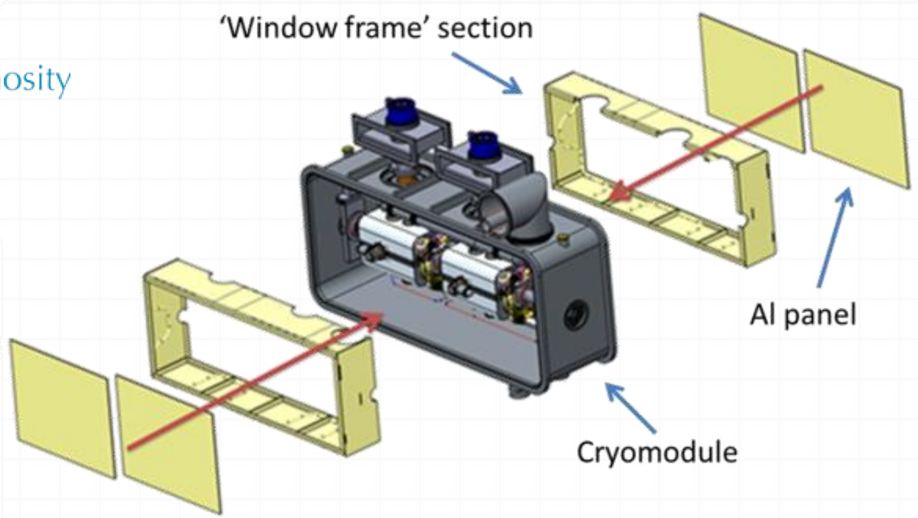


RFD

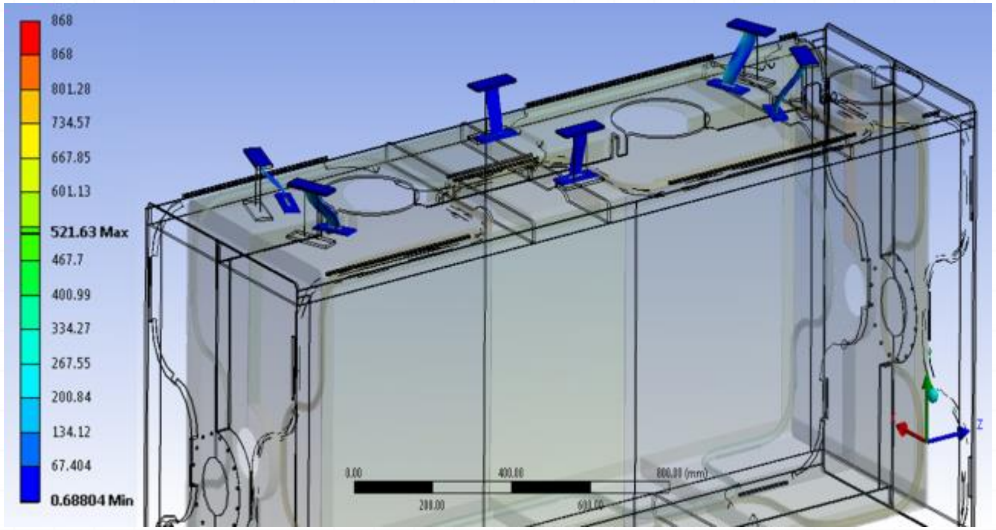


- Maximum acceptable magnetic field on the cavity: **1 μT**
- The external screen, in **mu-metal**, is not enough to shield the cavities
- One additional cold screen added per each cavity **(Aperam Cryophy)**

Thermal Shielding

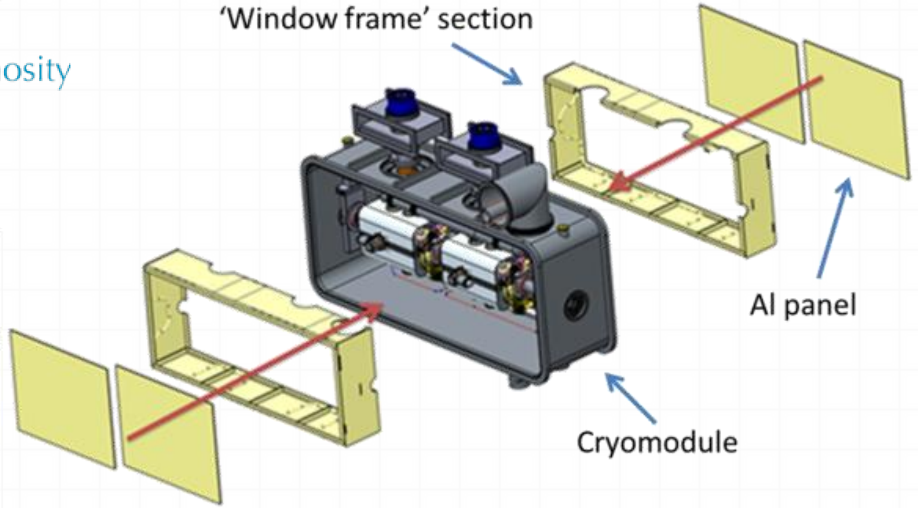


- Thermal screen: aluminium **AW 6061-T6**
- Thermalized with **He gas (50÷70 K)**
- Covered with MLI layers
- Goal: **minimise the heat losses by radiation** towards 2 K bath



- Flexure mounts in **titanium**
- Optimized to :
  - **sustain the shield weight**
  - **minimise the thermal stress** at the vacuum tank interface

Thermal Shielding



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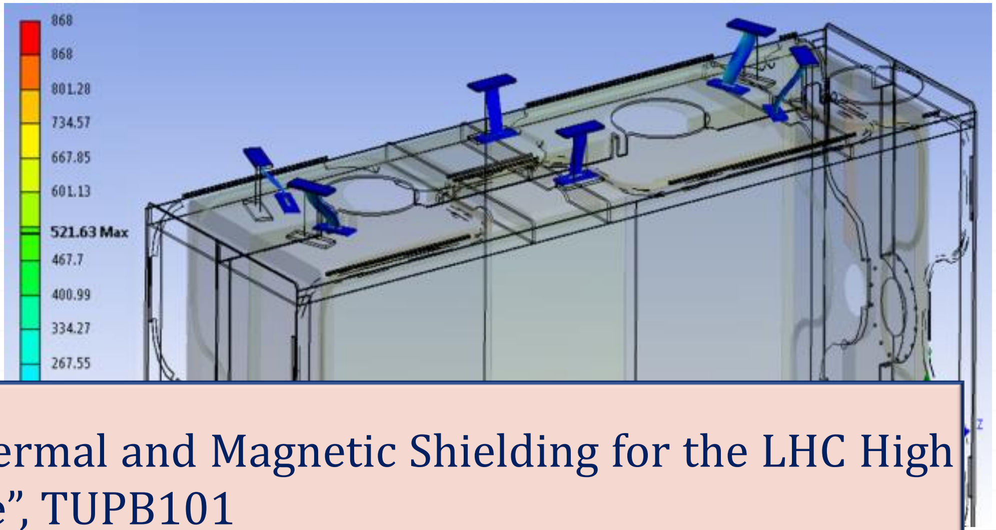
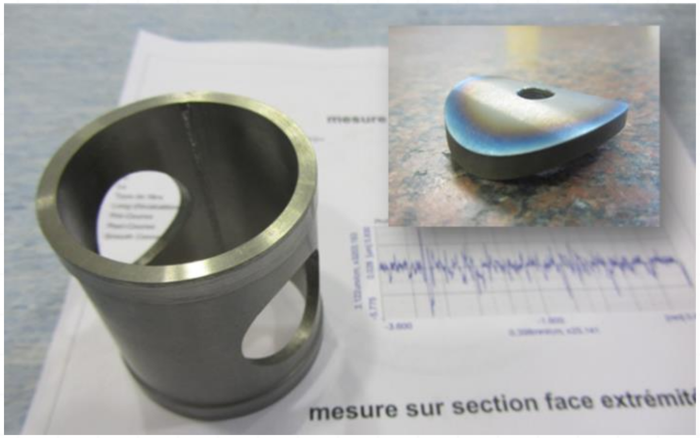


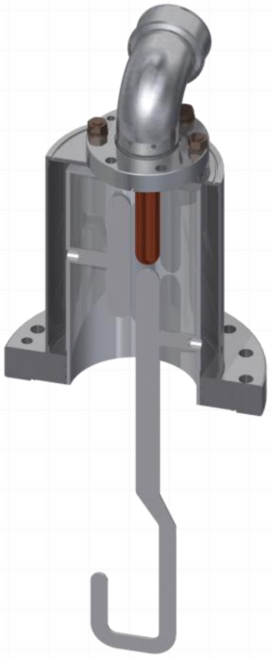
- Flexure mounts in **titanium**
- Optimized to :

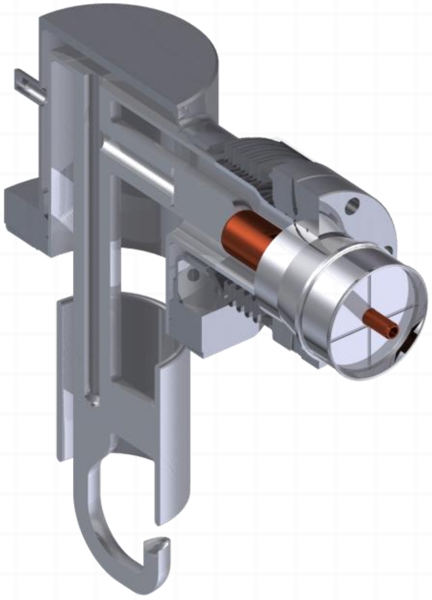
- N. Templeton, "Design of the Thermal and Magnetic Shielding for the LHC High Luminosity Crab-Cavity Upgrade", TUPB101

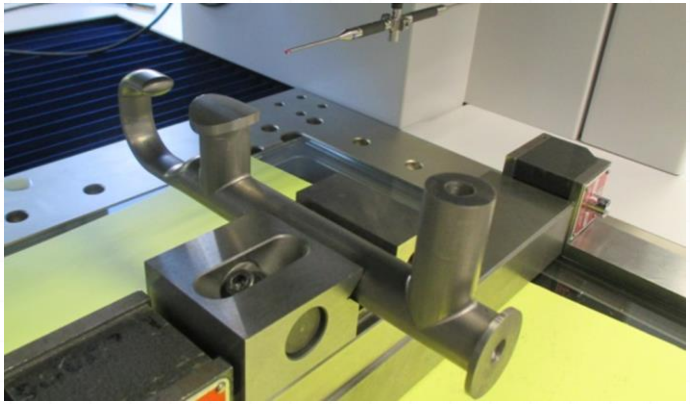
HOM

- Three HOM in DQW, two in RFD
- **Bulk Nb antenna**, He-cooled
- Coaxial lines evacuate **1 kW/HOM**
- **Fabrication started** at CERN




RFD


DQW



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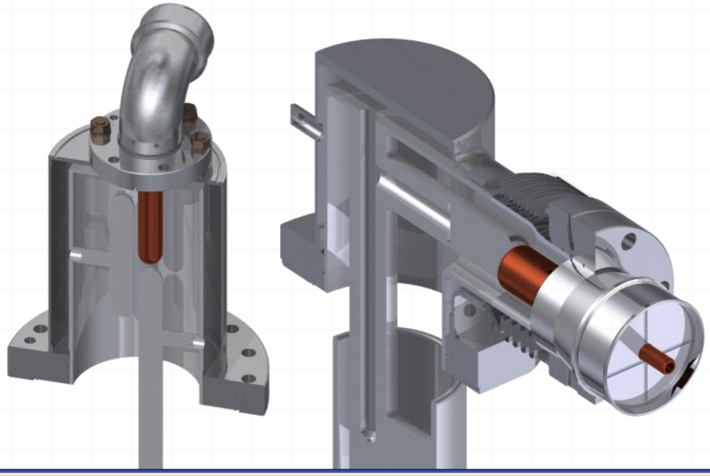
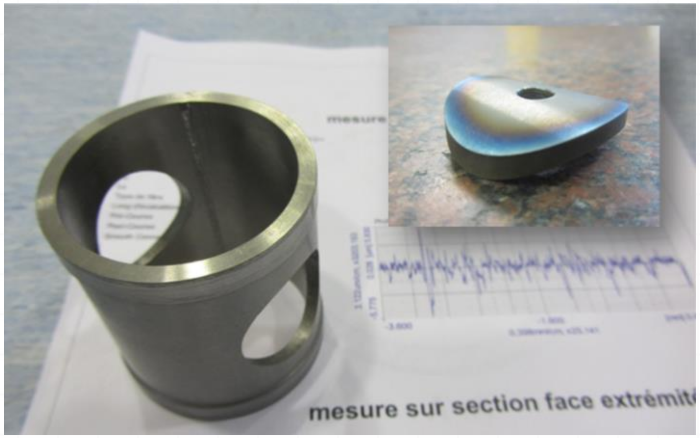
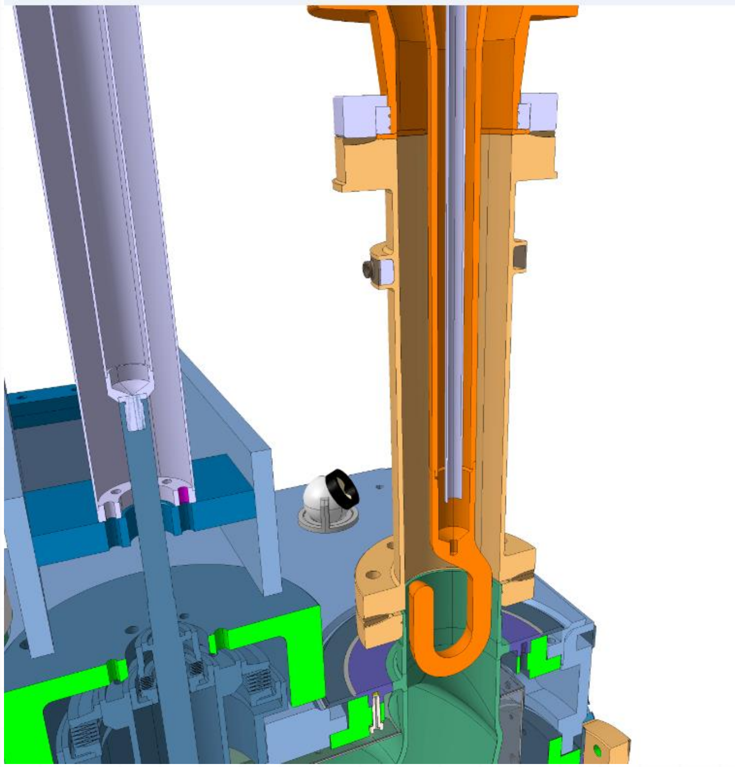


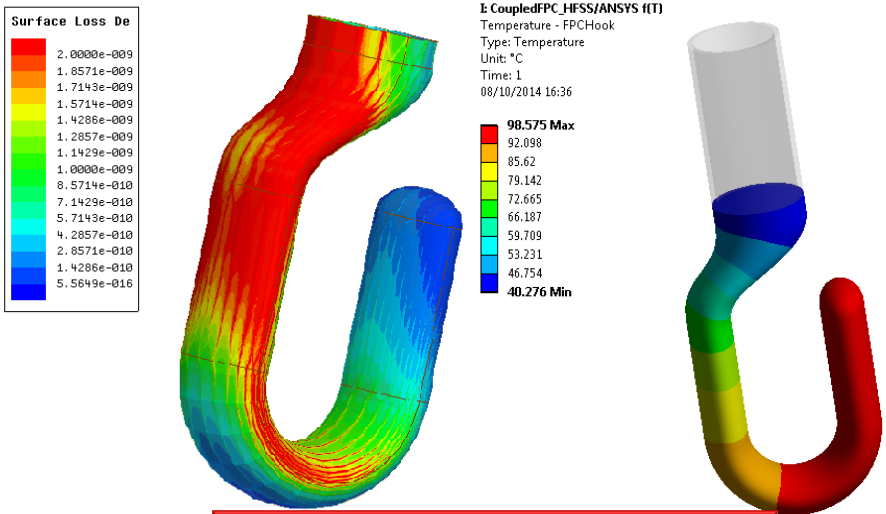


- B. P. Xiao, “Overview of Recent HOM Coupler Development”, **THBA04**
- A. R. J. Tutte, “FPC and HOM Test Boxes for HL-LHC Crab Cavities”, THPB081
- C. Zanoni, “Engineering Design and Prototype Fabrication of HOM Couplers for HL-LHC Crab Cavities”

FPC

- **RF power 80 kW**
- 3mm-thick **stainless steel** FPC can, intercepted with **He gas circuit**
- **Copper OFE antenna**, water-cooled
- Thermal loss on the antenna:
  - **DQW ~ 100 W**
  - **RF ~ 60 W**





FPC surface loss density distribution & temperature increase

- High temperature on the hook → high losses via radiation to the 2 K bath!
- **Iterative HFSS/ANSYS analysis** to evaluate T field on hook and radiation to cold mass
- With the final solution: **0.7 W/FPC to 2K**

FPC

- **RF power 80 kW**
- 3mm PC can,
  inter **uit**
- **Copp** r-cool
- Ther :
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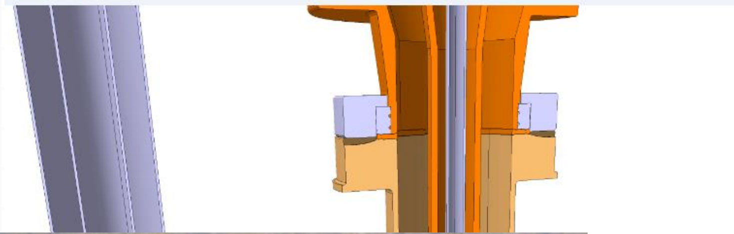
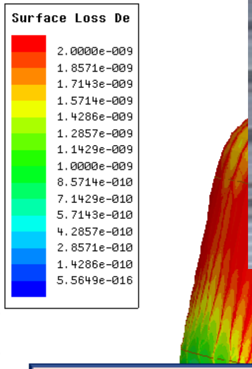


Prototypes machined at CERN



- High temperature on the hook → high losses via radiation to the 2 K bath!
- e
- With the final solution: **0.7 W/FPC to 2K**

& temperature increase

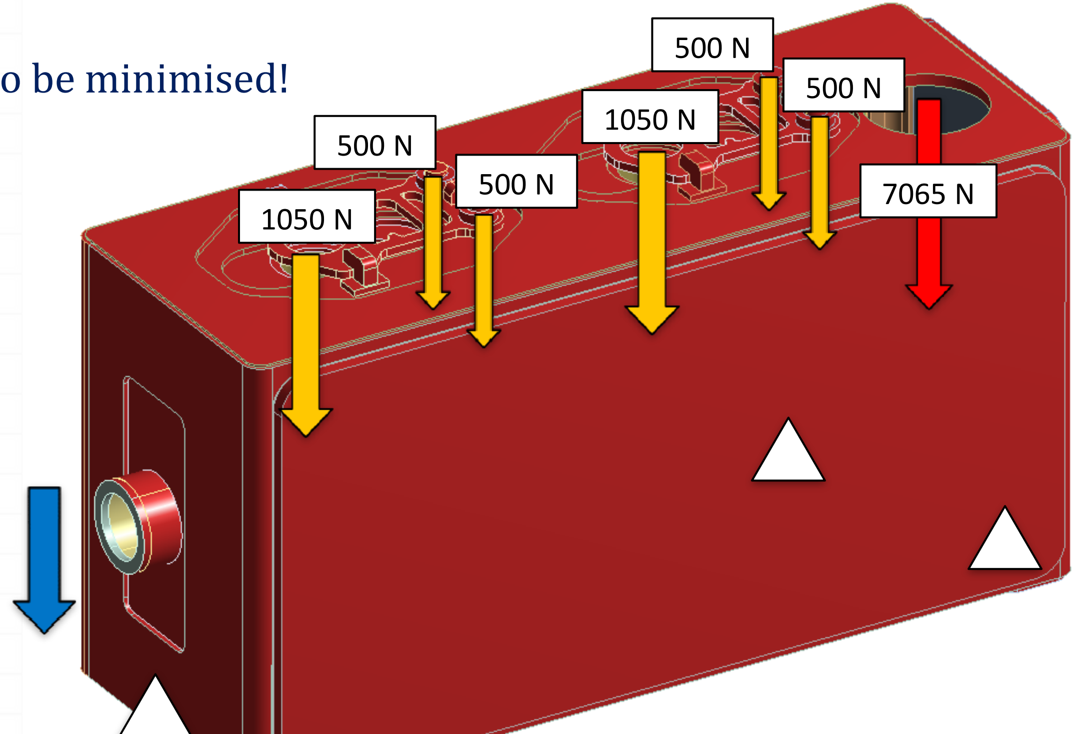
- S. Verdù, “Thermal Losses in Couplers of a SPS Double-Quarter Wave Crab Cavity”, THPB052

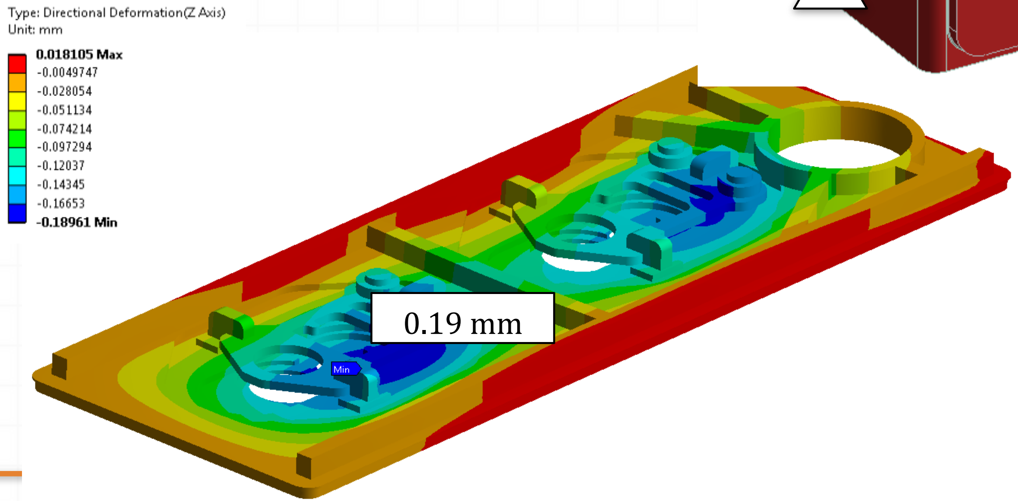
Vacuum vessel

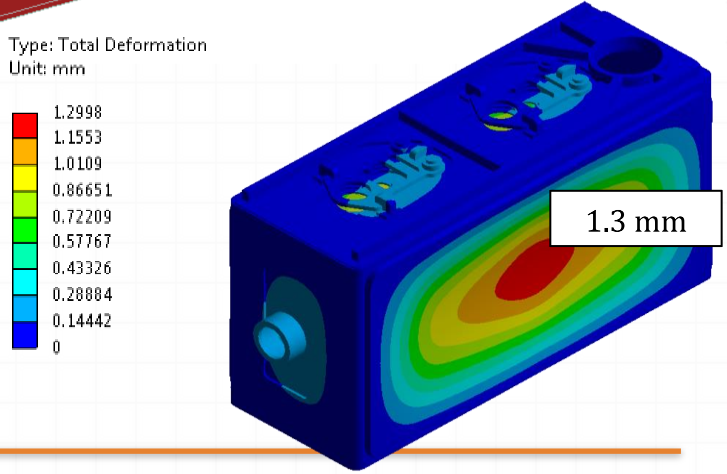
- Insulation primary vacuum
- Deformation at cavity interface to be minimised!
- Stainless steel / Aluminium

🟥 Pressure 0.1 MPa
△ Fixed support
⬇ Dressed cavity weight 1050 N
⬇ Pressure force for opening 7065 N
⬇ Gravity 9806.6 m/s^2

Load on top plate	
Weight [kN]	Pressure force [kN]
7.7	161.25







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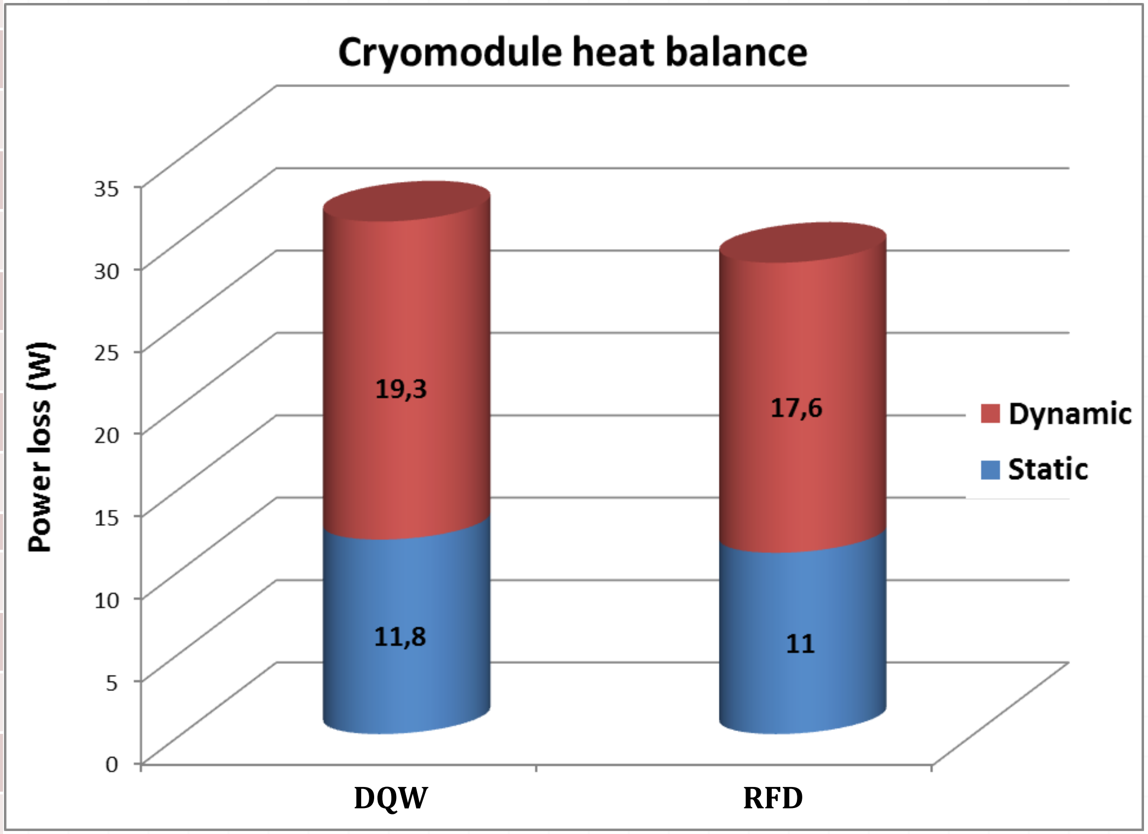
Heat Balance

	DQW		RFD	
	2K	80K	2K	80K
Static				
Radiation	3	35	3	35
CWT	0.2	2	0.2	2
Supports	0.8	30	0.8	30
FPC	4	100	4	100
Instrumentation	1	0	1	0
HOM/Pickup	2.5	10	1.7	10
Tuner	0.3	10	0.3	10
Total static	**11.8**	**187**	**11**	**187**
Dynamic				
Cavity	6	0	6	0
FPC	5.6	10	5.6	20
HOM/Pickup	7.2	120	5.5	80
Beam	0.5	0	0.5	0
Total Dynamic	**19.3**	**130**	**17.6**	**100**
TOTAL	**31.1**	**317**	**28.6**	**287**



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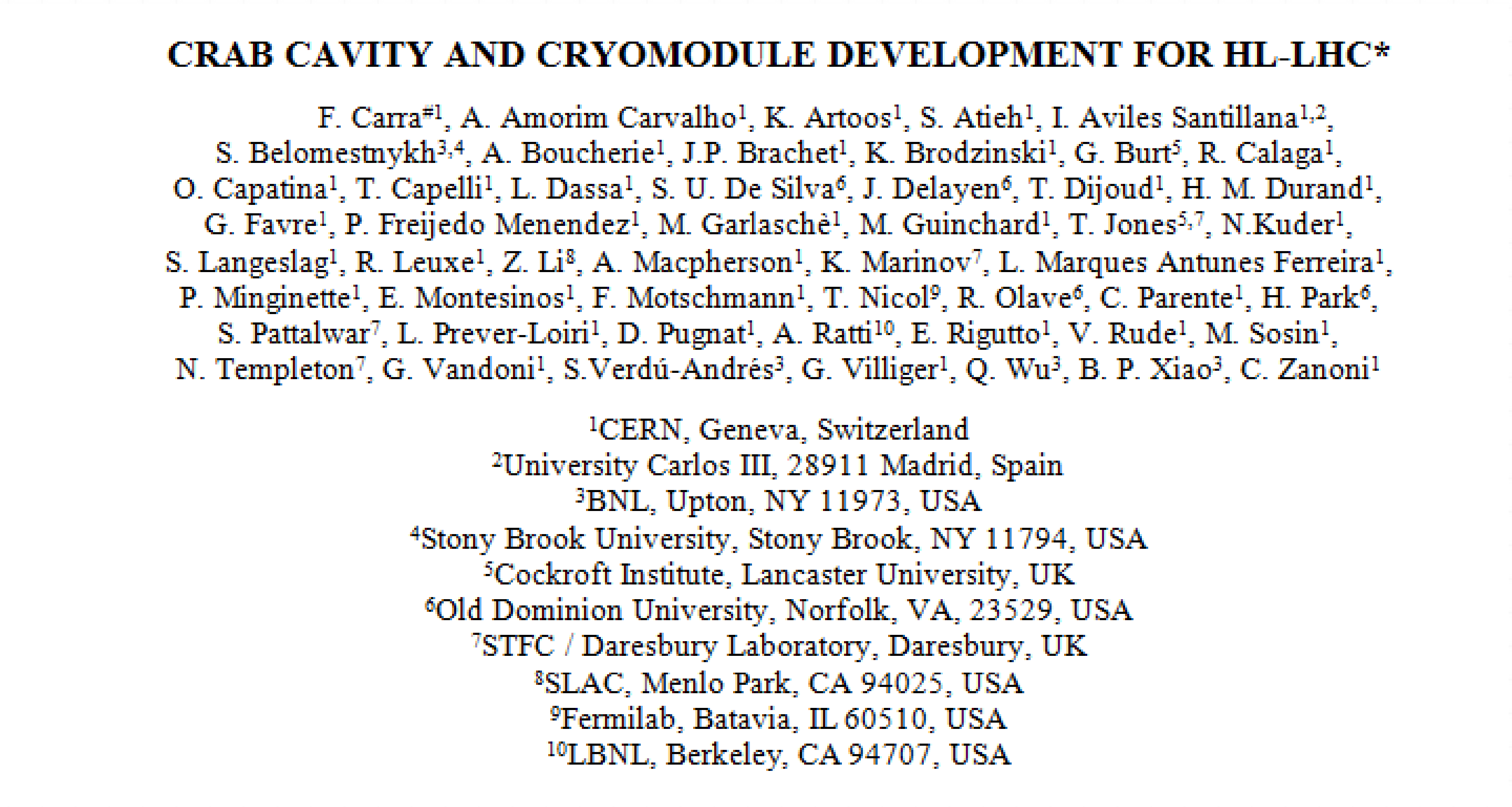
Summary

- **Crab cavities** are a key upgrade of the **HL-LHC program**, aiming to increase the LHC luminosity by a **factor of 10**
- Two different RF design have been proposed in the past years: **DQW** (vertical crabbing) and **RFD** (horizontal crabbing)
- The design of the cryomodules for testing in the SPS, prior to LHC installation, is smoothly advancing, thanks to the intense collaboration between CERN, UK and US
- **Maximum flexibility** (DQW/RFD, SPS/LHC) is one of the main goal of the engineering design
- Specification highly demanding: several solutions have **rarely or never been adopted at CERN**
- The design of the cryomodule is at an advanced stage and the **fabrication of specific components has already started**
- **No showstoppers in view of SPS tests in 2017/18!**

Acknowledgements



CRAB CAVITY AND CRYOMODULE DEVELOPMENT FOR HL-LHC*

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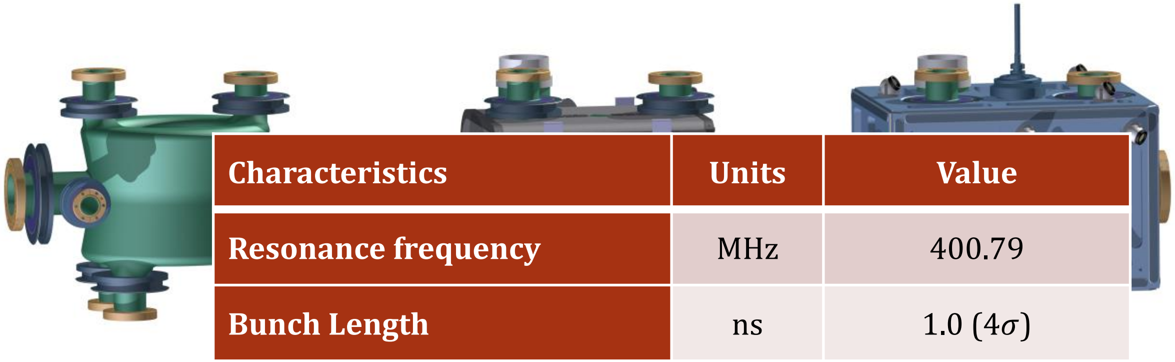
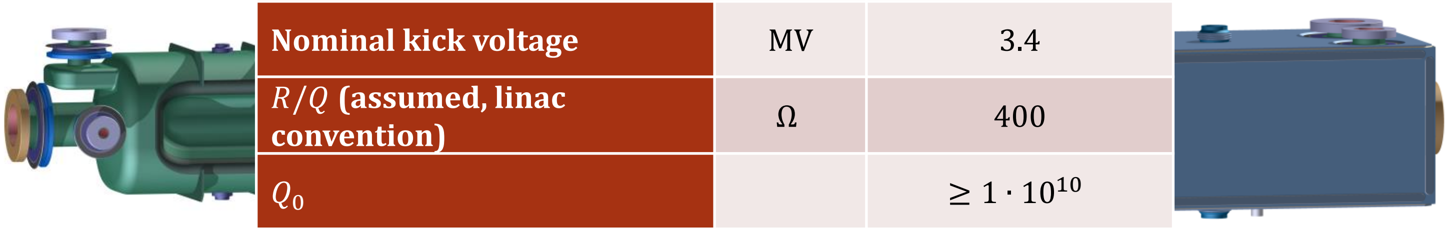
Thank you for your attention!

Backup slides

Dressed Cavity



DQW



RFD

Characteristics	Units	Value
Resonance frequency	MHz	400.79
Bunch Length	ns	1.0 (4σ)
Maximum cavity radius	mm	≤ 145
Nominal kick voltage	MV	3.4
R/Q (assumed, linac convention)	Ω	400
Q_0		$\geq 1 \cdot 10^{10}$
Q_{ext} (Fixed coupling range)		$3 \cdot 10^5 \cdots 5 \cdot 10^5$
RF Power	kW	80
Power coupler OD (50Ω)	mm	62
LLRF Loop Delay	μs	≈ 1
Cavity detuning	kHz	≈ 1.0

- RF design: s
- **Superfluid** protection)
- **Dressed ca** tuning + couplers

Acknowledgements

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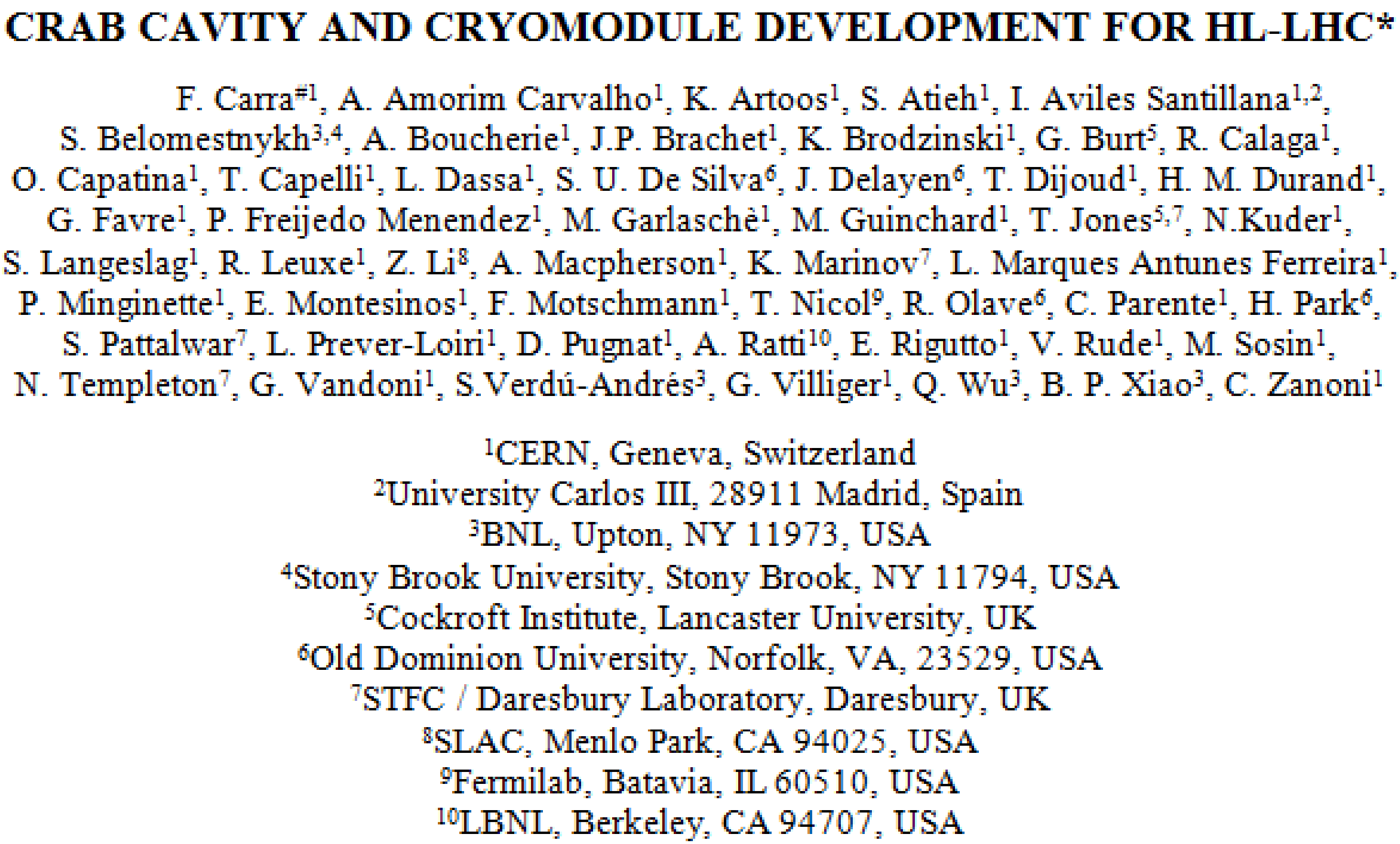

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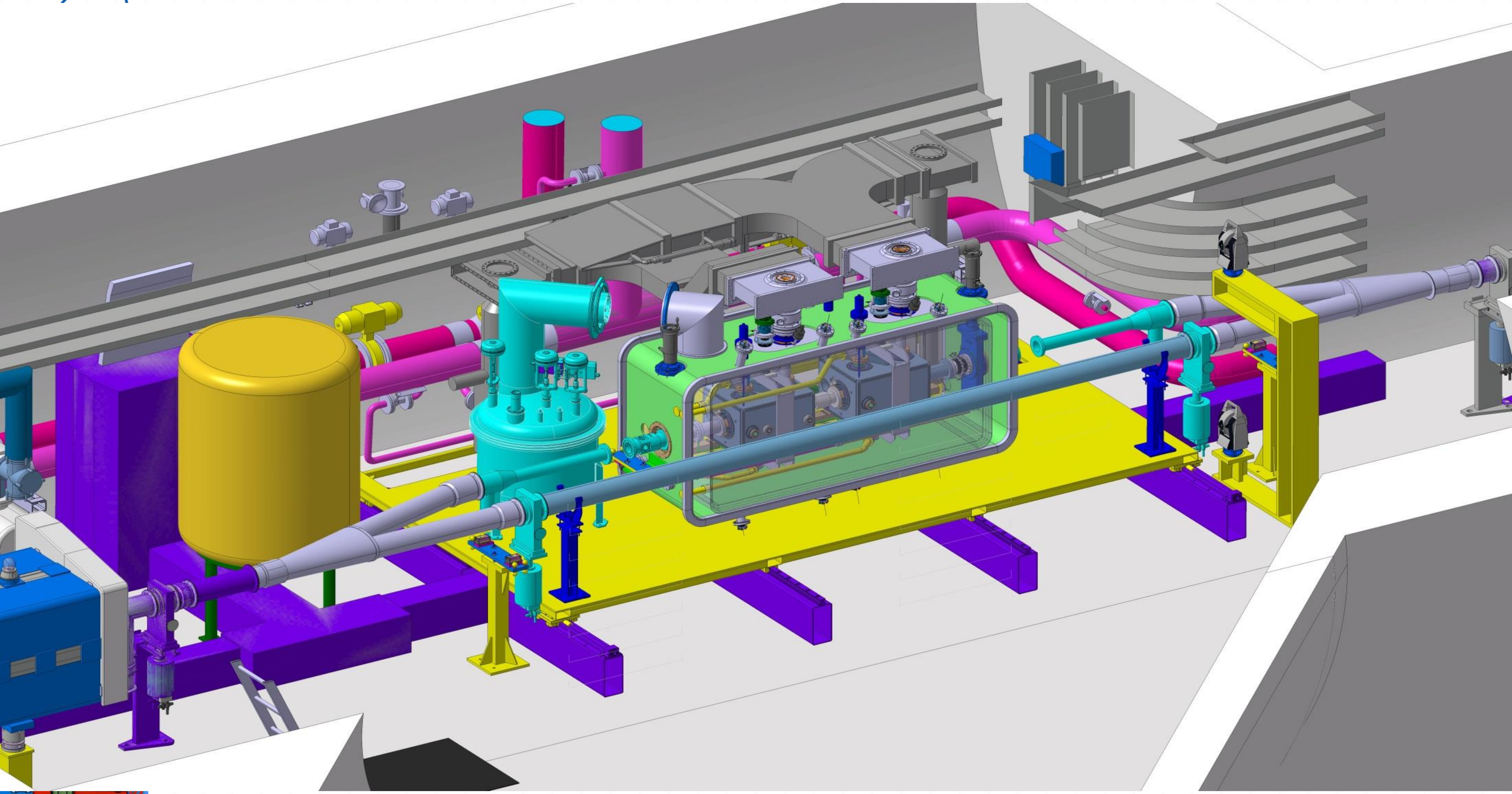
SPS: parking



SPS: operation