The vacuum system of the LHC experiments

Achievement and challenges for the future

Josef Sestak, on behalf of TE-VSC

6th of October 2023

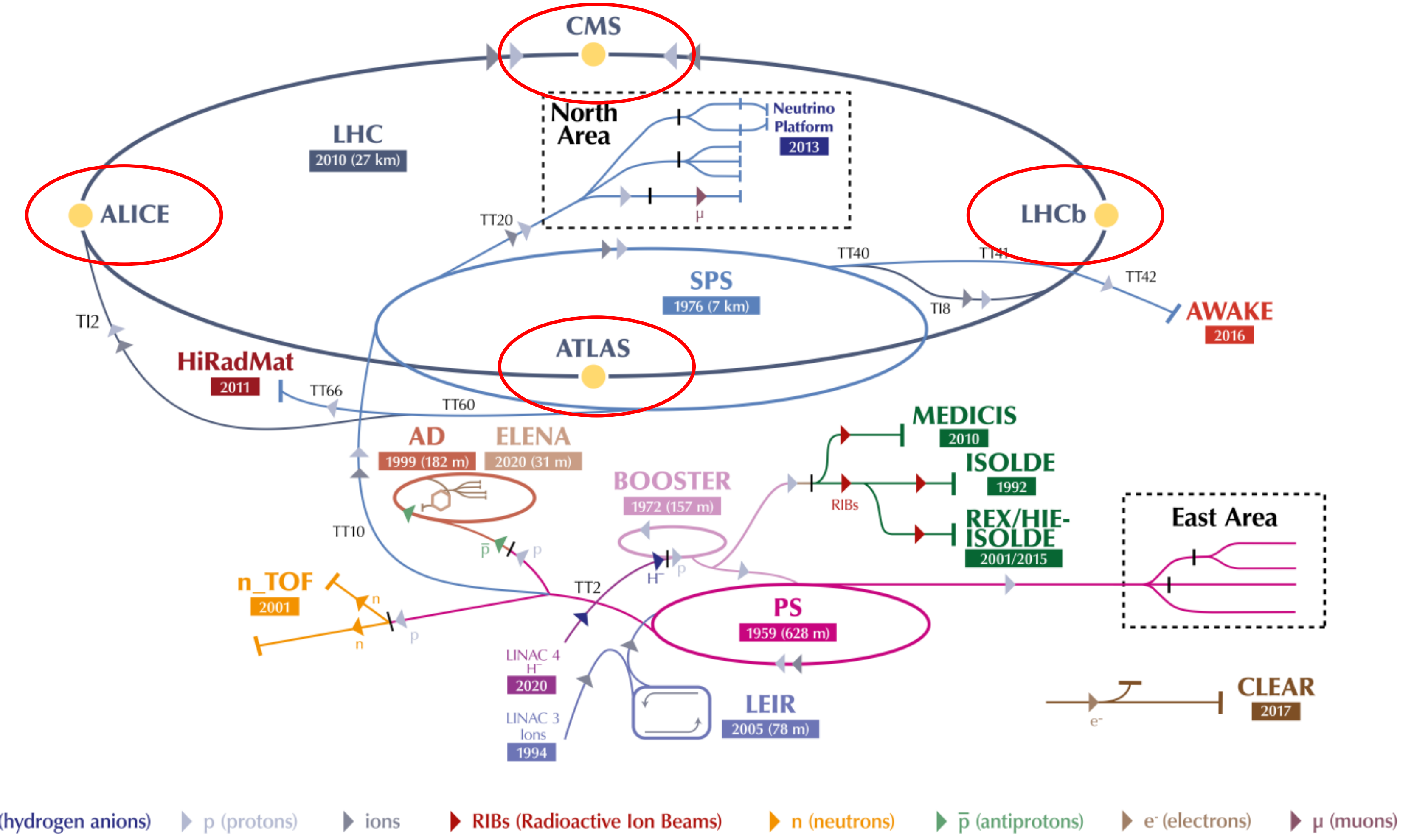
Content of the presentation

- **The complexity of the vacuum system of LHC’s experiments.**
- **Material, mechanical stability and manufacturing constraints.**
- **Production steps, installation and performance of experimental beampipes.**
- **Interface between the machine and LHC experiments.**
- **Present issue with Be pipes manufacturing.**

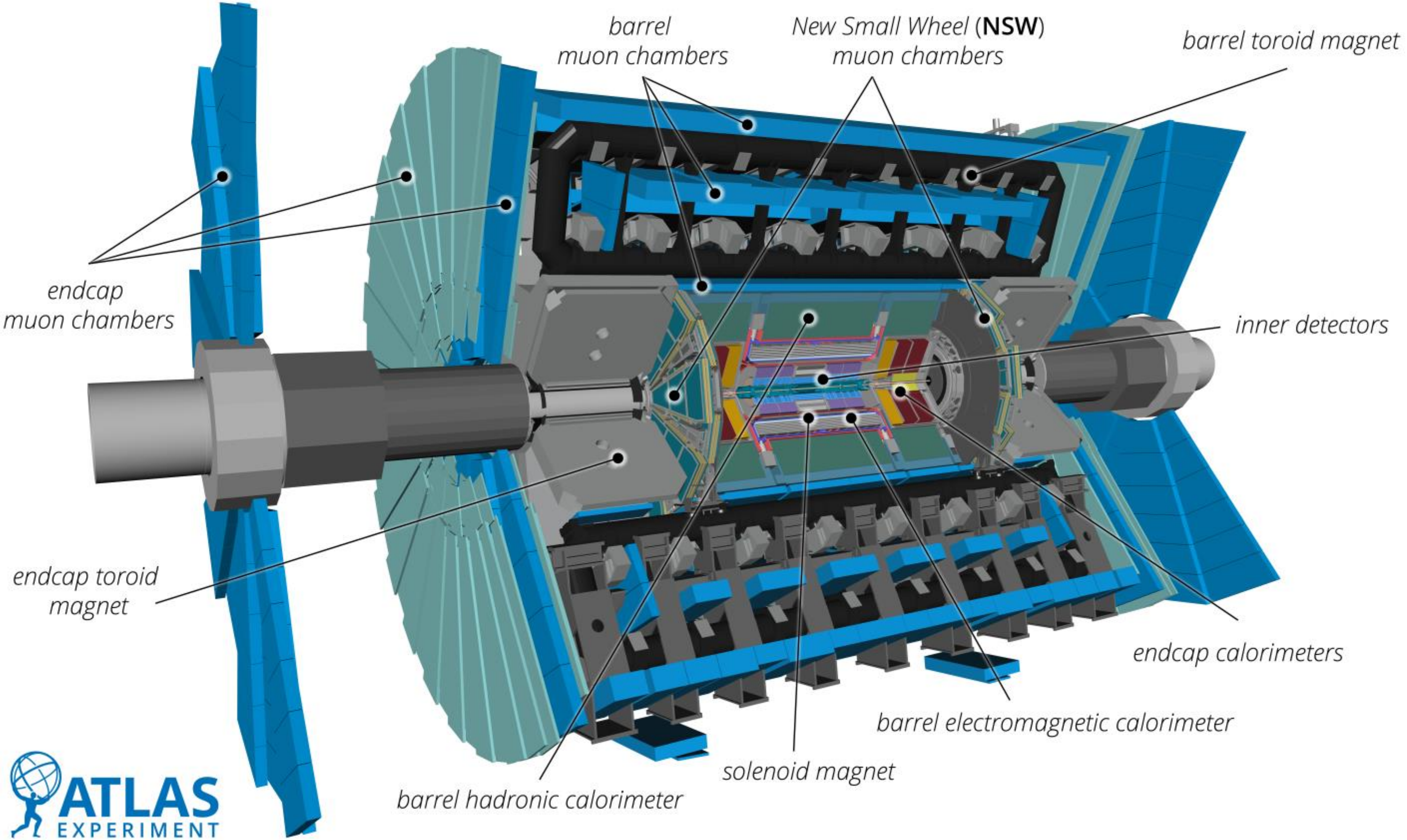
LHC Experimental beam vacuum

Beam vacuum sectors located in the LHC experimental caverns

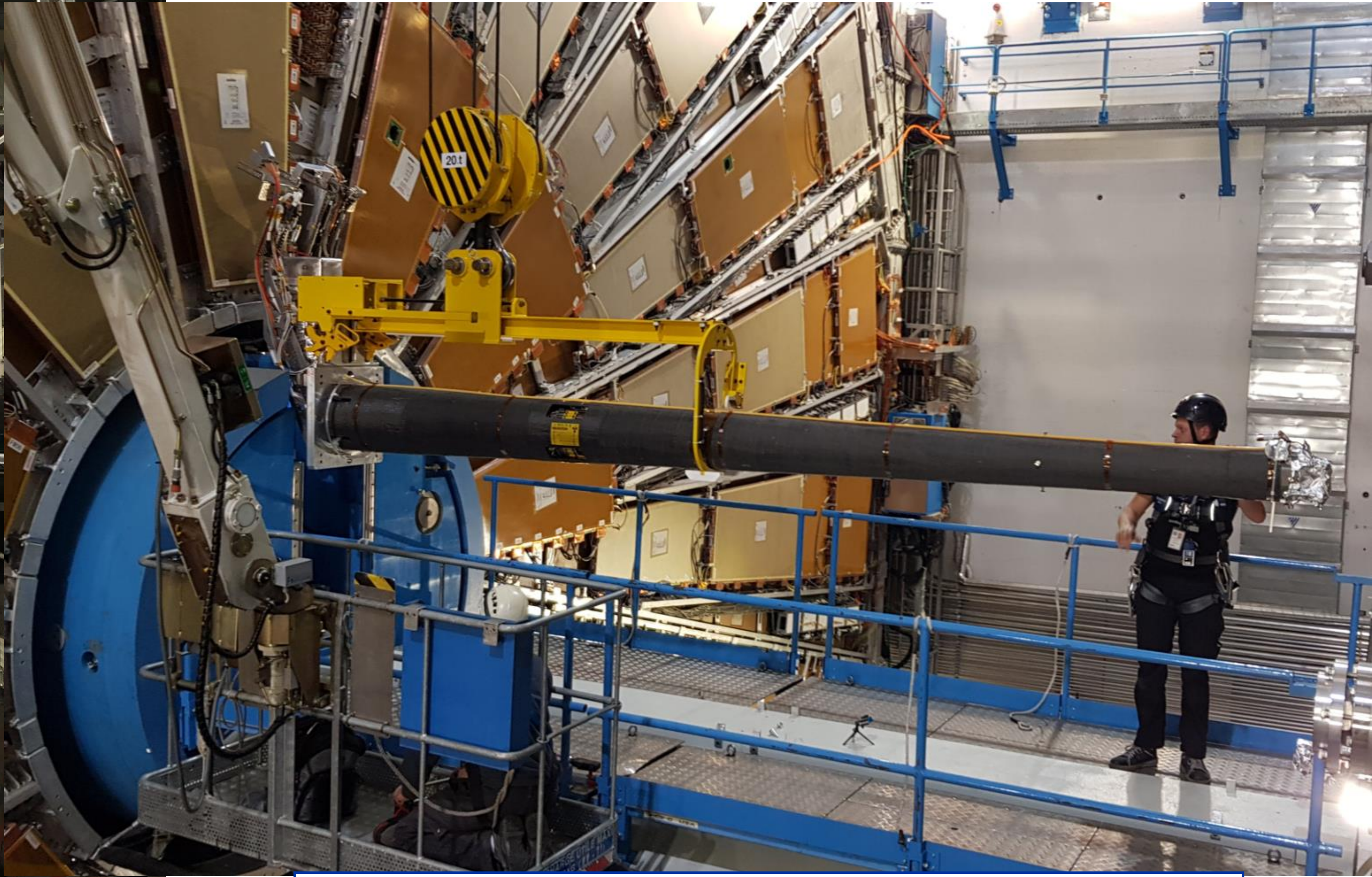
The CERN accelerator complex
Complexe des accélérateurs du CERN



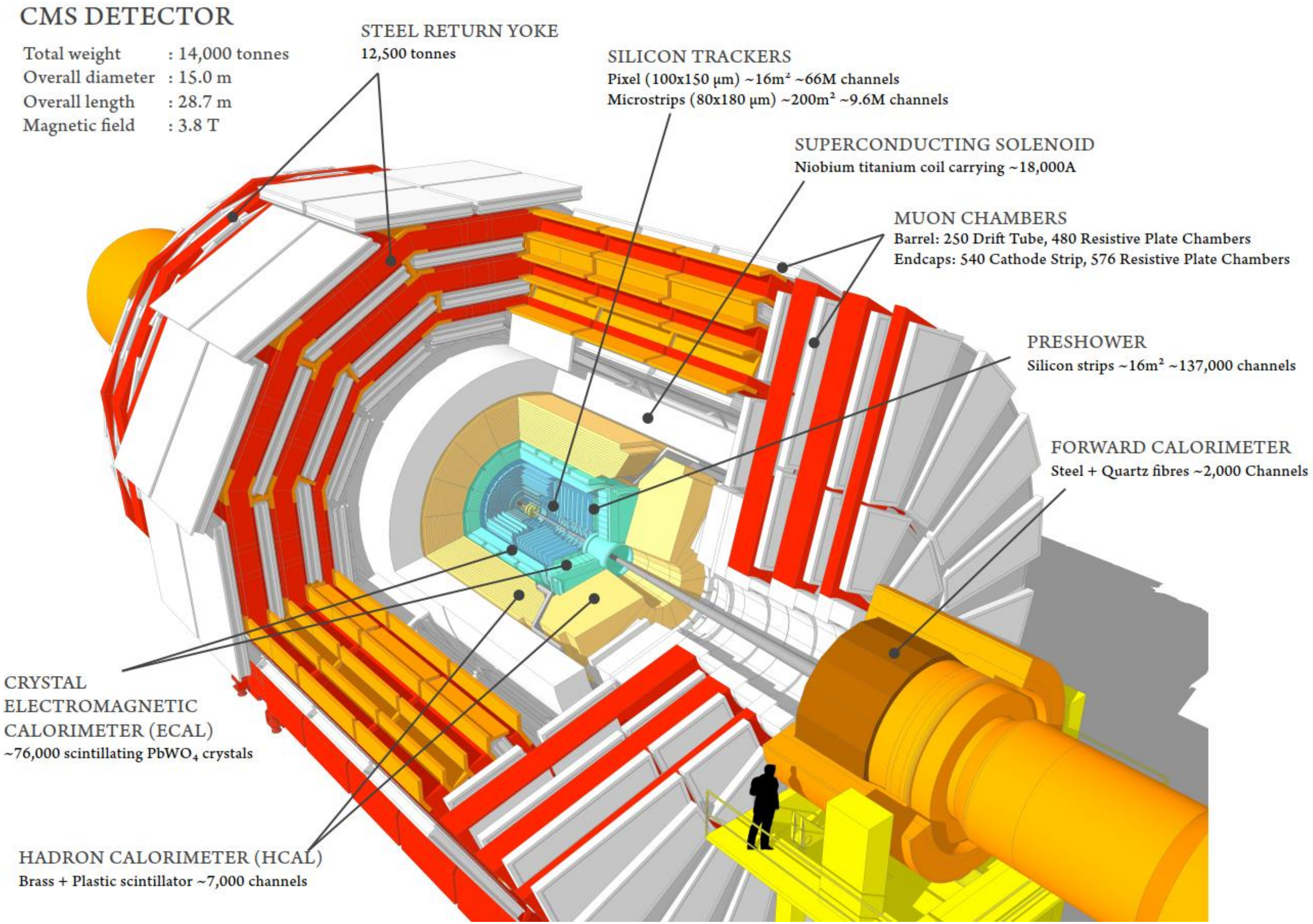
LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

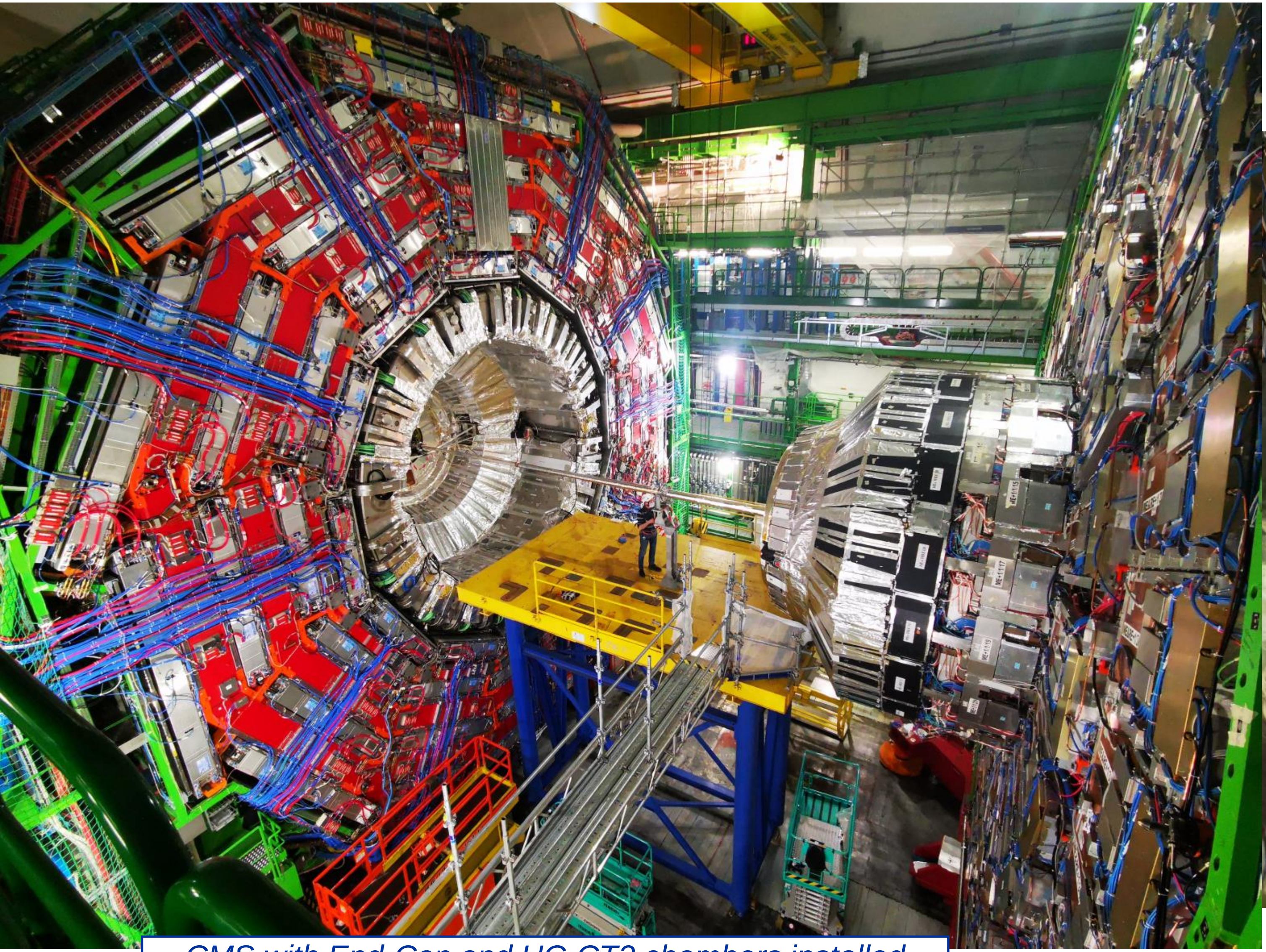

barrel
muon chambers
New Small Wheel (NSW)
muon chambers
barrel toroid magnet
endcap
muon chambers
inner detectors
endcap toroid
magnet
endcap calorimeters
barrel electromagnetic calorimeter
solenoid magnet
barrel hadronic calorimeter
ATLAS
EXPERIMENT

ATLAS forward region chamber within carbon cone support

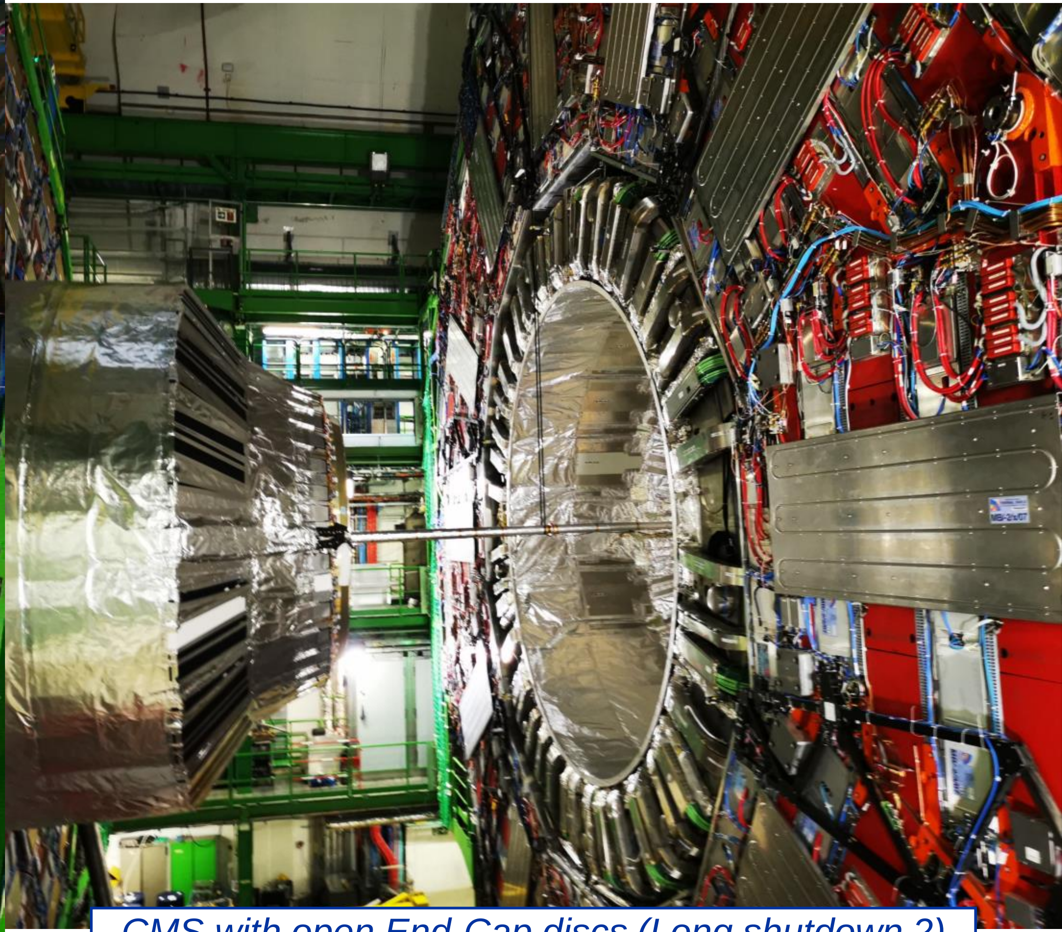


Removal of the ATLAS VJ chamber for Long Shutdown 2


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO₄ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

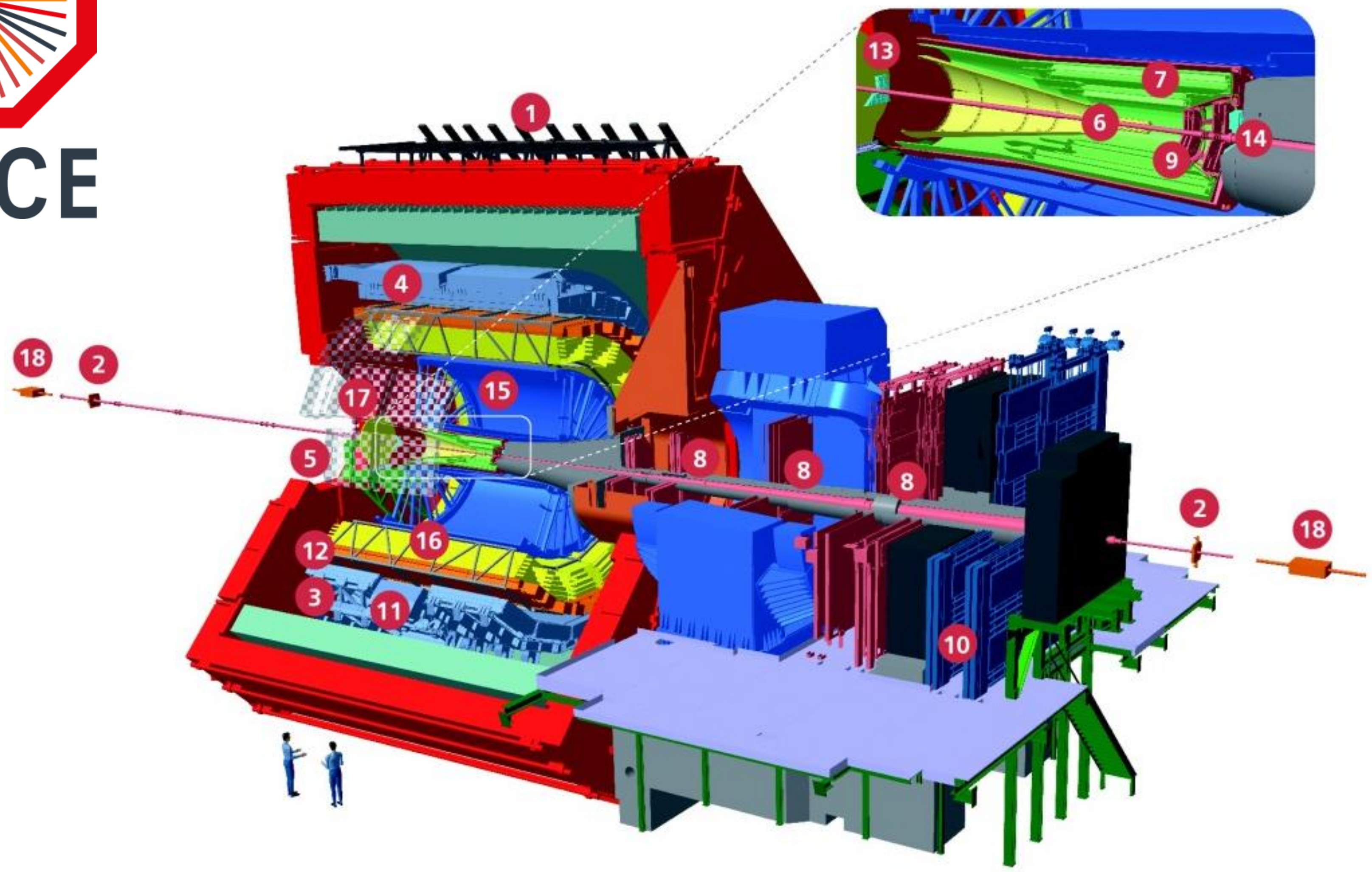


CMS with End-Cap and HC-CT2 chambers installed

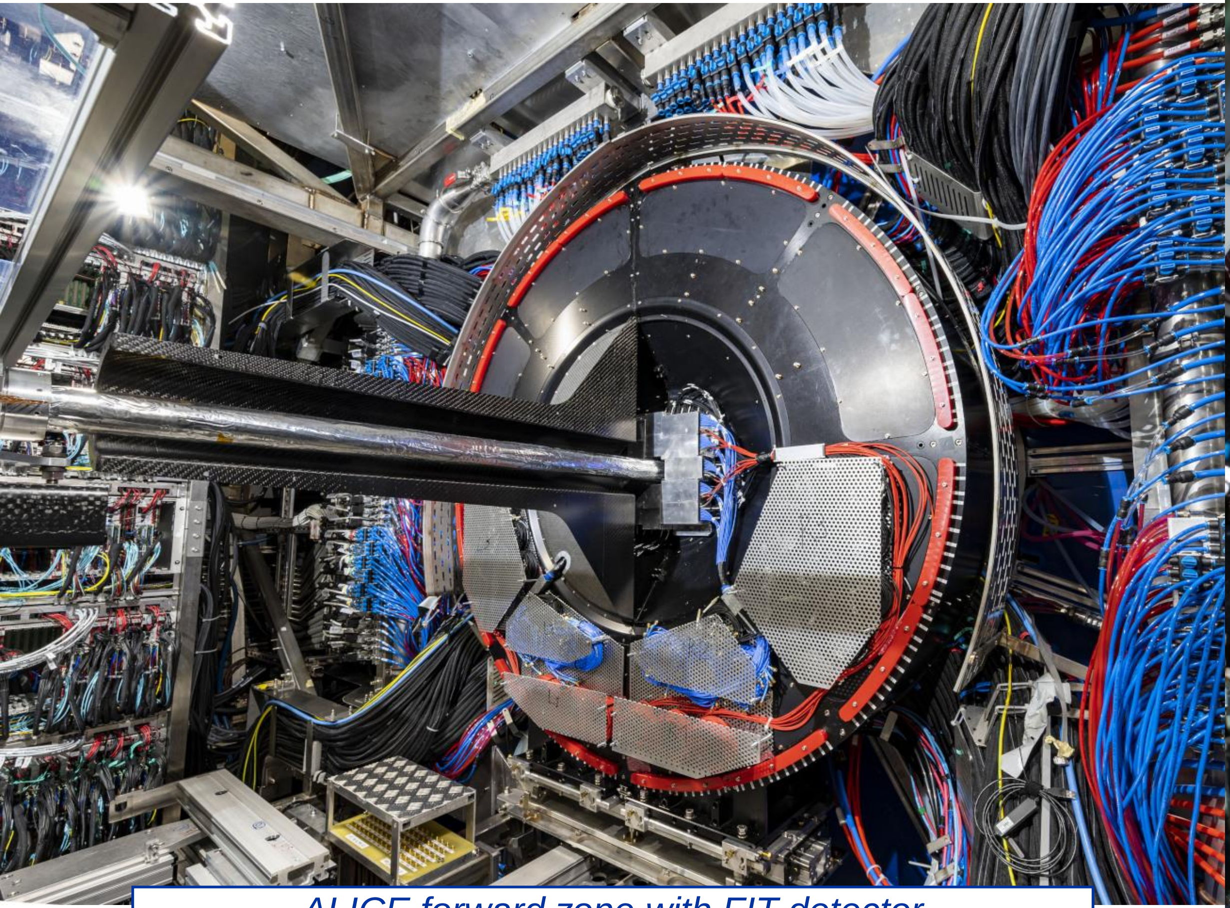


CMS with open End-Cap discs (Long shutdown 2)

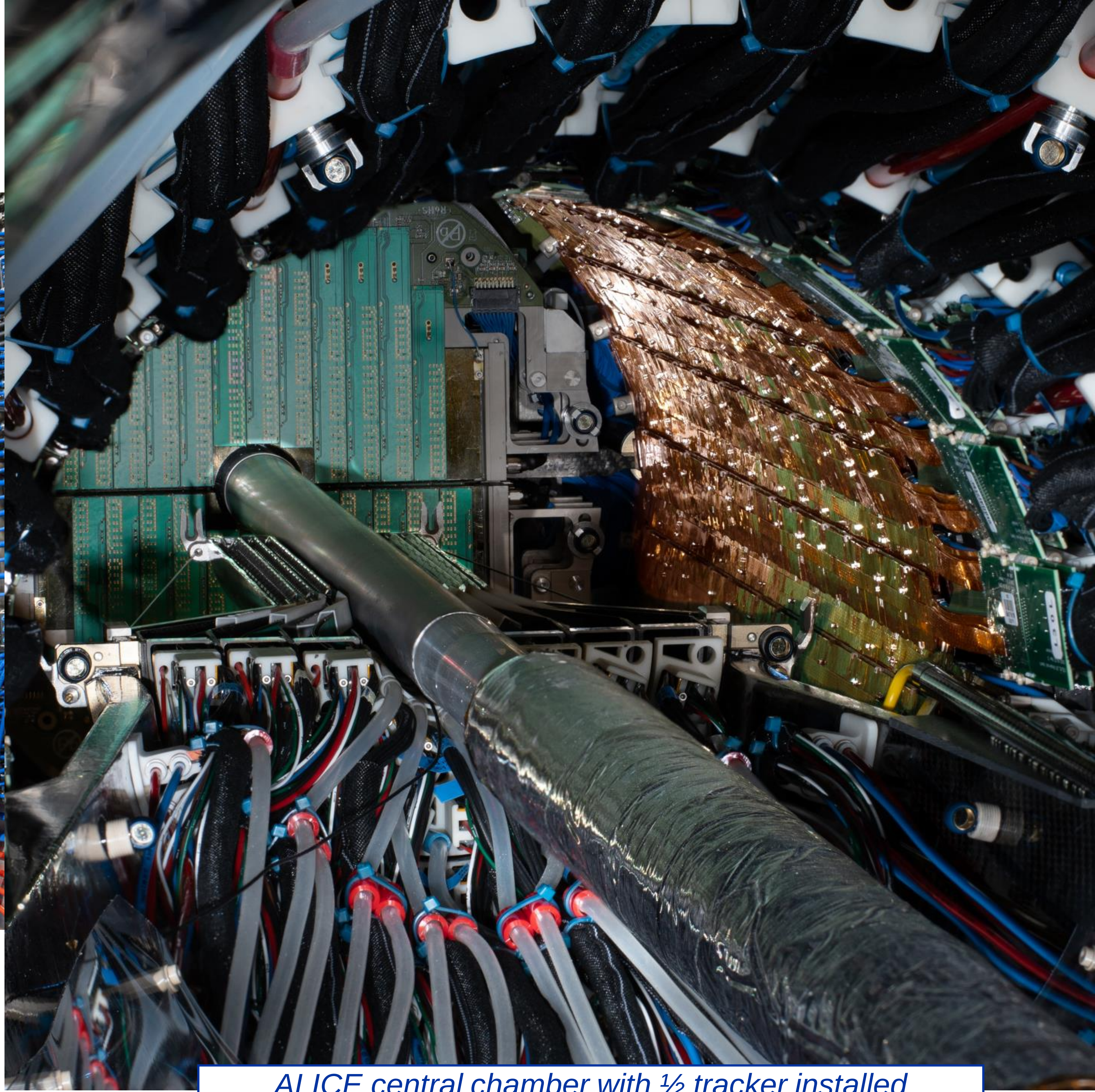
ALICE



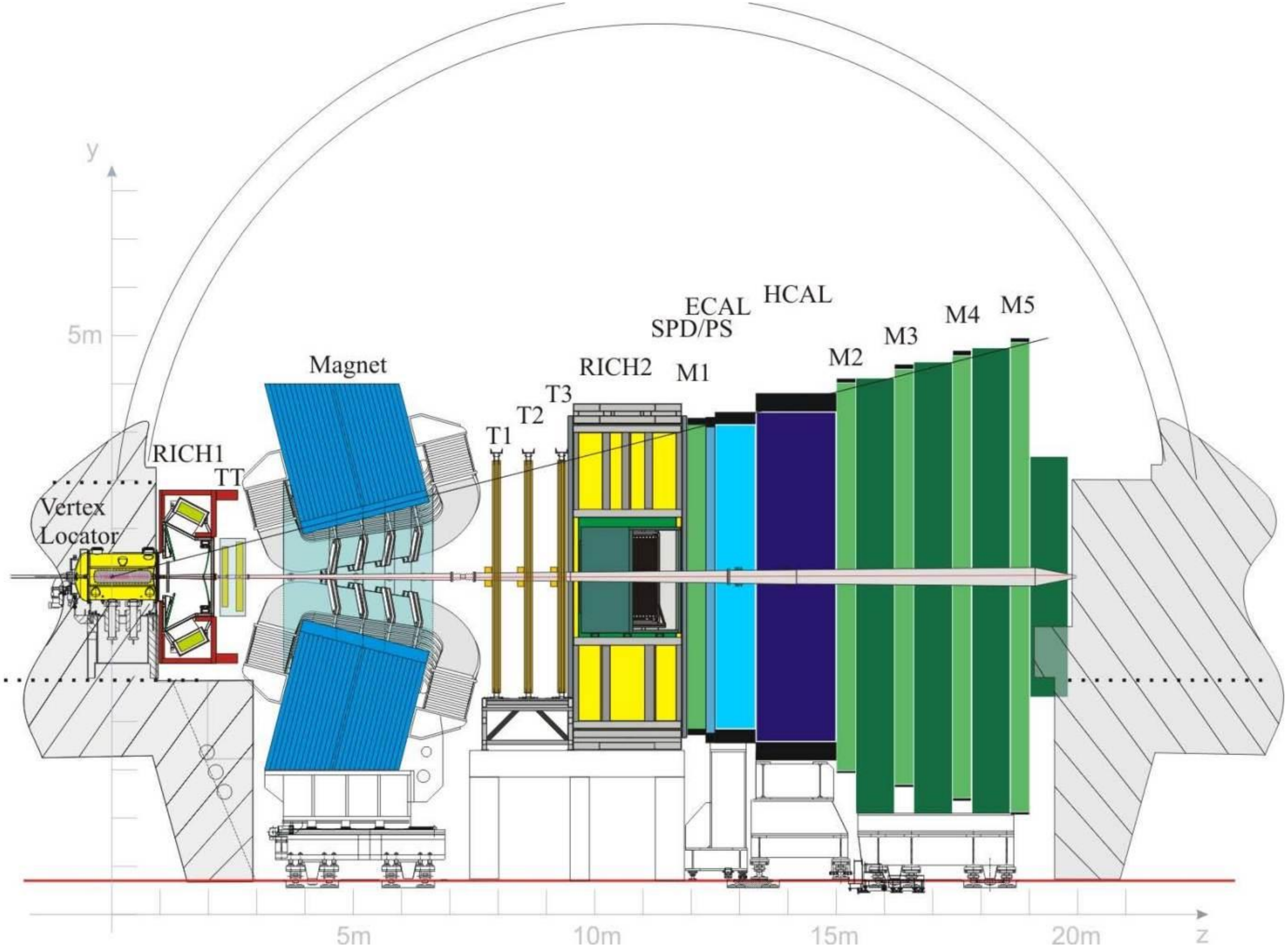
1. **ACORDE** | ALICE Cosmic Rays Detector
2. **AD** | ALICE Diffractive Detector
3. **DCal** | Di-jet Calorimeter
4. **EMCal** | Electromagnetic Calorimeter
5. **HMPID** | High Momentum Particle Identification Detector
6. **ITS-IB** | Inner Tracking System - Inner Barrel
7. **ITS-OB** | Inner Tracking System - Outer Barrel
8. **MCH** | Muon Tracking Chambers
9. **MFT** | Muon Forward Tracker
10. **MID** | Muon Identifier
11. **PHOS / CPV** | Photon Spectrometer
12. **TOF** | Time Of Flight
13. **T0+A** | Tzero + A
14. **T0+C** | Tzero + C
15. **TPC** | Time Projection Chamber
16. **TRD** | Transition Radiation Detector
17. **V0+** | Vzero + Detector
18. **ZDC** | Zero Degree Calorimeter

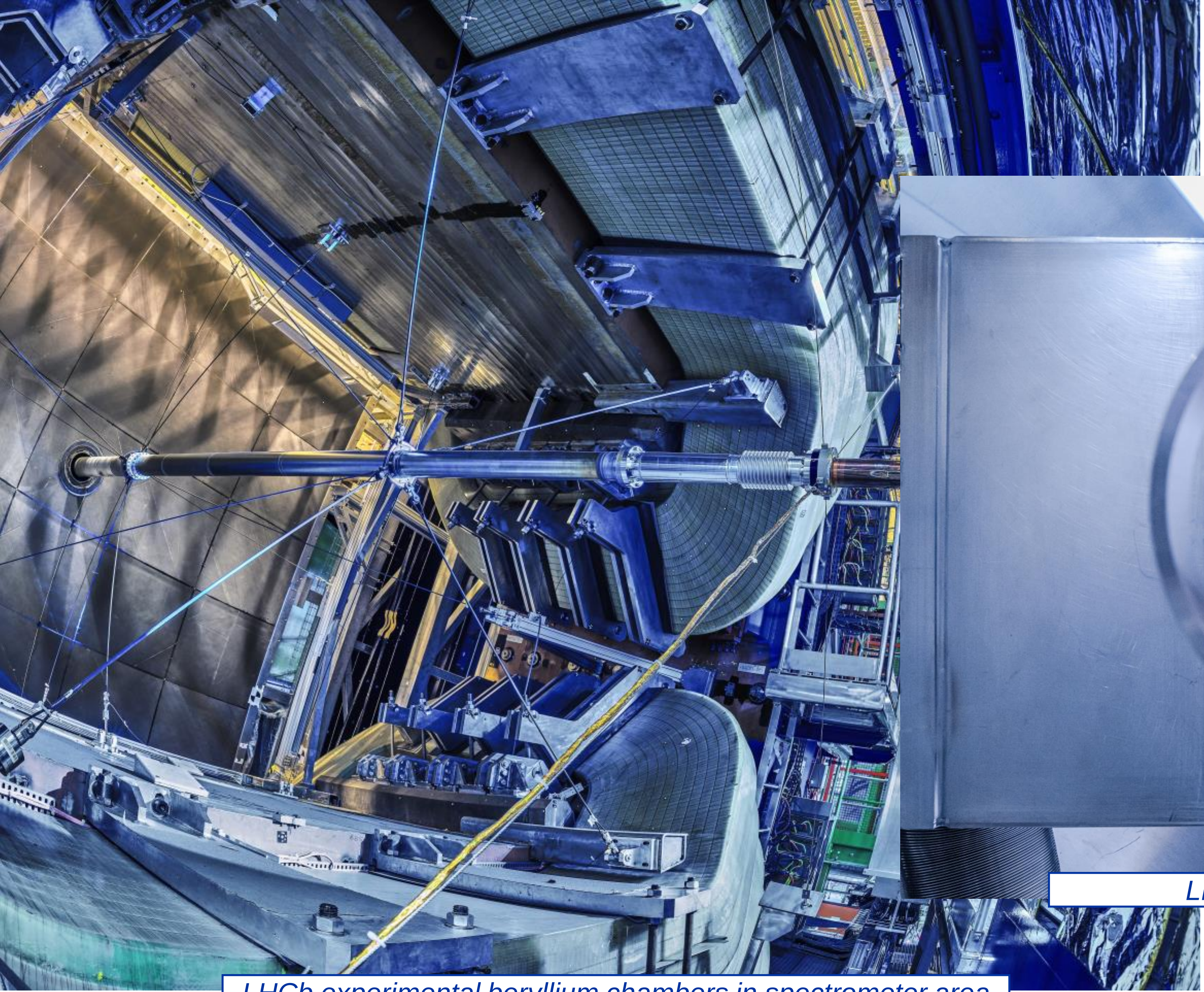


ALICE forward zone with FIT detector



ALICE central chamber with ½ tracker installed


y
5m
Magnet
RICH1
TT
Vertex
Locator
T1
T2
T3
RICH2
M1
ECAL
SPD/PS
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
z



LHCb experimental beryllium chambers in spectrometer area

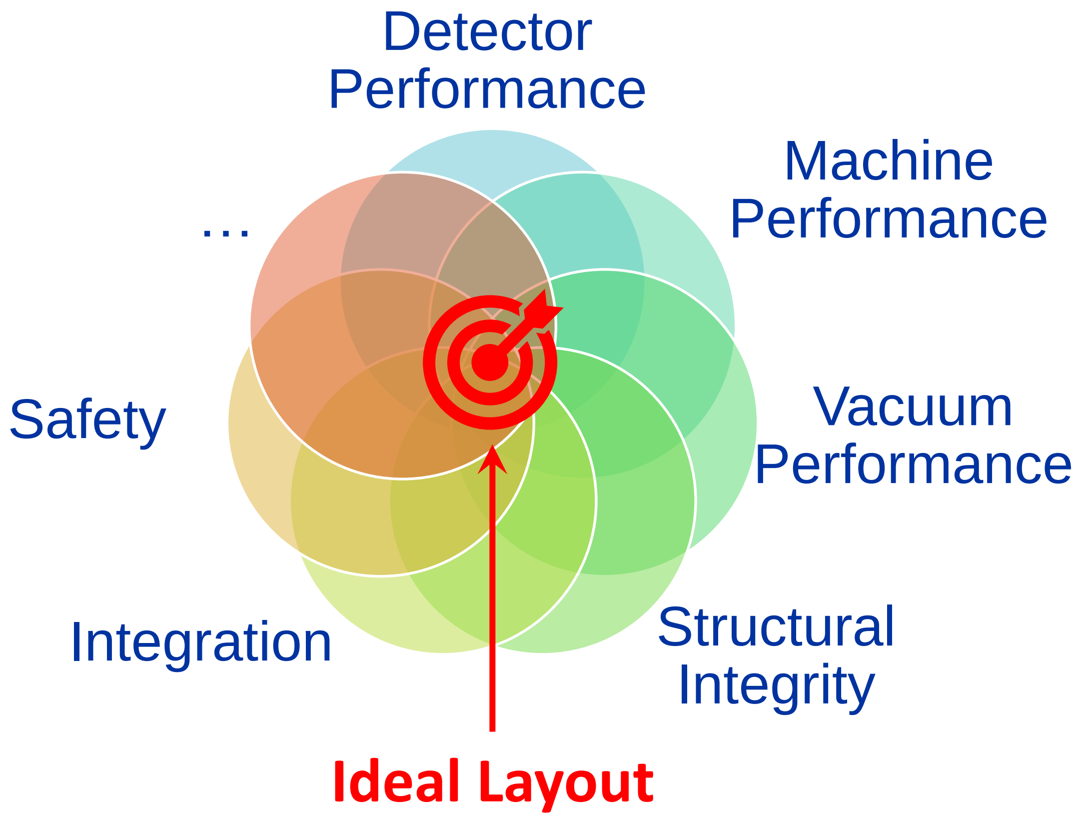
LHCb VELO as seen via SMOG cell

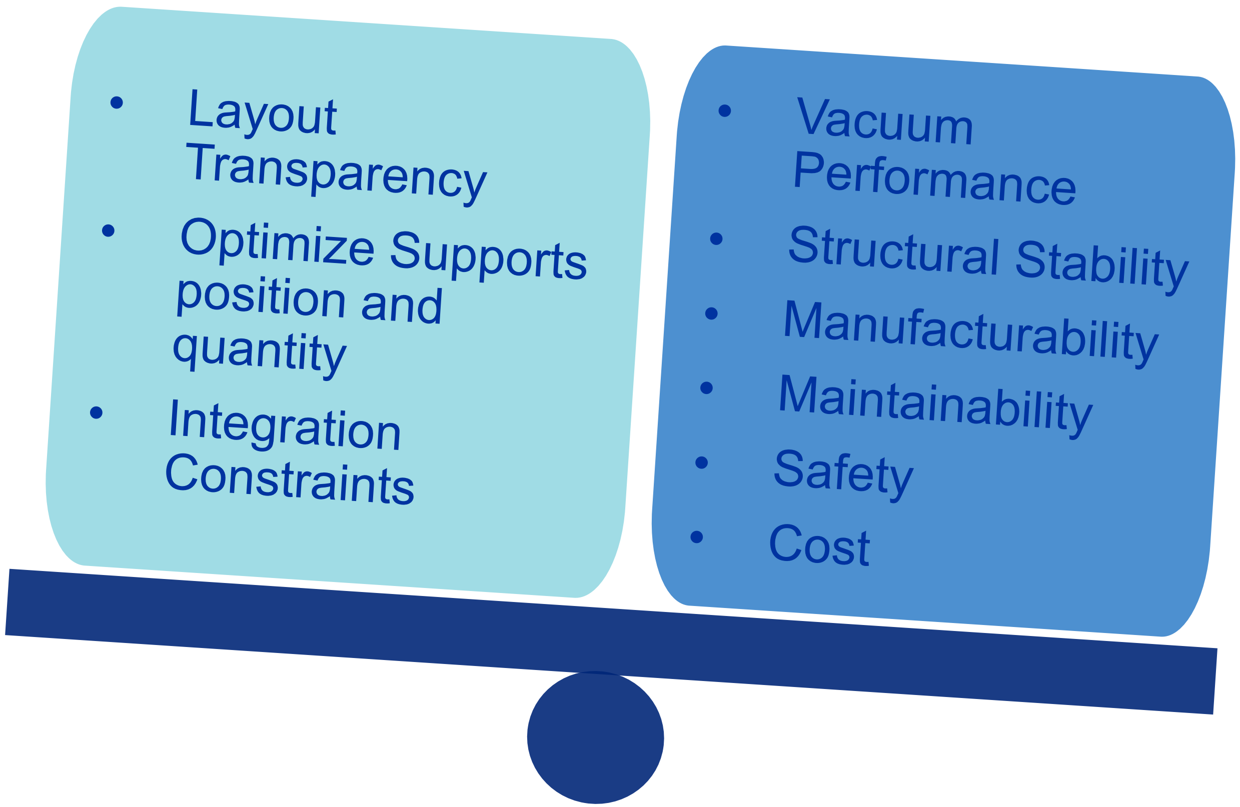
The complexity of the beam vacuum system of LHC’s experiments

For physics performance, the best vacuum chamber is no vacuum chamber.

Unknown physicist

Main challenges & Design approach



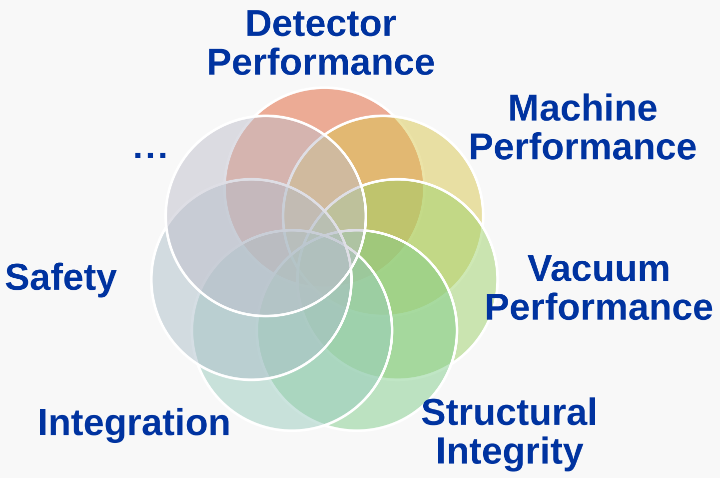


The best solutions come from the cooperative effort of many stakeholders.

A delicate balancing act several seemingly conflicting objectives!

Vacuum Design Approach

PROJECT REQUIREMENTS



PRELIMINARY DESIGNS

- Physics performance requirements
- Infrastructural constraints
- Technological feasibility

VACUUM AND STRUCTURAL VALIDATION

Vacuum Performance
•Pump-down
•Static Vacuum
•Dynamic Vacuum

Structural Integrity
•Support Reactions
•Deformation Under Load
•Yielding
•Buckling

Also Important:
•Manufacturability
•Integration
•Installation
•Maintenance

Experimental layout approval process

LHC machine stakeholders

YES → DETAILED DESIGN

NO

Material, mechanical stability and manufacturing constraints

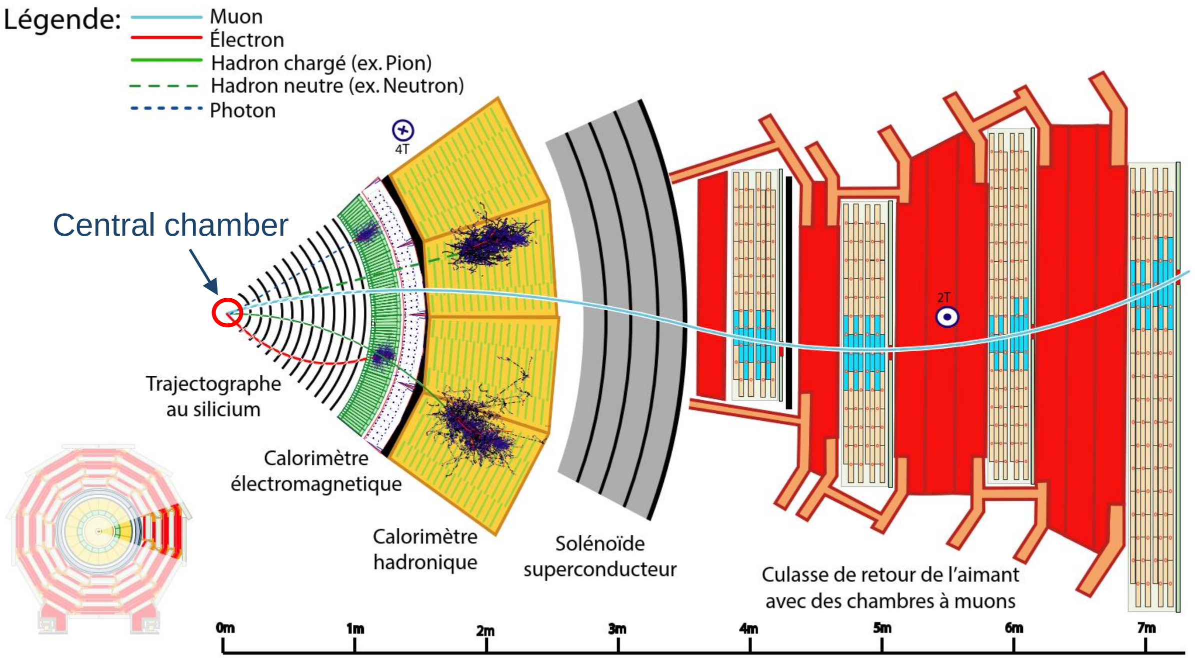
Straight tube is sometimes more than straight tube.

Detector performance and material selection for vacuum chambers

	X_O [mm]	λ [mm]
Beryllium	353	418
Aluminum based alloys	≈ 89	≈ 287
Ferrous based alloys	≈ 18	≈ 130

Transparency

Distance that colliding particle travels without interacting with surrounding material nuclei.



- **Radiation length** $X_O = \frac{716.4 \cdot A}{Z \cdot (Z+1) \cdot \ln(\frac{287}{\sqrt{Z}})}$

Applies for light particles

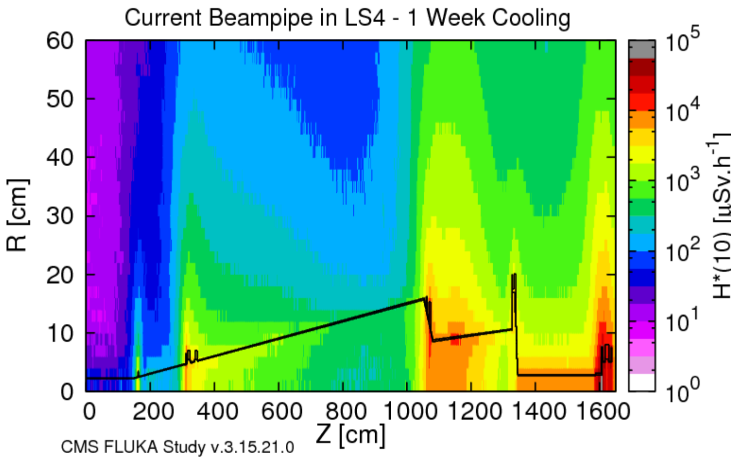
- **Interaction length** $\lambda = \frac{A}{N_A \cdot \sigma \cdot \rho}$

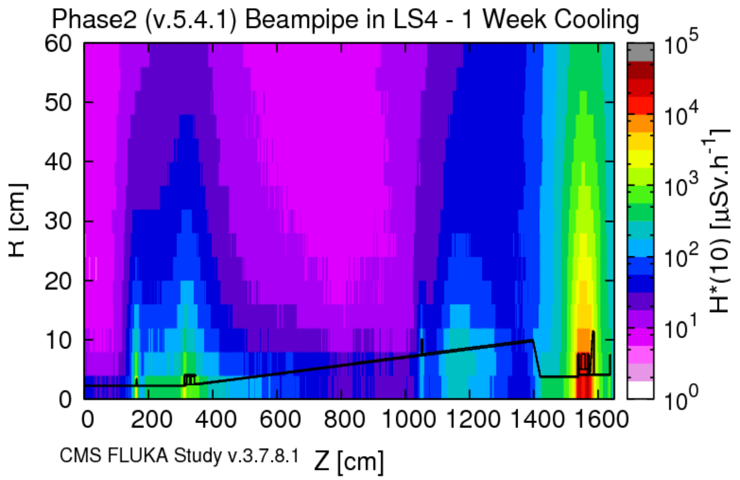
Applies for particles with strong interaction

where Z is atomic number; A atomic mass; N_A Avogadro's number; σ inelastic nuclear cross-section and ρ density of the material.

Detector performance and material selection for vacuum chambers

- **Beryllium S-200-F (98.5% pure Be)**
  - Powder metallurgy
  - Processed by vacuum or hot isostatic pressing
- **Aluminum EN-AW-2219**
  - Copper based aluminum alloy
  - Mechanical properties at elevated temperatures
  - Main segments of the chambers & flanges
- **Aluminum EN-AW-5083**
  - Magnesium based aluminum alloy
  - Mechanical properties at elevated temperatures
  - Corrosion resistance and weldability
  - Cold-worked sheets 0.3 mm for aluminum bellows





Equipment made of aluminum reduces dose obtained by personnel by factor ≈ 5

Detector performance and material selection for vacuum chambers

CERN specification
10 grains per wall-thickness
For wall-thickness 1mm
=
Average grain size 100µm

- **Aluminum EN-AW-2219**
  - Challenging microstructural requirements – grain size

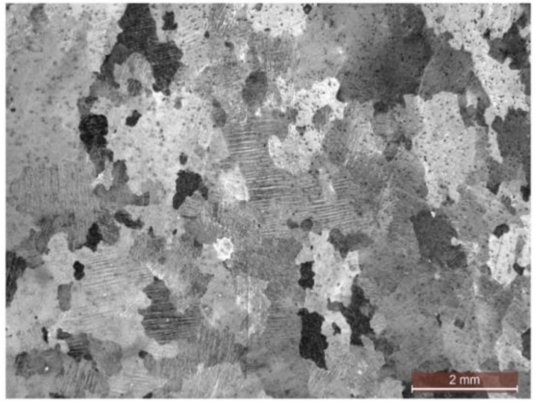


Image 1 specimen A04: Transversal section

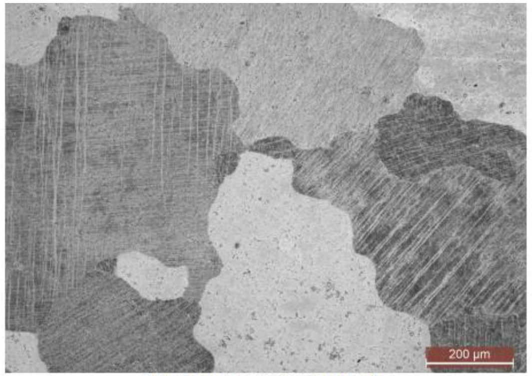
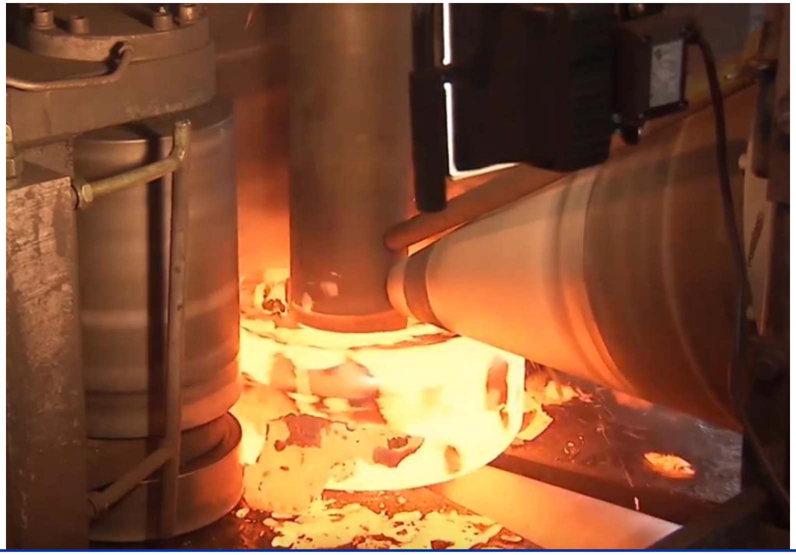


Image 1 specimen A04: Transversal section



Ring rolling of AW2219 for CERN vacuum chambers

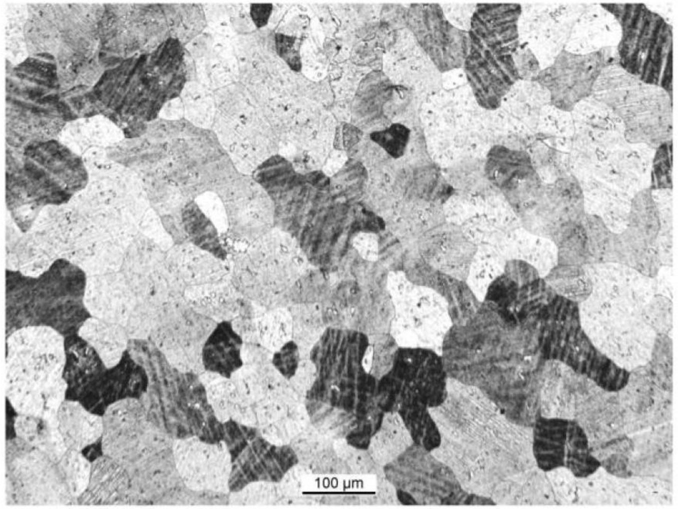
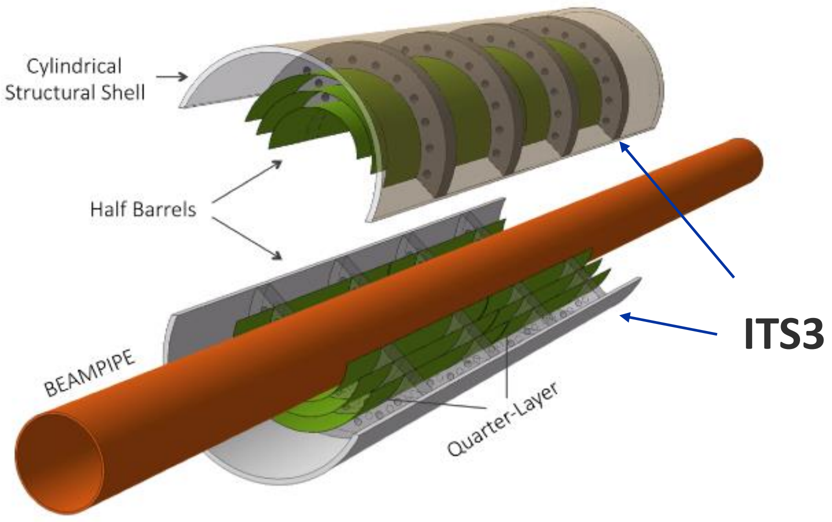


Fig. 2: microsection B366/4

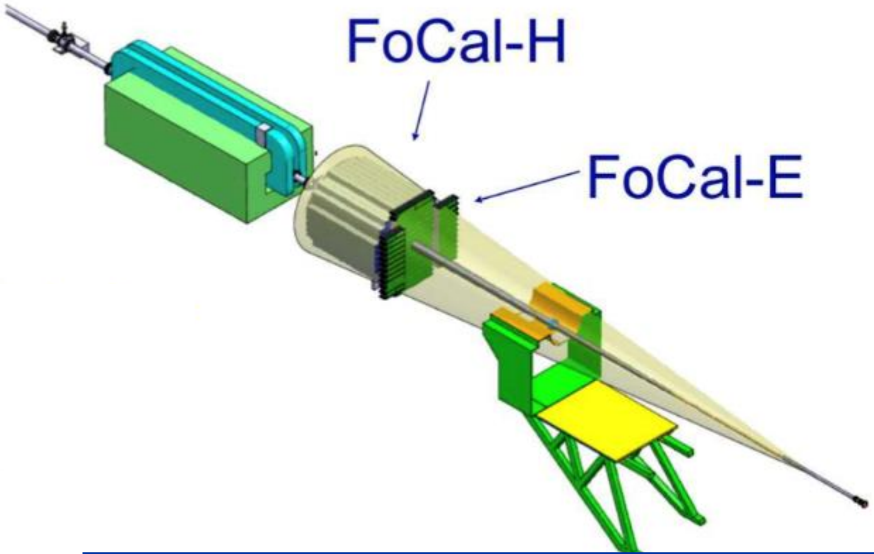
Mechanical stability (structural analysis)
ALICE upgrade for LHC Run4

Two projects with a significant impact on the vacuum layout are expected:

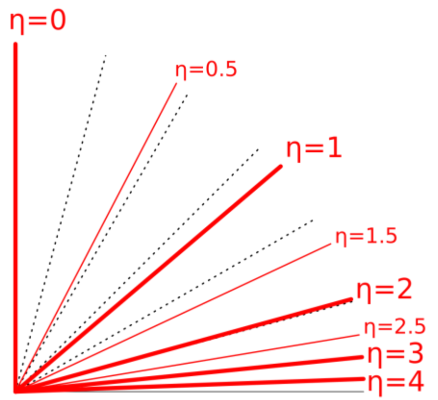
- New Vertex detector (ITS3) – the innermost layer positioned at only 18 mm (radially) from the interaction point.
- New Forward Calorimeter (FoCal), requires a low material budget within pseudorapidity angle 3 < η < 6.



ALICE tracker upgrade concept



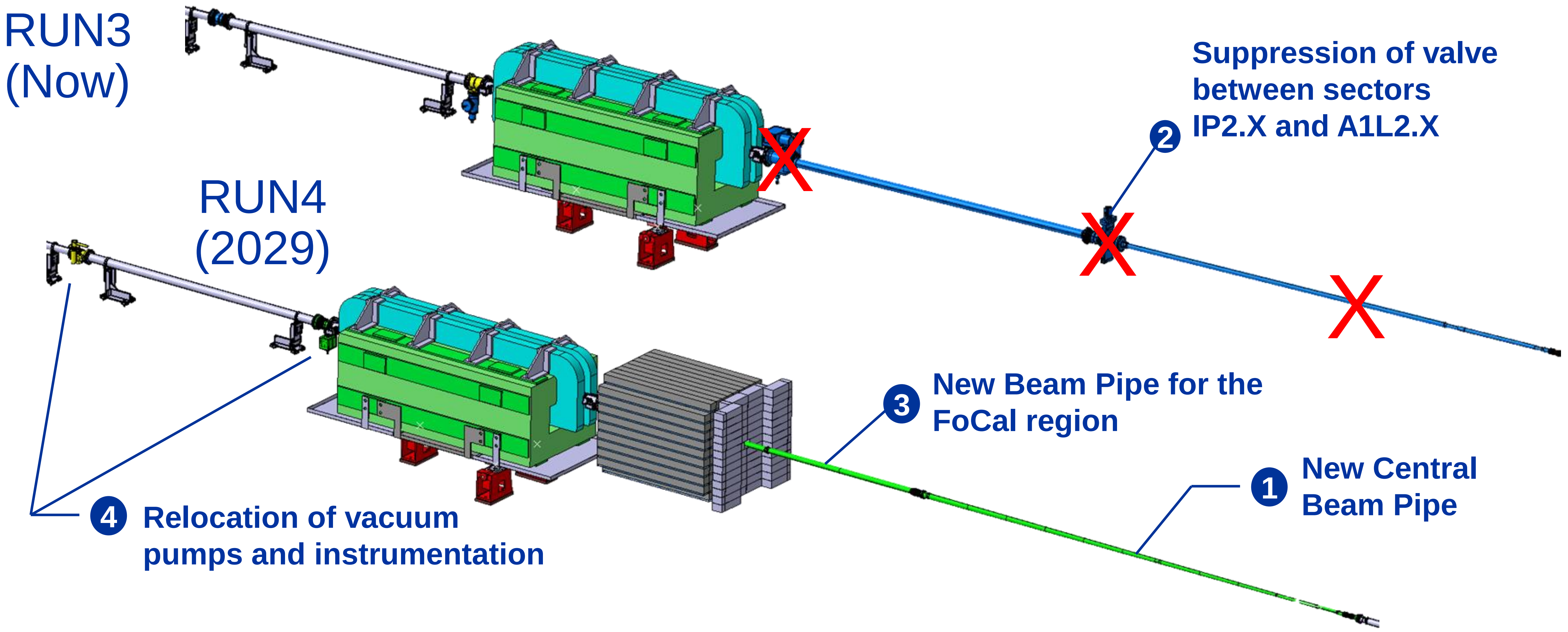
ALICE forward calorimeter upgrade



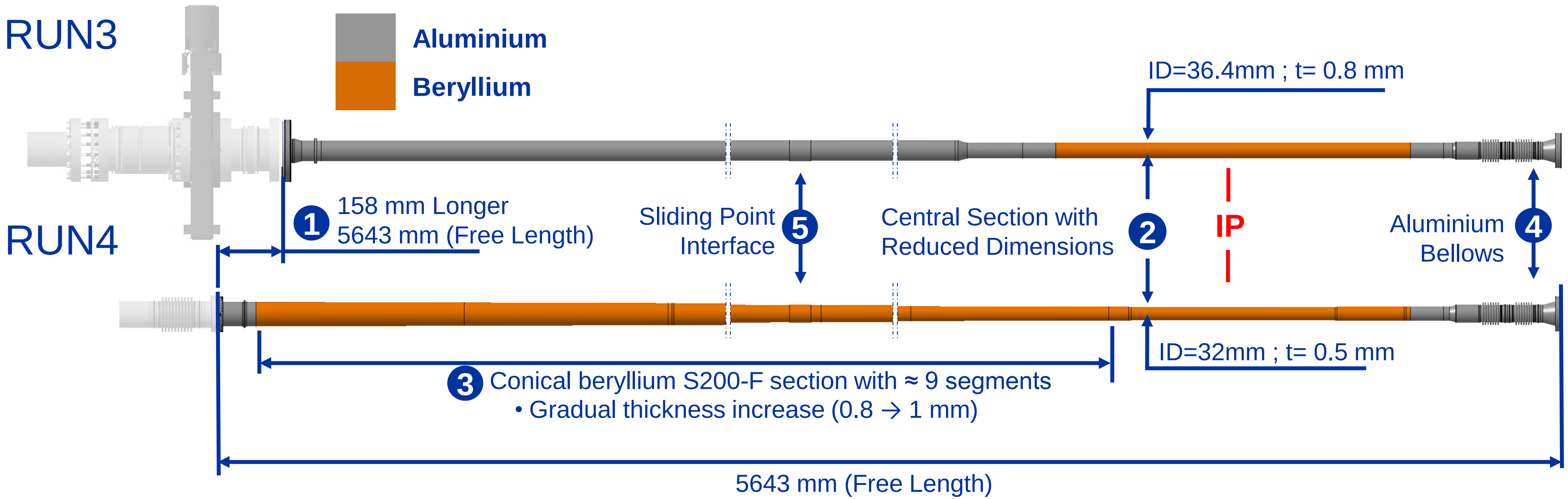
Pseudorapidity

A. Collaboration, "Letter of Intent for an ALICE ITS Upgrade in LS3," ALICE-PUBLIC-2018-013, 2018.
A. Collaboration, "Letter of Intent : A Forward Calorimeter (FoCal) in the ALICE experiment," CERN-LHCC-2020-009, 2020.

Mechanical stability (structural analysis)
ALICE upgrade for LHC Run4



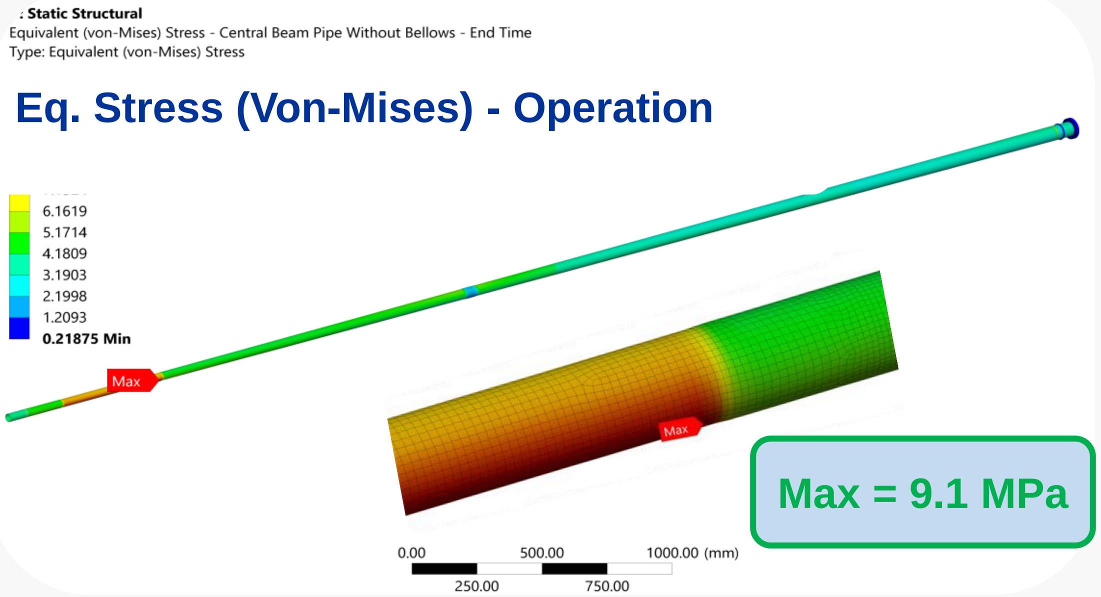
Mechanical stability (structural analysis)
ALICE upgrade for LHC Run4



Inner surface of the chamber coated by NEG (at CERN).
Temperature range for experimental chambers -40°C (during operations) to 250 °C (during commissioning).
Chamber operates at magnetic fields ≈ 2T.

Mechanical stability (structural analysis)

ALICE central chamber use-case



Eq. Stress (Von-Mises) - Operation

Max = 9.1 MPa

Beam Pipe Sag - Operation

Maximum Vertical Displacement = 0.06 mm

Natural Frequencies in Operation [Hz]: 52.3, 79, 183, 229.3

Buckling Analysis in Acceptance Test Configuration

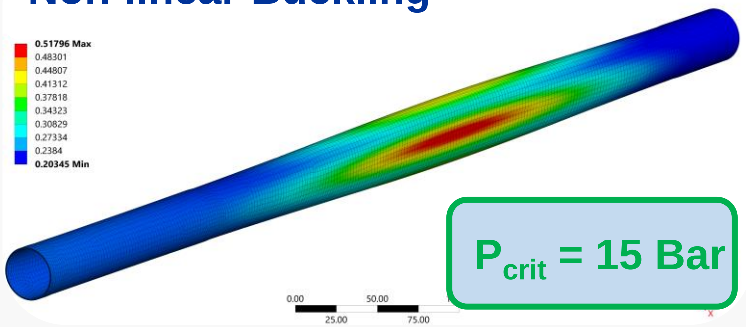
(Bake-Out Expansion : 20 mm [@250ºC])

Linear Local Buckling Analysis

Segment	P_{crit} [bar]
Be t=0.5mm	**24.5**
Be Cone t=0.8 mm	43.8
Be Cone t=0.9 mm	35
Be Cone t=1mm	35

Non-Linear Analysis of most critical segment:

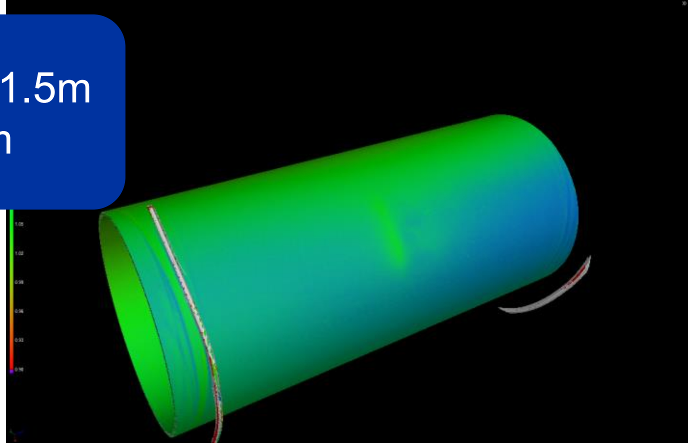
Non-linear Buckling



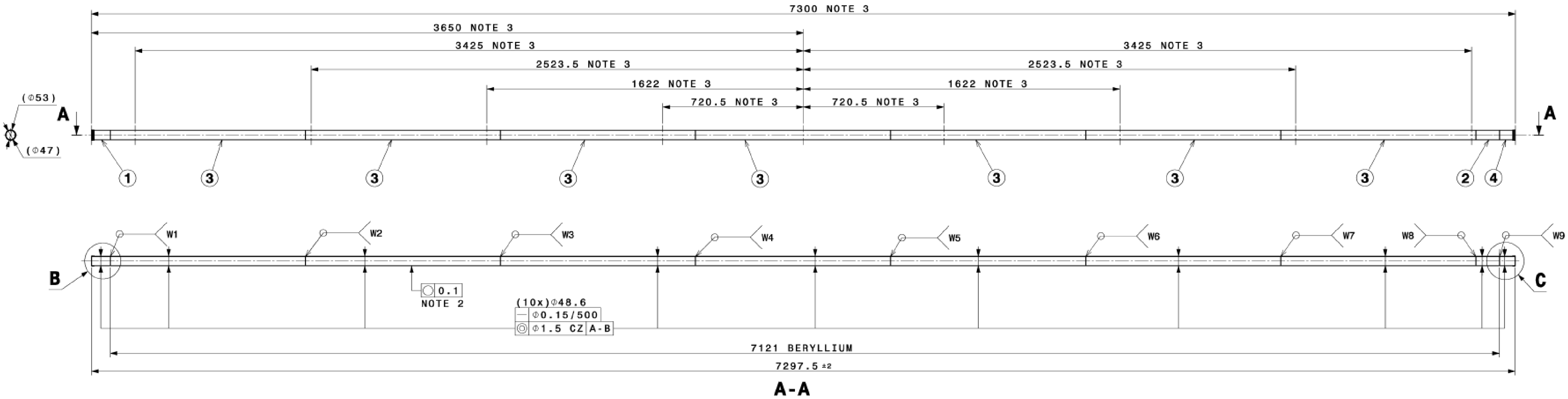
P_{crit} = 15 Bar

Manufacturing constraints

Max. workpiece size ≈ 1.5m
Resolution ≈ 50 µm

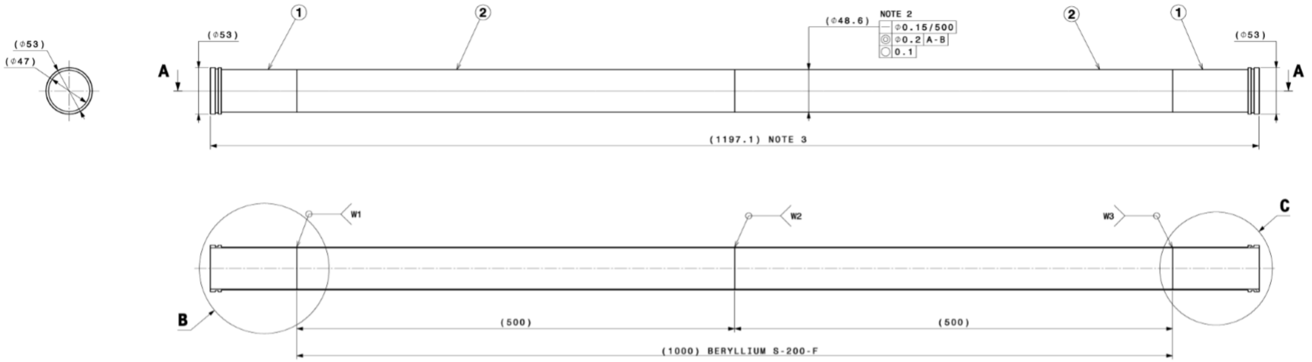


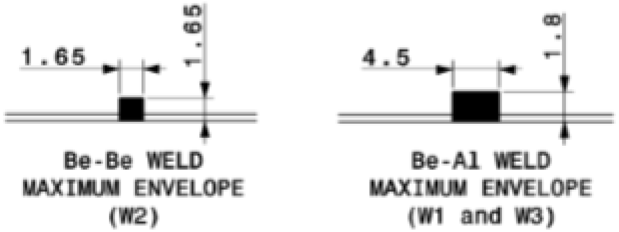
- **Precise machining of long tubular & conical segments**
  - OD/L ratio ≈ 1/20; segments with length up to 1000mm;
  - Stability during the machining (tolerances of straightness, circularity and concentricity during the welding);
  - Wall-thickness variation for thin segments 0.8mm – 1mm shall not exceed 0/+0.1mm;



Manufacturing constraints

- **Vacuum requirements**
  - Surface cleanliness according to the CERN standards for UHV and NEG coating.
  - Leak tightness *(not exceeding 10^{-10} mbar·l·s^{-1}).*
  - Outgassing rate *(not exceeding 10^{-7} mbar·l·s^{-1} - measured after bake-out cycle).*
  - Acceptable ratios for RGA mass peaks (residual gas composition).
- **Welding requirements**
  - Fusion welding – TIG or electron beam welding (No filler material allowed).
  - Number of welds to be minimized; No longitudinal welds are allowed; Weld envelope control.
  - Quality requirements ISO 13919-2 Level B (for EWB) ISO 10042 Level B (for TIG).





Production steps, installation and performance of experimental beampipes

Process covering full equipment lifecycle

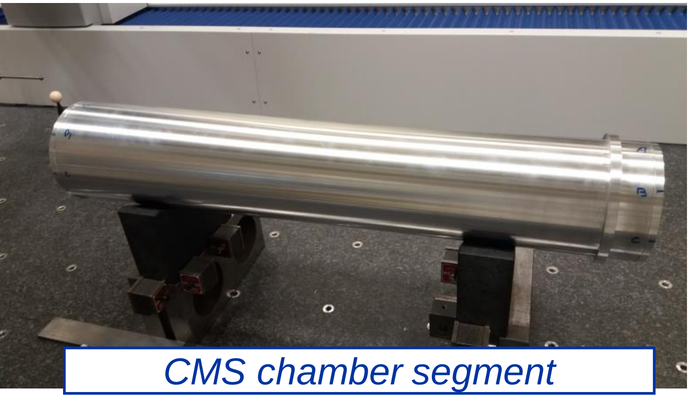
Production steps, installation and performance of experimental beampipes

Design → Production → **Post-production and Vacuum Validation** → **Installation and Commissioning** → Operation

PRODUCTION

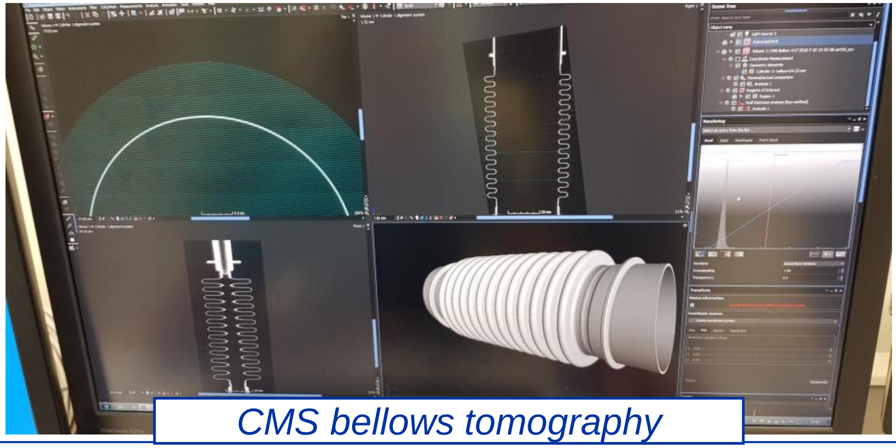
Raw material → Transformation (Machining) → Assembly (Welding)

Quality control at every step!



CMS chamber segment

CMS chamber segments



CMS bellows tomography

CMS TIG welding process

Production steps, installation and performance of experimental beampipes

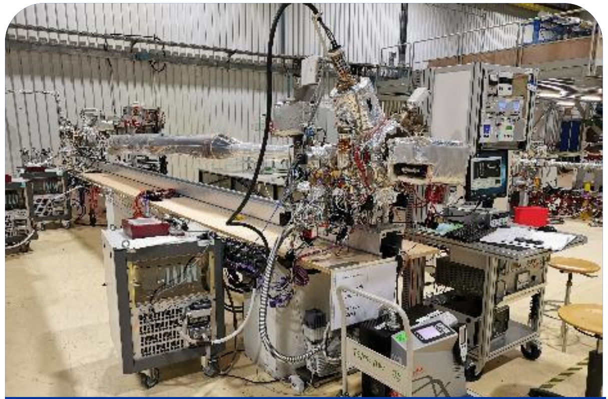
1. Final Chemical Cleaning
2. Visual Inspection
3. Vacuum Acceptance Test
4. Permanent Bake-Out Heaters
5. NEG Coating
6. Permanent Insulation
7. Final NEG Acceptance Tests
8. Visual Inspection

Validation Before NEG Coating (Visual Inspection, Vacuum Acceptance Test)

NEG Coating Validation (Final NEG Acceptance Tests, Visual Inspection)

After the chambers left the workshop, TE-VSC was responsible for a lengthy post-production process:

Chemical Cleaning



Vacuum Acceptance Tests

NEG Coating

Permanent Insulation Installation

Production steps, installation and performance of experimental beampipes

HF-CT2 Beam Pipe Endoscopic Inspection

Surface treatments (etching & degreasing)

NEG coating

Contactless Endoscopy:

- General imperfections.
- Conformity of functional features.
- Sealing surfaces.
- Internal surface integrity.

Surface treatments:

- Removal of potential surface contaminants.
- Removal of machining history (surface texture) to improve coating adhesion.

NEG coating:

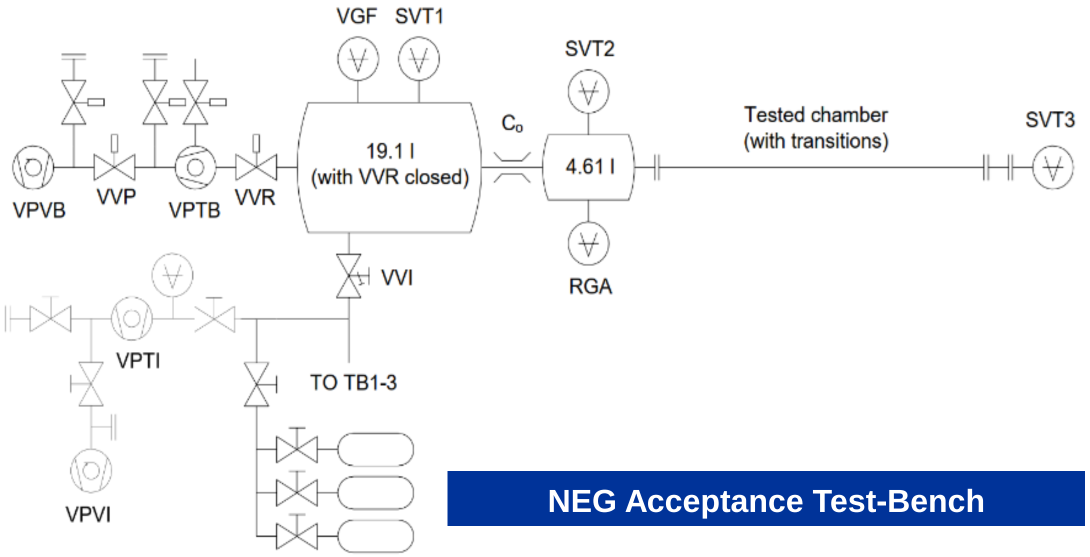
- Major production milestone.
- In some cases, considered as irreversible step.

Production steps, installation and performance of experimental beampipes

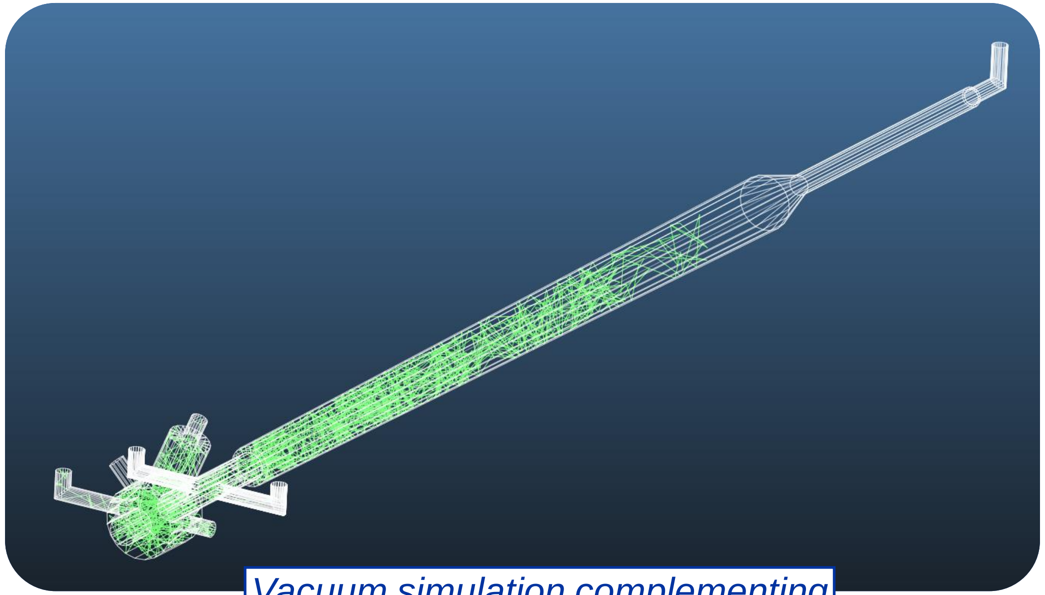
Final NEG Acceptance Test:

Pump-down and Leak Detection → RGA Before Bake-Out → Bake-Out & NEG Activation → 100% He Leak Detection → RGA and Ultimate Pressure → NEG Performance: H_2 Injection

Molflow Simulations → NEG Performance: H_2 Injection

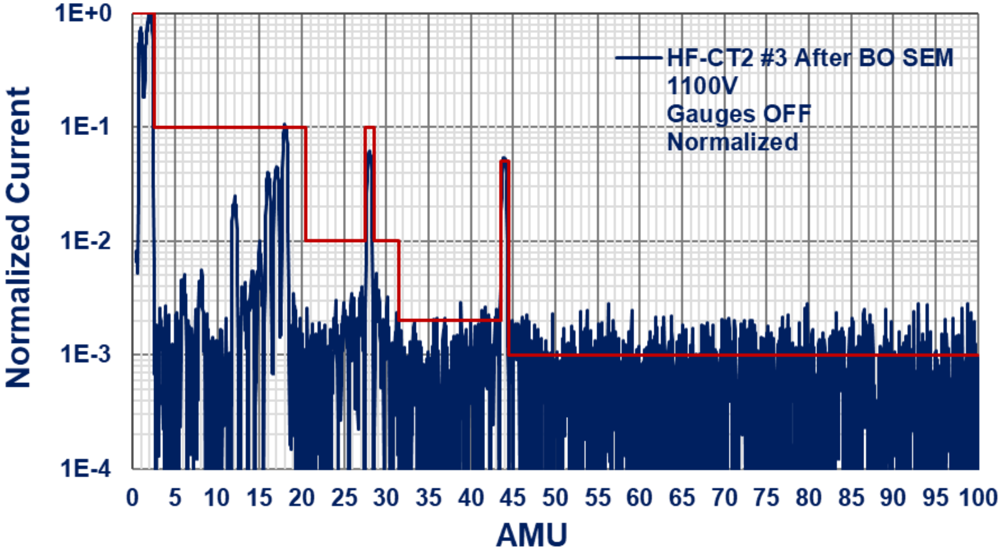


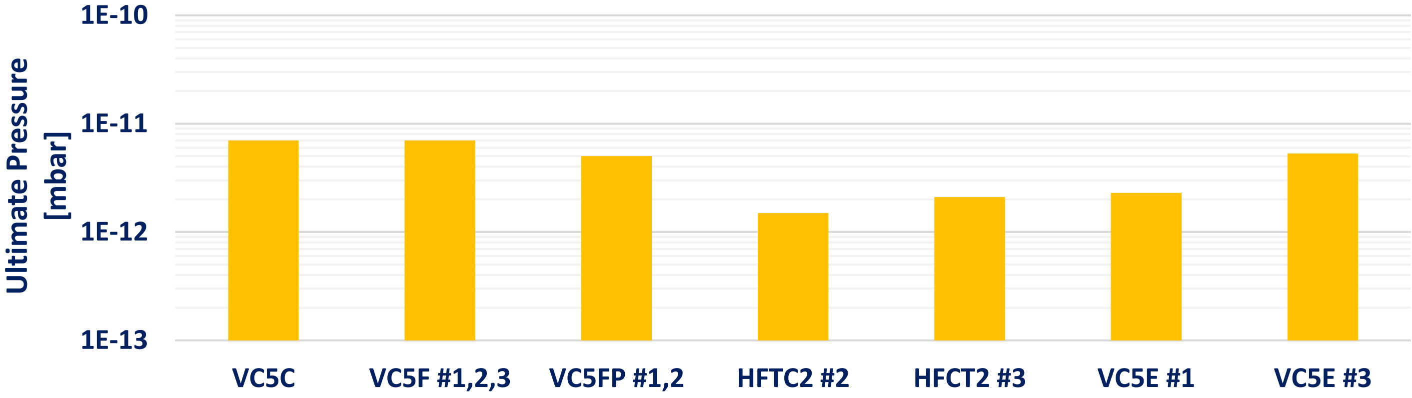
NEG Acceptance Test-Bench



Vacuum simulation complementing the acceptance test

Production steps, installation and performance of experimental beampipes



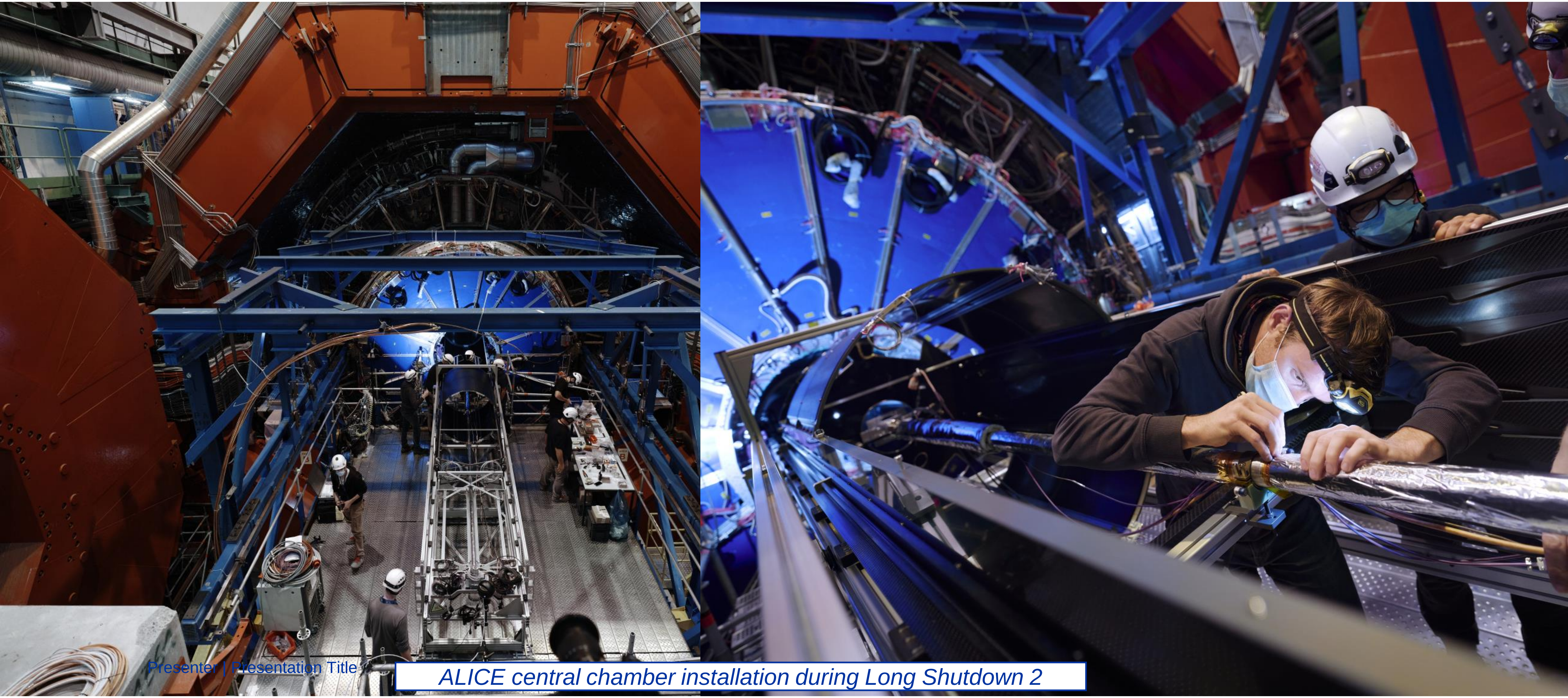


All beam pipes are free of contaminants.
Ultimate pressures measured at 10^{-12} mbar range.

Production steps, installation and performance of experimental beampipes

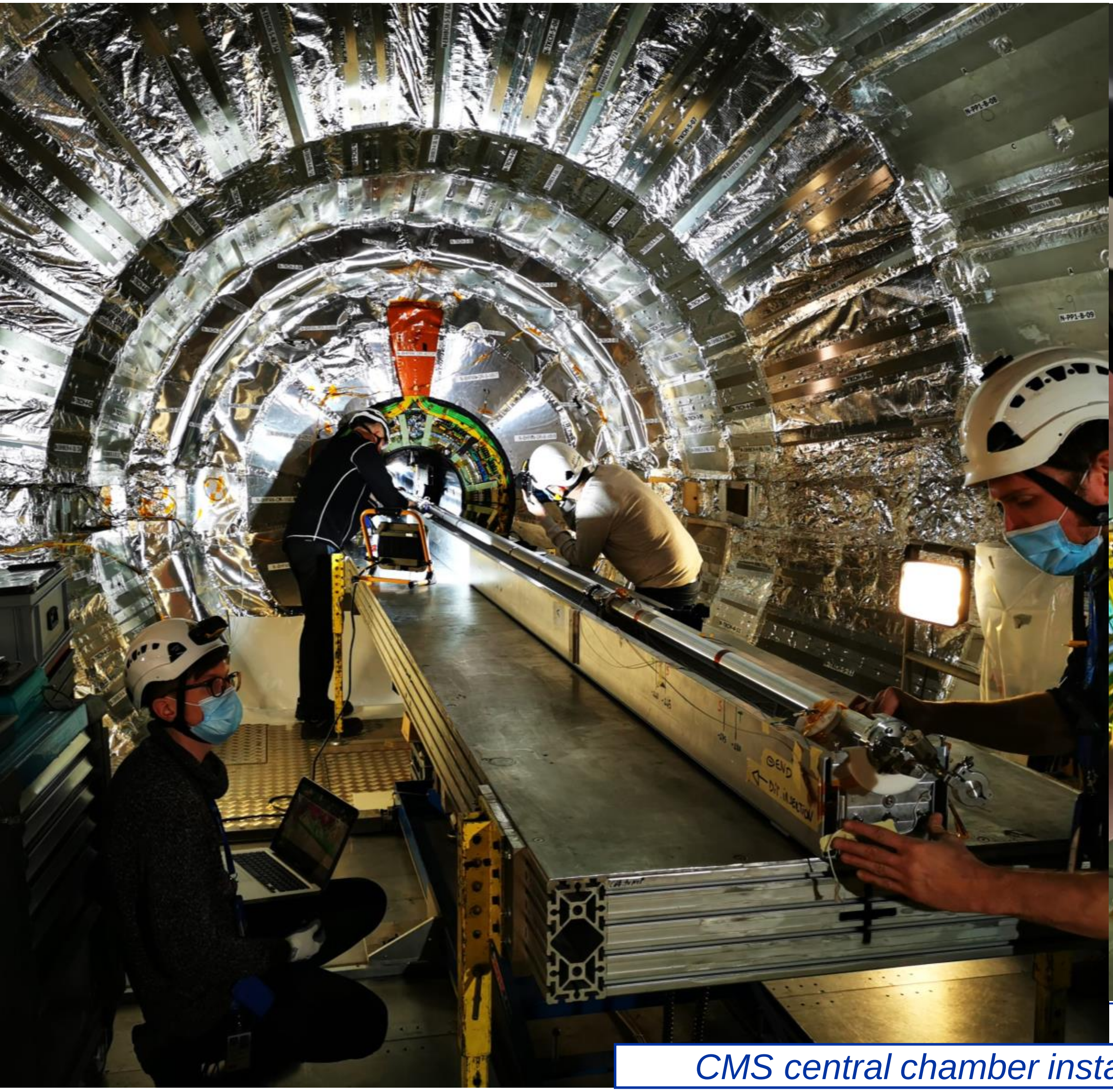
ALICE central chamber installation during Long Shutdown 2

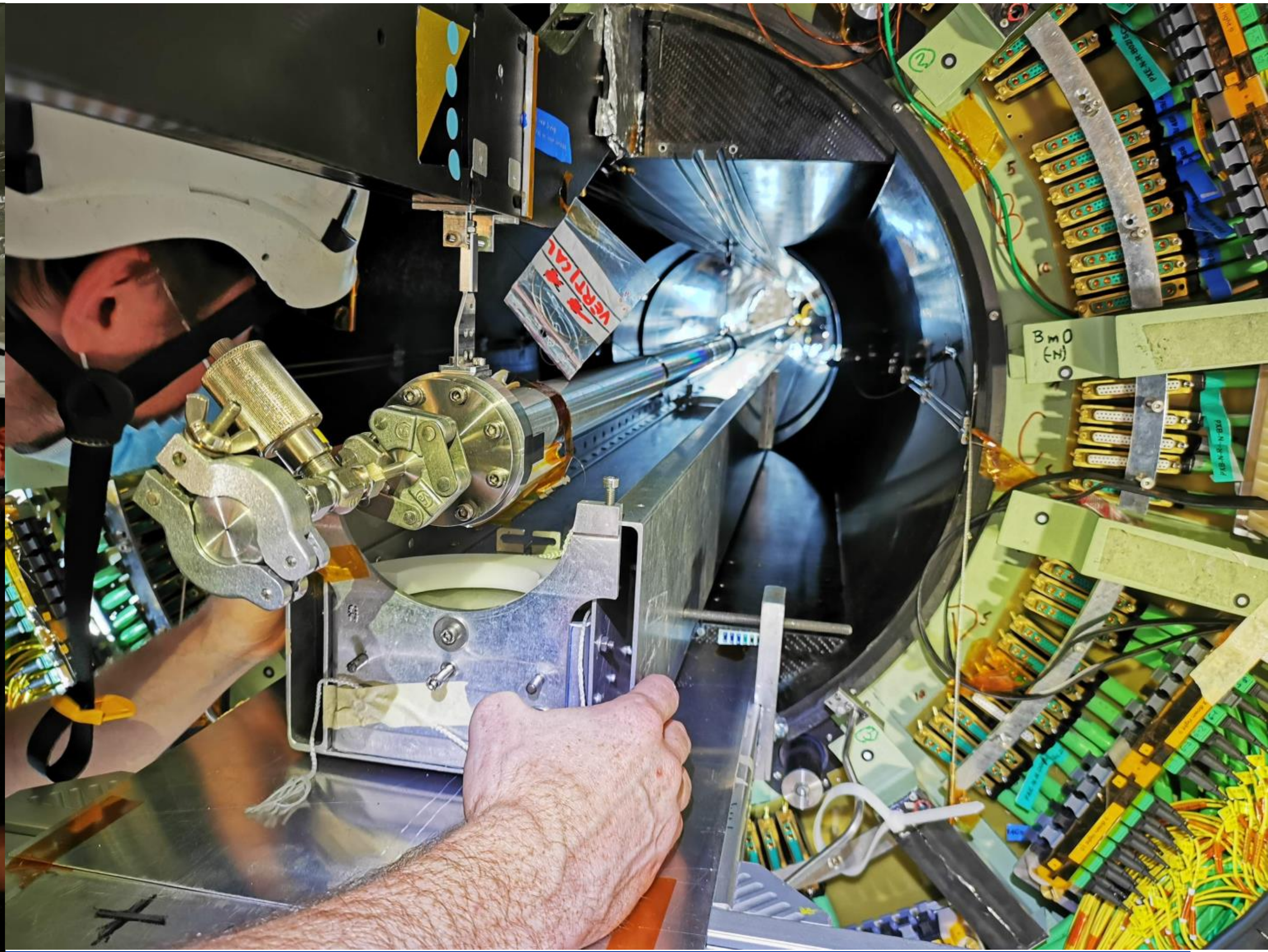
Production steps, installation and performance of experimental beampipes



ALICE central chamber installation during Long Shutdown 2

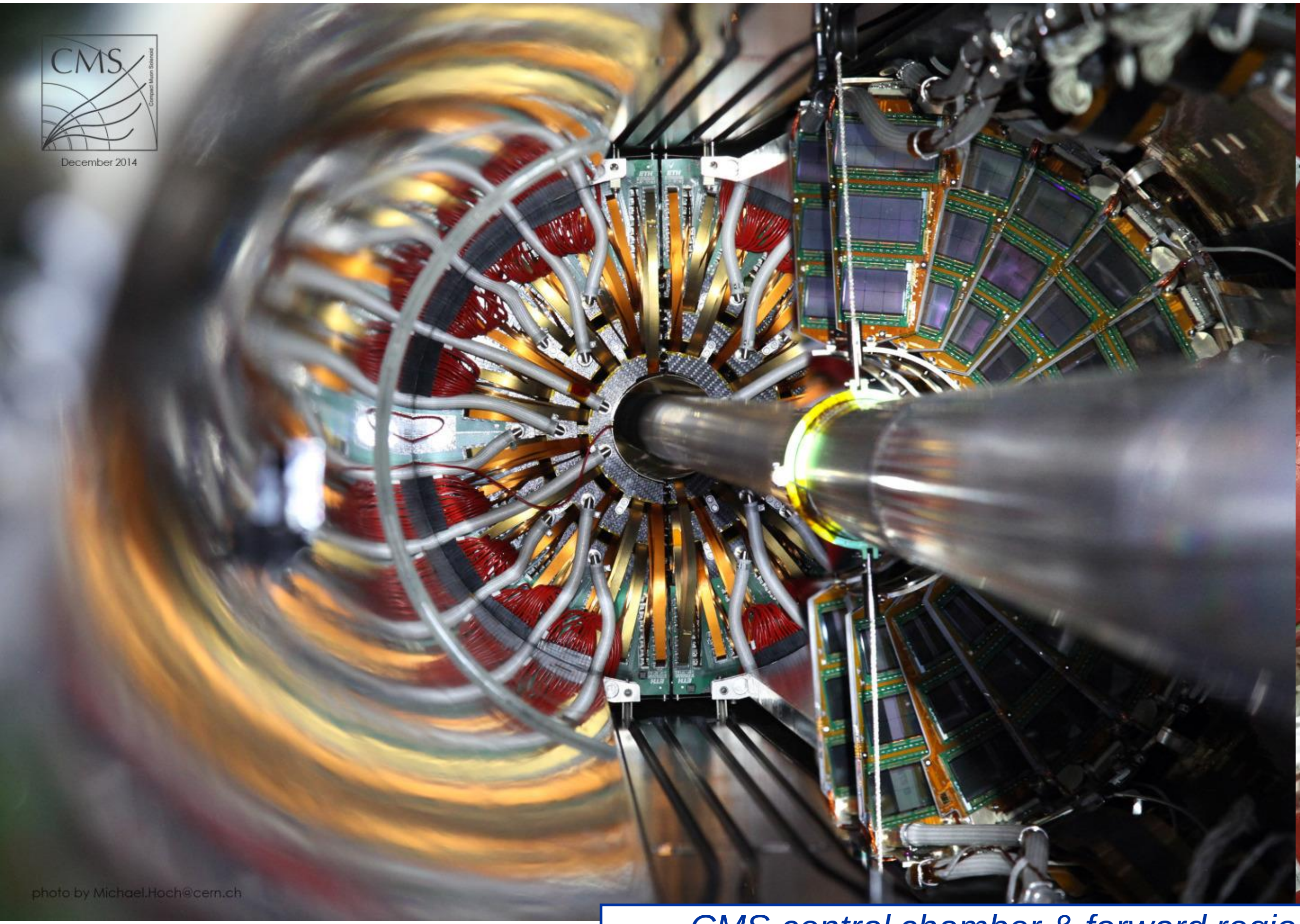
Production steps, installation and performance of experimental beampipes

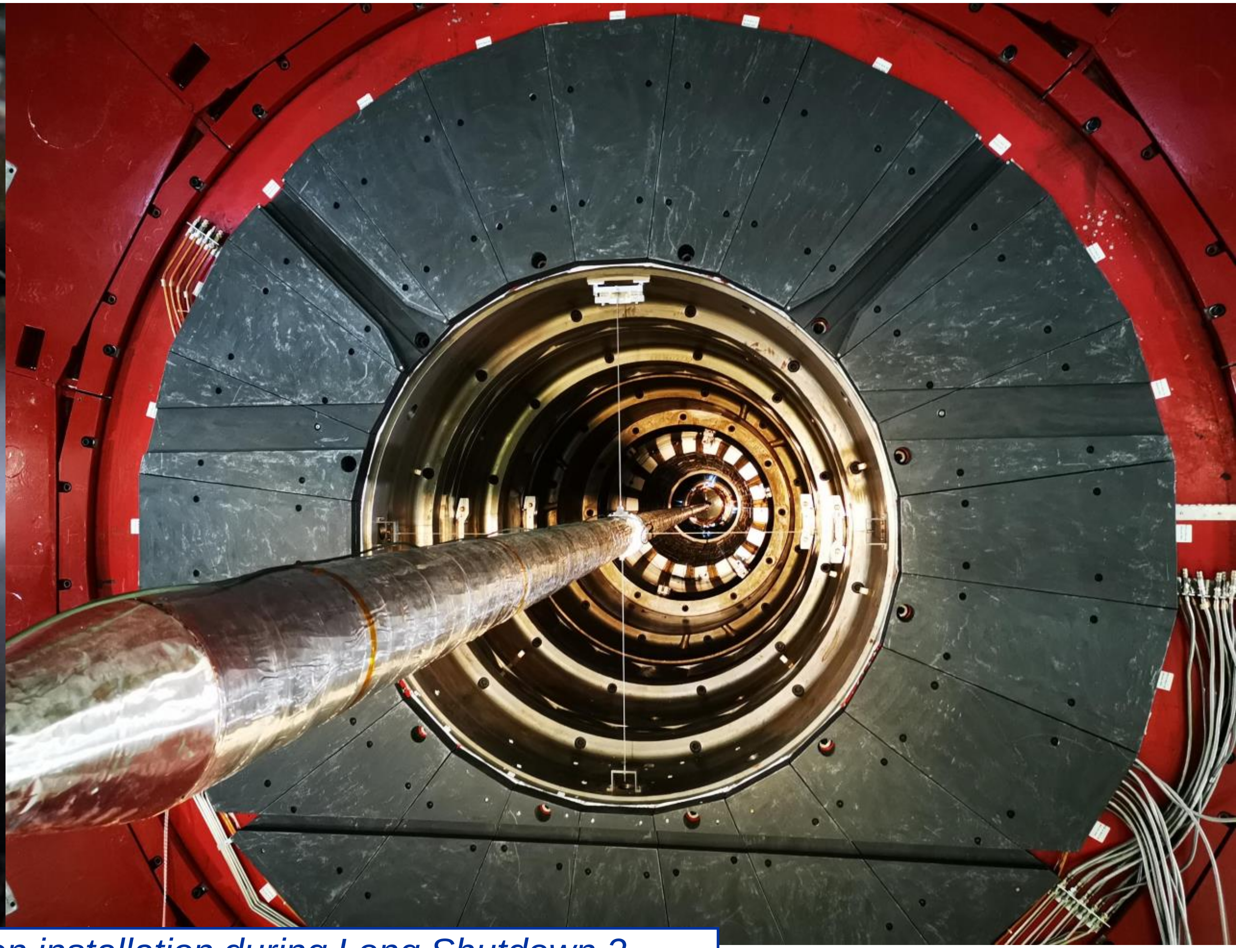




CMS central chamber installation during Long Shutdown 2

Production steps, installation and performance of experimental beampipes





CMS central chamber & forward region installation during Long Shutdown 2

Interface between the machine and LHC experiments

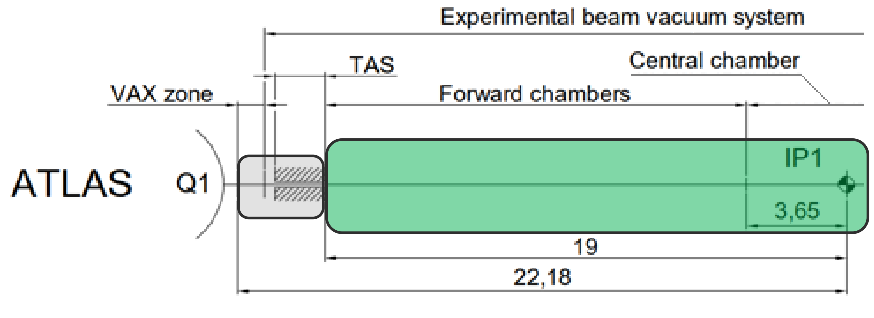
Front-end interface between IP sector and beam vacuum system of the machine

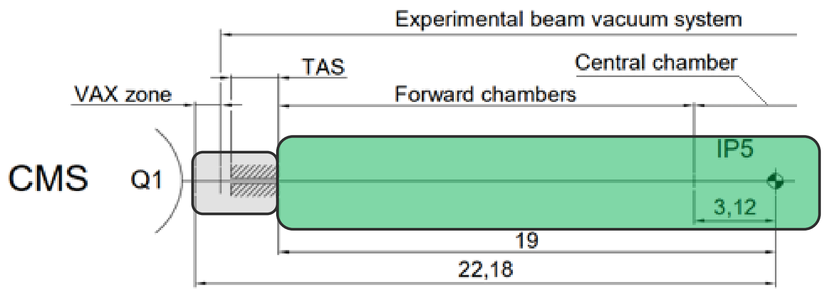
CMS forward region as installed during Long Shutdown 2

Interface between the machine and LHC experiments

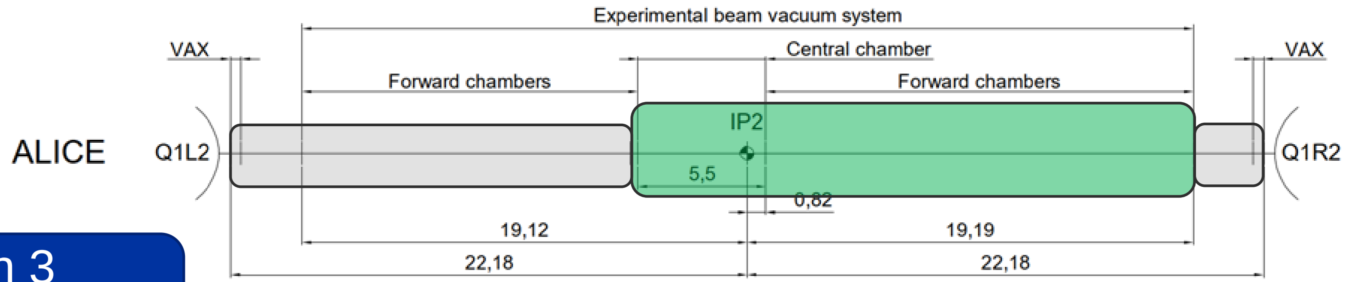
- **Green zone** (for ATLAS & CMS +/-19m from IP1 & IP5)
  - Experimental requirements are driving element for the design of beam vacuum system.
- **“Machine to Experiment”** (for ATLAS & CMS +/- 22.18 +/-19m from IP1 & IP5)
  - Experiment has limited requirements on the equipment within the zone.

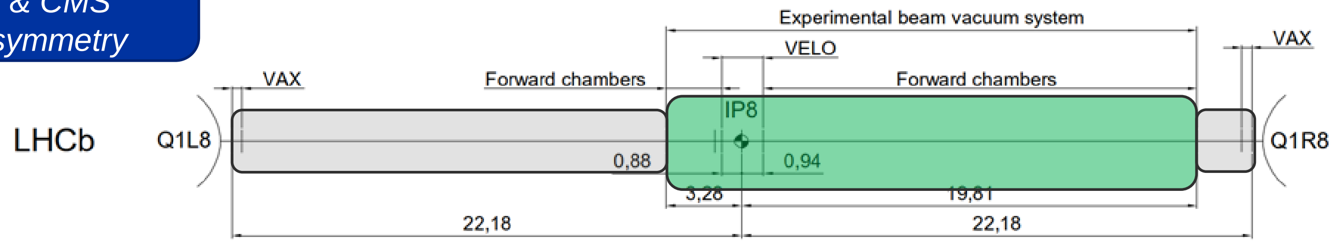
Forward “VAX” equipment is by its function indispensable for the experiment – Venting using ultra-pure neon every year





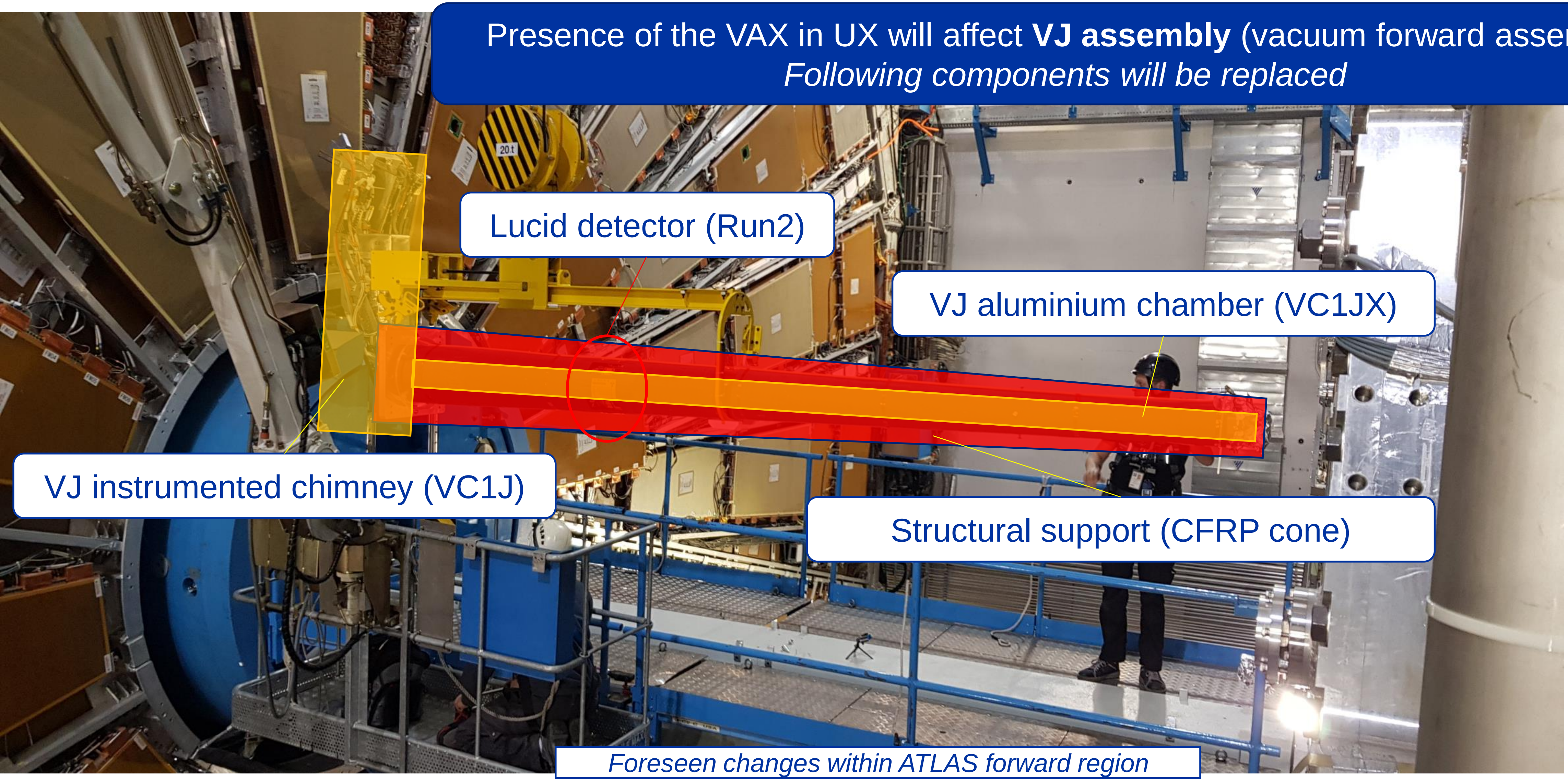
Run 3
ATLAS & CMS
Layout symmetry





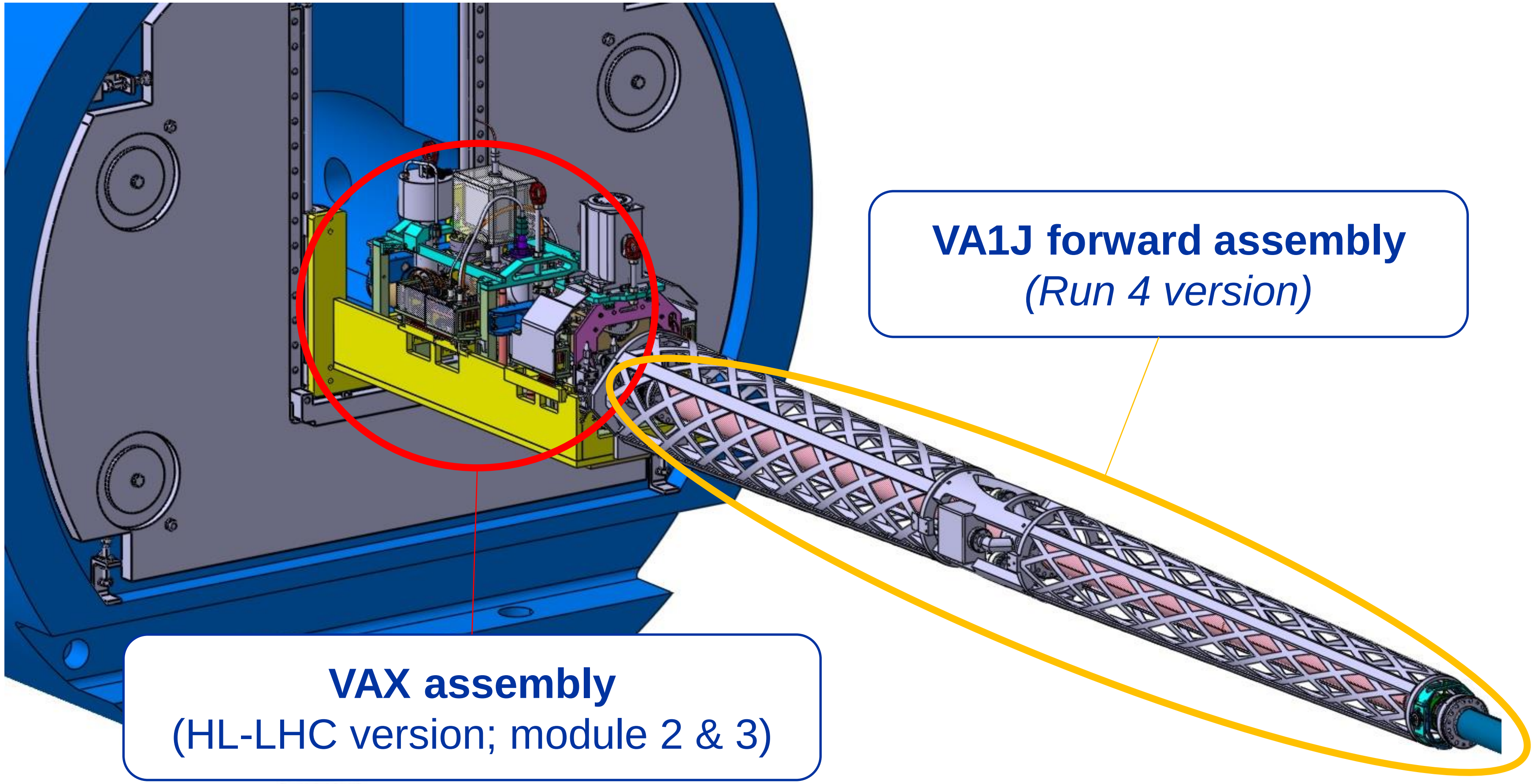
Interface between the machine and LHC experiments

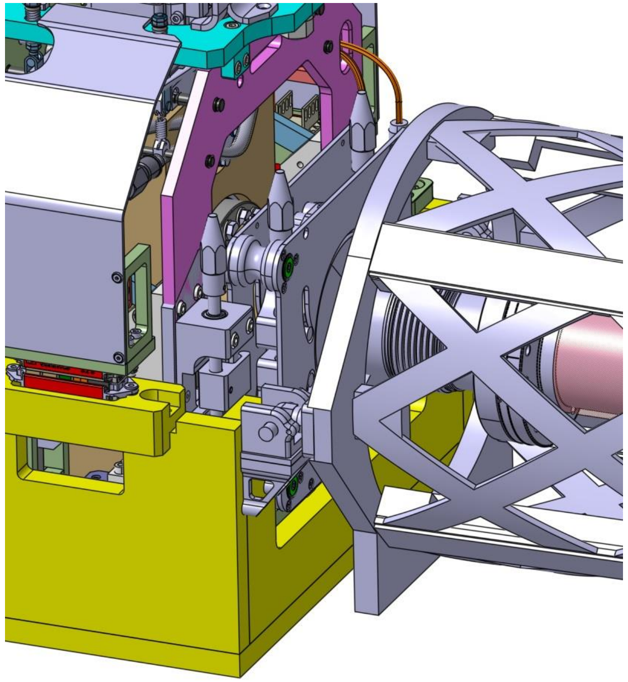
Presence of the VAX in UX will affect **VJ assembly** (vacuum forward assembly)
Following components will be replaced



Foreseen changes within ATLAS forward region

Interface between the machine and LHC experiments
ATLAS Experiment upgrade for Run4 (2029)

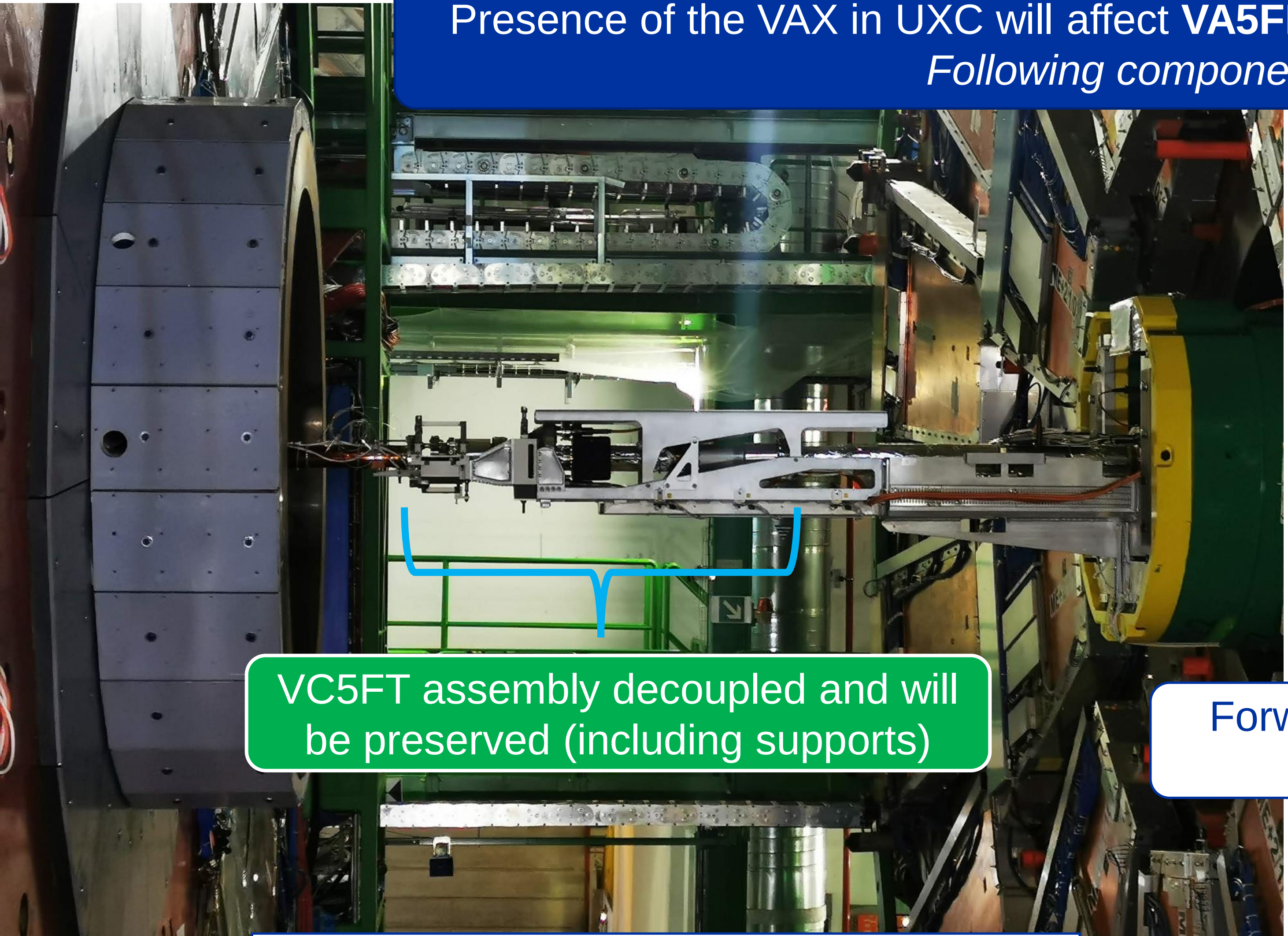




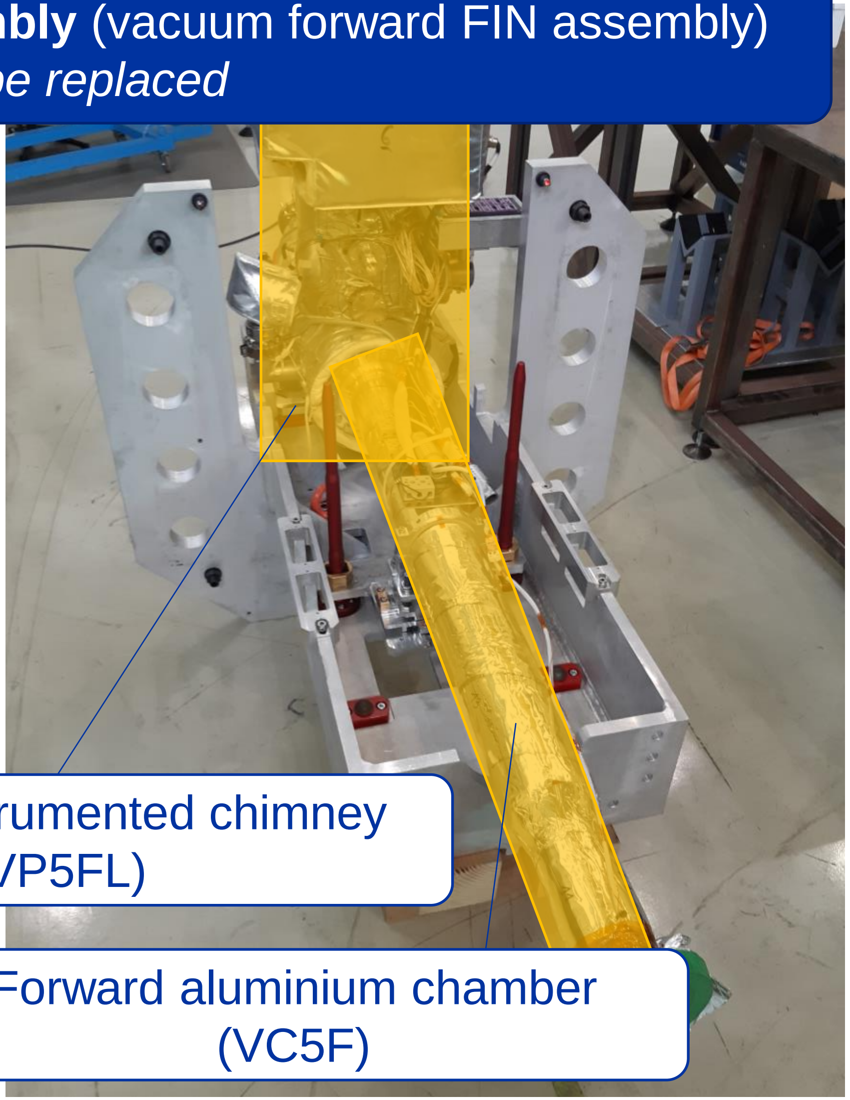
Connection VAX-to-IP

Interface between the machine and LHC experiments

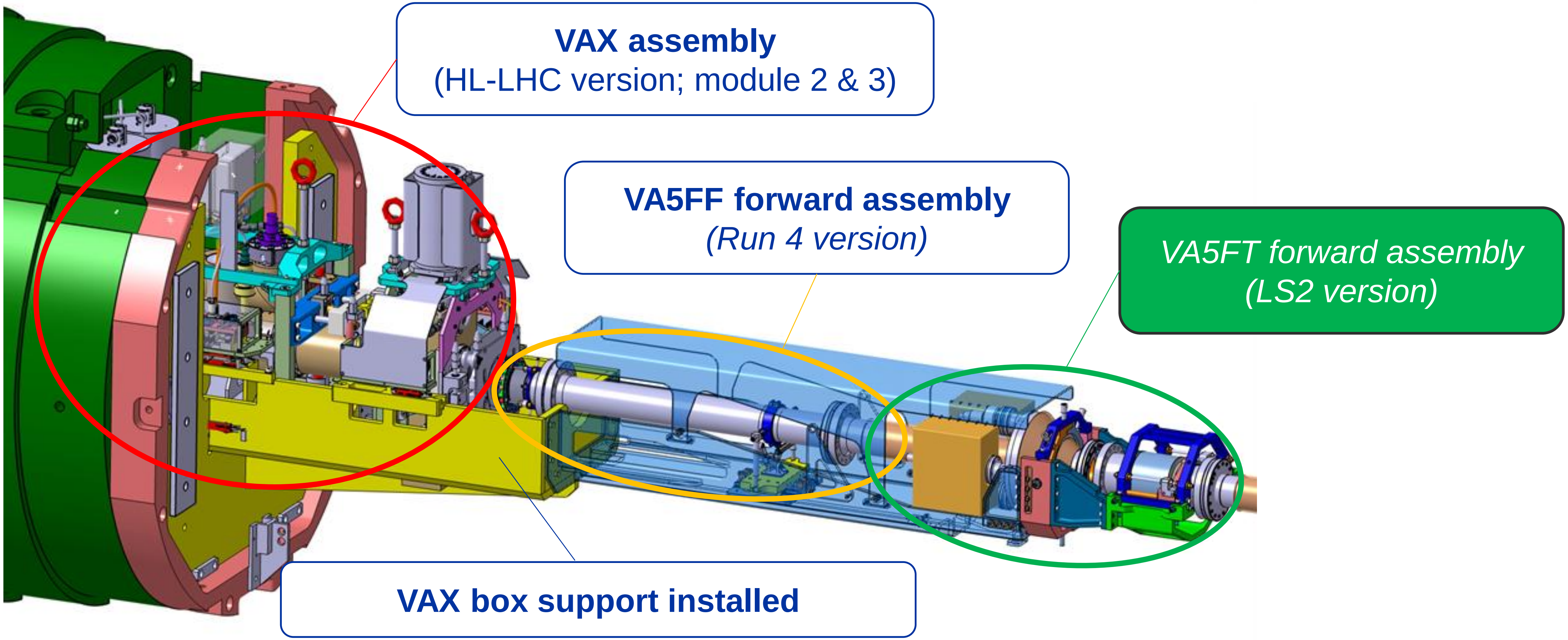
Presence of the VAX in UXC will affect **VA5FF assembly** (vacuum forward FIN assembly)
Following components will be replaced



Foreseen changes within CMS forward region



Interface between the machine and LHC experiments
CMS Experiment upgrade for Run4 (2029)



Present issues with beryllium beam-pipes manufacturing

Manufacturing of transparent chambers and its challenges

Present issues with beryllium beam-pipes manufacturing

CERN qualification criteria for production of beryllium chambers (chamber supply)	
	In-house / Outsourcing as requested by CERN
Project management	In-house
Detailed Design	In-house
Raw material	Can be outsourced
Machining	Can be outsourced
Cleaning	CERN insourced
Welding	In-house
Testing	In-house

No member state nor non-member state company with proven (or applicable) experience was qualified for the upcoming production campaign.

- **CERN is looking for machining vendors capable of:**
  - Machining of tubular and/or conical segments made of S-200-F beryllium metal (99.5% beryllium).
  - Assuming length of segments (750 mm – 1000mm) and precision as shown on slide 24.

Thank you for your attention

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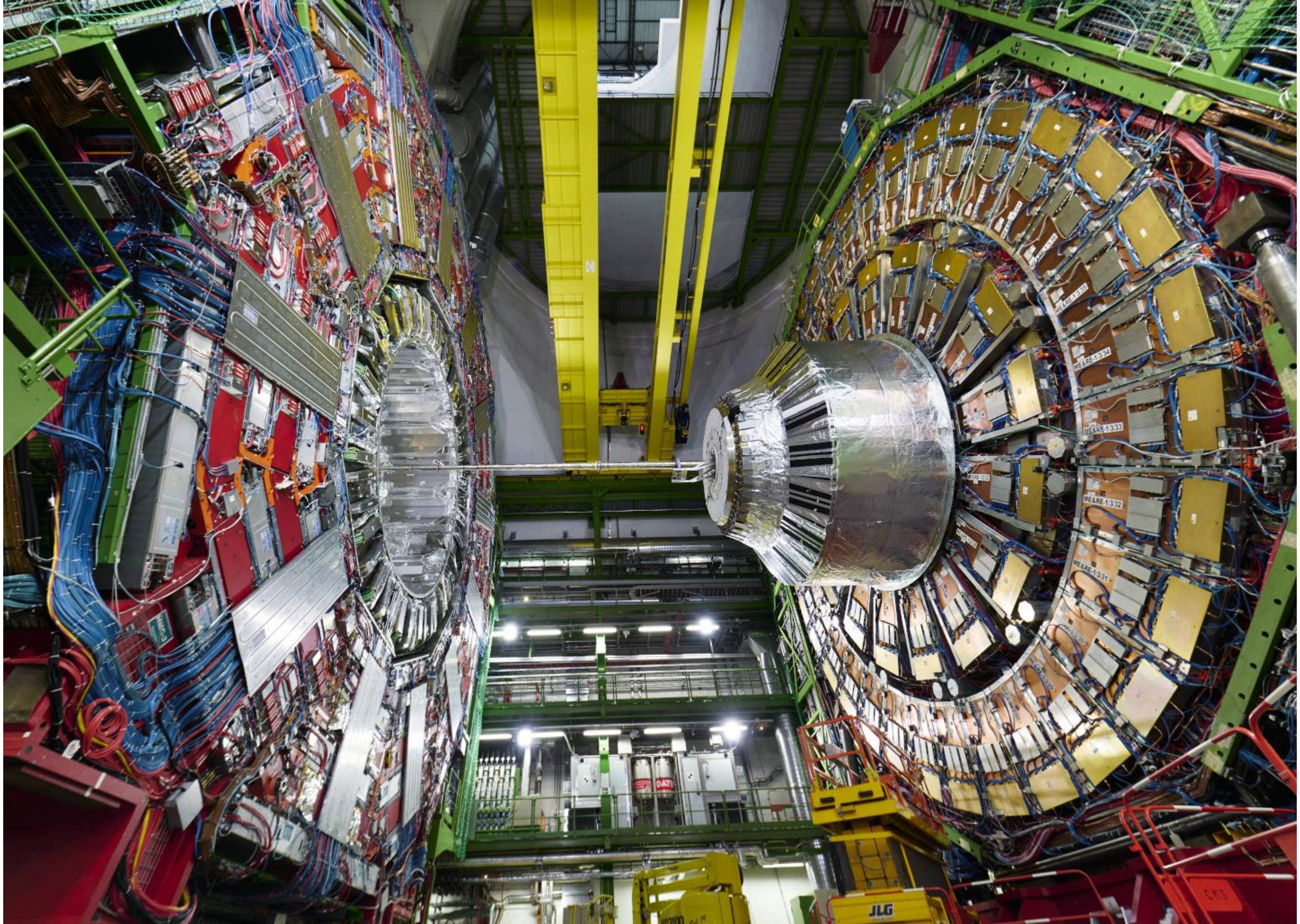
ME&RE-1/3/35
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JLG
CMS