MECHANICAL AND VACUUM STABILITY STUDIES FOR THE LHC EXPERIMENTS UPGRADE

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Abstract

In April 2015, the Large Hadron Collider (LHC) has entered its second operational period that will last for 3 years with expected end of the operations at the beginning of 2019. Afterward, the LHC will undergo a long shutdown (LS2) for upgrade and maintenance. The four LHC experiments, ATLAS, ALICE, CMS and LHCb, will experience an important upgrade too. From the design point of view, the LS2 experimental beam vacuum upgrade requires multi-disciplinary approach: based on the geometrical envelope defined by experiments, the vacuum chambers size and shape must be optimized. This included Monte Carlo pressure profile simulations and vacuum stability studies in order to meet the specific pressure requests in the interaction regions. Together with vacuum studies the structural analysis are performed in order to optimise chambers thickness and position of the operational and maintenance supports. The material selection for vacuum chambers in the experimental areas follows the CERN ALARA (as low as reasonably achievable) principle, too. This paper gives an overview of the LS2 experimental vacuum sectors upgrades. The most extensive design studies, done for the two experiments CMS and ALICE are discussed in detail.

INTRODUCTION

The Large Hardon Collider (LHC) has four interaction regions in which are located the experiments ATLAS, ALICE, CMS and LHCb. Experimental vacuum chambers installed in these regions must accommodate two colliding proton beams at energy of 7 TeV and up to intensity 2808 bunches per beam. Parameters like chamber aperture, thickness, material selection and supports position requested by the experiments need to be validated in order to meet design criteria for vacuum and mechanical stability. Our main task is to design, manufacture and install the experimental chambers, so that high quality physical data are collected while machine integrity is preserved.

EXPERIMENTAL LAYOUT AFTER LS1

Long Shutdown 1 (LS1) was focused mainly on the upgrade of experimental vacuum sectors of ATLAS and CMS. ATLAS experimental vacuum layout went through the major change. In order to accommodate the new 'Insertable B-Layer' detector, the diameter of the central chamber was reduced from 58 mm to 47 mm. New design of the central chamber consisted in 7 m long beryllium part, with thickness of 0.8 mm, equipped with aluminium 2219 conical flanges. Four upstream and downstream chambers up to inner triplet quadrupole absorber (TAS) were manufactured from aluminium 2219 alloy. This material change reduces the detector background and the induced radiation dose by a factor of about 5. As a baseline, all chambers were coated with a Non-Evaporable Getter (NEG) thin film. End-cap toroids on both sides were equipped with new remote controlled supports witch reduce the needed time for interventions.

CMS experimental vacuum upgrade consisted mainly on the replacement of the central beam pipe. Because of the new 4-layer PIXEL detector the diameter in the central part was reduced from 58 mm to 43.4 mm. The length of the beryllium part remained unchanged to 3.8 m with aluminium 2219 conical flange.

DESIGN APPROACH AND CRITERIA FOR EXPERIMENTAL CHAMBERS

The design of an experimental vacuum chambers is a multi-disciplinary engineering task. It requires to meet specific beam optics requirements, vacuum level, mechanical tolerances as well as experimental and maintenance requirements whereby some of these are affecting each other. Systematic approach ensures that all these criteria are properly classified and considered during the design of the new chambers.

Vacuum Requirements

Experimental vacuum chambers have to meet design criteria for ultimate pressure and critical beam current I_c. Stability of the vacuum system is driven by beam induced dynamic effects. Change of the gas density in time is defined by ion, photon and electron induced desorption, thermal outgassing, and pumping speed. The critical current corresponds to the beam current bellow which the pressure remains stable. In the experimental region where two beams shares the same vacuum chamber must apply the rule $2 \times 0.85A < I_c/2$, where 0.85A is the ultimate beam current [1]. Critical current simulations are performed on 1D simplified geometry defined as long cylindrical tubes. This model does not fit for some of the real geometries installed in the experimental vacuum sectors (for example complex pumping stations). Such assemblies needs to be analysed by dedicated Mote Carlo simulations in order to calculate gas conductance, outgassing rate and effective pumping speed. These values are then introduced in the 1D analytical model.

As baseline the NEG coating is mandatory for all experimental vacuum chambers and their components. NEG coating provides uniformly distributed pumping along the chamber and also minimize the effect of electron-induced desorption [1]. In addition there are

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residual gas density limits [2-4] set by each experiment in order to minimize background noise created by proton-gas scattering. This requirement is more stringent than the requested 100 h of beam lifetime.

Material Requirements

Materials for LHC experimental chambers need to follow set of specific requirements such as grain size, strength at high temperatures, corrosion resistance, manufacturability, weldability and compatibility with different surface treatments for the final NEG coating. Raw materials used for experimental chambers are subject to a strict metallurgy qualification after the reception at CERN [12]. Baseline for aluminium chambers is alloy 2219 – T6 processed by 3D forging. Alloy 5083 – H111 processed by cold working was chosen only for the production of aluminium bellows. These alloys have different chemical treatment needs to be used for NEG coating [5].

From the point of view of weldability, quality issues were observed for electron beam welds between alloy 2219 and 5083. Weld porosities were created due to vaporization of magnesium component in 5083 alloy. The adopted solution was to change the welding process to TIG [5]. Furthermore, the experimental chambers are installed in high radioactivity areas with estimated year dose of 10^5 Gy/year [6]. For this reason, the used materials must follow the ALARA principle ("as low as reasonably achievable"). Low Z materials such as aluminium reduce the induced activation rate more than 5 times compared to stainless steel.

Structural Requirements

The experimental chambers are thin-walled cylindrical or conical shells loaded by their own weight and 1 bar of atmospheric pressure. Therefore, the assessment of structural integrity is based on evaluation of failure mode due to elastic instability, i.e. buckling. Basic analytical approach [7] assumes long cylindrical geometries without any defects. Estimation of the critical pressure P_{cr} at which shell starts to collapse is defined by Young modulus E, Poisson's ratio μ of chamber's material, radius r and wall thickness t.

$$P_{cr} = \frac{1}{4}\frac{E}{(1-\mu^2)}\frac{t^3}{r^3}$$

For the experimental vacuum chamber the required design criteria impose a $P_{cr} \geq 6$ bar [8]. Verification of non-linear model, based on pre-deformed linear eigenvalue buckling shape and contain all operational loads and supports, allows to reduce design criteria for critical pressure to $P_{cr} \geq 3$ bar. The components requiring an additional assessment from the point of view of formability, strain behaviour and fatigue life are aluminium bellows. Their role is to compensate the thermal expansion during the chamber bake-out. Due to their small thickness (0.3 mm), they represents a weak point of the design.

CHANGES IN THE EXPERIMENTAL LAYOUT DURING LS2

The Long Shutdown 2 (LS2) will start in 2019. It will bring significant changes in the vacuum layout of the two experiments ALICE and CMS. The vacuum sector of ATLAS and LHCb will be completely dismounted in order to allow maintenance and upgrade works on the detector subsystems. The change of the ATLAS experimental layout consists in the replacement of VAP annular ion pump chambers allowing the insertion of a new layer of PIXEL detectors. For LHCb, the LS2 upgrade mainly consists in the installation of a new Vertex Locator (VELO) detector which is part of beam vacuum subsystem.

CMS LS2 Experimental Vacuum Upgrade

For the LS2 upgrade, it was decided to change all vacuum chambers starting from End-cap chamber up to the Forward chamber as shown on Fig. 1. Changes are motivated by ALARA safety considerations, which reflects increased activation of vacuum equipment in "post LS2" operation period. Redesigned shape of vacuum chambers (η = 4.9 to 5.54) allows improving detector measurement capabilities and meets the compatibility requirement for new HL-LHC Front Quadrupole Absorbers.

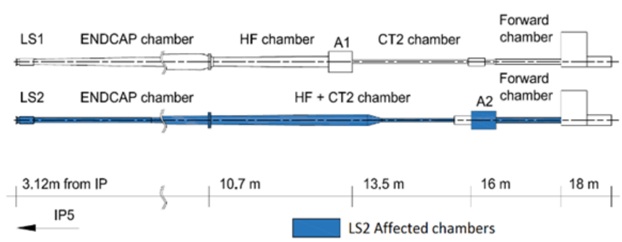

Figure 1: Chambers to be installed in CMS during LS2.

Vacuum Simulations for CMS Upgrade

Vacuum stability simulations were performed in order to evaluate the critical current. CMS beam pipes are fully NEG coated and in-situ heated at 200°C for 24 hours [9]. NEG coating provides distributed pumping speed for H_2, CO and CO_2. Ion pumps installed in the IP will provide sufficient pumping forCH_4, a gas not pumped by the NEG coating. The LS1 layout contains three diode ion pumps (Fig.1 – (A1) - 8 $l{\cdot}s^{-1}$ for N_2 at 10^{-6} mbar) located at 13.5 m from IP, in the LS2 layout these pumping stations will be removed. New possibility for integration of two new StarCell® VacIon plus 20 (20 $l{\cdot}s^{-1}$ for N_2 at 10^{-6} mbar) was found at 16.5 m from IP (A2).

Table 1: Critical current for CMS vacuum layout for maximum and 10% NEG pumping speed

	NEG 100% Ion pumps ON	NEG 10% Ion pumps ON	NEG 10% Ion pumps OFF
Critical current [A]	77	69	55

Table 1 shows examples of the critical current values for different CMS configuration.

Structural Analysis for CMS LS2 Upgrade

Vacuum chambers operate under the external pressure load of 1 bar with distributed load due to their own weight. Additional axial force is executed by bellows and due to the thermal expansion during bake-out. Non-linear buckling analysis shows that the minimum of critical pressure is equal to 7.5 bar on HF-CT2 chamber, which fulfils the design criteria. Maximum sag in operational position is in HF-CT2 bottleneck: 1.7 mm.

ALICE LS2 Experimental Vacuum Upgrade

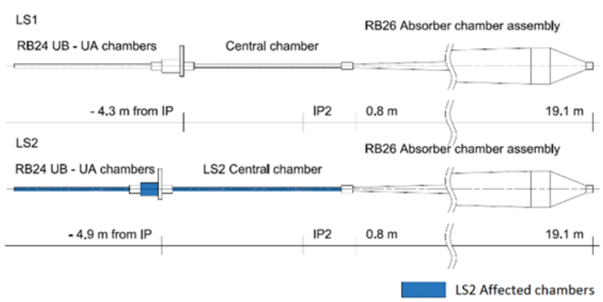

Figure 2: Chambers to be installed in ALICE during LS2.

During the LS2, the ALICE experiment will replace the Inner Tracking System (ITS) to improve vertexing and tracking capabilities. This change requires a new central chamber design (see Fig. 2) with reduced aperture down to 36.4 mm, total length of 5485 mm containing 888 mm long central beryllium part. Compared to the LS1 central chamber, the new chamber will be 665 mm longer. This extra length will be accommodated in RB24 zone (vacuum sector A1L2.X). This sector will contain a manual gate valve, a new aluminium annular ion pump and a new drift chamber.

Vacuum Simulations for ALICE Upgrade

ALICE LS2 vacuum simulations [10] were focused on the effect of a reduced aperture from 58 mm to 36.4 mm. The only change from the point of view of vacuum equipment is a new aluminium annular ion pump in RB24 zone. Selected results of the critical current are presented in Table 2.

Table 2: Critical current for ALICE vacuum layout for maximum and 10% NEG pumping speed [10]

	NEG 100% Ion pumps ON	NEG 10% Ion pumps ON	NEG 10% Ion pumps OFF
Critical current [A]	45	45	20

Structural Analysis for ALICE LS2 Upgrade

Structural analysis were performed [11] in order to validate the mechanical design of new central chamber. The critical pressure of central chamber (5.7) bar meets the design criteria. Maximum sag of the central part is 0.4 mm, which is within the limits accepted by the experiment.

CONCLUSIONS

This paper gives an overview of the experimental vacuum changes that will occur during the LS2. Vacuum, structural and material requirements were presented and discussed in order to provide the baseline for new vacuum layout design assessment. Detail studies of the ALICE and the CMS beam pipe upgrades were performed and are discussed as well. A parallel approach reflecting both vacuum and structural behaviour gives an important information for initial phase of the project when the feasibility study is needed.

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