SPECIFICATION OF NEW VACUUM CHAMBERS FOR THE LHC EXPERIMENTAL INTERACTIONS

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Abstract

The apertures for the vacuum chambers at the interaction points inside the LHC experiments are key both to the safe operation of the LHC machine and to obtaining the best physics performance from the experiments. Following the successful start-up of the LHC physics programme the ALICE, ATLAS and CMS experiments have launched projects to improve physics performance by adding detector layers closer to the beam. To achieve this they have requested smaller aperture vacuum chambers to be installed. The first periods of LHC operation have yielded much information both on the performance of the LHC and the stability and alignment of the experiments. In this paper, the new information relating to the aperture of these chambers is presented and a summary is made of analysis of parameters required to safely reduce the vacuum chambers apertures for the high-luminosity experiments ATLAS and CMS.

INTRODUCTION

The LHC experimental vacuum chambers were designed in the period 1994-2003. Central chamber apertures were frozen in 1999 to allow PIXEL detector designs to advance. This required decisions to be taken before civil engineering construction of experimental caverns had started and before the series production of machine magnets. Thus beampipe apertures were based on information available at the time, with some margin to ensure machine startup.

Chambers were integrated into the four LHC experiments in 2007/8 [1]. They have operated very successfully through the periods of commissioning and physics with no problems of aperture or vacuum performance. ATLAS and CMS now plan improvements to their PIXEL detectors. To take full advantage of the existing detector structures, whilst adding new detector layers will require a smaller diameter pipe.

The LHC is scheduled to stop for more than one year at the end of 2012. This will provide the time necessary to replace beampipes which are highly integrated in the centre of the experiments. ALICE plans for a new beampipe installed in a later long LHC shutdown.

REASONS FOR THE CHANGE

PIXEL detectors in ATLAS and CMS rely on state-of the-art silicon technology for maximum detector resolution and speed. This technology is inherently susceptible to radiation damage from collision products. Improvements in detector materials allow these devices to withstand expected LHC luminosity at smaller radii. ATLAS plans to add an 'Insertable B-Layer' (IBL) within the existing PIXEL detector [2] whilst CMS is developing a new, optimised 4-layer PIXEL detector [3].

These new detectors will both add redundancy in case of radiation damage and improve physics performance for b-tagging and light jet rejection.

The IBL will be assembled onto the new beampipe and installed as a package. The 4-layer pixel will be clam-shelled and installed around the beampipe. This approach requires a 4-fold symmetric detector and additional clearance to the beampipe, but allows beampipe installation and bakeout to be decoupled from detector installation. ALICE plans for an ultra-low mass tracker with thinned pixel sensors or monolithic pixel detectors. ATLAS and CMS have requested beampipe outer radii of 22.5 and 21.7 mm, respectively. ALICE requests a beampipe diameter of less than 19 mm, however as this is still under evaluation, details are not presented here.

DATA FROM OPERATION OF EXPERIMENTS

The aperture for the currently installed beampipes included some margin both for the alignment precision of the beampipe relative to the nominal beam axis and the stability of the detector over a run due to thermal, magnetic effects, and cavern movements.

Data collected by the detectors since the start of LHC operation have allowed the experiments to reconstruct both the instantaneous position of the beampipe relative to the detectors and interaction point and the stability of these positions with time (see Figure 1).

SURVEY OF CAVERNS AND EXPERIMENTS

Both ATLAS and CMS experiments are constructed in newly built underground caverns. The cavern floor and important support structures stability has been measured periodically by optical levelling starting early in the detector installation phase. References are deep rods in LHC tunnel and CMS cavern anchored at different levels in the ground down to 28 m.

In addition, hydrostatic levelling systems with capacitive sensors provide permanent monitoring of relative vertical movement at critical points.

Results have shown a maximum floor movement at the cavern centres. In these zones the ATLAS floor has moved up by nearly 2 mm during the last 7 years (see Fig.2). Contrarily, the CMS floor has moved down by nearly 1.5 mm during the last 4 years. For both caverns these movements continue, but level-off after detector installation has been finished and final load on the floor has been reached.

Experience gained during the assembly phase enhances the knowledge of the detector alignment precision taking into account individual conditions in both experiments. The achievable alignment tolerance for the new vacuum chambers can be estimated to 1.0 – 1.5 mm at 2σ, corresponding to 95.4 % confidence level (CL).

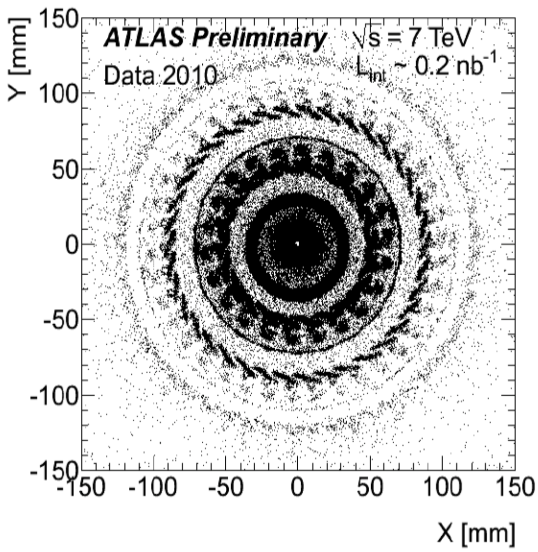

Figure 1: Example of a reconstruction of beampipe and PIXEL position using nuclear interaction tomography [4].

CONSTRUCTION AND MECHANICAL TOLERANCES

The central vacuum chambers in ATLAS and CMS range between 6.2 and 7.3 m in length. Mechanical tolerances for these chambers are required to be extremely strict. This allows the detectors to be as close to the LHC beam as possible, whilst maintaining sufficient beam stay-clear to the chamber walls. The material of choice for the central chambers is beryllium.

The first generation chambers were manufactured by turning and then welding tubular sections [5]; as a result it was possible to achieve good construction tolerances. The agreed construction tolerances for the ATLAS and CMS chambers were a straightness of 0.15 mm per 0.5 m, and a circularity of 0.1 mm. In fact, a straightness of 0.5 mm or better was achieved over the entire chamber lengths. The second generation ATLAS and CMS chambers will be smaller in diameter; however with gained experience, the manufacturer has agreed to the same construction tolerances.

The overall tolerances for ATLAS and CMS will deviate for the second generation due to differences in construction and assembly. Table 1 is a summary of the tolerances for each detector.

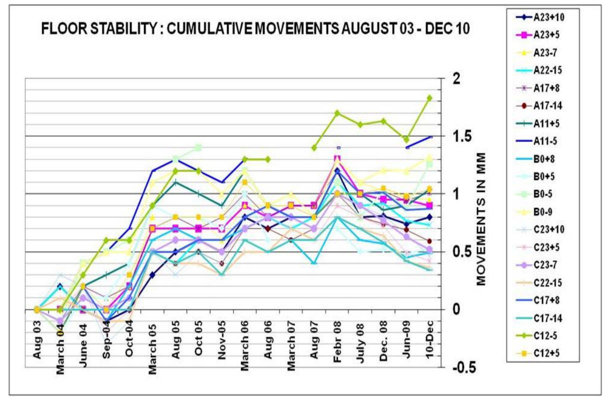

Figure 2: Time stability of the ATLAS cavern floor.

Table 1: Summary of Tolerances for Aperture Calculation

	CMS	ATLAS
Mechanical Construction	1.15 mm	1.95 mm
Installation Survey	1.6 mm	2.6 mm
Cavern Stability	1.5 mm	2.5 mm
Stability Margin	2.3 mm	0
Total tolerance	6.55 mm	7.05 mm

APERTURE COMPUTATION

In the design phase of the LHC [6], the so-called n_1 concept was introduced for the evaluation of the mechanical aperture. The detailed definition of this quantity can be found in Ref. [7] and the computation of n_1 is implemented in MAD-X [8]. It is also important to mention that the design criterion was to have $n_1 > 7\ \sigma$. n_1 is much more than the mechanical dimensions expressed in terms of the beam size. Indeed, tolerance budgets for a number of beam-dynamical quantities are included. This is certainly required in the design stage, when safety margin is a crucial point. Therefore, n_1 is a function of the mechanical size of the beam pipe and of the closed orbit, beta-beating, and, in particular, of the quality of the alignment of the chambers and magnets. This explains why one of the crucial points in the acceptance of the proposed central pipe for ATLAS has been the review of the mechanical and alignment tolerances. It is also clear that the configurations to consider are: injection energy (the beam has the largest beam size) and top energy for the high-beta optics [9] for the ATLAS-ALFA physics data taking (as this special optics configuration features a large and parallel beam around the collision point). By assuming the final tolerances as given in Section 5, then $n_1 = 20.7\ \sigma$ at the IP, with a minimum of 19.2 σ over the length of the central pipe. In the squeezed configuration at top energy, the central part of the experimental beam pipe will have a huge aperture, thanks to the small beta-values. However, for the high-beta optics, machine protection considerations (see Section 9) suggested to require that the beam stay-clear, namely the mechanical aperture reduced by the mechanical and alignment tolerances is such that the pipe remains in the shadow of the TAS, by about two millimetre radially.

VACUUM CONSIDERATIONS

The LHC vacuum system has been designed to ensure vacuum stability and beam lifetime of 100 h at nominal current of 0.56 A per beam [6]. The estimation of residual gas density profile in the experimental interaction regions is indispensable to verify the design, confirm the vacuum stability and beam life time and define the machine background effects generated by proton or ion-gas scattering. Additionally, dynamic beam vacuum such as ions, electron and photon stimulated gas desorption are the main source of gas and depends on the beam pipe surface properties and on the operating scenario.

Calculations performed for these smaller diameter chambers show no significant increase in static pressures, and a critical current of 30 A for CH_4, which is considered safe. Effects of electron and photon flux were analyzed. Due to the activated NEG-coated internal surface which gives both low secondary electron yield and photo-desorption yield, vacuum stability is ensured.

IMPEDANCE CONSIDERATIONS

The impedance of the experimental beam pipe with radii of 29 mm and 22.5mm were calculated for nominal LHC beam conditions using the matrix implementation of the Zotter/Métral formula [10], which is an exact multilayer analytical formula for an axisymmetric geometry with linear materials and infinite length implemented in a Mathematica code.

We can therefore estimate that the reduction of the Be beam pipe radius will result in 30% increase in power loss, reaching ~ W/m at 7 TeV with a bunch length of 1 ns. Theoretical considerations expect that the power loss due to the smooth 15 degree conical transition from the 29mm to 22.5 mm radius is negligible, which is confirmed by simulations with the ABCI code [11].

Besides, the effective longitudinal and transverse impedances increase since the ATLAS beam pipe radius reduction was calculated for both the conical transition and the 7.1 m long Be pipe and were found to be negligible with respect to the total impedance budget.

COLLIMATION AND MACHINE PROTECTION

With a decreased aperture, several performance limitations could arise. The smaller pipe could catch halo particles leaking out of the collimation system, causing an increased background during physics operation. This has been investigated through SixTrack simulations [12] and no issue was found within the resolution of the numerical simulations.

For machine protection, the maximum normalized machine (arc or triplet) aperture is smaller than the new pipe at injection or top energy with injection optics or low beta, so large-amplitude particles passing an arc are lost there first.

For high-β (> 90 m) operation the beam size remains effectively constant through the interaction region. Machine protection is ensured as long as the beampipe aperture remains in the shadow of other machine elements present between Q1 left and right of the IP. In ATLAS and CMS insertions these elements are fixed absorbers called TAS, having circular apertures of 17 mm radius.

CONCLUSIONS

Information obtained during the construction and first years of operation have shown that the experimental caverns and detectors are more stable than expected in the preliminary designs. Operation with beams during injection and collisions at low-β has confirmed that apertures are at least as good as expected.

This will allow the next generation of experimental beampipes in ATLAS and CMS to be reduced from 29 mm to 22.5 mm and 21.7 mm radius, respectively.

The effect of these smaller radii on beam impedance, vacuum, collimation and machine protection have been verified and found acceptable.

For high-β operation phases experiments will have to ensure the beampipe aperture remains in the TAS shadow by developing improved survey methods.

ACKNOWLEDGEMENTS

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