

VACUUM CALCULATIONS FOR THE LHC EXPERIMENTAL BEAM CHAMBERS

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Abstract

The vacuum stability is studied for the LHC experimental beam vacuum chambers of ALICE, ATLAS, and CMS. The present baseline design includes sputtered Non-Evaporable Getter (NEG) coating over the whole chamber inner surface providing distributed pumping and an antimultipactor coating. The data are presented for the dominant gas species (H_2 , CH_4 , CO and CO_2) in a baked system. It results that the distributed pumping is necessary for vacuum stability of CO . Lumped pumping with Sputter Ion Pumps (SIP) is also indispensable for the stability of CH_4 . The operational constraints with NEG technology are described.

1 INTRODUCTION

In the LHC accelerator, the gas pressure during operation, called hereafter ‘dynamic’ pressure, is dominated by beam induced effects, namely ion, electron and photon induced gas desorption from the chamber wall. In particular, the ions are accelerated by the space charge generated by the passage of one or more proton bunches, and impinge the wall with sufficient energy to desorb neutral molecules [1]. If the net gain in the production of molecules by ionisation, desorption and pumping is above unity, the pressure will diverge (ion-induced pressure instability [2 and ref. therein] with detrimental effects to the beam. The ions are created by the interactions of beam particles with the residual gas molecules, at a rate proportional to the beam current. One has, therefore, to make sure that the vacuum is stable at the ultimate beam current (0.85A) and energy (7TeV). Electron multipacting can enhance electron induced desorption, with a consequent significant pressure increase, and must also be avoided.

Even after the vacuum stability is assured, beam-gas interactions, and in particular nuclear scattering, bring to a reduction of the beam lifetime and, in the experimental regions, background noise to the detectors. The residual gas pressure must therefore be kept within the limits [3,4,5] imposed by each experiment.

In this paper, the vacuum stability is studied for the LHC experimental beam vacuum chambers of ALICE, ATLAS, and CMS, and the choice of materials justified. The LHCb experimental chamber has very different characteristics and will be treated in future publications.

2 VACUUM CHAMBERS LAYOUT

In the design of a beam vacuum chamber, the choice of the geometry, materials and pumping is determined by the compromise between vacuum and mechanical stability

requirements on the one side and the necessity to minimise the amount of material between the beam and the experiments on the other side. The mechanical stability is beyond the scope of this paper [6]. An example of beam pipe layout is shown in Fig. 1, and a detailed description of the LHC experimental beam vacuum chambers can be found in [7,4,8].

In order to ensure the vacuum stability of a warm chamber, one must maximise the gas pumping and reduce ion induced desorption. Moreover, to suppress electron multipacting, one must select surface materials with low secondary electron emission yield (SEY).

TiZrV sputtered NEG coating [9] represents a suitable candidate and has been chosen for the LHC experimental beam chambers. TiZrV sputtered NEG materials provide distributed pumping for H_2 , CO and CO_2 gas species, after activation at 200°C for about 24 hours [9]. Moreover, they are characterised by a low SEY after activation at a temperature between 160 and 200°C for 2 hours [10], even if saturated with H_2 , CO and CO_2 and low pressure water vapour [11]. The SEY can deteriorate after few exposures (about 10) to air at atmospheric pressure followed by reactivation, its maximum value remaining around 1.4 [12]. TiZrV sputtered NEG coating is suitable for coating of Be, which is estimated to be indispensable, due to the elevated SEY even after vacuum treatments [13]. For the CMS beam pipe, St707 NEG strips have been added to the baseline design to ensure vacuum stability also in the event that the TiZrV NEG surface is saturated.

For the stability and pressure constraints of CH_4 , lumped pumping must be provided. The number of pumps and their position has been decided to minimise massive objects close to the experiments. Special ion pumps with minimised mass have also been developed [14].

3 MODEL FOR VACUUM CALCULATIONS

In the model used for vacuum calculations [15], the rate of change of the number of molecules depends on the molecular diffusion along the chamber, the ion-induced gas desorption, gas pumping and photon-induced gas desorption. Ions are generated by beam-gas interactions. Electron induced gas desorption is neglected, since it is assumed that electron multipacting can be avoided, and because, for typical UHV materials, the quantity of gas desorbed by the electrons is estimated to be about a factor of 10 lower than by the photons. The critical current, I_c , defined as the current at which the gas pressure diverges, is a function of the induced desorption yield and the effective pumping (distributed and lumped pumping),

while it is independent of photon desorption. In the LHC machine, the vacuum is considered to be stable when the ultimate beam current is below 1/2 of the critical current. In the experimental regions, where there are 2 beams in the same chamber, it must be verified that $2 \times 0.85 \text{ A} < I_c/2$.

The model is called ‘single gas model’ because it assumes that each gas species, once ionised and accelerated to the wall surface, will only desorb molecules of the same species, so that each gas species is de-coupled from the others.

3.1 Input parameters

For the stability calculations, the ion-induced gas desorption yields from [16] for an *in situ* baked surface have been used, since the yields from NEG surfaces are not yet available. This choice was made because the coating is baked *in situ*, and because its SEY [10] and photon stimulated desorption yields [17] are comparable or lower than those of a bare metal surface after *in situ* bake out [13, 17]. Similarly, the ion desorption yields for NEG are assumed to be constant with surface coverage, given that both SEY and photon desorption yields are not very sensitive to the gas coverage.

The ion induced gas desorption yields depend on the ion mass and impact energy [18], increasing with the energy. The data taken from [16] were measured with $^{15}\text{N}_2^+$ incident ions. Their use is justified by the fact that in the ISR CO was the dominant gas species. For the calculations presented in this paper, it has been considered that, in the absence of magnetic field, the ion impact energy is greater than 1keV for CO and 10keV for H_2 [19] for β function values lower than about 30m. Data for ion impact energies larger than 3keV are not available. Given that the trend seems to saturate above 3keV, the maximum measured values are used. For larger β function, the ion impact energy is estimated to be of the order of 500eV for all ions [19], and the corresponding yield is considered. The effect of the solenoid field present in the ATLAS and CMS detector is to bend the ion trajectories. The ions will therefore impinge on the chamber wall at grazing rather than perpendicular angle of incidence. This effect, which has not been considered in the calculations, should be negligible for distances larger than 5m from the interaction point (IP), where the field intensity is below 10^2 Tesla. At locations closer to the IP, the ion impact energy is estimated to be relatively higher than without the magnetic field. Data on ion induced desorption yield at these energies and particularly at grazing angles of incidence are not yet available.

The dynamic pressure is dominated by photon stimulated desorption. In the LHC, the photons irradiating the experiments come mainly from the low β Triplets. In this paper, the dynamic pressure has been evaluated considering a photon flux to the experiments of the order of 10^{18} photons/s at design current (0.56A per beam) [20].

It was assumed that the photons irradiate uniformly the experimental chamber. This constitutes the highest expected flux and gives an upper bound for the pressure during beam operations. The photon desorption yield has been taken from [21], for photons at grazing incidence and 12eV critical energy, on *in situ* baked surfaces.

4 RESULTS

4.1 Critical current estimations

The NEG distributed pumping speed depends on the gas coverage over the surface, and deteriorates when the ‘saturation’ coverage is approached [9]. For all the experiments, the minimum distributed pumping speed required for ion induced desorption stability has been estimated to be $<1/100$ of the initial values. The corresponding critical current values are listed in Table 1.

Table 1: Critical current (A)

GAS	ATLAS	CMS	ALICE
H_2	10.9	45.5	13.4
CH_4	3.6	9.4	4.6
CO	3.6	3.7	4.5
CO_2	5.2	4.8	6.5

It can be concluded that sputtered NEG gives a large margin for the vacuum stability of getterable gas species.

4.2 Dynamic pressure

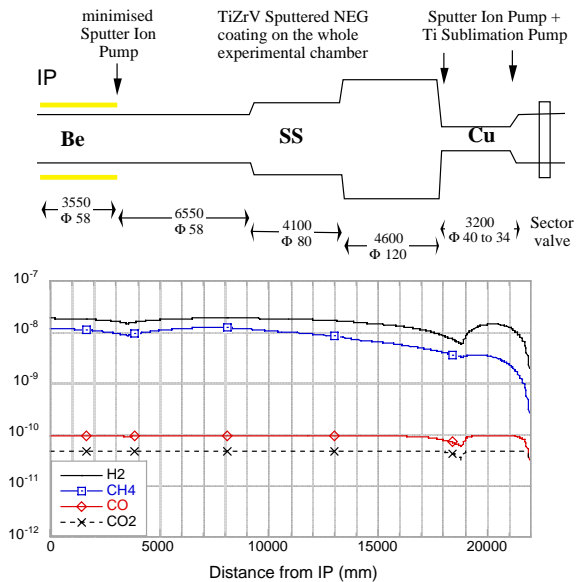


Figure 1: ATLAS beam pipe layout (dimensions in mm), and dynamic pressure (Torr) calculated at ultimate beam current ($2 \times 0.85 \text{ A}$), with 1/10 of the NEG pumping.

For the ATLAS and CMS experiments (high luminosity) the dynamic pressure is expected to stay below the limits imposed by the background noise, even with 1/10 of the NEG initial pumping speed (see Fig. 1) [22].

In the case of the ALICE experiment, the event rate to be measured is orders of magnitudes lower than for the other experiments. This imposes more stringent limits to

the residual gas pressure, which, according to the estimations carried out, are not met. For this experiment, the vacuum design will be validated when a more accurate estimation of the photon flux is available.

4.3 Operations with TiZrV sputtered NEG

The pumping capacity of TiZrV sputtered NEG is limited to about one monolayer [9]. Considering that the main gas load comes from photon desorption, and provided that most of the surface is coated (~99% [23]), the pumping capacity is estimated to be compatible with the foreseen yearly reactivation period.

After surface conditioning, when for safety reasons the vacuum chambers must be brought to atmospheric pressure clean gas is used to preserve the surface characteristics. In the case of TiZrV sputtered NEG, in order to limit the surface contamination to less than 1% of its full capacity, the required impurity level is estimated to be about 0.1ppm [23], which is orders of magnitude below what is available on the market. Special purification systems with liquid nitrogen traps and NEG filters are being designed and tested at CERN [24].

5 CONCLUSIONS

The ion induced pressure instability has been studied for the LHC experimental beam chamber of ALICE, ATLAS, and CMS, using the 'single gas model'.

- The design includes sputtered NEG to ensure the gas pumping necessary for ion induced desorption stability, and to prevent the occurrence of electron multipacting, given the low secondary electron yield after activation.
- In this frame, the vacuum stability at ultimate current can be guaranteed with only a small fraction (<1/100) of the initial NEG pumping speed. The most critical section is close to the IP (where the chamber has a small diameter and is far from lumped pumping). The values considered for the ion stimulated gas desorption yield were those of *in situ* baked metal surfaces.
- The reconditioning of NEG surfaces is planned to take place during the LHC annual shut down periods. Provided that a large surface area is coated (~ 99%), the NEG surface will be only partially saturated after a year operation. As a consequence, its pumping speed will suffice for the vacuum stability.
- After NEG activation, when it is necessary, for safety reason, to vent the chambers to atmospheric pressure, it is foreseen to use ultra-pure gas injection to preserve the NEG characteristics. The gas impurity content must be < 0.1ppm to limit the contamination of the TiZrV NEG surface to < 1% of its full capacity. A dedicated gas purification system is therefore required.
- Lumped pumping stations are also indispensable for the stability of methane (not pumped by the getter). Their number and location have been selected to

guarantee stability and minimise the mass in front of the detectors. Special ion pumps with minimised mass have also been developed.

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