ACHIEVEMENT AND EVALUATION OF THE BEAM VACUUM PERFORMANCE OF THE LHC LONG STRAIGHT SECTIONS

G. Bregliozzi, V. Baglin, S. Blanchard, J. Hansen, J.M. Jimenez, K. Weiss

CERN, Geneva, Switzerland

Abstract

The bake-out and activation of the TiZrV NEG coatings of the 6 km Long Straight Sections (LSS) of the Large Hadron Collider (LHC) is in its final step. After the bake-out and the NEG activation, the average ultimate pressure, over more than one hundred vacuum sectors, is below 10^{-10} Pa. Therefore, the nominal requirement for the four experimental insertions is fulfilled. The nominal performances are also ensured for all the insertions housing the collimator systems, the RF cavities and the beam dumping systems. The main difficulties encountered during the bake-out and the activation of the NEG coated chambers is presented and discussed. In particular, the acceptance test and the limiting factors of the reached ultimate pressures are addressed. Furthermore, the influence on the ultimate pressures of the beam components (collimators, beam instrumentation, etc.) is discussed.

Finally, preliminary results obtained from a NEG vacuum pilot sector installed in the laboratory and dedicated to the evaluation of the NEG performance is presented.

THE LSS BEAM VACUUM SYSTEM

The LHC is a particle accelerator that will ultimately collide protons beams at a centre-of-mass energy of 14 TeV. In the 27 km of circumference of the LHC accelerator, three completely different vacuum systems are present: 42 km of UHV beam vacuum at cryogenic temperatures, 6 km of UHV beam vacuum at room temperature (LSS) and 48 km of insulation vacuum for the helium distribution lines and the magnet cryostats. The UHV beam vacuum at room temperature (RT) serves as experimental or utility insertions. There are two high luminosity experiments located at LSS1 (ATLAS) and LSS5 (CMS) and two low luminosity experiments at LSS2 (Alice) and LSS8 (LHC-B), which also contain the beam injection systems. The two beams collide at these locations and are focused by superconducting low-beta triplets. LSS3 and LSS7 contain the collimation system for "cleaning" the proton beams. LSS4 contains the radiofrequency cavities for accelerating the protons and LSS6 the beam ejection system. Beam monitors are homogeneously distributed along the LSS vacuum sectors.

The LSS beam pipes are mainly made of 7 m long copper chambers (OFS). The inner diameter is 80 mm fitted with standard DN100 Conflat™ flanges. The thickness of the copper is 2 mm. A TiZrV non-evaporable getter (NEG) coating is used as baseline on the entire LSS vacuum sectors to ensure the required pressure and the low background to the experiments during the operation with beams. All these chambers are connected by means of stainless steel bellows equipped with RF copper screens to reduce the longitudinal impedance seen by the beam. Half of them are fitted with pumping and diagnostic ports. The sector valves which isolate the sectors at cryogenic temperature from the RT sectors are equipped with bellows and fitted with an ion pump and a set of gauges, generally a Pirani and a cold-cathode inverted-magnetron gauge. The pumping ports, which house the all-metal roughing valves necessary for the initial pump-down and for the pumping during the bake-out of each sector, are generally installed in the centre of the vacuum sector. At the end of the bake-out/NEG activation procedure, the all-metal roughing valve is closed and a pinch-off is installed. The final pumping of the RT vacuum system relies on the activated NEG coatings capable to pump the gases present in UHV system, *i.e.* H_2, CO, CO_2, H_2O and N_2 and O_2 in the case of leaks. Negligible pumping is also provided for methane (CH_4) due to the high dissociation energy for this molecule at metal surface and a 10^{-6} sticking probability at room temperature could be expected [1]. The NEG coatings do not pump noble gases and for that reason a limited number of sputter ion pumps capable to pump noble gases and also CH_4 are installed on each sector. The maximum distance between ion pumps is fixed at 28 m to avoid ion-induced pressure instabilities. After the activation of the NEG coatings, it is necessary to have on each sector a reliable measurement at low pressure ($<10^{-8}$ Pa). For that reason, a Bayard-Alpert (SVT 305) gauge capable to measure the pressure below the reliable operation range of the cold-cathode gauge (10^{-8} Pa) is always installed on the central bellow. During the bake-out/NEG activation procedure, a residual gas analyzer (BAZERS QMG422 with a QMA 125 head) mounted on a mobile turbo molecular pumping stations allow quantitative measurement of the residual vacuum after the bake-out/NEG activation procedure.

BAKE-OUT/ACTIVATION PROCEDURE

The bake-out/NEG activation procedure is shown in Fig. 1. The entire bake-out/NEG activation process is made using mobile heating and regulation equipment that are dismounted at the end of each cycle. However, because there will be many highly radioactive areas around the rings, permanently installed heating equipment may become mandatory to reduce the radiation dose to the personnel during future maintenance activities, especially in the LSS3 and LSS7 that contain the collimation system.

During the first part of the bake-out/NEG activation cycle, all the uncoated components, mainly the bellows and the instrumentations (gauges and RGA) are baked during 24 hours at 250°C and 350°C, respectively. The NEG coated beam pipes are kept at 120°C in order to prevent any absorption of water.

The second part of the bake-out/NEG activation cycle aims to activate the pumping properties of the NEG coatings. This is obtained by a 24 hours bake-out at 230°C. While increasing the temperature of the NEG beam pipes, the temperature of the non-coated components is reduced to 150°C for the bellows and to 180°C for the instrumentations. The whole cycle takes about 48 hours.

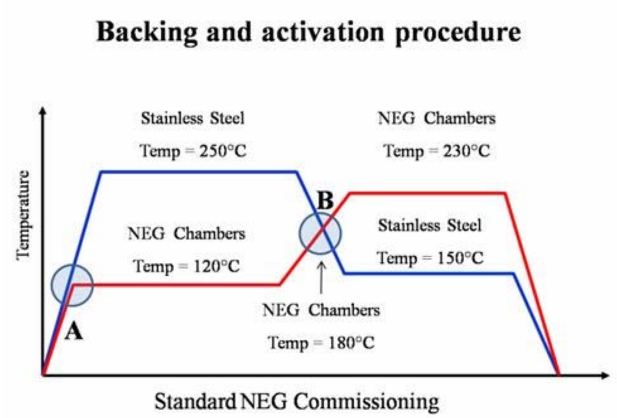

Figure 1: Schematic of the bake-out/NEG activation cycle of the TiZrV NEG coated beam pipes.

Figure 2 shows the typical pressure evolution measured by the cold-cathode gauges of a RT sector during the bake-out part. The pressure rise is dominated by the thermal outgassing of the NEG coated chambers and reaches the maximum when the NEG coating is at 120°C. Then, the NEG coated beam pipes are kept at 120°C in order to prevent any absorption of water and the temperature of the uncoated components is increased to 250°C. The thermal outgassing of the bellows and the equipments is negligible compared to the outgassing of the NEG coating.

The pressure rise during the activation of the NEG coatings is shown in figure 3. Also in that case the pressure is dominated by the thermal outgassing of the NEG beam pipes. However, when the NEG coating reaches 180°C the pressure start to decrease indicating that the NEG coating starts to be activated *i.e.* the beam pipe which was a source of gas before the NEG activation behave as a linear pump after activation. After 24 hours of activation at 230°C, the degassing of all the instrumentation and of all the ion pumps present on the sectors is performed.

The NEG coated beam pipes are activated at 230°C for different reasons: 1) possibility to shorter the activation time; 2) An activation temperatures lower than 230°C could create a non-uniform oxygen concentration profile along the film thickness resulting in a faster degradation of the pumping performances [2]; 3) A temperature higher then 200°C is needed to dissolve the carbon (C) accumulated on the surface of the NEG coatings in the bulk of the film [3].

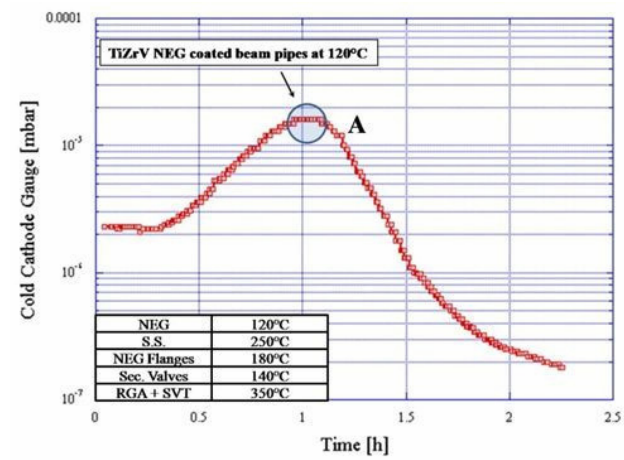

Figure 2: Pressure variation during the bake-out cycle.

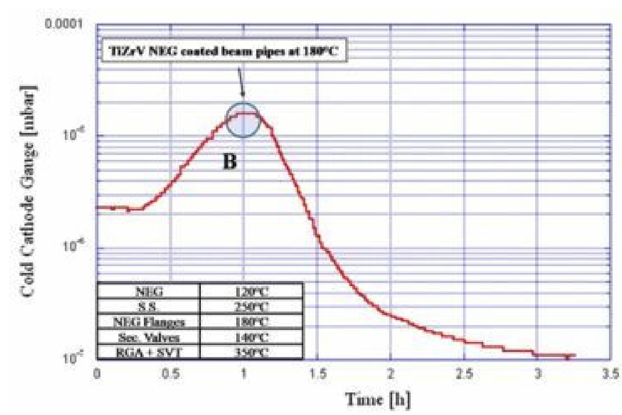

Figure 3: Pressure variation during the activation of the TiZrV NEG coated beam pipes.

ULTIMATE PRESSURE: LIMITATIONS

Figure 4 shows the pressure distribution measured over 100 BA gauges after the bake-out/NEG activation of the RT LSS vacuum sectors. The average pressure (N_2 eq.) is $8.5\cdot10^{-10}$ Pa. The measured ultimate pressure is limited by the total degassing from the stainless steel bellows, the RF copper screen, the elbow of the BA gauge and the gauge itself. The degassing measurements of a complete bellow with RF screen and a BA gauge with the filament on gave a degassing flow for H_2 of $5\cdot10^{-7}$ Pa.l.s^{-1}. Since the measured NEG pumping speed available at the gauge position is of 250 l/s for H_2, the corresponding ultimate pressure is $1.95\cdot10^{-9}$ Pa for H_2 ($8.2\cdot10^{-10}$ Pa N_2 eq.). This measurement confirms that the pressure readings in the ring are dominated by the local outgassing of the uncoated components. Calculations predict pressures in the low 10^{-11} Pa in the NEG coated beam pipes [4]. The ultimate pressure is dominated by the gases not pumped by the NEG coating: methane (CH_4) and Krypton (Kr), the second one being used during the coating process. For both Krypton and methane, the outgassing rate at room temperature was estimated around 10^{-19} $Pa.m^3.s^{-1}.cm^{-2}$ [2]. The hydrogen equilibrium pressure could be evaluated by the Sievert's law and is negligible at room temperature [5].

One of the major difficulties for the future operation of the LHC accelerator will be the monitoring of the pressure and the quantification of the saturation level of the NEG coatings in order to plan future bake-out/NEG activations during the shutdown activities. The pressure readings of the BA gauges, located every 30 m, provide an indication of the pressure in the vicinity of the gauge itself and could not be used as an indication of saturation level.

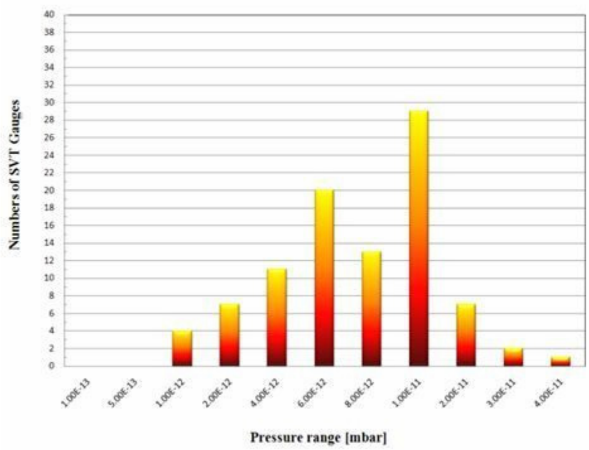

Figure 4: Ultimate pressure distribution on the TiZrV NEG coated beam pipes after activation.

THE VACUUM PILOT SECTOR

For the correct operation of the LHC, it will be necessary to regularly evaluate the level of saturation of the NEG coating in order to ensure the required average pressure during the operation with beams. Eight vacuum pilot sectors (Fig. 5), designed to quantify the real performance of the NEG coating using the hydrogen transmission method, will be installed close to the four experimental region of the LHC.

The length of each pilot sector has been fixed to 7 m for integration reasons. It will be made by 3 NEG coated copper beam pipes of 2.2 m and 2 stainless steel interconnecting modules with an integrated stainless steels RF screen. Both interconnecting modules will be "vacuum fired" and NEG coated. One module will be equipped with a BA gauge and a RGA. The second module will be equipped with a BA gauge and an all metal roughing valve connected to the hydrogen injection line.

The hydrogen transmission method allows quantifying the performance of the NEG coating along the 2.2 m of the beam pipes of the pilot sector. With this method, it is possible to accurately determine the saturation level of the NEG coating. Furthermore, the presence of a RGA will allow the precise evaluation of the residual gas densities on the vacuum pilot sectors close to the experimental region.

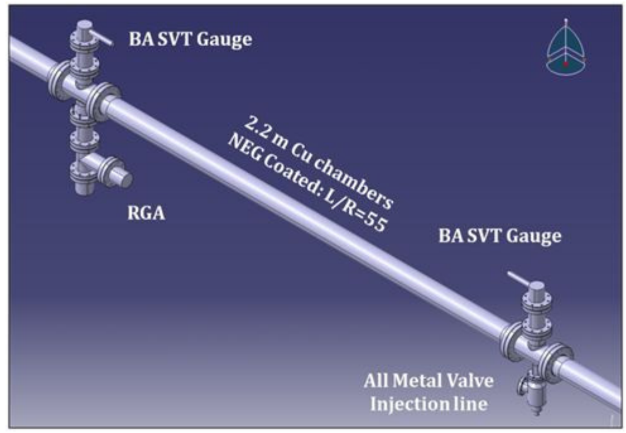

Figure 5: Schematic draft of the vacuum pilot sector.

CONCLUSIONS

The bake-out and the activation of the 6 km of TiZrV NEG coated beam pipes of the LSS is being completed. The average pressure measured over a range of 100 Bayard-Alpert gauges is $8.5 \cdot 10^{-10}$ Pa (dominated by the outgassing at the gauge location) ensuring the LSS vacuum requirements e.g. vacuum stability, beam life-time and low background to the experiments.

These performances have also been achieved in the collimation system area where a huge gas load coming from all the equipments is present. In these areas, the average pressure has to fulfill the 100 h of beam lifetime condition.

To estimate the real pumping speed and the saturation level of the NEG coating, eight pilot sectors will be installed close to the experiments regions where lower pressures are needed. These pilot sectors will allow scheduling the future bake-out and NEG activations during the coming LHC shutdowns.

AKNOWLEDGEMENTS

The work presented here is the result of several years of work and studies of many colleagues working with and in the field of vacuum science at CERN and in the world through collaborations. It would be a challenge in itself to name all the people involved. After so many years, the imminent start of the LHC in the coming months is the result of their effort.

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