

# LHC VACUUM SYSTEM UPGRADE DURING LONG SHUTDOWN 1 AND VACUUM EXPECTATION FOR THE 2015 OPERATION RESTART

G. Bregliozzi, V. Baglin, G. Lanza, P. Chiggiato, CERN, Geneva, Switzerland

## Abstract

At the beginning of 2013 the LHC accelerator stopped for the Long Shutdown (LS1) by the need to consolidate the magnets interconnects. During this period of time, despite the very good performances of the beam vacuum system during the 2010-2012 physic run, different activities were held in parallel by the VSC group so as to consolidate, improve and upgrades some dedicated area of the LHC accelerator. As example a campaign aiming the consolidation of some RF bridges was conducted, NEG coated inserts were installed as a permanent electron cloud multipacting suppressor in critical locations and boosting of pumping speed by the introduction of compact NEG cartridges were performed in special devices. In addition consolidation of different beam equipment such as collimators, BGI, BSRT, BQS, installation of news TCDQ and MKB to name some, were carried out.

In this paper a review of the main consolidations carried out during the LS1 in the beam vacuum system of the LHC are presented and discussed. Their impacts for the future operation are presented and finally a restart expected scenario for the LHC beam vacuum system is described.

## INTRODUCTION

During Run 1, after a successful scrubbing period held during the beginning of 2011, the LHC beam vacuum system operated with a life time due to nuclear scattering of more than 2000 h reaching 75 % of the design proton luminosity at 8 TeV in the centre mass with 2 x 1378 bunches, spaced by 50 ns, each populated by  $1.7 \cdot 10^{11}$  protons and a total beam current of 2 x 420 mA. Among other great performances achieved, the total pressure inside the high luminosity experiments were kept below  $3 \cdot 10^{-11}$  mbar with such beam parameters. These achieved performances, within specifications, could be reached thanks to the detailed studies, design and procurement of the systems together with dedicated vacuum validation tests prior installation and commissioning in the LHC tunnel. However, in order to prepare Run 2, several repairs, consolidation and upgrade are implemented during LS1. This paper will introduce these activities and the LHC restart.

## LHC ARCS

During LS1, all the LHC arcs were warmed up to room temperature (RT) to allow the consolidation of the magnet bus bars located at each magnet interconnects. In agreement with the recommendations of the tasks force

following the sector 34 incident, all the LHC Plug-In-Modules (PIM) are protected by half shells to mitigate the impact onto the beam vacuum system of potential arcing. Moreover, ~ 850 rupture disks were installed at each arc's quadruple to mitigate the bellows buckling along the beam line in case of He inrush. These rupture disks are equipped with an innovative non-return valve which protects the cold beam vacuum system from air in leaks due to degradation with time of the rupture disks. Penning gauges were also installed into the arcs at specific quadrupoles magnets, Q12 and Q13. These vacuum gauges will reduce the detection limit from  $10^{-9}$  mbar to  $10^{-11}$  mbar and, together with and upgraded cryogenic instrumentation, will allow a better monitoring of the electron cloud at cryogenic temperature.

Beside these consolidations, regular activities were done. RF ball test after warm up and before cool down were conducted to identify any buckled PIM. Identified critical non-conform PIM located mainly in the dispersion areas were also repaired together with others repaired during magnet exchanges. Helium leak tightness of the beam screen cooling capillary after several years of operation at cryogenic temperature was confirmed by monitoring the absence of He signal during warm up. Finally, all the cryogenic vacuum systems *i.e.* arcs and standalone magnets (SAM), were evacuated during at least 5 weeks to maximise the removal of residual gas (mainly water vapour) prior cool down.

## LONG STRAIGHT SECTIONS

Despite the cumulated length of the long straight section (LSS) represents only 14 % of the storage ring, the systems contains 88 vacuum sectors held at cryogenic temperature for a cumulated length of 1.4 km and 174 vacuum sectors held at room temperature (RT) for a cumulated length of 5.8 km.

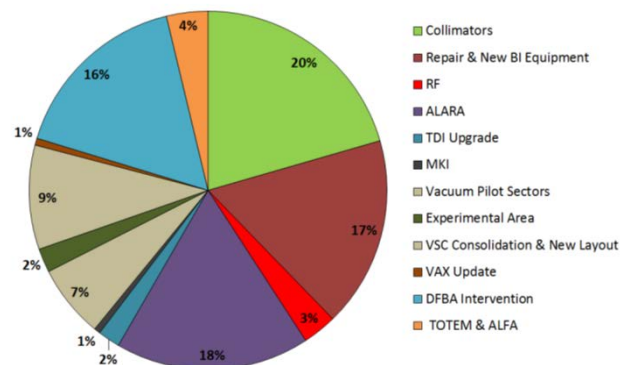


Figure 1: Percentage of all the LSS intervention as a function of beam pipe length.

The RT vacuum system relies on NEG coating technology and it is fully bake-able.

During LS1, 143 RT vacuum sectors were opened and then re-commissioned (*i.e.*  $\approx 5$  km) by NEG vacuum activation. Figure 1 shows a summary of the activities performed in the LSS as a function of the different activities. About 1/3 of this activity is due to vacuum system repair, consolidation and upgrade and 2/3 are due to other systems activities. The total cost for the industrial support manpower is  $\sim 3$  MCHF.

### Vacuum system

During the intensity increase in 2011, some RF bridges induced pressure spikes during physics fills as typically shown in Figure 2. These pressure spikes are due to beam induce sparking at RF bridges of the vacuum modules. As a consequence of these observations, a systematic X-ray analysis campaign of all the 1800 vacuum modules was conducted during 2 years. The result of this campaign showed that 96 RF bridges were non-conform and spread over a total of 52 RT vacuum sectors. The systematic repair decided for LS1 requested the opening of 29 RT vacuum sectors.

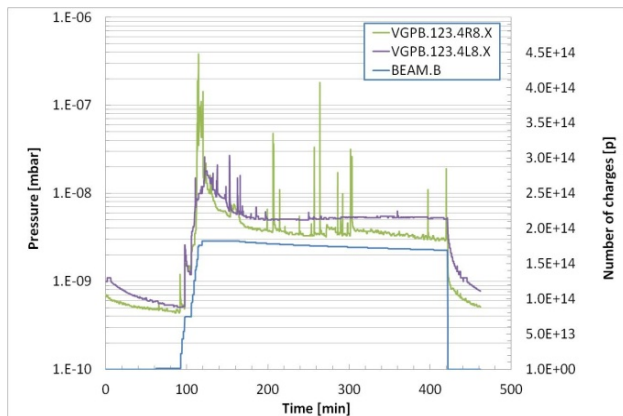


Figure 2: Typical pressure spikes observed in LSS 2 and LSS8 induced by sparking inside VAMTF modules.

Figure 3 shows typical RF bridges non-conformities (NC). On the left side, the NC implies a reduction of aperture with lose of RF contact. Its origin is due to a compression of the vacuum bellow VMAAF after installation, probably during bake-out. On the right side, the origin of the NC is due to beam induced heating as demonstrated by an X-ray image taken a couple of months before and showing a conform module. A detailed analysis revealed a weak design which cannot tolerate misalignment in the vertical plane larger than one mm. This particular module type, VAMTF, has been removed from the vacuum layout.

During run 1 while increasing the beam performances reducing the bunch spacing by 150 ns, 75 ns, 50 ns and 25 ns, the electron cloud showed up as expected. It built up in weaker areas of the machine *i.e.* unbaked RT location of common pipes, then unbaked RT location of single pipes then baked RT locations. In order to minimise the impact on the experiment's background of the pressure

increase due to electron stimulated molecular desorption, it was decided to install solenoids in these location during the winter technical stop 2010-11 *i.e.* 20 km of cables were wound around the vacuum chambers.

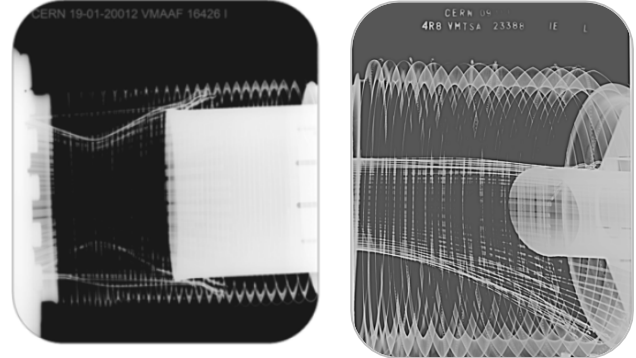


Figure 3: Typical RF bridges non-conformities.

These solenoids were powered ON during physics fill and powered OFF during machine development to allow scrubbing of the vacuum chamber walls. In 2012, most of the solenoids were switched OFF with the exception of the injection kickers (MKI) areas. During LS1, in order to minimise the background to the experiment, the solenoids located in the RT areas are replaced by upgraded RF bridges made of NEG coated transition tubes and the local pumping speed is increased with a 400 l/s NEG cartridge complementing the 30 l/s ion pumps. Figure 4 shows a RF bridge with and without the NEG coating before vacuum validation test in the VSC laboratory. Figure 5 shows a schematic of the upgrade done on the cold-warm transition with NEG cartridge, NEG coated RF bridge and solenoids still installed in the cryogenic area.

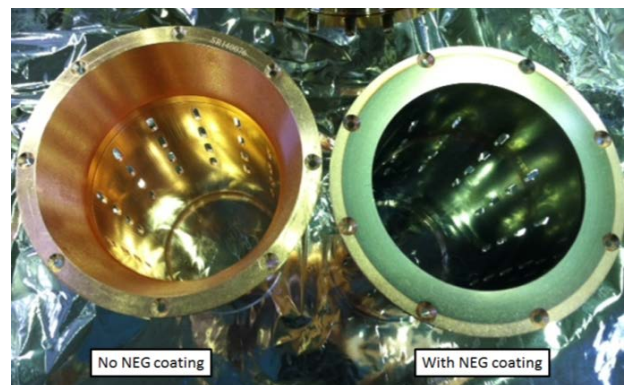


Figure 4: Comparison of the copper and NEG coated RF bridges before vacuum validation in VSC laboratory.

NEG cartridges were also installed in the cryogenic vacuum sectors of the SAM in order to pump the released gas during a magnet quench.

Finally, 88 x 400 l/s NEG cartridges were installed in the collimation areas (LSS3 and 7). According to the ALARA principle, this upgrade will avoid potential human intervention to re-activate the NEG films during future physic runs. The NEG cartridges are inserted into modified standard ion pumps and placed at each collimator extremity. The possibility to remotely re-activate the NEG cartridges allows maintaining a

sufficient pumping speed in case of large saturation of NEG coated beam pipes.

On the instrumentation side, dedicated vacuum pilot sectors for NEG ageing, synchrotron radiation and electron cloud monitoring were also installed in several vacuum sectors located in LSS 2, 7 and 8 [1].

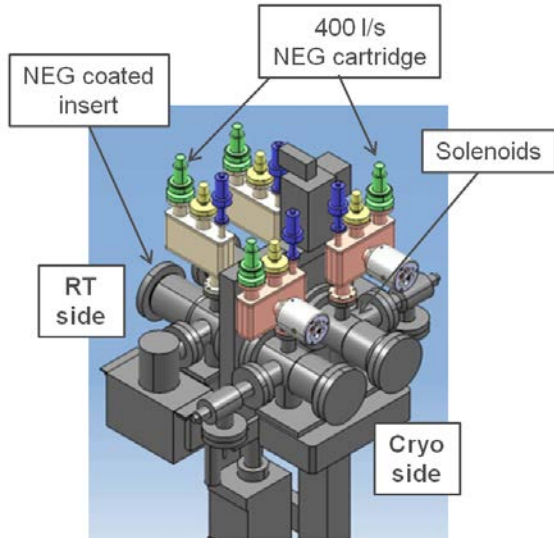


Figure 5: Schematic of the upgrade done on the cold-warm transitions.

### Other system

Many types of equipment of other systems were repaired, consolidated and upgraded during LS1. In order to guarantee the vacuum performances, each of this equipment was previously validated in VSC laboratory before installation into the tunnel. The validation consists in a bake-out cycle followed by leak detection, outgassing rate measurement and residual gas analysis to identify the presence of possible virtual leaks and contaminants. A total of ~ 400 components were tested, see Table 1 for the distribution vs clients [2].

Table 1: Client's distribution of tested components

	Collimation	BI	ABT	Alfa+ Totem
Total	210	80	65	20

The LHC collimation system is made of 3 stages. The part of the second collimation stage located in LS6, TCSP and all the third collimation stage located in LSS1, 2, 5 and 8, TCTP, was upgraded during LS1. These TCSP with carbon fibre jaws and TCTP with tungsten jaws have embedded beam position monitors (BPM) to allow a faster and more accurate positioning during beam operation [3].

The LHC beam injection system was also upgraded. In particular the 8 MKI located in LSS 2 and 8, had their non-kicked Cu beam tube getter coated and the impedance of the ceramic beam tube was further reduced by a modified beam screen [4]. In particular, 400 l/s NEG

cartridges with NEG coated transition tube were installed between each MKI tanks. Moreover, the BTV and BPM beam instrumentation (BI) equipments located upstream and downstream to the kicker magnets were NEG coated too, to reduce further possible pressure increase during beam operation due to electron cloud effects.

In LSS 6, the LHC dilution system was completed by adding a 5<sup>th</sup> diluter on the extraction line (MKB) and the cold mass protection was upgraded by adding on the beam line a third TCDQ mask.

In LSS2 and 8, the injection mask, TDI was upgraded following beam induced heating during Run 1 [5]. The Cu beam screen was replaced by a stainless steel one and the sliding point mechanism upgraded with ZrO<sub>2</sub> ball bearings. The boron nitride blocks were coated by Ti and the Al masks were Cu coated which allows reduction of the secondary electron yield during beam scrubbing. The 2 x 400 l/s ion pumping system was consolidated with 2 x 2000 l/s NEG cartridge. Finally, the TDI was sectorised with DN 250 gate valves in order to decouple the TDI from its surrounding allowing longer bake-out duration and opening the possibility of its exchange during beam operation if needed.

In LSS4, a RF module was exchanged by a new one. Several BI equipments such as beam position monitors (BPM), TV screens (BTV), beam gas injection systems (BGI), synchrotron light monitors (BSRT), wire scanners (BWS), Schottky monitors (BQS), were also repaired and consolidated following virtual leaks, mechanical and beam induced heating issues [5]. The pumping scheme was also upgraded with 12x 400 l/s NEG cartridge placed along the uncoated dampers beam tube, ADT.

Finally, 2 machine experiments were installed. A beam gas vertexing system, BGV, was installed in LSS 4 to monitor transverse beam profile and a crystal channelling experiments, LUA9, was installed in LSS7 to study future collimation schemes [6].

## LHC EXPERIMENTS

All the vacuum chambers to be installed for LS1 into the cavern were vacuum validated at the surface [7]. The main activity during LS1 was to exchange the Be beam pipe at the interaction point of ATLAS and CMS. The new pipes, with reduced aperture (47 mm instead of 54 mm in Atlas and 43.4 mm instead of 58 mm in CMS), allow to accommodate more room for detectors close to the vertex. To minimise the radioactivity of beam pipes, all the stainless steel chambers in ATLAS were replaced by Al ones. In both experiments, the NC RF contact of the vacuum chambers at the TAS position were exchanged and upgraded by the addition of a NEG coated transition tube and a NEG cartridge.

In LHCb, a leaking Be chamber was replaced providing, in the meantime room in the cavern to allow the detector maintenance. To avoid a complete dismounting of the vertex locator (VELO), the vacuum system was vented to neon. For this purpose, a special opening and closing procedures, which did not require a bake out of the VELO, were defined.



During Run 1, ALICE an experiment dedicated to ion physics, suffered from background coming from LSS 2 during proton physics. For this reason, NEG coated liners were inserted into 800 mm vacuum chambers to mitigate the electron stimulated gas desorption induced by the 2 counter circulating beams triggering an electron cloud despite the very large aperture. Figure 6a shows the pressure variation during fills number 2490-3090 in the ID800 and TDI area with indicated also the beam current variation. The integration of NEG coated liner (figure 6b) into the 30m long ID800 vacuum chambers will produce, in addition with the upgrade already described for the TDI, a further decrease of the pressure profile with an important decrease of the background in the ALICE experiments.

Finally, NEG cartridges and NEG coated transition tubes were also installed from the VAX area in front of Q1 to the TAN/recombination areas of the LSS 1, 2, 5 and 8 to minimise background to the experiments.

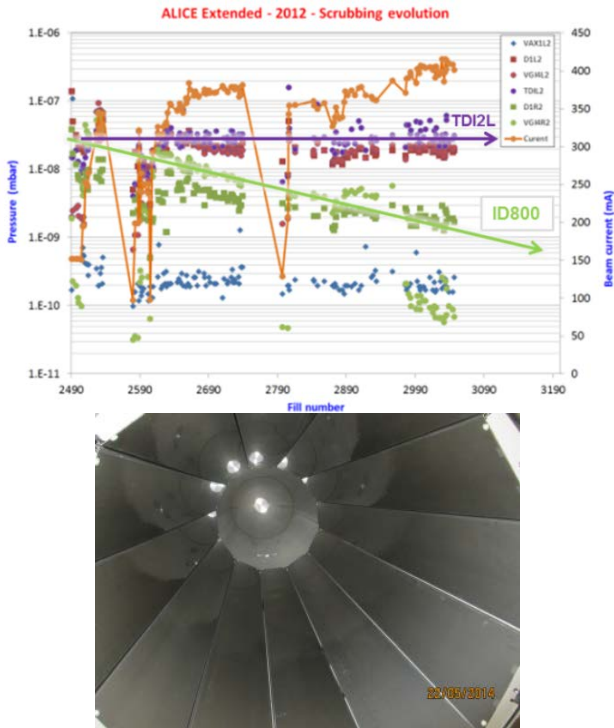


Figure 6: a) Beam current and pressure evolution in the ID800 and TDI during fill numbers 2490-3090 b) Picture of the NEG coated liner inside the ID800 vacuum beam pipe.

## RESTART OF LHC OPERATION

More than 90% of the beam pipes of the LHC were open to air during the LS1 and, as a consequence, the secondary electron yield (SEY) and the electron stimulated gas desorption ( $\eta$ ) will be reset for almost the entire machine. Experience from Run1 showed that the electron cloud can limit the achievable performance with 25 ns beams mainly through beam degradation at low energy and high heat load at high energy. For the vacuum point of view, the reset  $\eta$  could limit the beam intensity

and consequently the performances of the beam scrubbing. The expectation for the restart of the LHC, as shown in Figure 7, is that the previously scrubbed and then air exposed surface scrubs between 5-10 times faster (function of the needed SEY) than the "as-received" surface. For this reason it is estimated that all the new components installed during the LS1 (MKB, TCDQ, new dipoles and quadrupoles, etc.) will need a complete conditioning and will probably represent the limiting factor for beam intensity and bunch number increase during the first days of the planned scrubbing run during 2015.

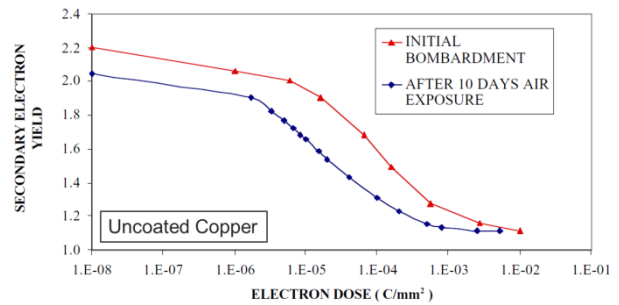


Figure 7: Secondary electron yield vs. electron dose for copper surface as received and for copper surface scrubbed and then exposed to air for 10 days [8].

Furthermore, as depicted in Figure 8, independently if the new surfaces are held at room temperature or kept at cryogenic temperature will behave the same, meaning that if the electron cloud activities is kept constant all along the beam pipes, both surfaces will reach the same SEY for the same electron dose bombarding the surface.

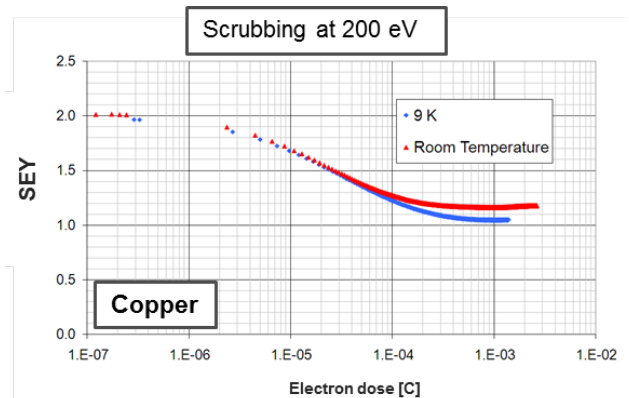


Figure 8: Secondary electron yield vs. electron dose for copper surface at room temperature and at 9K.

For all the room temperature areas with NEG coating a SEY lower than 1.2 is expected already at the beginning of the operation after bake-out at 180°C for 24h (Figure 9). This SEY will allow a comfortable operation even with 25 ns bunch spacing without activating any electron cloud effects being below the multipacting threshold [9].

Summarizing, during the scrubbing run foreseen at the beginning of April 2015 from the vacuum point of view are expected just some localized pressure increase. If necessary, temporary increase of the interlock levels of sector valves are put in place so as to do not interrupt

abruptly the scrubbing period by dumping the beam and if necessary by suppressing the electron cloud effects with the installed solenoid in the cold-warm transition of the SAM. Scrubbing periods with 25 ns will be even more efficient to reduce  $\eta$  allowing a smooth physics run at 50 ns. As shown in figure 10 a decrease of one order of magnitude on the dynamic pressure is expected after about 24h of accumulated beam time.

All the upgrades performed in the experimental area of ATLAS and CMS will assure an even further decrease of the background level. Moreover, the efforts for the new NEG coated liners installed in the ID800 chambers should allow ALICE to have a much lower background during the protons physics.

Operation at 25 ns beams will stimulate further gas desorption from the beam screens: pressure could increase again in the range  $10^{-7}$  mbar. A run at 25 ns above the threshold or with “doublets” is needed for further scrubbing and analysis [10].

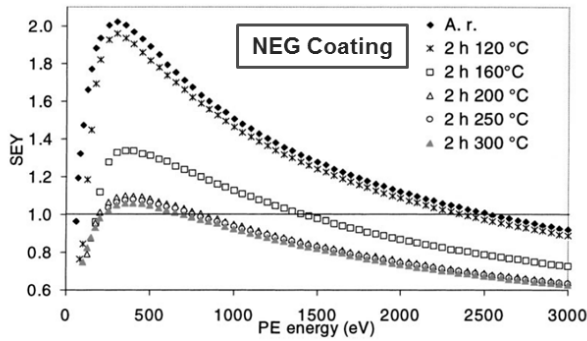


Figure 9: Secondary electron yield vs. electron energy for NEG coating after bake-out at different temperatures.

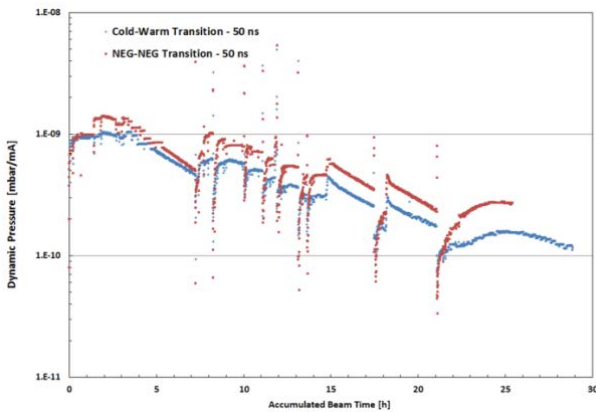


Figure 10: dynamic pressure increase in the Cold-Warm (CW) transition area and in the NEG-NEG area as a function of the beam accumulated time during scrubbing run in 2011 with 50ns bunch spacing.

Finally, after the LS1, the beam energy will approach its nominal value, leading to an increase of the synchrotron radiation critical energy that is proportional to the photon stimulated desorption yield, and the augmentation of the photon flux. The expected desorption due to synchrotron radiation is one order of magnitude higher than the one experienced in 2012. This source of gas will decrease too with the beam pipe conditioning.

## CONCLUSION

Following a successful Run 1, the LHC stopped during about 2 years to allow repair, consolidation and upgrade of systems. All the LHC arcs and  $\approx 80\%$  of the LSS were vented to allow these activities. During Run 1, the LHC vacuum system base line was proven to be valuable. Thus, the vacuum system was simply upgraded by adding more NEG coated surface and more pumping speed at identified weak positions. Dedicated instrumented areas were also implemented in order to provide a better monitoring of the LHC vacuum system performances. In 2015, the vacuum system will be subjected to electron stimulated gas desorption enhanced by beam induced multipacting at 25 ns and subjected also to synchrotron radiation induced gas desorption enhanced by the beam energy increase. Pressure rises will be observed along the ring due to conditioning of newly installed devices and reconditioning of the rest of the ring. After conditioning, the vacuum levels with nominal beams are expected to be within the design values.

## ACKNOWLEDGEMENTS

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