OTHER NON-SOLVED NC ACROSS THE LHC RING AND POTENTIAL IMPACT ON PERFORMANCES

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Abstract

During Run 1, several non-conformities across the ring with impact on machine performances were identified and planned to be solved during the long shutdown 1 (LS1). During this long shutdown, new non conformities were also produced and / or identified. In this talk, some of these non-conformities are presented and discussed together with their impact on machine operation, technical stops and LS2.

INTRODUCTION

Following Run 1, several consolidations and upgrades have been identified across the LHC ring. The activity which took place during almost 2 years represents a challenge not only in terms of volume but also in terms of quality.

Thanks to the training of non-expert personnel, application of procedures, systematic vacuum validation checks, write up of activity reports and quality control checks, the amount of remaining non comformity (NC) in the ring has been minimised. This paper presents an overview of these NC together with their impact on machine operation, technical stops and LS2.

SYSTEMS AT CRYOGENIC TEMPERATURE

Beam Vacuum System

One of the most critical equipment of the cryogenic vacuum system is the plug-in-module, PIM. These components are non-conform since the installation of the LHC. The first non-conform PIM was found by chance at QQBI.26.R7 in August 2007 after the warm up of sector 78. The origin of this NC has been traced back to a NC during manufacturing which was not properly documented and followed-up. Two bending angles of the RF fingers of the PIMs are out of tolerances which, as a consequence, might lead to buckling during warm up. In particular, the QQBI type PIM (interconnect quadrupole-dipole) are the most critical. A systematic check is therefore mandatory once the PIM temperature is higher than 120-130 K. Possible means of checks are RF ball test, tomography, x-ray and endoscopy. Moreover, a systematic repair of the PIM is done when magnets are consolidated [1]. For LS1, in parallel to the arc repair, the PIMs located at the arc extremity: QQBI.7R and QBQI.8L were consolidated. Today, after LS1, 13 % of the PIMs are consolidated *i.e.* 456 out of 3443. All RF-ball tests were ok before cool down. As shown in Figure 1, after the arc warm up, 2 PIMs were found buckled: in the arc 81 and the arc 12. It must be noted that the arc 12 was already warmed up in 2009. Therefore, systematic check of the PIM is needed even if an arc was already warmed up.

QQBI.14L1.B2 **QBQI.33R1**

Figure 1: The tow PIMs which were founded buckled following the LHC arcs warm up after Run 1.

The PIMs located in semi-stand-alone-Magnet (SAM) were all checked ok by tomography except D3-LU (QBUI.5L4) in LSS4L and D2-Q4 (QBQM.4R2) in LSS2R. These last two PIMs were repaired.

All the PIMS located in the inner triplets (IT) were checked ok by endoscopy. In the meantime, the aperture check confirmed the presence of a protrusion of small contact strip in Q1/Q2 of IT5R (at QQQI.2R5). This NC already observed in 2009 did not evolve since. Therefore, it was decided to classify this NC “use as is” during an ad-hoc meeting [2].

For LS2, if the consolidation strategy remains unchanged; no significant impact of this NC is expected. However, it must be remembered that, any warm up above 120-130 K during technical stop, (E)YETS or long shutdown will requires inspection to ensure proper operation of the LHC.

During Run 1, several UFO storms were observed in some specific area of the LHC, in particular s34 [3]. The beam line was inspected and cleaned again during LS1. A few small pieces of MLI/fibres were removed from s34: 99 for about 6 km of beam screen. However, there was no systematic presence of debris where high UFO rates are observed indicating that there is no clear correlation between the presence of debris and UFO storms.

Finally, as already announced by the TE-CRG team [4], all the beam screen heaters have been consolidated to allow heating to 200W (only Q20L2 is not operating). The upgrade of the beam screen valves in s34 with some SAM and semi-SAM was also done. The cryogenic system can therefore reach the same level of cooling capacity all across the ring. The local cooling capacity is homogenised and upgraded to ~ 2 W/m for the scrubbing. This will allow a full usage of the cryoplants available capacity (estimated at ~ 1.6 W/m per aperture).

Insulation Vacuum System

The 7 major leaks, which were created during thermal transient, were repaired during LS1. In s34, the repair of line M in the cold mass circuit of A27L4.M was done. In s45, the repair of the QRL line C of subsector B was achieved with the support of TE-CRG. The leaks in the QRL due to multiply bellows failure were repaired and managed with the support of TE-CRG.

As shown in Figure 2, the machine operated during Run 1 with several leaks above 10^{-5} mbar.l/s. Such large leak level required the use of additional turbo pumping. After LS1, most of the leaks are in the range 10^{-8} - 10^{-7} mbar.l/s which can be managed by simple cryosorption pumping. Only 6 leaks are in the range 10^{-7} - 10^{-5} mbar.l/s but can still be managed by the fixed turbomolecular pumping system. It is worth underlying that several leaks (>10^{-7} mbar.l/s) were created during LS1 due to collateral damage. Fortunately, these leaks could have been repaired. To this date, the vacuum insulation system behaves as expected.

During technical stops or long shutdown, any thermal transient occurring during quench of warm up will increase the risk of major leak. For LS2, several leaks will need to be repaired (IT5L, DFBAK, A23R8.M …).

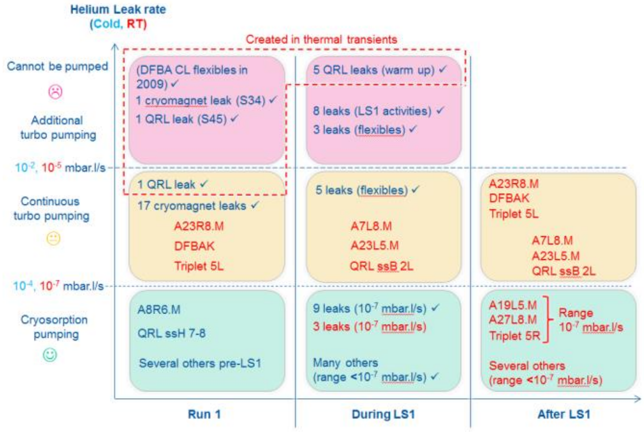

Figure 2: Time classification of leaks observed in the vacuum insulation system

SYSTEMS AT ROOM TEMPERATURE

5th Axis for Collimator

The 5th axis is defined as the possibility to move the collimator's vacuum vessel by +/- 10 mm. This functionality allows restoring the collimator performance in the case the jaws are locally damaged by a 7 TeV beam of less than 10^{11} protons for a tungsten TCTP. The onset of damaged is 5 10^{9} protons at 7 TeV [5].

In the current layout, the TCTs are installed between TAN and D2. In these recombination areas, the systems are very tight and the integration is very difficult. This is the case in particular in LSS 1 and 5 where the 5th axis is condemned. As shown in Figure 3, the vacuum system needs to accommodate the presence of sector valves, collimators, mask and BPMs. This can only be done by using connecting module not compatible with the 5th axis movement of the TCTPH and TCTPV.

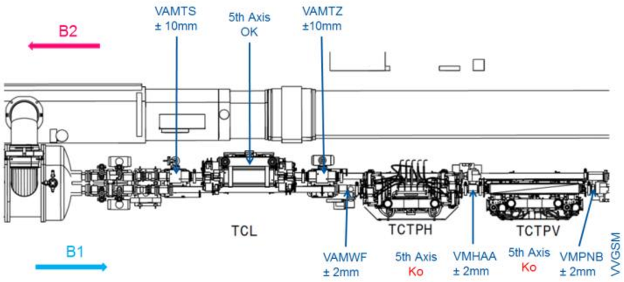

Figure 3: Schematic layout of the TAN-D2 area in C4L5 (courtesy Y. Muttoni EN/MEF).

In order to restore the 5th axis functionality, a new layout including new position of TCTs and new interconnecting modules (to be designed and procured) has to be validated.

The implementation of this new layout must take placed by YETS 2015, consequently, interventions in vacuum sectors A4L1, A4R1, B4L5, B4R5 must be planned. In the meantime, the collimator system cannot afford the risk to damage the TCTs limiting accordingly the machine operation.

RF Bridges Consolidation

The RF bridge is a fragile element of the room temperature (RT) vacuum system. This component ensures the electrical continuity and minimise the impedance at the connecting bellow between vacuum chambers. Its design, based on the LEP expertise and develop all around the world, is reliable within the working tolerance. In LHC, beside the large amount of such equipments, 1781, there is also a large amount of variants. Indeed, more than 40 different type of transition (circular, elliptical, race track, 52 mm to 212.7 mm etc.) are existing.

During Run 1, all these equipments were strongly solicited by the intense bunch current. In particular, some equipment, such as VMTSA (VAMTF), were identified as very sensitive to misalignment and all replaced by other equipment during YETS 2011 and LS1 [6,7]. Thus, the remaining RF bridges were systematically X-ray during Run 1 for inspection. A total of 96 NC were classified priority 1, P1. These NC were spread over 52 RT vacuum sectors (the LHC has a total of 185 RT vacuum sectors). In order to fix all these NCs during LS1, 29 RT vacuum sectors were specifically opened for this purpose.

To comply with the Quality Assurance Plan, a systematic visual inspection of all the vacuum modules was performed and 809 RF bridges were X-ray check at the end of LS1.

Following this campaign, 17 NC issued were classified P1, out of which 6 were repaired. So, 11 P1 NC issues need to be followed-up during Run2. These P1 NC are located in ten different vacuum sectors: B1R1.X, A4R1.X, C4L2.C, B4L2.C, A4R2.C, B4L5.B, A4L6.B, A4L6.R, A4R6.R and B5R7.B. These P1 NC will be repaired if opening of the vacuum sector is needed for performance reasons.

Despite the apparent large amount of remaining P1 NC, a large progress has been made in the work quality since the percentage of P1 NC is decreased from 6 % after LHC installation to 1 % after LS1. This good achievement must be placed in perspective to the large amount of RT vacuum sectors which were opened during LS1 (146 vacuum sectors) and in perspective to the more stringent tolerance as compared to the LHC installation (5 mm length tolerance for the bellow as opposed to 10 mm during installation).

It is worth mentioning also that new concepts of RF bridge are presently under development and ready to be vacuum and impedance qualified. As shown in Figure 4, this type of RF bridge do not have any sliding contact in such a way the electrical continuity is always guaranteed at a price of a relaxation in impedance tolerance. This RF bridge could be used in the future in high radiation areas of the LHC. However, it must be stressed that one limitation of such a system is the demanding alignment accuracy which is not always compatible with the field limitations. More dedicated studies are needed to validate this proposal.

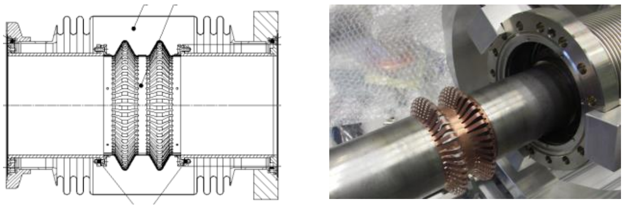

Figure 4: A possible new type of RF bridge for high radiation areas (courtesy J. Perez Espino TE/VSC).

MKBs Outgassing Rate

The LHC diluter magnets, MKB, suffer from a vacuum NC known since the LHC installation. The large outgassing rate of the kilos of epoxy material which is installed inside the unbaked vacuum is not compatible with the actual vacuum performance of the dump line. As a consequence, the vacuum system was partially upgraded during LHC installation by adding fixed turbomolecular pumps to faster the pump down. However, the large gas load and possibly the outgassed species, degraded up to the destruction several 400 l/s ion pumps during Run 1. For this reason, all the 400 l/s ion pumps were replaced during LS1.

However, further potential ion pump trips and destruction cannot be excluded during Run 2. As a consequence, replacement of ion pumps might be needed during technical stops or (E)YETS. Moreover, a development study of a new pumping scheme should be launched during Run 2 to allow implementation during LS2.

Bake-ability of Components

The LHC RT vacuum system is a bake able system by design. However, some components cannot be baked to nominal value with nominal heating rate and adequate bakeout system. The origin of such NC is usually mechanical and sometime electrical.

The consequence of such weakness can be harmful for the LHC Run 2. Larger gas load can be observed, longer bake out time might be needed (with increasing the risk of damage and increasing the exposure of personnel to radiation) and increase of the risk of leak are possible.

Impacts on operation are: increase of background to the experiment, increase of radiation to electronic and reduction of NEG coating life time. Impact on technical stops, (E)YETS are: longer intervention time, increase of the risk of leak during bake out, increase of radiation to the personnel. Impact on LS2 is possible upgrade of specific equipment or rejection of the equipment for installation in the ring.

The TCDQ installed in 115 m long vacuum sectors (A4L6.R and A4R6.B) were upgraded during LS1. These components were validated at the surface in an oven (*i.e.* not in the tunnel configuration) with a specific bakeout procedure having stops at 80 and 120 °C during temperature ramp up and ramp down. As a consequence of this temperature stop and the limiting heating rate to 13 °C/h, the bakeout duration of such a vacuum sector last 2 weeks. Despite the same procedure (with stops at 80 and 120 °C) was applied in the tunnel, a systematic leak appeared at the flange extremity of the 6 TCDQs. Several trials were needed to commission the vacuum sector within the leak tightness specification while degrading the heating temperature of the vessel.

Specific studies must be conducted during Run 2 to understand and eliminate the origin of the leak.

During Run 2, no impact is expected except a reduction of the NEG pumping speed / life time in the vicinity of the TCDQs. However, if for some reason the concerned vacuum sectors are requested to be opened during a (E)YETS, very long intervention time with large risk of leak opening during bakeout must be expected.

Modification and / or sectorisation of the TCDQ must be envisaged for LS2.

The BGI installed in 22 m long vacuum sectors (D5L4.B, D5R4.R) were upgrade during LS1. During the validation phase at surface, several leaks opened systematically on the same feed trough. Given the approaching closing date of the LSS4 with respect to the arcs cool down, in agreement with BE-BI, it was decided to reduce the bakeout temperature to 140 °C at 10 °C/h. This decision allowed to tested the BGI at surface and installed it, in due time, in the tunnel with the potential impact of performances as described earlier

During Run 2, developments should be conducted to reach LHC nominal bakeout performances (250 °C with 50 °C/h heating rate) to guarantee proper operation with LHC beams. A possible upgrade of this equipment during LS2 might therefore be expected.

The BWS installed in 35 m long vacuum sectors (E5L4.R, E5R4.B) were upgrade during LS1. Again, during the construction phase, this equipment could not be delivered on time with the required robustness at the bellow's weld. In agreement with BE-BI, it was therefore decided to reduce the bakeout temperature to 120 °C with 25 °C/h heating rate which allowed the validation at surface and tunnel installation accepting the impact of the system on the machine performances. Indeed, despite its expected relative cleanliness with respect to more complex equipment, the outgassing rate of the BWS in the present condition is as large as the outgassing rate specification of a LHC collimator (10^{-7} mbar.l/s) !

Similarly to the BGI case, developments should be conducted during Run 2 to restore the vacuum performances. Thus, a possible upgrade of this equipment during LS2 might be expected.

The crystal collimation system is an experiment to increase the efficiency of the LHC collimation (LUA9 experiment). Two goniometers were installed in B5L7.B and A4L7.B vacuum sectors of 37 and 45 m long respectively. After LS1, these equipments will be completed by 2 Cerenkov detectors located in vacuum sectors A5L7.B and IP7.B (30 and 83 m long respectively) [8]. Due to the presence of a piezzo electric material, the bakeout temperature of the goniometer is limited to 100 °C and 10 °C/h. Since it is planned to operate with low beam intensity and since the measuring system will be in parking position, screened by a standard circular Cu tube, when operating with nominal LHC beams, the hardware was installed in the LHC tunnel [9].

The system being installed and operated in a high radiation environment, developments are mandatory to restore the nominal bakeout performance (250 °C, 50 °C/h heating rate) of present and future devices in order to respect the ALARA principle.

Internal (Virtual) Leaks

All the equipments installed on the beam vacuum system during LS1 were qualified at surface before tunnel installation. A total of ~ 1200 components were tested [10]. During these tests, outgassing rate was measured, cleanliness was quantified and leak detection performed.

During the last process, external (from atmosphere) but also internal leaks were quantified. Internal leak, often called "virtual leaks", originates from diffused/trapped molecules in porous material or welds and closed volumes. Typical closed volumes are threaded holes for screws which have not been ventilated properly.

Figure 5 show a typical signature of internal leak. Once external leak have been eliminated, the complementary pumping system is switched off (in this case an ion pump). NEG is then the only remaining pumping system which does not pump noble gas and hydrocarbons. With time accumulation, if an internal leak (composed by air molecules) is present, Ar increase with time. The level of the internal leak can also be estimated from this measurement.

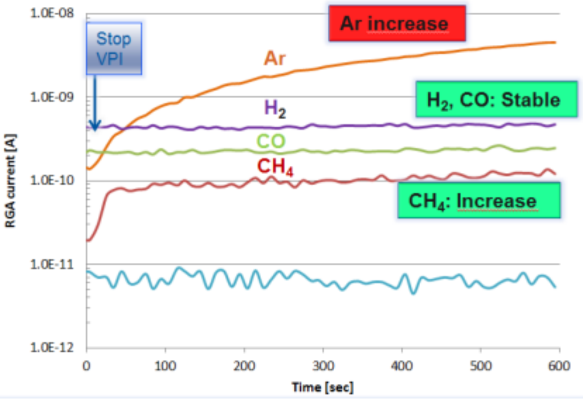

Figure 5: Typical signature of an internal leak (courtesy G. Cattenoz TE/VSC).

Two equipments, installed in the LHC ring during LS1 exhibit large internal leaks level: BQSV.5R4.B1 and TCSP.4L6.B2 with 5 10^{-7} and 6 10^{-7} mbar.l/s leak rate respectively. If needed, these equipments might be upgraded during LS2.

As a result of the internal leak, the leak detection sensitivity limit in the concerned vacuum sector is altered. If not spotted during the surface test, the field operator will spend (and lose) significant amount of time (~ day) to identify an external leak which is not existing! Moreover, this internal leak will progressively saturate the NEG coating in its vicinity and affect the conditioning level in the nearby stand alone magnets.

In the LHC, any leak rate of a vacuum sector must be $< 10^{-9}$ mbar.l/s, a level which saturates about a meter of NEG coating per year. Therefore, the leak rate per components must be $< 10^{-10}$ mbar.l/s.

Beam Induced Heating

Beam induced heating can be significant for some LHC equipments [11,12]. In order to optimise the impedance of the system, ferrites are inserted to damp the high order modes at specific location in some equipment. This is the case for MKI, Totem and Alfa roman pots and TCTP equipments. During operation, despite the ferrite will reduce the power loss (by lowering the quality factor Q of the resonance), the temperature of the ferrites increase due to the remaining power loss [13,14].

Figure 6 shows the specific outgassing rate of standard ferrites used at CERN and compared to baked stainless steel and vacuum fired stainless steel. These data were obtained followed a degassing treatment of the ferrite at 400 or 1000 °C. The specific outgassing rate is inversely exponentially dependent with the inverse of the temperature.

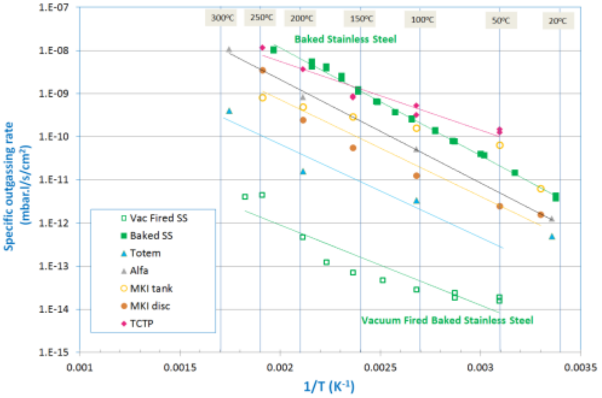

Figure 6: Specific outgassing rate of ferrites compared to baked stainless steel and vacuum fired stainless steel (courtesy G. Cattenoz TE/VSC).

Therefore, as shown in Table 1, increasing the ferrite temperature from RT to 50 °C will multiply its outgassing rate by 5. Increasing further the temperature, the ferrite outgassing rate can be multiplied by several orders of magnitude increasing significantly locally the vacuum pressure. Long term operation will then saturates the NEG coating and induce radiation to the electronic. Finally, the equipment will need to be repaired during LS2.

Table 1: Outgassing rate increase as a function of ferrite temperature

°C	50	100	150	200
q/q_{RT}	5	40	150	600

TDI

During Run 1, TDI was the source of background to the ALICE experiment while operating with proton beam. A possible origin of the beam induced pressure rise (in the 10^{-8} mbar range) is beam induced heating.

To allow exchange and/or reconditioning both LHC TDI were sectorised during LS1. The pumping speed was also upgraded by adding 2000 l/s NEG cartridges.

However, the TDI will still suffer from resistive wall (~ 400 W on jaws at injection and 60 W at flat top when jaws are in parking position) and trapped modes during Run 2. Therefore, despite that the TDI base pressure are back to nominal values (~ 10^{-10} mbar), beam induced heating could still stimulated thermal outgassing [12].

Thanks to the sectorisation, the TDI could be exchanged during technical stops or (E)YETs if needed. A new TDI system is presently under design for a possible implementation during LS2.

Damage and Potential NCs

During LS1, the vacuum system suffered from several collateral damages. As an example, bellows, beam pipe, valves were damaged or operated outside their working range. The conformity of these equipments was systematically checked and a repair was performed when needed. Two accidental venting of room temperature vacuum sector happened also. Those took place in June 2014 in vacuum sector A7L8.R (3/6) when a tractor snatched the pumping group just before s78 cool down and in vacuum sector A4L5.C (20/6) for unknown reason (local inspection revealed that the leak was placed at a loosely bolted flange). Finally, an uncontrolled pump down of the MKB's vacuum sector (BTD68.DB) was done the 18/6/2013. A port was sealed with Al foil which explodes during pump down. As a result, 1.5 month of *in-situ* cleaning was needed to restore the MKB's performance. The origin was traced back to a lack of documentation (the blank flange was removed from the port and replaced by an Al foil the Friday afternoon and documented by a phone call) and a lack of systematic inspection before pump down.

Obviously, the time needed to manage these collateral damages extended the requested time by the planning team to conclude the beam vacuum activity on the field.

For LS2, it is planned to continue to upgrade the quality level and reinforce the quality control teams. Progress must continue to provide systematic and well defined procedures, activity reports and quality control. In particular, a few teams, independent from the field team, are needed to perform these controls.

CONCLUSIONS

Many activities have been performed during LS1 with great success. However, despite all the precaution taken and the efforts made during the design, test, installation and commissioning phase, several NC could not be avoided and corrected in due time before tunnel closure.

In particular, the 5th axis for collimator is condemned for the TCTP located in the recombination area of LSS1 and 5. A few RF bridge (1% of the total) have been identified as critical. The MKBs large outgassing rate can provoke pressure spikes triggering beam dumps. Several installed equipments (TCDQ, BGI, BWS, LUA9) are not compatible with bake out specification or exhibit internal leaks (BQSV, TCSP). A few equipments containing ferrites are sensitive to beam induce heating *e.g.* TDI. If needed, any of these NC might be corrected either during technical stops, (E)YETS or LS2.

Quality has been an important aspect of the LS1: from design to commissioning. After a state of the art design and fabrication phase, vacuum tested performed at the surface have eliminated potential issues before installation into the ring. Quality control checks, performed in the tunnel, have allowed identifying potential issues while correcting them when possible. For

LS2, the use of dedicated and independent quality control teams is mandatory to increase the machine efficiency as requested for HL-LHC operation. Such teams are needed to control and document the work made all across the ring. An immediate consequence of such an approach is that the commissioning time of a "standard" room temperature vacuum sector will be increased from 3.5 weeks to about 4 weeks.

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