RECOVERING ABOUT 5 KM OF LHC BEAM VACUUM SYSTEM AFTER SECTOR 3-4 INCIDENT

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Abstract

During the sector 3-4 incident, the two apertures of the 2.8 km long cryogenic vacuum sectors of the CERN Large Hadron Collider (LHC) were brutally vented to helium. A systematic visual inspection of the beam pipe revealed the presence of soot, metallic debris and super insulation debris. After four month of cleaning, the beam vacuum system was recovered. This paper describes the tools and a methodology developed during this period, the achieved performances and discusses possible upgrades.

INTRODUCTION

The 19th September 2008, the 2 plug-in-modules (PIM) located between magnets C24R3 and Q24R3 of the arc 3-4 were destroyed. The consequence of this incident was a helium inrush inside the 2 beam vacuum tubes V1 and V2 due to the liquid helium flow of about 20 kg/s. Under the helium pressure, soot and debris of super insulation were spread along the 2 x 2.8 km vacuum sectors.

EXTEND OF THE DAMAGES IN THE BEAM VACUUM SYSTEM

After the incident, 5 double beams vacuum sectors (B6R3, A7R3, ARC 3-4, A7L4 and B6L4) were isolated by the sector valves. These valves were closed by the vacuum interlock system. The interlock was triggered by the pressure increases above 4 10^{-7} mbar at 4 positions: between vacuum sectors ARC 3-4/A7R3 and A7R3/B6R3 in the Long Straight Section (LSS) 3R and between vacuum sectors ARC 3-4/A7L4 and A7L4/B6L4 in LSS 4L. The arc valves of LSS 3R beside Q7R3 were closed 23”-24” after the event and the arc valves of LSS 4L beside Q7L4 closed 1’2”-1’3” after the event. The average propagation speed of the pressure front which triggered the interlocks is therefore about 35 m/s. The penning gauges in the room temperature vacuum sectors A7R3 and A7L4 were switched off when the pressure increased above 5 10^{-5} mbar, 2”-3” after the closure of the arc valves. One hour after the incident, the stand alone magnets and 75 % of the arc were still around 5 K. Access in the tunnel was made available when all the risk associated to any over-incident was eliminated.

Cryogenic Vacuum Sectors

The two vacuum sectors of the arc 3-4 and the vacuum sectors of the stand alones magnets Q6R3, Q6L4 were affected by the incident. The pressure in the arc was at 1 bar and the pressure in the stand alone magnets remained below 10^{-8} mbar. Obviously, the residual gas consisted mainly of helium. When the first PIMs, which interconnect two magnets, were cut by the beginning of October 2008, plugs equipped with safety valves were installed at the beam tube extremities to minimise the air and dust pollution of the arc region still at 200 K. A campaign of systematic visual inspection of the interconnections and of endoscopic inspection of the beam tubes was launched. The progressing rate of the endoscopic inspection of the beam tube was reduced by buckled PIM which blocked the aperture requiring further cutting by the mechanical teams. The endoscopic inspections revealed that the beam tubes were polluted by interconnects and soot debris and also by super insulation debris. The composition of the soot corresponded to that melted in the interconnection *i.e.* copper and stainless-steel. The soot size ranges from less than 1 µm to 80 µm [1]. Figure 1 shows examples of beam screens polluted with super insulation debris (left side) or soot (right side).

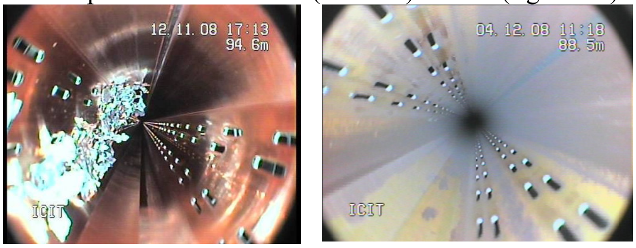

Figure 1: Left, example of A10L4.V2 beam screen polluted with super insulation debris. Right, example of Q19R3.V2 beam screen polluted with soot.

By the end of December 2008, 4.8 km of beam tube and 122 interconnections were inspected and documented. A total of 59 % of the beam tube were polluted by super insulation debris (MLI) and 19 % by soot. Figure 2 shows the debris distribution along sector 3-4. Most of the super insulation debris was observed at the extremity of the sector. However, these debris were spread from Q30R3 till Q7L4.

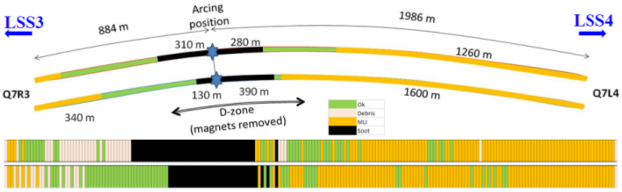

Figure 2: Debris distribution along sector 3-4.

Room Temperature Vacuum Sectors

After the closure of the vacuum sector valves triggered by the interlocks, the pressures in A7R3 and A7L4 *i.e.* the vacuum sector located between Q6-Q7 were at 1 mbar and $5\ 10^{-2}$ mbar respectively. The pressure in the other room temperature vacuum sectors of the LSS 3 and 4 remained below 10^{-11} mbar. Helium is not pumped by NEG surfaces. In order to check if the venting was made with pure helium, A7R3 was pump down to its nominal pressure of $6\ 10^{-11}$ mbar in less than three days. This demonstrates that these sectors were indeed vented with pure helium. After air venting, further investigation while opening parts of the vacuum sectors in A7R3 and A7L4 did not revealed any traces of soot or super insulation debris, only standard contamination could be identified by electron microscopy [2]

BEAM TUBE CLEANING

Super Insulation Debris

In parallel to the inspection work, tools were developed to clean the beam tubes in sector 3-4. Preliminary test of a vacuum cleaner were based on sucking technology with a mole perforated with holes. These tests were partially unfruitful. But successful harvest campaign were achieved by end November in the tunnel. It was then decided to develop a cleaning tool based on an automatic pumping/venting technology. To this mean a pump is mounted on one side of a sector and an air filter is installed on the other side. A cycle is set to 30" long, 20" pumping, 8" plateau and 2" venting. During this process, the pressure inside the vessel is reduced from atmospheric pressure to 800 mbar in 2" (as a comparison, during a standard arc pump down, the pressure is reduced by 200 mbar in one hour). The established air speed is 20 m/s which correspond to an estimated drag force on the section of 70 g [3]. As an example, in a 230 m long sector, 3.2 g *i.e.* 0.4 m^2 of super insulation debris were recovered in a single pumping/venting cycle. After the second cycle, 1.2 g *i.e.* 0.1 m^2 were recovered. However, only 100 bits of debris were recovered after the third cycle indicating that either there were no more debris left in the sector or the efficiency of the process was reduced to zero.

To clean further the beam tubes, a nozzle designed to blow nitrogen and attached to an endoscope's head was built and tested in the laboratory during January 2009 [4]. In this second step, a nozzle, which performance and position is controlled by an endoscope, is introduced inside the vacuum system to produce a local perturbation. The principle is to blow filtered nitrogen, at a rate of 2 bar.l/s, behind the beam screen and the PIM's RF fingers in order to allow the debris to be brought back inside the beam aperture where they can be suck up by the automatic venting/pumping device. Figure 3 shows a sketch of the system principle.

During the validation phase in the laboratory, 18 PIMs cut and recovered from the sector 3-4 were subjected to 2 successive passages for a total accumulated time of 8 minutes per PIM. The removal efficiency of the tool was found to be better than 90 %.

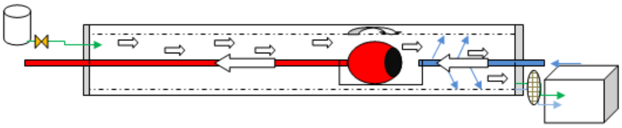

Figure 3: Nozzle and endoscope inserted in a beam aperture subjected to automatic pumping/venting cycles

After evaluation in the tunnel of the parameters such as the number of passages, the cleaning time per PIM, the cleaning time per beam screen and the nozzle opening, a detailed cleaning procedure was issued [5]. The maximum sector length to be cleaned was one half-cell (~ 50 m). A summary of the procedure is given below:

- 1st Step, automatic pumping/venting of the sector during at least one hour. At the end of this time, additional automatic pumping/venting of the so-called pumping hoses (vacuum ports at each quadrupole) during at least 15 minutes.
- 2nd step, 10 passages along the vacuum sector with the nozzle-endoscope tool and the automatic pumping/venting. During passage 1, 2 and 3, the nozzle-endoscope tool should be applied during 10 minutes at each PIM then 5 minutes are required. In the beam tube, the speed of the nozzle-endoscope tool is 3 to 4 m/minute. In case of an event visible by the endoscope camera, the operator shall insist with the tool to remove the event. The beam line is subjected to automatic pumping/venting during passages 1,2,3,4,9 and 10. Additional automatic pumping/venting of the pumping hose is installed in parallel during passages 5,6,7,8. After each passage, the debris are collected in a plastic bag for future documentation.
- 3rd step, endoscopic control. Once a sector has been cleaned, quality control is ensured by a systematic endoscopic inspection in both directions. Each beam position monitor, each PIM, each entrance, mid and end part of the beam screen and finally, each unexpected event are recorded by video. A report is issued at the end of the control.
- 4th step, validation of the cleaning of the sector and release of the sector for PIM welding.

This procedure, established by end February, requires a challenging mean cleaning rate of 50 m of beam tube per team and per day with a total of 3h15 min spent for the PIM cleaning. Obviously, the 2nd step was the longest of the procedure. Each PIM was cleaned during 1h5 min. Note that reducing the amount of passages from 10 to 5, *i.e.* 40 min per PIM, would gain 40 % of time at the price of a slightly lower quality.

In parallel to the establishment of the procedure, after discussions with beam experts and following the Chamonix workshop in 2009, it was agreed with the CERN management that a maximum of one fibre per half-cell and two debris (from super insulation or other) per magnet can be tolerated after the cleanup process!

Soot

After the removal from the arc 3-4 of 53 cold masses (13 MQ and 39 MB) for inspection and repair at the surface, the amount of beam screens polluted by soot to be cleaned in the tunnel was reduced to 6 (2 %).

The beam tubes polluted with soot needed to be cleaned *in-situ*. The cleaning process is based on a plug onto which foam is fixed. The assembly is used to sweep the interior of the beam screen. Up to 50 passages were done with a foam-plug wetted with alcohol followed by up to 15 passages which were done with a dry foam-plug.

As shown in Figure 4, the achieved results gave pretty good results given the accessibility and the difficulty to remove the soot in a 16 m long beam tube.

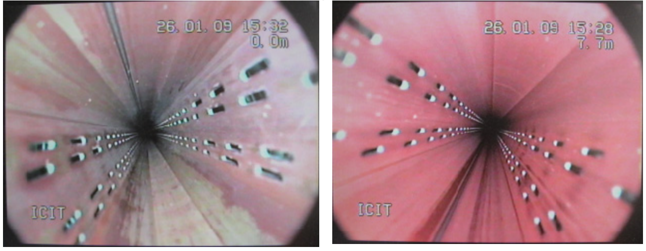

Figure 4: Left, example of results obtained after the soot removal of Q19R3.V2 (left) and A20R3.V2 (right).

It is believed that the traces seen on the left of Figure 4 are the signature of an oxidised surface resulting from the evaporation of a liquid.

ACHIEVED PERFORMANCES

All the beam tubes of the arc 3-4 were systematically cleaned. During the work in the tunnel, a day by day reporting and analysis of the cleanliness was settled. A total of 3 teams employed to clean the beam tube and 1 team for final endoscope analysis were deployed. Figure 5 shows the dashboard of the cleanup process. After the procedure set-up phase, the work progressed at the requested speed. By mid-May, *i.e.* 4 months after the beginning of the cleaning, all PIMs were delivered to the teams in charge of welding. Of course, the work did not progress without difficulties. Beside the difficulties associated with co-activities, the endoscopes were also damaged or the nozzle was stuck inside a PIM requesting to open the W below and cut the PIM.

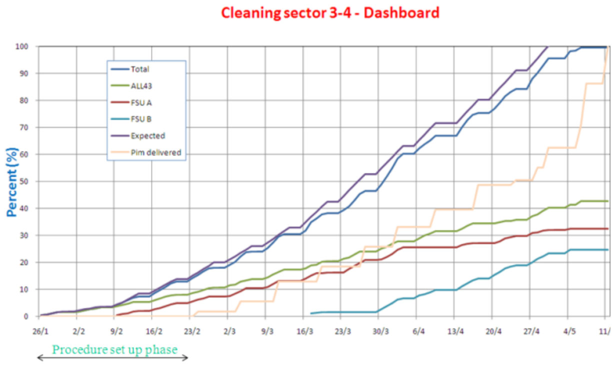

Figure 5: Dashboard of the cleanup process

Finally, the validation of the beam cleanliness by a simple endoscopic inspection was not always trivial. Figure 6 shows that indeed residues of fibre or super insulation are hardly identifiable. A total of 101 non-conformities left as "use as is" were recorded. 58 were assigned to super insulation debris, 38 to fibre and 5 to oxidation stains. All these non-conformities were documented and archived.

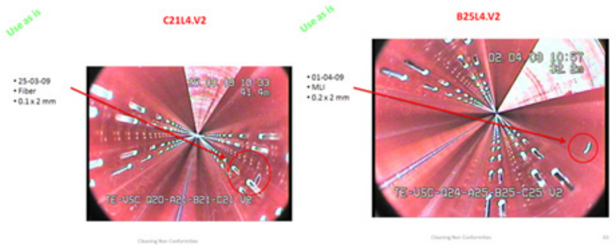

Figure 6: Examples of non-conformities left as "use as is" identified during the validation step

CONCLUSIONS

The incident of sector 3-4 spoiled all the beam tubes in the arc. It required the setting up of a team and the development of new tools and methodology to recover the beam tube. About 3 month were required to develop the tooling and perform the first inspections. 4.5 months were also used to define the methodology, clean the beam tube and perform the final endoscopic control. The challenge to leave the beam vacuum system without residue bigger than 1mm^2 and with less than 1 fibre per 50 m and less than 2 debris per magnet was achieved. It is worth mentioning that LHC is now operating with beams since several months without any noticeable sign of vacuum performance reduction in sector 3-4. In the advent of a similar event, it is estimated that the total intervention time will be about 5 months. At the price of a lower cleaning quality, 1 more month could be gained.

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