

## VACUUM SYSTEM – HOW TO GET READY FOR BEAM ?

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On behalf of the team in charge of cleaning the beam vacuum in sector 3-4

### Abstract

During the incident of sector 3-4, the two beam vacuum sectors of 2.8 km each and four insulation vacuum sectors *i.e.* 750 m were vented to atmospheric pressure. Besides the mechanical damages of the nested bellows and plug-in-modules due to the movement of the cold masses under the helium pressure, soot and debris of super insulation were spread inside the beam and insulation vacuum. The presentation will cover the extent of the damage from Q6R3 till Q6L4. The strategy deployed to repair, to clean and to qualify the damaged vacuum systems will be discussed. Scheduling and compatibility with beam operation issues will be also addressed.

### INTRODUCTION

The 19<sup>th</sup> September 2008, the 2 plug-in-modules (PIM) located between magnets C24R3 and Q24R3 were destroyed, probably due to a plasma glow caused by the electrical arc due to a bad electrical joint in a 12 kA bus bar of the so-called line M3.

The consequence of this incident was a helium inrush inside the 2 beam vacuum tubes V1 and V2. Under this helium pressure, soot and debris of super insulation were spread along the 2 x 2.8 km vacuum sectors.

In the first paragraph, the status of the beam vacuum system following the incident is given. The different means developed to recover the vacuum systems as well as their performances are described in the second paragraph. The current status, at the date of 1<sup>st</sup> of March 2009, and the schedule is discussed in a last paragraph

### EXTEND OF THE DAMAGES IN THE BEAM VACUUM SYSTEM

#### Cryogenic vacuum sectors

The cryogenic vacuum sectors of concern are the vacuum sectors of the stand alones Q6R3, Q6L4 and the two vacuum sectors of the arc 3-4.

Following the incident, the pressure in the stand alone remained below  $10^{-8}$  mbar. On the other hand, the pressures in the arc were at 1 atm. The 12 vacuum valves of the sectors B6R3, A7R3, ARC 3-4, A7L4 and B6L4 were closed thanks to the vacuum interlocks. The interlocks were triggered by the pressure increases above  $4 \cdot 10^{-7}$  mbar at 4 valves positions: between sectors ARC 3-

4/A7R3 and A7R3/B6R3 in LSS 3R and between sectors ARC 3-4/A7L4 and A7L4/B6L4 in LSS 4L. The arc valves of LSS 3R were closed 23''-24'' after the event and the arc valves of LSS 4L closed 1'2''-1'3'' after the event. The average propagation speed of the pressure front which triggered the interlocks in the beam tube is therefore about 35 m/s. The penning gauges in vacuum sectors A7R3 and A7L4 were switched off when the pressure increases above  $5 \cdot 10^5$  mbar, 2''-3'' after the closure of the arc valves.

A campaign of systematic visual inspection of the interconnections and of endoscopic inspection of the beam tubes was launched.

Out of 4 rupture disk installed in the arc at position Q8R3 and Q8L4, the rupture disk in Q8R3.V2 was burst and the rupture disk Q8R3.V1 was slightly deformed but not burst. These rupture disks are designed to burst at 1.5 bar absolute.

Interconnections in the vicinity (Q23R3 till A29R3) of the C24R3/Q24R3 interconnections were polluted by soot. Buckled PIMs and nested bellows were also observed. Most of the buckled PIMs were located in the V2 line (red beam) and extended till C13R3. The other buckled components were inside the damaged zone (D-zone) from Q20R3 till Q30R3.

The beam tubes were polluted by interconnects and soot debris and super insulation debris. Electron microscopy Analysis of the soot was performed. This analysis revealed that 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  $\mu\text{m}$  to 80  $\mu\text{m}$  [1]. Figure 1 shows examples of beam screens polluted with super insulation debris or soot.

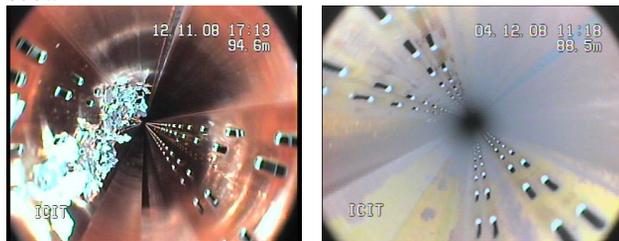


Figure 1: Left, example of A10L4.V2 beam screen polluted with super insulation debris. Right, example of Q19R3.V2 beam screen polluted with soot.

A hole in the beam screen and the cold bore in line V2 of C23R3 was also discovered during the systematic endoscopic inspection. This hole is located about 1 m

from QBQI.23R3.V2. Further inspection through the cold bore's hole indicated that it was positioned at the level of corrector magnets. This hole is a result of collateral damages.

Table 1 give an overview of the amount of beam screens of V1 and V2 lines polluted. In total 60 % and 20 % of the arc were respectively polluted by super insulation and soot. On average, areas from Q7R3 till A10R3, A34L4 till Q7L4 were polluted with super insulation debris. Areas from B19R3 till Q31R3 were polluted with soot. Other areas showed only minor traces of pollution.

	V1	V2	V1	V2	Total
Ok	54	39	26 %	18 %	22 %
MLI	124	129	58 %	61 %	59 %
Soot	35	45	16 %	21 %	19 %
Total	213	213	100 %	100 %	100 %

Table 1: Final status, after the incident, of the amount of beam screen polluted by soot or super insulation (MLI) debris.

After the removal from the D-zone 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. Therefore, most of the beam screens to be cleaned in the tunnel are polluted with debris of super insulation. Table 2 shows the amount of beam screens to be cleaned in the tunnel.

	V1	V2	V1	V2	Total
Ok	49	30	31 %	19 %	25 %
MLI	111	124	69 %	78 %	73 %
Soot	0	6	0 %	4 %	2 %
Total	160	160	100 %	100 %	100 %

Table 2: Final status of the amount of beam screen polluted by soot or super insulation (MLI) debris to be cleaned *in-situ*.

### Room temperature vacuum sectors

Following the incident and the closure of the vacuum valves, the pressures in A7R3 and A7L4 *i.e.* the vacuum sector located between Q6-Q7 were 1 mbar and  $5 \cdot 10^{-2}$  mbar respectively. It is worth mentioning that the pressure in the other room temperature vacuum sectors remained below  $10^{-11}$  mbar.

Opening parts of the vacuum sectors in A7R3 and A7L4 did not revealed any traces of soot or super insulation debris, only normal contamination could be identified by electron microscopy [2, 3]

## RECOVERING THE BEAM VACUUM SYSTEM

### Soot removal

The V2 line of B19R3, C19R3, Q19R3, A20R3, B20R3 and C20R3 polluted with soot needed to be cleaned *in-*

*situ*. The 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. Figure 2 shows a picture of the foam-plug inserted inside C19R3.V2 when cleaning the horizontal parts and the result of the cleaning with wet foam. It is worth mentioning that the passages with dry foam left the foam clean.

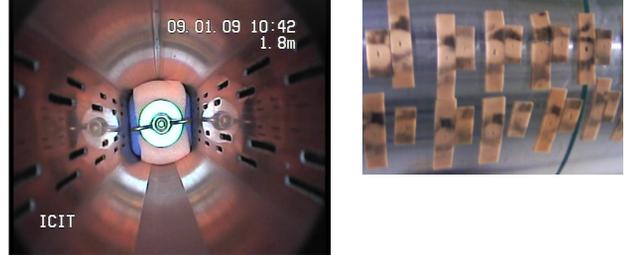


Figure 2: Foam-plug inserted inside. Left, cleaning of the horizontal parts of the beam screen C19R3.V2. Right, result of the cleaning with the wet foam.

The result of this action gave pretty good results given the accessibility and the difficulty to remove the soot. As an example, Figure 3 shows the result obtained in Q19R3.V2 and A20R3.V2.

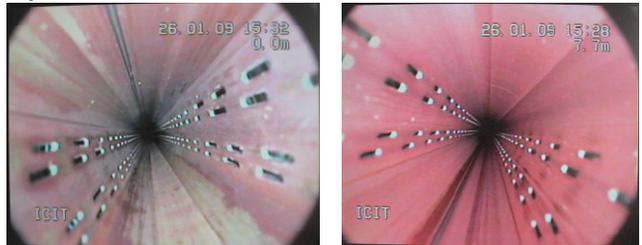


Figure 3: Left, example of results obtained after the soot removal of Q19R3.V2 (left) and A20R3.V2 (right).

It should be mentioned that the traces left behind this cleaning method are due to local oxidation of the beam screen surface. These traces, which are easily observable with grazing light, are a typical signature of residue which has been left after evaporation of a liquid. In our case, the traces are probably the result of the evaporation of an ice plug formed during the incident. The most affected beam screens by this phenomenon are C19R3.V2 and Q19R3.V2 located five half-cells ( $\sim 250$  m) from the incident point.

### Super insulation removal

Given the total length of elements to be cleaned, it was decided to cut all the QQBI (*i.e.* non-conform PIM) on top of the buckled PIMs to allow access inside the beam tube every 50 m.

The removal of super insulation debris is done in 2 steps.

The first step is based on an automatic pumping/venting of the sector to be cleaned. To this mean a pump is

mounted on one side of the sector and an air filter is installed on the other side. A cycle is about 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 about 20 m/s which correspond to an estimated drag force of 70 g [4]. This process is applied during at least 1 h (120 pumping/venting cycles).

The efficiency of this method is already pretty good in the sense that there were no more (or little) super insulation debris observables by the endoscope inside the beam screen after the first 10 pumping/venting cycles. As an example, in sector Q8R4 till Q13R4 (~ 230 m), 3.2 g *i.e.* 0.4 m<sup>2</sup> of super insulation debris were recovered in a single cycle. After the second cycle, 1.2 g *i.e.* 0.1 m<sup>2</sup> were recovered. However, only 100 bits of debris were recovered after the third cycle indicating that either there was no more debris in the sector either the efficiency of the process was reduced to zero.

Then a second step is used to remove debris which are located behind the beam screens or behind the RF fingers of the PIMs. 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 RF fingers to allow the debris to be brought back inside the beam aperture where they can be sucked up. Figure 4 shows a sketch of the system principle.

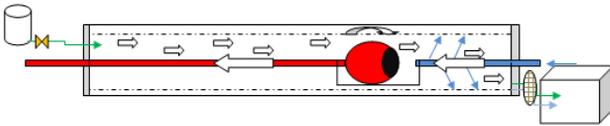


Figure 4: Nozzle and endoscope inserted in a beam aperture subjected to automatic pumping/venting cycles

The system efficiency was evaluated in the laboratory on 17 PIM samples collected from the campaign of QQBI cutting in sector 3-4 [5]. Those samples originated from positions in Q10, Q11, Q12, Q15, Q16, Q22, Q23, Q29, Q30, and Q33 of sector 4 Left. The result of this campaign is shown in Figure 5. For the study, a PIM was connected between two dummy sets of beam screen / cold bore assembly to mimic a realistic situation. After only two passages of the nozzle, the average removal efficiency is about 95 %. After dismantling of the PIM for inspection, it appeared that the remaining debris were located in corners which are not in direct view of the beam aperture. It should be underline that no debris of super insulation were found inside the beam screen or in the coaxial space, therefore, once a debris is released in the beam aperture space, it is removed by the pumping system.

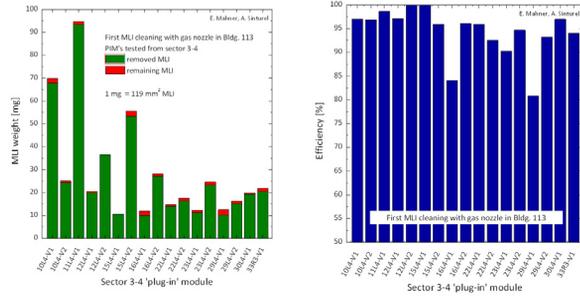


Figure 5: Results of the nozzle efficiency evaluation

During application of this process *in-situ*, it was found out that most of the debris recovered by this method were coming from the PIM position. About 2 to 4 times more super insulation debris are recovered from the PIM position than from the beam screen length. This fact is in agreement with the observation that more space are given to the debris to go behind the RF finger than behind the beam screen where the debris should go through the pumping slot and even through the electron shield in dipole magnet to enter the beam screen / cold bore coaxial space.

Of course, as far as the number of passage is increasing, the number of collected debris decreases. Figure 6 shows the evolution of the integrated cleaning efficiency of the nozzle system measured in sector 3-4. The result of this study shows that after 10 passages, 90 to 95 % of the super insulation debris has been removed from the beam tube. It is worth mentioning that during the study, about 700 to 1 000 debris of about 1 to 2 mm<sup>2</sup> were collected at the level of the filter. Therefore, if one would have reduced himself to 10 passages, one would have left about 50 super insulation debris *i.e.* about 1 debris per meter of beam tube.

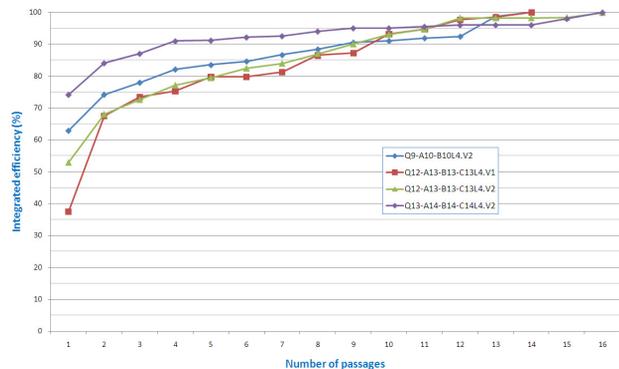


Figure 6: Integrated efficiency of the nozzle system as a function of the number of passages.

From the previous studies, a procedure to clean the beam tube in sector 3-4 was issued [6]. A summary of it is given below:

- 1<sup>st</sup> 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.

- 2<sup>nd</sup> 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.
- 3<sup>rd</sup> step, endoscopic control. Once a sector has been cleaned, quality control is ensured by a systematic endoscopic inspection. 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.
- 4<sup>th</sup> step, validation of the cleaning of the sector and release of the sector for PIM welding. In the absence of any quantitative information from the expert, a maximum of one fibre per half-cell and two debris (from super insulation or other) per magnet is tolerated.

### *Re-conditioning of the room temperature vacuum sectors*

Following the incident and the closure of the vacuum valves, the pressures in A7R3 and A7L4 *i.e.* the vacuum sector located between Q6-Q7 were at 1 mbar and  $5 \cdot 10^{-2}$  mbar respectively.

It should be stressed that one would have expected that these vacuum sectors would have been vented with pure helium. Indeed, despite air was pumped inside the beam aperture through the holes at the level of the interconnections between C24R3/Q24R3, the temperature of most of the cold masses in the arc was still below 5 K for a few hours. Therefore the arc was still pumping and only helium gas was in the vapour phase.

As shown in Figure 7, after evacuation by a turbomolecular pump, the room temperature vacuum sector previously held at 1 mbar was pump down back to its nominal pressure of about  $6 \cdot 10^{-11}$  mbar after only three days of pumping confirming the fact that these sectors were vented with pure helium (helium does not interact and does not saturate the NEG surfaces)!

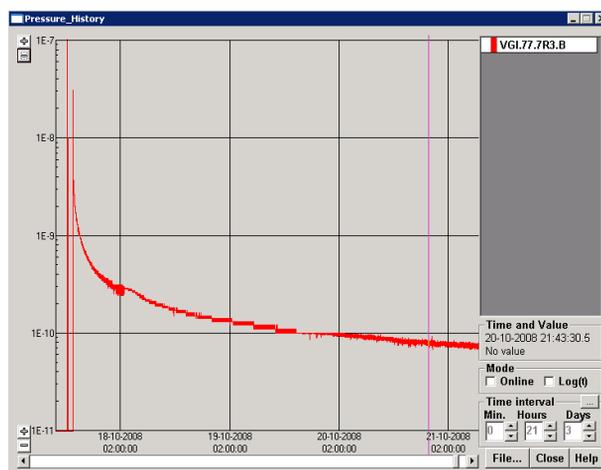


Figure 6: Recovery of the total pressure in sector A7R3.B after only three days of pump down.

## STATUS AND SCHEDULE

The room temperature vacuum sectors in A7R3 and A7L4 have been inspected and re-mounted. The vacuum sector A7L4 has been vacuum activated and is ready for operation. The vacuum sector A7R3 should be vacuum activated by week 20 when all the magnets in sector 3-4 will be reinstalled. The stand alone Q6R3 and Q6L4 were opened for endoscopic inspection. Since no traces of debris were found they were pump down.

In the arc, the amount of beam tubes to be clean is 12 sectors in the dispersion suppressor of 39 m long each, 62 sectors of half-cells of 52.8 m long each, 8 quadrupoles (7.7 m) and 21 dipoles (15.7 m).

So far, all the beam tubes from Q7L4 till Q29L4 and all beam tubes from Q7R3 till C16R3 have been subjected to automatic pumping/venting (80 % of the total). The 6 beam tubes polluted with soot have been also cleaned

Obviously, the main task is to remove the super insulation debris which are spread along  $\sim 4.1$  km. Beam tubes from Q7L4 till Q17L4 have been cleaned with the nozzle-endoscope system. Unfortunately, some super insulation debris were jammed in the RF fingers of several PIM which required the cutting of these bad PIM. After some week of training and procedure definition, a team of 3 people is able to clean almost a beam line of a half-cell per day. A team can therefore clean 2 half-cells per week. Endoscopic inspection and data documentation are performed at a rate of about a half-cell per day. So far,  $\sim 1$  km of beam tube is cleaned. A third team will be deployed in the coming days to speed up the rate of the cleaning. It is expected that the cleaning of the full sector 3-4 will be finished by end of April.

## CONCLUSIONS

The incident of sector 3-4 spoiled all the beam tubes in the arc. When access was possible in the tunnel, a systematic endoscopic inspection of the beam tubes was

launched in order to estimate the extent of the damages. After removal of the D-zone, about  $\frac{3}{4}$  of the beam tubes were polluted with super insulation debris. It was therefore decided to clean all the beam tubes left in the tunnel. A device to remove the super insulation debris was built and a procedure was defined and qualified. The rate of advancement of the work is about 2 half-cells per week and per team. Today, 25 % of the beam tube are cleaned. Fortunately, thanks to the vacuum interlock system, as shown by endoscopic inspection and vacuum performances, the vacuum sectors outside the arc 3-4 were saved from pollution. Therefore, only maintenance work is required in these areas.

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