CONSEQUENCES OF WARMING-UP A SECTOR ABOVE 80 K

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Abstract

There may be circumstances when a sector has to be partially or totally warmed-up to temperatures above 80 K, that is when thermal dilatation starts to play a role. Some equipment have been identify as presenting a risk, like the non-conform "plug-in" modules in the arcs. Because of motion induced by thermal dilatation, the electrical quality control (known as ElQA) may also have to be done again after cool-down.

The main reason identified so far for partial warm-up is the required maintenance of the cooling towers and the cryogenics plants. There is also the request from the vacuum group to periodically warm-up the beam screen to temperatures in the 100 K region to release and pump-out the gas crysorbed on the surface of the beam screen.

Observed and expected temperature conditions and statistics on failures of PIMs in sectors which have been warmed-up will be presented in this contribution. Methods to detect buckled PIMs will be described, as well as a recommended strategy for consolidation. Finally, the required electrical quality controls will also be described.

Introduction

The problem of the non-conforming "plug-in" modules (PIMs) was detected during the first warm-up of sector 7-8 in Summer 2007. Several modules were found buckled, with the RF fingers protruding into the vacuum chamber. A detailed analysis showed that the manufacturer had compensated an out-of-tolerance shape of the sliding part of the RF fingers by an abnormally large bending of the fingers in order to satisfy the requested electrical resistance. By doing so, the behaviour of the sliding fingers was changed from a stable behaviour over the complete stroke to an unstable one. The non-conformity was not reported in the manufacturing documents. These non-conforming PIMs are the main reason to worry about warming-up sectors above 80 K.

Already during the tests in SM18 a number of electrical faults, mainly degradation of insulation, were found during the first cool-down of the LHC magnets. As they were not identified during the initial tests at room temperature, their origin has been attributed to displacements induced by thermal contraction during cool-down. In the LHC tunnel, a small number of faults were also detected after the flushing of the helium circuits (mainly traced back to debris in the diode box) and during the cool-down in the tunnel (most notably the short in the interconnection cryostats in 7-8, the MCBC corrector in Q5L8 and the intermittent fault on interconnection in QQBI.22L8). The origin of these faults is again attributed to small movements generated by the thermal contraction during cool-down (or warm-up).

Expected thermally induced movements

The thermal contraction is not proportional to temperature over the full range from ambient to 1.9 K. Most of the contraction occurs between ambient and 80 K, as can be seen on figure 1 for 3 different grades of stainless steel. Indeed, only some 5 to 7 % of the total contraction occurs between 80 K and 1.9 K. For this reason, it has become common practice to consider 80 K as a limit below which thermal contraction no longer plays a significant role. Although this is certainly a valid statement for safety aspects, as well as for the PIM problem, it might not be applicable to insulation damages, where even very small movements could cause a fault, in particular if they are repetitive.

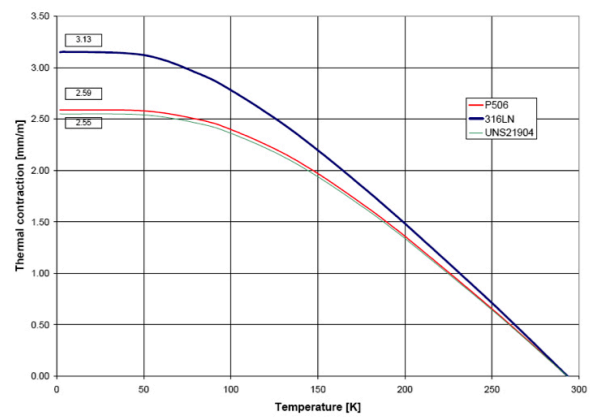

Figure 1: Thermal contraction between ambient temperature and 1.9 K

Strategy when a sector is fully warmed-up

We know that most, if not all, PIMs are non-conform and the only consolidation made so far was to systematically displace by 2 mm the SSS in order to decrease the vulnerability of the PIMs between any SSS and the downstream dipole by decreasing its span. As long as the PIMs themselves have not been consolidated, which may in fact never happen, the safest approach is to make the so-called "ball" or "sputnik" test, that is move a ball equipped with an RF transmitter from Q7 to Q7 by an air draft (see figure 2). This solution has given good results so far, with only one problem when a ball opened and lost its components in sector 1-2 (traced to a fatigue crack of the ball induced by the repeated shocks when the ball hits the end of the tested area). It recently became clear that although a higher speed of the ball reduces the time to do the test, velocities above 2 ms^{-1} could allow a ball to pass through a PIM with a single buckled RF finger. As so far there has never been a PIM found with only partially buckled fingers, the test with the ball is considered safe despite a ball diameter slightly lower than the smaller dimension of the beam screen.

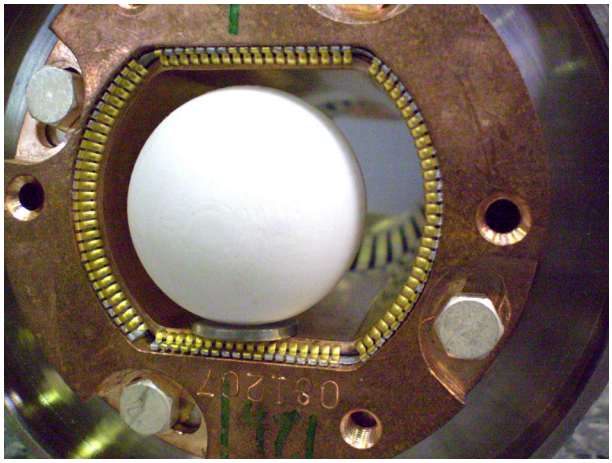

Figure 2: "Test ball" to detect buckled PIMs

Some 12 damaged PIMs were found in each of the first two sectors warmed-up before readjusting the position of the SSS. In the last two sectors warmed-up, the number of damaged PIMs was reduced to 3 per sector. Whenever a buckled PIM is found, the interconnection is opened and the modules of both beam lines are repaired. In addition, when a sector is at room temperature, the PIMs between Q7 and the first dipole at both extremities of the arcs and between Q11 and the interconnection cryostat are systematically repaired. By doing so, we should be safe during the maintenance periods of 4 to 5 weeks of the cooling and cryogenic plants. The case of the matching section during the period of maintenance periods of the cooling and cryogenic plants will be discussed below.

It still remains to be verified that a PIM which was not damaged during the first warm-up will stay safe. The statistics is very low, with only a few tens of PIMs having been warmed-up several times without buckling.

As for the electrical quality control, the baseline is to go through the full procedure at room temperature and then at cold, as during the installation. The reason behind this is that in most cases a sector is warmed-up for an intervention on magnets, hence touching the integrity of the electrical circuits. This electrical quality control must be compared to the leak detection, which is performed on any vacuum system when it is modified and must be considered as a recurrent activity.

Evolution of temperatures during partial warm-up

The maintenance of the cooling and cryogenic plants in sector 4-5 was performed as planned, which resulted in the installation being left floating for periods up to 4 or 5 weeks. The evolution of temperatures was closely followed-up in order to have a reference. The first observation was that the extremities of the continuous cryostat were warming-up at a rate of 10 K per day at temperatures below 40 K, decreasing to 5 K per day in the temperature range 60 to 80 K and 2 to 3 K per day at 110 K. Some temperature samples are shown on figure 3. The temperature in the last magnet at the extremity of the arc went up to about 120 K. But most of the magnets remained below 80 K even after 4 weeks of "floating" conditions.

The situation is quite different in the standalone cryostats of the long straight sections (LSS). There, the temperatures increase much more rapidly and already after two weeks some magnets were at 130 K. After 4 weeks, almost all magnets are above 80 K, with the highest one above 160 K. Sample measurements are shown on figure 4.

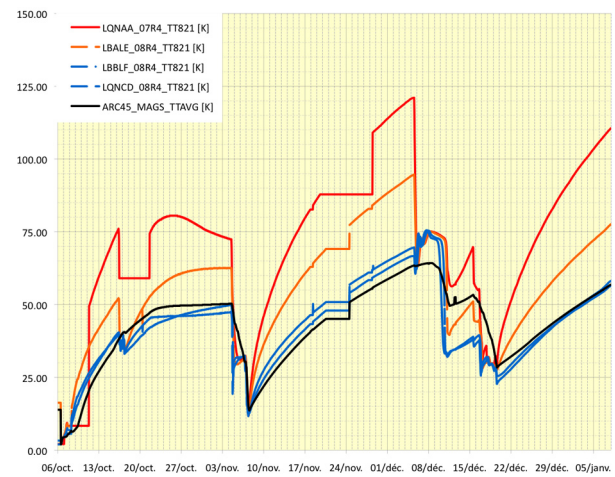

Figure 3: Evolution of temperature in the arc 4-5

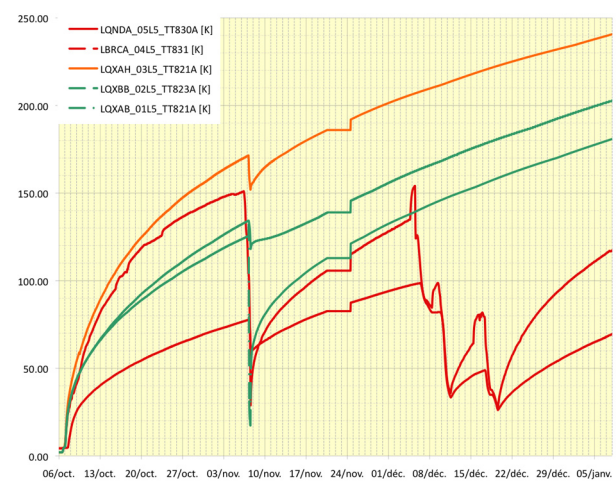

Figure 4: Evolution of temperature in the long straight section 5L

Consequence of a partial warm-up on the PIMs

Derived from the data shown in figure 1, the compression of a plug-in module is around 4 mm at 100 K and 11 mm at 150 K. Various simulations have shown that with compressions up to 8 mm from the nominal expanded position, there should be no significant permanent deformation of the RF fingers. Furthermore, the contact force between the fingers and the body, although reduced by the permanent deformation, remains above the specified value of 0.5 N per finger.

Tests on a bench produced results which differ from the simulation. The first set of tests, using a non-conform PIM recuperated from sector 7-8, required to expand the module by up to 7.5 mm beyond its nominal position before buckling could be induced when compressed. Permanent deformations of 1 to 4 mm of a small number of fingers were seen when returned to nominal position at cold after compressing the PIM by 10 mm from the nominal position. However, this test was not really representative, as the fingers were buckling in conditions significantly different from nominal. But it shows that there may be some margin before the buckling occurs when in nominal cold position. A second set of tests was done with a PIM in nominal extended (cold) position and blocking the fingers in this position before compressing by up to 10 mm, then returning the PIM to its initial position (see figure 5). Larger deformations, up to 6 mm were found, which do not agree with the calculations. A third set of tests produced results similar to the second one (see table 1). No plastic deformation could be produced for compressions from the nominal cold position by 2 mm, repeated many times. Note that these tests are made at room temperature and atmospheric pressure. They should, however, be reasonably representative for the behaviour at cold and under vacuum.

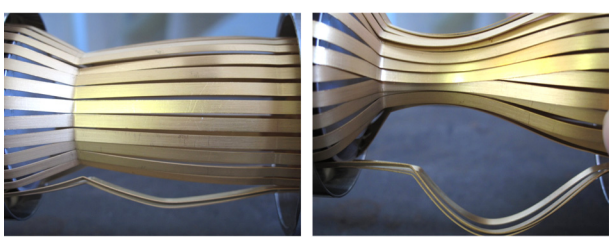

Figure 5: PIM forced to buckle on a test bench

Compression from cold position	Residual plastic deformation (test1)	Residual plastic deformation (test2)
2 mm	-	0 mm
5 mm	0.5 to 2.5 mm	0.1 to 0.7 mm
7 mm	1.2 to 3.5 mm	1.2 to 2.6 mm
10 mm	2.5 to 6.7 mm	2.2 to 6.3 mm

Table1: Plastic deformations of a non-conform PIM versus compression

Discussion

With the observed upper limit of the temperature at the extremities of arc 4-5, periods of up to 5 weeks without active cooling are acceptable. Table 2 shows the measured temperatures and the calculated compression for the first few interconnections. The largest compression is 3.6 mm between Q7R4 and the first dipole. The observed permanent deformations are compatible with beam operation, even though the experimental tests give worse results than the simulation, which could result in a potentially reduced aperture at the Q7. Nevertheless, as a systematic repair of the PIMs between the last Q7 and the first dipole at each extremity of all arcs will be done whenever an arc is warmed-up for other reasons and the situation should be safe after the shutdown 2009-2010. It has to be recalled here that this statement is based on the fact that the PIMs as designed have been validated in numerous tests before launching their production.

Magnet 1 (temperature)	Magnet 2 (temperature)	Calculated compression
Q7R4 (121 K)	MBB (95 K)	3.6 mm
MBB (95 K)	MBA (70 K)	2.3 mm
MBA (70 K)	Q8R4 (67 K)	0.1 mm
-	-	-
Q8L5 (75 K)	MBA (75 K)	0.8 mm
MBA (75 K)	MBB (75 K)	1.1 mm
MBB (75 K)	Q7L5 (95 K)	1.5 mm

Table 2: Measured temperatures and calculated compression of PIMs

The situation is less comfortable in the long straight sections, where the temperatures raise well above 150 K within a couple of weeks. The vulnerability of the PIMs in the long straight sections is lower because of a shorter span and, so far, we never had buckling in this area. But the PIMs are non-conform also in the LSS area. The proposal there is to systematically repair the PIMs whenever possible in the triplets, the D2Q4 doublets, as well as the Q5D4 and D3LU doublets in IP4. In order to respect the best ALARA practice, this consolidation should be done during the present (2008-2009) shutdown, at least in the triplets which will be more rapidly activated by the beam. If time or resources don't allow this systematic approach, the minimum is to do endoscopic inspection (requiring to warm-up to room temperature and in some cases to vent the adjacent vacuum sector), up and until the X-ray tomography instrument becomes available (August or September 2009). This equipment will then allow to inspect the PIMs (and other components in the interconnect) from the outside, under vacuum and at cold. The cold to warm transitions are not a problem as the RF fingers are in the room temperature part. There is one exception, however, the cold to warm transition at the extremity of Q1 towards the experiment which uses a PIM. But there should be not significant risk in this location as the span is much lower than elsewhere.

Consequences of a partial warm-up on the electrical quality control

At the temperatures reached at the extremities of the arc after an interruption of the cooling for 4 to 5 weeks, the induced expansion of any item will remain below 20% of its dimension. This relatively small displacement should not induce any damage on components built as designed. But a potential case could be an insulation

touching and rubbing on a not so smooth surface. Unlike a full warm-up followed by a cool-down in a shutdown, one can imagine several cycles of 4 to 5 weeks of floating followed by a cool-down to 30 or 40 K, hence increasing a potential damage to the insulation. Once more experience is gained with PIMs that have been fully warmed-up at least two times without buckling, one can also imagine letting the extremities drift to higher temperatures in order to stop the cryogenic plants and minimise the number of operators during shutdown periods. Based on this, it seems reasonable to systematically perform the ELQA-TP4 procedure (at least the HV test) before repowering the circuits. The time to do this is estimated to 2 weeks per sector, with some possible parallelism depending on the available test equipment. It requires the temperature in the magnets to be below the lambda point (2.1 K).

As the temperatures in the long straight sections drift much faster, hence inducing larger movements, the same systematic ELQA-TP4 test must also be done before repowering.

Summary and recommendations

The behaviour of the PIMs is better understood and the findings in the last two sectors which were warmed-up confirm that the most vulnerable module is the on between an SSS and the downstream magnet, even after the SSS have been displaced by 2 mm towards the dipole. Whenever a module is found damaged, the modules on both beam lines are repaired. In addition, the PIMs between the Q7 and the adjacent dipole, as well as the ones between the interconnecting cryostat and Q11 will be systematically exchanged when a sector is at room temperature. By doing so, leaving a sector floating over periods of 5 or more weeks should no longer be a problem. In the LSS, the proposal is to repair as soon as possible all PIMs. Until this is completed, endoscopic inspection is required until the X-ray tomography equipment is available.

As for the electrical quality control, the full procedure has to be applied whenever a sector is completely warmed-up. After a partial warm-up, the minimum is to perform the HV test at cold (below 2.1 K).

Acknowledgments

I wish to warmly thank all persons who contributed to this work, in particular D. Bozzini, N. Catalan, D. Duarte, B. Jenninger, S. Russenschuck, A. Siemko, J.-P. Tock, R. Veness, U. Wagner and L. Williams.