APERTURE RESTRICTION LOCALISATION IN THE LHC ARCS USING AN RF MOLE AND THE LHC BEAM POSITION MEASUREMENT SYSTEM

J. Albertone, S. Bartolome-Jimenez, C. Boccard, T. Bogey, E. Calvo, F. Caspers, M. Gasior, J.L. Gonzalez, B. Jenninger, L.K. Jensen, O.R. Jones, T. Kroyer, S. Weisz , CERN, Geneva, Switzerland
P. Borowiec, HNINP, Kraków, Poland

Abstract

Ensuring that the two 27km beam pipes of the LHC do not contain aperture restrictions is of utmost importance. Most of the ring is composed of continuous cryostats, so any intervention to remove aperture restrictions when the machine is at its operating temperature of 1.9K will require a substantial amount of time. On warming-up the first cooled sector, several of the sliding contacts which provide electrical continuity for the beam image current between successive sections of the vacuum chamber were found to have buckled into the beam pipe. This led to a search for a technique to verify the integrity of a complete LHC arc (~3km) before any subsequent cool-down.

In this paper the successful results from using a polycarbonate ball fitted with a 40MHz RF transmitter are presented. Propulsion of the ball is achieved by sucking filtered air through the entire arc, while its progress is traced every 54m via the LHC beam position measurement system which is auto-triggered by the RF transmitter on passage of the ball. Reflectometry at frequencies in the 4-8 GHz range can cover the gaps between beam position monitors and could therefore be used to localise a ball blocked by an obstacle.

INTRODUCTION

After the cool-down and warm-up of the first LHC sector it was found that several of the Plug-In Modules (PIMs) housing the sliding contacts which provide electrical continuity for the image current between successive sections of the vacuum chamber had buckled into the beam pipe (see Fig 1). This led to a search for a technique to verify the integrity of a complete LHC arc before any subsequent cool-down. X-ray films were initially used to locate the damaged interconnections, but this required the laborious removal of all outer sleeves to provide images of sufficient quality. It was then proposed to propel a ball equipped with an RF transmitter along the whole of the arc and to detect where it stopped, allowing only faulty interconnections to be opened. This idea hinged on the fact that the LHC beam position monitoring (BPM) system was auto-triggered and would therefore respond to signals induced on their electrodes. A radio frequency ball, the so-called “RF mole”, was therefore invented to allow such measurements to be performed.

INITIAL PROTOTYPING

Fast prototyping was required to test the RF mole idea in order to find a rapid solution for the localisation of the damaged PIMs in the first sector to be warmed-up at the LHC. A ball that could roll inside the beam screen aperture of 46.5mm by 36.9mm was thus required, made of a material transparent to radio frequencies (see Fig. 1). 3D drawings were produced in IGS format of two hemispheres that clip together to form a sphere with an outer/inner diameter of 34/30mm. The drawings were sent to a company capable of handling both Fused Deposition Modelling (FDM) and stereo-lithography techniques with a turn around time of only 2 days.

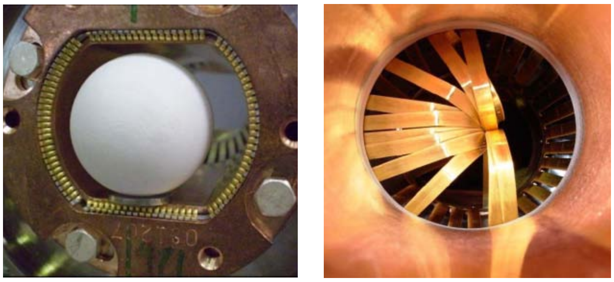

Figure 1: The RF ball inside the beam screen aperture and a Plug-In-Module (PIM) with buckled RF fingers

Two types of ball were tested: a polycarbonate ball obtained by FDM and an Epoxy ball obtained by stereo-lithography. Both were mechanically adequate (precision and surface smoothness), but only the polycarbonate solution was retained due to its high impact resistance and the fact that it was guaranteed chloride and fluoride free. The presence of either of these materials would pollute the vacuum chamber if small plastic scraps were left inside due to shocks received during passage of the ball.

A series of tests were performed inside a spare dipole magnet with the aim of optimising the air flow parameters required to propel the ball inside the vacuum chamber. The setup was very simple: a pump on one side equipped with a variable throttle valve to adjust the air flow sucked into the vacuum pipe, with the ball inserted on the other side. A wire attached to a spring scale was connected to the ball to allow the pulling force to be measured. A “BPM assembly” that has a larger aperture than the beam screen could also be inserted into the set-up, while a defective PIM with 2 buckled RF fingers was used to check that the ball was indeed stopped by this obstacle. The air flow itself was measured with a hot wire anemometer. The results from these tests are summarised in Table 1.

These results are compatible with $F = 0.3\cdot v^2$, where F is the force in g and v the velocity in ms^{-1}. The following issues were raised during these tests:

- The air flow inside the BPM assembly with a larger beam pipe cross section was found to be 30% lower than inside the beam screen.
- There was a risk that the ball passed through a damaged PIM with only 2 buckled RF fingers when the air flow was above 10ms^{-1}.
- There was a risk that air circulation around the ball could split the two hemispheres apart due to the corresponding Bernoulli forces.

Because of this last point it was decided to use a cyanoacrylate glue to bond the two hemispheres together to avoid a catastrophic break-up of the ball during its passage.

Table 1: Measured drag force versus air velocity

Air Flow ± .5 (ms^{-1})	3.5	6	8	9	10	11	13
Drag Force ± 1 (g)	4	10	18	23	32	34	41

THE RF BALL ELECTRONICS

The RF mole was designed in such a way as to be able to auto-trigger the LHC BPM system on its passage. The BPM system has an optimum response at around 40MHz and requires at least 3mV at this frequency on the BPM electrodes in order to activate the auto-trigger circuitry. The capacitive coupling between the copper electrodes of the ball and BPM was measured to be some -50dB. This implied that the 40MHz generator within the ball needed to generate voltages of at least 1V on the ball electrodes in order to trigger the BPM system on its passage. Coupled to this electronic requirement were two additional constraints:

- The ball needed to be lightweight, weighing less than 20g, in order to be efficiently propelled by the pumping system while still being stopped by a PIM with only a single buckled RF finger.
- The ball needed to have autonomy of several hours to allow the testing and localisation to be comfortably performed for a complete arc.

Taking all these factors into consideration the final design of the RF mole consists of a ball made up of two polycarbonate half shells equipped with two copper foil electrodes, covering most of the internal surface (see Fig. 2). The electrodes are driven by a 40MHz generator powered from a 3V lithium battery (∅ 20 mm × 1.6 mm, 2g). A high efficiency DC-DC converter is used to lower and stabilize the supply voltage to 2.4V for smaller current consumption. The converter also ensures that the generator remains operational even with the battery depleted down to 0.6V. Production of a 20V$_{\text{peak-peak}}$ signal at the electrodes with minimal power consumption is achieved by making the capacitance of the ball electrodes part of a resonant circuit, driven by a low voltage generator through a step-up transformer. The generator consists of a miniature quartz oscillator followed by three CMOS gates operated in parallel to minimize their overall on-resistance for efficient drive of the loaded transformer. In addition an auxiliary generator limits the duty cycle to a few thousand periods every 2ms. During the off-time the ball advances by some 4mm at its nominal speed of 2ms^{-1}, which is still only a fraction of the 24mm diameter of the BPM electrodes.

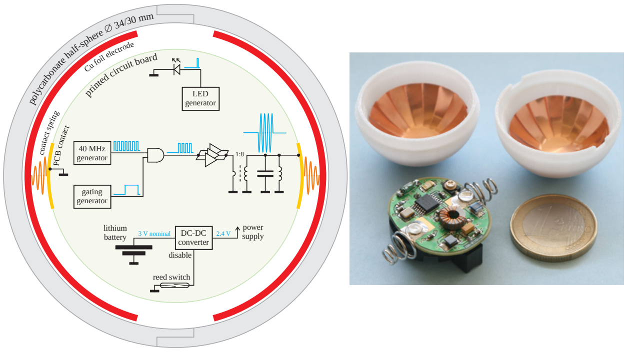

Figure 2: Schematic and exploded picture of the RF ball electronics.

The first tests were performed by switching on the ball and then gluing the half shells together in the tunnel. This only allowed the ball to be used once. For the later "production" tests, for which many balls were required, the lifetime of each ball was extended by providing the possibility to turn off the ball circuitry by applying an external magnetic field when the ball is not in use. This was achieved by equipping the ball circuit with a miniature reed switch. When the switch is actuated by placing the ball on top of a small permanent magnet, most of its circuitry is turned off, allowing the ball to stay in this stand-by mode for several months before significantly discharging the battery. This allowed the balls to be prepared in the laboratory and subsequently stored in this stand-by mode whenever not actively used for testing in the LHC tunnel.

The final ball electronics contains 5 integrated chips accommodated on both sides of a round printed circuit board of about the same size as the battery. The weight of the circuit with the battery constitutes about half of the 15g total weight of the ball. When equipped with a fresh battery, a ball can operate for ~50 hours, which is good for some 350km of travel at a nominal speed of 2ms^{-1}.

RESULTS

The continuous string of cryomagnets in an LHC sector (Arc & Dispersion Suppressors) is ~2800m long. A system of pumps and valves were installed on the beam pipe at the positions of the cold-warm transitions on either side, with a 10μm grid filter used to retain any dust sucked in with the air from the tunnel. The valves allowed the direction of the air flow to be chosen, with the possibility of reversing the flow to recuperate a ball blocked by a damaged PIM. Both the pressure and air speed were measured at each end. In order to start a test the ball was inserted at one end before connection of the pump. Once the pumps were installed on both ends, the pump at the other extremity to where the ball was inserted

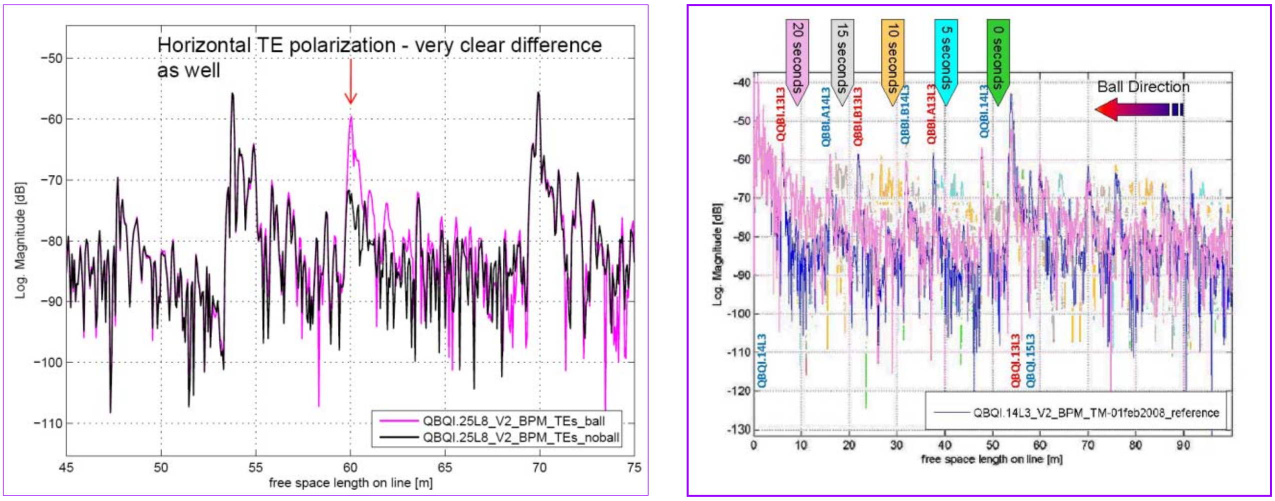

Figure 3: Results from static (left) and dynamic (right) microwave reflectometry measurements

was switched on, and the pressure allowed to drop by some 100mbar inside the beam pipe. The valve to allow filtered air into the beam pipe was then opened on the ball side, creating a rush of air to start the ball rolling. A steady state was rapidly attained, with a pressure drop of 200mbar between the two extremities, an air flow in the beam screen of $4ms^{-1}$ and a ball speed varying between 1.5 ms^{-1} and $2ms^{-1}$. This pressure drop and air speed is fully consistent with that expected inside a 2800m long pipe of beam screen dimensions, indicating that the air flow remains to a large extent inside the beam screen and that the pumping slots covering the length of the beam screen do not substantially modify the flow. The speed of the ball is reduced as the aperture increases, which occurs both in the PIM and in the BPM assembly. This effect, coupled with the fact that the BPM assembly is asymmetric meant that the ball had a preferred direction of motion and was liable to stop at the BPM assembly when this was not respected.

As the ball passed by each beam position monitor, located every 54m throughout the arc, the BPM system would register a trigger and so indicate passage of the ball. If the ball was stopped by an obstacle in the beam pipe, the triggers would cease, and the last BPM to trigger would indicate the location of the ball to the nearest 54m. Since all damaged PIMs to date have been found on quadrupole to dipole interconnections, this localisation has so far been sufficient to open and repair these aperture restrictions. Better localisation requires the use of microwave reflectometry.

Microwave reflectometry in the 4-6GHz range has been successfully used during LHC construction to localise to better than a metre any metallic objects left in the beam pipe [1]. It was indeed this technique that found the first damaged PIM module in the first LHC sector to be warmed–up. Once the arc is fully interconnected it is no longer possible to insert the dedicated microwave launcher used for these measurements. By substituting a BPM for this launcher, however, it is still possible to probe ±75m each side of the BPM location. Since the BPM electrodes radiate in both directions, the asymmetry of the installation has to be used to make sense of the observed reflections. In addition, due to the large variations in interconnection impedances when the machine is warm, difference measurements have to be used to locate the ball. Fig. 3 shows such a measurement, where the RF ball location is clearly visible when compared to the reference taken without the ball.

In addition to static measurements, dynamic microwave reflectometry has also been attempted, using a passive metallic ball for increased reflection instead of the RF ball. Fig. 3 also shows the result from this technique. The measurement was performed every 5 seconds and compared to the reference trace. The movement of the ball at ~$2ms^{-1}$ is clearly visible at distances of up to ±50m from the BPM acting as the microwave launcher. The use of a passive, metallic ball would make such a measurement possible even when the arc is cold, where use of the standard RF mole is excluded due to the necessity for a small, robust cryogenic battery.

CONCLUSIONS

The RF mole has been extensively used to verify the continuity of the continuous LHC cryostat both before cool-down and after warm-up. All sectors have now undergone such a test, which has not only qualified the arc aperture at warm, but has also allowed a large part of the LHC BPM system to be tested in parallel. In the sectors which have already been cooled-down and warmed-up, the use of this technique has greatly speeded up the repair of faulty PIM units by only requiring affected interconnects to be opened.

REFERENCES

[1] P. Borowiec, F. Caspers, T. Kroyer, Z. Sulek, and L.R. Williams, "The LHC Beampipe Waveguide Mode Reflectometer", PAC'08, Albuquerque, June 2007, p 1583 (2007).