MOBILE CT-SYSTEM FOR IN-SITU INSPECTION IN THE LHC AT CERN

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Abstract

At the European Organisation for Nuclear Research (CERN) the worlds largest particle accelerator ring, the Large Hadron collider (LHC), is being put into operation. It has been found useful to have a tool for diagnosis of the state of components in the interconnection regions of the LHC.

This tool, for non-destructive testing (NDT) must work without opening the interconnection elements, without breaking the integrity of the vacuum, and without the need to warm up the sector which would be costly and time consuming. In addition the NDT tool has to be transportable in order to position it anywhere around the 27 km long LHC ring.

The approach is an X-Ray inspection with the aim of an unambiguous representation of all structural elements in the interconnection regions of the LHC ring. The minimum criterion is to achieve an inspection result which allows verification of the correct position and integrity of all important components.

3D X-Ray computed tomography (3D CT) would be the ideal solution for such an inspection task. But due to the constraints in the LHC tunnel, especially the very limited space behind the LHC ring it is not possible to move an X-Ray source and a digital X-Ray detector completely around the interconnections. Therefore it was necessary to develop a mobile 3D X-Ray system which allows for a maximum scanning versatility within the given constraints and provide 3D results based on limited scan angles.

Such a mobile X-Ray system is presented in this paper as well as results from the inspections of the LHC ring interconnections.

In addition it will be outlined how the approach used in this system could be applied to other applications.

CERN

The European Organisation for Nuclear Research (CERN) is financed by 20 European Member States and offers particle accelerator installations for fundamental particle physics research. Accelerators boost beams of charged particles to high energies, before they are made to collide within detectors located at the points of collision. Collisions between fundamental particles, sub-atomic in size, but invested with enormous energy, momentarily create the environment within which particle physicists may study the properties of our universe that may have existed only small fractions of a second after its creation.

LHC

The Large Hadron Collider (LHC) [1] is the largest and most recent world-class facility for high energy physics to be added to the already existing CERN accelerator complex.
It is installed about 100 m below the surface of the Geneva Basin for the most part in a circular tunnel of nominal cross-sectional diameter 3.8 m and circumference 26.65 km (Figure 1).

Figure 1: The LHC Accelerator in its Underground Tunnel

Four distinct detectors, each installed in a large underground cavern, are located symmetrically around the LHC at the particle beam crossing points.
The LHC has been designed with 2 distinct beam tubes, to allow 2 counter rotating beams of protons or ions (one in each tube) at energies up to 7 TeV, to be brought into collision within the detectors, at a centre of mass energy up to 14 TeV and at a nominal peak luminosity of 10^{34} $cm^{-2}s^{-1}$.
In order, at reasonable operating costs, to achieve the high magnetic fields needed to steer and focus particle beams of this energy in the confines of the underground tunnel, superconducting magnets all operating in a bath of superfluid helium refrigerated to 1.9 K must be used.
Among more than 7500 superconducting magnets comprising the LHC, 1232 main-ring dipoles, each about 15 m long and 438 main-ring quadrupoles each about 8 m long have been installed and interconnected in the 8 arc regions occupying about 22.5 km of the accelerator circumference.

The Interconnect Zones

Each main-ring dipole and main-ring quadrupole is connected to its neighbours across a volume known as the interconnect zone. A schematic view of the various tubes containing cryogenic and electrical services as well as the thermal insulation vacuum and beam vacuum connecting one dipole magnet to the next across the interconnect zone is shown in Figure 2.

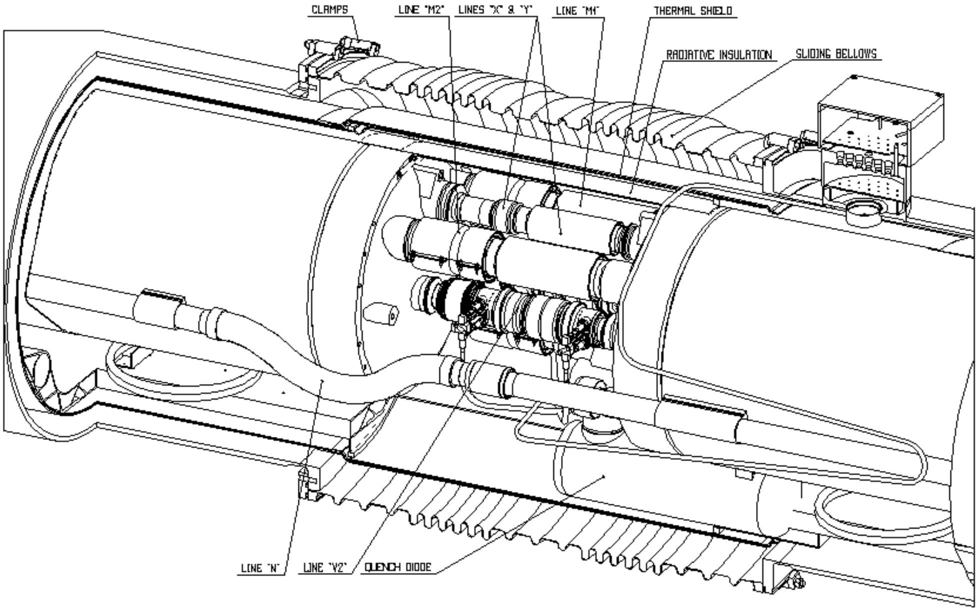


Figure 2: Schematic View of an Open Dipole-dipole Interconnect Zone of the LHC

Each interconnect zone between 2 adjacent superconducting magnets (Figure 3) has been completed using state-of-the-art industrial techniques.

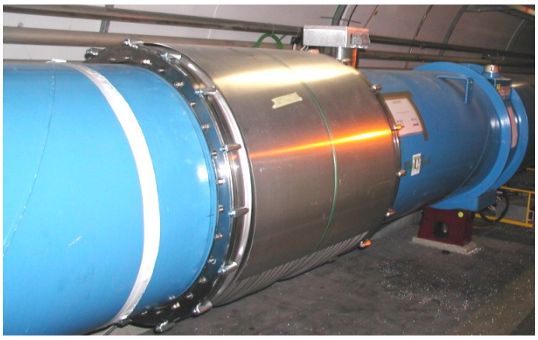


Figure 3: A Completed and Closed Interconnect Zone Between Two Dipole Magnets of the LHC

In the LHC arcs, more than 40’000 fusion welds on stainless steel piping and more than 60’000 junctions between superconducting cables have been made to ensure the continuity of cryogenics, electrical and vacuum services from magnet to magnet and ultimately around the entire machine. All the main ring magnets in an LHC arc are grouped and electrically connected in series to power sources supplying currents up to 13 kA.

The operational reliability of the completed machine depends directly on the diligence of the teams that carried out the interconnect assembly work according to specific procedures and heavily on the strict quality assurance program that was applied to ensure that this quality was rigorously and continuously maintained.

Nevertheless, even having followed stringent industrial quality control procedures during the design, the construction in industry and the assembly and commissioning at CERN of this complex machine, it is now recognised that in certain specific areas, reliability would have benefited from the huge experience gained the first time round. However, the LHC remains the only installation of its kind, with some known weaknesses inherent to a prototype, that need to be monitored.

Within the interconnect zones between the main ring superconducting magnets, (Figure 4) three areas of interest have been identified as needing periodic non-invasive inspection to ensure operational reliability.

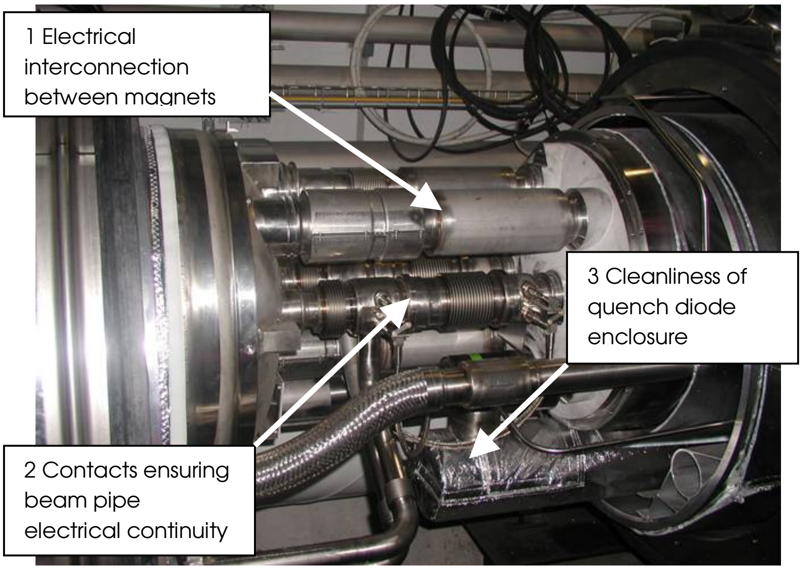


Figure 4: An Open Interconnect Zone Between Superconducting Magnets and the 3 Areas of Interest Requiring Periodic Non-invasive Inspection

Electrical Interconnection between Magnets

In each interconnect zone there are 6 electrical interconnections between magnets.
Each cable joint or splice is made inside a specifically designed cable junction box as shown in Figure 5 which allows the 2 cables together with 3 strips of tin/silver soldering alloy to be reliably and accurately superimposed and held firm while the soldering process is carried out.

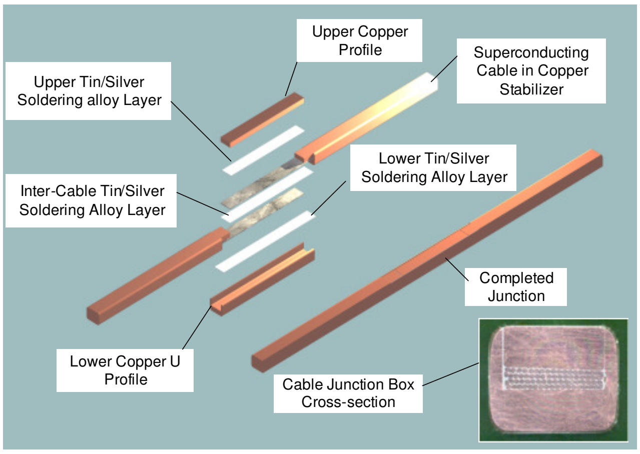
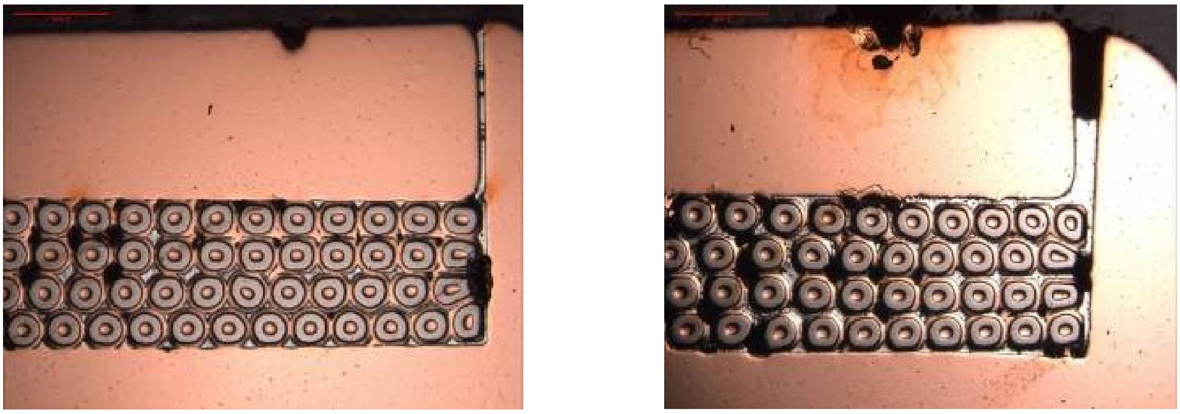


Figure 5: The Cable Junction Box

Whilst subjected to a controlled vertical compressive force ensuring intimate contact between all the component parts, the assembled junction is rapidly heated inductively to a fixed temperature where the added soldering alloy fuses with the residual layer binding the cable strands. The tight tolerances on the component parts of the box allow the molten soldering alloy to be retained inside by capillary action until the junction has cooled to below its solidification temperature. The heating power input, the compressive force and the temperature profile of the junction, are controlled and recorded over time and only if all post soldering data is normal is the junction accepted by the inductive soldering machine as part of the standard Quality Control procedures. Key soldering parameters are interlocked and any excursion outside their normal envelope leads to automatic interruption of the soldering process and an alarm to be issued. The mechanical strength of a soldered junction may however be seriously undermined where it suffers from an absence or insufficiency of the alloy to be added during the soldering process. Although tight controls systematically regulate the soldering process, the absence, (omitted through operator error) or insufficiency, of tin/silver alloy in the junction is nowhere reliably detected. The images in Fig 6 show macrographic cross sections of (a) a cable junction box containing adequate alloy and (b) a junction box either severely deformed or containing inadequate alloy, where gaps between the junction box components have not been completely filled by capillary action.

It is the possible omission of added alloy, leading to the undetected generation of mechanically weak or electrically unsound soldered junctions that has motivated the use of X-Ray Tomography as a supplementary quality control method.



(a)good (b) bad

Figure 6: Macrographic Cross Section of a Cable Junction Box

Contacts Ensuring Beam-pipe Electrical Continuity

It is of vital importance that the electrical continuity of the beam pipes in which circulate the particle beams is maintained across all the interconnect zones as electrical discontinuities lead eventually to instabilities in the circulating charged particle beams. During interconnection two elements called Plug-in Modules (PIM) (Figure 7) are inserted, one in each beam tube. To bridge from one magnet to the next and ensure the beam-pipe electrical continuity, these PIM are furnished with a complete ring of gold-coated RF contact fingers.

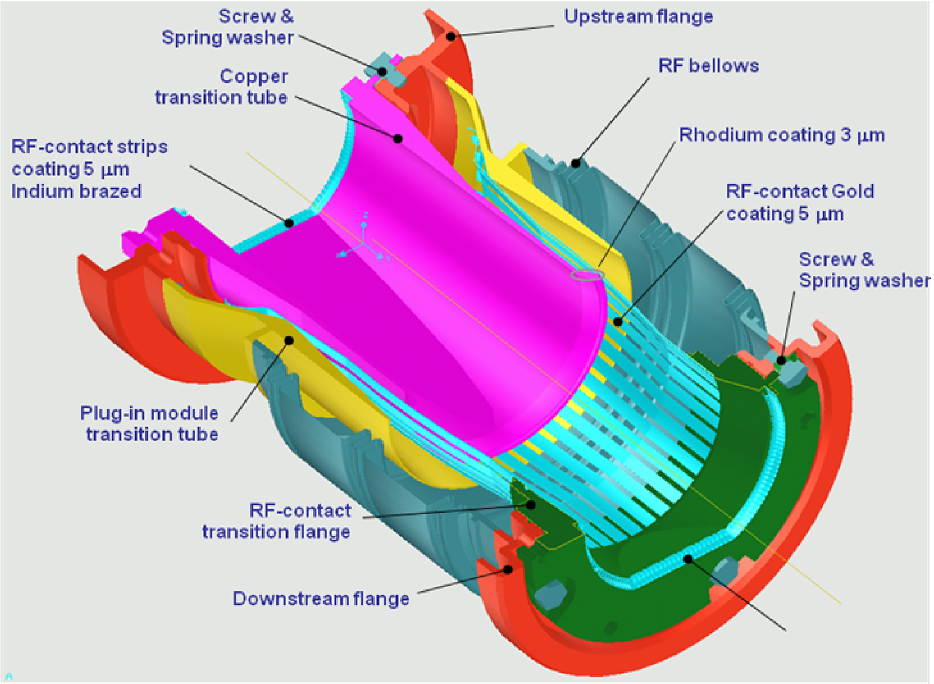


Figure 7: The Plug-in Module with its Gold-coated RF Contact Fingers

The plug-in module, just as all other components bridging each interconnect zone, has been designed to accommodate thermal contractions of the order of 50 mm, due to refrigeration from room temperature to 1.9 K and occasionally, expansions due to warming from 1.9 K to room temperature of the LHC main ring magnets.

The PIM lengthens during magnet cooling, and the elastic contact fingers are loaded as they slide under tension. During warm-up the reverse occurs, the PIM shortens, and the sliding contact fingers are then loaded in compression leading to a potential buckling failure mode.

It has been identified that a combination of incorrect as-manufactured shape of the contact fingers, combined with an out of tolerance distance of a few millimetres between the magnets may occasionally cause the contact fingers to buckle and obstruct the particle beam pipe if the interconnect zone is warmed from operating temperature to above about 60 K.
If such a partial warm-up of part of the accelerator is required then the X-ray tomograph may be used in the interconnect zones to obtain non-invasive pictures of the warmed PIMs to verify their integrity.

The Cleanliness of the Quench Diode Enclosure

The main-ring LHC magnets were all manufactured in industry, where, within industrial limits, all possible precautions were taken to ensure cleanliness throughout their production.
Underneath the left-hand end of each superconducting main ring magnet is an enclosure (see Figures 2 and 4) containing diodes and associated conductors which allow the electrical supply to be diverted around the magnet if it should transit from it's superconducting to a normally resistive state.

To cool these magnets initially from ambient temperature, they are ventilated from end to end with a high speed flow of cold helium gas.

Any debris that, despite the precautions taken, may remain inside the magnet from the manufacturing processes will tend to be displaced during initial cooling to the diode end and may accumulate there at the lowest point, in the diode enclosure. On rare occasions this accumulated debris, sometimes metallic, has reduced the insulation resistance of the diodes to ground.

In case of doubt concerning its electrical integrity, the X-ray tomograph will allow pictures of the contents of the diode enclosure in particular where debris is known to accumulate, to be obtained non-invasively.

The X-Ray Tomograph RayScan Mobile

Ordered by CERN, RayScan Technologies GmbH has designed a mobile X-Ray Computed Tomography System (CT) to carry out the inspection tasks described above within the tight space constraints imposed by the LHC tunnel. The RayScan Mobile is shown in figure 8 in its operational position at an interconnect zone between two main-ring magnets of the LHC.

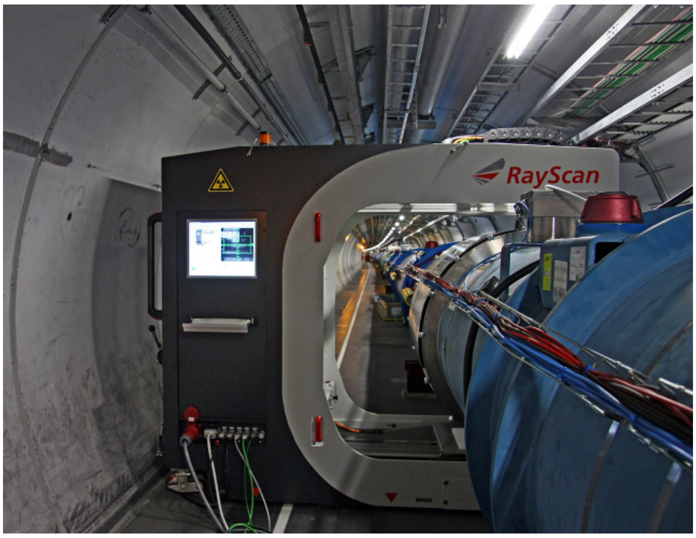


Figure 8: The X-ray Tomograph RayScan Mobile in Operation at the LHC

Radiation Safety Concept

For the purpose of radiation safety a controlled area is first set up around the interconnect zone to be inspected. This zone is delimited by means of light curtains positioned in a distance of 100 meters in front of and behind of the RayScan Mobile. These light curtains, if disturbed, are interlocked to shut down the X-ray source. The system is operated from a remote access station positioned just outside the controlled area.

Details of RayScan Mobile

The RayScan Mobile is designed to be pulled through the LHC tunnel by means of an electric tow-vehicle commonly used at CERN. To permit this, and its final manual positioning around the interconnect zone of interest the outer dimensions have had to be kept as small as possible, leading to limitations of overall width (1.0 m) and overall height (2.3 m).

These dimensional restrictions made it necessary to modify the HV-cable and the housing of the flat panel detector. In addition the axis drive motors as well as generator and cooling unit of the x-ray source had to be specifically re-designed.

The free space behind and below the interconnect zones of LHC-ring is extremely limited and it has not been possible therefore to apply a conventional 3D-CT concept [2, 3]. Instead, we have based the system on former achievements of the RayScan team, which have already been shown to work successfully in the automotive and aeronautic industries [4, 5].

Finally we developed a system and an algorithm for 3D-volume of interest-CT with very limited angular access. The image reconstruction is based on a "filtered shift and add" algorithm. Due to the very limited access, leading to extremely asymmetric sets of projections, it has been necessary to adapt and implement a new scan method with a new reconstruction algorithm which takes into account all available information. The reconstruction is optimized on a multiple core PC such that the reconstruction process may proceed in parallel with the scanning.

The system, the RayScan Mobile, is equipped with a 225 kV minifocus X-Ray-source and a 400 mm by 400 mm flat panel detector with 2048 by 2048 pixels, each of size 200 µm. Source and detector are both mounted on a 4 axis-manipulator system providing for translation and rotational movement. The maximum total translation of the source is 1.8 m whereas the detector translation is limited to 1.2 m. Both components can be rotated up to plus or minus 45°. So the kinematics of the system allows 3D-volume of interest-CT to be applied with virtual centres of rotation located at the components to be inspected in the interconnect zones.

In addition to the 3D scan, the RayScan Mobile also provides a Real-Time Radioscopy Mode. This is used to conduct an initial rapid inspection to obtain an immediate preliminary impression of the overall status of the interconnect zone and its components.

The Radioscopic Mode also serves as an online guidance for the definition and selection of the volume of interest to be inspected by 3D-volume of interest-CT.

Results

We have inspected the 3 specified areas of interest in a typical interconnect zone of the LHC under vacuum and cooled to operating conditions. The integrity of the components of interest in this zone could be clearly visualized.
The correct position and shape of all the gold-coated RF contact fingers inside the plug-in module was clearly determined as shown in Figure 9.

Figure 9: Plug-in Module, Sectional 3D display (left) and 2D-Cut Through 3D Volume (right)

In the left image, some of the RF contact fingers are displayed. The right image in figure 9 represents a virtual cross section of the PIM (taken along the red line of left image). From this information it can be clearly determined that all the contact fingers (see figure 7) which are within the scanned partial volume are perfectly located around a pitch circle.

Some of the results of the 3D inspection of the 6 electrical interconnections between magnets are shown in figure 10 and figure 11.

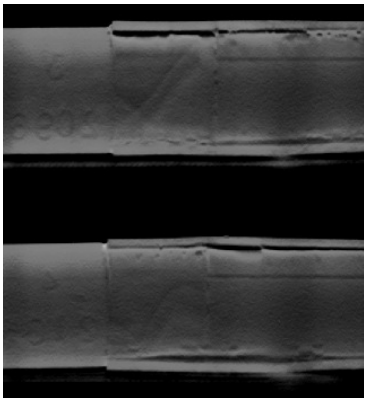


Fig. 10: 2D Layer Coplanar with Copper Surface of Cable Junction

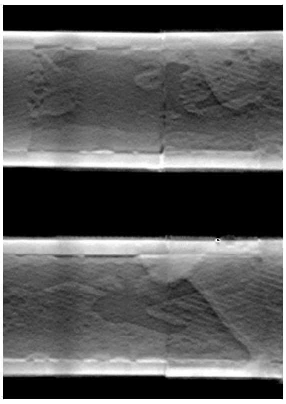


Fig.11: 2D Layer Coplanar with Superconducting Cables

Figure 10 shows a 2D layer from the reconstructed 3D volume. This layer is coplanar with the top surface of the upper copper profile of the cable junction box (see figure 5). We see the left hand end of the upper surface of the cable junction box where a minor defect in the soldering process has generated local unfilled longitudinal gaps between the cable junction box components.

Figure 11 also shows a 2D layer from the reconstructed 3D volume located at the left-hand end of the cable junction box but this layer is situated a few millimetres lower, at the interface between the two superconducting cables that have been soldered together (see figure 5). We see therefore the twist-pitch of the super-conducting cable and some minor imperfections in the horizontal solder filling between these cables.

In order to prove the ability of RayScan Mobile to detect defective components, a full-size mock-up representative in all respects of an interconnect zone has been built and defective components have been installed. All the defects introduced in this way have been detected.

Figure 12: Radioscopy of the Diode Enclosure from the Full-size Mock-up with Particle Debris (markings)

Figure 12 shows the Radioscopic image of an LHC quench diode enclosure installed in the mock-up and containing particles which in exceptional circumstances could cause short circuits to ground. A small pile of metallic debris, a ball and a small cylinder (each of diameter 4 mm) are clearly visible (see markings in Figure 12).

Conclusions

As a diagnostic tool, the X-ray tomograph RayScan Mobile has shown its worth, and it will take its place in the LHC maintenance tool-kit alongside a battery of equipment for making complementary assessments.

It is particularly useful however, as it is the only diagnostic tool at the disposal of the LHC maintenance teams that allows pictures and images of some internal components of the LHC accelerator to be obtained when it is closed, under vacuum, cooled to operating temperature and ready to run.

Literature

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