

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

L.R. Williams, F. Caspers, J.M. Dalin, J.P. Tock, CERN, Geneva, Switzerland
 C. Sauerwein, V. Haemmerle, I. Tiseanu, RayScan Technologies GmbH, Meersburg, Germany

Abstract

For the inspection of certain critical elements of the LHC machine a mobile computed tomography system has been developed and built. This instrument has to satisfy stringent space, volume and weight requirements in order to be transportable and usable to any interconnection location in the LHC tunnel. Particular regions of interest in the interconnection zones between adjacent magnets are the plug in modules (PIM), the soldered splices in the superconducting bus-bars and the interior of the quench diode container. This system permits detailed inspection of these regions without needing to break the insulation vacuum. Limited access for the x-ray tube and the detector required the development of a special type of partial tomography, together with suitable reconstruction techniques for 3 D volume generation from radiographic projections. The layout of the complete machine, the limited angle tomography, as well as a number of radiographic and tomographic inspection results is presented.

INTRODUCTION

The LHC comprises more than 7500 superconducting magnets. Among these, 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. Each main-ring dipole and main-ring quadrupole is connected to its neighbours across a volume known as the interconnect zone.

THE INTERCONNECT ZONES

Within the interconnect zones between the main ring superconducting magnets, three areas of interest have been identified as requiring non-invasive inspection to ensure operational reliability (Figure 1).

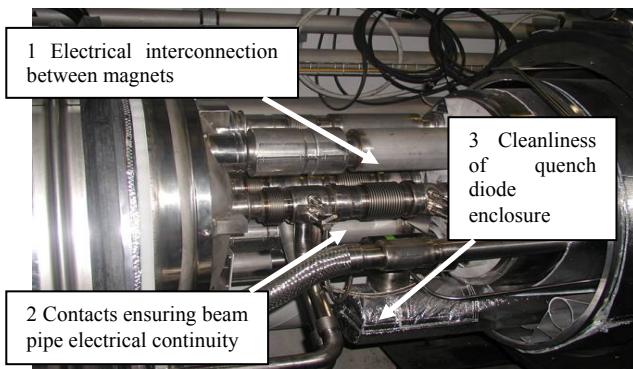


Figure 1: An open interconnect zone between superconducting magnets and the 3 areas of interest requiring periodic non-invasive inspection.

Electrical Interconnection between Magnets

In each interconnect zone there are 6 high current electrical interconnections between magnets. Each cable joint or splice has been made inside a specifically designed cable junction box 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.

Although tight controls have systematically regulated the soldering process, the absence, or insufficiency, of tin/silver alloy in the junction was nowhere reliably detected. The images in Fig 2 show macrographic cross sections of (a) a cable junction box containing adequate alloy and (b) a junction box either severely defomed 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.

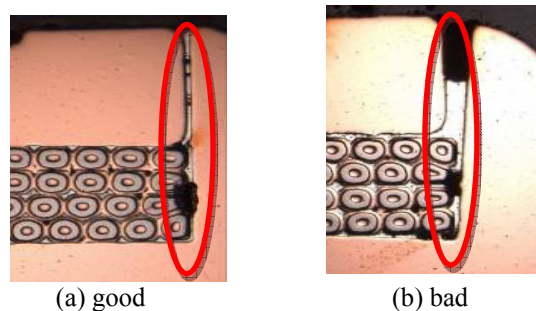


Figure 2: Macrographic Cross Section of Samples of a Cable Junction Box.

Contacts Ensuring Beam-Pipe Electrical Continuity

It is of vital importance that the electrical continuity of the beam pipes in which the particle beams circulate, 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 3) 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.

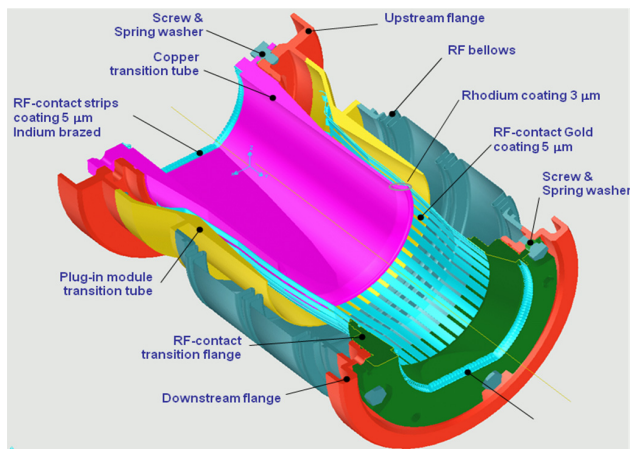


Figure 3: The PIM with its gold-coated RF contact fingers.

The PIM, has been designed to accommodate thermal contractions of the order of 50 mm, due to refrigeration from room temperature to 1.9K and occasionally, expansions due to warming from 1.9K 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. If 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 Box

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.

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 a diode end box (see Figure 1). On rare occasions this accumulated debris, sometimes metallic, has reduced the insulation resistance of the diodes to ground. The X-ray tomograph will allow pictures of the contents of the diode box in particular where debris is known to accumulate, to be obtained non-invasively.

THE RAYSCAN MOBILE X-RAY TOMOGRAPH

Ordered by CERN, RayScan Technologies GmbH has designed a mobile X-Ray Computed Tomography (CT) System (the RayScan Mobile) 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 4 in its operational position at an interconnect zone between two main-ring magnets of the LHC.



Figure 4: The RayScan Mobile X-ray Tomograph 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 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 (2.2 m) and overall length (2.25 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 to fit in the confined space available.

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, the system is based on former achievements of the RayScan team, which have already been shown to work successfully in the automotive and aeronautic industries [4,5].

Finally a system and an algorithm for 3D-volume of interest-CT with very limited angular access was developed. The image reconstruction is based on a “filtered shift and add” algorithm. 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 225kV minifocus X-Ray-source and a 400 mm by 400 mm flat panel detector with 2048 by 2048 pixels,

each of size 200 μm x 200 μm . Source and detector are both mounted on a 4 axis-manipulator system providing for simultaneous 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, the RayScan Mobile also provides a Real-Time Radioscopy Mode used to conduct an initial rapid inspection to obtain an immediate preliminary impression of the overall status of the interconnect zone and its components. Furthermore it 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 position and shape of all the gold-coated RF contact fingers inside the plug-in module was determined as shown in Figure 5.

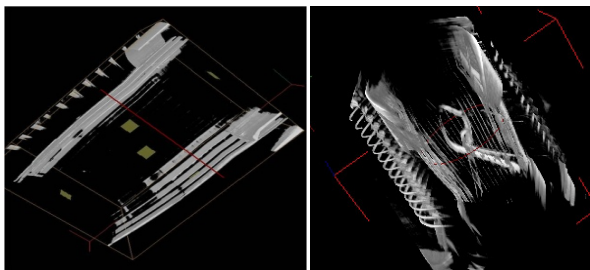


Figure 5: Plug-in module, sectional 3D display good (left) and damaged (right).

Some of the results of the 3D inspection of the 6 electrical interconnections between magnets are shown in Figure 6.

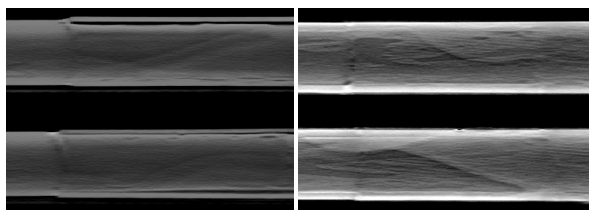


Figure 6: Left: 2D layer coplanar with copper surface of cable junction. Right: 2D layer coplanar with superconducting cables.

The left image in Figure 6 is a 2D layer from the reconstructed 3D volume that is coplanar with the top surface of the upper copper profile of the cable junction

box is shown. A minor defect in the soldering process has generated local unfilled longitudinal gaps between the cable junction box components. The right image in Figure 6 also shows a 2D layer from the reconstructed 3D volume that is situated a few millimetres lower, at the interface between two superconducting cables. 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.

OUTLOOK

In the near future a number of practical tests on a fully representative interconnection zone mock-up in a radiation bunker on the surface are foreseen, in order to constitute a catalogue of images obtained from known standardized built-in defects. This catalogue will be useful to bench mark the interpretation of the images obtained from the system during future diagnostic interventions on the LHC interconnect zones. In addition these tests will ensure thorough training of the operators.

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.

REFERENCES

- [1] LHC Design Report Volume 1 “The LHC Main Ring”, CERN June 2004 ISBN 92-9083-224-0.
- [2] M. Simon, C. Sauerwein, “Cone beam tomography for quality control and rapid product development”, *Insight*, 42(10), October 2000.
- [3] C. Sauerwein et al., “Multipurpose 3D computed tomography system”, 8th European Conference on Non-Destructive Testing ECNDT, Barcelona, Spain, 17-21 June 2002.
- [4] C. Sauerwein et al., “Extended 3D CT method for the inspection of large components”, 16th World Conference on Nondestructive Testing WCNDT, 30 August - 3 September, 2004.
- [5] C. Sauerwein et al., “Extended “3D Characterization of automotive parts by a novel multi-scan tomography system”, 4th International Conference Emerging Technologies in Non-Destructive Testing, Stuttgart, Germany, 2-4 April 2007.