OPERATIONAL EXPERIENCE WITH THE LHC WAVEGUIDE MODE REFLECTOMETER

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Abstract

The LHC microwave mode reflectometer (assembly version) reached operational status by the autumn of 2005. It is now routinely used in the LHC tunnel and on the surface to take data on the beam screens of the individual LHC magnets and also groups of magnets with lengths up to 100 meters. The reflectometer operates in the frequency range from about 4 GHz to 10 GHz and employs mode selective launchers. This paper discusses the operational aspects of the system as well as methods for clutter (fake reflection) elimination and procedures for cross-checks in case of a suspected obstacle or other fault.

INTRODUCTION

In several accelerators foreign objects were found in the beam aperture. In LHC, such obstacles would cause major disturbances. Therefore the detection and localization of such obstacles during LHC installation is highly desirable. Among a number of considered techniques, microwave reflectometry was chosen as a promising approach for quick and sensitive inspection of single beam screens and strings of interconnected magnets. This method is non-invasive, that is, there is no need to insert any tools into the beam screen, which is problematic for cleanliness and vacuum reasons. At present, reflectometry is used routinely during the installation of LHC, in parallel with visual inspection methods.

System overview

In Fig. 1 a sketch of the measurement set-up is shown. Measurements are done in the frequency domain on a network analyser. In the beam screen, waveguide modes are excited by custom couplers. Any discontinuity in the beam screen gives rise to reflections, which are displayed after appropriate signal treatment.

For the routine inspections, two waveguide modes are used, namely the first TE mode and the first TM mode. The use of two modes makes two independent measurements possible and thus provides redundancy and/or additional information about the properties of an obstacle. The couplers used to excite these modes have been designed, simulated and implemented. Besides having suitable RF properties these couplers must also be short enough to fit in the space between two installed magnets, about 15 cm. For more detail on the device the reader is referred to [1].

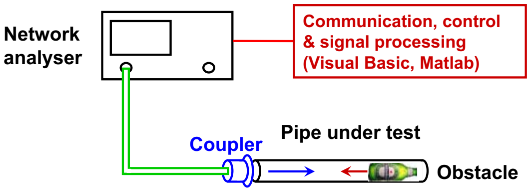

Figure 1: System overview of the LHC reflectometer. Please note the beer bottle is only one example of an obstacle – fortunately it would not fit into the LHC beam screen.

PRACTICAL APPLICATION

Using microwave reflectometry one cannot see obstacles as such. What is measured are the discontinuities in the RF properties of the beam screen. We refer to an obstacle as an object that in some way disrupts the continuity of the beam screen, such as a change in

- the beam screen geometry - a deformation or a protruding metallic object
- permittivity - a dielectric object
- permeability - a ferromagnetic object

Due to the small penetration depth in metals (≈ 1 μm in copper in the operational frequency range) for metallic objects the surface and shape are relevant, while for dielectric and ferrite objects it is the volume. To give an example, it has been found in simulations and measurements that a metallic M3 nut (outer diameter: 5.6 mm, height 2.6 mm) lying in the center of the flat beam screen side gives a reflection of about $S_{11} = -34$ dB for both modes. When the nut is moved to the round side of the beam screen, this signal reduces to -40 dB for the TM mode and to -45 dB for the TE mode. This variation of the sensitivity over the azimuth is due to the modes' field pattern [1].

Typical measurement data

For LHC magnets the operational frequency range was chosen as a trade-off between high spatial resolution (large bandwidth) and a combination of low insertion losses and low spurious-mode excitation, which requires limited bandwidth. The TE mode is operated between 4 and 6.6 GHz and the TM mode between 6 and 10 GHz. A resolution (6 dB peak width) of about 5 cm was obtained.

Fig. 2 shows typical data from a single LHC dipole installed in its slot in the tunnel. A few centimeters after the reflection from the coupler, the signal decreases to the noise floor, which is in the range of -55 dB for the TE and

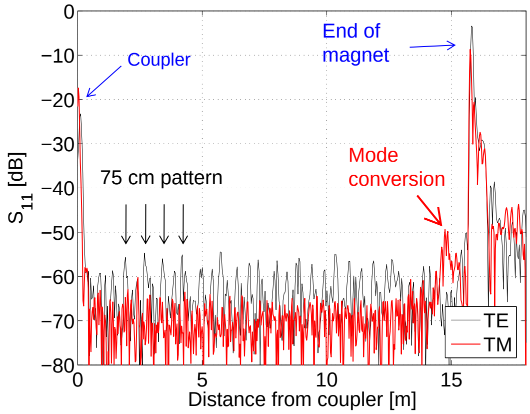

Figure 2: Data from a single fully assembled dipole with the TE mode (thin black) and TM mode (thick red). Waveguide dispersion and attenuation were removed numerically.

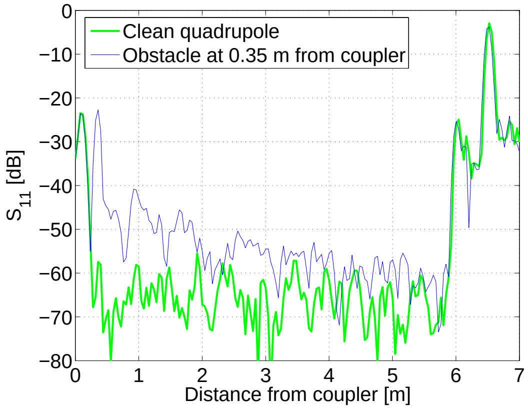

Figure 3: TE mode signal from a quadrupole containing a metallic obstacle compared to reference data from a clean magnet. Similar data were found for the TM mode.

-65 dB for the TM mode. Since the TE mode has also azimuthal wall current components going “across” the beam screen’s pumping slots, it can couple to the outside, i.e. to the space between the beam screen and the cold bore. As a result of this a structure with a period of 50 and 75 cm can be seen. These patterns are related to the periodicity of the pseudo-random pumping slot pattern (50 cm) and to the distance between the beam screen support rings (75 cm). In practise, this effect may limit the dynamic range achievable with the TE mode and complicate the interpretation of the data. Techniques for reducing these spurious periodic signals are currently under development.

The TM mode on the other hand is only weakly affected by the pumping slots. However, since it is a higher order mode, it is prone to mode conversion. Close to the end of the dipole in Fig. 2, a peak stemming from mode conversion to the TE mode can be observed. Other spurious effects that have to be coped with include:

- Reflections from cable connectors and internally in the network analyser
- Multiple reflections between interconnects
- Power “trapped” in interconnects for measurements over chains of magnets
- Coupling to beam positions monitors

For these reasons, a number of checks have to be performed to exclude false indications.

- The TE mode patterns can be correlated to magnets that were found to be clean
- Mode conversion and connector reflections can be identified by examining the peak’s dispersion characteristics
- Multiple reflections are related to the spacing of the preceding peaks.

Repeating the measurements on single dipoles within several weeks showed an excellent reproducibility of the results. The differences between subsequent measurements were generally of the order of -70 dB. This shows that the traces as plotted in Fig. 2 are not produced by noise but represent a characteristic signature of the magnet. Only the spurious peaks due to mode conversion may vary somewhat, since the electric contact between the coupler and the beam screen has some impact on this effect.

For measurements over longer sections a rise in noise floor due to multiple reflections was observed. This effect eventually limits the range of operation, since line attenuation is rather low compared to the system’s dynamic range.

OBSTACLES DETECTED IN LHC MAGNETS

In the beginning of installation in the LHC tunnel all magnets were checked visually before being interconnected. Reflectometry was used only for final checks of long chains of interconnected magnets, e.g. over 100 m. The expected signal of a metallic M3 nut, i.e. -40 dB, was taken as a preliminary acceptance criterium. A number of small isolated peaks (below -40 dB) were detected, but could not be confirmed visually. However, visual inspections are difficult even on a single magnet due to multiple light reflections inside the beam screen.

The signal from the first major obstacle found is shown in Fig. 3. Since the object was very close to the end of the quadrupole, it could be easily seen optically and removed. The object was made of steel, about cylindrical in shape with ≈12 mm length and ≈5 mm diameter. It was identified as belonging to a tool that is used during magnet assembly.

A very interesting case is shown if Fig. 4. In reflectometry with both the TE and the TM mode a distinct peak right in the middle of the magnet was observed; visual inspection yielded suspicious results, too. After blowing dry nitrogen into the not yet interconnected quadrupole a piece of metal swarf as shown on the right side in Fig. 5 was recuperated and the suspicious peak disappeared. Since this peak

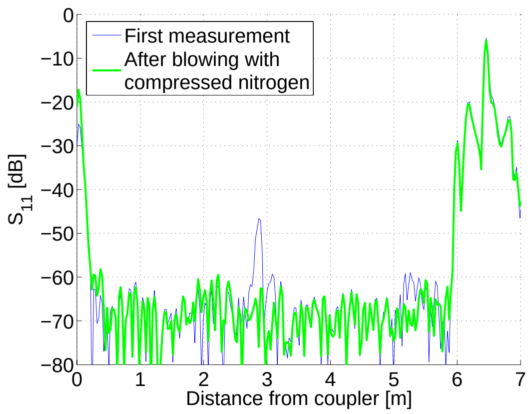

Figure 4: TM mode signal from a quadrupole before and after removal of a metal swarf as shown in Fig. 4.

Figure 5: Some of the obstacles found in magnets in the tunnel.

had been below −40 dB, the initial assumptions had to be revised. Now every peak clearly above the noise floor is considered as a potential obstacle and cross-checked with additional measurements, e.g. from the other side of the magnet. In case of strong suspicion, blowing with compressed nitrogen or endoscopy is used on the magnet under examination.

In some cases significant changes in the reflected signal were observed after such an intervention, which can be interpreted as stationary obstacles that changed their shape and therefore their "cross-section".

Suspected obstacles are classified according to

- the signal strength for each mode
- whether the obstacle was detected from both sides of magnet
- whether the signal changed after an intervention, such as blowing with compressed nitrogen.

As of mid June 2006, about 400 out of 500 installed magnets (which corresponds to about 25% of the LHC ring magnets) in the tunnel have been checked using reflectometry. 5 metallic obstacles have been removed and there are about 20 remaining suspicious cases, a third of them with strong indications. In addition to that, several small plastic pieces were found by optical inspections (see Fig. 5, in the center). Due to their tiny volume (≈ 1 mm^3) they did not give a signal above the noise floor in reflectometry.

ACTION TAKEN TO AMEND THE SITUATION

The obstacle problem is twofold. First, all significant obstacles already in the tunnel have to be removed. On single dipoles endoscopy and blowing with compressed nitrogen are the methods of choice, however there are ongoing discussions about what to do with suspected obstacles in interconnected magnets.

Second, it must be avoided that more magnets containing obstacles arrive in the tunnel. Careful analysis of the objects found so far showed that they can be grouped in two categories. A few probably found their way into the beam screen during the magnet transport and assembly at CERN. The majority of cases however are pieces of metal swarf coming from the beam screen manufacturing process and surviving all cleaning processes. The plastic pieces are probably fragments ripped off the plastic sheets in which the beam screens are wrapped when they arrive at CERN. This has triggered the following improvements:

- The beam screen cleaning procedure is being revised; controlled brushing of possible obstacles before chemical cleaning is under discussion as well as inspections of the beam screens before their insertion into the magnets.
- All beam screen equipped magnets will be inspected visually and by reflectometry during the final preparations on the surface. Thereafter the beam tubes will be sealed and kept closed right until magnet interconnection.

CONCLUSION

The LHC microwave reflectometer has been developed for inspection of the beam screens. It is now exploited as a standard tool during installation over lengths up to 100 m. Due to a number of spurious effects, careful analysis of the data is necessary. Together with visual methods reflectometry has been successfully applied to detect several obstacles of all kinds in the magnets. The discovery of these objects has led to improvements in the beam screen cleaning and inspection process.

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REFERENCES

[1] Kroyer, T., *Application of Waveguide Mode Diagnostics for Remote Sensing in Accelerator Beam Pipes*, CERN-THESIS-2005-061, 2005