EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN – ACCELERATORS AND TECHNOLOGY SECTOR

CERN-ATS-2009-009

Methods to detect faulty splices in the superconducting magnet system of the LHC

R. Bailey, B. Bellesia, N. Catalan Lasheras, K. Dahlerup-Petersen, R. Denz,
C. Robles, M. Koratzinos, M. Pojer, L. Ponce, R. Saban, R. Schmidt, A. Siemko,
M. Solfaroli Camillocci, H. Thiesen, A. Vergara Fernandez, CERN, Geneva, Switzerland
R.H. Flora, Fermilab, Batavia, USA and CERN, Geneva, Switzerland
Z. Charifoulline, INR RAS, Moscow, Russia and CERN, Geneva, Switzerland
M. Bednarek, E. Gornicki, P. Jurkiewicz, P. Kapusta, Henryk Niewodniczanski Institute of
Nuclear Physics, Kraków, Poland and CERN, Geneva, Switzerland
J. Strait, Fermilab, Batavia, USA

Abstract

The incident of 19 September 2008 at the LHC was caused by a faulty inter-magnet splice of about 200 nΩ resistance. Cryogenic and electrical techniques have been developed to detect other abnormal splices, either between or inside the magnets. The existing quench protection system can be used to detect internal splices with R>20 nΩ. Since this system does not cover the bus between magnets, the cryogenic system is used to measure the rate of temperature rise due to ohmic heating. Accuracy of a few mK/h, corresponding to a few Watts, has been achieved, allowing detection of excess resistance, if it is more than 40 nΩ in a cryogenic subsector (two optical cells). Follow-up electrical measurements are made in regions identified by the cryogenic system. These techniques have detected two abnormal internal magnet splices of 100 nΩ and 50 nΩ respectively. In 2009, this ad hoc system will be replaced with a permanent one to monitor all splices at the nΩ level.

Presented at the Particle Accelerator Conference (PAC09)
May 4-8 2009, Vancouver, Canada

Geneva, Switzerland
31 July 2009

METHODS TO DETECT FAULTY SPLICES IN THE SUPERCONDUCTING MAGNET SYSTEM OF THE LHC

R. Bailey, B. Bellesia, N. Catalan Lasheras, K. Dahlerup-Petersen, R. Denz, C. Robles,
M. Koratzinos, M. Pojer, L. Ponce, R. Saban, R. Schmidt, A. Siemko, M. Solfaroli Camillocci,
H. Thiesen, A. Vergara Fernandez, CERN, Geneva, Switzerland
R.H. Flora, Fermilab, Batavia IL 60510 U.S.A. and CERN, Geneva, Switzerland
Z. Charifoulline, INR RAS, Moscow, Russia and CERN, Geneva, Switzerland
M. Bednarek, E. Gornicki, P. Jurkiewicz, P. Kapusta, Henryk Niewodniczanski Institute of Nuclear Physics, Kraków, Poland and CERN, Geneva, Switzerland
J. Strait, Fermilab, Batavia IL 60510 U.S.A.

Abstract

The incident of 19 September 2008 at the LHC was caused by a faulty inter-magnet splice of about 200 nΩ resistance. Cryogenic and electrical techniques have been developed to detect other abnormal splices, either between or inside the magnets. The existing quench protection system can be used to detect internal splices with R>20 nΩ. Since this system does not cover the bus between magnets, the cryogenic system is used to measure the rate of temperature rise due to ohmic heating. Accuracy of a few mK/h, corresponding to a few Watts, has been achieved, allowing detection of excess resistance, if it is more than 40 nΩ in a cryogenic sub-sector (two optical cells). Follow-up electrical measurements are made in regions identified by the cryogenic system. These techniques have detected two abnormal internal magnet splices of 100 nΩ and 50 nΩ respectively. In 2009, this ad hoc system will be replaced with a permanent one to monitor all splices at the nΩ level.

INTRODUCTION

On 19 September 2008, during powering tests of the main dipole circuit in one of the eight LHC sectors, a faulty inter-magnet splice with R ~ 200 nΩ overheated and opened[1]. This produced an electrical arc, which resulted in substantial electrical and mechanical damage to this sector. To prevent future incidents of this type, it is imperative to detect any other faulty high-current joints in the LHC. The existing quench protection system (QPS) does not measure inter-magnet splice resistances with sufficient sensitivity to detect faulty joints of this type. A new system with adequate sensitivity is under development and will be implemented prior to the LHC restart[2].

In the mean time, other methods to search for faulty splices are being used. These include calorimetric measurements, in which ohmic heating from splice resistances is measured as a temperature rise in the superfluid helium system. Where excess resistance is suspected, follow-up measurements are made using precision voltmeters to directly measure the resistances of individual splices in the region indicated by the cryogenic measurements. Complementary measurements of splices resistances inside each magnet are made at the same time using the existing QPS in a special mode.

CALORIMETRIC MEASUREMENTS

The LHC cryogenic system is divided into subsectors, which typically contain 12 dipoles and four quadrupoles (two optical cells). The superfluid helium volume in each subsector is isolated from its neighbors by cryogenic plugs. Given the high sensitivity of the thermometers and the remarkable stability of the cryogenic system of the LHC, it is possible to measure temperature changes as small as a 1-2 mK over the time scale of an hour[3]. The heat capacity of a subsector corresponds to approximately 1 W/(mK/h); therefore resistive heating at the level of 1-2 W can be detected, corresponding to a resistance on the order of 20-40 nΩ at 7 kA. By measuring and fitting the rate of heating as a function of magnet current, an rms sensitivity < 15 nΩ is possible.

This technique is illustrated in Fig. 1, which shows the temperature in one dipole in sector 6-7 over a 4.5 hour period. The current was ramped to 5 kA and then 7 kA, and held at each current for 1 hour. A linear fit is made to T = f(t) during initial and final zero current periods, and during each of the high-current plateaus. Since superfluid helium effectively conducts heat throughout the common liquid volume, the measured dT/dt of all thermometers in a subsector are averaged, and the slope with zero current

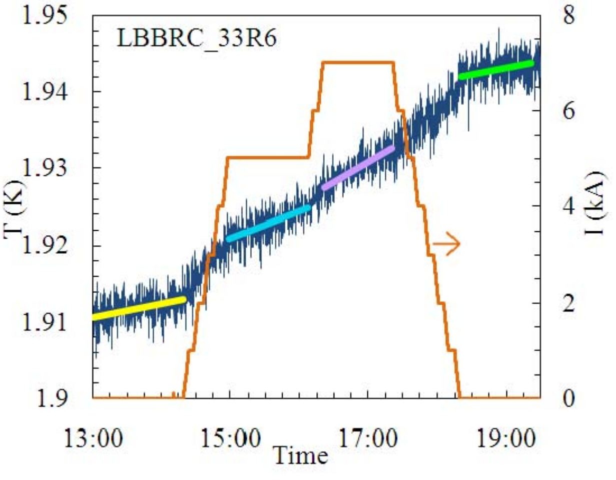

Figure 1: Measured T = f(t) for one thermometer during a power run of the main dipole circuit. Linear fits during periods of constant magnet current are shown.

is subtracted to yield the ohmic heating content. The dT/dt is converted to deposited power, using the actual heat capacity of the subsector at its measured temperature. Data from several runs of the type shown in Fig.1, which cover the range zero to 7 kA in roughly equal steps in I^2, are fit to a quadratic dependence on magnet current. The fit parameter is the total resistance in that subsector.

Fig. 2 shows the measured resistance per subsector for sector 6-7. The error bars returned by the least-squares fit are a measure of the scatter of individual measurements about the best fit for each subsector. The solid line represents the expected resistance per subsector. Ten of the 13 subsectors are of a standard length as described above. The central sub-sector is 1.5 times as long, and the end (dispersion suppressor) subsectors have 2/3 the number of dipoles.

The resistance in the central subsector (31R6-32L7) is 111±4 nΩ, compared with an expected 55 nΩ. The net excess resistance is 56±4 nΩ. Independent electrical measurements (see next section) found a resistance of 49 ± 3 nΩ in one of the dipoles in this subsector. This method also identified one subsector in sector 1-2 with an excess resistance of 108±5 nΩ, which was also confirmed electrically to be a high-resistance splice inside a dipole.

This method has been applied to the dipole (quadrupole) circuits in five (four) of the LHC sectors. Histograms of the calorimetrically measured total resistance per standard-length subsector are shown in Fig. 3. The two subsectors with confirmed resistive splices are not included in these plots, nor are the longer central and shorter end subsectors. The data are consistent with Gaussian distributions with means of ~35 nΩ and sigma of ~15 nΩ. This width is somewhat larger than the typical error bar from the individual fits to subsector data. This suggests additional systematic errors coming from small uncertainties in the cryogenic system settings. Since15 nΩ deposits only 0.7 W at 7 kA, detected in a helium bath>200 m long, this represents remarkable sensitivity.

A standard-length subsector contains 128 (104) splices in the dipole (quadrupole) circuit. Using all the data, including the non-standard-length subsectors but excluding those with known high-resistance splices, the mean resistance per splice is measured to be 271±9 pΩ (354±23 pΩ), consistent with the expected values.

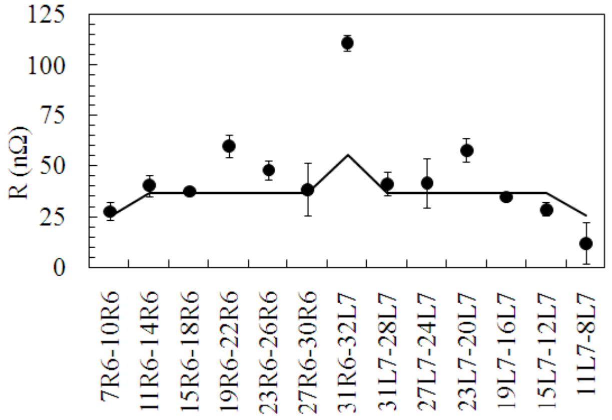

Figure 2: Total resistance in the dipole circuit in each sub-sector in sector 67, measured by the calorimetric method.

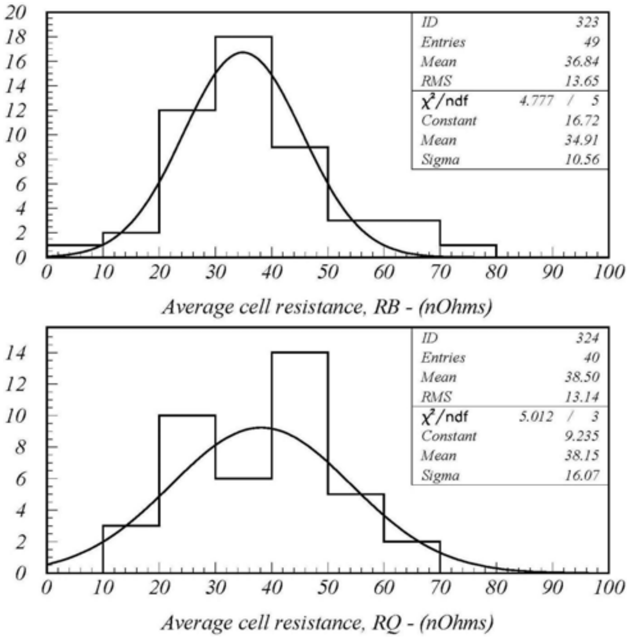

Figure 3: Histograms of main dipole and quadrupole circuit resistances in standard-length sub-sectors, measured by the calorimetric method.

Not all splices covered by the calorimetric measurements were electrically measured to confirm or deny the presence of excess resistance. The dipole distribution shows a slightly asymmetric tail on the high side, which may indicate the presence of one or more faulty splices with resistances of a few 10’s of nΩ. Table 1 shows, for each LHC sector, the 90% confidence upper bound on the maximum excess resistance, relative to the mean values shown in Fig. 3, that could exist in any subsector, based on calorimetry.

Table 1: 90% confidence upper bounds on possible excess resistances in nΩ, based on calorimetric measurements.

Sector Circuit	12	56	67	78	81
Dipole	111	26	32	32	3
Quadrupole	-	60	37	54	27

ELECTRICAL MEASUREMENTS

The calorimetric method measures the total resistance within one subsector, but cannot further localize it. To determine if excess resistance is in an inter-magnet splice, accurate voltmeters are connected to voltage taps available at room temperature on electrically adjacent magnets. Dipoles are powered alternately on the outgoing and return bus, and after every third dipole, the bus bars pass through a quadrupole. Thus the measurements covers two or three bus splices. Repeating measurements on the same pairs of voltage taps indicates an rms reproducibility error of 45 pΩ. The technique is labour and time intensive; therefore it was used only in subsectors deemed suspicious by the cryogenic analysis. In total 68 measurements were performed in five cryogenic subsectors, all on the dipole bus. No abnormal splice resistance was seen. The mean splice resistance is 311 pΩ, with an rms spread of 52 pΩ. (See Fig. 4.)

An electrical technique to identify faulty splices inside magnets was also developed. The "QPS snapshot" method uses the post-mortem system (2450 voltage measurements over 13 s with typical peak-to-peak noise of 4 mV), semi-automatically triggered at different current plateaus. The QPS measures voltage differences between two apertures of a dipole or two half-coils of a quadrupole, and therefore *differences* in splice resistances. QPS snapshot measurements were performed on five (four) sectors for the dipoles (quadrupoles). An example of the data for the 154 dipoles in sector 6-7 is shown in Fig. 5. A magnet (B32R6) with large resistance is clearly visible, which is in the cryogenic subsector identified as having excess resistance. Its resistance is measured to be 49±3 nΩ, consistent with the calorimetric measurements. Another magnet in sector 1-2 (B16R1) was identified by this technique with R = 100±3 nΩ, also consistent with the calorimetric measurements.

Fig.6 is a histogram of all of the snapshot measurements. The central peak has a width of about 2 nΩ. However there are long tails, which come from channels with extra electrical noise, and which may also include magnets with internal splices with R ~10 nΩ.

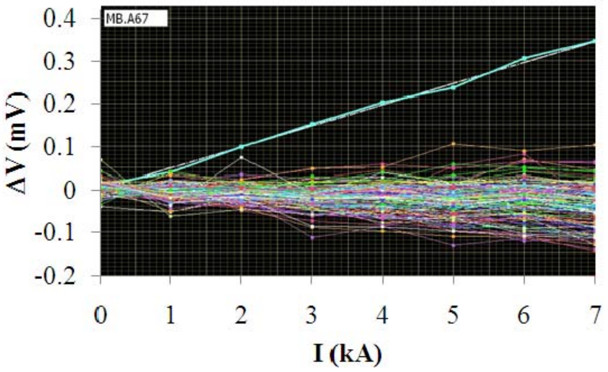

Figure 5: Voltage differences between two halves of all dipoles in sector 67.

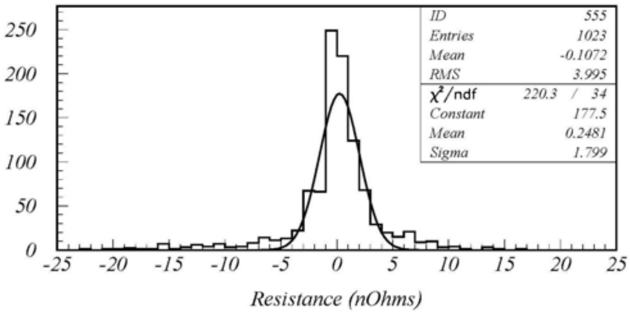

Figure 6: Histogram of electrical measurements of internal magnet splice resistance differences.

CONCLUSIONS

In order to avoid future incidents of the type that occurred on 19 September 2008 in the LHC, new techniques have been developed to detect faulty splices. The cryogenic system has proven capable of detecting ohmic heating from faulty splices with R>40 nΩ[3], allowing a global check of all high-current splices. The existing QPS has been used to check for faulty splices inside individual magnets, and ad hoc measurements with voltmeters have been used to check regions flagged by the cryogenic system. Both main dipole and quadrupole circuits have been surveyed in four of the eight LHC sectors, and the dipole circuit in a fifth has been surveyed with the cryogenic and follow-up electrical measurements. No additional bus splices with R>40 nΩ have been found. Two magnets with high-resistance internal splices have been identified and removed from the machine. As part of the re-commissioning of the LHC later this year, a full set of calorimetric and electrical measurements will be performed on the entire machine, with a combined sensitivity of <1 nΩ for all splices.

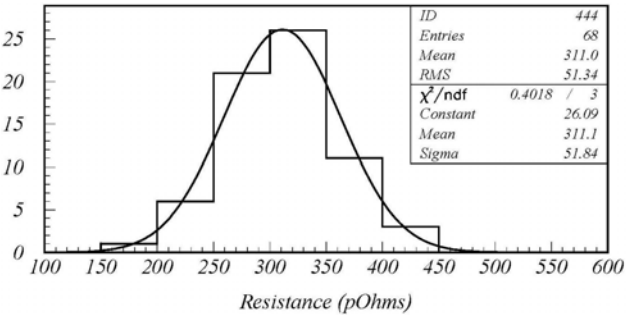

Figure 4: Histogram of electrical measurements of bus splice resistances.

ACKNOWLEDGMENTS

We would like to thank the members of the CERN technical staff who supported these measurements, especially the cryogenics operations crew, who carefully prepared the system that allowed these exquisitely sensitive measurements to be made.

REFERENCES

[1] M.Bajko et al. Report of the Task Force on the Incident of 19 September 2008 at the LHC, LHC Project Report 1168, 31 March 2009.

[2] R.Denz et al., Upgrade of the Protection System for Superconducting Circuits in the LHC, PAC'09, Vancouver, BC, Canada.

[3] L.Tavian, et al., Helium II Calorimetry for the Detection of Abnormal Resistive Zones in LHC Sectors, PAC'09, Vancouver, BC, Canada.