Determination of Interstrand Contact Resistance from Loss and Field Measurements in LHC Dipole Prototypes and Correlation with Measurements on Cable Samples

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Abstract— Loss and field errors due to ramping in LHC accelerator dipole magnets are mainly determined by the contact resistance between the strands of the magnet cable. It is therefore important to develop cables having sufficiently high contact resistance in the magnets in order to ease operation of the future LHC collider during ramping. In this paper the contact resistance R_c and its distribution in the magnet windings are determined for several dipole prototypes using both the measured loss and field errors during ramping of the magnet. We compare these results with interstrand contact resistance measurements made on short samples of the cables used in these magnets.

I. INTRODUCTION

The coils of superconducting accelerator dipole magnets like the ones designed for the future LHC proton-proton collider are usually made with Rutherford type cables consisting of two layers of twisted strands. The contact resistance R_c between crossing strands (or its inverse the contact conductance G_c) is an important parameter in the cable design. It influences the magnet behaviour in the following ways:

- Interstrand coupling currents over a twist pitch, when the field is changed, give field errors in the aperture and losses in the windings which are proportional to G_c and depend also on the *distribution* of G_c in the coil. To limit the field errors in the LHC dipole we require an R_c greater than $10 \mu\Omega$ which will give conductance differences of less than 0.1mS between parts of the magnet coils [1], [2]. Losses may cause quenches during ramping if locally G_c is very high.
- The contact resistance has an influence on the current redistribution (during field change) between strands over lengths longer than the twist pitch [3]. The ends of the magnet for instance are believed to generate a current unbalance in the strands proportional to $\sqrt{G_c}$, and may be partially responsible for the change of the field error with time observed in accelerators at injection.

The contact resistance in the magnet depends on many factors [4], [5], which are of course more easily studied on short cable samples than in complete magnets. We therefore made a study to see if we could correlate the R_c values found in magnet coils with those measured on short cable samples. At the same time we wanted to check if average R_c values measured with different methods (loss and field measurements) in the magnets gave the same result. Of particular interest to us is the measurement of the R_c *distribution* because of its influence on the field quality. We could so verify that the specification on the allowed conductance differences inside the magnet coils were reasonable.

We have performed our analysis on 12 model magnets that have been built by CERN, both single and double aperture 1m long models and five 10m long two aperture models [6], [7], [8], [9]. The R_c *distribution* inside the magnet coils was studied on four of the 10m models.

II. CONTACT RESISTANCES IN MAGNETS

A. Measuring Methods

TABLE I.
CALCULATED FIELD ERRORS DUE TO INTERSTRAND EDDY CURRENTS IN 10M LHC DIPOLE MODELS ASSUMING A CONTACT RESISTANCE (R_c) BETWEEN CROSSING STRANDS OF $10M\Omega$.

Harmonic number	Field(T) at $x=1cm$ at a ramp rate of 6.7mT/s(10A/s)
1	5.66E-04
3	1.80E-05
5	-1.84E-06
7	-1.16E-09
9	4.06E-08

The R_c values in the windings of the dipole model magnets are derived with two different methods. The first method, based on loss evaluation by means of voltage and current measurements on the magnet coils [10] during cycling, gives an average R_c for the whole magnet and approximate values for the two poles. The second method, based on field measurements during ramping [11] of the magnet, can in addition give more detailed information about the distribution of the contact resistance inside the magnet. We describe the magnetic method in more detail here. During ramping of the magnet the change in higher order field error harmonics are measured with help of a 75cm long rotating coil, while the change in the total field, including the main dipole component, is measured with narrow 1.5m long and 10mm wide stationary coils near the axis of the magnet. This last measurement is important since the calculated value of the dipole moment due to interstrand eddy currents in these and similar magnets is relatively high compared to the higher order harmonics (see Table I). The field errors in Table I are related to the components of the 2-dimensional complex expansion of the field $\mathbf{B}$ in the magnet cross section as:

$$B_y + iB_x = \sum_{n=1}^{\infty} C_n \left(\frac{z}{R_{ref}} \right)^{n-1} \dots (1)$$

According to (1) the components C_n give the field errors in Tesla at the reference radius R_{ref} . Here n is the harmonic number and $z = x + iy$ is the complex position vector.

To calculate the contact resistance distribution from the field errors we first establish the relation between the field harmonics and the R_c for each single cable in the magnet [1].

This relation can be put in the form $\vec{b} = M\vec{G}_c$. Here $\vec{b}$ is the field error vector, $\vec{G}_c (=1/R_c)$ is the crossing contact conductance vector and M is a matrix. Knowing the measured field errors we then find the unknown $\vec{G}_c$ distribution by

minimizing $\left| \vec{b}_m^r - M\vec{G}_c^r \right|^2$ where $\vec{b}_m^r$ is the measured field error vector. Since the number of parameters (cables) is often larger than the number of measured harmonics we derive in this case a solution by simultaneously minimizing the standard deviation of the $\vec{G}_c$ distribution. The solution found in this way is unique, but depends on the weighing factor applied to the standard deviation, and must be chosen so that

TABLE II.
COMPARISON OF RC VALUES (M Ω) DERIVED FROM LOSS AND FROM
FIELD MEASUREMENTS.

The apertures are marked Ap1 and Ap2, the two poles 'upper' and 'lower'.

Magnet	Loss or Field	Overall	Ap1	Ap2	Ap1, upper	Ap1, lower	Ap2, upper	Ap2, lower
MTP1A1	Loss	1.6	1.3	2.1	1.5	1.2	2.2	1.9
	Field	-	0.9	-	1.0	0.7	-	-
MTP1A2	Loss	6.5	6.4	6.5	6.3	6.5	7.2	6.0
	Field	-	-	9.3	7.1	5.8	7.2	13.1
MTP1A3	Loss	14.0	14.7	13.2	16.5	13.3	13.1	13.4
	Field	-	-	-	19.2	12.1	-	-
MTP1N1	Loss	4.2	4.2	4.2	4.3	4.0	4.3	4.0
	Field	-	-	-	-	-	-	-
MTP1N2	Loss	6.7	6.4	7.0	6.1	6.8	7.3	6.8
	Field	6.8	8.0	5.9	6.0	12.0	7.1	5.0

$\left| \frac{r}{b_m} - MG \right|_c^2$ remains sufficiently small. The main field component is always large but it was not always measured for all magnets. When it was not available we set the average contact resistance during the minimization procedure, equal to the one determined from loss measurements. The contribution to the field error from the outer layer cable is small due to the lower average field in this layer. Therefore these cables were grouped together in two blocks(B1 and B2 in Fig. 1), with constant R_C . Similar attempts to derive the R_C distribution were performed on SSC magnets[12].

A. Average contact resistance of magnet coils

In Table II we compare for both methods the measured average contact resistance in five 10m long, 2-aperture dipole

models. There is a reasonable agreement between the two measurements considering that the loss measurements give averages over the whole 10m long magnet while the field measurements are performed over 1 or 2 lengths of 0.75m of the magnet. In general the field measurements give larger differences in R_C for the poles then the loss measurements. This may be because the mutual inductance of the poles influences the voltage measured on the poles during the loss measurement.

A. Distribution of the contact resistor winding cross-section

The distribution of $G_c(=1/R_c)$ can be quite dissimilar for the same magnet. This is illustrated in Fig. 2 for a measurement at the same longitudinal position in the two apertures of a 10m model magnet. However the distribution of G_c over the length of a magnet seems to be similar. This can be seen from the measurement of magnet MTP1N2 taken 1.50m apart (Fig. 2 and Table III, position 1 and 2).

We could not find any systematic pattern in the G_c distribution of the four 10m model magnets measured. This is perhaps not surprising since these magnets were the first of this kind to be constructed and came from different manufacturers and used different cables. Furthermore each magnet coil was manufactured and cured separately.

To study the distribution of the contact conductance we determined the average values and their standard deviation for the inner layer cable of each magnet pole (Table III). This shows that the difference between poles is of same order as the standard deviation within a pole cable.

Fig. 1. A cross-section of the magnet coil of one aperture of the LHC 10m model dipole. The coil consists of an outer and an inner winding wound with a different cable. Shown are the names given to the coil regions (B1, B2) and cables (25-37) for the R_C distribution calculations.

TABLE III.
DISTRIBUTION OF CONTACT CONDUCTANCE $G_C (=1/R_C)$ IN THE INNER
LAYER CABLES.

G_{c1}, σ_1 is the conductance and its standard deviation for the upper pole cable, G_{c2}, σ_2 for the lower pole. Note that $1MS=1(\mu\Omega)^{-1}$

Magnet	Remark	G_{c1} (MS)	σ_1 (MS)	G_{c2} (MS)	σ_2 (MS)	$G_{c1}-G_{c2}$ (MS)
MTP1A1, Ap1	over one twist pitch over 1.5m length	1.158	0.805	1.558	0.718	-0.400
MTP1A2, Ap1		0.135	0.043	0.167	0.038	-0.033
MTP1A2, Ap2	1.5m	0.133	0.024	0.065	0.028	0.068
MTP1A3, Ap1		0.051	0.021	0.083	0.016	-0.032
MTP1N2, Ap1	position 1	0.158	0.065	0.080	0.048	0.078
MTP1N2, Ap1	position 2	0.171	0.060	0.070	0.069	0.101
MTP1N2, Ap2	position 1	0.137	0.036	0.175	0.050	-0.039
MTP1N2, Ap2	position 2	0.156	0.048	0.208	0.053	-0.052

Fig.2. Distribution of the contact conductance $G_c (=1/R_c)$ in magnet MTP1N2, in Aperture 1 (above) and Aperture 2 (middle and below), over lengths of 0.75m. The two G_c distributions in Aperture 2 were measured 1.5m apart. The distribution is given for the cables of the inner coil layer (black) and for the cable blocks of the outer layer (grey), see also Fig. 1.

A. Power loss distribution in the winding

Knowing the R_c distribution we can also easily derive the power distribution in the windings (Fig. 3) for a given ramp rate. This could be useful as a tool to study quenching of the magnet during rapid field changes.

III. COMPARISON WITH MEASUREMENTS ON SHORT CABLE SAMPLES

The contact resistance R_c between crossing strands is controlled by the resistive barrier surrounding a strand [4]. The contact surface area does not vary significantly between

the measured cables, and therefore does not modify R_c . A thin layer of oxides or other compounds, often semiconducting, created on the surface of a strand, is a very efficient barrier.

Unfortunately, in the course of the production, magnet coils have to be cured, i.e. sized and glued at elevated temperature and pressure. The curing temperature ranges between 160 and 190 C, and the pressure can be up to 100 MPa.

During curing the micro-contacts close hermetically, and the oxide barrier is dispersed due to the elevated temperature, hereby diminishing R_c . If in the finished coil, the contacts release during storage, a new barrier forms that may increase R_c .

If the micro contacts do not close hermetically during the curing, additional barrier may form on their surface, which increases R_c . We observed on the cables with SnAg coated strands that the increase in R_c due to the curing without pressure is equivalent to the increase in R_c due to the curing at full pressure, followed by a pressure release, while the temperature, and the curing time are the same [4].

As shown in [4] both the decrease and the increase of R_c are sensitive to the curing temperature. They are less sensitive to the curing pressure.

As a result of the condition of the contacts during and after curing, three levels of R_c can be expected in a magnet coil:

- a small R_c due to dissolution of the resistive barrier,
- an R_c larger than R_c of the virgin cable, if the contacts were not closed during curing, or relaxed after curing,
- an R_c equal to that of the virgin cable. This can happen occasionally in cables with particular SnAg coating.

In Table IV we compare the R_c of 12 model LHC magnets with R_c measured on samples of cables. Parameters of these magnets are given in [7], [8], [9].

The values of R_c in magnets are based on our loss measurements. To measure the values of R_c in samples of cables we used a DC method described in [4]. Only the inner layer cables are compared, since the inner layer of the magnet coil gives the main contribution to the measured loss.

The samples of cable measured by the DC method were prepared from the same cables, as were used in the magnets. The samples were measured 1) as received, 2) after a curing, equivalent to the curing of the magnet in which this cable was used, and 3) after curing and after the pressure on the sample was released and reapplied. The decrease of R_c after curing in cable samples means that the contacts were

Fig. 3. The power distribution in magnet MTP1N2, Aperture 2, average over a length of 0.75m.

TABLE IV.
COMPARISON BETWEEN THE R_C VALUES MEASURED IN MAGNETS AND ON SHORT SAMPLES OF CABLE.
The R_C values for cables printed in *italic* have been extrapolated based on analogous measurements. The cable samples were cured under conditions equivalent to the curing of the magnet in which this cable was used.

Magnet ID	± 20 R_c in mag	Rc in cable measured on samples of cable		
		Cable as received	Cable after curing	and Cable after pressure
	$\mu\Omega$			
Magnets with non coated strands				
MBSMS1	>30	83	0.52	
MBSMS2	>30	83	0.52	
MBSMS3	>30	83	0.52	
Magnets with SnAg coated strands				
MTP1A1	1.6	9.6	1.8	10.2
MTA3 CERN	1.4	6	1.4	10
MFISC	18	13	3.1	17
MBSMS4	3.3	16	2.8	30
MSA1E	3.0	3	0.7	2.6
MTA1E	1.8	3	0.7	2.6
MTA1H	6.7	3	0.7	2.6
MTP1N1	4.2	6.8	1.7	7.4
MTP1N2	6.7	5.3	2.2	8.3

hermetically closed during curing.

The R_C values in the magnets MBSMS1, MBSMS2, MBSMS3 were too high to be evaluated by the loss measurement method. From the field measurements we derived $R_C = 40 \mu\Omega$. The difference between the estimated lower limit of R_C in magnets, and R_C measured on samples of cable after curing suggests that the contacts were not hermetically closed during a part of the curing.

R_C measured in the magnets MTP1A1, MTA3CERN, and MBSMS4 corresponds to R_C measured on cable samples after curing. That means that the contacts were hermetically closed during all the curing.

R_C measured in the magnets MFISC, MSA1E, MTP1N1, and MTP1N2 corresponds to R_C measured on cable samples after pressure relaxation. This suggests that the contacts were not hermetically closed during a part of the curing.

R_C measured in the magnet MTA1E is between R_C for the cable just after curing, and R_C for the cable after pressure release. This could mean that part of the contacts were closed during the curing, while the rest remained open.

IV. CONCLUSION

There is a good correlation between the average R_C of a magnet determined from field and loss measurements. We could not find a systematic pattern in the R_C distribution in the coils of the four model magnets studied. The distribution does not seem to change much over the length of the magnet.

We found that it is possible to understand the average R_C in the magnets from the R_C measured on cable samples. It seems that in 8 of the 12 compared magnets the interstrand contacts were open during curing. In 3 magnets the contacts may have been closed during curing.

The next step is to understand the R_C distribution inside the coils, as well as the difference in evolution of the average R_C between magnets, and correlate them to the coil manufacturing.

REFERENCES

- [1] A. P. Verweij, R. Wolf, "Field Errors due to Interstrand Coupling Currents in the LHC Dipole and Quadrupole", CERN/AT-MA internal note 94-97, March, 1994.
- [2] L. Bottura, A. Faus-Golfe, L. Walckiers, R. Wolf, "Field Quality of the Main Dipole Magnets for the LHC Accelerator", Presented at the European Particle Accelerator Conference, Sitges, Spain, June, 1996.
- [3] A.P.Verweij, Electrodynamics of Superconducting Accelerator Magnets, Ph.D., Twente University (NI).
- [4] D. Richter, J., D. Adam, J-M. Depond, D. Leroy, R. Oberli, Cern, "Dc Measurement Of Electrical Contacts Between Strands In Superconducting Cables for the LHC Main Magnets", Presented at 1996 Applied Superconductivity Conference, Pittsburgh, U.S.A, August 25-30, 1996.
- [5] J-M. Depond, D. Leroy, L. R. Oberli, D. Richter, "Examination Of Contacts Between Strands By Electrical Measurement and Topographical Analysis", Presented at the Applied Superconductivity Conference, Pittsburgh, U.S.A, August 25-30, 1996.
- [6] The Large Hadron Collider - Conceptual Design, CERN/AC/95-05, 1995.
- [7] R. Perin, "Status of the Large Hadron Collider Magnet Development", IEEE Trans. On Magn., **30**, 4, 1579-1586, 1994.
- [8] R. Perin, "Status of the LHC programme and Magnet Development", IEEE Trans. On Appl. Sup., **5**, 2, 189-195, 1995.
- [9] N. Siegel, "Status of the Large Hadron Collider and Magnet Program", Presented at 1996 Applied Superconductivity Conference, Pittsburgh, U.S.A, August 25-30, 1996.
- [10] A. P. Verweij, D. Leroy, L. Walckiers, R. Wolf, "Analysis of the AC loss measurements on the One-Meter dipole model magnets for the CERN LHC", IEEE Trans. On Magn., **30**, 4, 1758-1761, 1994.
- [11] J. Buckley, D. Richter, L. Walckiers, R. Wolf, "Dynamic Magnetic Measurements of Superconducting Magnets IEEE Trans. Appl. Sup., **5**, 2, 1024-1027, 1995
- [12] A. Devred, T. Ogitsu, "Ramp-Rate Sensitivity of SSC Dipole Magnet Prototypes", KEK Preprint 94-156, December, 1994.