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LHC Note 242

**Analysis of the AC Loss Measurements on the One-Metre Dipole Model
Magnets for the CERN LHC**

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Abstract

Superconducting single- and twin-aperture dipole model magnets for the future CERN Large Hadron Collider have been built in industry and tested at CERN. In this paper the results of AC loss measurements are presented that are performed on 6 magnets all having a bore of 50 mm diameter and coils wound of 17 mm wide superconducting cables. The cables that are used in these models differ with respect to the filament diameter, the strand coating and the fact whether the cable is (partially) soldered or not. The energy loss, determined electrically as the difference between the stored energy and the extracted energy during a current cycle, consists mainly of filament hysteresis and inter-strand coupling loss. The hysteresis component is in fair agreement with calculations. The inter-strand coupling loss varies with about a factor 5 between the models due to a different contact resistance between crossing strands in the cable (varying in the range from 1 to 10 mW). Even for model magnets which are made with the same cable the inter-strand coupling loss can differ significantly.

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13th International Conference on Magnet Technology (MT13), Victoria, Canada,
20-24 September 1993

Geneva, Switzerland
02/08/94

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Abstract - Superconducting single- and twin-aperture dipole model magnets for the future CERN Large Hadron Collider have been built in industry and tested at CERN [1]. In this paper the results of AC loss measurements are presented that are performed on 6 magnets all having a bore of 50 mm diameter and coils wound of 17 mm wide superconducting cables. The cables that are used in these models differ with respect to the filament diameter, the strand coating and the fact whether the cable is (partially) soldered or not. The energy loss, determined electrically as the difference between the stored energy and the extracted energy during a current cycle, consists mainly of filament hysteresis and inter-strand coupling loss. The hysteresis component is in fair agreement with calculations. The inter-strand coupling loss varies with about a factor 5 between the models due to a different contact resistance between crossing strands in the cable (varying in the range from 1 to 10 $\mu\Omega$). Even for model magnets which are made with the same cable the inter-strand coupling loss can differ significantly.

I. INTRODUCTION

During charging and discharging of superconducting magnets energy is dissipated through several mechanisms. The main contributions are due to the magnetization of the superconducting filaments and to the coupling currents between the strands in the cable and between the filaments in the strands. Smaller contributions are caused by the ohmic loss in the connections between the poles and in the splices between the inner and outer layer, the magnetization of the iron yoke and the eddy currents in the copper spacers and in the collars. A good understanding of these loss components is important as they have a major impact on the installed cryogenic power and the quench propagation magnet to magnet protection scheme for the LHC. The inter-strand coupling currents cause field distortions during charging [2]-[3] and can reduce the quench current at fast discharges.

II. THEORY

The hysteresis component of the loss is mainly due to the magnetization of the superconducting filaments. This depends in first approximation rather linearly on the filament diameter and the critical current density. The hysteresis loss

per current cycle depends on the initial and final current values but in first approximation not on the ramp rate. A numerical model is used to calculate the filament hysteresis, analogous to the model described in [4].

A field change causes coupling currents that flow in the copper matrix between the filaments in a strand (inter-filament coupling loss) and coupling currents that flow between the strands in the cable (inter-strand coupling loss). The inter-filament coupling power per unit volume P_{ifc}/V during a field sweep with rate dB/dt is given by [5]

$$\frac{P_{ifc}}{V} = \frac{2\theta}{\mu_0} \left(\frac{dB}{dt} \right)^2, \quad (1)$$

with $\theta = \mu_0 (L_{Pf} / (2\pi))^2 \rho$, L_{Pf} the strand twist pitch and ρ the effective transverse resistivity of the strand. Taking into account the geometry of the magnet and by using results of short sample measurements [6] the inter-filament coupling power (in W) for one aperture of a dipole magnet, having a field factor of $7 \cdot 10^{-4}$ T/A, can be expressed by

$$P_{ifc} = 0.32 \cdot 10^{-4} (dI / dt)^2, \quad (2)$$

with dI/dt in A/s. The inter-strand coupling power depends strongly on the contact resistance between crossing strands in the cable. This cross contact resistance R_c can vary between about 1 and 100 $\mu\Omega$ due to several parameters: curing circumstances [7], deformation of the strands, soldering or impregnation of the cable, surface conditions of the strands and pressure applied transversely onto the cable [8]-[10]. The inter-strand coupling power in a cable can be calculated by modelling the cable by means of a network of nodes interconnected by strands or by resistances R_c [11]-[12]. The inter-strand coupling power per aperture P_{isc} (in W) is obtained by summation of the coupling power for each winding in the magnet and can be expressed by

$$P_{isc} = (0.0114 \frac{L_{P,s,i}}{R_{c,i}} + 0.0006 \frac{L_{P,s,o}}{R_{c,o}}) \left(\frac{dI}{dt} \right)^2, \quad (3)$$

with $L_{P,s,i}$ and $L_{P,s,o}$ the cable pitches (in m) of the inner and outer layer respectively, $R_{c,i}$ and $R_{c,o}$ the cross contact resistance (in $\mu\Omega$) in the inner and outer layer respectively

and dI/dt the ramp rate in A/s. The factors 0.0114 and $0.0006 \text{ V}^2\text{s}^2/(\text{mA}^2)$ depend on the geometry of the cable and the geometry of the coils of the inner and outer layer. Equation (3) shows that the coupling loss is mainly generated in the inner layer for similar cable pitches and contact resistances of the inner and outer layers. By using the network model and considering also the mutual interaction between the coupling currents [13] one can calculate the time constant $\tau_{e,calc}$ of the inter-strand coupling currents for a 1 m dipole model with a given cross contact resistance. Neglecting the effect of the outer layer, the time constant is expressed by

$$\tau_{e,calc} = 42 \frac{L_{P,s,i}}{R_{c,i}}, \quad (4)$$

with $\tau_{e,calc}$ in s, $L_{P,s,i}$ in m and $R_{c,i}$ in $\mu\Omega$. Note that substitution of (4) in (3) and neglecting the effect of the outer layer results in a similar relation as (1).

An ohmic loss is generated in the resistive connections between the poles and the splices between the inner and outer layers. The resistance depends on the current due to the magnetoresistivity of the connections.

Calculations show that the eddy current loss in the copper spacers and the collars (which consist of insulated plates of 5 mm thickness) and the magnetization loss in the iron yoke are small compared to the other loss components.

Combining (2)-(4) and taking into account the ohmic loss in the connections the energy loss E_{loss} (in J/cycle) of a magnet for one triangular current cycle I_1 - I_2 - I_1 with ramp rate dI/dt (in A/s) can be described by

$$E_{loss} = \frac{C_{res}}{(dI/dt)} + C_h + C_e \frac{dI}{dt} \left(1 - \frac{\tau_e(dI/dt)}{|I_2 - I_1|}\right). \quad (5)$$

C_{res} (in JA/s), C_h (in J) and C_e (in Js/A) are constants that depend on the currents I_1 and I_2 (both in A).

III. MEASUREMENT METHOD

By measuring the energy loss per cycle as a function of the ramp rate the three loss components as given by (5) can be separated. A measurement consists of one triangular cycle in which the current is ramped up with a given ramp rate from I_1 to I_2 and ramped down from I_2 to I_1 . Between the two ramps and after the ramp down the current is kept constant for at least 50 s in order to let the coupling currents decay to zero. During this cycle the current I and the voltage V are continuously measured and the average values during time intervals Δt of about 0.4 s are stored in a PC. The loss is calculated by summation of the incremental energies, so:

$$E_{loss} = \sum_n (V_n \cdot I_n) \Delta t, \quad (6)$$

which is equal to the difference between the stored energy during the ramp up and the extracted energy during the ramp down. Besides the total voltage over the magnet simultaneously also the voltages over the poles are measured in order to investigate the differences in the losses between the poles. Due to the mutual coupling between both layers it is not possible to determine if the loss is generated in the inner or outer layer, although voltage taps are present on the splice in between them. Theoretically however, the ratio of the loss between both layers can be estimated (e.g. (3)).

IV. DESCRIPTION OF THE MODEL MAGNETS

Fig. 1 pictures the cross section of the windings of one quadrant of an aperture. Although this geometry is the same for all the magnets, different cables are applied as can be seen in Table I. The main parameters of these cables are given in Table II. The field factor of the magnets is about $0.69 \cdot 10^{-3} \text{ T/A}$.

Fig. 1. View of the cross section of the windings of one quadrant of an aperture.

TABLE I
OVERVIEW OF THE MODEL MAGNETS

Magnet	Inner Layer	Outer layer	Single/Twin apert.
AN1/AN2*	I-1	O-4	Twin apert.
CE1	I-2	O-3	Twin apert.
EL1/EL3*	I-3	O-4	Twin apert.
EL2	I-3	O-3	Single apert.
HO1	I-3	O-1	Twin apert.
JS1	I-1	O-2	Twin apert.

* AN2 and EL3 are reconstructed versions of the AN1 and EL1 respectively in which the coil ends are impregnated.

V. RESULTS

For each magnet the energy loss of a triangular current cycle I_1 - I_2 - I_1 is measured during 6 to 20 ramp rates between 30 A/s and 250 A/s. For several magnets the loss as a function of the ramp rate is measured for two or more cycles with different I_1 and I_2 values in order to investigate whether the loss components depend on the current level.

The results of the cycles between 0 and 2.9 kA (corresponding to a central field sweep between 0 and about 2 T) are pictured in Fig. 2. The first term in (5), related to the resistance of the connections, is too small to be deduced

TABLE II
MAIN PARAMETERS OF THE CABLES

	Inner layer cables			Outer layer cables			
Name	I-1	I-2	I-3	O-1	O-2	O-3	O-4
Dimensions (mm ²)	17.0x2.04/2.50	17.0x2.04/2.50	17.0x2.04/2.50	17.0x1.30/1.67	17.0x1.30/1.67	17.0x1.30/1.67	17.0x1.30/1.67
# of strands	26	26	26	40	40	40	40
Ø strand (mm)	1.3	1.3	1.29	0.84	0.83	0.84	0.84
Cu/SC ratio	1.74	1.6	1.9	1.8	1.8	1.8	1.8
L _{p,s} (mm)	130	130	117	132	95	100	130
Ø filament (µm)	14	5	25	14	9.5	5	16
L _{p,f} (mm)	25	25	25	25	25	25	25
Soldering/coating	Partially sold. with SnPb	95%Sn/5%Ag coating	Tinned with 95%Sn/5%Ag	95%Sn/5%Ag coating	Partially sold. with SnPb	95%Sn/5%Ag coating	Sold. with PbSn

from the $E_{loss}(dl/dt)$ curve. Voltage measurements across the connections at constant current values give an average resistance per connection of about 0.5 to 1 nΩ.

The second order behaviour of the curves, due to the time constant τ_e of the inter-strand coupling currents (see (5)), can be clearly seen for the CE1 magnet.

To compare the results of different current cycles more easily, the constants C_h and C_e in (5) are divided by a factor $2*(I_2-I_1)$, so:

$$K_h = \frac{C_h}{2(I_2 - I_1)} \quad \text{in J/A or J/kA,} \quad (7a)$$

$$K_e = \frac{C_e}{2(I_2 - I_1)} \quad \text{in J/A/(A/s) or J/kA/(A/s).} \quad (7b)$$

The results in terms of K_h and K_e for all the cycles are listed in Table III. If not indicated the temperature is 1.8-2.0 K. The errors in K_h and K_e are about 5-10 J/kA and 0.1 J/kA/(A/s) respectively. The large error in K_h is mainly due to the noise of the power supply which makes it impossible to perform accurate measurements at small ramp rates.

Fig. 2. Energy loss per cycle and per aperture as a function of the ramp rate for the CE1, EL3, EL2, AN2, JS1 and HO1 (from up to down) magnets for a cycle between 0 and 2.9 kA. The solid lines represent fitting curves using (5) corrected for the resistive term $C_{res}/(dl/dt)$.

The hysteresis loss is numerically calculated using the Kim relation for the critical current density in the superconducting filaments $J_c = J_0 B_0 / (B_0 + |B|)$ for fields smaller than about 2 T. From magnetization measurements on short samples [6] the constants are determined to be about: $J_0 = 4.8 \cdot 10^{10}$ A/m² and $B_0 = 0.31$ T. For fields larger than 2 T a linear relationship is taken between the critical current density and the field. The calculated values $K_{h,calc}$ are shown in the last column of Table III. The calculations are in fair agreement with the measurements taking into account the error in K_h and the errors in J_0 and B_0 .

The coupling loss is dominated by the inter-strand coupling loss and seems to be independent of the current level. This indicates that R_c does not depend on the Lorentz

TABLE III
RESULTS IN TERMS OF K_h AND K_e SCALED TO ONE APERTURE

Magnet	Cool-down	I ₁ A	I ₂ A	K _h J/kA	K _e J/kA/(A/s)	K _{h,calc} J/kA
AN1	1	2975	10486	17	0.44	11
	2	2893	10982	11	0.57	11
AN2	1	0	2907	25	0.41	25
	1	2907	8551	14	0.42	11
CE1	2	0	2874	25	1.07	11
	2	2874	6035	8	1.15	5
	2	0	4355	16	1.25	9
	3	2874	8999	11	1.13	4
EL1	2	2893	10404	6	0.91	13
EL2	2	0	2907	27	0.48	26
	2*	0	2907	20	0.51	19
	2	2907	7363	8	0.55	12
	2*	2907	7066	7	0.51	8
EL3	3	0	2907	22	0.50	26
	3	2907	8056	11	0.49	12
	1	0	2874	23	0.85	32
	1	2874	8999	15	0.82	15
HO1	3	0	2907	25	0.23	31
JS1	2	2893	10982	4	0.41	9
	3	3966	10982	7	0.41	8
	3	2975	12055	8	0.40	9
	4	0	2975	21	0.42	22

* Measurements at 4.3K

force onto the cable and that R_c is not magnetoresistive.

For the EL2 model the coupling current losses at 4.3 K and 1.9 K are equal.

The results of the measurements on the poles (not included in Table III) indicate that the hysteresis loss does not vary among the poles. The coupling loss between the poles however, differs for most of the magnets with about 10-30%. This difference can cause relatively large skew harmonics at small fields during charging of the magnets [14] with the foreseen ramp rate for the LHC of about 10 A/s.

From the factor K_e , related to the coupling current loss, an estimation can be made of the average contact resistance between crossing strands using (3) and assuming $R_c = R_{c,i} = R_{c,o}$. As the loss is mainly generated in the inner layer the results are ordered with respect to the type of cable used for the inner layer (see Table IV).

For several series of measurements the accuracy of the results is sufficiently high to deduce the time constant τ_e of the inter-strand coupling currents by fitting the measurements to (5). The results (see Table IV) are in good agreement with the calculated values $\tau_{e,calc}$ using (4) and the obtained value for $R_{c,i}$. Table IV also shows that the magnets in which cable I-3 is used for the inner layer exhibit a different inter-strand coupling loss with a factor 4.

TABLE IV
AVERAGE INTER-STRAND COUPLING CURRENT CONSTANTS

Magnet	Cable for the inner layer	K_e J/kA/(A/s)	R_c $\mu\Omega$	$\tau_{e,calc}$ s	τ_e s
AN1	I-1	0.50	3.1	1.8	-
AN2*	I-1	0.41	3.8	1.4	-
JS1	I-1	0.41	3.8	1.5	1.6
CE1	I-2	1.16	1.3	4.1	4.6
EL1	I-3	0.91	1.6	3.2	-
EL3*	I-3	0.83	1.7	2.9	3.1
EL2	I-3	0.51	2.8	1.8	1.8
HO1	I-3	0.23	6.2	0.8	-

* See remark in Table I

VI. CONCLUSIONS

AC loss measurements have been performed on 6 one-metre dipole model magnets for the LHC by measuring electrically the stored energy during a linear ramp up and the extracted energy during a linear ramp down.

The filament hysteresis is in fair agreement with calculations.

The models exhibit a large inter-strand coupling loss during charging and discharging attributed to a small contact resistance between crossing strands of about 1 to 6 $\mu\Omega$.

Time constants of the coupling currents are measured in the range from 1 to 5 seconds and correspond well with calculated values.

The coupling current losses at 4.3 K and 1.9 K are equal.

The inter-strand coupling loss varies with about 10-30 % between the 4 poles of the twin aperture models. This can cause relatively large skew harmonics during charging with a ramp rate of 10 A/s as foreseen for the LHC.

The inter-strand coupling loss does not depend on the current level and does therefore not depend significantly on the Lorentz force onto the cable.

Magnets in which the same cable is used have shown to exhibit an inter-strand coupling loss which differs with a factor 4. The cross contact resistance depends therefore not only on the surface treatment of the wire and on the cabling process but can also depend on the way in which the cable isolation is placed, the time between isolating the cable and winding the magnet (oxidation effects) and the prestress level in the magnet.

ACKNOWLEDGEMENT

The authors would like to thank C. Giloux and B. Geroudet for performing part of the measurements.

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