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FOR THE LHC

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COUPLING LOSSES IN A SUPERCONDUCTING MODEL MAGNET FOR THE L.H.C.

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ABSTRACT

In the framework of a future Large Hadron Collider (L.H.C.) at C.E.R.N. high field (8-10 T) magnet models are in development. We have studied and measured the strand coupling losses in a single aperture, 1 meter long dipole. This dipole works at superfluid Helium temperature with a NbTi soldered cable. The calculations are based on the intrinsic decay time constant of the induced currents. This parameter has been obtained experimentally on a stack of magnet cables. The shape factor has been calculated for any dipole. Modelling the magnet as a transformer with a lossless primary and a secondary short circuited on a resistance representing the induced currents losses we have shown that the losses during a discharge may be calculated only from the simple measurement of the tension of the dipole after the current of the magnet becomes zero. Calculations and measurements are performed for discharges of magnet at high current rates (80 - 200 A/s). The results from calculations and measurements are in good agreement.

INTRODUCTION

A developement of high field (8-10 T) magnet models and prototypes is carried out for the Large Hadron Collider (L.H.C.) at C.E.R.N. [1][2]. This proposed superconducting collider is intended to be installed in the existing 27 km long tunnel of the L.E.P. (Large Electron Positron Colliding beam accelerator). The losses in the superconducting magnets during the ramping or the decay of the magnetic field are an important feature for the developement of superconducting cables and they have a major impact on the installed cryogenic power for L.H.C.

Subject of this report is the calculation and the measurements of the strand coupling losses for quick linear discharges in a model magnet.

MODEL MAGNET CHARACTERISTICS

This one meter long, 8 T nominal field, superconducting dipole has been designed and constructed in close collaboration with European Laboratories [3] and Industries. The superconducting coils are wound with a NbTi cable and are cooled by superfluid Helium at 1.8K to 2 K.

A cross section of the magnet is presented fig. 1 whereas further informations may be found in reference [3]. The winding of the first dipole consists of two layers of the same superconducting flat cable.

FIGURE 1 : cross-section of the magnet .

The main characteristics of the cable are listed in table 1. The cable of the model dipole is fully soldered. To get an high resistivity at low temperature ($\rho = 3.5 \mu\Omega\text{cm}$) to decrease the losses, 4.5 % of Indium has been included into the solder.

TABLE 1 : Main characteristics of the cable.

Cable geometry	
- side heights (mm)	1.31/1.66
- width (mm)	12.6
Number of strands	30
Strand diameter (mm)	0.84
NbTi filament diameter (μm)	10
Number of filaments	2460
Cu/Sc ratio	1.8
Twist pitch of the strand (mm)	25
Transposition pitch (cable) (mm)	114

A fondamentale parameter for the strand coupling losses of a cable is $\theta/1-N$ [4], where θ is the decay time constant of the coupling currents and N the demagnetization factor of the winding. $\theta/1-N$ is an intrinsic property of the cable whereas θ depends on the winding.

For a magnetic induction with following characteristics :

- perpendicular to the broad face of the cable,
- a linear time ramping of duration T from a steady state field down to zero,
- a linear spatial variation across the cable between the values B_1 and B_2 at $t=0$,

the expressions for the loss density w and the power density p are :

$$w = \frac{1}{\mu_0} \left(\frac{B_1+B_2}{2} \right)^2 \frac{\theta}{1-N} \frac{1}{T} \left(1 - \frac{\theta}{T} \left(1 - e^{-T/\theta} \right) \right) \quad (1)$$

$t < T$:

$$p = \frac{1}{\mu_0} \left(\frac{B_1+B_2}{2} \right)^2 \frac{\theta}{1-N} \left(1 - e^{-t/\theta} \right)^2 \quad (2)$$

$t > T$:

$$p = \frac{1}{\mu_0} \left(\frac{B_1+B_2}{2} \right)^2 \frac{\theta}{1-N} \left(1 - e^{-T/\theta} \right)^2 e^{-2(t-T)/\theta} \quad (3)$$

For the cable $\theta/1-N$ has been measured from a stack of short length cables and amounts to 4.7 s.

EVALUATION OF THE SHAPE FACTOR $1-N$ FOR A DIPOLE

Assuming that the tangential component of the dipole field is constant in a block of conductors, the inter-strand coupling currents in the cable are independant of the angular position. When the cables are submitted to a variable field, the induced currents through the $2c$ wide cable are represented by two current sheets K_1 and K_2 of opposite direction. They are located at $\pm c/2$ from the center of the cable (fig. 2a) at two radius denoted respectively by r_1 and r_2 . As the current is conservative K_1 and K_2 satisfy the relation :

$$K_1 r_1 = K_2 r_2$$

The magnetic induction created by the two current sheets in a block at the point A (fig. 2a) is given by [5] :

$$B(A) = \frac{\mu_0}{2} \sum_{n=1}^{\infty} K_1^n \left\{ \left(\frac{r_1}{r_0} \right)^{n+1} \left(1 - \left(\frac{r_0}{r_s} \right)^{2n} \right) + \frac{r_1}{r_2} \left(1 + \left(\frac{r_2}{r_s} \right)^{2n} \right) \left(\frac{r_0}{r_2} \right)^{n-1} \right\} \quad (6)$$

where n , odd (symmetry), is the range of the harmonic and K_1^n the n th harmonic of K_1 .

$$n = 2p+1 \text{ with } n \text{ integer ; } K_1^n = \frac{4}{\pi} \frac{\sin n\alpha}{n} K_1$$

FIGURE 2 : modelling of the coupling currents in a dipole.

The shape factor verifies the relation :

$$\frac{1-N}{1-N'} = \frac{B}{B'} \quad (4)$$

where B and B' are the resulting inductions of the same coupling currents (equal representative current sheet) but for windings characterized respectively by the demagnetization factors N and N' . By analogy with a torus, the demagnetization factor is zero for

the winding shown by figure 2b while $B'(A)$ amounts to :

$$B'(A) = \mu_0 K_1 \frac{r_1}{r_0} \quad (5)$$

The shape factor deduced from relations (4),(5) and (6) is then :

$$1-N = \frac{2}{\pi} \sum_{p=0}^{\infty} \frac{\sin(2p+1)\alpha}{2p+1} \left\{ \left(\frac{r_1}{r_0} \right)^{2p+1} + \left(\frac{r_0}{r_2} \right)^{2p+1} + \left(\frac{r_0 r_2}{r_s r_s} \right)^{2p+1} - \left(\frac{r_0 r_1}{r_s r_s} \right)^{2p+1} \right\}$$

The values of the shape factor are given for the various α corresponding to the conductor blocks in the dipole using the notations :

$$\frac{r_1}{r_0} = x_1 \quad \frac{r_0}{r_2} = x_2 \quad \frac{r_0 r_2}{r_s r_s} = x_3 \quad \frac{r_0 r_1}{r_s r_s} = x_4$$

$$\alpha = \frac{\pi}{2} \quad 1-N = \frac{2}{\pi} \left\{ \sum_{i=1}^3 \operatorname{arctg} x_i - \operatorname{arctg} x_4 \right\}$$

$$\alpha = \frac{\pi}{3} \quad 1-N = \frac{1}{\pi} \left\{ \sum_{i=1}^3 \operatorname{arctg} \frac{\sqrt{3} x_i}{1-x_i^2} - \operatorname{arctg} \frac{\sqrt{3} x_4}{1-x_4^2} \right\}$$

$$\alpha = \frac{\pi}{4}$$

$$1-N = \frac{1}{\pi} \left\{ \sum_{i=1}^3 \operatorname{arctg} \frac{\sqrt{2} x_i}{1-x_i^2} - \operatorname{arctg} \frac{\sqrt{2} x_4}{1-x_4^2} \right\}$$

$$\alpha = \frac{\pi}{6} \quad 1-N = \frac{2}{3\pi}$$

$$\left\{ \sum_{i=1}^3 \operatorname{arctg} x_i + \operatorname{arctg} x_i^3 + \frac{1}{2} \operatorname{arctg} \frac{x_i}{1-x_i^2} \right\} - \left\{ \operatorname{arctg} x_4 + \operatorname{arctg} x_4^3 + \frac{1}{2} \operatorname{arctg} \frac{x_4}{1-x_4^2} \right\}$$

For the studied model dipole the numerical values amount to :

$$1-N_{\alpha=\pi/2} = 0.95 \quad 1-N_{\alpha=\pi/3} = 0.94$$

$$1-N_{\alpha=\pi/4} = 0.92 \quad 1-N_{\alpha=\pi/6} = 0.88$$

THEORETICAL CALCULATION OF THE MAGNET LOSSES

The calculation deals only with the coupling current losses induced by the field perpendicular to the broad face of the cable in the straight parts of the

magnet supposed to be one meter long. These losses are dominant in the measured dipole magnet due to the geometry of the cable and the fast variation of the field. We have then neglected the losses due to the field parallel to the broad face of the cable and the losses in the superconducting strands (magnetization and inter filament coupling losses).

Using expressions (1) (2) and (3) the losses are evaluated for each block of conductors listed in fig.3 for a linear discharge from 10 kA down to 0 in 80 s ($dB/dt = 0.107$ T/s).

FIGURE 3 : flux lines distribution at $I = 10$ kA and numbers of the blocks.

Hypothesis for calculation :

- B_1 and B_2 : in each block B_1 and B_2 are supposed to be constant and equal to the mean values of the tangential induction component along respectively the inner and outer surfaces of the blocks given by the programme POISSON for $I = 10$ kA. A field distribution is given fig.3.

- $1-N$: considering the relative values of the losses in the different blocks, $1-N$ is calculated only from the blocks 1 and 2. Coupling losses being proportionnal to the mean induction variation speed, the current sheets modeling these currents in the blocks 1 and 2 are in the ratio of the mean induction in both blocks. The field in the block 2 is 80% of the field in the block 1. To calculate the shape factor of the blocks 1 and 2 the magnetic field is subdivided

in two parts : the first one which covers the two blocks ($-\pi/3 ; +\pi/3$) amounts to 80% of the field, the second part amounts to 20% of the field and covers only the first block ($-\pi/6 ; +\pi/6$).

$$1-N = 0.8 (1-N)_{\alpha=\pi/3} + 0.2 (1-N)_{\alpha=\pi/6}$$

$$1-N = 0.93$$

It appears that the shape factor in the tested model magnet is close to 1.

As $\theta/1-N$ is an intrinsic property of the cable which has been measured equal to 4.7 s, the decay time constant in the magnet is deduced to be :

$$4.7 \text{ s } (1-N) = 4.4 \text{ s.}$$

The losses calculation for each block are reported in table 2.

TABLE 2 : losses calculation for each block

n° block/ number of cables	B_1 (T)	B_2 (T)	Volume (cm ³)	w MJ/m ³	E (J)	$P_{\max}$ (W)
1/10	8.0	2.6	187	1.24	232	3.07
2/8	6.6	1.9	150	0.80	120	1.58
3/3	2.5	0.0	56	0.07	4	0.05
4/15	2.1	-2.4	280	<0.01	0.3	<0.01
5/6	1.1	-1.3	112	<0.01	<0.1	<0.01

The values for the dipole are :

- maximal dissipated power : $P_{\max} = 18.8 \text{ W}$
- total dissipated energy : $E = 1425 \text{ J}$

EXPERIMENTAL LOSSES MEASUREMENT.

The magnet is seen as a transformer with a lossless primary and a secondary short-circuited on a resistance (fig. 4). The secondary current represents the coupling currents.

The equations governing these circuits are :

$$V = L \frac{di}{dt} + M \frac{dj}{dt}$$

$$0 = R i + l \frac{di}{dt} + M \frac{dj}{dt}$$

FIGURE 4 : electrical modelling of the magnet.
($\theta = \frac{1}{R}$)

If I^0 represents the initial main current I and P_f the power dissipated in the resistance R the resolution of the equations leads to the following results :

$t < T$: linear magnet discharge $\frac{dI}{dt} = \frac{I^0}{T} = \text{constant}$

$$V = L \frac{I^0}{T} - \frac{M^2}{l} \frac{I^0}{T} \exp\left(-\frac{t}{\theta}\right)$$

$$P_f = \frac{M^2}{R} \left(\frac{I^0}{T}\right)^2 \left[1 - e^{-t/\theta}\right]^2$$

$t > T$: discharge ended $I = 0$

$$V = \frac{M^2}{l} \frac{I^0}{T} \left[1 - e^{-T/\theta}\right] \exp\left(-\frac{t-T}{\theta}\right)$$

$$P_f = \frac{M^2}{R} \left(\frac{I^0}{T}\right)^2 \left[1 - e^{-T/\theta}\right]^2 \exp\left(-2 \frac{t-T}{\theta}\right)$$

The total energy E is :

$$E = \frac{M^2}{R} \left(\frac{I^0}{T}\right)^2 \left\{ T - \theta \left[1 - e^{-T/\theta}\right] \right\}$$

The voltage across the magnet when $I=0$ ($t = T^+$) is noted V^0 , it amounts to :

$$V^0 = \frac{M^2}{l} \left(\frac{I^0}{T}\right) \left[1 - e^{-T/\theta}\right]$$

P_f and E may be expressed using V^0 :

$$E = \theta \frac{I^0}{T} V^0 \frac{T - \theta \left[1 - e^{-T/\theta}\right]}{1 - e^{-T/\theta}}$$

$$t < T: P_f = \theta \frac{I^0}{T} V^0 \frac{\left[1 - e^{-t/\theta}\right]^2}{1 - e^{-T/\theta}}$$

$$t > T: P_f = \theta \frac{I^0}{T} V^0 \left[1 - e^{-T/\theta}\right] \exp\left(-2 \frac{t-T}{\theta}\right)$$

The losses can be calculated from the measurements of θ and V^0 since T and I^0 are imposed.

V^0 and θ may be deduced from the decay of V when the discharge of the magnet is ended (logarithmic decrement method).

The Measurements are reported in table 3.

TABLE 3 : fast discharge measurements.

I^0 (kA)	dI/dt	T	θ	V^0	$P_{\max}$	E
test number	(A/s)	(s)	(s)	(mV)	(W)	(J)
5/1	80	62.5	5.0	14	5.0	320
5/2	100	50	5.0	19	9.5	430
5/3	125	40	4.9	30	18	640
8/4	125	64	4.9	31	19	1120
5/5	150	33.3	5.0	35	26	740
5/6	175	28.6	5.1	42	37	880
5/7	200	25	5.1	50	51	1020
3/8	110	27.3	5.0	25	13.7	310

V^0 has been extrapolated from the straight line of slope θ in semi logarithmic scale as the current cut is not perfect. It can be verified that the quantity $\frac{V^0}{1 - \exp(-T/\theta)}$ is approximately proportionnal to $\frac{I^0}{T}$ as theoretically expected (fig. 5).

FIGURE 5 : variation of $\frac{V^0}{1 - \exp(-T/\theta)}$ with $\frac{I^0}{T}$.

The value of θ amounts to $5s \pm 2\%$ for the eight tests. Compared with the theoretical value the relative error is 14 %.

Considering an initial current of 10kA we get from test n°4 the following results:

$$P_{\max} = 19 \text{ W} \quad E = 1420 \text{ J}$$

The theoretical results for this discharge are recalled:

$$P_{\max} = 18.8 \text{ W} \quad E = 1425 \text{ J}$$

The agreement is very good considering all the hypothesis done both for theory and measurement.

5. A. Hughes, T.J.E. Miller , Analysis of fields and inductances in air-cored and iron-cored synchronous machines. Proc. IEE , 1977 , 124 ,121-126.

CONCLUSION

The measurement of the voltage across the magnet is a very simple method to get the coupling current losses in a magnet. The results on the model magnet indicate small differences (10%) with the theoretical calculations. The results have to be confirmed by tests on other magnets.

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REFERENCES

1. G. Brianti, K. Hubner, The Large Hadron Collider in the L.E.P. tunnel. CERN 87-05
2. R. Perin, Progress on the superconducting magnets for the large Hadron collider. , IEEE Trans. on Magn. , 1988 , 24 , 734-740.
3. R. Perin, D. Leroy, G. Spigo, The first, industry made, model magnet for the Large Hadron Collider , IEEE Trans. on Magn. , 1989 , 25 , 1632-1635
4. A. M. Campbell, A general treatment of losses in multifilamentary superconductors, Cryogenics , 1982 , 3-16.