Experimental Study of CMS Conductor Stability

P.Fabbricatore (1), S.Farinon (1), F.P.Juster (2) R.Musenich (1) and C.Priano (1)

(1) INFN, via Dodecaneso 33, I-16146 Genova, Italy, (2) CEA Saclay, Dapnia, Gif/Yvette, France

***Abstract*--Several computations have been carried out in last years to evaluate stability against disturbances of the CMS coil. The results coming from finite element analysis have shown that the Minimum Quench Energy is between 0.43 and 0.85J depending on the model describing the transition from superconducting to normal state. The corresponding Minimum Propagating Zone is quite short, ranging between 10 and 20cm. This very short MPZ allows to perform experimental measurements on short samples. This has been done using circular samples (400mm in diameter) energized to 20kA by the transformer method. The applied field ranging between 3.5 and 6T, is provided by the Ma.Ri.S.A. facility at INFN Genova. A comparison between computations and experimental results is presented.**

I. INTRODUCTION

For stability we mean the ability of a superconducting coil or conductor to absorb a disturbance (local or distributed) without quenching. The transient analysis is needed to analyze the dynamic thermal and electrical processes occurring inside the winding after a heat release causes a local normal zone. In this case a small area of the winding becomes normal and the current starts to flow in the matrix causing ohmic dissipation. If the conductor is able to recover the superconducting state the coil is stable, otherwise the transited length starts to grow and the coil quenches. Following Wilson [1] we can introduce two important parameters: the Minimum Propagation Zone (MPZ) and the Minimum Quench Energy (MQE).

The MPZ is defined as a normal resistive zone in metastable thermal equilibrium with the superconducting zone around it. If a normal zone is bigger than the MPZ, the magnet will quench, if it is smaller it will recover to the superconducting state. The MQE is the minimum energy required to generate a MPZ. When performing transient analysis, we have to consider that the problem is three-dimensional, the medium is highly non-homogeneous and, at low temperatures, the thermal properties of the materials strongly depend on temperature. These conditions lead to solve the heat transient diffusion equations by using a finite element code. Our method consists in imposing a given disturbance of given energy and length and solving the equation describing how the normal zone (if any normal zone is created) increases causing a quench, or reduces restoring a full superconducting state. The codes involved are HEATING 7.3 and CASTEM. This approach was tested comparing calculated and experimental MQE for a coil model of DELPHI magnet [2]. In this paper we will discuss a new comparative study between experimental results and prediction of finite element codes. In this case the system under analysis is not as complex as a coil. We will show that, the relative simplicity of the system allows both a better understanding of experimental results and a reliable application of FEA.

II. TRANSIENT ANALYSIS STUDIES ON CMS COIL

In this section we will briefly summarize the most updated FEA results of the transient response to localized disturbances in CMS coil. Let's recall some basic parameters. The current sharing temperature T_g is defined as

$$T_g = T_c(B) - [T_c(B) - T_0]\frac{I_m}{I_c(B)}, \qquad (1)$$

where T_c and I_c are the critical temperature and the critical current at the operating magnetic field B [3]:

$$\begin{cases} T_c(B) = T_{c0}\left(1 - \dfrac{B}{B_{c20}}\right)^{0.59} \\ I_c(B) = I_c(1 - 0.096B) \end{cases} \qquad (2)$$

For a NbTi conductor the critical temperature at zero applied field is T_{c0}=9.25K and the second critical field is B_{c20}=13.9T. The CMS operating current and temperature are: I_m=19.5 kA and T_0=4.5K. From magnetic computation the conductor peak field (self field plus applied field) is B=4.6T. The critical current at peak field and operating temperature is Ic= 56 kA. By using those numbers we found:

$$\begin{cases} T_c(B) = 7.35\text{K} \\ T_g(B) = 6.35\text{K} \end{cases} \qquad (3)$$

Basic assumptions of the codes are:

- the material thermal properties are described as function of temperature and magnetic field: thermal conductivity K=K(T,B), electrical resistivity ρ=ρ(B,T) and specific heat C_p=C_p(T);
- the system is adiabatic and the initial temperature is fixed and uniform;
- the thermal disturbance is modeled as a constant power dissipated for a given time in a given region.
- the heat generation is temperature dependent. For T<Tc we have no dissipation, as T>T_g the current starts flowing into the Al matrix causing a Joule dissipation per unit volume.

The last assumption is correct if we assume that the exceeding current can be shared instantaneously by the whole Al-matrix, but because of the eddy currents this is not true. The appropriate way to describe the heat generation is in term of diffusion of the electrical field according to the equation:

$$\Delta\vec{E} = \frac{\mu_0}{\rho_{eff}}\frac{\partial\vec{E}}{\partial t} \qquad (4)$$

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P.Fabbricatore, Phone 39-010-3536340, Fax 39-010-313358, e-mail Fabbricatore@ge.infn.it

In HEATING we assume that the heat generation starts when $T \geq \frac{T_g + T_c}{2}$ imposing the dissipation calculated by solving.(4) with the finite element code ANSYS. The time dependent dissipation is shown in Fig.1. In CASTEM, both effects, current sharing and diffusion are taken into account. The model for the numerical computation schematised the winding as a parallelepiped where the plane X-Y represents a small portion of the Z-R section of the coil, and the longitudinal direction Z represents the coil azimuthal direction. Fig. 2 shows the used model.

Three different cases, with different locations of the disturbance, are studied:

- inside a single conductor ,
- near the Al-6061 reinforcement of the CMS conductor (simulating a crack in the resin at the interface with the Al-6061 reinforcement),
- between two cables with some epoxy resins in-between (simulating a crack of the inter layer insulation).

In Fig. 3 a typical time evolution of the normal zone calculated by using HEATING (for case 1) is shown. The squares show a transited zone, generated by a disturbance of 0.621 J, which recovers to the superconducting state, while the circles show that for a bigger energy the transited length grows causing the quench. From those calculations we can also estimate the MPZ length, 12cm, which develops in only 5ms. In Fig.4 the quench energy for different pulse duration is plotted. From these calculations we found a MQE of 0.62 J by using HEATING and 0.75 J by using CASTEM.

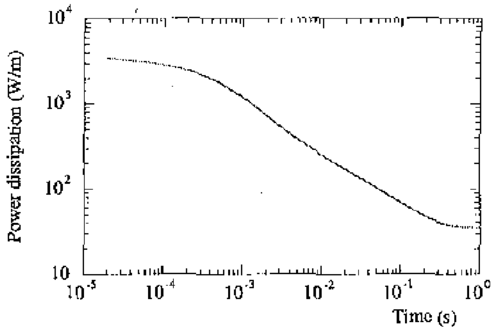

Fig. 1. Time dependent heat dissipation due to the current diffusion.

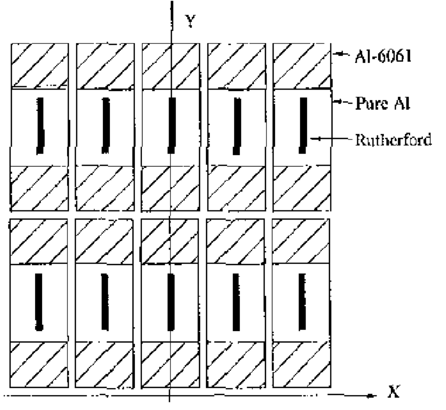

Fig. 2. X-Y section of the CMS winding model. The space between conductors is filled with fiber glass epoxy.

Same calculations have been carried out for case 2. We found a MQE of 3.51J (see results in Fig.5). For case 3 we found a MQE of 8.34J (Fig.6). In Table I, these results are summarised.

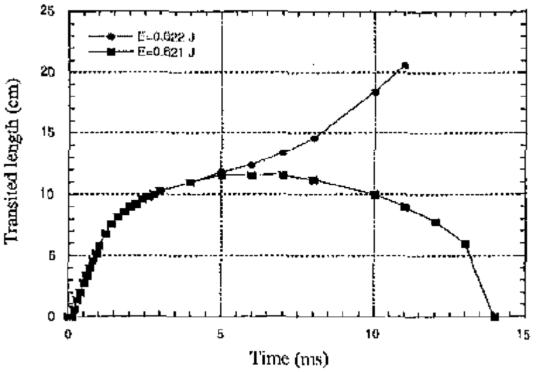

Fig. 3. Time evolution of the normal zone calculated for a disturbance of 1ms duration and 1cm length.

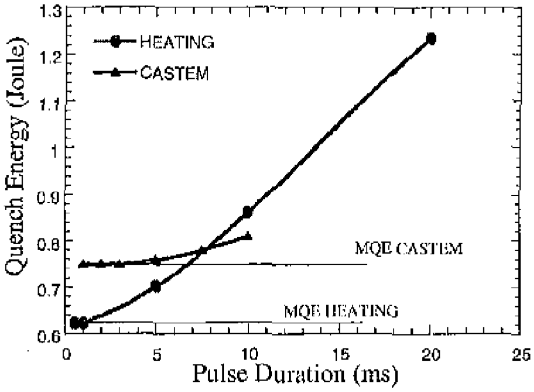

Fig. 4. Comparison of the quench energy vs. pulse duration calculated by using the two codes.

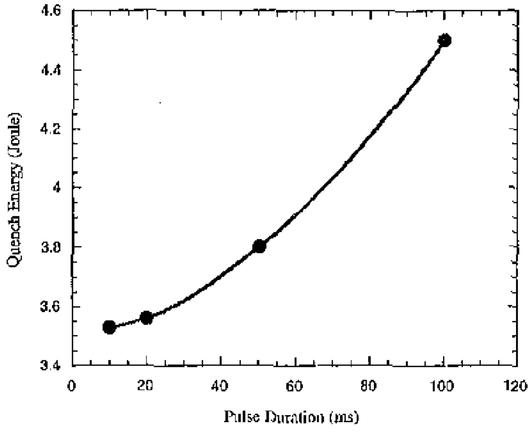

Fig. 5. CMS quench energy in case of resin crack at Al-alloy interface.

TABLE I

SUMMARY OF FEA RESULTS FOR CMS COIL STABILITY

CASE	MQE
Disturb inside conductor	0.62J
Crack in the resin at Al-alloy interface	3.51J
Inter-layer resin crack	8.34J

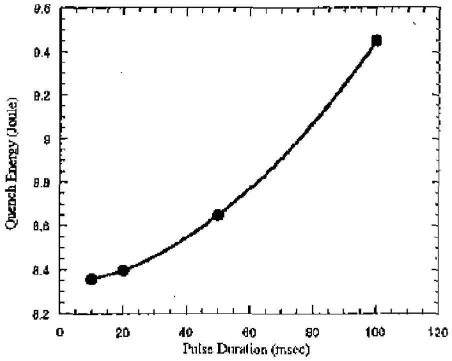

Fig. 6. CMS quench energy for an interlayer resin crack.

These calculations are very important for the coil design because we have found that we can have higher level of disturbance in insulation with respect to disturbance inside conductor (a factor 13 in MQE).

It is interesting to perform a check of the ability of the HEATING code in predicting quench energy of known systems. Some time ago we performed this kind of test, by evaluating the MQE of a mock-up coil of DELPHI magnet [2]. Presently we want to make a more relevant test on a system including a CMS type conductor.

III. TEST SAMPLE AND EXPERIMENTAL SET-UP

A special sample has been developed (at CEA and INFN) for test in the Ma.Ri.S.A. facility at INFN-Genova [4]. The sample, schematically shown in Fig. 7, is made of an external Al-Alloy ring (Height=70mm, O.D.=438mm, I.D.=428mm) containing an Al stabilized conductor (70x35mm), mechanically coupled through a soft-soldering process. The superconducting part is a Rutherford cable composed of 32 strands with Copper/SC ratio 1.25/1. The sample has been designed in order to have a maximum deformation of 1.5 ‰ when charged at 50kA in a 4.0 T magnetic field. This was done in order to perform critical current measurement in mechanical conditions similar to CMS coil. For its mechanical properties, and electrical configuration, this sample can be considered as a good example of CMS-type reinforced conductor (though the lay.-out is considerably different from actual CMS conductor). The sample was connected to the sample holder taking care to minimize the mechanical interaction between them (Fig. 8). The current is induced in the sample using the direct transformer method [5]: the magnet is the primary winding of the transformer and the sample the secondary one. The sample is indirectly cooled by He vapors at 4.2K.

The current flowing in the sample is determined by self-field measurements using a Hall probe placed just over the conductor in order to minimize the signal due to the external field, and maximize the self-field signal. Two voltage taps are soldered at the sample. As shown in Fig.9 the signal passes through a low noise amplifier and is then measured by a National Instruments DAQ board. An electrically isolated heater is glued to the internal part of the conductor.

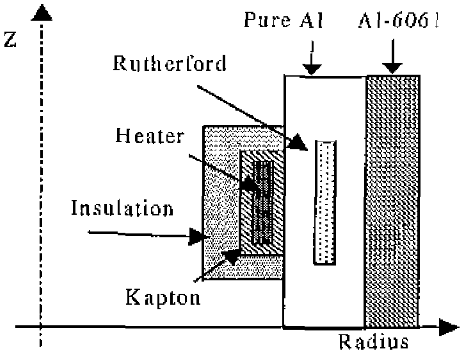

Fig. 7. Z-R section of the sample holder.

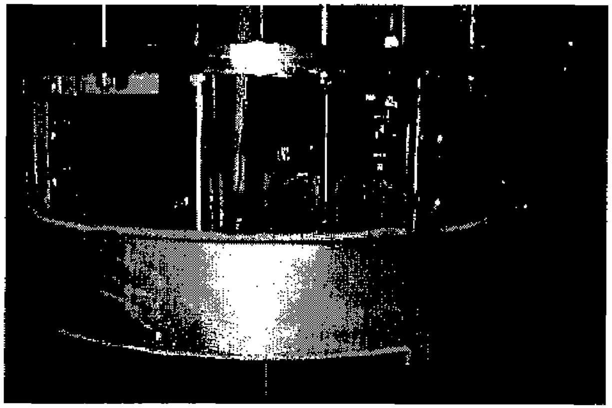

Fig. 8. Sample-holder.

The heater is used to give heat pulse to the conductor. At a fixed value of external field, sample current and temperature, a single square signal is sent to a power amplifier, which supplies current to the heater. The disturbance energy is determined by the pulse time (order of some ms) at fixed power (up to 750 W). During and after each disturbance the voltage signal (see Fig.10) is monitored to verify if a quench occurs . When the signal is sent to the heater, a trigger signal is sent to the DAQ board. It starts to measure the voltage signal at a scan rate of 1000 Hz. The measurements are then stored in a PC.

IV. EXPERIMENTAL RESULTS AND SIMULATIONS

As first step, the critical current of the sample was measured, in order to be sure to perform the stability experiment at a current level 35% of critical current (as in CMS coil). We measured a critical current of 60 kA at B=4.5T and T=4.22 K. As a consequence measurements performed around 21 kA and 4.5 T are those ones closer to the actual CMS coil condition . Measurements include different sample currents and external fields. Results are shown in Table II. In this kind of experiment it is important to know how the disturbance is seen by the conductor. Some information comes from the analysis of the signal at voltage taps. Fig.10 shows a typical signal for a disturbance inducing a quench. The time delay from t=0 (pulse starts at generator) at the quench time is an important parameter.

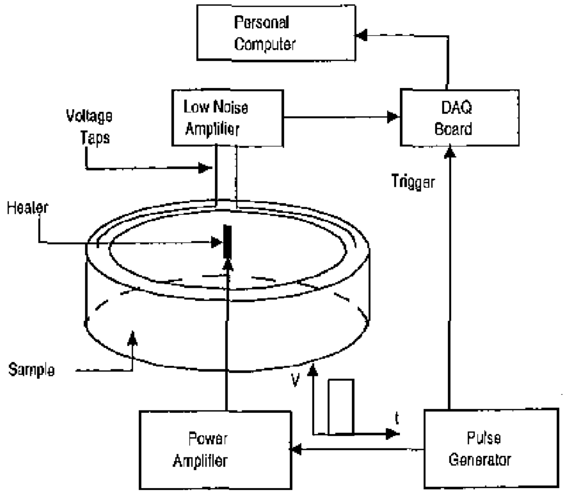

Fig. 9. Block diagram of the measurements system.

The delay (50 ms in our case) is related to the time needed by heat to diffuse through the insulation surrounding the heater. When performing simulations we sized the insulation between heater and sample just to fit the measured time delay. In this frame it can be interesting to look at the broadening of the disturbance. Fig.10 shows the result of a computation of heat diffusion through the heater, the pure aluminium and the Rutherford: in particular one can see how a disturbance, given in 5 ms at the heater, is seen by the SC cable in adiabatic conditions. The energy release occurs in a time of about 1 s; 22% of energy in the first 50 ms and 33% in the first 100 ms; i.e. we have to wait some time before a significant energy is transferred to the SC cable. Another aspect of measurement is related to the sample cooling. Since the sample is not in vacuum, but is directly cooled by helium vapor, we had to include the heat transfer to He gas. FEA results and comparisons with the experimental ones are shown in Table II.

In order to demonstrate that the measured quench energy is the MQE, we had to give both shorter disturbances at the same measured quench energy and higher disturbances in longer time.

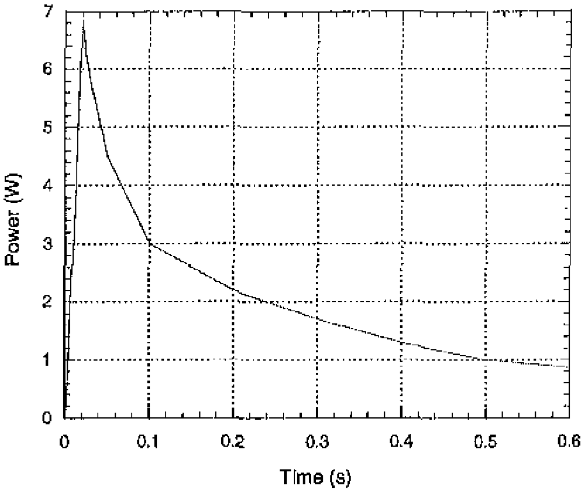

Fig. 10. Calculated power in the Rutherford cable for a disturbance given at the heater in 5 ms

TABLE II

RESULTS FROM EXPERIMENT WITH SAMPLE COOLED BY GAS

Meas.	Curr. (A)	B (T)	Δt (ms)	Energy (J)	Quench	Calc. values
A	30000	4.62	5 8	3.8 J 6.0J	NO YES	4.8 J
B	28600	4.42	8 9	6.0J 6.8J	NO YES	5.5 J
C	25000	4.80	9 10	6.8J 7.5J	NO YES	5.0 J
D	23200	4.12	5 10	3.8J 7.5J	NO YES	6.8 J
E	21500	4.88	9 10	6.8J 7.5J	NO YES	5.4 J
F	21200	4.31	7.5 10	5.6J 7.5J	NO YES	6.5 J

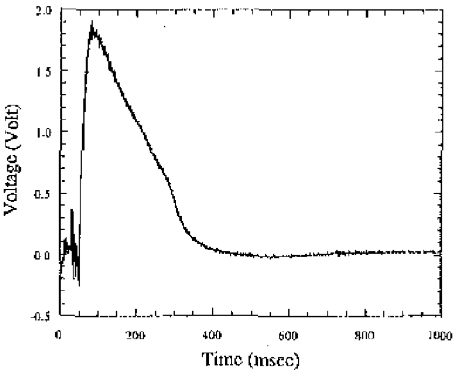

Fig. 11. Typical quench detection measure

Unfortunately we are limited by the amplifier power and by the fact that this kind of measurement is significant only if the Minimum Propagating Zone is localized. For disturbances longer than 10 ms at the heater, the MPZ is longer than our sample (1.3 m), and, consequently the measurement makes no more sense. However the experimental data are very close to simulations, so that we can state that the use of FEA helps in giving a satisfactory representation of dynamic processes occurring during localized transition to normal state. On this base we can assume that the computed Minimum Quench Energies of CMS coil (as shown in Figs. 3 to 6) are basically correct. In fact these values were taken into consideration when evaluating the possible disturbance spectrum in CMS coil [6].

REFERENCES

[1] M. N. Wilson, *Superconducting Magnets*, Oxford: Oxford University Press, 1983

[2] F. Juster, J.C.Lottin, L.Boldi, R.De Lorenzi, P.Fabricatore, R.Musenich, D.E.Baynham, P.L.Sampson, *IEEE Trans. on Appl. Superconductivity*, Vol.5, Nr.2, P.337, 1995

[3] M.S. Lubell, *IEEE Trans.Mag*, Mag-19, No 3 p.754-757 (1983)

[4] P. Fabbricatore, R. Musenich, C.Priano, E.Sirola *MT15 Proceedings*, Part2, p.1307

[5] P. Fabbricatore, R.Musenich *Handbook of Applied Superconductivity* B7.4 , p. 324, IOP Bristol 1998

[6] CMS Coil Collaboration, *Proceeding of The Magnet Project EDR*, Editor F.Kircher CEA/Saclay CMS Doc. 1998-148