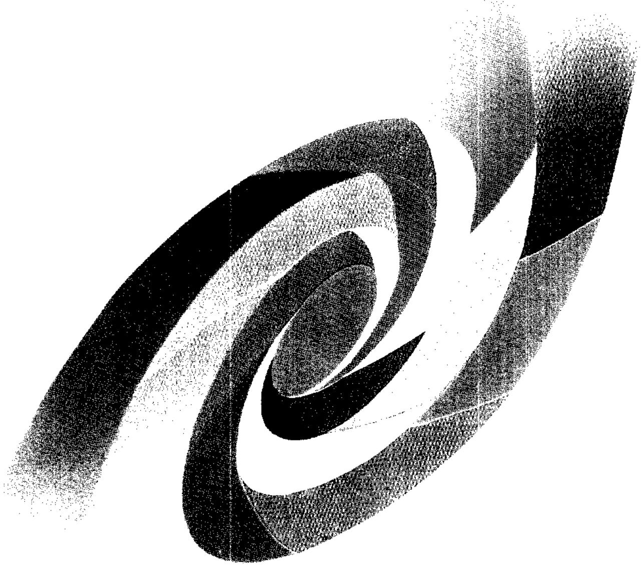
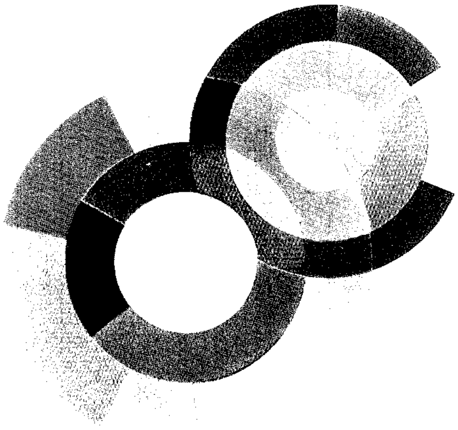
D!

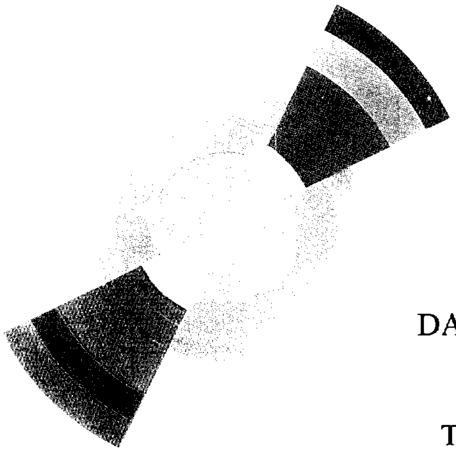
C.E. SACLAY
DSM

SERVICE TECHNIQUE DE CRYOGÉNIE ET DE MAGNÉTISME



SW9840





DAPNIA/STCM 98-06 August 1998

THERMAL STABILITY OF LARGE AI-STABILIZED SUPERCONDUCTING MAGNETS. THEOR~~I~~ETICAL ANALYSIS OF CMS SOLENOID

F.P. Juster, P. Fabbricatore

DAPNIA

Talk given at the 17th International Conference on Cryogenic Engineering (ICEC 17), Bournemouth (England), 14-17 July 1997

Couverture Sylvie Cabrit et Marc Sauvage

Le DAPNIA (**D**épartement d'**A**strophysique, de physique des **P**articules, de physique **N**ucléaire et de l'**I**nstrumentation **A**ssociée) regroupe les activités du Service d'Astrophysique (SAp), du Département de Physique des Particules Elémentaires (DPhPE) et du Département de Physique Nucléaire (DPhN).

Adresse : DAPNIA, Bâtiment 141
CEA Saclay
F - 91191 Gif-sur-Yvette Cedex

COMMISSARIAT A L'ENERGIE ATOMIQUE
DSM/DAPNIA/STCM

Rapport n° 6

Le 05/08/98

F.P JUSTER

Thermal stability of large Al-Stabilized superconducting magnets. Theor~~i~~tical analysis of CMS Solenoid

e

ICEC 17, Bournemouth
14-17 juillet 1998

Thermal Stability of Large Al-stabilized superconducting magnets. Theoritical analysis of CMS Solenoid

François-Paul Juster *, Pasquale Fabbricatore **

* CEA SACLAY - DSM / DAPNIA / STCM - 91191 GIF/YVETTE Cedex - France
**INFN, Sezioni di Genova, Via Dodecaneso 33, I-16146 Genova, Italy

The CMS detector magnet presently under design for the future Large Hadron Collider at CERN is an epoxy-impregnated structure, indirectly cooled by two-phase flow liquid helium. This magnet, based on aluminum-stabilized, mechanically reinforced conductor, is not cryostable : the heat generated by a thermal disturbance can be removed only by thermal diffusivity through the windings.

In order to study the thermal stability of the magnet, we have developed numerical codes able to predict the thermal behaviour of an anisotropic and non-homogeneous medium against thermal perturbations due to friction or epoxy cracking. Our 3D finite element codes can calculate the propagation or the recovery of a normal zone in a superconducting magnet, taking into account the current diffusion effect, which strongly affects the heat generated by a transition in the case of large Al-stabilized conductors.

Two different codes, CASTEM 2000 and HEATING are described in this paper. We present the results of the CMS Solenoid magnet stability analysis related to the size and duration of the thermal disturbance, the thermal properties of the conductor and the initial temperature of the magnet. The minimal energy required to initiate a quench in the magnet is found to be around 1 joule for a 64 x 22 mm^2 reinforced conductor carrying a 20 kA current under a 4-tesla magnetic field.

I. INTRODUCTION AND REVIEW OF THE BASIC CONCEPTS

The CMS (Compact Muon Solenoid) experiment is one of two large experiments approved to be installed on the Large Hadron Collider at CERN. The superconducting solenoid, which is the largest and most powerful ever designed, will provide a 4 teslas field in a 5.9-m-diameter and 13-m-long warm bore, leading to a stored energy of 2.7 GJ . The main technical choices are :

- the coil is subdivided into five modules ; each module is composed of four conductor layers,
- the modules are internally wound and vacuum epoxy-impregnated before assembly,
- the indirect cooling is given by two-phase liquid helium circulating in pipes connected to the structure in a thermosiphon mode,
- the conductor comprises three components : the NbTi Rutherford-type superconductiong cable, the high purity aluminum stabilizer and the mechanical aluminum alloy reinforcement (see fig. 1).

The CMS magnet is not cryostable. The heat generated by a thermal disturbance can be removed only by thermal diffusivity through the windings. In the present paper, we will not discuss about the perturbations which may occur in the magnet (bonding failure, epoxy crackings, conductor movement ...) and their expected level of energy, but we will calculate the maximal energy which can be locally dissipated without causing the quenching of the coil.

Wilson [4] introduced two important notions in the theory of stability of superconducting magnets against thermal disturbances : the Minimum Propagating Zone (MPZ) and the Minimum Quench Energy (MQE). The MPZ can be considered as a normal resistive zone, therefore producing heat by Joule effect, in metastable thermal equilibrium with the superconducting zone surrounding it. If a normal zone is formed with dimensions higher that the MPZ, a quench will develop. The MQE is the minimum energy required to form the MPZ. A thermal disturbance of an energy lower than the MQE will lead to the recovery of the superconducting state. Theoretically, the MQE corresponds to a punctual and instantaneous disturbance. In practice, the energy required to quench the magnet is the MQE for any disturbance whose size and duration are lower than, respectively, the MPZ and its formation characteristic time. For that study, we chose a numerical approach rather than an analytical formulation for several reasons :

1- the problem is not one-dimensional and the winding is a highly non-homogeneous medium,

2- at low temperatures, the thermal properties of the materials strongly depend on the temperature,

3- when a quench occurs, the current does not redistribute instantaneously from the cable to the aluminum stabilizer. During that transient phase, the heat deposited may be 2 orders of magnitude higher that the value given by an uniform current repartition in the stabilizer. This effect, known as "current diffusion effect", cannot be neglected in the case of high purity and large stabilizers. The over-energy due to this phenomenon is related to the release of magnetic energy and depends only on the size of the stabilizer. The associated time constant depends on both size and RRR. In our case, this time constant (a few seconds) is, as it will be shown below, two orders of magnitude larger than the MPZ formation time. It is therefore impossible to introduce the current diffusion effect as a simple fixed amount of energy in addition to the thermal disturbance.

Two laboratories CEA-SACLAY and INFN-Genova have separately modified existing 3D finite element codes to calculate the stability margins.

II. BASIC ASSUMPTIONS OF THE CODES

Both CASTEM (CEA-SACLAY) and HEATING (INFN-Genova) are finite element codes which can solve transient and non-linear thermal problems. Those codes have been modified to take into account the heat generated by the transition to the normal resistive state. The Table I shows the main conductor characteristics.

The basic assumptions of each model are as follows :

- The thermal properties (conductivity and specific heat) are described as functions of the temperature and the magnetic field; they are summarized in Table II. The RRR of aluminum is assumed to be 1000 at zero tesla field and 472 in the operating field due to the magneto-resistance. Three types of aluminum alloy reinforcement with different conductivities have been considered : Al 5083, Al 6061 and Al 6063. All the computations are made with the Al 6061 type (with the exception of the section V) which is, at the moment, planned to be used by the project management.

Table I . Conductor parameters

Pure aluminum area	612 mm^2
Copper area	21.34 mm^2
NbTi area	19.58 mm^2
Alloyed aluminum area	748 mm^2
Void area	7.35 mm^2
Conductor insulation	0.32 mm
Inter-layer insulation	0.40 mm
Ground plane insulation	1.0 mm
Number of strands	32
Nominal current	19500 A

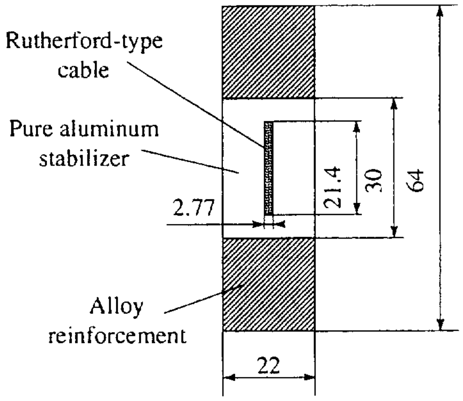


Fig. 1. CMS conductor (in mm)

- The electrical resistivity does not depend on the temperature, which is a reasonable assumption as the computations show that the temperature never exceeds 10 K.

- The initial temperature is 4.5 K. The system is adiabatic : the MPZ characteristic formation times are found to be several orders of magnitude lower than the characteristic time of thermal diffusion to the cold source.

- The thermal disturbance is described as a uniform power deposition in a given region during a given time ; this particular point will be discussed further. The chosen conductor for the computations is located in the first layer (see Fig.2), where the field is maximal and consequently the stability margin minimal.

- The current diffusion effect is taken into consideration. Previous studies [2,3] have shown that the assumption of instantaneous uniform current redistribution led to computed MQE increased of one order of magnitude.

The two codes differ in two points :

- The computations are carried out at a 4.6 T peak field by HEATING. In CASTEM, to take into account the fact that the field is not constant and equal to the peak value, we chose a moderated value of 4.1 T.

- In CASTEM, the current-sharing effect is included. The critical and current-sharing temperatures (T_c and T_{cs} respectively) for the nominal current are given in the following Table III. In HEATING, we make the assumption of an hard-edged transition at the mean temperature : $T_m = (T_{cs} + T_c)/2$. This assumption has been used as well in CASTEM computations but only in section III.

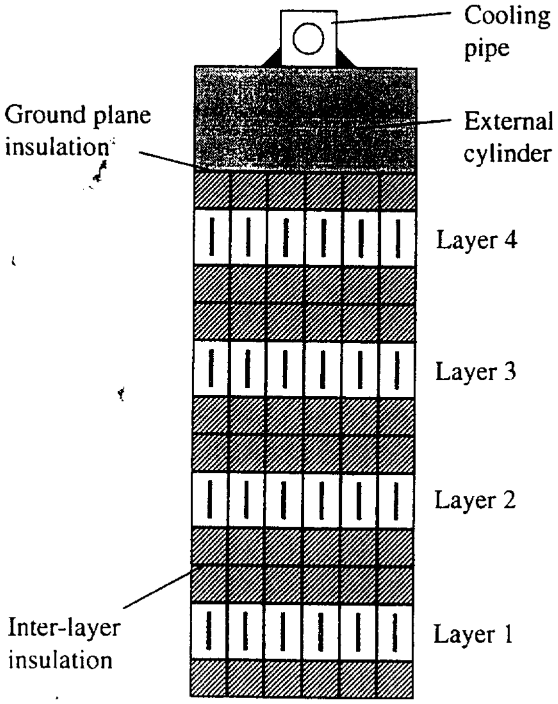


Fig. 2. CMS conductor layers (details)

Table II . Thermal and electrical properties of selected materials at 4.5 K and 4.6 T

Operating temperature	4.5 K
Aluminum thermal conductivity	1950 W/m.K
Aluminum effective RRR	472
Al 5083 thermal conductivity	3.5 W/m.K
Al 6061 thermal conductivity	10.7 W/m.K
Al 6063 thermal conductivity	35 W/m.K
Aluminum resistivity	$5.6\ 10^{-11}\ \Omega$.m
Copper resistivity	$3.0\ 10^{-10}\ \Omega$.m

Table III . Critical and current-sharing temperatures

Magnetic field	4.1 T	4.6 T
Current-sharing temperature	6.56 K	6.35 K
Critical temperature	7.55 K	7.35 K

The differences between properties at 4.1 T and 4.6 T are negligible (lower than 1 %).

III. COMPARISON BETWEEN THE CODES AND MAIN RESULTS.

We performed several computations with the aims of :
- comparing the 2 codes results under identical assumptions,
- evaluating the contribution of transverse heat conduction (for that point, 3 different geometries have been studied : one single conductor, one layer and the whole coil),
- estimating the influence of the hard-edged transition assumption.

The results are summarized in the Table IV. The codes are in a fair agreement (20 %) when compared under the hard-edged transition assumption.

As expected, taking into consideration the current-sharing effect rather than the hard-edged transition, leads to lower computed MQE.

We plot on Fig. 3 the evolution of the normal zone size of the heated conductor for two disturbance energies closed to the quench energy (0.429 et 0.430 joule). The curve shows a slope change at the point which corresponds to a transited length of 8 cm. At the beginning, as the heat pulse is deposited, the normal zone size grows rather quickly up to 8 cm in 1-2 ms . The study of the temperature maps shows that, because of its poor thermal conductivity, the reinforcement alloy does not significantly contribute to the phenomenon. As a consequence, this phase is characterized by pure longitudinal heat diffusion in the aluminum. When the reinforcement is warmed up, it acts as an heat sink which contributes to slacken the normal size zone expansion. This zone grows up to a metastable normal region of about 16 cm. Thus, depending on the energy deposited by the heat pulse, the region continues growing up (quench of the coil) or decays (recovery of the supraconducting state). The 16 cm MPZ develops in about **10 ms**.

In every case studied here (CASTEM or HEATING, hard-edged transition or current-sharing), the MPZ is reduced to one conductor. The heat diffusion characteristic times through the alloy reinforcement to the next conductor layer and through the insulation to the adjacent conductors are respectively a few hundred and a few tens milliseconds. Those values are larger than the typical 10 ms MPZ formation characteristic time calculated by both codes. As a consequence, **the transverse heat conduction to adjacent conductors does not significantly contribute to the stability margin** of the coil as it is shown by the small differences between MQE computed with the 3 types of geometry.

This fact has two important consequences on the coil design : the conductor insulation thickness may be increased without compromising the stability margin and it is not necessary to consider the setting up of thermal drains between the conductor layers.

TABLE IV . Main results, pulse length = 1 cm

Code	Geometry	Assumption	T_{cs}	T_c	Pulse	MQE
			K	K	ms	J
HEATING	whole coil	hard-edged at T_m	6.35	7.35	10	1.0
CASTEM	whole coil	hard-edged at T_m	6.35	7.35	10	0.81
CASTEM	whole coil	current-sharing	6.56	7.55	1	0.43
CASTEM	1 layer	current-sharing	6.56	7.55	1	0.43
CASTEM	1 conductor	current-sharing	6.56	7.55	1	0.42
CASTEM	whole coil	hard-edged at T_m	6.35	7.35	1	0.75
CASTEM	1 layer	hard-edged at T_m	6.35	7.35	1	0.74
CASTEM	1 conductor	hard-edged at T_m	6.35	7.35	1	0.64

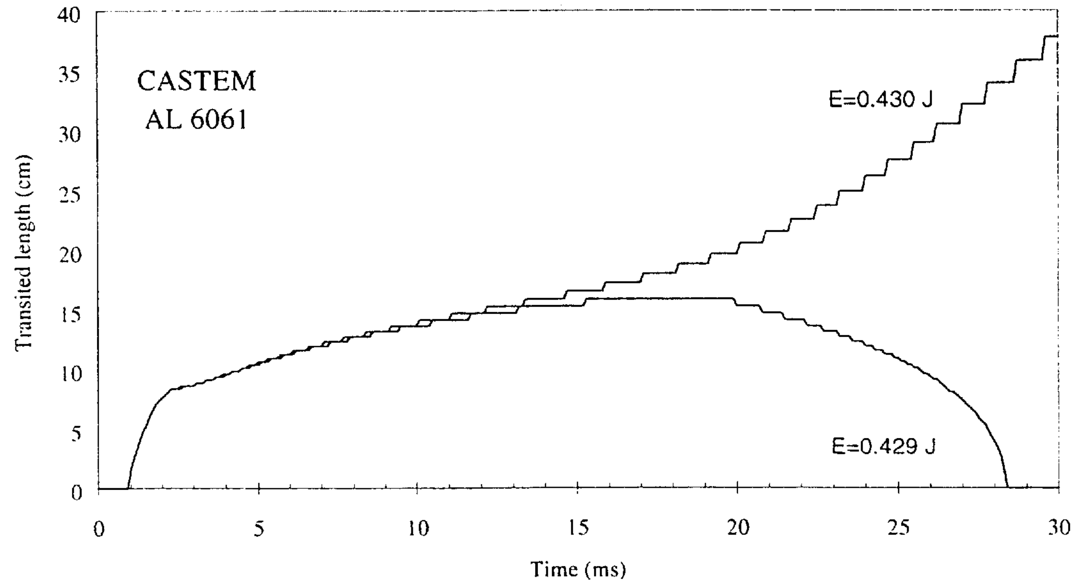


Fig. 3 . Transited length versus time

IV. LENGTH AND DURATION OF THE HEAT PULSE (CASTEM)

We calculate the dependance of the MQE as a function of the heat pulse length and duration. Figure 4 shows the quench energy versus the pulse duration in the case of a pulse length constant and equal to 1 cm (Al 6061 alloy). Figure 5 shows the quench energy versus the pulse length in the case of a pulse duration constant and equal to 1 ms. As expected, those dependances are found to be increasing functions. The quench energy does not depend on the disturbance for lengths up to 10 cm and for durations up to 2 ms. Those values must be related to the characteristic values of the first phase of the development of the MPZ (longitudinal heat diffusion in the aluminum) . We can insure that the computed quench energies for 1 cm and 1 ms heat pulse are the minimal quench energies.

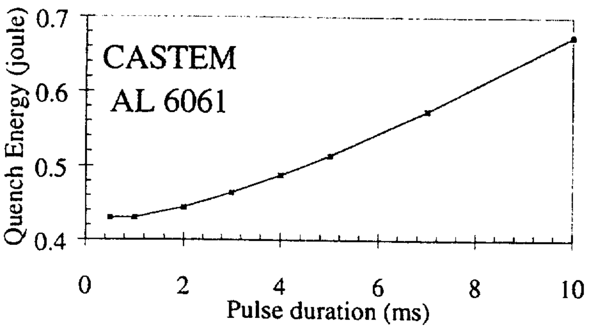


Fig. 4 . Quench energy versus pulse duration (Pulse length of 1cm)

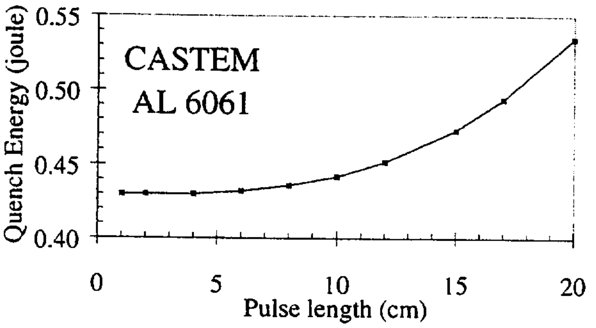


Fig. 5. Quench energy versus pulse length (Pulse duration 1 ms)

V. INFLUENCE OF THE ALLOY THERMAL CONDUCTIVITY (CASTEM)

The study of the temperature maps shows that the pure aluminum cross-sections of the warmed conductor are practically isothermal (temperature gradients lower than 10 mK). Due to the poor thermal conductibility of the Al 6061, the reinforcement cross-section exhibits during the transient resistive state, typical temperature gradients of 1-2 K. The available enthalpy margin of the reinforcement is consequently not efficiently utilized. To evaluate the effect of the alloy quality on the stability margin, we calculate the MQE for two other types of aluminum alloy : Al 5083 and Al 6063.

The results are summarized in Table V .

Table V . Influence of alloy quality
λ : thermal conductivity at 4.5 K

Type of aluminum alloy	λ W/m.K	MQE J
Al 5083	3.5	0.36
Al 6061	10.7	0.43
Al 6063	35	0.62

The use of Al 6063 alloy, which allows to take a better advantage of the enthalpy margin of the reinforcement, leads to significantly increased MQE. Though its conductivity is only one third of the Al 6061 one, the Al 5083 use leads to only a one sixth reduction of the MQE. Nevertheless, considerations about thermal gradients in the structure in normal permanent operation may exclude this possibility.

VI. OPERATING TEMPERATURE (CASTEM)

We calculate the dependance of the MQE versus the initial temperature . The results are summarized in Table VI. Depending on the maximum continuous length of conductor which can be manufactured, it may be necessary to plan electrical resistive joints between conductors, which would lead to local temperature rise up to 4.6 K. The results of this would be a 8 % degradation of the stability margin.

Table VI Influence of initial temperature

Initial temperature (K)	4.5	4.6	4.7	4.8	4.9	5.0
MQE (J)	0.43	0.40	0.37	0.34	0.31	0.28

VII. CONCLUSION

The numerical codes are in a 20 % agreement when used under identical assumptions and deliver absolute MQE in the range of 0.4 to 1 joule depending on the way the current-sharing effect is introduced. A more detailed study must be done to compare this level of energy to the energy actually dissipated by thermal disturbances. Whichever the current-sharing formulation, it has been shown that the transverse heat diffusion has no significant influence on the stability margin. This induces two important consequences on the design of the CMS magnet : thermal drains are useless and conductor insulation thickness can be increased without degrading the stability margin of the magnet. We showed as well that increased stability margin with identical conductor geometry may be achieved, if it is possible, by choosing Al 6063 aluminum alloy for the mechanical reinforcement of the conductor, rather than Al 6061 type as it is considered at present.

REFERENCES

1. Juster, F.P. , Fabbricatore, P. , Baynham, D.E. et al., Stability of Al-stabilized Conductors for LHC Detector Magnets, IEEE Transactions on Applied Superconductivity (June 1995) Vol. 5 n°2 377 380
2. Fabbricatore, P. et al., Stability of Al-stabilized Conductors for HEP Application, IEEE Transactions on Applied Superconductivity (June 1997) Sup. Vol.7 n°2 633 637
3. CMS Collaboration, The Magnet Project Technical Design Report, CERN/LHC 97-10 (2 May 1997), CMS TDR 1
4. Wilson, M.N., "Superconductings Magnets", Clarendon Press, Oxford 1983