16 QUENCH ANALYSIS

16.1 INTRODUCTION

The coil protection system, as shown in Fig. 16.1, is based on a Quench Back Cylinder (QBC)/dump resistor concept. The winding/QBC assembly works essentially as a current transformer, in which the winding acts as the primary circuit and the QBC as the secondary.

During normal coil operation, the power dissipated in the QBC due to eddy currents is negligible, given the very low current change rate. The ramp up time is 5 hours and the slow dumping, which is performed into a 2 mW resistor, has a time constant of 2 hours, as described in Chapt. 20.

During a fast dump on the other hand, the power dissipated in the QBC effectively contributes to driving the whole winding to a normal state.

The quench protection analysis is based on the electrical circuit shown in Fig. 16.1. Two different scenarios have been considered:

– normal external fast dumping,
– failure of the protection system.

Finite Element and analytical calculations were carried out to analyse the quench protection. The failure of the protection system has only been modelled by analytical calculations.

The calculations on the quench back give an average coil final temperature after fast discharge of 56 K, which corresponds to about 80 % of the 2.7 GJ initial magnetic energy extracted in the 50 mW protection resistor. The aluminium RRR influences the quench back characteristics when the RRR is less than 500; the average coil final temperature is calculated to reach just over 60 K and the energy extracted in the protection resistor is 74% of the initial magnetic energy.

A failure of the protection system has also been studied. In this case the maximum calculated temperature in the winding reaches about 150 K and there is a dependence on the aluminium RRR when the RRR is less than 100.

The stresses induced in the magnet due to current discharge are kept at a low level, i.e. a few MPa in the quench back cylinder.

16.2 QUENCH BACK PROTECTION

Rapid discharge mode creates a current decay which induces losses in the structure especially in the external cylinder, large enough to raise the temperature of the winding and to quench the layers successively in a typical time of 5 to 10 seconds. Joule effect due to the current in the aluminium stabiliser reinforces the quench back mechanism. The whole winding being entirely in the resistive state and the layers being in good thermal contact, the energy deposition in the winding is quite uniform.

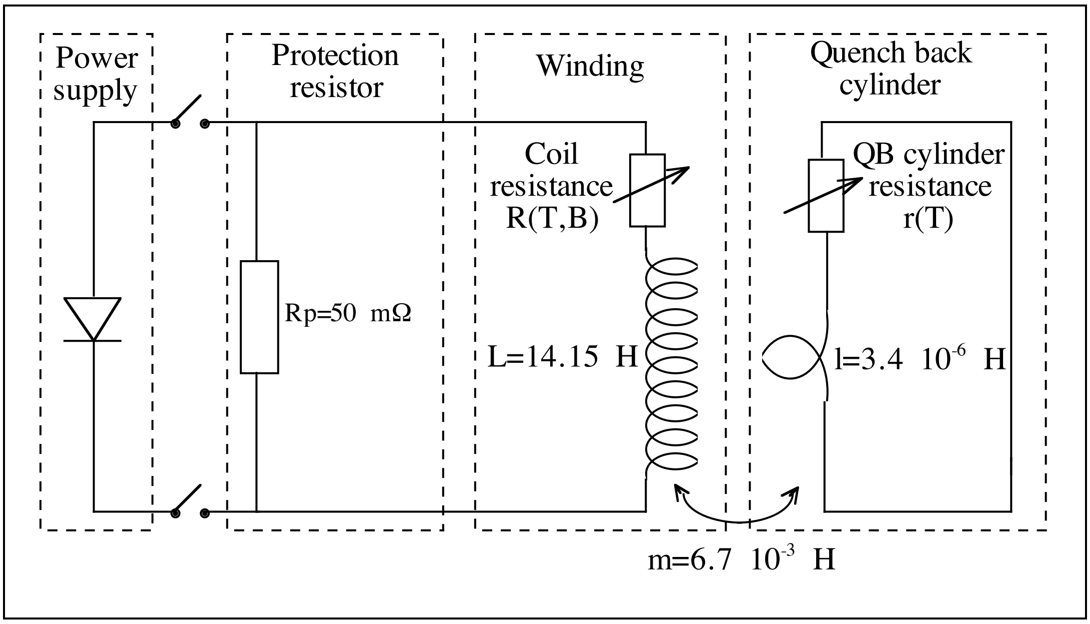

Fig. 16.1: Equivalent electrical circuit of the winding/shell configuration.

16.2.1 Quench back typical results

The post-quench-back coil temperature distribution has been estimated by finite element analysis [16-1, 16-2] and by analytical computations [16-2, 16-3, 16-4].

Typical results lead to the characteristics provided in Table 16.1. They are obtained by analytical calculations. These results correspond to the 12 mm thick quench back cylinder, the dump resistor of 0.050 W and an aluminium RRR of 1000.

Other simulations have been made by varying the following parameters: aluminium RRR, external cylinder thickness, dump resistor value. All calculations show that the quench back protection is efficient and leads to high extracted energy ratio of about 80% hence to low final temperatures in the coil together with a good temperature uniformity. The maximum temperature gradient calculated is 16 K, and thus the thermal stresses in the winding are therefore kept at an acceptable level. The current diffusion effect has not been taken into account as it increases the local dissipated power, hereby the propagation velocities, and therefore acts favourably for protection. It has been studied in [16-5].

Table 16.1
Quench back typical results.

Initial quench time	No quench	0 s	0 s
Breaker opening delay	0 s	0 s	16 s
Quench back delay *	7 s	7 s	7 s
Average coil final temperature	56 K	56 K	56 K
Hot spot temperature	-	61 K	70 K
ΔT max. within the coil	2 K	7 K	16 K
Extracted energy ratio	77 %		
Effective time constant **	212 s		
Magnet final resistance	0.05 W		

* delay to have the 4 layers quenched after breakers open.

** time when the current is $I = I_0 / e$ = 7173 A.

16.2.2 Comparison of the methods

The comparison of the results given by the FE calculations and the analytical calculations (see Table 16.2) show that the former calculations give lower coil temperature and higher extracted energy ratio than the latter calculations, since the analytical calculations do not take into account the heat conduction in the winding and the heat exchange with the quench back cylinder [16-2].

Nevertheless, the temperatures obtained with the analytical computations are presented for the quench back analysis as conservative upper bound temperatures.

Analytical computations:

The temperature dependence of the material specific heats and electrical resistivities are calculated with power law functions on given temperature intervals. The magnetic field effect is taken into account by adding to the resistivity at T = 4.2 K and 0 T a term corresponding to the magnetoresistance at T = 4.2 K and 2 T. The properties of aluminium at 0 T are provided in Table 16.3 for a RRR of 1000.

The propagation velocity calculations are performed with the material heat conductivities at liquid helium temperature, which lead to the following values:

- axial velocity: 0.09 m/s,
- radial velocity: 0.13 m/s,
- azimuthal velocity: 1.39 m/s (along the conductor).

Finite element computations:

The FE analysis takes into account the magnetic field and temperature dependence of the material thermal and electrical properties: the electrical resistivity, specific heat, heat conductivity values are obtained from the Cryocomp software database. The FE analysis also calculates the critical and current sharing temperatures as a function of the magnetic field in each layer, the effect of the magnetic field variation due to the eddy currents in the quench back cylinder, and the energy extracted by the liquid helium remaining in the cooling pipes at the beginning of the discharge until it is completely evaporated. Indeed, when the protection is triggered, the LHe feeding is stopped, but the cooling circuit is still full of liquid helium which extracts a small portion of energy from the magnet. Each layer is totally quenched when the temperature in this layer reaches the critical temperature threshold.

Table 16.2
Comparison of the calculation methods (RRR Al = 1000).

	FE calculations	Analytical calculations
Average final coil temperature	44 K	56 K
ΔT max. within the coil	15 K	16 K
Extracted energy ratio	84%	77 %

Table 16.3
Aluminium properties at 0 T for analytical calculations (RRR Al = 1000).

T (K)	4.2	10	15	20	30	40	50	60	70
r (10^{-10} W.m)	0.250	0.258	0.291	0.378	0.898	2.3	5.25	10.5	17.2
Cv (10^3 J/m^3.K)	0.759	4.01	11	24	85.1	210	395	579	764

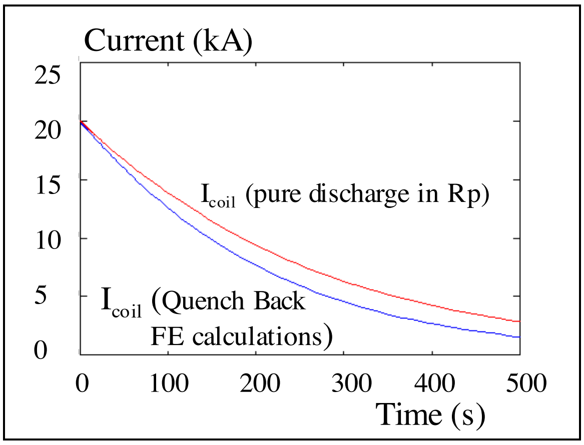

Fig. 16.2: Coil current during a fast discharge compared to a pure discharge in a L/Rp circuit.

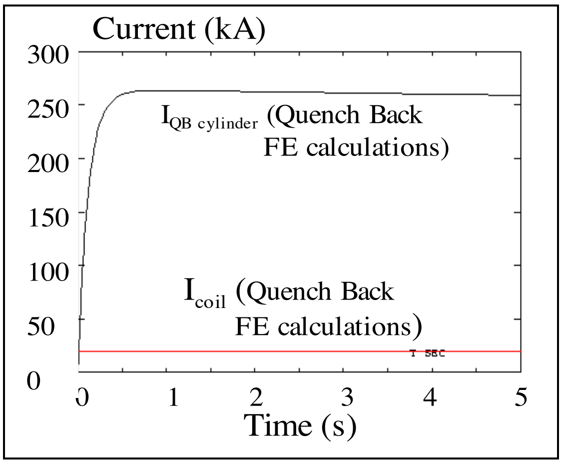

Fig. 16.3: Currents in the coil and the 12 mm thick quench back cylinder.

16.2.3 Quench back process

The FE calculations include the thermal diffusion and provide accurate description of the magnet behaviour during quench back. Typical graphs are provided on Fig. 16.2 and Fig. 16.3, and Fig. 16.5 to Fig. 16.8. These graphs correspond to an aluminium RRR equal to 1000. The inductances are constant. The eddy currents in the quench back cylinder increase rapidly during the first seconds following the trigger of the fast dump (Fig. 16.3).

The voltage at the connections of the coil during fast discharge is estimated at the beginning of the discharge to be 1000 V with a 0.050 W protection resistor bank. The voltage is distributed across turns and layers. The maximum resistive voltages are obtained between layers at their extremities according to Fig. 16.4. The maximum value obtained from these calculations is 530 V [16-6] for V2 and V3 (see Fig. 16.4). The insulation thickness is 1 mm and 0.5 mm respectively for layer to layer insulation and turn to turn insulation. These thickness allow to withstand high voltages so that the magnet is safe from over voltage during quench back.

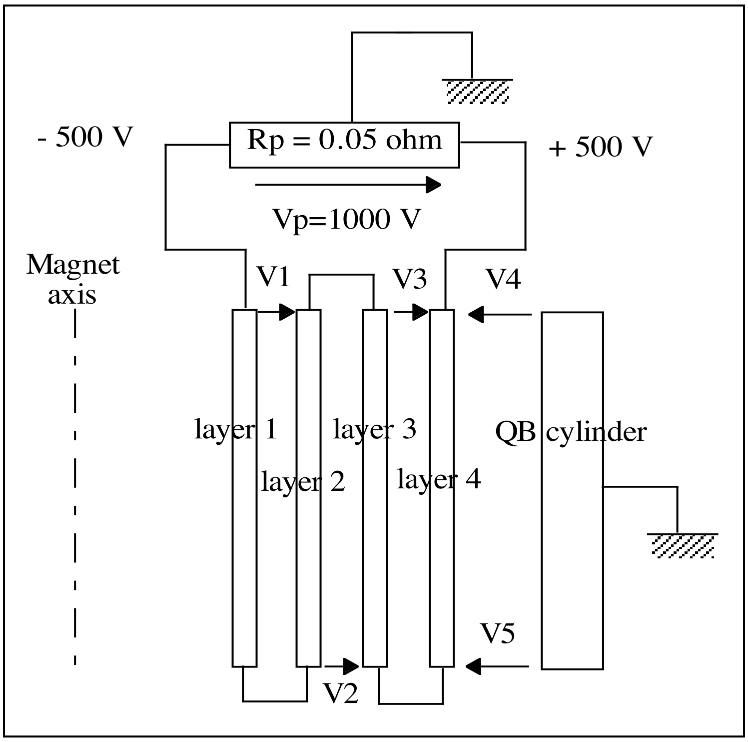

Fig. 16.4: Electrical connections between layers.

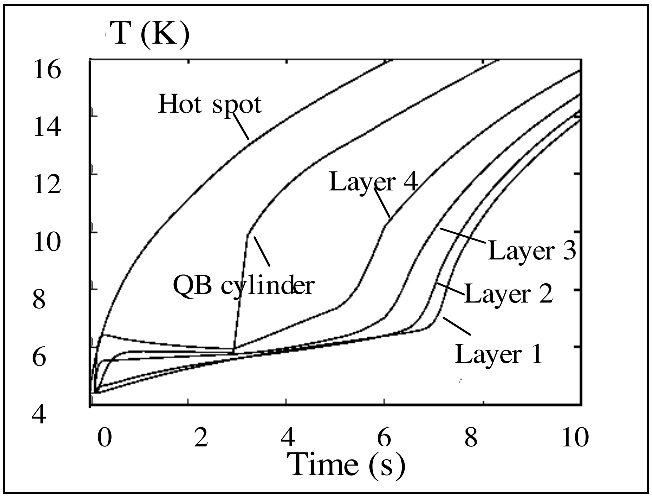

Fig. 16.5: Temperature increase at the beginning of fast discharge.

The first layer to quench is the fourth one, which is the closest to the quench back cylinder, then the neighbouring layer quenches and so on, as shown on Fig. 16.5 and Fig. 16.7.

It is possible to grade the conductor to have different material cross sections from one layer to the other, keeping the overall conductor cross section identical in the 4 layers.

The grading allows to diminish the required superconducting material quantity and to get the same enthalpy margin in each layer. It results in a more uniform heat dissipation in the 4 layers (Fig. 16.8) and it increases the stability margin.

The possible grading of the CMS conductor is described in a specific technical report [16-7]. The gradation parameters are:
– the aluminium stabiliser cross section,
– the superconducting material cross section.

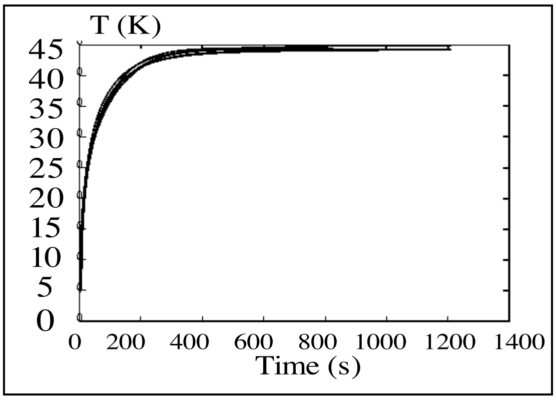

Fig. 16.6: Temperature increase during a fast discharge.

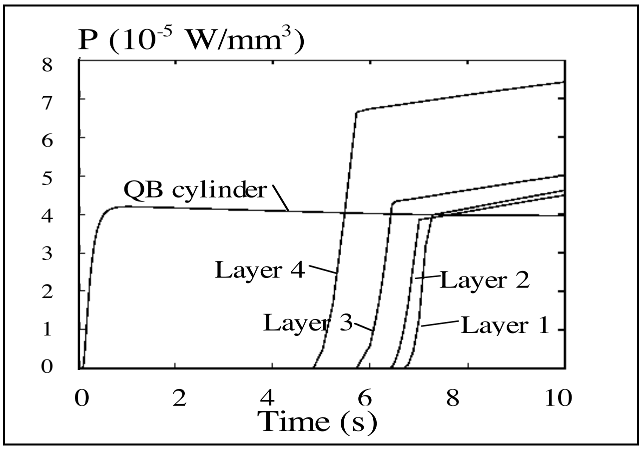

Fig. 16.7: Joule heat source in each layer and QB cylinder at the beginning of a fast discharge.

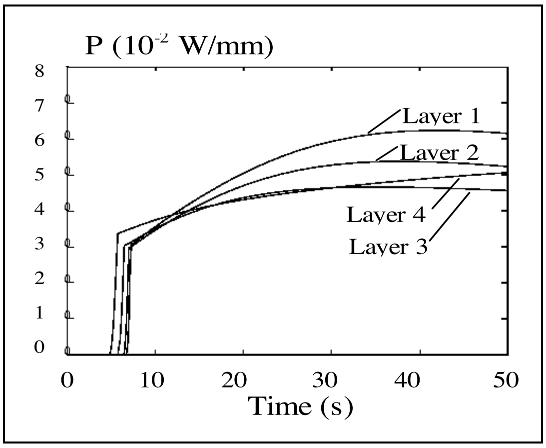

Fig. 16.8: Joule heat source in each layer: effect of grading.

16.2.4 Influence of parameters

Temperatures in the coil and extracted energy ratio have been calculated by varying the following parameters:

1. Quench back cylinder thickness : 5, 12, 18, 50 mm

The eddy currents in the quench back cylinder reach a value which depends on the thickness of the quench back cylinder, whereas current density stays constant at about 1.8 A/mm^2.

The part of the initial magnetic energy that is extracted in the protection resistor Rp is about 80%, when the thickness ranges from 5 to 50 mm.

The layers quench faster with thicker quench back cylinder: 11 s with a 5 mm thick cylinder, 3 s with a 50 mm thick cylinder.

The quench back cylinder thickness does not show a great influence on the quench back characteristics.

2. Protection resistor bank: 0.050 W and 0.025 W

Typical results of the influence of the protection resistor are given in Table 16.4, and [16-1, 16-2].

3. Aluminium RRR from 50 to 2800 taking RRR = r(273 K) / r(4.2 K)

The aluminium RRR influences the final temperature and a variation of the extracted energy ratio is mainly noticeable for RRR values lower than 500, as shown on Fig. 16.9 and Fig. 16.10, where Rp is equal to 0.050 W.

Table 16.4
Influence of Rp on quench back characteristics (RRR Al = 1000).

	Rp = 0.050 W	Rp = 0.025 W
Quench back delay *	7 s	20
Average final coil temperature	56 K	72 K

Hot spot temperature (no breaker opening delay)	61 K	86 K
Hot spot temperature (16s breaker opening delay)	70 K	97 K
Extracted energy ratio	78 %	48 %

* delay to have the 4 layers quenched after opening of the breakers.

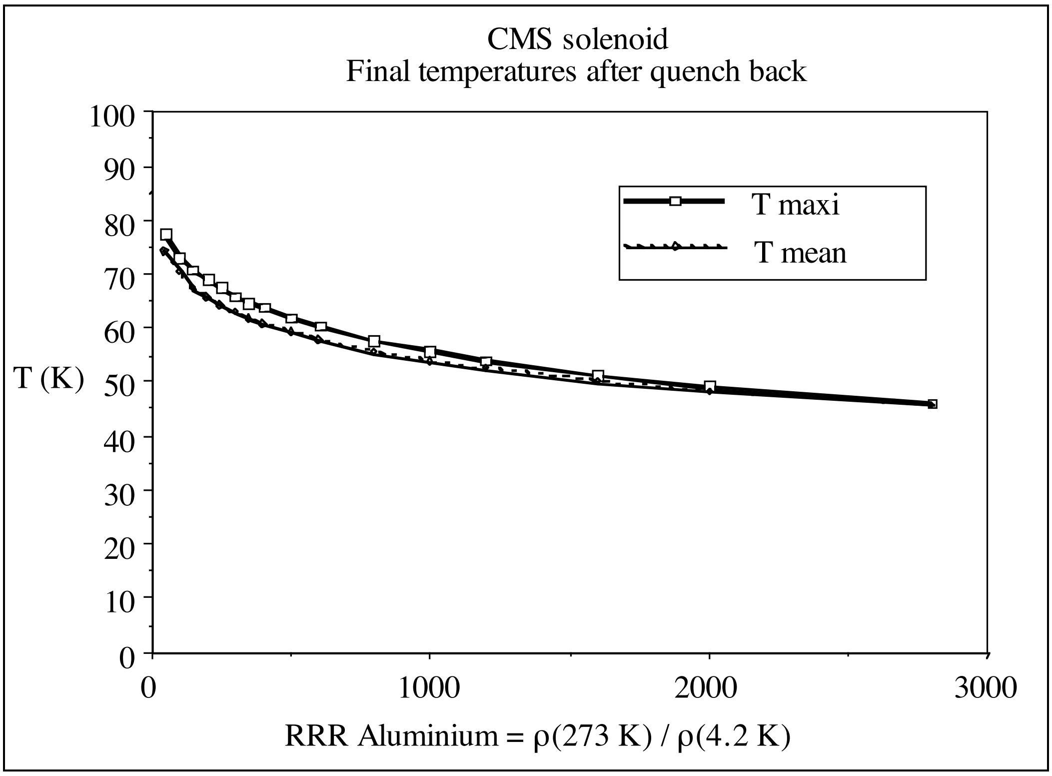

Fig. 16.9: Coil final temperature after quench back versus aluminium RRR.

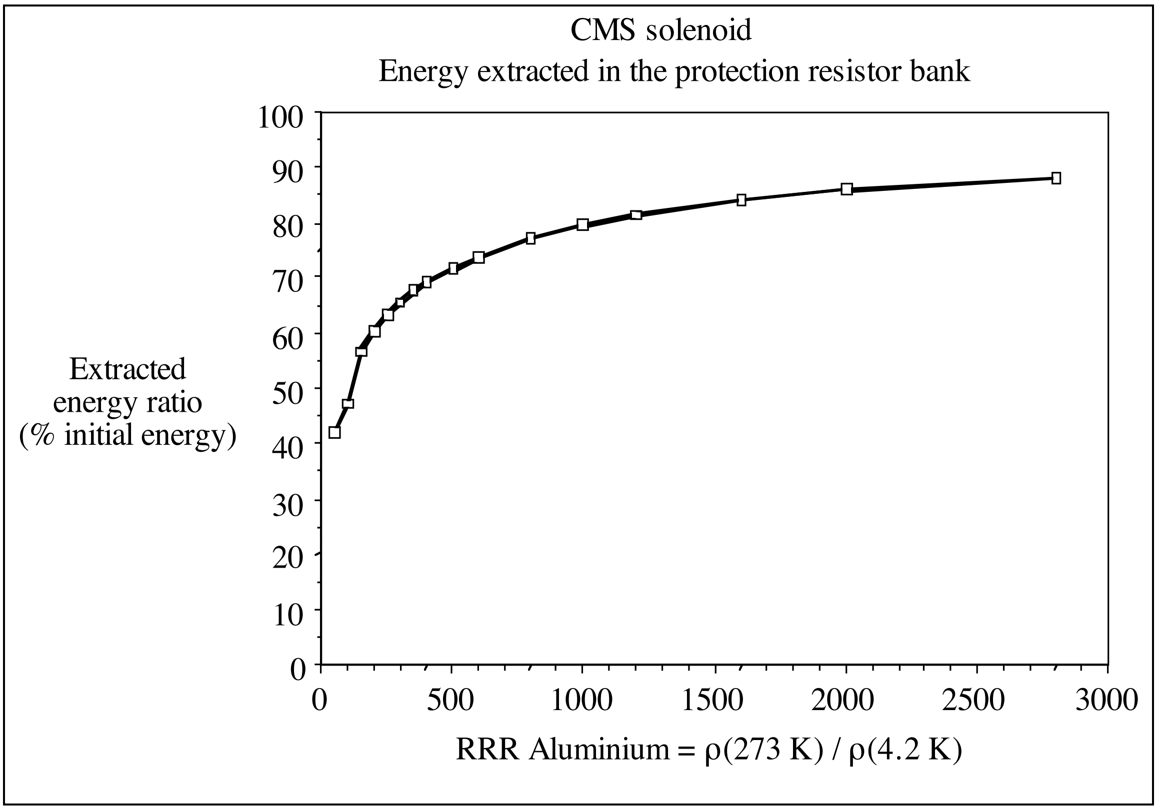

Fig. 16.10: Ratio of extracted energy versus aluminium RRR.

16.3 PROTECTION SYSTEM FAILURE

The entire stored energy will be dissipated within the coil in case of a protection system failure. The specific magnetic stored energy per unit mass is about 12.2 kJ/kg. When uniformly released into the coil it rises the temperature to 89 K.

Analytical computation results are presented in this chapter. As mentioned earlier, they do not include the effects of the heat conduction in the winding and heat exchange with the quench back cylinder. The temperatures obtained with the analytical computations are presented for the quench back analysis as conservative upper bound temperatures.

A finite element analysis will allow to confirm these results and will provide a calculated temperature field map to determine the stress level inside the winding after quench. The effect of discharging at low currents will also be studied.

16.3.1 Quench propagation typical results

Analytical computations have been performed to calculate the temperature distribution in the coil due to a quench located at the end of the coil [16-8]. This is a worst case situation which will causes both the highest temperature and the highest temperature gradient in the coil.

Typical results are reported in Table 16.5. In a first step the normal zone propagates at constant current. When the voltage across the coil reaches the capability of the power supply, as the normal zone develops both in length and temperature, the current starts to decrease and the quench back mechanism starts but much more slowly than in a normal dump.

Typical coil current profile is given on Fig. 16.11 where the quench back current profile is also plotted. Typical temperature profile is provided on Fig. 16.12 together with the quench back temperature profile.

Table 16.5

Quench values in case of protection system failure (RRR Al = 1000).

Effective time constant *	270 s
Axial quench velocity	0.09 m/s
Quench back delay **	100 s
Maximum temperature	146 K
Magnet final resistance	0.17 W

* time when the current is $I = I_0 / e$ = 7173 A.
** delay to have the 4 layers quenched.

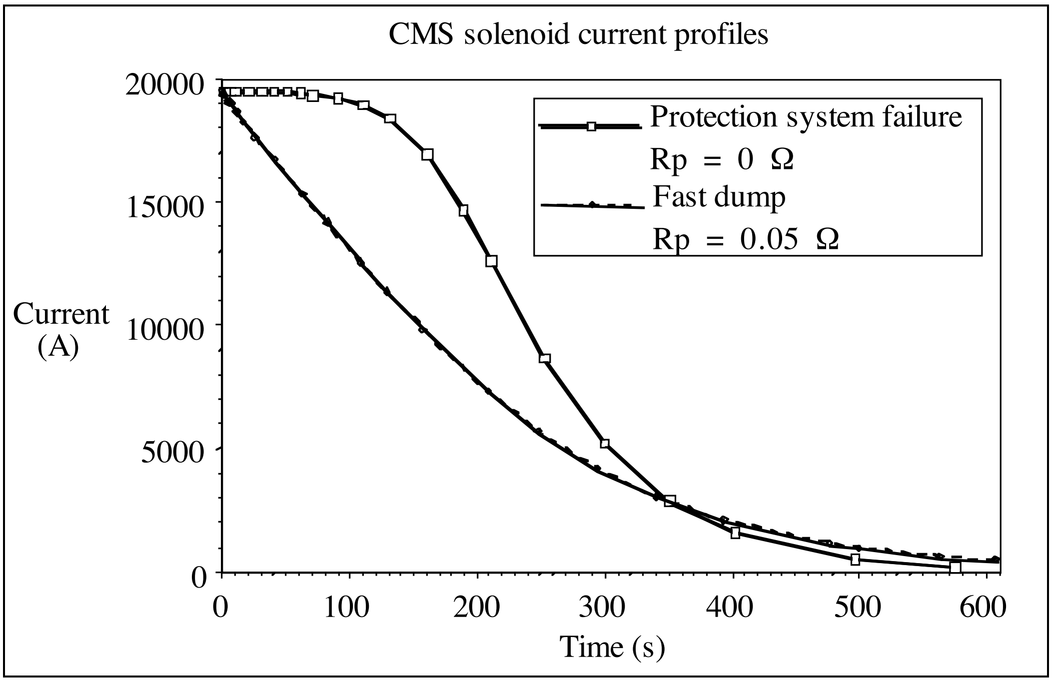

Fig. 16.11: Comparison of the current profiles with protection system failure and with fast dump.

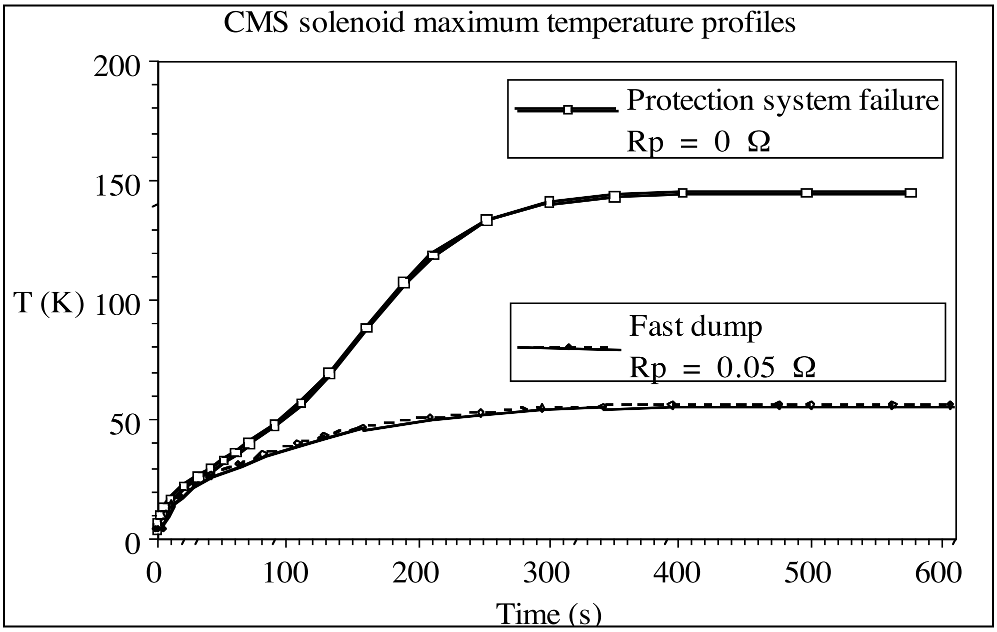

Fig. 16.12: Comparison of the coil temperature profiles with protection system failure and with fast dump.

16.3.2 Influence of parameters

The maximal and minimal temperatures have been calculated for several RRR by the analytical computation (Fig. 16.13).

For RRR greater than 100, these analytical calculations indicate after quench, a maximal temperature of about 150 K and a temperature difference within the coil of about 110 K.

16.4 INDUCED FORCES DURING DISCHARGES

As shown on Fig. 16.11, both in case of a normal external fast dump and a failure of the protection system, a fast decay of the current occurs in the winding, resulting in a fast decrease of the magnetic flux. Therefore eddy currents appear in the magnet elements which are electromagnetically coupled with the coil, i.e. the quench back cylinder, the external and internal vacuum tank, the screens and the iron yoke. Lorentz forces induce mechanical stresses in those elements.

At nominal current operation, the winding hoop strain is 0.15 %. The quench back cylinder strain is also 0.15 %, as it follows the coil expansion. This strain leads to a hoop stress of 125 MPa, in a quench back cylinder made of a 6082 aluminium alloy with a Young's Modulus of 77 Gpa.

During discharges, the stresses in the quench back cylinder due to the Lorentz forces are added to the above values. The results are given in Table 16.6 [16-9, 16-10]. Because of the low eddy current density in the quench back cylinder (1.8 A/mm^2) the Lorentz forces are low, hence the induced stresses are negligible compared to the stresses due to the coil deformation.

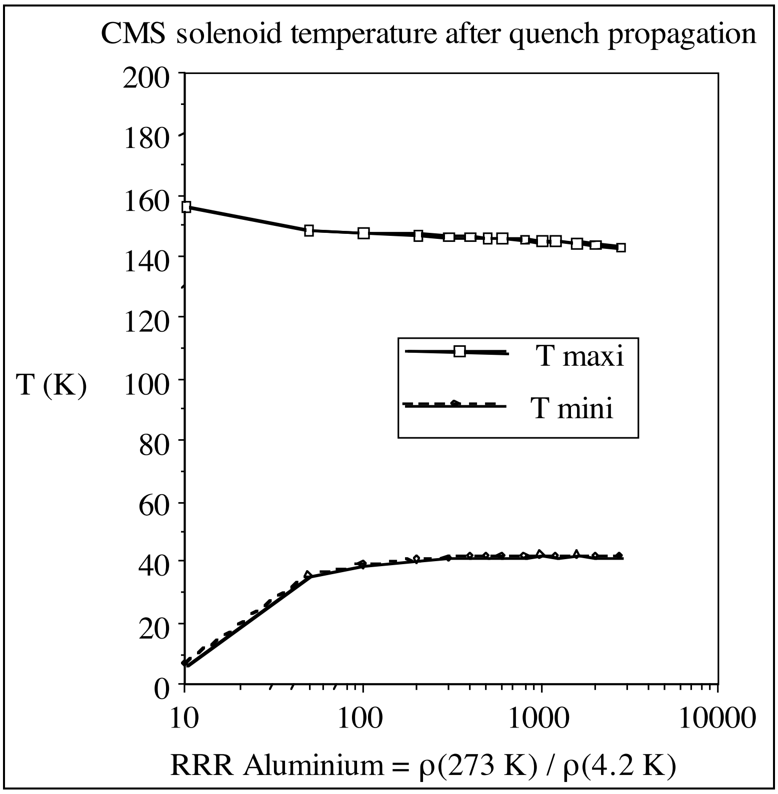

Fig. 16.13: Maximal and minimal temperature versus aluminium RRR, in case of failure of the protection system.

Table 16.6
Hoop stresses in the quench back cylinder.

	Lorentz forces	0.16% coil deformation	TOTAL
Nominal current operation		*125 MPa*	*125 MPa*
Normal external fast dumping	5 MPa	125 MPa	130 MPa
Protection system failure	7 MPa	125 MPa	132 MPa

In a first approach, one can say that the mutual and self inductances of the internal and external vacuum tanks are close to the quench back cylinder ones because of there similar geometries. As the electrical resistivity of stainless steel at room temperature is about 40 times greater than that of 6082 aluminium alloy at 4.4 K, the eddy currents in the vacuum tank are low. As a result the induced stresses are negligible.

To contain the forces on the screens, due to eddy currents during the discharge to acceptable levels, the screens will be cut into sectors.

A FE analysis to be done soon will allow to estimate the forces in the screens, the external and internal shells of the vacuum tank, and iron yoke, from the magnetic field map obtained with the FE computations.