Cryogenic design of a 800 kJ HTS SMES

B Bellin1,4, P Tixador1, M Deleglise2, J C Vallier3, S Pavard4 and C E Bruzek4
1 CNRS-CRTBT/LEG, B.P. 166, 38 042 Grenoble Cedex 09, France
2 SERAS, B.P. 166, 38 042 Grenoble Cedex 09, France
3 CNRS-CRTBT, B.P. 166, 38 042 Grenoble Cedex 09, France
4 NEXANS, 31 rue Industrie 59460 Jeumont, France
E-mail: boris.bellin@grenoble.cnrs.fr

Abstract. In the context of a DGA (Délegation Générale pour l’Armement) project, we have designed a 800 kJ SMES. The conductor is made with 3 or 4 Bi-2212 PIT tapes insulated and assembled by Nexans France. The operating temperature is 20 K. The cryogenic design of the SMES is presented. The thermal operation model was calculated using FLUX®, a F.E.M. (Finite Element Model) software. We present the results of the measurements of thermal and electrical resistances and the results of the tests on a small-scale double pancake coil.

1. Introduction
The development of high temperature superconductors (HTS) and in the meantime of the cryocoolers has enabled the use of superconductivity without cryogens. The applications, now called cryogen-free, working with the conduction cooling, are easier for the user. However some limitations exist. For example the development of eddy currents during transient modes in thermal links leads to energy dissipation. The contact interfaces, which have been deeply investigated [2], need to be measured.

The solution of using pancakes compared to layer-wound coils is adapted to the geometry of the HTS tapes. As an advantage it minimizes damage during winding by preventing the winding from layer-to-layer degradation. Further it is adapted to conduction cooling because there is only one interface between the cooling plate and the conductor. Finally if one pancake is damaged, only this one has to be replaced.

This DGA project is aimed to build a 800 kJ HTS SMES operating at 20 K. The winding consists of 26 stacked pancakes (\(\phi_o = 814 \text{ mm} \), \(\phi_i = 300 \text{ mm} \), \(h = 182 \text{ mm} \)). The conductor, assembled by Nexans France, is made of 3 or 4 Bi2212 PIT tapes, depending on its winding location within the coil [1]. The conductor is electrically insulated with kapton® and the winding is bonded by an epoxy film adhesive on OFHC-copper plates covered with an epoxy coating. For an easy and transparent cryogenics, the pancakes are conduction cooled in vacuum using a powerful Gifford-McMahon cycle cryocooler (19 W at 15.9 K).

In this paper we report on the design of the thermal connection between HTS coil and cryocooler and we present results on modeling and experimental evaluation for a test coil.
2. Cryogenic design of the SMES
The cooling is performed by two cryocoolers. One GM cryocooler cools the radiation shield and the current leads (see figure 1). The design of the thermal connection between the winding and the second cryocooler is presented below. The following targets have ruled this design:
1. Minimization of the temperature difference between the cryocooler and the hot spot in the winding under permanent operation.
2. Minimization of the cool down time, the dissipated energy during the charge and mainly during a discharge of the SMES (2 s and 2 ms).
3. Providing the electrical insulation during fast discharge (5 kV).

2.1. Losses
The losses in the steady state operation are within the conductor \( P_1 \) and in the electrical connections between the pancakes \( P_2 \).

The conductor operates at 0.8 \( I_c \) only at some locations. For the electromagnetic study it is considered to operate everywhere at 0.8 \( I_c \) with a resistive transition index of 15. This leads to an over estimation of the losses. The upper limit can be expressed:

\[
P_1 = E \cdot I = E_c \cdot I \cdot (0.8)^{15} \cdot I
\]

There are also losses localized at each electrical connection, especially for the inner connection due to the reduced space and the high magnetic field. The connections consist of copper pieces that are soldered on the winding and then soldered together with superconducting (SC) tapes. Measurements in magnetic fields up to 8 T at 20 K were done at CNRS-CRETA. We measured the electrical resistance of a sandwich “SC tape / copper / SC tape / copper / SC tape” with 64 mm\(^2\) for the contacts “SC tape / copper” and we found a resistance \( K \approx 0.2 \mu\Omega \). The losses can be expressed:

\[
P_2 = 26 \cdot K \cdot I^2
\]

The dissipated energy in transient modes, mainly discharging, is localized in the copper pieces where eddy currents develop (see 2.3.2) and in the conductor where hysteresis losses take place.

2.2. Thermal path from the winding to the cryocooler
The thermal path is made of OFHC copper. Its heat conductivity has got a maximum around 20 K and is well known under magnetic field. We use a mean value of 1000 W/m/K for the modeling. The cryocooler is connected to the winding by a heat distribution piece, flexible pieces and plates (see figure 2). The F.E.M. (Finite Element Model) software FLUX \(^\text{®} [3] \) showed that the heat distribution piece and the flexible pieces lead to a temperature rise of 1 K maximum referred to the cryocooler. The thermal interface between the Cu plate and the SC tapes is composed by adhesive kapton\(^\text{®} \) foil, epoxy adhesive film redux\(^\text{®} \) and epoxy coating on the Cu plates. This interface has been chosen...
because of its high dielectric strength (5 kV minimum) and rather high thermal conductivity. Below we call it HV (high voltage) interface. This HV interface as well as the interfaces between copper surfaces have been measured to model the total thermal path.

2.3. Thermal resistances

2.3.1. Thermal measurements

We have developed a simple experimental apparatus (see figure 3) to measure the thermal resistances. Temperatures are measured with cernox® sensors mounted on a G10 support. The flexible copper sample (250 mm long) is made of 50 copper foils 0.2 mm thick soldered at the extremities. A device that prevents movement due to vibrations of the cryocooler supports it. Our tests were performed in the temperature range 15-25 K, without regulation of the temperature of the cold source.

The measurement of the thermal conductivity of a 100 mm long 304 L steel sample with an accuracy of more than 90 % compared to data of NIST (National Institute of Standards and Technology) allows validating the experimental set up for our needs. The results are given in the table 1.

### Table 1. Results of thermal measurements

| Description                                           | Pressure (MPa) | Area (cm²) | Thermal conductance |
|-------------------------------------------------------|----------------|------------|---------------------|
| HV interface (kapton®/redux®/epoxy coating)           | -              | 5          | 0.05 W/K            |
| Soldered Cu foils / In / Cu (6 screws)                | 5              | 27         | 10 W/K              |
| Cryocooler / In / Cu (12 screws)                      | 6              | 32.5       | 100 W/K             |

![Figure 3. Experimental set up](image)

![Figure 4. Cu plates’ modeling](image)

2.3.2. Model

The design of split plates result from a compromise between the temperature rise in permanent mode and the eddy current losses during discharge. Our model for permanent mode (see figure 4) is one half of a disk, due to the symmetry, and we consider the worst case in which the inner and outer electrical connections are on the same half-part of the plate and have the highest distance to the cooling wing. The electrical connections are insulated from the plate by the HV interface so we modeled only one turn and its HV insulation. The temperature is fixed at 17 K on the wing and the electrical connections are heated. The model shows that the resistance of electrical connection must be lower than 0.2 μΩ in order to achieve a temperature difference of 1 K between the wing and the inner electrical connection.

The copper plates have been modeled with a 3-D model to calculate the dissipated energy during discharge. The model of the full SMES is made of half of the plates (13), for symmetry reasons, and only the solid ring part is modeled, where the eddy currents are highest. The calculation is made in harmonic operation. It gives 316 J dissipated during a discharge of 2 s. This is low in comparison to a first calculation of the hysteresis losses in the superconducting material which are ten times more.
2.4. Conclusion
In figure 5 we have represented the thermal path from the cryocooler to the hot spot. Our design gives a maximum temperature difference of 2.4 K using the cryocooler as a reference, with 0.4 K maximum in the thermal interfaces. The hot spot would be at 18.3 K, giving a margin of 1.7 K compared to the 20 K considered for the electromagnetic design. Less than 1 % of the stored energy is dissipated during the discharge in 2 s.

![Figure 5. Temperature rises](image1)

![Figure 6. Small-scale coil](image2)

3. Small-scale coil
A small-scale coil has been realized (see figure 6) to validate our design. It is made of two short pancakes connected by the inner electrical connection designed for the SMES. The cooling plates are connected through small wings to the cryocooler. The current leads are cooled at 77 K and at 20 K, fixed through an epoxy film adhesive. The cooling time is 10 hours. The outer electrical connection reaches 15 K without current. So the cooling system for the current leads is efficient.

The cooling and the electrical resistance of the inner electrical connection between the pancakes has been investigated. We have studied the variation of the temperature difference between the wings and the connection. First the connection has been heated with a variable power from 10 to 200 mW. The slope of the curve is 25 K/W, which is the same as obtained in the calculation of the model detailed in 2.3.2. It confirms the assumptions and the values used in our finite element model. Then the winding has been connected to a current supply. The variation of temperature is 1.6 K between 0 A and the operating current 300 A. It shows that the resistance of the inner connection should be optimized to reach the targeted temperature difference of 1 K.

4. Conclusion
The small-scale coil has given encouraging results. The 800 kJ SMES cryogenic design is defined and the cryostat is under construction. Our further study will take into consideration the cool down time after a discharge and the dissipated energy due to the diffusion of the eddy current.

Acknowledgments
The authors would like to thank A. Boulbes and G. Barthelemy for their technical and fundamental contributions. They wish to thank G. Meunier for discussions about the software FLUX®.

References
[1] Tixador P, Bellin B, Deleglise M, Vallier J C, Bruzek C E, Pavard S and Saugrain J M 2005 IEEE Trans. on Applied Superconductivity 15(2) pt. 2 1907-10
[2] Gmelin E, Asen-Palmer M, Reuther M, and Villar R 1999 J. Phys. D: Appl. Phys. 32 R19-43
[3] Cedrat & Cedrat Technologies, http://www.cedrat.com/