Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 67 (2015) 692 – 697

Physics Procedia

25th International Cryogenic Engineering Conference and the International Cryogenic Materials Conference in 2014, ICEC 25–ICMC 2014

Cryogenic design of the 43 T LNCMI Grenoble hybrid magnet

B. Hervieu[a]*, Ch. Berriaud[a], R. Berthier[a], F. Debray[b], Ph. Fazilleau[a], P. Manil[a], M. Massinger[a], R. Pfister[b], P. Pugnat[b], L. Ronayette[b], C. Trophime[b]

[a] *Commissariat à l'Energie Atomique et aux Energies Alternatives, Institut de Recherche sur les lois Fondamentales de l'Univers, Saclay, France*
[b] *Laboratoire National des Champs Magnétiques Intenses (LNCMI), CNRS-UJF-INSA-UPS,Grenoble, France*

Abstract

The association of two inner resistive coils (Polyhelix and Bitter) producing 34.5 T with an outer NbTi superconducting coil producing 8.5 T to obtain a 43 T hybrid magnet is a technical challenge. Accidental failure modes leading to complex electromagnetic behaviors and large transient dynamical forces should be anticipated. These considerations lead to a reinforced design and a thermo-hydraulic strategy to limit the overpressure. The cryostat has been designed with innovative thermo-mechanical supports sustaining the coil at 1.8 K-1200 hPa and the eddy current shield at 30 K, both being possibly overloaded by high dynamic forces in the worst accidental failure case.

Peer-review under responsibility of the organizing committee of ICEC 25-ICMC 2014

Keywords: Superconducting coil; hybrid magnet; thermo-mechanics; ferrules; superfluid helium; thermo-hydraulics

1. Introduction

Beyond electromagnetism, to develop a superconducting magnet in a hybrid context one needs to explore mechanical and electrical techniques with potentially high levels of energies and forces at low temperatures. The result of our studies is a massive cryostat where the coil mass is only 45% of the cryostat mass. The installation is connected to a 4500 liters dewar filled by a mid-range liquefier. The cryogenic architecture is also sized to support one quench per month with a back transfer of the helium from the cryostat to an external deported cryogenic

* Corresponding author. Tel.: +33-169-088-500
E-mail address: bertrand.hervieu@cea.fr

Peer-review under responsibility of the organizing committee of ICEC 25-ICMC 2014
doi:10.1016/j.phpro.2015.06.117

satellite. All the pipes, safety valves and burst disks are sized to keep the overpressure below 4 bar. Our calculations with Vincenta [15] show that the pressure doesn't exceed 3.5 bar in a full quench case and 3.9 bar in the full fault scenario. We have also developed an innovative thermo-mechanical ferrule to maintain the cold mass temperature at 1.8 K and the eddy current shield temperature at 30 K.

2. The superconducting hybrid magnet context

The Grenoble hybrid magnet, Fig. 1(a), will offer a modular experimental platform to the scientific community. Various combinations of maximum field values and useful warm bore diameters are summarized in Table 1. The 12 MW and 18 MW hybrid configurations to produce 34 T in 34 mm and 27 T in 170 mm bore, respectively, will be based on two different poly-helix sets without Bitter inserts whereas 17.5 T will be obtained in 375 mm diameter bore with the addition of a Bitter magnet insert. The main parameters of the superconducting (SC) magnet are given in Table 2.

Table 1. Modularity of the new Grenoble Hybrid magnet.

Magnet configuration	Power (MW)	Field (T)	Useful bore dia. (mm)
Hybrid	24*	43	34
Hybrid	12*	34	34
Hybrid	18*	27	170
Hybrid	12*	17.5	375
Superconducting	0.3**	8.5	800

* Magnet powering + water cooling pumps + cryoplant,

** Cryoplant alone

Table 2. Main parameters of the superconducting magnet.

Description	Values
Magnetic field at the center	8.5 T
Maximum magnetic field on conductor	9.92 T
Operational temperature	1.8 K
R_{in} coil	553 mm
R_{out} coil	960 mm
Height	1406 mm
Stored Energy	76 MJ
Inductance	3 H
Operating current	7100 A
Magnet weight	17 ton

For this particular SC magnet, we use the double pancake technology, an Eddy Current Shield (ECS) and a Rutherford Cable On Conduit Conductor (RCOCC) stabilized by a static bath of superfluid Helium at 1.8 K [1], [2]. As the length of the conductor for one double pancake is 240 m, the Gorter-Mellink regime through the 6 mm hole is not sufficient in our design. We used the internal energy of the superfluid Helium near the conductor to increase the temperature margin.

The cryostat (37.4 tons) is mechanically reinforced to resist the high forces acting on the cold elements, mainly the SC coil (0.94 MN) and the Eddy Current Shield: ECS (4.5 MN) in case of loss of a half Bitter coil (worst fault scenario). The SC coil mass is 17 ton and the total cold mass is 22.4 ton. The most critical parts of the cryostat are the ECS and the cold mass support ferrules [2], [3].

3. The cryogenic infrastructure

The cryogenic infrastructure, (Fig. 1a), is based on a 110-130 l/h liquefier and a 4500 liter volume Dewar [4]. The goal is to operate the liquefier with the dewar maintained at constant level of 4000 liter. This solution separates the liquefier from the thermal behavior of the coil in case of quench and gives the required autonomy for a slow ramp down of the magnet current in case of liquefier's failure. It allows to keep the magnet cold for a few tens of hours without liquefaction or to exceed temporally the liquefaction capacity. The LHe consumption is 110 l/h with an operating magnet energized at 1.8 K, and respectively 90 l/h or 72 l/h in standby condition at 1.8 K or at 4.2 K respectively.

In order to safely control the fluids in the magnet environment, the current leads and the valves have been transferred from the cryostat to a separate cryogenic satellite located in a limited magnetic stray field area (< 30 gauss). This satellite contains an expansion volume (cold buffer) to recover liquid helium from the coil cryostat during a quench [5], [6]. This strategy limits the helium overpressure and the hot spot temperature within the coil in any quench case by increasing the resistive zone to the all magnet because the liquid helium leaves quickly the coil environment. We expect to save 50 to 60% of the liquid helium from the cryostat in this buffer. To keep the coil environment clean, we make an indirect cooling of the cryostat with 2 heat exchangers. The estimated time to precool with the LN_2 and to cool-down with the He exchanger is around 50 days. The thermal characteristics of the cryostat and the satellite are given in Table 3 and Table 4.

4. The cryostat

The fault scenario has exceeded the common idea of a cryostat structure. In this exceptional situation the base plate must withstand heavy loads from the ECS (up to 4.5 MN), from the bore tube (up to 5.17 MN) and from the SC magnet support structure (up to 0.94 MN) [2], [3]. Finally, the design of our ferrules gives a relatively economic cryostat.

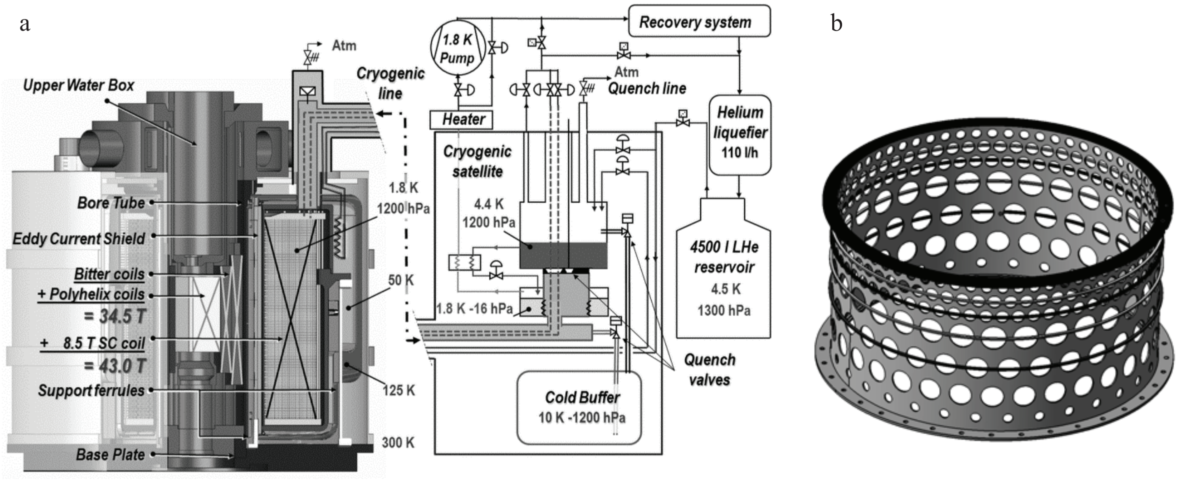

Fig 1. (a) Scheme of Hybrid magnet and its cryogenic infrastructure; (b) the SC magnet support ferrule.

The two ferrules and the shields are cooled in series. To reduce eddy currents, thermal shields are made of stainless steel and are physically cut in eight sectors, cooled in pairs. The four cooling circuits from 4.5 to 128 K are downstream regulated in parallel with warm valves. The impregnated coil is immerged in a superfluid pressurized helium bath at 1.8 K – 1200 hPa. The static helium consumption to maintain this cryostat at 1.8 K is 0.79 g/s, where 0.65 g/s are used in the thermalization circuits of the thermal shields and of the two ferrules.

Table 3. Thermal characteristic of the SC cryostat

Description	T He (K)	P (W)
Helium vessel	1.8	1.88
Coil junctions at 7100 A*	1.8	4.25
1st Level of the main ferrule	4.4	10.65
30 K ECS ferrule	10 to 22	45.00
2nd Level MF + 50 K shields	25 to 48	71.71
77 K ECS ferrule	77	236.00
3rd Level MF + 100 K shields	60 to 115	209.05

Table 4. Thermal characteristic of the satellite.

Description	T (K)	P (W)
Helium exchanger & valves	1.8	1.00
Lambda plate & conductors	1.8	4.36
Helium I vessel & valves	4.4	9.14
Current leads at 0 A (permanent)	4.4	9.76
Current leads at 7100 A (added)*	4.4	6.51
LN_2 shield	77.0	83.6

* Joules losses

5. The satellite

The satellite, (Fig 1.a), is a standard model initially developed for the SEHT and the Neurospin coils (same levels of power and cold volumes) at Saclay and adapted to the LNCMI magnet [6], [7]. A 1.5 m^3 cold buffer to recover a large part of the helium from the magnet in the case of quench has been added to complete the original design. The cooling circuitry has been oversized to use liquid helium instead of supercritical helium [4]. The cold buffer is maintained at 10 K ready to receive the helium from the quench valves as it has already been realized for the CLAS-DVCS solenoid in 2005 [5]. Due to the resistive current leads, the static helium consumption to maintain the satellite at 1.8 K is twice the consumption of the cryostat.

6. The cryogenic line

The cryogenic line incorporates the power distribution of the current (7100 A) and the cryogenic services to cool down and maintain the magnet at low temperature in a superfluid pressurized bath at 1.8 K and 1200 hPa. As the length of the cryogenic line is 15 m, the 1.8 K pipe has been over-sized to allow the extraction of the helium from the cryostat in 10 seconds in case of quench. The hydraulic diameter is 0.09 m and the temperature difference due to the heat load between the satellite and the coil is lower than 5 mK. As a vacuum failure cannot be eliminated in the fault scenario, this cryogenic line contains an insulating vacuum separation between the cryostat and the satellite. The cryogenic line losses are 4.5 W at 1.8 K, 4.5 W at 4.5 K and 28.2 W at 77 K, respectively.

7. The Eddy Current Shield (ECS)

The ECS is adapted from the former SC magnet [1], [8], [9], [10]. The ECS consists of 5 massive OFHC copper cylinders inserted in a specific shrink cylinder made of stainless steel. The ECS is located between the 100 K inner thermal shield and the SC coil cryostat. It is cooled down to 30 K to optimize the capture of the eddy currents induced by the resistive insert coils. The ECS is also used as a second inner thermal shield. The main goal of the ECS is to allow ramping up and down of the resistive insert coils at a maximal rate of 1 T/s without quenching the SC coil. The second goal is to protect the SC coil in the worst fault scenario (loss of half a Bitter coil), where the whole SC coil instantly quenches. Then the force levels are so high, that the massive base plate of the cryostat (stainless steel, 200 mm thick) reacts as a membrane and the dynamic effects amplifies the initial forces [3].

8. The support ferrules

The ferrules studied, Fig 1.b, for this project have an innovating design under CEA patent [11] (association of holes rows for a better thermal/electrical insulation with reinforcement flanges for a better mechanical stability). The ferrule thickness, the thermalization temperature positions, the number and dimensions of holes, and the reinforcement flanges have been optimized under CAST3M [12]. It has been modeled with solid finite elements for thermal calculation and shell finite elements for mechanical calculation of upper/lower/mid skin TRESCA equivalent stress and of buckling.

The SC magnet support must safely sustain a 950 kN vertical downwards force combined to a 98 kN horizontal force. It must be as long as possible to reduce thermal conduction and thermo-mechanical stresses from 300 K to 1.8 K (the thermal shrinking of the 1145 mm radius ferrule is about 3.5 mm). It must be as short as possible for a better mechanical stability (buckling). Its length is limited by the length of the outer cylinder of the He tank, which must be long enough to place 36 pre-stressed tie rods. The SC coil support structure final design is a 10 mm thick and 1200 mm long ferrule, made of 316L stainless steel. Our mechanical stability criteria is to keep the load multiplying factor for buckling above 20 and the mechanical stress below 50 % of the yield stress at room temperature. The thermal characteristics of the magnet ferrule are given in Table 5.

This ferrule is thermally divided into four quarters, cooled through the thermal shields by four parallel circuits, calculated with Hepak [13]. The multiple adjustment parameters of the design (hole diameters and number, number of row and hole position, thermalization temperature and position) make possible to use a single He flow for the thermalization between 4.8 K to 125 K.

The ECS ferrule is thermalized at 80 K and 30 K. It is mechanically more loaded in the fault scenario (4.05 MN vertical downwards and 0.1 MN horizontal) and must be shorter than 280 mm. Moreover its fixation must withstand a 4.5 MN upwards load. It has been designed in the same way as the SC coil ferrule. The actual design of this ferrule is composed of 2 half cylinders locked together and made of TA6V titanium alloy. Its dimensions are 1 m diameter, 280 mm in length and 24 mm of wall thickness.

Our mechanical stability criteria is to keep the load multiplying factor of buckling above nine and the mechanical stress below 33 % of the yield stress at room temperature. This ferrule is cooled to 80 K with LN_2 and to 30 K with the same 0.65 g/s mass flow of the 4.8/50/125 K shields thermalizing the SC coil ferrule.

Table 5. Thermal characteristic of the SC magnet ferrule

Description	T (K)	P (W)
Magnet Level*	1.8	0.3
1rst Thermalization**	4.8	9.3
2nd Thermalization**	50.0	59.0
3rd Thermalization**	125.0	104.0

* Conduction between 4.8 and 1.8 K

** These 3 thermalizations plus the 30 K ECF are cooled in series by the 0.65 g/s mass flow helium vaporized at 5 K.

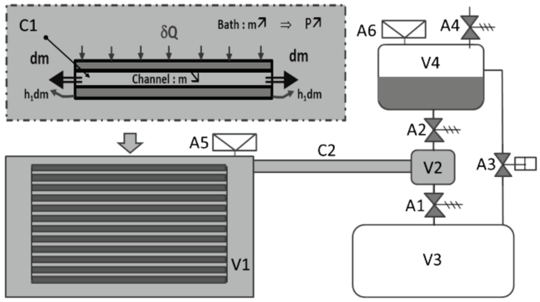

Fig 2. The thermo-hydraulic circuits.

9. Thermal analysis and thermo-hydraulics of the fault scenario

The fault scenario combines the worst insert burnout, a generalized quench of the SC coil without dump resistor and a major vacuum failure. This insert burnout results from short-circuits between Bitter magnet disks. The worst case is a simultaneous burnout of half the Bitter magnets. [2], [3].

The initial conditions are: 1.8 K and 1200 hPa for the conductor channels (C1), the helium vessel (V1), the cryogenic line (C2) and the 1.8 K exchanger of the satellite (V2). The helium vessel of the satellite (V4) is at 4.5 K. The cold buffer (V3) is at 10 K (Fig 2) [14].

The calculations have been computed with the Vincenta code [15] with the conservative conditions: At t = 0.1 s the coil is fully quenched, the initial temperature and pressure considered are 3 K and 1200 hPa. The water leak from the bore tube generates progressively 0.95 MW over a deviation of 11 s into the He vessel.

The Joule losses dissipated at the beginning of the quench are 1.2 MW given the distribution of the magnet field along the conductor. The heat flux transferred into the helium channel is 0.75 MW. The heated helium expands and is expelled into the bath provoking a pressure increase (Fig 2).

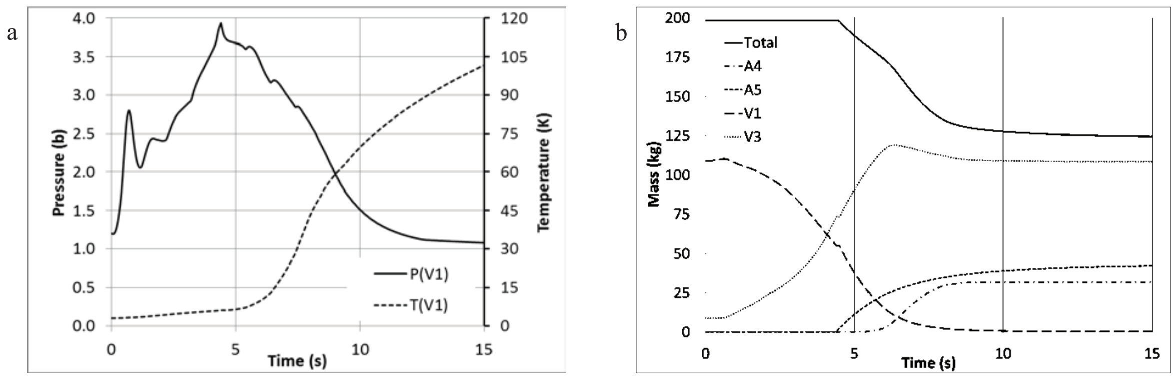

Fig 3. (a) Pressure and temperature in the helium vessel; (b) Mass repartition and mass losses.

The cryogenic circuits are sized to evacuate the helium as fast as possible from the cryostat to the cold buffer (V3) (C2 hydraulic diameter is 0.09 m) to limit the overpressure (see Fig 3.a). At this time the helium in the bath is in a pseudo-liquid state (6 K, 3.9 bar) and immediate opening of the burst disc decreases the pressure. As the He vessel (V1) is quite empty at t = 7 s, the temperature of the cryostat quickly increases due to the heat caused by the vacuum failure. The 1.5 m^3 cold buffer (V3) receives 60% of the total helium (Fig 3.b). 40% of the helium mass is lost through the burst disk (A5) of the cryostat and through the relief valve (A4) of the satellite. The maximal pressure induced in the middle of the conductor channel by the viscous friction is 44 bar reached at 2.7 s.

The same calculation with a quench without over-accident (discharge in the dump resistor and no vacuum failure) gives a 3.5 bars overpressure [14].

10. Conclusion

The particular behaviors of this hybrid magnet have modeled the characteristics of our SC coil well beyond the usual standards. The final studies have confirmed our reinforced design of the cryostat and the necessity to expel the helium in any quench case to prevent high pressure levels. The last estimation of the thermal losses is just equivalent to the minimal flow of the liquefier at constant level in the Dewar. The eventuality to support a quench per month in case of a resistive insert trip is one of the last critical points, because it provokes mechanical and thermal cycles and also because we lose 25 % of the helium. The LNCMI is on the way to change and upgrade its resistive coils power converters to minimize this risk. We have limited the overpressures below 4 bars in the most critical fault scenario, avoiding additional forces to the structure. The thermo-mechanical design of our ferrules is the key that makes cryogenics possible for this project.

Acknowledgements

The authors would like to thank the Hybrid Magnet team at LNCMI-Grenoble and CEA-Saclay and specially C. Meuris for her precious thermo-hydraulic contribution and her thermodynamics discussions and comments.

This work was supported by the French Ministry of Higher Education and Research in the framework of the “Investissements pour l’avenir” LaSUP (Large Superconducting User Platform), the CNRS and the EU-FP7-Infrastructure-2008-1, Funding scheme Combination of Collaborative Project and Coordination and Support Action, EuroMagNET II, Grant agreement number 228043.

References

[1] P. Pugnat and H. J. Schneider-Muntau, “Hybrid Magnets: Past, Present and Future”, IEEE Transactions on Applied Superconductivity 24, na (2014)
[2] P. Fazilleau, et al. “Final Design of the New Grenoble Hybrid Magnet," IEEE Transactions on Applied Superconductivity 22, 4300904 (2012)
[3] P. Manil, et al. “Dynamical response of a hybrid magnet structure featuring eddy current shield during transient failure mode”, IEEE Transactions on Applied Superconductivity 24, 4300306 (2014)
[4] L. Ronayette et al. “The Cryogenic System of the 43 T Hybrid Magnet of LNCMI Grenoble, France", Proceedings of the 12th International Institute of Refrigeration Conference (Cryogenics 2012) pp. 65-72, Dresden, Germany, September 11-14 (2012). ISBN : 9782913149939, ISSN : 01511637
[5] J. Ball et al. 2006, Superconducting solenoid for the CLAS DVCS experiment, Hadron structure – SPhN 2004-2006.
[6] W. Abdel Maksoud et al. 2010 Quench experiments in a 8 T superconducting coil cooled by superfluid helium, IEEE Transactions on Applied Superconductivity, vol 20, p 1989-1992.
[7] Ph. Bredy et al. 2010, Cryogenics Around the 11.7 T MRI Iseult Magnet, IEEE Trans. on Applied Superconductivity, vol 20, p 2066-2069.
[8] G. Aubert et al. 2004, Hybrid and Giga-NMR projects at the Grenoble High Magnetic Field Laboratory, IEEE Transactions on Applied Superconductivity, vol 14, p 1280-1282.
[9] A. Bonito Oliva et al. 2005, Preliminary Results of Final Test of the GHMFL 40 T Hybrid Magnet, IEEE Transactions on Applied Superconductivity, vol 15, p 1311-1316.
[10] A. Bonito Oliva et al. 2006, Investigation on ramp rate limitation on the superconducting magnet for the Grenoble 40 T Hybrid system, IEEE Transactions on Applied Superconductivity, vol 16, p 940-944.
[11] Patent numbers : EU EP2672492 –US20130327903 – FR2991809
[12] CASTEM 2000 une approche moderne du calcul des structures, P. Verpeaux, T. Charras, A. Millard.
[13] Hepak V3.4 1999, Computer program for calculating thermophysical properties of helium from fundamental state equations, Cryodata Inc http://www.cryodata.com.
[14] C. Meuris 2014, Montée de pression en cas de quench, Internal report CEA/DSM/IRFU/SACM.
[15] V. Amoskov et al. Validation of VINCENTA modelling based on the experiment with the model coil of the ITER central solenoid. Plasma Devices and Operations, Vol. 14, No. 1 (2006), p. 47-59.