Cryogenic Operation on the R3B-Glad Large Acceptance Superconducting Dipole at CEA Saclay

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Introduction

The R[3]B-Glad superconducting Magnet is a large acceptance dipole dedicated to the analysis of Reactions with Relativistic Radioactive ions Beams on the future FAIR facility at GSI Darmstadt. The original shape of the cryogenic tank and fluid distribution [1] was imposed by the compact design of the six tilted and trapezoidal racetrack coils. The coils, electrically connected in series in a butterfly-like magnet, provide the field integral of 4.8 T.m required for the experiments while ensuring the active shielding [3] [5]. They are imbedded into the coil casings with their covers, as in sarcophagi, and are indirectly cooled by means of copper braids fixed to the casings made of aluminum alloy. The very efficient two-phase helium thermosiphon keeps the magnet cold mass under 4.8 K. Its original features lie in the low slope (5°) of the heat exchanger tubes glued directly to the casings, as well as in its compact geometry [2] The whole magnet cold mass, weighing 21 tons, is supported by three cold-to-warm feet, each one being thermalized with dedicated cryogenic circuits. The magnet cooling down to 4.8 K as well as the 2-slope ramping, up to the nominal current of 3584 Amps, were successfully achieved during December 2013 in the large Saclay Test Facility.

Objectives

- To adapt the Saclay "W7X" Test Facility to the R[3]B-Glad cold mass, the major improvements were:
  - ✓ Specific cryogenic network connections to ensure successfully the cooling down.
  - ✓ Thermal simulation inside the W7X cryostat, to reproduce the real GSI thermal gradient from 300 K to 4.5 K applied to the three cold-to-warm feet.
- To check experimentally the efficiency of the cooling method with a two-phase thermosiphon.
- To reach the nominal operation conditions at 3584 Amps with a comfortable temperature margin, greater than **1.7 K.**

Summary

- The experimental campaign was successfully completed. This showed the smooth operation of the cryogenic system of the large test facility at Saclay. In its current configuration, it provides the suited cryostat with liquid helium at about 4.5 K, and has been specially adapted in order to cool down and to power the R[3]B-Glad magnet.
- The original thermosiphon layout maintains the nominal temperature of the coils at around 4.8 K.
- The original design of all contacts between surfaces: coils and coil casings, coils and shape wedges, coil boxes and pushing systems [5] has produced an unusual shape of the temperature evolution curve. In particular, the mechanical coupling between coils and coil casings, reinforced at the rise of magnetic forces, substantially increases the heat transfer. *(Fig. 1)*
- Finally, the operation of the R3B-Glad magnet in its nominal conditions, i.e. at a current of 3584 Amps, has been reached after a training period including five quenches. *(Fig. 3)*
- The magnet reached its operational current in one hour: at 2 A/s from zero to 2400 Amps, and at 0.5 A/s up to 3584 Amps with a temperature stability margin larger than 1.7 K.

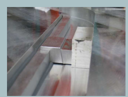
[1] Lottin J.P *et al. Cryogenic characteristics of the R3B-Glad magnet.* Presented at ICEC23-ICMC Wroclaw, Poland, 2010; pages 627-632
[2] Baudouy B. et al. *Modelling of a horizontal circulation open loop in two-phase helium,* Cryogenics 53, 2013 pp. 2-6
[3] Gastineau B. et al., *Progress in Design and Construction of the R3B-GlAD Large Acceptance Superconducting Dipole Spectrometer for GSI-FAIR",* IEEE Trans. Appl. Supercond., vol. 20, no. 3, June 2010, pp. 328 - 331
[4] Renard B., Genini. L. et al. *Ten years of cryomagnetic W7-X test facility construction and operation.* Cryogenics 51, 2011 pp.384-388
[5] Mayri C. et al. *Thermo-Mechanical Measurements on Impregnated Cu-NbTi Cable Stacks.* IEEE Transactions on Applied Superconductivity, Vol. 20, N° 3, June 2010

W7X Cryostat

R3B-Glad inside the Saclay Test Facility

Bird's eye view of the Test Facility

Refrigerator with a capacity of mixed operation:
Refrigeration: 15 g/s @4.2K
Liquefaction : 70 l/h
200 W@ 4.2K
Power Supply: 25 kA
Cryostat: F 5.2 m



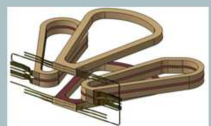
Heat exchanger pipes glued and clamped on the Aluminum casings

R3B-Glad

LHe phase separator

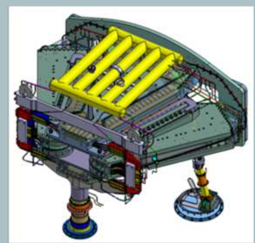
460 liters

Six tilted racetrack coils



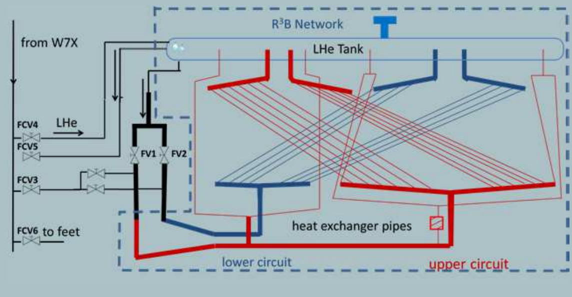
Due to the geometry of the magnet, the heat exchanger tubes are quasi-horizontal

View of the R3B-Glad cold mass



Two thermosiphon loops:
Upper and Lower Circuit: 26 heat exchanger pipes.
- 20 in the casing grooves
- 4 directly glued on the arches,
- 2 on the electrical connections plates

Hydraulic Network

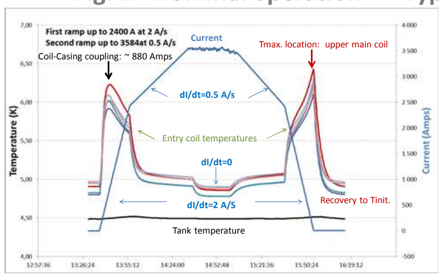


Schematic view of the cryogenic connection between "W7X" test station and R[3]B-Glad

The process of the helium flow, used for these tests, was consistent with the future cryo-plant conditions at GSI.
Six main valves (FV1,FV2, FCV3, FCV4,FCV5,FCV6) connect the test facility to R[3]B-Glad cold mass**.** The FCV3 ensures the cooling down phase bypassing the thermosiphon. During nominal operation, the JT valve FCV4 takes over the filling of the liquid helium tank; the return gas takes place through the FCV5 valve. Finally the FCV6 cools the feet. The two valves FV1, FV2 provide the helium from the tank to the casings by the upper and lower sets of heat exchanger pipes.

Results

Fig. 1 - Nominal operation



The maximum initial coil temperature is **4.97 K** at the entry of lateral upper coil. The temperature at the entry of main upper coil increases up to **6.23 K**, this maximum is observed during the current ramp-up for all coils**,** always at a current of ~ **880 Amps**; This temperature limit is certainly due to the occurrence of a better thermal contact between coils and casings, caused by the mechanical coupling strength, proportional to the square of the current.

Typical evolution of the coil temperatures

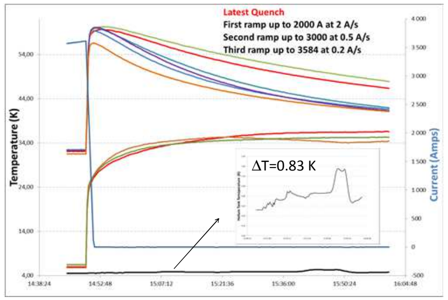
Thermal behavior

The temperature evolution of the coils is essentially subjected to two different phenomena :

- A thermal phenomenon due to AC losses in conductors and eddy currents in casings. Depending on the current variation that increases **the heating power by $\frac{dI}{dt}$ variation**
- A mechanical phenomenon due to the coils-casings coupling that improves **the heat transfer by $\sim B^2$**

At full current, the current sharing temperature is estimated at 6.7 K and the highest operational coil temperature is roughly 4.86 K; thus the temperature margin is equal to 1.81 K, thus greater than 1.7 K.

Fig. 2 - Quench

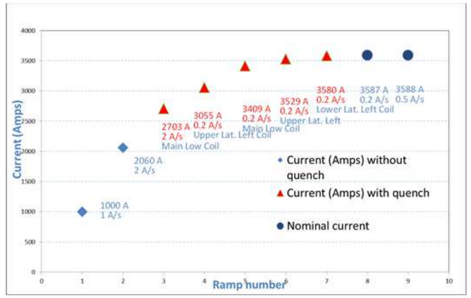


During the quench, the maximum coil temperature is 59.3 K, while the maximum casing temperature is 36.6 K. This ΔT value of about 30 K was well predicted by the simulation.

Magnet Safety System

Owing to the stored magnetic energy of 24.3 MJ, the threshold values of voltage and holding time were fixed to **100 ms@100mV**

Fig. 3 - Training Curve



On 5 December 2013, the cold mass reaches its nominal current of 3584 Amps after five training quenches, due to mechanical adjustment movements of the coils inside their casings.

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