# Design, Manufacture and Tests of a 4 Teslas $MgB_2$ Dry Magnet

Mario Kazazi, Christophe Berriaud, Clement Hilaire and Thierry Schild
CEA, IRFU F-91191 Gif sur Yvette Cedex, France.
**Raphael Pasquet SIGMAPHI, F-56000 Vannes - France**

***Abstract*—As part of a program that aims at developing design tools and technologies for dry $MgB_2$ magnets, a react-and-wind (R&W) $MgB_2$ solenoid operating at 10 K and medium field range (1 T up to 4 T) has been developed at CEA/Saclay. The prototype-coil is wound from approximately 2 km of a commercial $MgB_2$ wire and has a winding diameter of 200 mm, external diameter of 300 mm, and height of 200 mm. It has a nominal central magnetic field of 1 T and is placed in a 3 T background field generated by a classical NbTi magnet. The $MgB_2$ solenoid has been epoxy impregnated and then instrumented for low temperature testing. The tests have been successfully performed with a nominal current of 100 A, an operating temperature of 10 K, and a background field of 3 T. Current sharing measurements have been carried out to compare the coil critical current to the bare tape critical current. In this work, the magnet design, the manufacture, and the experimental results of the cryogenic tests are presented.**

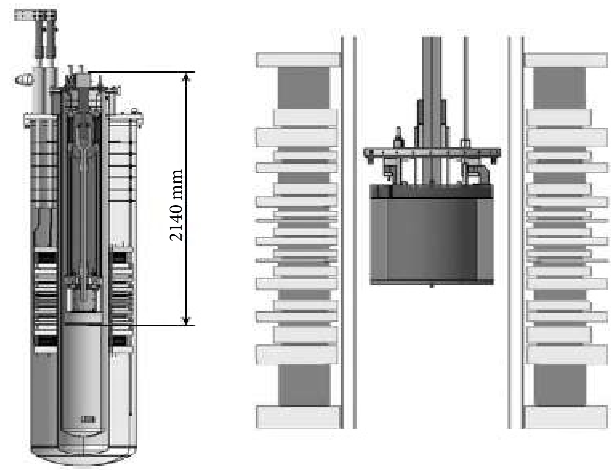


Fig. 1. View of the test facility with the solenoid installed on the insert (left) and a zoom that shows the $MgB_2$ solenoid at the center of H0 (right).

## I. Introduction

Since its discovery [1] $MgB_2$ superconductor has been subject to intense study for investigating the possibility of its application in magnet design. The critical temperature of 39 K, the high critical current density ($J_C$), and the comparatively lower cost than other available high temperature superconductors (HTS) make $MgB_2$ very attractive for industrial superconducting magnets, including magnetic resonance imaging (MRI) magnets.

In this direction, the CEA/Irfu institute, in collaboration with SigmaPhi, a French SME company, has lunched an R&D program that aims at developing design tools and technologies for dry $MgB_2$ magnets. An important part of this program is the characterization of the used superconducting wire, namely its physical properties at specified conditions. The wire under study is an ex-situ $MgB_2$ tape conductor [2] produced by Columbus Superconductors SpA. The Italian company is also a partner and has freely supplied this program with several configurations of $MgB_2$ wire, which are tested in the CEA laboratories in order to achieve optimal superconducting properties for dry $MgB_2$ magnets.

In the framework of this R&D program, a great amount of research has been done for the development of facilities and instrumentation for cryogenic testing, as well as for optimizing the manufacture process and winding technique of $MgB_2$ magnets. In particular, a new test facility for the characterization of R&W $MgB_2$ conductor has been developed and presented in [3]. Two $MgB_2$ double pancakes have been designed, fabricated, and successfully tested [4]. Furthermore, the preliminary quench protection studies related to the solenoid subject of this paper, including stability and quench propagation modeling, have been performed in [5].

This work reports on the design and the manufacture of an R&W $MgB_2$ solenoid operating at 10 K and medium range field (1 T up to 4 T). The results of the cryogenic tests and the experimental validation of the prototype by comparison to the bare conductor are also presented.

## II. Magnet Design

### A. Conductor

The conductor chosen for the solenoid winding is an R&W $MgB_2$ tape produced by Columbus and its main characteristics are illustrated in Tab. I. It consists of 19 $MgB_2$ filaments embedded in a nickel matrix with a OFHC copper strip for stabilization and quench protection. Given the low RRR of the nickel matrix, the presence of the copper stabilizer is necessary for the magnet protection and makes this tape suitable for magnet design. As all the $MgB_2$ conductors, it is sensitive to the strain and has a tensile strain limit of 0.6% with minimum bending radius of around 60-70 mm.

### B. Test facility

A test facility [3] has been built at CEA/Irfu for characterizing $MgB_2$ conductors and dry prototype magnets under representative conditions. It provides conduction cooling with variable temperature by means of a 2-stage GM cryocooler (RDK-408L2) produced by Sumitomo Heavy Industries. The

TABLE I
CONDUCTOR CHARACTERISTICS

| Parameters | Value | Unit |
|---|---|---|
| Conductor dimensions | 3.1 x 0.7 | $mm^2$ |
| Insulation thickness | 0.07 | mm |
| $MgB_2$ Cross section | 0.31 | $mm^2$ |
| Ni Cross section | 1.24 | $mm^2$ |
| Cu Cross section | 0.62 | $mm^2$ |
| Insulation type | Polyethylene braid | |

facility can operate under self-field or with a 3 T background field provided by a NbTi magnet, known as H0 [6]. The H0 magnet is cooled by liquid Helium at 4.2 K, has a warm bore with a diameter of 350 mm, and a field homogeneity of 350 ppm peak-to-peak in a sphere of 300 mm.
The distance between the center of H0 and the second stage of the cryocooler is 1.4 m which is quite long for conduction cooling. Hence, for the connection between the solenoid mandrel and the cryocooler, the CMS conductor [7] without its mechanical layer of aluminum alloy was chosen. This conductor has a high mechanical strength and maintains a high RRR value at cryogenic temperature, thus limiting the thermal gradient and the size of the connection.

### C. Characteristics of the $MgB_2$ solenoid

Considering that a field strength between 3 and 4 T is of interest for many $MgB_2$ applications, we have designed and constructed a solenoid magnet with a nominal center field of 1 T placed in a background field of 3 T. The operating temperature and the nominal current are fixed at 10 K and 100 A respectively. In order to allow the solenoid magnet to be integrated in the test facility (warm bore of 350 mm), the internal diameter was fixed at 200 mm and the external diameter at 280 mm, thus leaving an adequate margin from the aluminum shielding. The height was calculated to limit the maximum field at 2[illegible] of the central field. By taking into account these dimensions, a conductor length of 2 km was used for a solenoid winding of 44 layers and 2662 total turns. The magnet characteristics are summarized in Tab. II.

As shown in Fig. 2, the solenoid design is based on three main components:

- A winding mandrel made of copper and Ti6Al4V (titanium alloy) on which are soldered the lower end plate and the internal crown (negative terminal), with this latter being connected directly to the thermoelectric busbar of the insert,
- An intermediary crown in G10 (fiberglass polymer) that allows to insulate the negative terminal from the positive one,
- An external crown in copper that constitutes the positive terminal and is connected to the other thermoelectric busbar of the insert.

A winding mandrel of pure copper is not compatible with the $MgB_2$ conductor tape which has a nickel matrix with

TABLE II
MECHANICAL, ELECTRICAL AND MAGNETIC CHARACTERISTICS OF THE DESIGNED SOLENOID

| Parameters | Value | Unit |
|---|---|---|
| Internal radius | 100 | mm |
| External radius | 140 | mm |
| Height | 195 | mm |
| Number of layers | 44 | |
| Number of turns/layers | 60.5 | |
| Number of turns | 2662 | |
| Conductor length | 2 | km |
| Inductance | 1.14 | H |
| Nominal current | 100 | A |
| Nominal current density | 37.2 | $A/mm^2$ |
| Stored energy | 6839 | J |
| Nominal temperature | 10 | K |
| Center field | 1.07 | T |
| Field on the conductor | 1.29 | T |

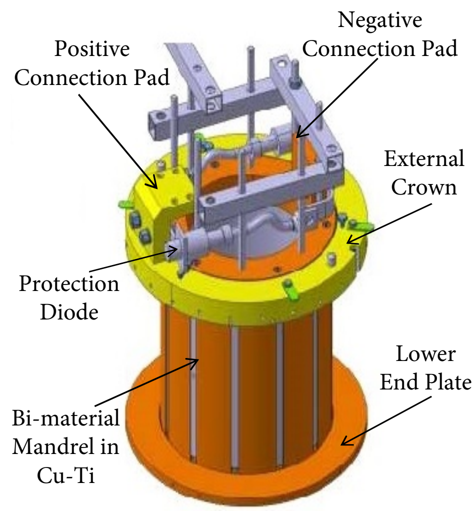


Fig. 2. A view of the copper/Ti6Al4V mandrel of the $MgB_2$ solenoid. The cold diode and the pads for the thermoelectric connection to the busbars of test facility are also shown.

a thermal shrinkage lower than that of copper [the thermal shrinkage coefficients are: 2.35 mm/m (Nickel), 3.14 mm/m (Copper), and 1.79 mm/m (Ti6Al4V)]. For this reason, a Ti6Al4V/copper mandrel has been designed in order to prevent high stresses and to keep the conductor in contact with the mandrel during the cool-down. In particular, the bi-material mandrel is obtained by brazing copper strips (1 mm thick) on the Ti6Al4V mandrel (10 mm thick). The brazing joints ensure a good thermal contact between the copper strips and Ti6Al4V mandrel and guarantee a homogeneous temperature of the mandrel and the winding.
The internal and external crowns, via the the bus-bars of the test facility (CMS conductor), have the function of driving the cooling and the current into the solenoid winding. The

connection with the insert bus-bars is made by means of the connection pads illustrated in Fig. 2. The negative pad is screwed into the internal crown and the positive one is screwed into the external crown. Indium wire is added to reduce the thermal and electrical contact resistances between the pads and the crowns. The conductor tape is soldered on the internal crown at the beginning of the winding, and on the the external crown at the end of the winding process. Solder joints are made using tin-lead solder.
For ensuring a good global thermal contact between turns and layers, the magnet has been epoxy vacuum impregnated by the French company SigmaPhi. The impregnated magnet instrumented with voltage taps and temperature sensors is shown in Fig. 3.

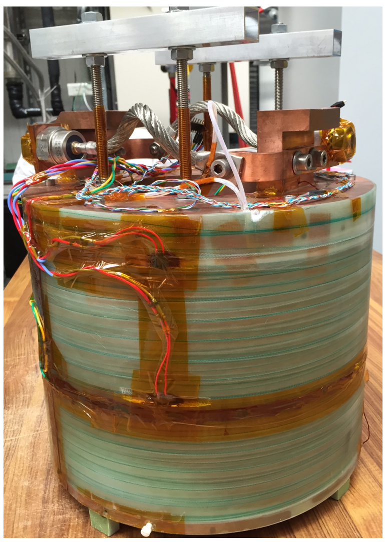

Fig. 3. Final design of the $MgB_2$ prototype magnet. It is equipped with a support structure for the integration to the test facility.

### D. Protection and stability

The stored energy density in the magnet is quite limited, namely 152 $\mathrm{J/kg}$ considering only the insulated winding. Thus, if we imagine to uniformly distribute all this energy in the solenoid winding, it would correspond to a temperature rise from 10 to 28.1 $\mathrm{K}$. Therefore, given these small values, we have decided to adopt a practical solution and protect the magnet by pure internal discharge through a 600 A cold diode [8].

A quantitative understanding of the magnet stability and its quench propagation behavior have been described in a previous publication [5]. In this preliminary quench study, the protection method was validated and a minimum quench energy (MQE) of 1.15 J was computed. Moreover, the normal zone propagation velocities (NZPV) were calculated as 17 $\mathrm{cm/s}$ along the azimuthal direction and as 3 and 13.5 $\mathrm{mm/s}$ for the radial and axial directions.
Currently, a campaign of quench propagation measurements has started and one of the main objectives is the validation of the calculated MQE and NZPV.

## III. Results and Discussion

### A. Instrumentation

The voltage taps were soldered onto the conductor during the winding process. We chose to solder a reduced number of taps in order to limit the risk of degradation of the conductor. The voltage taps, as schematically represented in the wiring diagram of Fig. 4, were vacuum impregnated with the winding. The temperature of the magnet is monitored with 3 Cernox

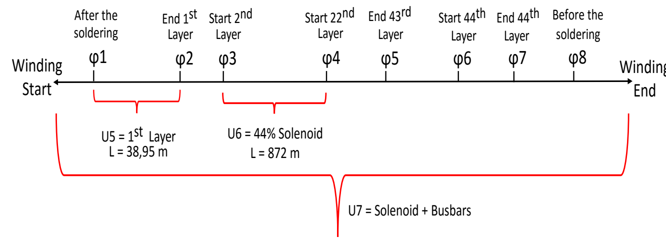


Fig. 4. Wiring diagram.

(T1, T2, and T3) sensors located at top and bottom of the magnet as illustrated in Fig. 5. Thus, we do not measure

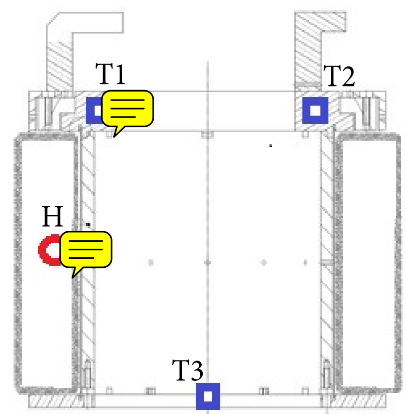


Fig. 5. A scheme of the magnet showing the positioning of the three temperature sensors (T1, T2 and T3). The red point H represents a possible hot spot during a quench

directly the temperature of the conductor, but we can estimate it by measuring the difference between T2 and T3.

### B. Critical Current and n-Value

The V-I curves and n-values for the compensated voltage of the inner layer, U5 in Fig. 4, are plotted as a function of magnetic field and temperature in Fig. 6. The system was cooled down to 10 $\mathrm{K}$, and then the critical current ($I_c$) was measured at various temperatures ranging from 10 to 30 $\mathrm{K}$, and current ramping rates from 0.1 to 1 $\mathrm{A/s}$. The field also was varied from 1 $\mathrm{T}$ (self-field) to 4 $\mathrm{T}$ (self + background field). The critical current is obtained with a superconducting criterion of 0.1 $\mu\mathrm{V/cm}$ and the n-values for the electric field range 0.01 - 0.1 $\mu\mathrm{V/cm}$. Due to bad control of the power supply, the plots in Fig. 6 show some spikes.

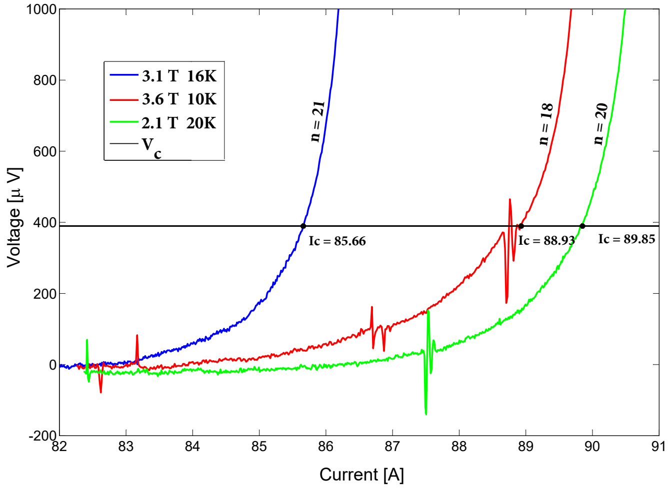


Fig. 6. V-I curves and n-values of the solenoid inner layer for different values of total field (self + background) and temperature.

### C. Experimental Validation

The aim of this section is to experimentally validate the design, manufacturing, and the winding technique used for the $MgB_2$ solenoid. The validation is done by comparing the critical current ($I_c$) of the solenoid magnet with that of a conductor sample as a function of the applied magnetic field. The comparison is performed for different temperatures ranging from 5 to 30 K. This $I_c(B)$ dependence is shown in Fig. 7 and is investigated with regards to possible degradation due to bending. The critical currents of the solenoid (symbols) are in very good agreement with those of the sample, represented with curves obtained by a Bottura-type fit [9]. Nevertheless, a few points are more distant from the fitting curves. It is important to notice that, as shown in Fig. 5, we do not measure directly the hot spot temperature (point H) but rather the top and the bottom of the magnet (temperature sensors T1, T2 and T3). In fact, the points which deviate more from the fitting curves correspond to critical current measurements where the temperature difference between T2 and T3 (represented with dT in the legend of Fig. 7) is quite large. The larger the value of dT, the larger the difference between the solenoid $I_c$ measurements and the fitting curve of the sample. In other words, a large dT is a sign that the temperature of the solenoid winding is not uniform. We noticed this dependence only after the data analysis, and we believe that the non-uniformity is due to a heat load dissipation from the internal part of the solenoid after a quench in the previous test.

However, this comparison validates the magnet design, and in particular the winding technique, by demonstrating that there is no appreciable degradation of the critical current in the solenoid inner layer. On the other hand, the results indicate that the system needs more time to reach a uniform temperature in the whole magnet (especially after a quench), and thus the tests should be performed accordingly.

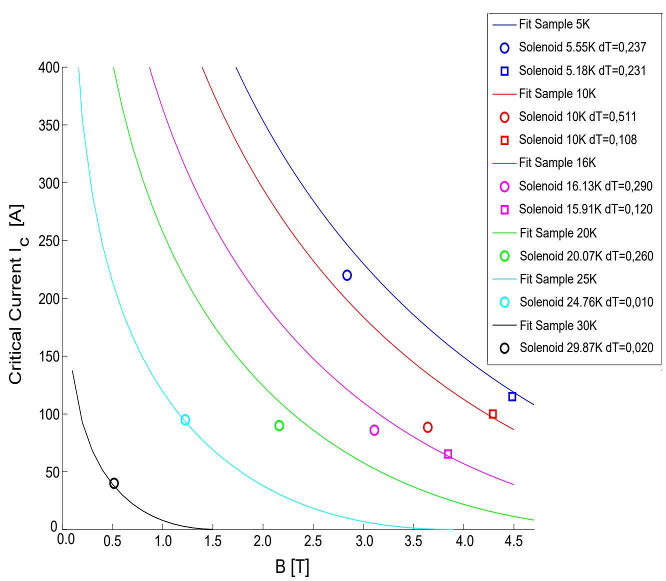


Fig. 7. The critical currents for the conductor sample (lines) and the solenoid magnet (symbols) as a function of magnetic field (B) at different applied temperatures (5-30 K)

## IV. Conclusion

In this paper the design, manufacturing, and experimental tests of an R&W $MgB_2$ solenoid magnet operating at 10 K and medium field range have been presented. In particular, the main components of the magnet, the instrumentation, and the protection method have been described. Critical current tests have been performed as a function of magnetic field and temperature. The results are in very good agreement with critical current tests performed on short samples, showing that there is no degradation of the wire during the winding and demonstrating the effectiveness of the design and manufacturing process.

Currently, the solenoid has been equipped with resistive heaters for NZPV measurements. A pick-up coil has also been installed on the magnet for improving the quality of the measurements and a new quench measurement campaign is ongoing.

## Acknowledgment

Mario Kazazi wish to acknowledge the financial support given by the CEA-Eurotalents program. Special thanks to Gianni Grasso, Matteo Tropeano (Columbus Superconductors SpA) and Frederik Forest (SigmaPhi), for the help and discussions during the development of the magnet.

## References

[1] J. Nagamatsu, N. Nakagawa, T. Muranaka, Y. Zenitani, and J. Akimitsu, “Superconductivity at 39 k in magnesium diboride,” *nature*, vol. 410, no. 6824, pp. 63–64, 2001.

[2] G. Grasso, A. Malagoli, M. Modica, A. Tumino, C. Ferdeghini, A. Siri, C. Vignola, L. Martini, V. Previtali, and G. Volpini, “Fabrication and properties of monofilamentary mgb2 superconducting tapes,” *Superconductor Science and Technology*, vol. 16, no. 2, p. 271, 2003.

[3] R. Pasquet, A. Bonelli, C. Berriaud, F.-P. Juster, H. Przybilski, B. Reynard, T. Schild, and L. Scola, “A new test facility to characterize react and wind conductor,” *IEEE Transactions on Applied Superconductivity*, vol. 24, no. 3, pp. 1–5, 2014.

[4] R. Pasquet, C. Berriaud, F. Forest, C. Hilaire, F.-P. Juster, A. Porhiel, T. Schild, L. Scola, and A. Taleb, "Design and test of a small react-and-wind mgb 2 double pancake," *IEEE Transactions on Applied Superconductivity*, vol. 25, no. 3, pp. 1–5, 2015.

[5] F. Juster, C. Berriaud, A. Bonelli, R. Pasquet, H. Przybilski, T. Schild, and L. Scola, "The preliminary study of the quench protection of an mgb2," in *American Institute of Physics Conference Series*, vol. 1573, 2014, pp. 746–753.

[6] T. Schild, G. Aubert, F. Beaudet, A. Bourquard, A. Chance, J. Fleiter, F. Nunio, L. Quettier, L. Scola, M. Schweitzer *et al.*, "A prototype for assessing the field homogeneity of the iseult mri magnet," *IEEE Transactions on Applied Superconductivity*, vol. 19, no. 3, pp. 2253–2256, 2009.

[7] B. Blau, D. Campi, B. Curé, R. Folch, A. Hervé, I. Horvath, F. Kircher, R. Musenich, J. Neuenschwander, P. Riboni *et al.*, "The cms conductor," *IEEE transactions on applied superconductivity*, vol. 12, no. 1, pp. 345–348, 2002.

[8] R. Pasquet, "Contribution au développement des aimants supraconducteurs mgb2 r & w refroidis par conduction solide." Ph.D. dissertation, Université Pierre et Marie Curie-Paris VI, 2015.

[9] L. Bottura, "A practical fit for the critical surface of nbti," *IEEE transactions on applied superconductivity*, vol. 10, no. 1, pp. 1054–1057, 2000.