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The behaviour of cryogen-free MgB₂ react and wind coils

Riccardo Musenich¹, Pasquale Fabbricatore¹, Stefania Farinon¹, Michela Greco¹, Marco Modica², Roberto Marabotto², Roberto Penco², Marco Razeti² and Davide Nardelli²

¹ Istituto Nazionale di Fisica Nucleare, Via Dodecaneso 33, 16146 Genova, Italy
 ² Ansaldo Superconduttori, Corso Perrone 73r, 16152 Genova, Italy

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Abstract

Although the critical temperature of MgB_2 is far below those of HTS materials, its simple composition, its upper critical field, the lack of weak links and the low anisotropy make it an interesting material for magnet applications. The low cost of magnesium diboride and the rather simple conductor manufacturing process triggered the interest of the industry and at present conductors are available in km order lengths. MgB_2 is a good candidate for MRI applications and also for particle accelerator magnet applications.

Several magnesium diboride coils were constructed and successfully tested in cryogen-free systems. Current values up to 320 A were reached at 14 K for react and wind pancake coils, whose behaviour is described in the paper.

1. Introduction

The construction of superconducting magnets is at present the most promising application of magnesium diboride. Despite the critical temperature of MgB₂ being far below the ones of HTS, the manufacturing of wires and tapes is easier and the cost of both raw materials and the process is lower. Moreover, the lack of weak links and the low anisotropy make magnesium diboride an interesting material for magnet applications. Pure MgB₂ shows a low irreversibility field but it is possible to enhance it by acting on the structure and on the morphology of the material. Recently, critical current densities of 1.7 \times 10^9 A m⁻² at 4.2 K and 5 T in multifilamentary SiC doped MgB₂ wires [1] as well as irreversibility field values up to 29 T at 4.2 K were reported [2]. Such values make MgB₂ a potential competitor of Nb₃Sn for magnet construction; however, at present, MgB₂ conductors produced in industrial lengths are limited to low field magnet application. Despite this limitation, it is possible to find several applications which take advantage of the high critical temperature, in particular cryogen-free magnets and/or magnets requiring a large temperature margin. At the state of the art, looking at the generation of low magnetic fields, magnesium diboride magnets could be serious candidates either for replacing water cooled copper magnets or for competing with NbTi magnets in particular applications.

Two different routes are followed to manufacture MgB_2 based conductors, both exploiting the powder in tube (PIT) technique: the *in situ* route, where precursor powders are inserted in metal tubes, and the *ex situ* route, where the already prepared MgB_2 powders are used.

Conductors, obtained using the *ex situ* method, are available in long lengths, are robust and suitable for react and wind magnets but, at present, are limited to low field applications, like MRI magnets. Actually, MRI being the largest technological application of superconductivity, we can affirm that such a limit does slightly affect the interest in these conductors. The react and wind technique needs care in the winding operation but avoids all the problems related to the high temperature treatment of the magnet, like the choice of thermally resistant insulating and structural materials.

With respect to *ex situ* conductors, the state of the art for *in situ* prepared MgB₂ allows the production of long length wires with good transport properties at higher field (engineering $J_c \approx 0.1$ GA m⁻² at 15 K, 4 T). Figure 1 shows the critical current of a 0.8 mm in diameter multifilamentary wire produced by Hyper Tech in Columbus (Ohio) following an *in situ* route. The Hyper Tech wires are available in lengths of the order of 1 km.

In situ conductors are intrinsically more fragile and more suitable for the construction of wind and react magnets. It worth noting that the heat treatment of a magnesium diboride



Figure 1. Critical current of a multifilamentary wire (0.8 mm in diameter) produced by Hyper Tech following the *in situ* route.

coil is not really a problem as the reaction temperature is around 700 °C, i.e. the same as for the Nb₃Sn coils, but it lasts only 20–30 min rather then 50–100 h. So, the MgB₂ react and wind magnets can be managed using the well known techniques and materials used for Nb₃Sn magnets. The transport properties of *in situ* conductors are already satisfactory for particle accelerator magnets such as bending dipoles for electron synchrotrons, cyclotrons and delivery lines for hadron therapy.

Ex situ conductors are produced by Columbus Superconductors in Genoa (Italy) for low field application (less then 1.5 T), e.g. MRI magnets. The Columbus production consists in nickel clad, copper stabilized, multifilamentary tapes [3]. The tapes are in-line heat treated in order to obtain ready-to-wind conductors in lengths between 1.5 and 2 km.

Several test magnets (both solenoids and pancake coils) were wound with the Columbus tapes and tested both in liquid helium and at various temperatures in a cryogen-free test facility.

2. Coil description

As the first aim of the construction was to verify the feasibility of MgB_2 coils, the winding operations were carried out in the workshop of Ansaldo Superconduttori using industrial techniques, i.e. using a standard winding machine. Since the beginning of 2002, one solenoid and 21 pancake coils were manufactured using the react and wind technique. The solenoid is a 6 layers, 162 turns coil wound with 80 m of monocore tape onto a 12 cm mandrel. The solenoid construction and the results of the test were already discussed elsewhere as well as the first pancake coils [4]. Anyway, the tests of pancakes No 10 and No 11, at temperatures above 10 K, will be reported in order to compare them with the tests on more recent pancakes.

The pancake coils (see figure 2) were manufactured by winding nickel clad magnesium diboride tapes onto 12 cm diameter coil formers. The outer diameter of all the coils is 20 cm. Pancakes No 1 to No 10 were wound with monocore tapes, pancakes No 11 and No 12 were wound with multifilamentary (7 filaments) tapes, while for pancakes No 13



Figure 2. Magnesium diboride based pancake coil.



Figure 3. Cross section of the monocore tape (a), of the 7-filament tape (b) and of the 14-filament, copper stabilized tape (c).

to No 21, copper stabilized, multifilamentary (14 filaments) conductors were used. All the tapes, shown in figure 3, were produced by Columbus Superconductors using the *ex situ* route and the on-line heat treatment.

In table 1 are schematically reported the characteristics of the pancakes whose behaviour is described hereafter. The three types of conductor used to wind the coils are indicated with the letters A, B and C, referring to the monocore tape, the sevenfilament tape and the copper stabilized tape, respectively.

For pancakes No 10 and No 11, 40 m single lengths of conductor were wound, obtaining 79-turn coils. The computed magnetic induction per ampere is 0.5 mT A^{-1} at the coil centre.

The stabilized tape being thicker, the number of turns of pancake coils No 13 to No 21 was reduced to 48, with a total conductor length of 24 m. As a consequence, the magnetic induction per ampere at the coil centre is 0.24 mT A^{-1} .

All the coils were insulated using a glass tape (0.1 mm thick) co-wound with the conductor, except the No 21 that is wrapped insulated, and a copper plate was glued behind all the winding. All the pancakes were impregnated with a resin cured at room temperature with the exception of No 14, which experienced a thermal treatment for the curing.

3. Experimental set-up

3.1. Critical current

The critical current of the tapes, defined by the electric field criterion $V_c = 1 \ \mu V cm^{-1}$, was measured in a



Figure 4. Scheme of the experimental set-ups for critical current. Left: cryogen-free (B up to 1.5 T); right: He flow VTI (B up to 5 T).

Table 1.	Characteristics	of the	pancake coils
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Pancake number	Year	Tape type	Tape length (m)	No of turns/conductor length
10	2003	А	100	79/40
11	2004	В	50	79/40
13-14	2004	С	50	48/24
16	2005	С	400	48/24
19	2005	C (twisted)	50	48/24
21	2005	С	1600	48/24 (from tail)

straight configuration as a function of temperature and applied magnetic field in two different test facilities, both of them schematically shown in figure 4.

In the first one, the two samples are positioned in a variable temperature cryostat inside the bore of a superconducting 5 T dipole magnet. The voltage taps are 4 cm apart, positioned in the homogeneous field zone ($\Delta B/B = \pm 0.2\%$). The sample holder can be oriented in order to allow the application of background field both perpendicular and parallel to the tape wide face. Two CERNOX thermometers and one Hall probe are inserted in the sample holder.

The second one is a cryogen-free facility cooled by a twostage cryocooler, and allows critical current measurements in the temperature range 12–80 K with applied magnetic field up to 1.5 T. The homogeneity zone ($\Delta B/B = \pm 0.1\%$) is ± 10 cm from the magnet centre. The temperature is measured using three CERNOX thermometers. The homogeneity of the temperature measured at the sample is within 0.2 K.

Both the test facilities are equipped with a couple of current leads with BSCCO bus bars.

3.2. Magnet test apparatus

The coils were tested both in a liquid helium bath using a standard cryostat, 250 mm in diameter, and in a cryogenfree apparatus, schematically shown in figure 5. The test apparatus is composed of a vacuum chamber 2 m in diameter, equipped with a couple of cryogen-free, HTS current leads and two cryocoolers (SUMITOMO SRDK-400BW-H and SRDK-408SW-H). One of them, having a cooling power of about 100 W at 50 K, is used to cool the first stage of the current leads via an electrically insulated heat exchanger. The system is able to carry 700 A in steady state conditions and up to 1000 A dynamically. The other cryocooler (5.4 W at 10 K) cools the magnet by means of a copper plate. Three heaters (MINCO Thermofoils) are glued on the copper plate and on the bus bars. A CERNOX thermometer (Lake Shore) positioned on the copper plate is used to control the temperature of the coil via a Lake Shore 340 temperature controller. The actual temperature of the coil is measured by three CERNOX thermometers hosted over the winding. The temperature homogeneity was measured within 0.7 K. As the system is designed to control the temperature up to 40 K, several spacers are inserted between the magnet copper plate and the cryocooler in order to limit the heater power. The electrical exits are connected to the current leads using two copper bus bars with BSCCO tapes soldered on them. The magnet cryocooler provides the cooling of the bus bars via an electrically insulated heat exchanger. The test apparatus allows performing magnet tests down to 12 K.

In order to measure the quench propagation, some coils were equipped with eight voltage taps. The voltage taps are positioned, starting from the inner electrical exit, after 0.1 m (2nd tap on 1st turn), 2.9 m (7th turn), 10.6 m (24th turn), 16.5 m (35th turn) and 24 m (48th turn). Taps 7 and 8 are positioned on the outer electrical exit. A fast acquisition system (HP 3852A), with a sampling rate of 1 kHz, is used to record voltage and current as functions of time.

4. Results and discussion

4.1. Coil tests

Figure 6 shows the quench current values for coil No 10 (monocore conductor) and coil No 11 (seven-filament



Figure 5. Scheme of the experimental set-up for the MgB_2 magnet test.



Figure 6. Quench current for coils No 10 (circles) and No 11 (diamonds).

conductor) versus temperature. At high temperature, i.e. above 30 K for No 10 and above 25 K for No 11, the quench current increases as the temperature decreases. At lower temperature, the slope of the I_q-T curve decreases and the quench current shows a tiny increase with temperature reaching a plateau at about 105 A for the pancake No 10 and 220 K for coil No 11.

The I_q-T curves of coils No 10 and No 11 can be related to a local heating depending on current, probably due to Joule dissipation in the joints between the superconducting tape and the electrical exits. The heating power generated at the inner exit of coil No 10, i.e. the one corresponding to the zone experiencing the highest magnetic field, was measured to be about 0.1 W at 100 A.

Figure 7 shows the quench current of pancake coils wound with copper stabilized tape. Coils No 14 and No 19 behave like the non-stabilized one and reach a plateau below 23 K. In contrast, coils No 13 and No 21 show a close-to-linear increase of the quench current with the temperature decrease. The higher quench current, 318 A, was reached by coil No 21 at 14 K. Pancake No 13 was tested down to 17.4 K and reached



Figure 7. Quench current values of coils wound with copper stabilized tapes.



Figure 8. Voltage–current (continuous line) and temperature (dashed line) curves of pancake No 13.

the maximum current value of 275 A. For comparison, the tape used to wind coil No 13 has a critical current at 20 K and 0.5 T of 220 A, while the one used for No 21 has $I_c = 300$ A in the same conditions. No training was observed for any pancake.

The quenches of pancake No 13 were announced by the increase of the voltage, as shown in figure 8 for the transition at 24.8 K. The V-I curves can be fitted using the power law $V \propto I^n$ with *n*-values between 10 and 18 showing that the coil current is clearly limited by the critical current of the tape. Nevertheless, a direct comparison with the measurements on the short sample is not easily done due to the strong inhomogeneity of the magnetic field of both the short sample and the coil. When critical current measurements are performed on large cables carrying high currents [5], it is problematic to define the magnetic field at the conductor due to the field inhomogeneity. Simple criteria have been applied in some cases [6, 7] but for conductors containing ferromagnetic materials this is not possible and a more accurate study is



Figure 9. Evolution of current and voltage for pancake No 16 during the quench at 30 K.

necessary. The distribution of the field in the pancake coil was computed at 200 A: the field at the MgB₂ filaments is rather homogeneous along the radial direction but, moving axially, the field appears strongly inhomogeneous, ranging from 0.1 to 0.6 T. Similarly, the field distribution in the short sample is far from being uniform. It is clear that this inhomogeneity introduces a difficulty in defining the critical field (the average field is not a valid criterion as the V-I characteristic is not linear) and leads to a non-uniform distribution of the current when approaching the critical value.

Using the criterion of the maximum field at the filament [6], the quench current of coil No 13 at 17.4 K, i.e. 275 A, corresponds to $B_{\text{max}} = 0.7$ T. The critical current of the short sample in the same conditions has the lower value of 190 A. Also considering the four filaments experiencing the higher values of magnetic field and calculating their average value [7], i.e. 0.5 T, the quench current of the coil is still higher of the short sample critical current, 260 A. The value is not far from the quench current but we have to consider that the critical current of the coil is higher as, by definition, it corresponds to V = 3 mV, i.e. about 290 A.

It is worth emphasizing that the coils were not damaged by the quench. Delay times up to 10 s in the breaker opening were set without affecting the later behaviour of the coils.

4.2. Quench behaviour

The evolution of the resistance of pancake coil No 16 was measured at 30 K. The relatively high temperature was chosen in order to have a current low enough to be constant during the quench (the current is limited by the voltage of the power supply). Figure 9 shows the current and the voltage drop between subsequent voltage taps as functions of time: note that after 5 s the current begins to drop as the coil voltage exceeds the maximum voltage of the power supply. Figure 10 shows the evolution of the internal resistance: the quench starts somewhere in the innermost six turns of the coil (between voltage taps 2 and 3) and after 1.9 s it propagates in the second group of 14 turns (between voltage taps 3 and 4). After 5.9 s,



Figure 10. Evolution of the internal resistance of pancake No 16 during the quench at 30 K.

the resistance starts to rise also in the third group of turns. As the radial dimension of 17 turns is 14 mm, we can deduce an upper limit for the radial propagation velocity of 3.5 mm s^{-1} .

5. Conclusion

React and wind pancake coils were constructed with continuous lengths of Ni/MgB₂ tape obtained by an *ex situ* PIT process. The coils were tested either in a liquid helium bath or conduction cooled in a cryogen-free system. The maximum current value reached by a cryogen-free pancake coil was 318 A at 14 K. The role of the copper core was demonstrated by comparison between the behaviour of the Ni/MgB₂ coils and of the Ni/Cu/MgB₂ ones. Quench propagation measurements showed a radial velocity less than 3.5 mm s⁻¹. No damage was observed after quenches, even introducing a delay up to 10 s in the protection system.

The more recent result of the R&D activity on MgB_2 coils is the double pancake wound by Ansaldo Superconduttori using a 1600 m continuous length of tape. The double pancake, 1.6 m outer diameter, 1.3 m inner diameter, 2×166 turns, is at present under test.

The results obtained on the coils described in this article, together with the results obtained by other groups [8, 9] demonstrate the feasibility of magnesium diboride magnets.

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