Behavior of MgB2 React & Wind Coils Above 10 K

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Abstract—React & wind magnesium diboride pancake coils and solenoids were constructed and tested. The solenoids (6 layers) were manufactured by winding a single length of MgB_2 tape (80 m) onto a 15 cm diameter, 15 cm high mandrel. The pancake coils were manufactured starting from a 40 meter long tape: the conductor was wound onto a 12 cm diameter coil former. The magnets were tested both in liquid helium and conduction cooled in a cryogen free apparatus. The results compared with the tape characteristics are reported.

Index Terms—Magnesium diboride, magnets, ${\rm MgB}_2$, superconducting tapes.

I. INTRODUCTION

T THE beginning of the year 2001, the interest of the scientific community, both in basic physics and in applications of superconductivity, was stimulated by the discovery of the superconducting properties of magnesium diboride (MgB₂) [1], an already known intermetallic compound. The reason of the interest is mainly related to its critical temperature ($T_c = 39$ K), surprisingly high for a simple binary compound that behaves like a BCS superconductor.

Even if the critical temperature of MgB_2 is the highest among BCS superconductors, it is far below those of HTS materials. However, the simple composition, the upper critical field higher than 20 T (up to 51 T at 4.2 K in highly disordered films parallel to the ab plane [2]), the lack of weak links and the low anisotropy, together with the low cost, make magnesium diboride an interesting material for technological applications. Soon after the discovery, the techniques developed to fabricate HTS conductors were promptly applied to MgB_2 and the potentiality of the material became evident. Several groups [3]-[7] were able to produce samples of both monocore and multifilamentary wires and tapes with critical current densities in the order of several GA/m^2 at 20 K and 0 T. The low cost of magnesium diboride and the rather simple conductor manufacturing process (leading to a conductor cost comparable with that of traditional low Tc superconducting wires), triggered the interest of the industry and, since two years, conductors have been available up to several hundreds meter lengths, opening the way to the construction of cryogen free magnets.

The main drawback of magnesium diboride seems to be the low irreversibility field. The critical current density of samples

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extracted by nondoped MgB₂ 100 m long tapes is in the order of 10^8 A/m^2 at 4.2 K and 5 T [8]. This value, one order of magnitude below the critical current density of Nb-Ti (~ $3 \cdot 10^9 \text{ A/m}^2$ in the same conditions), appeared limiting the application of the material to devices operating at low field (like MRI magnets) or to energy transport lines. MRI magnets being the largest technological application of superconductivity, we can affirm that such a limit does lightly affect the interest in this superconductor.

However, it is possible to enhance the transport properties by acting on the structure and on the morphology of the material. Recently, critical current densities of $1.7 \, 10^9 \, \text{A/m}^2$ at 4.2 K and 5 T in multi-filamentary SiC doped MgB₂ wires [4] as well as irreversibility field values up to 22.5 T at 4.2 K were reported [9].

Stimulated by the good transport properties of the new superconducting material, Ansaldo Superconduttori, Columbus Superconductors, INFM-LAMIA (National Institute for Physics of Matter) and INFN (National Institute for Nuclear Physics) started, in 2001, a collaboration with the goal of constructing MgB_2 magnets.

In order to avoid high temperature treatments of magnets, we chose to use the react & wind technique. This introduces some difficulties in the winding operations but it can be easily managed in the fabrication of large magnets. Moreover, the react & wind technique avoids the problems related to the choice of insulating and structural materials resistant to high temperatures. It must be remarked that in the case of MgB_2 powder-in-tube (PIT) conductors, the term "react & wind" makes sense only if the conductor contains precursor powders, i.e. if the in-situ route is followed. If the ex-situ technique is applied, it would be more correct to speak of "sinter & wind" method. Anyway, as the winding technology is not affected by this difference, we decided to use the more usual "react & wind" term.

II. CONDUCTOR PREPARATION

Although other methods are used to fabricate MgB_2 conductor samples [10], [11], the PIT is the most widely applied and the most promising for long lengths. Two routes can be followed in the framework of PIT technique: the in-situ (the tube is filled with the precursor powders) and the ex-situ (the tube is filled with MgB_2 powders) methods.

The tapes presented in this paper were prepared according to a technique developed by INFM-LAMIA and by Columbus Superconductors (Genova, Italy) in the last three years, following the ex-situ route [12]. Pure nickel tubes are filled with commercial MgB₂ powders (the powder density inside the tube is 1.3 g/cm³) and cold worked in several steps without intermediate annealing. As a final step, before wrapping the tape on the spool, a heat treatment at about 900°C is performed in argon atmosphere in order to enhance its transport properties; an

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Fig. 1. Cross section of the monocore tape (a), of the 7 filaments tape (b) and of the 14 filaments, copper stabilized tape (c).

in-line oven is used for this purpose. Monocore, multifilamentary, copper stabilized multifilamentary PIT tapes are prepared with this technique. For the copper stabilized conductors, iron was chosen as a diffusion barrier between copper and nickel.

Fig. 1 shows the cross section of a monocore tape and two multifilamentary tapes. The monocore tape, 4 mm \times 0.35 mm, has a total/superconductor ratio about 5, i.e. a superconductor section area of 0.28 mm². The 7 filaments Ni-clad tape, 3.5 mm \times 0.35 mm has a MgB₂ section area of 0.24 mm², i.e. a total/superconductor area ratio of 5. The 14 filaments, copper stabilized MgB₂ tape, 3.6 mm \times 0.65 mm, has a MgB₂ section area of 0.11 mm², i.e. a total/superconductor area ratio of 21.

At present, continuous lengths have been produced up to 440 m (for a multifilamentary stabilized conductor), but theoretically Columbus Superconductors can produce, without any modification of the tools, up to 1500 m.

III. COIL DESCRIPTION

As the 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 14 pancake coils were manufactured using the react & wind technique. The solenoid, shown in Fig. 2, was the first working MgB_2 magnet constructed and tested by the collaboration. It was manufactured by winding a single length of monocore tape (80 m) onto a 15 cm diameter, 15 cm high, mandrel. The coil, formed by 6 layers of 27 turns each, was fiber-glass insulated and impregnated with epoxy resin.

The layer transitions are one turn long, i.e. about 47 cm, so that the bending radius in the direction of larger inertia is about 20 m. The resulting bending strain is $8 \cdot 10^{-5}$, low enough for a safe joggle.

The computed central field per ampere of the solenoid is 1.35 mT/A.

The pancake coils (see Fig. 3) were manufactured by winding a single pancake of conductor onto a 12 cm diameter coil. Pancakes from #1 to #10 were wound with monofilamentary tapes, pancakes #11 and #12 were wound with multifilamentary nickel clad tapes while for pancakes #13 and #14, copper stabilized multifilamentary conductors were used.



Fig. 2. Magnesium diboride based solenoid.



Fig. 3. Magnesium diboride based pancake coil.

As regards pancakes #1-12, 40 m single lengths of conductor were wound obtaining 79 turn coils having external diameter 20 cm. The computed magnetic induction per ampere is 0.6 mT/A at the coil center.

The pancake coils #13 and #14 were wound using the copper stabilized tape shown in Fig. 1(c). The tape thickness being higher than those of the nonstabilized tapes, the number of turns was reduced to 60, for a conductor total length of 30 m. As a consequence, the magnetic induction per ampere at the coil center is 0.43 mT/A.

The coils were insulated using a fiber-glass tape co-wound with the conductor and a copper plate was glued behind the winding. All the pancakes were impregnated with a room temperature cured resin with the exception of #14, which experienced a thermal treatment for curing.

IV. EXPERIMENTAL SET-UP

A. Critical Current

The critical current of the tapes was measured in straight configuration as a function of temperature and applied magnetic



Fig. 4. Scheme of the experimental set-up for critical current.

field. Two conductor samples, 20 cm long, are soldered on a brass sample holder and connected together at the ends. The sample holder is positioned in a variable temperature, helium flow, cryostat inside the bore of a 5 T dipole magnet (Cryogenic Ltd) as shown in Fig. 4. The voltage taps are 4 cm apart, positioned in the homogeneous field zone. The sample holder can be oriented in order to allow the application of the background field both perpendicular and parallel to the tape wide face. The current is supplied by a 1000 A power supplier via a couple of current leads with BSCCO bus bars. Two CERNOX thermometers and a Hall probe are inserted in the sample holder.

B. Magnet Test Apparatus

The coils were tested both in a liquid helium bath using a standard cryostat, 250 mm diameter, and in a cryogen free apparatus, schematically shown in Fig. 5. The test apparatus is composed of a vacuum chamber of 1 m 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 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 current leads can work 8 minutes at 1000 A). The other cryocooler (5.4 W at 10 K) cools the magnet by means of a copper plate with a heater (MINCO Thermofoil) glued on it. 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 another CERNOX thermometer hosted over the winding. 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 cooling of the bus bars via an electrically insulated heat exchanger.







Fig. 6. Critical current vs. temperature of the 7 filaments Ni/MgB₂ tape.

Theoretically, the test apparatus could allow cooling down to 10 K. Actually, due to the heat load and to the thermal resistance of spacers and electrical insulation, the measurements were carried out above 15 K.

V. RESULTS AND DISCUSSION

A. Critical Current Measurements

The critical current of the samples was measured as a function of temperature and applied magnetic field, applying the electric field criterion $E_c = 1 \ \mu V/cm$. The measurements were performed both at constant temperature increasing the current and at constant current increasing the temperature. The results overlap. The estimated error on the critical current evaluation is 3%.

Figs. 6 and 7 show the critical current density as a function of the temperature for the MgB_2/Ni and the $MgB_2/Ni/Cu$ samples, respectively. Fig. 8 shows the critical current density as a function of the applied magnetic field for the MgB_2/Ni sample. All the data reported in the figures refer to the external applied field, without the contribution of self-field. The self-field depends both on the conductor lay-out and on the configuration of the experimental set-up. Generally, if no ferro-magnetic materials are present, it is proportional to the current flowing in the conductor. In nickel clad conductors, the self-field at the filaments has to be computed as function of both external magnetic field and current, taking into account the effect of nickel and, if

VOLTAGE

TAPS



Fig. 7. Critical current vs temperature of the copper stabilized tape.



Fig. 8. Critical current vs field of the 7 filaments tape.

present, of the iron barrier. This being a complex matter that is worth studying in depth, it will not be discussed here.

Despite the critical current of the 7 filaments tape being about twice that of the copper stabilized conductor in the same conditions, the critical current densities are not so different due to the lower superconductor section area of the latter. The J_c of the copper stabilized tape is slightly higher due to the optimization of the in-line thermal treatment. At 20 K, it reaches 10^9 A/m^2 with an applied field of 1 T and about $2 \cdot 10^9 \text{ A/m}^2$ with 0.5 T applied. All the measurements are performed with the magnetic field applied perpendicular to the wide face of the conductor. Previous measurements carried out on monocore tapes showed a difference within 10% [13].

B. Coil Tests

The test results of the solenoid are already described elsewhere [13]: it reached 53 A in liquid helium, with an induction value of 0.11 T at the conductor and 0.07 T at the magnet center.

Regarding the pancake coils, the tests in liquid helium were performed on coils #1-8, all wound with monocore tapes. During tests, the magnets were energized with ramp rates between 0.3 and 3.3 A/s.

Coil #8 reached the highest quench current among the pancake coils: 347 A at 4.2 K, corresponding to about 0.75 T at the conductor and 0.22 T at the coil center. As the critical current of



Fig. 9. Quench current of coils #10 (circles) and #11 (diamonds).

the monocore tape at 0.75 T and 4.2 K was about 750 A, the current is clearly limited by either local dissipations, like the joints with the electrical exits, or mechanical energy releases.

All the other coils were tested in the cryogenic free apparatus. Fig. 9 shows the quench current values of coil #10 and coil #11 vs temperature. At high temperature, i.e. above 30 K for #10 and above 25 K for #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 maximum value at about 105 A for the pancake #10. An analogous behavior was observed for coil #11, wound with the 7 filaments tape. In this case the maximum quench current was much higher with respect to coil #10, reaching 220 A below 23 K. Neither in coil #10 nor in #11 a smooth transition to the normal state was observed but quenches always occurred abruptly.

The I_q -T curves of coils #10 and #11 can be related to a local heating depending on current, probably due to the dissipation of the joints between the superconducting tape and the electrical exits. The heating generated at the inner exit of coil #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. Though 0.1 W could be considered a high value in a cryogen free coil, it has to be observed that the exits are directly cooled by the bus bars, connected to the low temperature stage of the cryocooler.

A different behavior was observed for the pancake #13, wound with a copper stabilized conductor. In this case all the quenches were announced by the increase of the voltage, as clearly shown in Fig. 10. The V-I curve can be fitted using the power law $V \propto I^n$ with *n*-values between 10 and 18. A comparison of the *n*-value with those measured on the short sample cannot be done due to the different conditions affecting the measurements: field inhomogeneity, temperature variation during the current ramp and possible temperature gradient inside the winding. The maximum current value of 275 A was reached at 17.4 K. The magnetic field at the conductor was 0.5 T while at the coil center was 0.12 T. For comparison, the critical current of the short sample at 0.5 T, extrapolated at 17.4 K, is 260 ± 20 A, very close to the quench current of the pancake.



Fig. 10. Voltage-current (continuous line) and temperature (dashed line) curves of pancake #13.



Fig. 11. Quench current values of coil #13.

The difference between coil #13 and the previous pancakes is the conductor used to wind them, copper stabilized with a metal/superconductor ratio of 20 for the former, only nickel clad with a metal/superconductor ratio of 4 for the latter. When the conductor is in current sharing mode, the matrix resistance, depending on the relative quantity and on the resistivity of the metals, is a very important parameter. Below 25 K, the resistivity of copper (RRR = 100) is about $2 \cdot 10^{-10} \Omega \cdot m$, while the resistivity of the nickel used for the conductor is about $10^{-9} \Omega \cdot m$. The resulting matrix resistance per unit length is $10^{-3} \Omega/m$ for the Ni/MgB₂ tape and $3 \cdot 10^{-4} \Omega/m$ for the Ni/Cu/MgB₂ tape. The test results of coil #13 are a clear indication that the matrix resistance plays an important role in the stabilization of the conductor (Fig. 11).

Of course, in order not to increase the overall current density, the average resistivity of the matrix must be reduced as much as possible. The insertion of copper in the conductor is a solution to this problem. In the tape used to wind coil #13 the matrix resistivity is 1.5 times lower than that of the equivalent tape without the copper core.

In view of construction of large magnets, it must also be remarked that low values of the matrix resistivity contribute to the coil protection in case of quench.

VI. CONCLUSION

React & wind pancake coils and one solenoid were constructed with continuous lengths of Ni/MgB₂ tape obtained by an ex-situ PIT process. The coils were tested either in liquid helium bath or conduction cooled in a cryogen free system. The successful results of the tests on the pancake coils are very encouraging and demonstrate the feasibility of magnesium diboride magnets with the react & wind technique: at 4.2 K, pancake coil #8 reached a maximum current of 347 A, generating a field of 0.75 T at the conductor. The maximum current value reached by a cryogen free pancake coil was 275 A (0.5 T at the conductor) at 17.4 K. The role of the copper core was demonstrated by the comparison between the behavior of the Ni/MgB₂ coils and of the Ni/Cu/MgB₂ one, the latter having reached higher quench current values after a power-law ruled increase of the voltage at the coil ends.

Aiming to applications in large magnets, like those for MRI, the R&D activities will continue in the direction of developing react & wind magnets. At present, pancake coil #14, wound with copper stabilized tape, is under test and a double pancake, is going to be wound with a 120 m long conductor.

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