Development of HTS Conductors for Fusion Magnets

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Abstract—In view of the development of cables for next generation Fusion Reactors research activities are carried out on all HTS materials available from industrial production. Preliminary design of a react and wind cable using Bi2212 wires is carried out, inspired by the Nb_3Sn cable for European DEMO. The design and construction of a 60 kA prototype cable made of coated conductors have been carried out. The strands in the cable are composed of a stack of coated conductor tapes (4 mm wide) embedded in a copper profile of 6.3 mm in diameter. Tapes and copper profiles are soldered together in order to obtain a mechanically solid strand and to keep the inter tape resistance at minimum, so that current can be easily redistributed among the tapes in a strand. The strands are fabricated in pieces 2 m long, but scaling up to industrial production should not present any major problem. A flat cable is manufactured by winding twenty strands around a central copper former; the cable will be inserted in a steel jacket for force flow cooling. The critical current of each strand was measured at liquid nitrogen in self field just after the manufacturing process (twisted and straight) and after cabling: no reduction of the critical current was observed. Two pieces of cable each 2 m long are going to be prepared and assembled to form a sample that can be tested in the EDIPO facility.

Index Terms—HTS cable, coated conductor, BSCCO, REBCO, Bi2212, Bi2223, fusion magnet, fusion cable.

I. INTRODUCTION

THE construction of the ITER fusion reactor is progressing and the completion of the machine is scheduled for 2019. In Europe the R&D phase for the next generation of fusion reactors (DEMO), which are supposed to prove the generation of the electricity at an affordable price, is just started [1]. The use of High Temperature Superconducting (HTS) materials is not excluded a priori, even if the most reliable and mature option is to use a graded $NbTi/Nb_3Sn$ coil [2]. There are various motivations for using HTS materials in fusion magnets [3], which in turn depend on the way the HTS material is integrated in the magnet system. If the price of the HTS cable is comparable to the one of the Nb_3Sn cable, one can imagine a graded coil with LTS and HTS sections, both operated at 5 K; in this case one motivation for using HTS material could be the larger temperature margin in the coil section more exposed to nuclear heating; indeed a large temperature margin could be an advantage for the cryogenic and cooling system. Another motivation could be the fact that the HTS section is more compact, which would save space for the blanket, as it was proposed in [4].

If the price of HTS materials gets sufficiently low (i.e. at least lower than the price of Nb_3Sn) it could be economically more convenient to make a full HTS magnet system, which may be still operated at 5 K; if the cost gets much lower than the one of Nb_3Sn and the in-field critical current at high temperatures is improved, it would be possible to exploit the most striking advantage of HTS materials, namely the possibility to operate at fields and temperatures not accessible to LTS materials. As an example of this use, a magnet system with Bi2212 cables operated at 20 K and 20 T was proposed in [5], even if the operating conditions were unrealistic.

At the Center for Research on Plasma Physics (CRPP) the main activity is designing, building and testing prototype cables for fusion magnets, with operating currents up to 100 kA, i.e. suitable for ITER or DEMO type reactors. This paper is mainly focused on the construction of a short prototype cable using coated conductor tape (REBCO). Preliminary designs of HTS cables for DEMO type magnets are also presented; all the HTS materials have been considered: REBCO tapes, Bi2212 wires and Bi2223 tapes.

II. Bi2212 CABLE DESIGN

Even if Bi2212 was one of the first HTS materials to come on the market, the relative low critical current density and the difficulties in manufacturing coils with long length of wires have prevented the use in applications. Recently a new over-pressure heat treatment [6] has allowed obtaining much higher critical current density and improving the reliability of the coil construction. Despite the improvement, the critical current in field is still strongly reduced at high temperatures, and Bi2212 is not suitable for operation at temperatures much higher than 15 K: indeed Bi2212 should be considered a high field superconductor rather than a high temperature superconductor.

The application of Bi2212 wires for a fusion magnet was first proposed more than 10 years ago. In [7] a prototype cable (round cable composed of 729 strand, each 0.8 mm in diameter) could carry 10 kA at 20 K and 12 T. In [5] the design of a magnet system using only Bi2212 was carried out, but the envisaged operating conditions were an astonishing and unrealistic 20 T and 20 K, at which even the present wires cannot provide sufficient current density. More recently [4] a graded magnet, consisting of an outer Nb_3Sn section and an innermost Bi2212 section, was proposed for the future Chinese Thermonuclear Fusion Reactor (CFETR); the main reason to use Bi2212 cables for the innermost section was the compactness of the HTS section which would free up space for the blanket. Both papers mentioned above are mainly focused on the magnet system, lacking details on the Bi2212

cable.

Despite Bi2212 is the cheapest of the HTS materials available on the market, the material cost of a Bi2212 cable for DEMO (5 K, 13.5 T) is still more expensive than the one of Nb$_3$Sn by a factor 2 to 5. Only at fields higher than 16 T or 18 T the material cost of a Bi2212 cable becomes lower than the one of Nb$_3$Sn.

There are various similarities between Bi2212 wires and Nb$_3$Sn wires: round wires with diameter from 0.6 to 1.5 mm, high temperature reaction heat treatments and small variation (few %) of I$_c$ over a narrow strain window (i.e. from -0.2% to +0.2%). Therefore one possibility is to adapt the React and Wind (R&W) design proposed for the DEMO Nb$_3$Sn cable [2] to Bi2212 wires. In short, the Nb$_3$Sn conductor for DEMO is composed of a flat cable assembled with 300 strands (1.5 mm in diameter). The cable is reacted on a 7 m diameter former and, after the reaction, a steel jacket is welded around the cable. After winding the Toroidal Field (TF) coil, whose minimum bending radius is 3.5 m, the strain state of the wires will be in the range comprised between -0.08% and +0.08%. The reasons for choosing the R&W technique are both technological and economic, as discussed in [2], and are still valid for a Bi2212 cable.

For the dimensioning (i.e. how much superconducting material is required) of a cable in conduit operated in forced flow cooling, it is important to point out that a sufficient temperature margin should be guaranteed. For example, in the Nb$_3$Sn cable for DEMO the temperature margin at the operating conditions (80 kA, 5 K, 13.5 T) is about 1.5 K. A simple way to estimate the operating current is to plot the reduced critical current as a function of the temperature at the operating field (13.5 T), as shown in fig. 1a: the data are for a Nb$_3$Sn strand for ITER. From fig. 1a it is clear that, if 1.5 K of temperature margin is required, the operating current at 13.5 T and 5 K should be only 65% of the corresponding critical current at 13.5 T and 5 K.

The same type of plot is shown in fig. 1b for a Bi2212 wire (data from [8]). The temperature dependence of the critical current is much flatter; it follows that even if the operating current is as high as 80% of the critical current (at 13.5 T and 5 K), the temperature margin is almost 3 K, i.e. twice larger than in the Nb$_3$Sn cable. Therefore the critical current (at 13.5 T and 5 K) of the cable could be about 100 kA for an operating current of about 80 kA. Assuming an engineering current density of 500 A/mm^2 at 13.5 T and 5 K, which is within the possibility of present industrial production, about 110 strand of 1.5 mm diameter will be needed to obtain a critical current of 100 kA. The 110 strands can be arranged in a two stages (7x16) flat cable, as shown in fig. 2. The cable is compacted down to 25% of void fraction. The Bi2212 cable is wrapped by copper wires (about 600 mm^2 of total cross section), which provide the protection in case of quench and make the handling easier and safer. A steel jacket with two cooling channels is welded around the cable as in the case of Nb$_3$Sn cable. After reaction heat treatment and coil winding the strain state of the Bi2212 strands will be between -0.07% and +0.07%. In the tensile region (+0.07%) I$_c$ would be

reduced (reversibly) by less than 0.5%, while in the compressive region (-0.07%) the irreversible reduction of I$_c$ would be about 1% (values estimated from [9]).

The longitudinal electromagnetic load will be taken by the steel jacket; the only load acting directly on the cable is the
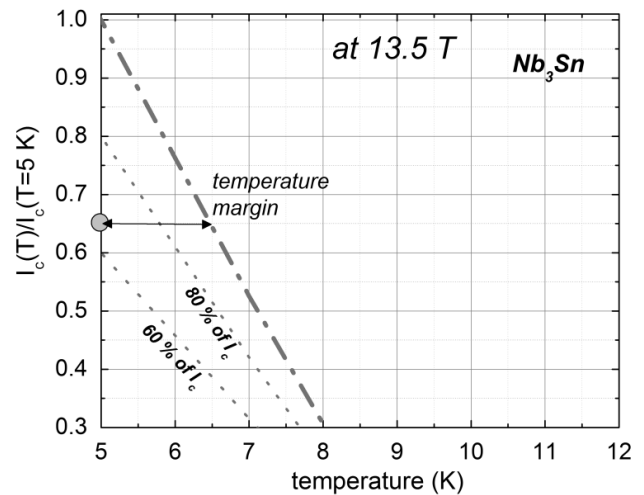

Fig. 1a. Reduced critical current versus temperature for an Internal Sn Nb$_3$Sn wire at 13.5 T. The values corresponding to 80% and 60% of the critical current are plotted. The intrinsic strain was -0.2%.
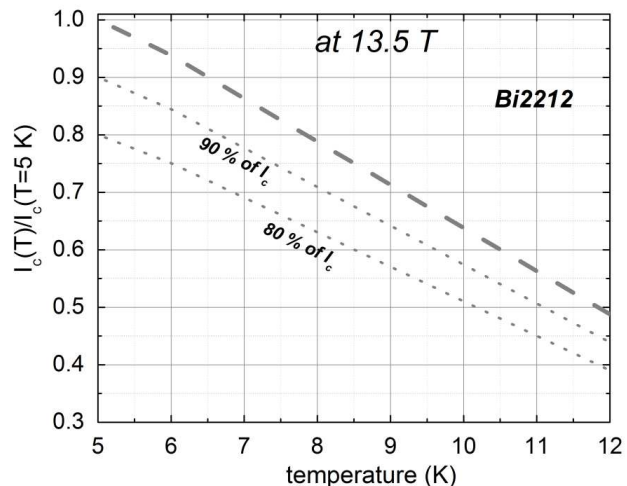

Fig. 1b. Reduced critical current versus temperature for a Bi2212 wire [8] at 13.5 T. The values corresponding to 90% and 80% of the critical current are plotted.
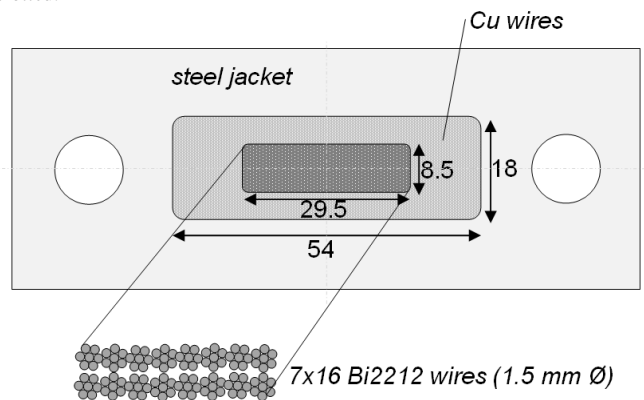

Fig. 2. Cross section of the Bi2212 cable for DEMO. It is composed of 7x16 Bi2212 wires (Ø1.5 mm) and surrounded by copper wires for stabilization. A steel jacket with two channels for cooling is welded around the cable.

electromagnetic transverse load. In the cable of fig.2 the transverse stress at operation (80 kA and 13.5 T) would be about 35 MPa. This value is below the value of 50 MPa reported for a Bi2212 Rutherford cable in [10] at which no reduction of the critical current was observed.

III. PROTOTYPE COATED CONDUCTOR CABLE

Coated conductors are the newcomer in the family of industrially produced HTS materials. In contrast with Bi2212, the superconducting ceramic phase is formed during the manufacturing of the tape. Therefore the main issue in preparing a cable with coated conductors is the accumulation of strain resulting from the strand fabrication, the cabling process and the winding of the final coil. The main advantages for fusion applications, with respect to Bi2212 wires and Bi2223 tapes, are the large strain window (up to 0.6% tensile strain), the potential of low cost production and the high critical current densities in field at temperature > 20 K, due to the much higher irreversibility fields of REBCO than those of Bi2212 and Bi2223.

A. Cable design

In fig. 3 the reduced critical current versus temperature is plotted for a coated conductor tape (data from [8]) as a function of the temperature. In case of coated conductors the temperature dependence is even weaker than the one of Bi2212 wires (see fig. 1b). Therefore it could be possible to operate the cable at 90% of the critical current but still having 3 K of temperature margin. At an operating current of 80% the temperature margin will be 6 K, four times larger than in the case of Nb_3Sn.

Various cabling method have been proposed in order to manufacture cables using tapes: stacked tapes in copper [11], Roebel cable [12], CORC cable [13], and round hollow wires, proposed by Nexans [14]. At CRPP a variation of the stacked tape concept was chosen [15]. The stack of tapes is sandwiched between two semicircular shells (called also copper profiles), twisted and soldered. By twisting the strand before soldering the strain on the superconducting layer is kept

at a minimum. The soldering process is carried out in order to obtain a solid strand without voids and for ensuring a low inter-tape resistance, which helps current redistribution. The strands are then used to manufacture a flat cable, which can also be considered as a Rutherford cable with a flat copper core. The function of the copper core (it is 56 mm wide and 5 mm thick in the manufactured prototype cable) is to provide enough copper cross section for protection and to reduce the bending strain of the strands at the edges of the cable. In this prototype cable the bending radius of the strands at the cable edge is set at about 360 mm, which is higher than the critical bending radius (240 mm).

The parameters of the cable, like the copper core dimensions and the cable twist pitch, have been selected so that enough copper is present in the cable while the strain due to the bending of the strands at the cable edges is minimized. The optimization of the cable parameters is discussed in detail in [14]. A schematic cross section of the cable under preparation is reported in fig. 4.
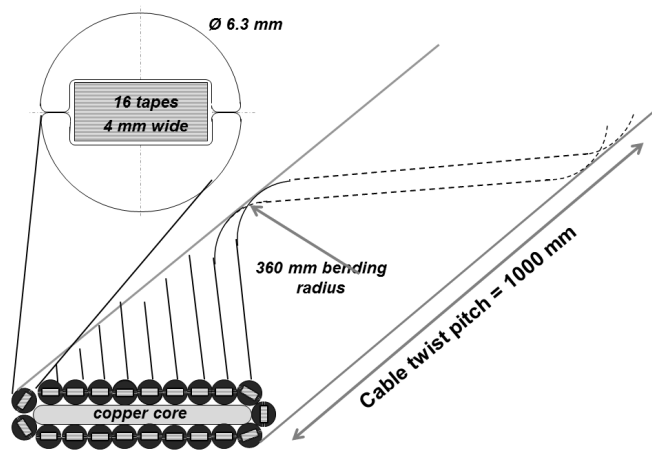
Fig. 4. Schematic cross section of the prototype cable made with coated conductors. The cable twist pitch is 1000 mm, while the strand twist pitch is 320 mm. The bending radius for the strands at the cable edge is 360 mm.

B. Cable construction

A first prototype cable was manufactured using standard tape from Superpower (type SCS4050, 4 mm wide). First the tape was coated with eutectic SnPb solder by immersion in a bath of molten solder (temperature about 200°C); a reel to reel process was used, with a speed of several cm/s; a colophonium solution was used as flux to improve the wettability of the solder.

The semicircular copper profiles were delivered by Precimet SA in pieces 3 m long; continuous production is also possible. The profiles were produced by cold rolling, which induced a relative large cold work hardening. Therefore an annealing heat treatment at 200°C for about 30 minutes was used to soften the copper (re-crystallization heat treatment). There were two reasons to apply the annealing heat treatment: first, the cabling is easier at laboratory scale, because the annealed strands are softer and easier to deform plastically. Second, it was observed (see [16] for details) that in the strands made with non-annealed copper the soldering between the two semicircular profiles breaks at relatively large bending
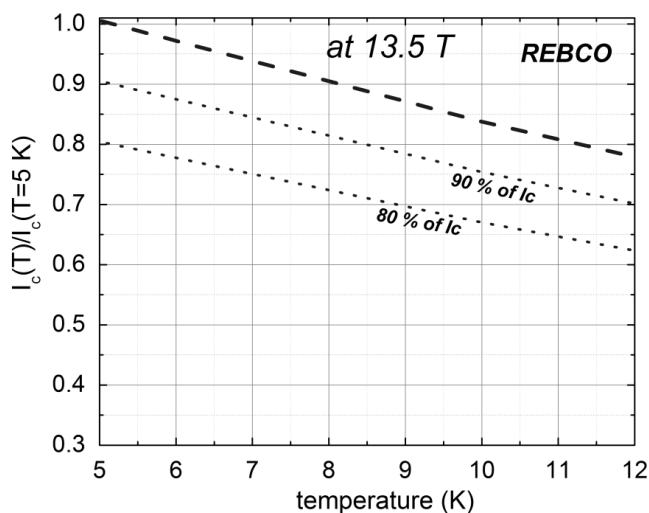

Fig. 3. Reduced critical current versus temperature for a REBCO tape [] at 13.5 T. The values corresponding to 90% and 80 % of the critical current are plotted.

radius. Instead the strands made with annealed copper profiles could be bent to smaller bending radius without breakage of the soldering connection. After annealing the copper profiles were coated with eutectic SnPb solder.

Twenty strands, each 2 m long and 6.3 mm in diameter, were assembled by stacking 16 tapes between two copper profiles (in total 320 tapes are present in the cable); each strand was kept together using short pieces of plastic tubes. After the assembling, the strands were twisted (320 mm twist pitch) by clamping the strand between two chucks about 1800 mm apart: one was kept fixed while the other was rotated till the desired twist pitch is reached. The twisted strands are soldered by immersion in a bath of molten solder (continuous process). The industrialization of this process for continuous production (several kilometers) should not present major technical challenges. Assembling and twisting could be carried out in line: the strand would be wrapped with a wire or tape in order to keep all the elements together (instead of the plastic tube) and twisting could be applied by a rotating pick-up spool.

Because of the short length of the prototype cable (2 meters) the cabling process was carried out entirely by hand. The strands were placed on the copper core one by one, using several small clamps to keep the strands in position. The annealed soft copper was easily bent by hand without much force. Despite the difference in bending stiffness (due to the
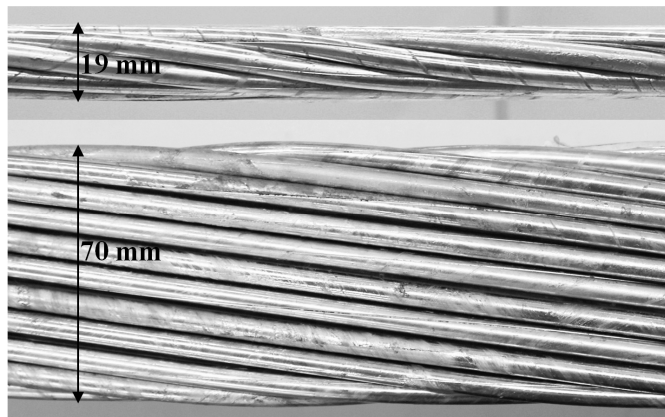

Fig. 5. View of the prototype cable made with REBCO tape, from the edge (top) and from the wide side (bottom).
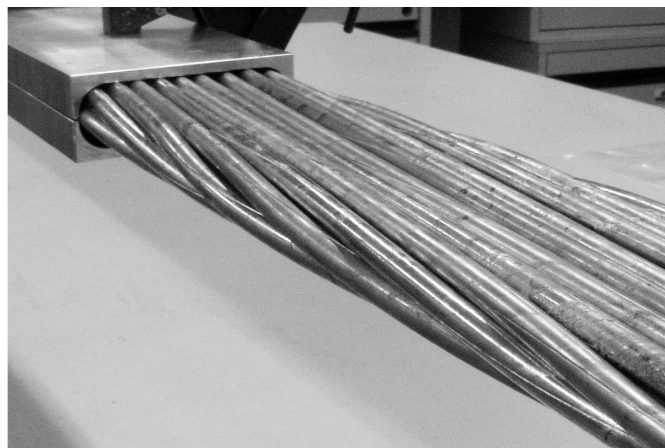

Fig. 6. Picture of the prototype cable prepared at CRPP. The jacket is a mock up made of aluminum.

difference between hard and easy bending for the stack of tapes), the cable dimensions were rather uniform along the length. Photographs of the cable taken from the wide side and from the edge are shown in fig. 5. A steel jacket will be welded around the cable; an aluminum mockup of the jacket is shown in fig. 6. The supercritical helium will flow in the space between the strands and the jacket.

A second cable section identical in size to the first cable is in preparation with tapes from Superox; the two cable sections will be assembled together, so that they can be tested in SULTAN or EDIPO facilities, where currents up to 100 kA are supplied by a superconducting transformer. The operation at such high current is possible only if the resistance of the circuit connecting the superconducting transformer with the two cables is lower than few nano-ohms. For this reason particular care is taken in the design of the terminations.

At the ends of each strand the tapes are cut longer than the copper profiles and they have been staggered, so that every tape has about 15 mm of the side in correspondence with the ceramic layer exposed (i.e. not covered by other tapes). The tape orientation at both ends of each strand is the same, because the sample length is exactly 6 times longer than the strand twist pitches. Small deviations have been corrected using a hand tool. The staggered ends at each end of the cable will be inserted and soldered in copper blocks, in which rectangular grooves have been machined; the copper blocks are the current terminations for the cables. In this way every tapes has the ceramic side (over 15 mm) in direct contact with the copper block terminals.

C. Preliminary test at 77 K

All the strands were measured at 77 K after the fabrication process (i.e. the strands were twisted and soldered and measured straight): the range of critical current was between 1050 A and 1150 A in self field, while the n value was between 20 and 25. Seven strands were also measured after the cabling process, i.e. after they were put in the cable (bending at the cable edges). As it was expected from a test on a short strand [16], no reduction of the critical current was observed for these seven strands; also the n value was not reduced. The critical current of more than half of the tape employed for the construction of the cable was measured at 4.2 K and 12 T; from these measurements the critical current of the cable is estimated to be between 57 kA and 61 kA (at 4.2 K and 12 T).

D. Design of a DEMO class cable

Based on the experience accumulated in the development of the prototype cable described above, two possible layouts for a DEMO class cable (operating currents of about 80 kA, corresponding to a critical current of 100 kA at 5 K and 13.5 T) are proposed (see fig. 7). In order to accommodate a larger number of tapes, it could be possible to change the aspect ratio of the stack from rectangular to square: for example 34 tapes 4 mm wide, or 24 tapes each 3 mm wide. The stack with 4 mm wide tape could be stacked and assembled in a strand of 7.8 mm in diameter and the final

TABLE I
MAIN PROPERTIES OF CABLES FOR FUSION MAGNETS

name	Cu cross section	Operating current	Temperature margin	Status
TF cable (Nb$_3$Sn) - ITER	513 mm^2	68 kA	0.7 K	Cables in construction since 2012
Nb$_3$Sn - DEMO	688 mm^2	82 kA	1.5 K	Prototype in construction [2], test planned in 2015
REBCO - DEMO	560 mm^2	80 kA	3 K to 6 K	Preliminary design completed (this work)
Bi2212 - DEMO	600 mm^2	80 kA	3 K	Preliminary design completed (this work)
REBCO prototype	790 mm^2	50 kA	6 K	Prototype in construction (this work), test planned within 2014

cable will be made with 16 of these strands. In this case the core of the cable could be made of steel instead of copper, because the copper cross section in the strands (680 mm^2) is enough to protect the magnet during a quench. The stack with 3 mm wide tape could be stacked and assembled in a strand of 6.1 mm in diameter and the final cable will be made with 26 of these strands. A schematic cross section of the two designs is reported in fig. 7. With the continuous improvement of the critical current density, it is expected that the total number of tapes required could be further decreased, resulting in a smaller number of strands. The manufacturing and test of two short samples (50 cm) of the two types of strands is under way. A summary of the cable for fusion magnets described in this work is presented in Table I.
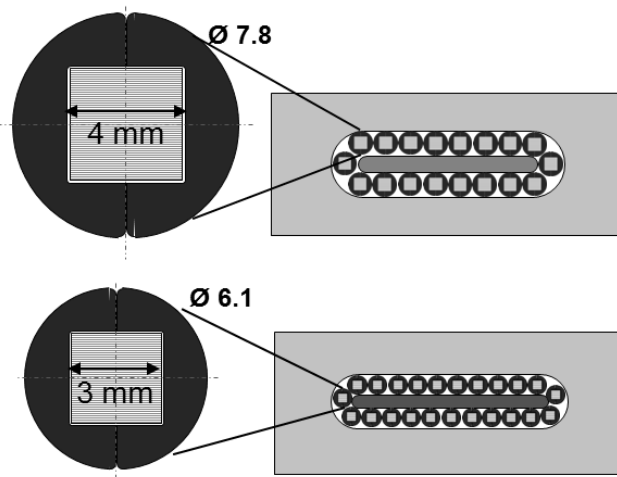

Fig. 7. Schematic cross sections of two possible DEMO type cables made with coated conductor tape. Top: option with 4 mm wide tape (cable core is made with steel). Bottom: option with 4 mm wide tape (cable core is made with copper).

IV. BI2223 CABLE: STRAND CONSTRUCTION TRIAL

Similar to coated conductor, the Bi2223 tapes with silver sheath can be stacked and soldered between two copper half round profiles, but in contrast to coated conductors the maximum tensile strain is limited to 0.25%.

The Bi2223 tape from Sumitomo (DI-BSCCO type H) was selected [17]. First the dependence of the critical current from the twist pitch was measured for a single tape. The twisting was applied at room temperature, and then the critical current measured at 77 K in self field. The results are plotted in fig. 8: the onset of the reduction in critical current is between 250 mm and 350 mm. Therefore, for the construction of a first trial stacked strand, the twist pitch was set at 400 mm. The twisted strand was prepared with a stack of 13 tapes,

assembled and soldered between two copper profiles, resulting in a strand of 8 mm in diameter. The preparation was similar to the one discussed in section III.B.

The reduced critical current versus bending radius is plotted in fig. 9 for the twisted strand made with 13 DI-BSCCO tapes. In the same figure also the curve for the twisted strand made with REBCO tapes (used for the cable in section III) is also reported. The onset of the critical current reduction is located at a bending radius much longer than for the REBCO strands, mainly because of the low critical tensile strain of Bi2223 tapes (0.25%), while in coated conductors it is about 0.6%.

Once the number of strands in the cable is set, the cable twist pitch is proportional to the bending radius of the strand at the cable edge. Therefore for the Bi2223 cable a relative long twist pitch would be required (> 2000 mm) because the
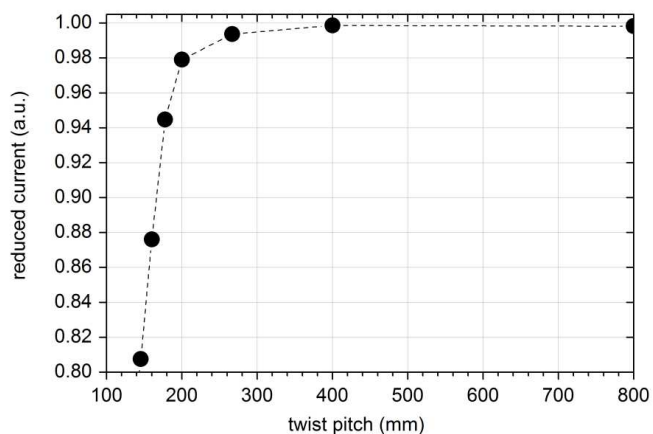

Fig. 8. Reduced critical current versus twist pitch for a DI-BSCCO tape type H. The twist pitch was applied at room temperature.
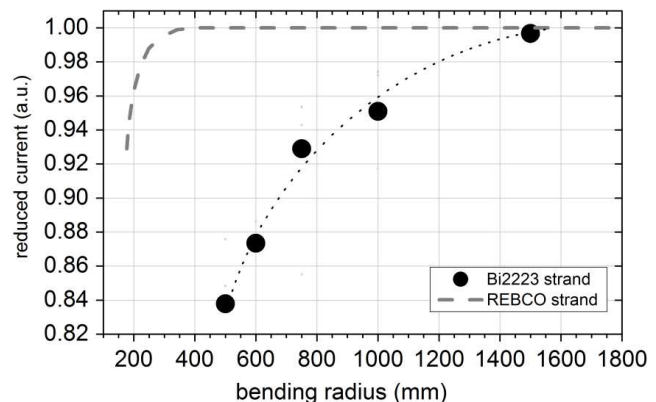

Fig. 9. Reduced critical current versus bending radius for the test strand (8 mm in diameter) made with 13 DI-BSCCO tapes. The dot line is a guide for the eye. The dashed line is for the 6.3 mm diameter strand, made with coated conductor tape, described in III (data are from [12]).

strands can be bent only down to 1200 mm ~ 1500 mm.

In order to achieve shorter cable twist pitches (i.e. shorter bending radius for the strand) it would be convenient to use Bi2223 laminated with steel (for example Sumitomo DI-BSCCO type HT), not because of the higher tensile strength, but because of the higher critical strain (0.4%) due to the pre-compression from steel; the preparation of a stacked strand with reinforced tape is more complicated, because a low temperature melting point solder alloy should be used, in order to avoid melting the solder used for the lamination. Eventually pre-tensioned steel strips could be incorporated in the stack made of non-reinforced tapes. Another option, which is not available anymore from industry, is to use dispersion strengthened AG/Mg alloy, which would also lead to higher critical strain.

Because of the large current capacity of the Bi2223 strands, a smaller number of strands is required than in the case of coated conductor tapes. Therefore it would be possible to arrange the strands around a circular copper core; the main advantage is that in a round cable a short cable twist pitch can be obtained even if the bending radius of the strands is relatively long.

V. SUMMARY AND OUTLOOK

The main activities at CRPP are focused on the development of fusion cables using coated conductors. In fact despite the continuous improvement in the engineering critical current density for all the HTS materials, coated conductor tape should be considered the most promising one, mainly because, being the newest arrived on the market, it has larger room for improvement, especially regarding low cost production. Moreover REBCO is the only HTS materials which can be potentially used at fields over 12 T and high temperature (> 30 K). The design of a flat cable with twisted stacked strands, incorporating coated conductor tapes, was carried out. One prototype cable, about 2 meters long was manufactured and a second one is in preparation. The cable is composed of 20 strands, each containing 16 tapes 4 mm wide. The critical current of 7 strands out of 20 was measured before and after the cabling, and no reduction was observed. Extrapolating the values of the critical current measured on the tapes at 12 T and 4.2 K, the critical current of the cable is expected to be about 60 kA, and the operating current could be between 50 kA and 55 kA with temperature margins of 6 K and 3 K respectively. A second cable section is now being manufactured; the two cables will be assembled in a sample which can be measured either in SULTAN or EDIPO facility. Relying on the accumulated experience, two cables (using coated conductor tapes) were designed for a DEMO class (80 kA) magnet; test strands are in preparation.

The preliminary design of an 80 kA cable made with Bi2212 wires has been carried out. The cable has an operating current of 80 kA at 5 K and 13.5 T, and it is suitable for a DEMO type fusion reactor.

The fabrication of a trial strand with Bi2223 tapes was completed, but the limited tensile strain of the Bi2223 tapes

make the application more difficult than for coated conductor tapes.

Despite the technological challenges that should be overcome, the most important improvement before HTS materials could be applied in fusion magnets on large scale would be the decrease in the production cost, by at least an order of magnitude.

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