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Citation: Giunchi, Giovanni, and Bruno Coppi. "MgB₂ Coil Options for Fusion Poloidal Magnets." IEEE Transactions on Applied Superconductivity 20.3 (2010): 1610–1613. Web. ©2010 IEEE.

As Published: <http://dx.doi.org/10.1109/TASC.2010.2043664>

Publisher: Institute of Electrical and Electronics Engineers

Persistent URL: <http://hdl.handle.net/1721.1/71160>

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

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MgB₂ Coil Options for Fusion Poloidal Magnets

Giovanni Giunchi and Bruno Coppi

Abstract—A hybrid solution is proposed for the IGNITOR research fusion machine by using of superconducting coils for some poloidal magnets, in association with high field copper magnets for the central solenoid and for the toroidal field coils. The choice to be made among the various superconductors is based on the materials performances in high magnetic field, on the mechanical strength of the conductors and on the cost of manufacturing large coils. In this study we analyze a coil based on MgB₂, a “medium temperature” superconducting material that we expect will avoid, in association with others high temperature superconductors, the use of liquid He in future machines. The external poloidal magnet, 5 m in diameter and subjected to a magnetic field of 5 T, represents a real test bench of the technical issues which should be addressed in the exploitation of the future fusion reactors. To fulfil the technical characteristics of the selected magnet we must optimize the fill factor of the superconducting MgB₂ wires, increasing the presently obtained 30% value. Accordingly, the effective current density in the superconducting wire should be of about 1500 A/mm² (@10 K, 5 T), a value which is compatible with the present best MgB₂ laboratory short wires, doped by C or SiC.

Index Terms—Fusion machine, MgB₂ coil, plasma magnetic confinement, superconducting joint, superconducting poloidal magnets.

I. INTRODUCTION

THE choice of classical magnets versus the superconducting ones in the fusion most advanced machines is presently justified by the needs to perform experiments to learn the physics of plasmas under fusion conditions and by the high fields needed to ensure macroscopic plasma stability. In this respect a limited duration of the plasma life and an overall negative energy balance of the research-like fusion machines is not a strong concern.

In this paper, in the framework of an advanced fusion machine, like the present design of the IGNITOR project [1], we consider the possibility to insert in the wider of the Poloidal Field (PF) coils, a superconductive solution. This coil is characterized by a medium magnetic field value, in the range of 4 T ÷ 5 T, and by a diameter of several meters. It represents a good benchmark because it is present in any toroidal magnetic confinement machine and its medium value of magnetic field together with its large dimension are good challenges for several superconducting materials, ranging from the low temperature to high temperature ones. Typically for the IGNITOR machine, the PF coil has an external diameter of 5 m and, when

carries 5.6 MA of current, sees a maximum magnetic field of 5 T. In the more recent design of the IGNITOR machine the various copper electromagnets have an initial working temperature of 30 K and this temperature increases, during the power shot, over several decades. In such conditions a superconducting PF external magnet, which is meters far from the hottest part of the machine, may be managed without modifying appreciably the cryogenic system, assuming that its temperature may range between 10 K and 20 K. We should give technical hints that support the use of the new superconducting material, MgB₂, in this range of temperatures and of magnetic fields. This material appears to compete with the more sophisticated high field superconducting materials, like the A15 class (Nb₃Sn or Nb₃Al) and with the present High Temperature Superconductors (HTS) which are too costly and of lower mechanical strength.

II. SUPERCONDUCTING WIRES CHARACTERISTICS

The main characteristics of the superconducting wires are related to their operative temperatures in high magnetic field, to their current density, to their mechanical strength, to the cryogenic system safety and efficiency and to the manufacturing costs of the wires and the magnets.

Even after several decades of the superconducting applications and the discovery of superconducting materials of different nature, altogether these characteristics are responsible that only two materials are used in the practice of the large magnets manufacturing: the metallic NbTi and the intermetallics Nb₃Sn (of the A15 family). Both superconductors work essentially at low temperature: at 4.2 K or less. The hope to apply higher temperature material remains today limited to small magnets or long cable, due to several restriction in the materials performances.

A. Low Critical Temperature Materials

The majority of the big magnets, like that in use for the particle accelerators, detectors or fusion machines have been built with NbTi wires and are cooled by Liquid He [2]. The limiting magnetic field of this material, at a reasonable current density, is about 7 T at 4.2 K and 8.5 T at 1.8 K. The NbTi is metallic, so it can be drawn in very thin filaments, can be stranded and does not require any thermal treatment to reach the superconducting state. This means that with NbTi wires the superconducting magnets can be built using conventional winding machines.

When more intense magnetic fields must be produced, today the material of choice is the Nb₃Sn or Nb₃Al, which is at developmental stage. These superconductors are much more performing in magnetic field (they can be applied up to about 20 T) and have a higher critical temperature (respectively 18 K and 23 K) than NbTi (9.5 K). Nevertheless the applicability of these superconductors, due to their A15 intermetallic structure, is very limited by the intrinsic brittleness, that prevents to bend the superconducting wires at strain larger than 0.3%. The only way

Manuscript received October 21, 2009. Current version published May 28, 2010.

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Digital Object Identifier 10.1109/TASC.2010.2043664

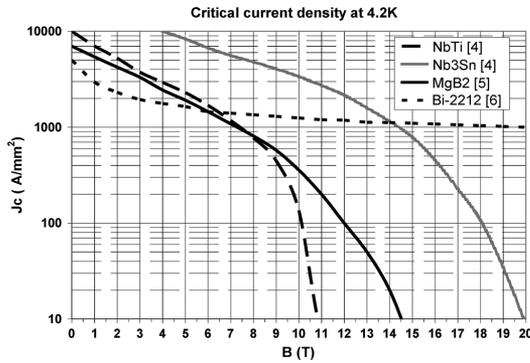


Fig. 1. Critical current density, at 4.2 K, of representative Low Tc and High Tc superconducting wires.

to produce magnets with Nb₃Sn is to wind a ductile metallic precursor wire at the approximate dimensions of the final coil, than submit all the coil to a thermal treatment at about 700°C, for several days. This peculiar and technologically demanding process, named “wind & react”, is currently applied for small magnets (several tens of cm wide) and only few examples are reported for the larger magnets, like the central solenoids or the toroidal magnets needs for the fusion machines, meters wide, as the TRIAM device where the toroidal field is 8 T at the center and 11 T on the conductors [3]. The alternative Nb₃Al material, even if it is similar to Nb₃Sn, is less brittle in the superconducting state, so there is hope to wind it in the superconducting state. The other drawback of Nb₃Al is that the superconducting state of the wires can be induced by a very critical heat treatment at high temperatures (larger than 1800°C) and with very stringent operative conditions, that prevent an easy scalability of the process at high production rates.

B. High Critical Temperature Materials

The high critical temperature materials, like borides (MgB₂), oxides (YBCO and BSCCO) and the more recent iron pnictides present critical temperatures ranging from 39 K to 110 K. In the case of the oxides very high upper critical magnetic fields are observed (larger than 50 T), so these materials appear as the appropriate solution for the future high field applications. In Fig. 1 are compared the critical current densities as function of the magnetic field at 4.2 K, of the most representative wire conductors both of the low Tc and high Tc class. The oxide materials, among which we report the more representative wire candidate, Bi-2212, present even more severe brittleness than the intermetallic. The other important representative of the oxide class, the YBCO, needs to be applied in textured form, in order to prevent grain boundary barriers to the currents. Due to this characteristic, this material is developed in form of thin tapes deposited on metallic substrates with highly oriented characteristics. The processes to obtain these so called “coated conductors” are very elaborated and today this thin film are used only in small magnet prototypes. An other open question regards the mechanical strength of the oxides materials: they need to be reinforced with stainless steel, reducing drastically the critical current density of wires or tapes. For the tapes there is a further issue related to and how it is possible to assembly these tapes in order to have more uniform unoriented characteristics. Even

TABLE I
MgB₂ PROPERTIES (H_{irr} DATA FROM [7])

Tc (K)	39	
Coerence Lenght (nm)	(//ab) 6	(//c) 3
Hex cell axis (nm)	a=b=0.3083	c= 0.3520
H _{irr} (T) @ 4.2K	(pure) 12	(SiC doped) 17
" @ 10 K	" 9	" 13
" @ 20 K	" 5.2	" 7.5
Density (g/cm ³)	2.63	

TABLE II
BEST CRITICAL CURRENT DENSITIES OF MgB₂ SHORT WIRES

MgB ₂ short wires	Jc* (10K@5T)	Jc* (4.2K@10T)	Ref.
nanoSiC dop/PIT (Karlsruhe)	700	200	5
HE mill+nanoC/PIT (Dresden)	-	600	10
SiC dop/PIT (Ohio)	200 ^s	200	11
C dop/Mg-RLI (Milano)	260	80	12
SiC dop/Mg-RLI (Tsukuba)	1500 ^s	700	13

if some clever assembly like the Roebel superposition of the tape has been developed to realize transposition of the tapes, it is doubtful that a tape like superconductor can serve for large magnets where orientation effects are more difficult to manage. Furthermore the oxides present a very low rate of propagation of the normal zone: a characteristics that make more difficult to protect the magnet from accidental quenches.

No attempt up to now has been devoted to the manufacturing of large magnets with the oxide superconductors: this may be due both to the cost of the superconducting material and to the technical difficulties. Nevertheless there is no doubt that, in the future, the high fields of the magnetic confined fusion machine will be realized with high temperature superconductors of appropriate characteristics, but in the mean time other solution must be practiced.

The MgB₂ material is borderline, in the class of high temperature superconductors, having a critical temperature of 39 K. In Table I are reported the main structural and superconducting data of MgB₂. This quite new superconductors, as ceramic, has several peculiarities with respect to the other materials: 1) an easy processability and potential low cost of the raw materials; 2) a less brittleness and an higher mechanical strength in comparison with the intermetallic and the oxides superconductors; 3) a critical current density that, after appropriate doping, is intermediate between the NbTi and Nb₃Sn, at 4.2 K and in the high fields range, as reported in Fig. 1; 4) a very low density.

The use of MgB₂, after eight years from the discovery, is today yet at developmental stage and only few coils of a size of about a meter have been built [8], [9]. As far as the quality of the MgB₂ superconducting material, there are many promising lab scale results that indicate a large improvement of the in field properties by doping and by reducing the grain size at submicronic level.

In Table II are reported the today best performances measured on MgB₂ wires on short samples.

Furthermore, being a lamellar superconductor, also the MgB₂ shows orientation effects in the deposited textured thin film, like oxides, even if less pronounced.

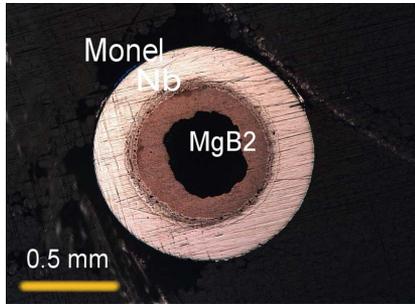


Fig. 2. Typical cross section of MgB_2 hollow wires, obtained by the RLI process. The MgB_2 material surrounds the internal black hole.

The corresponding critical currents (up to 10^5 A/mm^2) and B_{c2} values (up to 40 T) are very high and can compete with the oxide coated conductors.

III. THE MgB_2 OPTIONS

Two routes are used to produce the MgB_2 superconductors: the “ex situ” route where the MgB_2 powders are subjected to a thermal sintering, and the “in situ” route where the elemental B and Mg are mixed and reacted at high temperature to obtain directly a densified product, according to the needs. It is a common experience that the “ex situ” technique allows to produce wires and tapes in an easier way, by the conventional Powder in Tube (PIT) technology [8], while the “in situ” techniques are able to produce more dense and performing materials [5], but at the expense of more elaborate processing, like the hot pressing sintering. Among the “in situ” routes, several processing technologies have been introduced to obtain long wires. Among these we mention a particular type of PIT process: the “Continuous Tube Filling & Forming (CTFF) [9] and a quite new processing route: the Reactive Liquid Infiltration (RLI) [14]. This technology produces peculiar hollow wires, as in Fig. 2, and is based on the natural Infiltration of melted Mg inside a boron powders preform [15]. This new technology is particularly promising, allowing to produce long wires (more than hundred meter long) [16] and massive bodies particularly compact and robust [17]. The dimension of the original boron powders affects the transport properties of the MgB_2 material and the submicronic powders, like that ones used in the wires production, realize the higher critical current density.

With the same RLI process it is possible also to dope the MgB_2 with C or SiC nanopowders, increasing in such a way the critical current density at high magnetic fields [18].

Considering the design of an MgB_2 cable for large magnets, we must considered several main issues related to the superconducting properties of the cable: (1) low losses during the steep charge or discharge of the coils; (2) a large stability by the RLI process margin against quench, 3) a robust structure to resist to the magnetic forces, and the manufacturing process should be viable for its high degree of technical reproducibility and for an acceptable cost. From the construction of the large magnets with low T_c wires it is known that a cable should be preferably made by stranded assemblies of fine wires, in close contact with a stabilizing high thermal conducting metallic part (Al or Cu) and reinforced by a stainless steel armature. In order to fulfill these characteristics with the MgB_2 material it is preferable to use fine

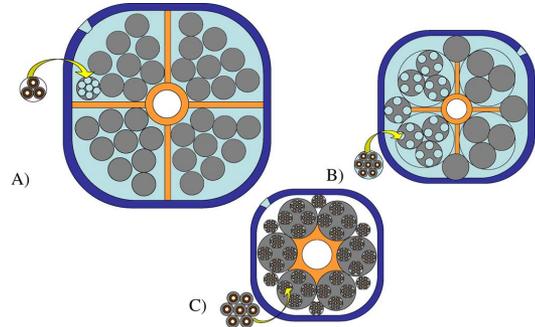


Fig. 3. MgB_2 cables made by different assemblies of braided fine wires, wound around a copper duct and compounded with a stabilizing metal, inside a stainless steel sheath.

round wires more than tapes. The RLI process is able to easily produce these fine wires up to thicknesses of few tens of microns of the superconducting materials and, even in presence of the peculiar hollow morphology, these wires present an yield flexural strength, larger than 200 MPa and a minimum bending radius of 140 mm, for wire diameters of 1.1 mm [19]. This value will be significantly lower for finer wires and open the possibility to use of “react & wind” technique in the manufacturing of large coils.

To guarantee a good cable packing in the manufacturing of the coil, we propose a squared cable. The different assemblies of braided wires, schematized in Fig. 3, and named A, B and C, represent different ways of packing of the strands, all to be wound around the central duct and compounded by Al or other low melting alloys, inside the stainless steel armature.

Inside the cable, the copper duct allows the passage of the cryogenic fluid and is surmounted by 4 (or 6) helicoidally wound fins used for a better cooling of the strands. Considering all the materials of the cable, we estimate for it an overall superconducting fill factor of 3.1%, 4.2% and 3.7% (respectively for A, B, C assemblies), assuming that the superconducting fill factor of the single wire will be about 30%.

It is expected that a maximum magnetic field of 10 T can be tolerated by the MgB_2 at 4.2 K. In these conditions, the today best critical current density of the superconducting wires is 700 A/mm^2 (@4.2 K, 10 T), therefore we estimate a limiting critical current for the designed cables of 25.2 kA, 18.4 kA and 10.5 kA (@4.2 K, 10 T), for case A, B and C respectively. These figures can be further improved by increasing the superconducting fill factor of the single wires, i.e., by a reduction of the hollowness of the MgB_2 wires derived by the RLI process.

IV. CABLING AND POLOIDAL MAGNETS DESIGN

The poloidal magnets of the fusion machines, either of tokamak type or of heliotron type, are large circular magnets of diameter of several meters. They are subjected to medium high magnetic field, in the range from 4 to 10 T. The largest of these kind of magnets (a diameter of 11.5 m, with peak field of 6.5 T on the conductor) was built for the LHD fusion machine with NbTi wires and it was operative in 1998 [20]. In the IGNITOR machine project there are 16 magnets of this kind and the largest one, the #P14 coil, has the following dimensions: external diameter = 5 m, internal diameter = 4.6 m, height = 0.67 m. The maximum field that the conductor of this

TABLE III
DIFFERENT CABLES FOR THE #P14 POLOIDAL COIL OPERATING @10 K, 5 T

	Cable edge (mm)	turns	N wires	I cable (kA)	Cable length (m)	J cable (A/mm ²)	I wire (A)	J wire (A/mm ²)
A	34	6 x 20	756	46.6	1800	40.3	62	1300
B	25	8 x 27	448	25.9	3240	41.5	58	980
C	20	10x32	210	17.5	4800	43.8	83	1165

magnet will experience is 5 T. The 2000 IGNITOR machine was designed with all copper conductors cooled at 30 K, but recently it has been proposed also the use of a superconducting MgB₂ coil, at 10–15 K, for the larger poloidal coil. The selected poloidal coil will be energized with a total of 5.6 MA, which means mean current density in the coil of 43 A/mm².

The above designed cables have all a squared cross section and their quite different cross areas can be further tailored by changing the diameters of the wires, to match the need inductance of the magnet. In Table III are reported the typical cable dimensions that result from the assumption of a reasonable fine wire diameters (0.45 mm, 0.5 mm, and 0.55 mm respectively for A, B, and C) for the poloidal coil #P14, above mentioned.

Due to the low density of the MgB₂ wires and to the compounding Al we can assume an overall mean density of the cable of 3, resulting a total weight of the coils of 6.25 tons, to be compared with 14.5 tons of a corresponding copper coil.

To manage cables of acceptable length, the coil may be divided in joined pancakes (respectively 4, 9, and 8 for A,B, and C), corresponding to cable length of 450 m, 560 m, and 600 m.

The cables A and B are composed by four helicoidally wound subcables that are reacted in advance and, after worth, are assembled around the central copper duct. The cable C is composed by twelve helicoidally wound subcables, reacted in advance.

All the cables assemblies are covered by a steel sheath and compounded with a stabilizing metal (i.e., by injection or co-extrusion with Al or others low melting metals).

The whole assembly will speed up greatly the cable manufacturing for typical lengths of the order of a km, and consequently will reduce the cable cost. As tentative exercise, we evaluate the materials cost of these MgB₂ superconducting coils, respectively made by 1380 km, 1452 km and 1008 km of MgB₂ wires, assumption of a reasonable cost of these wires of 10 euros/kAm. For all the three coils assemblies we estimate a cost of the wires of about 840 k euros, which can be considered relatively low, due to the size of the magnet.

The cable and wires currents, reported in Table III, can be compared with the experimental values of MgB₂ at the operative temperature of 10 K and in applied magnetic field of 5 T. Assuming a safety margin of 40%, the MgB₂ single wires should have, at the said conditions, a critical current respectively of about 85 A, 81 A and 115 A (case A,B,C), corresponding to a critical current density ranging from 1400 A/mm² to 1800 A/mm² (@10 K, 5 T). These figures are about two times larger than the present measured current densities for a RLI type MgB₂ wire doped by carbon and are in the range of values for the best RLI wires doped with SiC nanopowders.

The selected poloidal magnet #P14 will be energized in 4 seconds to a total current of 5.6 MA: this issue imposes an high

quality of the superconducting wires, with small losses in rapid changing fields. We have checked that our RLI MgB₂ wires, charged by increasing currents at the high rate of 100 A/sec show no appreciable voltage increase due to losses.

V. DISCUSSION AND CONCLUSIONS

The feasibility of a hybrid machine for plasma ignition and fusion studies that are the objective of the IGNITOR project, has been discussed referring to the adoption of a superconducting material in the largest poloidal field coil. Among the medium and high T_c superconductors, the use of MgB₂ superconducting wires appears technically viable and represents the more economical solution. Among other solutions round wires can be easily produced according to the “in situ” RLI process. For this purpose new robust cabling options are introduced, where we can profit of the more friendly “react and wind” procedure. To energize the largest poloidal magnet #P14, subject to a maximum magnetic field of 5 T, we estimate that the present best MgB₂ critical current densities allow to operate at 10 K. The cooling is designed to have pressurized He gas, flowing in the inner channel of the cable. This preliminary study has been focused mainly on the superconductor wires characteristics, but several other key issues must be addressed in order to validate any aspect of this hybrid superconducting solution. The insertion of poloidal superconducting magnets in a normal conducting fusion machine, like the IGNITOR machine designed for high density plasmas, represents a hybrid solution that presently is unique in the world, as far as the size and the power of the magnets are considered. A substitution of other magnets with superconducting coils also seems to be feasible and is now under evaluation.

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