Magnesium Diboride Magnets for Future Particle Detectors

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Abstract—**Since 1978, when the CELLO magnet was manufactured, superconducting detector magnets have been wound using NbTi based, Aluminum stabilized conductors. However, other choices are possible and Magnesium Diboride (MgB_2) could be an attractive alternative. Magnets wound with MgB_2 can be operated at relatively high temperature (10 to 20 K), therefore increasing the cryogenics efficiency. Efficiency is not the only advantage in using MgB_2 instead of NbTi: higher operating temperature and higher temperature margin lead to higher enthalpy margin, which means very stable magnets. In addition, MgB_2 is much cheaper respect to High Temperature Superconductors. The cost comparison between Al stabilized NbTi magnets and MgB_2 magnets must be made considering the entire fabrication process.**

Index Terms—**Detector magnets, MgB_2, superconducting magnets.**

I. Introduction

MAGNESIUM diboride (MgB_2) is a superconducting material which does not exhibit transport properties comparable with those of other practical superconductors, so far. In particular, its irreversibility field is low, making it unsuitable for high field applications. However, due its characteristics and the relatively low cost of the wires, it finds application in niche sectors, where the magnetic field is low, but where a relatively high temperature respect to 4.2 K and high stability are required. Among them, the most important and widely applied in magnet technology is the open MRI produced by ASG Superconductors [1], [2]. Another important application, involving large amount of MgB_2, is the construction of the superconducting links at CERN [3]. In the field of particle accelerator magnets, the use of MgB_2 conductors to wind superferric magnets was proposed several years ago [4] but it was never applied, so far. A full-length prototype of sextupole corrector for the High Luminosity upgrade of the LHC was designed and constructed [5] and recently, a supeferric dipole demonstrator was constructed at CERN using a conductor obtained by cabling 18 MgB_2 wires around a copper core [6]. Due to its low density, titanium clad MgB_2 conductors were proposed to wind magnets for space applications [7], [8], [9], [10].

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Superconducting magnets for particle detectors are generally large solenoids generating fields in the range of 0.5-2 T with few exceptions, like the 3 T magnet of AMY at the TRISTAN storage ring [11] and the 4 T solenoid of the CMS experiment at the LHC [12]. Of course, other, albeit less common, configurations are possible, such as toroids, a notable example of which is part of the huge magnetic system of the ATLAS detector [13]. Despite the low field, due to their large bore, detector magnets store a large amount of energy, ranging from tens of MJ to 2.7 GJ in the case of CMS [14]. Since the late ‘70s, when the CELLO solenoid was manufactured [15], detector magnets have been grounded on the concept of dynamic stability, basing their design on NbTi composite conductors bonded to high residual resistivity ratio (RRR) aluminum and on indirect cooling. Since 1984, such a bonding has been obtained by co-extrusion [14]. Aluminum, in parallel to the superconducting cable, increases the heat capacity per unit length and limits the dissipation in the case of a local transition to the normal state, thus ensuring high stability against energy releases. Moreover, it limits the magnet weight and allows the requirement of radiation transparency to be fulfilled when calorimeters must be placed outside the magnet. This is a common requirement for detector magnets, many of which are thin solenoids having radiation length less than 2 [14], [16]. The wide experience in constructing and successfully operating detector magnets wound with aluminum stabilized conductors suggests that this should be the way forward for future projects.

However, other choices are possible and magnesium diboride could be an attractive alternative. The peak field at the conductor of most of the detector magnets does not exceed 2.5 T and the current density is low, so that the properties of MgB_2 are perfectly adequate to this application. Magnets wound with MgB_2 can be operated at relatively high temperature (10 to 20 K), therefore increasing cryogenic efficiency. Higher operating temperature and higher temperature margin lead to higher energy margin, which means very stable magnets.

Magnesium diboride wires ensures also good radiation transparency, being composed by low atomic number, low density materials. In addition, despite MgB_2 wires being more expensive than NbTi wires, they are much cheaper compared to other High Temperature Superconductors like REBCO and BiSCCO.

Differently from NbTi, MgB_2 is a brittle material, so the conductors are characterized by a minimum bending radius (critical radius). However, the size of detector magnets is large enough that the critical radius is never reached.

The cost comparison between Al stabilized NbTi magnets and MgB_2 magnets must be made taking into account the entire fabrication process, including co-extrusion, and the operational costs.

II. Benefits of Magnesium Diboride Conductors

The main benefits of MgB_2 conductors are related to its high critical temperature, about 39 K. This makes it possible to operate magnets at relatively high temperature, up to 20 K, achieving several advantages related to both cryogenic efficiency and stability. The most evident is the increase of the refrigerator coefficient of performance (COP) up to a factor of five with respect to systems operating with liquid helium. Also Also, the higher temperature is advantageous for efficient conduction cooling, as the thermal conductivity of many materials increases with temperature. As an example, the thermal conductivity of aluminum 6061 alloy increases by a factor of five and fiberglass-epoxy by a factor of three, if temperature is raised from 4.2 K to 20 K. The improvement of the conduction cooling results in higher temperature homogeneity and allows the applications in high heat load environment.

Another important issue is the magnet stability that is directly related to the energy margin. In the range 4 K to 20 K, i.e., much lower than the Debye temperature, the specific heat capacity of solid materials increases as the cube of the temperature:

$$c \propto \left(\frac{T}{\theta_D}\right)^3$$

Fig. 1 shows the specific heat capacity of a magnesium diboride wire. Therefore, even if the temperature margin is set at the same value, a magnet operating between 15 K and 20 K is much more stable than a magnet operating at 4.2 K, because its energy margin is up to a factor of 30 higher. Quench events due to sudden energy releases become very unlikely in MgB_2 magnets. The only quench triggering event is a lack of cooling power which can result from a failure of the refrigeration system.

A consequence of the high energy margin is that aluminum is not required for stabilization.

Of course, although the probability of a quench is very low, it is necessary to protect the magnet. In case transparency to radiation is requested, aluminum in parallel is the best choice but a very high RRR is not required. Nor is the excellent bonding ensured by co-extrusion necessary. A less delicate process like soft soldering can be used.

The many advantages of MgB_2 are contrasted by a number of problems that must be approached with caution. These include the fragility of the material and the low quench propagation velocity. The former, although not involving limitations in the winding procedure due to the large bending radius of detector solenoids, must be considered at the design stage: the stress normal to the conductor due to the compressive axial forces can damage the MgB_2 wires and must be carefully managed. The latter must be dealt with subdivision protection, taken to the extreme, if necessary, of controlled insulation or non-insulation winding. Detector magnets, which generally do not have to be rapidly charged/discharged, are particularly suitable for the application of the insulation-free protection method.

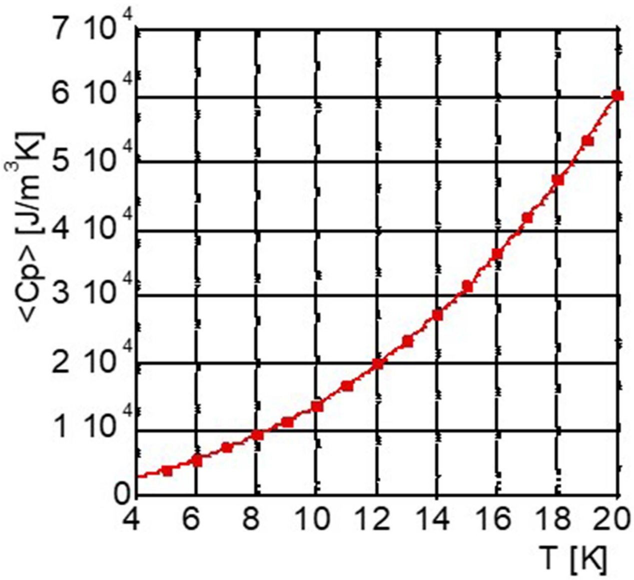

Fig. 1. Average specific heat of MgB_2 wire.

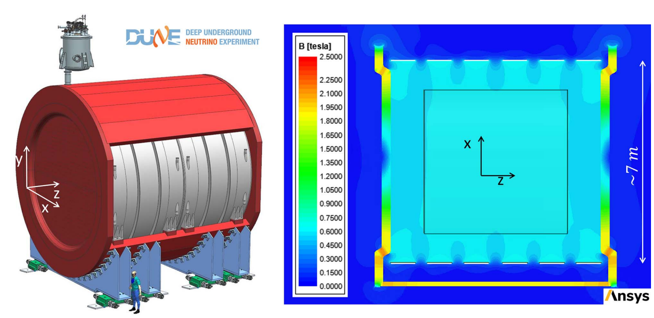

Fig. 2. Scheme of magnet configuration and field map.

III. Future Detector Magnets

The idea of using MgB_2 for detector magnets arose during the preliminary design of the large solenoid for the DUNE (Deep Underground Neutrino Experiment) near detector [17], triggered by the current lack of availability of NbTi, aluminum stabilized conductors. The solenoid (SPY), approximately 7 m in diameter and 7 m long, is a modular magnet with partial return yoke which generates about 0.5 T at the center. It will surround a high-pressure argon TPC (time projection chamber) with an electromagnetic calorimeter. The most recent design envisages six coils spaced so as to optimize the field homogeneity at the TPC. Fig. 2 shows a view of the magnet and the field map.

In the baseline design the conductor is a NbTi Rutherford cable stabilized with pure aluminum. As in other large detector magnet the conductor will be internally wound on an aluminum alloy cylinders [18], [19]. These cylinders will have multiple functions: mechanical structure to support the radial forces, indirect cooling medium and quench back protection. Once the six coils are wound and impregnated, the magnet will be assembled by connecting the flanges of the winding cylinders and splicing the conductors. The subdivision of the magnet

TABLE I
MAIN CHARACTERISTICS OF THE SPY@DUNE IN THE NBTI-BASED DESIGN

Number of coils	6
Number of turns per coil	120
Number of layers	1
Type of conductor	Al stab. NbTi cable
Operating current	4585 A
Current density	32 A/mm^2
Inductance	3.1 H
Magnetic flux density (center)	0.52 T
Magnetic flux density (peak)	0.9 T
Stored energy	32.5 MJ

in six coils simplifies the construction, allows optimizing the field homogeneity and also allows the compressive stress on the conductor to be managed by supporting the axial forces with intermediate flanges.

The main characteristics of the SPY magnets are reported in Table I.

Comparing the characteristics of the magnet, in particular the low peak field at the conductor and the very low current density, with the properties of industrially produced magnesium diboride conductors [20], it is evident that SPY is an ideal magnet in which to apply the new technology. Therefore, in parallel to the design based on the conventional technology, the section of Genoa of the Italian National Institute for Nuclear Physics (INFN-Genova) is initiating a research and development to verify the possibility of making the magnets with a conductor based on MgB_2 wires. Due to the magnet large dimension, the research focuses on conductors based on ex-situ wires.

At 20 K, 1 T the engineering critical current density of undoped, ex-situ wires produced by ASG Superconductors is more than 500 A/mm^2 [18], and the critical current is 430 A (1 mm wire), 720 A (1.33 mm wire), more than 1000 A (1.53 mm wire) [21]. To reach 4585 A it is necessary to cable several wires, the number of which depends on their diameter. For example, the cable can be obtained by threading 18 wires with a diameter of 1 mm. In this case, the temperature margin is about 3 K that results in an energy margin of about $2{\cdot}10^5$ J/m^3. The wires could be cabled around an aluminum core, similarly to the sub-cables of the CERN superconducting links [3] or cabled together with aluminum wires. However, a large solenoid wound with such cables could be mechanically weak, due to the axial compressive forces. A possible solution is the use of a cable in channel obtained by soldering the cable in the groove of an aluminum or aluminum-nickel alloy profile. In principle, the operating current could be reduced by a factor of 6 increasing the inductance to 110 H. Such a choice would allow using a single wire, possibly soldered in the channel of an aluminum strip.

Assuming that a liquid hydrogen thermosyphon is ruled out for safety reasons, the refrigeration system would be based on the circulation of gaseous helium. Another possible solution is the use of cryocoolers with the caveat that, due to the large size of the magnet, an efficient system, such as hydrogen filled heat pipes, is required to ensure temperature homogeneity. Anyway, in case of either energy black-out or failure of the refrigerator, no cooling fluid reservoir is available, therefore the magnet temperature would start to rise. To prevent the magnet from quenching, the protection system must activate the discharge. Here again, the relatively high operative temperature and the consequent high heat capacity, plays in favor: as the calculated heat load is about 90 W, being the cold mass about 24 tons, the time to discharge the magnet, before the critical temperature at the operative condition is reached, is more than one hour.

Another magnet has been examined as a possible candidate for being wound with a magnesium diboride conductor. This is the magnet for the ALICE3 experiment at the LHC [22]. The final configuration of the ALICE3 magnet is not yet fully defined but it should be a compensated solenoid 7.5 m long with a free bore of 1.5 m radius. The magnetic flux density requirement is more stringent: the value at the magnet center should be 2 T and consequently, the peak field will range between 2.4 T and 2.7 T. The highest peak field requires carbon doped MgB_2 and an operating temperature lower than 20 K. At 15 K, the critical current density is almost a factor of 2 higher than at 20 K while the benefits of high operative temperature, although reduced, are still high.

There are no special requirements about radiation transparency, so that, in principle, the conductor can be a copper-based cable in channel, even if aluminum remains an option to be considered to limit cost and weight.

Research and development will begin in the near future, linked to the activity on the SPY@DUNE magnet.

IV. CONCLUSION

MgB_2 could be an excellent candidate to replace NbTi in magnets for which the generation of high field is not required, such as solenoids for particle detectors. Detector magnets wound with MgB_2 conductors can operate at temperatures between 15 K and 20 K resulting in several benefits.

Consequences of the higher operative temperature are higher stability respect to magnets operating in liquid helium with the same temperature margin, better indirect cooling due to higher thermal conductivity, and higher COP of the refrigerators. In MgB_2 conductors for detector magnets, aluminum is required for protection, not as stabilizer, therefore high purity and co-extrusion are not necessary.

The design of detector magnet should be rethought on the bases of the characteristics of MgB_2 conductors and on the pros and cons resulting from the higher operative temperature, including the low quench propagation velocity. For example, the quench issue of MgB_2 detector magnets could be addressed with the controlled insulation technique, particularly suitable for magnets that do not require fast charge/discharge.

INFN-Genova is starting a research and development aiming to demonstrate the feasibility of detector magnets based on magnesium diboride.

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