Dry cryomagnetic system with MgB$_2$ coil

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Abstract. MgB$_2$ may be the future superconducting wire material for industrial magnets due to its higher operation temperature and potentially lower cost than low temperature superconductors (LTS) have. We designed a compact cryomagnetic system with the use of MgB$_2$. The possibility of creating a magnet with a central field of 5 T from a commercial MgB$_2$ wire by the “react and wound” method was investigated. The magnetic system is cooled by a cryocooler through a copper bus. The magnet has a warm bore diameter of 4 cm. The design of a magnet consisting of three concentric solenoids is proposed: an internal one of high-temperature superconductor (HTS), an average of MgB$_2$, and an external of NbTi. The operating current of the system is 100 A. Two pairs of current leads are used. A separate pair of current leads for powering NbTi coil allows testing of MgB$_2$ and HTS coils in an external field. The load curves for each of the magnets are calculated.

1. Introduction

In comparison with the LTS materials, MgB$_2$ is characterized by higher values of the critical temperature, $T_c \approx 39$ K, and the higher critical magnetic field, $H_{c2} \approx 60$ T. This material finds application in energy transport systems, but much more interest is caused by the possibility to use it in magnetic systems. Solenoids made from this superconductor can be used in magnets, superconducting turbine systems, motors, magnetic focusing and separation systems, magnetic energy storage devices. The main development direction for the use of modern magnets based on MgB$_2$ wires are MRI devices [1]. Due to the specific application, the designed coils have a large internal diameter allowing to place inside them a human body or some its parts.

Due to the high critical temperature of MgB$_2$, it becomes possible to design cooling systems using cryocoolers and solid nitrogen [2]. However, there exists a problem of wire performance degradation under bending strain which impedes manufacturing solenoids with small diameters, especially from ex situ MgB$_2$ wires produced by powder-in-tube (PIT) technology. Usually for the production of solenoids with diameters less than 15 cm the “wound and react” technology is used, which avoids the occurrence of bending stress during winding. This technology allows to make a MgB$_2$ coil with a high critical current value and, as a consequence, with a high value of the central magnetic field [3]. However, in this case the obtained parameters are affected by additional stages of the technological process such as a homogeneous annealing. That is acceptable for the wire manufacturer or industrial production, but users, who want to make themselves a MgB$_2$ coil, have some additional difficulties. We have investigated a possibility to create a cryomagnetic system based on modern commercially available MgB$_2$ wire without homogeneous annealing. The following parameters were set for the system design:

- The diameter of the warm bore is not less than 40 mm.
The shaft height of the magnet is not less than 100 mm.
- The cooling system does not contain liquid refrigerant.
- The maximum magnetic field on the axis of the bore of at least 5 T.
- The maximum operating current 100 A.

Sketch of the cryomagnetic system is shown in Figure 1. The RDK 408D2 cryocooler and the MgB₂ wire manufactured by Columbus Superconductors SpA were used as a basis for the system.

2. MgB₂ wire

Photo of a bare wire cross-section is shown in Figure 2. The wire of 1.0 mm diameter contains 37 MgB₂ filaments, each of them is enclosed by the Nb barrier and placed in Monel matrix. The MgB₂ filaments take up about 13.5% of total cross-section area of the wire. The wire is stabilized by a copper layer electro-deposited on its surface.

Dependence of critical current on external magnetic field is shown on Figure 3. Measurements were carried out at liquid helium in magnetic field applied perpendicular to the wire axis. The critical current at $H = 5$ T is about 55 A. Despite the fact that the critical temperature of the MgB₂ is much higher than the temperature of liquid helium, we have to design a cryomagnetic system with an operating temperature of 4.2 K because of such a low value of the wire critical current. The possibility of using MgB₂ wire for coil application at temperatures above 4.2 K was considered in our previous work [4].

As we have intend to wound a coil, we measured the transport properties of the wire under bending deformation with diameter $D = 8$ cm. At $H = 5$ T the critical current decreased about 1.8 times. In our previous work we have shown that critical current is noticeably reduced with reduction of bending diameter [5]. We can expect that for $D = 5$ cm the critical current will be 20% less than for $D = 8$ cm and the current density, which is necessary to obtain the field $H_{coil} = 5$ T at the coil center, is estimated as $J_c = 3 \times 10^3$ A/cm² (we neglected, that the field on the coil winding is higher than at the center). For the MgB₂ coil a current in the inner loop restricts the operating current.

Thus, to make a coil with an internal diameter of 8 cm and a maximum magnetic field in the center of 5 T, we need 34 km of the MgB₂ wire (winding density 0.785). The coil should have the height of 30 cm, the outer diameter of 45 cm and the weight of over 300 kg. Obviously, a magnet based on this coil cannot compete with widely used NbTi magnets.

To optimize the space inside the cryostat we proposed magnet design consisting of three concentric solenoids, namely a pancake HTS coil inside, a MgB₂ one in the middle and a NbTi solenoid outside. Presence of the inner coil allows us to use a larger diameter for MgB₂ solenoid winding and so to diminish decrease of the critical current of the MgB₂ wire caused by a bending stress. In addition, this will
reduce influence of magnetic field on $I_c$ in the middle coil. As seen in Figure 3, the critical current of the MgB$_2$ wire becomes more than 100 A, when magnetic field is reduced down to 4 T. This value exceeds the operating current of our system.

![Figure 3](image)

**Figure 3.** Dependence of critical current on external magnetic field for MgB$_2$ wire. The field direction is perpendicular to wire axis. Open circles - in the absence of bending stresses; closed circles - bend on the form with $D = 8$ cm.

Mechanical properties of HTS tapes allow us to make the inner solenoid with a small inner diameter without loss of critical current [6]. Due to high critical currents at 4.2 K in high magnetic fields of up to 5 T, HTS tapes are very suitable to make inserts in magnets [7]. To make the inner solenoid we used the 4 mm HTS tape produced by SuperOx. The critical current of the tape exceeds 100 A in $H = 5$ T at $T = 4.2$ K [7]. The coil consists of 10 double pancakes: the two upper and two lower ones have 27 turns, and 4 medium double pancakes have 30 turns. The remaining transition pancakes are asymmetric, a larger layer has 37 turns, a smaller layer 30. Calculation of the field produced by the HTS coil was carried out by the finite element method using the COMSOL multiphysics package.

**Table 1. Parameters of coils**

|                      | HTS      | MgB$_2$  | NbTi  |
|----------------------|----------|----------|-------|
| Diameter of wire (mm)| 4 mm     | 1        | 0.5   |
| Inner diameter (mm)  | 64       | 80       | 100   |
| Winding density      | 0.725    | 0.8      |       |
| Outer diameter (mm)  | 76       | 93       | 138   |
| Height (mm)          | 80       | 120      | 140   |
| Total length of wire (m)| 195    | 3473.7 |       |
| Total number of turns| 482      | 714      | 19684 |
| Average number of turns in the layer | 119 | 259     |
| Load factor (mT/A)   | 6.9      | 6.12     | 63.6  |
To investigate influence of magnetic field on current in the MgB$_2$ coil we separated current leads of the outer NbTi coil from common leads supplying the inner and outer coils. That allows us to test MgB$_2$ and HTS coils in external magnetic field.

![Loading curves of coils](image)

**Figure 4.** The loading curves of the NbTi, MgB$_2$ and HTS coils.

Parameters of the made coils are presented in Table 1. The calculated load curves for each coil are shown in Figure 4. The load factors calculated from the load curves are presented in Table 1.

3. Summary
The original design of the cryomagnetic system was propose taking into account the parameters of modern commercially available MgB$_2$ wires. It was shown that for the time being the transport characteristics of commercial wires are insufficient to make (using the “react and wound” technology) a solenoid producing magnetic field of 5 T. We have proposed magnet design consisting of three concentric solenoids. The inner coil is pancake HTS coil, the middle coil is MgB$_2$ soleniod, and the outer coil is NbTi solenoid. The load curves for each of the coils are calculated. Afterwards we plan to manufacture the designed cryomagnetic system and study the characteristics of the MgB$_2$ coil in an external magnetic field.

The main obstacles preventing manufacture of a MgB$_2$ solenoid with the “react and wound” technology are both low values of critical currents of industrial wires in high magnetic fields and a serious degradation of $I_c$ under bends with diameters less than 100 mm. Such a manufacture becomes possible if the critical current in the 1mm wires achieves 240 A (taking into account a degradation under bending). In this case one can make a 5 T solenoid with internal diameter of 8 cm and overall dimensions of about 15 cm.

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