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A Versatile Bulk Superconducting MgB_2 Cylinder for the Production of Holding Magnetic Field for Polarized Fuels and Targets

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The production of an internal magnetic field in a compact space is a challenging problem, and a versatile solution is being pursued. The property of a bulk hollow superconductor is exploited in order to trap a specific configuration of magnetic field, which could shield the interior from externally applied fields. This can be achieved by applying the desired magnetic configuration during the cooling process through the transition temperature. This solution, in the longitudinal field configuration, would be useful for polarized fuel for nuclear fusion test. The transverse field configuration, instead, would be useful for transversely polarized nuclear target. A bulk superconducting magnesium diboride, MgB_2, cylinder has been characterized measuring the interior field retention, the capability to exclude an externally applied field and the corresponding long-term stability performance. The measurements have been done just in its center at 1 T transverse magnetic field at around 13 K. The present programs are focused on mapping the trapped field along the symmetry axis, at higher magnetic field, and at lower working temperature in a transverse magnetic field. Afterwards, the cylinder will be tested in a longitudinal field, but also prepared in a transverse field and then immersed in a longitudinal field to test its capability on shielding the latter. In the context of an electron scattering experiment, such a solution will minimize beam deflection and energy loss of the reaction products, while also will eliminate the heat load to the target cryostat from current leads that are required for superconducting electromagnets. In the context of polarized fuel for fusion its use is straightforward, because the system can trap the magnetic field required during fuel production, and then provide the holding field for its transfer in fusion test facilities.

KEYWORDS: Polarized Nuclear Targets, Cryogenics, Superconductors

1. Introduction

In various activities, which involve polarized nuclear substances, magnetic fields are required in order to mantein their magnetization. Specifically for this contribution, the main purpose is to provide holding fields for polarized fuel in fusion tests [1] and for spin effects studies in nuclear and subnuclear physics [2]. A hollow bulk superconductor can host inside polarized substances, provide the required holding fields and also shield external fields [3,4]. This feature is an important improvement with respect to a conventional coil–based solution [5]. Additional advantages include minimal space needed to fit in the experimental environments, maximal field compactness, absence of heat load from current leads and ability to operate without stabilizers, and furthermore in the case of MgB_2 low mass and low atomic number, *Z*, therefore the reaction products, in the path of the material, experience less energy losses.

Polarized hydrogen, or deuterium, targets require cryogenic temperatures, and for this the cooling of MgB_2 can be easily matched, or incorporated within the cooling system.

Finally, the system can be easily moved from the preparation site and transported in the experiments, or test facilities. The MgB_2 as a superconductor has comfortable critical current, critical field, transition temperature (39 K), and machinability [6].

2. Preliminary Test on an MgB_2 Prototype Cylinder and System Commissioning

A picture of the system is shown in Fig. 1 [7]. For the feasibility studies, as a sample, a prototype cylinder of MgB_2 is used, made by the Reactive Liquid Infiltration (RLI) process [6], 86 mm long with a 39 mm outer diameter and a nominal thickness of two mm, which tapers at the edges to one mm. In the following a brief description of main components is reported, details are available in Ref. [7].

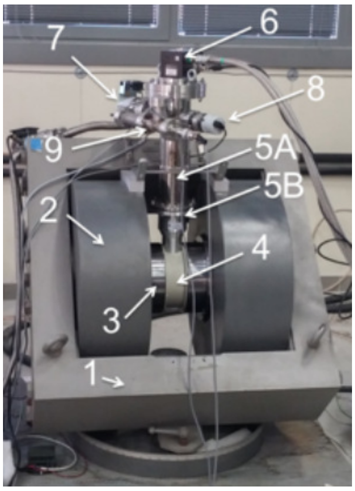

Fig. 1.: Picture of the overview of the setup. Magnet: iron yoke (1), coils (2) iron poles (3). In a nylon support (4), fixed to the poles, the bottom aluminum chamber (5B) of the vacuum system is inserted, connected to a stainless steel chamber (5A) fixed to the yoke thanks to two arms, on which a ring is welded. A cold head (6) is placed on top of the vacuum chamber, a turbomolecular pump (7) is connected to one side. Two additional service flanges are available for a pressure sensors (8), and electrical feedthroughs (9).

Mechanical refrigerator – The superconducting cylinder is cooled by a cold head (Edwards 6/30). The lowest temperature reached is 11.1 ± 0.1 K. The sample temperature is controlled by a resistive heater, clamped on the 2^{nd} stage of the cold head, with a CLTS sensor on it for its control and monitoring by the Oxford Instruments ITC-503S [8].

External magnet – The magnetic field is provided by a VARIAN electromagnet (model V3603) with a nominal maximum current of 180 A. A power supply (Agilent 6692A), remotely controlled via a GPIB interface, allows to feed 110 A, providing a field of 980 mT, measured in the middle of the poles by a Hall sensor (Arepoc HHP-NU).

Vacuum system and thermal insulation –The vacuum system consists of two cylindrical chambers, in stainless steel and in aluminum (5A and 5B in Fig. 1). The stainless chamber has a CF100DN flange on the top for the cold head, and on the side a CF63DN for a turbo pump (Agilent Turbo-V 81-M) backed by a scroll pump (Varian SH110) and two CF40DN: one for a Penning gauge (Pfeiffer PKR 251), and the other for a T connection for two feedthroughs, carrying wires for the Hall probes, temperature sensors, and the heater. A Pirani gauge (Pfeiffer PRT81) is connected on the inlet of a scroll pump, backing the turbo pump.

The MgB_2 cylinder fit in a copper sample holder (simply named “sample can” – F in Fig. 2), fixed on the copper rod, which is in turn connected to the 2^{nd} stage (10 K nominal temperature) of the cold head. Surrounding this is a 3 mm thick cylindrical copper thermal shield connected to 1^{st} stage (77 K nominal temperature). Thin indium strips were used in all thermal joints. The aluminum chamber has an outer diameter of 70 mm and a wall thickness of 3 mm. Two sets of strips, made with three layers of Myoflex ([8]), were wound around the 62 mm diameter thermal shield, for the insulation of it from the aluminum chamber. Two set of strips, about 2 cm wide, were wound around the sample can and copper rod, for the insulation of them from the copper thermal shield. The pressure stays below 10^{-6} mbar at room temperature, and reaches 10^{-8} mbar, when the cold head is at the minimum temperature.

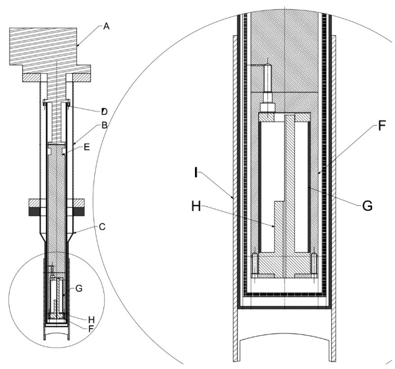

Fig. 2.: Drawing of the cold head and the inner parts of the chamber and the cylinder holder: cold head (A≡6 in Fig. 1), stainless steel vacuum chamber (B≡5A in Fig. 1) aluminum vacuum chamber (C≡5B in Fig. 1), copper thermal screen connected to first stage of cold head (D), copper rod connected to second stage of cold head (E), copper chamber which hosts the cylinder – simply named "sample can" in the text (F), MgB_2 cylinder (G), PFTE Hall probe holder (H), nylon support (I ≡ 4 in Fig. 1).

Temperature measurement – The temperature is monitored by a calibrated Rhodium Iron (RhFe) sensor from Oxford Instruments [8] placed on the bottom of the sample can.

Control and data acquisition – LabView and C routines are used to (1) adjust the Oxford ITC-503S heater controller, (2) control and record the power supply of the external magnet, readout and record (3) pressure values (via the Pfeiffer TPG256A multigauge), (4) temperature sensor resistances (via the Keithley 199 System DMM/Scanner), and (5) magnetic fields (via the Arepoc USB2AD controller).

Thermal cycle – About 7.5 h are required to cool from room temperature to near 13 K (Fig. 3). Using the cold head heater at full power (65 W), it takes about one hour to heat the sample can to 60 K, which is done after each test to ensure a complete transition before the next cool down and test. The trapped field disappears at the MgB_2 critical temperature (39 K). One and a half hours are needed to cool back to near 13 K, usually before ramping down or up the magnet, we wait at least one hour at the lowest temperature.

Results – Although a prototype MgB_2 cylinder was used, the results were promising. A typical *trapped field cycle* is shown in Fig. 3. With a field applied, the sample is cooled from room temperature to about 13 K. After the system stabilizes at the minimum temperature, the external field is ramped to zero, while the residual field of the MgB_2 cylinder is measured. In Fig. 3 at the maximum external field of 980 mT, with a current of 110 A, 942 ± 1 mT were trapped. The trapped field can be preserved for days, unless a spike, due to instabilities in the cold head, destroys it. We observed every 2.5 hours a temperature spike on the RhFe temperature readout, which in some case reduce the performance of the cylinder.

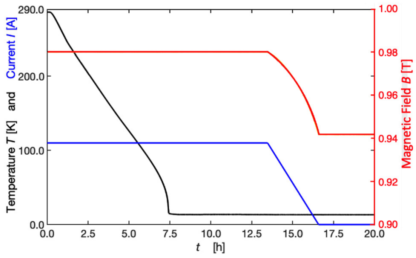

Fig. 3.: Field cooling from room temperature. Current (–) applied to the magnet, temperature (–) recorded by the RhFe and magnetic field (–) measured by the Hall probe.

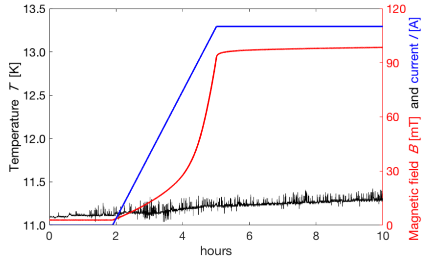

Fig. 4.: Shielding after the Zero Field Cooling. Current (–) applied to the magnet, temperature (–) recorded by the RhFe and magnetic field (–) measured by the Hall probe.

A typical *shielding cycle* is shown in Fig. 4. After cooling down and waiting at least for one hour, the magnet is ramped up. The cylinder shields most of the field generated by the external magnet (980 mT), with a small residual magnetic field penetrating the volume inside it.

Moving the MgB_2 cylinder – The planned scheme for using an MgB_2 magnet and shield, after its preparation, requires it to be moved into the experimental apparatus. Also trial moves were performed: the vacuum chamber containing the MgB_2 cylinder was removed from the magnet by a crane with the system connected to the vacuum pumps, and the cold head powered during the test. The trapped field was maintained during removal and return with no detectable field losses [7].

3. Upgrading of the System for Systematic Studies

The feasibility studies on the prototype cylinder provide promising results both for the Field Cooling (FC) and the Zero Field Cooling (ZFC) [7]. Since trapped and shielded fields depend on temperature, more stability of it is required and possibly also lower value for it. Therefore a new cold head is under test (RDK-415D from SHI Gryogenics Group) with a nominal temperature of 40 K (1^{st} stage) and of 4 K (2^{nd} stage).

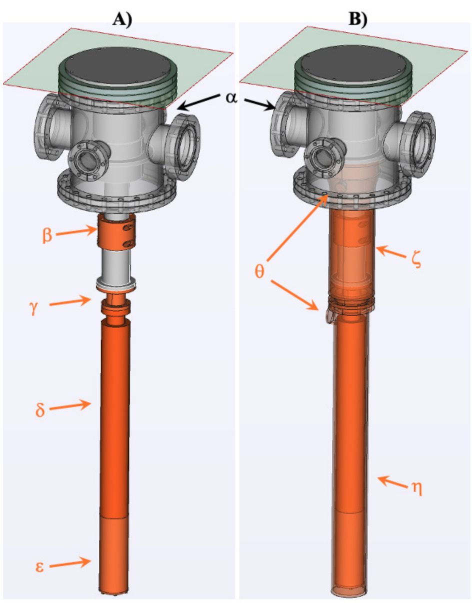

Fig. 5.: Drawing of the upgrading of the connection for the new cold head:
A supplementary chamber has been added (α) connected on the top of the two existing ones.

A) On the 2^{nd} stage:
a new heater (β) is clampled, a new connection (γ) allowing the mounting of the 2^{nd} to the existing copper rod (δ), on the bottom of which the existing sample can (ϵ) is connected.

B) On the 1^{st} stage:
a new top copper shield(ζ) with two ports (θ) only one is visible in the drawing, and a new bottom shield (η) with one port (θ). The ports (θ) allow the passage of wire cabling for the sensors in the sample can (ϵ).

The changes shown in Fig. 5, have been required to match the new cold head to the existing vacuum chamber and to the sample can and copper rod. The copper shield has to be completely changed, and has been designed in two parts (ζ and η in Fig. 5), adding two new access port (θ) on the top shield (ζ) for the cableling of sensors in the sample can.

In addition more sensors are installed inside the cylinder, in order to have measurements of the magnetic field in a radial position in the center of the symmetry axis of it, and on its boundary. A drawing of the sample can (transparent) and the details of the hall probes, their holder, and a supplementary temperature sensor (calibrated Oxford Instruments Cernox [8]) is shown in Fig. 6 and Fig. 7. The Cernox will provide information on the temperature homogeneity on the time needed for the thermalization of the cylinder. The copper cover of the sample can, shown with the bolts in Fig. 7, can be removed with the possibility of exchanging cylinders without removing the delicate connections of the Hall probes and the Cernox. Moreover, it has been shown that the size of the boron powder used for the synthesis of MgB_2 affects its properties [6, 9], in particular the critical current density and the trapped field value [10]. Therefore, we will investigate the trapping and shielding performance of newly produced MgB_2 cylinders as a function of the boron powder granularity.

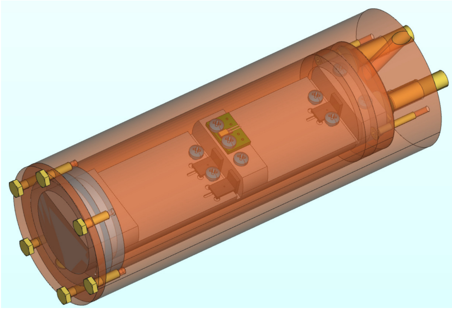

Fig. 6.: Drawing of the sample can (transparent), containing the MgB_2 (transparent), which in turn contain the Hall probe holder, which is detailed Fig. 7 on the side.

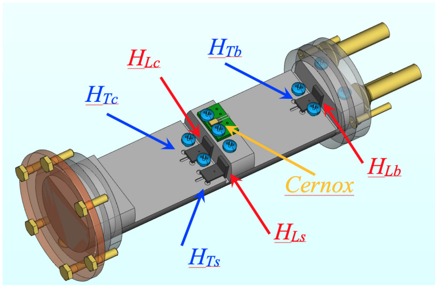

Fig. 7.: Cernox and Hall probes, the labels mean: *H* "*Hall probe*", *T* "*Tranverse*" field, *L* "*Longitudinal*" field, *c* "*central*" position, *s* "*side*" position, *b* on the "*boundary*".

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