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A versatile bulk superconducting MgB_2 cylinder for polarized targets and nuclear fusion fuels

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The production and maintenance of an internal magnetic field in a compact space is a challenging problem, and a versatile solution is being pursued. This is based on the property of a bulk hollow superconductor to trap a magnetic field inside it, that is very interesting for fundamental physics and industrial applications too. Our goals are to provide an intense magnetic field in a small region. Compactness, transportability, no power connections, capability of maintaining a high magnetic field and shielding surrounding magnetic fields are the most attracting characteristics of a MgB_2 bulk. A preliminary feasibility study on a test cylinder showed very promising results. We are upgrading the system for better controls and systematic studies of the required material and geometry for application in transverse polarized nuclear targets for fundamental physics investigations, and for the proposal of polarized nuclear fuel for test in fusion facilities.

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1. Introduction

Polarized nuclear substances require proper magnetic field in order to maintain their magnetization. For this contribution the main purposes are in the field of spin effects studies in nuclear and subnuclear physics,[1] and also for polarized fuel in fusion tests.[2] Hollow bulk superconductors can host inside them polarized substances, providing the required holding fields and simultaneously shielding external fields.[3, 4] This feature is an important improvement with respect to a conventional coil–based solution, because it includes minimal space needed to fit in the experimental environments, maximal field compactness, absence of heat load from current leads, and 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 environments, which can be also exploited for the MgB_2 cooling requirement.

Finally, the system can be moved from the preparation site and transported to the experiments, or to the test facilities. The MgB_2, as a superconductor, has suitable values of critical current, critical field, critical temperature T_c=39 K, and workability.[5]

2. Preliminary test on an MgB_2 test cylinder and system commissioning

A preliminary feasibility study has been performed building a dedicated apparatus shown in Fig. 1.[6] For the commissioning of the system a test cylinder of MgB_2 was used, 97 mm long with an outer diameter of 39 mm and a nominal thickness of two mm, which tapers at the edges to one mm. The cylinder was produced by the Reactive Liquid Infiltration (RLI) process.[5]

A detailed description with the results of the preliminary measurements has been published.[6] In the following, a brief description of the main components of the commissioning apparatus is reported, as a starting point for the recent upgrading. – *The mechanical refrigerator*: the superconducting cylinder was cooled by a cold–head (Edwards 6/30). The lowest temperature reached was 11.1 ± 0.1 K, but a stable operational temperature was usually ≈ 13 K. The cylinder temperature is controlled by a resistive heater, clamped on the 2nd stage of the cold–head, and a CLTS-2B temperature sensor(Micro–Measurements) glued on it, both managed by an Oxford Instruments ITC-503S.[7] – *The external magnet*: an old VARIAN electromagnet (model V3603), nominal maximum current of 180 A, powered by 110 A power supply (Agilent 6692A), remotely controlled via a GPIB interface, provides a maximum field of 980 mT, as measured in the middle of the poles by a Hall sensor (Arepoc HHP-NU), installed inside the cylinder. – *The vacuum system*: the vacuum system consists of two cylindrical chambers, in stainless steel and in aluminum (5A and 5B in Fig. 1). The stainless chamber, 5B, has a DN100CF flange on the top for the cold–head, and on the side a DN63CF for a turbo pump (Agilent Turbo-V 81-M), backed by a scroll pump (Varian SH110) and two DN40CF flanges: 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 cylinder holder ("cylinder–can"), fixed on the copper rod, which is in turn connected to the 2nd stage (10 K nominal temperature) of the cold–head. Surrounding this is a three mm thick cylindrical copper thermal shield, connected to the 1st stage

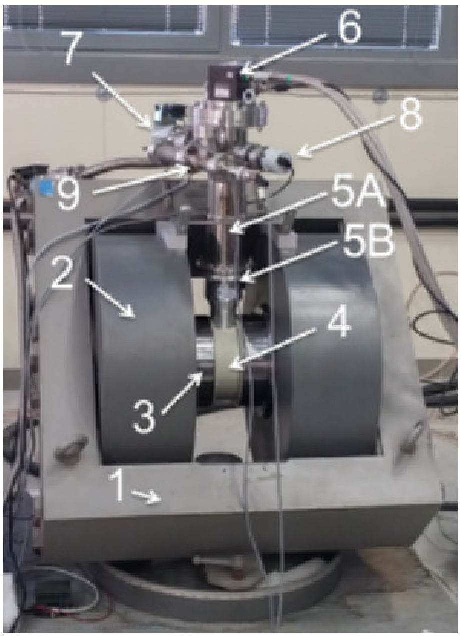

Figure 1: Picture of the overview of the setup. Magnet: iron yoke (1), coils (2), iron poles (3). In a nylon support (4), fixed to the poles, the bottom aluminum chamber (5B) of the vacuum system is inserted, connected to a stainless steel chamber (5A) fixed to the yoke thanks to two arms, on which a 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).

(77 K nominal temperature). Thin indium foils were used in all thermal joints, taking accurate care on good contacts along the 1^{st} and 2^{nd} stage. The aluminum chamber has an outer diameter of 70 mm and a wall thickness of 3 mm; to thermally insulate the copper shielding from it, we use sets of strips, made with three, or more, layers of Myoflex,[7] wrapped around the 62 mm diameter copper shield. Two set of strips, about 2 cm wide, were wrapped around the cylinder–can and the copper–rod extension of the 2^{nd} stage, 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. – *The control and the data acquisition*: LabView and C routines are used to control the heater via the Oxford ITC-503S, to monitor and record the temperature below the cylinder–can, to control and record the power supply of the external magnet, to readout and record pressure values (via the Pfeiffer TPG256A multigauge), to read out the temperature sensor resistances (via the Keithley 199 System DMM/Scanner), and the magnetic fields (via the Arepoc USB2AD controller). – *Thermal cycle*: about 7.5 h are required to cool from room temperature ($\approx$ 297 K) to about 13 K. This process is monitored by the RhFe sensor in contact with the bottom side of the cylinder–can. Using the cold–head heater at full power (65 W), it takes about one hour to heat the cylinder–can to 60 K, which is done after each test to ensure a complete transition of the MgB_2 cylinder from the superconductive to the normal state before the next cool down and test. The trapped field disappears at T_c. One and a half hours are needed to cool back to about 13 K, usually before ramping down, or up, the magnet, we wait at least one hour at the lowest temperature.

2.1 Results of the feasibility study under commissioning

Although a test MgB_2 cylinder was used, the results were promising. – *The cylinder magnetization* is obtained via the so called Field Cooling (FC) process, which implies that the cylinder is cooled below T_c ($\approx$ 39 K) in presence of an applied external magnetic field B_{ext}. After the system is stable at the minimum, or chosen, temperature ($\approx$ 13 K, or higher) B_{ext} is ramped to zero, while the trapped field B_{trapp} of the MgB_2 cylinder is measured. We obtained B_{trapp}=942 ± 1 mT at our minimum operational temperature ($\approx$ 13 K), applying B_{ext}=980 mT. The performances for various temperatures have been published.[6] B_{trapp} can be preserved for days, unless a temperature spike recorded by RhFe sensor, due to instabilities in the cold–head, destroys it. This problem motivates the choice of a better cooling system, because the spike reduces the performance of the cylinder, and does not allow to pursue systematic studies. – *The magnetic field shielding* is obtained by the so called Zero Field Cooling (ZFC) process, which requires to cool down the cylinder below T_c and then to apply B_{ext}, by ramping the magnet up to B_{ext}=980 mT. The cylinder is able to almost completely shield B_{ext}, as just a small residual magnetic field was detected inside it.[6] The ZFC processes showed higher sensitivity to the spike problems than the FC processes. – *Moving the MgB_2 cylinder*: the planned scheme for using an MgB_2 cylinder as magnetic field generator and magnetic shield, after its preparation, requires it to be moved into the experimental apparatus. 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.[6]

3. Upgrading of the preliminary system for systematic studies

The feasibility studies on the test cylinder provided promising results both for FC and ZFC procedures.[6] With the purpose of pursuing systematic studies, as a result we improved various components of the feasibility system (Fig. 1), following the knowledge acquired in its commissioning, and, in addition, having at disposal some cylinders with known production procedures. The geometry of the cylinders is close to the tested one, and produced using boron powders with different grain sizes. Cylinders were labeled as P40, P100, P160, since the grain size was smaller than 40 µm, 100 µm and 160 µm respectively. As documented in a review publication[9] of the inventor of the RLI production technique of the cylinders, the stability properties and super–currents are connected to the grain size: roughly the lower the grain size of the boron precursor, the better the transport performances, but the worse the stability.

We need to test the performances of the MgB_2 bulk cylinders accurately for nuclear target applications, knowing, not only the field in the center, but also along the radial coordinate, and along the axial coordinate in the middle and at the edge of the cylinder, in order to estimate the homogeneity in the region, where the target might be hosted inside the cylinder itself. In addition of more Hall probes installed in the inner space of the cylinder, the FC and ZFC processes depend on temperature, therefore we implement a read out of the temperature inside the cylinder too, useful also for the correction of Hall sensor sensitivity, which is temperature dependent too. The heart of the upgrading consists mainly in: a new–cold head (Fig. 2), a new sensors' holder (Fig. 3), which will be installed inside the cylinder, and a new mechanical design, which allows to easily exchange the cylinders.

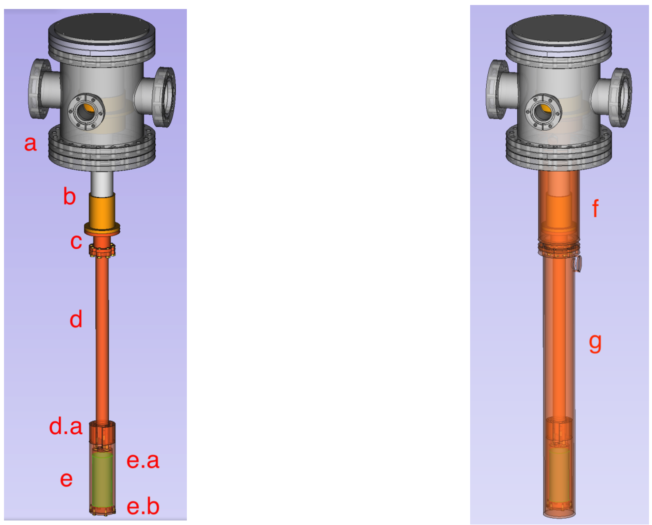

Figure 2: Drawing of the upgrading of the cold–head to match the system of Fig. 1 for systematic studies. Left side picture: a – supplementary chamber has been added connected on the the top flange 5A in Fig. 1; b – new cold–head (1^{st} stage in transparence, 2^{nd} stage visible); c – adapter for the new cold–head to the previous extension; d – new extension: d.a – heater pits machined directly on the extension; e – cylinder–can, e.a – cylinder; e.b – bolts for removing the bottom cover of the cylinder-can, for the exchanging the cylinder. Right side picture: f – top part of the thermal shield connected to the 1^{st} stage; g – bottom part of the shield.

The improvements following the previous description are listed in same order: – *The mechanical refrigerator*: a new cold–head (RDK-415D from SHI Gryogenics Group) is installed, with a nominal temperature of 40 K (1^{st} stage for 35 W of heating power) and of 4 K (2^{nd} stage for 1.5 W of heating power). – *The external magnet*: a new supply, 200 A / 50 V (CAEN-OCEM model NGPS 200-50 Enhanced), controlled via a LAN connection, allows us to feed the maximum current supported by the magnet up to 168 A, providing a field of 1 200 mT. – *The vacuum system*: in order to host the new cold–head a new stainless steel chamber (a in Fig. 2) has been installed, hosting two DN63CF and two DN40CF flanges, for servicing the connections for the new sensors. The chamber is connected to the previous upper stainless steel chamber (5A in Fig. 1) and host the new cold–head on the top flange. The wire connections for the magnetic field and the temperature sensors are connected on Sub-D-15 DN40CF feedthrough fixed on the servicing flanges of the new chamber (a in Fig. 2). The previous vacuum system remains unchanged. For the exchanging of the cylinder we remove the new chamber, which hosts the cold–head and all connections for the sensors (Fig. 2). We remove the thermal shielding (f and g), open the bottom cover (e.b), remove the installed cylinder (e.a) and install the new one. – *Temperature measurements*: the temperature is monitored by the same calibrated rhodium–iron (RhFe) sensor fixed below the bottom cover (e.b in Fig. 2) of the cylinder–can, and by the new calibrated cernox sensor, installed on the sensors' holder (Fig. 3). The hall probe sensitivity is affected by the temperature, therefore the knowledge of the temperatures of the sensors' holder allows corrections with respect to the calibrated data (given for 297 K). – *Control and data acquisition*: the labview and C–routines are upgraded to control and read the new sensors, we add new temperature sensors on the Keithley 199 System DMM/Scanner, and the new hall probes on the Arepoc USB2AD controller. For distinguishing the Hall probes we use in subscript acronyms, indicating probe positions and magnetic fields measured: the first letter indicates the position along the axial coordinate (middle, or edge), the second one indicates the position with respect to the radial coordinate (center, or radial), the last one indicates the orientation of measured magnetic field (longitudinal, or transverse) with respect to the axial coordinate as shown in Fig. 3.

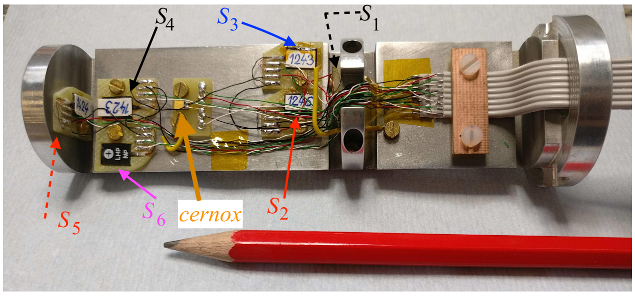

Figure 3: The new sensors' holder for the temperature sensor (cernox) and the magnetic field sensors (Hall probe). $S1_{\mathrm{mcl}}$–middle center longitudinal, $S2_{\mathrm{mct}}$–middle center transversal, $S3_{\mathrm{mrt}}$–middle radial transverse, $S4_{\mathrm{ect}}$–edge center transverse, $S5_{\mathrm{ecl}}$–edge center longitudinal, $S6_{\mathrm{ert}}$–edge radial transverse.

3.1 Commissioning of the upgraded system

As a new result of using the new cold–head, cooling down from room temperature ($\approx$ 297 K), we reach a temperature on the RhFe sensor $T_{RhFe} \leq 8$ K $\pm$ 0.1 K in 3.5 h, and on the cernox sensor $T_{cernox} \leq 15$ K $\pm$ 0.1 K in 5.5 h, faster than before, and with the evidence of the presence of thermal equilibrium also inside the cylinder.

The new heaters hosted in pits (d.a in Fig. 2), machined directly on the extension of the 2$^{\mathrm{nd}}$ stage, with a CLTS sensor on it for its control and monitoring by the Oxford Instruments ITC-503S.[7], give us a better and more comfortable control on the temperature and reduce drastically the time required for heating the cylinder and bringing it back at the required working temperature. As a result, we can study the behavior of the cylinder as a function of the temperature, as shown in Fig. 4, where without power on the heaters, we recorded three flux jumps.

We performed measurements setting the heater temperature at 9 K, 11 K, 13 K and then 15 K, before preventing the flux jumps. And in Fig. 5 we report the last measurements where flux jumps are not present and the penetrating field is lower, showing a better performance of shielding. In conclusion, the system is well tuned for the investigation on the characteristics of the available cylinders, or on other ones produced after our accurate investigations of their performances, which allow us to provide answers on the requirements for the applications in our research interests.

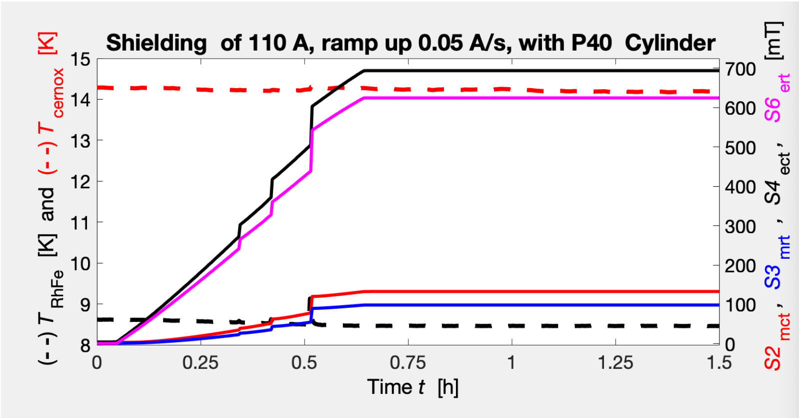

Figure 4: Ramp up of the magnet after ZFC: magnetic field values (continuous lines) and temperature values (dashed lines).

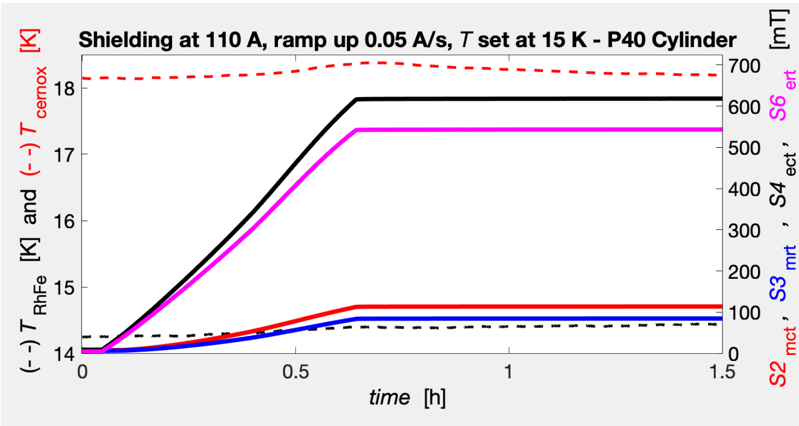

Figure 5: Ramp up of the magnet after ZFC. The penetrating field values are smaller than those in Fig. 4.

References

[1] D. Carman *et al*. Nucl. Instr. Meth. A **967** (2020) 163898.

[2] R. Engels *et al*. Phys. Rev. Lett. **124** (2020) 113003.

[3] D. Frankel *et al*. IEEE Trans. Magn. **15** (1979) 1349.

[4] J. F. Fagnard, *et al*. Supercond. Sci. Technol. **25** (2012) 104006.

[5] J. J. Rabbers *et al*. Supercond. Sci. Technol. 23 (2010) 125003.

[6] M. Statera *et al*. Nucl. Instr. Meth. A **882** (2018) 17.

[7] Oxford Instruments Direct Cryospares – *www.cryospares.co.uk*.

[8] G. Giunchi *et al*. Int. J. Mod. Phys. B **17** (2003) 453.

[9] G. Giunchi in *MgB_2 Superconducting Wires: Basics and Applications* edited by R. Flükiger (World Scientific, 2016, Singapore).