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A facility for testing bulk superconducting hollow MgB_2 cylinders for the production and shielding of magnetic fields for polarized targets and nuclear fusion fuels

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The challenging magnetic problem of producing internal fields in compact spaces can be solved by high temperature superconducting bulk materials, such as MgB_2, promising tools for trapping magnetic fields around polarized substances, while excluding external fields, as required for fundamental physics studies in scattering experiments. They are also of great interests, as they allow to easily generate holding fields for accumulation and transport of polarized fuel in nuclear fusion tests. A facility has been commissioned, which allows to control the bulk superconductor temperature down to 8 K with to a cold head, driven by a helium compressor, thus satisfying eco-sustainability requirements. The facility is able to test various superconducting hollow MgB_2 cylinders, each sintered starting from boron powders having different grain sizes, and it allows to measure the holding and shielding capabilities, together with the corresponding long–term stability. The facility is equipped to map the trapped fields, inside the cylinder along the symmetry axis and radially, as a function of both the temperature and the applied magnetic field. The measurements have been performed in transverse magnetic fields up to 1.2 T, limited by to the available magnet in our lab. After its preparation for transverse field generation, the sample can be moved into longitudinal magnetic fields, shielding the latter, while still keeping the former fields. In the context of an electron scattering experiment, such a solution minimizes beam deflection and the energy loss of reaction products, while also eliminating the heat load to the target cryostat from current leads that would be used with conventional 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 it can provide the holding field for its transfer in fusion test facilities.

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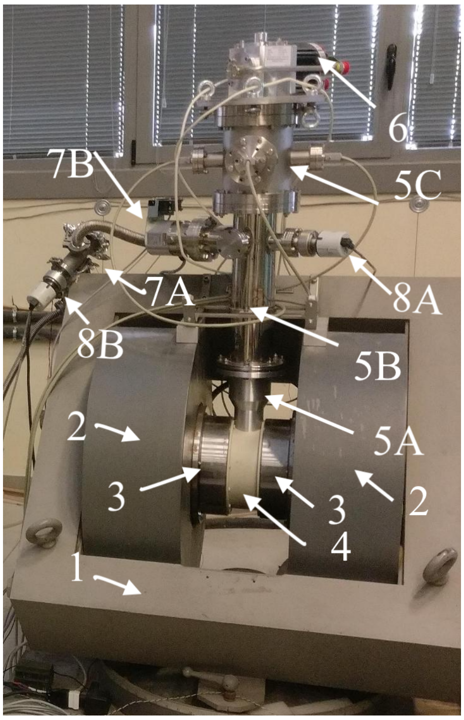

Figure 1: Picture of the setup. Magnet: iron yoke (1), coils (2), iron poles (3), nylon support (4), fixed to the poles, inside the bottom aluminum chamber (5A) of the vacuum system, connected to a stainless steel chamber (5B) fixed to the yoke thanks to two arms. On the 5B chamber another stainless still chamber (5C) is connect, on the top of which a cold–head (6) is fixed. Two turbomolecular pump (7A-7B) are connected in cascade. Two penning gauges (8A-8B) monitor respectively the vacuum in the chamber 5B and on the back of the turbo 7B. There various servicing feedthroughs for Hall, pressure and temperature sensors.

1. Introduction

Polarized nuclear substances require proper magnetic fields 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 house 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 requires minimal space 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, 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 experiments, or test facilities. The MgB_2, as a superconductor, has suitable values of critical current, critical field, critical temperature (T_c=39 K), and machinability [5].

2. Characterization system for MgB_2 hollow cylinders

A preliminary feasibility study was performed [6], with test MgB_2 bulk hollow cylinders, produced by the Reactive Liquid Infiltration (RLI) process [5]. From the experience gained on this preliminary study a facility for systematic studies of similar geometries but of different production procedures, has been designed and commissioned and shown in Fig. 1 [7].

In this contribution the essential information is reported for understanding preliminary results obtained and still under systematic studies and investigations. The present facility can be summarized as in the following:

– *Cryogenic unit*: a cold–head (SHI-Sumimoto RDE-418D4, 6 in Fig. 1), borrowed from our colleagues [8], driven by its helium compressor (F–50H), with nominal cooling power and temperature respectively on first stage of 42 W and 40 K, and on the second stage of 1.8 W and 4 K, which allows us to cool down to ≈ 8 K the cylinder holding can (cylinder–can e in Fig. 2) .

– *Magnet*: an old VARIAN copper, normal conducting electromagnet (model V3603) is powered with a 200 A / 50 V (CAEN-OCEM model NGPS 200-50 Enhanced), which is controlled via a LAN connection. At the maximum allowed current for the magnet (168 A), we measured a magnetic field up to 1.2 T in the middle of the poles by a Hall sensor (Arepoc HHP-NU).

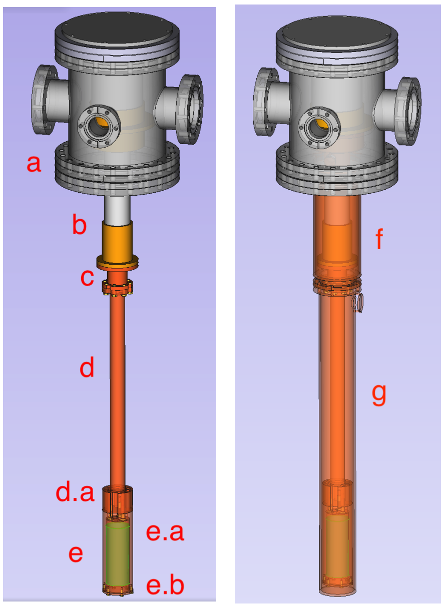

Figure 2: Drawing of the 5C, which can be disconnected from the 5B chamber of Fig. 1, keeping in vacuum connections.

Left side picture:
a – supplementary chamber 5C hosting cold head and sensors connections;
b – new cold–head (1st stage in transparence, 2nd stage visible);
c – copper adapter for the new cold–head to the previous extension;
d – copper new extension: d.a – heater pits machined directly on the extension;
e – copper cylinder–can, e.a – MgB_2 hollow cylinder; e.b – brass bolts for removing the bottom cover of the cylinder–can, for exchanging cylinders.

Right side picture:
f – top part of the copper thermal shield connected to the 1st stage;
g – bottom part of the copper thermal shield.

– *Vacuum system*: the vacuum system consists of three cylindrical chambers, starting from the bottom one (5A in Fig. 1) in aluminum, and other two (5B and 5C) in stainless steel. The aluminum chamber has an outer diameter of 70 mm and a wall thickness of 3 mm; to thermally insulate the copper shielding (g in Fig. 2) from aluminum chamber, we use sets of strips, made with three, or more, layers of Myoflex [9], wrapped around the 62 mm diameter bottom copper shield (g in Fig. 2) Two set of strips, about 2 cm wide, were wrapped around the cylinder–can (e in Fig. 2) for its insulation from the copper thermal shield (g in Fig. 2).

The stainless steel chamber 5B hosts the vacuum sensor (a Penning cold cathode gauge), a turbo (80 l s^{-1} of pumping speed), backed by another turbo pump (70 l s^{-1} of pumping speed), in turn backed by a dry scroll pump. The stainless steel 5C chamber hosts the cold–head and the wire connections for the read–out of magnetic field and of the temperature sensors through Sub–D–15 DN40CF feedthroughs (Fig. 1).

– *Inner parts of vacuum system*: for the exchanging of the cylinder the chamber 5C, can be removed with a crane, keeping 5B and 5A chambers (Fig. 1) fixed on the magnet support. Then it is possible to remove the bottom copper thermal shielding (g in Fig. 2), open the bottom copper cover (e.b), remove the installed cylinder (e.a), and insert another one to be characterized.

The MgB_2 cylinder fits in the holder ("cylinder–can") and inside it the aluminum sensors' holder fits, which hosts sensors for the magnetic field and temperature measurements, as shown in Fig. 3.

The pressure stays below 10^{-6} mbar at room temperature, and reaches 10^{-8} mbar, when the cold–head is at the minimum temperature.

– *Field and temperature monitoring and measurements*: the heart of the system is show in Fig. 3.

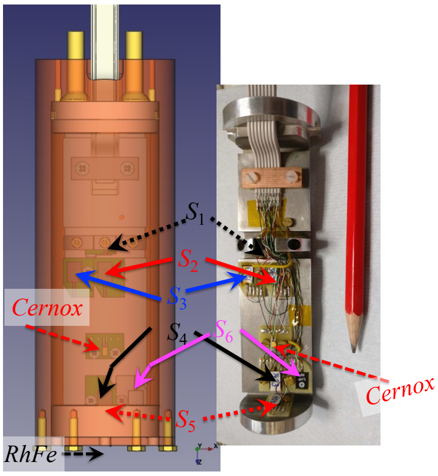

Figure 3: The new sensors' holder for the temperature sensor (cernox) and the magnetic field sensors (Hall probe) and line used in the plots.

Temperature sensors:

(- - -) T_{RhFe} Temperature read by the Rhodium Iron,

(- - -) $T_{C.ox}$ Temperature read by the Cernox,

Hall Sensors:

(· · ·) S_{1mcl} middle center longitudinal,

(——) S_{2mct} middle center transverse,

(——) S_{3mrt} middle radial transverse,

(——) S_{4ect} edge center transverse,

(· · ·) S_{5ecl} edge center longitudinal,

(· · ·) S_{6ert} edge radial transverse.

The sensors' holder is fixed on the cylinder–can, which is screwed on the heater (d.a in Fig. 2) and stays inside the hollow MgB_2 cylinder, when it is installed, just sliding it in the cylinder–can. Then copper cover (e.b.) is screwed on it, on the bottom of whom a calibrated rhodium–iron (RhFe) sensor (Oxford Instruments), glued on a thin copper–slice, is fixed with two of the six M5 brass bolts, shown on the bottom of the left picture in Fig. 3. The Cernox (Oxford Instruments) temperature sensor, is installed inside the cylinder on the holder of sensors. We observed heating power released on the sensor holder, induced from the powering of the sensors, therefore we use for it aluminum, in order to have a better thermal conductivity between the holder of the sensors and the sample–can.

– *Control and data acquisition*: LabView C routines and Bash scripts are used to pilot the Oxford ITC-503S heater controller, to control and record the power supply of the external magnet, to readout and record pressure values, via a multigauge controller (TPG256A from Pfeiffer–Balzers), to measure temperature sensor resistances via the well known technique of four wires through a multimeter scanner (Keithley 199 System DMM/Scanner), and acquire magnetic fields via a module (Arepoc USB2AD controller), capable of powering and control six Hall probes.

– *Thermal cycle*: with the upgraded system we have decreased the mass of copper–rod, connected to the 2nd stage, by reducing its diameter from 50 mm to 25 mm, (d in Fig. 2), from the flange, required for the connection to the adapter for the new cold–head, to the bottom part (d_2 in Fig. 2), which remain at 50 mm in diameter, in order to drill pits and host in them cartridge heaters. As a result we reduced the time to cool down the system from room temperature to the minimum temperature (~ 8 K), recorded by RhFe sensor in three and a half hours. In the upgraded system we gain also a better control on the thermalization of the whole system, thanks to the Cernox temperature sensor, mounted inside the cylinder on the sensors' holder, about one additional hour is required to reach the lower temperature (13 K), recorded inside the cylinder, and then start the ramping of the magnet for magnetization, or shielding, measurements. The time required to heat up over the the critical temperature and come back to the minimum temperature, is less than one hour.

We gain good control and monitoring on overcoming the critical temperature, and on reaching the minimum, or desired, temperature.

3. Methods and measurements

To evaluate both the trapping and the shielding capabilities of the MgB_2 cylinders, we used two different procedures to cool the samples down to T_F (the final lowest temperature, or the one set fixing a proper heating of the cold–head heater), below T_C, the critical temperature.

The first one consists in cooling the cylinder in the presence of an applied magnetic field, B_C. After reaching a stable T_F, the field is slowly reduced to zero. This procedure triggers the generation of super–currents, developing magnetic fields comparable to B_C. This procedure, know as Field–Cooling (FC), in view of our applications and interests, we named simply *magnetization*.

The second one consists in cooling the cylinder with B_C equal to zero. After reaching a stable T_F, the field is slowly increased up to a maximum value. In this case, the super–currents will try to generate a magnetic field, opposed to the external one, thus shielding its presence. This procedure, known as Zero–Field–Cooling (ZFC), we named simply *shielding*.

We can investigate the best working condition as a function of the temperature, which is more stable with fixing a proper heating power, thanks to the ITC-503C temperature controller and ramping rate of the magnet.

We can also check the different behavior with respect to the applied magnetic field, B_C.

We are able then to characterize different production procedures of the cylinders, distinguished by the labels P40, P100 and P160, which means that the boron grain precursor (P) have a maximum size of 40 µm, 100 µm and 160 µm respectively. The original powder size is obtained starting from crystalline boron flakes (99.5 % purity), crushed and sieved respectively to particle sizes $\leq$ 40 µ, $\leq$ 100 µ, and $\leq$ 160 µ. Roughly the smaller the grain size, the greater the transport characteristics, but, on the contrary, the lower the thermal stability as the temperature and magnetic field decrease[11].

After a series of modifications and improvements from the initial design [6], the apparatus has been successfully commissioned [7], and is ready for proper characterization of high temperature superconducting materials in a cylindrical tubular form, which fit the geometry of an inner diameter greater than 30.0 mm, an outer diameter less than 38.7 mm, and a maximum length of 116 mm.

– *Moving the MgB_2 cylinder*: the planned scheme for using a 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]. 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 to more Hall probes installed inside the hollow cylinder, a Cernox temperature sensor is installed on the sensors holder: the FC and ZFC processes depend on temperature, and the Hall sensors sensitivity too.

The heart of the upgrading was mainly: the new–cold head (Fig. 2), the new sensors'–holder (Fig. 3), and a new mechanical design, which allows to easily exchange the cylinders.

Using the new cold–head, cooling down from ≈ 297 K, we reach a temperature on the RhFe sensor $T_{RhFe} \leq 8$ K ± 0.1 K in 3.5 h, and on the cernox sensor $T_{cernox} \leq 15$ K ± 0.1 K in 4.5 h, faster than with the preliminary system [6], and with the control on the thermal equilibrium also inside the cylinder on the sensors' holder.

The new heater cartridges are hosted in pits on the bottom (d.a in Fig. 3) of the 2$^{\mathrm{nd}}$ stage extension, with a CLTS temperature sensor on it for control and monitoring by the Oxford Instruments ITC-503S [9] . This arrangement gives better and more comfortable controls on the temperature, reducing drastically the time required for heating the cylinder and bringing it back to the required working temperature.

Results include evidence from a P40 cylinder of instabilities (known as flux–jumps) as shown in Fig. 4. We can monitor and record simultaneously all the sensors. In the picture we report the transverse sensors' measurements, because we can prepare the cylinder in the transverse magnetic field of 980 mT. In the center of the cylinder the field higher than ≈ 100 mT is penetrating. Increasing the temperature ($T_{\mathrm{RhFe}} \gtrsim 14$ K) as visible from the (- -) T_{RhFe} and (- -) T_{cernox} we can overcome the flux–jump instability having a little better behavior of the shielded magnetic field (Fig. 5).

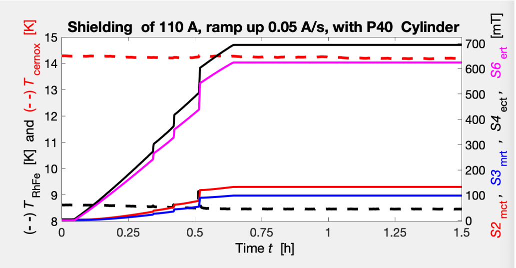

Figure 4: Ramp up of the magnet after ZFC: magnetic field values (continuous lines) and the temperature values (dashed lines) for a P40 Cylinder.

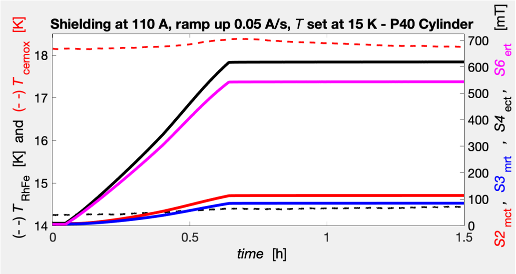

Figure 5: Ramp up of the magnet after ZFC at $T_{\mathrm{RhFe}} \gtrsim 14$ K: penetrating field values smaller than those in Fig. 4.

We got better performance of MgB_2 using P100 hollow cylinder at $T_{\mathrm{RhFe}} \lesssim 16$ K. The autogeneration of magnetic fields is shown in Fig. 6. In this case the cylinder is capable of maintain in its middle 970 mT, when we cooled down with an external field of 980 mT and after the ramping down of the magnet to zero current. For this cylinder we did not observe flux–jumps from our minimum temperature below the cylinder–can($T_{\mathrm{RhFe}} \sim 8$ K).

With the above P100 cylinder we can also keep the field with a very good stability for more than 340 hours (Fig. 7). The measurement just stopped for problem on the cooling water circuit of the cryo–drive.

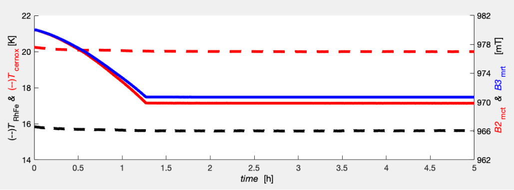

Figure 6: P100 cylinder: ramp down of the magnet after FC: magnetic fields (— lines) and temperatures (- - lines).

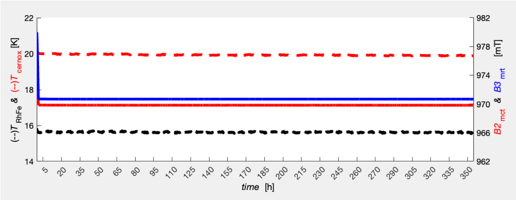

Figure 7: P100 Cylinder: long–term stability after FC preparation of Fig. 6.

The working point at $T_{\mathrm{RhFe}} \lesssim 16$ K is also suitable for the shielding procedure, which shields 970 mT, applying an external field of 980 mT. Also in this case the cylinder is capable of shielding the above fields for 1480 h. We stopped by ourselves the measurements, which is well over the requirement for our purposes.

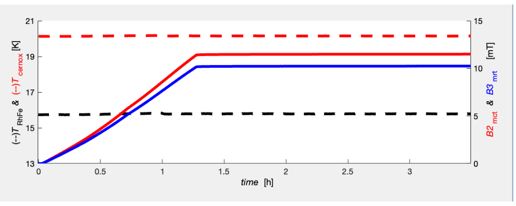

Figure 8: P100 cylinder: ramp up of the magnet after ZFC. Magnetic fields (— lines) and the temperatures (- - lines).

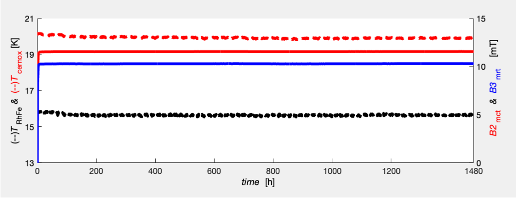

Figure 9: P100 cylinder: ramp up of the magnet after ZFC. Long–term stability after ZFC preparation of Fig. 8.

4. Conclusions

The facility for testing bulk MgB_2 hollow cylinder has been updated and commissioned. We have very nice control on temperature and on the map of the internal magnetic fields. We have the possibility to test different cylinders, P40, P100 and P160, and found good performance for the P100 production procedure.

The facility allow us to test the behavior of the cylinder for its applications on polarized fuels and nuclear polarized targets, providing specific characterization on various parameters: production procedure, temperatures, applied magnetic fields, ramping speeds and long–term stabilities. We can perform specific and systematic measurements and provide also the field map inside cylinders.

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