Published in final edited form as:

Physica C Supercond. 2013 March 15; 486: 26–31. doi:10.1016/j.physc.2012.12.013.

Field performance of a prototype compact YBCO “annulus” magnet for micro-NMR spectroscopy

Blair Gagnon, Seungyong Hahn*, Dong Keun Park, John Voccio, Kwangmin Kim, Juan Bascuñán, and Yukikazu Iwasa

Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Abstract

A prototype compact annulus YBCO magnet (YP1070) for micro-NMR spectroscopy was constructed and tested at 77 K and 4.2 K. This paper, for the first time, presents comparison of the 77-K and 4.2-K test results of our annulus magnet. With a 26-mm cold bore, YP1070 was comprised of a stack of 1070 thin YBCO plates, 80- μ m thick and either 40-mm or 46-mm square. After 1070 YBCO plates were stacked “optimally” in 214 groups of 5-plate modules, YP1070 was “field-cooled” at 77 K after being immersed in a bath of liquid nitrogen (LN₂) with background fields of 0.3 and 1 T and also at 4.2 K in a bath of liquid helium (LHe) with background fields of 2.8 and 5 T. In each test, three key NMR magnet field-performance parameters—trapped field strength, spatial field homogeneity, and temporal stability—were measured. At 4.2 K, a maximum peak trapped field of 4.0 T, equivalent to 170 MHz ¹H NMR frequency, was achieved with a field homogeneity, within a $|z| < 2.5$ mm axial space, of ~3000 ppm. YP1070 achieved its best field homogeneity of 182 ppm, though at a reduced trapped field of 2.75 T (117 MHz). The peak trapped fields at 4.2 K were generally ~10 times larger than those at 77 K, in direct proportion to ~10-fold enhancement in superconducting current-carrying capacity of YBCO from 77 to 4.2 K. Temporal stabilities of ~110 and ~17,500 ppm/h measured at 77 K, with trapped fields respectively of 0.3 and 1 T, show that temporal stability deteriorates with trapped field strength. Also, temporal enhancement of trapped fields at 4.2 K was observed and reported here for the first time.

Keywords

Compact annulus magnet; Micro-NMR spectroscopy; Spatial homogeneity; Temporal stability; Trapped field; YBCO plate

1. Introduction

As NMR (Nuclear Magnetic Resonance) applications expand widely, NMR magnets of standard RT (Room-Temperature) bore, 54 mm or even greater, may not be ideal—in terms of cost, space, and ease of operation—for “micro-NMR spectroscopy” in which chemical

*Corresponding author. Address: MIT-FBML, BLDG NW14-3209, 170 Albany Street, Cambridge, MA 02139, USA. Tel.: +1 617 253 4161; fax: +1 617 253 5405. syhahn@mit.edu (S. Hahn).

and biological sample sizes are less than 10 μl [1–3]. Therefore, there are economic, technical, and logistical incentives to develop compact NMR magnets with a RT bore size much less than the standard 54 mm, catered to this rapidly growing field of micro-NMR spectroscopy. Currently, all commercially available NMR magnets are wound with Low Temperature Superconducting (LTS) wires, NbTi and Nb₃Sn. However, the large magnetic foot-print, high magnet cost, and expensive liquid helium (LHe) requirement for cooling have kept all-LTS NMR magnets from being easily accessible for small-scale research institutes. Although High Temperature Superconducting (HTS) wires that can carry substantial amounts of current at temperatures beyond the range of LTS wires (>10 K) may provide an ultimate solution for “helium-free” NMR magnets, to date HTS have been applied only to >23 -T NMR magnets [4–6], in part because no techniques, with the exception of MgB₂ [7,8], have been developed to make HTS superconducting joints, thereby making persistent-mode HTS magnets unfeasible.

Recently, a new type of “annulus” NMR magnet comprised of a stack of HTS bulk and/or plate annuli has been proposed and is currently being developed [9–12]. Key benefits of the new HTS annulus magnet include: (1) compactness that enables a small footprint, magnetic as well as physical; (2) LHe-free operation that leads to significant reduction of operation cost; and (3) intrinsic persistent-mode operation that eliminates the need of current leads and consequently makes the entire magnet system very simple. Since 2009, we have been engaged in a 2-phase program whose ultimate target is to design, construct, and test a 300-MHz/38-mm RT bore compact NMR magnet for micro-NMR spectroscopy. Currently Phase 1 is in progress to complete a prototype 100–200 MHz/9 mm magnet. The key components include: (1) an annulus magnet comprised of a stack of thin YBCO “square annulus” plates, manufactured by American Superconductor Corporation (AMSC) and/or YBCO bulk (~ 10 mm thick) annuli prepared by Japan Railway Technical Research Institute; and (2) a volume of solid nitrogen nominally at 10 K that surrounds the annulus magnet [9,13]. The “trapped” field is induced in the annuli assembly by a process generally known as field cooling (FC), in which a portion of the field generated by a background magnet is “trapped” by the superconducting annulus magnet as the background field is decreased to zero. Currently in Phase 1 of this 2-phase project, a prototype 100–200 MHz/9 mm bore magnet is being constructed. Previously, we have constructed and tested a pilot magnet, YP750, consisting of 750 plates, each 40-mm square and 80- μm thick with a 26-mm center hole [13]. Since then, additional YBCO plates were received and, combined with the plates used in YP750, a new annulus magnet, YP1070, consisting of 1070 plates (but no bulk annuli) has been constructed and tested at 4.2 K in a bath of LHe as well as at 77 K in a bath of LN₂. This paper presents experimental results that include construction (key parameters of the plates, module test, stacking optimization, and final assembly), tests (setup, measurement technique and procedure), results (trapped field, spatial homogeneity, and temporal stability measured at 77 and 4.2 K) and discussion.

2. Construction of YP1070

2.1. Comparison between old and new plates

Table 1 presents key parameters of the old (from YP750) [13]) and new plates. The YBCO plates were cut originally from the AMSC coated conductor. Therefore, the critical current of the YBCO plates is anisotropic; the longitudinal critical current, J_{cl} is ~20% larger than the transverse critical current, J_{ct} as seen in Table 1. To mitigate this anisotropy, each plate is stacked in an orthogonal way [5], i.e., aligning the longitudinal and transverse plate directions in an alternating repeating pattern during the stacking. The new plates, having an improved average critical current density compared with that of the old ones, are 46-mm square with the same overall thickness, 80 μm , and center bore diameter, 26 mm [13]. The enlarged size and improved critical current density have resulted in a higher trapped field in these plates. Fig. 1 is a photograph of both a 40-mm plate and a 46-mm plate placed next to each other. Fig. 2 displays an example of the trapped fields of the old and the new single plate within an 8 mm $\times$ 8 mm field-scan area in the center of the 26-mm bore measured at 1 mm above the surface of each plate. The procedure and field measurement technique for this scan is described later in the paper. On average, the trapped fields of the new plates increased by ~50%.

To compare the trapped field performance between square and circular plates, the four edges of selected “square” annuli were trimmed to form “circular” annuli. Fig. 3 presents trapped field scans measured at 1 mm above each plate, (a) square (before trimming) and (b) circular (after trimming). In general, the trapped field strengths of “circular” annuli were only ~60% of those of “square” annuli while the difference in field homogeneity between them is not significant. To obtain higher trapped fields, we decided to use square annuli rather than circular ones.

2.2. Module test and optimization

To obtain the largest field strength and best homogeneity, we optimized the stacking order of each plate in YP1070 in three steps. First, we grouped the new plates randomly into 5-plate modules. Second, we measured the trapped fields of the 64 new 5-plate modules using a specially designed module test tool of <1% measurement uncertainty [13]. Finally, we stacked 214 modules (the new 64 plus the old 150 YP750 modules) from the midplane (axial center of the stack), placing the largest trapped field modules at the midplane and progressively smaller trapped field modules away from the center, while maintaining axial field symmetry about the midplane, with the smallest trapped field modules at the ends of the stack.

The module test procedure is as follows: (1) place the LN_2 container, including a test module at a fixed position, above the Nd-Fe-B cylindrical permanent magnet ($\varnothing$ 63.5 mm $\times$ 12.7-mm thick, surface field: 0.25 T) – the module is still at room temperature; (2) fill LN_2 into the container, turning the module superconducting; (3) with the module at 77 K and now superconducting, lift the container from the permanent magnet, inducing a trapped field in the module (this process of decreasing field in the module is known as field-cooling, FC); and (4) wait 5 min after the conclusion of the FC process and measure the trapped field with

a Hall sensor. Fig. 4 presents 214 5-plate modules in descending order of trapped field, with Module 1 assigned the maximum trapped field and Module 214 assigned the minimum trapped field. There are 150 modules of 40-mm plates and 64 modules of 46-mm plates.

2.3. Final assembly of YP1070

Fig. 5 presents an axial center trapped field vs. axial position plot for YP1070 comprising 214 modules of the field range 3–21 mT, which was measured at 77 K. The location of each module in YP1070 was assigned in descending order of its center trapped field away in both positive and negative axial directions from the midplane (axial center). This was to maximize not only the mid-plane field strength but also the axial symmetry about the mid-plane. Table 2 presents the key parameters of YP1070.

3. Test of YP1070

3.1. Test setup

A 5-T conduction-cooled all-LTS background magnet having a 300-mm RT bore was used for field cooling YP1070 both at 77 K (LN₂) and 4.2 K (LHe). The field homogeneity of the LTS magnet within a 6-cm DSV (Diameter Spherical Volume) is 1.2%. Key parameters of the background magnet are summarized in Table 3 together with those of a 3-D field mapper used for 2-D *X–Y* and axial field scans of the LN₂ tests where a Styrofoam container was used to house a volume of LN₂ and provide open access for the field mapper. For axial field measurement along its axis, YP1070 was placed in a 9-mm RT bore LHe cryostat; no 2-D *X–Y* scans were taken in the LHe tests. Fig. 6a presents a close-up view of YP1070. measurements of which overall uncertainty was less than 1% [14].

3.2. Test procedure

The following is a generalized procedure for an FC test of YP1070.

- i. Place YP1070 in its Styrofoam container for the LN₂ tests; in a custom-made cryostat for the LHe tests. In either measurement, the cryogen holder is in the RT bore of a background magnet.
- ii. Align the midplane of YP1070 to that of the background magnet.
- iii. With YP1070 still at room temperature, energize the magnet to a target (field-cooling) field.
- iv. Fill the cryogen (LN₂ or LHe) either into the LN₂ container or the LHe cryostat. At either temperature YP1070 is fully superconducting. After waiting for >30 min to establish thermal equilibrium within YP1070, decrease the background field slowly, at a rate of #1 mT/s, to zero. This field-cooling (FC) process creates a trapped field in YP1070.
- v. Because a trapped field decays logarithmically in time, set time to zero at the moment when the FC process is done and the trapped field is largest. Mark the time for each sub-sequent field measurement to this reference point.

- vi. For LN_2 tests, using the 3-D field mapper, measure the axial (z : magnet axis) and radial (X – Y) fields.
- vii. Follow this field mapping with field-decay measurements of the trapped field at the midplane for a period of 0.5–2 h. For LHe tests, map only the axial field, followed by trapped field decay measurements lasting 2–14 h.

A greater FC field has an advantage and disadvantages on trapped field, observed experimentally with 77 and 4.2 K tests. The advantage is a greater “final” trapped field—note that the initial trapped field decays with time. The disadvantages are diminished field homogeneity and temporal stability. The diminished field temporal stability leads to a reduced “trapping efficiency,” defined here as the ratio of the “final” trapped field to the initial background (FC) field. Note that diminished temporal stability somewhat lessens the advantage of a greater FC field. Thus, in each LN_2 and LHe tests, two FC fields were applied, sequentially, as seen in Table 2. First, in order to determine the peak trapped fields of YP1070 at 4.2 and 77 K, we applied FC fields of 1 T (for 77 K tests) and 5 T (4.2 K tests). Second, 70% of the peak trapped field from the first test was chosen as an FC field—70% was arbitrarily chosen as a compromise between a loss of 30–35% in trapping efficiencies and enhanced field homogeneity and temporal stability.

4. Results and discussion

4.1. Trapped field strength and spatial homogeneity

Knowing that the typical sample size in micro-NMR spectroscopy is less than 10 μl , which may translate into a cylindrical volume of $\varnothing 2 \text{ mm} \times 3 \text{ mm}$, here we investigated the spatial field homogeneity of YP1070 within $|r| < 2 \text{ mm}$ and $|z| < 2.5 \text{ mm}$. The first LN_2 test was completed with an FC field of 1 T. At 30 min after completion of the FC process, the axial field was measured from 40 mm above and below the center of the magnet with the 3-D field mapper. The peak trapped field was 0.43 T for that test. For the second LN_2 test, the FC field was set to 0.3 T which is 70% of the previous peak trapped field of 0.43 T. As before, we waited 30 min to measure the axial field and measured a peak trapped field of 0.27 T. Fig. 7 shows the trapped field vs. axial distance plots from both LN_2 tests. Within the $|z| < 2.5 \text{ mm}$, the overall field homogeneity is 4920 ppm with the peak trapped field of 0.43 T while it is reduced to 1180 ppm with that of 0.27 T.

For the LHe tests, the axial fields were measured at 120 min. Field mapping of YP1070 for an FC field of 5 T determined a peak trapped field of 4.0 T. The FC field of the next test was set to 2.8 T (70% of the previous peak trapped field), in which a peak trapped field of 2.75 T was measured. Fig. 8 presents axial field scans from both the 5 and 2.8 T tests. Within the $|z| < 2.5 \text{ mm}$, the overall field homogeneity is 2980 ppm with the peak trapped field of 4.0 T while it is reduced to 182 ppm with that of 2.75 T.

Fig. 9 shows all four field-scan results normalized to the respective peak: 4.0 T for LHe tests and 0.43 T for LN_2 tests. It can be seen that, with decrease in FC field and operating temperature, homogeneity is improved in general. Table 2 includes the overall axial field homogeneity values for all four tests. With decrease in temperature, we have an increase in overall axial field homogeneity.

Each 2-D X - Y field scan was made in a bath of LN_2 at 30 min after field trapping. The 3-D mapper was axially positioned at the center of YP1070 ($z = 0$) and scanned over a $10 \text{ mm} \times 10 \text{ mm}$ span about the axis at the midplane. Fig. 10 shows the X - Y scan results of (a) 1-T and (b) 0.25-T tests. Within $r < 2$ -mm circle, field homogeneity of 175 ppm was measured from the 0.25-T test and 400 ppm from the 1-T test.

4.2. Long-term temporal stability

Fig. 11 shows all four temporal stability results, with the fields normalized to respective trapped fields after the FC processes. Each field was measured at the center of YP1070. The time zero in Fig. 11 corresponds to the time when field measurement began, delayed from completion of an FC process, 30 min in the LN_2 test and 120 min in the LHe test. In general, the smaller the background field or the lower the operating temperature, the better the temporal stability. Note that in both LHe tests, the normalized trapped fields actually increased over a period of time. This “field enhancement” was greater for the 2.8-T test (over a period of the entire measurement time span) than that of the 5-T test (over the first 100 min). This phenomenon was confirmed by multiple measurements. Currently, additional experiments to further investigate this phenomenon are planned.

5. Conclusion

A prototype compact NMR magnet (YP1070), an “optimally stacked” assembly of 1070 thin (86- μm) YBCO “square annuli” of 26-mm bore, was constructed and tested. The stacking optimization process began by grouping 1070 square annuli into 214 5-plate modules and measuring the trapped field of each module. The process proceeded by stacking the 214 modules into YP1070 according to their trapped fields, starting from the midplane (best) and in descending order towards the bottoms and top ends while maintaining axial field symmetry about the midplane. Four main tests were performed on YP1070, two tests at 77 K (LN_2) including one with a background (field-cooling) field of 1 T and the other with an FC field of 0.3 T and two tests at 4.2 K (LHe) including one with an FC field of 5 T and the other of 2.8 T. Field-cooled at 4.2 K from a maximum possible field strength of 5 T, YP1070 generated a trapped field of 4.0 T, equivalent to 170 MHz ^1H NMR frequency, with a field homogeneity of ~ 3000 ppm within a $|z| < 2.5$ -mm axial space. It improved its field homogeneity to 182 ppm when field-cooled from 2.8 T, though its trapped field dropped to 2.75 T (117 MHz). The obtained field homogeneity is still too large when compared with the nominal value of < 1 ppm in conventional NMR magnets. To improve the spatial field homogeneity of this type of a “stacked NMR magnet,” the optimization of the stacking order with different trapped field capacity modules should be further investigated, not to mention that the shimming process, active and/or passive, is essential. Measured temporal stabilities were ~ 200 ppm/h and $\sim 17,500$ ppm/h when field-cooled from 0.3 to 1 T, respectively. Generally, the trapped fields at 4.2 K were ~ 10 times greater than those at 77 K, in nearly direct proportion to a ~ 10 -fold improvement in the superconducting current-carrying capacity of YBCO from 77 to 4.2 K. Further research is scheduled focusing on spatial homogeneity improvement as well as the temporal enhancement of trapped fields at 4.2 K.

Acknowledgements

The authors thank the National Institute of Biomedical Imaging and Bioengineering of the Nation Institutes of Health for support of the work reported here. They would also like to thank Alex Zhu-kovsky for designing a special LHe cryostat for this prototype compact YBCO annulus magnet, David Johnson for making parts, and Stéphane Bermond for Fig. 3.

References

- [1]. Lin WC, Fedder G, A Comparison of Induction-Detection NMR and Force-Detection NMR on Micro-NMR Device Design, Carnegie Mellon University (CMU-RI-RT-01-06), 2001.
- [2]. Magin RL, Webb AG, Peck TL, Miniature magnetic resonance machines, IEEE Spectrum 34 (10) (1997) 51–61.
- [3]. Sweedler JV, Magin RL, Peck TL, Webb AG, Microcoil based micro-NMR spectrometer and method US Patent 6097188, 2000.
- [4]. Iwasa Y, Bascuñán J, Hahn S, Tomita M, Yao W, High-temperature superconducting magnets for NMR and MRI: R&D activities at the MIT Francis Bitter Magnet Laboratory, IEEE Trans. Appl. Supercond 20 (3) (2010) 718–721.
- [5]. Weijers HW, Trociewitz UP, Markiewicz WD, Jiang J, Myers D, Hellstrom EE, Xu A, Jaroszynski J, Noyes P, Viouchkov Y, Larbalestier DC, High field magnets with HTS conductors, IEEE Trans. Appl. Supercond 20 (3) (2010) 576–582.
- [6]. Kiyoshi T, Choi S, Matsumoto S, Zaitse K, Hase T, Miyazaki T, Hamada M, Hosono M, Maeda H, Bi-2223 innermost coil for 1.03 GHz NMR magnet, IEEE Trans. Appl. Supercond 21 (3) (2011) 2110–2113.
- [7]. Li XH, Ye LY, Jin MJ, Du XJ, Gao ZS, Zhang ZC, Kong LQ, Yang XL, Xiao LY, Ma YW, High critical current joint of MgB₂ tapes using Mg and B powder mixture as flux, Supercond. Sci. Technol 21 (2008) 025017.
- [8]. Yao W, Bascuñán J, Hahn S, Iwasa Y, A superconducting joint technique for MgB₂ round wires, IEEE Trans. Appl. Supercond 19 (3) (2009) 2261–2264. [PubMed: 20671806]
- [9]. Iwasa Y, Hahn S, Tomita M, Lee H, Bascuñán J, A persistent-mode magnet comprised of YBCO annuli, IEEE Trans. Appl. Supercond 15 (2) (2005) 2352–2355.
- [10]. Nakamura T, Itoh Y, Yoshikawa M, Oka T, Uzawa J, Development of a superconducting magnet for nuclear magnetic resonance using bulk high-temperature superconducting materials, Concepts Magn. Reson. B 31 (2007) 65–70.
- [11]. Kim SB, Takano R, Nakano T, Imai M, Hahn S, Characteristics of the magnetic field distribution on compact NMR magnets using cryocooled HTS bulks, Physica C 469 (2009) 1811–1815.
- [12]. Ogawa K, Nakamura T, Terada Y, Kose K, Haishi T, Development of a magnetic resonance microscope using a high T_c bulk superconducting magnet, Appl. Phys. Lett 98 (2011) 234101.
- [13]. Hahn S, Voccio J, Bermond S, Park DK, Bascuñán J, Kim SB, Masaru T, Iwasa Y, Field performance of an optimized stack of YBCO square “annuli” for a compact NMR magnet, IEEE Trans. Appl. Supercond 21 (3) (2011) 1632–1635. [PubMed: 22081753]
- [14]. National instrument accuracy calculator, <http://www.ni.com/advisor/accuracy/>.

Fig. 1. Photograph of both old (40-mm square) and new (46-mm square) YBCO plates with thickness and center bore size unchanged. Their average critical current density is also improved.

Fig. 2.

Example of 2-D (X - Y) trapped field scans, measured at 1 mm above each single plate surface, of the old (a) and the new (b) plate within an 8 mm × 8 mm area over the $\varnothing$ 26 mm bore.

Fig. 3. 2-D (X - Y) trapped field scans, measured at 1 mm above each single plate surface, of: (a) the “square” annuli (before trimming); and (b) the “circular” annuli (after trimming). The center hole sizes are identical, $\varnothing$ 26 mm.

Fig. 4.

Measured (77 K) axial center trapped field of 214 5-plate modules, placed in descending order of trapped field: black squares for 150 modules of 40-mm plates; red circles for 64 modules of 46-mm plates. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 5. Measured (77 K) axial center trapped field vs. axial location plot of YP1070 containing 214 modules.

Fig. 6.
Photographs of YP1070. (a) Close-up view; (b) before installed into cryostat.

Fig. 7.

Trapped field vs. axial distance from midplane plots for YP1070 at 77 K. Black squares: 1-T FC field; red circles: 0.3 T. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 8.

Axial field scans along the YP1070 axis from the LHe tests. Green triangles: 5-T FC field; blue diamonds: 2.8 T. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 9.
Peak-normalized trapped field distributions.

Fig. 10.

2-D X-Y field scan results measured in a bath of LN₂ at 77 K with background fields of (a) 1 T and (b) 0.25 T.

Fig. 11.
Normalized temporal decays from all four tests.

Table 1

Key parameters of old and new YBCO plates.

Parameters	Values	
	Old	New
<i>Physical configuration</i>		
Square width (mm)	40	46
Center hole i.d. (mm)	26	
YBCO thickness (μm)	0.8	
Substrate thickness (μm)	75	
Substrate material	Ni-W alloy	
Stabilizer	None	
Overall thickness (μm)	80	
<i>Performance</i>		
$J_{cl} \pm @ 77 \text{ K}, 0.2 \text{ T (mA/cm}^2\text{)}$	0.7	1.0
$J_{cl} @ 77 \text{ K}, 0.2 \text{ T (mA/cm}^2\text{)}$	0.5	0.8
$B_{\text{Trapped}} @ \text{ center, } 77 \text{ K (mT)}$	2–3	3–6

Table 2

Key magnet parameters and performances of YP1070.

Parameters	Values			
	LN ₂ (77 K)	LHe (4.2 K)		
<i>Magnet configuration</i>				
Square width; height (mm)	46; 85.6			
Number of plates (40 mm; 46 mm)	1070 (750; 320)			
Number of modules (40 mm; 46 mm)	214 (150; 64)			
Number of plates per module	5			
<i>Operation and performance</i>				
Field-cooling (FC) field (T)	0.3	1.0	2.8	5.0
Maximum trapped field, B_p @ center (T)	0.27	0.43	2.75	4.0
Axial field homogeneity @ $ z < 2.5$ mm (ppm)	1180	4920	182	2980
Radial field homogeneity @ $ r < 2$ mm (ppm)	175	400	-	-
Field decay (temporal stability) (ppm/h)	-110 ^a	-17,500 ^a	+410 ^b	-650 ^b

^a Measured at 1.5 h after temporal decay testing began.^b Measured at 10 h after temporal decay testing began.

Table 3

Key parameters of 5-T background magnet and the 3-D mapper with Hall sensor.

Parameters	Values
<i>Background magnet</i>	
Magnet i.d.; o.d. (mm)	327; 415
Magnet height (mm)	338
Diameter of RT bore (mm)	300
Operating temperature (K)	3.9–4.9
Maximum field @ 84 A (T)	5.0
B_z homogeneity @ 6 cm DSV (ppm)	1.2%
<i>3-D field mapper with a Hall sensor</i>	
X – Y field scan spans (mm)	100×100
Mapping resolution (mm)	0.2
Sensing area (mm ²)	0.05×0.05
Sensitivity @ 77 K (mV/mT)	97.9
Sensitivity @ RT (mV/mT)	91.7