First-Cut Design of a Benchtop Cryogen-Free 23.5-T/25-mm Magnet for 1-GHz Microcoil NMR

Dongkeun Park, Fangliang Dong, Wooseung Lee, Juan Bascuñán, and Yukikazu Iwasa

***Abstract*— As a preliminary work, we have completed a 12.5-mm-cold-bore high-temperature superconducting (HTS) REBCO magnet prototype and successfully operated it up to 25 T at 10 K cooled by a cryocooler only, without liquid helium. In this paper we present the first-cut design of a cryogen-free all-REBCO 23.5-T/25-mm-warm-bore magnet having a high homogeneity of <0.1 ppm over a 1-cm diameter of spherical volume for a benchtop 1-GHz microcoil NMR spectroscopy. We also investigate a shielding design to reduce a 5-gauss fringe field radius to ≤1.5 m. This benchtop magnet will incorporate all the innovative design and operation concepts validated by the prototype magnet: 1) all-HTS composition and operation at above 4.2 K; 2) no-insulation winding technique with an extra shunting that makes this high-field REBCO magnet compact, mechanically robust, and self-protecting; 3) a single coil formation that leads, compared with the traditional multi-nested high-field NMR magnet, to simpler and more affordable manufacturing processes; 4) operational temperature-controlled screening-current reduction method which reduces peak stresses within the REBCO coil and field errors; and 5) cryogenic design for conduction-cooling operation.**

***Index Terms*— Benchtop, Conduction Cooling, Ultra-High-Field Magnets, No-Insulation, Nuclear Magnetic Resonance, REBCO Magnets.**

I. Introduction

NUCLEAR magnetic resonance (NMR) spectroscopy has become an indispensable analysis tool in cutting-edge science and technology fields. Because the performance of NMR improves with field strength, the demands of NMR user communities have been and continue to be important stimulus for the development of high-field magnets. We proposed a concept of a benchtop 1-GHz microcoil NMR spectroscopy (Micro1G) that employs a more affordable and compact high-field magnet that occupies a small footprint than a conventional ≥1-GHz NMRs, and successfully demonstrated a non-NMR-quality small-scale conduction-cooled high-temperature superconducting (HTS) REBCO magnet prototype up to 25 T as a preliminary work [1]–[3]. Since September 2022 we have started a 4-year R&D program to design, construct, and test a benchtop cryogen-free 23.5-T/25-mm-warm-bore all-REBCO magnet for Micro1G.

Although we believe that success of Micro1G will impact the basic design and approach of the future ultra-high-field magnets including NMR, e.g., an inefficient low-temperature superconducting (LTS) magnet that now surrounds an HTS insert will be replaced by all-HTS magnets, the HTS REBCO magnet technologies for NMR application have technical challenges to be addressed as follows:

1) Screening-current-induced field (SCF) and stress (SCS) for field quality and mechanical robustness, respectively – screening currents, induced in the REBCO superconducting layer by time-varying field affect the center field intensity, homogeneity, and more seriously mechanical stresses within the winding. We will adopt our successfully validated screening-current reduction method, called, a temperature-controlled charging sequence (TCCS) that changes the coil temperature during charging the Micro1G magnet to keep its critical current margin as small as possible, i.e., staring at the higher temperature and lowering the temperature with the charging current increases. Note that the screening currents are reduced as the critical current margin gets reduced [3].

2) Quench protection – Because of very slow normal zone propagation (NZP) velocity in HTS, it is very difficult to detect an early stage of quench, which may result in permanent damage of the hot spot. We demonstrated that our proposed extra-shunted no-insulation (NI) winding can effectively solve this problem against over-heating and sudden-discharging failure [2], [4]. Mechanical issues of unbalancing forces which intrinsically occur in multi-nested NI magnets can be the mitigated by our single solenoidal coil approach.

3) Cost effective engineering design – it is always very challenging to make a research design practical, reliable and cost-effective. We adopt the innovative extra-shunted NI winding technique to the pioneering benchtop single-coil magnet design to address this challenge.

In this paper, as a first step to Micro1G, we present and discuss the first-cut design of a 23.5-T all-REBCO magnet, fringe-field shielding design, here a passive shielding, conduction-cooling cryogenics, and an overall system concept.

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D. Park, F. Dong, J. Bascuñán, and Y. Iwasa are with the Francis Bitter Magnet Laboratory (FBML)/Plasma Science and Fusion Center (PSFC), Massachusetts Institute of Technology (MIT), Cambridge, MA 02139, USA. (e-mail: dk_park@mit.edu).

W. Lee was with the FBML/PSFC, MIT, Cambridge, MA 02139, USA. He is now with Gwangju Center, Korea Basic Science Institute, Buk-gu, Gwangju, 611856, South Korea. (e-mail: wlee2022@kbsi.re.kr).

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TABLE I
KEY PARAMETERS OF THE FIRST-CUT DESIGN OF AN UNSHIELDED BENCHTOP REBCO MAGNET

Parameters		Notch1	Notch2	Notch3	Regular	Notch4
REBCO tape width; thickness	[mm]			4; 0.065		
Winding ID $2a_1$; OD $2a_2$	[mm]	63.25; 126.30	62.47; 126.30	64.55; 126.30	60.00; 126.30	83.79; 126.30
Axial extent b_1; b_2 (spacers included)	[mm]	-8.67; 8.67	-17.34; -8.67 / 8.67; 17.34	-26.01; -17.34 / 17.34; 26.01	-104.04; -26.01 / 26.01; 104.04	-112.71; -104.04 / 104.04; 112.71
Number of DPCs		2	2	2	18	2
Turns per DPC		970	982	950	1020	654
Tape length per DP	[m]	289	291	285	299	216
Total tape length required	[m]			7,540		
Total inductance	[H]			16.8		
Operating current, I_{op}	[A]			179		
Designed* center field @ I_{op}	[T]			23.5		
Operating temperature, T_{op}	[K]			≤ 10		
Designed homogeneity* @ 1 cm DSV	[ppm]			0.100 (peak-to-peak)		
5-Gauss fringe field radius (unshielded)	[m]			2.37 (axial); 1.88 (radial)		

* assuming constant current density in the winding. i.e., no screening current effect are taken into account here.

II. BENCHTOP NMR MAGNET DESIGN

A. REBCO Magnet

Key design specifications of the magnet for Micro1G are: 1) 23.5-T center field with a ϕ25-mm room-temperature (RT) bore and a ϕ60-mm winding inside diameter (ID); 2) field homogeneity of <0.1 ppm over 5-mm-DSV or 5-mm-diameter, 10-mm-length cylindrical volume; 3) 5-gauss fringe field radius of ≤1.5 m; and 4) Cryogen-free operation with a cryocooler. Here, we first consider an unshielded magnet design.

We select a REBCO tape for this magnet as in the prototype magnet because it is still the most promising and practical conductors for high-field application with its high in-field performance at above 23.5 T, high strength, and availability on long-piece length (>300 m). High-strength (nickel-alloy laminated) Bi-2223 conductors cannot meet our designed high-current-density specification and reinforced Bi-2212 conductors are not yet commercially and technically mature for high-field/high-stress magnet applications. Our proposed Micro1G magnet is a multi-notched single solenoidal coil, a stacked of 26 extra-shunted no-insulation (NI) double-pancake (DP) coils, with a high-homogeneity. Table I shows key parameters and specifications of the first-cut designed magnet. Although our final target imaging volume is ≤5-mm-diameter, ≤10-mm-length cylindrical volume for microcoil NMR samples, we have optimized the magnet to have 0.1 ppm (peak-to-peak) in a 10-mm DSV. This approach can minimize the high-order error terms and thus can secure high homogeneity with less reliance on shimming. SCF, described above, on the homogeneity will be further investigated for the next step. We optimize the number of DP coils and their turns while keeping the outer diameter (OD) of all DP coils same for joints between outermost turns from adjacent DP coils. Fig. 1a presents pictorial details of initially designed Micro1G magnet composed of 26 DP coils and show the magnetic field distribution in the magnet. We intend to use 4-mm wide 65-μm thick REBCO tapes. Estimated critical current, I_C, of each coil by using a short sample data of old SuperOx 4-mm REBCO tape [5], a quite conservative estimation since REBCO manufacturers recently have been impressively enhancing J_C of the tape in the field, is well above an operating current, I_{op} of 179 A even at the weakest I_C point at the top and bottom DP coils in Regular coil section. We adopt a notched-single coil design to improve the field homogeneity of our Micro1G, a relatively short and thick magnet. Note that notch coils increase degrees of freedom for design optimization. Generally, the low orders of spherical

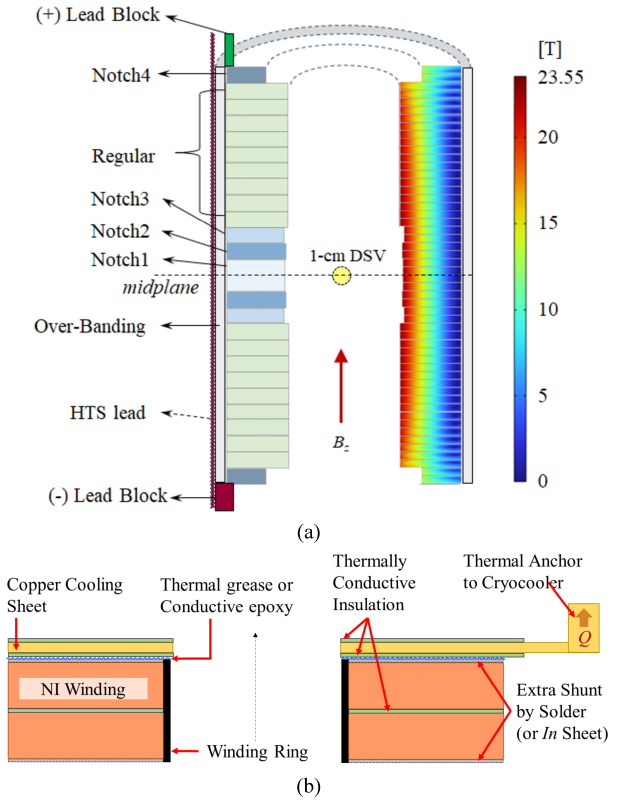

Fig. 1. Drawing of the first-cut designed Micro1G magnet configuration: (a) to-scale drawing with pictorial details and magnetic field distribution in the magnet; (b) schematic concept of a proposed extra-shunted NI DP coil.

harmonic terms ≤4th order can be easily compensated by shims or fine refinement of design (e.g. a few turns adjustment), but the high orders >4th orders, relatively small, are harder to shimmed away. Significant field errors will be added for the as-built Micro1G because of manufacturing tolerance and SCF that mostly affect low order harmonic terms. To achieve the ultimate homogeneity goal for Micro1G of <0.1 ppm at ≤5-mm-diameter, ≤10-mm-length cylindrical volume, we will first apply our HTS shims [6]–[8], then ferromagnetic shims [9], [10], and finally rely on RT shims. A major risk underlying this All-REBCO magnet may be a delicate nature of the ceramic based REBCO conductor, especially with thin 5-μm-thick copper electroplated on both sides, that requires delicate handling, winding, and assembling to prevent the REBCO conductor from degrading I_C performance or damaging. We experimentally verified that even with a resistive spot in one of DP coils, the prototype magnet was stably operated at 25 T thanks to superior stability of extra-shunted NI winding technique [3]. We apply the extra shunting on the NI winding surfaces by low-temperature solder or cold-pressed indium sheets as shown in Fig. 1b. Quenches initiated from a local conductor defect and a sudden current discharging, caused by an external power supply failure in driven-mode magnets like our Micro1G, may be the most conceivable fault modes that can be prevented by the extra-shunted NI winding and, if necessary, in-parallel external shunt resistors [4].

B. Shielding Design – Passive Shielding

To reduce the 5-gauss fringe field radius to ≤1.5 m, there are two options: active shielding and passive shielding. Here, based on our preliminary analysis [11], we explore a passive shielding by using an iron. Generally, an iron-shielding structure adds a significant weight, and the material poses challenges because of its nonlinear magnetic properties that also varies with ambient temperature. We propose an iron yoke that surrounds the main coils inside the cold chamber. An increased weight may be of help to reduce high-frequency mechanical vibration caused by cryocooler operation. The iron yoke can limit a 5-gauss fringe field, contribute an extra field to the center, and shields the magnet from an external interference field such as of moving elevators, passing cars that might be significant for a benchtop application. We first design an iron shield to have a minimum volume, i.e., weight, of iron surrounding the magnet. OD of the iron is 350 mm, and the height of the cylinder is 400 mm. With the thickness of iron of 35.6 mm, a total weight is about 140 kg, still compact and lightweight for such a benchtop magnet as shown in Fig. 2. The iron will distort the field homogeneity at the target volume. For the final design, we will further investigate two shielding options and re-optimize the coil dimension to generate target homogeneity.

C. Mechanical Aspect

With 179-A operating current, the Micro1G magnet has a maximum axial pressure on DP coils near midplane of ~134 MPa, which is safe enough not to degrade the REBCO DP coils [12], [13] and hoop stress of <520 MPa by energization

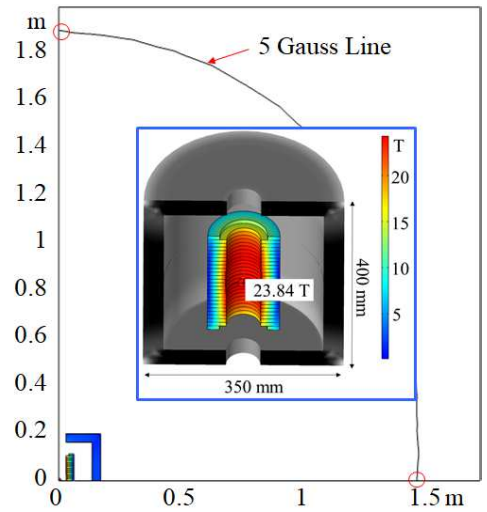

Fig. 2. A 5-gauss line computation result with an iron yoke. Inside a blue box, magnetic field of the coil and the center field are shown.

only without taking SCS into account, can be manageable by applying winding tension, over-banding, and our proposed screening-current-reduction by TCCS [3]. The radial pressures within the DP coils are always compressive and a pre-compression by winding tension of 30 N (115 MPa) will compensate a tensile hoop stress during energization. A preloading will be necessary to ensure that the Micro1G magnet maintain elastic behavior and to prevent excessive deformation or sudden movement of the stacked DP coils during cooldown and energization. On the innermost crossover sections of the Micro1G DP coils, the exerted axial forces toward the midplane can damage the unsupported crossover turn and degrade its I_C, observed in our previous experience [14]. To reinforce the crossover turns, we will affix the additional REBCO tape by soldering, i.e., double-layered REBCO tape, on the crossover turns to enhance mechanical strength and current-carrying capacity. Detailed SCS analysis will be performed to see the maximum allowable operation with the finally fixed design. Another notable mechanical aspect is a vibration from a cryocooler, critical in NMR application, and a proper vibration isolating system will be designed and applied

D. Cryogenics

We propose a conduction-cooled magnet system using a two-stage cryocooler. The 1st stage with a cooling power of 50-W@50-K cools a radiation shield and copper leads connecting to room temperature leads. The main cooling backbone is thermally anchored to the 1-W@4.2-K (and 8-W@10-K) 2nd-stage. A stack of DP coils in the magnet design will be conductively cooled via copper sheets which are electrically insulated by thermally conductive polyimide films as shown in Fig. 1b. We have validated with the prototype magnet that it was cooled to 4 K with the similar area of copper cooling sheets with the proposed magnet DP coil surface area. These copper sheets will be thermally anchored to the 2nd-stage of the cryocooler via copper blocks by soldering or pressing with Apiezon N grease. The coils will be cooled and stably operated because of this cooling path through which heat, generated

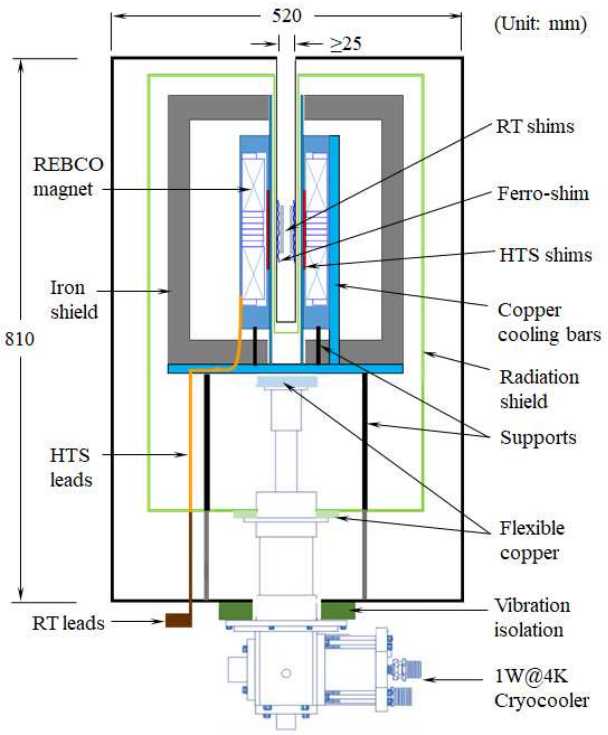

Fig. 3. A schematic view of the Micro1G overall system.

by turn-to-turn resistance during charging, can be removed from the NI DP coils; note that only outer side surface contacts LHe, without cooling sheets between DP coils, in conventional DP stacked solenoid magnet operated in LHe bath, i.e., our cooling method has larger contact areas to the cooling source—higher thermal stability. We design to use 0.4-mm thick hardened temper copper (99.9%) sheets as this thermal spacer, and it can keep the coil temperature uniform at ≤10 K [1]. To apply the TCCS which requires adjusting coil temperature, we will use heaters installed within the cooling path or inserted between DP coils (numbers and positions are to be determined).

III. Overall System Design for NMR Spectroscopy

The Micro1G magnet will be installed in a dedicated ≥25-mm-RT-bore cryostat equipped with ferromagnetic shim pockets. Fig. 3 shows a conceptual drawing of a cross-section of Micro1G overall system. The magnet and iron-shield assembly, may be replaced with an active shielding coil set, will be mounted on the flange by support rods or concentric triple supports and the 2nd stage of a cryocooler will keep the magnet and iron-shield cold at required operating temperature. A vibration isolation pad and flexible copper will be applied to minimize the vibration effect to NMR scanning. Note that this configuration is a conceptual draft and development of an effective vibration isolation system is one of the important targets for the next step.

HTS shim coils will be located within 5-mm annular space, and a RT shim set (OD: 24.8 mm, ID: 17 mm) will be installed after magnet completion. Dynamic shimming for the RT shim coils may be required to compensate any temporally changing field errors by REBCO screening currents and/or a magnetic moving part in the cryocooler. A customized 1-GHz microcoil NMR probe of 16-mm OD will be developed during the project period by collaboration with Nanalysis Scientific Corp to capture the first NMR signal from Micro1G after fully shimmed and reached to a target homogeneity. A field-frequency lock system will be also considered for use in this driven-mode magnet. We will use a RF console for the NMR demonstration at the MIT Francis Bitter Magnet Laboratory.

IV. Conclusion

In this paper, we present the first-cut design of a benchtop cryogen-free 1-GHz microcoil NMR (Micro1G) magnet having ϕ25-mm RT bore, placeable on a workbench with its small fringe field; it saves precious space, another limited resource in most labs. Further magnet optimization is required by considering cost-effective conductor selection, e.g. grading with combination of 3 mm and 4 mm tapes, effective shielding and shimming design as the next step to Micro1G.

The NMR-based structural biology community is still conducting research primarily with ≤900 MHz, and eagerly anticipates higher operating frequencies. We envision this Micro1G without relying on LHe at all to become a very powerful and affordable research tool positively impacting the entire NMR community.

References

[1] D. Park, Y. H. Choi, and Y. Iwasa, "Design of a Tabletop Liquid-Helium-Free 23.5-T Magnet Prototype Toward 1-GHz Microcoil NMR," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1–5, Aug. 2019.

[2] D. Park, W. Lee, J. Bascunan, H. M. Kim, and Y. Iwasa, "A Cryogen-Free 25-T REBCO Magnet With the Extreme-No-Insulation Winding Technique," *IEEE Trans. Appl. Supercond.*, vol. 32, no. 6, pp. 1–5, Sep. 2022.

[3] W. Lee, D. Park, J. Bascuñán, and Y. Iwasa, "Construction and test result of an all-REBCO conduction-cooled 23.5 T magnet prototype towards a benchtop 1 GHz NMR spectroscopy," *Supercond. Sci. Technol.*, vol. 35, no. 10, p. 105007, Oct. 2022.

[4] F. Dong *et al.*, "On fault-mode phenomenon in no-insulation superconducting magnets: A preventive approach," *Appl. Phys. Lett.*, vol. 121, no. 19, p. 194101, Nov. 2022.

[5] T. Benkel *et al.*, "REBCO Performance at High Field with Low Incident Angle and Preliminary Tests for a 10-T Insert," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 3, 2016.

[6] Y. Iwasa, S. Hahn, J. Voccio, D. Keun Park, Y. Kim, and J. Bascuñán, "Persistent-mode high-temperature superconductor shim coils: A design concept and experimental results of a prototype Z1 high-temperature superconductor shim," *Appl. Phys. Lett.*, vol. 103, no. 5, pp. 4–6, 2013.

[7] D. Park, J. Lee, J. Bascunan, P. C. Michael, and Y. Iwasa, "HTS Shim Coils Energized by a Flux Pump for the MIT 1.3-GHz LTS/HTS NMR Magnet: Design, Construction, and Results of a Proof-of-Concept Prototype," *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, pp. 1–5, Apr. 2018.

[8] D. Park, J. Lee, J. Bascuñán, Z. Li, and Y. Iwasa, "Publisher Correction: Prototype REBCO Z1 and Z2 shim coils for ultra high-field high-temperature superconducting NMR magnets," *Sci. Rep.*, vol. 11, no. 1, p. 8640, Dec. 2021.

[9] J. Y. Jang *et al.*, "Reproducibility of the field homogeneity of a metal-clad no-insulation all-REBCO magnet with a multi-layer ferromagnetic shim," *Supercond. Sci. Technol.*, vol. 33, no. 2, p. 025005, Jan. 2020.

[10] S. Iguchi *et al.*, "Advanced field shimming technology to reduce the influence of a screening current in a REBCO coil for a high-resolution

NMR magnet," *Supercond. Sci. Technol.*, vol. 29, no. 4, p. 045013, Apr. 2016.

[11] D. Park, J. Bascuñán, P. C. Michael, and Y. Iwasa, "A Tabletop Persistent-Mode, Liquid-Helium-Free, 1.5-T/90-mm MgB2 'Finger' MRI Magnet for Osteoporosis Screening: Two Design Options.," *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, Apr. 2018.

[12] R. Gupta *et al.*, "High Field, Large Aperture HTS Solenoid for Axion Dark Matter Search," in *25th International Conference on Magnet Technology*, 2017.

[13] R. Gupta *et al.*, "Status of the 25 T, 100 mm Bore HTS Solenoid for an Axion Dark Matter Search Experiment," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1–5, Aug. 2019.

[14] D. Park *et al.*, "MIT 1.3-GHz LTS/HTS NMR Magnet: Post Quench Analysis and New 800-MHz Insert Design," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1–4, Aug. 2019.