Development plan for a persistent 1.3 GHz NMR magnet in a new MIRAI project on joint technology for HTS wires/cables in Japan

Y. Yanagisawa[1], Y.Suetomi[2,1], R.Piao[1], K.Yamagishi[3,1], T.Takao[3], M.Hamada[4], K.Saito[4], K.Ohki[5], T.Yamaguchi[5], T. Nagaishi[5], H.Kitaguchi[6], H.Ueda[7], J.Shimoyama[8], Y.Ishii[9], M.Tomita[10], and H.Maeda

[1]RIKEN, [2]ChibaUniversity, [3]SophiaUniversity, [4]Japan Superconductor Technology,Inc., [5]Sumitomo ElectricIndustries,Ltd., [6]National Institute for Materials Science, [7]Okayama University, [8]Aoyama Gakuin University, [9]Tokyo Institute of Technology, [10]Railway Technical Research Institute, [11]Japan Science and Technology Agency

Abstract

The present article briefly overviews the plan for a new project on joint technology for HTS wires/cables and describes the development plan for the world's highest field NMR magnet, which is a major development item in the project. For full-fledged social implementation of superconducting devices, high temperature superconducting (HTS) wire is a key technology since they can be cooled by liquid nitrogen and they can generate a super-high magnetic field of >>24 T at liquid helium temperatures. However, one of the major drawbacks of the HTS wires is their availability only in short lengths of a single piece of wire. This necessitates a number of joints being installed in superconducting devices, resulting in a difficult manufacturing process and a large joint resistance. In Japan, a large-scale project has commenced, including two technical demonstration items: (i) Development of superconducting joints between HTS wires, which are used in the world's highest field 1.3 GHz (30.5 T) NMR magnet in persistent current mode; the joints performance is evaluated based on NMR spectra for proteins. (ii) Development of ultra-low resistive joints between DC superconducting feeder cables for railway systems. The project starts a new initiative of next generation super-high field NMR development as well as that of realization of better superconducting power cables.

1.Introduction

The Japan Science and Technology Agency (JST) started the JST-Mirai Program in November 2017; the Japanese word Mirai means Future in English. In this program, researchers set up development targets of great social impact to reach the stage where practical applications of technology can be verified, or achieving the Proof Of Concept (POC) stage. A project team including the authors proposed "Social implementation of super-high field NMRs and DC superconducting cables for railway systems, through advancement of joint-technology between high temperature superconducting wires" and was chosen as one of the large scale projects.

Superconducting magnets are widely used in devices such as NMR, MRI, high field magnets, maglev transport, accelerators and nuclear fusion reactors. NMR and MRI are already commercially available and are established as world-wide businesses. A commercial maglev line, the Chuo Shinkansen with superconducting magnets, is under construction and will open in 2027 in Japan. It is also well known that the discovery of Higgs′ particles awarded the Nobel Prize in Physics in 2013 was based on the experiments performed using the superconducting large accelerator at CERN.

Although superconducting technology is spreading in various fields, the use of low-temperature superconducting (LTS) wires, i.e. NbTi and Nb3Sn,requireexpensiveliquidhelium,yetcanonlygeneratefieldslowerthan24Tduetotheir lowcriticalmagneticfields.

To realize full-fledged commercialization of superconducting devices, the use of high-temperature superconducting (HTS) wires is preferred, since they can be cooled by more cost-efficient liquid nitrogen and they can generate a much higher magnetic field 〉 30 T at liquid helium temperatures.

However, one of the major drawbacks of available HTS wires is the short maximum length of a wire piece, typically 〈500 m. Therefore, a large number of joints are required when HTS wires are used in a superconducting device. Such joints complicate the manufacturing process of devices and also can degrade the performances.

Based on this background, the project aims to develop jointing technologies between HTS wires, which will be applied to (i) a super-high magnetic field persistent NMR magnet and (ii) HTS DC power transmission cables for railway systems. The development aims to advance the full-scale social implementation of HTS devices and to have a major impact on future society and industry.

In the present article, we briefly overview the plan for the project. Special emphasis will be made on the development plan for a 1.3 GHz (30.5 T) NMR magnet operated in persistent current mode.

2. The basic scheme of the project

2.1 Fundamental technology: Joints for HTS wires/cables

Firstly, we will develop fundamental technologies for jointing HTS wires and those for HTS cables. Then, to verify the practicality and effectiveness, the jointing technologies will be applied to (i) high field magnets and (ii) HTS DC cables. They are described as follows.

2.2 Super-high field persistent NMR magnet (POC1)

We will develop a NMR magnet generating a field intensity of 30.5 T, corresponding to a 1HNMR frequency of 1.3GHz, operated in persistent current mode using superconducting joints between HTS wires. By using this magnet, we will obtain high resolution solid-state and solution NMR spectra for a trace amount of protein(e.g.amyloidβ). Through the NMR measurements, the performance of the superconducting joints and their applicability to high-field NMR will be verified. The technical concept of the magnet and R&D plans will be described in Section 4.

2.3 Longer superconducting DC cables (POC2)

The DC power transmission system is mainly used for railway systems in urban areas. If substations for a railway are inter-connected with HTS cables, electric power loss will be reduced. However, due to restrictions on vehicles that transport cables to the installation site, the cable length is limited to several hundred meters. In this project, we will develop on-site inter-level joints between superconducting cables with ultra-low resistance. The running performance test of trains will be carried out on a test railway track to verify the applicability of the jointed cables.

Table. 1. Technical concepts of 1.3 GHz NMR magnet

Coil	LTS + HTS (series connected)
Type of HTS wire	A: Bi-2223 + REBCO B: Bi-2223
Winding	Layer-winding
Coil temperature	4.2 K
Joint	Superconducting

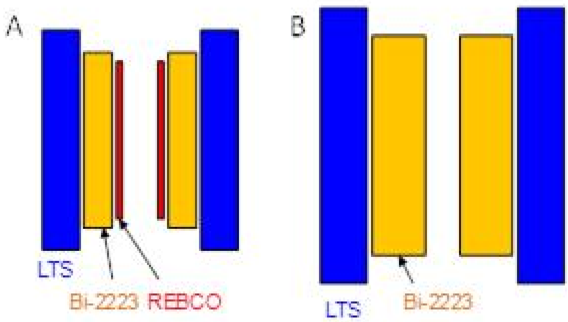

Figure. 1. Two schematics of the coil cross section of 1.3 GHz NMR magnet (not to scale).

3. Organization and schedule

The R&D for the joint technologies and the POCs is being carried out by four collaborative research groups, centering on the Program Manager (PM) H. Maeda. The groups and the group leaders (GLs) are as follows. A lot of other institutions participate in the groups.

▪ Joint Fundamental Technology Group:
GL J. Shimoyama (Aoyama Gakuin University)

▪ Super-High Magnetic Field NMR Magnet POC Group:
GL Y. Yanagisawa (RIKEN)

▪ Social Impact of High Magnetic Field NMR Demonstration Group:
GL Y. Ishii (Tokyo Institute of Technology)

▪ Superconducting Cable for Railway POC Group:
GL: M. Tomita (Railway Technical Research Institute)

The project started in November 2017. The period of the project is ten years, if we successfully pass two milestones, which occur in the fourth year (2020) and in the seventh year (2023). The total budget is about 4 billion yen over 10 years.

4. Development of 1.3 GHz (30.5 T) NMR

In this section we describe in more detail the technical concept of the persistent mode 1.3 GHz NMR magnet (POC1), R&D plans and preliminary results on persistent HTS coils.

4.1 Technical concept of 1.3 GHz NMR magnet

In 2014, a Japanese team, including researchers in the present project team, succeeded in the development of a 1.02 GHz (24.0 T) NMR magnet as the world's highest high-resolution NMR system, operated in a power-supply driven mode, with an HTS innermost coil . In the present project, we will develop an NMR magnet with much higher field of 1.3 GHz (30.5 T). From the viewpoint of operation and temporal stability of the magnetic field, the persistent current mode is the best way to operate the magnet. To achieve persistent current mode operation, the use of superconducting joints is essentially important because the magnet requires many numbers, several tens or more, of joints to be installed in a limited space. **Table. 1** describes technical features of the 1.3 GHz NMR magnet. It comprises LTS outer coils and HTS inner coils. All the coils are cooled by liquid helium at 4.2 K. Two options for the HTS inner coils have been examined so far, using either REBCO/Bi-2223 or Bi-2223 inner coils (see Options A and B respectively seen in **Figure. 1**). From the viewpoint of magnet size, the former is better due to the high current density operation of the REBCO coil. On the other hand, for preventing coil degradation due to strong electromagnetic forces, the latter is preferred. The layer winding method is employed since it can reduce the number of joints and also provides a homogeneous magnetic field for NMR. The LTS and HTS coils are connected in series and operated in a single persistent current circuit with a LTS (NbTi) PCS. This operation is of advantage from the standpoints of magnetic field decay and coil protection. Such a magnet requires both HTS-HTS and HTS-LTS superconducting joints as shown in **Figure. 2(a)**. To realize a permissible field decay of 0.01 ppm/h, the total circuit resistance in the magnet must be <1 nΩ.

4.2 R&D plan

In the first stage (2017-2020), we will develop a medium-field (9.4 T, 400 MHz) NMR magnet with an HTS inner coil with several pairs of superconducting joints to provide a persistent current mode operation. In previous work, we made similar LTS/HTS NMR magnets operated in a power supply driven mode. Through NMR measurements, we will evaluate the performance of the joints and prove the applicability to NMR magnets. In parallel, we will develop a 30 T-class superconducting magnet using an existing LTS outer magnet installed in NIMS: the magnet is of a similar configuration to the 1.3 GHz NMR magnet, i.e. LTS and HTS (Bi-2223+REBCO) coils, to establish HTS magnet technology under the influence of strong electromagnetic forces. Such technology is indispensable since small wire degradation inside the magnetcan collapse the persistent current mode operation. In addition, a beyond-900 MHz (21.1 T) NMR magnet with Bi-2223 inner coils in power supply-driven mode will be operated. This magnet will be used to develop techniques for correcting instability and inhomogeneity of the magnetic field due to the large volume of the HTS coils, and to develop advanced measurement technology for a 1.3 GHz NMR. A numerical simulation of the screening current induced magnetic field will be conducted to reduce its harmful

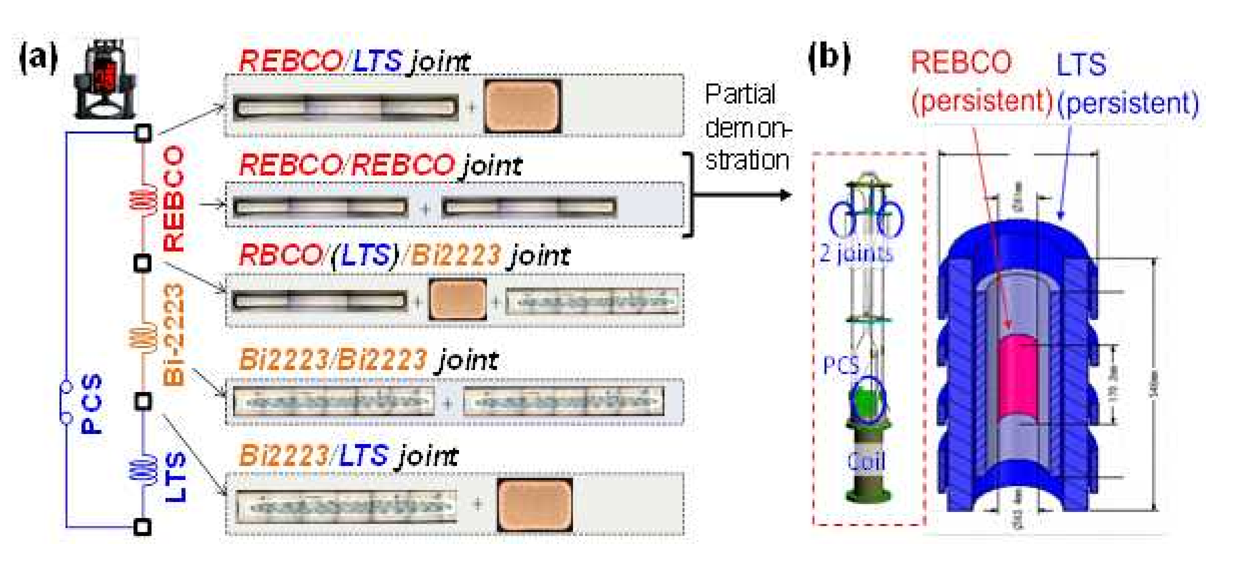

Figure. 2. (a) Schematic of an example coil circuit in a 1.3 GHz NMR magnet (option-A in Figure 1). (b) A persistent current 400 MHz (9.39 T) LTS/REBCO NMR magnet with a primitive REBCO inner coil.

effect on the temporal stability and spatial homogeneity of the magnetic field. Through these R&D efforts, we will optimize and finalize the design of the 1.3 GHz NMR magnet.

In the second stage (2021-2023), we will fabricate a piece of the HTS inner coils for the 1.3 GHz NMR magnet with superconducting joints and persistent operation. We will also construct a 1.3 GHz NMR instrumentation system including a spectrometer and various kinds of probes for solid-state and solution NMR.

In the third stage of the development (2024-2026), we will complete the 1.3 GHz (30.5 T) NMR magnet and operate it in persistent current mode. We will demonstrate super-high sensitivity and high resolution NMR measurements for trace amounts of protein samples including amyloid β.

4.3 Preliminary results on a superconducting joint and a persistent HTS coil

After the first superconducting joint between REBCO wires demonstrated by a Korean research group, several groups succeeded in developing superconducting jointing methods for REBCO wires (e.g. refs.). As a R&D effort in the present project, we have already started to develop a 400 MHz (9.39 T) LTS/HTS NMR magnet (see **Figure. 2(b)**) with intermediate grown superconducting (iGS) joints between REBCO wires. This R&D aims to achieve the first persistent current mode NMR magnet with superconducting joints for HTS wires as a partial demonstration of the 1.3 GHz NMR magnet.

Figure. 3 shows an example of critical current-magnetic field (Ic-B) characteristics of an iGS joint sample obtained at 4.2 K in a magnetic field parallel to the joint plane. The joint sample shows a high critical current of >400 A in the magnetic field range of 0 – 10 T. Although Ic-B characteristics still depend on samples and we have to improve yield rate in jointing process, the result shows the high suitability of the joint being used in a NMR magnet.

We have made prototypes of the REBCO inner coil for the 400 MHz LTS/REBCO NMR magnet. Figure. 4 shows a 4.2 K self-field operation result on a prototype coil installing a REBCO PCS with iGS joints. It is clear that the coil was successfully operated in persistent current mode for over 350 min. The decay of the magnetic field was not observed to the accuracy of a Hall sensor.

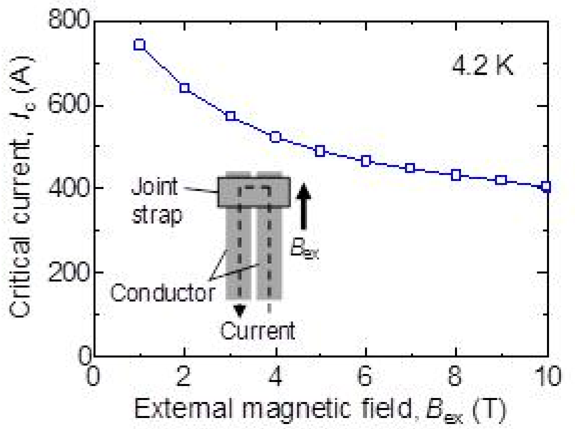

Figure. 3. I_c-B characteristics of a joint sample of REBCO wires in magnetic fields parallel to the joint plane measured at 4.2 K. I_c was determined with a voltage criterion of 1 μV.

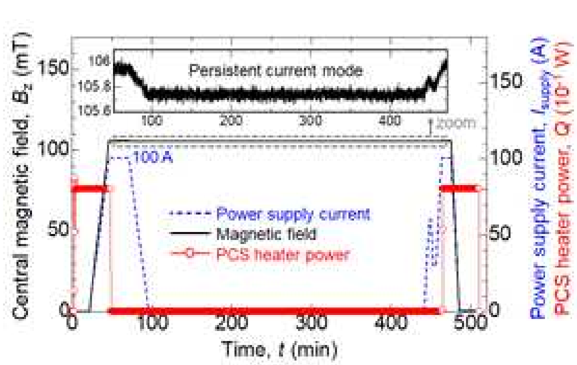

Figure 4. A persistent current mode operation of a prototype REBCO inner coil for the 400 MHz LTS/REBCO NMR magnet operated at 4.2 K in a self-field.

We will make further R&D investigations on HTS (both REBCO and Bi-2223) inner coils with various kinds of superconducting joints such as REBCO/REBCO joint, Bi-2223/Bi-2223 joint, REBCO/NbTi joint and Bi-2223/NbTi joint, which has already been developed in our project. The coils will be tested both in self-fields and in the 400 MHz NMR magnet. The results will provide a knowledge-base for the design, fabrication and operation of the persistent 1.3 GHz NMR magnet.

5. Social impact of the realization of 1.3 GHz NMR

Over the past decade, structures of important proteins related to fatal brain diseases such as Alzheimer's disease, Parkinson's disease and prion disease has been clarified by solid-state NMR. These structures give important information for grasping the causes and measures of the diseases. A higher magnetic field can drastically increase the sensitivity and resolution of solid-state NMR spectra. If a 1.3 GHz NMR is realized there will be a big impact on pharmacy and medicine, as well as development of material sciences.

In addition, we believe that if the development of super-high field NMR magnets in persistent current mode succeeds, the technology will spread to other devices such as MRI, contributing to a full-fledged commercialization of superconducting devices.

Acknowledgement

The present project is supported by the JST Mirai-Program Grant Number JPMJMI17A2. Part of the R&D work was carried out in the RIKEN Junior Research Associate Program, a collaboration between RIKEN and Chiba University, and a collaboration between RIKEN and Sophia University.

References

〔1〕http://www.jst.go.jp/mirai/jp/uploads/saitaku2017/JPMJMI17A2_maeda.pdf

〔2〕 T. C. Cosmus and M. Parizh, Advances in whole-body MRI magnets, IEEE Trans. Appl. Supercond. 21 (2011) 2104-2109

〔3〕 M. Uno, Chuo Shinkansen project using superconducting maglev system, Japan Railway & Transport Review 68 (2016) 14-25

〔4〕 CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B 176 (2012) 30-61

〔5〕 D. C. Larbalestier, J. Jiang, U. P. Trociewitz, F. Kametani, C. Scheuerlein, M. Dalban-Canassy, M. Matras, P. Chen, N. C. Craig, P. J. Lee and E. E. Hellstrom, Isotropic round-wire multifilament cuprate superconductor for generation of magnetic fields above 30 T, Nat. Mat. 13 (2014) 1-7

〔6〕 Y. Xiao, H. Ma, D. McElheny, S. Parthasarathy, F. Long, M Hoshi, R. Nussinov and Y. Ishii, Aβ(1–42) fibril structure illuminates self-recognition and replication of amyloid in Alzheimer's disease, Nat. Struct. Mol. Biol. 22 (2015) 499-505

〔7〕 Superconductors drive trains, Nat. 542 (2017) 275

〔8〕 K. Hashi, S. Ohki, S. Matsumoto, G. Nishijima, A. Goto, K. Deguchi, K. Yamada, T. Noguchi, S. Sakai, M. Takahashi, Y. Yanagisawa, S. Iguchi, T. Yamazaki, H. Maeda, R. Tanaka, T. Nemoto, H. Suematsu, T. Miki, K. Saito and T. Shimizu, Achievement of 1020 MHz NMR, J. Mag. Res. 256

(2015) 30-33.
[9] H. Maeda, T. Yamazaki, Y. Nishiyama., M. Hamada, K. Hashi, T. Shimizu, H. Suematsu, and Y. Yanagisawa, eMagRes 5 (2016) 1109.
[10] Y. Yanagisawa, H. Nakagome, K. Tennmei, M. Hamada, M. Yoshikawa, A. Otsuka, M. Hosono, T. Kiyoshi, M. Takahashi, T. Yamazaki, H. Maeda, Operation of a 500 MHz high temperature superconducting NMR: towards an NMR spectrometer operating beyond 1 GHz, J. Magn. Reson. 203 (2010) 274–282.
[11] Y. Yanagisawa, R. Piao, S. Iguchi, H. Nakagome, T. Takao, K. Kominato, M. Hamada, S. Matsumoto, H. Suematsu, X. Jin, M. Takahashi, T. Yamazaki and H. Maeda, Operation of a 400 MHz NMR magnet using a (RE:Rare Earth)Ba2Cu3O7-xhigh-temperature superconducting coil: Toward sanultra-compactsuper-highfield NMR spectrometer operated beyond1GHz,J. Magn. Reson. 249 (2014) 38–48.
[12] T. Matsuda, T. Okamura, M. Hamada, S. Matsumoto, T. Ueno, R. Piao, Y. Yanagisawa and H. Maeda, Degradation of the performance of an epoxy-impregnated REBCO solenoid due to electromagnetic forces, Cryogenics 90, 47-51 (2018)
[13] K. Kajita, T. Takao, H. Maeda, and Y. Yanagisawa, Degradation of a REBCO conductor due to an axial tensile stress under edgewise bending: A major stress mode of deterioration in a high field REBCO coil's performance, Superconductor Science and Technology 30, 074002 (8pp) (2017)
[14] K. Kajita, S. Iguchi, Y. Xu, M. Nawa, M. Hamada, T. Takao, H. Nakagome, S. Matsumoto, G. Nishijima, H. Suematsu, M. Takahashi and Y. Yanagisawa, Degradation of a REBCO Coil Due to Cleavage and Peeling Originating from an Electromagnetic Force, IEEE Transaction on Applied Superconductivity 26, 4301106 (2016)
[15] H. Ueda, M. Fukuda, K. Hatanaka, K. Michitsuji, H. Karino, T. Wang, X. Wang, A. Ishiyama, S. Noguchi, Y. Yanagisawa and H. Maeda, Measurement and Simulation of Magnetic Field Generated by Screening Currents in HTS Coil, IEEE Trans. Appl. Supercond. 24 (2014) 4701505
[16] Y. Park, M. Lee, H. Ann, Y.H. Choi and H. Lee, A superconducting joint for GdBa2Cu3O7−δ-coatedconductors,NPG Asia Mater. 6 (2014) e98
[17] X. Jin, Y. Yanagisawa, H. Maeda and Y. Takano, Development of a superconducting joint between a GdBa2Cu3O7−δ-coatedconductorandYBa2Cu3O7−δ bulk:towardsasuperconductingjointbetweenRE(RareEarth)Ba2Cu3O7−δ-coatedconductors,Supercond. Sci. Technol. 28 (2015) 075010
[18] K. Ohki, T. Nagaishi, R. Piao, T. Kato, D. Yokoe, T. Hirayama, Y. Ikuhara, T. Ueno, K. Yamagishi, T. Takao, R. Piao, H. Maeda and Y. Yanagisawa, Fabrication, microstructure and persistent current measurement of an intermediate grown superconducting (iGS) joint between REBCO-coated conductors, Supercond. Sci. Technol. 30 (2017) 115017.
[19] K. Yamagishi, T. Takao, Y. Suetomi, K. Ohki, T. Yamaguchi, T. Nagaishi, H. Kitaguchi, K. Saito, M. Hamada, R. Piao, Y. Yanagisawa and H. Maeda, Towards the realization of a persistent current 1.3 GHz NMR using superconducting joints -Test

results of a REBCO inner coil for a persistent 400 MHz (9.39 T) LTS/REBCO NMR-, MC-18-028/ASC-18-028, IEEJ (2018) (written in Japanese)

[20] R. Matsumoto, H. Iwata, A. Yamashita, H. Hara, G. Nishijima, M. Tanaka, H. Takeya, and Y. Takano, Applied Physics Express 10 (2017) 093102.

[21] H. Heise, W. Hoyer, S. Becker, O.C. Andronesi, D. Riedel and M. Baldus, Molecular-level secondary structure, polymorphism, and dynamics of full-lengthα-synucleinfibrils studied by solid-stateNMR,PNAS 102 (2005) 15871-15876

[22] Patrick C. A. van der Wel, Jo´ zef R. Lewandowski, and Robert G. Griffin, Solid-State NMR Study of Amyloid Nanocrystalsand Fibrils Formed by the Peptide GNNQQNY from Yeast Prion Protein Sup 35p,J. Am. Chem. Soc. 129 (2007) 5117-5130