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Towards a 1.3 GHz (30.5 T) NMR: Persistent-mode NMR magnet with superconducting joints between high-temperature superconductors

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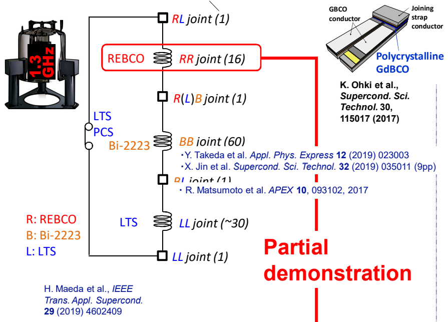
1. Introduction: towards a 1.3 GHz (30.5 T) NMR magnet

Our ultimate goal is to develop a high-resolution 1.3 GHz (30.5 T) nuclear magnetic resonance (NMR) magnet operated in the persistent-mode. The magnet requires superconducting joints between HTSs and those between an HTS and a low-temperature superconductor (LTS). Towards this goal, we have been developing persistent-mode HTS inner coils to be operated in a 400 MHz (9.39 T) NMR magnet and here we present the first prototype of an inner coil wound with a single piece (RE=rare earth)Ba$_2$Cu$_3$O$_{7-x}$ (REBCO) conductor. The coil and a newly developed REBCO persistent current switch (PCS) are connected with intermediate grown superconducting (iGS) joints with high critical currents in external magnetic fields. To evaluate the performance of the joints in an ultimately stable and homogeneous magnetic field in a real NMR magnet system, the coil is operated in the persistent-mode, generating 0.1 T, in a 9.3 T background magnetic field of a persistent-mode LTS outer coil for 1 year.



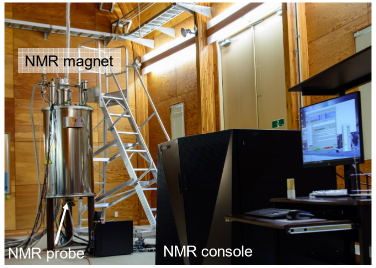
Intermediate grown superconducting (iGS) joint

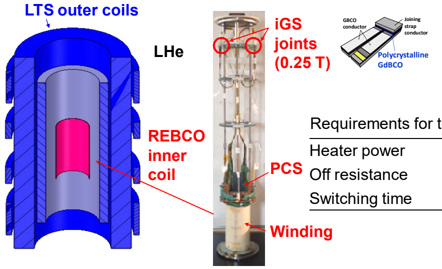
K. Ohki et al., *Supercond. Sci. Technol.* 30, 115017 (2017)

- Y. Takeda et al. *Appl. Phys. Express* **12** (2019) 023003
- X. Jin et al. *Supercond. Sci. Technol.* **32** (2019) 035011 (9pp)
- R. Matsumoto et al. *APEX* **10**, 093102, 2017

H. Maeda et al., *IEEE Trans. Appl. Supercond.* **29** (2019) 4602409

2. Parameters of a 400 MHz (9.39 T) LTS/REBCO NMR in the persistent-mode



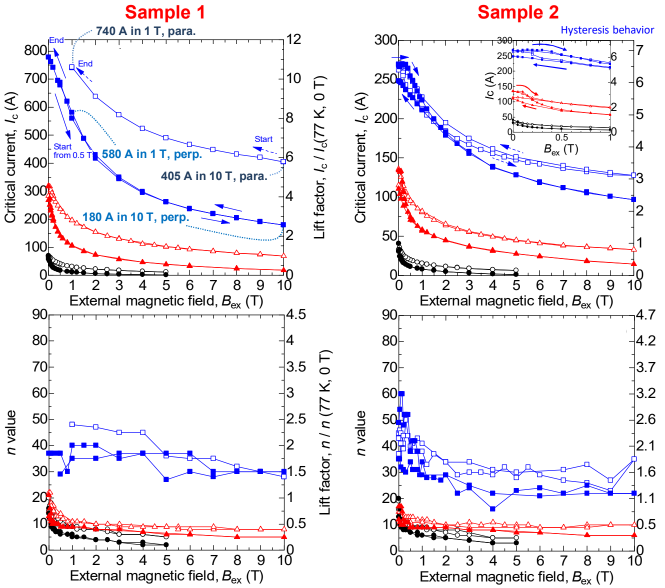


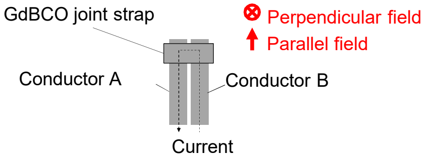
Requirements for the PCS in LHe	
Heater power	<10 W
Off resistance	>0.1 mΩ
Switching time	<100 s

	Unit	REBCO inner coil	LTS outer coils
Coil conductor	-	REBCO (SEI), without outermost copper electroplating layer	Nb$_3$Sn and NbTi
Bare conductor width : thickness	mm	4.05 : 0.14	-
Insulated conductor width : thickness	mm	4.1 : 0.19	-
Conductor critical current at 77 K	A	~200	-
Conductor length	m	37.2 + 1.2	-
ID : OD : Height	mm	81.5 : 83 : 148.5	132.6 : 289.3 : 546
Total turns	-	144	-
Number of layers	-	4	-
Coil constant	mT/A	1.066	68.96
Self-inductance	mH	0.75	69.8
Mutual inductance	mH	0.053	
PCS conductor	-	REBCO (SEI), without outermost copper electroplating layer	NbTi/CuNi
Joint type	-	Homogeneous iGS joint (SEI-SEI)	Solder
Self-field operation at 77 K			
Measured coil critical current	A	123 (at 0.01 μV/cm)	-
Measured PCS critical current	A	>107 (at 0.01 μV/cm)	-
Measured joint critical current	A	R: 45.6, L: 17.3 (at 1 μV)	-
Self-field operation at 4.2 K			
Estimated coil critical current	A	>1100[*1]	-
Estimated PCS critical current	A	>1100[*2]	-
400 MHz operation at 4.2 K			
Estimated coil critical current	A	>1100[*1]	-
Estimated PCS critical current	A	370[*2]	-
Operating current	A	92.7	134.8
Magnetic field, Z0	T : MHz	0.09882 : 4.207	9.296 : 395.8
Z2 harmonic	Hz/cm^2	0.00	
Z4 harmonic	Hz/cm^4	-211	
Maximum BJR	MPa	63.3	-
Local field intensity at joints	T	0.25	-

3. In-field current transport characteristics of iGS joint samples

	Unit	Sample 1	Sample 2
REBCO conductor		A: SEI (PLD) B: SEI (PLD)	A: SEI(PLD) B: SEI(PLD)
I_c(77 K, 0 T)	A	70	41

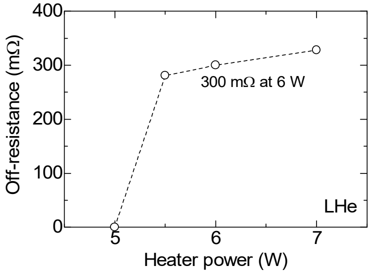


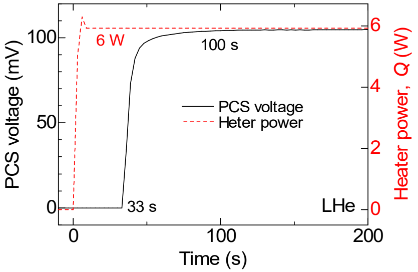


- These results show the potential of high current transport characteristics of the iGS joint in external magnetic fields.
- In the present 400 MHz LTS/REBCO NMR magnet, the joints of the REBCO inner coil are located in the field of ~0.2 T. Therefore, the current transport property of the iGS joint is sufficient.

4. Development of a REBCO PCS operated in liquid helium

Requirements for the PCS in LHe	
Heater power	<10 W
Off resistance	>0.1 mΩ
Switching time	<100 s

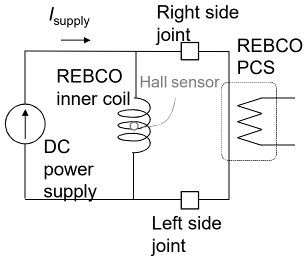


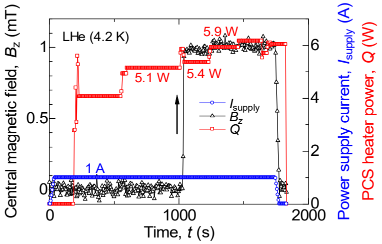


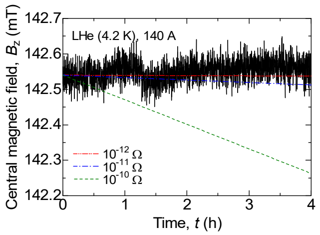
- The resistance of the PCS arose at a heater power of 5.5 W and it showed 300 mΩ at 6 W.
- The PCS voltage started to arise after 33 s of the initiation of heater input and became a steady state in 100 s.

⇒These PCS performances fulfilled the required specifications for the REBCO inner coil used in liquid helium.

5. Fabrication and self-field tests of a REBCO inner coil in LHe



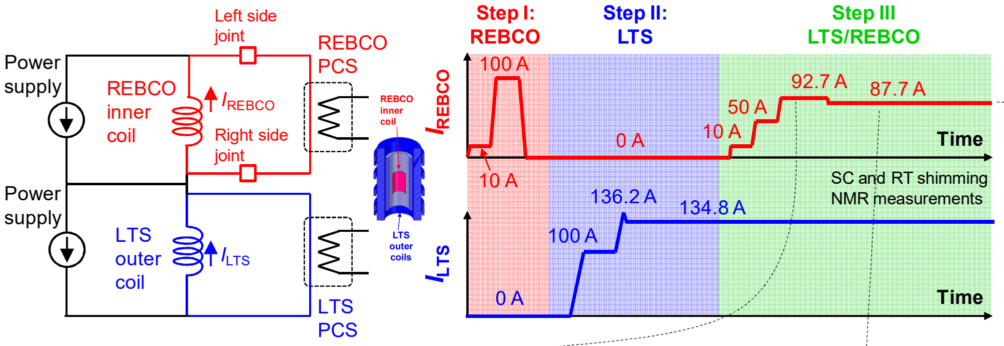


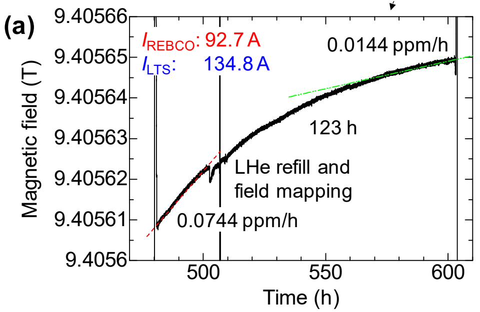


We charged the coil to **140 A** under a PCS off-state with a 6 W heater input. After turning the PCS to the on-state, the power supply current was reduced to 0 A.

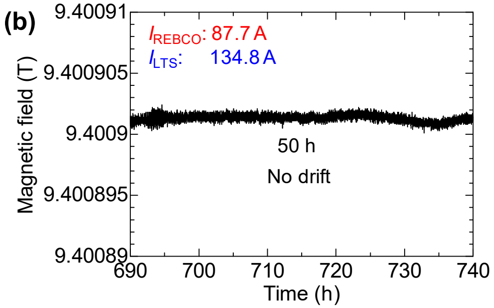
⇒The measured field shows no significant decay to the accuracy of the Hall sensor

6. One-year persistent-mode operation of the 400 MHz (9.39 T) LTS/REBCO NMR magnet and NMR measurements

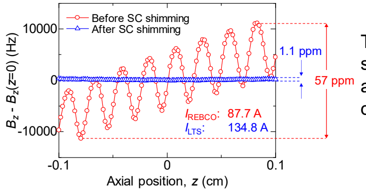




The magnetic field drifts with time in the positive polarity due to the relaxation of screening currents in the REBCO inner coil

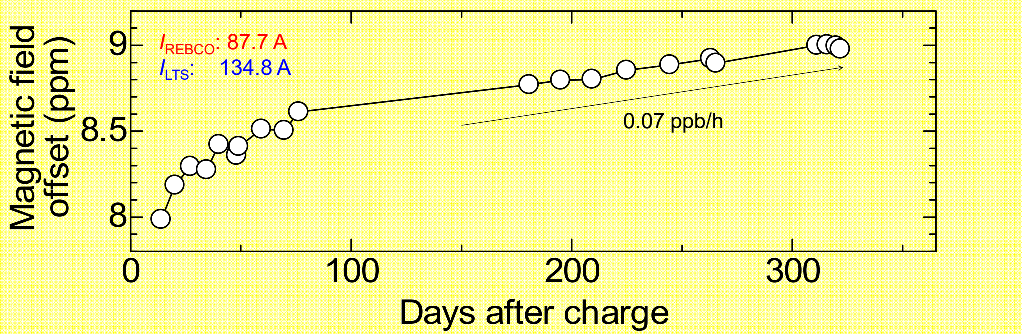


The drift of the magnetic field is fully stabilized by an current sweep reversal (overshooting)



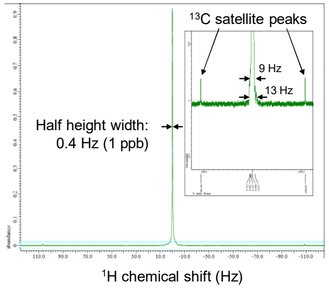
The spatial field homogeneity improved with superconducting shim coils and the peak-to-peak amplitude of the magnetic field profile was sufficiently decreased for RT shimming.

Magnetic field stability over 1 year



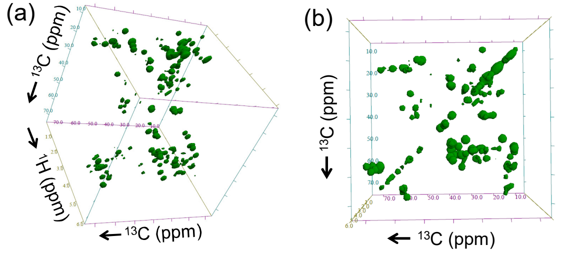
The long-term stability of the magnetic field measured by NMR signal observation of the same sample without the field lock operation. The positive drift rate became farther smaller but was still positive 6 months after the charge. The drift rate was 0.07 ppb/h (0.024 Hz/h). This result shows that the superconducting joints have been perfectly functioning.

NMR spectrum line shape



- The quality of an NMR spectrum line shape, which represent the homogeneity of the magnetic field, is excellent.

3D NMR spectrum



(a) A HCCH-TOCSY spectrum on^{15}N,^{13}C-labeled 0.1 mM GB1 (protein G - B1 domain, 56 amino-acid residues) in D2O with phosphate buffer. The in-plane axes are ^{13}C chemical shifts and the depth direction is ^{1}H chemical shifts. The spectrum was obtained using a RT solution NMR probe under a field-frequency lock operation. (b) The perspective view of the ^{13}C-^{13}C plane of the spectrum. The measurement was made overnight and the good spectrum shows that the temporal change of the field homogeneity was sufficiently small for long-term NMR measurements.

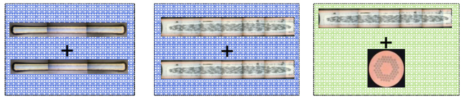
7. Conclusions and future plans

- In the present work, we have succeeded to demonstrate the first persistent NMR with superconducting joints between REBCO conductors.
- We will also develop a REBCO inner coil with many joints (>10) and a Bi-2223 inner coil to be tested at 400 MHz.


HTS inner coil


400 MHz LTS/HTS NMR

REBCO-REBCO joint **Bi2223-Bi2223 joint** **Bi2223-NbTi joint**



- Design optimization
- High-field generation technology

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