High Field All High Temperature Superconducting Magnet

Sangwon Yoon[1], Jaemin Kim[1], Kyekun Cheon[1], Seungyong Hahn[2], Hunju Lee[1] and Seung-Hyun Moon[1]

[1] SuNAM Co., Ltd. 103 Seongeun-ri, Wongok-myeon, Anseong-si, Gyeonggi-do, 456-812, Korea.
[2] National High Magnetic Field Laboratory, Florida State University, 2031 East Paul Dirac Drive, Tallahassee, FL 32310, US

Email: kkcheon@i-sunam.com

June 14, 2016 (STH40/HP110). The discovery of oxide superconductors, which have higher critical temperatures, and, more importantly, higher irreversibility fields, opens new possibilities for fabricating superconducting magnets generating magnetic fields larger than ~23 T. The development of processes that fits these brittle oxides into wire (actually tape) form with mechanically strong metals yields high temperature superconducting (HTS) wires capable of withstanding hoop stresses experienced in high field magnets. Along these lines one could claim optimistically that even a 100 T magnet is in principle attainable [1].

SuNAM has developed a proprietary process for making 2nd Generation (2G) superconducting wires, based on co-evaporation of the constituent metals and subsequent heat treatment at carefully controlled temperatures and oxygen pressures [2], and has been producing 2G wires with piece lengths in the range of 100 ~ 200 m. We also worked on HTS magnets which utilize our wires, and we fabricated two conduction-cooled 4 T magnets with a room temperature bore of 100 mm and 200 mm, respectively [3]. Subsequently, in early 2014, we set sail for a new goal of generating fields higher than 20 T with HTS only, neither hybrid of HTS and LTS nor of HTS and resistive, and also not relying on nested structures.

The electromagnetic design and mechanical analysis of the 20 T all HTS magnet was performed by MIT while SuNAM constructed the magnet. The magnet consists of 26 Double Pancake (DP) coils with a winding inner diameter of 35 mm and an outer diameter of 171.9 mm. The overall height is 327 mm. We adopted a multi-width (MW) design where wires with different widths – 4.1, 5.1, 6.1, 7.1, and 8.1 mm – were used. We reported earlier that the MW design reduces the wire usage compared to a single-width wire winding [4]. We used $GdBa_2Cu_3O_{7-x}$ (GdBCO) tapes with stainless steel substrates, with a total thickness of 140 μm including 15 μm copper stabilizers at both sides. The minimum I_c of the tape is 150 A at 77 K and self field for a 4.1 mm tape, and those for other tapes are proportional to the tape width. The estimated peak hoop stress is 286 MPa, half of the 95 % I_c retention stress of a GdBCO tape. The total peak tensile strain is 0.48 % including a peak bending strain (of 0.31 %) which is still in the range of 95 % I_c retention strain of the GdBCO tape, > 0.5 % [5]. Progressively wider tapes from coil center to ends were employed; with 4.1 mm at the center, up to 8.1 mm at ends, to reduce current densities where the highest perpendicular fields are applied. The DP coils were wound with a no-insulation (NI) technique to overcome the difficulty in protection [4].

Coil I_c s of each DP were measured at 77 K by immersing the coils in liquid nitrogen. The stacking order among same width coils was determined by the coil I_c values so that we can get a current margin as large as possible at the operating condition. For example, in case of a 4.1 mm width wire, the DP coil having the highest coil I_c was put to the center because the parallel field to the tape plane is the highest there. After stacking, DP coils were joined with indalloy (52In48Sn) solder using 10 cm long GdBCO tapes to connect DP to DP at about 500

K. Each joint's resistance was measured at 77 K and 4.2 K. The average joint resistance is 62 nΩ and 52 nΩ, respectively.

Finally the magnet was immersed in liquid helium. Figure 1 shows assembled magnet and a helium Dewar for testing the magnet at 4.2 K. In the first ramping, the magnet reached 21.1 T before developing a voltage. After warming up the magnet, we found slight deformations in a couple of DP coils, applied mechanical reinforcements and experimented again. The magnet was charged with the ramping rate of 10 mA/sec and reached 26.4 T at the coil current of 242 A, which, to our knowledge, is the highest field among all-HTS magnets [6]. After that, the magnet was discharged with the same rate down to 148 A, and then the ramp rate was increased to 15 mA/sec to save experiment time. Figure 2 shows the time evolution of coil current, magnet voltage, and magnet central field. The ramping was stopped for several times to check the voltage (middle red line) and the magnetic field (top blue line) behaviour resulting from no-insulation charging effect. The charging time constant was estimated as 947 seconds from the analysis of the magnet voltage with the equivalent circuit equation of NI coil [4].

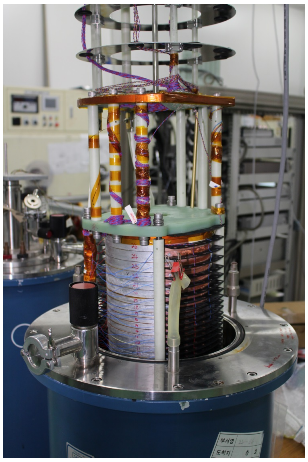

Fig. 1 Assembled magnet and liquid He Dewar.

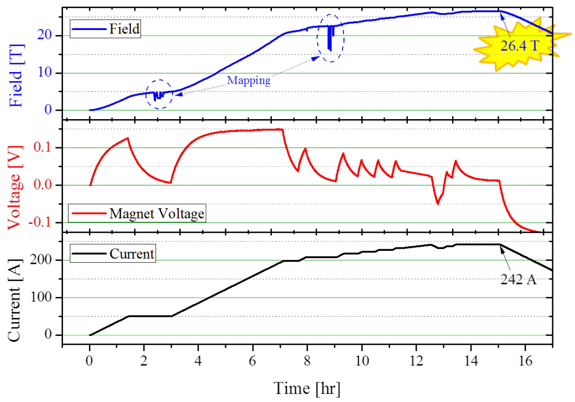

Fig. 2 Test results in liquid He at 4.2 K. About 15 hour after the start of ramping the magnet reached 26.4 T (top blue line) at a power supply current of 242 A (bottom black line).

We thus confirmed that we can construct a high-field magnet with our wire by combining NI and MW technology. We're working on a 400 MHz HTS high uniformity NMR magnet with Korea Basic Science Institute and many collaborating institutions including NHMFL [7], and are also planning to manufacture a magnet with a central field higher than 35 T.

References

[1] Yukikazu Iwasa and Seungyong Hahn, "First-cut design of an all-superconducting 100-T direct current magnet", *Appl. Phys. Lett.*, **103**, 253507 (2013).

[2] J.-H. Lee, H. Lee, J.-W. Lee, et al., "RCE-DR, a novel process for coated conductor fabrication with high performance", *Supercond. Sci. Technol.*, **27**, 044018 (2014).

[3] S. Yoon, K. Cheon, H. Lee, et al., "Fabrication and Characterization of 4-T/203 mm RT Bore 2G HTS Magnet With No-Insulation Method", *IEEE Trans. Appl. Supercond.*, **24**, 4602904 (2014).

[4] S. Hahn, Y. Kim, D. K. Park, et al., *Appl. Phys. Lett.*, **103**, 173511, (2013).

[5] H. Shin and M. J. Dedicatoria, *Supercond. Sci. Technol.*, **26**, 055005 (2013).

[6] S. Yoon, J. Kim, K. Cheon, et al., "26 T 35 mm all-GdBa2Cu3O7–x multi-width no-insulation superconducting magnet", *Supercond. Sci. Technol.*, **29**, 04LT04 (2016).

[7] Kwang Lok Kim, Sangwon Yoon, Kyekun Cheon, et al., “400-MHz/60-mm All-REBCO Nuclear Magnetic Resonance Magnet: Magnet Design”, *IEEE Trans. Appl. Supercond*., **26**, 4302604 (2016).