

# REBCO coil operation in gaseous helium and solid nitrogen

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(Received 24 June 2019; revised or reviewed 28 September 2019; accepted 29 September 2019)

## Abstract

The paper gives the results of the experiments with a model two-section REBCO solenoid cooled by either gaseous helium (GHe) or sub-cooled/solid nitrogen (SN2) in (50-77) K temperature range. The major cooling source was a single-stage cryocooler Sumitomo CH-110 with the cooling power of 175 W and 130 W at 77 K and 50 K respectively. The coil itself was not directly conduction cooled. We compare the time taken by both coolants to obtain the temperature of the magnet of about 50 K and the homogeneity of the temperature distribution within the cryostat. Test results for the coil operation in solid nitrogen together with the comparison of its critical properties in SN2 and GHe are also presented.

*Keywords:* HTS magnet, 2G HTS coil, REBCO coated conductor, sub-cooled liquid nitrogen, solid nitrogen, gaseous helium

## 1. INTRODUCTION

With the advent of cryocoolers and commercial high temperature superconductors (HTS) the search for a cryostat design for superconducting (sc) magnetic systems with no liquid cooling agents has begun. "Dry" sc devices cooled with gaseous helium (GHe) at low temperatures [1, 2] as well as complete cryogen-free conduction cooled sc magnets placed in vacuum [3, 4] were investigated worldwide. Since HTS magnets have wider operational temperature range, nitrogen in different phase conditions was considered as a candidate for HTS magnets cooling. A few R&D projects concerning HTS magnets operated in solid nitrogen (SN2) are known today [4, 5, 6, 7]. At 50 K SN2 heat capacity is 1.5 times greater than that of metals, providing better thermal stability in comparison with conduction-cooled magnets. Together with relatively large thermal diffusivities in the 50-70 K range, SN2 can enhance the magnet's effective thermal mass. In other words, it can play role of a coolant and a stabilizer at the same time [6].

The National Research Centre "Kurchatov Institute" (NRC KI) has been working since 2017 on the high gradient magnetic separator based on REBCO tapes [8], [9]. In spring 2019, the HTS split magnetic system was completed and successfully tested in SN2 [10]. The design of the separator cryostat with a cryocooler makes it possible to use both nitrogen (in liquid, sub-cooled or solid state) as well as gaseous helium as a coolant. The two cooling schemes have their pros and cons. Thus, additional experiments with a model REBCO coil cooled by either SN2 or GHe were performed. The experimental details of the HTS coil operation with different coolants are presented and compared in the following sections.

## 2. HTS COIL & TEST RIG

Table I lists the key parameters of the small two-section layer-wound HTS magnet used in our experiments. Both magnet sections were wound with the 4 mm copper stabilized REBCO tape in kapton insulation produced by SuperPower. Each section contained internal joints and was equipped with protective shunts. The photo of the coil is given in Fig. 1.

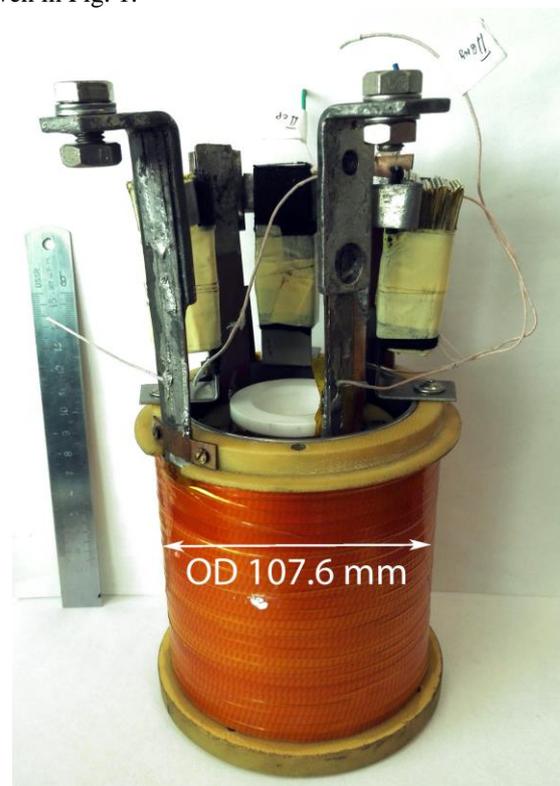


Fig. 1. The photo of the two-section REBCO magnet (together with the protection shunts) used in the experiments.

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TABLE I  
PARAMETERS OF THE REBCO MAGNET.

Section	Inner	Outer
Inner diameter, mm	50	90
Outer diameter, mm	74	107.6
Height, mm	80	106
Number of layers	60	44
HTS tape length, m	222 (3pieces/ 2 joints)	341 (2pieces/ 1 joint)
HTS tape	SuperPower SCS4050 4 mm x 0.1 mm (50 $\mu$ m Hastelloy, 2x25 $\mu$ m copper with RRR=57) in kapton wrapped insulation $I_c$ (77 K, s. f.) = 93 A	

Fig. 2 shows the 3D sketch of the assembled test rig. During the experiments the HTS coil (or its standalone outer section) was housed inside of a copper shield playing the roll of a cooling radiator in a 420 mm bore cryostat. The major cooling source was a single-stage cryocooler Sumitomo CH-110 with the cooling power of 175 W and 130 W at 77 K and 50 K respectively. The copper cooling radiator was connected to the cold head via copper thermal bridges. During the cool down, the coil surrounded by a volume of coolant (sub-cooled/solid nitrogen or gaseous helium) was not directly conduction-cooled. Nevertheless, the method allowed us to cool the magnet down to  $\sim$ 50 K with the both cooling agents. Three PT thermometers sensors were mounted at selected locations, as it is shown in Fig. 2.

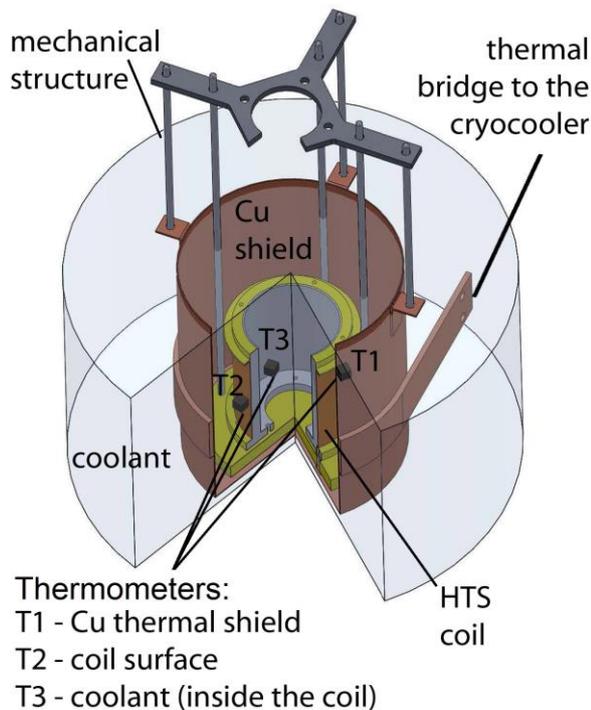


Fig. 2. The 3D sketch of the assembled test rig and the locations of three PT thermometers: T1 – copper shield, T2 – the surface of the HTS coil, T3 – the coolant inside the coil.

### 3. TEST RESULTS

#### 3.1. Comparison of cooling process for the HTS coil in GHe and SN2.

At the beginning of the test program we conducted a few experiments with the different coolants to compare the time, needed to obtain 50 K magnet temperature and to reveal the peculiarities of the two cooling schemes. We worked both with the assembled two-section HTS magnet as well as with its standalone outer section.

In the case of nitrogen used as a coolant the following procedure was employed. Firstly, the cryostat with the magnet was filled with LN2 at 1 atm. Next, with the cryocooler turned on, LN2 was sub-cooled and solidified from the copper cooling radiator attached to the cold head. In the case of helium, the same cryostat with the HTS coil and radiator inside was inflated with warm GHe up to the pressure of about 1.1 atm. The cooler was turned on. When the temperature of the gas was about 60 K corresponded to the pressure drop inside the cryostat down to 0.5 atm an additional portion of the warm gas was added to restore the initial pressure.

Fig. 3 shows cooling curves for the outer section of the HTS coil measured at the three PT thermometers' locations: T1 (on the Cu thermal shield), T2 (on the coil surface) and T3 (immersed into the coolant inside the coil).

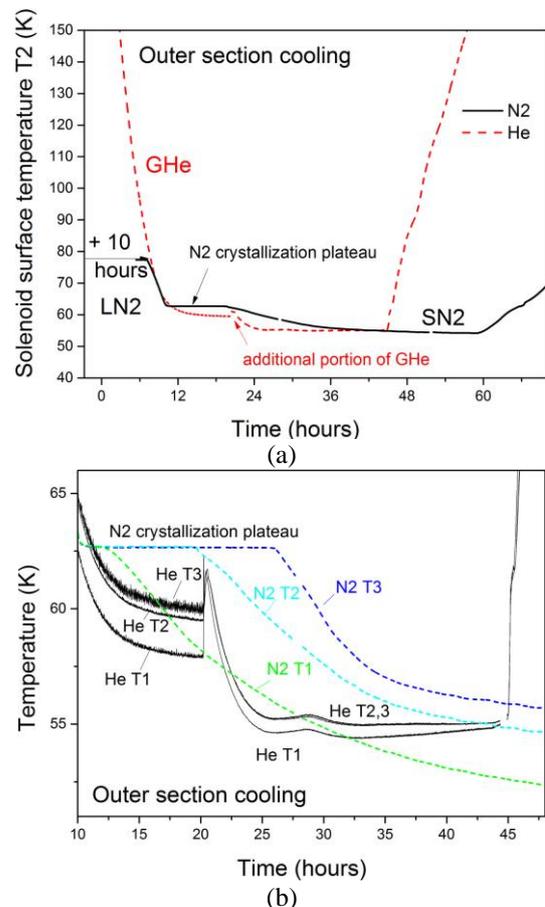


Fig. 3. The outer magnet section cooling with SN2 and GHe: a – the coil surface temperature (thermometer T2), b – comparison of readings of all the three thermometers for the operation in GHe & SN2.

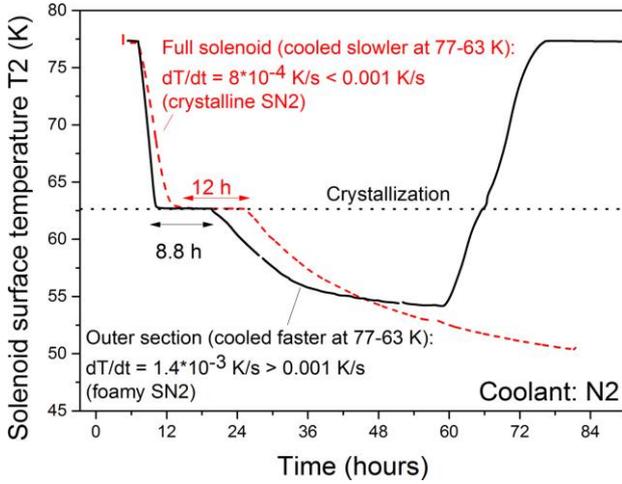


Fig. 4. Comparison of the cooling process with SN2 of the two-section HTS solenoid (the red curve) and its outer section only (the black curve).

Fig. 3a shows the temperature of the outer section measured by the thermometer T2 for the both coolants. The cryocooler was able to cool the magnet in gaseous helium from 300 K to 55 K in 46 hours, while it took 10 hours less (~ 36 hours) in the case of nitrogen. In other words, we could save the time starting our work with liquid nitrogen at 77.3 K, whereas the experiments with GHe started with a warm 300 K gas. The plateau on the N2 curve at 63.15 K indicates the liquid–solid phase transition. Before the N2 solidification the cooling rate of about  $1.4 \cdot 10^{-3}$  K/s was very close for the both coolants, but at lower temperatures the curves differ. Fig. 3b gives the results of the same experiment in an enlarged scale for all the three thermometers for SN2 and GHe operation around 60 K. It can be seen, that the temperature gradients between the cooling radiator, magnet and coolant are much larger for SN2 in comparison with GHe. The reasons are the lower thermal diffusivity and the absence of convection in the solid coolant. Another possible reason could be a poor thermal contact between the solid refrigerant and the HTS coil surface [7].

The comparison of the cooling processes in SN2 for the two-section HTS solenoid and its outer section only is given in Fig. 4. Despite the fact that the cryostat design didn't allow us to observe the N2 liquid-to-solid phase transition directly, some conclusions can still be made. Since the cold mass of the outer section itself was less than for the full magnet, the cool down process was faster with the average  $dT/dt$  of about  $1.4 \cdot 10^{-3}$  K/s, whereas for the full two-section solenoid it was equal to  $0.8 \cdot 10^{-3}$  K/s. It is interesting to note, that, as it was shown by other groups, LN2 must be solidified slowly in order to obtain crystalline rather than foamy SN2. The threshold cooling rate is ~ 0.001 K/s [7]. Thus, it can be concluded that in our experiments with the full solenoid we obtained crystalline SN2 with better cooling properties and foamy SN2 for the outer section.

This statement was also indirectly confirmed by the behavior of the curves after solidification. The temperature of the full solenoid in crystalline SN2 decreases faster,

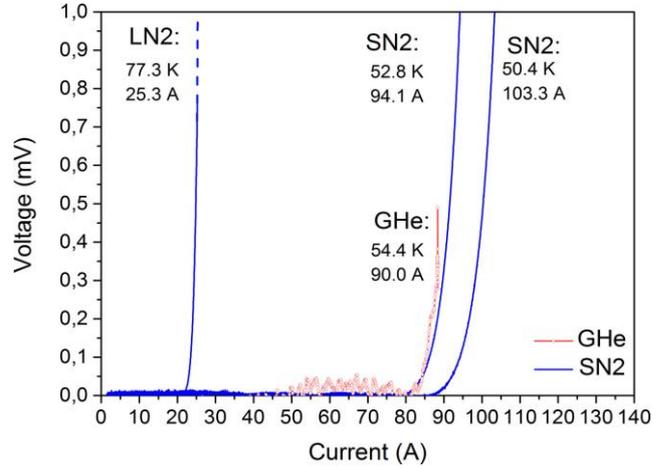


Fig. 5.  $V$ - $I$  curves for the standalone outer coil section measured in solid nitrogen and gaseous helium.

whereas the outer section temperature line seems to be almost saturated after 60 hours of the cryocooler operation.

### 3.2. Comparison of the HTS coil critical currents in SN2 and GHe.

Fig. 5 gives the  $V$ - $I$  curves for the standalone outer section of HTS solenoid measured in SN2 (the blue curves) and GHe (the red curve). The dependency of the critical current vs. temperature for the outer magnet section is shown in Fig. 6. It can be seen that the achieved critical properties of the coil do not depend on the coolant.

### 3.3. SN2 REBCO coil operation.

The comparison of  $I$ - $B$  curves measured at different temperatures in N2 is given in Fig. 7. The total magnetic field of REBCO coils is a combination of the fields generated by transport current and screening current induced in sc layers [11]. This is the reason why the both curves in Fig. 7 demonstrate a slight hysteresis during the charge/discharge process. The maximal currents achieved in the experiments were consistent with the critical properties of the REBCO tape in the corresponding external magnetic field.

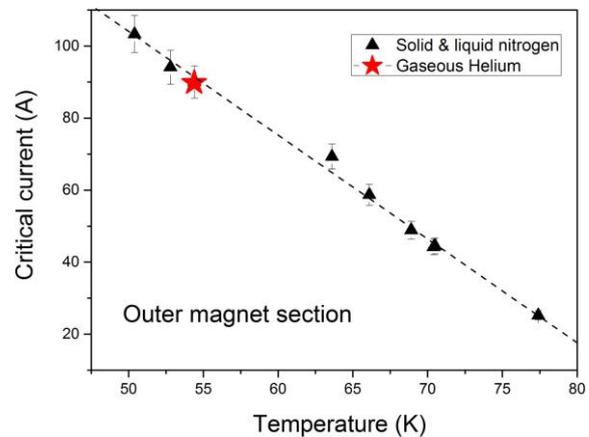


Fig. 6. Critical current ( $1 \mu\text{V}/\text{cm}$  criterion) vs. temperature plot for the outer magnet section measured in liquid/solid nitrogen and in gaseous helium.

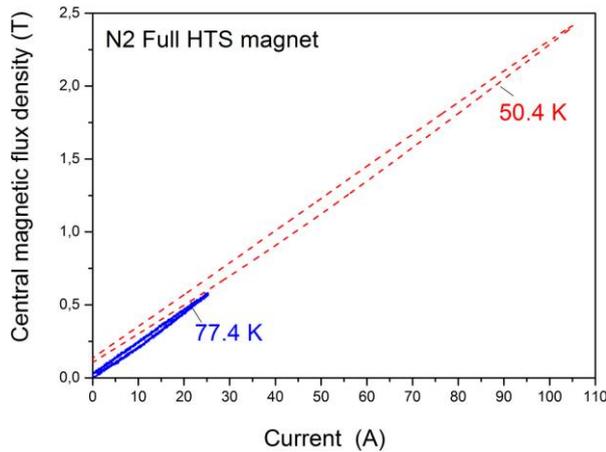


Fig. 7. Magnetic field in the centre of the full two section solenoid vs. current measured in liquid/solid nitrogen.

## RESULTS AND DISCUSSION

Working toward HTS high gradient magnetic separator we have conducted an additional research on the model REBCO solenoid cooled by either sub-cooled/solid nitrogen or gaseous helium in 50 – 77 K range. The comparative experiments showed that the both coolants are interchangeable in the terms of critical currents achieved by the HTS coil. Using LN2 instead of warm GHe helped us to save 10 hours of the cooling time, but the temperature gradients appeared to be larger in SN2, whereas GHe maintained much more uniform temperature environment around the magnet. It was also confirmed that slower cooling process with the cooling rate less than 0.001 K/s is preferable since it allows to get crystalline (not foamy) SN2 with better cooling properties. The magnetic field generated by the HTS solenoid at 50 K in SN2 corresponded to the critical properties of the HTS tape.

Basing on this preliminary test program we initiated the extended tests on the full-scale separator REBCO coils, including persistent mode operation and stability investigation (to be published elsewhere).

## ACKNOWLEDGMENT

The work was supported by the Russian Ministry of Science and Education through the agreement № 14.604.21.0175, 26/09/2017, RFMEFI60417X0175. The authors are very grateful to Mrs. Maria A. Demytyeva for her help with the proof reading of this paper.

## REFERENCES

- [1] E. Sheehan, J. Pfothenauer, F. Miller, and O. Christianson, "Quench detection and protection of an HTS coil", *IOP Conf. Ser.: Mater. Sci. Eng.*, 278 012182, 2017.
- [2] O. P. Anashkin, V. E. Keilin, I. A. Kovalev, A. V. Krivykh, I. I. Akimov, and A. K. Shikov, "Cryogen-free HTS coil placed in a heat-exchange gas", *Cryogenics*, vol. 42, pp. 295–297, 2002.
- [3] H. Miyazaki et al, "Progress in the development of conduction-cooled REBCO magnets for ultrahigh-field MRI systems", *IEEE Trans. Appl. Supercond.*, vol. 27, no.4, 4300805, 2017.
- [4] L. Liu, Y. Chen, H. Zhang, W. Chen, X. Pan, M. Xu, X. Yang, and Y. Zhao, "Quench behavior comparison between solid nitrogen and conduction cooled REBCO coated conductor", *IEEE Trans. Appl. Supercond.*, vol. 28, no. 8, 6602905, 2018.
- [5] J. Ling, J. Voccio, S. Hahn, T. Qu, J. Bascuñán, and Y. Iwasa, "A persistent-mode 0.5 T solid-nitrogen cooled MgB2 magnet for MRI," *Supercond. Sci. Technol.*, vol. 30, 024011, 2017.
- [6] Y. Iwasa, "Towards liquid-helium-free, persistent-mode MgB2 MRI magnets: FBML experience," *Supercond. Sci. Technol.*, vol. 30, 053001, 2017.
- [7] T. Nakamura, I. Muta, K. Okude, A. Fujio, and T. Hoshino, "Solidification of nitrogen refrigerant and its effect on thermal stability of HTSC tape," *Physica C*, vol. 372, pp. 1434–1437, 2002.
- [8] D. N. Diev, V. M. Lepelin, M. N. Makarenko, A. V. Polyakov, V. I. Shcherbakov, D. I. Shutova, and M. I. Surin, "REBCO split coil magnet for high gradient magnetic separation", *Proc. 27<sup>th</sup> ICEC & ICMC, Oxford, England, 3-7th September 2018*, 502, 012105, 2019.
- [9] D. N. Diev, V. M. Lepelin, M. N. Makarenko, A. V. Polyakov, V. I. Shcherbakov, D. I. Shutova, and M. I. Surin, "HTS high gradient magnetic separator prototype," *Prog. in Supercond. and Cryogen.*, vol. 20, no 4, pp.1-5, 2019.
- [10] D. N. Diev, V. M. Lepelin, M. N. Makarenko, A. V. Polyakov, V. I. Shcherbakov, D. I. Shutova, and M. I. Surin, "Test results of HTS split magnet for high-gradient magnetic separator," to be presented in EUCAS 2019, Glasgow, UK.
- [11] H. Ueda, Y. Imaichi, T. Wang, A. Ishiyama, S. Noguchi, S. Iwai, H. Miyazaki, T. Tosaka, S. Nomura, T. Kurusu, S. Urayama, and H. Fukuyama, "Numerical simulation on magnetic field generated by screening current in 10-T-class REBCO coil", *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, p. 4701205, 2016.