Demonstration of kA-Class Rutherford Cables using MgB_2 Wires for an Energy Storage Device Suitable for a Liquid Hydrogen Indirect Cooling

T. Yagai, M. Takahashi, R. Inomata, T. Takao, T. Onji, T. Komagome, Y. Makida, T. Shintomi, N. Hirano, T. Hamajima, A. Kikuchi, G. Nishijima and A. Matsumoto.

***Abstract*—Superconducting Magnetic Energy Storage (SMES) has been a promising option amongst potential other storage devices to support world-wide demands for introducing more renewables into the utility grid. If MgB_2 strands are used for SMES, liquid hydrogen, one of the renewables, could be used not only as a clean energy source but also as a coolant for the superconducting device. For large-scale coil design, mechanically fragile multi-filament strands should be used for their low AC loss feature considering that the transport current inside the coil would be always changing. To realize such a design, we designed and fabricated the large current capacity for AC-use Rutherford cable, together with experimental tests for its feasibility assessment. Based on the latest test results and development of commercial MgB_2 strands with high mechanical strength, and this research and development of kA-class cable at liquid helium temperature for extrapolating the critical current (I_c) at hydrogen temperature, we believe this approach has the potential to make a practical SMES device with MJ capacity. In this paper, the world's largest-capacity AC cable design and test results including critical current evaluation under several background field strengths are shown, and the stability and current re-distribution are also discussed.**

***Index Terms*—Superconducting Magnetic Energy Storage, MgB2, liquid hydrogen temperature, large-scale Rutherford Cable.**

I. Introduction

RECENTLY, energy storage devices have been drawing technological attention due to the rapid increase in power generation from renewable energy sources into utility grids [1]. As demonstrated over 50,000 times load-leveling field test, Superconducting Magnetic Energy Storage (SMES) with several MJ capacity is still one of the most promising devices for stabilizing the power grid [2] [3]. Alongside the rapid development of liquid hydrogen supply chain, the SMES made of a superconducting commercial wire attracts both scientific and commercial interests because liquid hydrogen can be used not only as an energy source without emitting carbon into atmosphere when it's burned, but as a coolant for superconducting materials. In terms of the critical temperature, T_c, of the material, MgB_2 round wires with a T_c around 39 K seems suitable. Another option might be REBCO tape, which has much higher T_c, however, making large-scale coils with the tape reportedly causes serious critical current degradation of the coil due to de-lamination between the substrate and the superconducting layer [4].

Compared to REBCO tapes going with delamination issue and being hard to produce with long-length, MgB_2 round wire has been rapidly commercialized and become affordable during the last decade. Not only the cost reduction of the large-scale coils, but easier handling in the winding process based on its circular cross-section, are big advantages for coil applications.

As for coil applications, these should be classified into DC and AC ones. In terms of the DC applications, the coils for Magnetic Resonance Imaging (MRI) have been making progress because the applied background field strength was at most several tesla, which is below the critical field of MgB_2. To ensure mechanical strength and avoiding degradation of I_c, fine, monofilament strand types have been chosen for some studies and showed good performance in Rutherford cables [5]. Focusing on a mechanical strength of multifilament MgB_2 wires for handling, a multi-filament strand was also introduced by A. A. Amin, which had a rectangular cross-section, for making single-wire coil winding, which would not suffer from complex bending and deformation [6]. There are some works accomplished making multi-stranded, Rutherford cables without serious I_c degradation by using thin wires (almost half diameter of our wire), with less-number of strands [5]. As for the availability of the strands to Rutherford cables, a demonstration has been made by L. Kopera. The cables have made using multi and single filament and the cable critical currents were showed in both 20 K and 4.2 K, in which the cable with multifilament one had

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T. Yagai, M. Takahashi, Ryo Inomata and T. Takao are with the Department of Applied Science and Technology, faculty of Science and Technology, Sophia University, 7-1, Kioi, Tokyo, 102-8554, Japan (e-mail: tsuyoshi-yagai@sophia.ac.jp).

Taiki Onji, is with Railway Technical Research Institute, 2-8-38, Hikari-cho, Kokubunji, Tokyo, Japan

T. Komagome is with Mayekawa MFG, 3-14-15, Botan, Koto, Tokyo, 135-8482, Japan.

Y. Makida and T. Shintomi are with High Energy Accelerator Research Organization., 1-1, Oho, Tsukuba, Ibaraki, 305-0801, Japan.

N. Hirano is with National Institute for Fusion Seience , 322-6, Oroshi-cho, Toki, Gifu, 509-5292, Japan.

T.. Hamajima is with Tohoku University, 6-6-05, Aoba, Aramaki, Aoba, Sendai, 980-8579, Japan.

A. Kikuchi, G. Nishijima and M. Matsumoto are with Ntional Institute for Materials Science, 1-2-1 Sengen, Tsukuba, Ibaraki, 305-0047 Japan.

less Ic and seemed to be not optimum for applications need large current capacity cables [7].

To introduce the wire into large coils with continually changing current flow, the assembled cable with multi-filamented strands would be the best to lowering AC losses during operation. Our project named ASPCS to develop SMES coils with stacked Double Pancake (DP) coils has almost been completed [8]-[10]. A demonstration of a three-DP device with 10 kJ stored energy, indirectly cooled by liquid hydrogen will be performed by the end of 2021. The DP coils were wound with several types of thin Rutherford cable, by both Wind and React (W&R) and React and Wind (R&W) methods. We decided to adopt the latter for larger-scale cable and coil fabrication through several tests and the ease of handling [11], [12]

On the other hand, the issue of introducing multi-filament strand has been investigated in the last project, in which the cables with 600 A rated current in 10 kJ coil system showed unpredictable deterioration [13]. Through that project, it was observed that strands made with Continuous Tube Filling and Forming (CTFF) [14] were seriously damaged due to deformation in its cross-section, even when the applied bending strain was well below the permissible one. During the research activity, new strands have been developed by SamDong Co. Ltd, consisting of Nb seamless tubes for Mg and B packing, making it stronger against cross-sectional deformation [15]. In this paper, we will report test results of basic performance, stability and current re-distribution of newly developed kA-class Rutherford cable for changing current use, aiming for applying future MgB_2 SMES with MJ capacity.

II. Strand Selection and Cable Preparation

A. Strand Choice for a Rutherford Cable with large-current capacity

The strand specifications that we chose for making kA-class Rutherford cable is shown in Table I. The diameter is 0.83 mm, identical to that by HyperTech Research Inc. fabricated with the CTFF method. While the MgB_2 fractions are almost identical, the Cu fraction, 30% in the SamDong wire, is much larger than the 12% for HyperTech 30-NM strand. The critical current density Jc provided by the supplier is 900 A/mm^2 at 2 T, 20 K, which is preferable for our cable design. The remarkable feature of the strand is very high permissible bending strain before heat treatment, as high as 6 %, which is much larger than that of HyperTech strand of 4 %. This allows us to make a wider cable containing a large number of strands to achieve high transport current [10], [11], [13].

B. Conductor design considering bending strain distribution

As for the twist pitch decision, we firstly consider the thermal stability of the cable in the worst situation of full quench for all strands. We already published how to design a thermally -stable cable assembly, see [10]. As a consequence, we decided to make 24-strand Rutherford cable.

Next, we calculated the relation between maximum bending strain and cable twist pitch. The result is shown in Fig. 1. The strain distribution was estimated by spatial curve theory that we already introduced for the cable design work [10], [11]. The maximum strain is around 4.5%, which is below the permissible limit. After adjusting the cable compaction, the resultant cable width and the thickness were 10.2 mm and 1.55 mm, respectively. Total length of the cable for demonstration was around 20 m, which depended on the purchased wire length. The specifications of the designed cable are summarized in Table II.

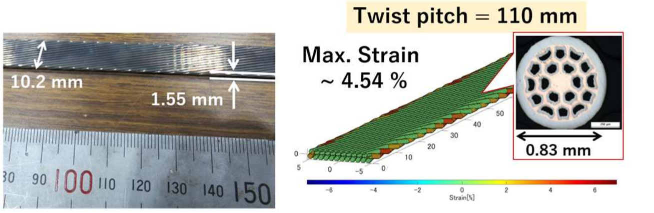

Fig. 1. Rutherford cable design result and the photo of the cable (after heat treatment). Maximum strain is around 4.5 % which is below the permissible one.

TABLE II
Rutherford Cable Design Parameters

Items	Values
Twist pitch	110 mm
Cable width	10.2 mm
Cable thickness	1.55 mm
Length produced	20 m
Max. strain	4.54 % before heat treatment
Cable length	625 mm
Heat treatment	straight
Insulation	None
Expected Ic at 2 T, 20 K	1.9 kA

III. Experimental Setup

A. The kA-class Cable Demonstration settings

The conductor tests were performed in the device at the National Institute for Fusion Science. The SULTAN-like but much smaller device is shown in Fig. 2. A pair of conductors, the

TABLE I
Specification of MgB2 Round Wire

Items		Values
Strand Diameter		0.83 mm
Number of filaments		18 +1 Cu
Jc at 20 K, 2 T		900 A/mm^2
Ratios of constituents	MgB2	16 %
	Nb	22 %
	Cu	30 %
	Monel	32 %
Permissible strain	Before heat treatment	> 6 %
	After heat treatment	0.24 %
Heat treatment condition		650°C, 1 hr, Ar

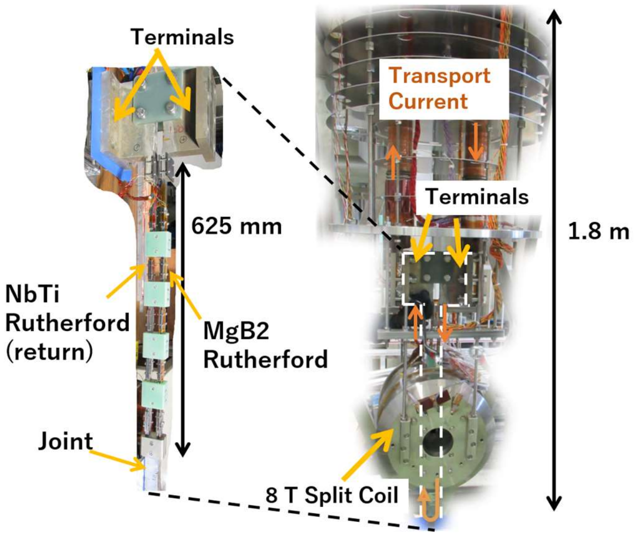

Fig. 2. The test device of Rutherford cable performance at NIFS.

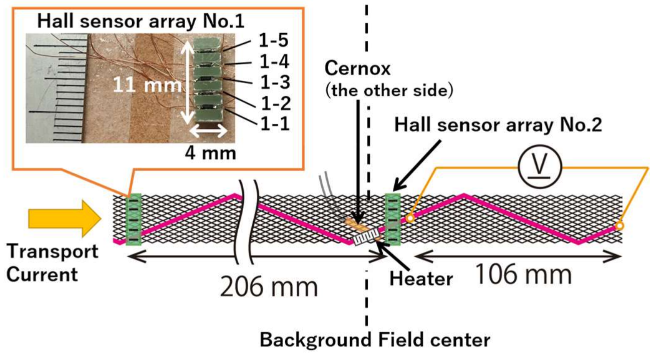

Fig. 3. Schematic of measurement setting. A heater for quench initiation is located at the background field center. One of two Hall-sensor arrays was equipped at 206 mm from a heater and close to a heater The sensor HG-166A is 1.5 mm square, 0.6 mm in thickness.

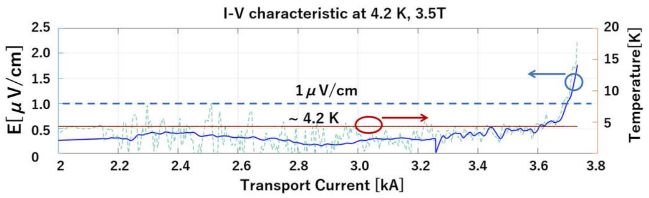

Fig. 4. Typical wave form of voltage runaway as a functions of transport current. A solid horizontal line shown here is the temperature around the field center, which indicates the voltage occurrence was caused by over current under the field of 3.5 T.

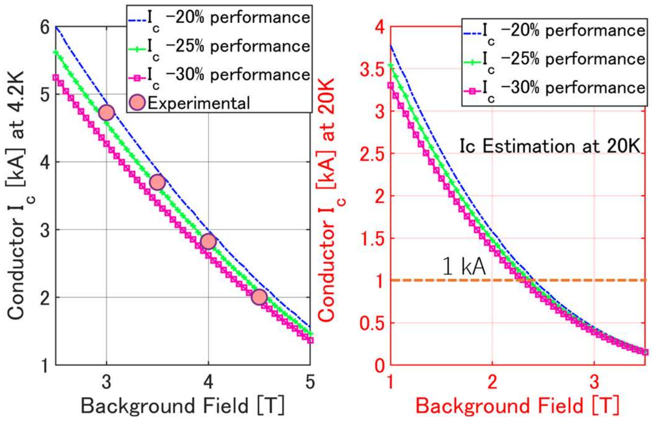

Fig. 5. I_c of the cable at various background fields. The curves at 20 K are the numerical estimations assuming the same deterioration observed at 4.2 K. Larger than 1 kA in 2 T field would be successfully expected.

Rutherford test sample through which the transport current is supplied and a Nb-Ti Rutherford cable for return current are soldered at the bottom joint. The lengths of the conductors are around 625 mm, being held between a pair of stainless steel plates 3 mm in thickness and fastened with four GFRP blocks to endure against electromagnetic forces under the background magnetic field.

The background field is applied by Nb-Ti split coil located at around the center of the conductors, that has around 100 mm uniform field region, with a maximum 8 T. The liquid helium pool cooled device is connected to power supply which can provide up to 10 kA transport current.

B. Measurement setup

To conduct the evaluation of cable performance, and voltage taps, a Cernox temperature sensor and Hall-effect sensor arrays using HG-166A are settled on the cable as shown in Fig. 3. A heater is located at the background field center to allow straightforward quench initiation. The voltage taps are equipped at the down-stream side of the transport current flow direction, separated by a distance of 106 mm, which is almost equivalent to the twist pitch. The strands that the taps equipped are the adjacent two strands on which the heater was attached, so that the transport current would be promptly shut down with the shortest time lag of voltage runaway. In addition to the voltage measurement, a well-calibrated temperature sensor was glued on the other side of the heater and thermally insulated from the coolant by epoxy to detect the cable temperature elevation. The resistance of the heater is estimated as 2.75 Ω at 4.2 K, and a thermal equilibrium calculation showed the heater would reach temperature of 150 K when a heater current of 2.5 A was applied for 0.5 s.

IV. Experimental Results

A. Ic-B Characteristics

A typical wave-form of the measured relation between transport current and voltage is shown in Fig. 4. A background field of 3.5 T is applied. The dashed line parallel to the horizontal axis indicates the electric field criterion of 1μV/cm applied. The electric field trend (blue solid curve) is obtained by digital smoothing of the noisy dashed curve. The solid line parallel to the horizontal axis is the temperature, which shows a constant

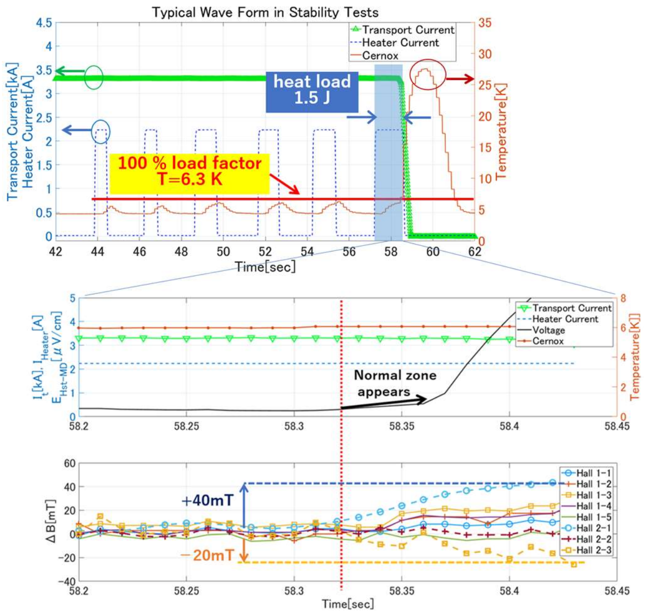

Fig. 6. Test result of quench initiation by heater current. The current re-distribution is observed by two hall-sensor arrays after normal zone appears.

4.2 K around the center of the background field. The estimated I_c based on the criterion is around 3.7 kA.

Figure 5 indicates the I_c dependence on the background magnetic field. The points in Fig. 5 are derived from the I-V curves, an example of which is as shown in Fig. 4. The curves in Fig.5 are calculated based on the J_c characteristics of the strand provided by SamDong, multiplying by a deterioration factor to be chosen for experimental data fit. A deterioration of 25 percent seems to provide a good fit. Assuming that the deterioration would not change at other operating temperatures, the expected cable I_c at 20 K from a database provided by SamDong would be around 1.5 kA [15][16], which is enough to achieve the design current in liquid hydrogen cooled condition.

B. Stability Test

In addition to the I_c test, a stability test was also performed. The heater of 0.27 Ω resistance at 4.2 K is able to induce a 145 K temperature elevation on the strand surface when a 2.5 A current is applied for 0.5 s, in accordance with the thermal equilibrium calculation. The background field strength 3.5 T is selected for this test, because a temperature elevation of just a few Kelvin at this field is sufficient to cause a transition to the normal state, causing the voltage to increase rapidly under the constant transport current around 3 kA, which indicates nearly 100 percent load factor of the conductor.

The upper part in Fig. 6 shows the wave forms when square-waves heater current is applied with monotonically increasing durations until quench (shown as a dashed line). The line with triangle markers represents the constant transport current of around 3.2 kA, and the solid bumpy line in orange shows the temperature detected by the Cernox sensor. An additional horizontal line indicates the temperature corresponding to a 100 percent load condition, which is about 6.3 K under the operating condition of around 3.2 kA transport current in 3.5 T. The last heat pulse, with a duration around 1.1 s, apparently initiated a quench, with the temperature rapidly increasing even after the heater pulse ended. The lower part of Fig. 6 is an enlargement around the time 58 s, just showing voltage elevation and self-magnetic field variations detected with the Hall sensor array catching the field component across the conductor width produced by the current along the conductor axis. The solid lines show the field variation measured by a set of sensors at a location 200 mm away from the heat source, and dashed lines with marks indicates the variation at the location close to the heat source. The field change detected by the sensors far from the heater (solid lines) shows less amplitude than that close to the heater. The field change at the center of the conductor, on which the heater is installed, showed 20-mT field strength reduction from the field around the conductor with constant and uniform current distribution. The reduction is estimated to be equivalent to one-fifth of the original current of two adjacent strands caused by the quench initiation. On the other hand, the sensor near the conductor edge detected a 40 mT increment of the field strength, for which we couldn't give any quantitative explanation so far. It might be the current concentration, proportional to the distance between the quench point and the strands that carry excess current transferred from the temporarily degraded strands. And the maximum amplitude of variations at the location far from the heater showed a 20 mT field strength rising, suggesting the current distribution might be more complex. We think further investigation must be done through thermal equilibrium simulation for estimating the temperature profile across the width and along the conductor length, together with precise measurements of magnetic field variation with higher spatial resolution.

V. Conclusion

As commercially-available MgB_2 wires have been improving a mechanical strength and superconducting characteristics, a kA-class Rutherford cable for one order larger capacity than current SMES systems was designed and fabricated. The straight cable successfully demonstrated its high performance at the NIFS test facility, under the condition of 4.2 K liquid helium pool cooling with up to 5 T background field. Although the small deterioration of I_c was observed, the cable I_c in 20 K liquid hydrogen temperature with 2 T background field was estimated around 1.5 kA, much larger than the I_c of 10 kJ SMES coils, which will be demonstrated within this year. The stability test has indicated 1.5 J was the minimum quench energy. Current re-distribution has also been observed, but quantifying the phenomenon to assess the stability of the large-scale cable will require further study.

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