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PERFORMANCE OF MGB$_2$ SUPERCONDUCTOR DEVELOPED FOR HIGH-EFFICIENCY KLYSTRON APPLICATIONS

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Abstract

An 8-km long MgB$_2$ wire for a prototype klystron magnet was made and evaluated. The wire was made by a typical in situ method; it has 10 filaments and 0.67 mm in outer diameter. The homogeneity of I_c of this wire was evaluated by several methods. Deviation of I_c values in short sample wires was very small. In addition, the current sharing temperature of the MgB$_2$ magnet (made of two reels of wire 2.9 km long each) agreed well with the estimated value of the I_c-B-T properties in short sample wires. Based on the obtained results, it can be said that the I_c properties of the entire wire length are quite uniform.

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Performance of MgB_2 Superconductor Developed for High-Efficiency Klystron Applications

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***Abstract*—An 8-km long MgB_2 wire for a prototype klystron magnet was made and evaluated. The wire was made by a typical *in situ* method; it has 10 filaments and 0.67 mm in outer diameter. The homogeneity of I_c of this wire was evaluated by several methods. Deviation of I_c values in short sample wires was very small. In addition, the current sharing temperature of the MgB_2 magnet (made of two reels of wire 2.9 km long each) agreed well with the estimated value of the I_c-B-T properties in short sample wires. Based on the obtained results, it can be said that the I_c properties of the entire wire length are quite uniform.**

***Index Terms*—Critical current, high energy efficiency, homogeneity, MgB_2 wire.**

I. Introduction

The critical temperature of magnesium diboride is 39 K [1], which allows equipment containing MgB_2 wires and magnets to be made highly energy-efficient and liquid helium-free. Magnetic resonance imaging (MRI) using MgB_2 wires 1.6 km in length made by the *ex situ* method has already been implemented as the first practical use of MgB_2 [2]. *Ex situ* MgB_2 wires of over 3 km long were developed for making a magnet [3]. MgB_2 wires made by *in situ* method were also reported. A coil made with a 300-m long wire [4] and a coil with a 1.7-km long wire for MRI use [5] were successfully implemented. The use of MgB_2 is not limited to magnets; MgB_2 wires have been used as power cables in superconducting (SC) links at CERN [6] and in the Best Paths project [7].

For klystron use, we need DC solenoid magnets for focusing the electron beam. The power efficiency of the magnet is important because in an design option of the Compact Linear Collider 380 GeV (CLIC-380 GeV), the number of klystron magnets reaches 4,000–5,000 [8]. The power consumption of a typical copper magnet for klystron applications is 20 kW for cooling the Joule heat of the magnet [9], and in the case of a Nb-Ti superconducting magnet without liquid helium, the AC plug power is 6 kW, as shown in a previous study [10]. To achieve high efficiency magnets for klystrons (klystron magnets), we developed an MgB_2 wire and a magnet that can be operated at high temperatures and have low power consumption.

In the design of the MgB_2 prototype solenoid magnet, to achieve high efficiency, it is important to reduce heat penetration from room temperature to low temperature (superconducting coils) and to make the current leads of the magnet finer [11]. We chose the outer diameter of the MgB_2 wire to be 0.67 mm, thinking about workability of the coil winding. In addition, as the magnetic field at the magnet center is 0.7–0.8 T, two reels of 2.9-km long MgB_2 wires were needed. The homogeneity of MgB_2 wires is a very important characteristic, but there are not so many previous studies evaluating km-class MgB_2 wires. A 1.7-km long MgB_2 wire was wound as a coil and the good homogeneity of this wire was shown [5].

We made and cut an 8-km long wire to obtain two wires of 2.9 km length. We measured the I_c values of short wires sampled from the ends of these 2.9 km lengths i.e., at the 2250 m and 5150 m positions in the 8 km length, and then evaluated the I_c homogeneity. The data of I_c vs. the longitudinal position in the MgB_2 wire, in which a unit length is several km long, has not been reported in previous studies. These data can contribute to further research and practical applications of MgB_2 wires and magnets. A MgB_2 klystron magnet made by the Wind&React method was successfully operated, and the I_c homogeneity of the wire as a magnet was evaluated.

II. Experimental Details

A. 8-km Long MgB_2 Wire

The MgB_2 wire for the klystron magnet, with a unit length of 8 km, was made by the *in situ* method as follows. Magnesium powder (>99.8%) and boron powder (>98.5%, <250 nm; Pavezyum nano Boron) were mixed at a molar ratio of Mg: B = 1: 2 without a carbon dopant, because at high temperatures and in low magnetic fields a pure MgB_2 wire has higher J_c than a carbon-doped MgB_2 wire [12]. Ten filaments with a Fe barrier sheath and a Cu bar as a stabilizer were embedded into a Monel sheath, then cold-worked to be 0.67 mm in outer diameter. The unit length reached 8085 m at 0.67 mm diameter, and the wire was cut at the 150 m, 2250 m, 5150 m, and 8050 m positions as shown in Fig. 1.

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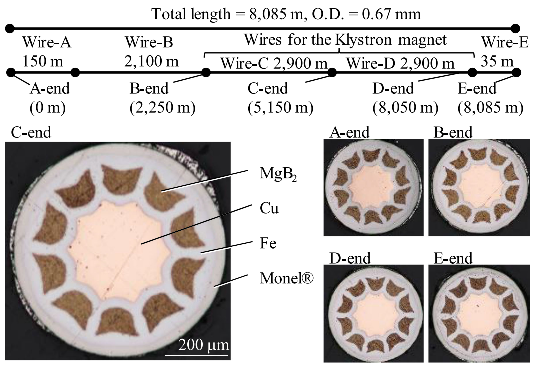

Fig. 1. Cross-sections of the MgB_2 wire. A-, B-, C-, D-, and E- ends are sampled from 0 m, 2250 m, 5150 m, 8050 m, and 8085 m positions respectively.

The lengths of the five resulting MgB_2 wires were 150 m as Wire-A, 2100 m as Wire-B, 2900 m as Wire-C, 2900 m as Wire-D, and 35 m as Wire-E. Two 2900-m long wires, Wire-C and Wire-D, were insulated with a glass braid and served for making the klystron magnet by the Wind&React method. The thickness of the insulation is typically 80 μm. If you need thinner insulation, Al_2O_3 layer can be used as the insulation as described in [13]. The ends of Wire-C are identified as B-end (2250 m) and C-end (5150 m), and those of Wire-D are C-end (5150 m) and D-end (8050 m).

Fig. 1 shows cross-sections at each end; almost the same cross-sections were obtained from 0 m to 8085 m of the wire. The MgB_2 filling factors of cross-sections obtained from B-, C-, and D- ends were 29.2%, 28.7%, and 28.9%, respectively. The sintering condition of this wire was 600°C for 6 h.

B. Measurement of I_c and Its Deviation in Short Sample Wires

The operating temperature of the klystron magnet was estimated as 20 K or higher, so the I_c-B-T properties of short samples picked from near the B-, C-, and D- ends were measured at 20 K, 25 K, and 30 K. The I_c values were measured by the typical four-probe method. The length of all short sample wires was 35 mm; the temperature of the wires was controlled using helium gas cooling and a heater. The criterion of the electric field was 1 μV/cm, and the distance between voltage taps was 5 mm. I_c values obtained from these three samples show the long-range homogeneity.

The short-range uniformity was evaluated by the I_c distribution as follows. To evaluate the I_c distribution of the wire, a lot of I_c data are required, so the distribution was obtained by I_c measurement with liquid helium bath cooling. The I_c values were measured by the typical four-probe method. The length of all short sample wires was 50 mm. The criterion of the electric field was 1 μV/cm, and the distance between voltage taps was 5 mm. The number of samples was twenty-one, and they were sampled from near the D-end. From the I_c values of these samples, the standard deviation σ was calculated, and the I_c distribution was evaluated with the normal distribution as the short-range homogeneity.

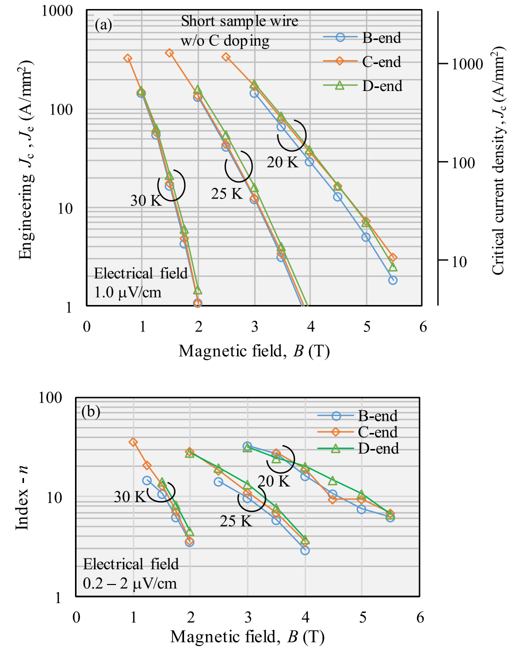

Fig. 2. (a) J_e (J_c)-B-T properties obtained from three short sample wires. (b) Index-n obtained from V-I curves on I_c measurement.

C. Homogeneity Evaluation of the MgB_2 Wire in a Magnet

Unlike in high-temperature coated conductors, the I_c values of the MgB_2 wire cannot be measured along the wire's longitudinal direction with liquid nitrogen bath cooling. Instead, we can evaluate the homogeneity of the wire by making a magnet and measuring the current sharing temperature T_{cs} of the magnet. Here, T_{cs} means the temperature at which some resistive voltage is generated in a part of the coil winding.

The method of measuring T_{cs} is written in the reference [11] and can be summarized as follows. First, achieve a steady state by bringing the coil winding to a certain temperature at a certain operating current I_{op}. Here, the coil winding was conduction-cooled by a cold head and the temperature distribution in the coil winding was estimated to be smaller than 1 K. Next, raise the temperature slowly and obtain the temperature at which some voltage generates resistivity of the normal zone in the coil winding. Then, the I_{op} dependence of T_{cs} (T_{cs}-I_{op}) can be obtained by changing I_{op}. We can also estimate T_{cs}-I_{op} from the I_c-B-T of the short sample wires. If the measured values agree with the estimated ones, it means that almost all the wires wound as a magnet have the same I_c-B-T properties.

Main specifications of the magnet are as follows. The inner diameter of the coil: 337 mm; the coil length: 136.6 mm; the number of turns in a coil: 2432, and the number of coils: 2. Details of these specifications are also written in reference [11].

III. Results and Discussion

A. I_c Values Measured at 20-30 K

Fig. 2(a) shows the results of I_c measurement obtained at 20–30 K. Distances from B-end to C-end and from C-end to

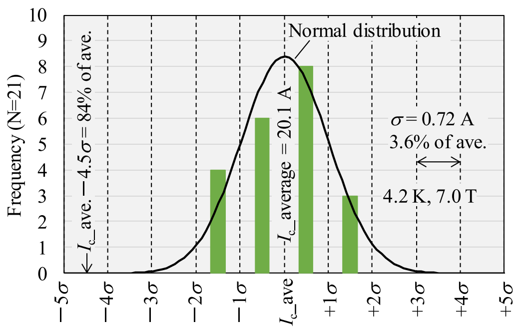

Fig. 3. I_c distribution measured with short wire samples from near D-end of the 8-km MgB$_2$ wire. $I_{c\cdot min}$ was assumed as $I_{c\_ave} - 4.5\sigma$.

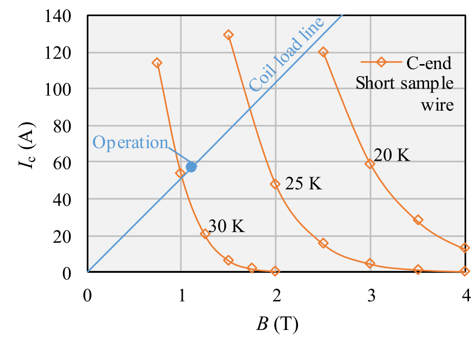

Fig. 4. $I_c - B - T$ properties measured from short sample wire (C-end) and coil load line of the klystron magnet. Operational current is 57.1 A and maximum magnet field is 1.06 T.

D-end were both 2900 m. The J_e and J_c were calculated from the cross-sectional area of the wire, filling factors of MgB$_2$ and I_c values. Deviation in J_e-B-T in these three samples at 20 K has been registered, but at 25 K and 30 K the properties were almost the same. These results show the possibility of superior homogeneity at practical temperatures across approximately 6 km of the wire length.

Fig. 2(b) shows the n values obtained from V-I curves for the I_c measurements shown in Fig. 2(a). There are some fluctuation on B dependences of n-values, but we can roughly summarise that the value n is 30 or higher in the condition of $J_c = 1$ kA/mm^2.

B. I$_c$ *Distribution Evaluated at 4.2 K*

Fig. 3 shows the I_c distribution at 4.2 K and 7.0 T measured with twenty-one short wires sampled every 70 mm from near the D-end. The averaged value of I_c (I_{c_ave}) was 20.1 A and the standard deviation (σ) was 0.72 A, which was 3.6% of I_{c_ave}. If the minimum value of I_c (I_{c_min}) is defined as $I_{c\_ave} - 4.5\sigma$, the I_{c_min} is 16.9 A and 84% of I_{c_ave}. According to the definition of the normal distribution, the probability that the sampled wires have lower I_c than I_{c_min} is 0.00035%. Based on these results, we can assume that the I_{c_min} of the entire 8-km wire is 84% of I_{c_ave}.

C. I_c *Homogeneity of the MgB$_2$ Wire Evaluated in a Magnet*

According to the design of the klystron magnet using Wire-C and Wire-D, the rated operational current is 57.1 A, and the maximum magnetic field of the coil winding is 1.06 T [11]. Fig. 4 shows a comparison between the coil load line of the magnet and the I_c-B-T property obtained from a short sample wire at the C-end. From this graph, we can estimate that the T_{cs} of the magnet at $I_{op} = 57.1$ A is 29 K. To estimate T_{cs} with high accuracy, the B values of the short sample wire (from the C-end) at $I_c = 57.1$ A and $T = 20$, 25, and 30 K were read out from Fig. 2. Then the (B, T) relation at $I_c = 57.1$ A was plotted in Fig. 5. The dashed line shows the fitting curve of the (B, T) relation at $I_c = 57.1$ A. Here, the maximum magnetic field in the coil winding in the case of $I_{op} = 57.1$ A is 1.06 T, so we can calculate from the fitting function written in Fig. 5 that T_{cs} at $I_{op} = 57.1$ A is 29.5 K. We can also estimate the T_{cs} values at other operating currents using the same method.

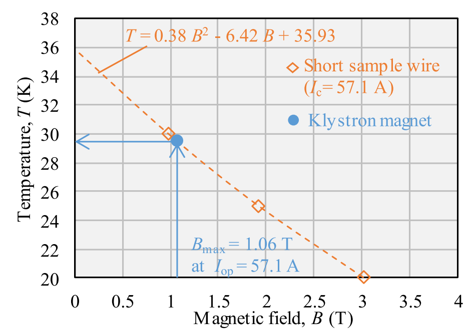

Fig. 5. B vs. T at $I_c = 57.1$ A obtained from I_c-B-T properties of short sample wire (C-end). The dashed line shows a fitting quadratic fitting function.

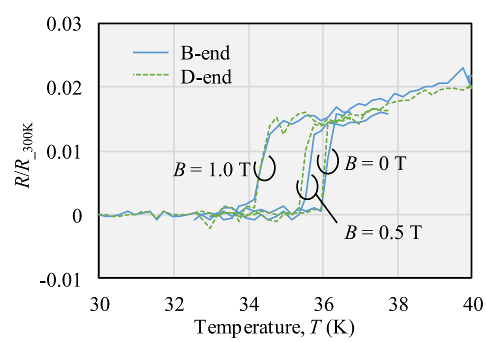

Fig. 6. Measurement results of temperature dependence of resistivity of short sample wires.

As shown in Fig. 5, T_{cs} at 0 T is expected to be 35.9 K. This estimation was confirmed by additional measurements as follows. The temperature dependence of the resistivity of a short sample wire was measured by the AC four-probe method (16 Hz, 10 mA) with the Quantum Design Physical Property Measurement System. Fig. 6 shows the results of measurements of the samples from the B-end and D-end whose lengths were both 10 mm. The vertical axis shows resistivity normalized by the value at 300 K. As shown in Fig. 6, 36.0 K is the threshold temperature for a measurable non-zero resistivity, and this value agrees well with the expected value from the fitting function shown in Fig. 5. Therefore, we can also estimate the T_{cs} values in the magnetic field range of 1 T or less.

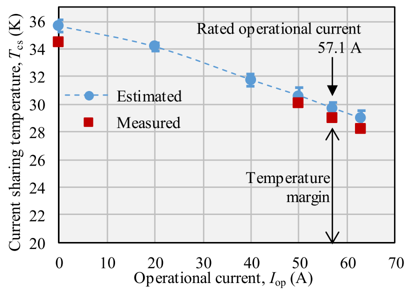

Fig. 7. Comparison of measured and estimated values of T_{cs}.

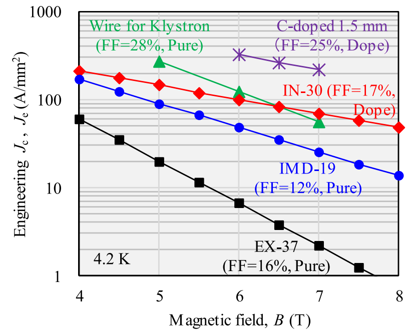

Fig. 8. Engineering J_c of MgB_2 wires measured at 4.2 K. Wire for klystron is the wire reported in this paper. J_e values of IN-30, IMD-19 and EX-37 were shown in a previous study [17]. The C-doped 1.5 mm wire was made by the *in situ* method and reported in our past study [4].

Fig. 7 shows I_{op} dependences of estimated and measured T_{cs} values (T_{cs}-I_{op}). The amplitudes of the error bars on the estimated values reflect the deviations of I_c-B-T in the three samples shown in Fig. 2. The T_{cs} were measured under a few values I_{op}. The largest I_{op} at T_{cs} measurement was 63 A, which was larger than the rated operational current (57.1 A), and the smallest one was 10 mA. All measured T_{cs} values agreed well with the estimated values within 1 K. This means that there is no I_c degradation in the coil winding, and the I_c-B-T properties of this wire are quite uniform. The reason for the difference between the measured T_{cs} values and the estimated ones could be the delay in temperature measurements.

As shown in Fig. 7, there is a 9 K or larger temperature margin at the rated $I_{op} = 57.1$ A, if the magnet is operated at 20 K as the temperature of the coil winding. According to the results of the quench tests, this temperature margin may be reduced [11]. Therefore, the magnet can be used at higher operational temperature, e.g., 25 K.

D. Next Steps

The I_c variation of the MgB_2 wire was small enough, and the magnet performance represented by T_{cs} was nearly equal to the estimated value. It can be said that the MgB_2 wire has ideal homogeneity for the Wind&React method.

The ideal process for making MgB_2 magnets is said to be the React&Wind method, so we should develop MgB_2 wires which can be used for the React&Wind method without I_c degradation. In the previous study, the bending tolerance of the MgB_2 wire at room temperature was the same as the one reported in this paper; the reversible bending radius of the wire sintered at 600°C for 6 h was 137 mm [14]. On the other hand, the inner radius of the coil for the klystron magnet is 168 mm. This indicates that the klystron magnet can be made with the MgB_2 wire using the React&Wind method.

In general, superconducting wires are expected to be used in magnetic fields higher than 1.0 T. For example, according to the previous studies, the maximum magnetic fields of 1.5 T MgB_2 MRI are 3.0 T [15] and 2.7 T [16]. For using MgB_2 wire in such intermediate magnetic fields, a carbon additive should be mixed into MgB_2 filaments. The J_c value at 20 K of the MgB_2 wire with 3% carbon additive made by Hitachi Ltd. is higher in the range of external magnetic fields of 2.3 T or more [12].

Fig. 8 shows the J_e properties of several MgB_2 wires at 4.2 K. Here, FF means the filling factor of MgB_2 in the cross-section of each wire, and Pure or Dope means non-carbon doped or carbon-doped MgB_2 wire. IN-30, IMD-19 and Ex-37 are the typical MgB_2 wires made by *in situ*, IMD and *ex situ* method, respectively [17]. The wire for klystron magnets has higher J_e compared to other typical wires in 6.5 T or lower magnetic field. In addition, C-doped 1.5 mm wire was made by Hitachi Ltd. [4] and it has the highest J_e between 6 T to 7 T. It is expected that J_e values of the C-doped 1.5 mm wire are higher than those of the wire for klystron applications in 3 T or lower magnetic field mainly due to the carbon additive.

In this study, the MgB_2 klystron magnet was made by the Wind&React method with non-carbon doped MgB_2 wire. In the next step, we will make a magnet by the React&Wind method. If a higher magnetic field is needed, the carbon-doped MgB_2 wire will be selected.

IV. Summary

The homogeneity of the 8-km long MgB_2 wire was investigated by three measurements: (i) I_c-B properties at 20–30 K of three short wires sampled from every 2900 m, (ii) I_c distribution at 4.2 K of twenty-three short wires sampled from every 70 mm, and (iii) T_{cs}-I_{op} at the klystron magnet made with two reels of 2.9-km long wires. The results of evaluation of the homogeneity is summarized as the following four points:

1) Short wires sampled every 2.9 km have almost the same I_c-B-T properties at 20–30 K. This shows possibility of superior homogeneity across the wire of approximately 6 km in length.
2) Standard deviation of I_c values at 4.2 K was 3.6% of the average value of I_c, I_{c_ave}. The minimum value of I_c assumed as $I_{c\_ave} - 4.5\sigma$ is expected to be 84% of I_{c_ave}.
3) The T_{cs} values measured for the klystron magnet agreed well with the estimated values from I_c-B-T properties of the short sample wires.
4) It can be said that the performance of the 8-km long wire was uniform enough to make MgB_2 coils and magnets.

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