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著者	Vyatkin V. S., Otabe E. S., Ohya M., Matsushita T.
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Current-carrying capacity of single layer cable using superconducting Bi-2223 tapes in parallel magnetic field

V.S. Vyatkin[1, 2], M. Kiuchi[1, 2], E.S. Otabe[1, 2], M. Ohya[3] and T. Matsushita[1, 2]

[1]Department of Computer Science and Electronics, Kyushu Institute of Technology,
680-4 Kawazu, Iizuka 820-8502, Japan
[2]Advanced Low Carbon Technology Research and Development Program,
Japan Science and Technology Agency
[3]Osaka Works, Sumitomo Electric Industries, Ltd.,
1-1-3 Shimaya, Konhana-ku, Osaka 554-0024, Japan
vyatkin@aquarius10.cse.kyutech.ac.jp

Abstract

It was theoretically shown by the authors that the current-carrying capacity of superconducting DC power cable can be enhanced by choosing a force-free configuration under a parallel magnetic field produced by the current flowing back in the outer shielding conductor. This was experimentally checked for a single layer cable using Bi-2223 tapes in an applied parallel magnetic field. It was found that the current-carrying capacity took on a peak value under the force-free condition for the total magnetic field including the self-field. This shows that the proposed structure is suitable for practical DC power transmission. The possibility of the innovative DC superconducting power cable with multi-layers with higher current-carrying capacity is discussed.

1. Introduction

The authors proposed a new superconducting DC cable with high current-carrying capacity by introducing the so-called longitudinal magnetic field effect, i.e., the enhancement of the critical current density of a superconductor in the parallel magnetic field [1-4]. The essential points are (i) to use the current that flows back in the outer shielding conductor to apply the parallel magnetic field to the inner conductor and (ii) to realize the force-free configuration for the superconducting tapes of the inner conductor under the given parallel magnetic field. It was shown theoretically that the current-carrying capacity can be increased from that in conventional cables [5-7].

It is necessary, therefore, to check if this field configuration is useful for present HTS superconductors. In this work Bi-2223 tapes are used, since the field and field-angle dependence is not so much different from that of REBCO coated conductors in a relatively weak magnetic field inside power cables with moderate current-carrying capacities. Low costs of Bi-2223 tapes are also beneficial. We examined the critical current of a single layer cable using Bi-2223 tapes. It was found that the critical current had a peak value under the condition that the total magnetic field was parallel to the winding direction of the tapes. This agreed with our prospect, indicating that compact superconducting DC cable of 10 kA class or higher using Bi-2223 tapes can be realized by designing multi-layered cable based on the present scheme. Thus, the proposed cable is promising for transmission of large electric power in the future.

2. Experimental

We used type H Bi-2223 tapes of Sumitomo Electric Industries of 4.3 mm wide and 0.23 mm thick with the self-field critical current of about 200 A at 77.3 K. In order to measure the critical current of the tape in the parallel magnetic field, 13 tapes were arranged in parallel to the axis on a cylindrical Bakelite bobbin of 18.5 mm in diameter. Figure 1 shows Sample A with the straight tapes. The separation between the voltage terminals was 29.5 mm. This sample was placed in the center of a Bi-2223 coil that produced the magnetic field. The range of the uniformity of the magnetic field was about ±1.0% over the region of 90 mm along the axis and 20 mm in diameter. The DC current was supplied with a 6 kA current source and the voltage was measured with a nanovoltmeter. Figure 2 shows an example of the current-voltage curve. It was found that the curve is smooth up to the electric field of 100 μV/cm. The critical current was determined with the electric field criterion of 1 μV/cm. The *n*-value is about 10-12.

The dependence of the critical current on the parallel magnetic field is shown in Fig. 3. It is found that the critical current is almost constant up to 0.1 T and then, decreases with increasing magnetic field. This result is compared with the characteristics of a single tape. The observed critical current of Sample A in the self-field is about 10% larger than that of the single tape multiplied by the tape number, 13. This improvement can be ascribed to elimination of the normal component of the self-field due to the cylindrical symmetry in the cable configuration.

The result in Fig. 3 shows that the critical current density does not appreciably decrease up to 100 mT due to a small Lorentz force in this field configuration. This is a superior point in comparison with conventional multi-layer cables in which the superconductors suffer a normal field that deteriorates the critical current. However, under the parallel magnetic field of 100 mT, the magnetic field that the superconductors feel is not parallel to the tapes due to the self-field. The idea of force-free configuration suggests that the critical current can be enhanced by making the superconductor parallel to the total magnetic field.

Under the condition of the transport current of 2.80 kA, the transverse self-field is estimated to be 56 mT. If we focus on the condition of the highest longitudinal magnetic field of 100 mT up to which the critical current density is kept almost constant, the angle of the magnetic field on the outer surface of the superconductor is estimated to be 29.5◦. Hence, the superconducting tapes were tilted by 15◦, the mean angle that the tapes experience. Figure 4 shows Sample B wound with the twisted tapes. The same experiment was carried out for this specimen to determine the critical current. The observed critical current is shown in Fig. 5. The result of straight Sample A is also shown for comparison. It is found that the critical current is higher than that of Sample A and takes a maximum at around the longitudinal magnetic field of 80 mT. Although this field value is slightly smaller than the aimed value, 100 mT, the difference is not so large. Thus, the critical current characteristics can be improved by distributing the tapes parallel to the magnetic field.

The direction of the external magnetic field is also important. The external magnetic field should increase the longitudinal component of the magnetic field created by the twisted cable (self field). In the Fig. 5 shown also the result for Sample B when magnetic field in opposite to the optimal direction. Self field in this case decreases the external magnetic field. The current-carrying capacity in low fields decreases more than one for straight Sample A.

3. Discussion

The improvement of the critical current in Sample B proves that the proposed innovative cable is promising by designing the structure correctly. This technique can be extended to multi-layered cables with higher critical current even for Bi-2223 tapes. The diameter of the bobbin should be slightly larger than the present one in practical cables. The winding strain can be reduced, and the critical current can be improved because of a further reduction in the normal field component at the edges of the tapes. In the case of multi-layered cable, the parallel magnetic field can be strengthened by the twisted current, and it is not necessary to twist the tapes so tightly in the inner layers. This is also beneficial, since it reduces the difference in the angle between the field and current in each layer.

We suppose a three-layer cable, for example. If the diameter is of the innermost layer is increased to 25 mm, the critical current of this layer will be increased to 3.7 kA. Those of the outer layers will not be appreciably deteriorated by twisting suitably, although the self-field will increase up to about 170 mT. As a result, it is expected that the total current-carrying capacity of 10 kA can be achieved. On the other hand, if we consider a conventional three-layer cable of the same size, the critical current of the innermost layer will be 3.5 kA. But those of outer layers will be significantly decreased due to the self-field.

For a detailed comparison based on the analysis, we need to measure the magnetic field and field-angle dependence of the critical current density of a Bi-2223 tape, as shown in [6, 7].

Summary

We carried out a simulation measurement for the innermost layer of superconducting cable made of Bi-2223 tapes. The critical current took a peak value under the condition that the winding direction is parallel to the total magnetic field. It can be expected that this scheme is useful for realizing compact superconducting DC cable with high current-carrying capacity.

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Figure Captions

Fig. 1. Sample A with straight tapes

Fig. 2. Current-voltage curve of Sample A in the self-field at 77.3.K

Fig. 3. Critical current of Sample A vs parallel magnetic field. The characteristics of a single tape multiplied by 13 are also shown for comparison.

Fig. 4. Sample B with twisted tapes

Fig. 5. Critical current of Sample B vs parallel magnetic field. That of Sample A is also shown for comparison.

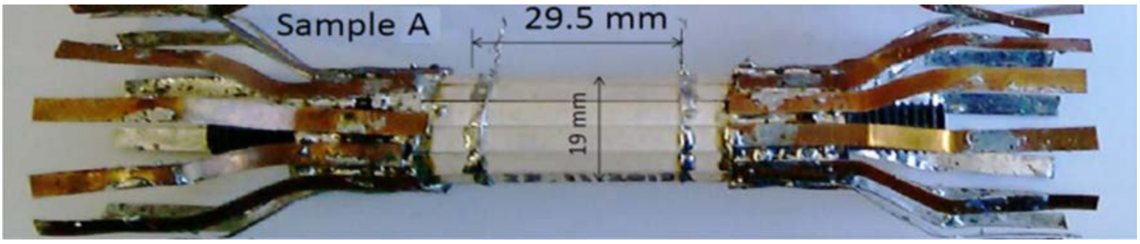

Figure 1; V.S. Vyatkin *et al*.

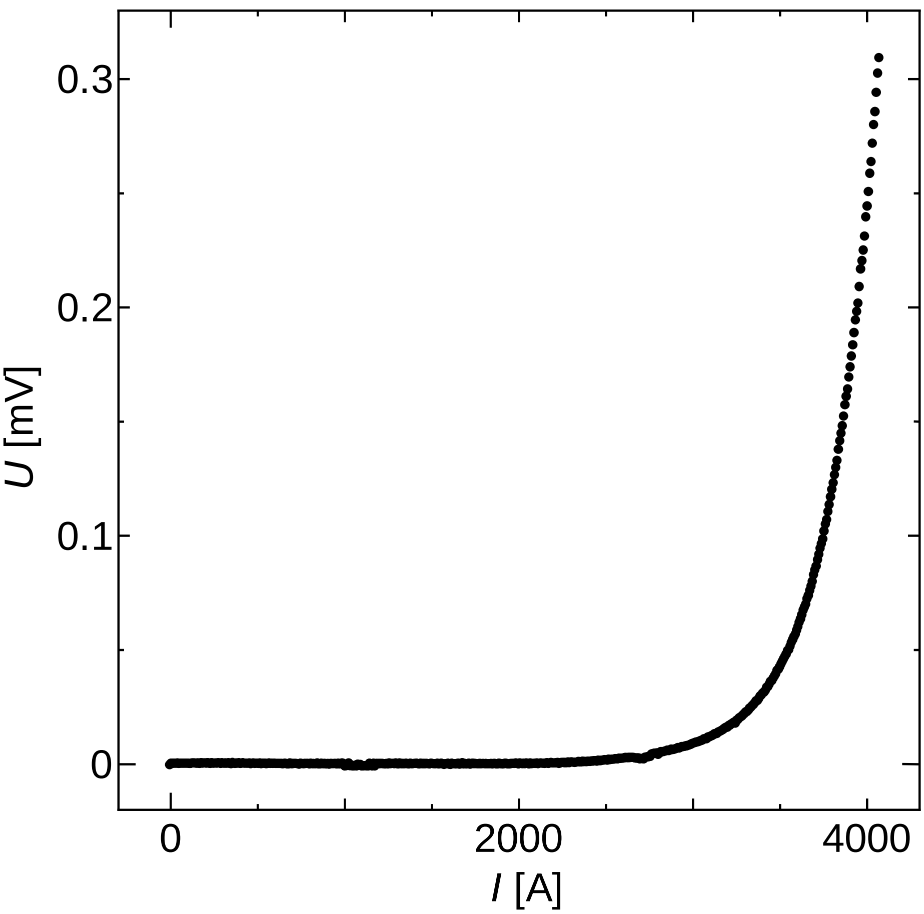

Figure 2; V.S. Vyatkin *et al*.

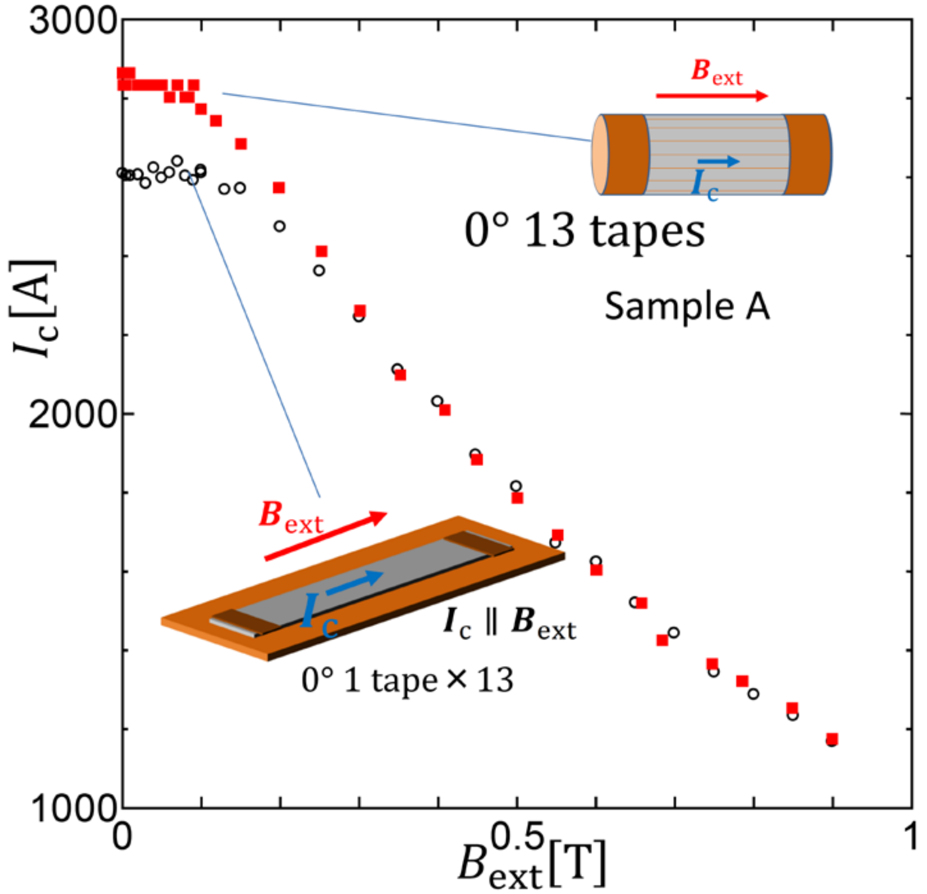

Figure 3; V.S. Vyatkin *et al*.

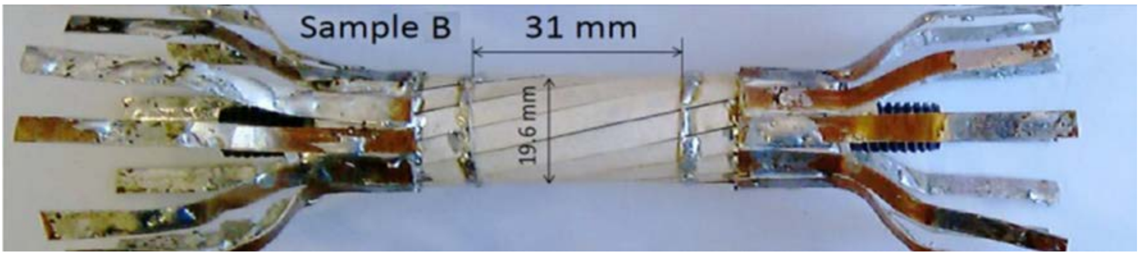

Figure 4; V.S. Vyatkin *et al*.

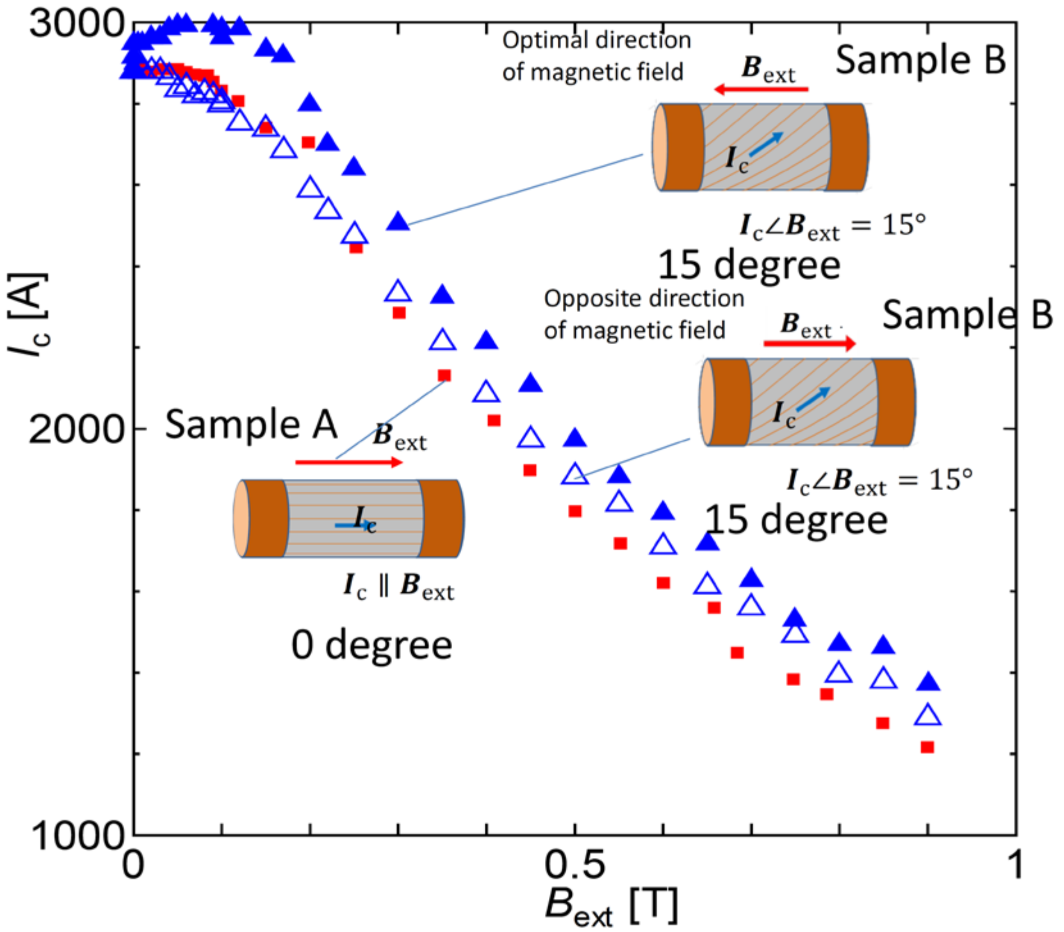

Figure 5; V.S. Vyatkin *et al*.