Innovative Superconducting DC Cable Using the Longitudinal Magnetic Field Effect

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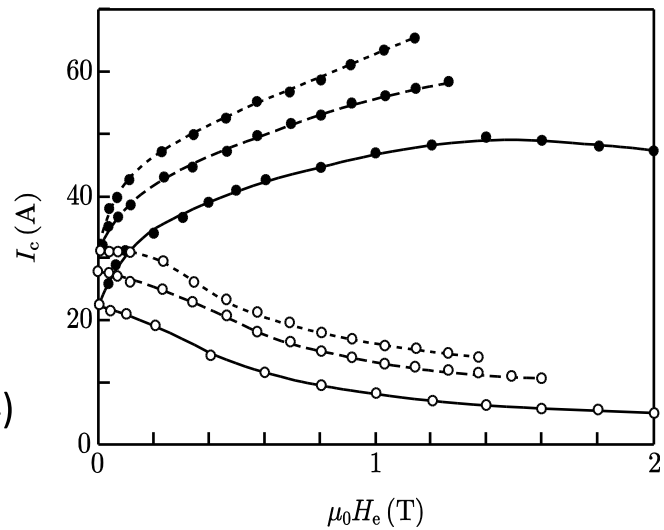
1. Introduction

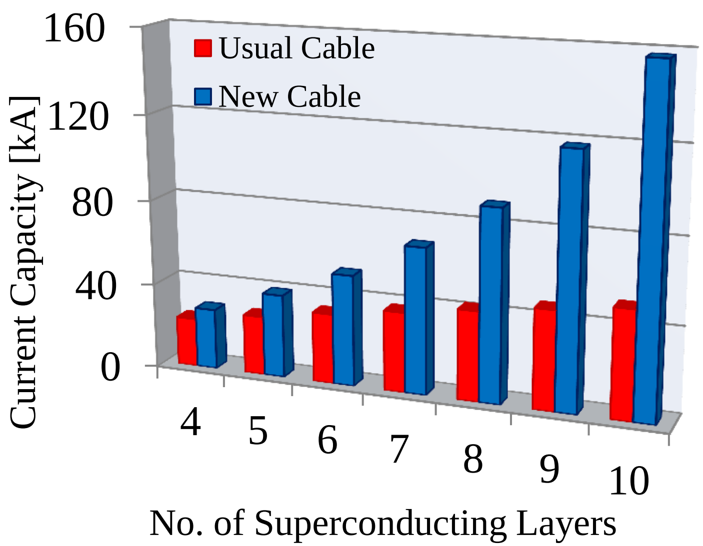
In a parallel magnetic field, J_c in metallic superconductors increased dramatically (longitudinal magnetic field effect)

Cullen & Novak
(Nb_3Sn tape, 1964)



Application of this effect to superconducting DC power cable was proposed. (T. Matsushita *et al.*, SUST **25** (2012))

Assumption; similar J_c properties in REBCO coated conductors as those in Nb_3Sn tapes

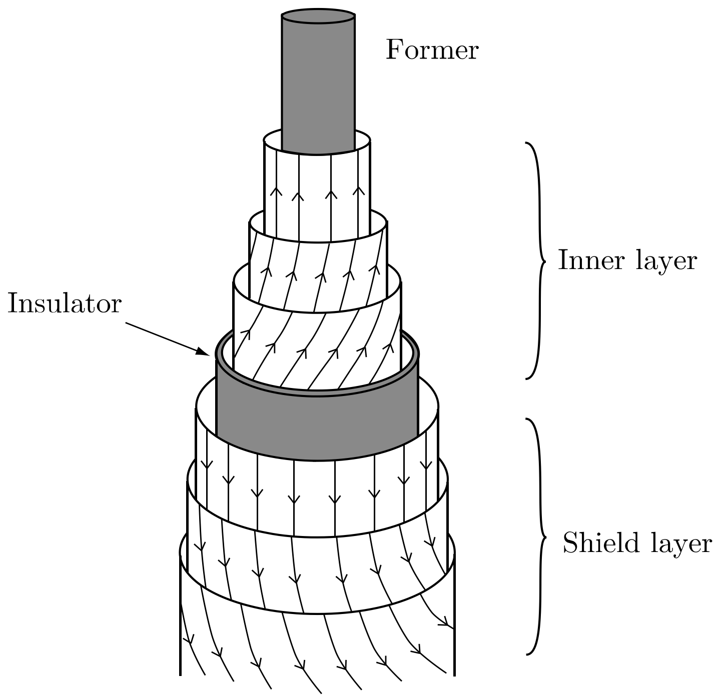


Concept of force-free cable

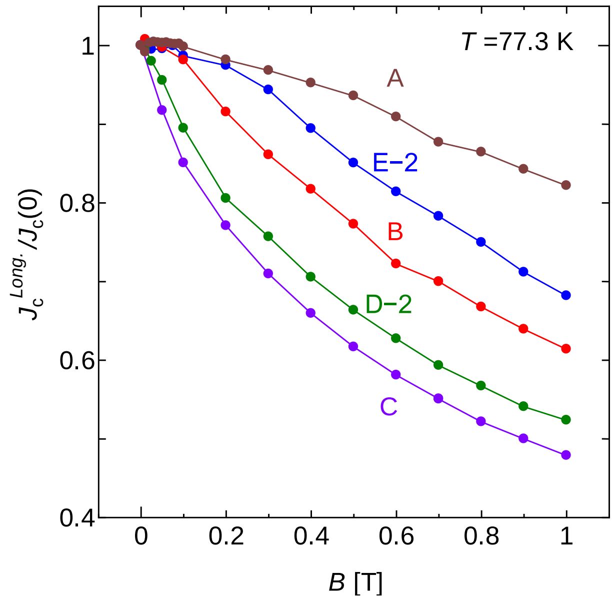
Shield layer is twisted so that the current flowing back in this layer applies a longitudinal magnetic field to the inner conductor region.

Superconducting tapes in the conductor region are arranged so that the force-free structure is attained under a longitudinal magnetic field produced by the shielding current.

Inner conductor region also produces a longitudinal magnetic field (paramagnetic effect)



However, the J_c does not enhance in the longitudinal magnetic field for commercial REBCO coated conductors!



The force-free structure is not optimum, and it is necessary to find out the new structure that can utilize the higher J_c in the longitudinal magnetic field.

2. Design of Innovative Superconducting DC Cable

Number of layers; n

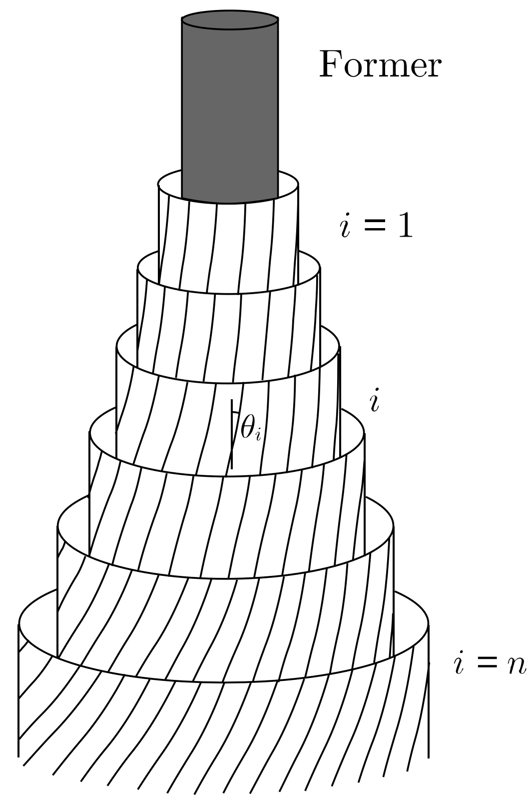
i-th layer

tilting angle from the axis; θ_i

$$\theta_i = \frac{2i-1}{2n}\theta_{\mathrm{m}}$$

winding radius; $R_i = R_0 + id$

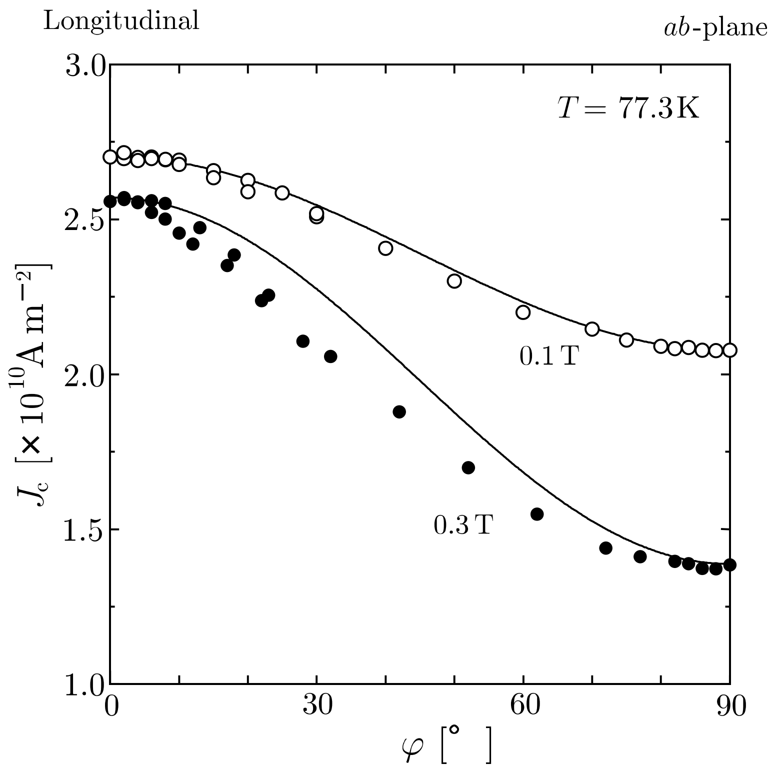
(d; tape thickness)

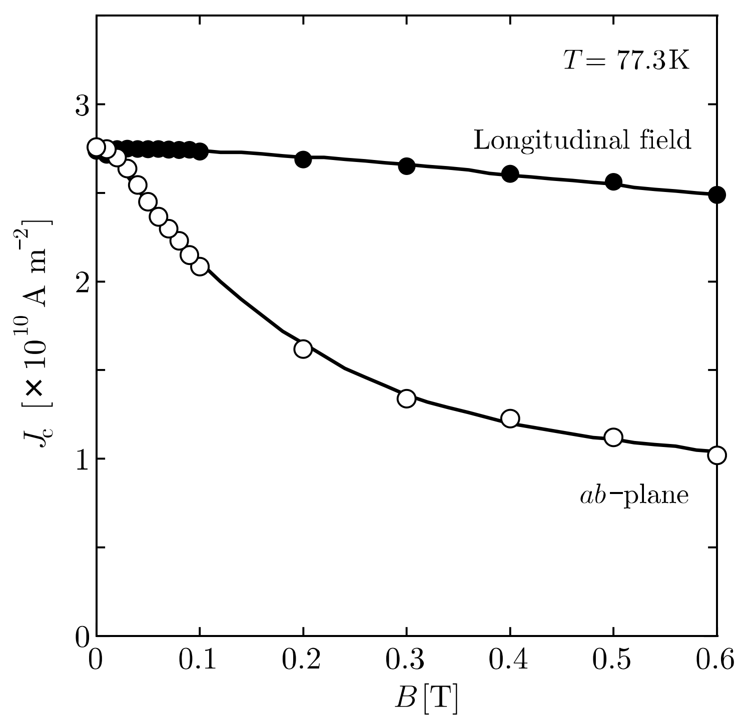


Field and field angle dependence of J_c

$$J_c(\varphi) = \frac{1}{2}(J_{cM} + J_{cm}) + \frac{1}{2}(J_{cM} - J_{cm})\cos 2\varphi$$

$$J_{cm} = J_c(\varphi = \pi/2)$$
$$J_{cM} = J_c(\varphi = 0)$$





$$J_{cM}(B) = \sum_{j=0}^{7} K_{Mj} B^j \qquad J_{cm}(B) = \sum_{j=0}^{7} K_{mj} B^j$$

Engineering critical current density; $J_{\mathrm{e}} = (t/d)J_{\mathrm{c}}$

(t; thickness of superconducting layer)

Current flowing in the i-th layer; $I_i = 2\pi R_i J_{\mathrm{e}i} d$

External longitudinal magnetic field produced by the current flowing in the shield conductor; B_{ext}

Magnetic field on the i-th layer

longitudinal $$B_{i\parallel} = \sum_{k=i+1}^{n} \frac{\mu_0 I_k}{2\pi R_k} \sin\theta_k + B_{\mathrm{ext}}$$

transverse $$B_{i\perp} = \sum_{k=1}^{i-1} \frac{\mu_0 I_k}{2\pi R} \cos\theta_k$$

Total magnetic field on the i-th layer

magnitude $$B_i = ({B_{i\parallel}}^2 + {B_{i\perp}}^2)^{1/2}$$

angle $$\varphi_i = \theta_i - \tan^{-1}(B_{i\perp}/B_{i\parallel})$$

Current-carrying capacity (critical current)

$$I_{\mathrm{c}} = \sum_{i=1}^{n} I_i \cos\theta_i$$

Critical current density of the i-th layer

$$J_{\mathrm{c}}(\varphi_i) = \frac{1}{2}[J_{\mathrm{cM}}(B_i) + J_{\mathrm{cm}}(B_i)] + \frac{1}{2}[J_{\mathrm{cM}}(B_i) - J_{\mathrm{cm}}(B_i)]\cos 2\varphi_i \equiv J_{\mathrm{c}i}$$

Iteration method

$$J_{\mathrm{c}i} = f(J_{\mathrm{c}1}, J_{\mathrm{c}2}, \cdots, J_{\mathrm{c}n})$$

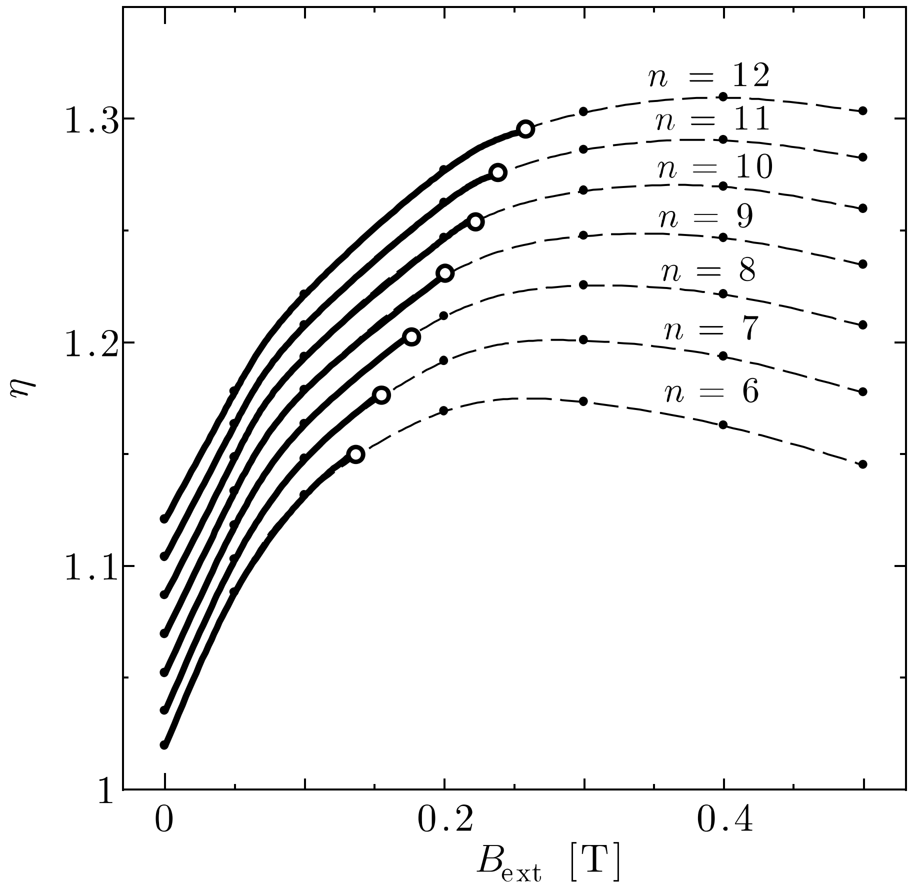
Initial condition; $J_{\mathrm{c}1}{}^{(0)} = J_{\mathrm{c}2}{}^{(0)} = \cdots = J_{\mathrm{c}n}{}^{(0)} = J_{\mathrm{cM}}(B = 0)$

Current –carrying capacity of usual superconducting cable

$$I_0 = \sum_{i=1}^{n} I_i(B_{\mathrm{ext}} = 0,\ \varphi_i = \pi/2)$$

Enhancement factor of current-carrying capacity

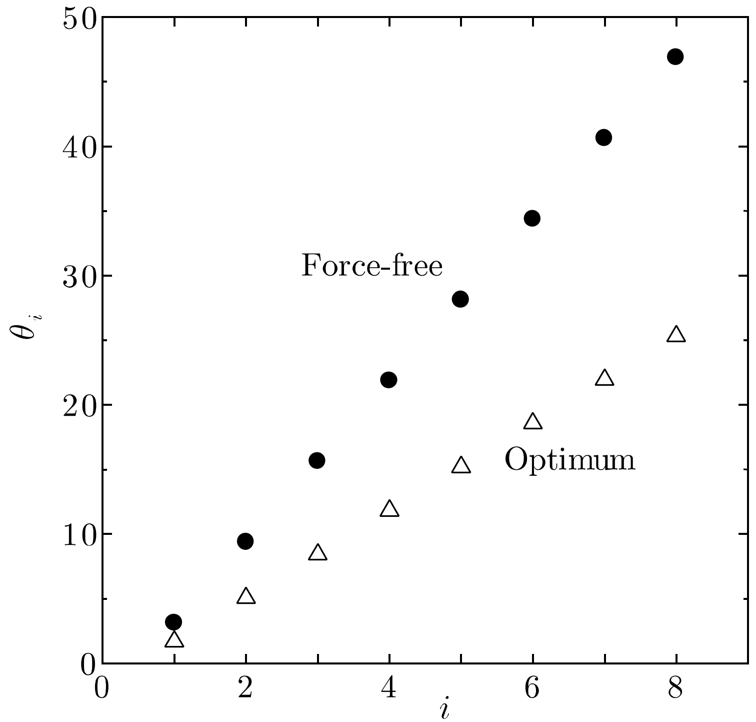
$$\eta = I_{\rm cm}/I_{\rm c0}$$



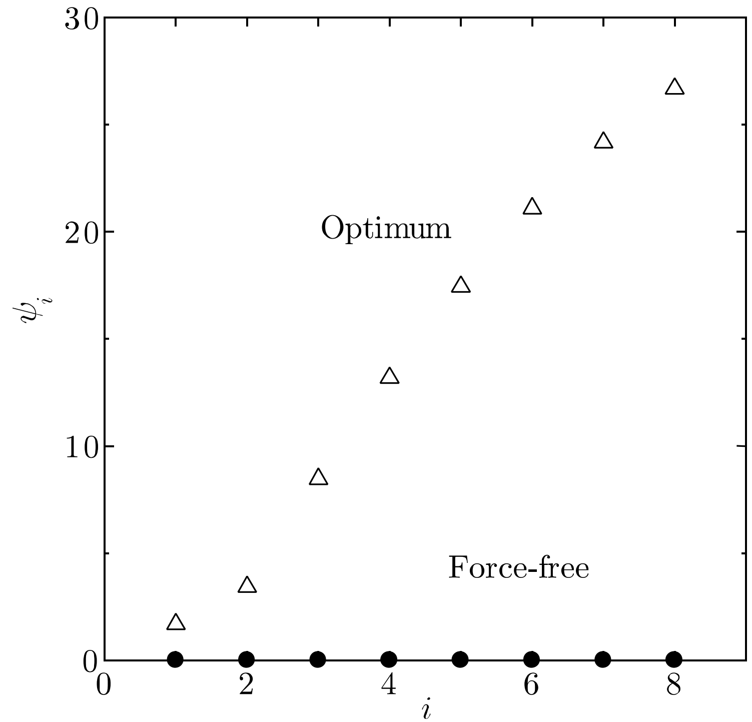
The current-carrying capacity can be enhanced by introduction of the proposed cable structure.

This scheme is applicable also for Bi-2223 tapes.

Winding structure of the cable



Distribution of twisting angle

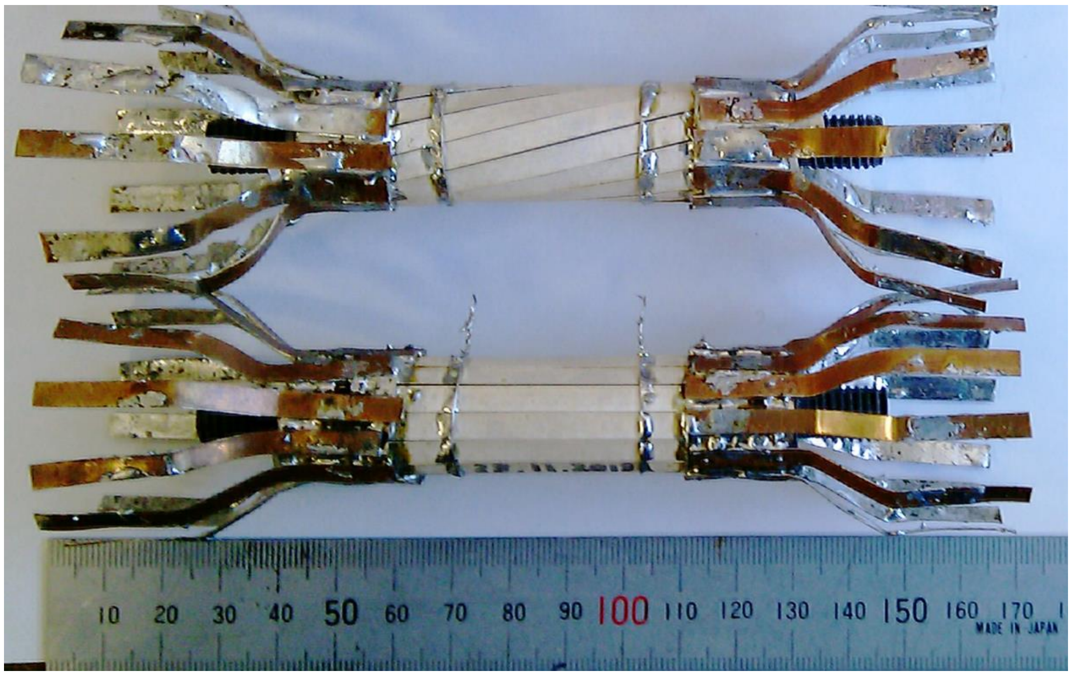


Field angle in each layer

It is expected that J_c in the longitudinal magnetic field can be improved in the future. In this case the force-free structure will be optimum.

3. Preliminary experimental research

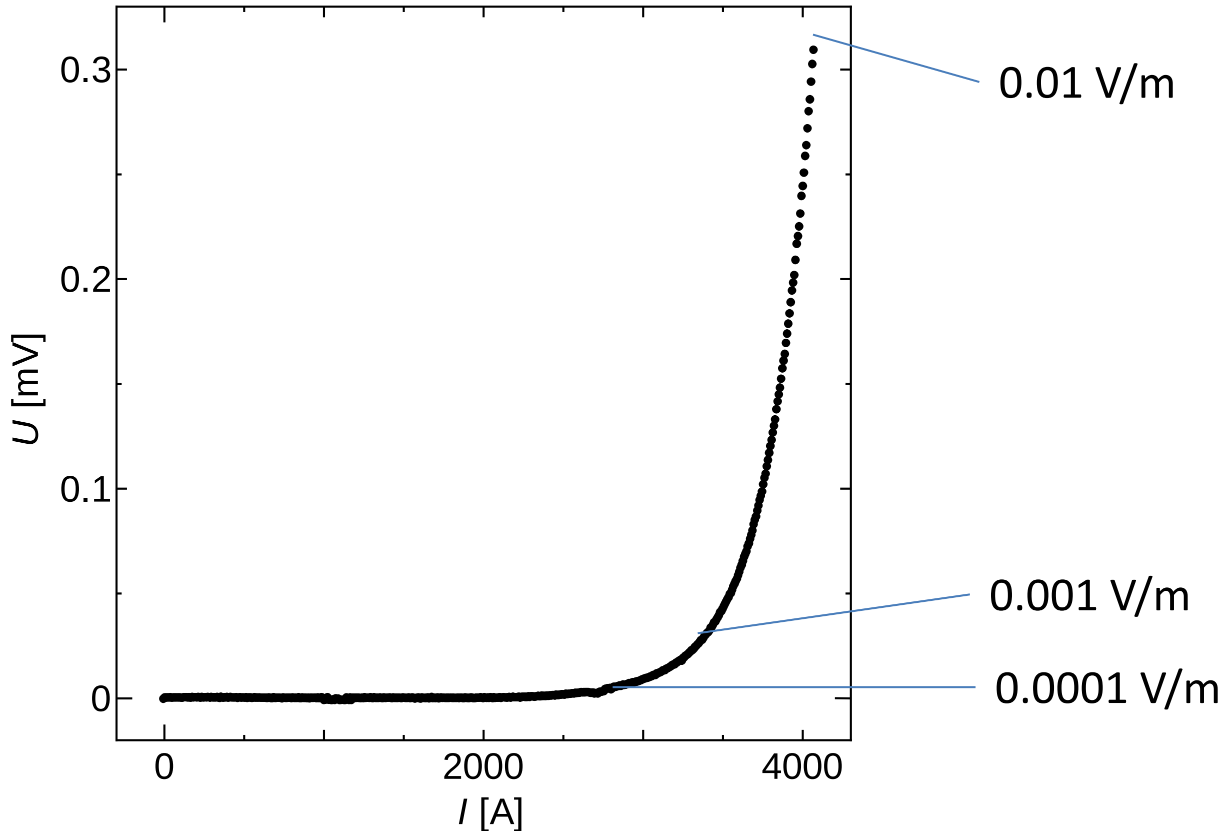
One-layer cable simulation with Bi-2223 tapes



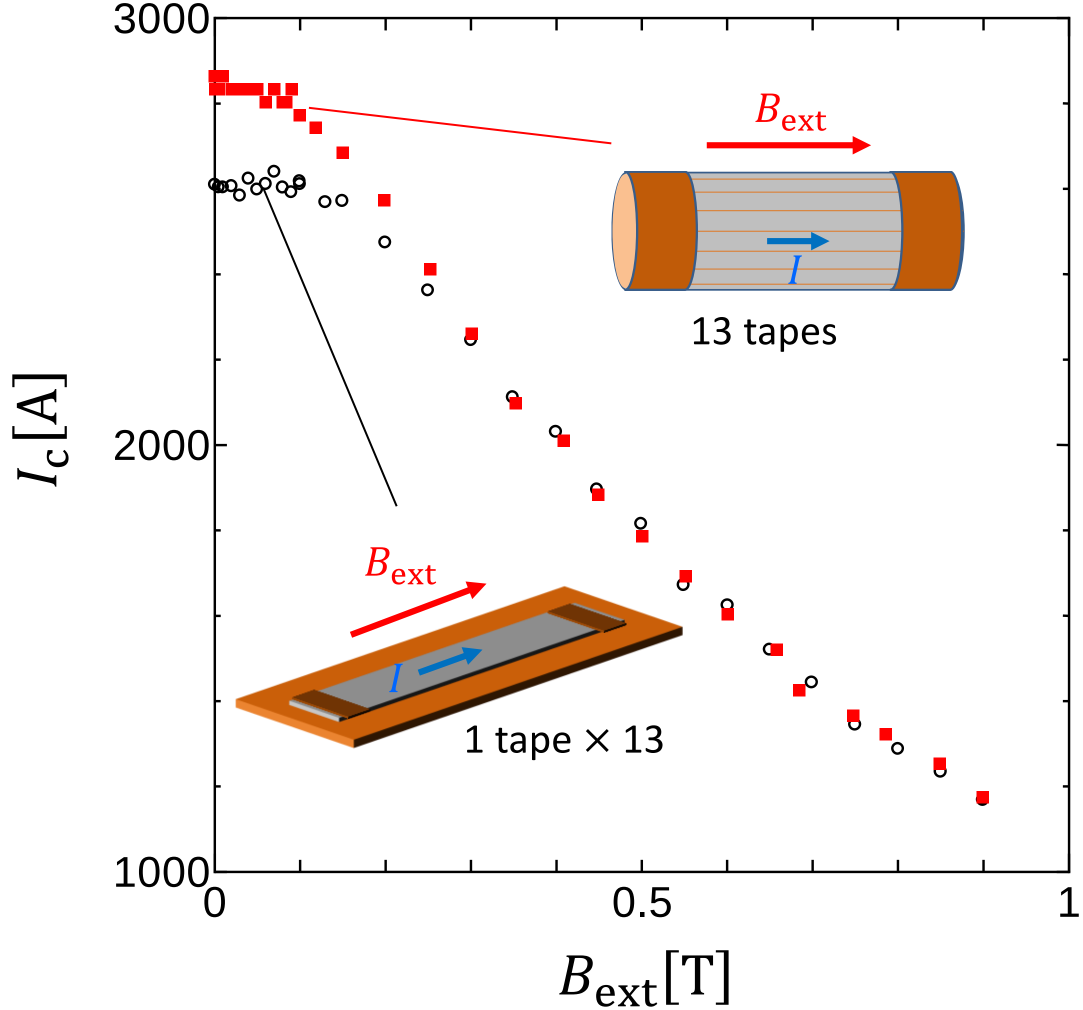
Tilted by
15 degrees

No tilt

Bobbin; about 20 mm in diameter
No. of tapes; 13
Longitudinal field is applied with a superconducting magnet



Smooth current-voltage curve is measured



(E_c= 1.0×10^{-4} V/m)

Higher I_c in the cable configuration is attributed to elimination of the normal field component.

I_c is almost constant up to 0.1 T

At 0.1 T the total magnetic field is not parallel to the superconducting tapes

It is expected that I_c can be increased by making the tapes parallel to the total magnetic field

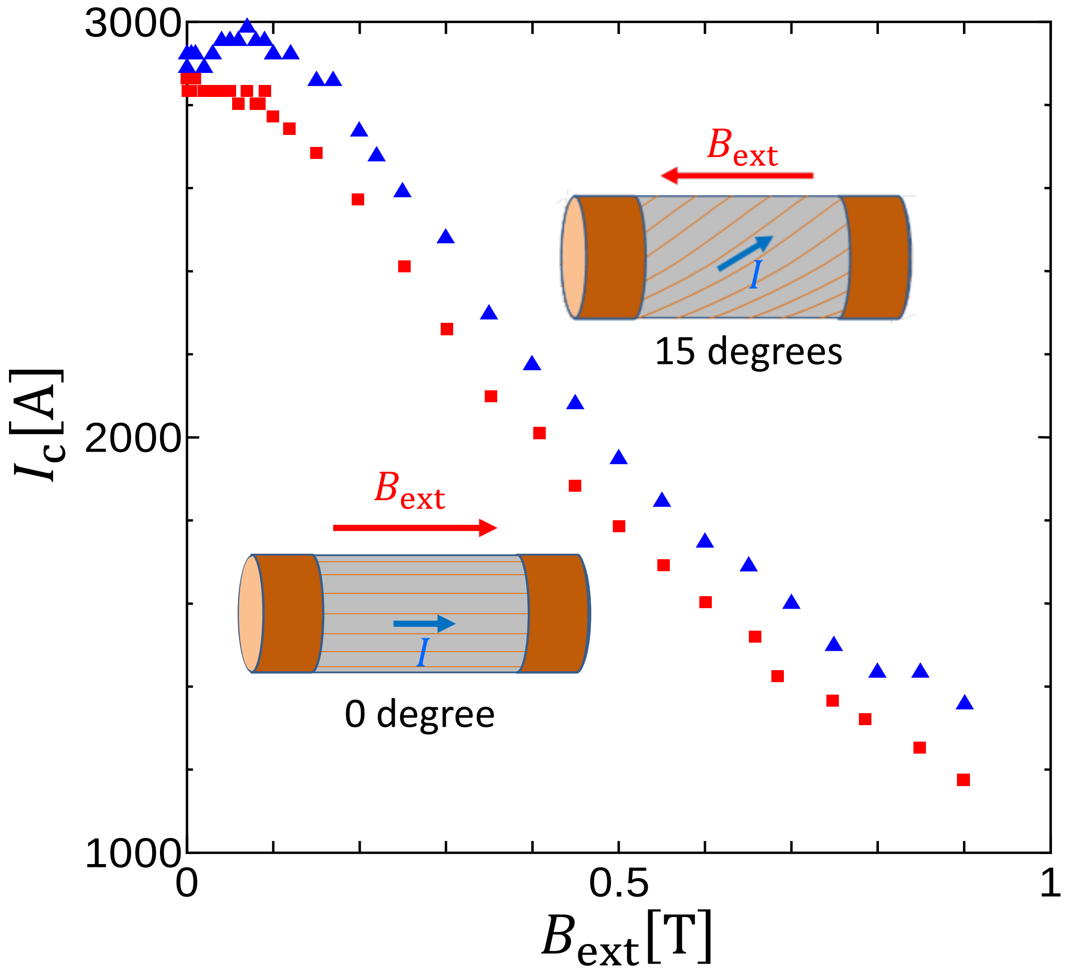
self-field: $B_\phi = \dfrac{\mu_0 I_\mathrm{c}}{2\pi R} = 56\ \mathrm{mT}$

field angle on the outer surface (φ): $\tan\varphi = \dfrac{B_\phi}{B_\mathrm{ext}} = \dfrac{56}{100} = 0.56$

⇨ $\varphi = 29.5^\circ$

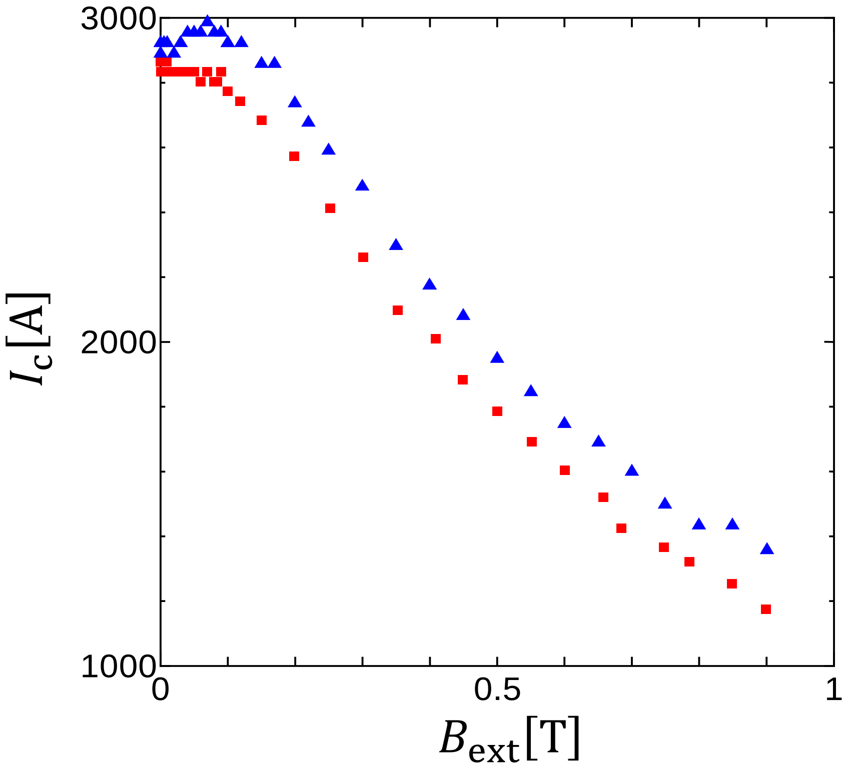
Angle of magnetic field: 0(inner surface) $\sim$ φ (outer surface)

⇨ Tapes are twisted by 15°



I_c is increased and has a peak at about 0.08 T for a twisted cable. The peak field is close to the aimed value, 0.10 T.

The concept of the innovative cable is proved.



Development of innovative cable of about 20 kA with Bi-tapes is promising.

It is because the maximum self-field is about 0.2 T;

serious degradation of I_c in conventional cables

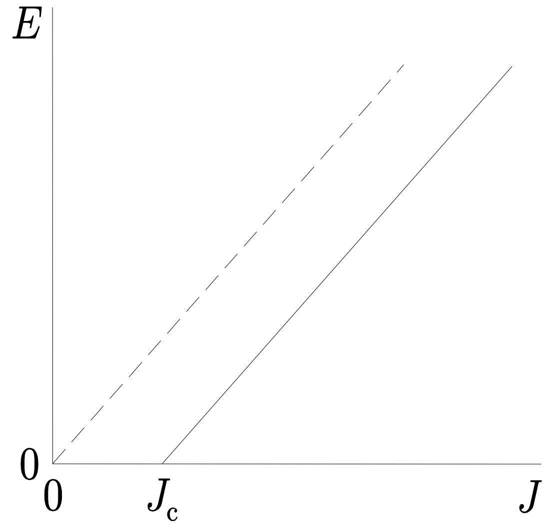
no appreciable degradation of I_c in the proposed cable

4. Fault-current limiting function in F-F cable

The principle of fault-current limiter of the resistive type:

appearance of high resistance at a current exceeding the critical density J_c

(utilization of the nonlinear property)



In this case, if J_c can be actively reduced, it is more effective.

In the force-free cable J_c is enhanced by application of longitudinal field.

⬇

J_c can be remarkably reduced by elimination of the longitudinal field.

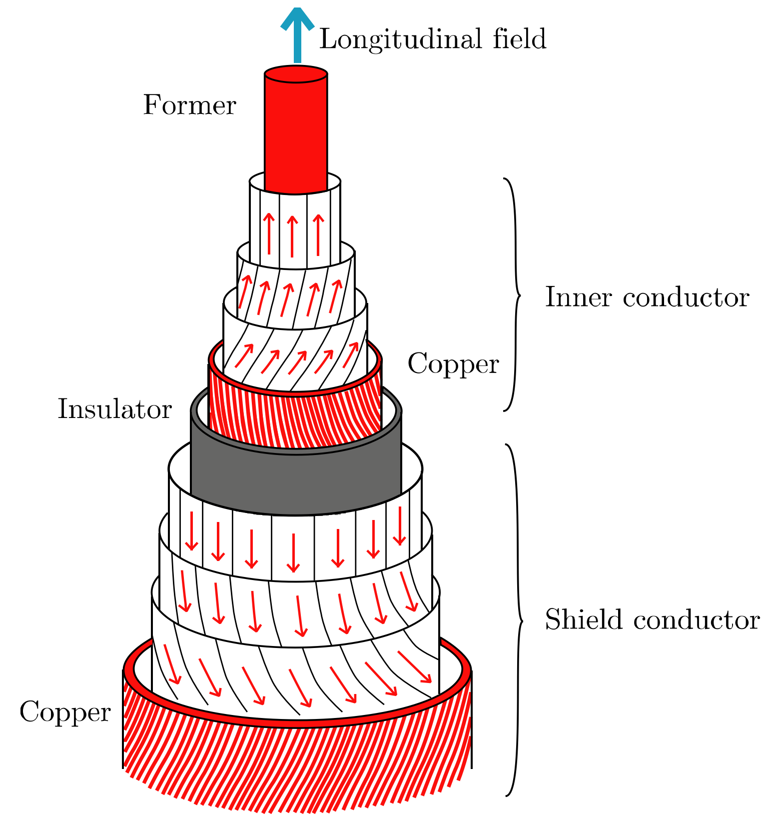
（This kind of operation cannot be achieved in conventional cables）

Design of cable

(a) The current-carrying capacity of the outer shield conductor is designed to be slightly smaller than that in the inner conductor.
(Beneficial from the viewpoint of cable cost)

(b) Copper wires in the outer shield region are twisted in the opposite direction to the superconductor to reduce the longitudinal magnetic field.

(c) Copper wires in the inner conductor region are twisted in the opposite direction to the superconductor to reduce the longitudinal magnetic field.



These make the resistive transition of the inner conductor to take place easily.

Force-free cable is assumed

I/I_t	Ratio of current flowing in Cu[%]	
	Conventional cable	**Force-free cable**
0.95	0	0
0.97	0	1.8
1.00	0	4.6
1.02	2.0	10.9
1.04	4.0	17.1

For the case of twisting angle of 35◦ for cupper wires
(The ratio is doubled for 40 ◦)

The increase in the temperature is not assumed.

5. Summary

We proposed the superconducting force-free DC cable with high current-carrying capacity. The back current in the shield conductor is used to produce an axial magnetic field and the force-free structure is introduced in the inner conductor winding under the axial magnetic field.

However, present commercial coated conductors cannot transport high critical current due to weak links of grain boundaries. For realization of this cable, development of high quality coated conductor is indispensable.

Then, we proposed the innovative superconducting DC cable with optimized wining structure that can be used for present coated conductors and Bi-tapes. Appreciable enhancement of the current-carrying capacity is predicted.

Summary (2)

One-layer simulation experiment was conducted with Bi-tapes. The critical current showed a peak under the parallel condition of current and magnetic field. This verifies the applicability of the proposed innovative cable with high efficiency.

The fault-current limiting function can be added to these cables by properly designing the copper wires for stabilization.