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Lightweight and large-current HTS stacked tape conductor

Shuhei Kawai, Masae Kanda, Yury Ivanov, Edmund Soji Otabe, *Member, IEEE* and Sataro Yamaguchi

***Abstract*—More electric aircraft (MEA) is one of the technical trends in the aviation field, and its merits are high safety, lightweight, easy to control, and good economy. Boeing 787 consumes almost ten times more electric power than conventional aircraft, so the power cable weight is ~ten times heavier than that of traditional aircraft. As a result, we need a lightweight and large current power cable for MEA. The power cable's conductor weight is heavy because of low voltage and large current in airplanes. We proposed developing high-temperature superconducting (HTS) DC cables because DC cables are more lightweight than AC cables. Its structure is a stacked conductor, and the current direction of each layer is opposite, and HTS tapes are insulated from each other. We also do not use the heavy copper former. We use the current lead resistance to make the current balance of each HTS tape. We made several types of stacked conductors in the laboratory using Bi2223 and RE123 tapes and tested them. Here, we report two experimental results; one is a twelve-layer stacked conductor using the Bi2223 tapes, and its shape is straight. The second one is to test the bending and twisting of a six-layer stacked conductor. Bending and twisting are necessary to lay the stacked conductor in any direction. The critical currents are 1196 A for the twelve-layer conductor, 639 A for the six-layer straight conductor, 607 A for the six-layer bent conductor, and 615 A for the six-layer twisted conductor.**

***Index Terms*—MEA, HTS power cable, aviation application, stacked conductor, current lead resistance, current imbalance**

I. INTRODUCTION

More Electric Aircraft (MEA) [1, 2] was proposed to enhance safety and improve the economy of aircraft from the beginning of the 21st century, and its concept was applied to B787 as the first major passenger aircraft [3]. The electric power system is more accessible to monitor during operation and lighter than the airplane's auxiliary power system. Therefore, the B787 uses the electric power system instead of the mechanical and compressed air systems, and the total electric output power of B787 is ~1.4 MVA. It is almost ten times higher than the same class conventional aircraft in the present time (2023). The technical successes of B787 will lead to the spread of electric power, which will apply to the other auxiliary power systems, such as hydraulic pressure, in the next generation of airplanes. As a result, MEA needs lightweight generators, motors, and power cables.

The power cable is ~4.4 kg/km/A for the aluminum aviation cable and ~5.5 kg/km/A for the aluminum copper cable for the three-phase AC. A short-term target value of the weight-to-current length cable is ~ 1.0kg/km/A. If we count a single HTS tape weight, current, and length, the weight-to-current length is only 0.03 ~ 0.05 kg/km/A. Therefore, the total specific weight of the HTS cable will be around 0.5 – 0.6 kg/km/A; the tape represents only a small fraction.

The B787 take-off weight is 230’000–250’000 kg, and if we apply the superconducting cables to the B787, we can save the cable weight from 450 ~ 950 kg if the superconducting cable can achieve ~ 0.5 kg/km/A. It is a small portion of the total weight, and we should consider additional weight from the power converters for the DC cables, but one of the goals is to develop a new lightweight cable because of MEA.

However, aircraft cannot connect to the Earth's potential electrically during their flight time, and since the air pressure is low at high altitudes, the insulation voltage in the air is low. Therefore, the maximum voltage in an airplane is set by present regulations at around 400 V.

The weight of the cable includes the cable conductor, cryostat, and cryogen to estimate the weight-to-current length and does not include the refrigerator in the estimation. Since the refrigerator is heavy and consumes a lot of power, we use the latent heat of the cryogen. For example, the latent heat of the liquid nitrogen to gas nitrogen is 199.3 [kJ]/kg at 77 K, 1 atm, and it is not small enough to keep the cable at a low temperature because the cable length is not long and the cryostat diameter is small, which are not like the transmission line on Earth. Therefore, the additional liquid nitrogen weight is less heavy than a refrigerator if the cryogenic pipe's heat leaks and the terminal's current lead is low. In addition, if we use liquid hydrogen as the airplane's fuel, we can use its cold to keep the superconducting cable at a low temperature.

The other aspect of using DC cable is the use of power converters. Since the AC generators are connected to the engine, the frequency of the AC output power is variable. The electrical power distribution system supplies 230 V AC three-phase, 115 V AC three-phase, and 28 V DC power to the load in B787. Therefore, we now use several different power converters [3].

If we use AC and the magnetic field leaks from the cable, we should consider the AC induction near the cable. Since a leak AC magnetic field induces electric noise, it will be severe for large currents. It hurts avionics and the other instruments in the airplane. It is the third reason for our proposal.

Because of these technical reasons, we proposed a DC cable for aviation [4] with a stacked conductor structure. The current direction of each layer is opposite, and we used the Bi2223 tapes and reported the first experimental results [4]. One of the

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positive results was that the average critical current of the stacked conductor is ~20% higher than the single Bi2223 tape, and therefore, we can make a lighter conductor cable in principle. However, the electric circuit of the stacked conductor tapes was connected in series [4], and all currents of the Bi2223 tape were the same completely in the experiment. Since we usually need a large current for the electric power devices, we should connect HTS tapes of the electric circuit in parallel. We should consider the current imbalance problem [5, 6]. If the current imbalance is severe, the total current of the stacked conductor is low, and we cannot make a lightweight cable. Therefore, we should solve the problem. Roebel conductor is one of the technical solutions for the current imbalance problem, and the researchers applied its idea to the cable conductor and published the experimental results for the RE123 tape [7, 8].

The Robel conductor structure can be applied to REBCO tapes, but unfortunately, it is inadequate for Bi2223 tape if we cut the tape because of its superconducting filament structure. In addition, we need to transpose the HTS tape to balance the current even if we do not cut some parts of the HTS tape. Therefore, the Roebel conductor has a complicated structure.

The other candidate conductor is also made from the REBCO tape, called CORC [9,10]. The CORC is applied to the magnet conductor, and its current is higher than 1 kA.

On the other hand, one of the authors (SY) proposed the current-lead-resistance method (CLRM) [11, 12], and it is available to apply to Bi2223 tapes and RE123 tapes without transpose structure, and some of the CLRM experiments have been done [13, 14] for a Bi2223 six-layer stacked conductor, and the average critical currents of the Bi2223 tape always were higher than the single Bi2223 tape in the experiments.

We describe the new experimental results of the proposed scheme in the paper, and one is to make a twelve-layer straight-stacked conductor and perform the critical current experiments. The second experiment is to bend the stacked conductor and measure its critical current because the cable layout depends on the airplane design, and we cannot apply the straight cable everywhere inside the airplane. When we install the cable, we must turn it along the path to connect the power source and the electric devices. The magnetic field profile around the bending cable differs from the straight cable. Therefore, the critical current will be different from the straight-stacked conductor.

When we mount a superconducting cable in an airplane as the R&D, we should get permission from the captain of the airplane and the authority for the individual case. In the first case, we cannot directly connect the superconducting cable to the airplane mechanism.

II. Basic Proposal of Stacked Conductor

We originally proposed the stacked conductor for a short power cable, which is lightweight, small in diameter, and low voltage, especially in DC cable applications [4]. Figure 1 shows the stacked conductor's cable cross-section and electric circuit. The shunt resistors are inserted to measure the individual current of the HTS tape. The copper cables and the current lead conductors for individual HTS tapes are connected in series. These connections make the current balance because of the resistances of these circuits. The load is shortening at the terminal.

The outermost tape is named 1+ and 3- for a six-layer stacked conductor. Fortunately, airplanes use low-voltage power systems, such as 400 V, in the regulation. Therefore, the thickness of each insulation layer can be thinner than ~ 0.5 mm, and the total thickness of the stacked conductor is not considerable, even if we insulate all HTS tape.

The test voltage of the aviation cable is 1.8 kV in regulation, and the insulation voltage of 50 μm Kapton tape is higher than 15 kV for penetration breakdown. In the preliminary experiment, we measured the breakdown voltage for creeping discharge, which is higher than 4.2 kV/10 min. in liquid nitrogen at 1 atm.

The narrow gap between the tapes and the opposite current direction of each layer is better for enhancing the critical current of the tape [15, 16, 17]. The current direction of each layer is opposite to minimize the magnetic field on the tape, especially for the perpendicular component of the magnetic field to the surface. As a result, the leak magnetic flux from the power cable is minimal because of a multipole configuration of the individual tape current. It is suitable for the superconducting conductor to increase the critical current and reduce the magnetic field effects on the other aviation instruments.

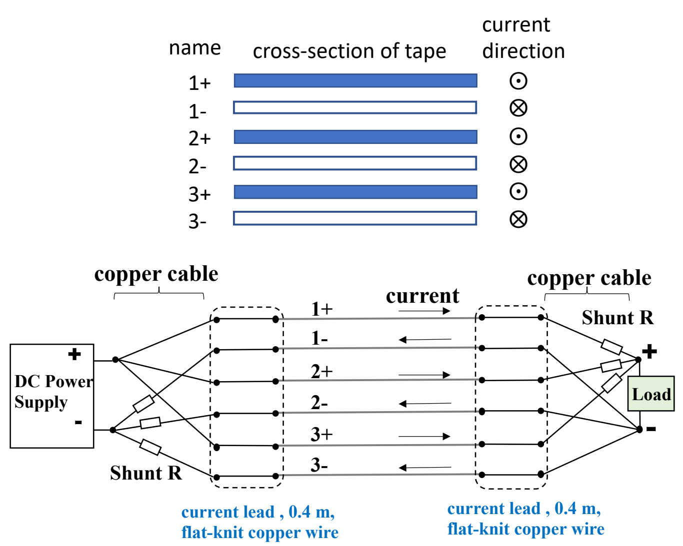

Fig. 1. Cross-sectional view of the stacked conductor, the current directions, naming rule of the tapes (upper), and an electric circuit for the connection power source, load, current leads, and cables (lower).

The other difference of the usual power superconducting cable is not to use a metal former. Since the mechanical strength of HTS tape is weak, we need to use the metal former at the center to make a long power cable, and it is a standard design of the superconducting cable [18, 19]. Indeed, it is necessary to make a longer cable because we should pull the cable into a long cable cryostat for several hundred meters to one kilo-meters. At that time, the pulling force is ~ several hundred kg

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force in the transmission lines of grid. As a result, 50 to 70 % of the cable weight comes from the metal former. However, aviation's power cable length is shorter than 200 meters, and we do not apply strong force to pull into the cryostat. Therefore, we do not use the heavy metallic former.

Applying the stacked conductor as the DC power cable for the airplane is also suitable because it is lighter than the AC cables. We compare the capabilities of DC and AC cables to transfer the same electric power, and the ratio of the electric power to the cable conductor is almost 2 to 4 times higher for the DC cable (see Table 1) [20], and therefore the DC cable's conductor be lighter than the AC cable for the same power transmission. It depends on the electric circuit, so we use DC high-voltage power transmission (HVDC) for long transmission lines [21], even in the conventional power grid, especially for the renewable energy (RE) transmission line [22].

Therefore, the proposed DC stacked conductor is the lightest cable suitable for aviation applications. We will discuss this aspect and the weight-to-current per length in the last section using the experimental data.

TABLE I

TRANSMISSION POWER, CONDUCTOR NUMBER AND THEIR RATIO FOR DC AND AC CONVENTIONAL CABLES

	Copper/Al_AC Transmission		Copper/Al_DC Transmission	
	three phase	**single phase**	**mono-polar**	**bi-polar**
Number of Conductors (CN)	**3**	**2**	**2**	**2 or 3**
Transmission Power (TP)	$\frac{\sqrt{3}\, I_m \times V_m}{2} \cos\varphi$	$\frac{I_m \times V_m}{2} \cos\varphi$	$I_m \times V_m$	$2\, I_m \times V_m$
TP / CN	$\sqrt{3}/_{6} \cos\varphi = 0,289 \cos\varphi$	$^{1}/_{4} \cos\varphi$	$^{1}/_{2}$	$1 \sim {}^{2}/_{3}$

I_m: *peak current of conductor*
V_m: *peak voltage of conductor*

Therefore, the proposed DC stacked conductor is the lightest cable suitable for aviation applications. We will discuss this aspect and the weight-to-current per length in the last section using the experimental data.

In addition, even if we use a superconducting power cable, we should pay attention to the cable loss for AC applications. It is called AC loss, and it depends on many physical processes of the cable system, and the superconductor generates heat by AC. Therefore, the rated current should be low for AC cable and high for DC cable for the same critical current.

As a result, the first choice of the power cable should be DC. Figure 2 shows our basic proposal for the aviation power transmission line. Since generators are connected to the jet engines directly in an airplane, they are usually three-phase AC generators, and their frequencies depend on the rotation frequencies of the jet engine. The output power of the engine depends on flight conditions and requirements. As a result, their frequency should be variable. Therefore, we set the AC/DC converter near the generator and transfer the DC power to the DC load directly or to the DC/AC converter near the AC load.

The proposal is different from the present transmission lines, such as B787 [3], and the total optimization should be necessary for the airplane and sometimes give us another design. However, when we apply the superconducting power transmission line, we must start from the configuration of Fig. 2. These are the fundamental conditions to develop the superconducting power cable for aviation.

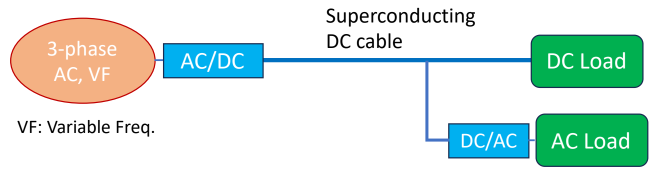

Fig. 2. Proposal of DC transmission line for aviation as the lightest cable.

III. EXPERIMENTAL SETUP AND EXPERIMENTAL RESULTS

We report two sets of experiments in the paper. We made a twelve-layer straight-stacked conductor and performed the critical current experiment. We also made one six-layer stacked conductor and measured the critical currents for straight, bending, and twisting shapes. We used Bi2223 tapes for all experiments. The critical current is 190 ~ 200 A at 77 K for self-field, the 50 micro-meter copper alloy plate is used as the reinforced material, and the tape's width and thickness are ~ 4.2 mm and ~ 0.35 mm. The production name is "Type HT-CA." Unfortunately, we do not know the number of filaments inside the tape.

A. Twelve-layer straight-stacked conductor

Figure 3 shows the schematic configuration and the photo of the twelve-layer straight-stacked conductor. We use the Bi2223 tapes for the conductor, and all Bi2223 tapes are insulated by a half-lapped Kapton tape (50 µm). The electrode to connect the copper current lead and the Bi2223 tape is made by the copper plate, and its width and thickness are 20 mm and 1 mm, respectively. The solder connects the Bi2223 tape to the electrode, and the electrode connects with the copper current lead by the bolt. It is a hand-made stacked conductor in our laboratory.

All Bi2223 tape conductors connect with a DC power source and a load through the individual copper leads in parallel, and the circuit is equivalent to Figure 1 (lower). It means we used the CLRM to balance each tape current. We also use the open cryostat and measure the individual currents by the shunt resistors and voltages of the Bi2223 tapes, like in the previous experiments [4].

Figure 4 shows the cross-section of the stacked conductor, its size, the direction of each HTS tape current, and the tape name. The cross-section size is 4.5 mm wide and 7.6 mm thick, and the specific weight is 268.8 kg/km, including the insulators. For example, we call the tape 1- as one minus, and the minus sign means the tape is connected to the negative electrode of the power supply, and the plus sign means the tape is connected to the positive electrode. Therefore, the current direction of each tape is opposite. The average gap between the Bi2223 tapes is 0.28 mm, five times thicker than the Kapton tape thickness. The current direction is opposite each other like the six-layer stacked conductor.

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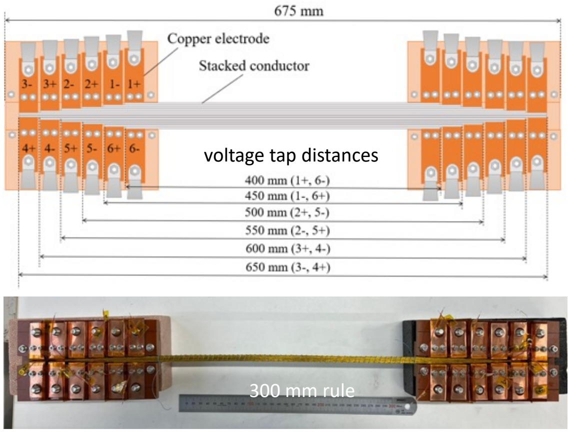

Fig. 3. Schematic configuration of the twelve-layer straight-stacked conductor and its photo.

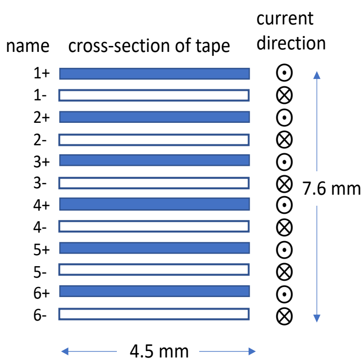

Fig. 4. Schematic configuration of the twelve-layer straight-stacked conductor and its photo.

Figure 5 shows the current-voltage characteristics of the stacked conductor tapes. The horizontal axis is the total current of the tapes, and the vertical axis is the electric fields of the individual tapes. The electric fields for tapes 3+, 3-, 4+ 4- are relatively high for the other tapes.

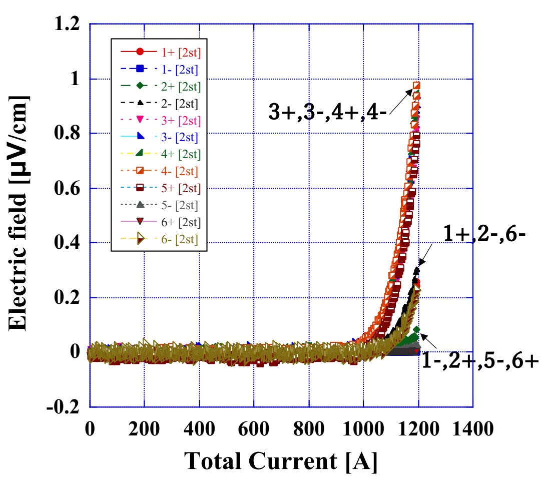

Fig. 5. Critical current measurement of the twelve-layer straight-stacked conductor.

We defined the critical current of the stacked conductor by tape 4- for safety reasons, and the critical current is 1196 A at the temperature of 77 K.

However, the individual currents of the tapes are different, and Figure 6 shows the current distribution of each tape at a total current of 1196 A. The tape current's average and standard deviation is 199.3 ± 3.4 A, 5 % higher than the critical current of the single Bi2223 tape. Since the tape 4- current is 198 A, lower than the average current, we will improve the critical current if the current balance is higher. We will discuss this in the next section in detail.

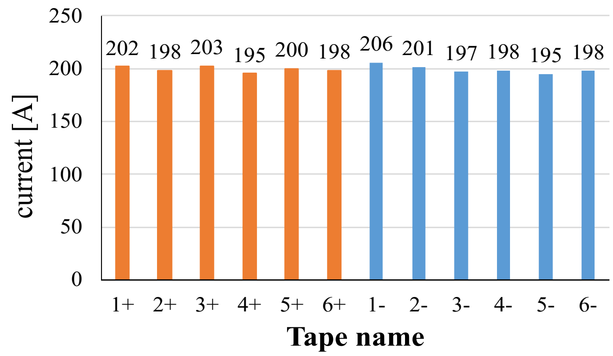

Fig. 6. Current distribution of Bi2223 tapes at a total current of 1196 A, which is the critical current of the stacked conductor.

B. Bending and twisting experiment of the six-layer stacked conductor

When we install a power cable, we must bend it along a path to connect the power source and the application instruments. Figure 7 shows the stacked conductor and how to bend the stacked conductor. The current direction is ±X-axis for the straight stacked conductor, and turning on the X-Y plane is easy but hard to turn on the Y-Z and Z-X planes. Therefore, we need to twist the cable before bending it.

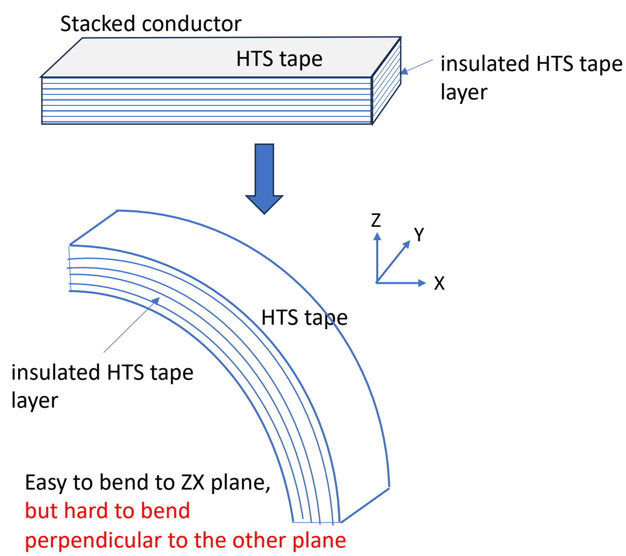

Fig. 7. Stacked conductor configuration and bend direction.

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The magnetic field around the stacked conductor changes with the conductor shape, bending and twisting; therefore, the critical current of the stacked conductor depends on the shape.

We made the six-layer stacked conductor, and both terminals are set on the insulation boards like in Fig. 3. Since the stacked conductor connects two insulation plate boards, it is easy to twist the board 90 degrees and bend the conductor at any angle. All Bi2223 tapes are insulated by Kapton tape completely; as a result, the average gap between the tapes is 0.28 mm for straight configuration.

Figure 8 shows the conductor photos, twisted and bent by 90 degrees inside the open cryostat. Since the conductor length is 425 mm, the twist pitch length is 1700 mm, and the bending radius is 160 mm (R160) in the experiment. We also set the Hall element to measure the magnetic field at tape 3- side as the standard monitor sensor and measure the perpendicular magnetic field to the tape surface because the critical current of the Bi2223 tape is sensitive to its magnetic field, as shown in photos, and the naming rule is the same as Fig. 4. We can see the current lead flexible copper current lead in the pictures.

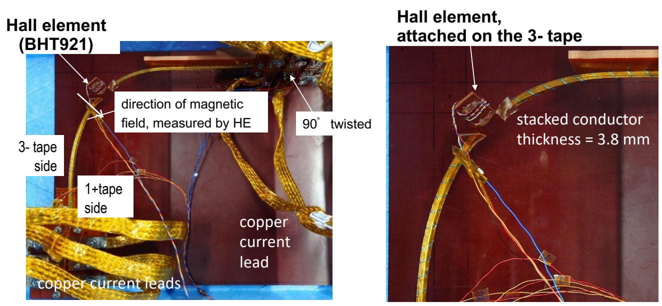

Fig. 8. Pictures of the stacked conductor of 90 degrees twisted and bent.

Figure 9 shows the current-voltage characteristics of the stacked conductor. The horizontal axis is the total current of the stacked conductor, and the vertical axis means the individual electric fields of the Bi2223 tapes. The electric field for tape 3- is highest for the other tapes, and it determines the critical current of the stacked conductor, and it is 591 A for the twisted and bent conductor. However, the tape 3- current is the lowest for the other tapes at the total current of 591 A, and therefore if we can control the current distribution of the stacked conductor much more, we may increase the critical current.

We performed several experiments for several configurations of the stacked conductor, and the critical currents are summarized in Table 2. The critical current of the single Bi2223 tape is ~190 A, and the average critical current of the straight shape is 213 A (= 639/3), which is 12 % higher than that of the single tape. The compressive strain of the bending is ~ 0.078 %, which is lower than that of thermal contraction. The axial tensile might be almost zero because the tape could be slid on the surface of each other. Therefore, the mechanical strain did not have a large effect on reducing the critical current. It is the usual behavior observed in previous experiments [15, 16, 17]. However, when we bent the stacked conductor by 90 degrees for 425 mm long, the critical current was down to 607 A. One of the suspicious reasons is a considerable gap between the tapes because both ends of the stacked conductor are fixed, and the average gap should be large by bending. We had several experimental results and observed low critical current for a considerable gap between the tapes in the stacked conductors [17, 23].

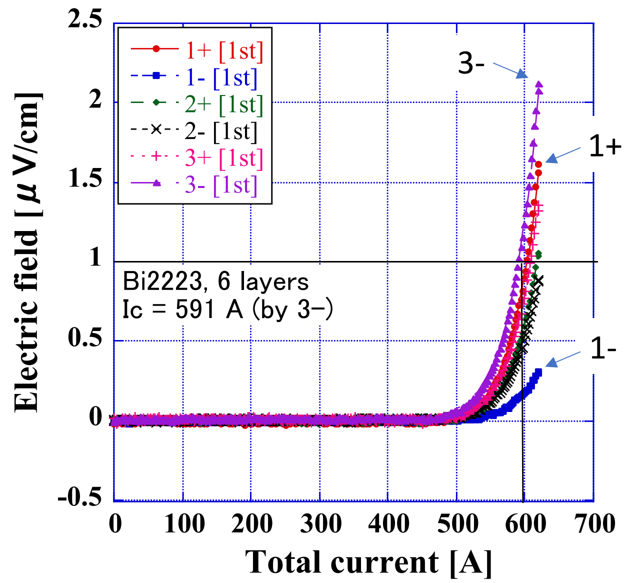

Fig. 9. Critical current measurement of the six-layer stacked-conductor.

On the other hand, we twisted the stacked conductor by 90 degrees for 425 mm length, and the critical current is down to 615 A. It is larger than that of the bending case. The tensile strain of the twisting is estimated to be ~ 4.0 $\times 10^{-8}$ % in the experiment. Therefore, it does not have a large effect on reducing the critical current. Finally, we twist and bend the stacked conductor and measure the critical current. It is 591 A, still larger than the single Bi2223 tape. It was the first trial to bend and twist the stacked conductor, and we continued to improve the critical current performance for any direction.

TABLE II

RESULTS OF CRITICAL CURRENT MEASUREMENTS FOR THE TWELVE- AND SIX-LAYER STACKED-CONDUCTOR

shape	Critical current [A]	comments
straight	1196	12-layer
straight	639	6-layer
Bend, 90-degree	607	6-layer, 425 mm length
Twist, 90-degree	615	same as above
Twist and Bend	591	same as above

IV. FUTURE EXPERIMENTS AND PERSPECTIVE

We performed all experiments using Bi2223 tape, but RE123 tape is lighter than Bi2223 tape, and therefore we made some stacked conductors from RE123. Table 3 shows the parameters of Bi2223 and RE123 tapes, their stacked conductors, and the weight-to-current per length. RE123 is called a coated conductor, and the copper is coated as the cover layer. The thickness of the copper layer is 20 μm in Table 3, in which we estimated the weight-to-current per length for the same insulation layer. It includes the weight of the cryogenic pipe and all the parts to make the cable [4]. However, we should pay attention to the short circuit, and Bi2223 tape is usually vital for the large short circuit current [24].

The other parameter is the insulation layer. We measured the stacked conductor weight, and the insulation layer needs to be more lightweight. We measured the breakdown voltage between two HTS tapes, touched like the stacked conductor. One is insulated by half-lapped Kapton tape, and the other tape is not insulated. Kapton tape is 50 μm thick and 12 mm wide, but the breakdown voltage is higher than DC4.2 kV/10 min. Making a light cable may be a creeping breakdown and too high. We will use thin Kapton tape, with a thickness of 25 μm, which is commercially available for the next experiment, and we can reduce the total weight of the stacked conductor.

The other insulation layer aspect is the stacked conductor's critical current. When the gap between tapes is narrow, the critical current of the stacked conductor is high [17, 23]. Therefore, the thin insulation layer reduces the stacked conductor's weight and increases the critical current. Consequently, we aim to improve the weight-to-current per length ~ 2 times from Table 3. We included the weight of the cryostat, which includes the inner and outer pipes, the insulation material, the support of the inner pipe, and the liquid nitrogen inside the inner pipe, to estimate the weight-to-current length of the cable in Table III.

TABLE III
COMPARISON OF BI2223 AND RE123 TAPES FOR STACKED CONDUCTOR

		signle tape	stacked conductor	comments
Bi2223	size [mm] width × thickness	4.2 × 0.35	4.5 × 3.8 4.5 × 7.6	6 & 12 layers for the stacked conductor
	weight [kg/km]	13.0	134.4 ~ 268.8	
	critical current [A]	~190	639 ~ 591, 1196	
	weight-to-current length [kg/A/km]	-	0.503 ~ 0.436 0.604	for straight (6 & 12 layers), twist & bend (6 layers), weight-to-current length includes the cryogenic pipe weight
RE123	size [mm] width × thickness	4.5 × 0.15	4.7 × 2.6 4.7 × 5.2	copper layer = 20 [micron-m]
	weight [kg/km]	4.5	83.4	
	critical current [A]	~200	-	
	weight-to-current length [kg/A/km]	-	-	
cable material without conductor and its insulation		175.0 [kg/km]		we should add the weight of the conductor

The transmission power of the stacked conductor is 240 kW to 400 kW for a voltage of 400 V. Therefore, we can apply the cable to an airplane like B787 [3] because its power cable transfers 250 kVA/line from the generator. Therefore, our test production cable is available to apply to an airplane now. One of the cross-sectional designs is shown in Fig. 10, referred from Fig. 7 in Ref. [4]. The HTS tapes' width and insulation are ~ 6 mm, and the HTS tape number is 6 to 20 because the thickness of the HTS tape and the insulation is ~ 0.45 mm. The inner pipe diameter is ~ 12 mm, and the outer diameter is ~ 18 mm, as shown in Figure. We also consider a large-size cable design and the outer diameter of the cryogenic pipe is ~ 40 mm, and these parameters depend on the requirement of the airplane.

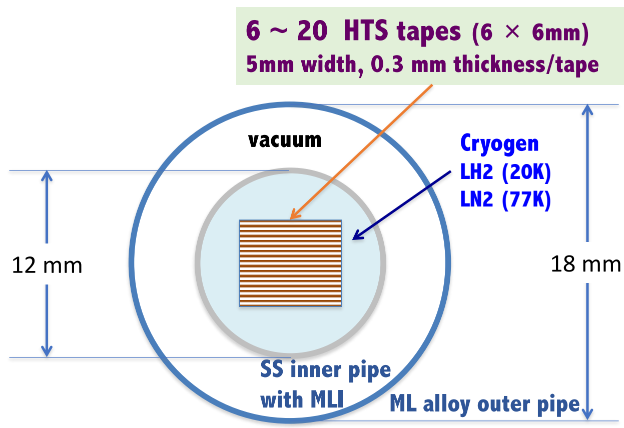

Fig. 10. One of the cross-sectional designs, which includes the cable and the cryostat for aviation [4]

Because of these situations, we are trying to find a collaborator to make an aviation cable system, including the terminal cryostat and cooling system, and test it in the air.

The role of the authors;
The proposal was shown initially by S. Yamaguchi and discussed with all the authors at each step.
The experiments were done mainly by S. Kawai and partially by M. Eguchi, M. Kanda, and S. Yamaguchi.
S. Kawai did the data gathering, and S. Yamaguchi did the analysis. All authors discuss the experimental results, and S. Yamaguchi did the paper writing, and M. Kanda and Y. Ivanov edited it with S. Yamaguchi.

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