A proposal for a lightweight, large current superconducting cable for aviation

Sataro Yamaguchi\textsuperscript{1,2,\textcopyright} and Masae Kanda\textsuperscript{1,3}

\textsuperscript{1} Center of Applied Superconductivity and Sustainable Energy Research, Chubu University, Kasugai Aichi 487-8501, Japan
\textsuperscript{2} Department of Electrical Engineering, Chubu University, Kasugai Aichi 487-8501, Japan
\textsuperscript{3} Department of Astronautics and Aeronautics, Chubu University, Kasugai Aichi 487-8501, Japan

E-mail: yamax@isc.chubu.ac.jp

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Abstract

More Electric Aircraft (MEA) is one of the most important subjects for designing the next generation of aircraft. Since we cannot ground the electric power systems of a flying aircraft and the air insulation voltage is lower at high altitude, a low voltage, direct current (DC) aircraft electrical system is preferable for a MEA. Since the current must be high to supply high power, we consider high temperature superconducting (HTS) technology because it handles large currents well. We propose a new HTS cable in this paper. The cable uses a stacked conductor, with oppositely directed current in each HTS tape, a structure that has already been shown to be feasible for low voltage cables. It enhances the critical current compared to a single tape conductor, especially for Bi2223 tape. In order to avoid a current imbalance in the stacked conductor, we use the current lead resistance rather than a Roebel conductor design. Then the critical current remains high, and this is confirmed by measurements. The cryogenic pipe will be made of magnesium-lithium alloy, one of the lightest metals available at the present time. We estimate the weight-to-current ratio per unit length to be less than 0.5 kg/A/km at the liquid nitrogen operational temperature of 77 K, lighter than conventional copper cable. If instead we use liquid hydrogen at 20 K, we expect a value less than 0.1 kg/A/km, which is one of the lowest presently achievable values and satisfies the requirements for MEA.

Keywords: superconducting power cable, lightweight, large current, aviation, MEA

(Some figures may appear in colour only in the online journal)

1. Introduction

The highest priorities for an aircraft are safety and light weight. The electric power system can be used to help realize these requirements. Existing aircraft use four different types of power control systems: the hydraulic system, the air pressure system, the electrical system, and the mechanical system for the control and auxiliary systems of the airplane. Fortunately, the electrical system is usually lighter than the hydraulic, the air pressure and mechanical systems. Also, at present it is difficult to continuously monitor the nonelectrical systems during use, which is important to ensure safe operation, but an electrical system is easy to monitor. Therefore, a new concept using mostly electrical systems was proposed, called ‘More Electric Aircraft’ (MEA) \textsuperscript{[1, 2]}. The power consumption of the MEA electrical system will be lower than the previous combined systems and will reduce CO\textsubscript{2} emissions.

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However, there are other constraints on an aircraft electrical system. High voltage is dangerous because we cannot electrically ground an airplane to the earth. It easily causes the surrounding air to breakdown, electrically connecting the aircraft to the atmosphere, particularly at high altitudes and low air pressure at which large aircraft fly. Therefore the use of high voltage is prohibitive in an airplane. For this reason, as well as other advantages for safe and efficient operation and reduced weight, low voltage direct current (DC) power has been preferred to alternating current (AC). Since large current is needed to satisfy the high power requirements of the electrical systems, we consider a high temperature superconducting (HTS) cable for the electrical distribution system.

In order to construct a lightweight electrical cable, we started several years ago to develop the conductor for a superconducting DC power cable, based on the fact that the current density of a high temperature superconductor tape is almost 200 times higher than for copper.

The superconducting cable is composed of the electrical conductor, a cryogenic pipe, the terminal cryostats, and the current leads. A terminal cryostat is located at each end of the superconducting cable and partially encloses one of the current leads that connects the HTS tape to the external power supply and the loads. The current lead is usually made from copper strands. Since a large temperature difference appears along its length, between the ambient temperature and low temperature HTS tape sides, its design should minimize the heat leak into the HTS side.

A superconductor has a critical superconducting current that sets an upper limit on the superconducting state. If the superconducting cable consists of multiple HTS tapes, the currents in the tapes should be equalized in order to maximize the total current capacity of the cable. This problem of ‘current imbalance’ was originally studied in 1990s for the superconducting strands in a superconducting magnet, in order to avoid a sudden quench of the magnet [3, 4]. For HTS power cables, the Roebel conductor design was initially considered [5]. Its principle is the continuous transposition or ‘braiding’ of the HTS tapes along the length of the cable in order to balance the current. However, its critical current is reduced by more than half because parts of each HTS tape must be cut in order to transpose them. We therefore considered other designs. The new design will enhance the critical current of the conductor, and the final aim is to make a light weight and larger current conductor for the aviation.

For the cryogenic pipe and cryostats, stainless steel (SS) is a common material, but its density is high and the system can be heavy. Therefore, we looked for alternative materials and designs for the cryogenic pipe.

In this paper, we propose a new structure for the HTS conductor, a ‘stacked conductor,’ and the current leads, that uses the resistance of the current lead strands to remove the current imbalance [4]. The HTS tape is not transposed or cut, so the total critical current remains high and the cost of the conductor is reduced. A new material to make the cryogenic pipe is also proposed. Experimental results for these systems are described.

### Figure 1.
Cross-section of the stacked conductors, showing the HTS tapes, their names and current directions.

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### 2. Proposal for a new cable

The superconducting cable is composed of two main parts: the conductor, which is connected to a current lead at each end, and the cryogenic pipe that contains the conductor and the cryogenic coolant. This section describes a new cable system that includes the conductor structure, the method to connect the current lead to the HTS tapes, and the material for the cryogenic pipe.

#### 2.1. Conductor structure and current lead connection

The cross-section of the proposed new cable conductor, called a ‘stacked conductor,’ is shown in figure 1. It uses Bi2223 tape reinforced with SS tape.

An SS tape layer is bonded to each side of the Bi2223 tape, not shown explicitly in the figure. Each SS layer is 50 μm thick and the total thickness of the three-layer tape is 350 μm. Figure 1 shows the cross-section of the stacked HTS tapes, the tape name, and its current direction. The outermost tapes of the stack are labeled ‘1+’ and ‘3−’. The current in adjacent tapes is oppositely directed (white and dark). The HTS tapes are insulated from each other at the operating voltage. Each is covered by a half-lapped winding of insulating Kapton tape that has a tape thickness of 0.1 mm. The insulation voltage was measured to be greater than 2 kV at a pressure of 1 atm and temperature of 77 K. The stacked opposite-current structure helps to minimize the total magnetic flux of the cable that is self-generated by the carried current, and the similar structure had been tested for the fault current limiter coil [6]. The magnetic field outside the cable remains weak even at large cable current, without any additional magnetic shielding. It also minimizes the magnetic field perpendicular to each HTS tape surface and therefore perpendicular to the superconducting current inside the tape, an effect that enhances the critical current of the tape. The design is most effective for the interior Bi2223 tape layers that are sandwiched inside the stack [7, 8]. As we anticipated, measurements show that the total critical current of the cable is enhanced. This structure is effective and achievable for low voltage cables because the insulation layer is thin; it works for aircraft because of the low voltage of the electrical system, less than 1 kV. The same structure could also be used to reduce AC power losses in an HTS cable.
For many reasons, cryogenic pipes separated by a vacuum. For aviation applications, the highest priority is light weight. The cryogenic pipe is composed of inner and outer pipes, made of copper strands insulated from each other. Each strand is connected individually to one HTS tape and to its own independent terminal on the other end. This configuration was used partly because of its flexibility, since it allows the performance of the HTS tapes in the stacked conductor to be tested individually, but it is important for other reasons.

In the actual cable system for aviation, the heat leak through the current lead represents the major heat leak of the entire cable because the cable itself is short. It is necessary to minimize the heat leak to preserve the cryogenic temperature of the system and obtain the lightest weight cable system. The Peltier current lead (PCL) [9] is almost the only design able to control the current in its attached HTS tape because its impedance is higher than the impedance of the HTS tapes. The second measured the magnetic hysteresis character of the stacked conductor. The last measured the critical current of the stacked conductor and the current balance of the HTS tapes. The second measured the magnetic hysteresis character of the stacked conductor. The last measured the structural strength of the ML alloy in terms of the Charpy impact value, used to measure fracture toughness, at room temperature and at 77 K.

### 3. Experimental results

We performed four types of experimental tests. The first measured the critical current of the stacked conductor and the current balance of the HTS tapes. The second measured the magnetic hysteresis character of the stacked conductor. The last measured the structural strength of the ML alloy in terms of the Charpy impact value, used to measure fracture toughness, at room temperature and at 77 K.

#### 3.1. Critical current and hysteresis of the stacked conductor

Figure 3 shows the results of the critical current measurement for the six tape conductor. The critical currents of the two outermost HTS tapes 1+ and 3− are smaller than for the four interior tapes, so to allow each tape to carry the largest possible current and thus maximize the total critical current of the cable, two separate power supplies were used. One connected the 1+ and 3− tapes in series and the second connected the other four tapes in series. Then the current in the two outermost HTS tapes were measured to be 221.0 A for tape 1+ and 221.3 A for tape 3−. The critical currents of the interior tapes were 252.2 A for tape 1−, 242.0 A for tape 2+, 238.2 A for tape 2−, and 255.3 A for tape 3+. For a single tape in self-field condition, the critical current is only 180 A to 190 A, so the improvement is larger than 20%. The total critical current of the stacked conductor was higher than 700 A usually use thick SS for the inner and outer pipes, but they are heavy because the SS density is high and a corrugated or bellows-type pipe is required to handle bends in the cable. Therefore, we looked for a new lightweight pipe material. Eventually, we selected magnesium-lithium alloy (ML alloy) as the candidate material, particularly for the outer pipe because its density is lower than that of carbon fiber reinforced plastic (CFRP). Welding and cold rolling can be used to form the ML alloy. Originally developed for automobile wheels, since 2019 it has been used commercially for the outer case of lightweight notebook computers in Japan. Table 1 compares the densities of several pipe materials.

We also tested CFRP for the inner pipe and polycarbonate (PC) for the outer cryogenic pipe because of their low densities and the fact that the thermal expansion and contraction of CFRP are lower than for SS. However, CFRP proved unsuitable for the vacuum chamber between the pipes because of its high outgassing rate.

#### 2. Cryogenic pipe material

The cryogenic pipe is composed of inner and outer pipes, separated by a vacuum. For aviation applications, the highest priority is light weight. For many reasons, cryogenic pipes

### Table 1. Densities of ML alloy and other materials.

| Material                                           | Density [g cm\(^{-3}\)] |
|----------------------------------------------------|--------------------------|
| Acrylonitrile butadiene styrene (ABS)              | 1.03                     |
| Polycarbonate (PC)                                 | 1.23                     |
| Magnesium-Lithium alloy (ML alloy)                 | 1.36                     |
| Carbon fiber reinforced plastic (CFRP)             | 1.60                     |
| AZ31 (Mg-Al-Zn alloy)                              | 1.82                     |
| Aluminum                                           | 2.69                     |
| Steel                                              | 7.89                     |

Figure 2(a) shows the connection of the power supply, the current leads, the HTS tapes, and the load. The current lead is made of copper strands insulated from each other. Each strand is connected individually to one HTS tape and to its own independent terminal on the other end. This configuration was used partly because of its flexibility, since it allows the performance of the HTS tapes in the stacked conductor to be tested individually, but it is important for other reasons.

In the actual cable system for aviation, the heat leak through the current lead represents the major heat leak of the entire cable because the cable itself is short. It is necessary to minimize the heat leak to preserve the cryogenic temperature of the system and obtain the lightest weight cable system. The Peltier current lead (PCL) [9] is almost the only design able to reduce the heat leak to the desired degree. Figure 2(b) shows the proposed PCL setup for the stacked conductor, which will be tested in a future experiment.

This current lead structure also avoids the current imbalance in the HTS tapes. The copper strand of the current lead controls the current in its attached HTS tape because its impedance is higher than the impedance of the HTS tape inductance. For DC, all strands have the same resistance, so their currents are the same. This method is useful for shorter cables, up to 1 km. Since the copper strand resistance is the same for low-frequency AC, the same method will work. The Peltier part of the current lead can also play an important part in the current balance, because it uses a thermoelectric semiconductor that has a resistance that is usually higher than that of the copper strand.

#### 2.2. Cryogenic pipe material

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![Figure 2](image-url)
in each direction (approximately the sum over the individual tapes). This behavior is typical for a conductor made with Bi2223 tape [7].

We also tested a different stacked conductor configuration that had three adjacent HTS tapes connected in parallel, with current in one direction, and the remaining three HTS tapes were connected in parallel with the same current, but in the opposite direction, using a single power supply. The critical current of the stacked conductor was reduced to $\sim 380$ A because the perpendicular magnetic field on each HTS tape was not cancelled. Nevertheless, the HTS tape currents balanced to within 5%, due to the resistance of the current lead strands.

To investigate the AC performance of the stacked conductor, we measured its magnetic hysteresis. Several Hall sensors were placed on the surface of the stacked conductor to measure the magnetic fields perpendicular to the HTS tape surfaces. The HTS tapes were connected in series to a single power supply. The waveform of the AC is shown in figure 4. The rise and fall rates of the current were $\pm 1$ A s$^{-1}$, and in between the maximum currents were held constant at $\pm 100$ A, $\pm 150$ A and $\pm 200$ A for 2 min. The data sampling time was 1 s.

Figure 5 shows the experimental results for the current versus the magnetic field. The period of the current waveform is $\sim 1000$ s, and it is slow experiment, therefore the hysteresis character is nearly DC.

For the hysteresis test, we believe that all the HTS tapes were in the superconducting state during the experiment because the current was lower than the critical current. The experiment was started from zero magnetic field, but the field did not return to zero during the nominally current-free state after the supplied current was turned off. This indicates that there was a residual current inside the HTS tape. According to the data from the Hall sensors, the magnetic field profile was not always uniform across the tape [10]. If the nonuniformity is not small, the residual magnetic field may be large and the system becomes unsuitable for use on a plane. Fortunately, the magnetic field of a stacked conductor is much weaker than that of a single tape carrying the same current, so this problem is significantly reduced.
3.2. Charpy impact value

At low cryogenic temperatures, we also need to pay attention to the brittleness of the materials used for the cryogenic pipe. Therefore we performed a Charpy impact experiment for the ML alloy at liquid nitrogen and room temperatures [11], using seven samples. The experimental results and their average values are plotted in figure 6.

The average values were 102.4 kJ m$^{-2}$ at liquid nitrogen temperature and 101.9 kJ m$^{-2}$ at room temperature, although the median value was somewhat higher at room temperature. The average values are nearly the same and are higher than the value for aluminum alloy. Therefore ML alloy should be suitable for a lightweight cryogenic pipe and cryostat.

4. Summary of experiment and its perspective

Finally, a design for a cable using the stacked conductor and the cryogenic pipe was tested. The cross-section is shown in figure 7.

A stacked conductor consisting of six HTS tapes was installed inside the cryogenic pipe. The outer pipe was ML alloy with a thickness of 1 mm. The inner pipe was SS, and its diameter was 12 mm and its thickness 0.12 mm. The width of the Bi2223 HTS tape was 5 mm, and its thickness 0.35 mm.

The region between the inner and outer pipes was a vacuum. Therefore, the inner pipe was buckling free even for thin pipe thickness because it experiences an expanding force from the coolant inside. Some sections of the inner pipe were made from bellows pipe in order to absorb the shrinkage of the SS at low temperatures, but its weight was still moderate. The diameter was still large enough to insert a larger stacked conductor of 20 HTS tapes (shown in the figure) that can carry a high current. The volume inside the inner pipe and the weight of the liquid nitrogen (LN2) cryogen it contains can be used to estimate the total weight of the cable system per unit length, as shown in table 2.

Table 2. Weight per unit length of the cable system.

|                      | Weight/length [kg/km] |
|----------------------|-----------------------|
| Sum of the inner & outer cryogenic pipes | 111.3                 |
| HTS tapes (6 layers)  | 134.4                 |
| Liquid nitrogen       | 56.1                  |
| Other parts           | 7.6                   |
| Sum                  | 301.8                 |

Table 3. Rated current and weight-to-current per unit length at different temperatures for the 6 and 20 tape conductors.

| Configuration | Temp. [K] | Rated current [kA] | Weight–to-current per length[kg/A/km] |
|---------------|-----------|--------------------|---------------------------------------|
| 6 tapes       | 77        | 0.6                | 0.503                                 |
|               | 20        | 3.0                | 0.101                                 |
|               | 77        | 2.0                | 0.319                                 |
| 20 tapes      | 20        | 10.0               | 0.064                                 |

Table 2 does not include the weight of the terminal cryostats nor the current leads, since their specifications depend on the requirements of the electrical load, power supply, and other conditions. Typically, these elements are designed to minimize the heat leak from the current leads. If the maximum operational current of the cable is taken to be 600 A, based on the measured critical current at 77 K, we can estimate the weight-to-current ratio per unit length. The result is shown in table 3.

The total critical current of the stacked conductor was assumed to be proportional to the number of HTS tapes. Since conventional copper cables are usually single-core, two cables are needed to complete an electrical circuit. The proposed HTS configuration already includes two conductors carrying currents in opposite directions. Its weight-to-current per length is
less than 1.0 kg/A/km even at liquid nitrogen temperature with only six tapes, which satisfies the requirements for a DC cable for aviation applications [12].

The AC power loss of a single Bi2223 tape is high, but a stacked configuration made with the second generation coated conductor Y(Re)123 can expect much lower AC losses at commercial transmission frequencies (e.g. 50–60 Hz) and higher frequencies (400 Hz, and 600 Hz). As a next step, the AC losses will be estimated from the experimental data of figure 5.

Figure 2(b) shows a stacked conductor that uses PCL to connect to the outside, in order to reduce the total heat leak of the HTS cable system. The PCL also reduces the required quantity of cryogen, therefore it is a subject to investigate for the actual application. It is necessary to optimize the design of the PCL, including the Peltier semiconductors and the copper strands of the current lead, to minimize the heat leak and the weight of the PCL. Fortunately, the volume of the PCL thermoelectric semiconductors is typically smaller than that of the copper strands of the current lead, so the weight of the PCL is not heavy.

One disadvantage of the stacked conductor is that it cannot be easily bent in the plane parallel to the tape surface. However, it can be bent if it is first twisted by 90 degrees and this method can be used to install the cable system into the airplane [8].

Table 2 also omits the weights of the vacuum pumping system and the refrigerator. Since the vacuum pumping system is not light weight, we propose that it should not be used during flight. The vacuum inside the cryogenic pipe can be pumped out while the airplane is on the ground, then the vacuum valve closed and the pumping system disconnected from the airplane. Since the refrigerator is heavy and also consumes considerable electric power, the cooled liquid cryogen should also be pumped into the system before a flight. The cable should be well-insulated to maintain the low temperature during flight.

In conclusion, we have shown the possibility of making practical HTS DC electrical power cables for aviation that meet the projected requirements for MEA aircraft. As the next step, we plan to fabricate such a cable and analyze its actual fault current modes [12].

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ORCID iD

Sataro Yamaguchi @ https://orcid.org/0000-0002-0338-6418

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