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# Construction of a Flux Modulation Superconducting Machine for Aircraft

A. Colle, T. Lubin, S. Ayat, O. Gosselin, J. Leveque

**Abstract**—The increasing of drives towards More Electric Aircraft (MEA) or the development of electric propulsion aircraft calls for MW-class electrical machines with more compact and power dense designs. One way is to explore the use of superconducting materials to create a high magnetic field in order to reduce the mass of ferromagnetic components. This paper presents the design and construction of a brushless axial flux superconducting machine. The brushless topology satisfies the aeronautics industry requirements in terms of maintenance, while the axial configuration ensures an optimal use of the anisotropic HTS tapes. The machine is classed as partially superconducting, only the inductor is made with superconducting materials. A special design concerning the use of a stationary cryostat is presented. This improvement reduces significantly the electromagnetic air-gap length. A 50kW prototype is manufactured with a minimal mass objective. The prototype constitutes a first step to a scale-up MW-class machine design.

**Index Terms**—Axial Field Machine, High Temperature Superconductors, Superconducting Motor, Synchronous Machine

## I. INTRODUCTION

Five electrical architectures are currently available for a possible electrical propulsion aircraft [1]. These technologies provide reduced fuel burn, noise, and greenhouse gas emission due to the combustion of the fossil fuel. The turboelectric configuration is currently one of the most popular electrical architectures for the air-transportation of tomorrow. In a turboelectric airplane, the electrical generators convert the turboshaft power into electrical power, which is then distributed to several electrical motors that drive the fans. Hence, electrical storage systems are no longer required for this architecture. However, the efficiency of this structure strongly depends on the power density of the electrical machines, and on its integration with a boundary layer ingestion (BLI) design.

In parallel, the MEA is developed by the aerospace industry. It consists of replacing all currently pneumatic, hydraulic and mechanical systems by electrical devices. So the electric power need will continue to increase through the next generation of aircraft. Different projects and their objectives are listed in the Table I [2]. In the literature, several researches have been completed concerning the superconducting machines in aeronautics

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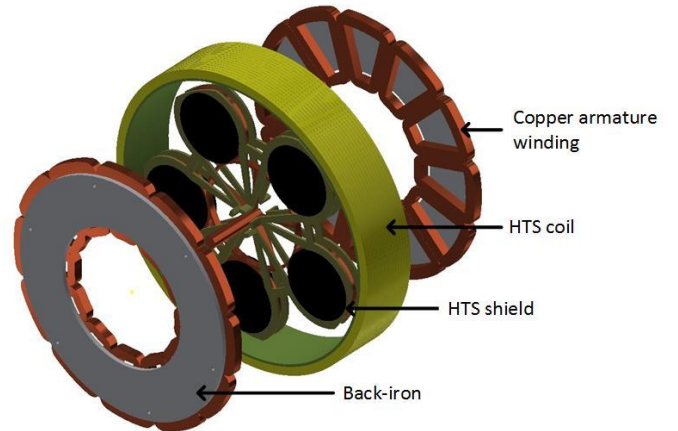


Fig. 1. Exploded view of the superconducting machine's active components

TABLE I  
ELECTRICAL PROPULSION AIRCRAFT PROJECTS [2]

Project Name	Electrical architecture	Electrical power (MW)	PtM (kW/kg)
BOEING SUGAR	Parallel hybrid	Motor: 5,3	5
NASA N3X	Turboelectric	Generator: 30 Motor: 4	10 10
ESAero	Turboelectric	Generator: - Motor: -	8 5

[3]-[7]. One main observation was that this disruptive technology could reach a higher power-to-mass ratio when integrated into electrical machines.

This paper is focused on the design and construction of a partially superconducting electrical machine, called flux modulation machine. For this machine, High Temperature Superconductors (HTS) are used. These superconductors are chosen because of an accessible price and a lighter refrigeration system compared to a machine using low temperature superconductors. The topology of the studied machine is described in Fig. 1. The design resulted in a brushless axial flux machine. One of the key design objective was to avoid all the maintenance and safety issues of a brush system and the additional weight of a

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rotating diode system. As shown in Fig. 1, superconductors are present exclusively in the inductor. A solenoid coil is composed by HTS tapes, which create a magnetic field along the axial direction. The field modulation is obtained by HTS bulks, also called magnetic shields. The principle of the modulation is explained in details in section II of this paper. The armature winding is composed by a three phase copper winding placed on each side of bulks. The flux crossing the copper winding change when shields are rotating, which induces a back-electromotive force to the armature winding terminals.

The first part of the paper describes the topology of the superconducting inductor and the different material which will be used. In a second part, the design of a 50kW prototype is explained with the goal to reach the highest power-to-mass ratio. Finally, some technical choices done during the construction are explained. The prototype is currently in construction and the first tests are expected to be soon.

## II. TOPOLOGY OF THE INDUCTOR

This prototype of flux modulation machine is classed into the partially superconducting machine where the armature coils remains made of conventional copper conductors. The use of superconductors for the inductor is well suited due to the near absence of AC losses. A fully superconducting machine, which have both the field and armature windings made with superconductors, needs more effort concerning the AC losses management with the rotating speed of an aircraft application [8].

The two active parts of the inductor are:

- An HTS coil built with the first generation of HTS tape (Sumitomo new type H DI-BSSCO®). This element produces an axial magnetic field. Future work include the test with a YBCO coil in order to compare the performance with both generation of tapes.
- Several HTS bulks are used to modulate the magnetic flux density. The diamagnetic behavior of the bulks is used to deviate the flux lines obtained with the HTS coil, like a magnetic shield. A round shape bulk is chosen because its production with single or multi-seeds growth exist in large size (radius > 4 cm). The material of these bulks is YBCO or MgB<sub>2</sub>. These two materials will be tested. The advantage of MgB<sub>2</sub> bulks is a lighter mass material than YBCO bulks. On the contrary shielding performances are better with YBCO bulks. YBCO shields will be tested first.

So the inductor is the combination of the HTS coil and the HTS bulks. Both 3D and 2D magnetic flux density distributions are shown in Fig. 2. Just behind a shield, the magnetic flux density is very low and increase quickly with the distance to the HTS bulks. Therefore, the flux modulation is better when the copper windings are placed near the magnetic shields. Thus, there is a strong interest to reduce the space between the shields and the armature winding. A new topology was used to reduce the air-gap length and will be described in a latter section. In Fig. 2, the HTS bulk is considered as a perfect diamagnetic material. In this case, no flux cross through the shield. In reality, some flux vertices penetrate into the material from the external

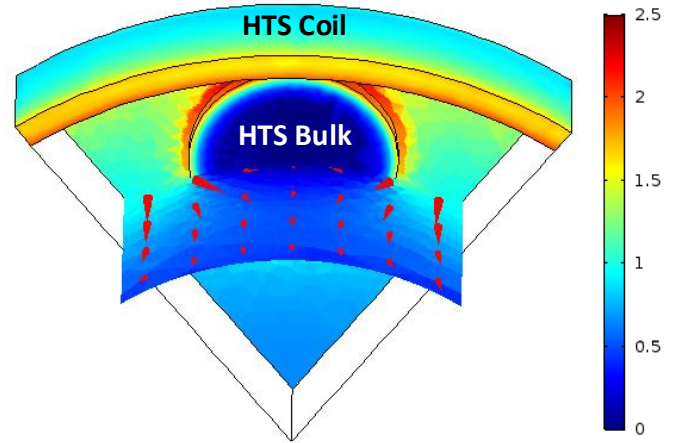


Fig. 2. Magnetic field distribution behind a HTS bulk

TABLE II  
SPECIFICATIONS OF THE 50KW PROTOTYPE

Type	Value
Poles-pairs	5
HTS coil diameter	353 mm
HTS coil length	69 mm
HTS coil thickness	10,5 mm
HTS bulk radius	40 mm
HTS bulk center	114,5 mm
Total air-gap	2 mm
Critical current density	230 A/mm <sup>2</sup>
Outer radius copper coil	145 mm
Inner radius copper coil	84 mm
Thickness copper coil	9,5 mm
Width copper coil	13 mm
Estimated weight	20 kg

surface. This penetration depends on the cooling temperature but also on the external magnetic field applied. At a sufficiently low temperature, the critical current in HTS shield is so high that the length of penetration is very thin compared to the radius of the bulks. Therefore, the diamagnetic hypothesis is not so far from the reality.

## III. TECHNICAL CHOICES

A flux modulation machine prototype of 50 kW with a rotating velocity of 5000 rpm is constructed. This particular machine exists with a radial [9] or an axial [10] structure. To answer the need of an aircraft application, the superconducting machine was designed with the highest power density. The study of performances conducts to an axial flux machine. In application like electrical motor, the use of HTS tapes in operation at liquid nitrogen (77K) has poor performances. So, the HTS elements are cooled at about 30K. The parameters and the results of the sizing are represented in the Table II.

### A. Cryogenic part

The cooling system is composed by a CP110 helium compressor package from Cryomech which supply an AL325 cold head of a Gifford-MacMahon type. Another compressor, CP380, is used at room temperature to insure the flow of helium cooled by the cold head. As the system work in a closed loop, a

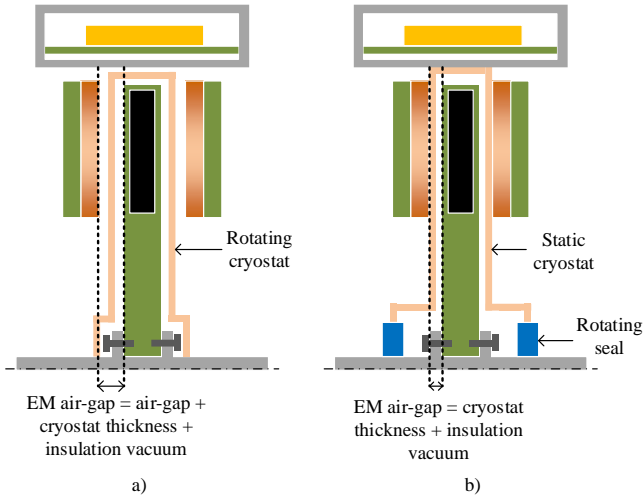


Fig. 5. a) Typical structure of a partial superconducting machine b) Structure proposed with a static cryostat

cryogenic recuperator is necessary between the cold head at low temperature and the compressor CP380 at room temperature. The cooling system is able to extract 30W of losses at 20K and 80W of losses at 30K is demonstrated [11]. In the cooling loop, the HTS magnet is placed near the cold head. The performance of the HTS tape depends on temperature, while the shielding performance of the HTS bulks are good until 50K. Therefore, the magnetic shields cooling is done after the magnet cooling because the increased in helium temperature due to its circulation is less critical.

The choice was made to work with two different cryostats (Fig. 5). The first one does not rotate and contains the HTS magnet which avoids a brush system. The HTS coil is fixed on a G-10 support cantilevered with the room temperature cryostat. The choice of the material and the design of the support reduces much of the thermal conduction losses. The magnet is composed of 6 coils of 75 turns of Sumitomo type H Di-BSSCO tape. A picture of all these elements are presented in Fig. 6. Each coils are separated by a thin copper layer in order to homogenize the temperature of each superconducting tape, so a conduction cooling is done. As a precaution, current leads are placed in a liquid N<sub>2</sub> bath. The size of the copper leads between 77K and 30K is given by [12]:

$$LI / A \cong 6 \times 10^6 \quad (1)$$

where  $L$ ,  $A$  and  $I$  are respectively the length, the section and the current of the copper leads. So the section and the length of the current leads are respectively 6mm<sup>2</sup> and 145mm, it was designed to supply the magnet with a critical current of 230A at 30 K.

Critical current of each coil was measured with immersing in a liquid nitrogen bath. In Fig. 7, the dependences of voltages on coil transport current is shown. The test criteria of the critical electrical field used is 1  $\mu$ V/cm. The wire length for each coil is around 155 m. Therefore, the critical voltage is 15,5 mV. The value of the critical current is reported in the Table III for the six coil. Two coils present a higher critical current than the oth-

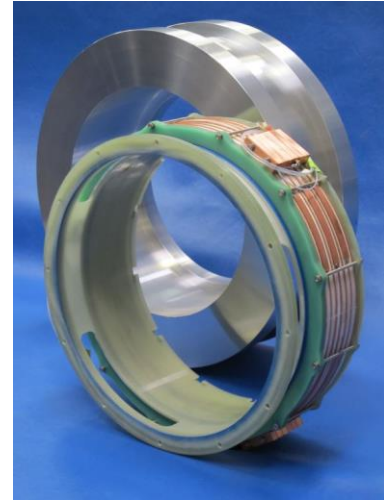


Fig. 6. The superconducting magnet and its static cryostat

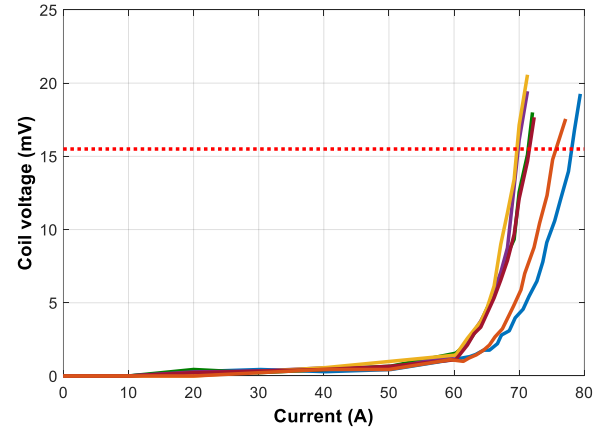


Fig. 7. E-J characteristics of the 6 Di-BSSCO coils cooled with liquid nitrogen

TABLE III  
CRITICAL CURRENT OF THE SUPERCONDUCTING MAGNET

Coil number	$I_c$ (A)
#1	77,5
#2	71,1
#3	71,2
#4	70,6
#5	71,7
#6	76,2

ers. So, these coil will be placed at the extremity of the superconducting magnet where the magnetic constraint are higher. The critical current at 77 K is in accordance with the theoretical expectation.

A specific design was conducted for the second cryostat. Usually in a partial superconducting machine, this cryostat rotates with superconducting elements inside [13]-[15]. However, in this project, a non-rotating cryostat is developed. This topology permits to obtain an electromagnetic air-gap of 2mm with a cryostat thickness of 1mm. Fig. 5 shows the reduction of air-gap thickness in using the static cryostat.

Inside this cryostat, there is five HTS bulks made with YBCO material. Four seeds on the top was necessary to fabricate a disc of diameter 80mm with an optimal crystal growth. After the

melt textured process, the surface of the bulks need to be polished because of the small air-gap. Fig. 8 shows the YBCO discs before and after polishing. In order to fix the HTS bulks and transmit the torque a G-10 support is designed. Carbon fiber rings are placed between the bulks and the support to prevent thermal and mechanical damages. A scheme of the HTS bulks cooling and mechanical design is presented on the Fig. 9. The cryogen circulates in both ways through a static cane. Then, the inlet and outlet flows are separated by cryogenic seals. At the end of the cane, the helium penetrates into a duct made with copper pipes. These pipes surround the HTS bulks to cool them.

### B. Non-cryogenic part

As indicated previously, in a partially superconducting machine the stator is common to classical electrical machine. In line with the ‘design for mass’ criterion, a double-layer concentric winding is chosen. Concentrated windings have a shorter end-winding length compared to distributed windings, this shortening reduces weight and facilitates the manufacture and repairs of coil [16]. However, the drawback of this kind of windings results in the presence of more harmonics. These harmonics will generate eddy-current losses in every conductor parts. Therefore, special attention was paid on the choice of material. There is no ferromagnetic tooth, so the armature windings are not protected against flux change. So rectangular type-8 Litz wire was used to reduce eddy-current losses while conserving a good filling factor. These coils are placed on each side of the second static cryostat containing the HTS bulks, as showed in Fig. 1 and Fig. 5b. As the cryostat is static and see the flux modulation of the rotating YBCO discs, its materials has to be non-electrical conductive. So the cryostat is made in alumina, which has a high electrical resistivity ( $\sigma=10^{14}\text{-}10^{15}\text{ }\Omega\text{m}$ ) and also a moderate thermal conductivity ( $k=20\text{-}30\text{ W/mK}$ ) in order to evacuate the losses of the copper coil.

A thin hollow cylinder of laminated Si-Fe is used as a support for armature windings. The back-iron has the advantage to diffuse the heat generated by copper coils and offers a greatest surface for the cooling.

A picture of one alumina static cryostat with the armature winding and the back-iron is shown in Fig. 10. The five pole pairs conducts to a armature winding with twelve copper coils.

## IV. CONCLUSION

A 50 kW superconducting machine prototype was designed with a constraint on the mass. The development of a static cryostat has permit to reduce the air-gap length comparable to a classical synchronous electrical machine. This reduction of air-gap increases the performance of the superconducting machine. The main components of the optimized prototype are constructed such as the HTS coil and its cryostat, the HTS pellet and the static cryostat with the armature winding. The construction of some mechanical supports and the mechanical balance remain to be done. The superconducting machine is expected to be tested soon.

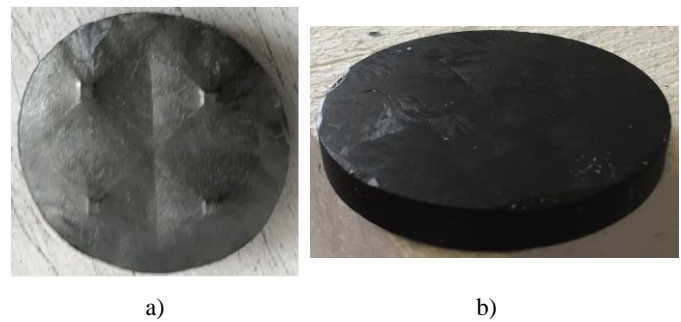


Fig. 8. A HTS bulk a) before polishing b) after polishing

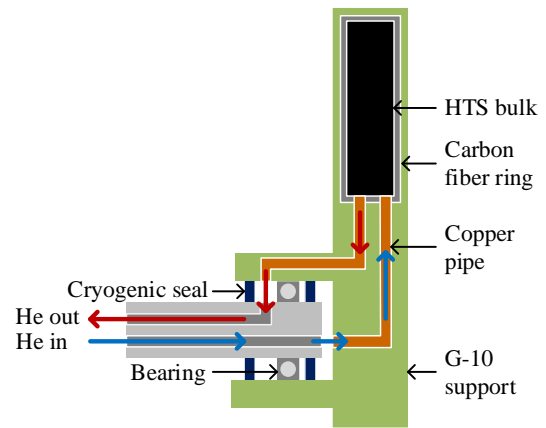


Fig. 9. Scheme of the rotating cryogenic cooling



Fig. 10. Static cryostat with the armature winding

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