Preliminary Assessment of New Armature Winding Concepts for High-Speed Superconducting Motors

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***Abstract*—Superconducting (SC) motors are nowadays being proposed for zero-emission aviation. Their specific power and power density are under various studies to assess their feasibility in such an application. This paper preliminarily assesses two novel armature winding concepts for SC motors, based on the concentric-racetrack-coil (CRC) concept and the direct-liquid-cooling (DLC) technology. The two armature winding concepts result in conceptual designs of a fully SC motor (FSCM) and a partially SC motor (PSCM), respectively. The specific power and power density of the conceptual designs are assessed by comparing them with aviation-oriented goals and with other reference motor concepts. The results show that the CRC SC winding concept for FSCMs can reach and even exceed the higher specific power goal of 25 kW/kg. The DLC copper winding concept for PSCMs is quite close to the lower specific power goal of 12.7 kW/kg. Improvements in the PSCMs and better utilization of their materials can be expected to fulfill the lower goal. Then the copper armature winding with CRC and DLC will be a potential solution considered for applying PSCMs to electrifying aircraft.**

***Index Terms*—Aircraft, armature winding, direct liquid cooling, high speed, power density, racetrack coil, specific power, superconducting motor.**

I. INTRODUCTION

ZERO emission transportation is considered to solve the environmental and climate crisis. The transportation sector is responsible for one sixth of world's greenhouse gas emissions. High-speed and high-frequency technologies offer a partial solution for the future energy conversion needs. However, the high-speed technology without new innovations cannot be used to electrify passenger class aircraft. One of the promising technologies to fulfill the requirement of the future zero emission aviation is superconducting (SC) machines [1], [2], [3], [4], [5], [6]. SC machines can be generators or motors. Motors for propulsion are the key component in the drive train of electrified aircraft. The power level of the propulsion could be mega-watt per motor. The power level is hard to achieve with conventional electric motors, e.g., those used in electric vehicles or more-electric aircraft. High power density motors are needed to link the goal of zero emission, the need for sufficient propulsion power and the critical requirement of compactness and low weight.

SC motors have a high torque density due to the fact that superconductors at cryogenic temperatures can carry more than ten times higher current density than copper conductors. Thus, they are being studied for aircraft electrification [7], [8], [9], [10], [11] especially after the successful demonstration of SC generators for the wind energy application [12], [13], [14]. SC machines for aviation other than wind energy are being both conceptually designed in [15], [16], [17], [18] and experimentally demonstrated in a few projects like a 400 kW fully SC motor demonstrator [19], and a liquid hydrogen cooled SC generator [20]. Airbus has initiated an international research project ASCEND which studies the possibility of cryogenically cooling the whole powertrain of an airplane [21], [22], [23]. The concept applies liquid hydrogen and liquid nitrogen as the coolants to enable superconductivity at different cryogenic temperatures for various power devices including SC motors. Evaporated hydrogen can be used for the energy storage of fuel cells. The concept is building a promising path towards fully electric aircraft with zero emission.

An SC motor is usually a synchronous machine. The rotor excites the main magnetic field by its high temperature superconducting (HTS) field winding. The stator has an armature winding in which symmetrical poly-phase currents flow and an electromagnetic (EM) torque is produced. The armature winding can also be superconducting by employing multi-filamentary SC wires, e.g., BSCCO, MgB_2, in a cryogenic environment. Such an SC motor is called a fully superconducting motor (FSCM) [24], [25], [26]. The armature winding can otherwise be made of copper wires operated at the room temperature. Such an SC motor is called a partially superconducting motor (PSCM) [27], [28], [29]. Compared to the copper armature winding (CuAW) of an PSCM, the SC armature winding (ScAW) of an FSCM is capable of producing a much higher torque density due to its higher current loading capability. However, the ScAWs of an FSCM is much more complicated and expensive. CuAWs will obviously be a technically and economically more feasible option if they can also reach the goals of specific power and

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power density of a propulsion motor for aviation. Then ScAWs may not be necessarily considered.

This paper preliminarily assesses two novel armature winding concepts for high speed SC motor applications regarding the specific power (i.e., power-to-weight ratio) and power density (i.e., power-to-volume ratio). One winding concept is an ScAW using our recently proposed concept of concentric-racetrack-coil (CRC) distributed windings [30]. This concept is used for FSCMs. The other winding conceput is a CuAW using an advanced direct-liquid-cooling (DLC) technology developed by our research group [31]. This concept is used for PSCMs where the DLC is employed into the CRC concept. The objective of the paper is to evaluate the possibility of using a CuAW in a PSCM for aircraft propulsion and finds out the performance distance between PSCMs using the DLC CuAW and FSCMs using the CRC ScAW, thereby investigating the potential of the SC motor concepts.

II. CONCENTRIC RACETRACK COIL CONCEPT

Concentric racetrack coils (CRCs) have been proposed for the design of full-pitch distributed windings with racetrack coils [30]. The number of slots per pole per phase q can be either $q = 1$ or integers larger than 1 (i.e., $q = 2, 3, 4, \ldots$).

A. Used for ScAW

The CRC concept initially aimed at solving the limitations of minimum bending radius of SC wires on the coil shape. Racetrack coils have currently been the only choice that simply ensures the minimum bending radius. In comparison, conventional diamond coils are sharply bent and twisted at the end winding and this will break the SC wires. Before the invention of CRC, racetrack coils had hardly been able to form balanced three-phase distributed windings since the adjacent coils could not avoid touching or crossing each other at the end winding. Thus, tooth coils or concentrated windings with fractional slots per pole per phase had been the only option for applying racetrack coils to armature windings. Compared to concentrated windings, distributed windings have much lower main flux leakage in the air gap especially when the magnetic airgap is relatively large, which is the case for an SC motor. Thus, achieving distributed winding arrangement with the CRC concept is an effective way to increase the torque density of an SC motor. CRCs form a double-layer distributed winding as depicted in Fig. 1. Each coil's span is a full pole pitch. Each coil can be fabricated with double pancake coils. Three phases are balanced. A larger number of q can be achieved by adding concentric coils inner to the original coil [30].

B. Used for CuAW With DLC

Direct liquid cooling (DLC) has been applied to a conductor with copper Litz wires around a cooling conduit in the center of the conductor [31], [32]. As illustrated in Fig. 2, the DLC technology prefers tooth coils due to simple integration of the steel cooling conduit into the copper conductor. Diamond coils are very hard to apply such cooling conduits. This limitation again hinders the feasibility of distributed windings. Similar to the SC winding, CRCs enable the use of distributed winding with direct-liquid cooled racetrack coils. As PSCMs have a significantly large magnetic air gap, using tooth coils or concentrated windings will cause considerable flux leakage in the air gap. Thus, the enabling of distributed windings can boost the torque density of PSCMs.

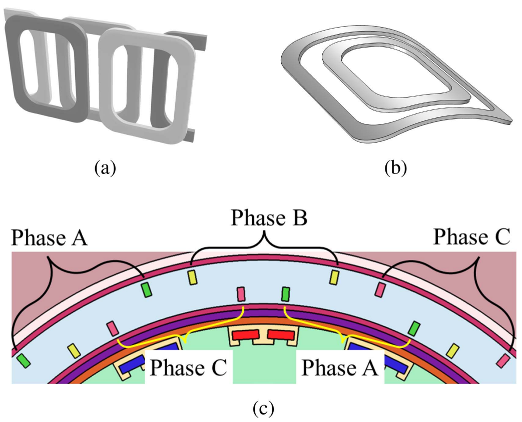


Fig. 1. SC CRC concept: (a) double-layer racetrack coils, (b) concentric coils for $q = 2$, (c) distributed winding layout with $q = 1$.

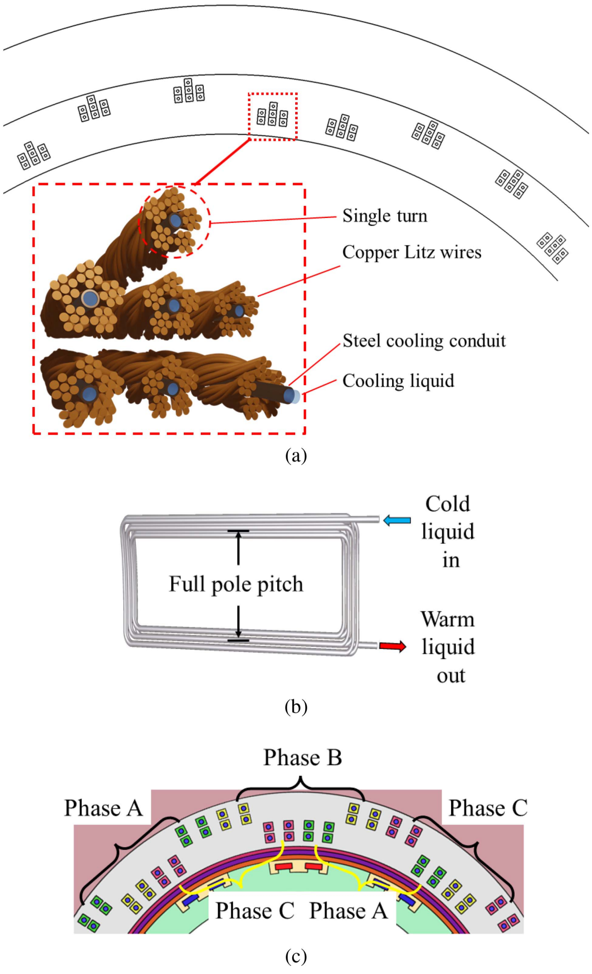


Fig. 2. Copper CRC concept with DLC: (a) double-layer winding with $q = 1$ and the multiple turns per coil, (b) cooling conduit in a single coil, (c) double-layer distributed winding layout with $q = 2$.

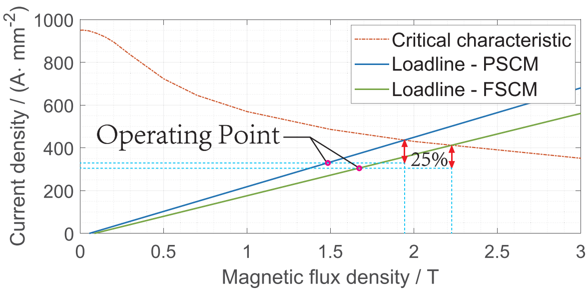
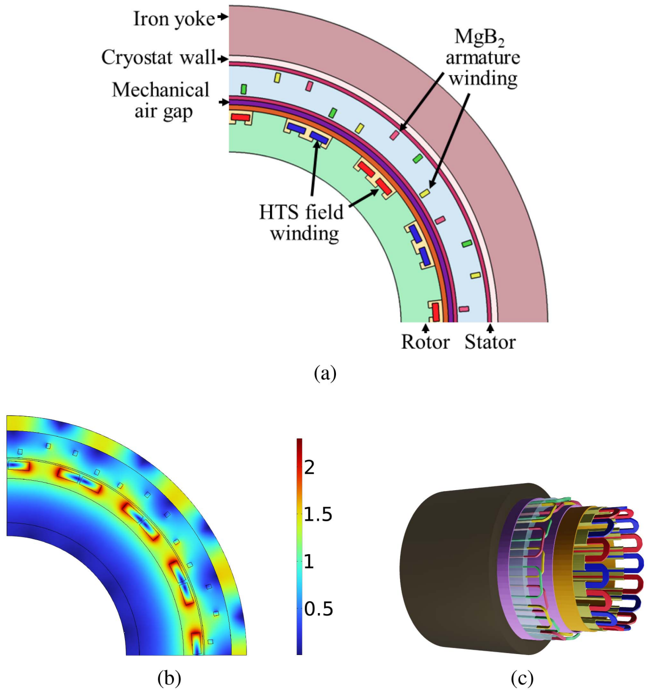


Fig. 3. Load lines and operating points of the REBCO field winding. The operating point is located $K_{\mathrm{safe}} = 0.25$ far from the intersection between the load line and the critical characteristic. The critical characteristic of the REBCO tape wire refers to [33].



(a)

(b)

(c)

Fig. 4. FSCM concept: (a) topology schematic, (b) magnetic flux density distribution at rated load (T), and (c) 3D exploded view.

Furthermore, DLC is a direct cooling technology and thus enables the use of G10 fiberglass as the armature winding supporting material. Employing fiberglass aims at a significant reduction of motor weight since G10's mass density is about one fourth of steel's mass density. G10 is reinforced with epoxy resin for greater strength but it has a low thermal conductivity. Cooling inside the conductor can avoid heat dissipation through G10.

III. SC MOTOR CONCEPTS FOR ARMATURE WINDING ASSESSMENT

The motor's rated power is 3 MW. The rated speed is 4500 rpm and the rated voltage 3 kV. The motor specifications refer to [15] and the cryogenic cooling method with liquid hydrogen refers to [15], [16]. The motor designs have been optimized for the maximum torque per unit length by parameter sweeping with finite element methods in COMSOL. The motor runs in the $I_{\mathrm{d}} = 0$ mode, meaning that the direct-axis current of the armature winding is controlled to stay zero.

The SC materials are simply modeled as a material with the zero conductivity and unit relative permeability. The non-linear resistivity is not modeled since it is not needed to model the AC loss in the study. The operating current density of the REBCO field winding of the FSCM and PSCM concepts is determined with the intersection between the load line and the critical characteristic of the REBCO tape wire, as illustrated in Fig. 3. The field perpendicular to the tape width is used. The current and critical current of each round MgB$_2$ wire of the SC armature winding of the FSCM concept fulfill the following equation:

$$N_{\mathrm{MgB}_2} = \frac{\sqrt{2} I_{\mathrm{n}}}{(1 - K_{\mathrm{safe}}) I_{\mathrm{crit}}} \tag{1}$$

where N_{MgB_2} is the number of MgB$_2$ wires per Rutherford cable, I_{n} is the rated current, I_{crit} is the critical current of each MgB$_2$ wire, and $K_{\mathrm{safe}} = 0.25$ is the safety margin. The critical current I_{crit} refers to [34]. The wire is round so no anisotropy of the critical current density occurs.

A. FSCM Concept With CRC ScAW (FSCM-CRC)

The FSCM concept is depicted in Fig. 4. It has 8 pole pairs. Its SC rotor has a REBCO HTS field winding. The rotor has no iron thereby reducing the weight. Liquid hydrogen flows in each coil assembly to directly cool the REBCO coil. The SC stator has a three-phase armature winding made from MgB$_2$ Rutherford cables as explained in [30]. The Rutherfold cable combines multiple filaments of each MgB$_2$ wire and multiple twisted MgB$_2$ wires to minimize the AC loss. The stator has a fiberglass structure to support all the armature winding coils. Liquid hydrogen flows in each coil assembly to directly cool the MgB$_2$ coils. An iron yoke is placed in the outermost layer of the stator to confine the magnetic flux inside the motor. The thickness of the iron yoke has been minimized to reduce the weight while keeping acceptably low leakage fields. The stator yoke is warm and its bore encloses a cylindrical cryostat. The rotor and stator (except the iron yoke) share the same cryostat. Thus, the magnetic air gap length is as small as 8.4 mm which refers to the designed number in [15]. The cryogenic temperature of both the rotor and stator is 20 K. The design parameters are summarized in Table I.

B. PSCM Concept With CRC-DLC CuAW (PSCM-CRC-DLC)

The PSCM concept is depicted in Fig. 5. It has 6 pole pairs. Its SC rotor has a REBCO HTS field winding. The rotor has no iron thereby reducing the weight. Liquid hydrogen flows in each coil assembly to directly cool the REBCO coil. The room-temperature stator has a three-phase armature winding made from the copper conductors with DLC. The current density of the copper conductor is as high as 55 A/mm^2 according to the simulation in [32]. The stator also has a fiberglass structure to support all the armature coils. Most of the heat from the copper winding is designed to be cooled by the internal forced water. An iron yoke is placed in the outermost layer of the stator to confine the magnetic flux inside the motor. The thickness of the iron

TABLE I
SPECIFICATIONS AND DESIGN PARAMETERS OF THE FSCM AND PSCM

Parameters	**FSCM-CRC**	**PSCM-CRC-DLC**
Rated power	3 MW	
Rated speed	4500 rpm	
Line voltage	3000 V	
Number of phases	3	
SC safety margin	25%	
Stack Length	134.7 mm	192.2 mm
Air gap diameter	447.6 mm	470.8 mm
Outer diameter	542.4 mm	606.2 mm
Magnetic air gap length	8.4 mm	11.7 mm
Operating temperature (field)	20 K	20 K
Operating temperature (armature)	20 K	393 K
Number of pole pairs	8	6
Fundamental frequency	600 Hz	450 Hz
Number of slots per pole per phase	1	1
Number of turns per field pole	400	750
Field current density	308 A/mm^2	322 A/mm^2
Number of turns per armature coil	10	7
Armature current density (RMS)	224 A/mm^2	55A/mm^2
Power factor	0.974	0.998

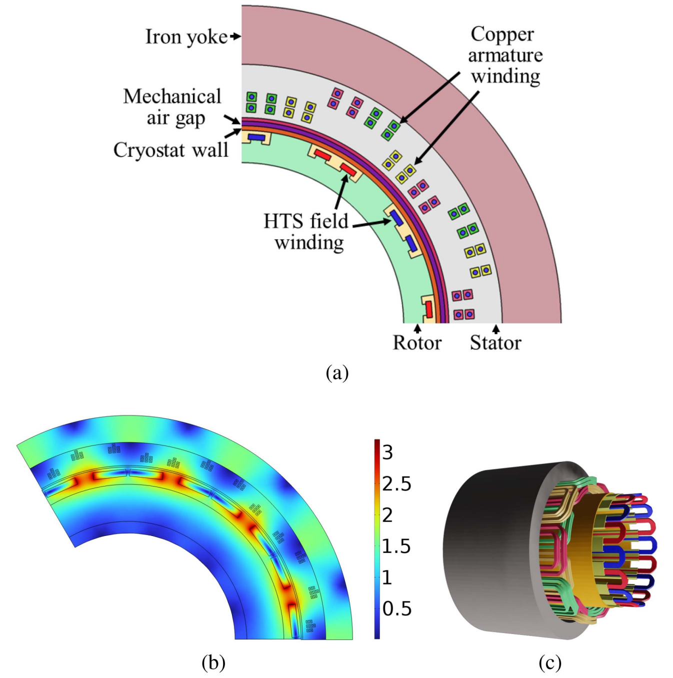


Fig. 5. PSCM concept: (a) topology schematic, (b) magnetic flux density distribution at rated load (T), and (c) 3D exploded view.

yoke has been minimized to reduce the weight while keeping acceptably low leakage fields. The rotor has a cryostat on its outermost layer. Thus, the magnetic air gap length of the PSCM is 11.2 mm which is larger than that of the FSCM. The length refers to the designed number in [15]. The stator is fully warm. The design parameters are summarized in Table I.

IV. PERFORMANCE ASSESSMENT

The conceptual design of the FSCM and PSCM has only covered electromagnetic parts, i.e., the active materials. The mass of the supporting structures has not been designed in detail. We therefore estimated the range of specific power based on various active/total mass ratios in the literature. The ratios range from 0.449 to 0.662 for an FSCM [15], [26] and from 0.495 to 0.544 for a PSCM [15], [16]. Cryogenic cooling devices and the coolant are not included in the mass. The coolant for DLC is not included in the mass of the PSCM.

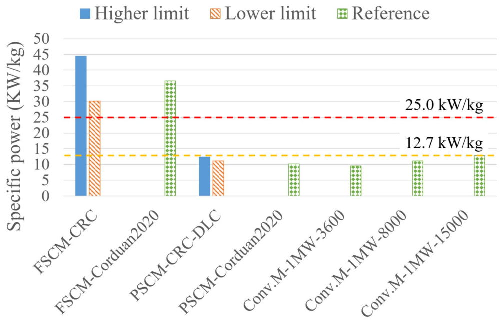


Fig. 6. Comparison of specific power between motors and with the goals. FSCM-CRC and PSCM-CRC-DLC are the 3 MW conceptual SC motor designs of the paper. FSCM-Corduan2020 and PSCM-Corduan2020 are the 3 MW conceptual SC motor designs in [15]. Conv.M-1MW is the 1 MW conventional motor developed for aviation with different rated speeds: 3600, 8000 and 15000 rpm, summarized in [27].

Two goals of specific power are considered in the assessment. One is 12.7 kW/kg, which is the goal for the fully turbo-electric concept aircraft N3-X discussed in [15]. The other is 25 kg/kW, which is the target of future electrically-propelled commercial aircraft [2], [27]. Advanced conventional motors that have been developed for aviation are used as a reference of specific power [27]. There are no power density goals for assessment but the power density implies how large the space of the motor takes up in an airplane. The Esson's coefficient [35] of the FSCM, PSCM and reference motors is also compared to show how efficient the materials are utilized to build the motor.

The specific power is compared in Fig. 6. Only the fully SC motors (FSCMs) can reach the goal of 25 kW/kg even considering the lower side of FSCM-CRC. This means that our proposed FSCM concept with CRC has the potential to be applied to electrified aircraft. The partially SC motors are however far from 25 kW/kg but some of them are rather close to (PSCM-CRC-DLC) or even reach (Conv.M-1MW-15000) the lower goal of 12.7 kW/kg. The proposed PSCM-CRC-DLC has the specific power between 11.2 kW/kg and 12.4 kW/kg, which are slightly lower than the goal of 12.7 kW/kg. A few improvements can be considered to fill in the gap. One option is to increase the rated speed. As seen from the conventional motor trends from Conv.M-1MW-3600 to Conv.M-1MW-15000, increasing the rated speed from 3600 rpm to 15000 rpm can lift the power level. However, the mechanical design for tolerating a higher speed will become more challenging. Another option is to reduce the iron yoke's thickness as analyzed in [26]. The challenges will then become how to meet the requirement of electromagnetic interference (EMI) and finding a way to avoid excessive eddy current losses in electrically conductive materials in vicinity of the motor.

The power density and the Esson's coefficient are both given in Fig. 7. The distance of power density between the fully and

Fig. 7. Comparison of power density and the Esson's coefficient. FSCM-CRC and PSCM-CRC-DLC are the 3 MW conceptual SC motor designs of the paper. FSCM-Corduan2020 and PSCM-Corduan2020 are the 3 MW conceptual SC motor designs proposed in [15].

partially SC motors is not as large as that of specific power. This means partially SC motors tend to use more heavy materials, such as iron and SC field winding, to compensate the loss of the main magnetic field excitation, compared to the fully SC motors. Seen from the Esson's coefficient, when compared to the reference cases (FSCM-Corduan2020 and PSCM-Corduan2020), our proposed fully SC motor concept (FSCM-CRC) has made good use of the materials but the partially SC motor concept (PSCM-CRC-DLC) has not. This shows that it is needed to improve the design of the PSCM-CRC-DLC concept for better utilizing the materials. This also shows that the PSCM-CRC-DLC concept has the room to improve and it is potentially capable of reaching or exceeding the goal of 12.7 kW/kg via other design routes. For instance, the direct-water-cooling should be more wisely integrated into the SC motor concept.

V. CONCLUSION

Two novel armature winding concepts based on the CRC concept have been proposed for high-speed SC motors for aviation applications. The CRC concept is to realize distributed windings with racetrack coils. The first concept is ScAW so the motor is fully SC. The second concept is CuAW so the motor is partially SC but the DLC technology is introduced to boost the torque production. The fully SC motor concept with the CRC ScAW can exceed the specific power goal of 25 kW/kg and could be used for larger aircraft. The partially SC motor concept with the CRC DLC CuAW can be rather close to the lower specific power goal of 12.7 kW/kg and could be considered for smaller aircraft. Improvements and better utilization of materials of the PSCMs can be expected to fulfill the lower goal. Then the CuAW with CRC and DLC will be a potential solution considered for applying PSCMs to electrifying aircraft.

In the next phase of the study, detailed design of the CRC-DLC winding will be conducted for determining the cooling parameters (e.g., volume flow rate, flow speed) and sizing the conduit and Litz wires. The results will be used to verify the assumptions of the PSCM concept proposed in the paper. Detailed mechanical and cryogenic cooling design need to be done for more accurately estimating the total mass and then the specific power of the proposed SC motor concepts. Studying the effects of rated speed on the specific power is also needed to reveal how high the speed should be to reach specific power goals for PSCMs. The speed study is also expected to check if FSCM concepts may not need a high rated speed since the specific power goal would have been achieved at a relatively low rated speed. In addition, cost and efficiency have not been considered yet to limit the use of SC wires. They will both be included in future studies to restrict parameter sweeping or optimization. AC losses of the SC windings will then be modeled and considered in the conceptual design.

The presented study is a preliminary assessment of the two novel armature winding concepts and basically an electromagnetic assessment. Mechanical design and analysis of the two winding concepts and the cryogenic cooling design will separately be studied in later stages of the research. The CRC ScAW is targeted for FSCMs and the CRC-DLC CuAW is for PSCMs. The cryogenic cooling method for the field winding is likely to be conduction cooling while for the armature winding it is still open to conduction cooling and liquid hydrogen cooling. Thermal design and analysis need a comprehensive study in the future work.

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