A Review of Superconducting Electric Machines with On-Board Cryocoolers

Jianqiao Xiao[1], Kiruba S. Haran[2], Sangkwon Jeong[3], William Sixel[4], and Justin Scheidler[4]

[1]Hinetics Inc. Champaign, IL 61820, USA
[2]University of Illinois Urbana Champaign, Dept. of Elec. and Comp. Engr., Urbana, IL 61801, USA
[3]Korea Advanced Institute of Science and Technology (KAIST), Dept. of Mech. Engr., Daejeon, Korea
[4]NASA Glenn Research Center, Cleveland, OH 44135, USA

***Abstract*—This paper reviews the evolution and emerging direction of superconducting electric machines that employ on-board cryocoolers integrated directly into the rotor, eliminating the need for cryogenic fluid coupling and, in some cases, rotary seals. Traditional low-temperature superconducting (LTS) machines relied on external cryogenic systems and liquid helium transfer couplers, which introduced excessive complexity, poor reliability, and significant parasitic energy losses. The advent of high-temperature superconductors (HTS) has enabled compact, closed-cycle cryocoolers that support self-contained, fluid-free refrigeration architectures suitable for rotating applications. This paper examines the key technological challenges associated with on-board cryocooler integration and reviews three representative efforts by KAIST, NASA, and Hinetics, each illustrating distinct strategies and milestones toward practical implementation. KAIST demonstrated early proof-of-concept for rotating machines with on-board cryocoolers, NASA developed a shaft-integrated Stirling-type pulse tube cryocooler for a 1.4 MW hybrid-electric motor, and Hinetics achieved full-scale validation of a self-contained HTS rotor incorporating a commercial Stirling cryocooler and spoke-suspension torque tube. Collectively, these achievements confirm the technical feasibility of on-board cryogenic refrigeration and highlight steady progress toward compact and efficient superconducting rotating systems across various applications. Embedding cryocoolers directly within the rotor enables practical, efficient, and commercially viable superconducting propulsion technologies.**

***Index Terms*—Cryogenics, electric machines, superconductivity**

I. Introduction

Superconducting (SC) motors and generators eliminate the resistive loss in windings, offering significantly higher specific torque and efficiency, making them ideal for aerospace and heavy-duty mobility applications [1], [2]. However, thermal management design has become the major challenge for practical SC machines, since the superconductors that are useful to electric machines can only operate below 100 K. At this temperature, compact refrigeration is challenging because of the severe Carnot limit on efficiency and heightened thermal leakage at large temperature gradients [3]. Traditional cryogenic thermal management systems involve separated, bulky equipment outside of the machine and bidirectional fluid exchange through transfer couplers. However, such cooling systems that rely on centralized, stationary cryogenic refrigerators introduce complexity, inefficiency, and instability, diluting the benefit brought by superconductivity.

Over the past decade, there has been strong interest in superconducting machines for aircraft propulsion applications, where safety is paramount and reliability is critical to economic viability. Cryogen-free, self-contained approaches to rotor cooling may be the only practical solution for this application. Efforts to integrate cryocoolers directly into the rotor of SC machines have emerged in research that seeks to realize compact, modular, self-contained, and energy-efficient systems. On-board cryocoolers, broadly defined as refrigeration architectures integrated with the machine that eliminate dependence on externally supplied cryogens during operation, obviate the dependence on auxiliary fluid coupling by embedding the cooling system on the machine itself. This leads to compact packaging and improved reliability. While sub-component-level advancements remain necessary to address challenges such as high centrifugal and vibration load, unreliable power transfer, and limited warm-end heat rejection, recent prototypes have successfully demonstrated on-board cryogenic refrigeration systems, paving the way for practical deployment.

Recent research and advances in on-board cryocooler architectures motivate a timely assessment of cryogen-free superconducting machine concepts. Although numerous review articles exist on superconducting electrical machines and cryogenic technologies separately, there has not been a dedicated review of those employing on-board cryogenic refrigeration. The recent emergence of several prototype systems motivates a comprehensive review of this rapidly developing field. The review includes both fully integrated on-board cryocooler systems and related cryogen-free architectures that have contributed to the development of this concept. This paper consolidates the state of the art, identifies common technical challenges and enabling technologies, highlights future research directions, and reviews the historical development and current implementation of these architectures. This paper begins by reviewing the historical development of LTS machines. Then it examines three specific efforts to integrate cryocoolers directly into HTS SC rotating machines by Korea Advanced Institute of Science and Technology (KAIST), National Aeronautics and Space Administration (NASA), and Hinetics.

II. Previous developments of LTS motors and generators with valuable lessons

The first SC machine, the 3250-hp, 200-rpm "Fawley motor," was built in the United Kingdom in 1966 [4], followed by programs at MIT [5]–[9], Westinghouse [10], [11], General Electric [12], and the Japanese Super-GM project [13]. All machines employed NbTi superconductors (Tc $\approx$ 9.2 K) in the DC field winding only, as superconducting armature windings would offer no reduction in AC losses and would exacerbate the thermal management challenge, especially for high-power scale-ups. Their cryogenic cooling was based on closed-loop liquid helium systems. Most designs placed the superconducting field on the rotor, which required shaft-mounted liquid helium transfer couplers that proved mechanically complex and prone to excessive seal wear, leading to high maintenance needs and low reliability. Operating near 4 K imposed further challenges, as removing just 1 W of heat at this temperature requires about 74 W input power at room temperature under the ideal Carnot Coefficient of Performance (COP), with real input power far higher. Although prototypes generally operated successfully, none achieved true commercialization by mass deployment. As highlighted in [12], persistent obstacles include unreliable cryogenic systems, large mechanical stresses on torque tubes and coil supports, non-uniform thermal shielding, stringent manufacturing tolerances, high costs, and dependence on dedicated cryocoolers.

Recent progress in SC machines focuses on transportation applications where high power, high torque density, and high efficiency are the primary drivers. The design differ by application. Aerospace propulsion places the strongest emphasis on mass and volume reduction, requiring high specific power, relatively high operating speed, and tight integration of the cryogenic system with the machine [14]–[19]. Ship propulsion prioritizes high torque density at low speed and high overall power, with comparatively greater tolerance for system mass but stronger emphasis on modularity, redundancy, and serviceability [20]–[23]. Automotive and other land-transport applications place greater emphasis on torque delivery over a wide drive range, practical packaging, and continued operation during transitions between superconducting and non-superconducting states [24]–[26].

III. Transition from Open Helium Cooling to On-Board Refrigeration

As discussed earlier, cryogenic fluid transfer coupling has been a primary source of unreliability in the stable operation of SC machines. Extensive efforts have been made to reduce or eliminate this coupling, especially after the discovery of HTS in the mid-1980s, which increased the critical temperature from 4 K to about 35 K and expanded the range of feasible refrigeration methods [27]. Open-loop cooling, where cryogen is vented after refrigeration, is not scalable or economical for transportation or power generation applications; thus, closed-loop systems incorporating cryogenic refrigerators are deemed necessary. Although some rotational coupling is unavoidable, the coolant routed through it and the placement of the interface between the stationary and rotating sides can be configured to improve overall practicality. These architectures can be classified into three categories based on how the liquid coolant is transferred to the rotor. This section examines various coupler placement strategies, reviews representative prior designs, and evaluates the corresponding challenges and advantages of each configuration.

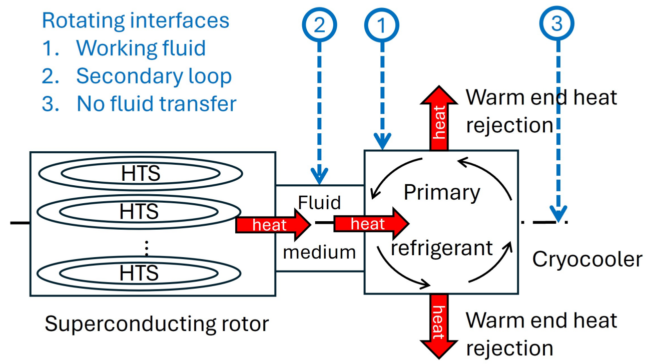

Fig. 1. Topologies of the rotating structure

Fig. 1 proposes a classification framework for superconducting electric machines based on refrigeration architecture. The system consists of a cryocooler that circulates a primary refrigerant, such as helium gas, to remove heat from the cold end and reject it to the warm ambient. In practice, the cryocooler cold head often cannot be placed in direct contact with the HTS coils because of geometric constraints. A secondary cooling loop may therefore be introduced to distribute the refrigeration power and to reduce the temperature gradient across the HTS coil assembly. This secondary loop may use a cryogenic fluid in either single-phase or two-phase operation. Fig. 1 also identifies three possible locations for the rotating interface: (1) within the primary working-fluid circuit, where the compressor remains stationary while the cold end rotates; (2) within the secondary cooling loop, where the interface to the cold head remains stationary while the interface to the HTS coils rotates; and (3) outside the complete refrigeration assembly, where the cryocooler rotates together with the cryogenic rotor without involving any secondary cooling loop.

For rotating interface at location (1), the refrigerant directly participates in the cooling cycle on the stationary side and absorbs heat from the rotor's active region. One such example is transferring liquid helium from the stationary helium liquefier. Although this direct-cooling approach is conceptually simple, it requires a dynamic cryogenic coupling that demands reliable sealing, which is technically challenging. To avoid cryogenic sealing, an alternative approach within the same architecture transfers room-temperature compressed gas instead of liquid helium. This method has been adopted in systems such as the Suprapower and EcoSwing projects, which employ two-stage Gifford–McMahon (GM) cryocoolers and high-pressure helium transferred through specially designed gas rotary joints. In practice, these implementations encountered issues such as limited sealing performance and orientation-dependent behavior [28], [29].

Instead of transferring the primary working fluid, a secondary cryogenic cooling medium may be circulated through the rotor at location (2). This approach was adopted by General Electric for its HTS generator, in which the secondary coolant absorbs heat within the rotor and is subsequently re-cooled by an external stationary Gifford–McMahon (GM) cryocooler [30]. By decoupling the rotor cooling from the primary working fluid, this architecture allows greater flexibility and potential improvements in heat transfer. Examples include Siemens's use of a liquid-neon thermosiphon [31] and American Superconductor's configuration with an external cryocooler positioned at the non-driven end of the shaft [22]. While these systems may appear compact, most rely on GM cryocoolers with remote cold-head expanders and heavy helium compressors connected by long, high-pressure lines. These auxiliary components are essential for operation but are often omitted from published illustrations of the machines.

Rotary transfer can occur not only within the secondary loop but also between the primary and secondary loops. This concept, known as "direct heat exchange," was proposed in Japan, where the heat exchanger was divided into stationary and rotating sections, allowing heat transfer and rotary transfer to occur simultaneously. A rotating cryogenic helium circulation pump with a magnetic drive was validated in a small-scale model [32]. Fig. 2 shows a rotational–stationary heat exchanger based on a counter-flow shell-and-tube design, in which cryogenic helium from the turbo-Brayton refrigerator flows through the primary (stationary) tubes and exchanges heat with helium on the secondary (rotating) side.

To eliminate the liquid rotary coupler, a natural solution is to place the refrigeration device directly on the rotor, requiring only the electrical supply to be transferred. This approach, known as an on-board cryocooler with no fluid transfer, indicated by location (3) in Fig. 1, represents the most straightforward cooling architecture. Zhang et al. first proposed an on-board regenerative cryocooler, which reduces transfer thermal leakage and can eliminate the need for a cryogenic transfer coupling [33]. This concept remained at the design stage until KAIST researchers implemented it with Stirling or Stirling-type pulse tube cryocoolers for HTS rotors in the early 2000s [34]–[36]. Integrating a cryocooler into the rotor creates a self-contained unit, reducing overall system cost and improving reliability. In a Department of Energy (DOE) project carried out by Reliance Electric Company in the USA, a test rig for a rotating cryocooler demonstrated no performance degradation up to 1500 rpm [37]. Such a consolidated rotor can retrofit into existing stator frames, localize cooling only where cryogenic temperatures are required, reduce pipe and flange complexity, and thus improve overall system efficiency.

Other tentative rotor-cooling concepts have also been explored. Although many of these designs remain conceptual, they can generally be classified within the three refrigeration categories discussed previously. One example shown in Fig. 3 is the rotary cooling system proposed by Caughley et al. In this design, the cryocooler remains stationary while the rotor is cooled via local circulation of helium gas [38]. While innovative, this approach still relies on gas sealing, which may affect its long-term reliability. This concept falls into the second category, in which a secondary cryogenic cooling medium is circulated. On-board thermal-storage approaches, such as solid nitrogen or thermal batteries, have also been studied [39], [40]. However, because their cooling capability is limited by finite thermal capacity, they are inherently transient and cannot replace continuous on-board cryocooler operation. Fundamentally, the challenges of rotary transfer can be characterized by three key questions: what medium is transferred, which components rotate versus remain stationary, and at what speed the rotor operates. Table I presents representative superconducting machine developments and categorizes them according to Fig. 1 together with their rotary transfer medium. The examples are selected to demonstrate the distinguishing features of each refrigeration architecture rather than to provide an exhaustive survey of all reported superconducting machine efforts.

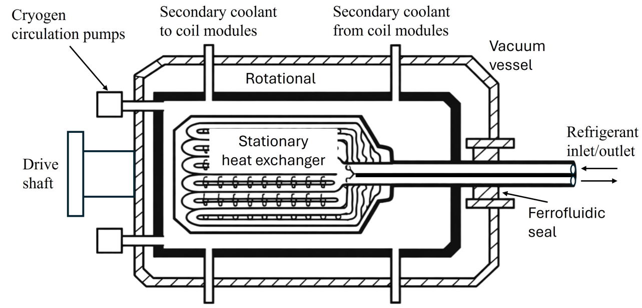

Fig. 2. Rotational-stationary heat exchanger [32]

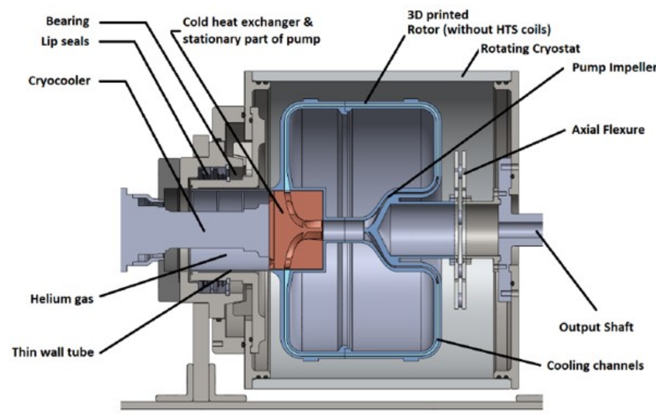

Fig. 3. Rotor with a stationary cryocooler and locally circulating helium gas [38]

IV. Challenges of the On-board Cryocooler

A. Structural integrity

Though on-board cryocoolers eliminate the need for rotary fluid transfer and thus make practical superconducting machines possible, several technical challenges must be matured before large-scale production and deployment. The foremost concern is maintaining structural integrity of the cryocooler under high rotational speeds with an axisymmetric design. Recuperative cryocoolers, which circulate working fluid continuously through a closed loop, tend to generate centrifugal

TABLE I
REPRESENTATIVE SUPERCONDUCTING ELECTRIC MACHINES CLASSIFIED BY REFRIGERATION ARCHITECTURE

Category in Fig. 1	Group, year published	Fluid transfer site	Medium transfered in/out, circulation method	Power [W]	RPM	Rotor Temp. [K]	Ref.
1	EcoSwing, 2019	Working fluid	Gaseous helium, part of a GM cryocooler	3.6 M	15	30	[41]
1	Reliance Electric, 2002	Working fluid	Gaseous helium, part of a reverse Brayton cycle cryocooler	735 k	1800	33	[42]
1	GE, 2006	Working fluid	Gaseous helium, part of a customized GM cryocooler	112 M	3600	30	[43]
2	AMSC, 2011	Secondary loop	Gaseous helium, cooled externally with a GM cryocooler cold box	36.5 M	120	30	[44]
2	ASUMED, 2020	Secondary loop	Gaseous helium, cooled externally with a custom cryocooler	1 M	6000	30	[45]
2	Doosan, 2016	Secondary loop	Gaseous helium, cooled externally with a cryocooler cold box	5 M	213	27	[46]
2	Siemens, 2007	Secondary loop	Liquid helium/ 2 phase helium, circulated through thermosiphon	4 M	3600	25	[47]
2	Strathclyde, 2020	Secondary loop	Liquid nitrogen/ 2 phase nitrogen, liquid nitrogen immersion cooling	n/a	300	77	[48]
3	KAIST, 2011	Electrical power	None, rotor-mounted cryocooler	n/a	240	60	[36]
3	NASA, 2020	Electrical power	None, rotor-mounted cryocooler	1.4 M	6800	50	[49]
3	Hinetics, 2025	Electrical power	None, rotor-mounted cryocooler	5 M	3000	50	[50]

pressure gradients and unbalanced dynamic forces that complicate rotor balancing. In contrast, regenerative cryocoolers employ oscillating gas flow within confined passages; when aligned along the rotation centerline, they produce negligible net momentum and remain balanced.

Among regenerative coolers, the Stirling cryocooler offers high thermodynamic efficiency in a compact form factor, whereas the Stirling-type pulse tube cryocooler eliminates moving parts at the cold end, avoiding the need for precise displacer alignment. These cryocoolers are typically designed for moderate cryogenic temperatures (50-80 K), insufficient compared with the thermal leakage of traditional superconducting machines. Therefore, minimizing heat load and optimizing thermal contact between the cryocooler's cold head and the superconducting windings are critical. The development of dedicated cryocoolers tailored for large-scale superconducting rotors with high heat lift remains essential to achieving higher performance and integration levels.

Axial reciprocating motion of the compressor introduces vibration along the shaft. Although dynamic balancers can mitigate reaction forces, they transmit periodic impulses to the rotor mount. Some systems employ double-acting linear compressors, in which two opposing pistons counteract each other to cancel vibration, as shown in Fig. 4. However, in such designs, the working-fluid transfer lines must be routed off-center, and the design requires careful assessment of centrifugal loading and potential flow imbalance.

B. *Warm end heat rejection*

Heat rejection from the on-board cryocooler presents another major challenge. For systems requiring more than 20 W of cooling at 50 K, the waste heat that needs to be dissipated is approximately 1 kW because of the low coefficient of performance (COP). While water-cooling is technically feasible, air-cooling is often more practical since it avoids the complexity of liquid transfer. Therefore, efficient heat-rejection mechanisms are needed to enable the cryocooler's aftercooler to discharge heat directly to the surrounding air, whether the rotor is stationary or rotating.

Fig. 4. Stirling cryocoolers: single compressor (left) and dual compressors with a transfer tube (right)

C. *Other challenges*

Other challenges, including long-term vacuum retention, cryocooler vibration isolation, and thermal management within the rotor, are generally less critical than the major issues of structural integrity, power delivery, and heat rejection discussed above. These secondary concerns can often be addressed through established engineering practices once the primary mechanical and thermal constraints are resolved. The following sections review three on-board cryocooler development efforts from KAIST, NASA, and Hinetics, each illustrating a distinct approach to overcoming these key challenges in on-board cryocooler integration for superconducting rotors.

V. KAIST'S ROTATING CRYOCOOLER PROGRAM

KAIST has been a leading contributor to the development of on-board cryogenic refrigeration for superconducting rotors. The group first designed a dedicated rotating cryocooler and later built a cryogenic rotor test rig, successfully demonstrating that a cryocooler can operate reliably under rotation. This achievement provided important proof of concept that on-board refrigeration is feasible, moving the technology closer to practical superconducting machines with self-contained cooling loops on the rotor. The results also showed that rotation itself does not significantly disturb cryogenic gas dynamics or degrade cooling performance, since the expansion space volume of a Stirling cryocooler is typically small enough to remain thermally equilibrated. In contrast, the pulse tube volume of a Stirling-type pulse tube cryocooler may be influenced by centrifugal force because of its inherently nonequilibrium thermodynamic nature. Although a detailed analysis on acoustic streaming (or secondary flow effect) due to rotation in the pulse tube remains an interesting subject for future research, the results clearly indicate that the cooling performance of a conventional pulse tube cryocooler is not adversely affected by centrifugal force, as reported in the reference [37]. Instead, the primary limitation lies in heat rejection at the warm end of the cryocooler.

As one of the first implementations of a rotating cryogenic refrigeration system, KAIST integrated a single-stage coaxial Stirling-type pulse tube cryocooler into a HTS motor configuration in 2005. The system achieved a no-load temperature of about 100 K, and the axisymmetric design of the cryocooler exhibited no adverse effects during high-speed rotation. The study demonstrated that the rotational environment had negligible influence on the cryocooler's performance, though the centrifugal effects could become more prominent in larger systems. Building on this work, Ko et al. later implemented a Stirling-type coaxial pulse tube cryocooler in an 1800-rpm HTS motor mock-up, confirming the feasibility of direct on-board cryogenic cooling for superconducting rotors [34].

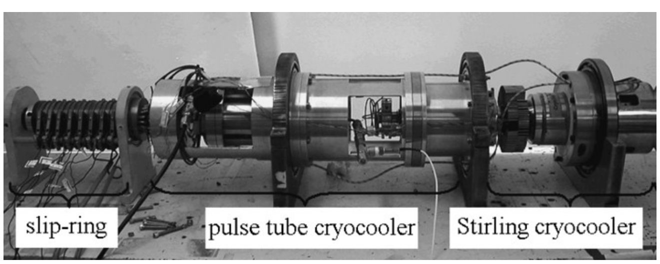

Fig. 5. KAIST hybrid pulse tube cryocooler rotation test [35]

Subsequent development focused on a rotating hybrid pulse tube cryocooler shown in Fig. 5, where a Stirling cryocooler pre-cooled the regenerator of a pulse tube stage to achieve lower cold-end temperatures. The cryocooler maintained stable operation under rotation, with only a small temperature degradation of about 3 K under no-load conditions. However, it did not reach the predicted 40 K target temperature, likely due to insufficient heat rejection at the warm end. Building on these efforts, the research group developed an HTS motor prototype in 2011 cooled by an on-board pulse tube cryocooler, shown in Fig. 6 [36]. The cryocooler provided 5 W of cooling at 56 K, sufficient to maintain YBCO field windings below their critical temperature. Mounted directly on the rotor, the cryocooler remained in mechanical and thermal contact during rotation, demonstrating a compact and effective integration approach. The prototype operated successfully at 240 rpm with a rotor current of 75 A, validating the practicality of coupling a pulse tube cryocooler with rotating HTS machinery.

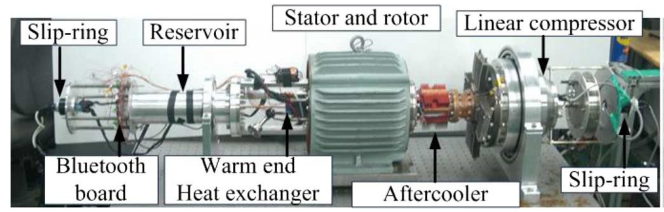

Fig. 6. KAIST electric motor powered with an on-board Stirling-type pulse tube cryocooler [36]

VI. NASA HEMM Program

The High Efficiency Megawatt Motor (HEMM) is a 1.4 MW partially superconducting electric machine developed for aircraft propulsion [49], [51]. It has an advantage in compatibility with conventional aircraft interfaces. It uses the same mechanical and electrical connections and operates with an aircraft coolant (MIL-87252 PAO at 60 °C, which was selected in part for its suitability to also directly cool the motor's stator winding). A core element of the project is to develop a rotating Stirling-type pulse tube cryocooler, mounted inside the shaft as shown in Fig. 7, that provides 50 W heat lift at 50 K and conductively cools the superconducting rotor. The main challenges for the cryocooler in the rotating environment include the heat rejection at the warm end and the centrifugal effects on the gas dynamics and solid components.

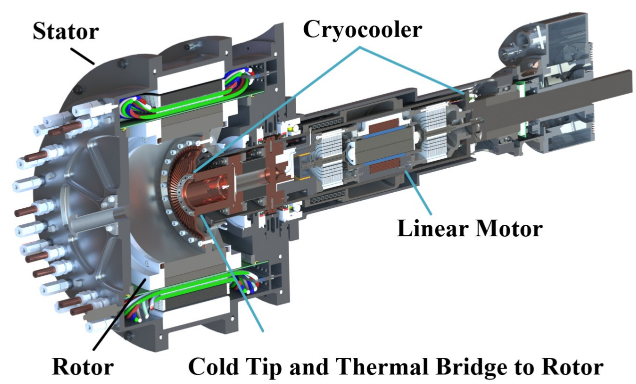

Fig. 7. NASA HEMM cut-away diagram

The HEMM cryocooler is a Stirling-type pulse tube cryocooler. It uses a Redlich-type, moving-magnet, linear reciprocating motor mounted on flexure bearings to drive a piston, which generates a travelling acoustic wave in the helium gas that, in turn, causes the cooling effect of the Stirling cycle.

The design decisions can be found in [52]. Stirling-type pulse tube architecture enables an axisymmetric structure with no moving part in the cryogenic region. The coaxial layout aligns with the cantilevered rotor design, which reduces the heat leakage, and the decision to use a single compressor simplifies the mechanical integration to the motor and heat rejection.

The cryocooler design was conducted using a specialized commercial software for modeling Stirling, Gifford-McMahon, and other periodic-flow thermodynamics devices. The cryocooler, including the linear motor, was then optimized using the tools built into the commercial software for maximizing heat lift, with the shaft's inner diameter (110 mm) being the main constraint. The design was also iterated with the consideration of pressure vessel mechanics, the 2D effects that needs to be countered by the flow straighteners, and the detailed electromagnetic and thermal analysis of the linear motor. Two prototype linear motors were tested [53]–[55], which demonstrated their stable operations near resonance, with an expected life time of more than 10^7 cycles.

A liquid jet impingement cooling system was selected for the warm-end heat rejection because it can achieve an extremely high heat transfer coefficient, reducing the surface area necessary and thus drag. Further, it can be designed for full flow at the thermal worst case (startup while stationary) but optimized for minimized losses while rotating, where the heat transfer is enhanced by the rotation of the shaft and the flow rate can be throttled to reduce drag. The design was first optimized with empirical correlations for heat transfer and simple predictions for drag and pressure drop, which were later refined with detailed conjugate computational fluid dynamics modeling to more accurately predict performance.

Challenges concerning cryocooler-machine integration involve a room-temperature rotary face seal and an effective thermal link between the cryocooler cold tip and the rotor. The rotary seals are needed to contain the liquid coolant used for jet impingement at near room temperature from ambient pressure, as well as vacuum (on the rotor-side). The shaft's high surface speed combined with the need for low leakage and low drag meant no commercial off-the-shelf (COTS) seal was found to be adequate for the application. A customized mechanical face seal was determined to be acceptable. A rotordynamic analysis confirmed the shaft's dynamic displacement would be small enough to avoid degrading the seal's leak and wear rates [56]. The conductive thermal link between the cryocooler and the rotor must find a balance among (1) minimal temperature gradient, (2) robust yet torsionally compliant mechanical structure, and (3) careful design for thermal expansion. The final design achieved this balance through a dispersion-strengthened copper, and the structure was cryogenically tested in a full-scale rotor [57], [58]. This test also demonstrated the ability to conductively cool a MW-class rotor with less than 12 K temperature gradient between cold head and superconducting coils. NASA is expecting more challenges to finalize the cryocooler and its integration into the motor (e.g., the impact of vibration on the motor's life and a more reliable rotor excitation method).

VII. Hinetics' CRUISE and CHEETA Programs

Building on the concept of eliminating fluid coupling for compactness and efficiency, Hinetics has pursued the development of a compact SC rotor as a fully self-contained system, requiring no auxiliary support systems beyond the power excitation leads. This integrated design targets a power output of 10 MW at approximately 3,000 rpm, aiming primarily at electrified aircraft propulsion [50]. To remove the need for liquid cryogen transfer, a COTS Stirling cryocooler is mounted at the center of the rotor shaft. Thermal straps connect the cold finger to the cryogenic coil holder via a dedicated conduction cooling path, as illustrated in Fig. 8. The overall thermal design is further optimized by minimizing heat leakage through the spoked torque tube. High-g vibrations and substantial centrifugal loads impose significant mechanical and operational challenges on all major components, particularly the cryocooler. De-risking experiments on critical subcomponents have been carried out since 2022, with positive outcomes confirming the viability of the integrated design. In 2025, a full rotor assembly incorporating both the on-board cryocooler and spoked torque tube was successfully demonstrated. The following paragraphs provide a more detailed discussion of the cryocooler and spoked torque tube de-risking activities as well as the development and testing of the full-scale demonstrator. The de-risk activities are summarized in table II.

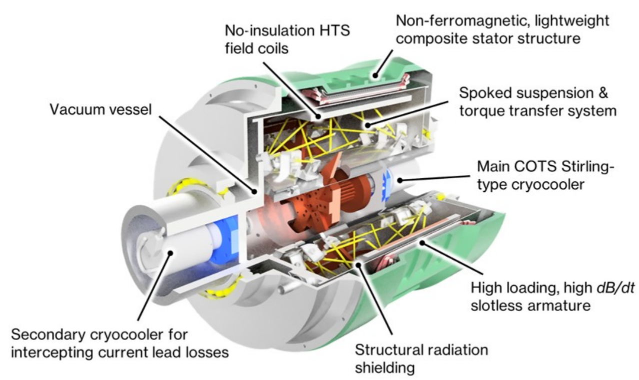

Fig. 8. Hinetics' SC motor topology

High-g acceleration testing validated the cryocooler's tolerance to severe vibration, since on-board cryocoolers are subjected to unusually high g-loads and centrifugal forces that current commercial units were not originally designed to withstand. Vibration testing was conducted in accordance with MIL-STD-810H, applying a maximum acceleration of 50 g to the cryocooler. During shock events, only minor degradation in cold-end temperature was observed, and performance returned to nominal levels once the shocks ceased.

The rotation test aimed to identify unknown phenomena that could affect cryocooler performance during sustained high-speed rotation. The experiment was comprised of two parts: (1) a long-duration test in which the cryocooler operated at full load at 45 K for 100 hours, and (2) an overspeed test at 25% above the nominal rotational speed. In both cases, the performance was evaluated by monitoring the cold-head temperature under a constant heat load. Interestingly, the results showed a consistent performance improvement under rotation compared to the stationary case. This enhancement is attributed to improved convective heat transfer at the warm-end heat rejector during high-speed rotation.

TABLE II
SUMMARY OF DE-RISKING EXPERIMENTS BY HINETICS

Subsystem	Primary risk	De-risking experiment	Outcome
Cryocooler (vibration)	Vibration and shock-induced performance degradation	MIL-STD-810H vibration/shock test	Stable cold-head operation; only transient temperature perturbation; recovery to nominal performance
Cryocooler (rotation)	Rotation induced performance loss	100-hour full-load operation at 45 K + 25% overspeed test	Stable operation; no degradation; slight performance improvement attributed to enhanced warm-end convection
Spoked torque tube	Structural failure under load	Static load test + full-speed dynamometer operation	Verified torque transmission capability and structural integrity
Spoke termination	Failure at fiber termination points	Termination tensile strength testing	High strength efficiency (termination strength approaching fiber breaking strength)
Rotordynamics	Rotordynamic instability	Analytical modeling + Finite element analysis + impact testing	Agreement between models and experiments; stable operation at rated speed
Full rotor assembly	System-level integration	10 kW, 1000 rpm subscale rotor operation	Successful integrated operation; compact fully rotor-contained refrigeration system

Following the development and validation of the on-board cryocooler, attention was directed toward minimizing the thermal load imposed on the cooling system. Since the on-board cryocooler inherently limits the available cooling power through dimension and weight constraints, improving the rotor's thermal insulation became a key design objective. A major focus of this effort was the development of a novel spoke-suspension torque tube. In a conventional torque tube, heat leakage through the torque transmission path can be substantial. The proposed spoke-suspension design, employing Kevlar fiber elements, reduces this heat leakage to only a fraction of that, thereby easing the cooling burden on the cryocooler [59]. Development of such a torque tube system presents several challenges, notably maintaining rotordynamic stability and fabricating its complex structural components. The machine's rotordynamics have been evaluated through analytical modeling, finite element simulations, and experimental impact testing, with results showing strong agreement across all methods [60]. A full-scale rotor has been fabricated and successfully operated at rated speed using a dynamometer. The structural integrity of individual spoke terminations has also been experimentally verified, achieving consistently high strength efficiency, defined as the ratio of termination breaking strength to rope breaking strength. In addition, reliable manufacturing techniques have been established for producing the complex shaft geometry. A static load test performed on the assembled spoke system confirmed its torque transmission capacity. Together, these experiments validated the spoke system's torque rating, rotordynamic stability, and manufacturability. A subscale machine was constructed as a proof-of-concept demonstrator. The rotor incorporated Hinetics' compact on-board cryogenic system and was retrofitted into the stator of an induction machine. Designed for a power rating of 10 kW at 1,000 rpm, the demonstrator featured twelve racetrack-shaped superconducting coils, a spoke-suspension torque tube, and a COTS Stirling cryocooler. All key technologies—including the on-board cryocooler, spoke-suspension system, thermal insulation scheme, and assembly process—were validated using this platform.

The demonstrator was first successfully operated in April 2025 as shown in Fig. 9 [61]. A notable achievement of this effort is the high degree of compactness: the refrigeration and insulation systems are fully integrated within the rotor, maintaining an external geometry comparable to that of a conventional machine, with no auxiliary equipment extending beyond the stator envelope. The machine has since completed 60 consecutive hours of operation to demonstrate its reliability, and further experiments, including load tests, are ongoing.

Fig. 9. Hinetics' SC motor demonstration

VIII. DISCUSSION

This section discusses and compares the approaches taken by the three institutions. Table III compares the thermal budgets of the NASA and Hinetics rotors with that of the Siemens 400 kW machine cooled by neon. Although the total refrigeration requirement is similar across these systems at 20-30 W, the corresponding machine ratings differ substantially. With comparable refrigeration power, the NASA and Hinetics designs achieve over 3× and 10× the Siemens machine's rated power, increasing machine output per unit refrigeration by approximately 3× and 16×, respectively.

This improvement is achieved by operating at a higher HTS temperature (50 K compared with 25 K for the Siemens machine, as shown in Tables I and III) together with improved

TABLE III
ROTOR KEY NUMBERS AND THERMAL BUDGET COMPARISON

	Siemens 400 kW [62]	Hinetics 5 MW [50], [63]	NASA 1.4 MW [57]
Torque tube [W]	8	1	11.4
Other connections [W]	1	n/a	5
Current leads [W]	5	12	4.4
Radiation [W]	1	4.5	4.2
Neon convection [W]	1.5	n/a	n/a
HTS heat generation [W]	4.5	2	3.3
Increased damper T [W]	3	n/a	n/a
Rotor envelope diameter [mm]	n/a	758	300
Rotor envelope length [mm]	n/a	320	231
Field coil current [A]	50 (no load)	134	57
Total [W]	24	19.5	28.2

thermal insulation. These design choices introduce three primary engineering considerations: the rotating cryocooler selection, the improved thermal insulation, and the warm-end heat rejection. These three aspects are discussed in the following sections.

A. Rotating cryocooler selection

A cryocooler rotating with the rotor is critical to on-board refrigeration. It must provide the required cooling capacity at the operating temperature, while satisfying stringent constraints on rotational compatibility, compactness, light weight, and long-term reliability.

Fig. 10 compares the operating temperature and cooling capacity of major cryocooler types, with the operating region of superconducting electric machines and the thermal budget of the NASA and Hinetics machines overlaid. The cryocooler categorization presented here is intentionally high-level and is based on the thermodynamic cycle. Within each cryocooler type, numerous architectural variations exist, including free-piston and split Stirling configurations, coaxial and inline pulse tube designs, and single- and multi-stage implementations, each involving distinct design trade-offs beyond the scope of this review. GM, Stirling, pulse tube, and reverse Brayton cryocoolers provide operating regimes suitable for superconducting machines. Among these, GM cryocoolers offer the highest cooling capacities and lowest operating temperatures and have therefore been widely adopted in stationary superconducting machines. However, current GM implementations rely on rotary valves and reciprocating displacers that complicate integration within a compact, rotationally balanced rotating rotor [64].

To date, all reported demonstrations have adopted regenerative cryocoolers such as Stirling and pulse tube types. This convergence reflects the favorable combination of compactness, axisymmetric geometry, and technological maturity. Recuperative cryocoolers employ continuous fluid circulation through distributed components such as heat exchangers, turbomachinery, and connecting flow passages. In contrast, regenerative cryocoolers confine the oscillating working fluid within a compact regenerator, making the current implementations more readily integrated into a rotating rotor [65]. Nevertheless, this distinction arises from present engineering implementations rather than the thermodynamic cycles themselves. Future advances may enable more cryocooler types for on-board refrigeration and should remain an active area of research. The three reported on-board refrigeration efforts have adopted different development strategies. Hinetics pursued a retrofit approach by adapting an existing Stirling cryocooler and experimentally demonstrated stable operation for 103 h at 3000 rpm [50]. NASA and KAIST, in contrast, are developing clean-sheet pulse tube cryocoolers that eliminate moving components at the cold end. These efforts demonstrate the feasibility of rotation-compatible cryogenic refrigeration using current technologies while pointing out innovations needed toward systems requiring higher refrigeration power.

As shown in Tables I and III, all three on-board concepts operate the cryocoolers near 50 K, compared to 30-35 K at which other superconducting refrigeration systems operated. With limited refrigeration capacity, on-board systems put emphasis on improved thermal insulation while accepting a higher operating temperature. This elevated temperature limits HTS current density and thus machine performance. clean-sheet design of compact, high-capacity rotating cryocoolers remains a key enabler to balance cooling capacity, mechanical robustness, and system maturity.

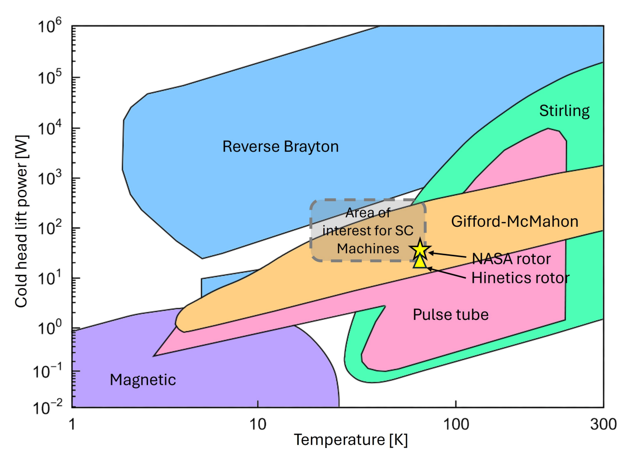

Fig. 10. Operating regions for multiple cryocoolers (modified from [66])

B. Insulation and heat leakage

As shown in Table III, existing on-board cryocoolers provide only 20–30 W of refrigeration while supporting multi-megawatt machines. Under this limited cooling budget, every watt of parasitic heat reduces the cooling available for the HTS windings and elevates the HTS operating temperature. Parasitic heat enters the rotor primarily through the structural conduction, current leads, and thermal radiation. Figure 11 illustrates the equivalent thermal network of the Hinetics 5 MW rotor as one representative implementation. Although the detailed thermal architecture varies among machines, these fundamental heat-transfer mechanisms remain common.

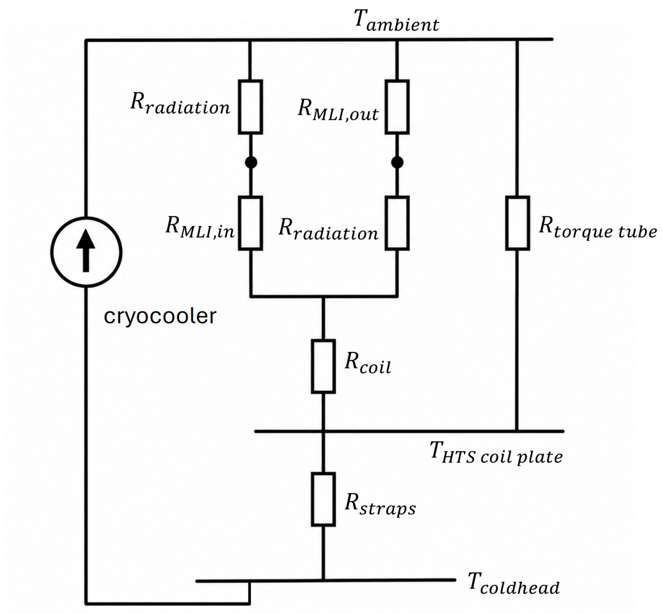

Fig. 11. Equivalent thermal circuit of Hinetics' 5 MW machine (modified from [67])

Structural conduction is often the largest heat path because the rotor support structure, commonly refered to as the torque tube, must simultaneously transmit mechanical torque while providing thermal isolation. Reducing conductive heat leakage requires decreasing the thermal conduction path by reducing the material cross-sectional area or increasing its length. However, these same geometric changes reduce the mechanical strength and stiffness of the torque tube, resulting in an inherent trade-off between thermal insulation and structural performance.

This trade-off can be understood from the governing relationships. The torque capacity is given by $M = R\sigma_y A$, where M is the torque transmitted, R is the torque tube radius, σ_y is the material yield strength, and A is the load-bearing cross-sectional area. In contrast, the conductive heat transfer coefficient is also proportional to A. Therefore increasing the structural area therefore improves torque capacity but simultaneously increases conductive heat leakage.

The thermal-mechanical optimization of torque tubes has been studied for conventional cylindrical designs [68], which transmit torque primarily through shear. These analyses show that large-diameter, thin-walled, and long torque tubes are thermally favorable but are ultimately limited by machine diameter and structural stiffness. More recently, spoke-supported torque tubes have been proposed to transmit load primarily through tensile members rather than shear [59]. Since the tensile strength of most structural materials exceeds their shear strength, spoke-supported designs can achieve the same torque capacity with substantially lower conductive heat leakage. This advantage is reflected in Table III, where the Hinetics machine exhibits significantly lower torque-tube heat leakage than conventional architectures. The associated stiffness and rotordynamic performance, however, depend strongly on the specific spoke geometry and currently require case-by-case analysis.

Reducing heat leakage alone is insufficient because the power cost of refrigeration increases rapidly as temperature decreases. Consequently, removing heat at the highest practical temperature is more efficient than rejecting the same heat directly at the HTS operating temperature. [69] shows that ”two discrete cooling stations” reduces the cooling input power needed to less than 1/4 that of ”one end station” based on the Carnot refrigeration requirement. Such interception can be performed by either a multi-stage cryocooler or multiple discrete cryocoolers. The concept has been reflected in Hinetics two-cryocooler configuration, with the main cooler operating at about 50 K, while the secondary cryocooler operates at 80 K to intercept heat conducted through the current lead. This principle is reflected in KAIST's dual-stage cryocooler and Hinetics' dual-cryocooler configurations, where secondary refrigeration is provided for thermal shielding and precooling [50], [70]. In the future, a wider selection of cryocoolers optimized for different temperature ranges, more mature dual-stage rotating cryocoolers, and improved thermal isolation of HTS windings are expected to enable superconducting machines with higher power.

Radiation heat leakage is governed by the Stefan–Boltzmann equation $Q = \sigma\epsilon A(T_h^4 - T_c^4)$, where σ is Boltzmann constant, ϵ is emissivity, A is the area of radiating surface, T_h and T_c are the warmer and colder surface temperature, repsectively. Radiation heat transfer exhibits a strong dependence on the temperatures of the surrounding surfaces, as well as their emissivity and exposed area. Radiation shielding methods are primarily based on reducing emissivity such as multilayer insulation (MLI), or reflective metal coating. However, in rotating superconducting machines, these techniques are constrained by limited radial space, the need to accommodate rotating components and penetrations, and the large centrifugal forces encountered during operation. Compression of MLI under centrifugal loading can reduce layer spacing and degrade its thermal performance, limiting the achievable reduction in radiative heat leakage [71].

C. Warm end heat rejection

The cryocooler must reject not only the heat lifted from the rotor but also the compressor input power, which can be expressed as $\dot{Q}_{reject} = \dot{Q}_{lift} + \dot{Q}_{input}$. Thus, the warm-end thermal load is often several times greater than the useful refrigeration load. Unlike stationary cryocoolers, which typically reject heat through large radiators or liquid cooling loops, onboard refrigeration must dissipate the heat within the limited volume of the rotating machine while maintaining reliable operation from standstill (minimum air flow) to maximum operating speed (maximum structural stress).

The heat rejected to ambient $\dot{Q}$ can be expressed with $\dot{Q}_{reject} = Ah\Delta T$ whereas A is the heat exchange area, h is the heat transfer coefficient, and ΔT is the temperature difference between the heatsink and the ambient air. This relationship indicates three design variables: increasing the heat transfer coefficient through liquid cooling or enhanced airflow, increasing the available heat transfer area, or allowing a larger temperature rise at the warm end. Each strategy introduces its own engineering trade-offs. Increasing the heat exchanger area competes with the limited rotor volume, increasing the heat transfer coefficient often requires additional components such as blowers, liquid circulation, or more complex heat exchangers, and increasing the allowable temperature rise degrades cryocooler cooling capacity and coefficient of performance.

KAIST and Hinetics currently employ direct air cooling and NASA utilizes liquid cooling. Direct air cooling is attractive because it preserves the fully self-contained nature of on-board refrigeration, whereas liquid cooling reintroduces thermal transfer couplings between the rotating and stationary components. However, maintaining adequate air-cooling performance over varying ambient conditions and rotor speeds, particularly during stationary operation, remains challenging. Current demonstrations primarily rely on finned heat sinks or liquid channels, while future designs may further improve heat rejection through advanced heat exchanger geometries, heat pipes, or localized coolant circulation within the rotor. Continued innovation in warm-end thermal management will likely be as important as advances in cryocoolers and insulation.

IX. Conclusion and Outlook

Numerous efforts have been made to develop superconducting motors and generators utilizing either LTS or HTS. These technologies offer several potential advantages over conventional machines, including higher specific power, improved energy efficiency, and reduced system size. Despite these promising attributes, no laboratory-developed superconducting rotor has yet achieved disruptive impact within the existing industry. A key lesson learned from past LTS and HTS prototypes is that effective cryogenic cooling of the rotating system is not merely a technical detail but a critical factor that ultimately determines the system's practical viability. This paper has reviewed various research and development efforts focused on the implementation of on-board cryocoolers for superconducting motor applications. The integration of a cryogenic cooling system for an HTS rotor entails addressing multiple critical requirements, including low cost, compactness, lightweight design, rapid cool-down capability, low power consumption, high reliability, minimal noise and vibration, and stable temperature control. Collectively, these desired attributes can be encapsulated in an aspirational goal: invisibility of cryogenic cooling. The implementation of a on-board cryocooler directly on the superconducting rotor offers the potential to approach this invisible refrigeration functionality, thereby enabling the revolutionary transition of superconducting motors and generators from laboratory prototypes to commercially viable products.

The future outlook for superconducting machines in aviation propulsion, pod-mounted marine systems, and power generation is promising because of the benefits in terms of specific power and efficiency and the rapidly improving economics due to increased availability of HTS tapes driven largely by the nascent fusion industry. In aviation, superconducting technology could be a key enabler for next-generation electric and hybrid-electric aircraft, especially for large commercial transport aircraft that require megawatts of power, by reducing the inefficiency and mass overhead imposed by the electrical system. Furthermore, electric motors offer inherently high efficiency independent of altitude and across broad operating ranges, directly translating to reduced operational costs and extended endurance. The machines currently under development are also approaching their maximum achievable efficiency, with projected efficiencies exceeding 99% even for partially superconducting designs. With many of the designs employing limited or no ferro-magnetics, these machines also tend to have less supply chain constraints and exhibit less noise and vibration (thus, potentially less maintenance) compared to traditional machines. Despite significant technological progress in recent years, several significant hurdles must be overcome before superconducting machines are widely adopted in commercial applications. To fully mature these machines, future research must address key questions about complexity and reliability. A primary focus should be on features that are new to the relevant industries being targeted. Chief among these is the cryogenic system and all the auxiliaries associated with it. Simplifications offered by the use of onboard coolers as described in this review could help in this direction, but they need long-term validation. Additionally, to extract the maximum benefit out of the superconducting electric machines, complementary motor drives, potentially with high-frequency wide-bandgap power electronics capable of driving low-inductance machines with clean current waveforms, would also be required. For highly regulated industries, such as aviation, reliability and fault tolerance need to be confirmed, and extensive testing in the relevant environment is required to retire risks and gather data for certification. With continued development and testing, superconductivity-enabled propulsion may be available for the next generation of aircraft, and potentially earlier in terrestrial and marine applications.

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