M2Or3J-01

Rotating Machines for the Cryo-Electric Planes

Status and Development Issues

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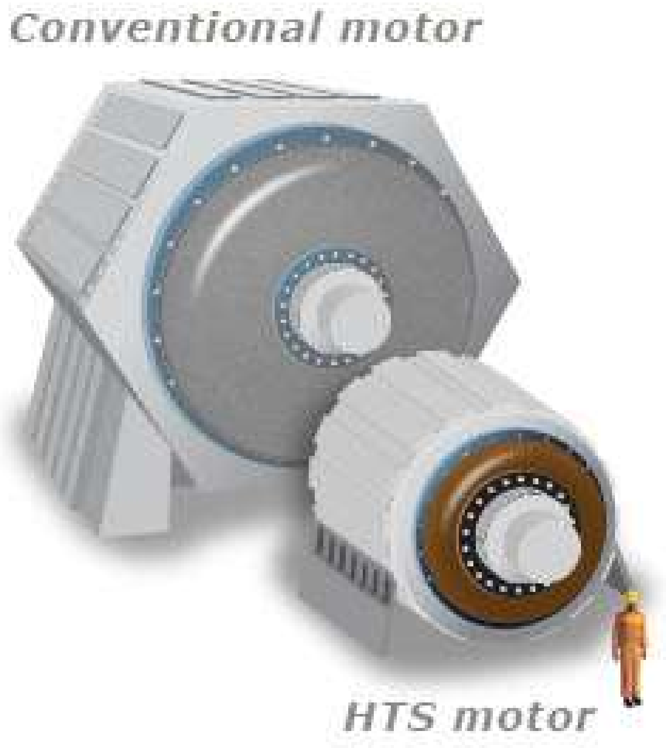
SUPERCONDUCTING ROTATING MACHINES

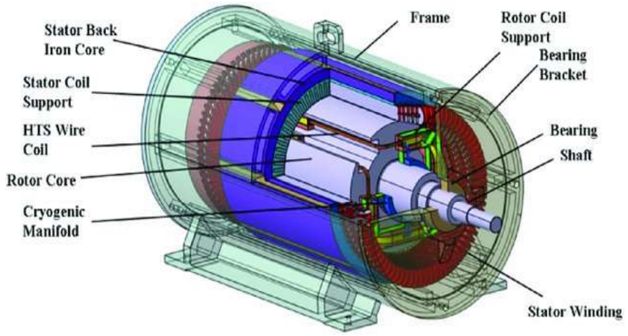
OUTLINE

- SC Machine Configurations
- Machines built in past for on-ground applications
- Challenges for building machines for cryo-electric planes
- Airplane Machines under development
- Development work needed to achieve prototypes for cryo-electric planes by end of this decade
- Outlook

Ground based motors

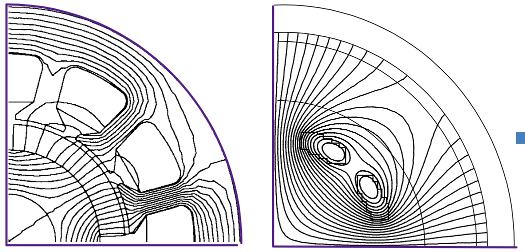


SUPERCONDUCTING MACHINE CONFIGURATIONS



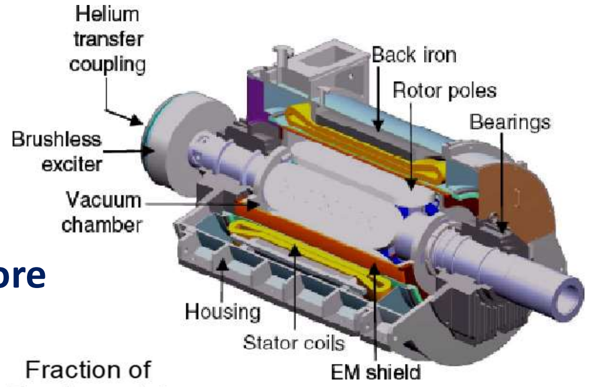
PM & Conventional

Iron-Core



Air Core HTS

Air-Core



Harmonic Order	Fraction of Fundamental
1	1
3	0
5	$5.977 \cdot 10^{-4}$
7	$7.394 \cdot 10^{-6}$
9	0
11	$6.074 \cdot 10^{-8}$
13	$1.542 \cdot 10^{-10}$
15	0
17	$1.032 \cdot 10^{-11}$
19	$-3.381 \cdot 10^{-14}$

Harmonics generated by field winding in stator

Harmonic Order	Fraction of Fundamental	
	Radial	Tangential
1	1	1
3	-0.057	0.116
5	$3.869 \cdot 10^{-4}$	$7.097 \cdot 10^{-3}$
7	$4.567 \cdot 10^{-5}$	$-1.153 \cdot 10^{-3}$
9	$-7.546 \cdot 10^{-5}$	$-4.378 \cdot 10^{-4}$
11	$4.55 \cdot 10^{-6}$	$-4.586 \cdot 10^{-5}$
13	$-8.935 \cdot 10^{-7}$	$1.027 \cdot 10^{-5}$
15	$5.559 \cdot 10^{-7}$	$4.827 \cdot 10^{-6}$
17	$-1.149 \cdot 10^{-8}$	$5.882 \cdot 10^{-7}$
19	$-2.729 \cdot 10^{-9}$	$-1.475 \cdot 10^{-7}$

Harmonics generated by stator AC winding on the rotor surface

- Harmonics generated inside an air-core HTS synchronous machine are extremely small
- Lower harmonic content eases machine component design and simplifies external control systems

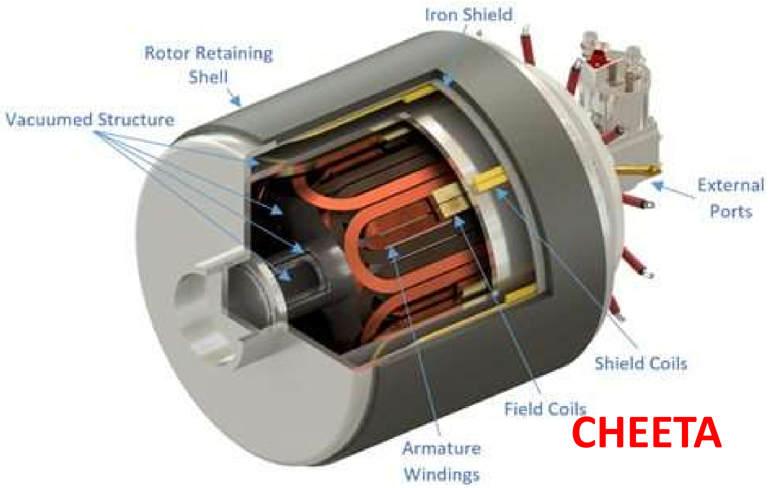
In iron core machines, flux jumps between teeth cause magnetostrictions, mechanical vibrations and noise

MOTIVATIONS FOR USING SUPERCONDUCTORS

Current focus is on two specific applications:

- Highly power dense and efficient motors and generators for aircraft applications
- Offshore large wind turbine generators requiring high torque density and efficiency, and low cost
- Compared to Conventional Machines, Superconducting machines can;
  - Increase machine efficiency beyond 99% (reducing losses by as much as 50%)
  - Reduce size and mass by a factor of 3 or more
- Provide improved reliability with long lasting windings - nearly zero degradation of coil insulation at cryogenic temperatures

There is little common ground between these two applications



CHEETA

Photo: Fraunhofer Institute for Wind Energy Systems

Docking Maneuver: Workers prepare to link the 3.6-megawatt Ecoswing superconducting generator [blue] to a machine that simulates the torque and other aspects of a wind turbine [gray].

A FEW PREVIOUSLY BUILT MACHINES USING BSCCO

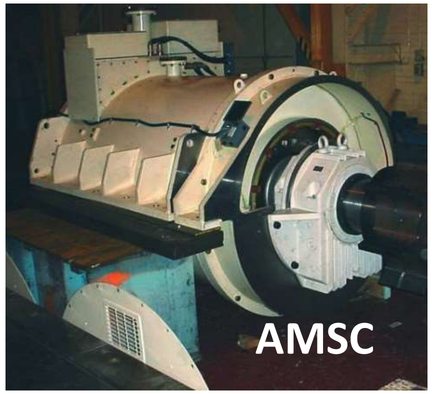
- Built primarily for on ground applications
- Goals – high efficiency, compactness
- Weight not very important

Photo: Fraunhofer Institute for Wind Energy Systems

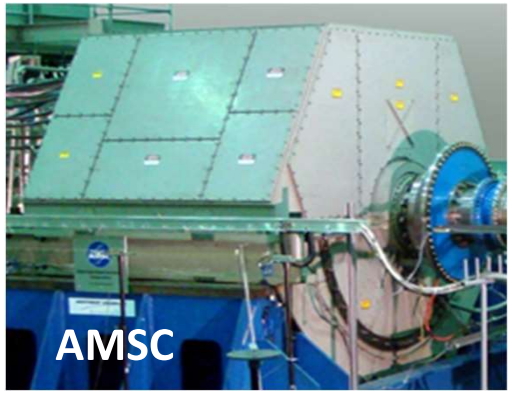
Docking Maneuver: Workers prepare to link the 3.6-megawatt Ecoswing superconducting generator [blue] to a machine that simulates the torque and other aspects of a wind turbine [gray].

3.6 MW, 12 rpm

8 MW, 1800 rpm



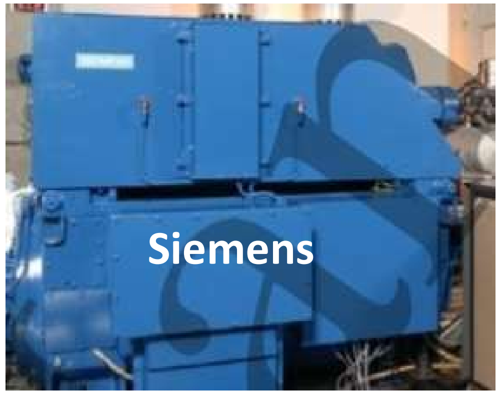
5 MW, 230 rpm



36 MW, 120 rpm

3.7 MW, 1800 rpm

0.7 MW, 1800 rpm



4 MW, 3600 rpm

Technologies used in these machine are not suitable or scalable for airplane applications

NASA DEFINED REQUIREMENTS FOR AIRPLANE MOTORS

NASA's Fixed Wing Project (currently the Advanced Air-Transport Technology Project) has defined goals for the next three generations of aircraft for commercial aviation.
Below are electrical machine requirements for an example turboelectric-aircraft concept.

- Table summarizes minimum requirements for motors and generators for aerospace applications
- All technology options are open (conventional and superconducting)
- Technology Readiness Level (TRL) of each options could be the most important feature

	Generators	Motors	NASA-SBIR
Number of units	2	15	
Power rating	30,000 hp (22.4 MW)	4,000 hp (3 MW)	1-5 MW
Assumed weight	2,200 lb (1,000 kg)	520 lb (236 kg)	
Power Density	22 kW/kg	13 kW/kg	20 kW/kg
Assumed efficiency	99.3%	99%	98%
Rotational speed	6,500 rpm	4,500 rpm	

References:
1. Felder J L, Brown G V, Kim H D and Chu J 2011 Turboelectric distributed propulsion in a hybrid wing body aircraft Proc. 20th Int. Society for Airbreathing Engines (Gothenburg, Sweden, 12–16 Sept. 2011)
2. NASA SBIR Phase I, March 13, 2023 – Page 288 -- NASA%20Proposal%202023/2023%20SBIR%20Phase%20I%20Solicitation%20-%20PDF.pdf

These guidelines are being used for developing HTS motors and generators for airplanes

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CURRENT AEROSPACE MOTOR DEVELOPMENT PROGRAMS

Conventional / PM

- PM – RTX motor (??)
- PM - GE motor (??)
- PM - Marquette motor (20 kW/kg, > 95%, additively manufactured coils)
- PM - Texas A&M (13 kW/kg, 94%, axial-gap)
- PM - Honeywell (13 kW/kg, >95%)
- Advanced PM Wire - AML (26 kW/kg)
- Wright motor (10 kW/kg, conventional coils)
- Mako - Aerospace (34 kW/kg, Switched Reluctance)

Hybrid SC / HC-AL

- HINETICS - ARPA-e Cruise Hybrid (5 MW, 3000 RPM) - **M3Or2G-03**
- VUW-NZ homopolar (22 kW, 25000 RPM) – **M4PL1**
- VUW-NZ Hybrid (100 kW, 4500 RPM) - **M3Or2G-01**
- Safran Hybrid (axial-gap, flux modulation, 260 kW, 5000 RPM)
- NASA – Hybrid (1.4 MW, 6800 RPM) **M2Or3J-02**
- Hypertech Induction Motor (20 kW/kg, LNG)
- Toshiba (??)

All SC

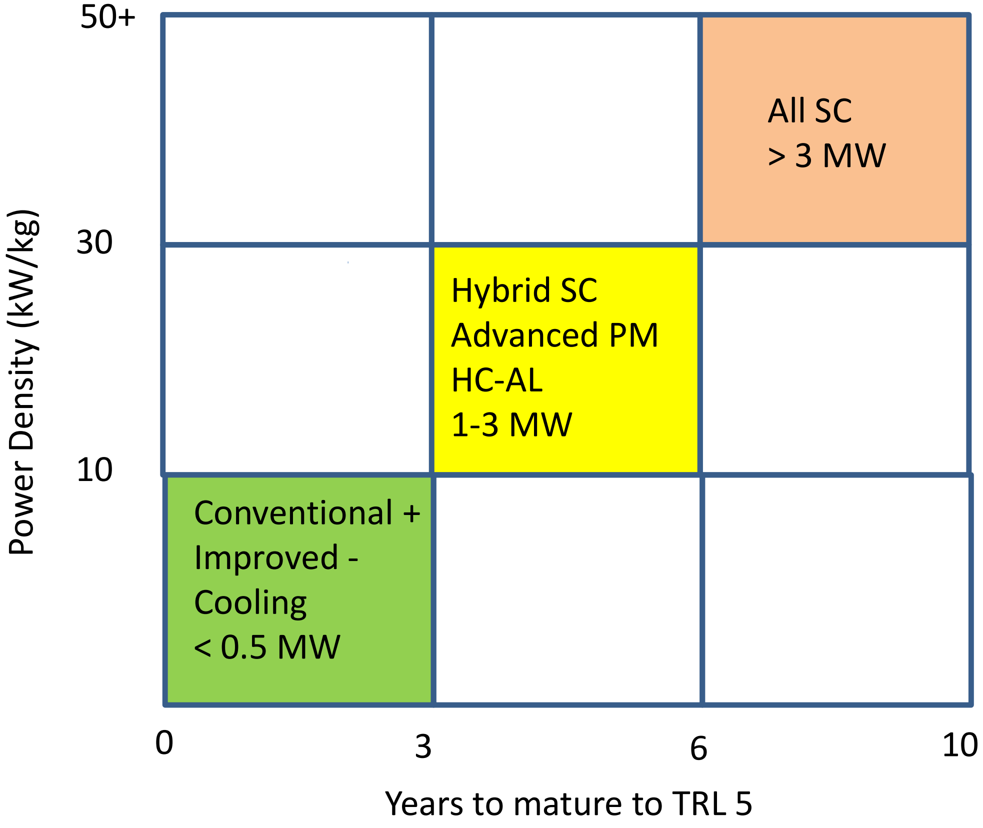
- VUW-NZ All SC (3 MW, 4500 RPM) **M3Or2G-01**
- CHEETA – All SC (2.5 MW, 4500 RPM) **M1Or3G-07**
- Raytheon – All SC (2.5 MW, 5000 RPM) **J1Or1A-02**
- UC-Santa Cruz – All SC (Switched Reluctance)
  - **M2Or3J-04**
- Univ. of Tokyo – All SC (5.5 MW, 5000 RPM)??

Most power density and efficiency estimates lack substantiation with design and prototype/test experience

ELECTRIC MACHINES DEVELOPMENT TIME-LINE

POSSIBLE STEPS

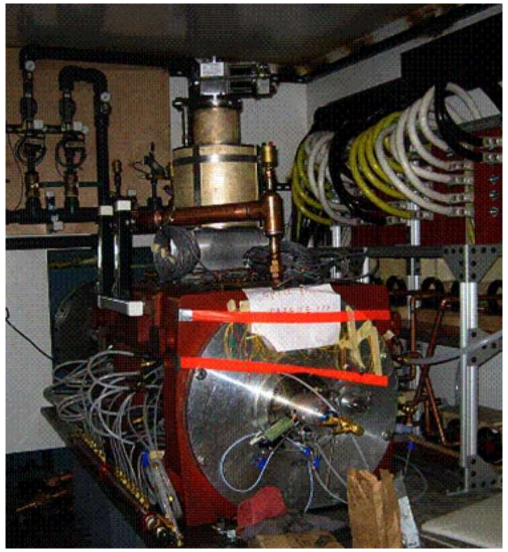
- Near Term (< 3 yrs) with aggressive cooling, but limited power-density and efficiency improvements
  - Synchronous
  - Induction
  - PM
- Mid Term (3-6 yrs) with LH2 Fuel Dump – Improved power-density and efficiency
  - Hybrid superconducting
  - Advanced PM
  - High Conductivity Aluminum (HC-AL)
- Long Term (> 6 yrs) with LH2 Fuel Dump – Best power-density and efficiency
  - All superconducting



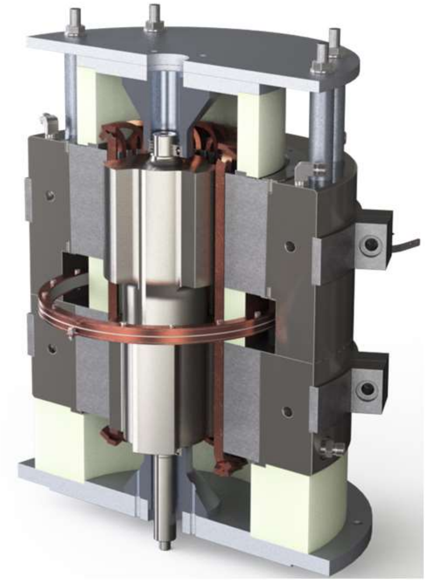
These timelines require considerable focused development effort

FOCUSING THIS TALK ONLY ON SUPERCONDUCTING MOTORS AND GENERATORS

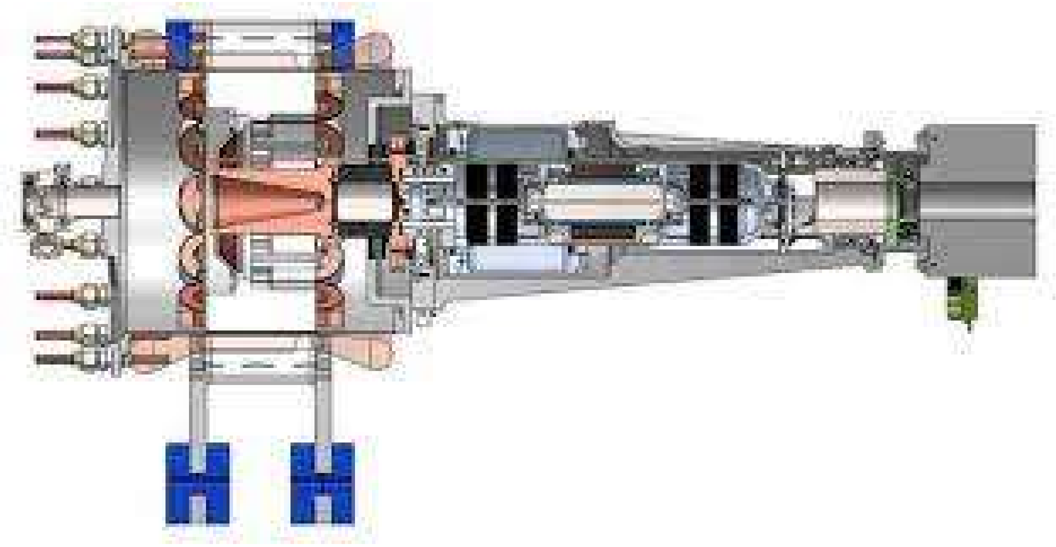
HIGH SPEED SC MOTOR DEMONSTRATIONS



GE AC Homopolar
5MW @ 35 krpm, 9 kW/kg
Tested: 1 MW @ 10.5 krpm



VUW-NZ AC Homopolar
22 kW @ 25 krpm
Under testing: 2023
Demonstrated at 18 krpm



NASA Synchronous motors
1.4 MW@ 6800 rpm, 16 kW/kg
Under development

Many motors conceptualized but lacking details about performance goals and construction/testing schedule

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COIL COOLING AND THERMAL MANAGEMENT SYSTEM (TMS)

CHALLENGES

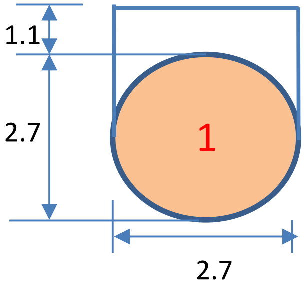
- **ASSUMPTION**: Fuel (LNG, LH2, ..) cannot be used for cooling directly inside a motor
- Cooling system design must include
  - Maximum allowable temperature for the conductor
  - Temperature rise through conductor insulation thickness
  - Voltage withstand capability
- Develop cooling systems for transporting motor thermal load to the fuel dump
- Make TMS system compact and lightweight for airplane applications

Power-density and efficiency projections must include details for the thermal management system

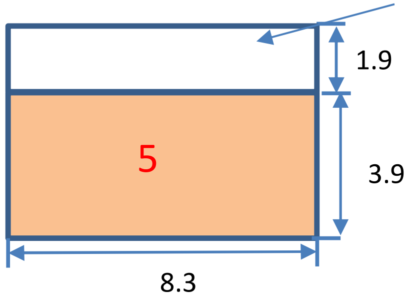
COMPARATIVE TURN CONFIG FOR DIFFERENT CONDUCTORS

ASSUMPTIONS

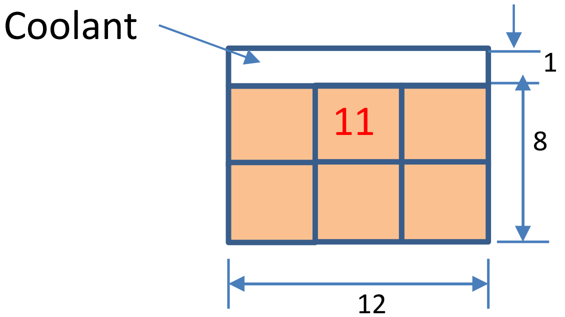
- A single armature-turn carrying **1100 A-rms** selected
  - Turn length = 650 mm
  - Field from rotor = 0.65 T
  - Frequency = 150 Hz
- Comparing conductors cooled at different temperatures
- All conductors use possible configurations based on Commercial Litz Wire Catalog



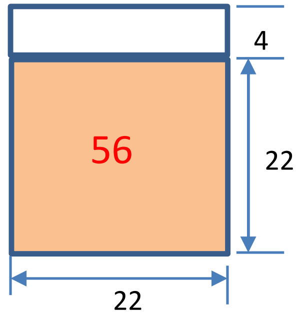
MgB2 @23K LH$_2$
Turn CS:**10** mm2, SC-FF = 0.15
54 strands @0.32mmϕ
Mass = 0.03 kg



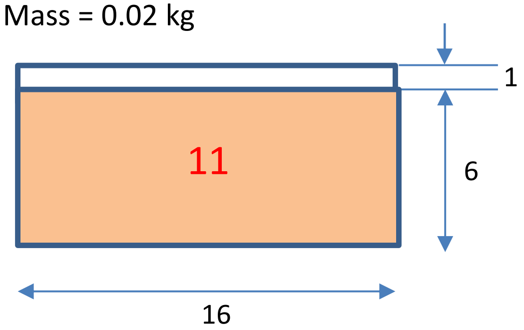
Hyper-AL RRR = 600 @23K LH$_2$
Turn CS:**48** mm2, AL-FF = 0.3
12080 strands@0.032mmϕ
Mass = 0.02 kg



AL RRR = 30 @23K LH$_2$
Turn CS:**110** mm2, AL-FF = 0.22
27000 strands@0.032mmϕ
Mass = 0.05 kg



AL RRR = 30 @135K N$_2$
Turn CS:**558** mm2, AL-FF = 0.23
8460 strands@0.13mmϕ
Mass = 1.32 kg



AL RRR = 30 @320K Novac
Turn CS:**111** mm2, AL-FF = 0.55
63 strands@1.02mmϕ
Mass = 0.09 kg

Numbers in each turn indicate relative cross-sectional area

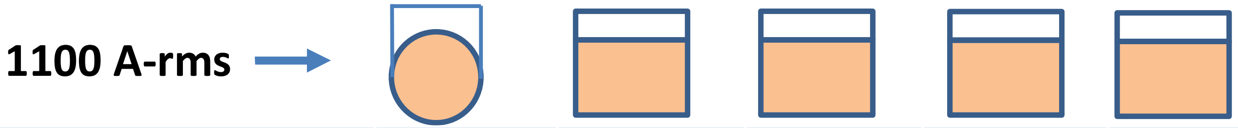
All dimensions in mm

Important to compare different conductors with their cooling needs

SC MOTOR STATOR CONDUCTORS AND COOLING OPTIONS

Constraint: Only inert coolants are considered inside the machines

- Stator winding cooling limitations for a 3 MW machine
- Stator employs different conductors and cooling options
- Cooled turn length = 650 mm



Parameter	MgB2	Hyp-AL	AL	AL	AL
Conductor cable type	Round	Litz	Litz	Litz	Litz
Coolant type	GHe	GHe	GHe	GN2	Novec
Operating temp., K	23 ± 3	23 ± 3	23 ± 3	135 ± 15	320 ± 30
Cooled turn mass, kg	0.03	0.02	0.05	0.25	0.09
Current density, A/mm2 (includes coolant channel)	99	23	10	2.0	10
Loss ratio Eddy/DCI2R	N/A	0.98	0.06	0.05	0.06

Conclusions:

- Motor Power density adversely impacted by turn current density
- Must include cooling limitations of stator winding while comparing alternate concepts
- MgB2 @20K is most attractive
- Hyper-AL @20K is 2nd best
- AL @320K is comparable to AL @20K
- AL @135 K (LNG thermal dump) is least attractive

Following conductors require development:

- MgB2 cable - 0.32 mmϕ strands with 10 μm filaments
- Hyper-AL cable - 0.032 mmϕ strands

Cooling system limitation must be addressed for each design approach

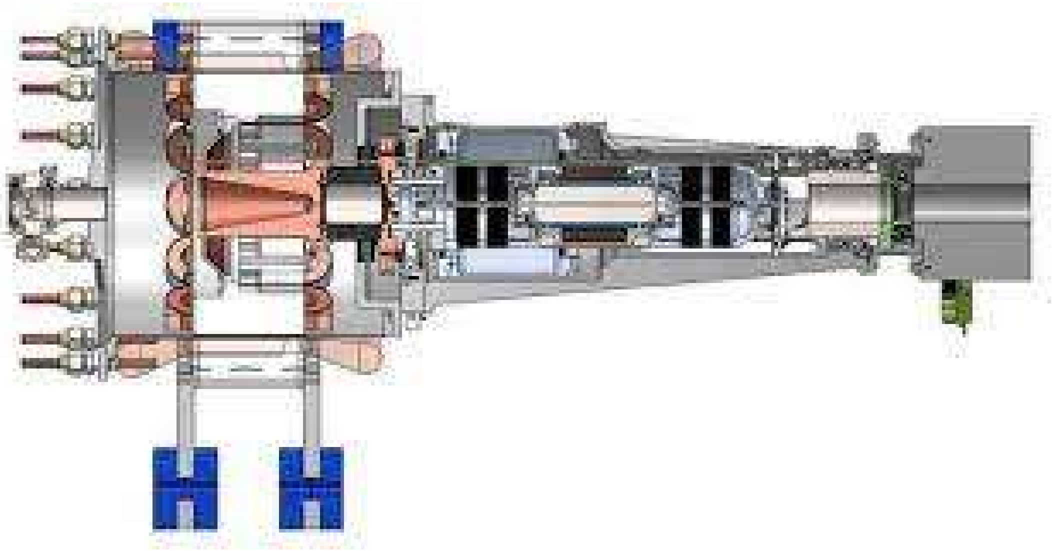
SUPERCONDUCTING FIELD WINDING AND CONVENTIONAL ARMATURE WINDING

HYBRID SUPERCONDUCTING MOTORS

NASA HIGH-EFFICIENCY MEGAWATT MOTOR (HEMM)

- NASA is constructing a 1.4 MW iron core motor
- Rotational speed 6,800 rpm (12-pole machine)
- Rated frequency 680 Hz
- Power density goal 16 kW/kg
- Efficiency target >98%
- Rotor: Salient pole with REBCO coils - conduction cooled to 62 K
- Rotor Cooling: In-shaft Stirling cryocooler
- Stator: conventional copper coils
- Expecting 3x lower losses and weight than current aircraft motors and generators

Ref: Scheidler, J.J. et al, "Thermal vacuum chamber demonstration of a cryocooled, HTS rotor for a 1.4 MW electric machine for electrified aircraft propulsion", Paper # 4LPo1E-01 Presented at ASC-2022



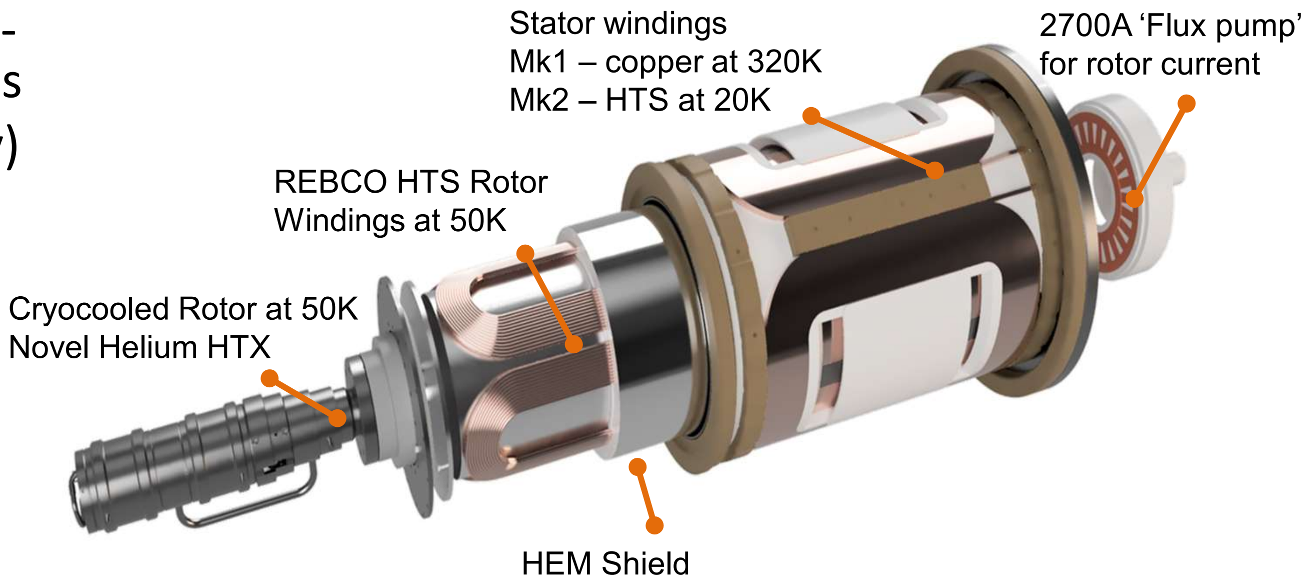
Key Features

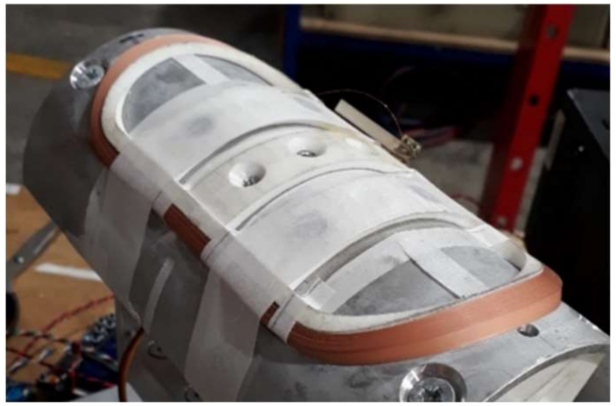
- Uses standard aircraft cooling systems
- Direct drive at optimal turbomachinery speeds (no gearbox)
- Wound field can be shut off if a fault occurs (Very important issue)

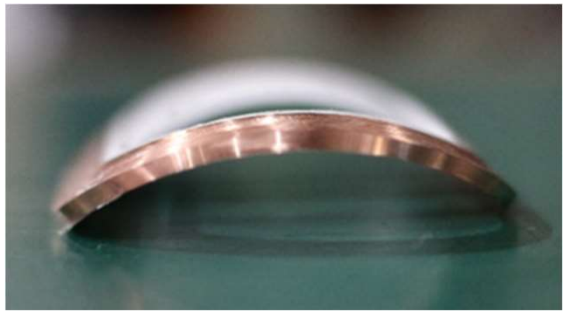
Good test bed for qualifying the cooling system for the superconducting rotor

VUW-RRI 100 kW, 4500 RPM MOTOR (2025)

- 100 kW, 4500 RPM motor under construction -- a test- bed for evaluating different technologies
- Motor 360 mm in dia and 550 mm long (axially) has an efficiency target of 96.4%
- Race-track saddle coils used for both rotor and stator
- Field coils conduction cooled to the structural support cylinder
- Rotor cooled with a cryocooler integrated within the shaft
- A 2.8 kA flux pump integrated on the rotor powers field coils
- Stator race-track saddle shaped coils using copper Litz wire
- Rotor and stator saddle coils - already practice built with REBCO tape







S.S. Kalsi, J. G. Storey, J. M. Brooks, G. Lumsden and R.A. Badcock, "Superconducting Synchronous Motor Development for Airplane Applications - Mechanical and Electrical Design of a Prototype 100 kW Motor", Print ISSN: 1051-8223, Online ISSN: 1558-2515, DOI:10.1109/TASC.2023.3242629

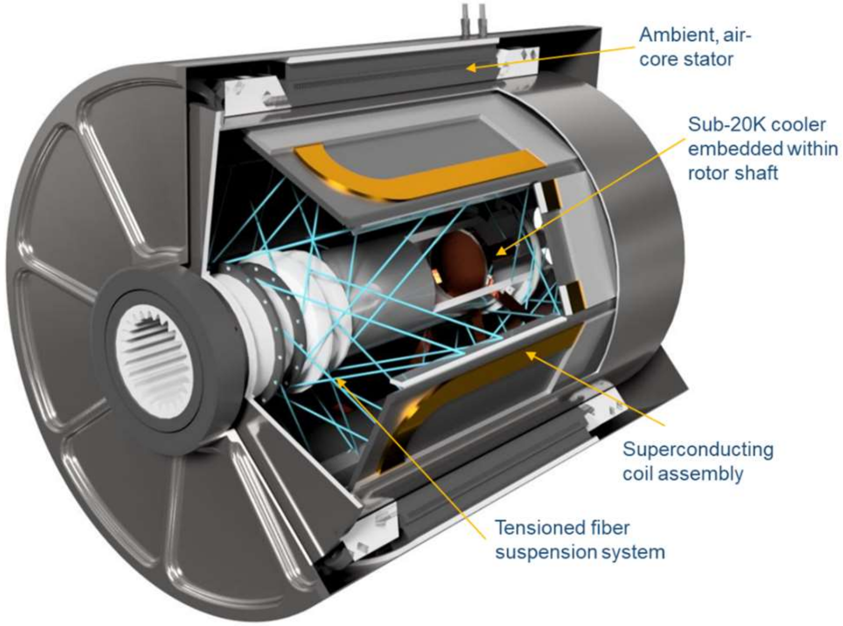
Test bed for developing and qualifying air-core rotor and stator components

ARPA-E CRUISE: PARTIALLY SUPERCONDUCTING MOTOR

- Hybrid air-core synchronous motor
- Conduction cooled REBCO field winding
- Stirling-cycle cooler integrated within a low-loss rotor
- High Magnetic fields – 10X conventional machines
- Coil suspension and torque transfer system with tensioned fibers
- High power-density with high 'ampere-turns' of excitation and "armature" windings, featuring
  - No ferromagnetic components
  - High air gap flux density
  - Large electrical loading
- Goal: 10 MW, 3000 RPM propulsion motor weighing less than 250 kilograms. Demonstrate 5 MW motor by **2025**

Provides near-term validation of superconducting rotor technologies

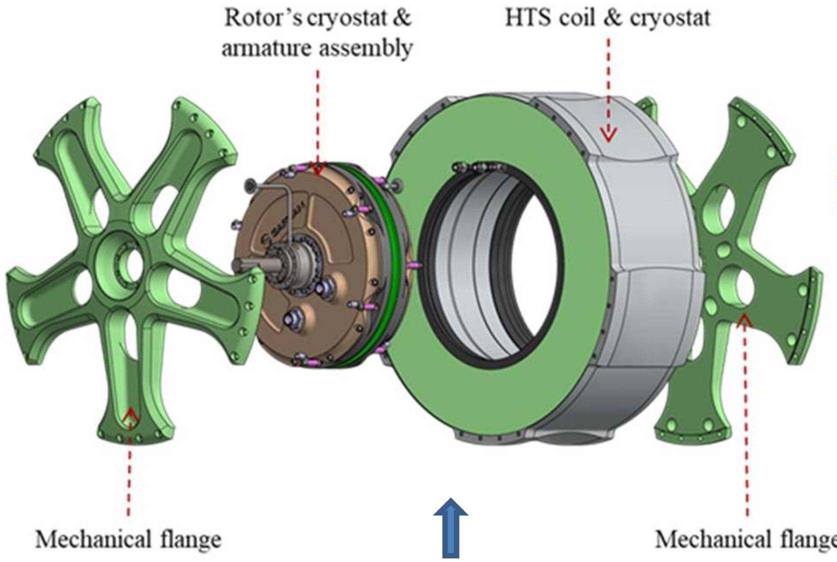
Metric	State of the Art	Target
Specific power (active)	*10 kW/kg*	*50-60 kW/kg*
Efficiency	*96%*	*99.4%*
Single stage cryocooler	35 K (no load)	<20 K (no load)
Cryogenic rotor heat-load	100 W	10 W
Airgap flux density	1 T	3-4 T
Armature ac field	500 T/s	5000 T/s

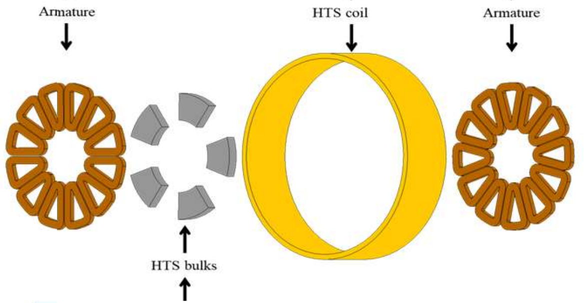


SAFRAN FLUX MODULATION MOTOR

- Large magnetic field can be produced from HTS wires and magnets without a need for iron core
  - $\frac{R^2L}{M}$ is increased by the removal of iron
  - $\boldsymbol{B}$ can be increased or kept constant
- Large current density can be carried in HTS or cryogenically cooled armature
  - **H** can be increased with reduced losses
- Operating temp. 30 K achieved with GHe

Validates superconducting technologies in a small rating





Key Components

Complete Construction in 2023.

Parameter	Value
Speed	5000 rpm
Power	261 kW
Mass (active)	21 kg
Mass (total)	120 kg
Power density	2.2 kW/kg
Efficiency	95.3%
Voltage	310 V
Current	280 A

References:
1. R. Dorget, S. Ayat, R., A. Cipriani, J. Leveque, J. Labbe, T. Lubin, M. Sitko, J. Tanchon, and J. Lacapere, "Construction of a 250 kW Superconducting Flux Modulation Prototype for Aircraft Application', Presented at ASC22 in Honolulu 23-28, 2022
2. R. Dorget, S. Ayat, R., Biaujaud, J.M. Gaillard, A. Cipriani, J. Tanchon, J. Lacapere, T. Lubin and J. Leveque, "Superconducting flux modulation machines for Aircraft propulsion", EFATS-2021
3. R. Dorget, S. Ayat, A. Cipriani, J. Lévêque, J. Labbé, T. Lubin, M. Sitko, J. Tanchon, J. Lacapère, "Superconducting flux modulation machines for hybrid and electric aircraft", EFATS-2022

SUPERCONDUCTING FIELD AND ARMATURE WINDINGS

ALL SUPERCONDUCTING MOTORS

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VUW-RRI 3 MW, 4500 RPM MOTOR - 2030

- Robinson Research Institute (RRI) Victoria University of Wellington is developing superconducting motors for aircraft applications
- Final goal: Build all superconducting 3 MW motor at 4500 RPM using the following steps;
  - 100 kW, 4500 RPM motor with REBCO field coils and conventional copper stator
  - 3 MW, 4500 RPM motor with REBCO field coils and conventional copper stator
  - 3 MW, 4500 RPM motor with REBCO field coils and superconducting stator
- Field winding powered with flux pumps constructed in-house
- Cryocooler integrated within the shaft cools rotor coils
- Some features of these machines are included in the following viewgraphs

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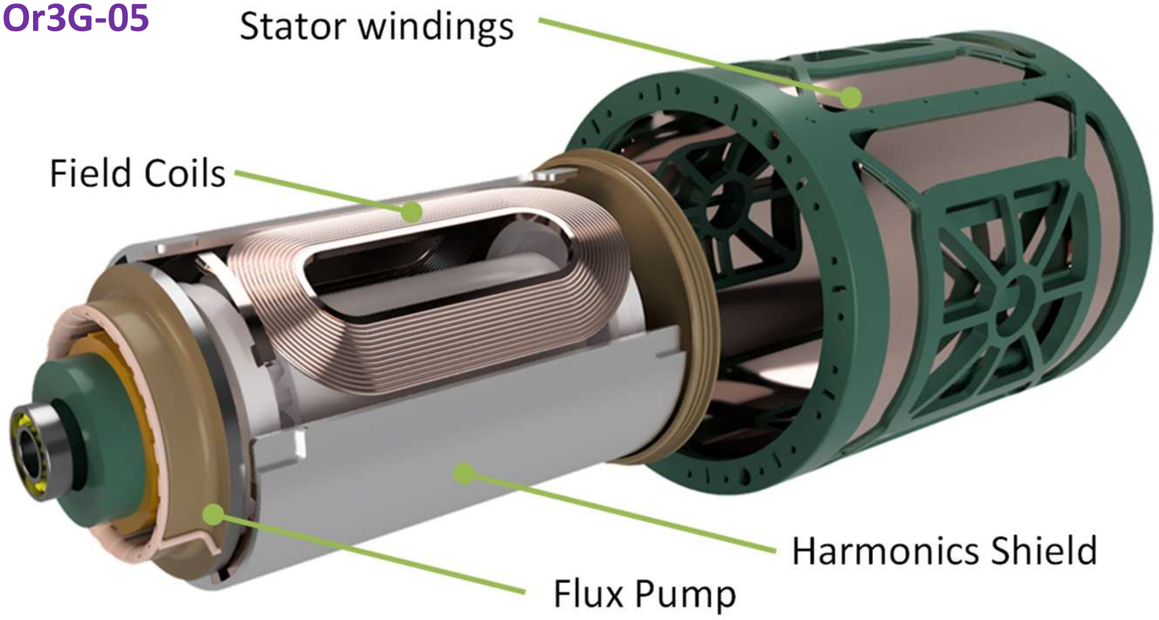
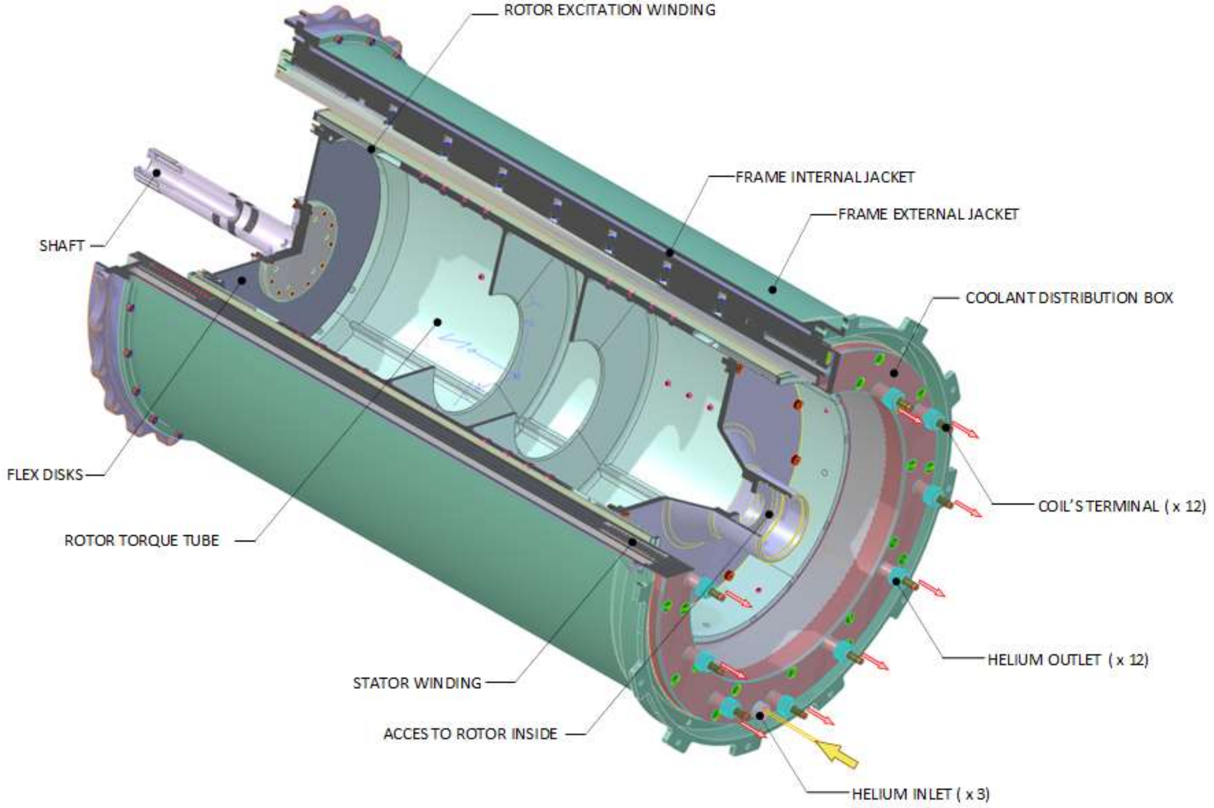


S. S. Kalsi, R. A. Badcock, J. G. Storey, K. A. Hamilton and Z. Jiang, "Motors Employing REBCO CORC and MgB2 Superconductors for AC Stator Windings," in IEEE Transactions on Applied Superconductivity, vol. 31, no. 9, pp. 1-7, Dec. 2021, Art no. 5206807, doi: 10.1109/TASC.2021.3113574.

End goal: Build and test a 3 MW, 4500 RPM Motor by 2030

RAYTHEON SOARING 2.5 MW, 5000 RPM MOTOR

- Raytheon developing a 2.5 MW, 5000 RPM motor
- An ALL-SC-Motor -- both rotor and stator employ superconducting coils
- Field winding is powered with a flux pump integrated on the rotor
- Stator winding uses low AC loss superconductors operating at nominal 20 K
- Cooling system based on the available LH2 sink



Most Challenging Project: Opting for a fully superconducting motor

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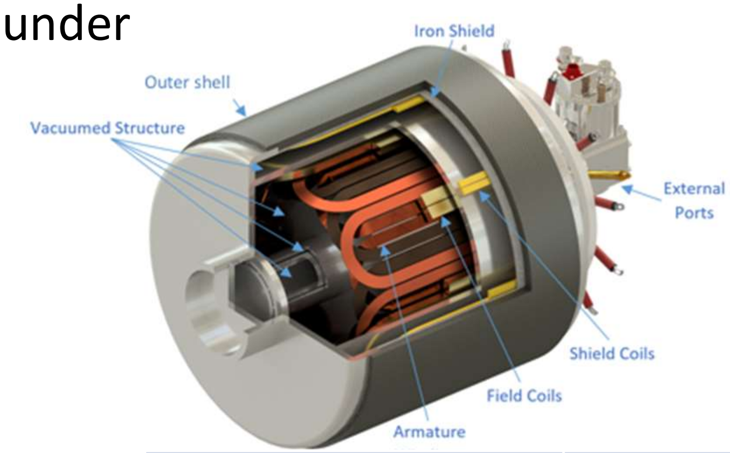
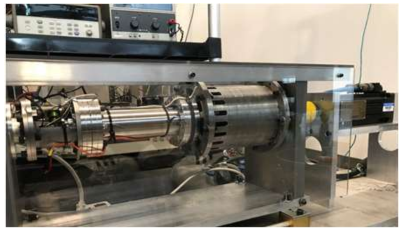
CHEETA – FULLY SUPERCONDUCTING LH2 COOLED MOTOR

- CHEETA is developing 3-5 MW, 4500 RPM motors under a NASA-ULI program **M3Or2G-03**
- Goal: ALL-SC-Motor; both rotor and stator coils employing superconductors
- Motor has a stationary hydrogen cooled, superconducting armature employing MgB2 wire
- MgB2 wire with fine filament diameter for reducing AC losses and operation at nominal 25 K
  - High conductivity aluminum is a possible alternative
- REBCO field coils on shaft operated at about 40-50K
- Component tests in progress, motor prototype by **2025**



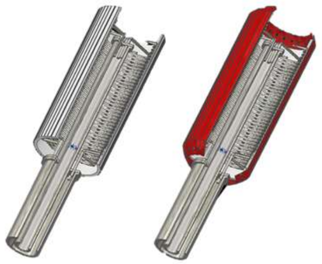
Nominal power (MW)	2.5
Nominal speed (rpm)	4500
Number of poles	8
Outer Diameter [m]	0.5
Machine total length [m]	1.00
Active length [m]	0.87
Average torque [Nm]	7045
Air-gap flux density [T]	0.63
Total loss [W]	2656
Active weight [kg]	13

Component development:



Rotor mounted cryogenics

Superconducting coils



LH2 heat exchangers

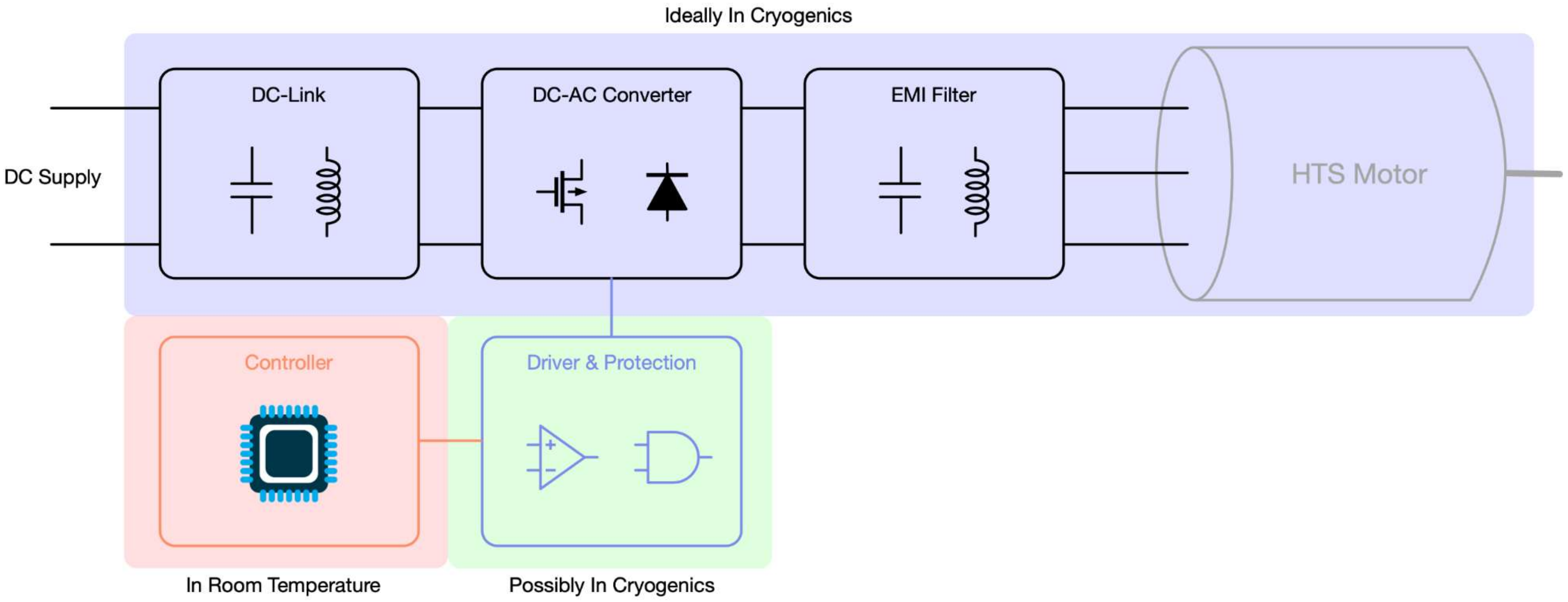
Encouraging: Early demonstration of technologies for a fully superconducting machine

Balachandran, T., Lee, D., Salk, N. and Haran, K.S., 2020, March. A fully superconducting air-core machine for aircraft propulsion. In *IOP Conference Series: Materials Science and Engineering* (Vol. 756, No. 1, p. 012030). IOP Publishing.

ELECTRIC DRIVE REQUIREMENTS

DESIRABLE ATTRIBUTES:

- Megawatt capability
- Compact and Light-Weight
- High Efficiency
- Low harmonic content
- Low voltage / large-current
- Cryocooled for high efficiency, compactness and light-weight
- Handle large fault currents due to a motor fault



Wadsworth, Aaron, Brandon Pais, Shaun Kyle, Duleepa J. Thrimawithana, Rodney A. Badcock, Andrew Lapthorn, Bill Heffernan, Rachel A. Oliver, David J. Wallis, and Martin Neuberger. "Evaluating Common Electronic Components and GaN HEMTs Under Cryogenic Conditions." In *2021 IEEE Southern Power Electronics Conference (SPEC)*, pp. 1-6. IEEE, 2021. doi: 10.1109/SPEC52827.2021.9709441.

Development of electric drive with above stated characteristic is highly desirable

ELECTRICAL FAULT MANAGEMENT

- Fault management on the aircraft electrical grid needs to be addressed up front
- All rotating machines must withstand faults without seriously impacting the grid
- Typical possible faults requiring early attention are,
  - Turn-turn shorts in stator coils, especially in permanent magnet machines where excitation can't be turned off
  - Peak fault current could be easily 20X rated current (for xd" = 0.1 pu) in a typical air-core machine
  - Such high currents could severely damage a machine and its associated equipment
  - As all machines are expected to be tied through a common DC bus, it would be prudent to include fault handing capability in the electric drives associated with an individual machine
  - Include fault current limiting capability in the common DC bus as well as in individual machines
  - Need robust quench detection and protection systems for both AC and DC coils

High power (~40 MW) airplane electric grid needs early attention to the fault management

NEED FOR SIGNIFICANT COMPONENT DEVELOPMENTS

- Low AC loss conductors for fields up to 1 T and 500 Hz
  - Superconductors REBCO, MgB2, Bi2212, …
  - High Conductivity Aluminum (Hyper-AL)
- Hyper-AL availability with RRR ~ 600 at reasonable cost and schedule
- MgB2 and Bi2212: low loss conductors at reasonable cost and schedule
- MgB2 and Bi2212: coil manufacturing technology requiring wind-and-react approach
- HTS conductors for the field coils on the rotor – strain tolerant with high Je at high fields
- Compact, lightweight and high efficiency refrigerators (AMAC) and Heat Exchanger with fuel
- Field excitation coil development and testing
- Rotor cooling with on shaft coolers
- Superconducting coil on rotor powering with brushless exciters, like Flux Pumps
- Reducing current lead losses for AC coils
- Electric Drives (~1000 V, high-current) compact, light and efficient
- Test facility for testing motors rated up to 5 MW, 3-6000 RPM

Targeted funding is needed for component developments listed here

SUGGESTIONS FOR GOVERNMENT ROLE

- Set goals for 'The Cryo-Electric Flights' with Multi-year Funding
  - Next Generation Electric Machines Virtual Roadmap Workshop , May 31-June 01, 2023 (Good start)
- Select a Single Prime for each complete system development
- Tie component development to the Prime's committed schedule
- Develop Test facility (/facilities) ASAP for testing motor prototypes
- Example: Air New Zealand's Mission Next Gen Aircraft – 2030

Air New Zealand seeking innovators for next generation aircraft - Media releases | Air New Zealand

For most efficient development, award multi-year program for a given system under a single prime

QUESTIONS