IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

Rotating Machines Using High Temperature Superconductors

Past, Present and Future

Swarn Kalsi
Kalsi Green Power Systems
Princeton, NJ, USA
em: skalsi@KalsiGPS.com

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

Superconducting Rotating Machines

OUTLINE

- SC Machine Configurations
- High Speed SC Machines
- Low Speed SC Machines
- Airplane Machines
  - AC Homopolar
  - Wound Rotor
- Outlook

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

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

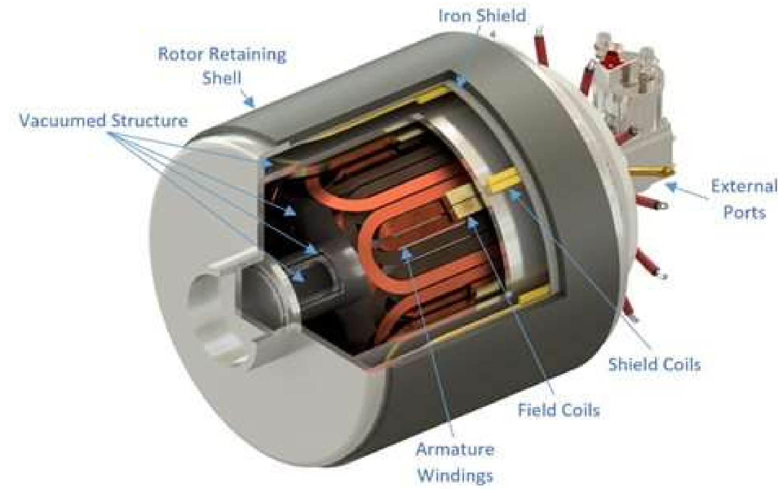
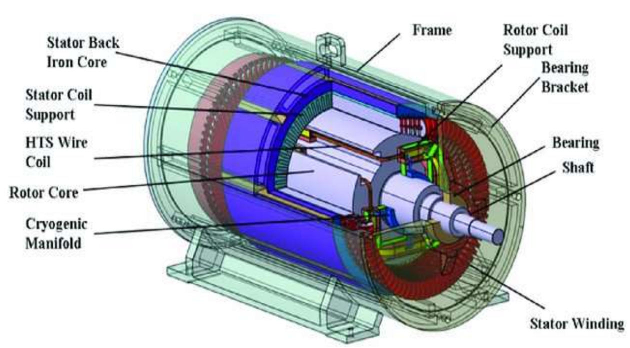


Photo: Fraunhofer Institute for Wind Energy Systems

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].

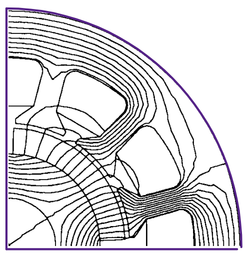
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

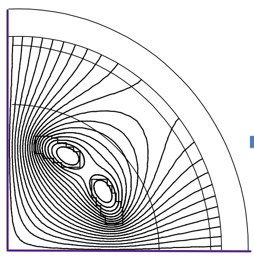
SUPERCONDUCTING MACHINE CONFIGURATIONS



PM & Conventional

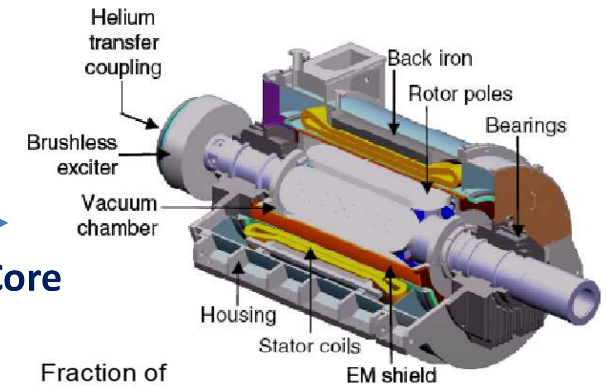
Iron-Core





Air Core HTS

Air-Core



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

Harmonic Order	Fraction of Fundamental
1	1
3	0
5	$5.977\cdot10^{-4}$
7	$7.394\cdot10^{-6}$
9	0
11	$6.074\cdot10^{-8}$
13	$1.542\cdot10^{-10}$
15	0
17	$1.032\cdot10^{-11}$
19	$-3.381\cdot10^{-14}$

Harmonics generated by field winding in stator

Harmonic Order	Fraction of Fundamental: Radial	Fraction of Fundamental: Tangential
1	1	1
3	-0.057	0.116
5	$3.869\cdot10^{-4}$	$7.097\cdot10^{-3}$
7	$4.567\cdot10^{-5}$	$-1.153\cdot10^{-3}$
9	$-7.546\cdot10^{-5}$	$-4.378\cdot10^{-4}$
11	$4.55\cdot10^{-6}$	$-4.586\cdot10^{-5}$
13	$-8.935\cdot10^{-7}$	$1.027\cdot10^{-5}$
15	$5.559\cdot10^{-7}$	$4.827\cdot10^{-6}$
17	$-1.149\cdot10^{-8}$	$5.882\cdot10^{-7}$
19	$-2.729\cdot10^{-9}$	$-1.475\cdot10^{-7}$

Harmonics generated by stator AC winding on the rotor surface

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

Examples of High-Speed Machines Built and Tested

- 1000 hp, 1800 rpm synchronous motor by Rockwell/AMSC (2000)
- 5000 hp, 1800 rpm synchronous motor by AMSC (2001)
- 8 MVAR, 1800 rpm synchronous condenser by AMSC (2004)
- 4 MW, 3600 RPM generator by Siemens (2007)
- 3.6 MW, 1800 RPM motor by TECO-Westinghouse (2015)

HIGH SPEED MACHINES EMPLOYING HTS ONLY

1000 HP, 1800 RPM Synchronous Motor (2000)

- First motor jointly built by AMSC and Baldor/Rockwell Automation
- 1000 HP, 1800-RPM, 4-pole
- Field Winding - BSCCO-2223 conductor @25 K
- Armature Winding – Diamond type copper coils
- HTS rotor coils cooled with liquid neon
- Tested in the Summer 2000
- Met performance expectations

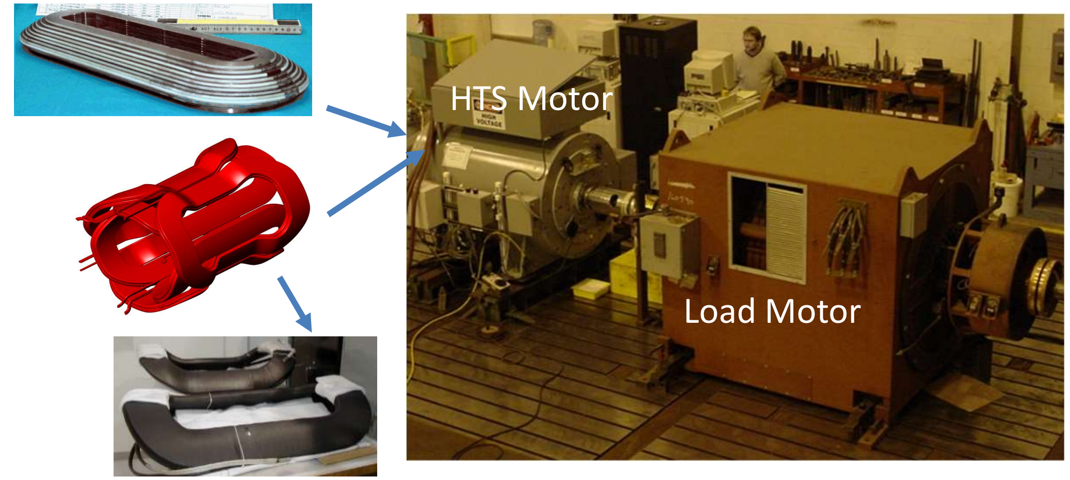
Field Winding on the Rotor

AC Winding on the Stator

Encouraging progress on this motor motivated AMSC to built 5000 HP motor

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

AMSC 5000 HP Construction and Testing (2001)



GOALS:

- 5000 HP, 1800-RPM, 60 Hz motor
- Line voltage 6.6 kV
- Air-Core machine – No iron in stator or rotor coils
- Field Winding – stacked BSCCO-2223 pancake coils
- Closed-loop cooling system used G-M cryocooler
- Armature Winding – Single layer copper coils
- Copper coils cooled with fresh water
- Frame dimensions:
  1.1 m dia x 1.6 m long
- Weight – 6.8 ton
- Efficiency – 97.7%
- Copper coils cooled with fresh water

TEST RESULTS:

- Factory load testing completed per IEEE 115
- Achieved motor efficiency: 97.7%
- 1/3 reduction in volume compared to the industry standard
- 40% reduction in losses compared to the industry standard

Parameter	Design	Measured
Line Voltage, kV	6.6	6.6
Phase Current, A	329	330
Rating, hp	5000	5000
Xd, pu	0.32	0.30
Xd’, pu	0.28	0.23
Xd“, pu	0.16	0.17
Back EMF, pu	1.043	1.035

World’s most powerful HTS industrial motor to date

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

Siemens 4 MVA, 3600 RPM Generator (2007)

Design Parameters for the 4 MVA Siemens Machine

Nominal power	4 MVA
Rated speed	3600 rpm
Rated voltage	3~60 Hz AC 6.6kV
Rated current	350 A
Nominal torque	10.6 k Nm
Degree of protection	Int. Protection Code 44
Bearings	Sleeve bearings
Rules	Germanischer Lloyd
Total dimensions of the machine (including cryocooler) LxWxH	3.7m x 2.5m x 1.8m
Shaft height	500mm
Foot print LxW	1.9m x 1.2m
Total weight	6.9 t

Electrical Parameters of the 4 MVA HTS Machine

Synchronous reactance x_d, unsaturated	0.51 p.u.
Synchronous reactance x_d, saturated	0.33 p.u.
Transient reactance x_d'	0.28 p.u.
Subtransient reactance x_d''	0.15 p.u.
Rotor inductance	28 H
Transient time constant T_d'	700 s
Subtransient time constant T_d''	0.01s

Data

Output:	4 MVA
Voltage:	6,6 kV
Speed:	3600 rpm
Frame size:	500 mm
Efficiency:	98,7 %
HTS wire:	6 km

Hybrid machine – HTS rotor and Conventional Stator

Ref: W. Nick, M. Frank, G. Klaus, J. Frauenhofer, and H. Neumuller, "Operational Experience with the World's First 3600 RPM, 4 MVA Generator at Siemens", IEEE TAS, Vol. 17, No. 2, June 2007

Generator was successfully tested

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

TECO-WESTINGHOUSE 3.6 MW 1800 RPM MOTOR (2015)

- REBCO field coil around salient rotor poles
- Conventional stator with iron teeth
- Table below compares volume, power density and efficiency with a conventional induction motor operating on the ship with those of the PM and HTS 2G motors
- HTS REBCO motor had higher efficiency and power density than both induction and PM motors

Type of Motor	Power Density (x 100 kN/m2)	Volume (m3)	Efficiency (%)
Induction	0.26	0.8	96.37
Permanent	0.42	0.56	97.62
HTS 2G Field Winding	0.53	0.41	98.72

HTS motor offers little benefit over PM motor in iron-core machines

Figure 7. 3.6 MW 1800 RPM ship propulsion motor. © 2015 IEEE. Reprinted, with permission, from [22].

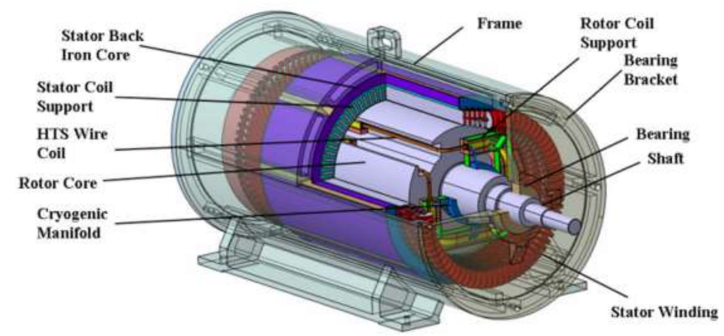


Figure 8. A conceptual design of HTS propulsion motor. © 2015 IEEE. Reprinted, with permission, from [22].

Ref: Supercond. Sci. Technol. 30 (2017) 123002

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

SuperVAR®

Dynamic Synchronous Condenser

AMSC – 8 MVAr Condenser →

Hoeganaes, Tennessee

HIGH SPEED SC MACHINES

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

SUPERVAR® PROTOTYPE PROJECT DESCRIPTION (2004)

Similar to a conventional synchronous machine but with better performance

- Fast reacting transient dynamic voltage support and stability (leading and lagging VARS) at a multiple of the machine rating
- Reduced operating costs over conventional condensers - Low losses even at partial load
- Generates very low levels of harmonics - requiring no filters
- Operates at line voltage on the low side of transmission to distribution transformer
  - Stator provides distribution level voltages
  - No additional transformer needed in most applications

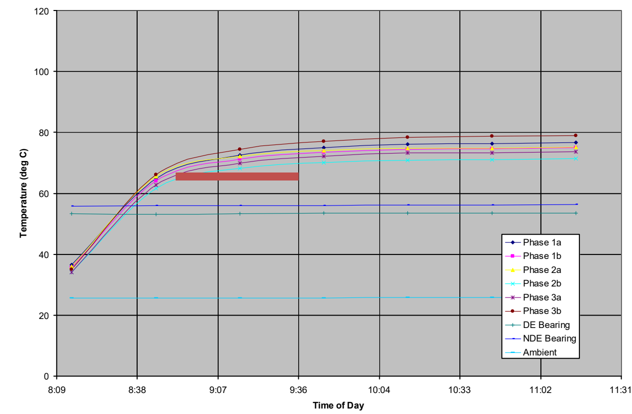
Rating	8 MVAR
Voltage	13.8 kV line to line
Ambient Temp	-30° to +40°C
Losses	1.5% rating at 8MVA
	Including 30kW 480V auxiliary power

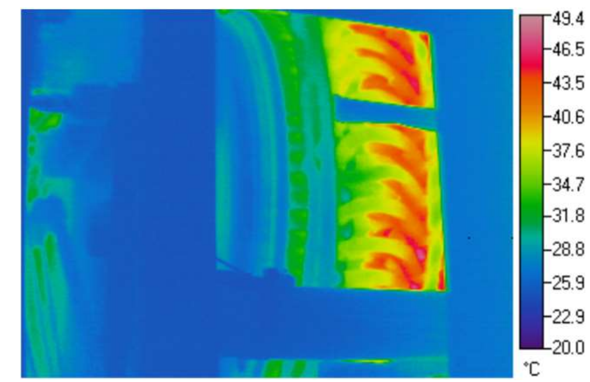
SUPERVAR has significant benefits over conventional machines

Ref: S. S. Kalsi, et al "Discussion of Test Results of a Superconductor Synchronous Condenser on a Utility Grid', IEEE TAS, Vol., 17, No. 2, June 2007

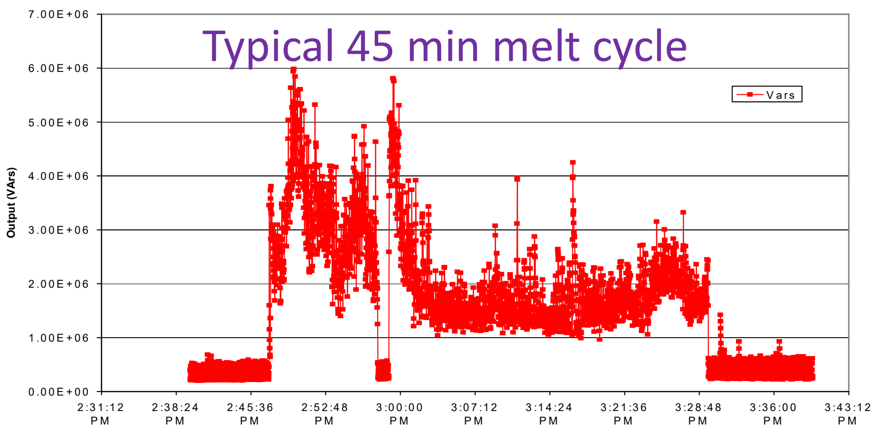
REAL LIFE OPERATION ON TVA GRID (2004)

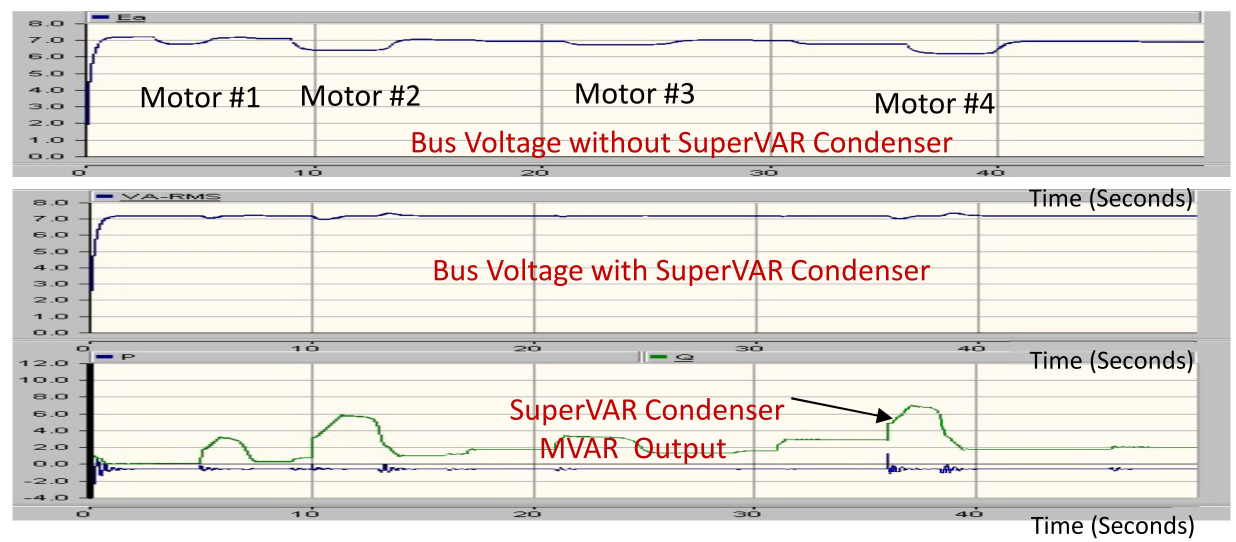
- Installed on TVA grid in Gallatin, TN on 10 October 2004
- Operated for 1 yr flawlessly
- ±8 MVAR capability verified
- Machine reacted quasi-instantaneously to transients due to arc furnace operations





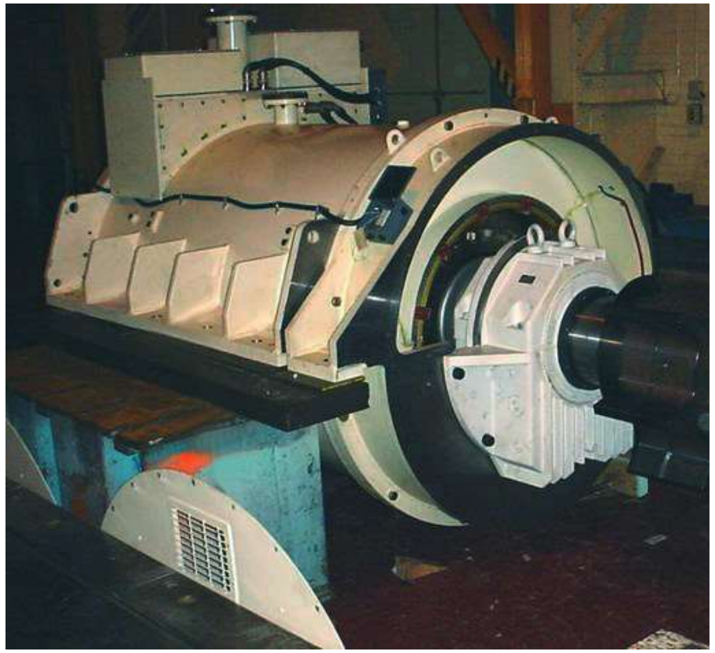
- Designed temperature rise ≤ 120°C at 40°C ambient temperature
- Stator end turn temperature monitored using infrared camera





Demonstrates that an HTS machine can handle substantial stator fed harmonics

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

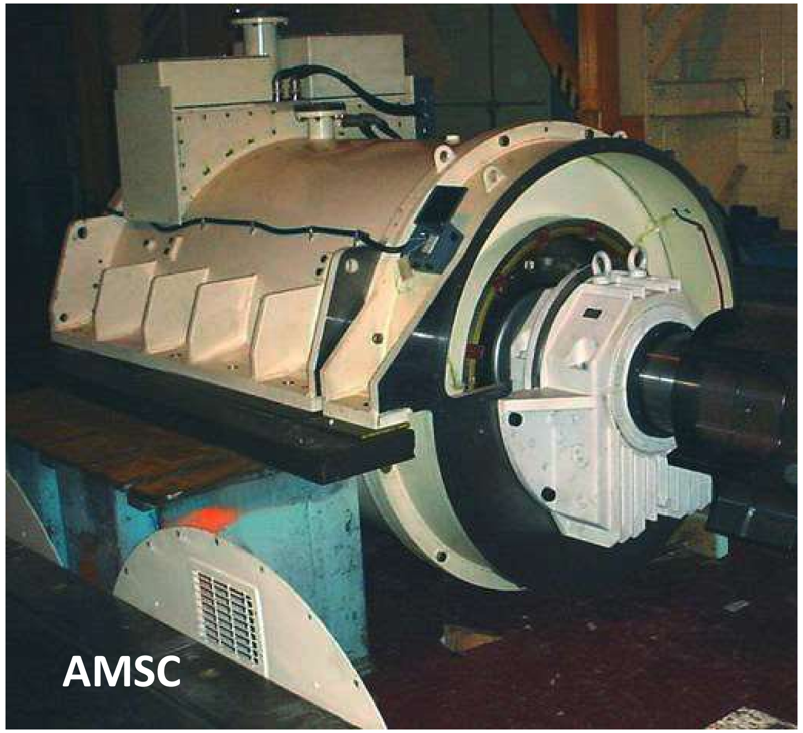


- 5 MW, 230 RPM Ship Propulsion motor (2003)
- 36.5 MW, 120 RPM Ship Propulsion motor (2008)

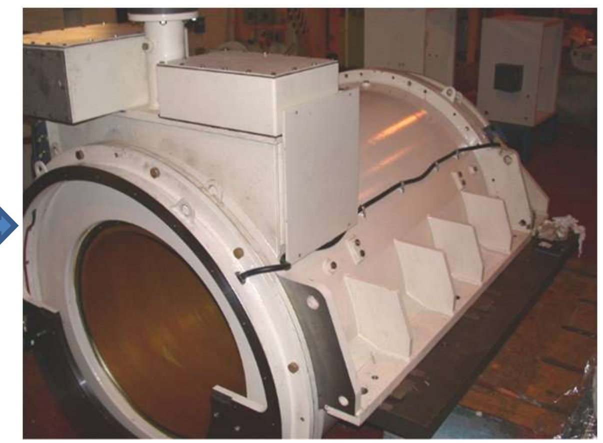
LOW SPEED MACHINES

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

AMSC 5 MW Ship Propulsion Motor (2002)



Coils employed Litz cable with small strands transposed into a flat cable



Completed Stator

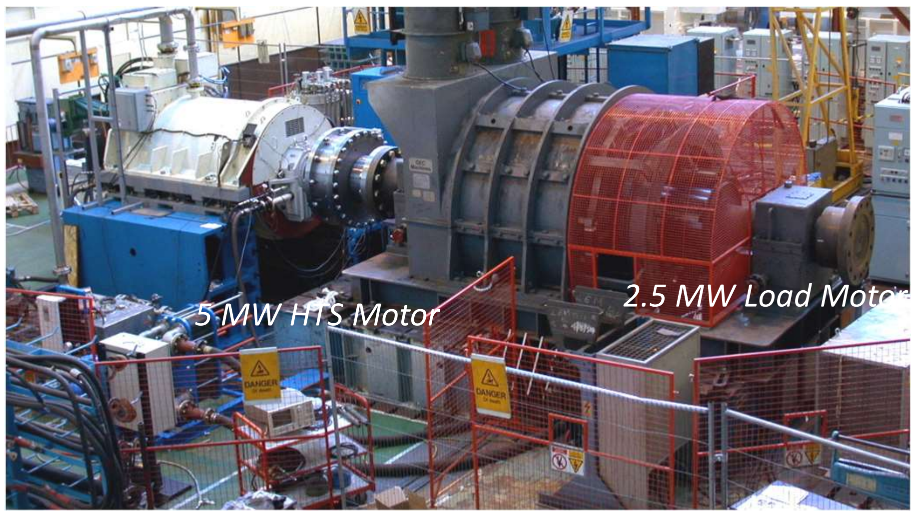
All subsystems were tested prior to assembling in the motor

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

TESTING OF THE 5 MW SHIP PROPULSION MOTOR (2003)

Part-Load Testing in Factory

- No-Load IEEE 115 Std.
  - Motor Parameters
  - Efficiency
- Full torque at ½ speed
- Limited Structure borne Noise Data
- Operation on a Drive

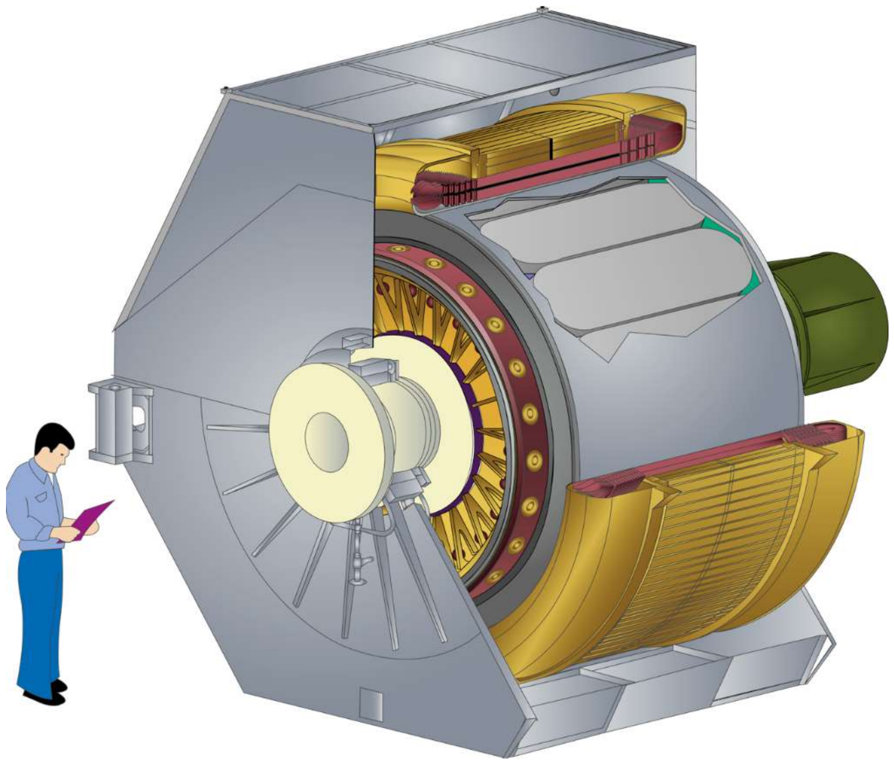


Full-load Testing at CAPS

- Motor was delivered to CAPS in July 2003.
- Motor was coupled to a pair of 2.5 MW squirrel cage induction motor dynamometers
- Motor load test results were reported at the ASC-2004 conference in September 2004

Full-load testing was conducted by simulating ship propulsion load

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).



Ship Propulsion – AMSC (2008)

36.5 MW, 120 RPM Motor

LOW SPEED SC MACHINES

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

Built 36.5 MW Based on 5 MW Experience (2007)

- Designed and built the motor to power the next generation of Navy ships
- ONR contracted AMSC to deliver the 36.5 MW, 120 RPM motor, integrated with a commercial Variable Frequency Drive
- Attractive Feature: For the same torque, the motors are compared on basis of weights;
  - 75 tonnes HTS motor,
  - 280 tonnes[1] for an advanced induction motors
  - 400 tonnes[2] for a QE2 synchronous motor
- 36.5 MW motor design was based on the 5 MW motor technology.

Parameter	Value
Rating	36.5 MW
Line Voltage	5.8 kV
Speed	120 RPM
Synchronous reactance, Xd	0.37 pu
Transient reactance, Xd’	0.32 pu
Sub-transient reactance, Xd”	0.24 pu
Efficiency	97.1%

1 Scaled from ALSTOM IPS Induction Motor

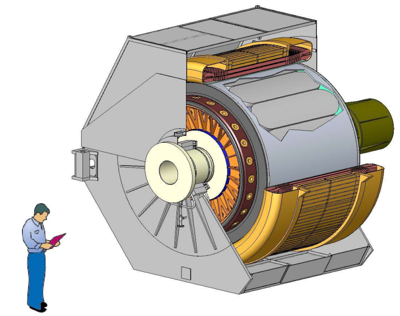
2 http://www.qe2.org.uk/engine.html

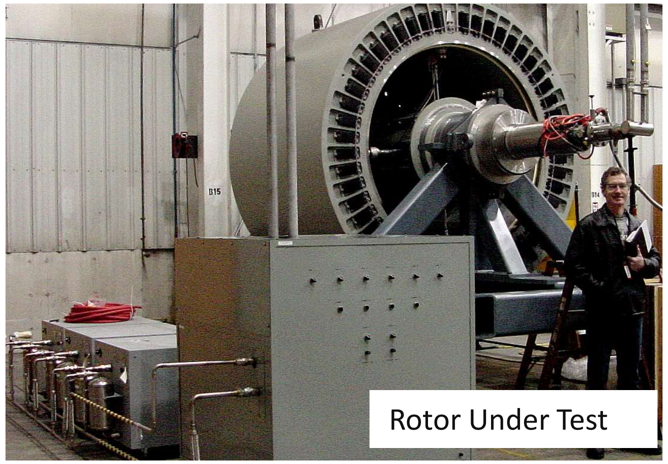
This 36.5 MW motor still holds world record for being the largest capacity motor ever built in a single frame

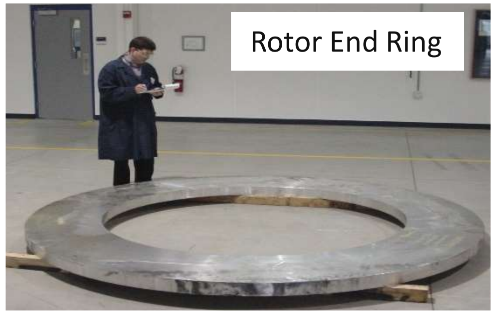
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

36.5 MW Ship Propulsion Motor Components (2007)

- AMSC built a 36.5 MW, 120-RPM HTS ship propulsion motor for ONR
- Motor weighs 75-tonnes, including stator and rotor cooling systems
- Delivered to ONR in 2008

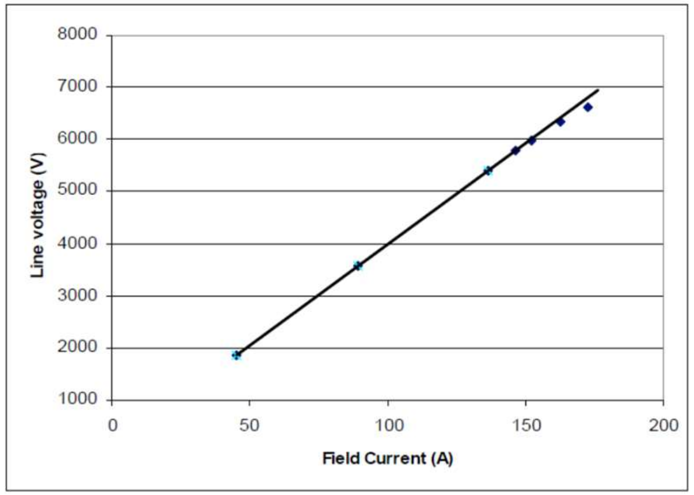




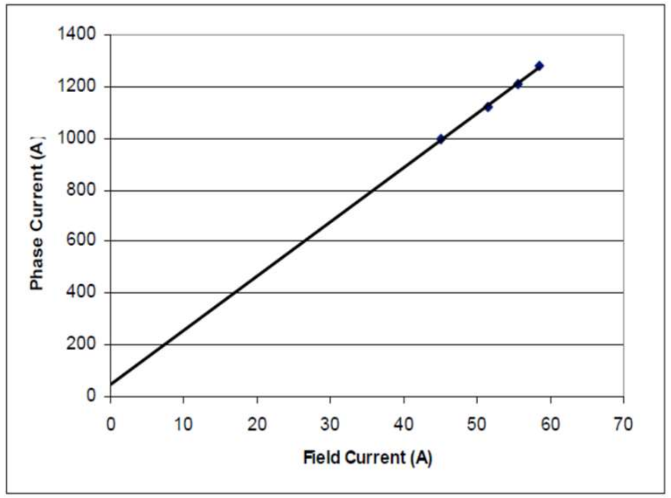


All components were tested/inspected before releasing them for final assembly

36.5 MW Motor –Test Results (2008)



OPEN-CIRCUIT TESTING



SHORT-CIRCUIT TESTING

Parameter	Design	Measured
Design Power	37.2 MW	---N. A.---
Voltage	5.8 kV	6.6 kV
Current	1.275 kA	1.28 kA
Stator Winding Temperature	Class F to meet Class B	80.5 C (based on resistance and scaled to 40C inlet)
Efficiency	97%	97%

DESIGN VS. MEASUREMENTS

- Design, development and manufacture of the direct-drive ship propulsion motor was validated by the successful factory testing.
- The full power testing of the 36.5 MW HTS motor system was conducted by the Navy operated land-based test site in Philadelphia

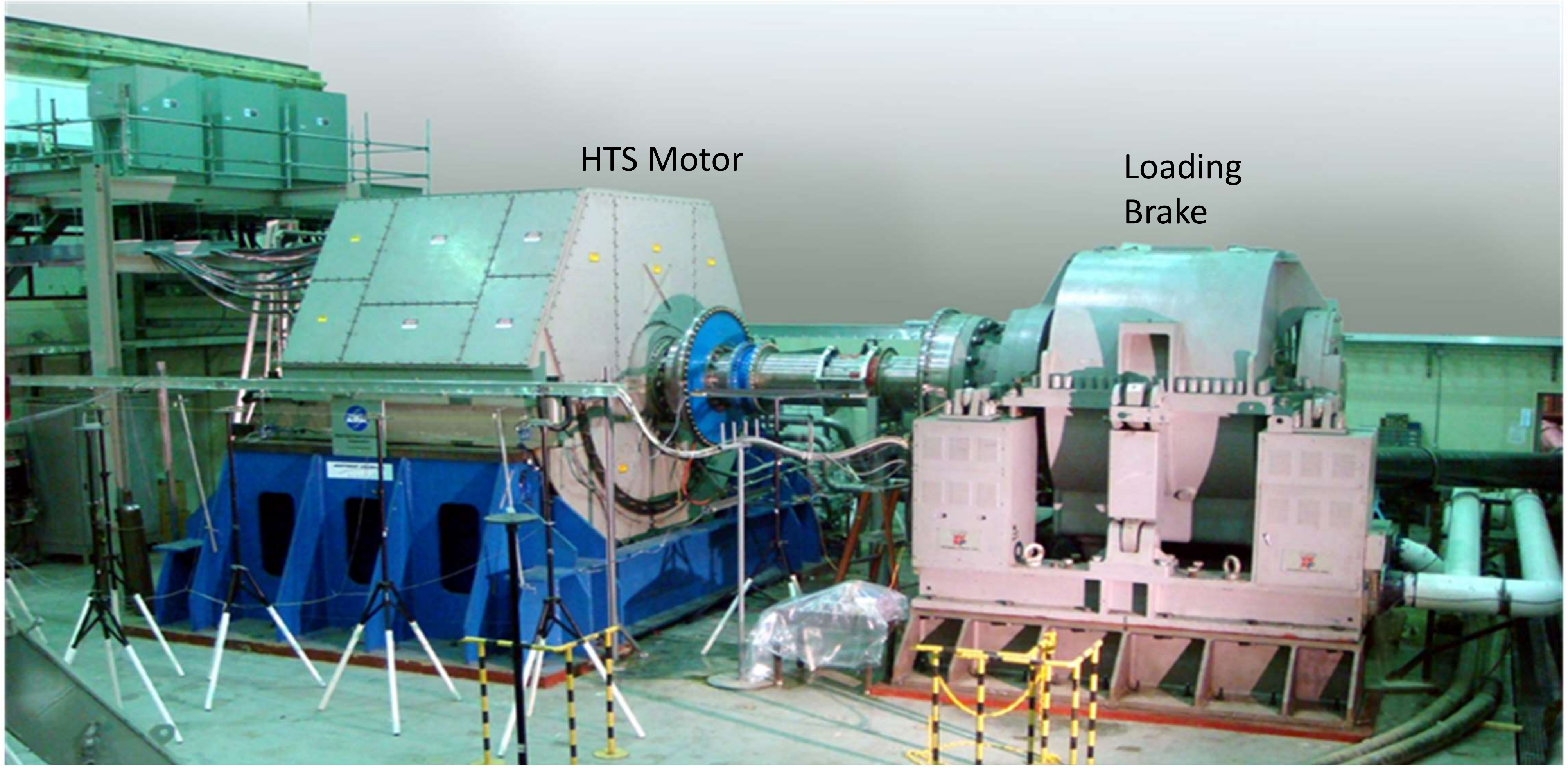
*Ref: Bruce Gamble , Greg Snitchler and Tim MacDonald, **"Full Power Test of a 36.5 MW HTS Propulsion Motor"**, IEEE Transactions on Applied Superconductivity (Volume: 21 , Issue: 3 , June 2011), pages:1083-1088*

The most powerful motor ever was successfully load tested by the Navy satisfying all design requirements

KGPS

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

36.5 MW Motor Under Load Testing at Navy Test Facility (2008)



The motor was successfully tested to full-load by US Navy - meeting all design objectives

WIND TURBINE GENERATORS

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

HTS Pole for a Wind Turbine Generator (2011)

- A pole made for a 10 MW class wind turbine generator by AMSC
- Employed 2G REBCO wire
- The pole was built and tested in 2011
- Demonstrated feasibility of building large magnets with REBCO coated conductors

Ref: G. Snitchler et al., "10 MW class superconductor wind turbine generators," IEEE Trans Applied Superconductivity, vol. 21, no. 3, p. 1089, June 2011

Coil manufacturing technology demonstrator for building large HTS pole with REBCO wire

ECO 5 3.6 MW WIND TURBINE GENERATOR (2018)

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 Generator by ECO 5

Source:
IEEE Spectrum,
Aug. 2018

The Only tested superconducting wind power generator

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

Two kind of machines under consideration

- AC Homopolar
- Wound Rotor

AIRPLANE APPLICATIONS

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

NASA Defined Requirements

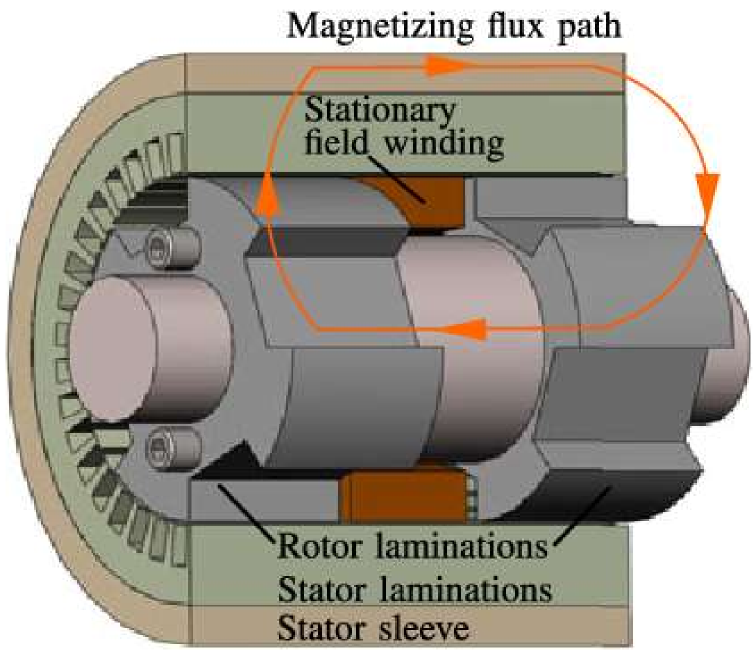
NASA's Fixed Wing Project (currently the Advanced Air-Transport Technology Project) has defined goals for the next three generations of aircraft for commercial aviation. Below are electrical machine requirements for an example turboelectric-aircraft concept.

	Generators	Motors
Number of units	2	15
Power rating	30,000 hp (22.4 MW)	4,000 hp (3 MW)
Assumed weight	2,200 lb (1,000 kg)	520 lb (236 kg)
Assumed efficiency	99.3%	99%
Rotational speed	6,500 rpm	4,500 rpm

Ref: 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)

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

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).



- 5/1 MW, 35000 RPM generator by GE (2009)
- 10 kW, 24000 RPM motor by VUW (2022)

AC HOMOPOLAR MACHINES – ULTRA HIGH SPEED

NO WINDINGS ON THE ROTOR

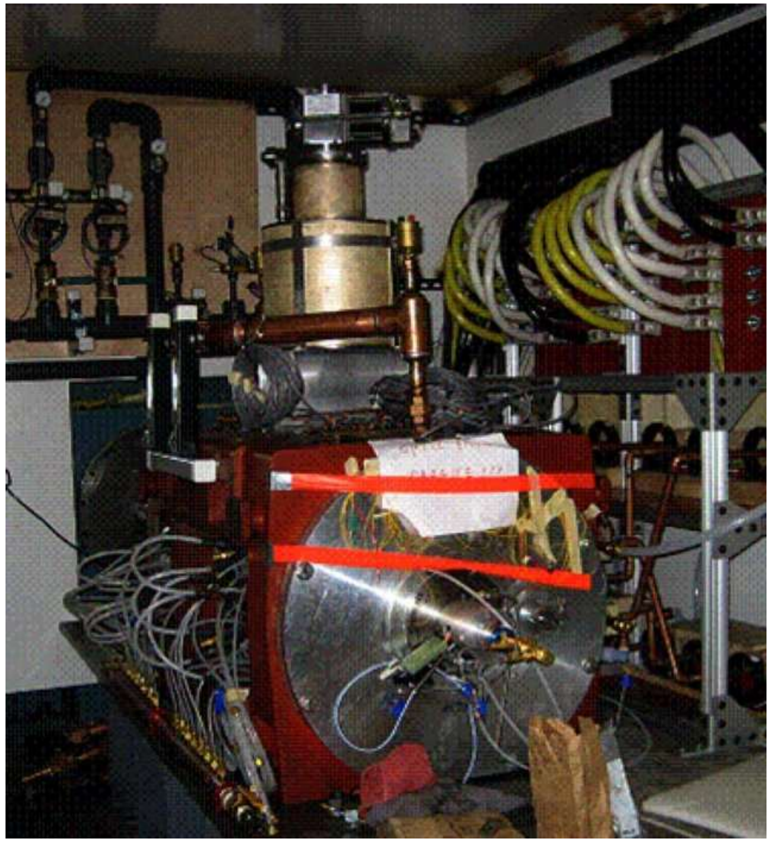
GE 5 MW Homopolar Generator (2009)

- 5 MW Homopolar Synchronous Generator for Air Force Research Lab
- Factory tested to 1 MW
  - Test speed 10,500 rpm
  - Resistive load
  - Efficiency at 1 MW = 97%
- Satisfied Airforce contract requirements

TABLE I
DESIGN PARAMETERS OF AN AFRL HIGH-SPEED HTS HIA

Parameter	Value
Power, MW	5
Rated speed, rpm	35000
Voltage, V	670
Poles	6
Frequency, Hz	1750
Efficiency at FL, %	98
Synch reactance, p.u.	0.7
Gap flux density, T	1.8
Field Ampere-Turns	45,000
Diameter, cm	50
Length, cm	50
Active Length, cm	21.6
Machine weight, kg	500
Cryogenic weight, kg	45.5
Total Machine weight, kg	545

Power Density = 9 kW/kg



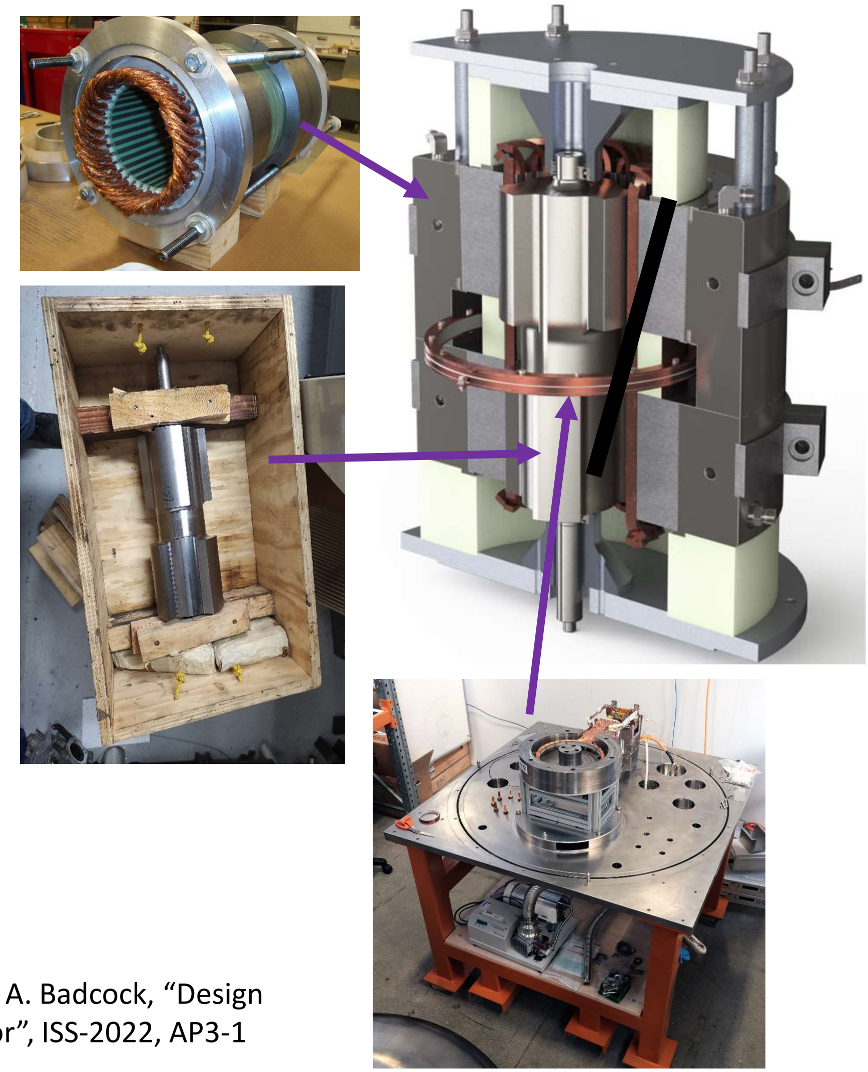
Generator on test stand

Ref: K. Sivasubramaniam, et al, 'Development of a High Speed HTS Generator for Airborne Applications', IEEE Trans. on Applied Superconductivity, Vol. 19, No.3, June 2009, p. 1656

VUW-RRI 10 kW Homopolar Motor (2022)

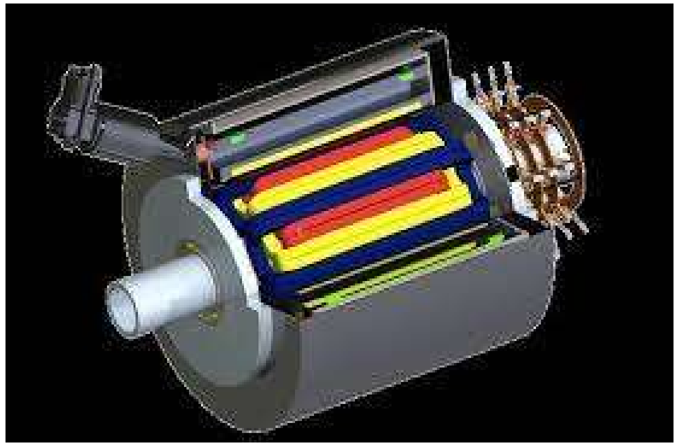
- 10 kW, 25000 RPM homopolar synchronous motor is under construction
- All components have been built and bench tested
- Final assembly is progressing
- No-load testing for motor characterization will begin in January 2023
- Load testing will be conducted at an outside facility

Parameter	Value
Motor rating, kVA	15
Rated line voltage, V	264
Rated current, A	33
Number of poles	6
Rated speed, RPM	25,000
Rated frequency, Hz	1,250
Rated field current, A	370
Efficiency at rated load, %	85
Overall axial length, mm	394
Overall diameter, mm	410
Mass of machines, kg	334



Motor is being assembled for testing beginning Jan. 2023

Ref: K. A. Hamilton, S. S. Kalsi, J. G. Storey, D. A. Carnegie, and R. A. Badcock, "Design and Build of a High-Speed AC Homopolar Superconducting Motor", ISS-2022, AP3-1



Airplane motors and generators (compact lightweight efficient)

- NASA 1.4 MW motor
- VUW 3 MW, 4500 RPM motor
- SOARING 2.5 MW, 5000 RPM motor
- CHEETA 5 MW, 4500 RPM motor – INSIDE OUT CONFIGURATION
- SAFRAN HTS Bulk Motor

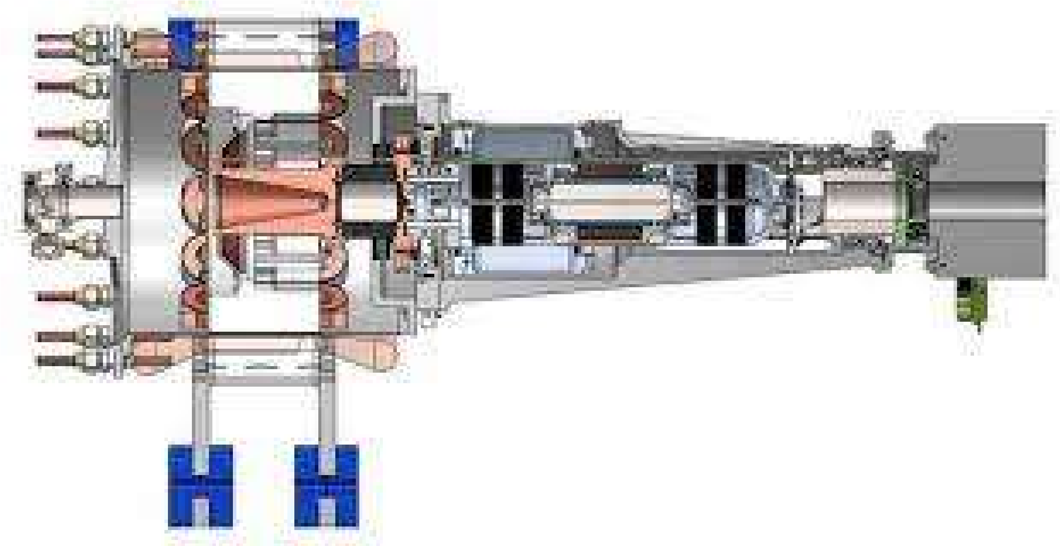
WOUND ROTOR AIRPLANE MOTORS

CURRENTLY UNDER DEVELOPMENT

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

NASA High-Efficiency Megawatt Motor (HEMM)

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



Key Features

- Uses standard aircraft cooling systems
- Direct drive at optimal turbomachinery speeds (no gearbox)
- Can be shut off if fault occurs (wound field)

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

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

VUW-RRI 3 MW, 4500 RPM MOTOR

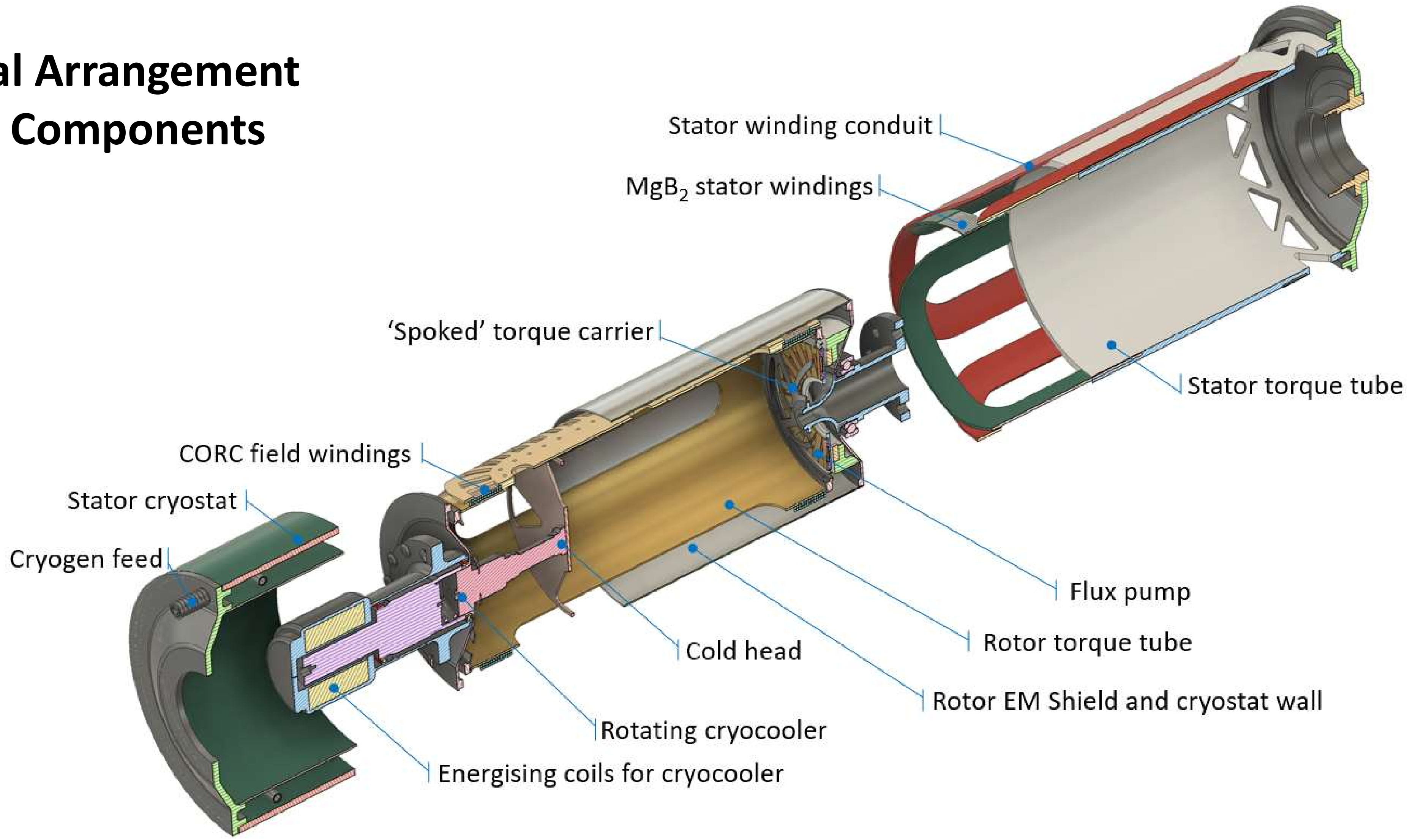
- Robinson Research Institute (RRI) Victoria University of Wellington is developing superconducting motors for aircraft applications
- Final goal: Build all superconducting 3 MW motor at 4500 RPM using the following steps;
  - 100 kW, 4500 RPM motor with REBCO field coils and conventional copper stator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

Parameter	3 MW Motor Specs.	100 kW Prototype Motor Specs
Nominal Rating, kW	3,000	100
Number of phases	3	3
Nominal DC bus voltage, V	1,500	1,500
Number of poles	4	4
Rated rotational speed, RPM	4,500	4,500
Rated frequency, Hz	150	150
Rotor field excitation coil temp., K	40	40
Stator operating temp., K	20	300
Power source	Electric Drive	Electric Drive

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

VUW-RRI 3 MW, 4500 RPM MOTOR - LAYOUT

Conceptual Arrangement of Various Components



VUW-RRI 100 kW, 4500 RPM Motor (2023)

- 100 kW, 4500 RPM motor under construction to serve as 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
- REBCO CORC cable used for the field coils on the rotor
- Field coils are conduction cooled to the structural support cylinder
- Support cylinder is cooled with a cryocooler integrated within the shaft
- Field coils powered with a 2.8 kA flux pump integrated on the rotor
- Stator race-track saddle shaped coils built using copper Litz wire
- Both rotor and stator coils have been practice built using copper cables

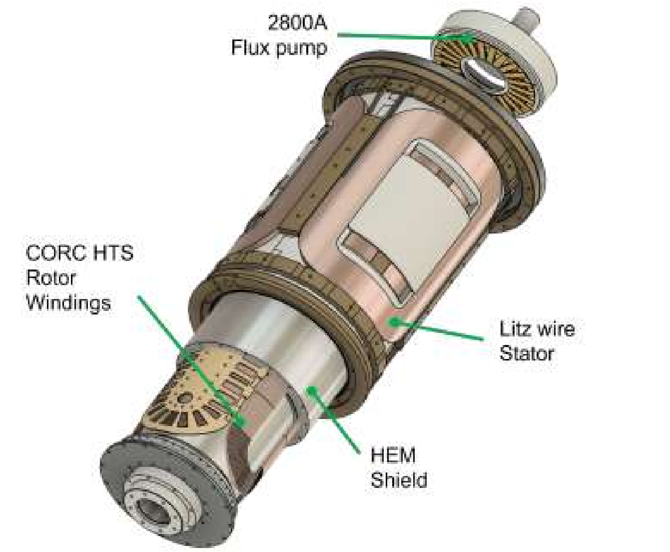
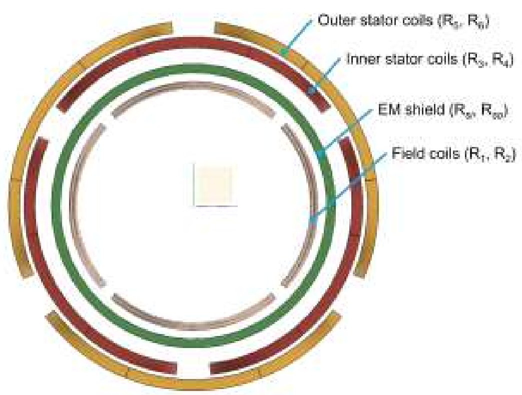


Fig. 1. 100-kW motor exploded view showing HTS rotor, litz wire stator and 2800A HTS Dynamo.



Ref: S. S. Kalsi, J. G. Storey, J. M. Brooks, G. Lumsden and R. A. Badcock, “Mechanical and electrical design of a synchronous superconducting aircraft motor”, Presented at ASC-2022, Paper #ASC2022-4LPo1D-09

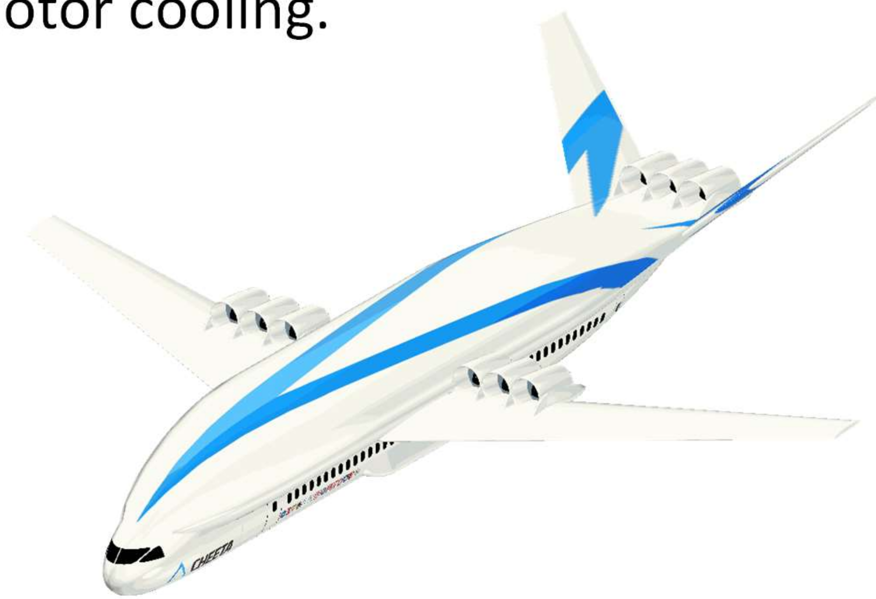
Raytheon Soaring 2.5 MW, 5000 RPM Motor

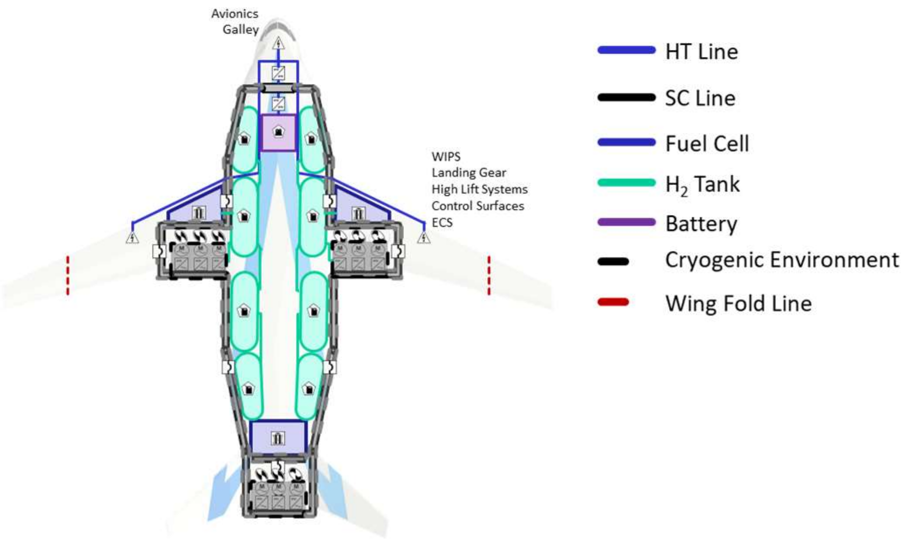
- Raytheon is developing a 2.5 MW, 5000 RPM motor under an ARPA-e program
- Goal: build an ALL-SC-Motor -- both rotor and stator employ superconducting coils
- Field winding is powered with a flux pump integrated on the rotor
- Stator winding uses low AC loss superconductors operating at nominal 20 K
- Motor is cooled with a magnetic cryocooler

Most Challenging Project: Opting for a fully superconducting motor

CHEETA – SC POWERTRAIN FOR HYDROGEN-ELECTRIC AIRCRAFT

- Hydrogen-electric aircraft with synergistic use of LH2 for energy storage and cryogenic cooling
- For all motors, assuming 68 % of available enthalpy of vaporization in fuel allocated for motor cooling.





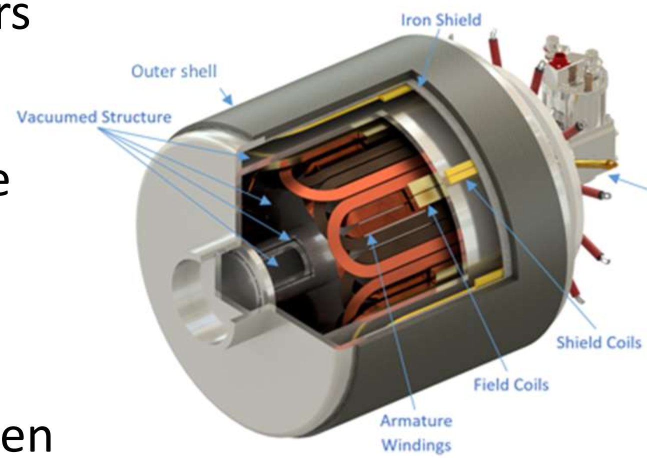
Main Parameters

Total Energy	1068 GJ
Propulsive power	40 MW
Mission length	8 hrs
Amount of fuel (LH2)	14833 kg
Number of motors	16
Motor Power	2.5 MW
Motor Speed	4500 rpm
LH2 Boil-off rate	0.01 kg/s
Cooling budget	4.3 kW

Stautner, W., Ansell, P.J. and Haran, K.S., 2022. CHEETA: An All-Electric Aircraft Takes Cryogenics and Superconductivity on Board: Combatting climate change. *IEEE Electrification Magazine*, *10*(2), pp.34-42.

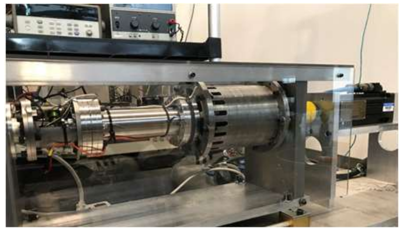
CHEETA – Fully superconducting LH2 cooled motor

- CHEETA is developing 3 - 5 MW, 4500 RPM motors under a NASA-ULI program
- Motor specifications are summarized in the table
- Goal is to build an ALL-SC-Motor; both rotor and stator coils employing superconductors
- This motor configuration has a stationary hydrogen cooled, superconducting armature
- Stator winding uses MgB2 wire with fine filament diameter for reducing AC losses and operates at nominal 25 K
  - High conductivity aluminum is a possible alternative
- REBCO field coils operated at about 40-50K
- Component tests by 2022, motor prototype by 2024



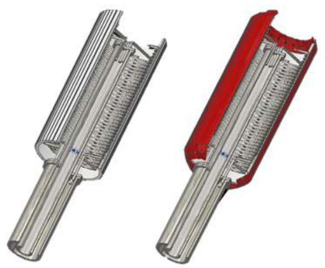
Nominal power (MW)	2.5
Nominal speed (rpm)	4500
Number of poles	8
Outer Diameter [m]	0.5
Machine total length [m]	0.75
Active length [m]	0.87
Average torque [Nm]	7045
Air-gap flux density [T]	0.63
Total loss [W]	2656
Active weight [kg]	13

Component development:



Rotor mounted cryogenics

Superconducting coils



LH2 heat exchangers

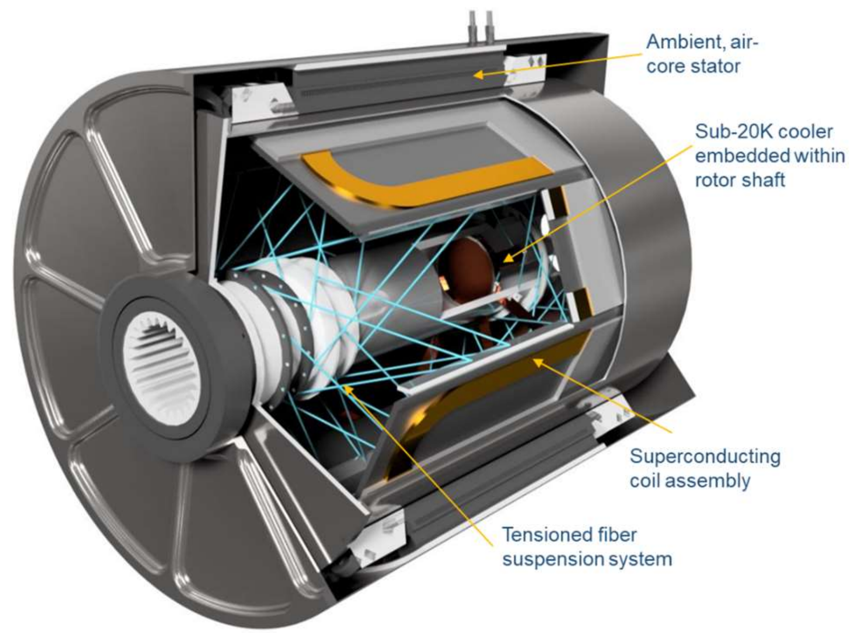
Balachandran, T., Lee, D., Salk, N. and Haran, K.S., 2020, March. A fully superconducting air-core machine for aircraft propulsion. In *IOP Conference Series: Materials Science and Engineering* (Vol. 756, No. 1, p. 012030). IOP Publishing.

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

ARPA-E CRUISE: PARTIALLY SUPERCONDUCTING MOTOR

- Partially superconducting air-core synchronous motor
- Conduction cooled field winding
- Stirling-cycle cooler integrated with a low-loss rotor
- Magnetic fields an order of magnitude higher than conventional machines
- Coil suspension and torque transfer system with tensioned fibers
- Increase specific power with higher 'ampere-turns' of excitation and "armature" windings, featuring
  - Removed ferromagnetic components
  - Increased air gap flux density
  - Increased electrical loading
- Goal: 10 MW, 3000 RPM propulsion motor weighing less than 250 kilograms. Demonstrate 5 MW motor by 2025

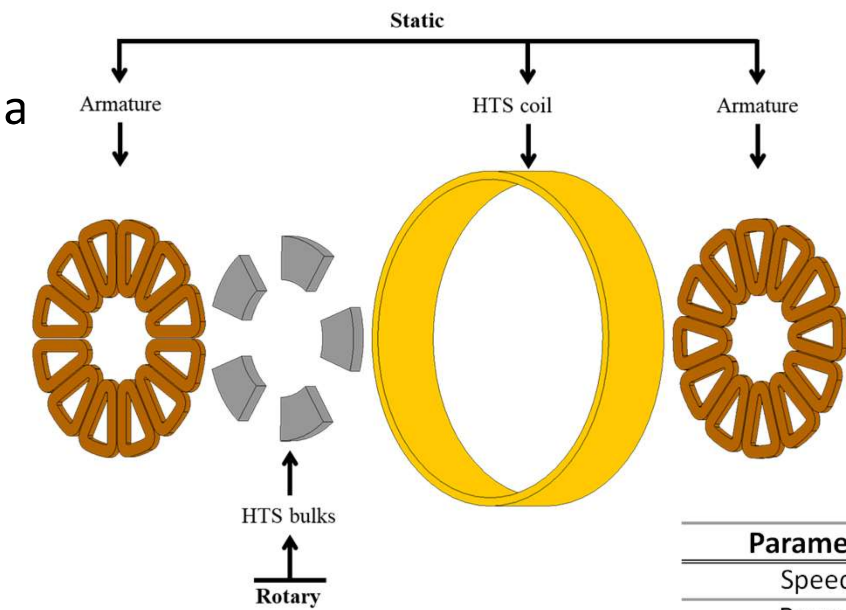
Metric	State of the Art	Target
Specific power (active)	*10 kW/kg*	*50-60 kW/kg*
Efficiency	*96%*	*99.4%*
Single stage cryocooler	35 K (no load)	<20 K (no load)
Cryogenic rotor heat-load	100 W	10 W
Airgap flux density	1 T	3-4 T
Armature ac field	500 T/s	5000 T/s

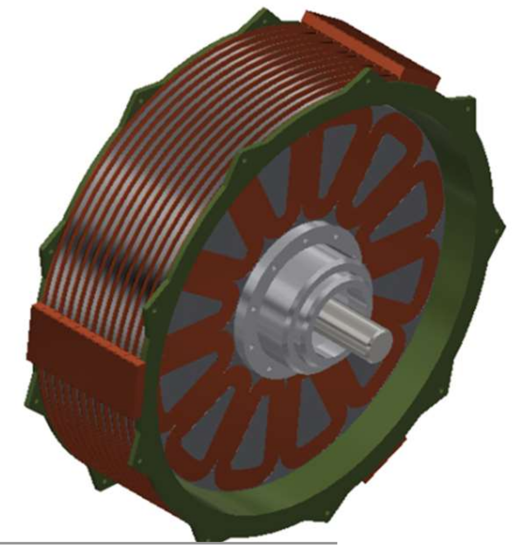


IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

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
  - B can be increased or kept constant
- Large current density can be carried through and HTS or cryogenically cooled armature
  - H can be increased with reduced losses
- **Specific power can be increased without increasing the speed**





Construction and Testing in 2023

Parameter	Value
Speed	5000 tr/min
Power	261 kW
Mass (active)	21.4 kg
Mass (passive)	*~127 kg*
Specific power	*~1.8 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

AIRBUS ASCEND TESTING FACILITY

- Airbus test stand 'ASCEND' for testing motors and other supporting sub-systems needed for an aircraft
- Three-year project includes the following features;
  - Cryogenic electrical protection systems
  - AC and DC distribution utilizing superconducting cables
  - Motor control unit cooled to cryogenic temperature
  - Superconducting motor
  - Cryogenic system based on cryocoolers; could be converted to LH2 storage for future aircrafts (large cooling power)
- Motor test capability includes;
  - Mechanical power of 500 kW at 5000 RPM
  - DC supply bus at 300 V
  - Limit switching current to < 2000 A
  - Available coolant temp. of 25 K and conductor temp. < 35 K

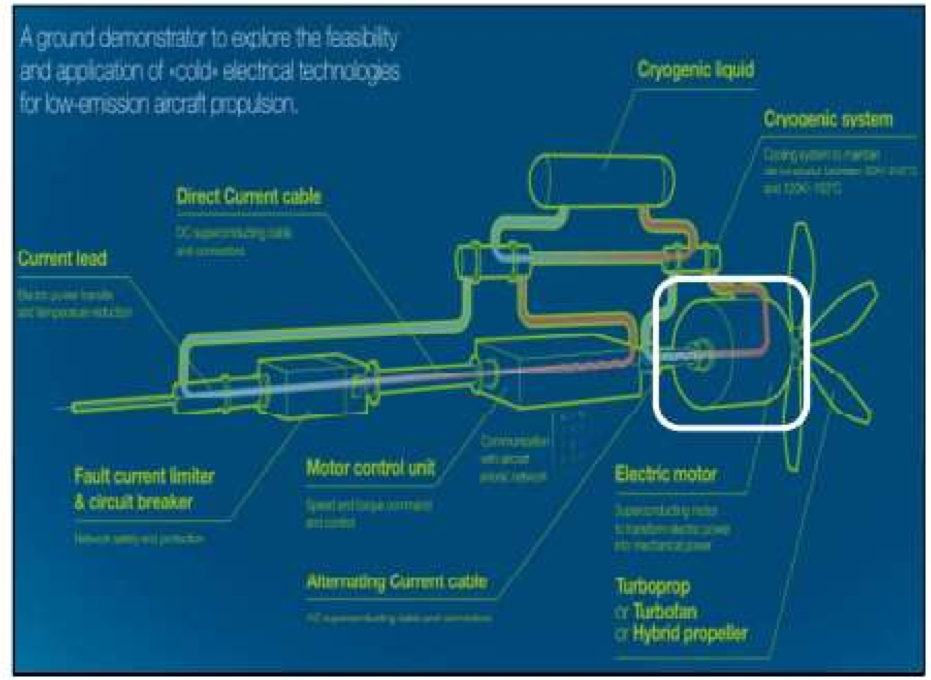


Fig 1. All components of the cryogenic powertrain

This facility is expected to test emerging technologies for aircraft applications

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

GE ~15 MW Wind Power Generator

- GE is developing a ~ 15 MW wind power generator under a DOE program
- Generator employs stationary DC field winding constructed using low-temperature NbTi coils
- Field coils are cooled with a stationary cryocooler, thus avoiding complications of coolant and power transfer to the rotor
- AC armature winding rotates inside the field coil assembly – it is constructed and cooled using established industry practices
- Power is collected from the rotating armature through brushes

Ref: M. Parizh, et al, "High-power Superconducting Wind Generator", ISS-2022 29 November 2022

GE believes generators rated > 15 MW could compete with the conventional technology

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

What will make HTS Machines Attractive?

- HTS technology amply demonstrated – need for economic viability:
  - Low-cost HTS wire and
  - Reliable and affordable cooling system
- **MUST**: Improve wire performance (e.g., extended window of operation in terms of higher temperature and magnetic field and lower cost)
- Building HTS machines by leveraging synergies of off-the-shelf-components
- Designing machines by including dynamic variation of operating parameters (e.g., temperature, excitation, amount of fuel and environment)
- HTS machines may have sweet applications where other technologies are not feasible; Example: Aircraft Motors and Generators, and > 20 MW wind power generators
- An affordable and reliable HTS technology may extend its applications to central power stations, wind turbine generators, ship propulsion and industrial motors

Future of the HTS technology looks very promising

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March, 2023.
This invited presentation AP5-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

Questions