

Homopolar superconducting AC machines, with HTS dynamo driven field coils, for aerospace applications

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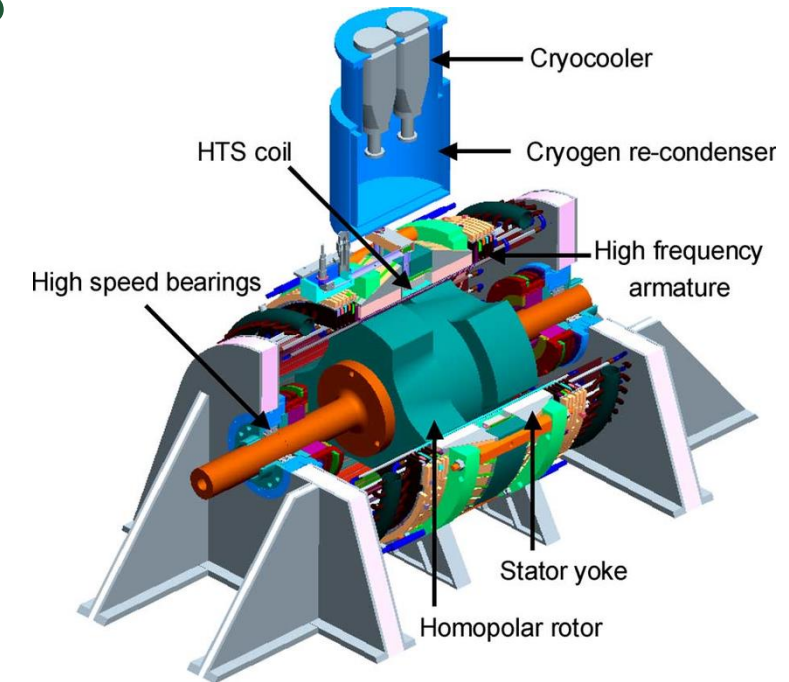
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Homopolar HTS AC Machines

OUTLINE

- Aircraft motor specifications
- Preliminary design
- Field winding concept
- Dynamo excitation concept
- Preliminary design details
- Outlook

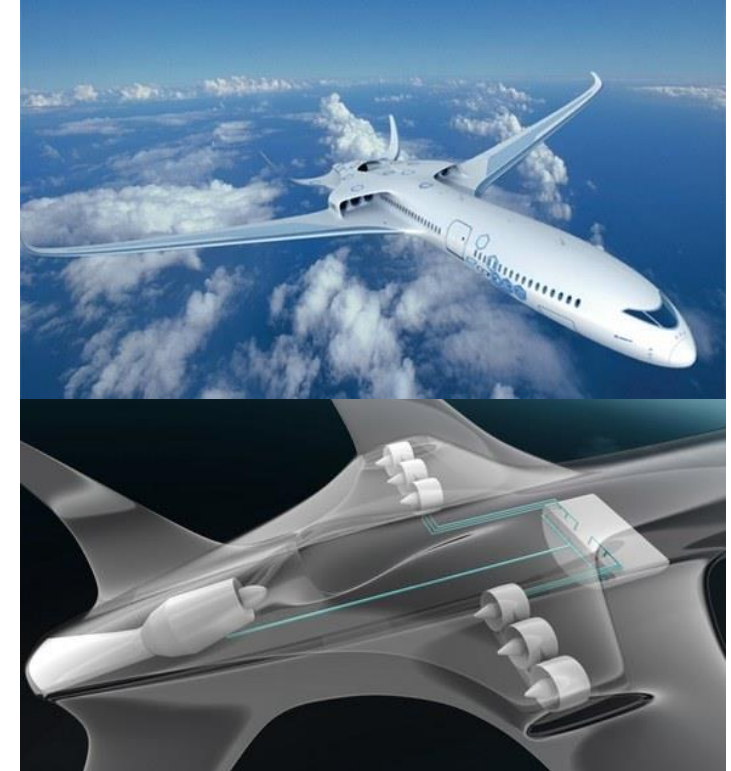


Credit: Sivasubramaniam K, Zhang T, Lokhandwalla M, Laskaris E T, Bray J W, Gerstler B, Shah M R and Alexander J P 2009 *Development of a high speed HTS generator for airborne applications* IEEE Transactions on Applied Superconductivity **19** 1656–61

Reliable means for transferring coolant and excitation power to the HTS field winding are must

Aircraft Motor Specifications

Parameter	Value
Motor Rating	2 MW
Motor Speed	25,000 RPM
Line Voltage	~1000 V
Rated power factor	0.9 lag
Rotor diameter	< 500 mm
Axial length	< 800 mm
Field excitation winding	REBCO
Operating temperature	50 K

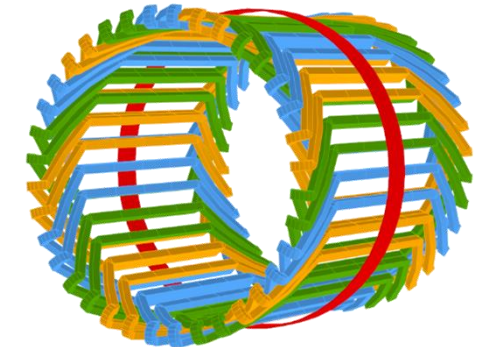
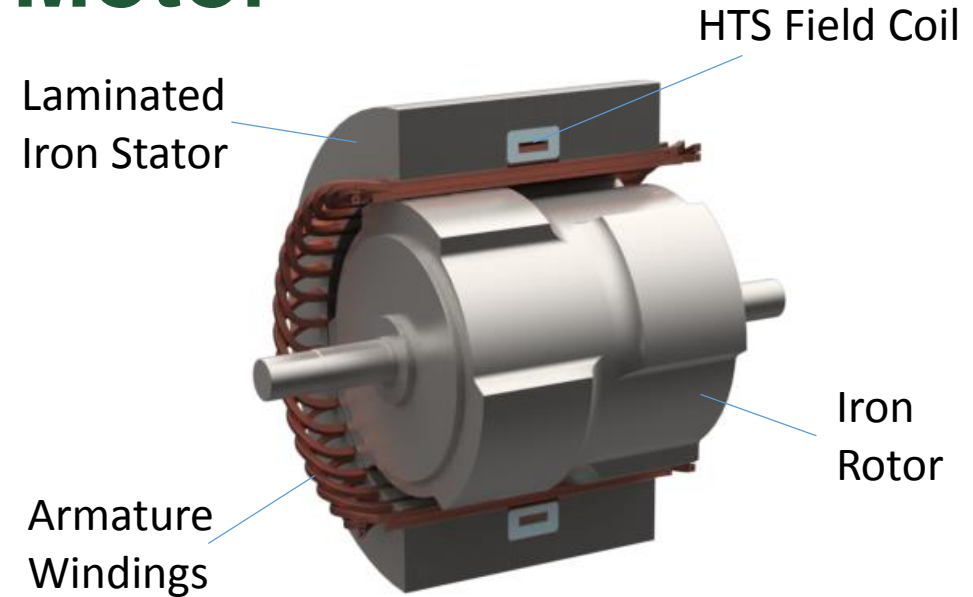


<https://www.wired.com/2013/07/eads-ethrust-hybrid-airliner/>

High speed, low mass motor for hybrid-electric aircraft

2 MW 25000 RPM Homopolar Motor

- Synchronous machine with 6-poles
- Field coil material rare-earth-barium-copper oxide (REBCO) cryocooled to 50 K, 364 A
- Stator material 10JNEX900 Super Core
- Rotor material Carpenter Steel's Aermet 310 magnetic steel
- Litz copper wire 3-phase liquid-cooled armature winding, 6 A/mm² strands
- Magnetic bearings and partial-vacuum motor housing to reduce drag
- Field winding excited with a brushless dynamo

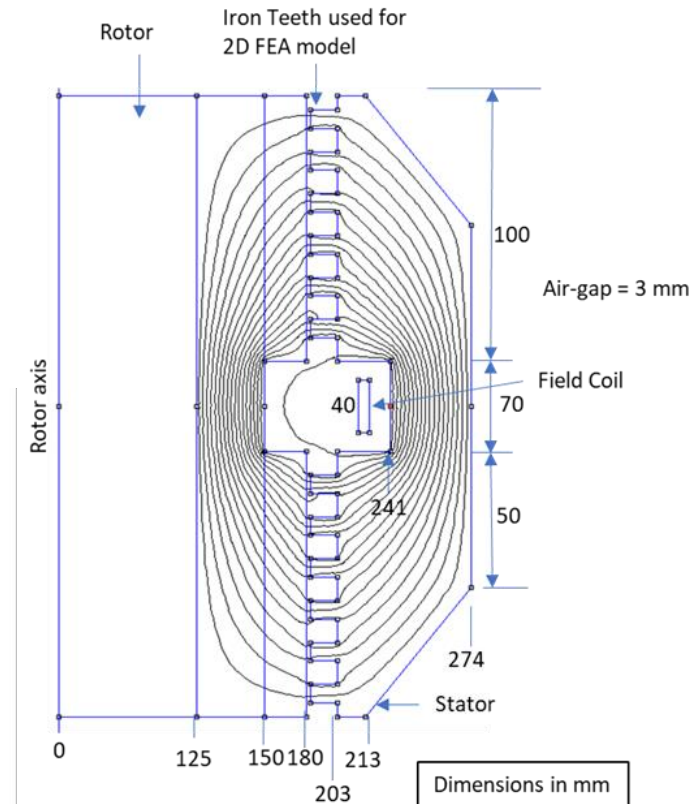
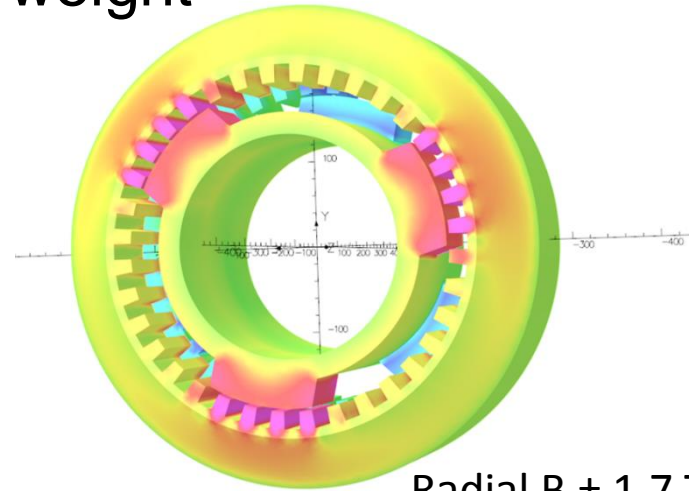


Double-Layer Armature

Superconducting field coil enables megawatt ratings

Finite-Element Method Analysis

- Design refined using static 2D FEMM and motional 3D Opera
- Axial length 450 mm, diameter 548 mm
- Chamfered stator to minimize weight
- Active pole length 100 mm
- Power rating 2020 kVA
- Machine mass 381 kg
- Power density 5.4 kW/kg

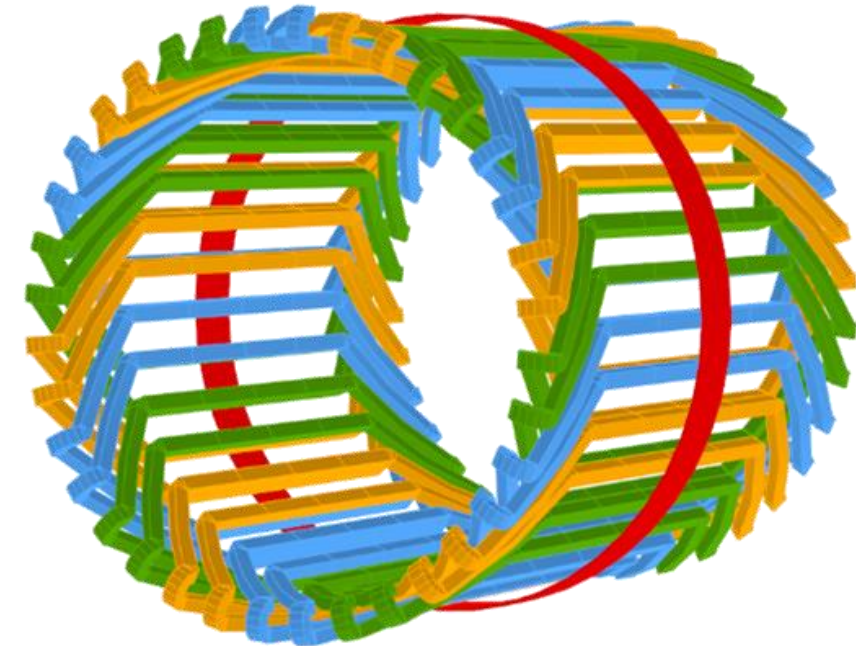


Slots shown above are fictitious – they account for available teeth cross-section to carry magnetic flux

Efficiency at full load 99.1 %

Field Harmonics at 25,000 RPM

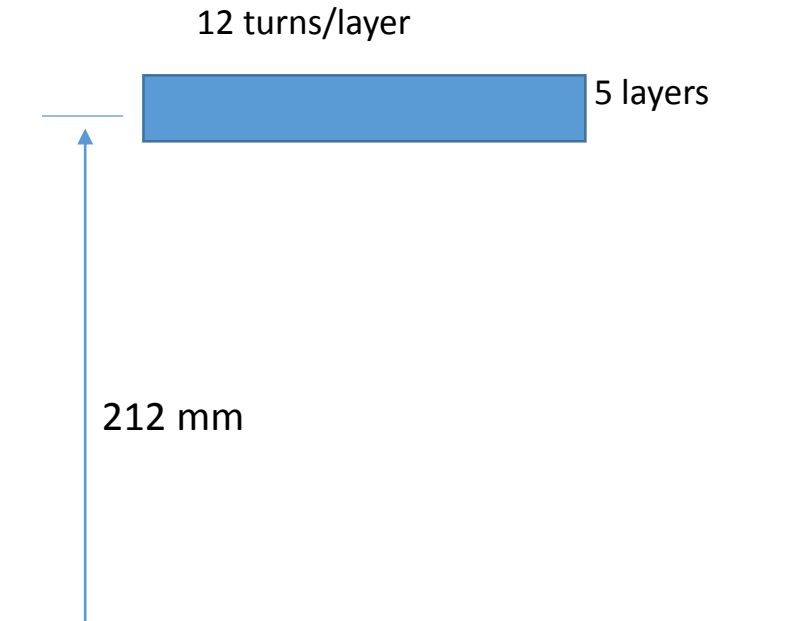
Harmonic	Field(G)	Fraction of fundamental
1	3512	1
3	71.9	0.02
5	162.8	0.046
7	78.4	0.022
9	118.6	0.034
11	39.3	0.011
13	40.6	0.012
15	33.4	0.009



Most harmonics are small and are not expected to be problematic

HTS Field Winding Design

- Field coil mean diameter = 424 mm
- Field coil cross-section = 40 mm x 8 mm
- Number of turns = 60
- Conductor type – REBCO 3mm wide
- Field coil inductance 1.19 mH
- Field current, 188 A (no-load) and 364 A (full-load)
- Field winding excited with a brushless flux-pump dynamo
- Dynamo regulates the field current

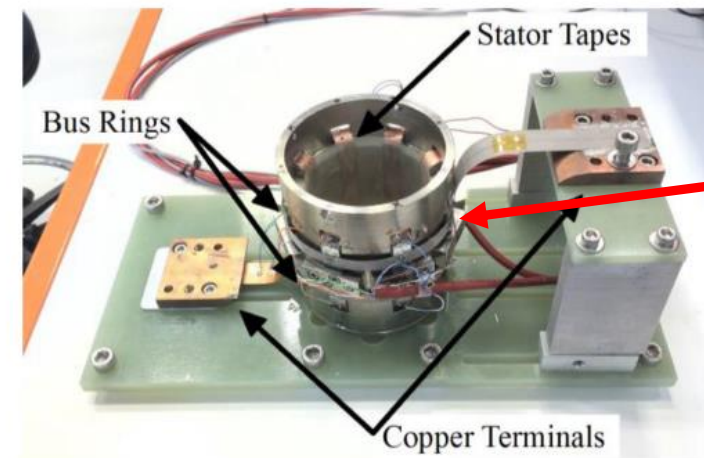
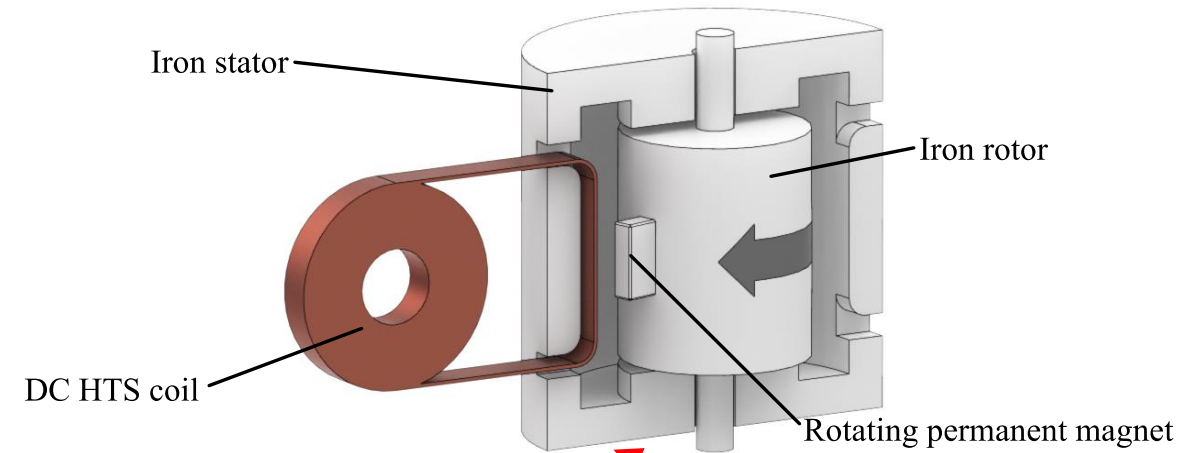


Simple circular coil construction

HTS Dynamo Concept

- Field coils excited wirelessly for minimizing thermal conduction into cold environment
- Brushless exciter (HTS Dynamo) shown here can supply currents greater than 1 kA

Hamilton et al., IEEE Trans. Appl. Supercond. 29, 5200705 (2019)



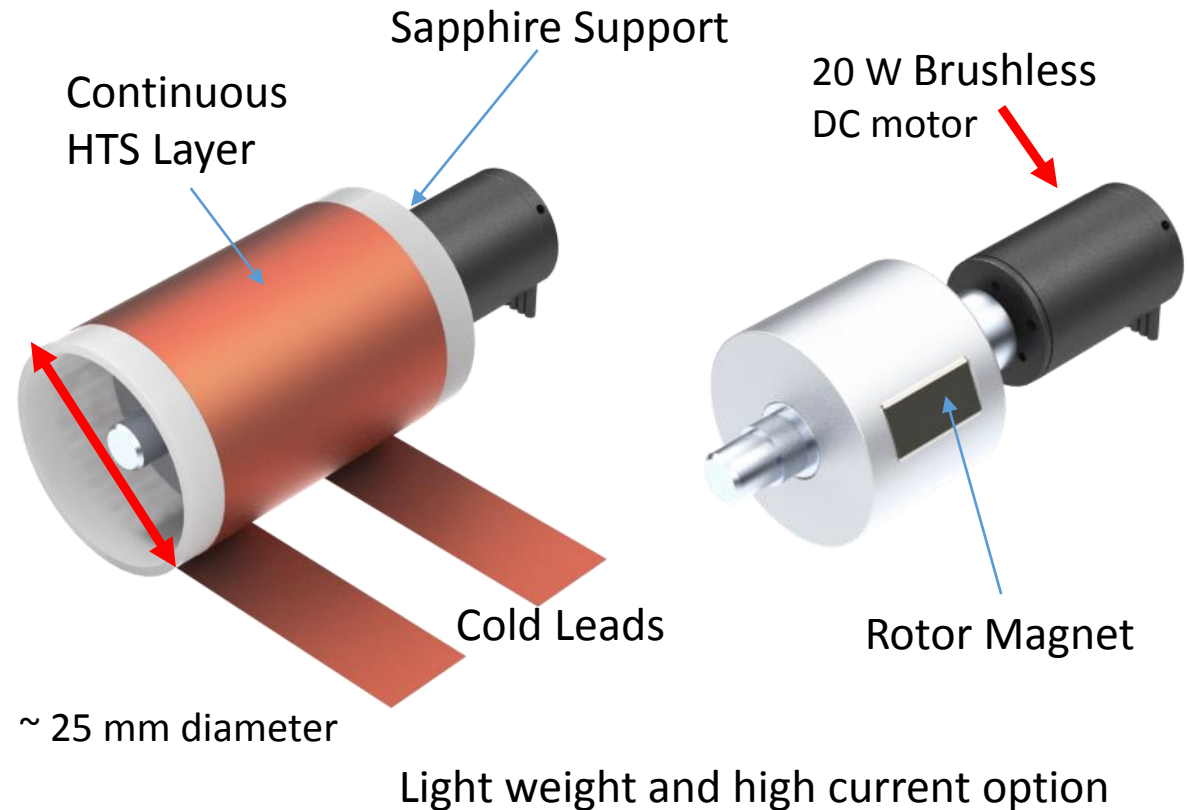
This dynamo concept has been successfully built and demonstrated by RRI-VUW

HTS Dynamo Concept

- “Barrel” HTS dynamo concept to be integrated with the field coil

Performance comparison

	Current Leads	Dynamo
Thermal conduction through cryostat, W	30	30
Thermal conduction through exciter, W	36	4
Total thermal load, W	66	34
Power input to refrigerator, kW	1.94	1.05
Weight of refrigerator, kg	4	2



50% reduction in thermal load and refrigerator mass

Preliminary Design Summary (with HTS Dynamo)

Parameter	Value
Power Rating, kVA	2020
Output power at full-load, MW	2000
Line voltage, V-rms	1292
Phase current, A-rms	922
Overall axial length, m	0.45
Overall diameter, m	0.56
Mass of the machine alone, kg	381
Mass of cryo-cooling system, kg	3
Total mass, kg	381
Efficiency at full-load, %	99.1
Cryocooler load, W	38*
Other parameters of interest	
Rated speed, RPM	25000
Number of poles	6
Frequency, Hz	833

Parameter	Value
Field winding details	
Number of turns	60
Field winding critical current- no-load, A	621
Field winding critical current – rated-load, A	560
Field winding current at rated load, A	364
HTS wire width, mm	3
HTS wire length, m	84
Operating temperature, K	50
Stator winding details	
Active length under each pole, mm	100
Number of armature turns/ph	16
Number of armature circuits	6
Number of coils in armature	36
Number of turns/coil	8
Field coil inductance, mH	1.19

Parameter	Value
Machine component weight summary	
- Shaft, kg	5
- Rotor yoke, kg	76
- Poles, kg	21
- Stator case, kg	50
- Cooling system, kg	2*
Total machine mass, kg	380
Total system mass, kg	380
Torque density, N*m/kg	2.06
Power density, kW/kg	5.4
^a Calculated using Ref: Ray Radebaugh, "Ray Radebaugh "Cryocoolers for Aircraft Superconducting Generators and Motors", NIST, AIP Conference Proceedings 1434. 171 (2012): doi: 10.1063/1.4706918	

* Calculated using Ref: Ray Radebaugh, "Ray Radebaugh "Cryocoolers for Aircraft Superconducting Generators and Motors", NIST, AIP Conference Proceedings 1434. 171 (2012): doi: 10.1063/1.4706918

Outlook

- Homopolar concept presented here represents a reasonable option for aerospace applications in near term
- Most sub-systems of this type of machines have been built and tested
- Motors and generators could be built by integrating suitably sized components
- Other options are being pursued to achieve higher power densities and efficiencies

Questions

