High Efficiency Megawatt Motor Conceptual Design

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Motivation

- NASA is investing in Electrified Aircraft Propulsion (EAP) research to improve the fuel efficiency, emissions, and noise levels in commercial transport aircraft

- The goal is to show that one or more viable EAP concepts exist for narrow-body aircraft and to advance crucial technologies related to those concepts.

- Electric Machine technology needs to be advanced to meet aircraft needs.

Outline

- Machine features

- Importance of electric machine efficiency for aircraft applications

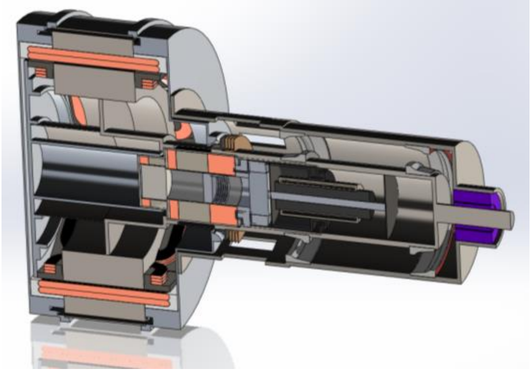
- HEMM design requirements
- Machine design
- Performance Estimate and Sensitivity

- Conclusion

NASA High Efficiency Megawatt Motor (HEMM)

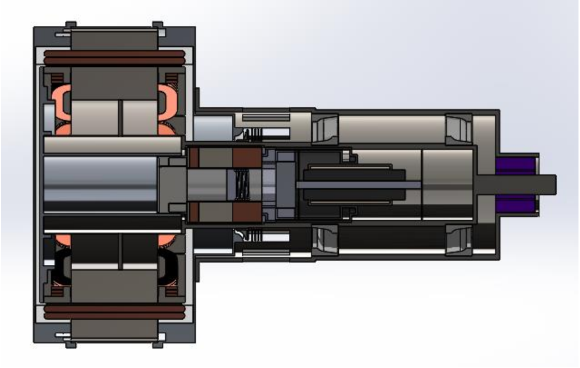
Power / Performance

- HEMM is a 1.4MW electric machine with a stretch performance goal of 16 kW/kg (ratio to EM mass) and efficiency of >98%



Machine Features

- partially superconducting (rotor superconducting, stator normal conductors)
- synchronous wound field machine that can operate as a motor or generator
- combines a self-cooled, superconducting rotor with a semi-slotless stator



Vehicle Level Benefits

- Uses standard aircraft cooling systems
- Direct drive at optimal turbomachinery speeds (no gearbox)
- Can be turned off if fault occurs (not permanent magnet)

Linkage Between Efficiency and Thermal

Waste Heat

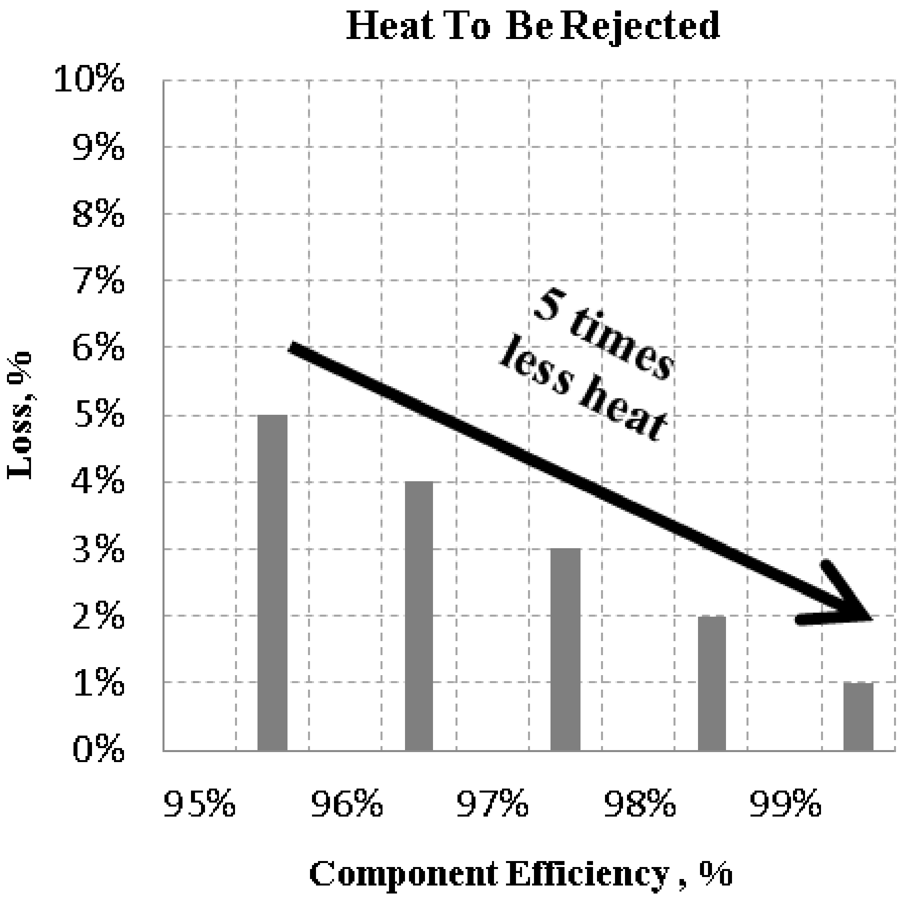
- Although at first glance the difference between a 95% and 99% efficient machine may seem insignificant, it is actually quite consequential because the losses, which manifest themselves as heat, are five times lower for the 99% case compared to the 95% case

Low Component Rejection Temperature

- Electric Machines 105-220°C
- Converters 85-150°C

Challenges

- Rejection of large amounts of low grade heat from aircraft



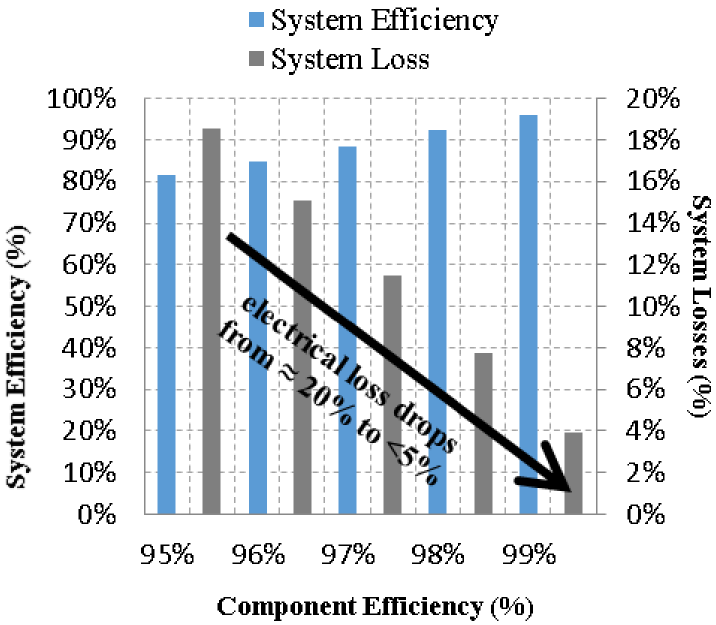
Losses from Multiple Conversions Add Up

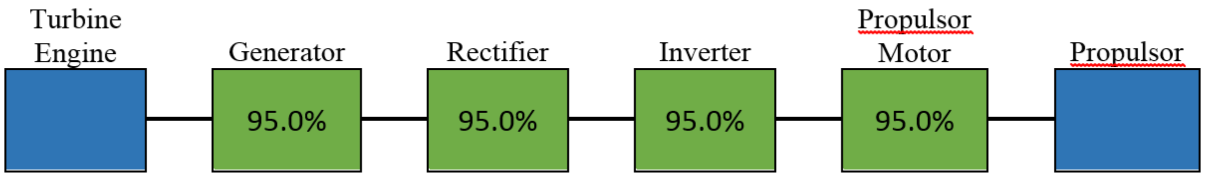
Conversion Losses

- Each conversion from mechanical to electrical energy has an associated loss (electric machines)
- Each conversion from one from of electrical to another has an associated loss (converters)

Potential Solutions

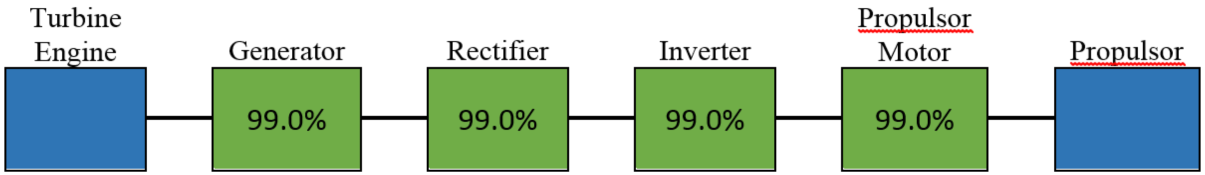
- More efficient conversions (machines, converters)
- Power Architectures with minimal conversions





81%

Figure 3. State of the Art Electrical Components



96%

Figure 4. Highly Advanced Electrical Components

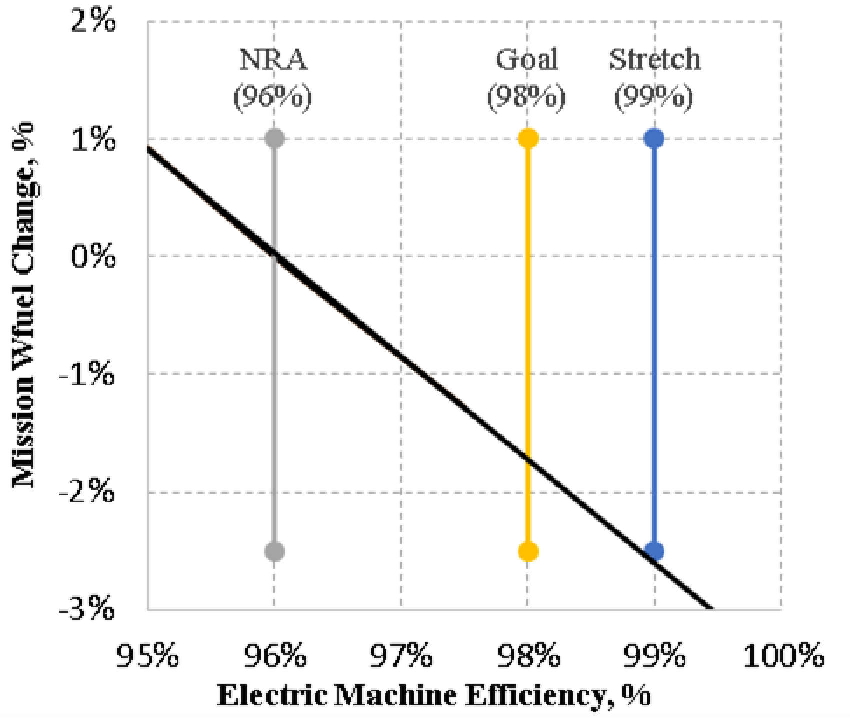
STARC-ABL Fuel Burn Sensitivity to Machine Efficiency

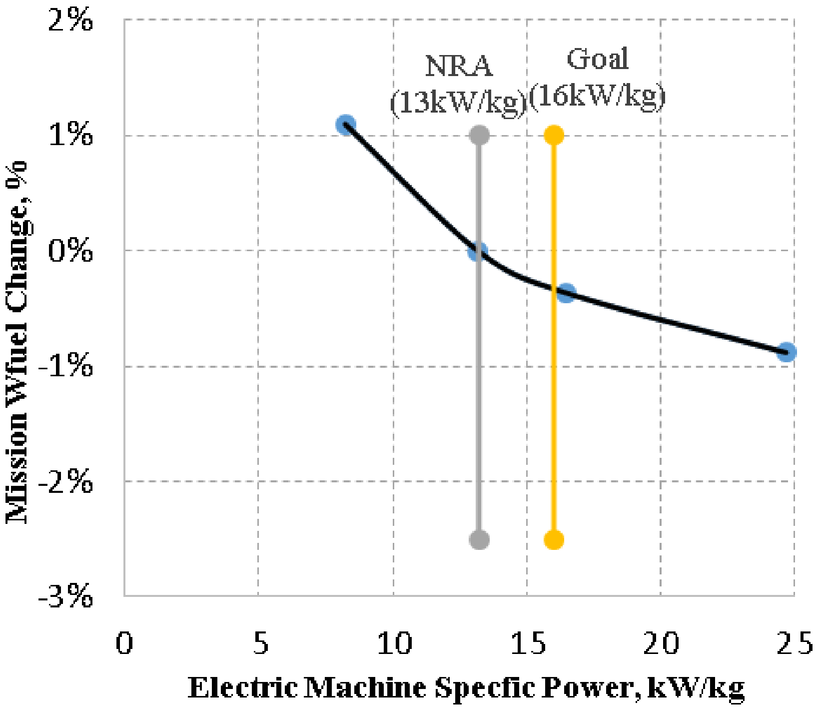
Sensitivity

- A 1% fuel burn improvement from machine weight reduction would require doubling specific power from 13kW/kg to 26 kW/kg
- A 1% fuel burn improvement from machine efficiency would require a 1.3% machine efficiency improvement.

Takeaway

- For STARC-ABL the fuel burn is more sensitive to efficiency than weight at the performance point we are working around

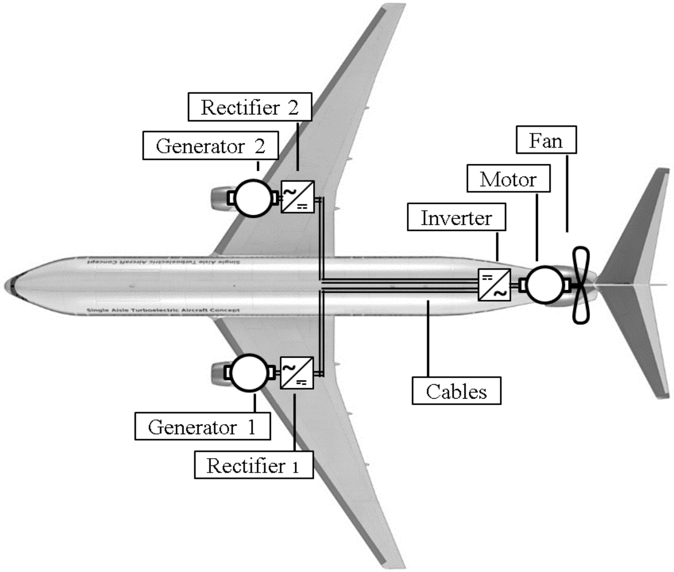




HEMM Motor Requirements Tied to STARC-ABL Design

HEMM is designed to operate as

- a ***1.4 MW generator*** or motor
- with ***direct drive*** from the ***low spool*** of a geared turbofan sized for STARC-ABL



Electrical Machines

- Two 1.4 MW generators mounted near turbines
- One 2.6 MW motor driving tail cone thruster

Geared Turbofan

- HP Spool = ? rpm
- LP Spool = 6800 rpm (generator connects here)

Tailcone Thruster

- Fan = 2514 rpm
- Diameter = 80.2”
- Hub/Tip Ratio = 0.3
- Hub Diameter = 24.1”

HEMM Motor Requirements Tied to STARC-ABL Design

Table 1. HEMM Prototype Requirements

Requirement	Rationale
The rated operating power shall be 1.4MW or greater	From generator power requirements in 2016 STARC-ABL Aviation paper
The specific power of the electric machine shall be greater than 16 kW/kg	Combination of STARC-ABL sensitivity analysis and Hybrid Gas Electric subproject goals
The efficiency of the electric machine shall be greater than 98% with a stretch goal of 99%.	Combination of STARC-ABL sensitivity analysis and Hybrid Gas Electric subproject goals
The rated operating speed shall be 6800 RPM	From concept design of STARC-ABL with geared turbofan low spool speed
The thermal management approach shall be based on fluid cooling with an inlet temperature of 60°C and the use of materials rated to 220°C when possible.	Based on a UTRC NRA study of a parallel hybrid single-aisle aircraft with a 1MW motor connected to each turbofan.

HEMM Machine Design

Machine

- HEMM utilizes superconducting field winding to achieve high specific power and efficiency goals simultaneously
- HEMM has an integral cryocooler which is conductively thermally linked to the superconductors to avoid limitations related to having a separate cryogenic fluid cooling system.

Integral Cryocooler

- A cryocooler is being designed that can lift 50W of heat from a 50K cold tip and reject to a 330K ambient environment. This cryocooler is also intended to be light weight (<10kg), small diameter (<100mm), and able to withstand 6800RPM rotation about its central axis such that it can be integrated in the shaft of the HEMM.
- HEMM will interface with the aircraft in the same way as any standard electric machine, avoiding the additional mass, volume, and infrastructure which would be required with a traditional superconducting machine.

Table 2. Motor Design Parameters

Parameter	Value
Motor	Wound field synchronous
Rated Power	1.4 MW
Rated Speed	6800 RPM
Rated Voltage	1200V
Rated Current	360A
Layout	
Poles	12 pole
Phases	9

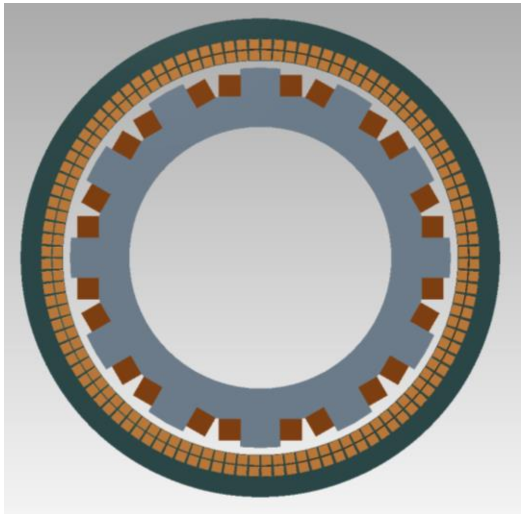


Figure 8. Motor Cross Section

HEMM Stator Design

Electromechanical Features

- 9 phases to allow minimization of the harmonic content and yield a slight performance
- Semi-slotless stator with thin teeth primary serve to locate and remove heat from the winding
- Litz wire used in windings which are exposed to high strength oscillating magnetic field
- Single turn winding to achieve desired output voltage

Mechanical Features

- stator of the HEMM also functions as the vacuum enclosure for the rotor
- direct liquid cooling loop, which circulates from a manifold at the inner surface of one end winding, across the length of the air gap, around the other end winding, back through a series of channels in the backiron, and finally across the outer diameter of the first end winding

Challenging aspects

- Cooling of Litz wire

Table 3. Stator Design

Parameter	Value
Type	Semi slotless
Iron	
Inner Diameter	306mm
Outer Diameter	377mm
Stack Height	125mm
Slots	108
Slot Width	8mm
Slot Depth	19.5mm
Skew	3.33 degrees
Cooling Channel	3.5 mm
Winding	
Number of Phases	9
Layout	Lap, 2 Layer, Over/Under
Number of Turns	1
Litz Wire	8x8 mm, 6000 strands x 40AWG
Coil Slot Span	9
Phase/Group Offset	6/2

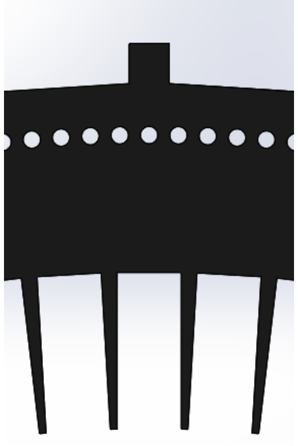


Figure 8. Stator Cross Section

HEMM Rotor Design

Electromechanical Features

- Twelve pole, unlaminated, cobalt iron rotor
- Wound field with dc superconducting coils utilizing relatively mature rare-Earth barium copper oxide (REBCO) wire that is available in long lengths

Mechanical Features

- Integral cryocooler in drive shaft
- Features to minimize heat leak into rotor
  - Torque tube
  - Lead wire design
  - Radiation reduction

Challenging aspects

- Structural integrity of superconductors
- Functionality of cryocooler under 6800 RPM rotation.

Table 4. Rotor Design

Parameter	Value
Type	dc wound field
Iron	
Inner Diameter	between 189.4 to 200mm
Outer Diameter	300mm
Length	125mm
Number of Poles	12
Tooth Width	34mm
Coil	
Rated Current	51.5A
Number of Turns	916 turns per pole
Coil Cross Section	14.9 mm wide x 16.75 mm tall
Operating condition	62.8K temperature, 2T field
Conductor	YBCO superconductor 4mm x 0.065mm

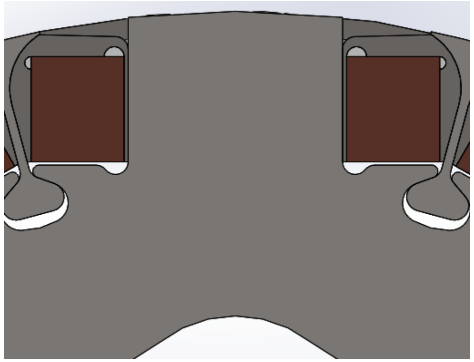


Figure 10. Rotor Cross Section

HEMM Thermal Conditions

Approach

- Temperature conditions used for the electromagnetic analysis of the HEMM machine were found through separate thermal finite analysis, and imposed as fixed temperatures for this work

Stator

- Found anisotropic thermal conductivities for the windings based on the properties of the Litz wire and the potting compound
- Found loss estimates from EM analysis
- Used simpfied FEA model to capture geometry and boundary conditions of fluid loop
- Significant uncertainty in this analysis; tests are planned to reduce that uncertainty

Rotor

- Estimated rotor heat load including: radiation heat transfer, heat leak through the torque tube, heat leak through the power leads for the rotor winding, windage losses, and rotor core losses.
- Rotor core loss is difficult to estimate
  - source is the eddy current and hysteresis losses induced by high order multiples of the stator fundamental frequency, and
  - loss data for the magnetic material at these frequencies and temperatures does not exist.
- Tests are planned to reduce that uncertainty

Table 5. Thermal Conditions

Component	Temperature (°C)	Temperature (K)
Stator core	60	333
Stator windings	135	408
End turns	135	408
Rotor core	-213	60
Rotor coils	-213	60

HEMM Estimated Performance

Approach

- Initial electromagnetic performance was estimated using a commercial motor sizing code
- Key parameters are used to define the operating condition of the motor, the rotor and stator magnetic circuit, and the rotor and stator windings.
- Trade space was explored through manual iteration
- Other modeling and FEA modeling packages were used to perform solid modeling of the motor, detailed 3D thermal, stress, electromagnetic analysis, and also cryo cooler sizing.

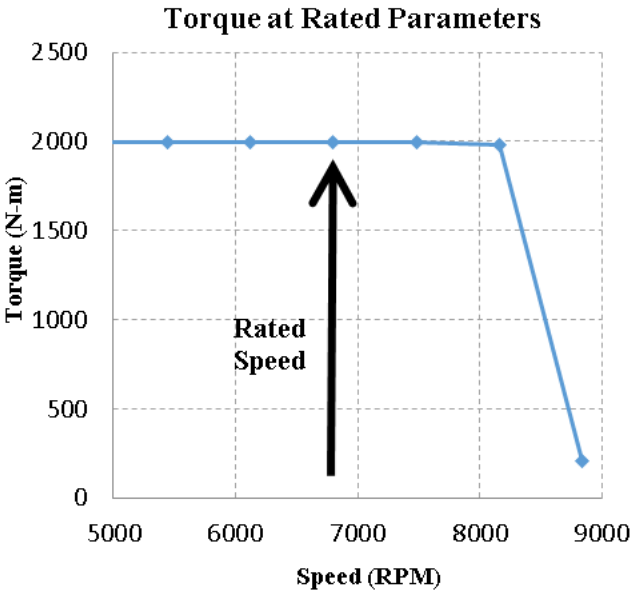


Figure 11. Torque at Rated Parameters

Table 6. Electromagnetic Mass Estimate

Component	Mass (kg)
Stator core	21.5
Stator winding	13.77
Rotor core	29.7
Rotor coils	9.4
Total Electromagnetic Mass	74.4
Total Electromagnetic Mass (+10% margin)	81.9

Table 7. Loss Estimate

Component	Loss (kW)
Electromagnetic Losses	9.3
Stator Core	3.9
Stator winding (I^2R)	4.6
Stator winding proximity	0.8
Rotor core	0.009
Rotor coils	0
Other Losses	4
Cryocooler Power	2
Bearings	1
Vacuum Seals	1
Total Losses	13.5
Total Losses(+20% margin)	16.2

HEMM Requirements vs. Estimated Rated Performance

Table 8 - Design vs. Requirements

Requirement	Estimate Performance
The rated operating power shall be 1.4MW or greater	1.42MW
The specific power of the electric machine shall be greater than 16 kW/kg	17.4 kW/kg
The efficiency of the electric machine shall be greater than 98% with a stretch goal of 99%.	98.9%
The rated operating speed shall be 6800 RPM	6800
The thermal management approach shall be based on fluid cooling with an inlet temperature of 60°C and the use of materials rated to 220°C when possible.	compliant

HEMM Performance Sensitivity Analysis

Trends

- Stator current >400A helps specific power, but slightly reduces efficiency
- Rotor current >50A helps specific power and slightly improves efficiency
- Performance is least sensitive to the range of air gaps considered

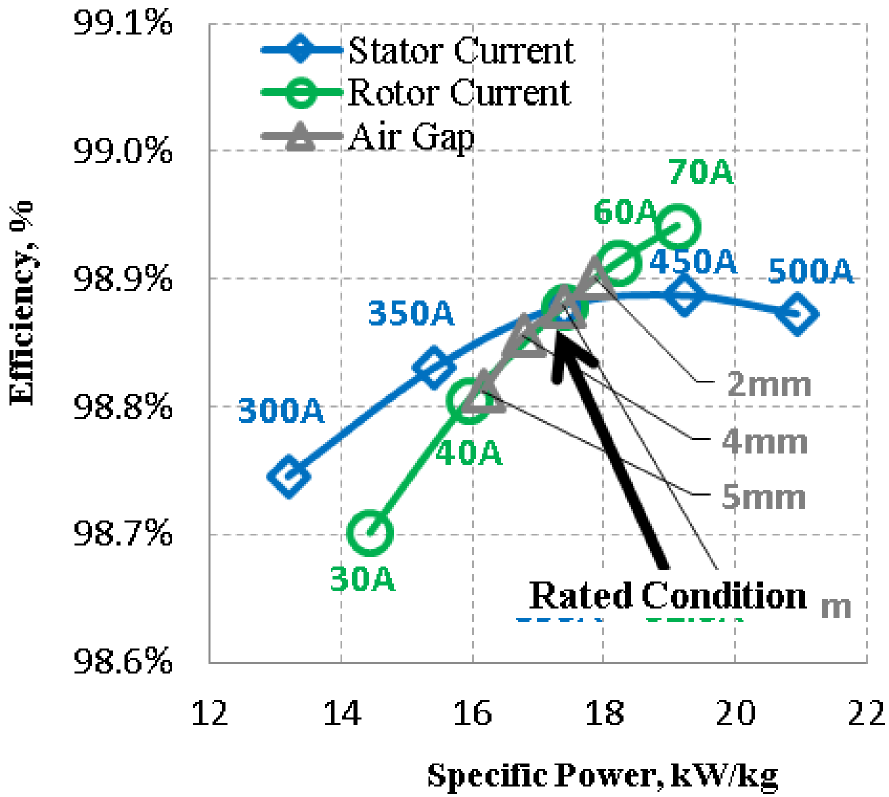


Figure 12. Efficiency vs. Key Parameters

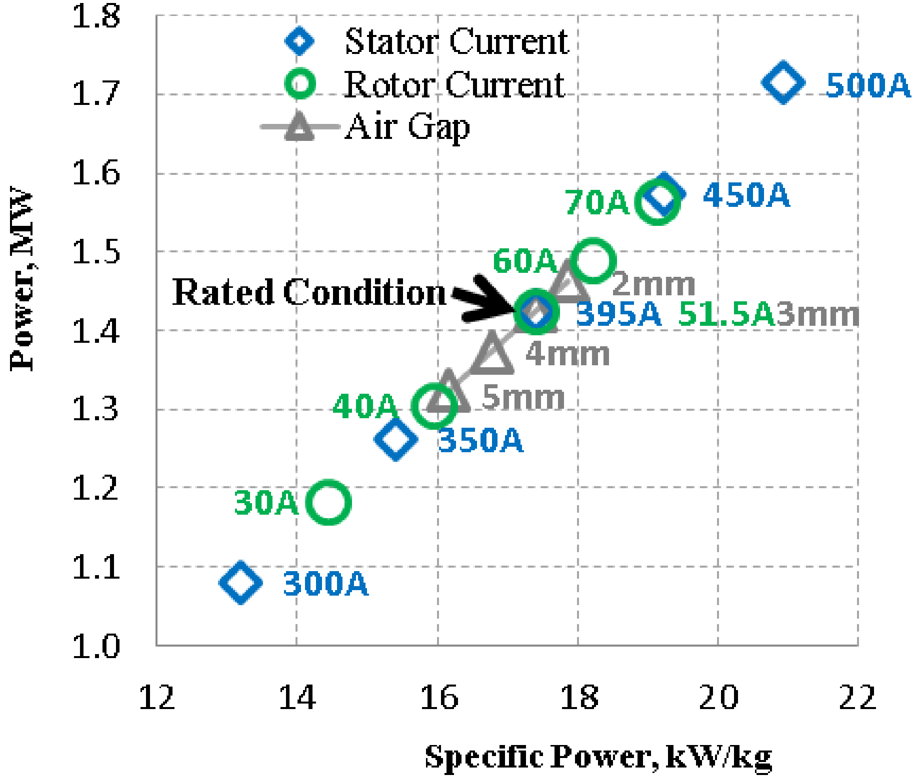
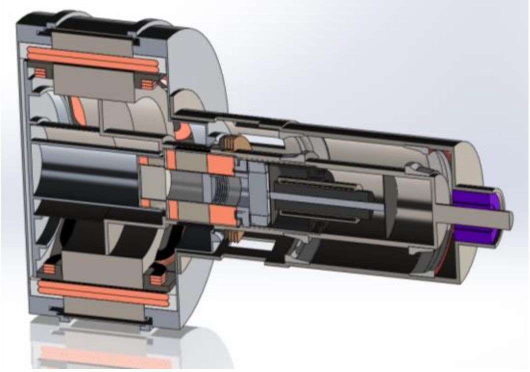


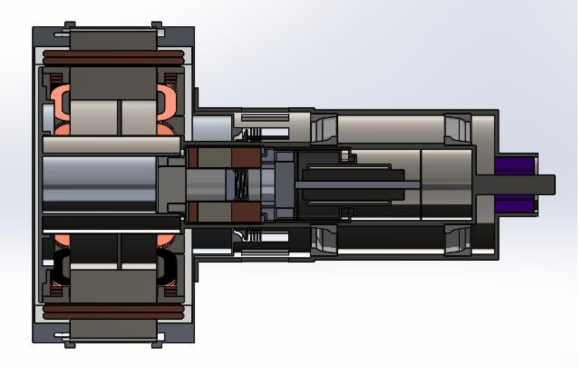
Figure 12. Power vs. Key Parameters

Summary

Key Points

- The High Efficiency Megawatt Motor (HEMM) being designed at NASA Glenn Research Center is a wound field partially superconducting machine.
- The goal of this effort is to develop an electrical machine with efficiency >98% and specific power when ratioed to electromagnetic mass >16kW/kg.
- A design has been completed and electromagnetic analysis shows that it will achieve the required performance if critical design aspects close thermally and structurally.
- Key parameters are the maximum continuous stator current, the maximum continuous rotor current, and the air gap. A power and performance sensitivity analysis was performed against those key parameters





Acknowledgments

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