National Aeronautics and Space Administration

HEATheR

HIGH-EFFICIENCY ELECTRIFIED AIRCRAFT THERMAL RESEARCH

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THE PROBLEM

- Megawatt electrical systems produce a large amount of waste heat:

RVLT/thin-haul:
1 MW power,
200 kW heat

Short-haul hybrid/single-aisle partial turboelectric:
3 MW power,
600 kW heat

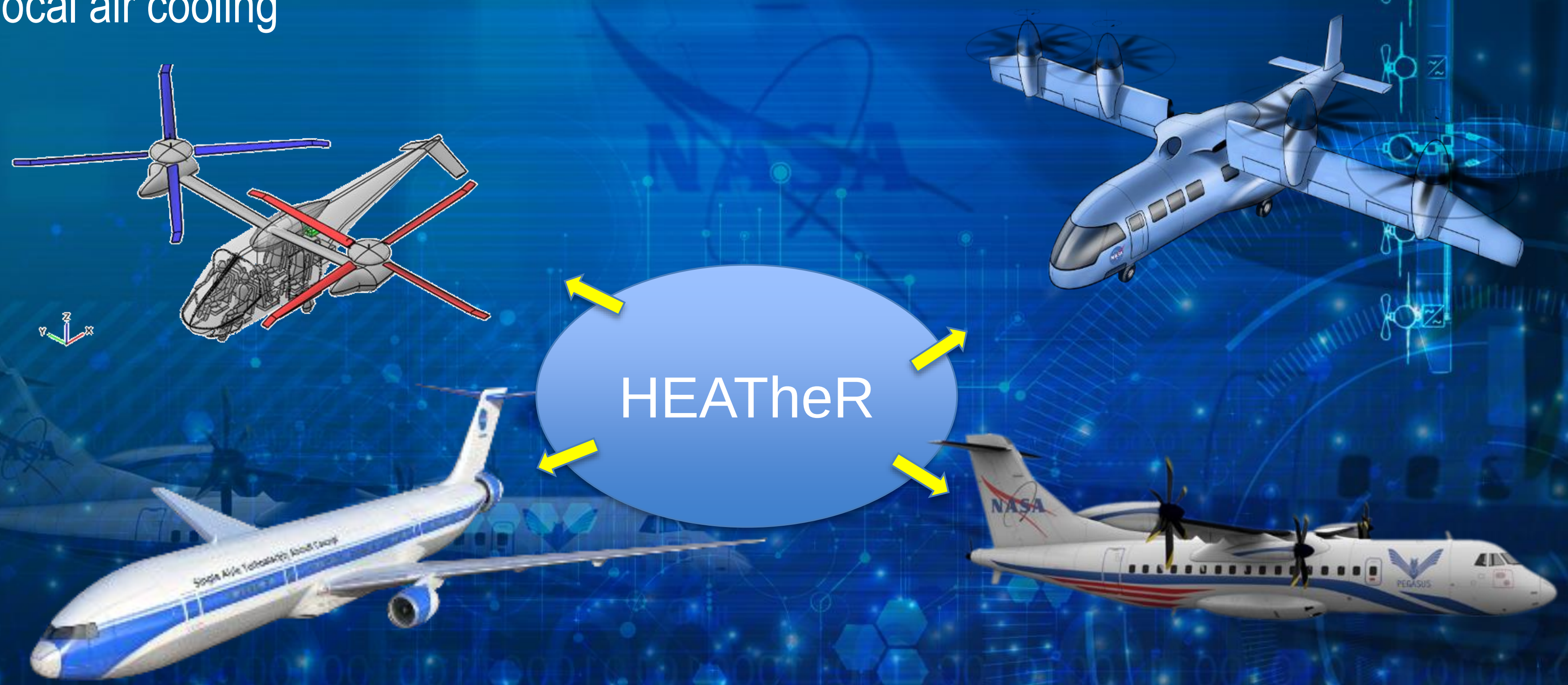
Single-aisle full turboelectric:
30 MW power,
6 MW heat

- The waste heat has low rejection temperatures (<200 °C)

- **Problem**: Current aircraft systems produce large amounts of low-grade waste heat and so require large, heavy thermal management systems that cause drag.

THE GOAL

Come up with a breakthrough MW-size power system that can be operated with local air cooling



IDEA—USE LOCAL PASSIVE THERMAL MANAGEMENT

Aircraft with MW electric power manage waste heat by

- Moving the heat from the source to a heat exchanger using a pumped fluid
- Dumping heat into
  - The fuel (fraction of loss is recovered by preheating fuel)
  - The airstream
    - Ram scoop under aircraft (pure drag and weight penalty)
    - Engine fan air duct (fraction of loss may be recovered, but usually even higher drag)

Our solution is to determine the amount of heat that can be removed locally and reduce the heat load to that level by

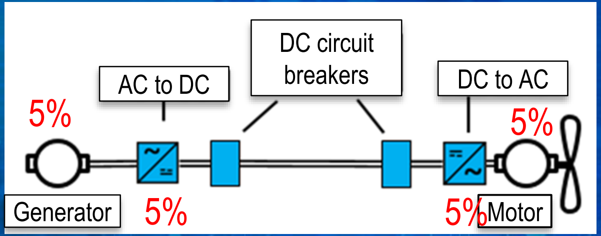
- Estimating local heat removal limit with
  - Finned heat exchangers
  - Unmodified OML
- Getting losses below the limits for local heat management

New thermal management technology	Fluid cooling	Air cooling	Outer mold line cooling
Needs to be invented	Adds mass, drag	Adds drag	No substantial penalty

IDEA—MINIMIZE THERMAL LOAD

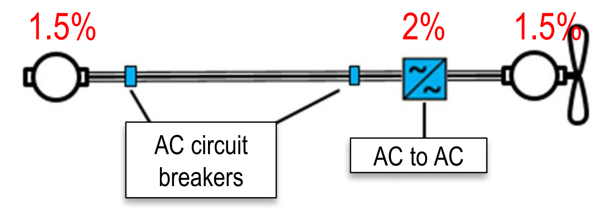
- Build a power system with 4x lower losses
  - Eliminate half of the conversion steps and associated components, losses components, and complexity
  - Make extremely low loss components

State of the art



20% Heat

HEATheR

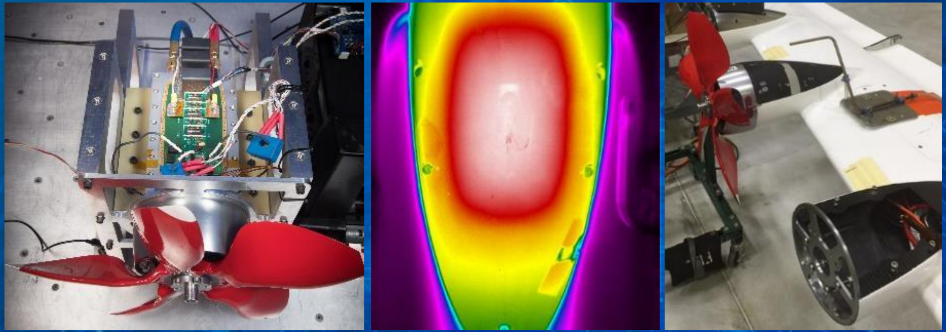


5% Heat

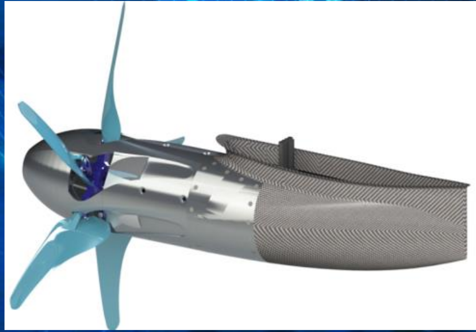
EXAMPLE: ≈10 kW , MOTOR DRIVE

- We have demonstrated this idea at a very small scale on one component in ground testing and are now designing a flight version for X-57 Mod 4.

FY16 AATT
GIMC HEIST motor drive



FY17 AATT
Lab, wind tunnel, and HEIST test



FY18 GIMC SCEPTOR
11-kW passively cooled motor drive for X-57 Mod 4

Feasibility Assessment

COMPONENT

HEMM Feasibility: Build low-loss flight-weight electric machine

- Superconducting operating under rotating stress
  - 100 m/s (6800 RPM) spin demonstration
- Cryocooler at weight, size, and under rotating stress
  - <10 kg, <90-mm diameter, 6800 RPM
- Slotless stator cooling
  - 500-A stator with temperatures <200 °C

Converter Feasibility: Build low-loss flight-weight converter

- Multilevel to reduce voltage per power switch
  - At least three levels
- Interleaving to allow large power switches to have a higher effective switch frequency
  - At least two stage interleaving
- Zero cross switching
  - Hardware demonstration of function

SUBSYSTEM

Thermal: Can MW power system thermal losses be passively cooled?

- Determine maximum heat load for OML cooling on three aircraft concepts
  - Model with supporting subscale test results
- Determine maximum heat load for local air cooling
  - Model

Power: Can MW power system losses be reduced by a factor of 4?

- Determine HEAThER power system configuration for reference vehicles
  - Is HEAThER heat load 4x less than SOA DC system
- Determine if stability and fault management significantly impact heat load
  - After addition of fault management and stabilizing power features, is heat load within 10% of system without these features?

AIRCRAFT

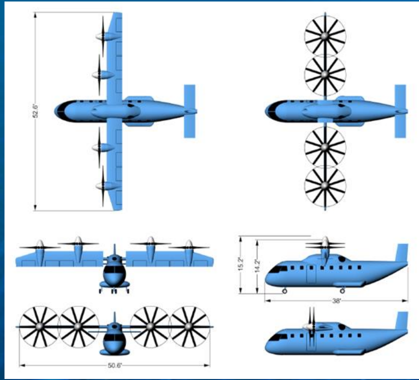
Can we show performance and operational cost benefits for three reference MW air vehicles using HEATheR technology?

- Vertical takeoff and landing:
  - Can we find a configuration with sufficient reliability to eliminate mechanical backup systems?
  - Can we use local cooling and direct-drive motors to eliminate oil pump loops and complexity?
- **Short haul**:
  - Can we eliminate liquid cooling loops for this type of aircraft?
- **Single aisle**: Assess fuel burn benefit
  - Does system close with a fuel burn benefit >5% ?
  - Is there an emissions benefit?

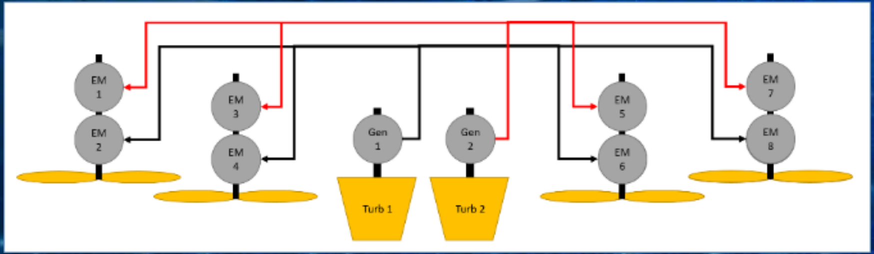
Aircraft Modeling

- We are increasing fidelity of EAP aircraft reference concepts by building out better subsystem models for electrical power and thermal.

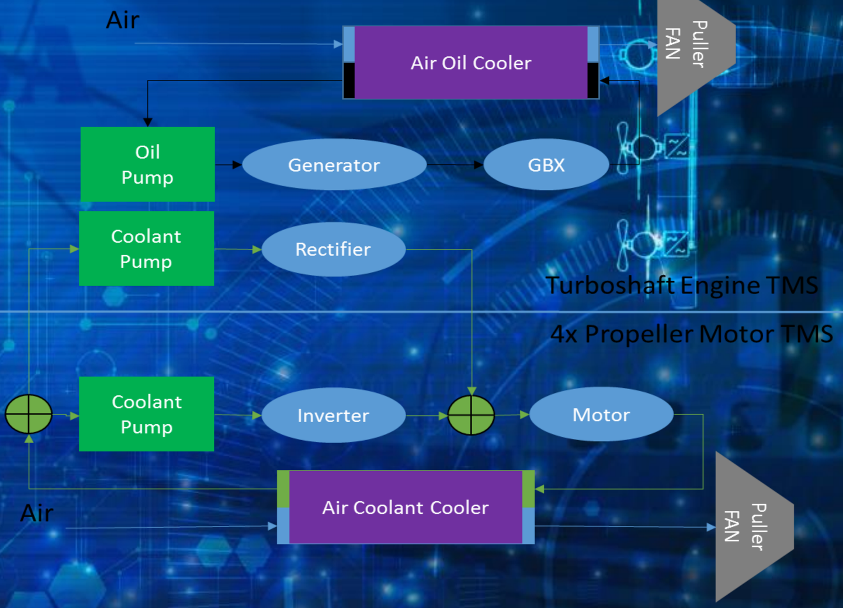
Aircraft Level



Power System



Thermal System



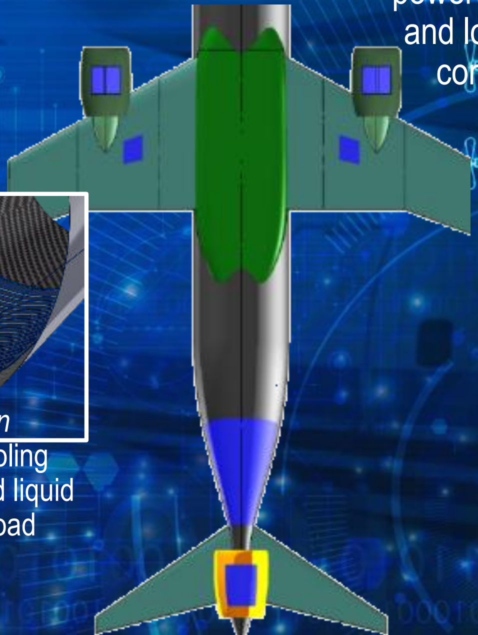
Aircraft Modeling

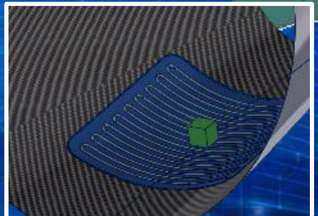
- We are using computational fluid dynamics as a tool to determine how much heat transfer we can get through the skin of an aircraft under different flight conditions.

Computational Fluid Dynamics

Thermal

Dedicated OML cooling patches located near powertrain components and low structural load concentration zones





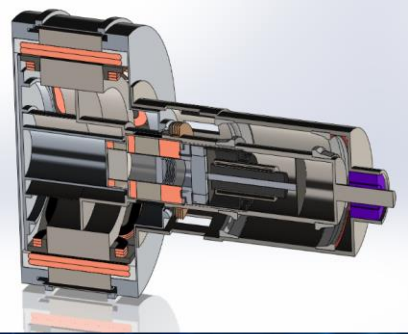
Concept Illustration

Component on cooling patch with pumped liquid to distribute heat load

HIGH-EFFICIENCY MEGAWATT MOTOR (HEMM)

- **Challenge**: Can't have motors with high specific power and low loss unless there is a breakthrough
- **Physics**: A better magnet results in a better motor: induction, coil, permanent magnet, superconductor
- **Solution**: Superconducting motor without the cryogenics on the airplane

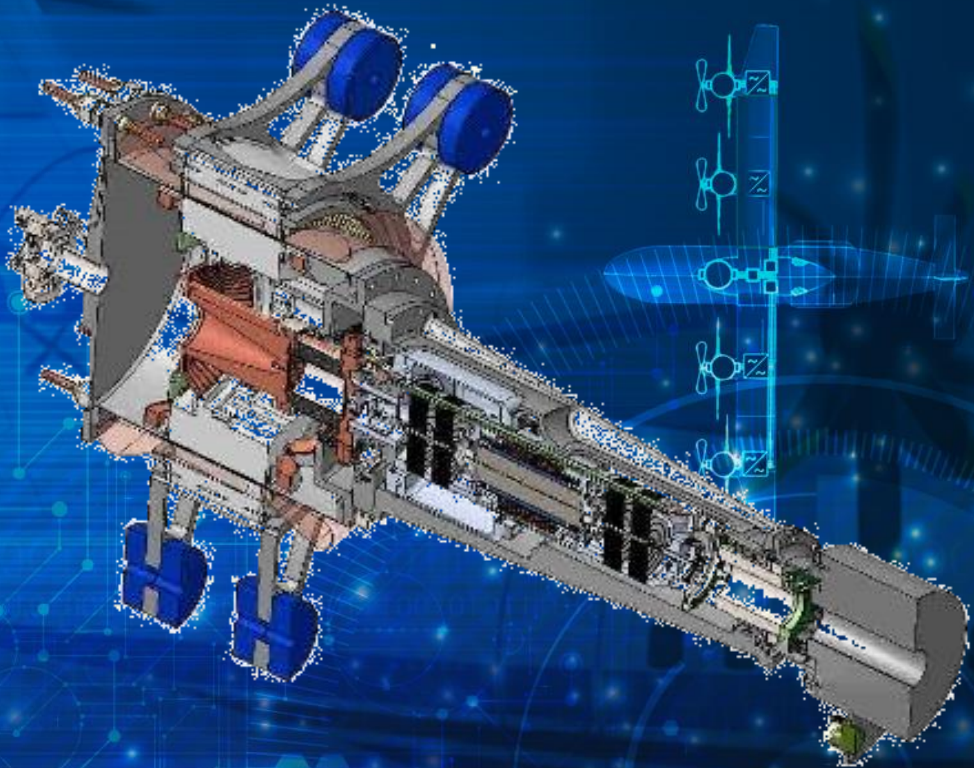
- **Key Feasibility Items**:
  - Wound field, superconducting DC rotor
  - Integrated cryocooler
  - Slotless stator
- **Benefits**:
  - Superconductors readily available in mile-long pieces from multiple vendors
  - Direct drive (no gearbox)
  - Can be shut down

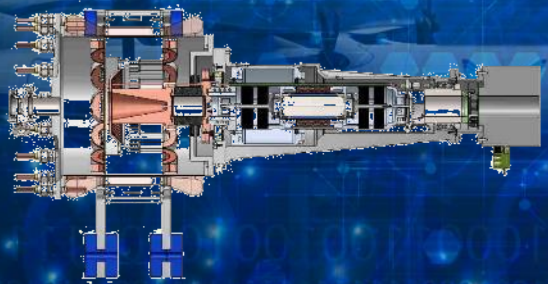


HEMM Overview

- Ratings:
  - 1.4MW, 6800 RPM, 1000V
  - >98% efficient, electromagnetics specific power 16kW/kG

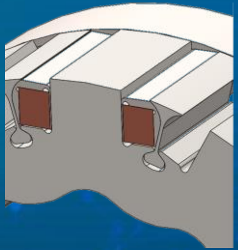
- Operational Benefits:
  - Integrates into standard aviation systems like a conventional motor
  - Direct drive of fan, propeller, or rotor (no gearbox)
  - Can be shut down in failure scenario



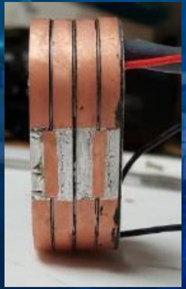


HEMM Subcomponents

Wound field, superconducting DC rotor

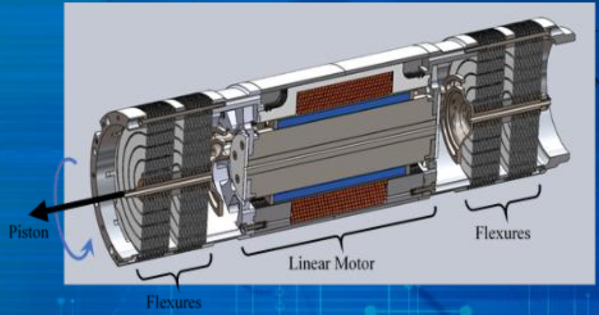


Rotor with conductive cryogenic cooling for superconductors

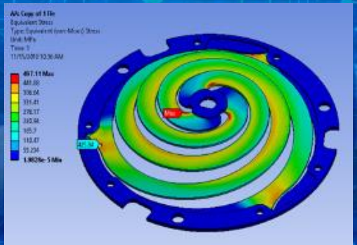


Four layer superconducting coils without insulation

Integrated cryocooler

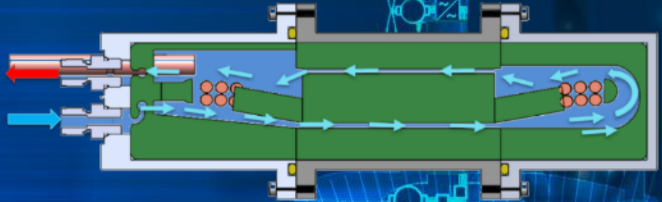


Cryocooler sized to fit inside motor shaft

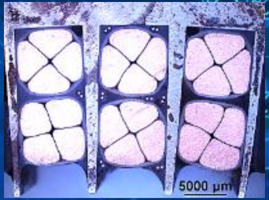


Cryocooler uses linear motor supported by flexures that act as bearings

500 Amp Slotless Stator



integrated cooling loop



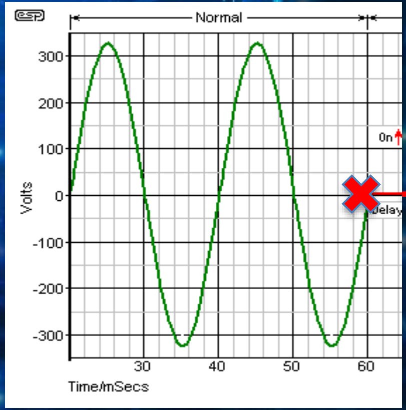
Semislotless with custom Litz Wire

Single Turn Winding

HEATheR Converter

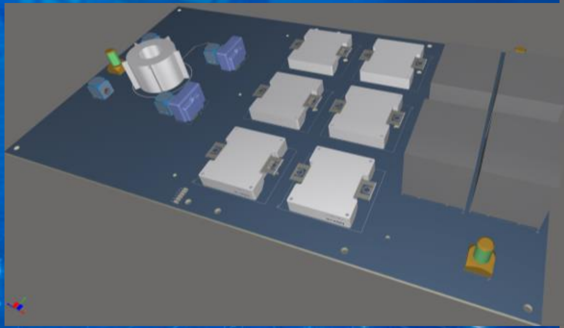
- **Challenge**: High-power switches are slow, resulting in large losses, high ripple current, and high filter mass
- **Our Solution**: AC-AC converter with an advanced configuration, switches, and connection to the power system

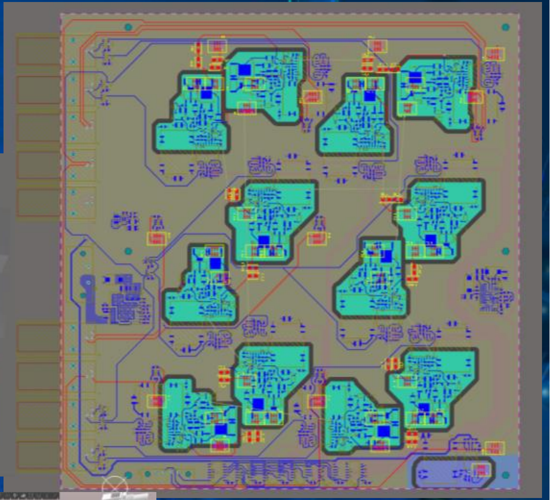
- **Key Feasibility Items**:
  - Zero cross switching with correct output voltages
  - Interleaving to allow large power switches to have a higher effective switch frequency
  - Multilevel topology to reduce voltage per power switch
- **Benefits:**
  - Low loss
  - Low ripple current
  - Low mass

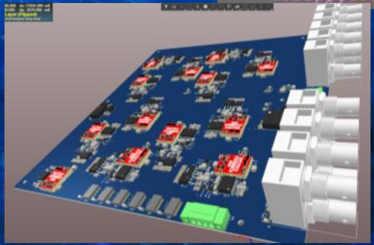


HEATheR Converter Subcomponents

- Concept Design still in work.
- Some barrier subcomponents identified
- 72 kW prototype boards build to work out
  - FPGA control approach
  - Switch timing
  - Basic Interleave, Multilevel issues

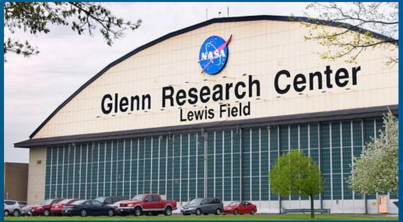






NASA TEAM AND EXTERNAL PARTNERS

NASA Team



- Propulsion and power models
- Component feasibility demonstration

- Fixed-wing aircraft models

- Thermal modeling

- VTOL aircraft modeling
- CFD to determine heat limts

External Partners

Aurora FLIGHT SCIENCES A BOEING COMPANY

Assess HEATheR for Lightning Strike

United Technologies

Thermal management recommendations and modeling

Parker Aerospace

Motor high-altitude operation, certifiability, manufacturability