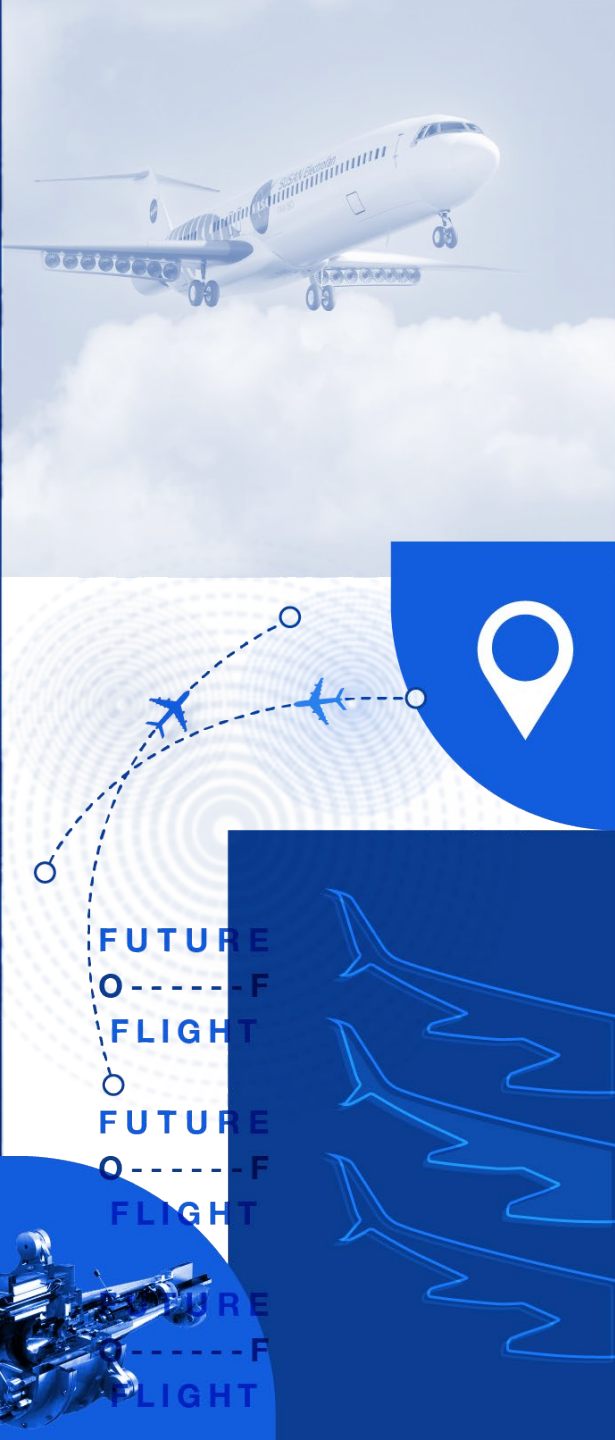
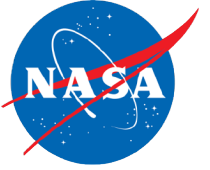




National Aeronautics and
Space Administration



NASA AERONAUTICS

Can it fly?

Technical Challenge 10.1: Focused Technologies for EAP Demonstrator

AAVP/AATT Technical Seminar
Andrew Woodworth Ph.D., NASA Glenn Research Center
March 28th, 2025

Background: What is electrified aircraft propulsion?

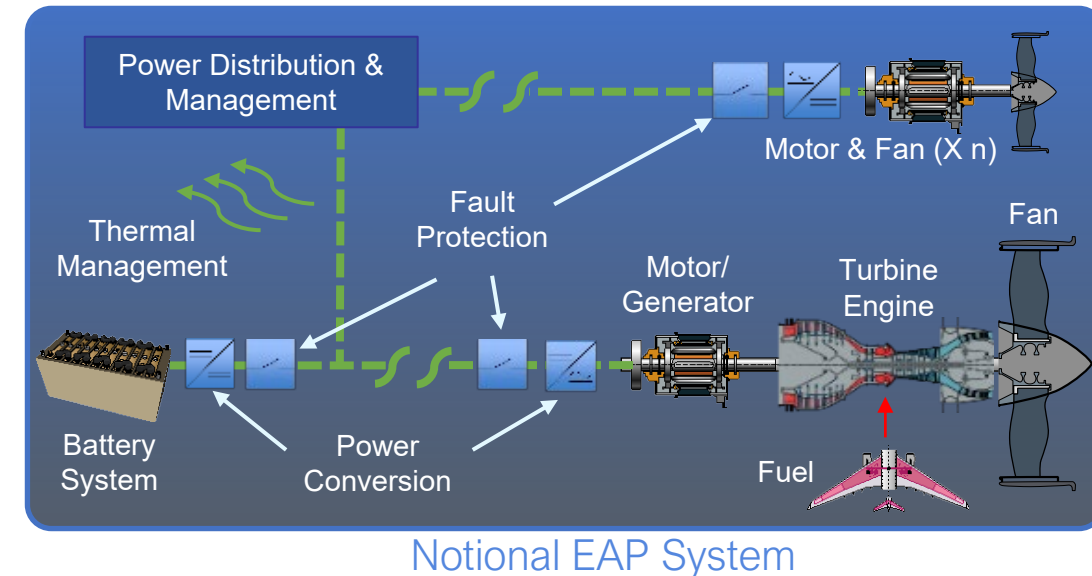
EAP is the partial or complete electrification of an aircraft's propulsion system

- All electric: stored energy in battery or like device is the only power source and electric motors are the only propulsion
- Hybrid: combination propulsion from a turbine and stored energy (e.g. battery)
- Turbo electric: energy is produced by turbine/fuel/generator and propulsion achieved by electric motors

Electrified aircraft propulsion (EAP) brings benefit through enabling efficiencies in the turbine and/or aerodynamics

EAP Systems

- Electric machines
 - Motors
 - Generators
 - Combination of both
- Power conversion
 - Solid state electronics
 - Solid electronics
 - Inverters (DC to AC)
 - Converters (AC to DC)
 - DC/DC converters (changes or regulates DC voltages)
- Fault protection (circuit breakers)
- Thermal management
- Propulsion controls
 - Matches the sources and sinks of energy in the system to create an operable system that is fault tolerant
- Distribution (cables/ busbars/connectors-not addressed in this work)
- Batteries and battery management (not addressed in this body of work)



Background: Why megawatt scale?

- Single Aisle aircraft comprise the largest segment of commercial aircraft
- Impacting technology for the transport class requires MW-scale systems



Market	Regional Air Mobility	Regional Turboprops & Turbofans	Single Aisle
Passengers	1-19	20-150	150-more
Speed	≈150-250 mph	≈300-400 mph	≈500-700 mph
Range	≈100-500 miles	500-1500 miles	1500-3500 miles
Power	≈1MW	1 to 5 MW	3 to 30MW
Heat	≈200 kW waste heat	200kw to 1MW waste heat	600kW to 6MW waste heat

Megawatt-class focuses on single-aisle and larger to impact >90% of global fuel usage

Background: Relationship to AATT Investments

Advanced Air Vehicle Program (AAVP) /Advanced Air Transport Technology Project (AATT)

Are EAP aircraft viable for 2030-35? (est. 2014)

Technical Challenge 5.2: Electrified Aircraft Propulsion (EAP) Viability

- Viability of EAP is not well known in 2014 and therefore this is to both help determine what if any future investment would be made
- Determine what if any interest industry has in EAP

Can it fly? (est. 2019)

Technical Challenge 10.1: Focused Technologies for EAP Demonstrator

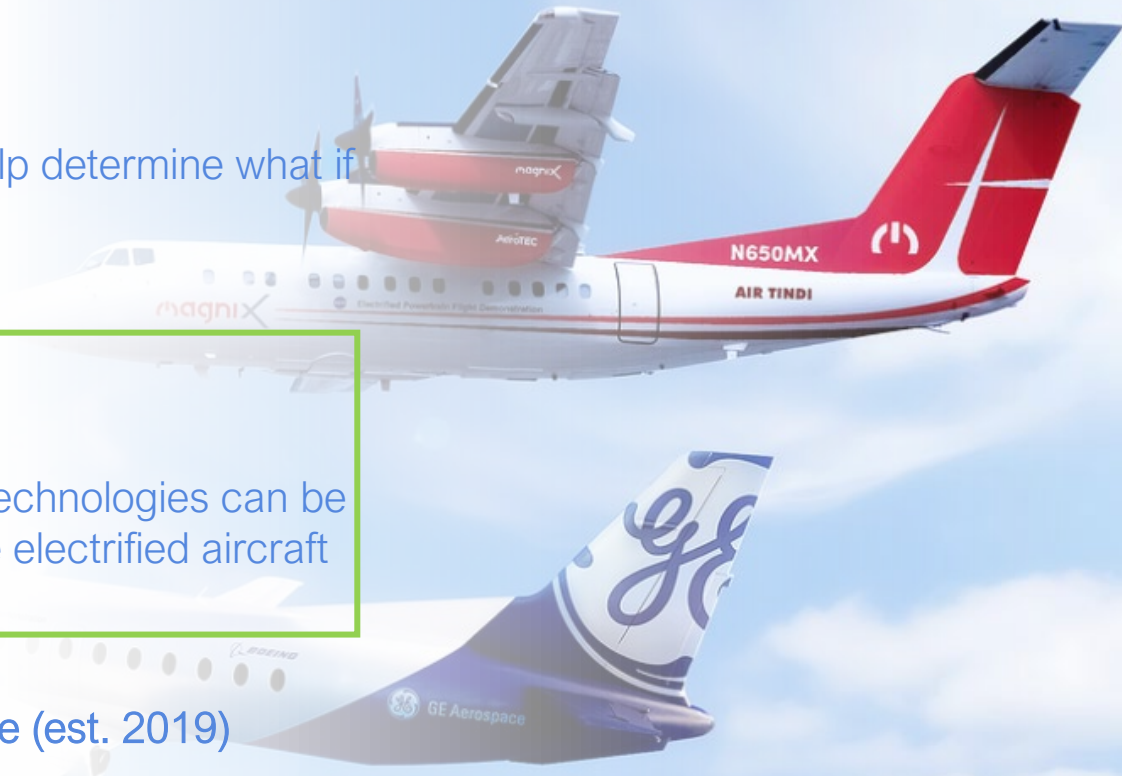
- Established to confirm that megawatt-scale electric aircraft powertrain technologies can be safely and successfully demonstrated for use in regional and single-aisle electrified aircraft propulsion (EAP) vehicles.

Emerging Technical Challenge (eTC) – Seed for the next technical challenge (est. 2019)

Is superconducting technology ready to contribute? (est. 2024)

Technical Challenge: 10.2: High Power EAP

- *The next step for EAP development is to push for technologies that extend systems beyond the MW scale*



Background: Are EAP Aircraft Viable for 2030-35?

Technical Challenge 5.2: Electrified Aircraft Propulsion (EAP) Viability

How TC 5.2 laid the groundwork for TC 10.1

➤ Technical Challenge 5.2: Metrics

Specific power density (mass) has always been an issue for aircraft

- Increasing the specific power density of motors was a critical technological achievement of the Wright brothers*
- Adding electrical components increases mass and therefore lightweighting is critical*
- Terrestrial megawatt systems do not share this issue*

Increasing voltages is necessary to increase specific power density

- Power = voltage x current*
- Power loss = (current)² x resistance*
- Increasing voltage decreases electrical current, reducing the size and mass of the conductors while also decreasing loss*

Increasing efficiency is critical to decreasing the size and complexity of the thermal management system

- EAP systems require a distributed thermal management system*
- Thermal systems not only add mass but also drag (application dependent)*

Metrics for 1 kVA or greater power electronics

Performance Metrics	Specific Power (kW/kg)	Efficiency (%)
Minimum	12	98.0
Goal	19	99.0
Stretch	25	99.5

Metrics MW scale electric machines

Performance Metrics	Specific Power (kW/kg)	Efficiency (%)
Goal	13.2	96.0

Establishment and meeting of key metrics have helped push the technological edge

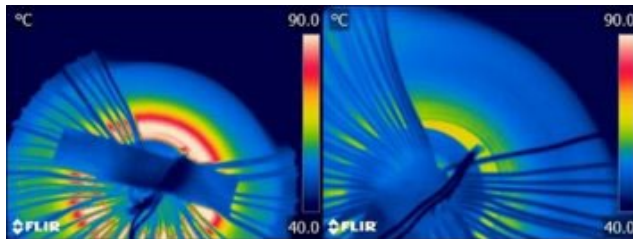
Background: Are EAP Aircraft Viable for 2030-35? (con't)

How TC 5.2 laid the groundwork for TC 10.1

➤ Are EAP Aircraft Viable for 2030-35? (est. 2014)

Technical Challenge 5.2: Electrified Aircraft Propulsion (EAP) Viability

- Multiple aircraft design concept studies indicate that hybrid propulsion systems can lead to block fuel savings
- NRA-sponsored machines and inverters demonstrated substantial improvements in specific power and efficiency
- An EAP-relevant, soft-magnetic alloy class was matured from laboratory demonstration to component application
- Simplified, subscale powertrains and full-scale components tests completed in NEAT testbed at sea level (altitude capability added later)
- NASA and industry investment in EAP expanded beyond this subproject with considerable momentum



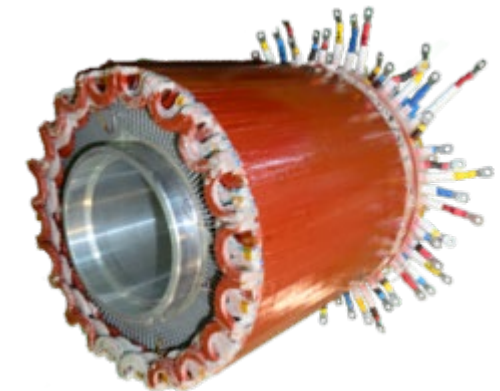
Thermal image of a magnetic core made of NASA's soft magnetic materials



NASA Electric Aircraft Testbed (NEAT)



NASA's STARC-ABL Concept Vehicle



NRA sponsored electric machine
credit Kiruba Haran (UIUC)

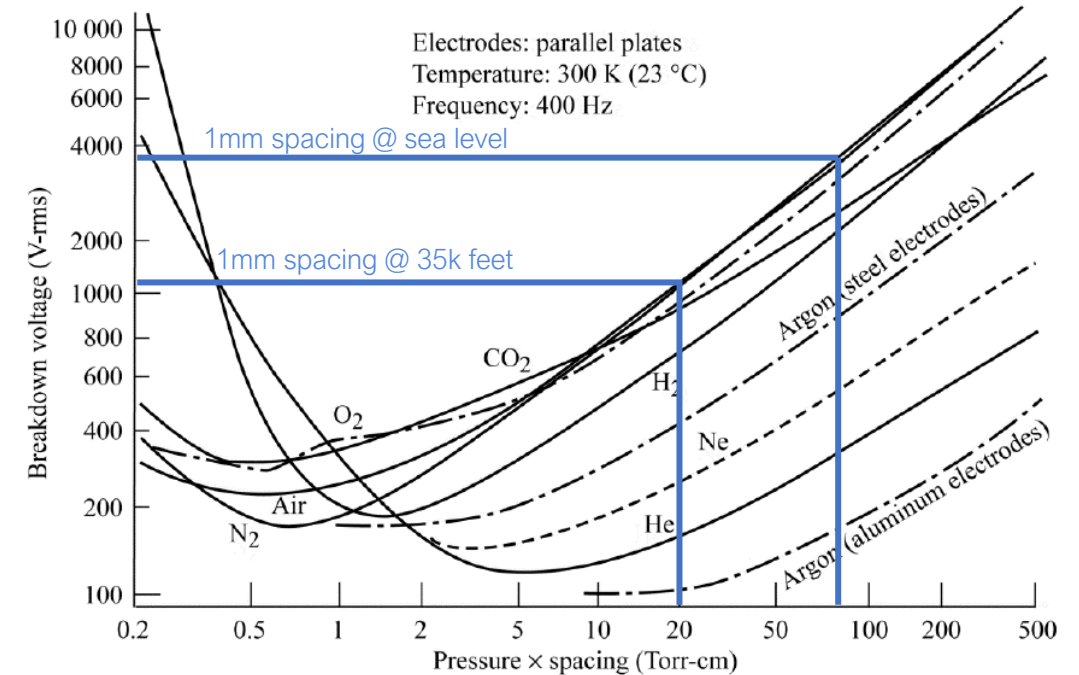
Are EAP Aircraft Viable for 2030-2035? **Answer: YES!**

Background: Can it Fly?

10.1: Focused Technologies for EAP Demonstrator

- Aimed to have a technology readiness sufficient to impact a flight demonstration
- State-of-the-art in 2019 was only 250kW, (a long way from 1 MW)
- Address key tall poles facing adoption EAP systems
 - Operation at altitude EAP components identified as tall pole
 - Paschen's law indicates increasing voltages above state-of-the-art 270V creates safety and operability concerns
 - Testing of systems was necessary, as well as further development of components to be flight-like
 - Fault Management
 - Flight-like DC circuit breaker technology
 - Propulsion controls: How operability of an EAP system is maintained through fault conditions
 - Improving power quality through advanced inductor filters
- Thermal systems for distributed heat loads needed to be addressed

Paschen's Curve



Source: NASA-HDBK-4007

Targeted technologies for near-term flight demonstrations advance knowledge base and readiness for regional and larger planes

Technologies: Testing

The NASA Electric Aircraft Testbed (NEAT)

Created for AATT to perform R&D on MW-class powertrains:

- Propulsion controls
- Power quality and stability
- System-level effects
- Characterization and evaluation of new technologies such as high-performance machines, inverters, control algorithms, fault and thermal management systems

Altitude chamber (60kft-max) brought online to enable component and systems tests

- ✓ GE MW scale machine and altitude integration tests
- ✓ NASA ULI program's MW machine with integrated power electronics
- ✓ magniX 650 kW motor and drive
- Partnership with ARPA-E to test ASCEND motors (current test program) :
 - Wright Electric 2 MW motor
 - RTRC 250 kW sub-scale version of ultra-high power density MW-class machine



Reducing risk for flight demonstrators and products through ground tests at the NASA Electric Aircraft Testbed

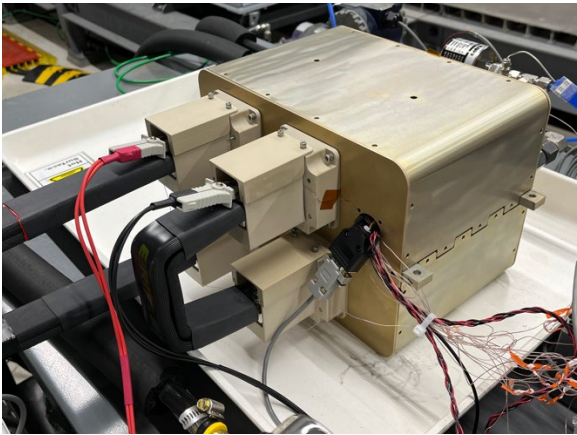
Technologies: Fault Management

Naval Post Graduate School (NPS), GE, and RTX Solid-State Flight-Weight Breakers

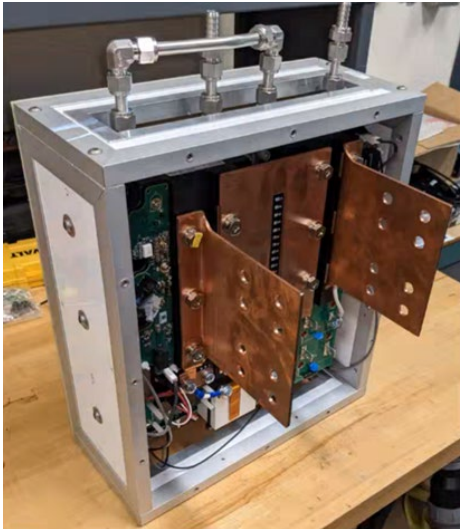
Transport-class electrified airplanes require safety systems that can interrupt a megawatt of DC power in 100 microseconds or less and weight ~10 X less than current state-of-the-art to protect personnel, aircraft, and powertrain components.

- ✓ GE, RTX and Navy Postgraduate School met or surpassed all the expected goals showing NASA KPPs can be achieved.

Metric	Minimum Goal	Expected Goal	Stretch Goal
Specific Power (kW/kg)	50	100	200
Voltage (kV)	0.8	1	≥2
Current (A)	800	1000	>1000
Response (μs)	250	100	10
Efficiency (%)	99.3	99.5	99.97
Altitude Capability (ft)	25,000	35,000	51,000



RTX solid-state breaker
credit RTX



NPS solid-state breaker
credit NPS

Circuit breaker technology can meet established goals for safe, flight-weight EAP powertrains

Technologies: Power Electronics

GE SLIM flight-weight inverter competed and tested at NEAT

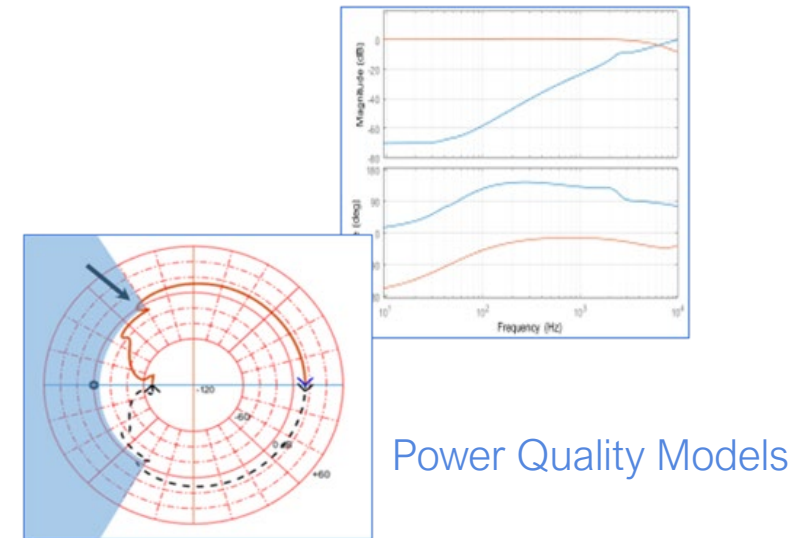
- Goals: power conversion peak efficiency of 99% and power density at of 19kW/kg for active components
- Uses high speed GE's ultra-high efficiency and high voltage Silicon Carbide (SiC) power devices
- Represents the first step towards a lightweight flight-worthy inverter to enable hybrid-electric aircraft applications

In-house 250 kW, 1000 V Inverter

- Design challenge to develop novel inverter technologies
- Compatible with new specific power dense electric machines
- Novel design reduces switching losses, filtering requirements
- Pressurized housing allows altitude operation
- Addresses thermal challenges

Addressing powertrain stability and power quality

- Bus stability analysis for representative powertrains
- Impedance modeling and measurement
- Objective is to provide guidance on system stability, power quality, future standards development for MW powertrain



Power Quality Models



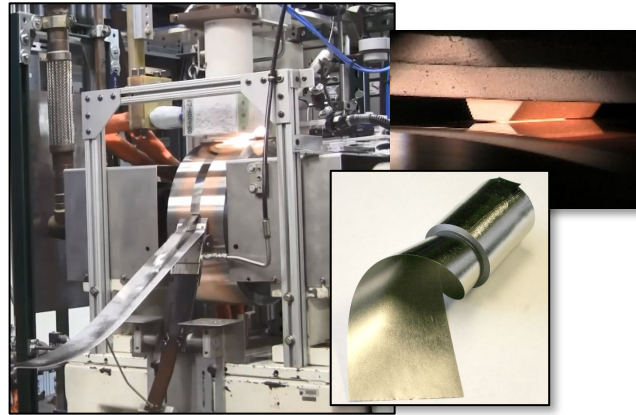
NASA 250 kW Inverter

Power electronics technologies maturing at a fast pace

Technologies: Soft Magnetic Induction Filters (Materials)

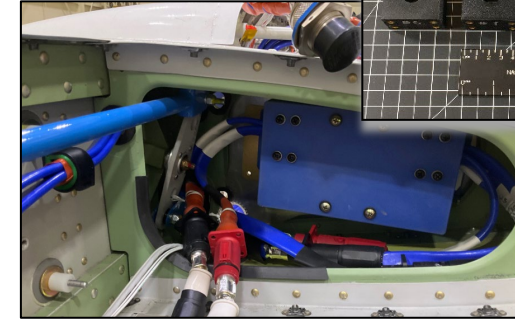
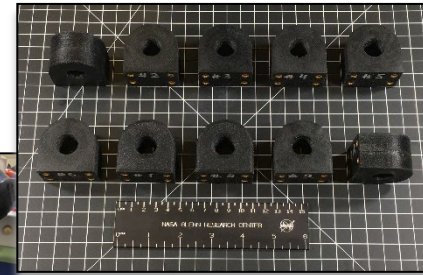


Vacuum induction furnace



Planar flow caster and amorphous ribbon

Common mode chokes
integrated into flight
rated packaging for X-57



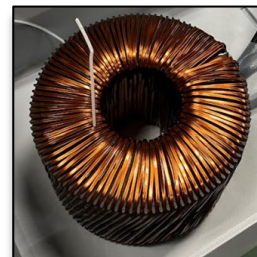
Filter assembly
mounted into
wing web

Key accomplishments:

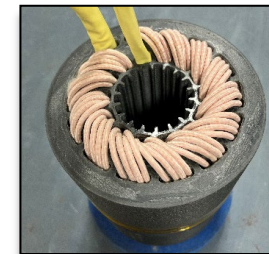
- Provided a wide range of prototype cores to industry, academic, and government power electronic designers
- Developed new alloys that improve the useful temperature range and enable gapless cores through a wide range of permeability
- Improved modelling and design capability
- 25%-75% reduction in mass/volume over SOA materials in the same application



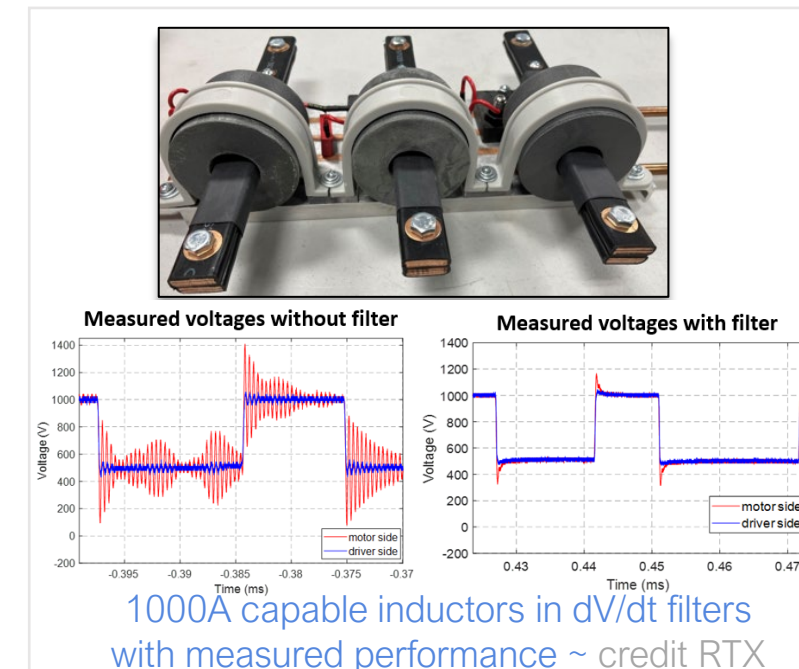
Various chokes with custom packaging



Graded permeability
load inductor



Dual active bridge:
40% lighter than ferrite



Technologies: Electric Machines

UIUC/HINETICS developing 1 MW slot less permanent magnet machine for direct drive

- Tested 300 kW unit at partial power and speed
- Providing projected efficiencies $> 97.5\%$ at University of Illinois POETS lab
- Verified full speed for the motor and full stator current loading

Testing of state-of-the-art machines at NEAT

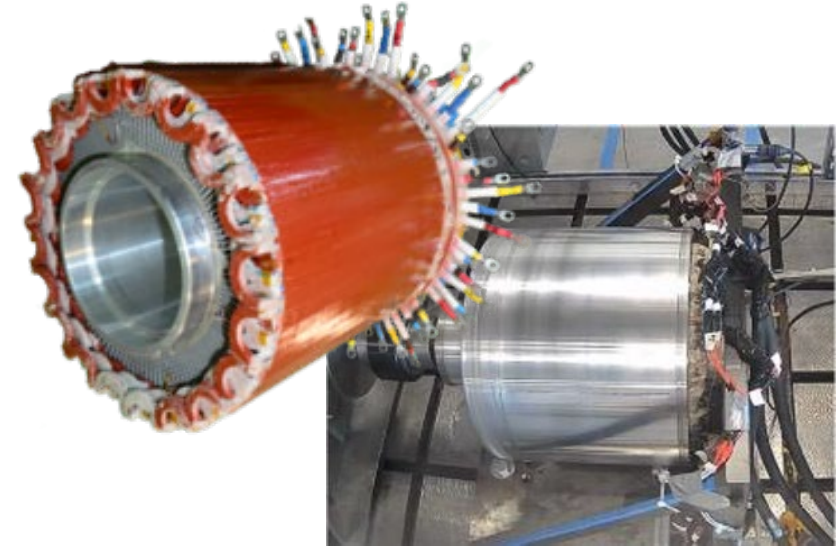
- 3 tested, 1 in progress, 1 in the queue (more interest has been expressed)

High Efficiency Megawatt Motor (eTC)

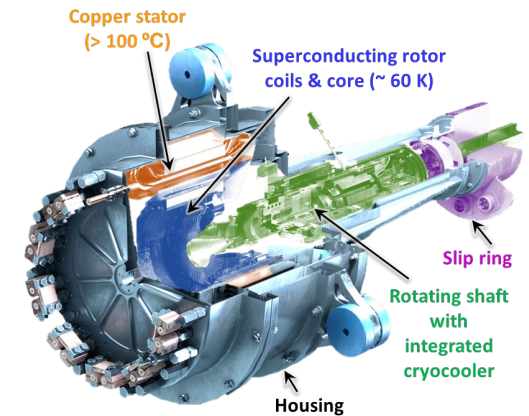
- 1.4 MW, 16 kW/kg and $> 98\%$ efficient

Key Lessons Learned

- MW scale specific power dense machines have highly coupled thermal, mechanical and electromagnetic components
- Co-design of power electronics & machine is critical
 - Low impedance of these machines requires decreasing total harmonic distortion and decreasing noise from power electronics is critical



300kW NRA sponsored electric machine
credit Kiruba Haran (UIUC)



High Efficiency Megawatt Motor (HEMM)

Technologies: Thermal Management

Mega watt scale aircraft require 100s of KWs of cooling in a distributed system

- Low-grade thermal rejection was limited to <300 kW.

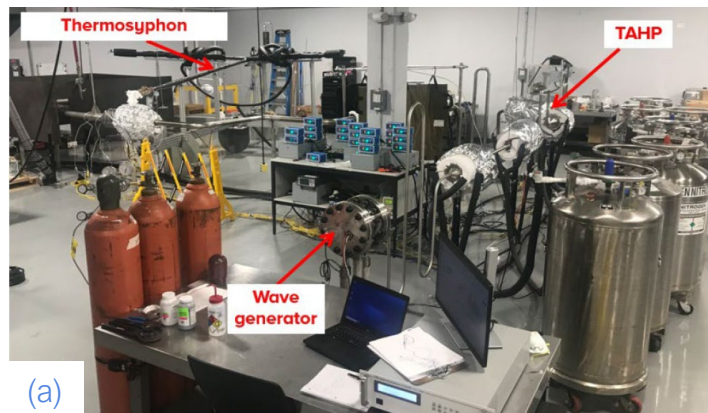
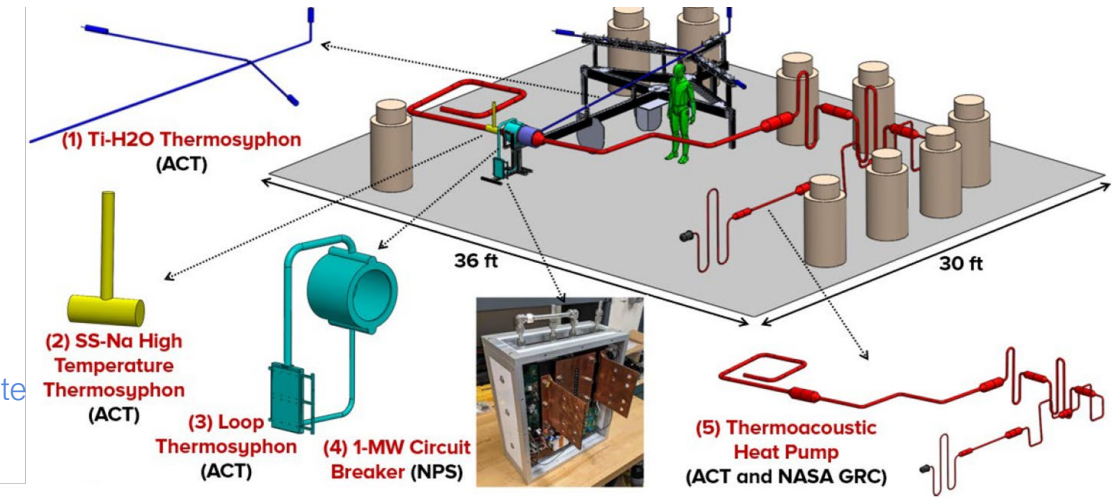
Demonstrates an aircraft-sized solid-state integrated thermal management system.

- Demonstrated acoustic waves combined with heat pipes can cool a single-aisle electric aircraft powertrain as shown in Fig. (a)
- Solid-state power electronic modules can be effectively integrated and cooled with solid-state acoustic refrigeration shown Figs. (b, c)
- Aircraft waste heat can be reused and redirected during flight even under g-loading conditions

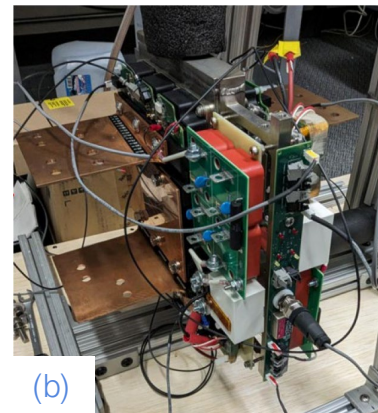
Develop five new technologies:

1. Aircraft sized 300K-500K thermosyphon for deicing
2. Aircraft-sized 800K-1000K thermosyphon for combustion
3. Aircraft-sized loop thermosyphon flat plate for modules
4. MW-scale flight-weight, power electronics compatible cold plate (integrated with solid state breaker) with solid-state thermal system (no pumped fluids required for higher reliability)
5. Aircraft-sized acoustic heat pump for no-moving part refrigeration and waste heat exergy amplification

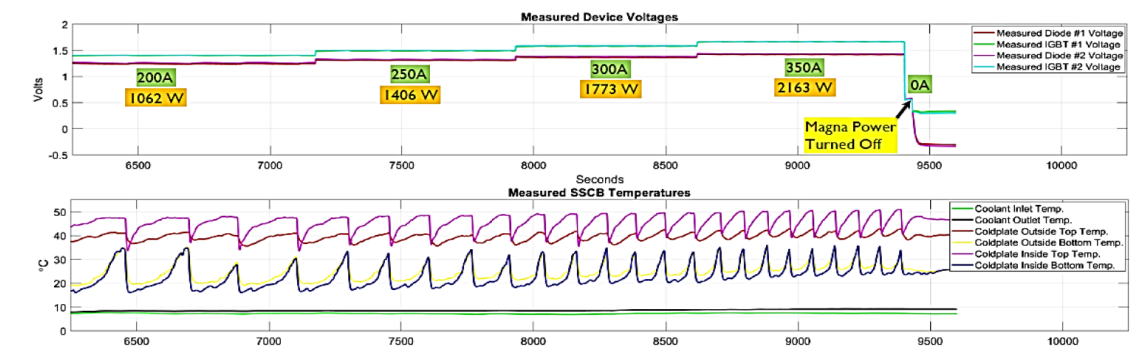
Partners: U. Michigan, JPL, Naval Postgraduate School, Thermavant, and Advanced Cooling Technologies, Inc.



(a)



(b)



(c)

Technologies: Propulsion Controls

Turbine Electric Energy Management (TEEM): to optimize energy usage of a hybrid-electric propulsion system during transient operation. (TACP/TTT developed concept)

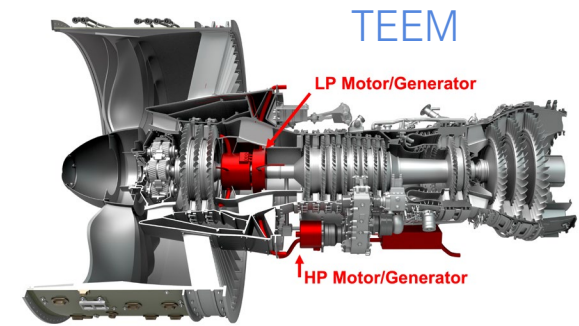
- Hardware in the loop real-time demonstration of a controls concept
- Real-Time turbofan simulation for Engine shaft speed, torque, and inertia are expressed by a pair of electric motors

Test Results from TEEM Control System Test at NEAT

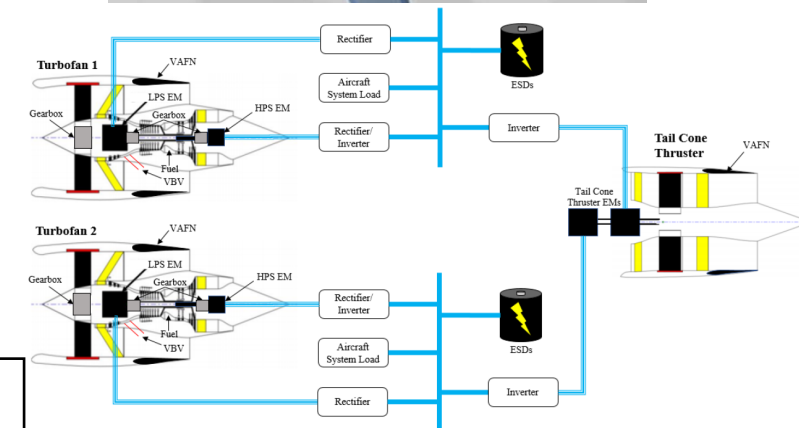
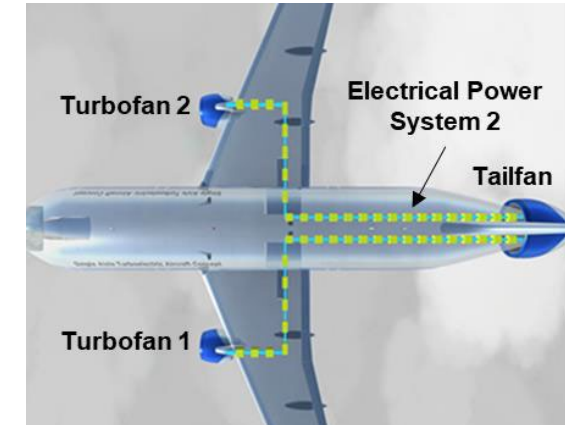
- Demonstrated the ability of TEEM to dynamically alter shaft speed to maintain the designed operating line performance during engine transient operations.
- Demonstrated dynamics of full-scale hybrid turbofan model and mechanically coupled EM system using *Adaptive Sliding Mode Inertia Controller and Scaling* algorithm though hardware-in-the-loop testing

Single-aisle Turboelectric Aircraft with Aft Boundary Layer Propulsion (STARC-ABL)

- Identified multiple failure modes and reversionary control approaches to retain as much performance as possible while maintaining operability
- Identified the need for a redundant DC bus in the concept
- Hardware in the loop testing of controls concept
 - Subscale STARC-ABL power system and turbomachinery shaft loads using NEAT h/ware
 - Real-time simulation of control system and turbomachinery dynamics



STARC-ABL



Propulsion controls provides a vital link between the components and the aircraft as a system

Relationship to the Electric Powertrain Flight Demonstrator Project

Demonstrators identify gaps in technology, integration, standards and regulation that need to be addressed for commercialization

The EPFD Project

- Maturing MW class technology
- Maturing integration of EAP with an airframe
- Addressing standards and regulatory gaps

TC 15.2 and 10.1 Contributions

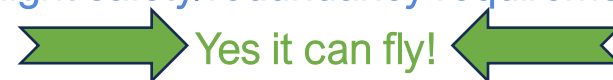
- EPFD adopted metrics that were derived from technology maturation efforts
- NEAT testing of EPFD systems
 - GE MW scale machine and altitude integration tests
 - magniX 650 kW motor and drive
- Planned flight demonstrations are directly incorporating AATT-sponsored TRL-6 components and TRL-4+ powertrain test results



Electric Propulsion Flight Demonstrators

➤ We have now demonstrated that both our NASA KPPs and flight safety/redundancy requirements can be achieved.

TC 10.1: Focused Technologies for EAP Demonstrator



Yes it can fly!

Background (con't): Emerging Technical Challenge (eTC)

Development of TC 10.2 *Technical Challenge 10.1: Focused Technologies Demonstrated for EAP Demonstrator*

Technology not deemed ready to impact a flight demonstration

Electric machine insulation solutions

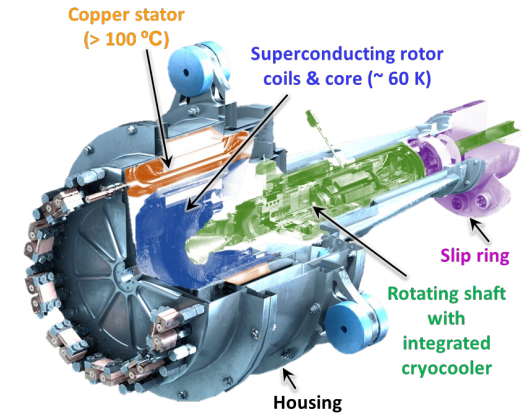
- Focused on supporting HEMM by evaluating off the shelf material solutions
- Developing new materials that solve thermal issues specific power dense machines face

High Efficiency Megawatt Motor

- Partially superconducting
- 1.4 MW, >98% efficient, 16 kW/kg (electromagnetic specific power goal)

Superconducting machines

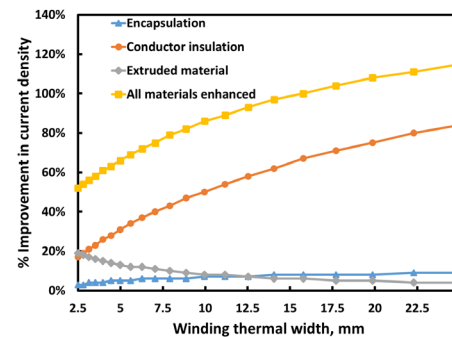
- Previous work identified AC loss (heat generated) in the machine stator was too great
- Refocused team on solving AC loss problem



High Efficiency Megawatt Motor



Electric machine insulation solutions



Superconducting Machines

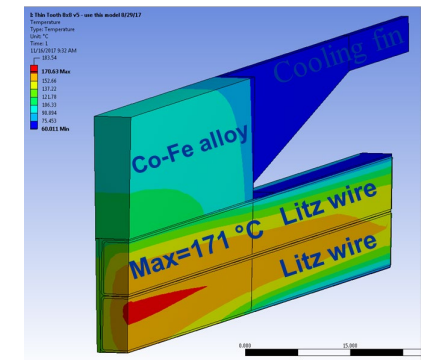
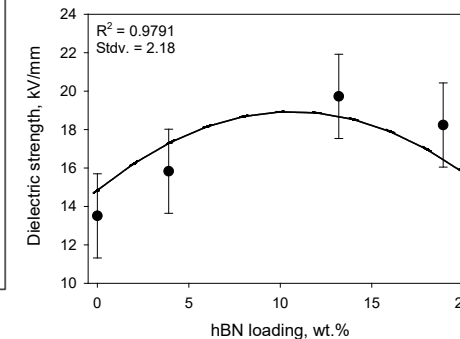
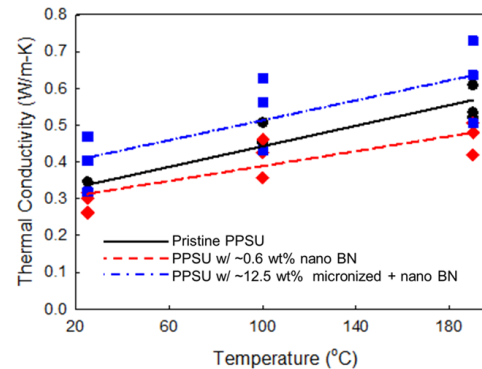
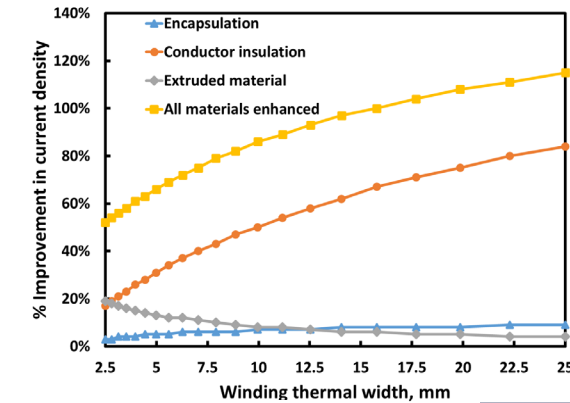
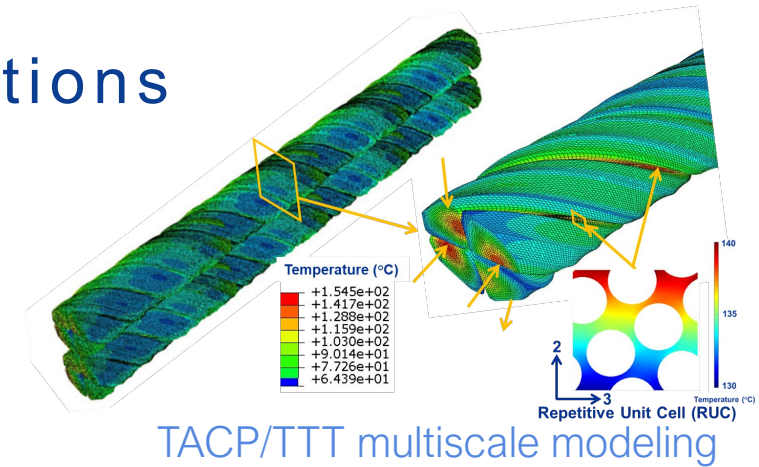
eTC Results: Electric Machine Insulation Solutions

Thermal management of power dense megawatt scale electric machines is a significant challenge

- Driven by thermally insulating nature of electrical insulation and potting materials
- Specifically of challenge in the stator comprised of 4 or more different materials
- 30% of loss (heat generated) is in the stator

Develop materials that meet electric and mechanical requirements while increasing the overall all thermal conductivity

- Used modeling to both set key performance parameters and show impact on stator performance
- Moderate improvements of all the materials has a significant benefit to performance
 - The stator is a composite material
- Materials developed in the lab were able to achieve key performance parameters
- Evaluated lifetime ageing of developed material
- Feed this information back into the development process



Significant improvements in electric machine performance through materials development is activable

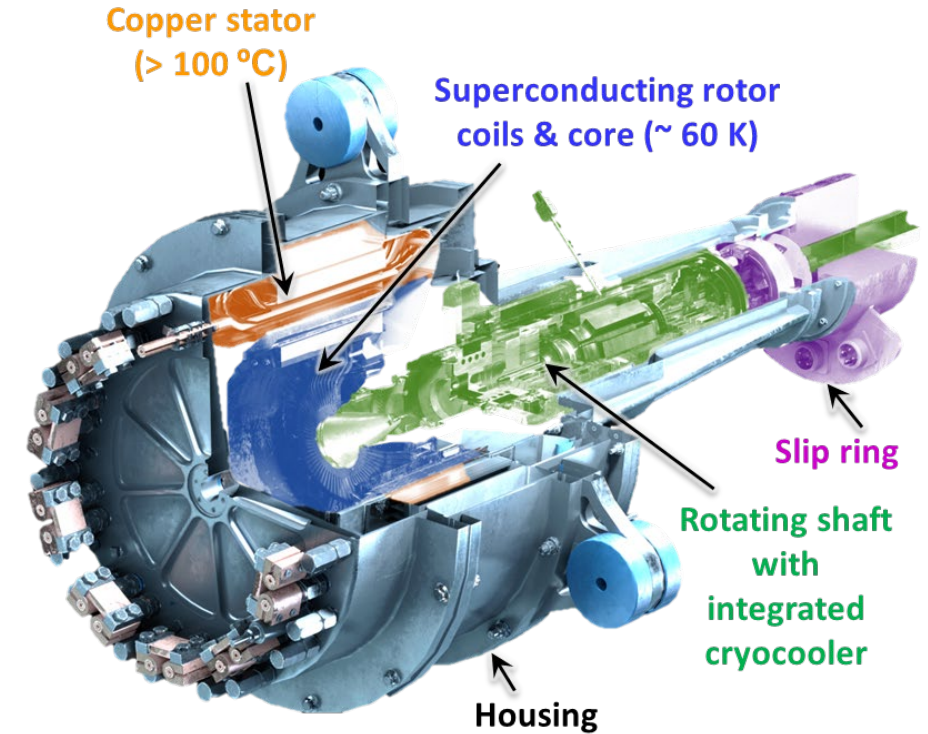
eTC Results: Electric Machines

Heigh Efficiency Megawatt Motor (eTC)

- 1.4 MW (can be a motor or generator)
- >98% efficient, 16 kW/kg (electromagnetic specific power goal)
- Superconducting Rotor (DC), ambient Cu- Litz wire stator
- Completed design of HEMM to near CDR level

Successes

- 1st ever demonstration of a practical cryogen-free (conductive) superconducting MW-class rotor
- Derisked cryocooler designed to rotate at high speed
- Demonstrated fabrication and direct cooling of full-scale stator



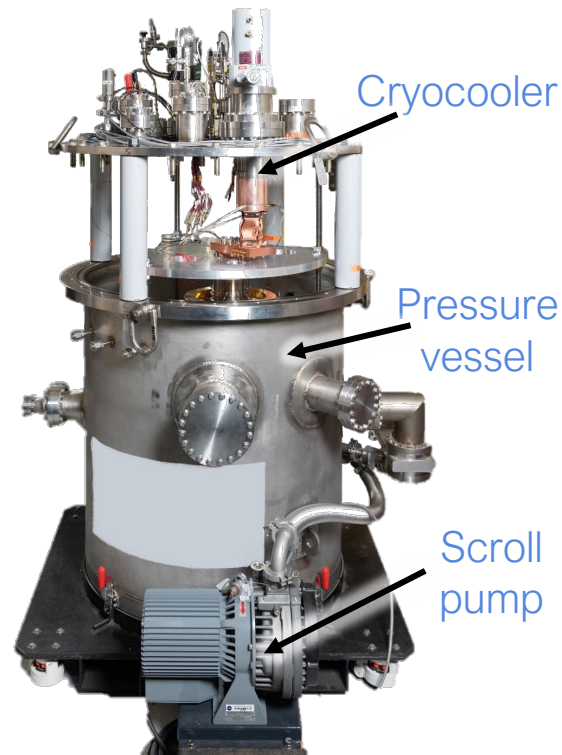
Heigh Efficiency Megawatt Motor (HEMM)

eTC Results: Superconducting Machines

- *Development of test facilities to properly characterize and explore AC loss*
- *New superconducting wires developed through SBIR efforts to address AC loss mechanisms*
- *Development of HEMM rotor gave more insight into constructing machines with superconducting elements*

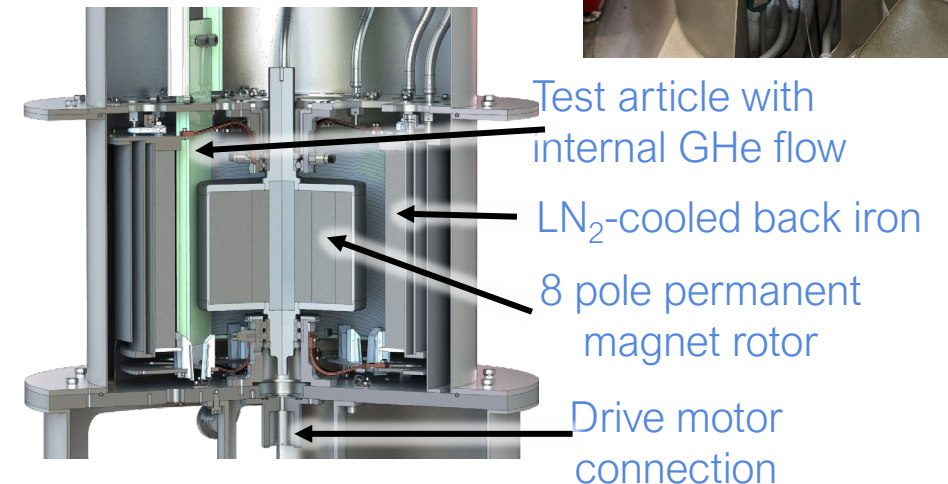
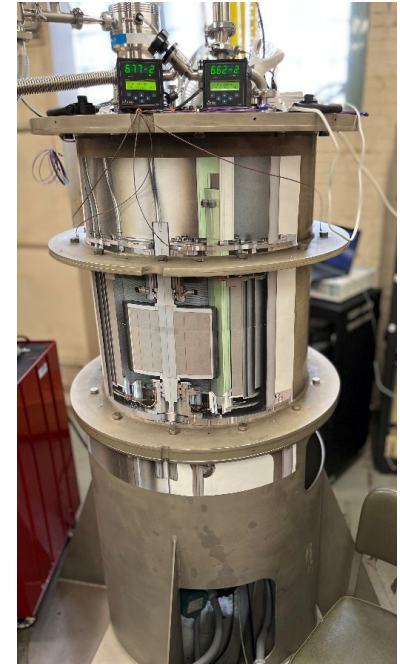
ICE-Box

- Wide range of test articles – single wires to components or assemblies up to about Ø0.75 m x 1 m
- Current vacuum capability: ~10⁻³ torr (warm) to ~10⁻⁵ torr (cold)
- Cryocooler Lift Capacity
 - Primary AL-325:
79W @ 20K
or 100W @ 25K
 - Designed for secondary / cold wall cryocooler, but not currently installed
- Inert gas backfill capable



Superconducting AC Coil Tester

- ~20 K and up
- 0-400 Hz electrical frequency
- 0.4-0.5 T magnetic field produced by spinning rotor
- Test article cooled with cryocooled gaseous He (GHe)
- Loss target: ~5 – 50 W
- Expected tare: < 2 W



What's next: TC: 10.2 High Power EAP

Electrified Aircraft propulsion systems of 10MW or greater

- System analysis and integration studies of one or more high power EAP concepts
- Propulsion controls and fault management studies of high-power EAP systems
- Superconducting machine technology
- Compatible power electronics

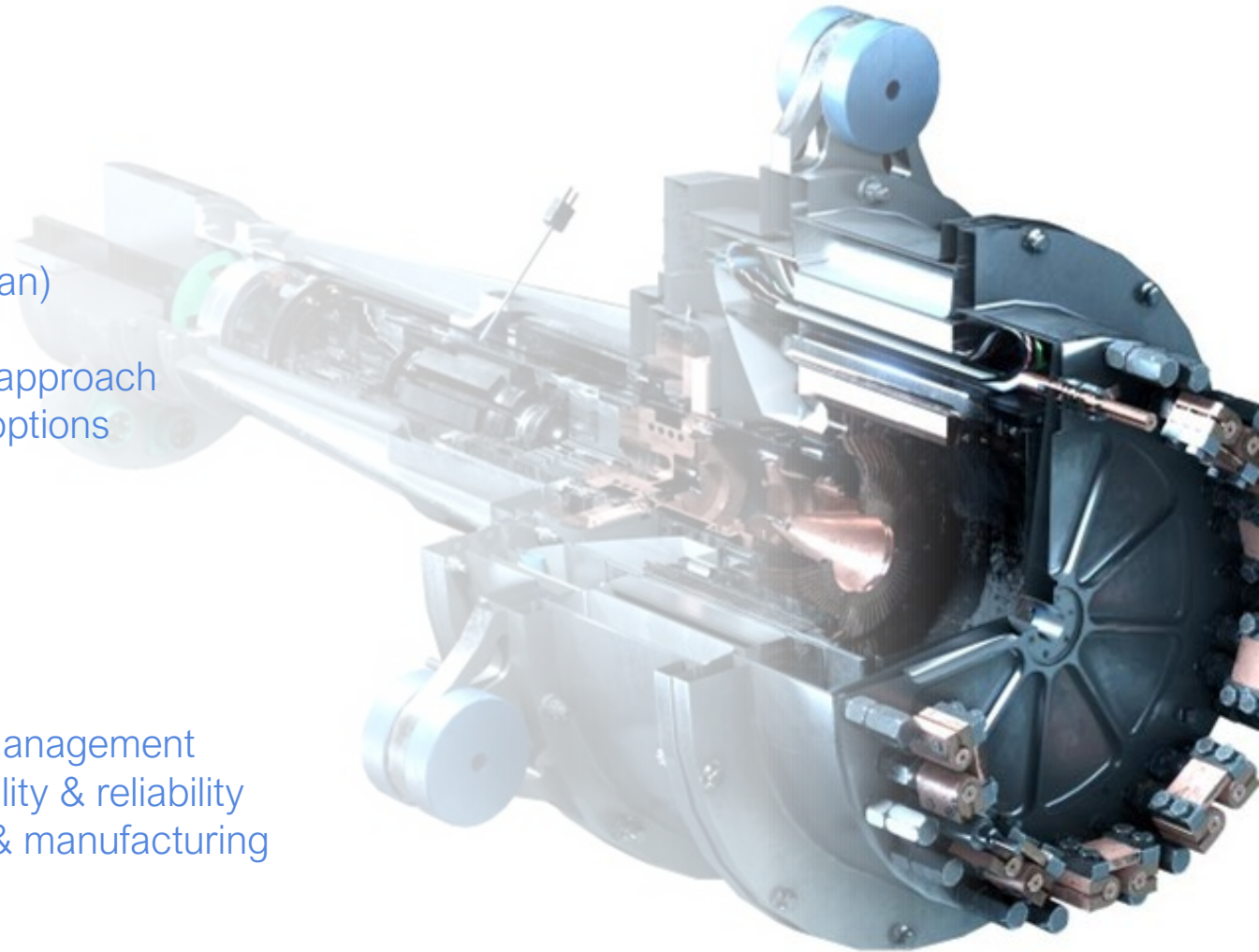
Is superconducting technology ready to contribute to EAP?

Robust Superconducting (SC) Machine

- Preliminary design for 5 MW machine (capable of driving a fan)
 - Superconducting rotor
 - Low AC loss stator winding and thermal management approach
 - Down-select among fully SC and fully cryogenic options
 - Subscale machine and drive TRL 3 demo
- Overall thermal management approach
- Robust cryo-capable 5 MW drive

Key Challenges

- Low AC loss stator
- Issues arising from high current
- Safe high voltage systems
- Weight
- Thermal management
- Power quality & reliability
- Materials & manufacturing



Wrap Up

Are EAP aircraft viable for 2030-35? (est. 2014)

Technical Challenge 5.2: Electrified Aircraft Propulsion (EAP) Viability

- Yes, they are viable
- NASA and Industry investments greatly expanded
- Key enabling metrics set

Can it fly? (est. 2019)

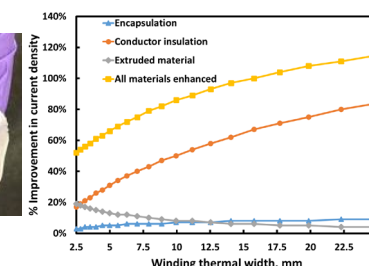
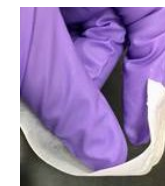
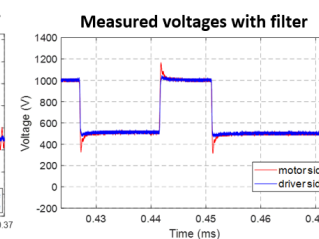
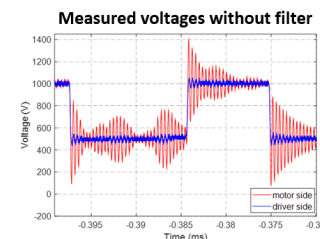
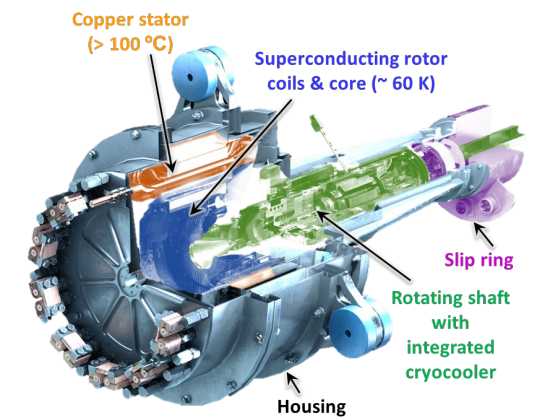
Technical Challenge 10.1: Focused Technologies for EAP Demonstrator

- Yes, megawatt-scale electric aircraft powertrain technologies can be safely and successfully demonstrated for use in regional and single-aisle electrified aircraft propulsion (EAP) vehicles.
- Key technical barriers bought down
 - Technology development
 - Testing
- Has impacted EPFD

Is superconducting technology ready to contribute? (est. 2024)

Technical Challenge: 10.2: High Power EAP

- The next step for EAP development is to push for technologies that extend systems beyond the MW scale is underway!



Stakeholders

Advanced Air Vehicle Program's *Advanced Air Transport Technology Project*, *Hybrid Thermally Efficient Core Project*

Integrated Aviation Systems Program
Electrified Powertrain Flight Demonstrator Project

Transformative Aeronautics Concepts
Project's *Transformative Tools and Technologies Project* and *University Innovation Project*

Project Management:
Amy Jankovsky

Technical Leads:
Rodger Dyson, Andrew Woodworth

Team Leads

Electric Machines: Ralph Jansen with support from Andy Provenza

Superconducting Systems: Gerry Brown with support from Justin Scheidler

Power Electronics: David Avanesian, Matt Granger

Materials: Alex Leary, Andrew Woodworth

Thermal Management Systems: Rodger Dyson

Controls & Fault Management: Don Simon

NASA Electric Aircraft Testbed: Joe Haglage and Nuha Nawash