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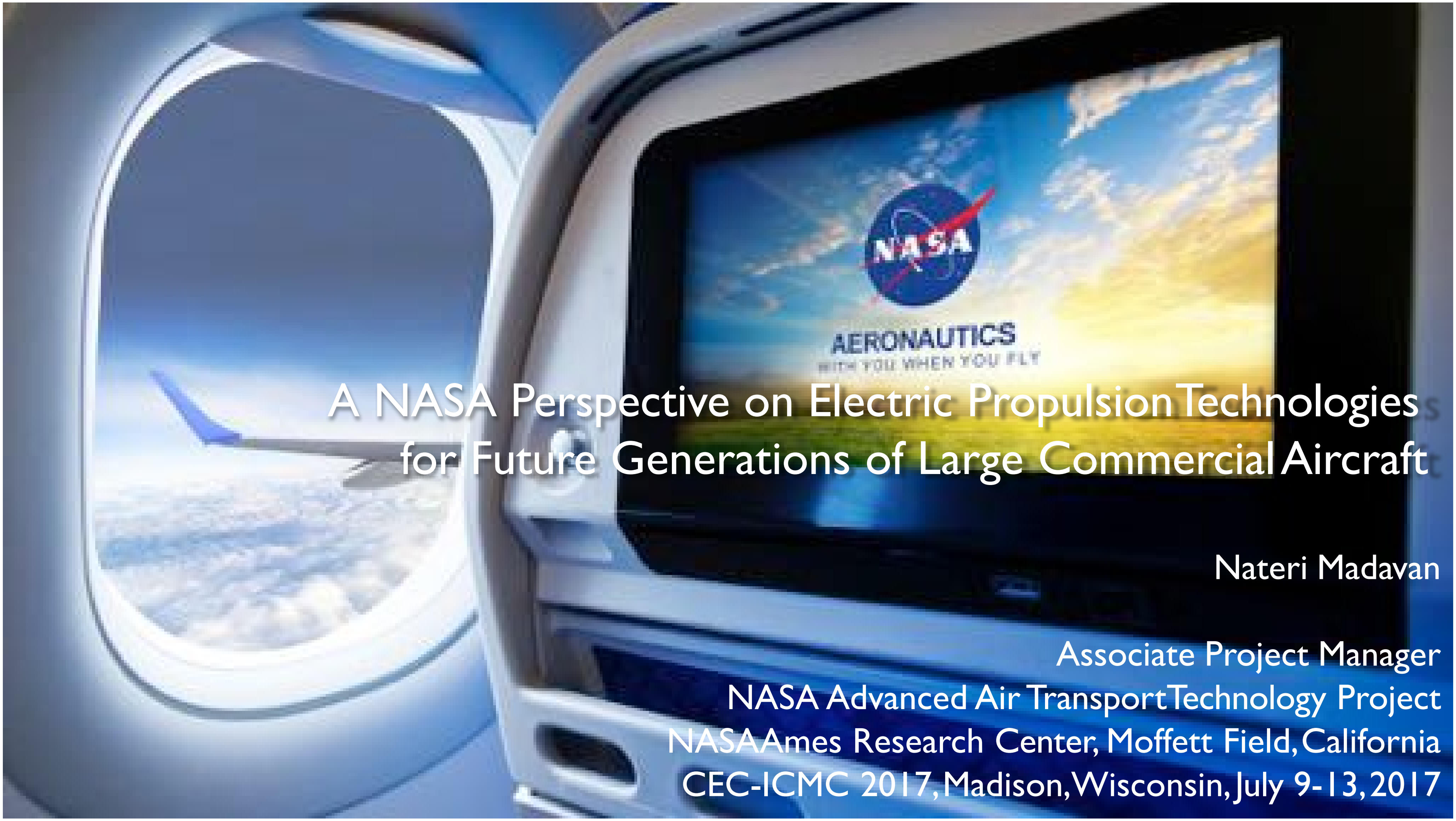

A NASA Perspective on Electric Propulsion Technologies for Future Generations of Large Commercial Aircraft

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NASA Vision for the Future of Aviation

- A radical increase in new and cost-effective uses of aviation
- The skies will accommodate thousands of times the number of vehicles flying today
- Travelers will have the flexibility to fly when and where they want in a fraction of the time that it takes today
- All forms of air travel will be as safe as commercial air transport is today
- Subsonic transports will remain the backbone of long-haul global and domestic travel
- Carbon and noise footprints from aviation will be significantly reduced

U.S. leadership for a new era of flight

Global Growth in Commercial Aviation

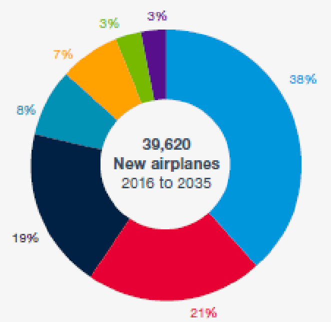
Tremendous opportunities

- Huge demand
- $5.9T market over next 20 years
- Need for speed

Enormous Challenges

- Competitiveness
- Environment
- Operations
- Safety

Delivery demand is diverse

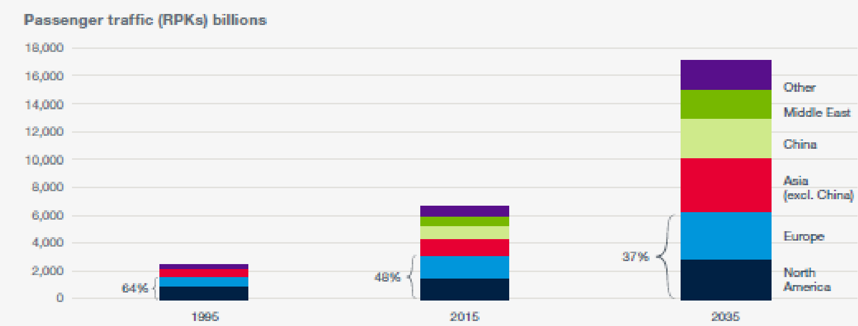


Region	New airplanes
Asia	15,130
North America	8,330
Europe	7,570
Middle East	3,310
Latin America	2,960
Africa	1,150
CIS	1,170
Total	39,620

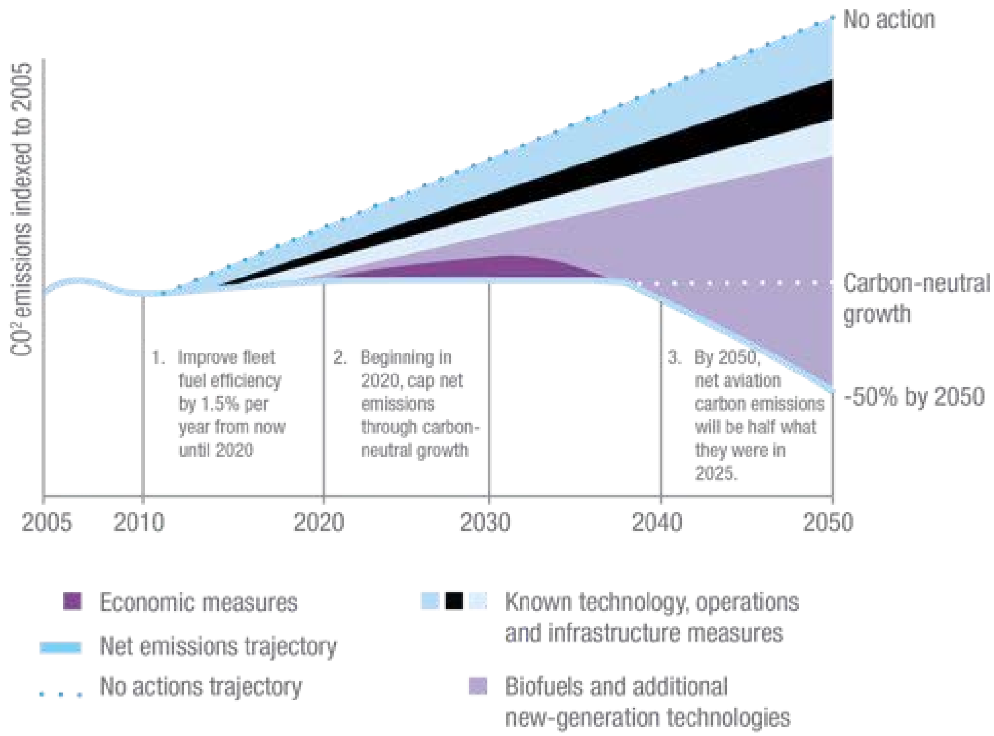
Over 39,000 New Aircraft required (replacement and growth) over the next 20 year period ($5.9T)

Growth in Airline passenger traffic at annual rate of 4.8%, and Air Cargo traffic at 4.2% over the next 20 years

Air travel becoming more diverse geographically



The Aviation Grand Challenge



Reduce carbon footprint by 50% by 2050…in the face of increasing demand, while reducing development, manufacturing, and operational costs of aircraft, and meeting landing/takeoff noise and NOx regulations

Source: http://aviationbenefits.org/environmental-efficiency/aviation-and-climate-change/our-climate-plan/

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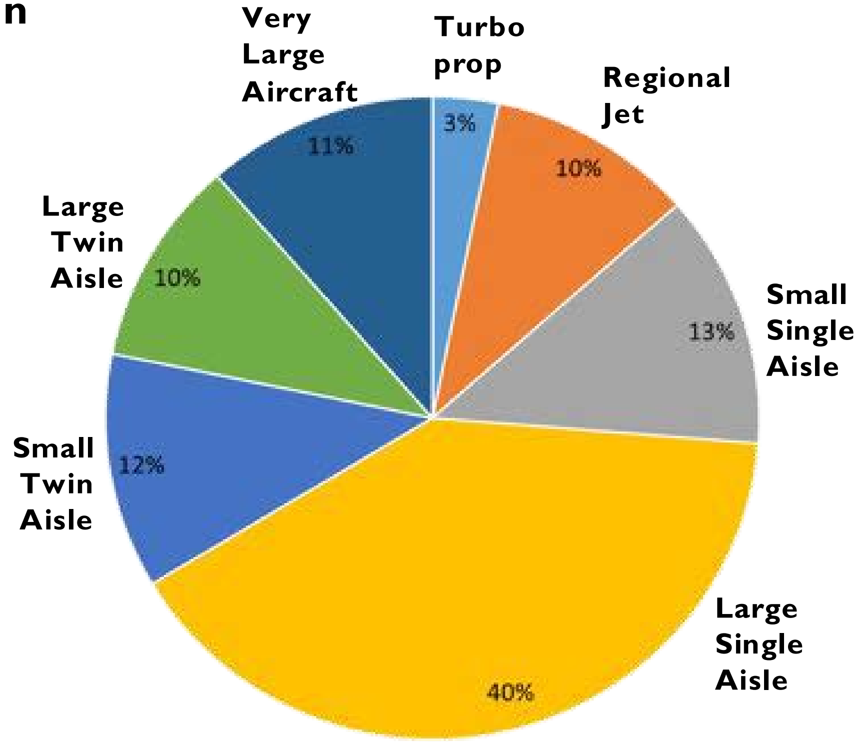
Why Focus on Commercial Transports

2012 Fuel Consumption



100+ passenger aircraft consumed 87% of fuel!

2012 Fuel Consumption, FAA US Operations Data. Analysis by H Pfaender, GA Tech

NASA Perspective on Commercial Aviation Electrification

Explore alternative propulsion systems that can *reduce carbon, noise, and emissions* from commercial aviation

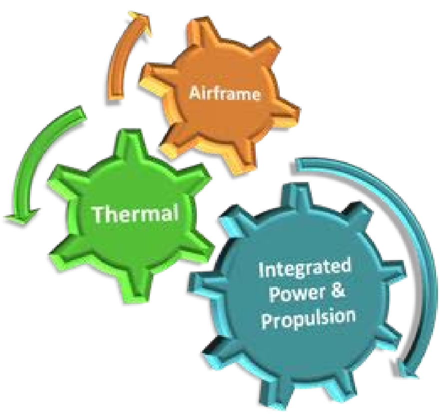
Promise of cleaner, quieter systems

Potential for vehicle system efficiency gains (use less energy)

Leverage advances in other transportation and energy sectors

Address aviation-unique challenges (e.g., weight, altitude)

Recognize potential for early learning and impact on smaller or shorter range aircraft



Key Challenges

Electrical system weight

Energy storage capabilities

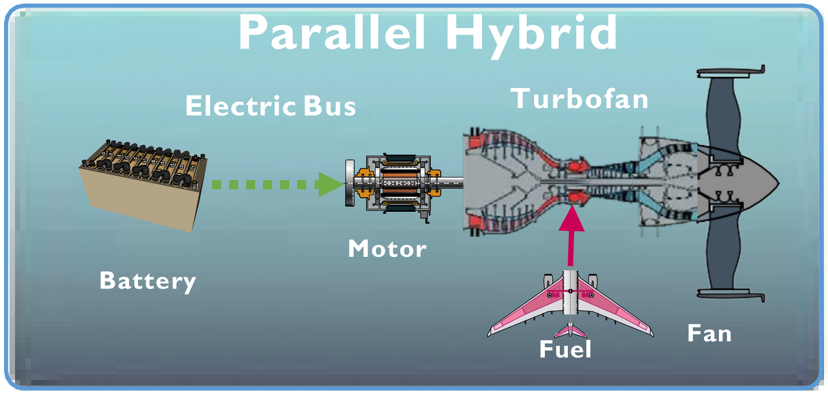
Thermal management

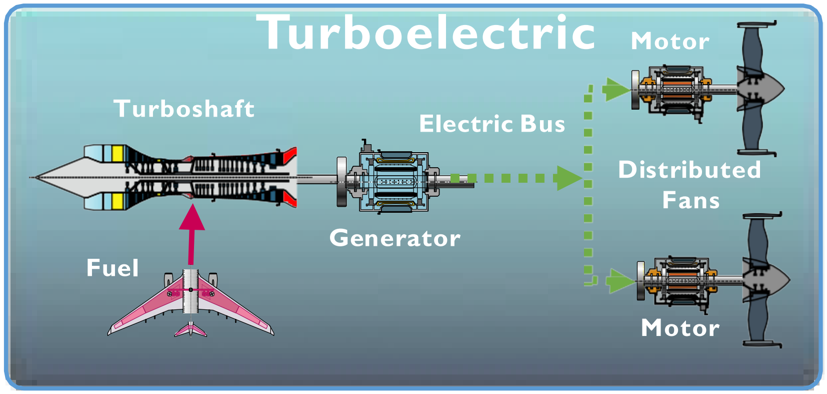
Flight controls

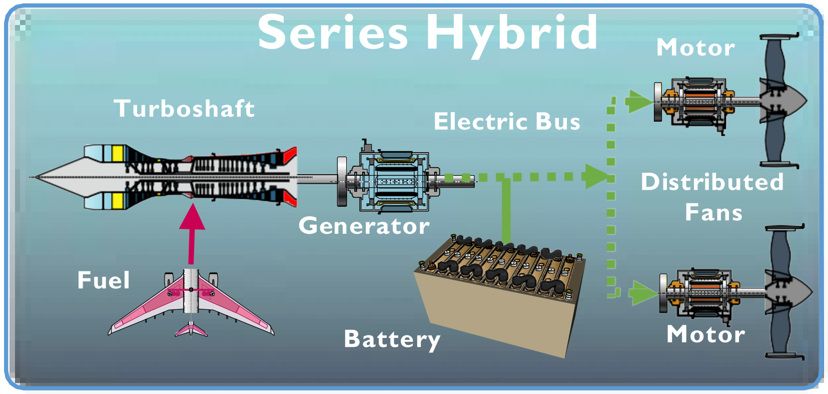
Safety

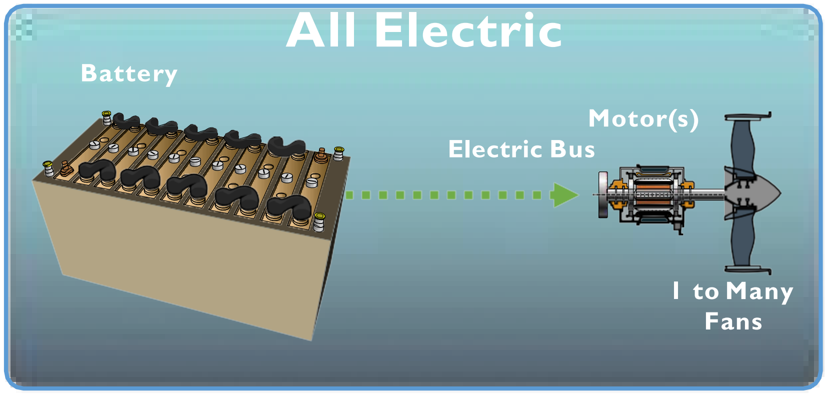
Certification

Electric Aircraft Propulsion Architectures





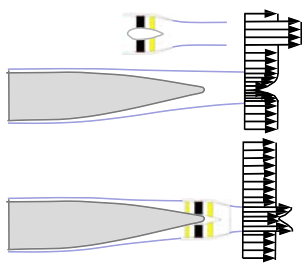




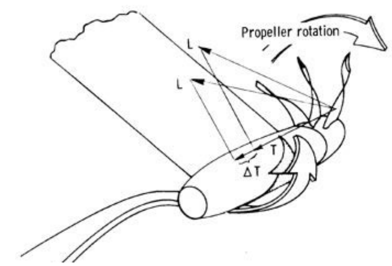
Electric Propulsion Enables Exciting Configuration Options

Flexibility to move power around aircraft and integrate propulsion with airframe

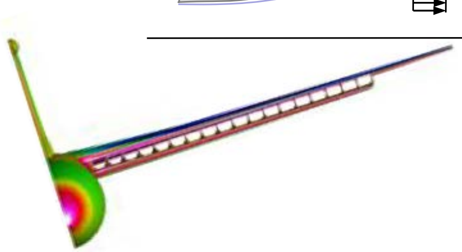
Boundary Layer Ingestion: Allows propulsion systems to energize boundary layers without distorted flow entering turbine core



Wing Tip Propulsors: Allows energizing wing tip vortices without penalty of small turbomachinery



Common Technology Requirement: *Increased efficiency and specific power in electric drive systems, thermal management systems, power extraction, and/or energy storage*



Distributed Propulsion: Allows effective increase in fan bypass ratio through distributed propulsors

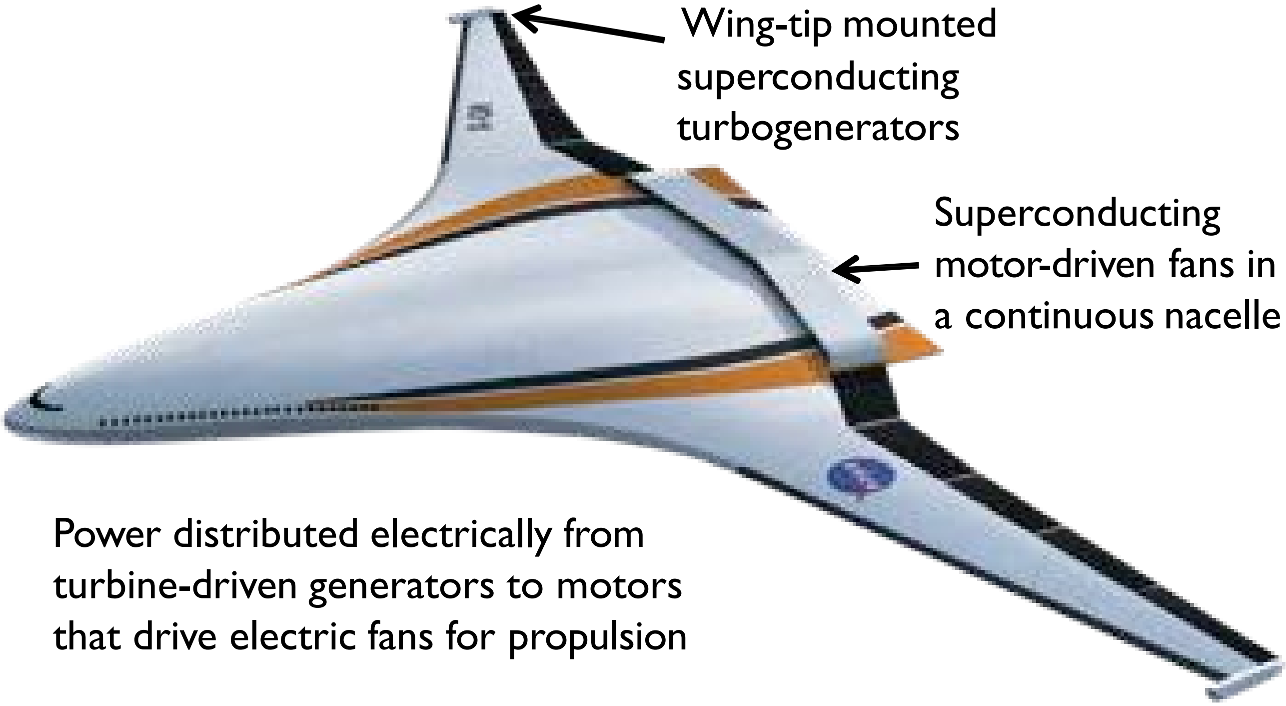
Lower Carbon Designs: Reduces combustion-based propulsive power (and emissions) using electric motors and/or on-board "clean" energy storage

The NASA N3-X Superconducting Concept Aircraft

N3-X is a Technology Collector Design showing future potential of Fully Turboelectric, Distributed Propulsion, and Boundary Layer Ingestion

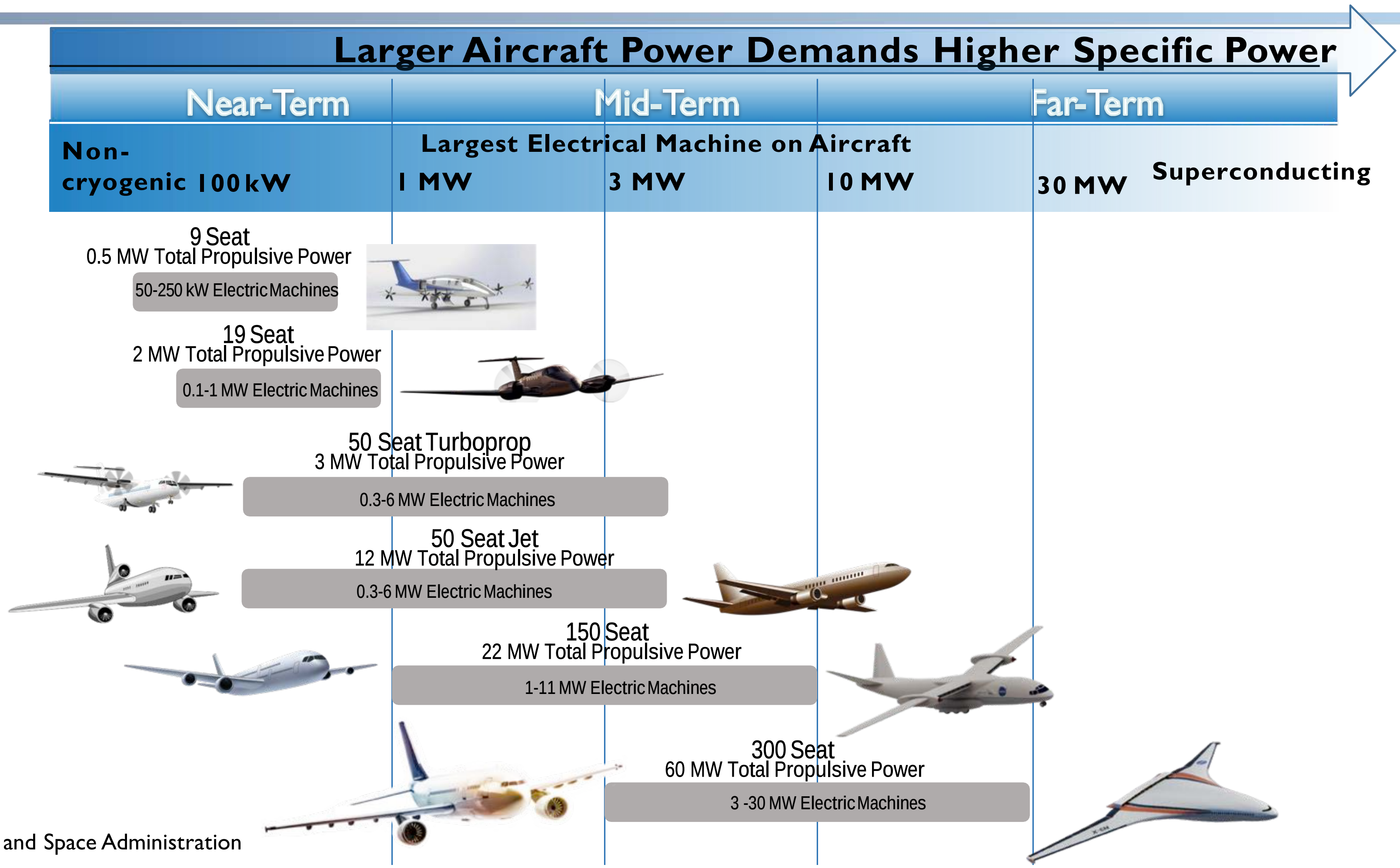
70% Fuel Burn benefits
(vs. CY2000 baseline)

20% Fuel Burn Benefits
(vs. HWB with ultra high bypass turbofans)



Ref: Kim H.D., et al, Aircraft Engineering and Aerospace Technology Journal, 2014

Where Can Cryogenic Systems Take Us?



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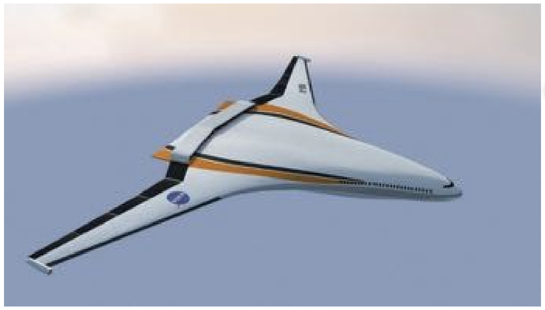
Superconductivity Enables Large Electric Air Vehicles



NASA N3-X

- Fully Turboelectric, 300 passenger
- Increased Fan Area, Boundary Layer Ingestion
- Superconducting Power and Transmission
- ~70% Fuel Savings relative to CY2000 baseline
- ~20% Fuel Savings relative to Advanced Hybrid Wing Body Baseline

Airbus/Rolls-Royce E-Thrust

- Fully Turboelectric
- Increased Fan Area, Boundary Layer Ingestion
- Superconducting Power and Transmission

ESAero ECO-150

- Fully Turboelectric, 150 passenger
- Increased Fan Area, High L/D wing
- Both Superconducting and Ambient Temperature versions
- ~60% Fuel Savings Relative to CY2000 Baseline

Cryogenic Powertrain Research

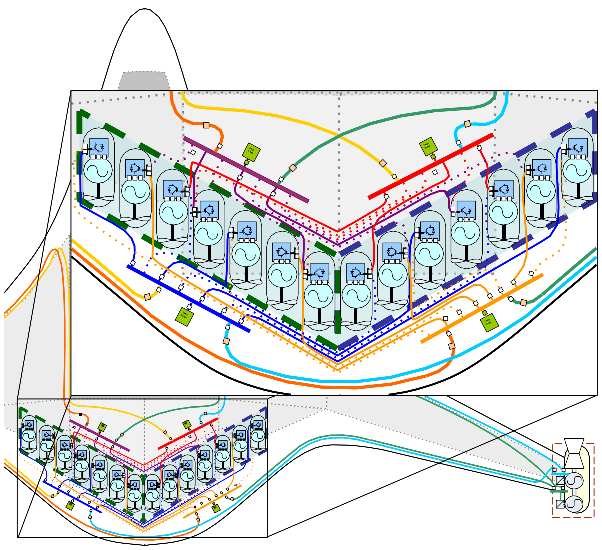
Detailed Architecture Analysis conducted by GE & Rolls-Royce NA

Power system:

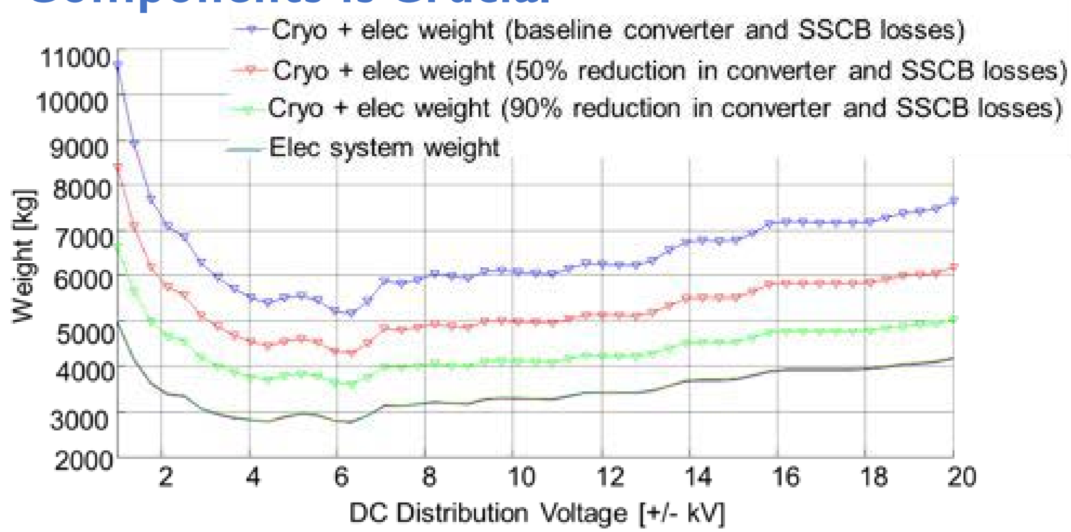
- Electrical machines
- Power converters
- Energy Storage
- Cables

Protection system:

- Solid State Circuit Breaker
- Superconducting Fault Current Limiters



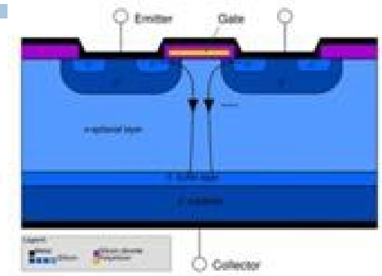
Electrical Efficiency of Cryogenic Components is Crucial

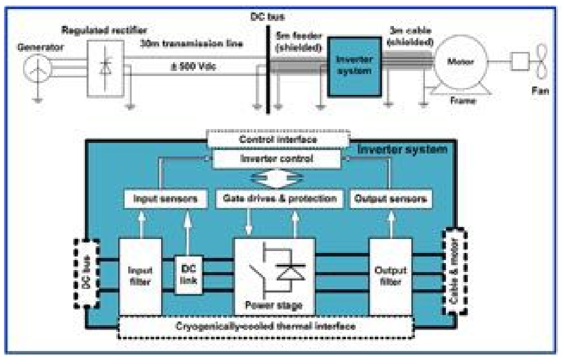


Cryogenic Power Converter Research

MTECH Cryogenic Inverter

- 2009 start SBIR program
- Demonstrated potential for > 25 kW/kg, > 99%



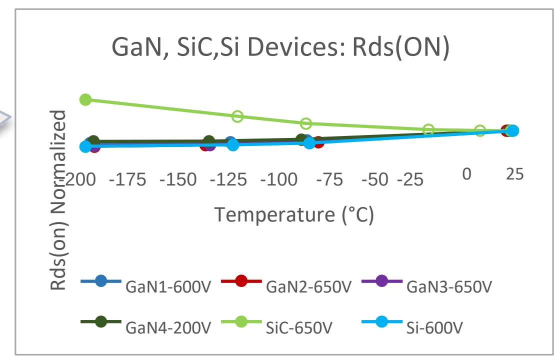


Boeing/UTK Cryogenic Inverter

- 1 MW operation with 26 kW/kg, >99% eff.
- LNG or LH2 operation
- 1000V input, 200-3000 Hz output
- 3-level Active Neutral Point Clamped Configuration
- Si CoolMOS technology (TRL 4 by 2019)

GaN Devices Offer Increased Performance

- GaN devices operate at low temps
- Results indicate potential efficiency gains
- ON resistance decreases for GaN and Si
- GaN has lower Gate to Source threshold voltage
- U of Illinois NRA 200kW inverter incl. cryo operation characterization



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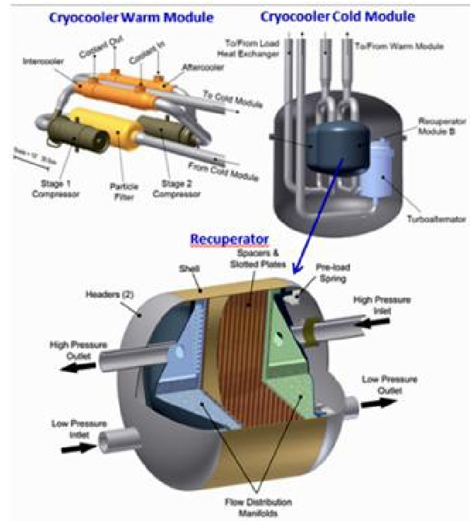
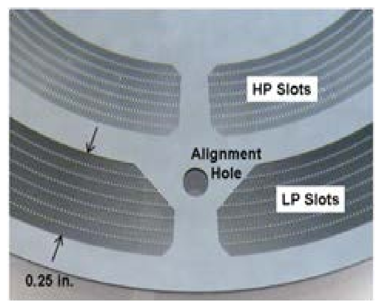
Advancing Cryocooler Technology to "Flight Weight"

Creare SBIR

- State-of-Art cryocooler specific mass is 18 kg/kW-input at 30% of Carnot
- Goal is 3 kg/kW-input at 30% of Carnot in Brayton cooler
- SBIR focus is on a high performance recuperator





Recuperator plate

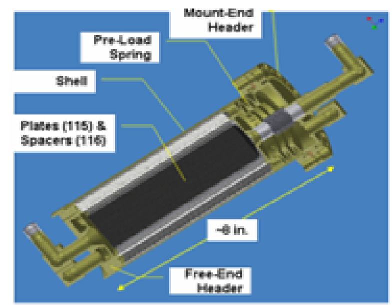
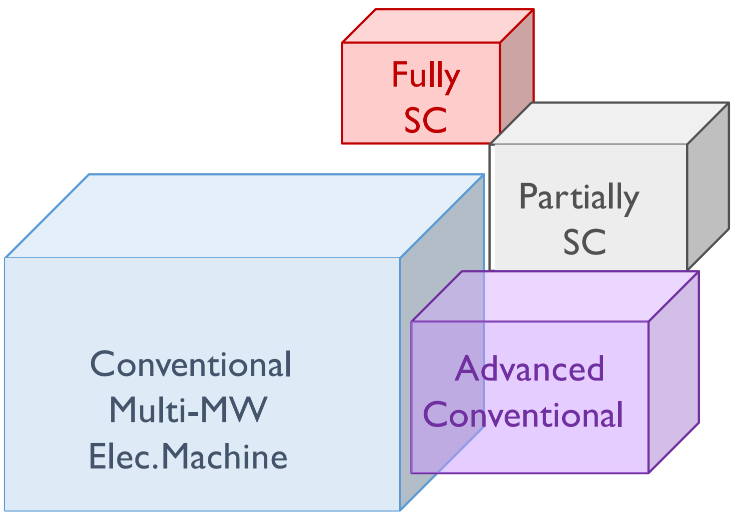
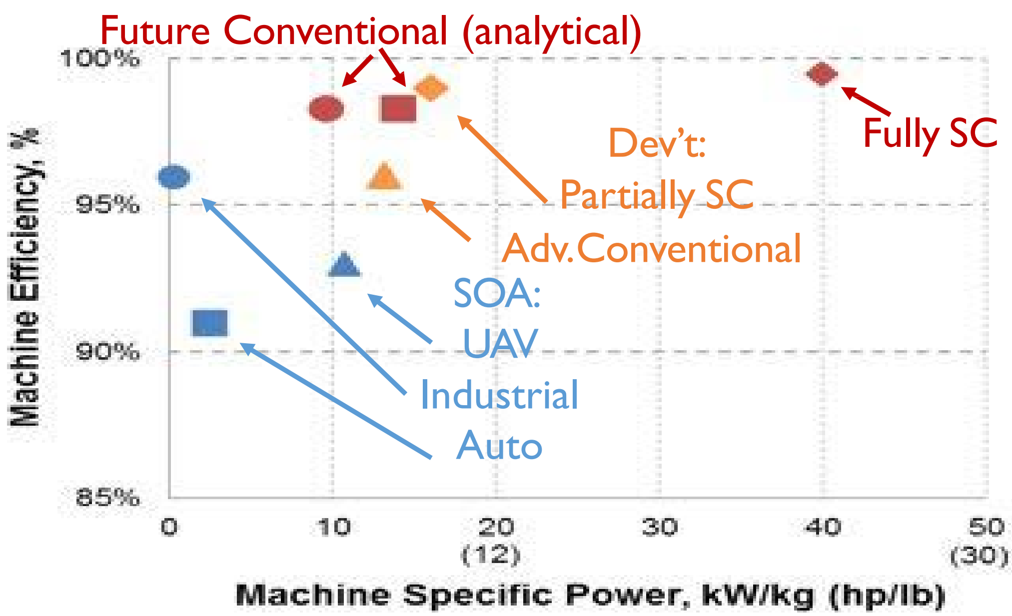


Figure 3. Silicon Micro-Machined Recuperator
Recuperator stack

The Promise of Superconducting Machines with High Specific Power and Efficiency

- Superconducting technology has a dramatic impact on electric machine volume, mass (specific power), and efficiency
- NASA studies show that increasing motor efficiency from 96% percent (Advanced Conventional) to 99% will reduce fuel burn an ***additional*** 2 percent and improve thermal management by a factor of 4





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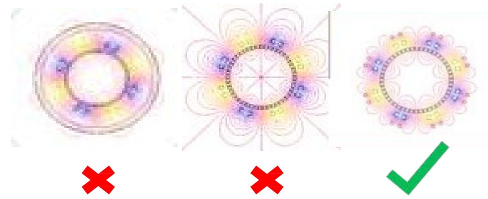
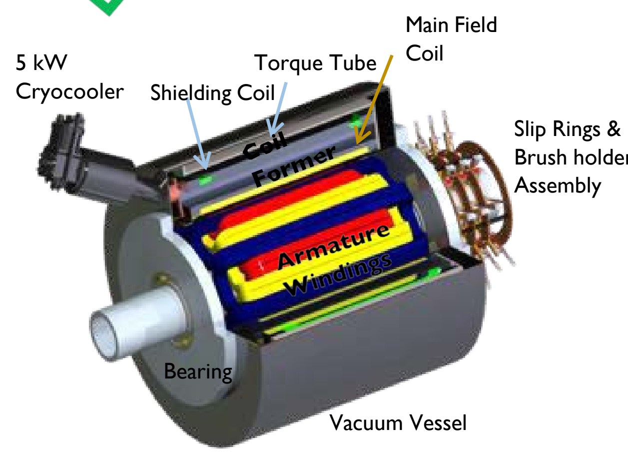
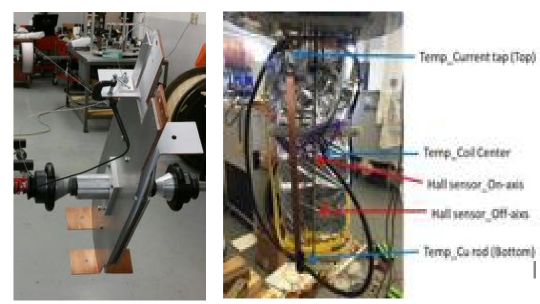
U of Illinois High Field, Partially Superconducting Machine

- U of Illinois, Ohio State, MagSoft, AFRL collaboration on NASA LEARN award
- Conduction-cooled, "air-core" SC machine leveraging available MRI-magnet technology
- Active magnetic shield eliminates field outside motor while maximizing "air gap" flux density
- Peak fields up to 10 Tesla
- High field SC (e.g., Nb_3Sn, YBCO)
- Address key technical feasibility questions: high field SC coils, cryogenic TMS, structural integrity, motor power density
- Specific power estimates upto 56 kW/kg for 20 MW, 6000 rpm machine with HTS windings





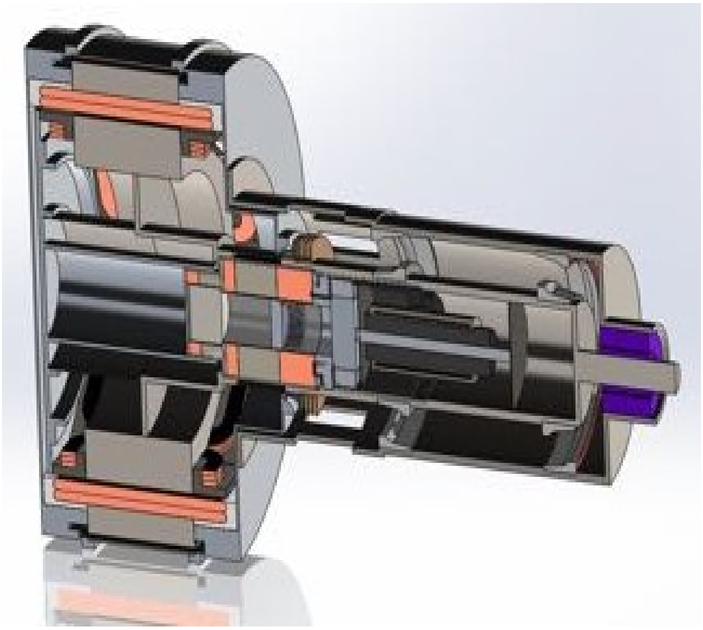
Full-size, conduction-cooled, **6 Tesla** Nb_3Sn coil demonstrated



NASA High Efficiency Megawatt Motor (HEMM)

Topology

- 1.4MW wound-field synchronous motor with a stretch performance goal of 16 kW/kg and efficiency of 99%
- Conductively self-cooled, DC superconducting rotor windings combined with slotless stator
- Exceptional specific power and efficiency without external cooling weight penalty commonly attributed to SC machines

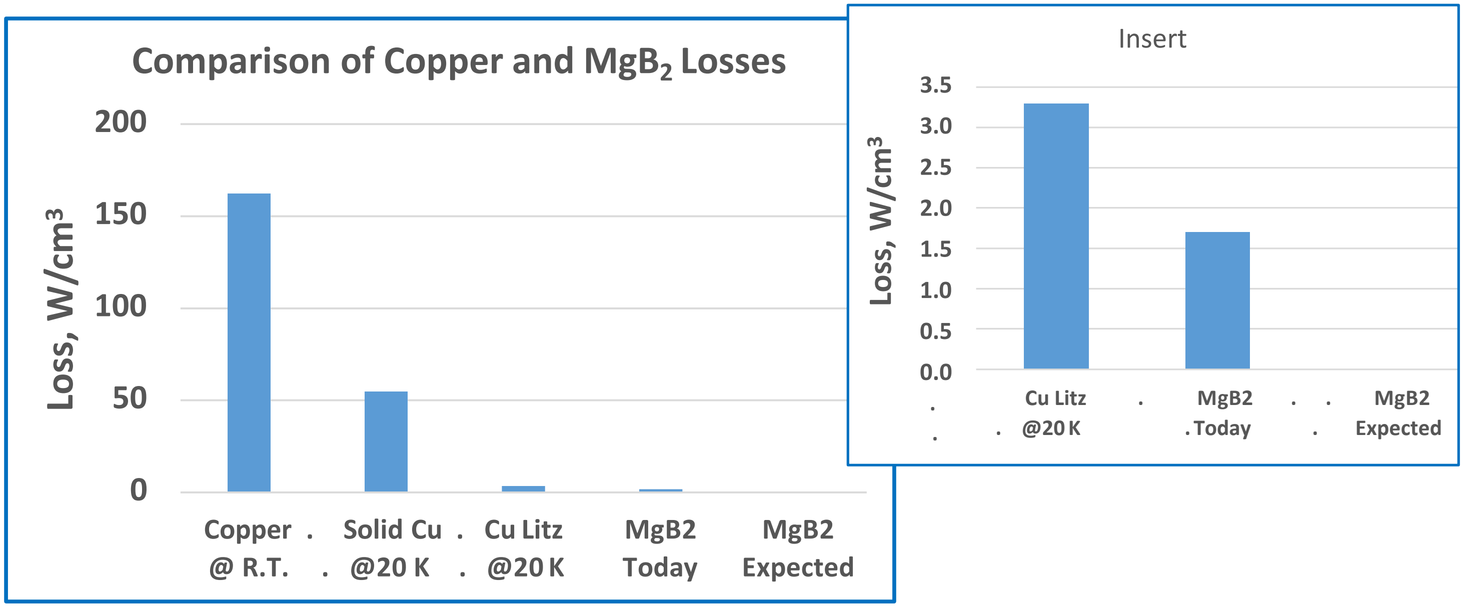


Key Features

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

Fully SC Machines Face Loss Challenges in AC Fields

Cooling copper lowers losses, but fully SC machines have most potential



Today's MgB_2 wire has 1% of the loss of room temperature Cu in AC stators
Today's MgB_2 has half the loss of Cu Litz at 20 K
Future MgB_2 will be an order of magnitude better than Cu Litz at 20 K

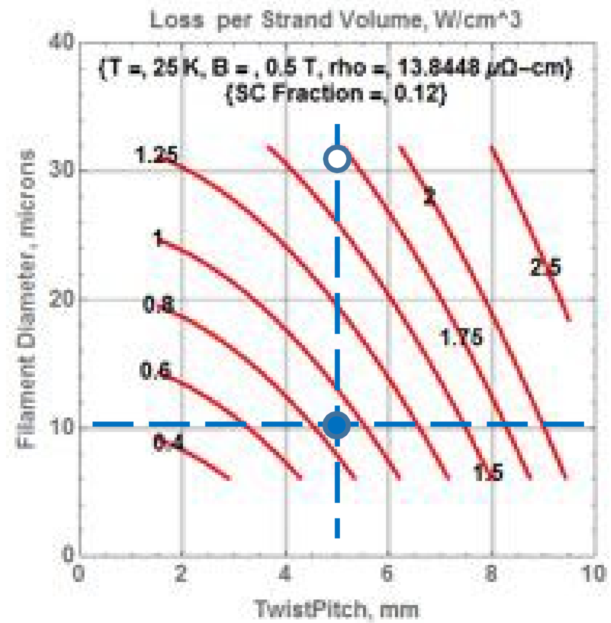
Reducing Losses in AC Stator Requires Litz-like Wire

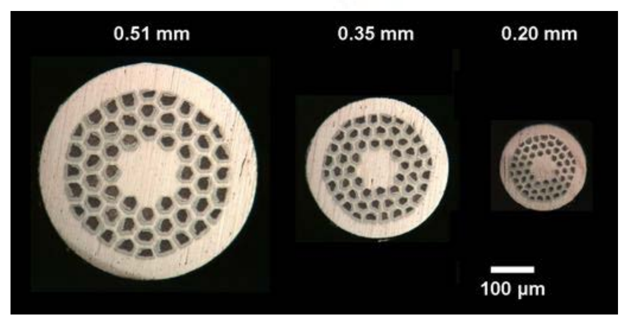
SC wire development driven by calculated (theoretical) AC losses

Solution is fine, tightly twisted filaments

↓Hysteresis Loss, need fine filaments
↓Coupling Loss, need tight twist
↓Transport Loss, usually negligible

SBIR work by Hyper Tech Research

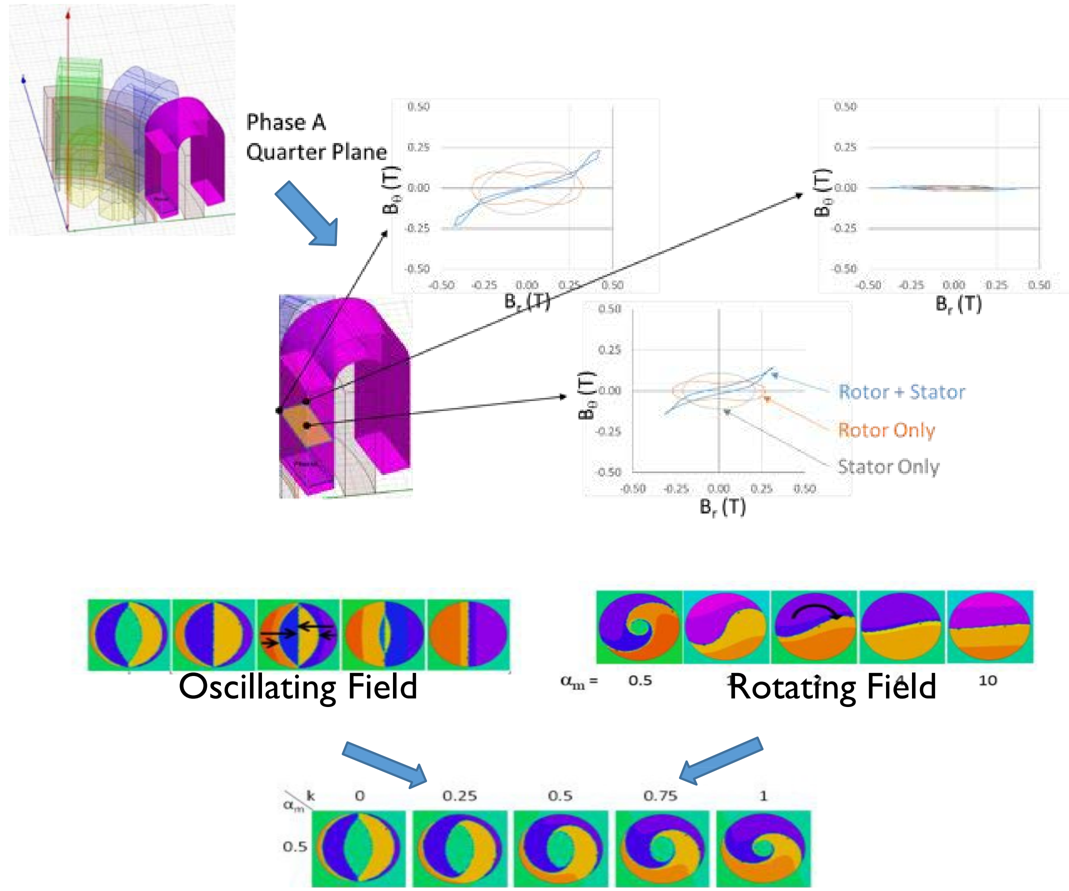




Hyper Tech Research wire configuration options developed under SBIR

Fully Superconducting Machine Development

- Understand complex magnetic fields in real machines
- Conceptual design of fully SC machines
- Superconductor AC loss models (NRA with Applied Magnetics Lab/U of Houston), including new treatment for elliptical fields
- Construction of an AC loss facility with elliptical field capability through NRA investment at FSU Center for Advanced Power Systems

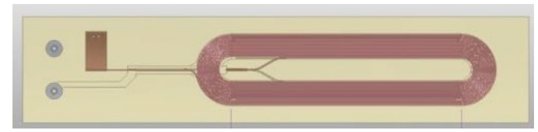


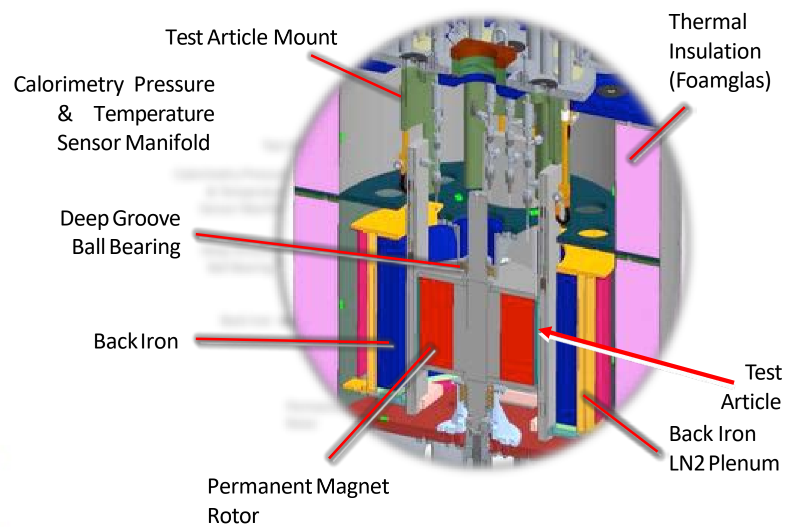
Elliptical Field (superimposed oscillating and rotating)

Testing Capability to Verify AC Loss in Coils at 20°K

- Measure MgB_2 superconductor losses at 20K to 30K
- Accommodate relevant coil size (~6 cm wide by 20 cm long); Magnetic field ~ 0.5 T in ~6 cm radial gap between rotor and back iron; Field frequency from 0 to 400 Hz electrical; Coil current up to 400 A at up to 400 Hz frequencies
- Complements AFRL LN2 test rig by extending capability to LH2 temperature
- Facility planning complete, rotating core under construction

Coil Test Article

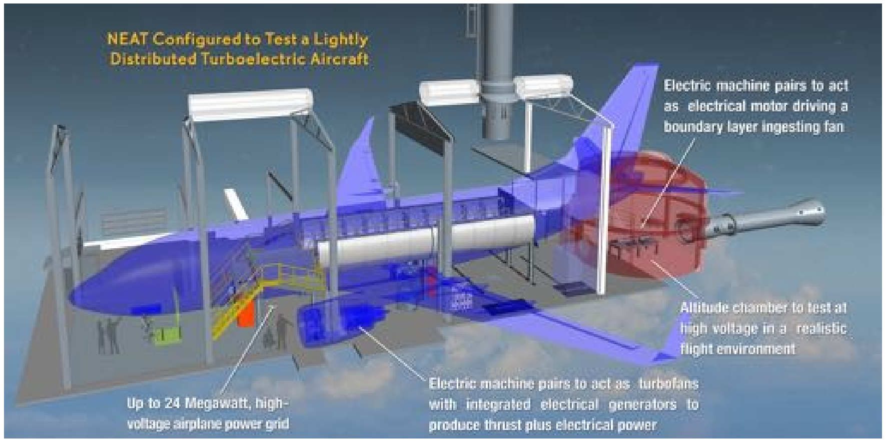




Coil testing rig with permanent magnet rotor

Full Powertrain Testing Capabilities at NEAT Facility

- Reconfigurable NASA Electric Aircraft Testbed (NEAT) being developed to support full-scale large aircraft powertrain testing for community use
- Infrastructure for up to 24 MW input power with regeneration, cryogenic fluid and fuel handling fuel, multi-MW cooling, and 120,000 feet altitude flight environment capability
- Plans to demonstrate high fidelity turbo-generation and ducted fan transient emulation, test MW-class research motors, inverters, and single- and multi-string powertrains



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The Path Forward…

- Work both ambient temperature and superconducting solutions
- Scale up from regional jets to large single-aisle and beyond
- Advance core technologies: turbine-coupled motors, generators, power system architectures, power electronics, thermal management, flight controls
- Develop modeling/simulation tools needed
- Demonstrate technology at components, subsystems, and system level
- Viable concepts with net reduction in energy use, noise, and emissions

Exciting times ahead! Need your help!

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