The Electrifying Future of Air Transportation

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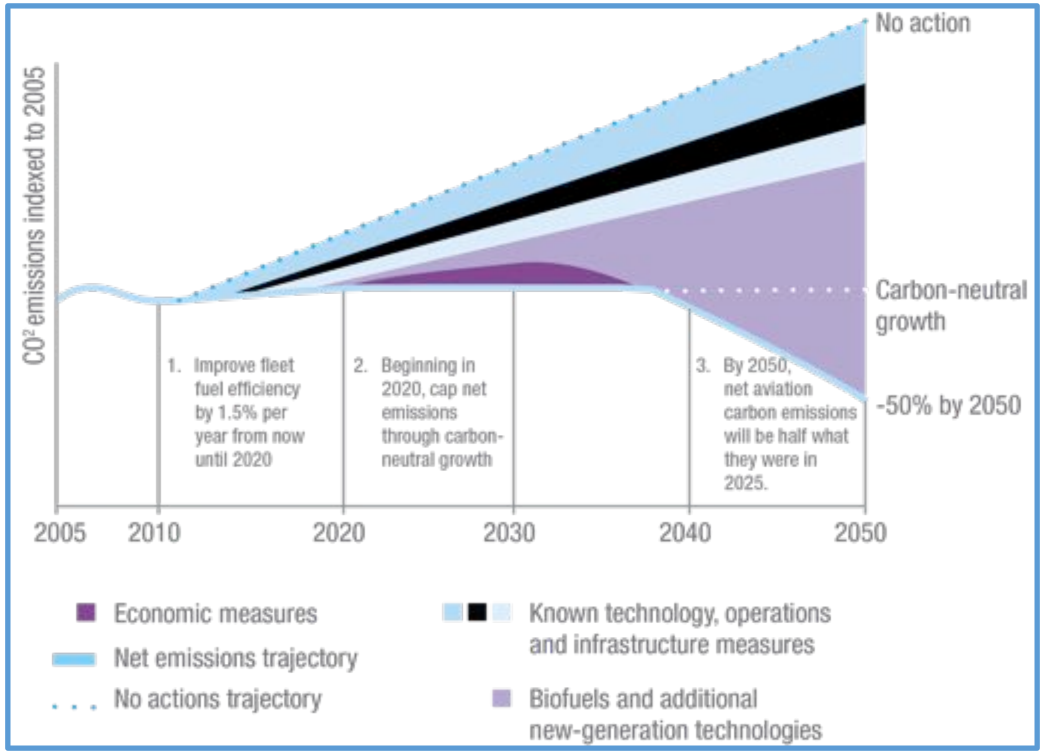
NASA Vision for the Future of Commercial Aviation

The Era of Aviation Electrification

- This era is unfolding now!
- Completely transform aviation and air travel
- Open up the skies to new ways of moving people and cargo
  - Drones, personal air vehicles, on-demand urban air mobility
- Lead to radically new and better designs for commercial subsonic transport aircraft

Images courtesy of: Amazon, Airbus, Vision, Joby, NASA

The Aviation Challenge: Sustainable Growth



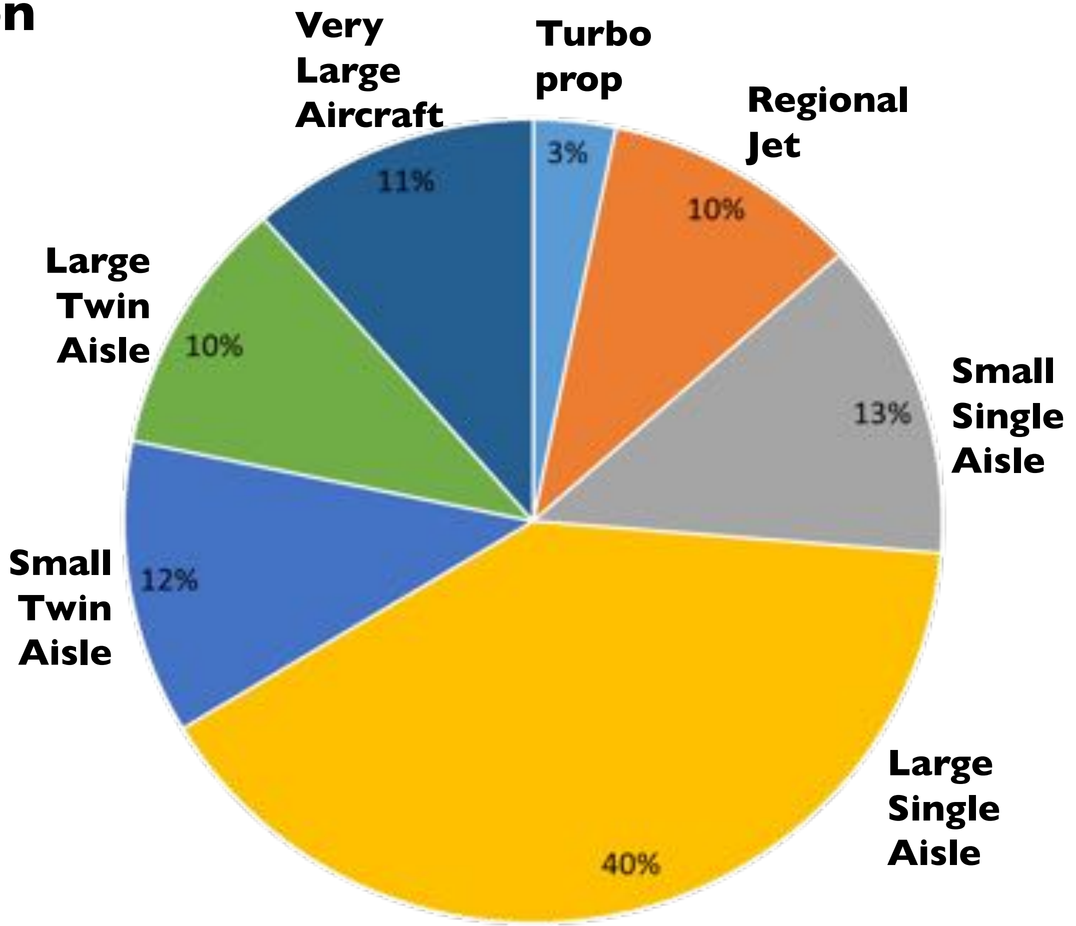
Reduce carbon footprint by 50% by 2050, while…

- meeting increasing demand
- meeting landing and takeoff noise regulations
- meeting emissions regulations
- reducing aircraft development, manufacturing, and operational costs

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

Why Focus on Commercial Transport Aircraft?

2012 Fuel Consumption



100+ passenger aircraft consumed 87% of fuel!

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

Targeting Large Transports will Benefit Range of Aircraft Sizes

2015 → 2035

Largest Electrical Machine On Aircraft

Non-Cryo | 100 kW | 1 MW | 3 MW | 10 MW | 30 MW | Super Conducting

9 Seat/0.5 MW Total

50 kW – 250 kW

19 Seat/2 MW Total

100 kW – 1 MW

50 Seat/3 MW Total

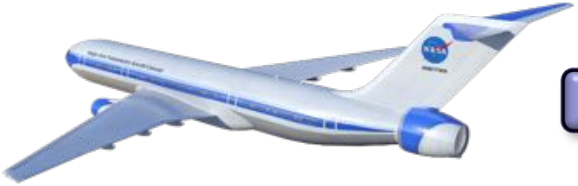
300 kW – 3 MW

150 Seat/22 MW Total

1 MW – 11 MW

300 Seat/60 MW Total

3 MW – 30 MW

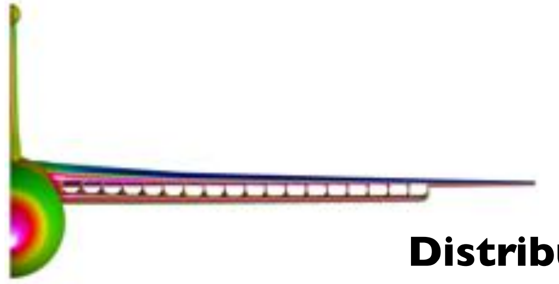


Left side of power range bar denotes is smallest motor that yields net benefit for a partially electrified airplane. Right side is the size of a generator for a twin turboelectric system for a fully electrified airplane

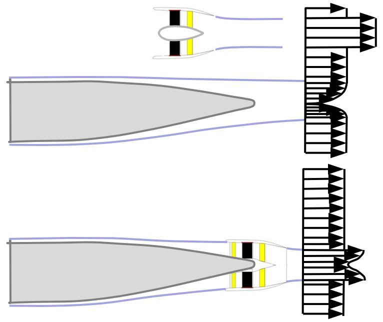
1 MW electric machines identified as a key initial focus with impact on multiple seat classes

Making Electrification Work: Offsetting Electrical System Penalties

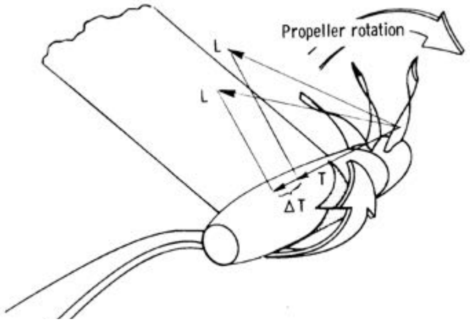
- Improve aerodynamic and propulsive efficiency
  - Distributed propulsion, Boundary layer ingestion, Wing-tip propulsion
- Target weight reductions in other systems
- Use stored energy judiciously
- Leverage flexibility offered by decoupling of power and propulsion functions
- Think exciting configuration options beyond "tube-and-wing"



Distributed Propulsion



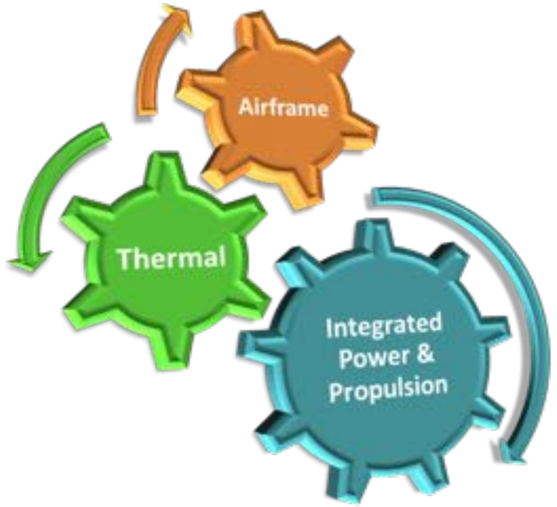
Boundary Layer Ingestion



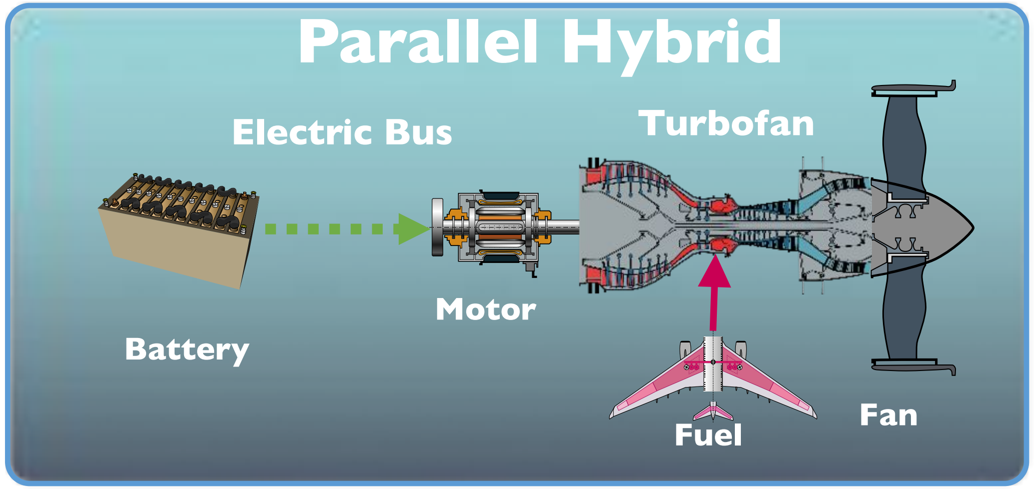
Wing Tip Propulsors

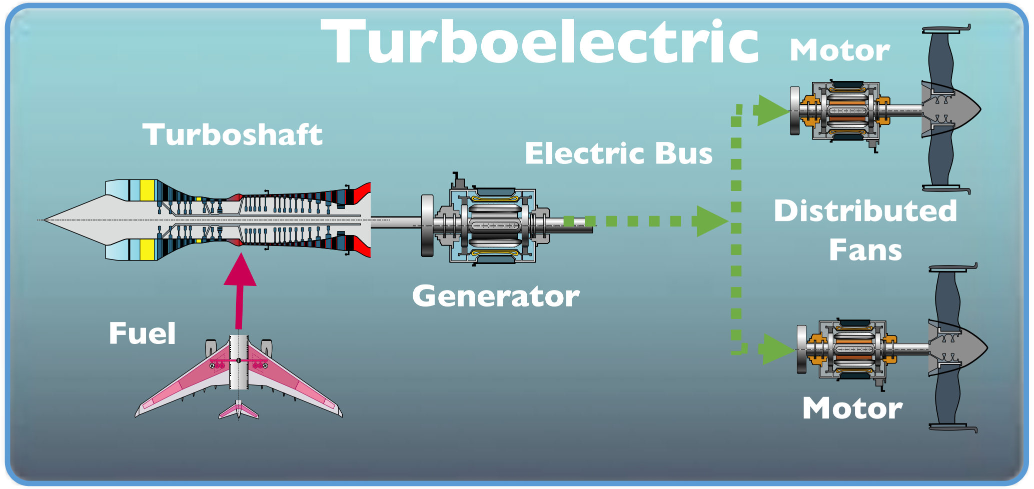
Electrification: Key Technical Challenges

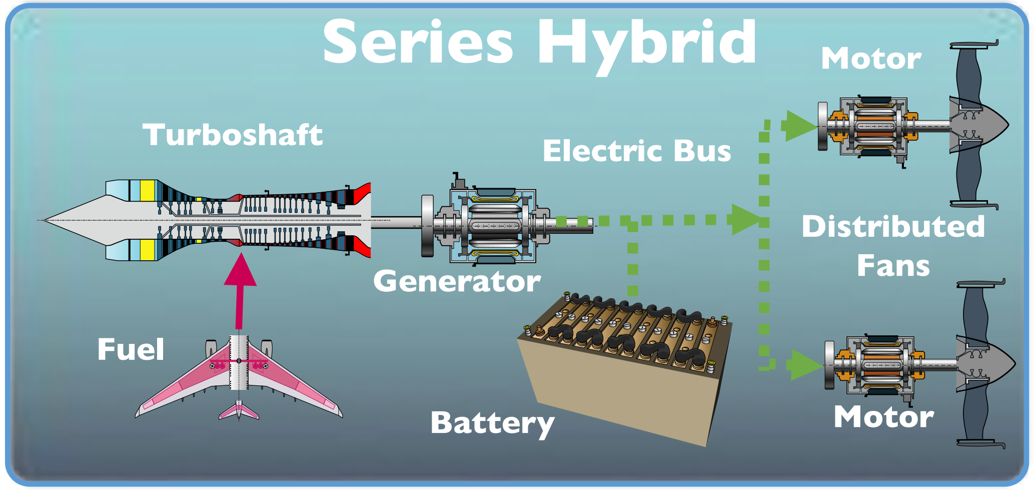
- Electrical system weight and efficiency
- Energy storage capabilities
- High voltage
- Thermal management
- Flight controls
- Safety
- Certification

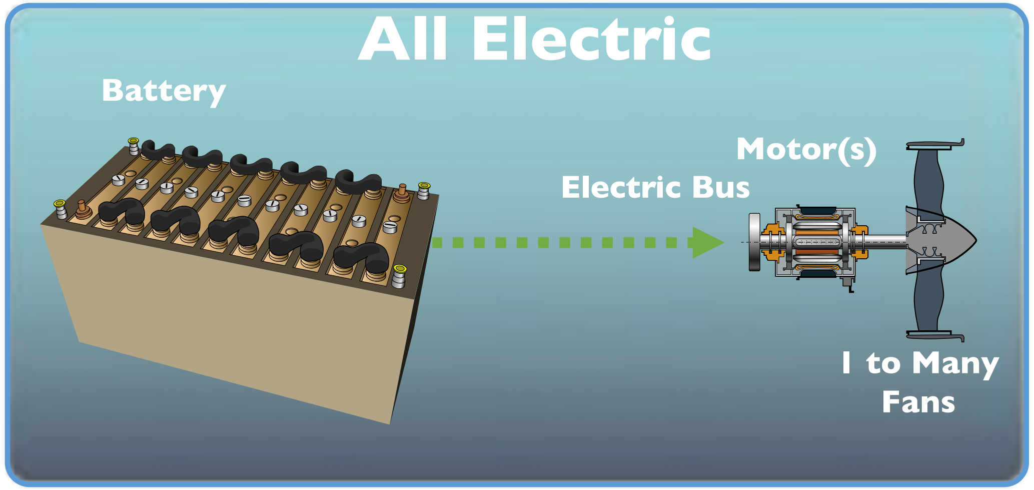


Electrified Aircraft Propulsion Architectures









Future Electrified Aircraft Concepts

Near-Term Concepts

- Parallel hybrids with judicious use of stored energy during mission
- Ongoing work with RR and UTRC
- Ambient temperature partially turboelectric
- High efficiency and high specific power electrical systems operating at much higher voltages than current aviation standard

Boeing Sugar Volt

NASA STARC-ABL

Far-Term Concepts

- Superconducting turboelectric systems augmented with some stored energy use
- Multi-kV power architectures with very high efficiency and specific power electrical systems

NASA N3X

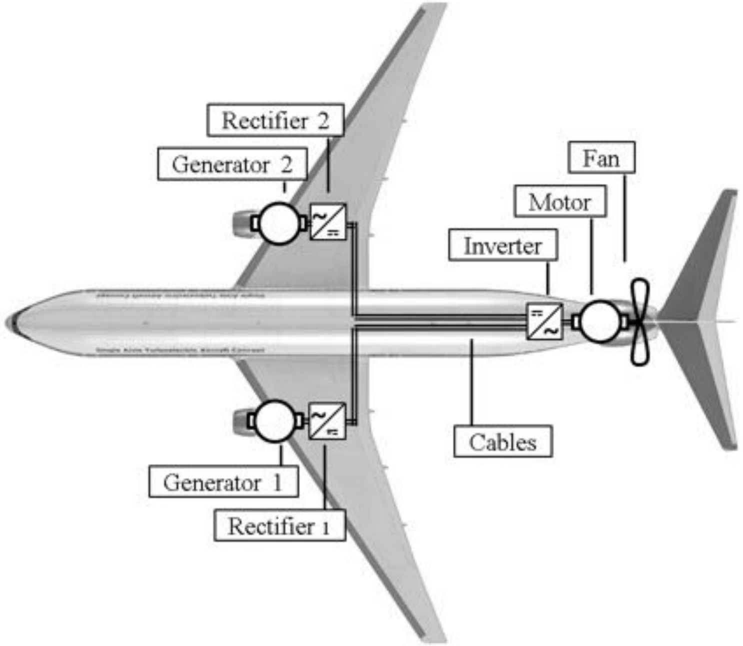
Airbus/RR eThrust

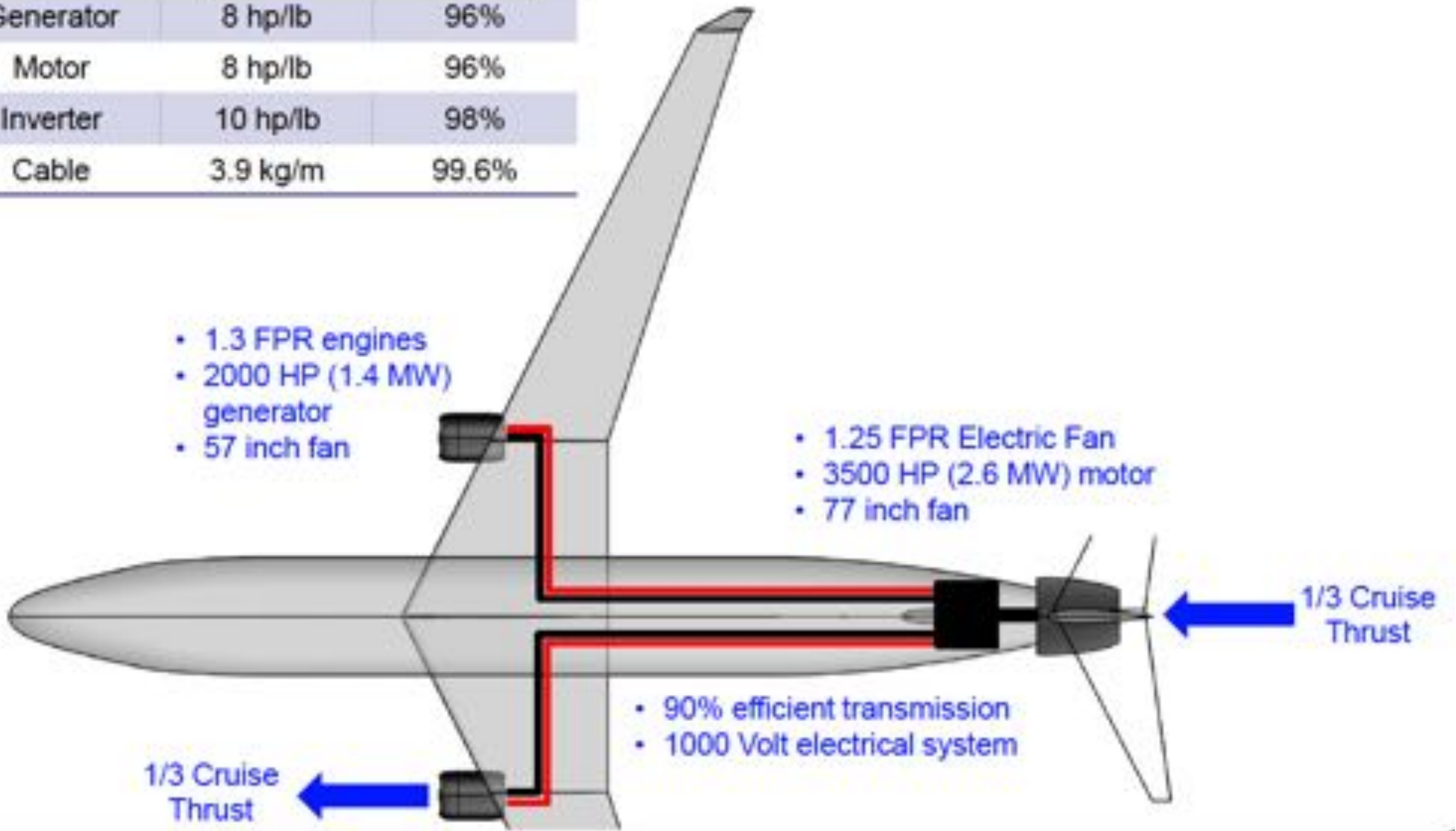
Starc-ABL Powertrain Architecture

7-12% fuel (and energy) savings relative to baseline advanced aircraft with no improvements in energy storage technology

Electrical Component Assumptions

Component	Spec Pwr/Wt	Efficiency
Generator	8 hp/lb	96%
Motor	8 hp/lb	96%
Inverter	10 hp/lb	98%
Cable	3.9 kg/m	99.6%

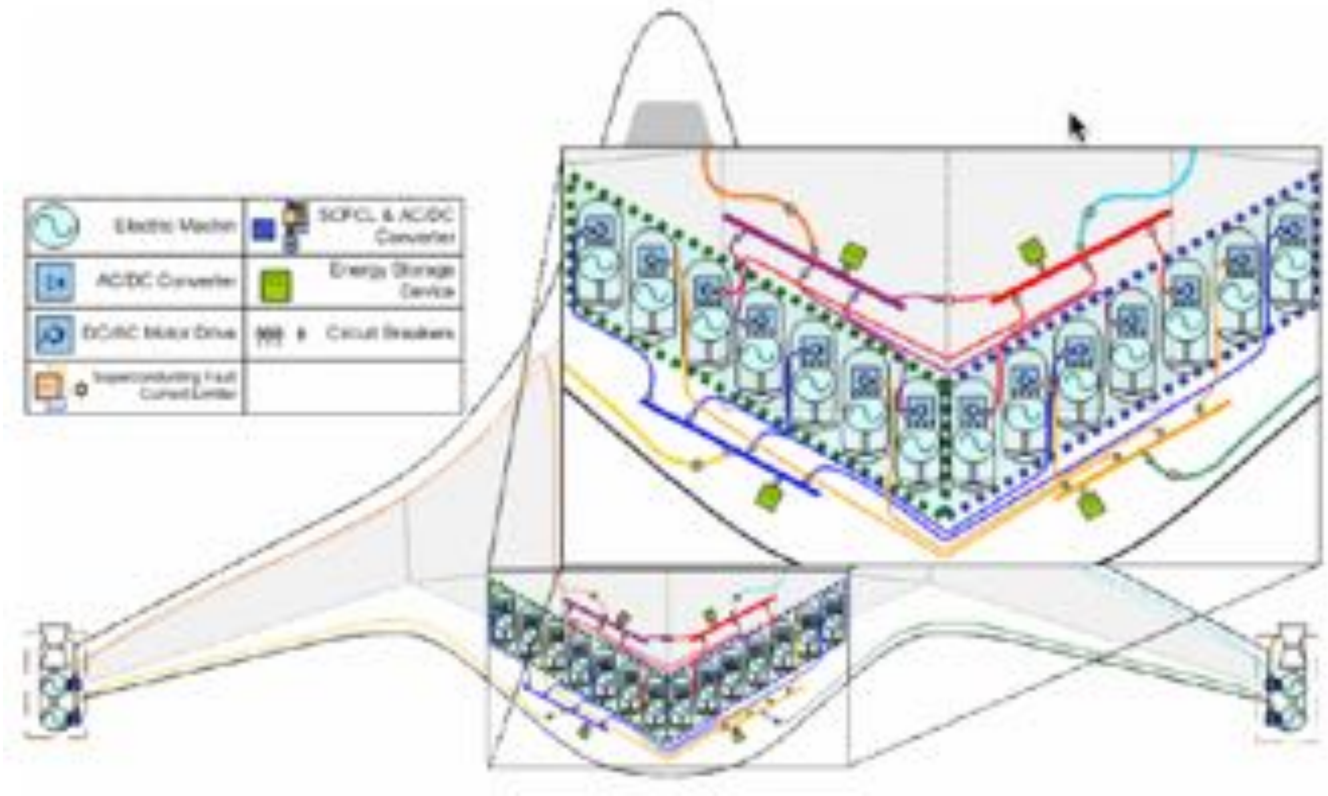


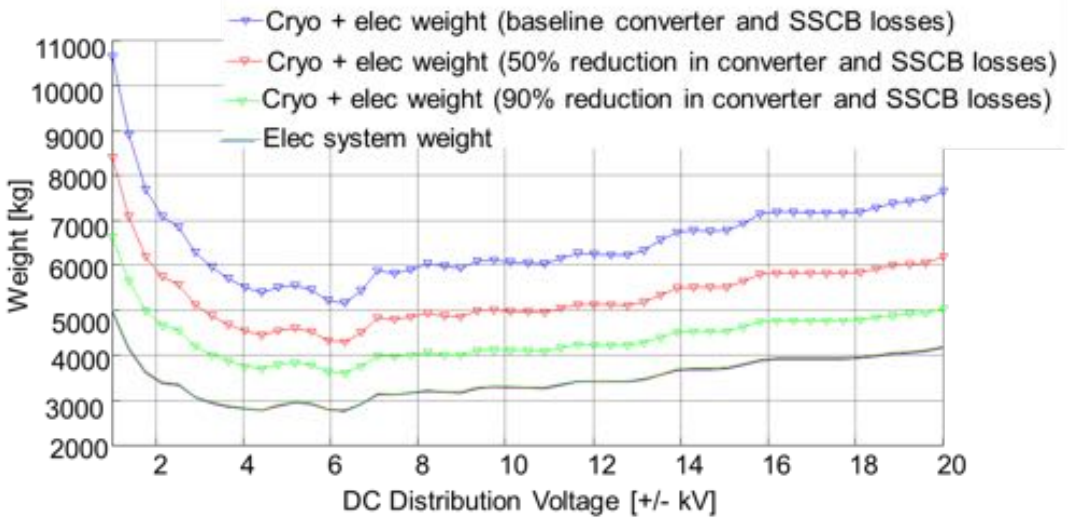


N3-X Superconducting Powertrain Architecture

Detailed Architecture Analysis conducted by GE & Rolls-Royce NA

2 30 MW Generators and 14 4.3 MW Motors





Electrical Efficiency of Cryogenic Components is Crucial

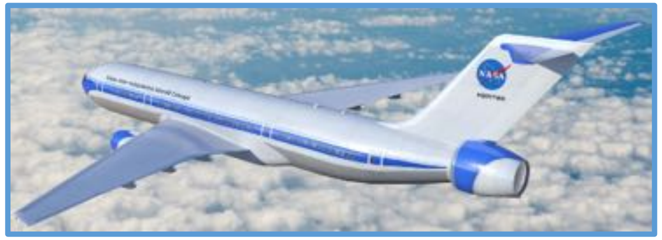
DC Bus Voltages in 4-8 kV Range

NASA Electrified Aircraft Propulsion R&T Investments

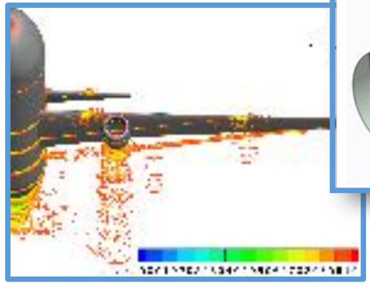
Technology development targeted toward large commercial aircraft

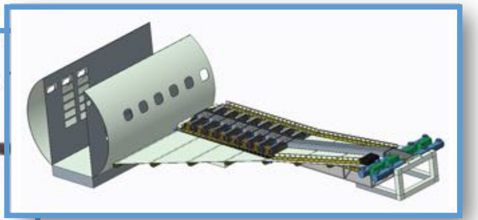
- Propulsion System Conceptual Design
- High Efficiency/Specific Power Electric Machines
- Flight-weight Power Systems and Electronics
- Integrated Flight Simulations and Testing
- Turbine-Generator Integration and Control
- Enabling Materials for Machines and Electronics

Architecture Exploration

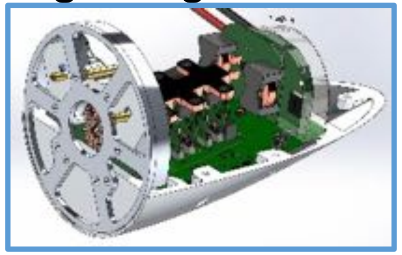


Powertrain, Controls and Flight Simulation Testbeds and Advanced CFD



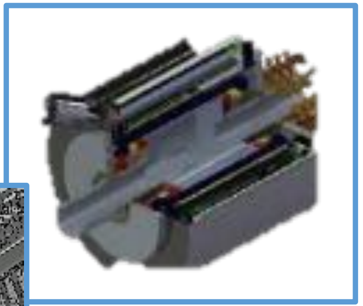


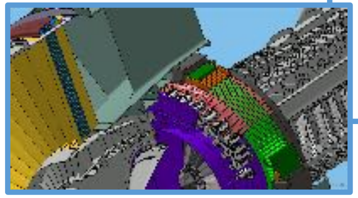
Novel Designs for Flightweight Power



Advanced Materials

Superconducting and Ambient Motor Designs



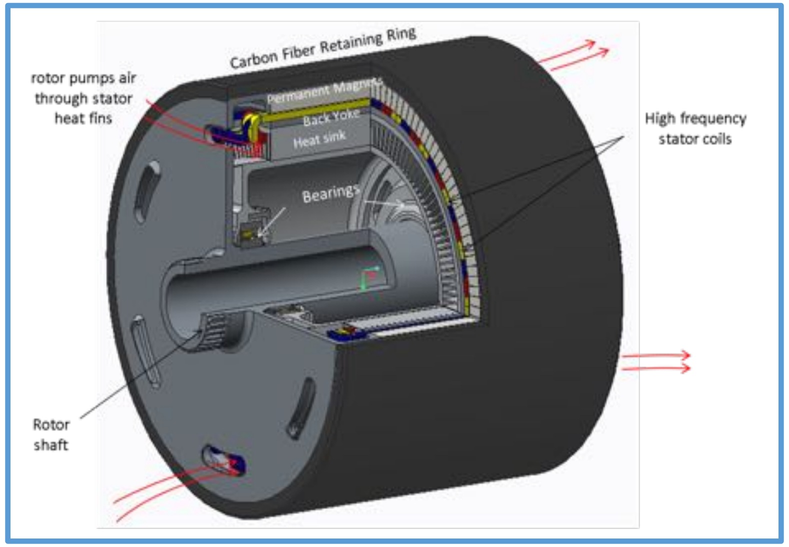


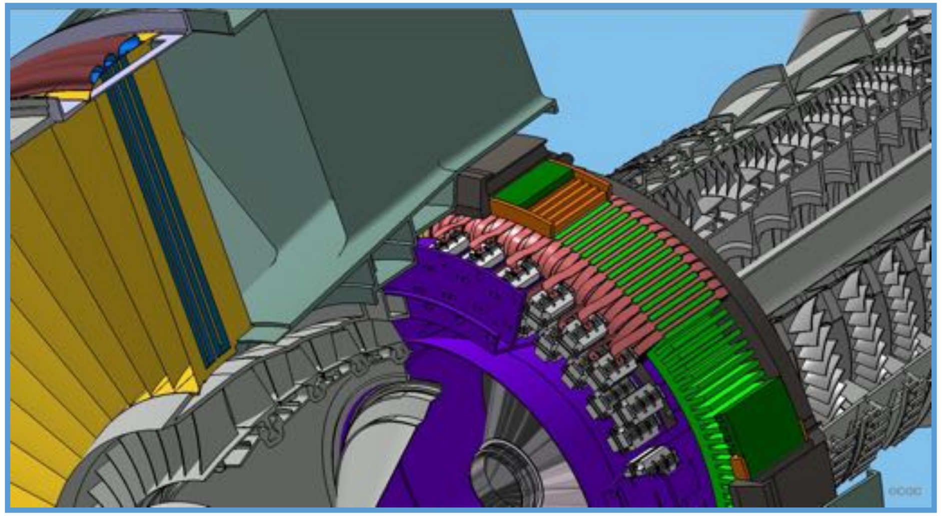
Ambient Temperature Electric Machines

Scalable high efficiency and specific power (96%, 13 kW/kg) MW-class non-cryogenic motors

U of Illinois Permanent Magnet Motor

- U of Illinois, UTRC, Automated Dynamics
- High pole-count, ironless motor with composite rotor
- Modular, air-core armature
- Modular, passively-cooled drive with wide-bandgap devices integrated with motor





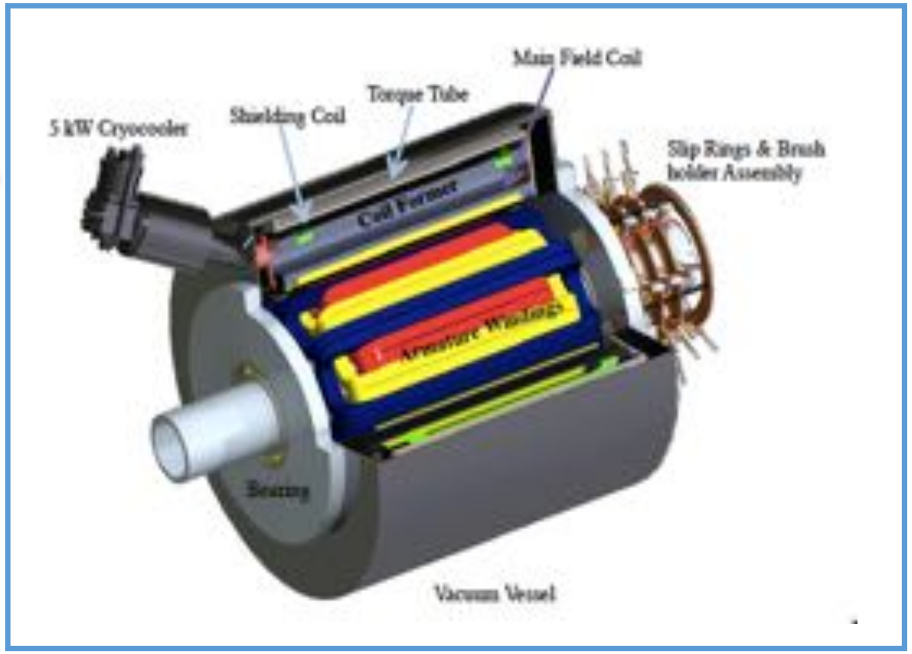
Ohio State University Ring Motor

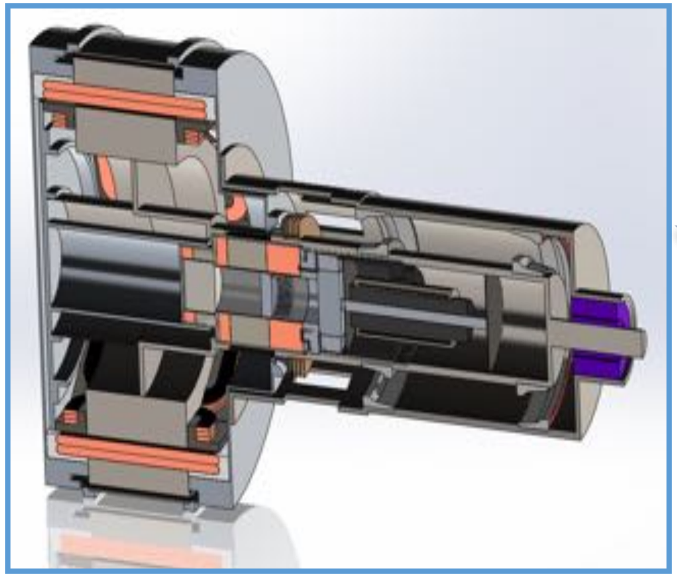
- Motor integrated on LPT spool of CFM56 engine
- Reversed (ring) concept with integrated, direct cooling based on Variable Cross-Section Wet Coils (VCSW) coil design
- Extensive testing of concept at three power levels

Partially Superconducting Machines

U of Illinois High Field Partially SC Motor

- U of Ill, Ohio State, MagSoft, AFRL collaboration on NASA 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
- Specific power estimates up to 56 kW/kg for 20 MW, 6000 rpm machine with HTS windings





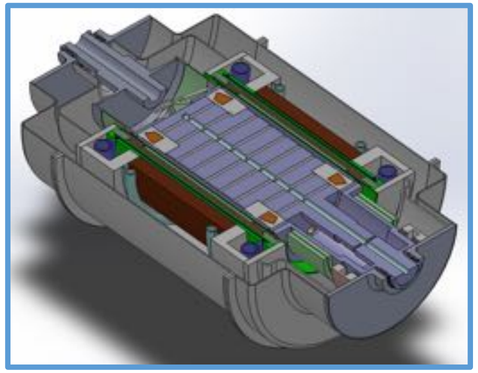
NASA High Efficiency Megawatt Motor (HEMM)

- 1.4MW wound-field synchronous motor with a stretch performance goal of 16 kW/kg specific power and 99% efficiency
- Conductively self-cooled, SC rotor windings combined with slotless stator
- Exceptional specific power and efficiency without external cooling weight penalty commonly attributed to SC machines
- Direct drive at optimal turbomachinery speeds (no gearbox)

Fully Superconducting Machines

Fully Superconducting Machine Conceptual Design

- Detailed concept design completed of 12MW fully superconducting machine achieving 25 hp/lb (41 kW/kg) (collaboration with Navy, Air Force, Creare, HyperTech, Advanced Magnet Lab, U of FL)
- Plans to build and test fully superconducting electric machine test at 0.5 MW level



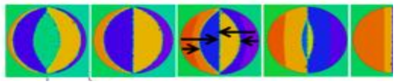
Testing Capability to Verify AC Loss in Coils at 20°K

- Measure MgB_2 superconductor losses at 20K to 30K
- Accommodate relevant coil size and current, magnetic field and frequency
- Complements AFRL LN_2 test rig by extending to LH_2 temperature
- Facility planning complete, rotating core under construction

Fully Superconducting Machines …contd.

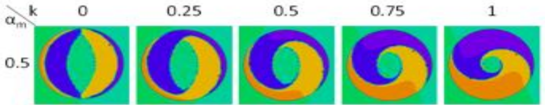
Supercond. AC Loss Model Development

- 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 at FSU Center for Advanced Power Systems

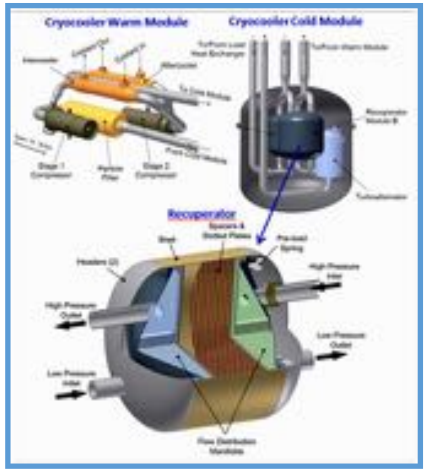


Oscillating Field

Rotating Field



Elliptical Field (superimposed oscillating and rotating)

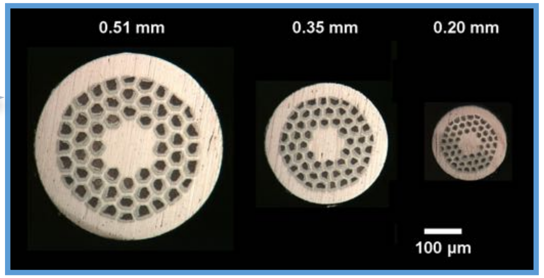


Lightweight Cryocooler Technology Development

- Creare turbo-Brayton cryocooler development under NASA SBIR
- Goal is 3 kg/kW-input at 30% of Carnot (6x better than current SOA)

MgB_2 Wire Development by Hyper Tech Research

- Demonstrated capability to fabricate 10 micron diameter wire filaments
- Reducing losses in AC stator requires Litz-like wire with fine, tightly twisted filaments



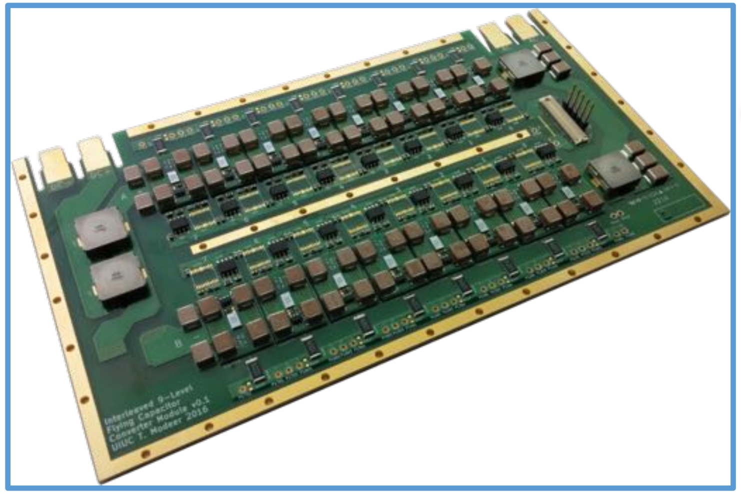
MgB_2 wire config options

Flight-Weight Power Converters

NASA Sponsored Inverter Research Specifications: 1 MW, 3 Phase AC output, > 1 kV DC bus, 19 kW/Kg and 99% specific power and efficiency (26 kW/Kg, 99.3% for cryo)

GE SLIM (SiC Lightweight Inverter for MW Power)

- 1.7/2.5 kV SiC MOSFET modules
- 3 level topology
- FPGA based controller
- Advanced filter design



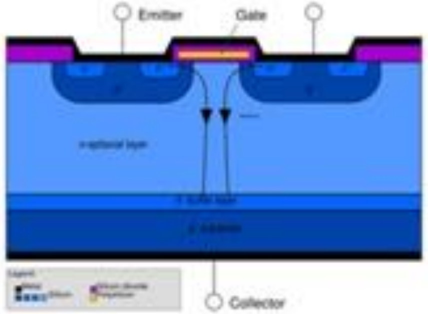
U of Illinois GaN-based Inverter

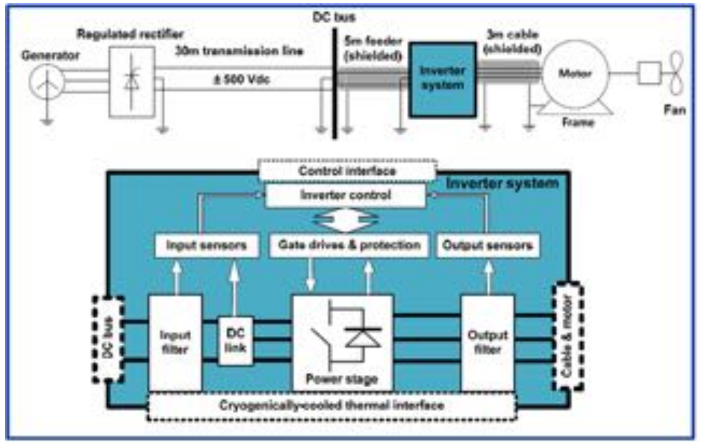
- Flying capacitor multi-level (9-level) topology to minimize current and torque ripple and AC losses
- Capacitor-based inverters with potential to offer much higher power density than inductor-based designs
- Higher equivalent switching frequency
- 200 kW prototype demonstration in 2018

Cryogenic Power Converters

MTECH Cryogenic Inverter

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



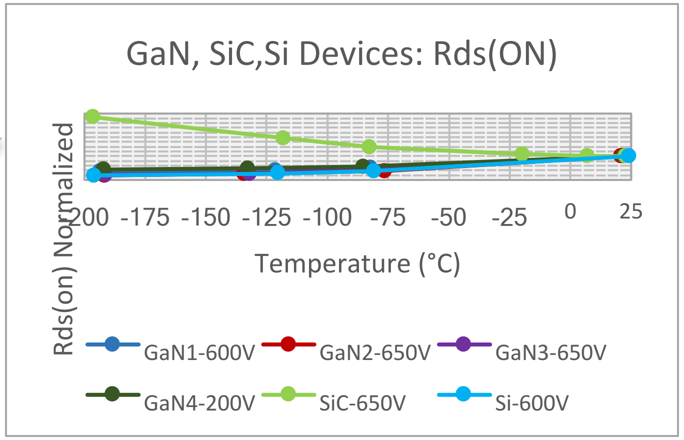


Boeing/UTK Cryogenic Inverter

- 1 MW operation with 26 kW/kg, >99% efficiency
- LNG or LH2 operation
- 1 kV 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



Turbine High Power Extraction

GE Power Extraction Test on F110 Engine

- Collaboration between GE, AFRL, and NASA
- Upto 1 MW power offtake, 250 kW from turbine low spool and 750 kW from high spool at altitude conditions
- Engine continued to generate conventional thrust
- Understand impact of high power extraction on engine operability

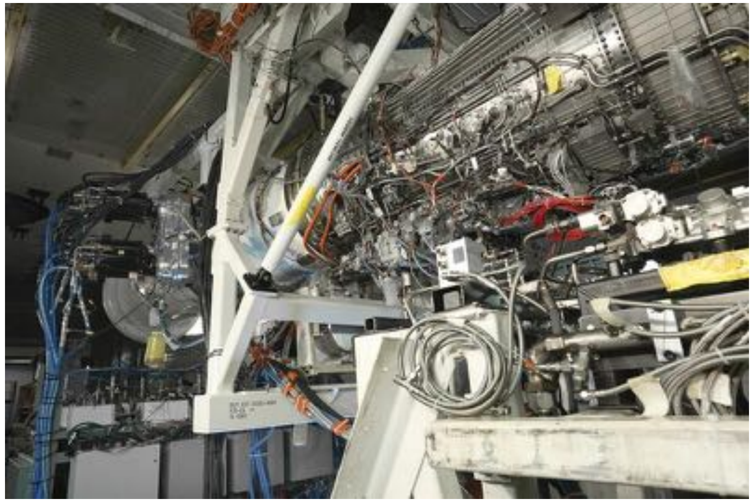
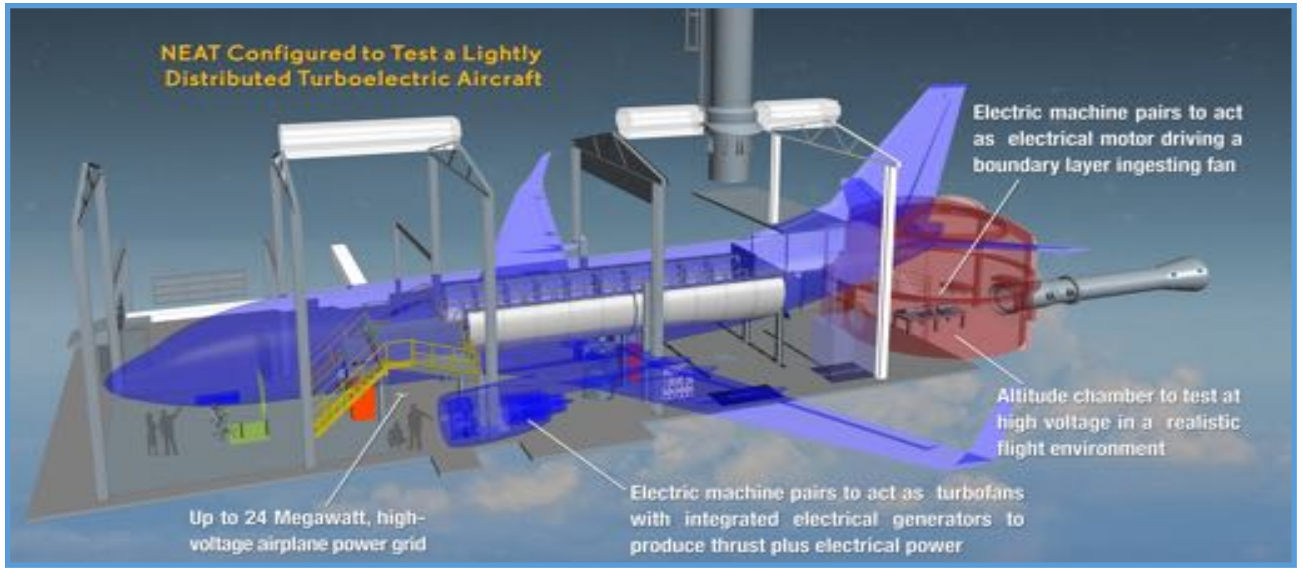


Image courtesy of: Aviation Week

NASA Electric Aircraft Testbed (NEAT) Facility

- Reconfigurable testbed to support full-scale large aircraft powertrain testing
- 24 MW input power, cryogenic handling, multi-MW cooling, and 120K ft. 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



Electrification: The Promise

Energy usage reduced by more than **60%**

Harmful emissions reduced by more than **90%**

Objectionable noise reduced by more than **65%**

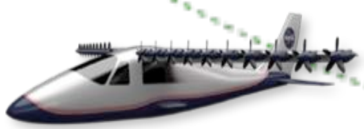
Advanced configuration with fully integrated hybrid electric propulsion and airframe

2040

Increasingly electric aircraft propulsion with minimal change to aircraft outer mold lines

2030

Gain experience through integration and demonstration on progressively larger platforms



2020

The Path Forward…

- Work both ambient temperature and superconducting solutions
- Scale up from regional jets to large single-aisle and beyond
- Advance core technologies including turbine-coupled generators, motors, power system architectures, power electronics, thermal management, flight controls
- Demonstrate technologies at component, subsystem, and system level
- Focus on viable concepts offering net reductions in energy use, noise, and emissions

Exciting times ahead! Need your help!