NASA’s Electric Aircraft Propulsion Research: Yesterday, Today and Tomorrow

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Yesterday

Grand Question:

- Is there something here?

Focus: MW Scale Aircraft

- Regional
- Single aisle
- Wide body

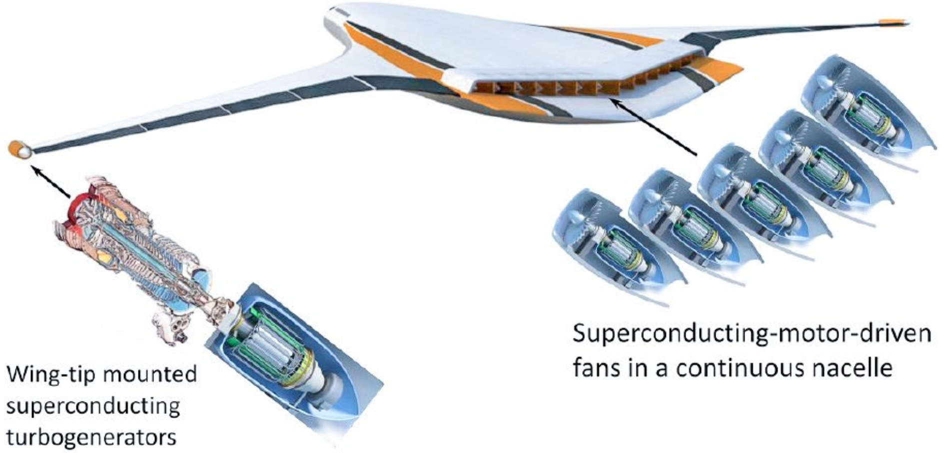
Studies

Starting in 2014 more than 13 trade studies have been conducted

- Wide ranging trade studies
  - Cryogenic and non-cryogenic hybrid electric distributed propulsion
  - Airframe integration
  - Thermal systems
  - Hybrid electric systems
  - Controls
- Partners have included
  - Boeing
  - General Electric
  - Empirical Systems Aerospace
  - United Technologies (now Raytheon)
  - Rolls-Royce North America
  - Georgia Tech

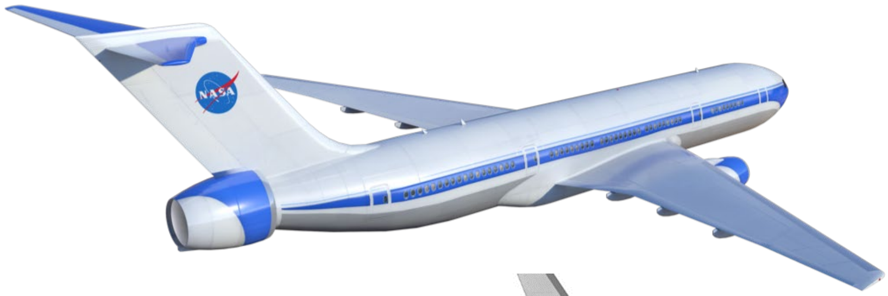
Concepts

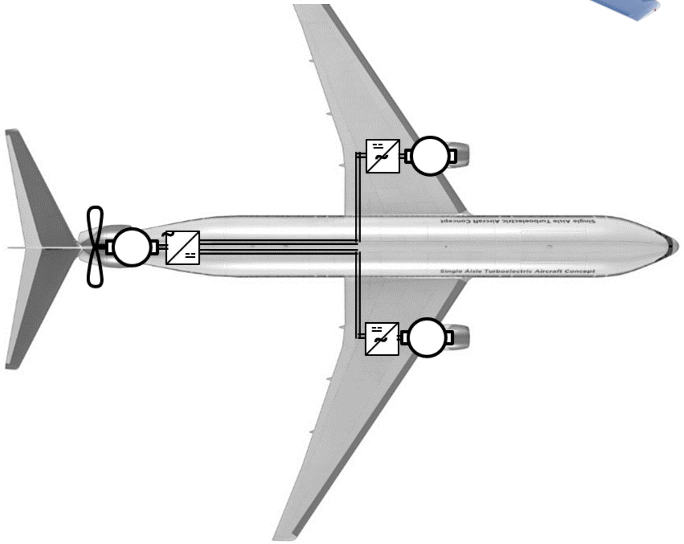
N3X



- Turboelectric
- 40 MW
- Superconducting machines and buss
- Boundary layer ingestion

STARC-ABL



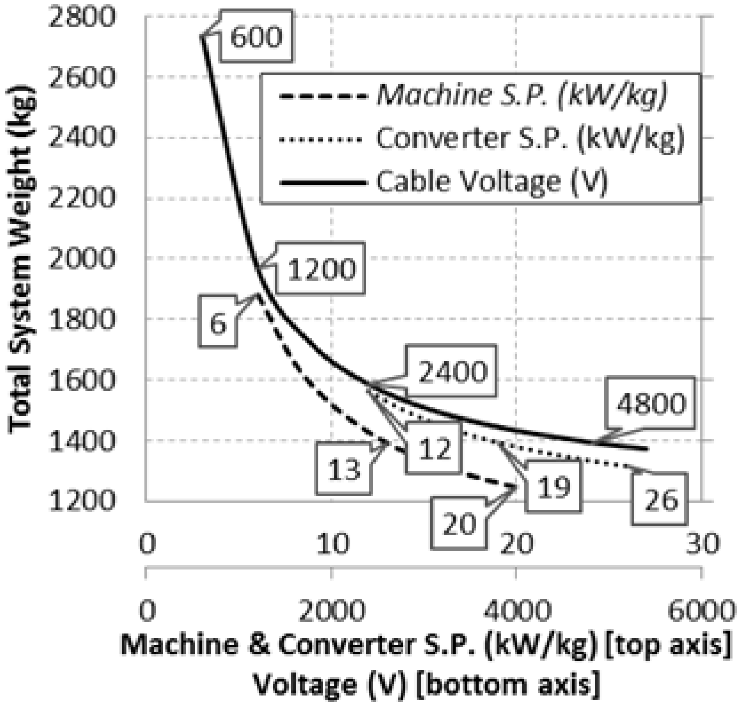


- Partial- turboelectric
- 2.5 MW tail cone thruster
- Boundary layer ingestion

Goals

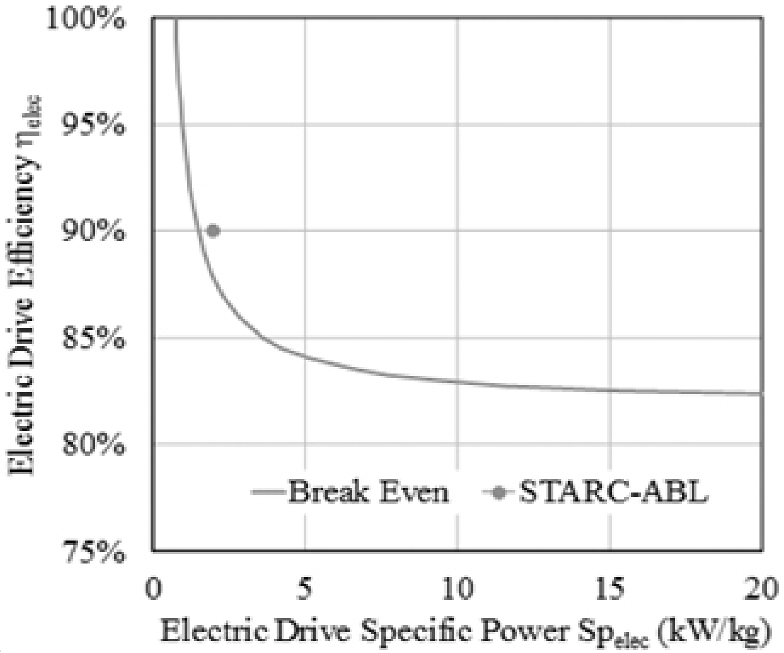
1 MW motor goals

	Specific Power (kW/kg)	Specific Power (hp/lb)	Efficiency (%)
NRA Goal	13.2	8.0	96.0



1 MW inverter goals

	Specific Power (kW/kg)	Specific Power (HP/lb)	Efficiency (%)
Minimum	12	7.3	98.0
Goal	19	11.6	99.0
Stretch	25	15.2	99.5



Metrics developed for NASA's STARC-ABL partial turbo electric concept

Haran, K. *Electrified Aircraft Propulsion: Powering the Future of Air Transportation*: Cambridge University Press, 2021.

Technology Development

Inverters:

Goal of 1 MW operation, 99% Efficient, 19kW/kg, ≥1kV

- “Silicon-carbide Lightweight Inverter for Megawatt-power” (SiC based)
  - GE Global Research PI: Satish Prabhakaran
  - Continued development to TRL6 continued with GE
- “Modular and Scalable High Efficiency Power Inverter for Extreme Power Density Applications” (GaN HEMT based)
  - U.C. Berkley / U. of Illinois PI: Robert Pilawa
- “Ultra-light Highly Efficient MW-Class Cryogenically-Cooled Inverter for Future All-Electric Aircraft Applications” –SiC device based
  - Goal Metrics: 26kW/kg and 99.3% efficient
  - Achieved: 99.34% and 26.16kW/kg
  - Boeing Inc. PI: Shengyi Liu
- HLMC (High Lift Motor Controller) 13kW, 98% efficient, air cooled, mass 1kg (SiC device based)
  - POC: Dave Avanesian
  - Designed to meet X-57 high lift motor requirements

Motor :

Goal of 13kW/kg , 1MW 96% efficient

- “High Speed, High Frequency Air-core Machine and Drive”
  - U. of Illinois PI: Kiruba Haran
  - NASA TM: Andy Provenza
- “10 MW Ring Motor”
  - Ohio State U., PI: C. G. Cantemir;
- NASA In-house effort , 98% Efficient, 16kW/kg, 1.46MW (on going)
  - High Efficiency Mega watt Motor (HEMM)
  - Partially Superconducting
  - NASA-PI: Ralph Jansen

Take away: Invested in a significant portfolio of work that showed feasibility

Today

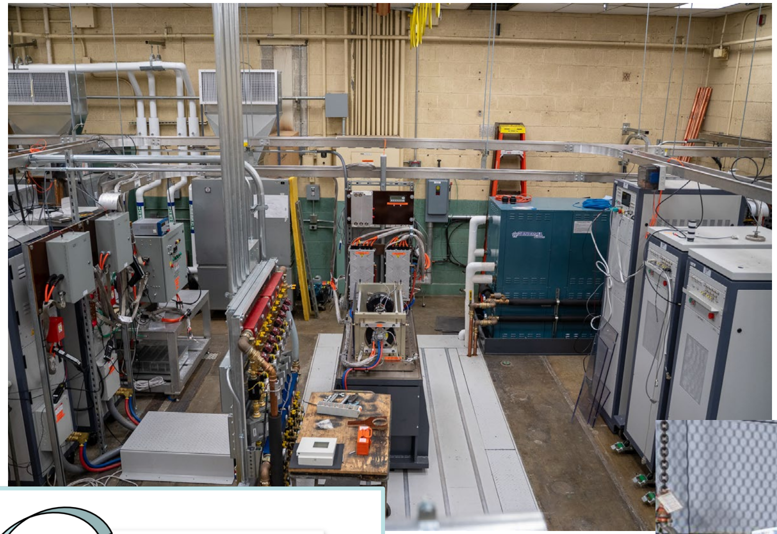
Grand question:
Will it fly?

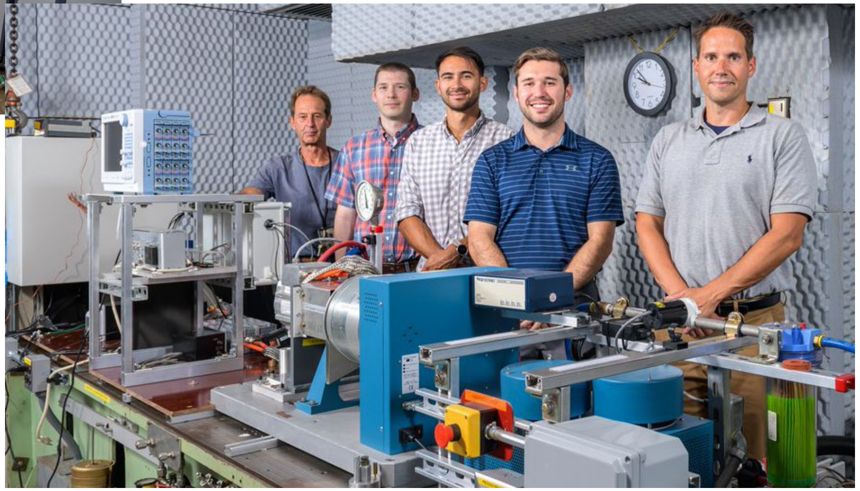
Focus:

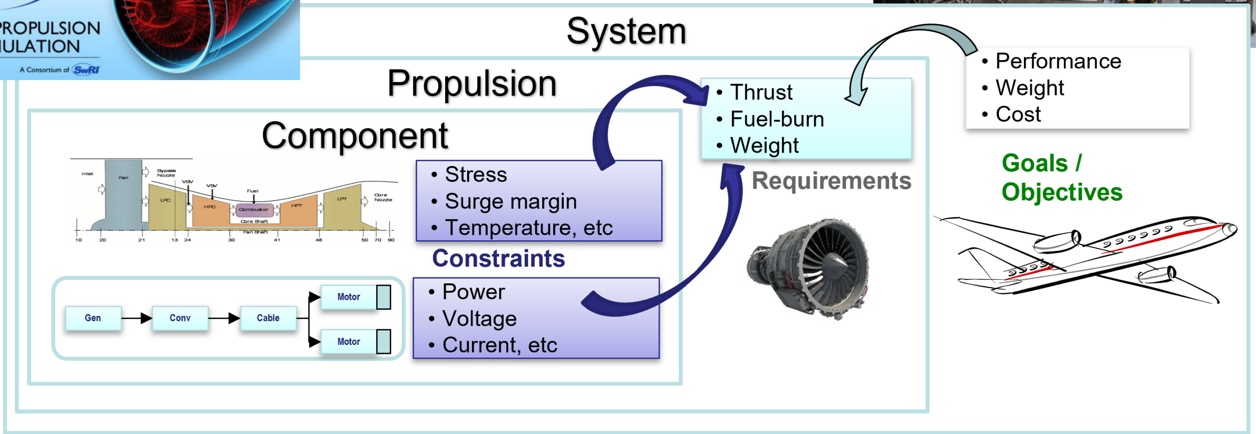
- Regional & single isle aircraft
- 1-5 MW systems (~1 kV, ~1 kA)
- Hybrid electric or partial turbo electric
- Is it safe?

Urban Air Mobility

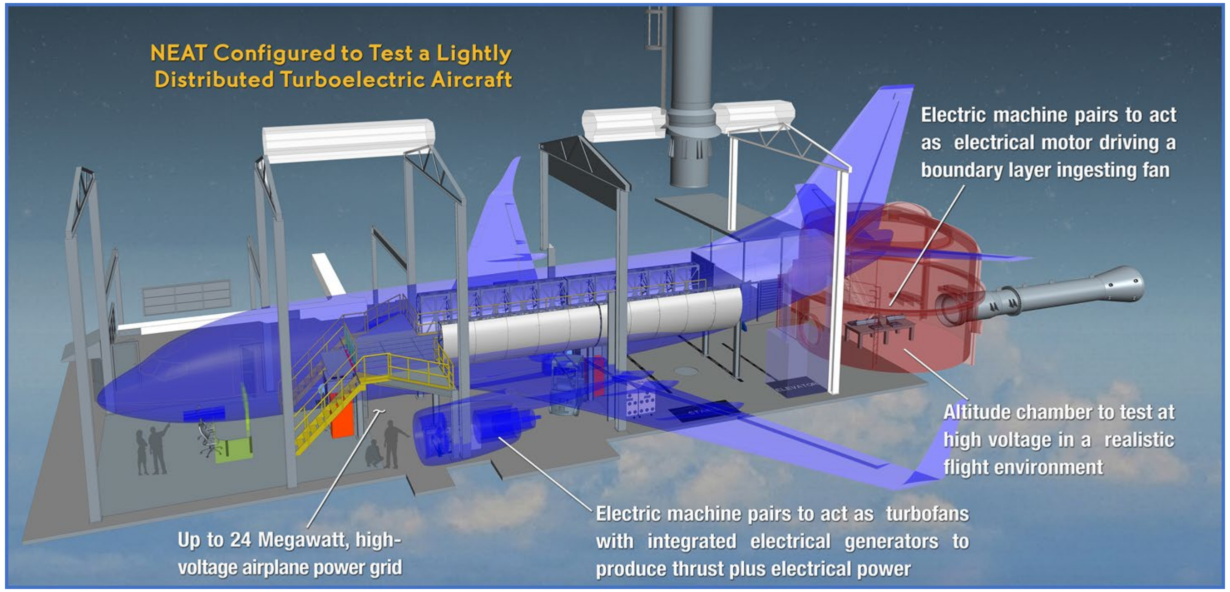
- Sub MW level (non-transport class)
- Standards and regulations
- Analysis tools
- Testbed development
- Validation
- Motor research
- Power quality







NASA Electric Aircraft Testbed (NEAT)



Recent Accomplishments

- Altitude testing with GE Avation
  - GE Claims World First With High-Voltage High-Altitude Power Demo*
- Testing of OSU/UW ULI project
- TEEM system control test
- STARC-ABL control system test
- MW EAP power system impedance modelling validation test

- Can test megawatt (MW) electrical systems at altitude
- Can test MW scale power systems, controls and a variety of configurations
- MW scale power levels complicates test run at kW or lower levels

* https://aviationweek.com/shownews/farnborough-airshow/ge-claims-world-first-high-voltage-high-altitude-power-demo

A Portfolio from Materials to Machines

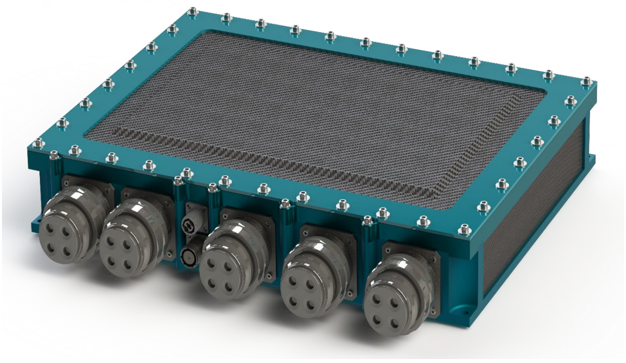
NASA in house

- High voltage materials
- Electric machine insulation materials
- Soft magnetic materials for advanced power electronics
- Superconducting machines (>16kW/kg, >98% efficient)
- Multi inverter with low total harmonic distortion (THD)
- Solid state batteries (goal 500 Wh/kg)

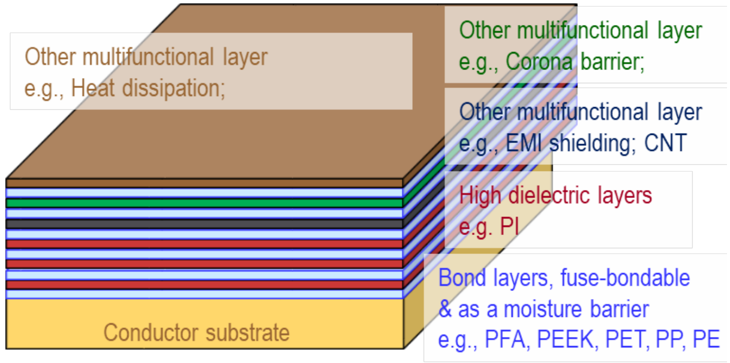
Partnered:

- GE SLIM inverter
  - Carried forward from previous work
- Hinetics MW Machine
  - Continued from UIUC work

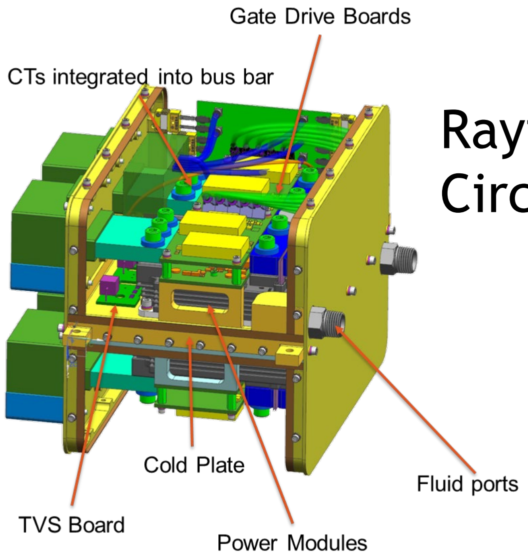
Low THD inverter



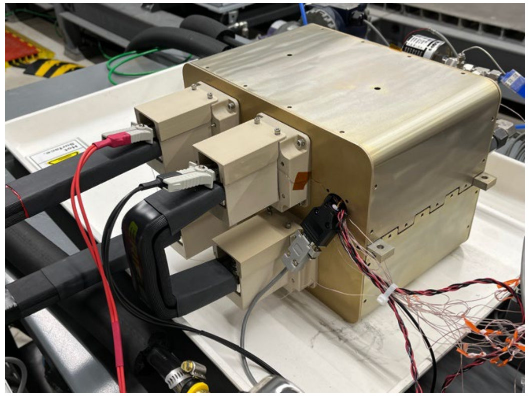
HV Material MMEI development



Fault Management



Raytheon
Circuit Breaker



Credit: *Raytheon Technologies*

DC Circuit Breaker

- *MW scale, ~1kV, 1000A, < 100 μs response, > 100kW/kg, >99.5% efficient + altitude*
- Pratt and Whitney (P&W, *RTX, and Collins Aerospace*)
- General Electric Aerospace
- Naval Post-Graduate School

Fault Management (continued)

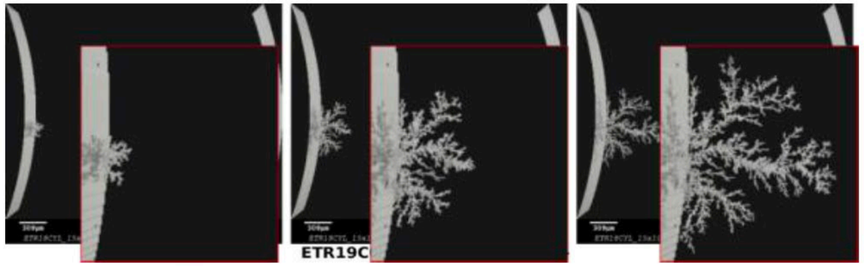
- Power quality filtering
  - Custom devices from NASA soft magnetic materials
  - Basic material to component
  - Designed for advanced use with advanced power devices
  - Partnered with RTRC and GE Aerospace
- Lifetime modeling for insulations system
  - Partnered with GE Aerospace and RTRC

Power Quality Filtering

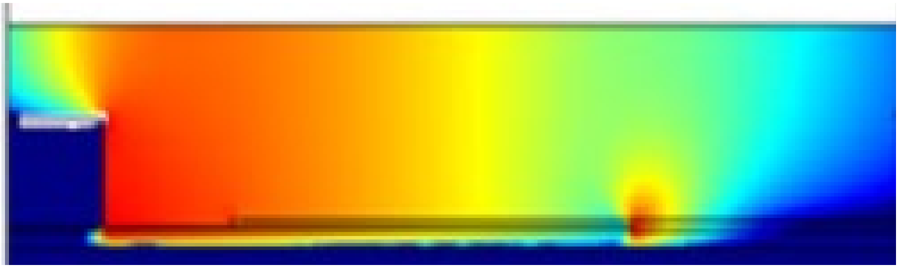
Credit: NASA GRC

Credit: Raytheon Technologies

Material lifetime modeling



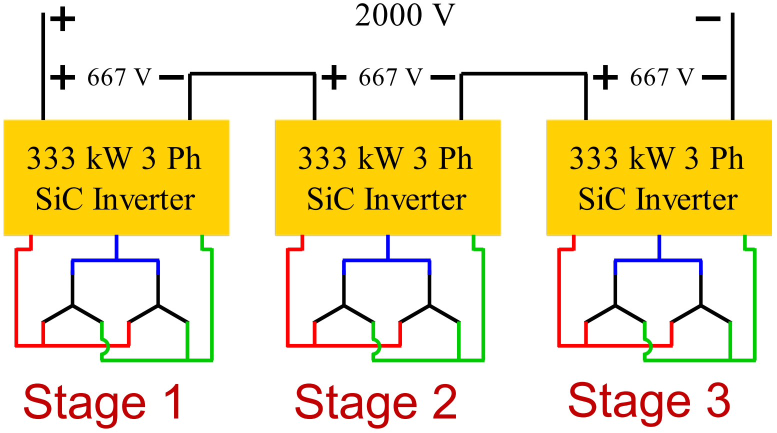
Credit: Raytheon Technologies



Credit: GE Aerospace

University Leadership Initiative (ULI) lead by The Ohio State University

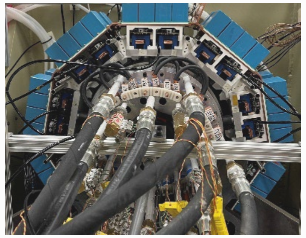
2 kV 1 MW Integrated Modular Motor Drive for Turbo Electric Aircraft

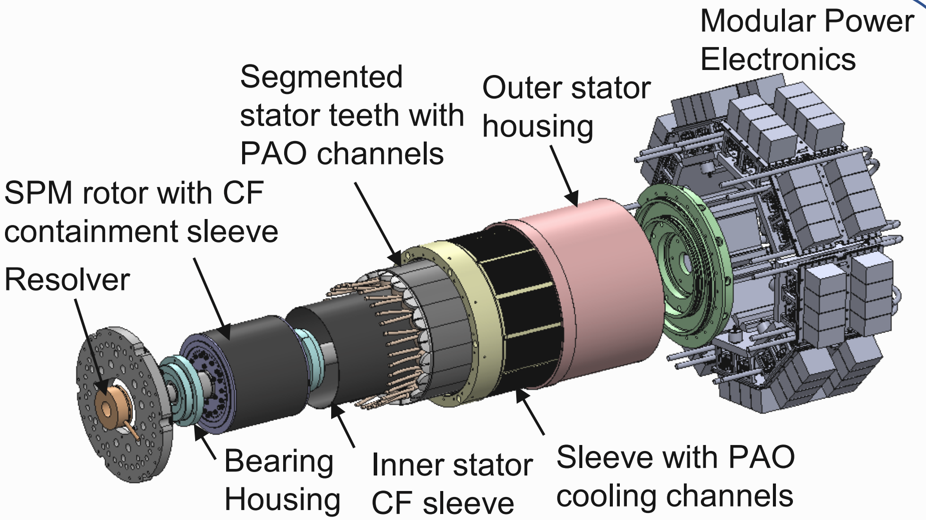


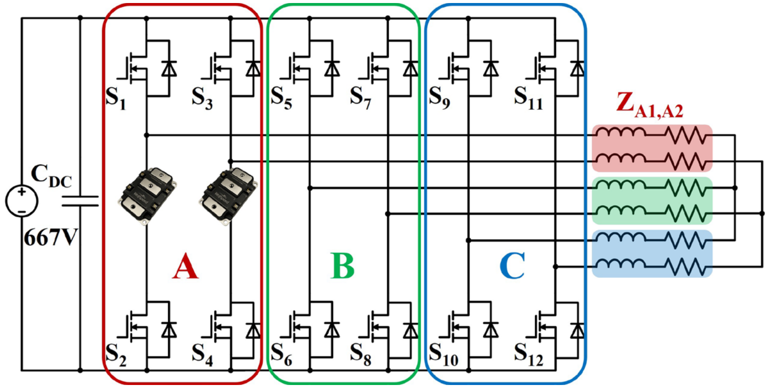
System diagram of the 2kV 1MW IMMD system

Vol. Power Density : 13.5 kW/L

Mass. Power Density: 9.0 kW/kg







Single-stage configuration

- Three-stage architecture ensures reduced voltage stress and improved fault tolerance
- The 18-slot / 12-pole SPM machine uses double-layer concentrated windings
- Stator slots are filled with polyalphaolefin (PAO) for both cooling and insulation
- Rotor is forced air cooled with hollow shaft channels
- Modular SiC based power electronics operates at 40 kHz
- The system is designed to be partial discharge free at high altitude (56,000 feet)

POC: Professor Jin Wang, The Ohio State University (wang.1248@osu.edu)

X-57/Maxwell

162 kW - takeoff
461 VDC - nominal
538 VDC - max

- Advance the Nation's ability to design, test, and determine airworthiness of distributed electric and aero-propulsive coupling technologies, which are a critical enablers for emerging, advanced air mobility markets
- The value of X-57 lies in advancing the Nation's ability to design, test, and certify electric aircraft, which will enable entirely new markets

https://www.nasa.gov/specials/X57/index.html
https://nasa.gov/x57
https://nasa.gov/x57/technical

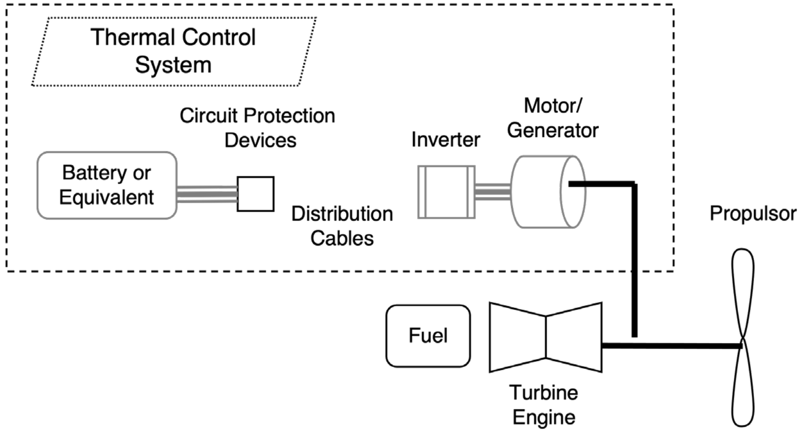
Electrified Powertrain Flight Demonstration (EPFD)

EPFD project:
- Partnership with U.S. industry to establish and demonstrate integrated megawatt-class powertrain systems

EPFD Goals:
- Accelerate US industry technology readiness and competitiveness
- Facilitate new aviation industry S – Curve for electrification
- 2030-2035 Entry Into Service: Next generation thin haul, regional and Single-Aisle markets

Regulations and Standards will play a large role:
- NASA is partnering with industry to identify the regulatory and standards gaps that may exist for the highest priority electric technologies and gather data to support future regulations and standards development

Awardees:
- GE Aerospace
- magniX



EPFD

Vision Product Performance Parameters

Key Performance Parameter (KPP)#	Key Performance Parameter (KPP)	Full Success Single Aisle Part 25	Minimum Success 19 PAX Thin Haul Part 23
KPP-1	Total Power level of the Integrated MW-Class Powertrain System	2MW	500kW
KPP-2	Power Level of individual electrical components	1MW	250kW
KPP-3	Operating Voltage of the Integrated MW-Class Powertrain System	1000V	500V
KPP-4	Altitude Capability of the Integrated MW-Class Powertrain System	40,000 ft.	20,000 ft.
KPP-5	Specific Power of the Integrated MW-Class Powertrain System	1.25 kW/kg	0.5 kW/kg
KPP-6	End to End loss of the Integrated MW-Class Powertrain System	20%	
KPP-7	Mission Fuel Burn/Energy Reduction	4% for Part 25 Transport Aircraft	10% for Part 23 Transport Aircraft

Will be collecting relevant sets of data
- Integrated ground system development, integration and test
- Flight airworthiness/safety and mission assurance

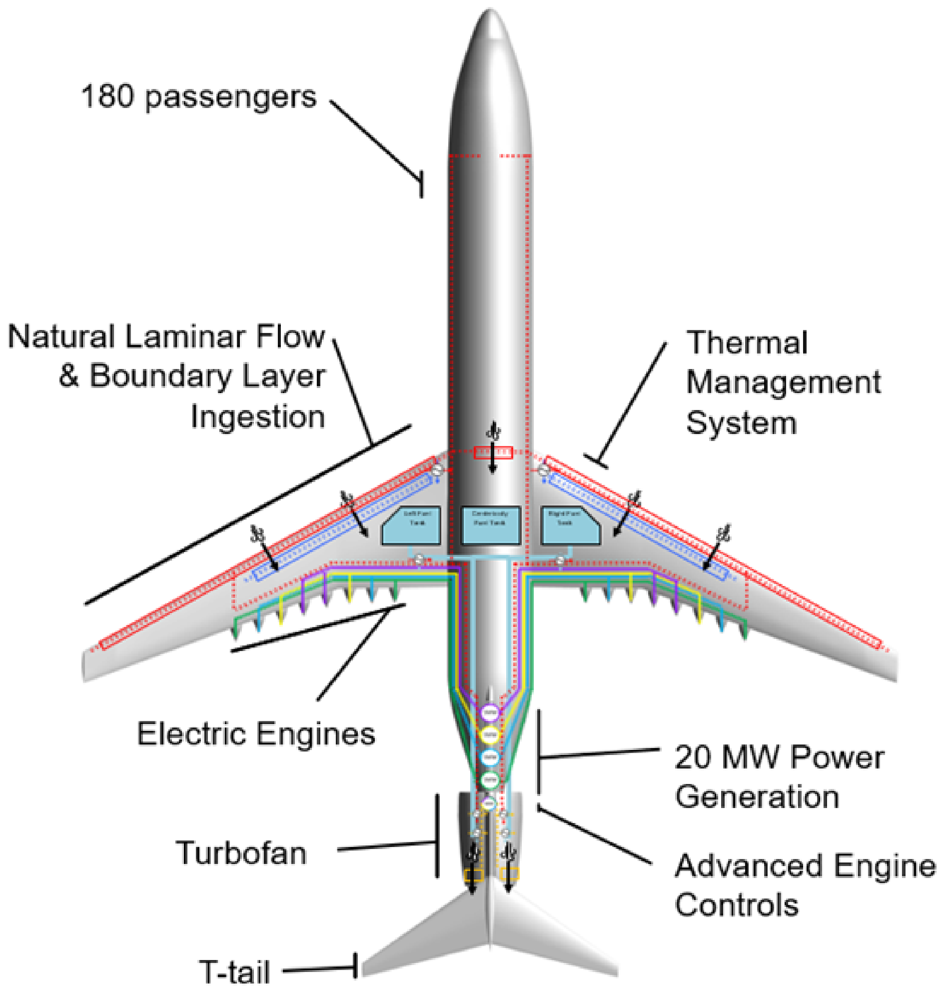
Take away: Rapid maturation underway

Tomorrow

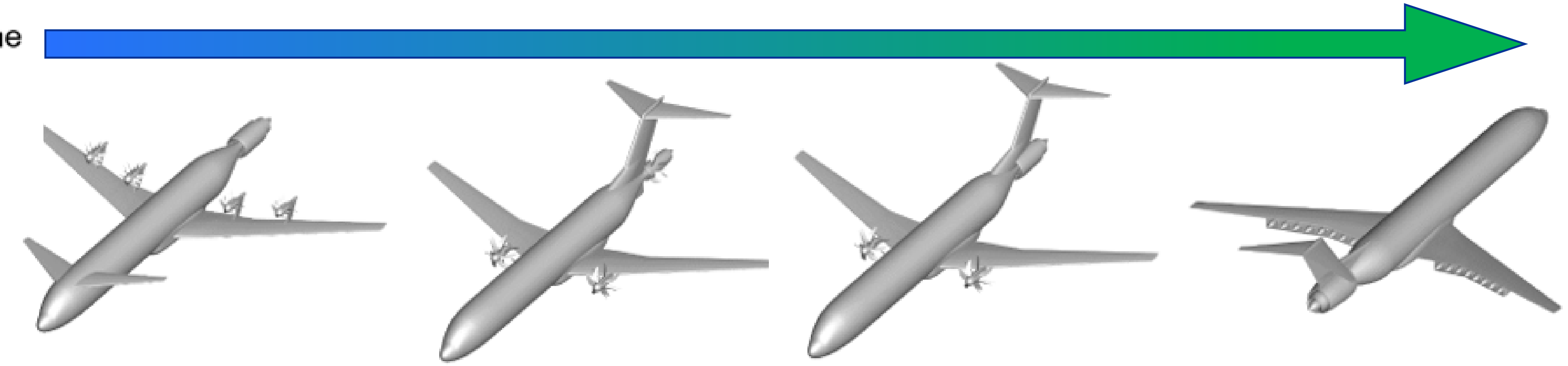
Grand Question:
What is next?

- Will the next level of electrification require a >10 MW system?
  - Single aisle and wide body?
  - Fully turboelectric?
- A wider variety of energy sources?
  - Batteries?
  - Sustainable aviation fuel (SAF)?
  - Hydrogen?
    - Liquid or gaseous?
  - Fuel cells?

SUSAN

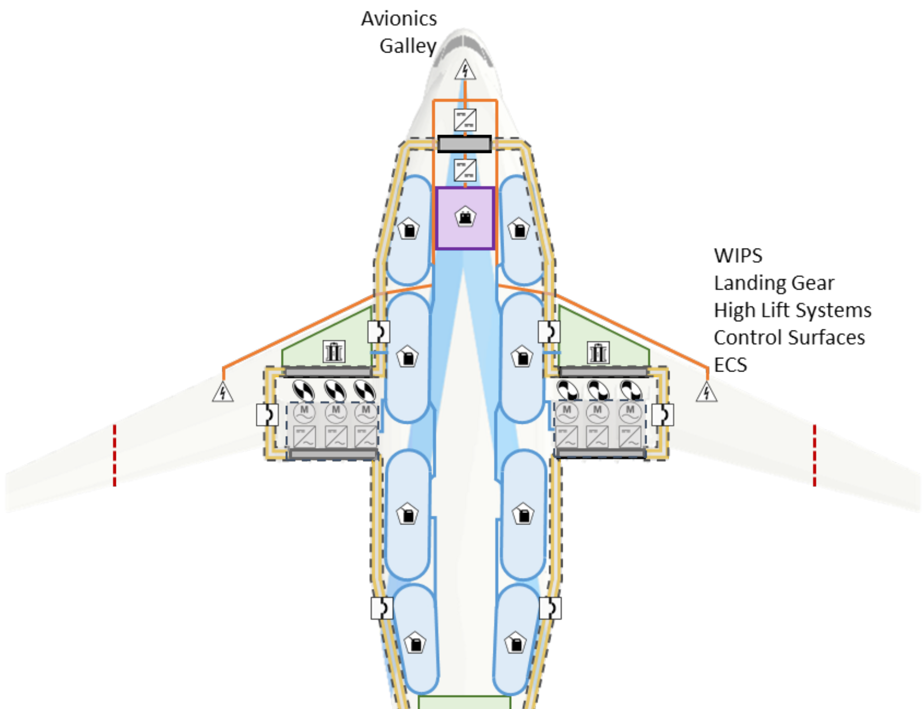


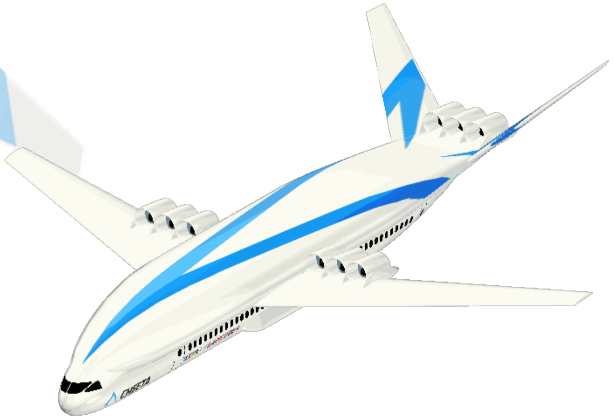
- The SUbsonic Single Aft eNgine (SUSAN) Electrofan trade study is being conducted to determine if a 50% emissions reduction can be achieved while retaining the range and speed of large transport aircraft
- Low and medium fidelity analysis is being conducted to trade aircraft configurations
- Four 5 MW turbofan driven generators (20 MW total) power the wing mounted electric engines
- Relatively small, in-flight rechargeable batteries are used for climb boost and to improve turbofan operability
- A single use battery provides power if the turbofan fails
- The power system must be extremely light weight and highly efficient to reduce aircraft mission energy use.
- 1-3 KV buss- trade studies being conducted



SUSAN V0 SUSAN V1 SUSAN V2 SUSAN V3

Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA)





- Architecture:
  - Hybrid centralized/distributed
  - Peak DC power: 25 MW
- Power transmission:
  - Redundant superconducting power transmission
  - ± 270 VDC
- Superconducting motors:
  - Peak shaft power: 2.5 MW
- Cooling:
  - H_2 liquid: Motor and transmission cable
  - H_2 vapor: Inverter and current leads
  - Ram-air HEX: Fuel cell

POC: Professor Ansel, University of Illinois Urbana-Champaign (ansell1@illinois.edu)

Integrated Zero-Emission Aviation (IZEA)

Led by Florida State University

How might passenger aircraft change to provide air travel in a CO_2-restricted world?

Liquid hydrogen fuel

Electric!

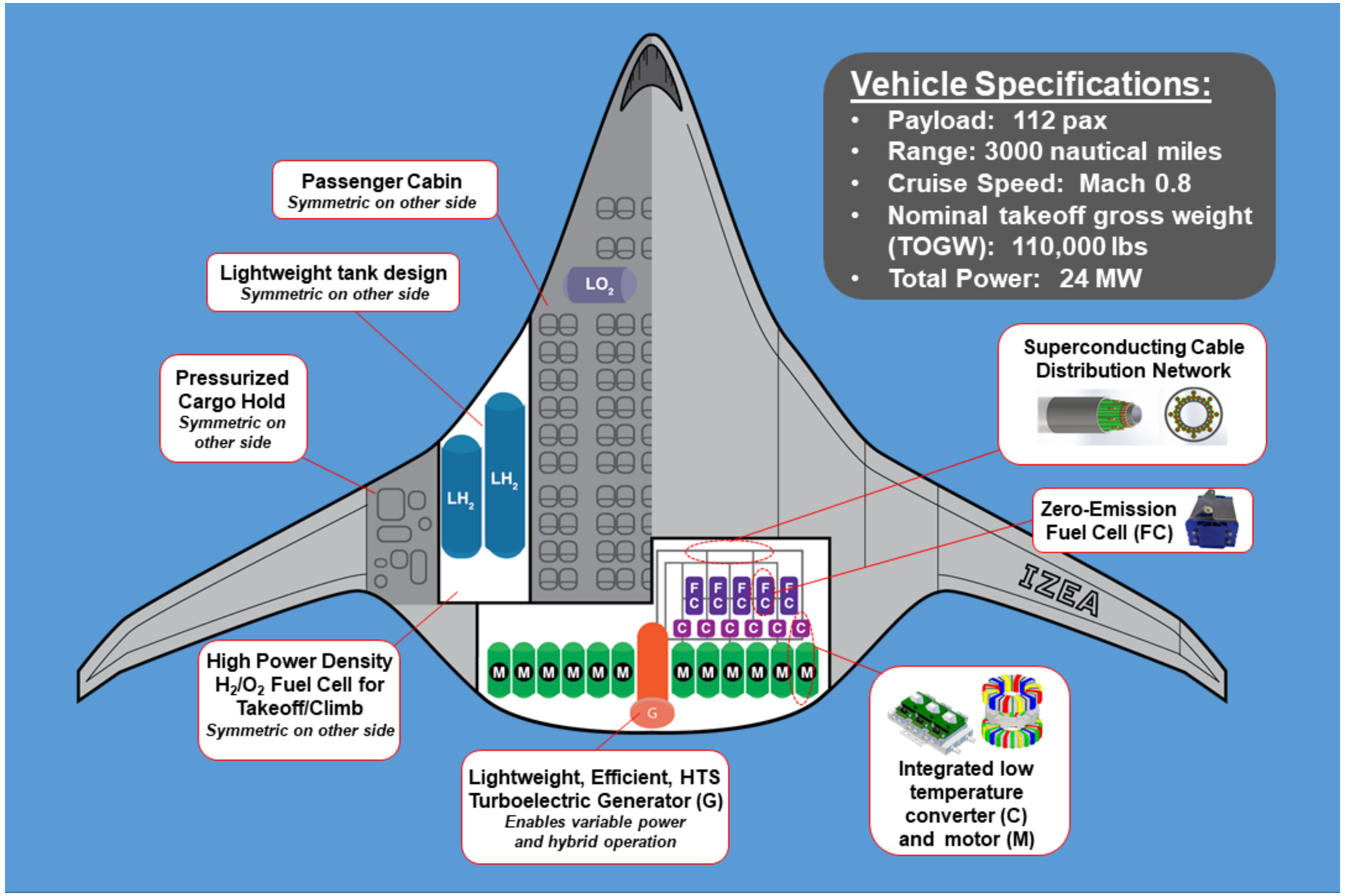
Turbine generator

Motorized propulsors

Fuel Cells

Efficient power systems

Superconductor Power Transmission



POC: Professor Lance Cooley, Florida State University (ldcooley@fsu.edu)
Backup POC: Lou Cattafesta, Illinois Institute of Technology (lcattafestaiii@iit.edu)

AACES 2050

- Advanced Aircraft Concepts for Environmental Sustainability
- 2045-2050 EIS "Beyond-Next Gen" advanced concept studies
  - 2050 Marketplace (payload/range/speed)
  - Alternative Energy Scenarios (e.g. H2, LNG, Methane, Electrified, 100% SAF)
  - Explore 2020s, Demo 2030s, Impact 2040s
- Promising Technology/Architectures
  - Advance promising longer-term concepts for 2045-2050
    - e.g., adv airframes (shielding, adaptive) and alternative propulsion
  - Advanced aircraft structures to enable highly integrated configurations
- Support Aviation Community with NASA-unique contributions
  - Reduced uncertainty of aviation emissions and noise impacts
  - Tools & Methods for Reduced Lifecycle Costs & Environmental Impact

Take aways:

- The next step will increase in complexity and require more integration
- Significant investment in generating next generation of concepts

Takeaways

- Early study’s set challenging, reasonable and meaningful targets
  - Feasibility was determined
- Moving rapidly from concept to reality
  - 2035 EIS for hybrid electric is achievable
- Significant investment in the next generation of concepts
- Beyond 2035 concepts are out there, but the level integration and complexity will demand even more innovation

Thank you!

- Special thanks to the PEASA ’23 organizers for inviting this presentation
- NASA’s Advanced Air Transport Technology Project/Power and Propulsion subproject (Amy Jankovsky, Manager)

Abstract

- NASA has been making investments since ~2015 in technologies related to electric aircraft propulsion. These investments span all-electric with our four passenger X-plane and electric vertical lift studies, to regional flight demonstrators and targeted technology maturation programs. These latter two areas are focused ultimately on reducing fuel burn and overall energy use in transport-class aircraft, with the goal of reducing carbon impact of aviation on our planet. Key technology contributions include such as electric machines, power electronics, cables/bus bars, fault management systems, controls and systems studies, and enabling materials. Today we are seeing the fundamental technology investments manifest themselves in flight demonstrations, that are aimed at impacting aircraft entering service 2035-2040 time range.   These efforts have largely been aimed at megawatt scale technologies that can enable hybrid electric or mildly distributed airplane concepts. While these concepts offer benefits to regional and single isle aircraft it is thought that a more fully electrified propulsion system requiring greater than 10 MW of distributed power offers more possible pathways to configure the propulsion-airframe system to gain new efficiencies. A few examples of this are NASA's SUSAN distributed electrofan concept and NASA University Leadership Initiatives such as CHEETA and IZEA that champion turbo-electric concepts. These concepts utilize combination of advanced technologies such as, fuel cells, power dense electronics and power dense electric machines and superconducting technologies. How much or which of these concepts will be adopted by industry is unclear, however another step function in electrifying aircraft propulsion is now on the horizon.