The University of Texas at Austin
Center for Electromechanics

UT-CEM Industrial Advisory Panel

Advanced Rotating Machines II

- **Brushless Doubly Fed Motors for Aircraft Propulsion**
- **Dual-Mode Pulse Power Unit for Directed Energy Applications**

Joe Beno

Center for Electromechanics

The University of Texas at Austin

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NASA Fact Sheet: *NASA Aeronautics 10-Year American Aviation Plan*

- **President's FY 2017 budget: $790 million to NASA's Aeronautics Research Mission Directorate to accelerate *aviation energy efficiency, advance propulsion system transformation and enable major improvements in aviation safety and mobility*. First step in 10-year plan to achieve the most critical outcomes outlined in NASA's Aeronautics long term vision and strategy.**

FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26
$642M	$640M	$790M	$846M	$1,060M	$1,173M	$1,287M	$1,294M	$1,308M	$1,218M	$830M	$839M

- **$3.1B (41%) 10 year, inflation adjusted, increase in Aeronautics funding.**

Propulsion Serves as Primary Focus for 2 of 6 NASA Aeronautics Research Strategic Thrusts

- **Safe, Efficient Growth in Global Operations**
- **Innovation in Commercial Supersonic Aircraft**
- ***Ultra-Efficient Commercial Vehicles***
- ***Transition to Alternative Propulsion and Energy***
- **Real-Time System-Wide Safety Assurance**
- **Assured Autonomy for Aviation Transformation**

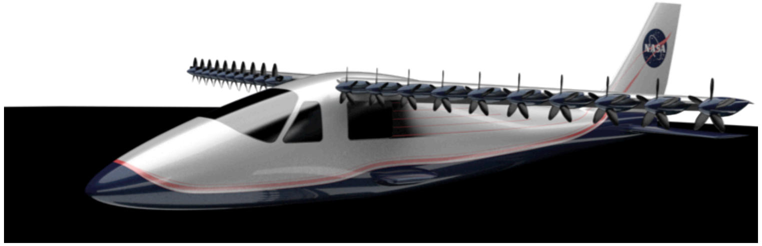
Distributed Aircraft Propulsion

Today: **Most jet-powered transport aircraft have thrust-generating engines under wings or on fuselage – minimizes aerodynamic interactions with vehicle operation/control.**

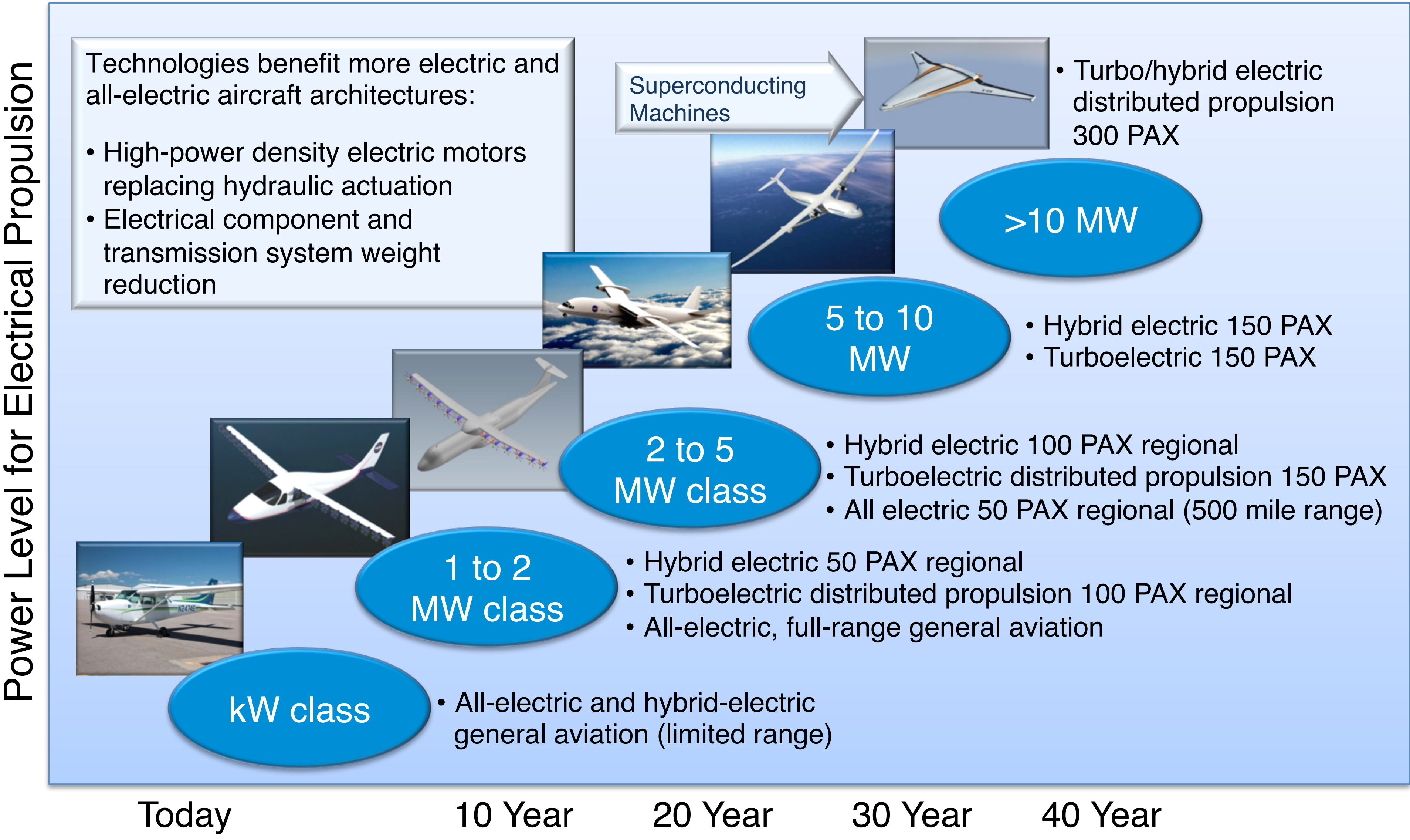
New Technology: **Advances in computational and experimental tools and new technologies in materials, structures, and aircraft controls, etc., enable a high degree of integration of the airframe, propulsion, and powertrain with improved vehicle operation/control.**

Tomorrow: **Improved efficiency and reduced emissions through (hybrid) electric powertrain *and* distributed propulsion integrated in airframe to improve aerodynamics and further improve efficiency.**

- **Systems Studies for N+3 timeframe: 60% energy use reduction; 90% Nox reduction; 30-60% db reduction in effective perceived noise**



Projected Timeframe to Tech Readiness Level 6



Power Level for Electrical Propulsion

Technologies benefit more electric and all-electric aircraft architectures:

- High-power density electric motors replacing hydraulic actuation
- Electrical component and transmission system weight reduction

Superconducting Machines

- Turbo/hybrid electric distributed propulsion 300 PAX

>10 MW

5 to 10 MW

- Hybrid electric 150 PAX
- Turboelectric 150 PAX

2 to 5 MW class

- Hybrid electric 100 PAX regional
- Turboelectric distributed propulsion 150 PAX
- All electric 50 PAX regional (500 mile range)

1 to 2 MW class

- Hybrid electric 50 PAX regional
- Turboelectric distributed propulsion 100 PAX regional
- All-electric, full-range general aviation

kW class

- All-electric and hybrid-electric general aviation (limited range)

Today

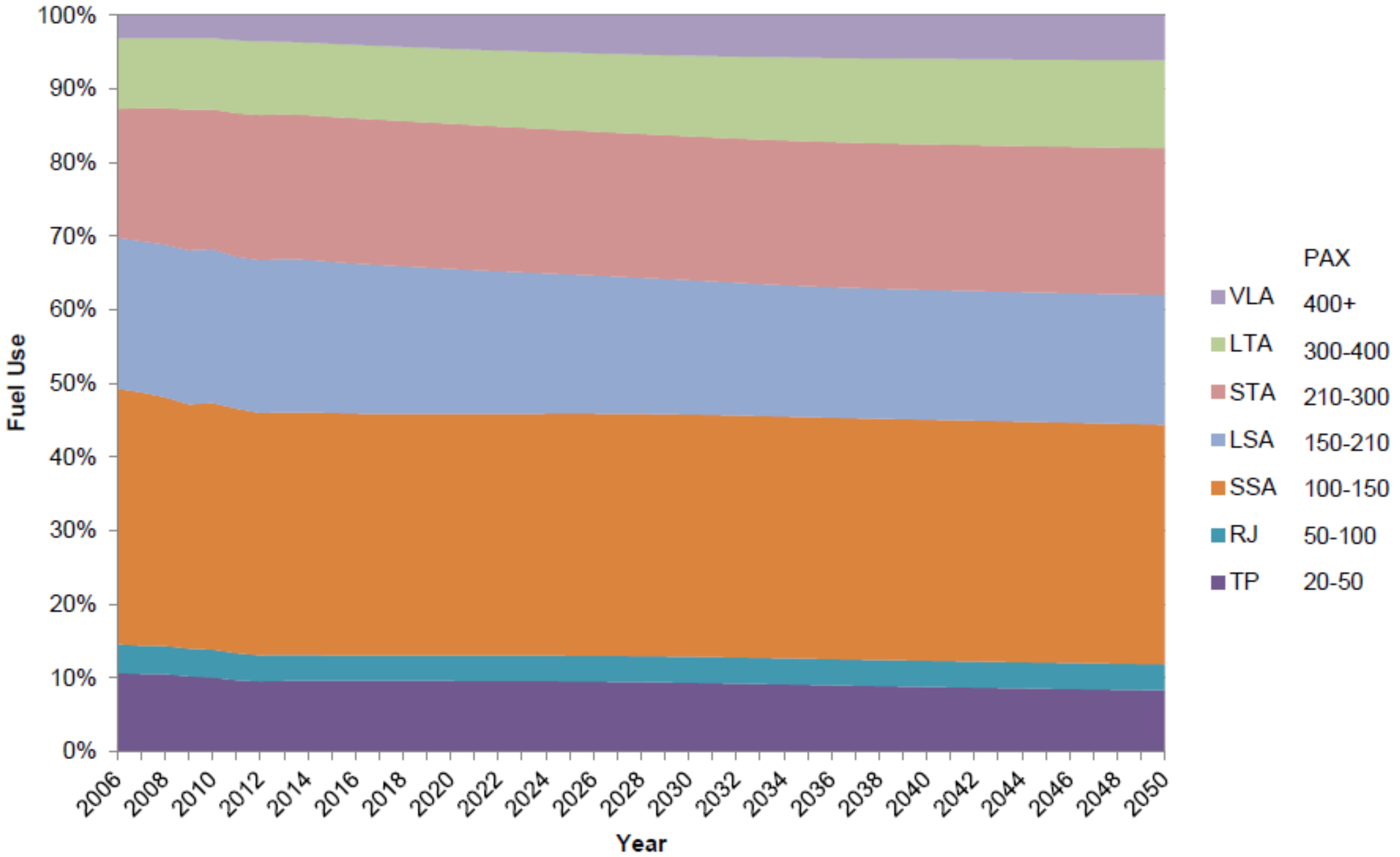
10 Year

20 Year

30 Year

40 Year

AATT Scope: Fuel Use by Vehicle Classes

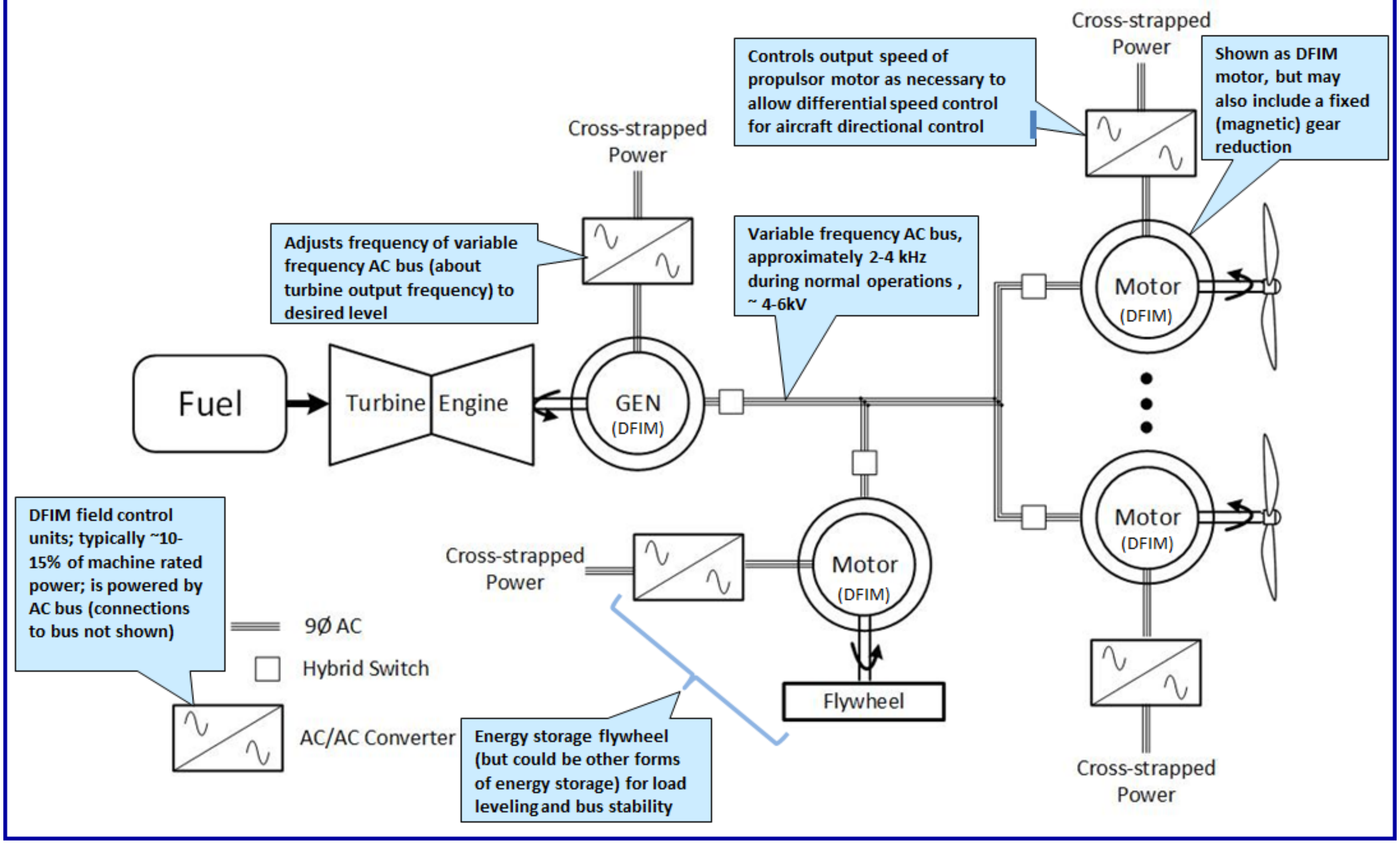


85% of fuel use is in small single-aisle (100-150 pax) and larger classes; regional jets and turboprops account for only 15% of fuel use

Based on FAA Terminal Area Forecast (TAF) for US Operations; Courtesy of Ga Tech

High Voltage
Hybrid Electric Propulsion

Variable Frequency/DFIM System



Controls output speed of propulsor motor as necessary to allow differential speed control for aircraft directional control

Shown as DFIM motor, but may also include a fixed (magnetic) gear reduction

Adjusts frequency of variable frequency AC bus (about turbine output frequency) to desired level

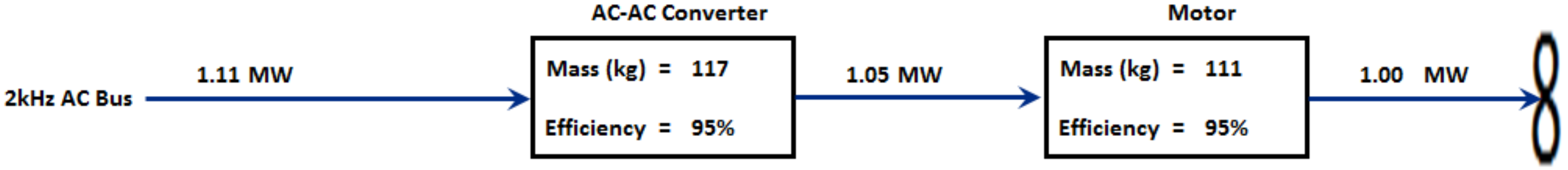
Variable frequency AC bus, approximately 2-4 kHz during normal operations , ~ 4-6kV

DFIM field control units; typically ~10-15% of machine rated power; is powered by AC bus (connections to bus not shown)

Energy storage flywheel (but could be other forms of energy storage) for load leveling and bus stability

Why Brushless Doubly Fed Propulsion Motors?

Traditional Singly Fed (SF) Propulsor Motor



2kHz AC Bus → 1.11 MW →

AC-AC Converter
Mass (kg) = 117
Efficiency = 95%

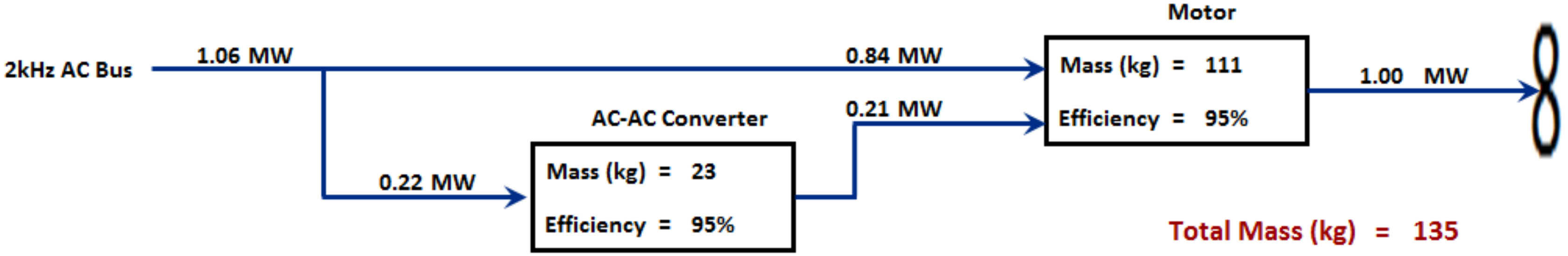
→ 1.05 MW →

Motor
Mass (kg) = 111
Efficiency = 95%

→ 1.00 MW

Total Mass (kg) = 228
Net Efficiency = 90%

BT-CEM Brushless Doubly Fed (BDF) Propulsor



2kHz AC Bus → 1.06 MW
0.84 MW →
0.22 MW →

AC-AC Converter
Mass (kg) = 23
Efficiency = 95%

→ 0.21 MW →

Motor
Mass (kg) = 111
Efficiency = 95%

→ 1.00 MW

Total Mass (kg) = 135
Net Efficiency = 94%

Specific Power and Efficiency[1]	
9.00	Motor specific pwr (kW/kg)
9.00	Converter specific pwr (kW/kg)
95%	SF Motor efficiency
95%	BDF Motor efficiency
95%	Converter efficiency

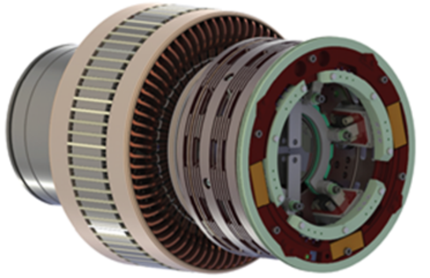
1. Source: National Academy of Science 20 Year Projections for Commercial Aircraft Electric Propulsion (Commercial Aircraft Prpoulsion and Energy Systems Research, Commitee Report, National Academies Press, 2016).

Where else can we reduce mass 40% AND improve efficiency 4% ??

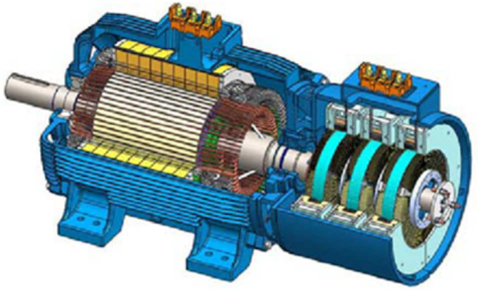
Dual Fed Machines Without Slip Rings

Most Promising Doubly Fed Machine Approaches:

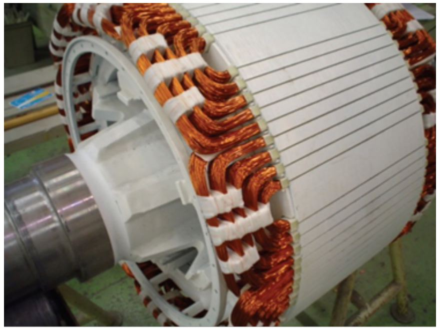
- Synchronous Generator Brushless Exciter
- Rotary Transformer
- Brushless DFM
  selected approach
- Doubly Excited Brushless Reluctance Motor (DRBRM)



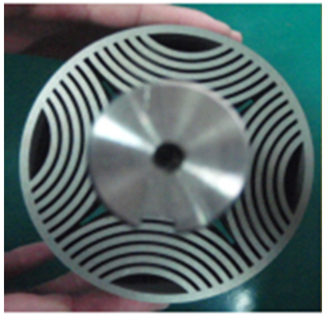
WEG EM group brushless exciter with rotating rectifier assembly



WEG 3 phase machine with rotary transformer (on right of picture)



BDFM squirrel cage rotor optimized for two different pole-pair combinations



DEBRM rotor

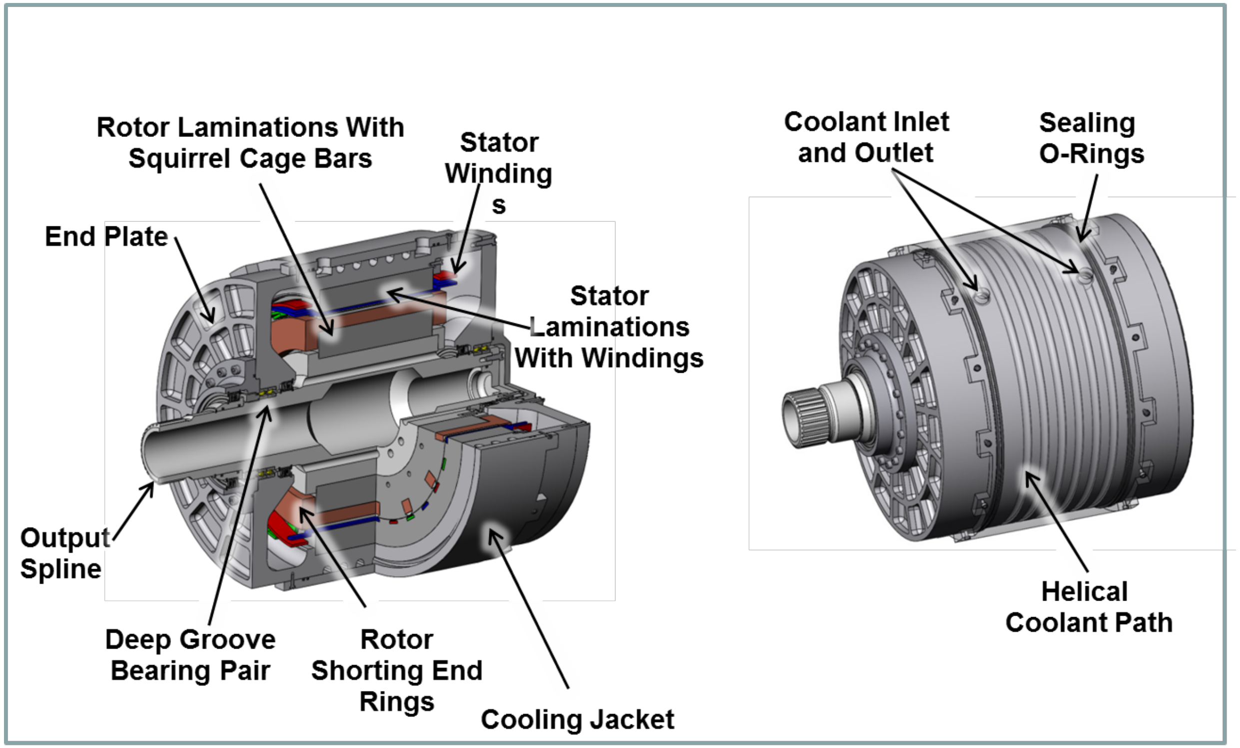
Conceptually, DFMs without slip rings have two stator segments and a single rotor.

- "Power Winding" portion of dual fed machine that is directly connected to AC power bus and produces ~ 80% of total machine rated power
- "Control Winding" portion of dual fed machine that is connected to AC power bus via power electronics and produces up to ~ 15% – 20% of total machine rated power
- The rotor often can have one set of conductors that interact with both stator segments or can have a separate set of conductors for each stator segment
- The two stator segments can be separate or often can share slots on a common lamination stack

BDFM Propulsor Development

- **Integration with NASA Programs: NASA N+3 timeframe**
- **3 Generations of Prototype Demonstrations**
  1. **20 – 50 kW BDFM: Controls development focus; validate BDFM propulsor approach**
     - ➢ **Manufacturing Partner – primarily advisory**
  2. **250 – 500 kW: high power density stator technology and moderately high speed induction rotor technology**
     - ➢ **Manufacturing Partner – participate in design for manufacturing, fabrication of components; assembly and testing**
  3. **1 MW: Upgraded high speed rotor, upgraded stator, and lightweight/composite materials in housing and endplates**
     - ➢ **Manufacturing Partner – significant role in design, fabrication, and testing especially for components that are not major deviation from the 2d generation system**
- **Manufacturing Prototype**
  - ➢ **BT-CEM in support role**
  - ➢ **Manufacturer leads and controls effort**

250 kW Second Generation Prototype BDFM



Objectives: **Advance State of the Art in high speed BDFM**

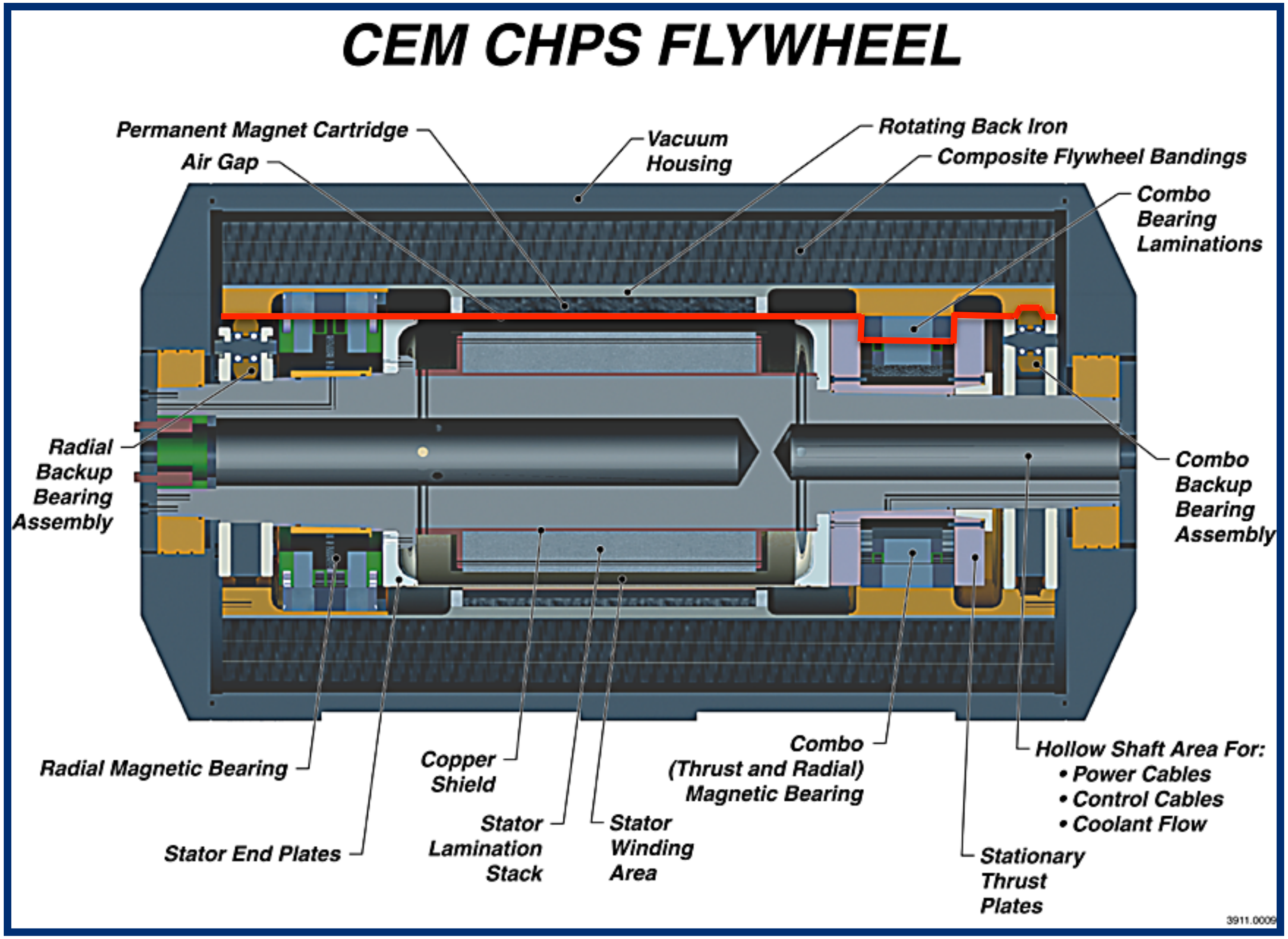
- **Build on 1st Generation controls development.**
- **~10x increase in power.**
- **Integrate UT-CEM high power density stator technology and moderately.**
- **Integrate UT-CEM high speed induction rotor technology.**

Dual-Mode Pulse Power Unit for Directed Energy Applications

CHPS Model Overview

Key Objectives:

- Fit through 26” hatch
- Emphasize rotor safety
- Ready for follow-on demo



Power = 7-12 MW peak and 3- 4 MW rms; Delivered energy ~19 MJ; diameter < 24 inches

CHPS Requirements Overview

CHPS	**Parameters**	**Baseline Characteristics**	**Comments** ***(CHPS-2000 Specification)***
Power per machine	P_{chps}	7 MW peak 3.25 MW rms	*(~5MW peak; < 350 kW rms)*
Delivered energy	E_{del}	6.7 MJ (can do 19MJ)	
Speed	ω_n	20,000 rpm	High speed for size reduction *(same)*
Minimum operating Speed	ω_{min}	14,142 rpm	@ 50% depth of discharge of flywheel *(same)*
Voltage	V_{LL}	8-15 kV	~ 10-20 kV dc at rectifier output *(same)*
Number of Poles	Poles	10	High value to reduce back iron thickness *(similar)*
Duty cycle	Charging (CHPS) Discharging (CHPS)	7 MW for 1 s 1.4 MW for 4 s	6 seconds between discharges *(N/A)*
Shock Load	Transient Bearing Capacity	39g, 11 ms half sine wave pulse	Substantial upgrade to CHPS-2000 requirement
CHPS Characteristics			
Topology	Inside-out		*(Similar to CHPS-2000)*
Excitation type	Permanent magnets		*(Similar to CHPS-2000)*
Bearings	Magnetic		*(Similar to CHPS-2000)*
Structural support	Composite banding		*(Potential for advanced composites technology upgraded from CHPS-2000)*

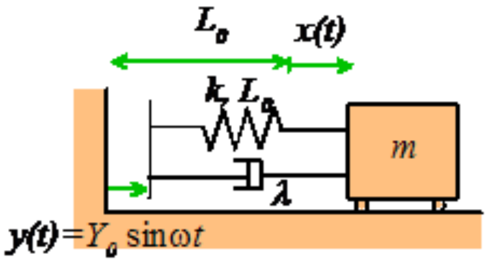
CHPS Bearing: General Comments

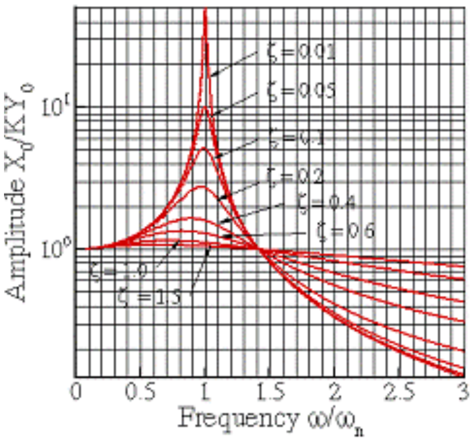
(Addressing Ship Shock Environment with High Performance Flywheels)

Gimbal Mount; wide airgap active magnetic bearings with short travel vibration isolation system:

- **Shock requirement can be met with short travel vibration isolation system and/or back-up bearings**

Vibration Isolation System (VIS): Base Excited Mass Spring Damper System





ω = 286 rad/s = 45 Hz

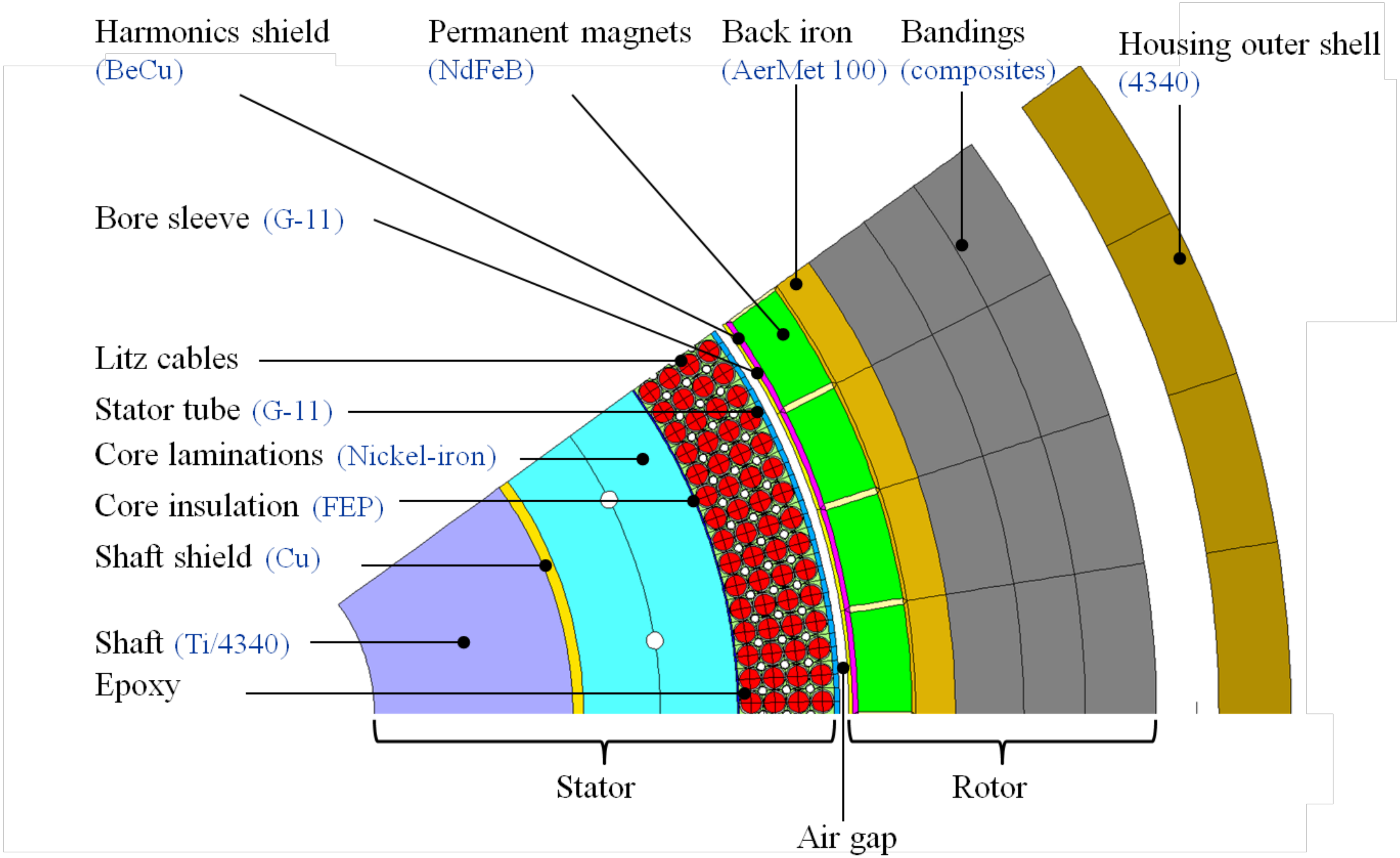
$\omega_n < 15$ Hz (VIS design requirement)

$\omega/\omega_n > 3$; Light damping (<50%)

Short travel VIS (< 5mm) can reduce CHPS stator displacement by ~>50% (e.g., physical air gap at 2.5 mm is OK; can add VIS travel to reduce this air gap requirement)

CHPS Motor/Generator EM Design

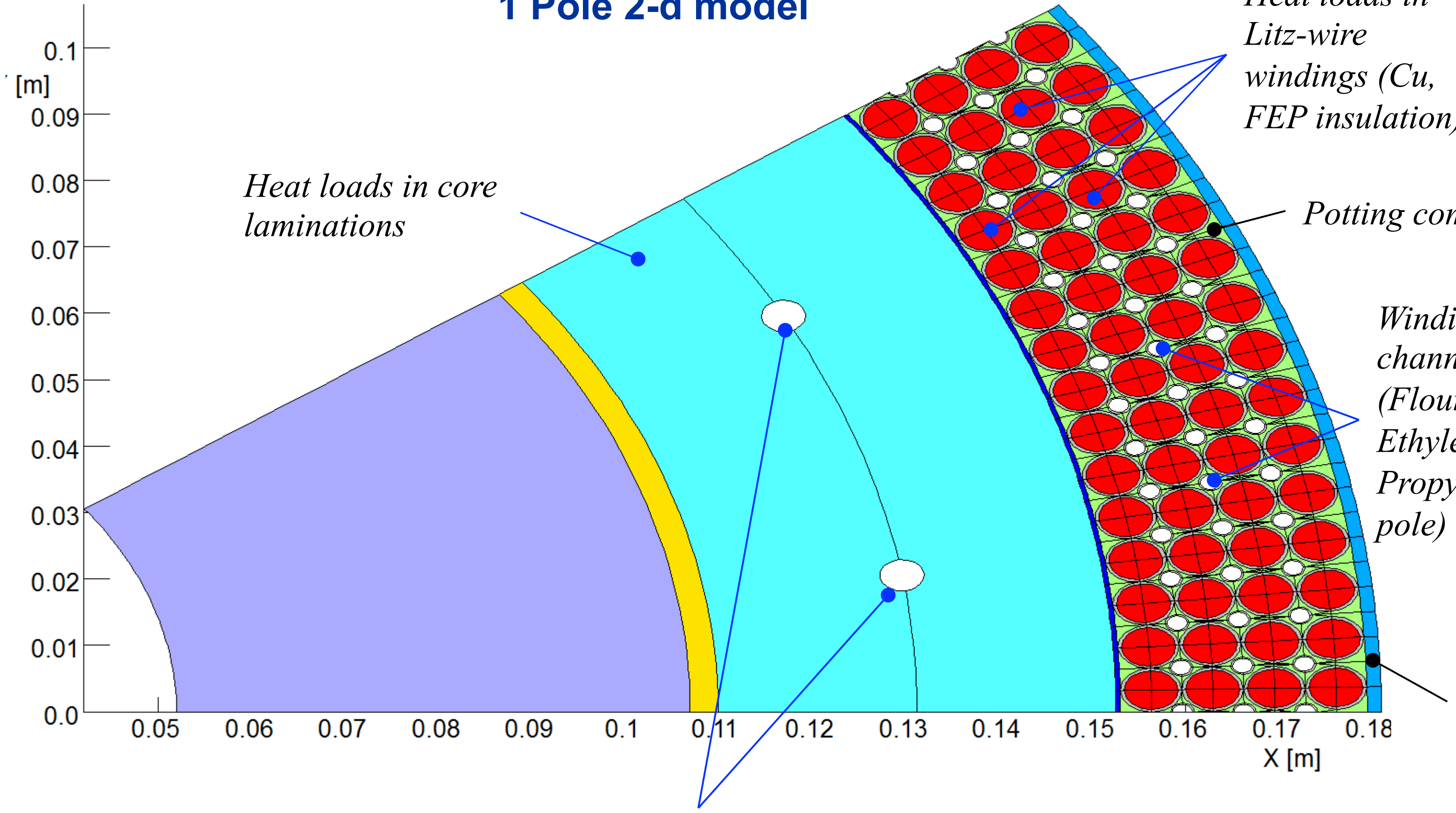
Design Iteration 4



Stator Thermal Design

Thermal Management Features

1 Pole 2-d model



Heat loads in core laminations

Heat loads in Litz-wire windings (Cu, FEP insulation)

Potting compound: Epoxy

Winding cooling channels (Flourinated Ethylene Propylene, FEP,45/ pole)

Stator tube (G-11)

Core cooling channels (2/pole)

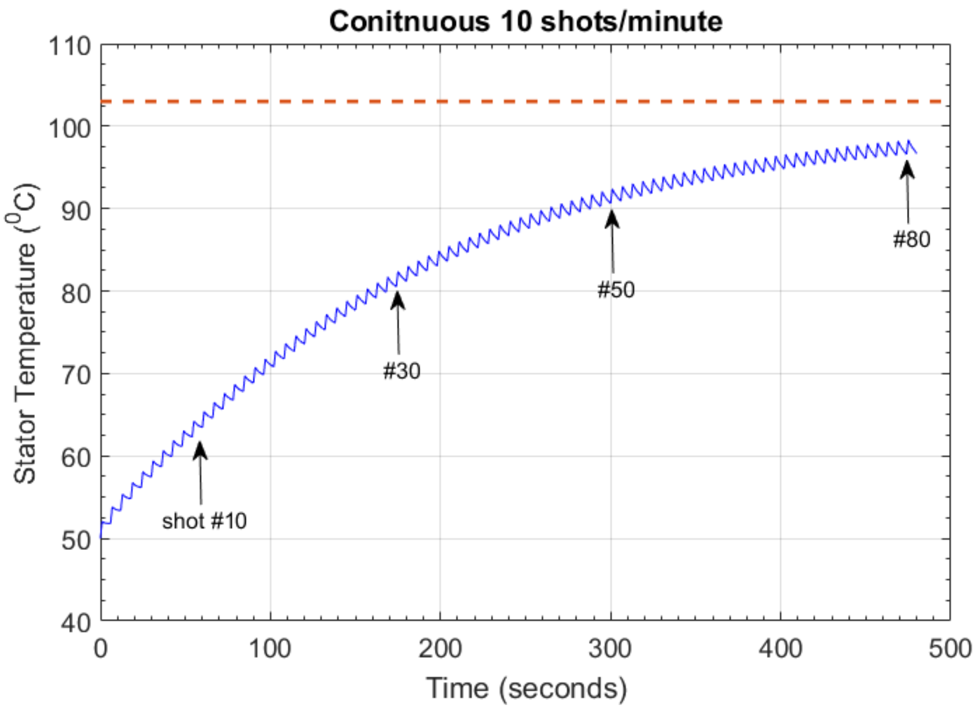
Note: Temperature limits of materials in winding area: $T_{max} < \sim 200\ ^0C$

Stator Thermal Design

Transient thermal analysis results: Stator only

- CHPS stator temperature increases as CHPS operates between 7 MW (charging) and 1.4 MW (discharging) to support multiple consecutive EMG shots

- During this time the ship power system is providing constant power (14 MW)



- ➢ Achieved continuous 10 shots per minute:
  - Slightly increased active length
  - Reduced number of turns per pole
  - Adjusted Litz wire cross section
  - Redistributed cooling tubes

- ➢ Maximum (asymptotic stator temperature is 103 ^{0}C)

Rotor Safety
Follow ANSI-AIAA Standard

- Standard ANSI/AIAA S-096-2004; “Space Systems – Flywheel Rotor Assemblies” – *only relevant high performance, composite rotor standard*
  - All parts of rotors for manned and unmanned spacecraft
  - Works with DoD Mil Handbook 17, Polymer Matrix Composites
  - Fracture Critical Part – catastrophic hazard if the part cracked or failed
  - Basis for Margin of Safety calculations
    - “A” Basis Allowable – strength value which at least 99% of the population values are expect to fall above, with confidence level of 95%
    - “B” Basis Allowable – strength value which at least 90% of the population values are expect to fall above, with confidence level of 95%
  - For composite and metal parts: Design Safety Factor > 1.5
  - For metallic parts: design safety factor on yield > 1.1
  - Fatigue Life for manned spacecraft flywheels > = 4 times expected service life. (Terrestrial applications can likely use 1.5-2 factor)

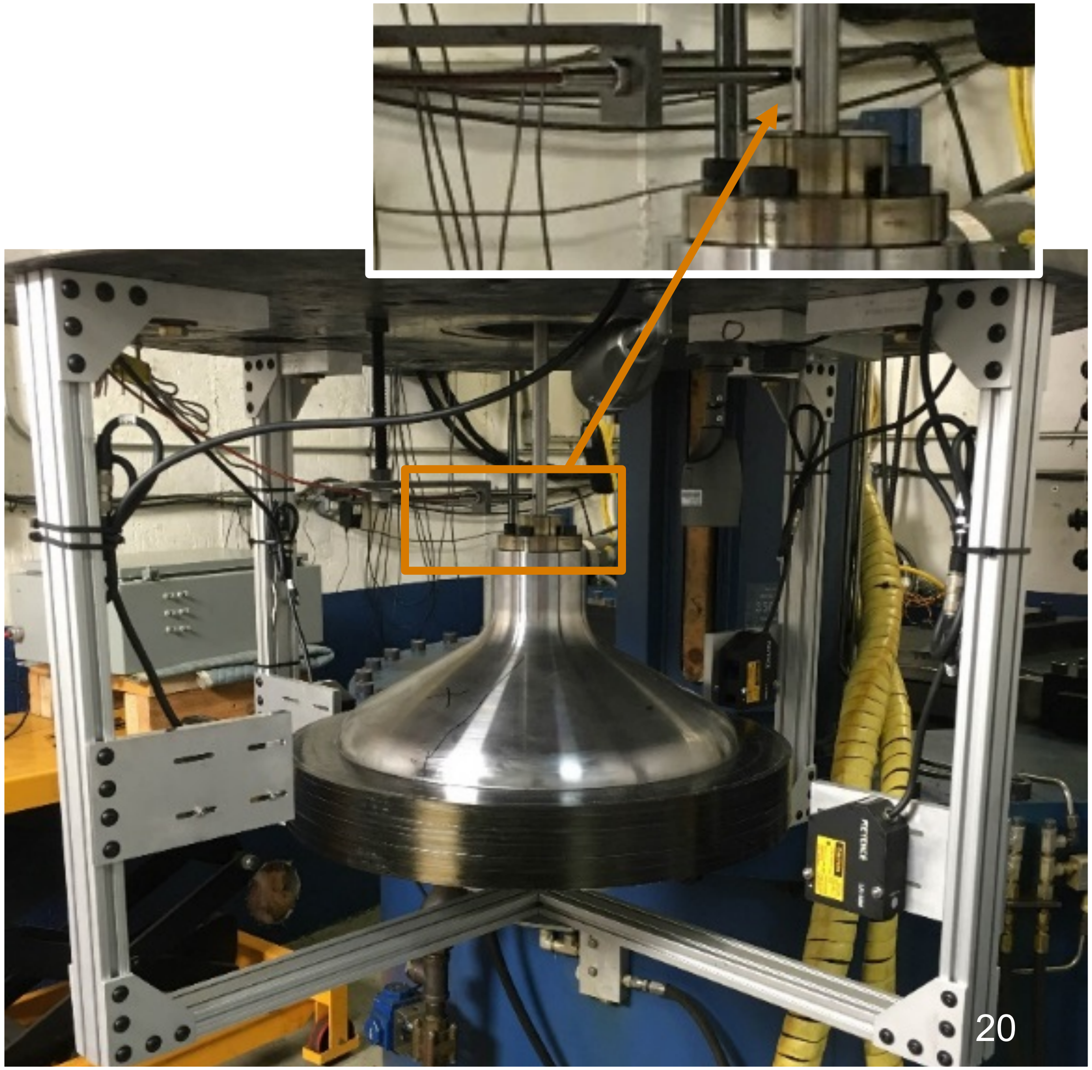
Rotor Safety
Incorporate CEM Mechnical Fuse

Rotor mechanical fuse -- outer flywheel ring separates from inner rings at approximately 10% overspeed

- Creates rotor imbalance that can be sensed by magnetic bearings as feedback safety signal to slow rotor speed
- Enables test to monitor rotor health – speed at which separation occurs is periodically monitored to identify material degradation
- CEM developed technology, demonstrated to be very repeatable
- Critical feature of rotor safety strategy, above and beyond ANSI-AIAA standard.

Spin Test

- Test was conducted in a vacuum ~90 millitorr
- Radial growth was measured with 4 laser probes placed in opposing pairs.
  - 0°-180° pair was located towards the top of the banding
  - 90°-270° pair towards the bottom.
- Vibration was measured using TDI's proprietary crack detection system (sensors, software).
- Two potential methods to detect mechanical fuse deployment: Radial Growth and Spindle Vibration



Relationship with CEM Mission

Mission

Perform leading edge basic and applied research in electrical and mechanical engineering, with a special emphasis on applied engineering leading to prototype development in electromechanical devices and systems with high specific power, force, and/or energy storage or other unique attributes. Imbedded in this mission is educating and developing students and CEM staff members into engineering leaders of tomorrow.

Vision

For CEM to be internationally renowned in its mission area.

For CEM's people to be internationally renowned in their areas of expertise.

Stop