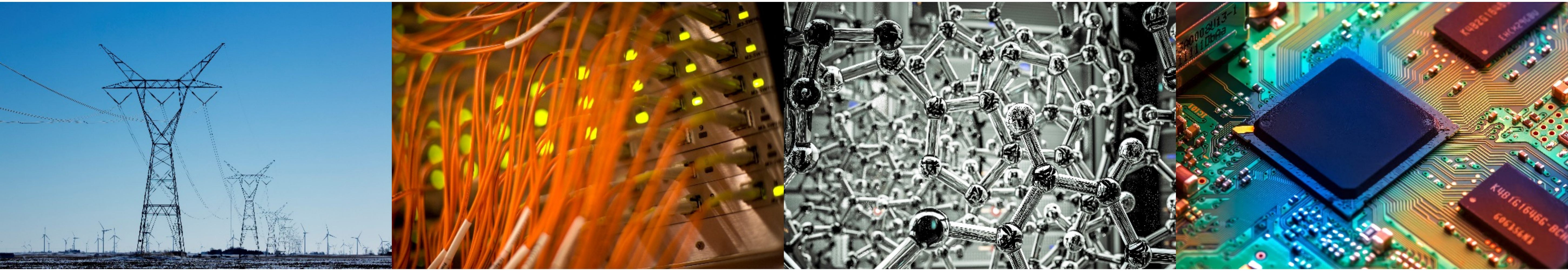
Electric/Hybrid-Electric Drives for Aircraft Propulsion

Kiruba Haran



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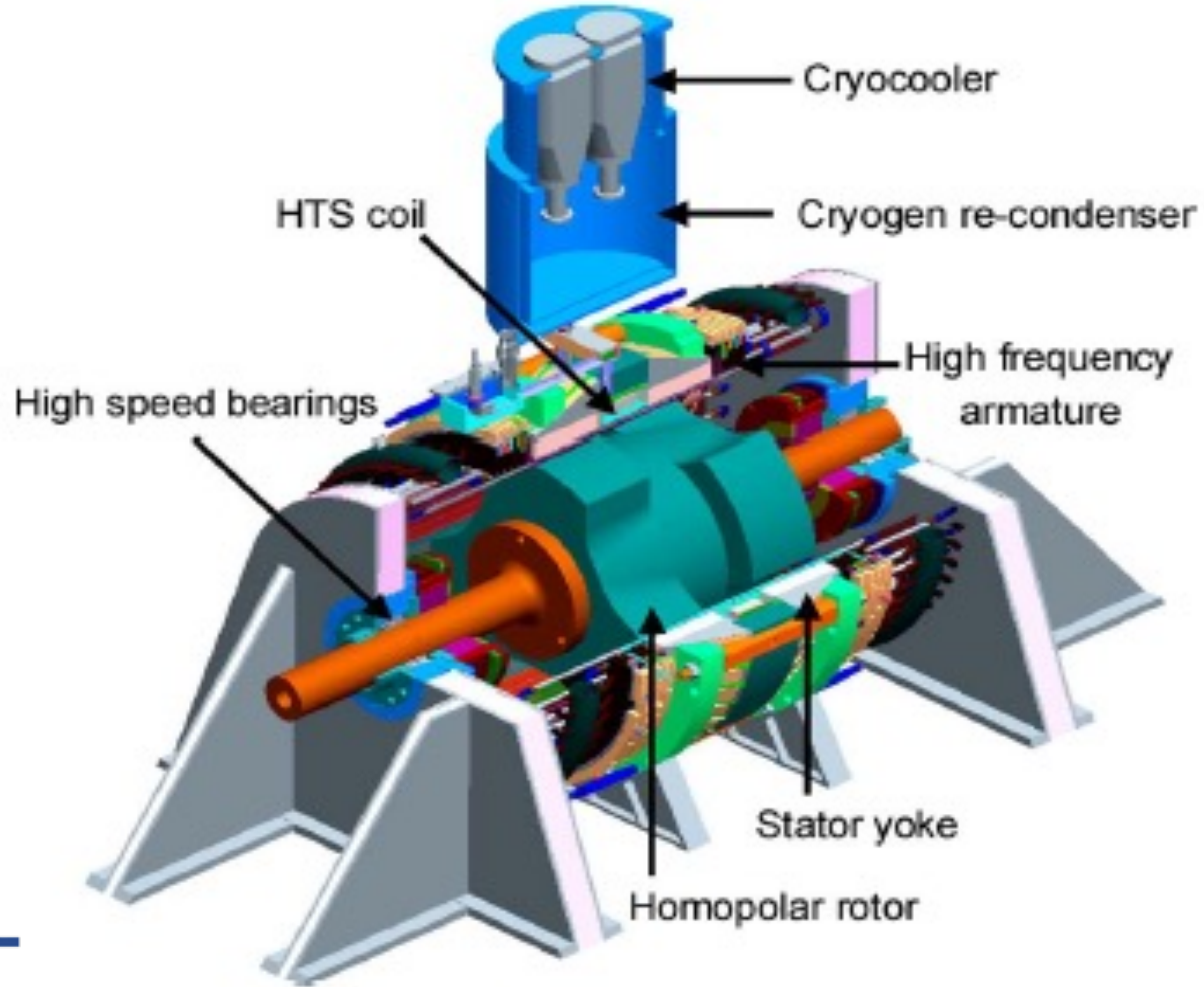
Outline

- Introduction
- Non-cryo: high frequency machines
  – Use-case: parallel hybrid engines, STARC-ABL
- Cryo: superconducting machines
  – Use-case: hydrogen powered airplane (CHEETA)
- Discussion

Airborne Electric Power

- Multi-Megawatt (up to 5MW) power for DEW systems
- Megawatt scale demo, 2003 – 2007; 13kW/kg, 97% efficiency
- Dynamic capability: 0-100% power in < 1 msec
- 2.75kHz ‘air core’, water-cooled armature
- Field MMF: ~50,000 AT’s, HTS at 30K
- 35,000 rpm, 14” iron core rotor

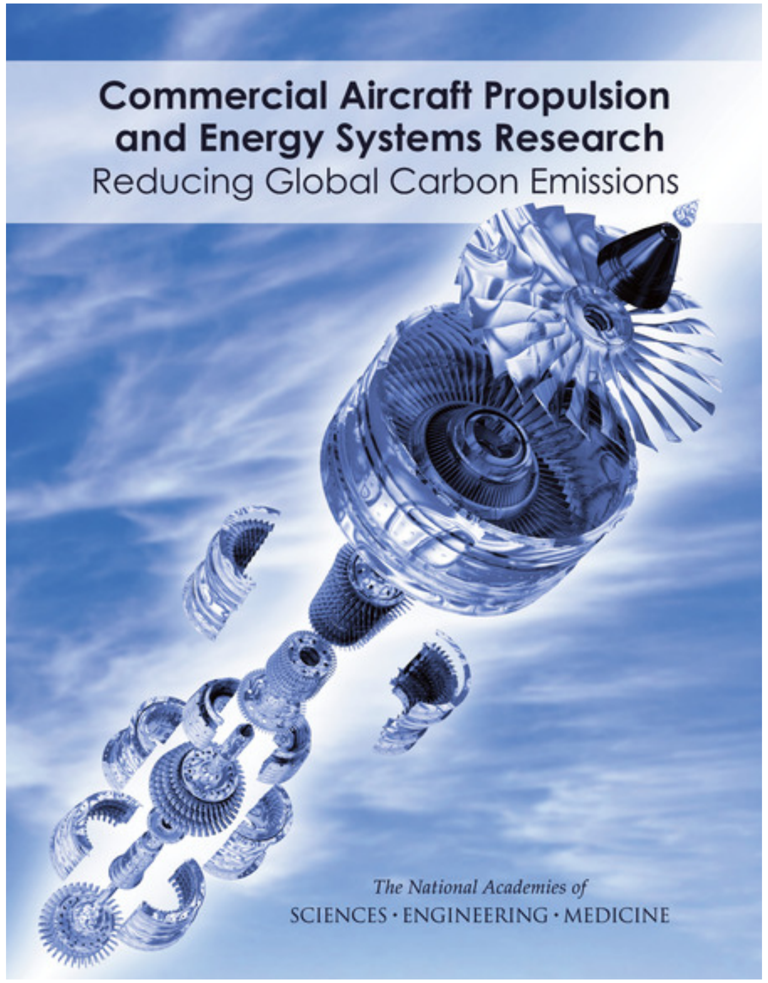


Requirements for electric propulsion

TABLE 4.2 Electrical System Component Performance Requirements for Parallel Hybrid, All-Electric, and Turboelectric Propulsion Systems

	Electric System [a]		Battery [b]
Aircraft Requirements	Power Capability (MW)	Specific Power (kW/kg)[c]	Specific Energy (Wh/kg)
General aviation and commuter			
Parallel hybrid	Motor <1	>3	>250
All-electric	Motor <1	>6.5	>400
Turboelectric	Motor and generator: <1	>6.5	n/a
Regional and single aisle			
Parallel hybrid	Motor 1-6	>3	>800
All-electric [b]	Motor 1-11	>6.5	>1,800
Turboelectric	Motor 1.5-3; Generator 1-11	>6.5	n/a
Twin-aisle			
Parallel hybrid	Not studied		
All-electric	Not feasible		
Turboelectric	Motor 4; generator 30	>10	n/a
APU for Large Aircraft	Generator 0.5-1	>3	Not studied

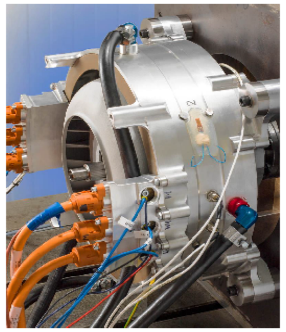
[a] Includes power electronics.
[b] Total battery system and usable energy for discharge durations that are relevant to commercial aviation flight times, nominally 1-10 hours. Values shown are for rechargeable batteries; primary (nonrechargeable) batteries are not considered relevant to commercial aviation.
[c] Conversion factors: 1 kW/kg = 0.61 HP/lb; 1 kg/kW = 2.2 lb/kW = 1.64 lb/HP.



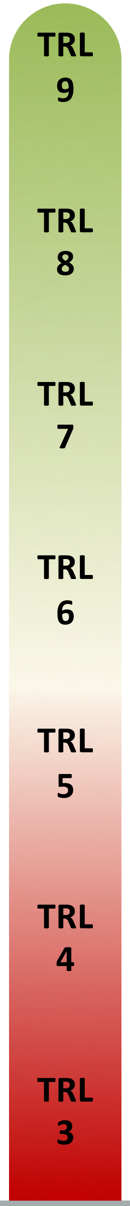
State-of-the-art

UTAS Variable Frequency Starter Generator: 250 kVA, 7200–16000 rpm; Oil spray cooling; wound-field synchronous machine; 6-pole, variable frequency: 360 – 800 Hz, 235 V, many functions, ~2 kW/kg; Efficiency ~95%

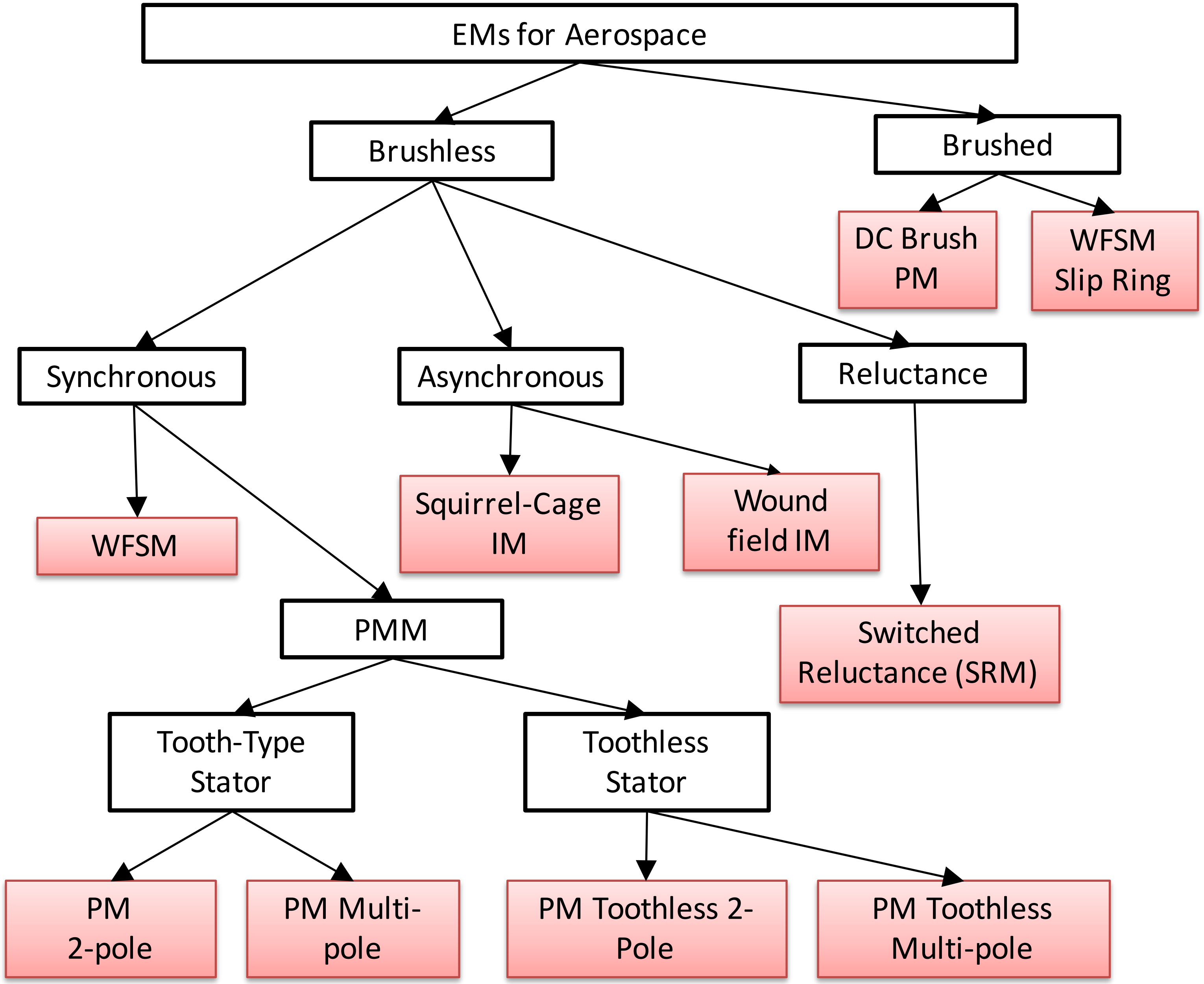
Siemens propulsion motor: 200-250 kW, 1300-2500 rpm; Aggressive cooling, with direct cooling of copper; high coolant temperature level (90-100 ºC); Optimized EM design,; minimized structural weight; 5 kW/kg (30Nm/kg); Efficiency > 95%;



GE/AFRL HTS HIA: 5MW, 35,000 rpm design, demo at 2.2MW, 10,500 rpm; Field regulation with HTS field coil; Liquid Neon cooling; Flywheel energy storage to ride through pulse loading; 13kW/kg; 97% efficiency,



Aerospace Electrical Machines



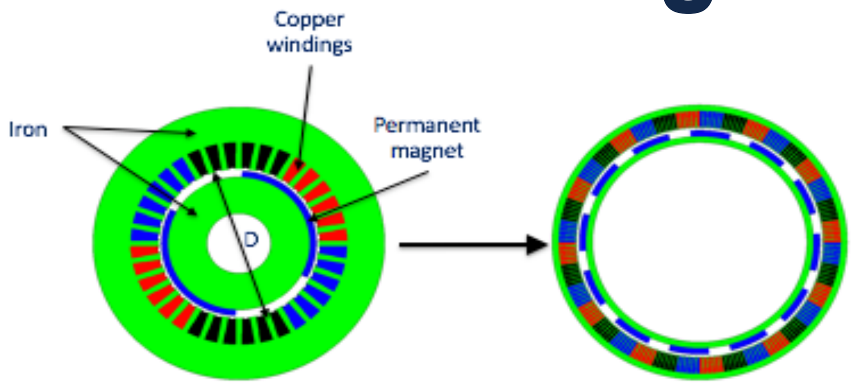
List of Abbreviations
IM = Induction Machine
SRM = Switched Reluctance Machine
PM = Permanent Magnet
WFSM = Wound Field Synchronous Machine

Electric Machines Rated by Key Characteristics Extended from [1]

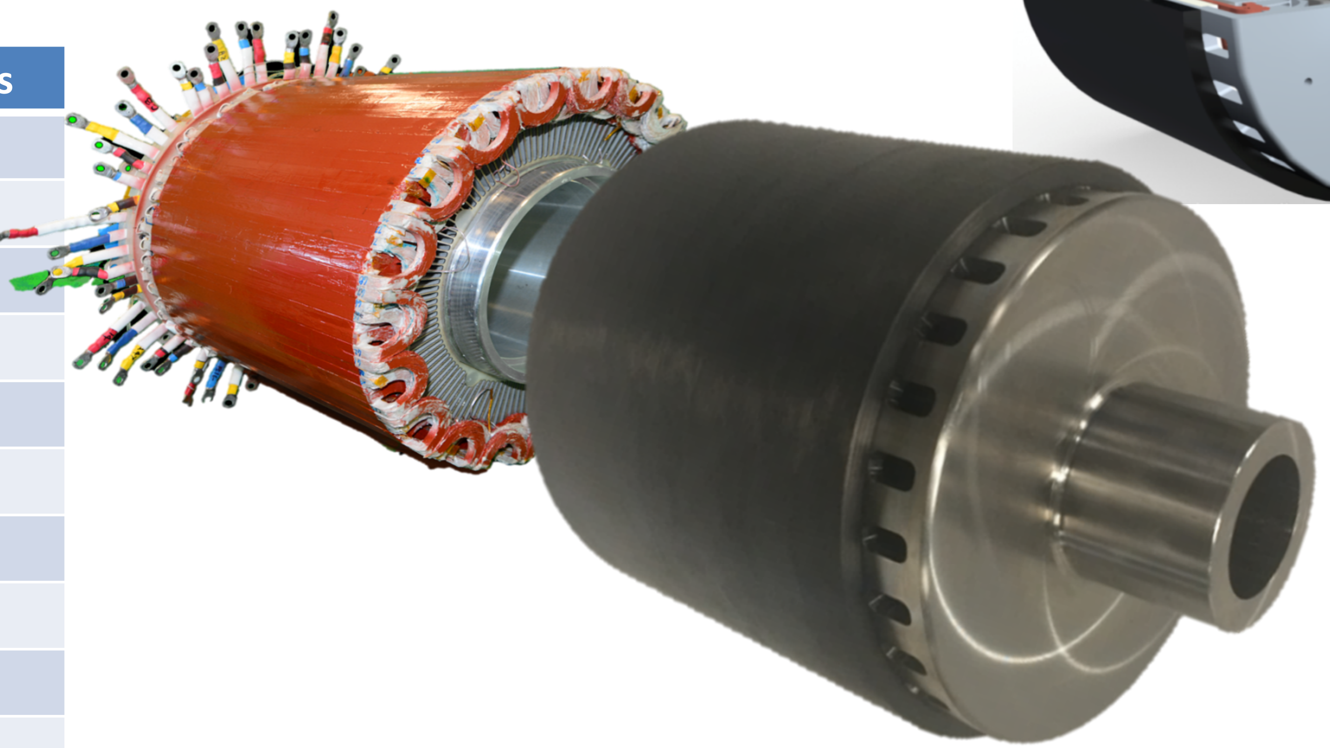
Key Characteristic	WFSM	IM	SRM	PM 2-pole	PM Multi-pole	PM Toothless 2-pole	PM Toothless, Multi-pole
Rotor Losses	6	6	6	10	10	10	10
Stator Losses	8	8	8	9	10	8	9
Windage Losses	4	5	1	9	9	10	10
Rotor thermal limitations	7	8	10	4	4	4	4
Cooling options	5	5	5	9	9	10	10
Rotor Mechanical Limitations	4	5	7	9	9	10	10
Torque-to-inertia ratio	6	5	7	9	9	10	10
Torque pulsation	6	9	3	6	6	10	10
Compatibility with bearings	9	5	5	9	9	10	10
High speed capability	3	5	7	9	9	10	10
Short circuit behavior	9	10	10	4	4	3	3
Machine complexity	6	7	10	9	9	8	8
Current density	10	7	7	10	10	8	8
Power density	7	7	8	10	10	8	8
TOTAL	90	92	94	116	117	119	120

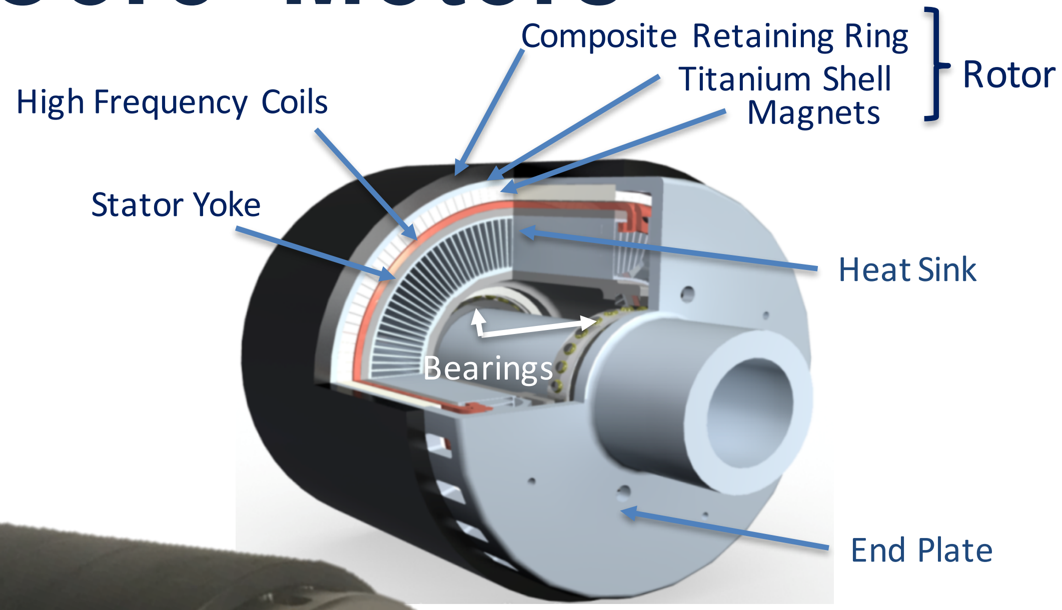
[1] Evgeni Ganev, "Selecting the Best Electric Machines for Electrical Power-Generation Systems," IEEE Electrification Magazine, December 2014

NASA NRA: High Frequency ‘Air-Core’ Motors



Key parameters	Values	Units
Rated power	1	MW
Rated torque	665	Nm
Rated efficiency	97	%
Specific power	13	kW/kg
Total machine weight	167	lbs
Machine active weight	89	lbs
Nominal speed	15,000	rpm
Line-to-line voltage (rms)	650	V
DC bus voltage	±500	V
Cooling, forced air	>20	m/s





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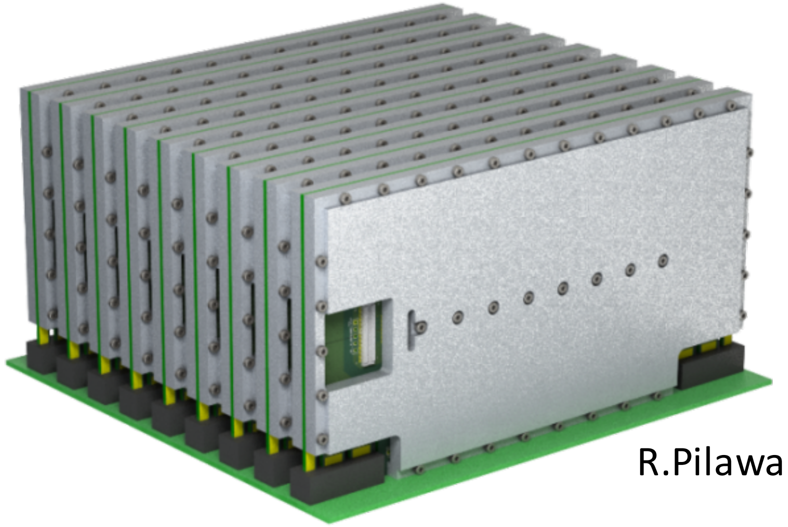
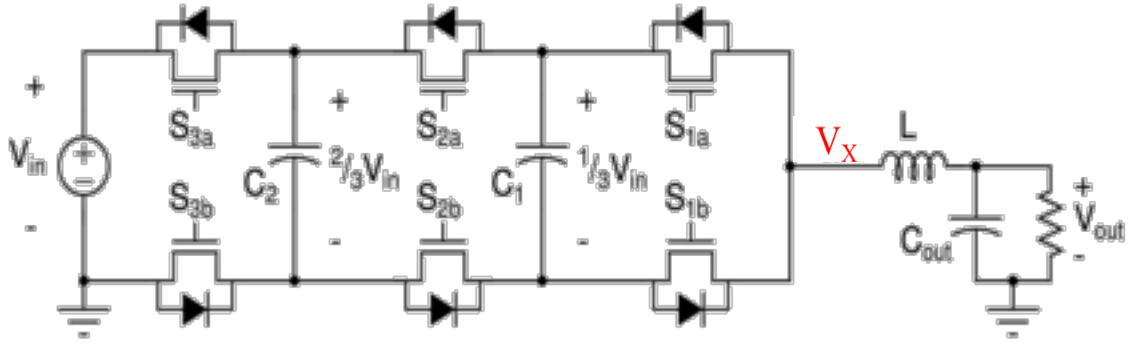
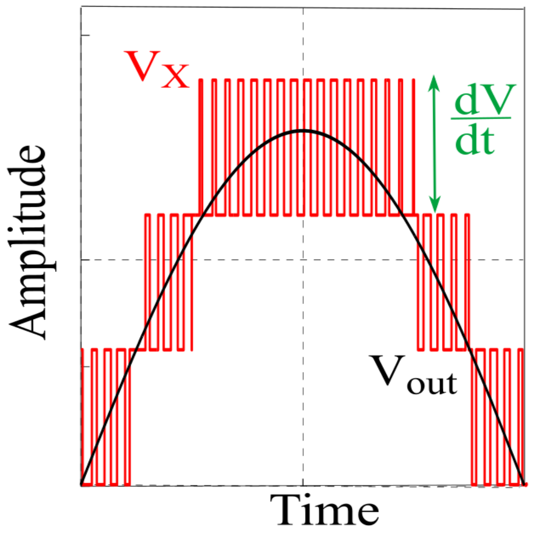
Multi-Level Inverters



Modular, GaN inverter, Illinois



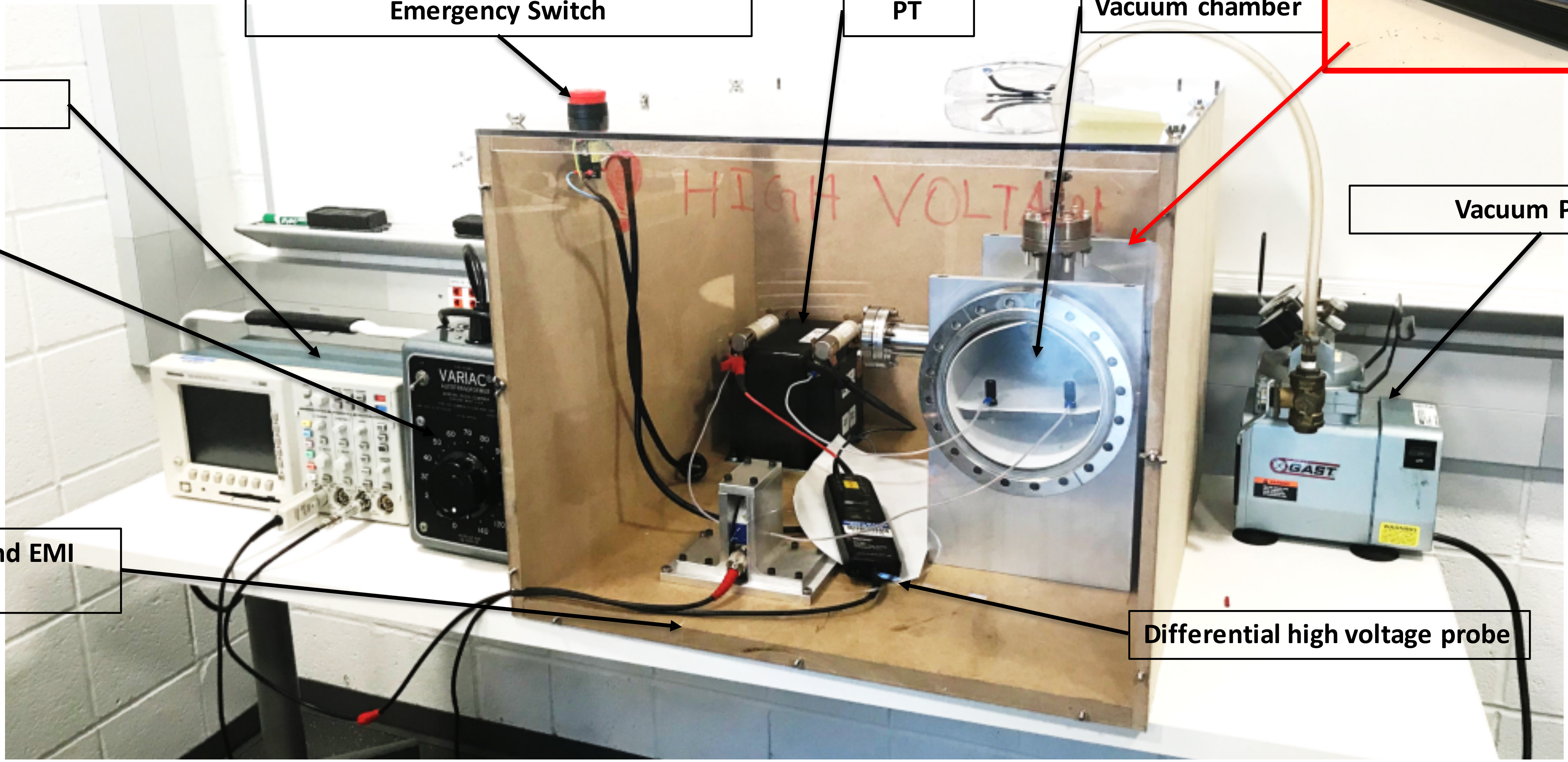


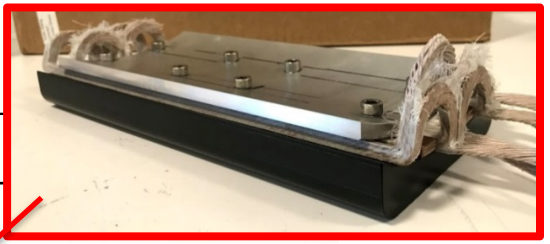
SiC inverter, GE

Key Parameter	2-Level Inverter	Multilevel Inverter
Switch Stress (dV for dV/dt)	V_{in}	$V_{in}/(N-1)$
V_x, Output Ripple Amplitude	V_{in}	$V_{in}/(N-1)$
V_x, Output Ripple Frequency	f_{SW}	$f_{sw} \times (N-1)$
Output Filter Size	L_{2level}	$L_{2level}/(N-1)^2$

[1] T. Meynard and H. Foch, “Multilevel conversion: high voltage choppers and voltage-source inverters,” PESC ’92

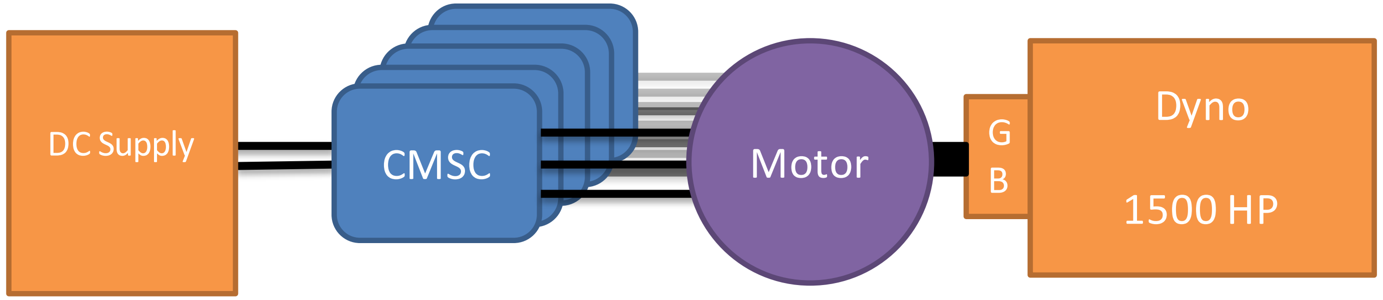
Component qualification - reliability

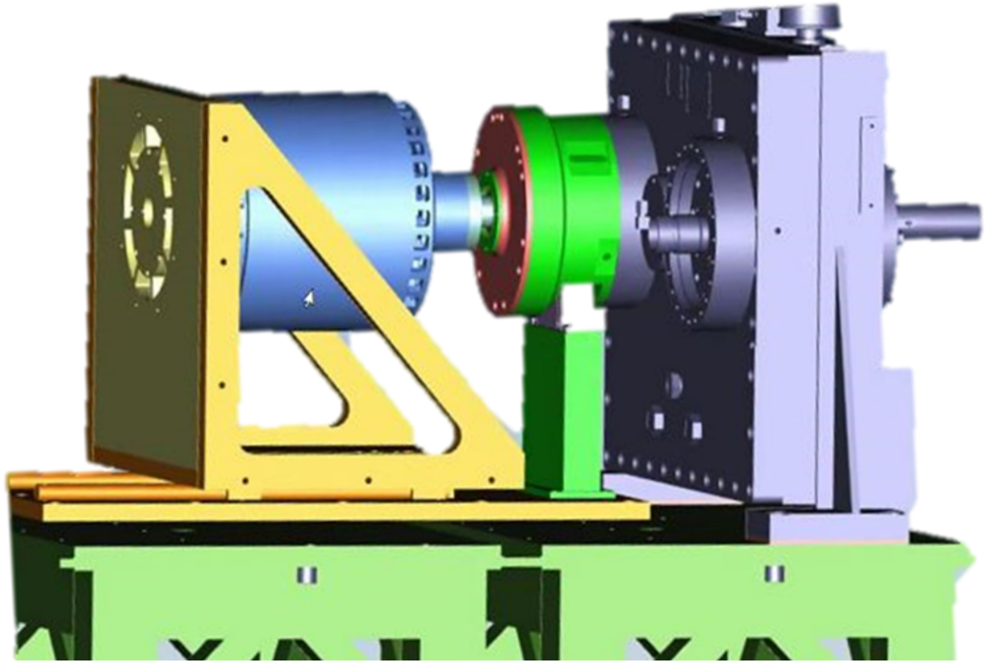




PD Test on Windings; Data fed into deep NN to predict impending failure

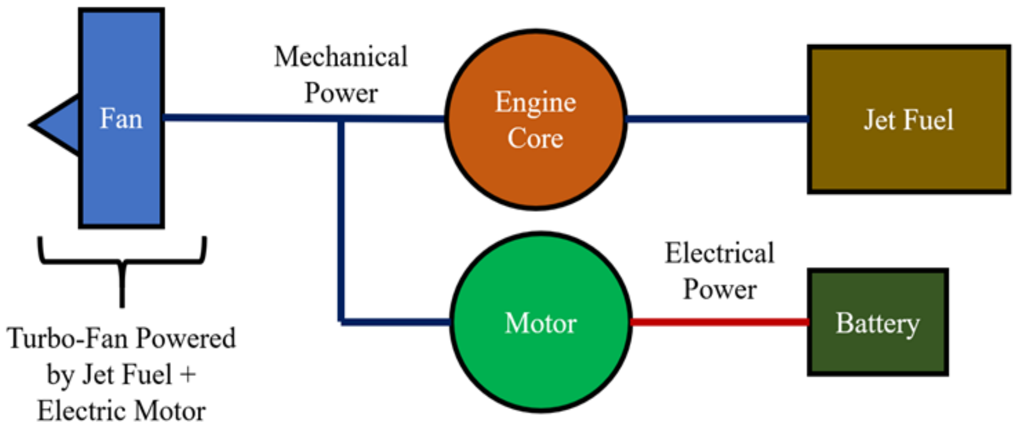
Sub-system qualification

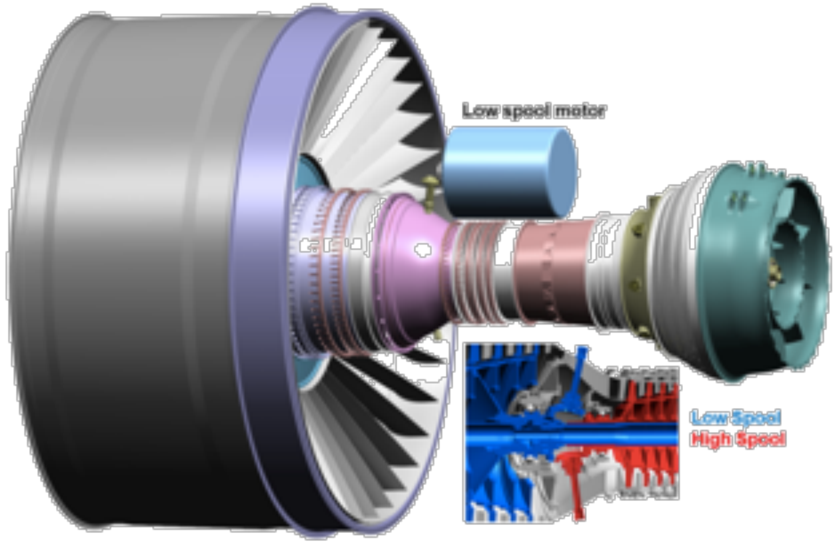




- Motor modules driven independently with multiple B-787 CMSC's at Collins Aerospace
- Characterize Machine Parameters
  - Back-EMF, Open Circuit Voltage, Synchronous reactance, Short Circuit Current
- Load Machine as a Generator
- Performance Characterization
  - Map motor performance at various speeds and loads
- Control and Stability
  - Apply step torque (current) command to motor and monitor control response and stability

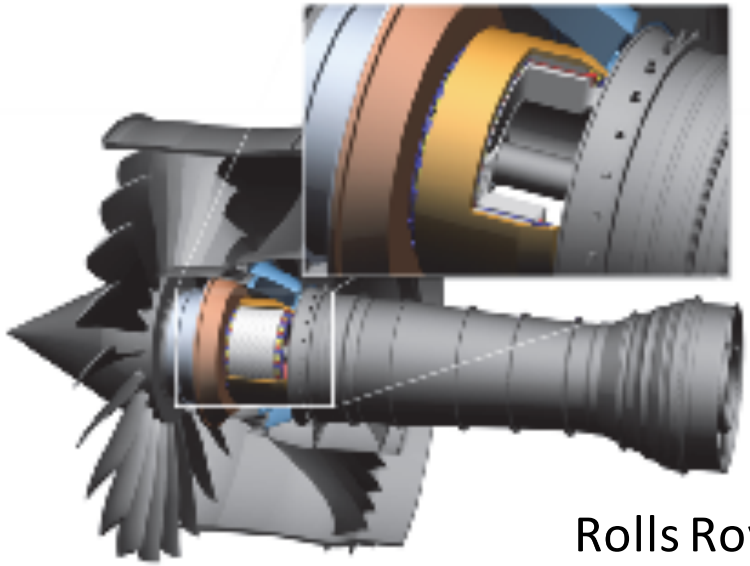
Use-case 1: Parallel Hybrids





UTC

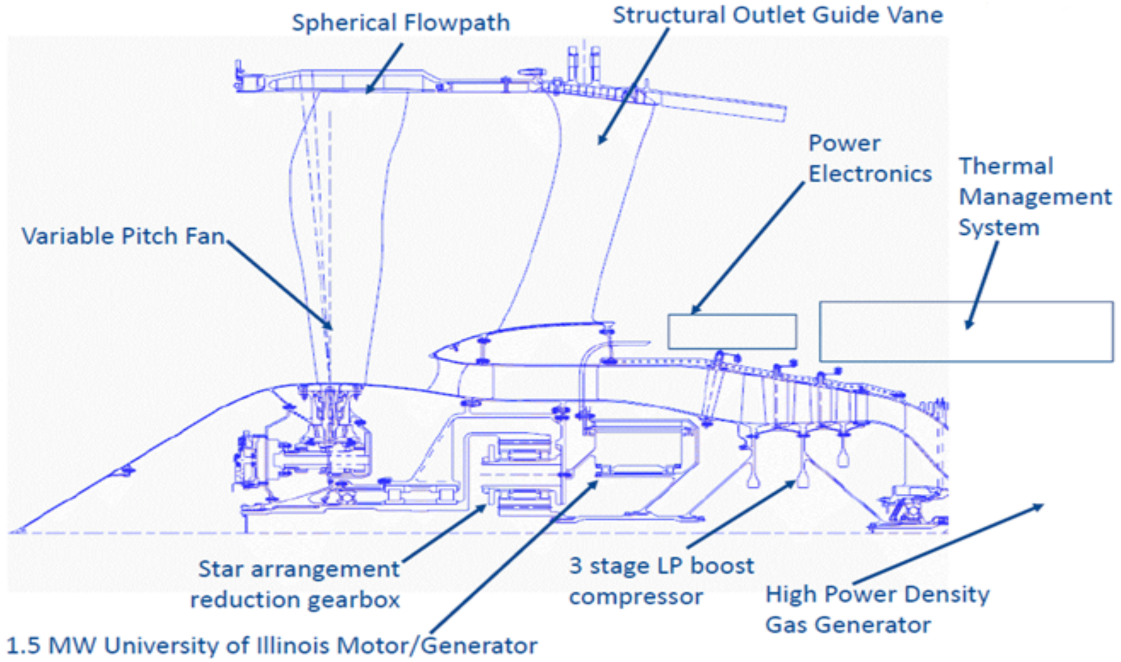
- Up to 4000 hp, embedded in engine
- Integration constraints
- Gearbox and lube system available
- High speed
- Broad Torque-speed profile

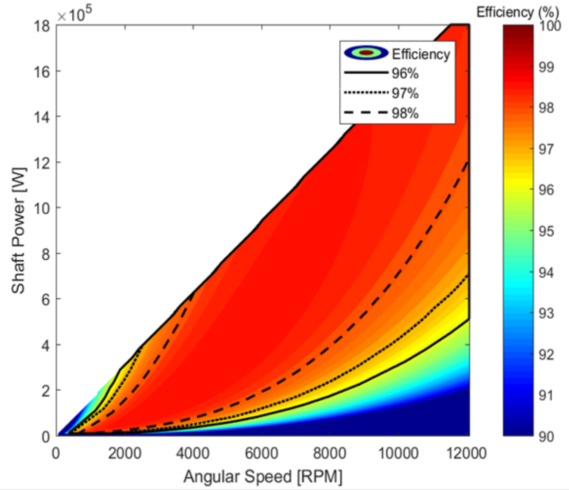


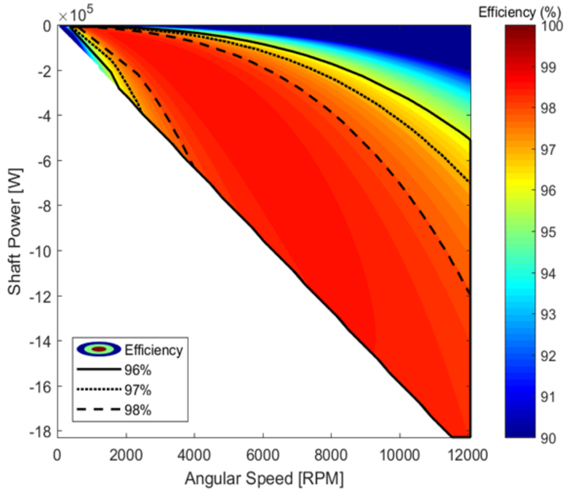
Rolls Royce 'EVE'

1.8MW engine integrated motor

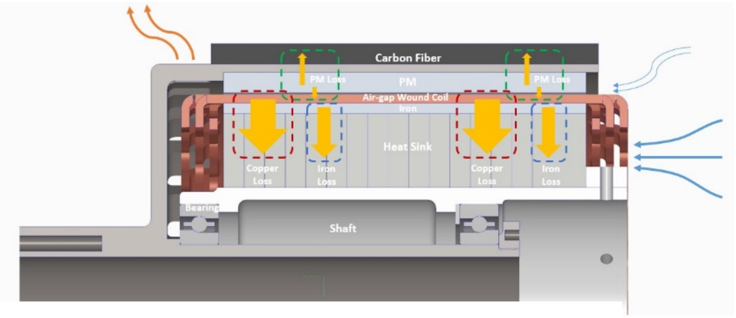
Machine Primary Metrics		
Rated Torque	1495	Nm
RPM	11,500	
Total Weight	132	kg
Total Volume	0.123	m^3
Total Length	0.32	m
Active Length	0.282	m
Outer Rotor Diameter	0.387	m
Efficiency	98.40%	
Slot Current Density	9.8	A/mm^2
Gap Flux Density	1.07	T
Component Dimensions		
Retaining Ring Depth	9	mm
Magnet Depth	20	mm
Air Gap Thickness	1	mm
Winding Depth	5	mm
Stator Yoke Depth	9	mm
Loss Breakdown		
DC Loss	11276	W
AC Loss	2224	W
Iron Loss	2382	W
Windage Loss	12812	W
Thermal Assumptions		
Inlet Temp	40	C
Coolant Mass Flow	0.5	kg/s
Coolant Axial Speed	25	m/s



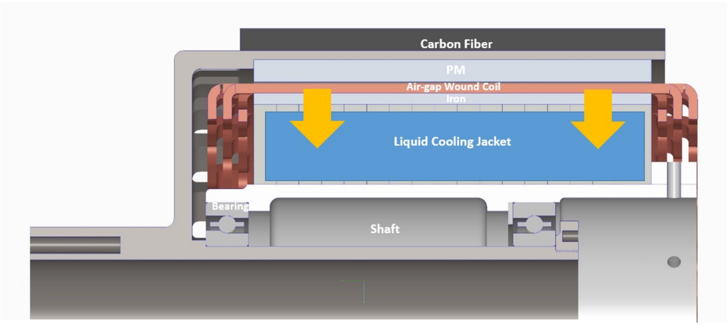




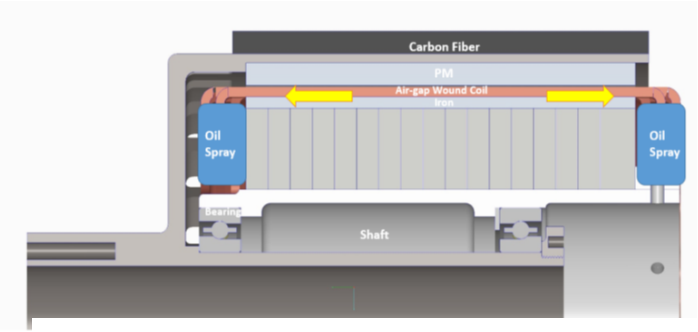
Integration opportunities - cooling



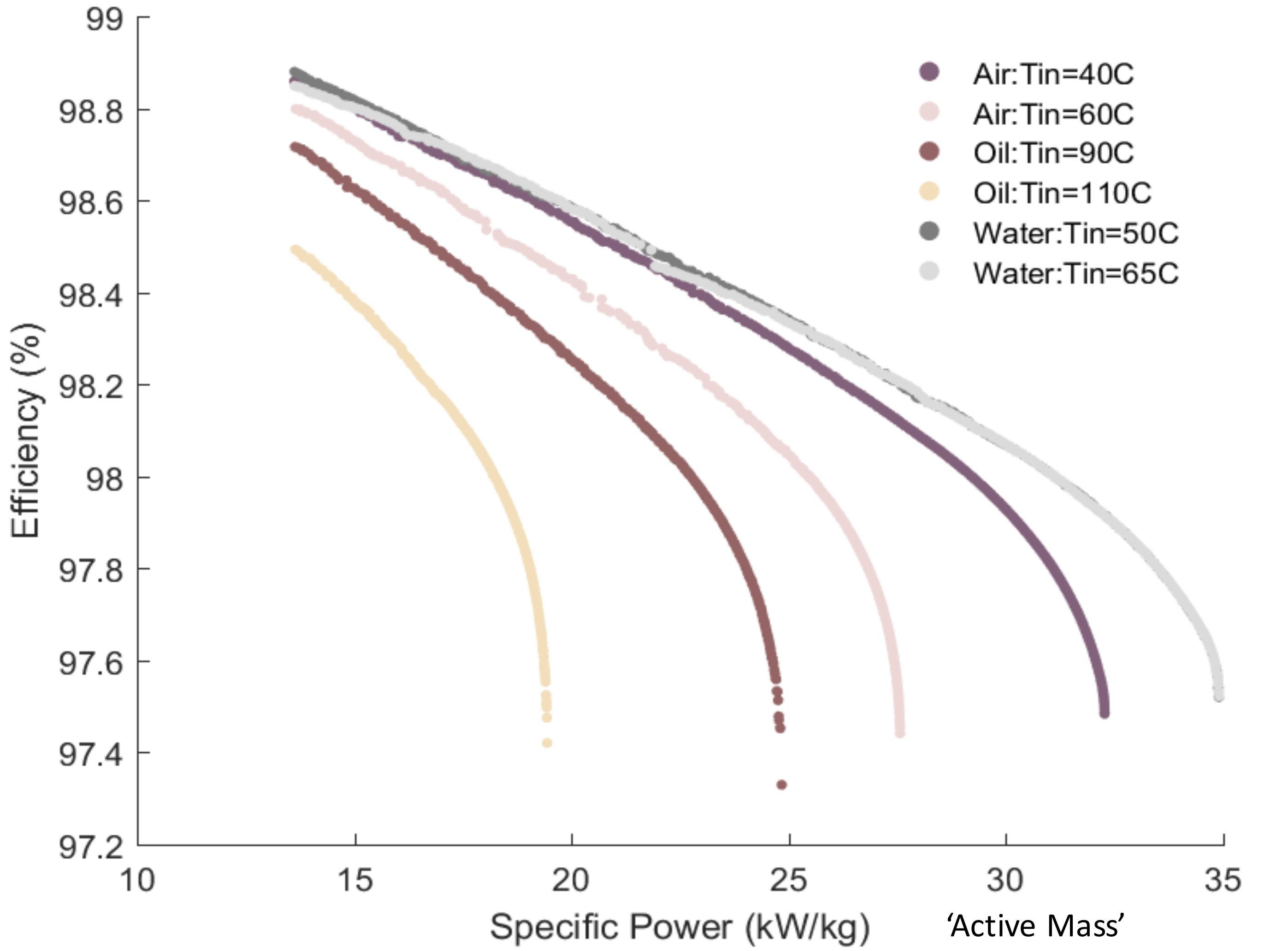
Forced Air Cooling



Indirect Liquid Cooling

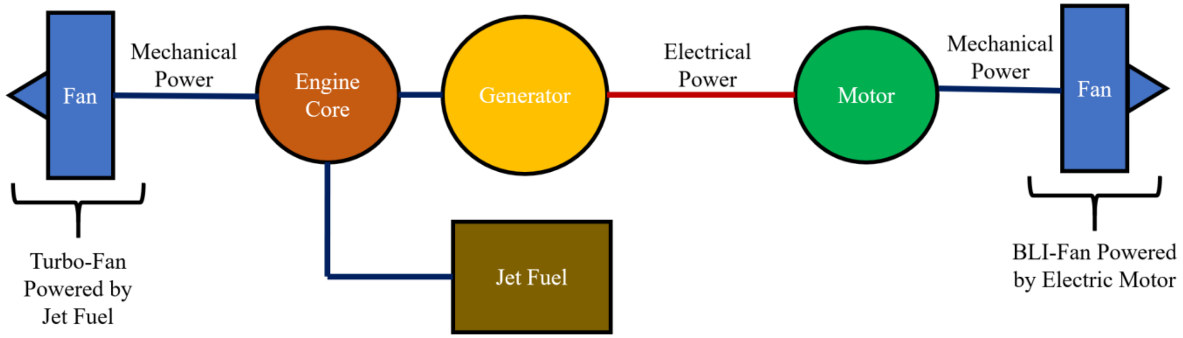


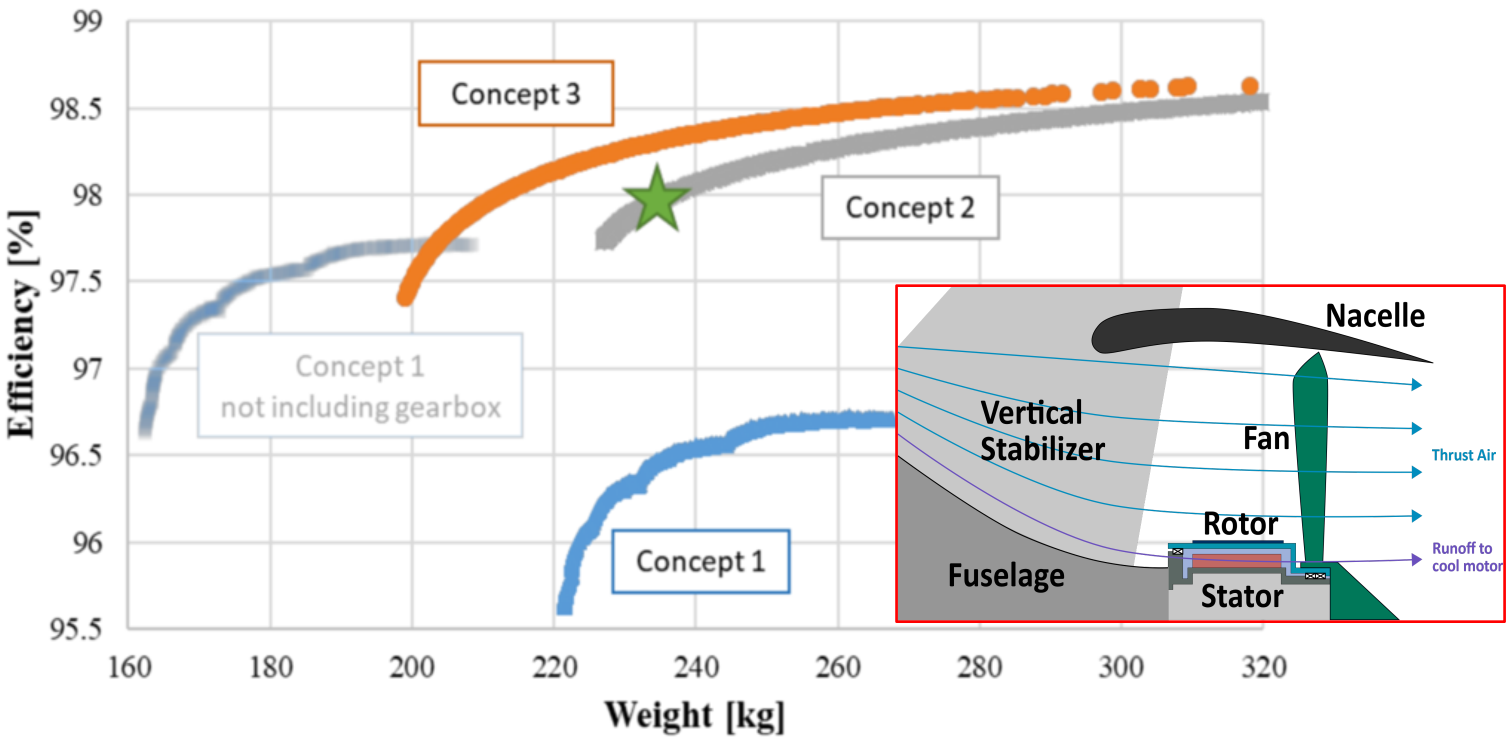
End Spray Cooling



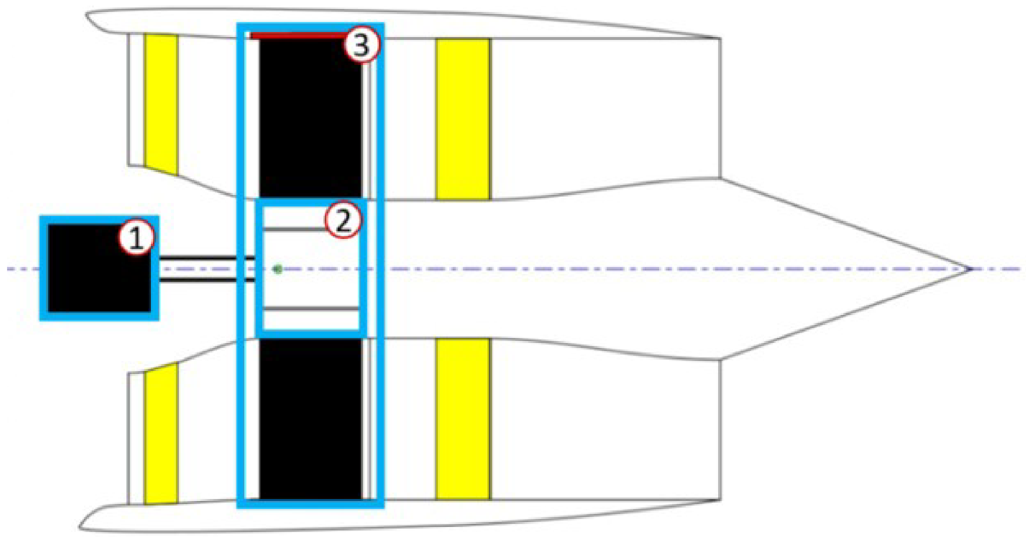
Pareto-Fronts of Motor Efficiency and Specific Power During Takeoff

Use case 2: STARC-ABL

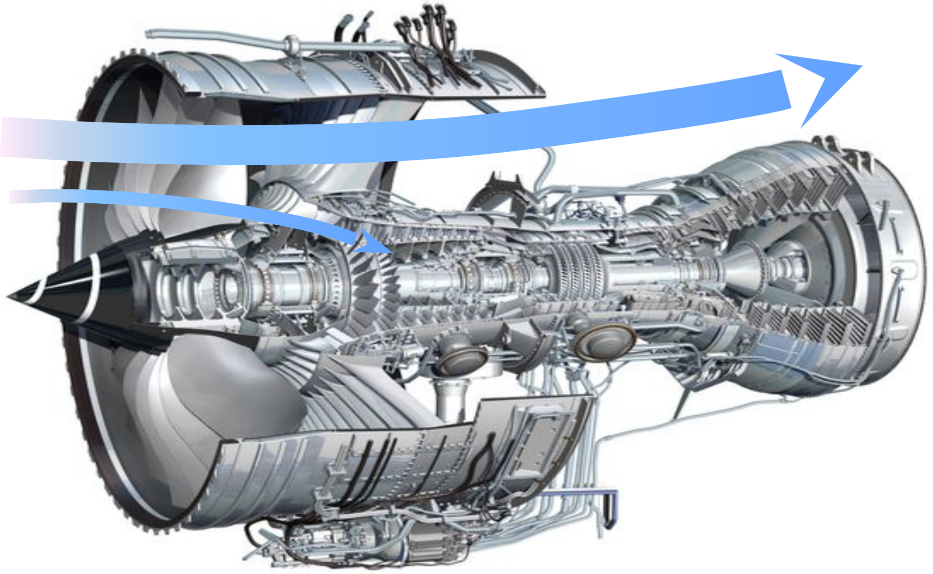




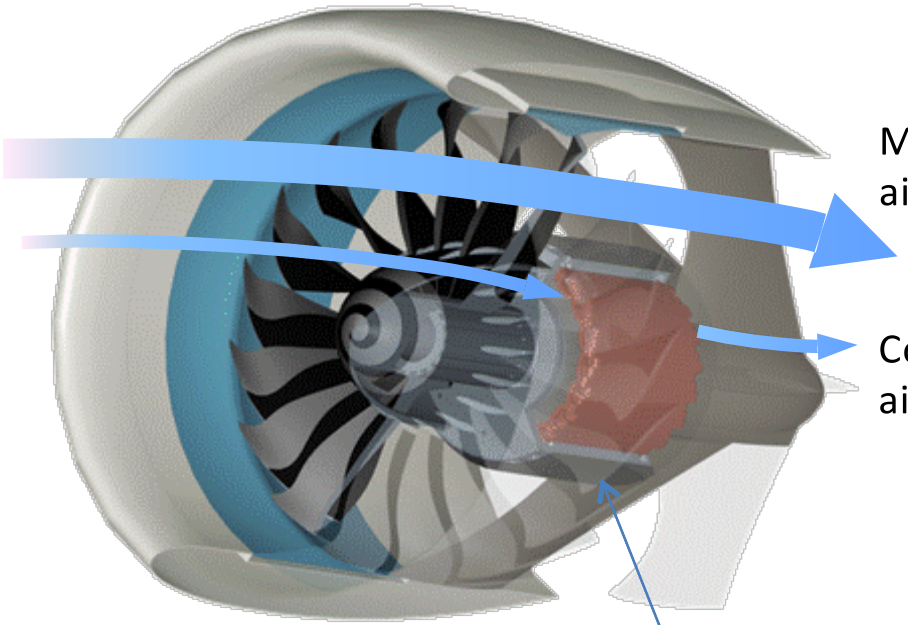
Tailcone Propulsor

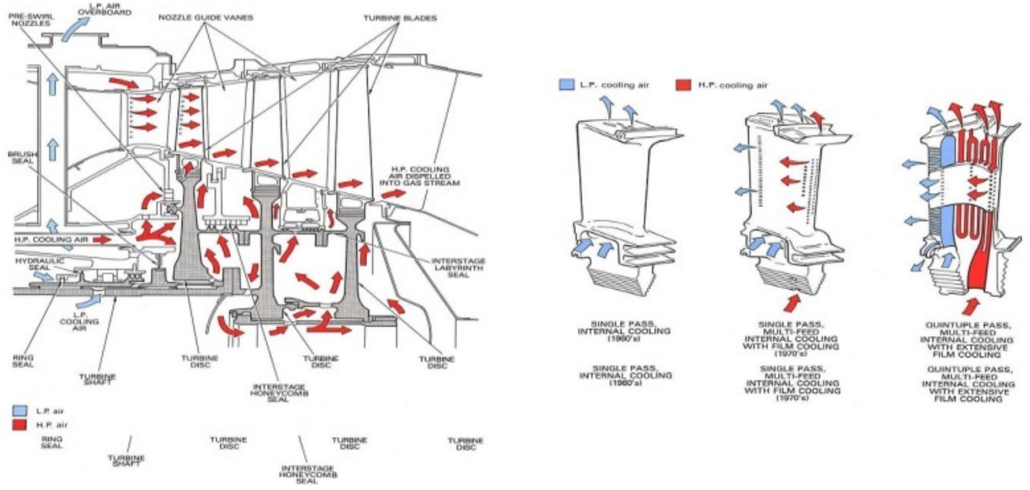


Integrated electric propulsor



Rolls Royce, Trent 1000





https://aerospaceengineeringblog.com/turbine-cooling/

For 1 MW motor, heat-load ~20 kW;

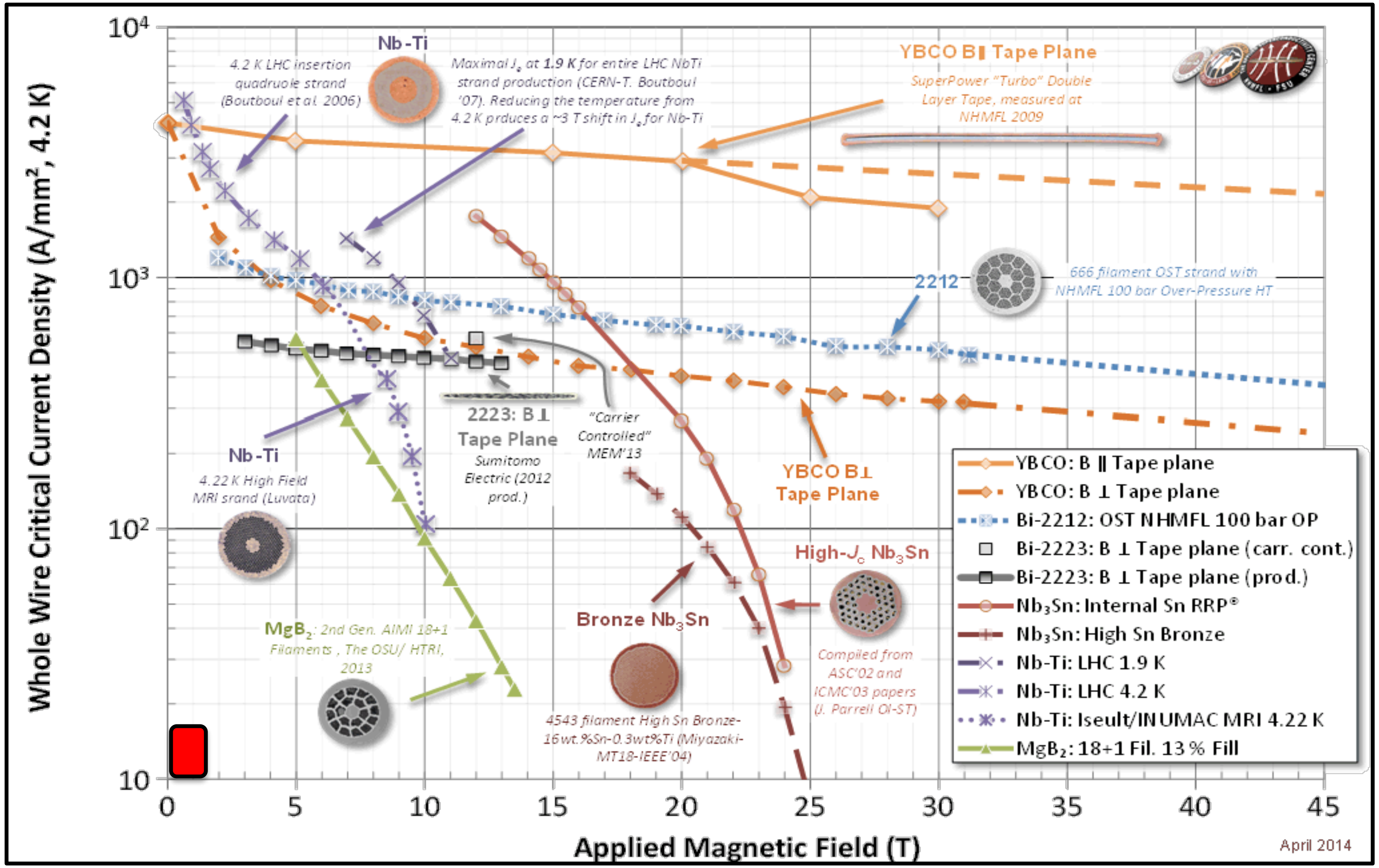
Allowable air rise ~ 1/3 x 150 K = 50 K

Air velocity through heat sink ~ 20 m/s;

Internal pressure drop ~ 100 Pa => 'Losses' < 1kW

Required m-dot ~ 0.3 kg/s ('By-pass ratio' ~ 100)

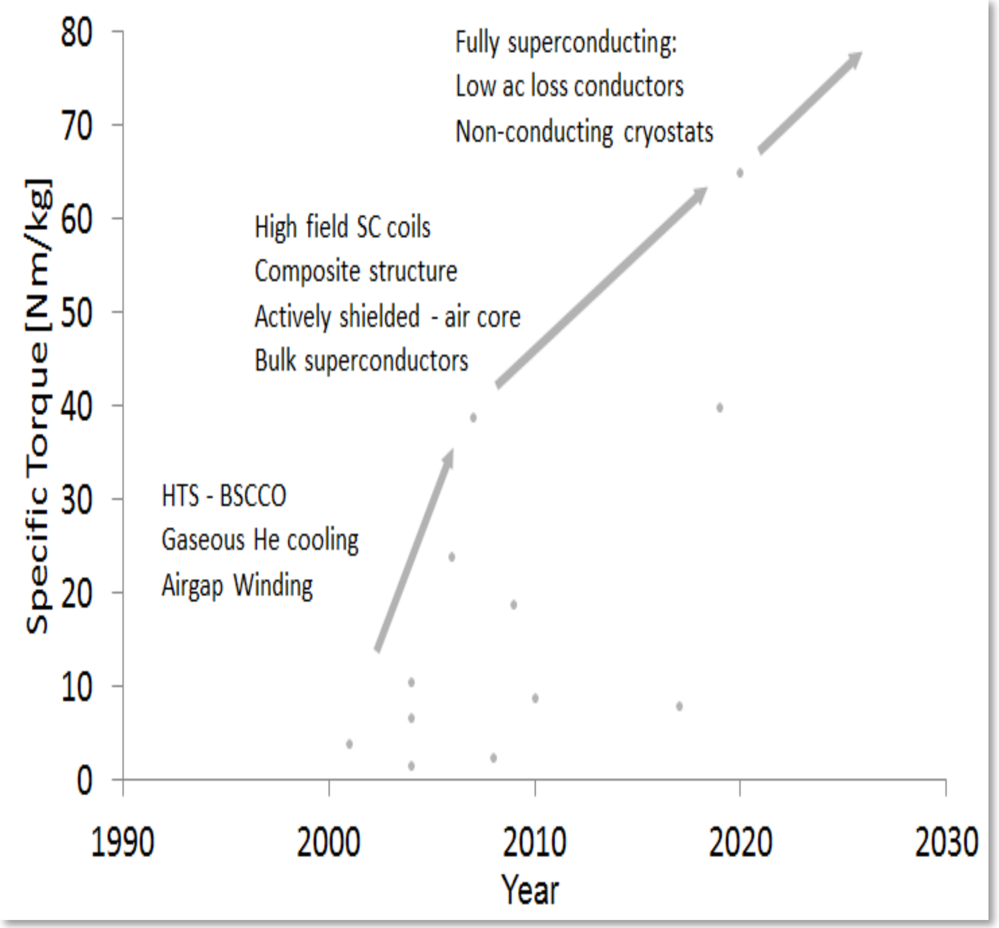
Superconducting machines



Source: The National High Magnetic Field Laboratory

Benefits

- High specific power: eliminate ferromagnetic material, higher air-gap flux density (5 – 10X current levels)
- High efficiency: Eliminate core and Ohmic losses; improved efficiency at off-design points. (> 99%)
- Thermal management: Requires cryo-cooling, but airplane level heat-load reduced by a factor of ~5 (10-20% of total power in conventional solutions).
- Partial discharge and arcing: Fully superconducting power system can enable distribution of tens of MW's of power at significantly lower voltages than with conventional conductors.

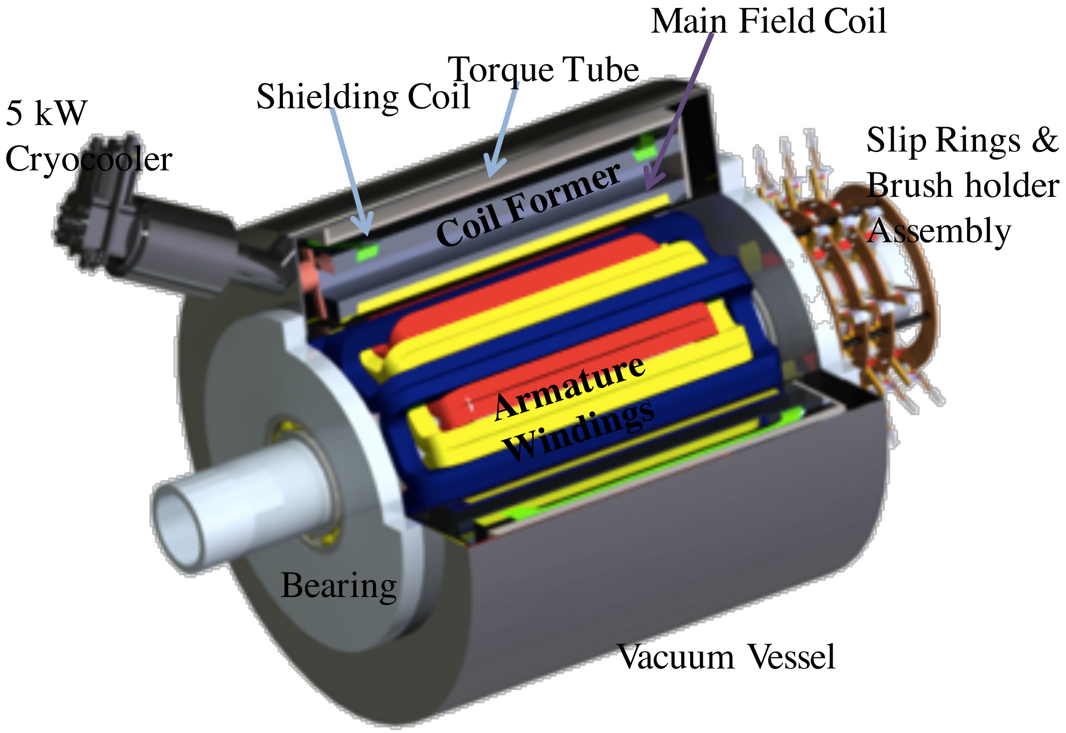


> 99% efficiency direct drives at >25kW/kg

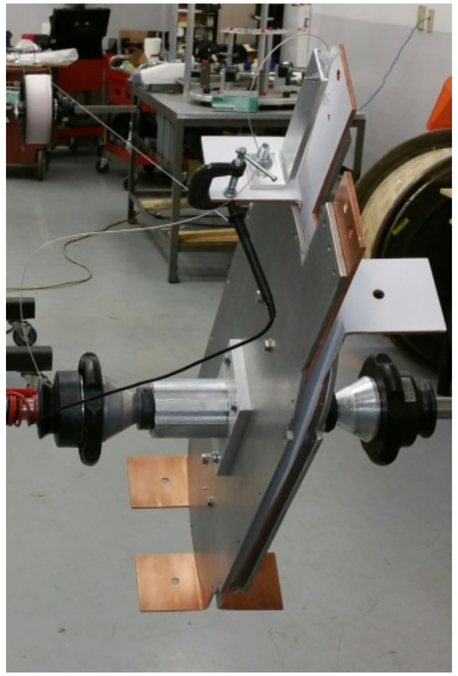
Haran KS, et al. "High power density superconducting rotating machines—development status and technology roadmap". Superconductor Science and technology. 2017

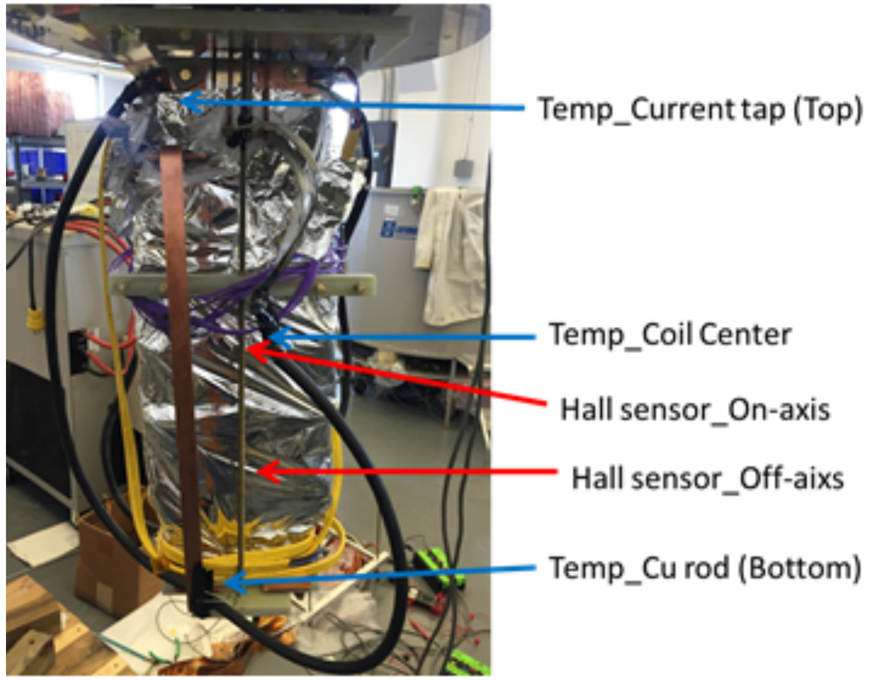
High Field ‘Air-core’ Machines

NASA LEARN Award (NNX15AE41A)



Full Size Coil Tests





Components demonstrated. Nb3Sn coils at 6T.

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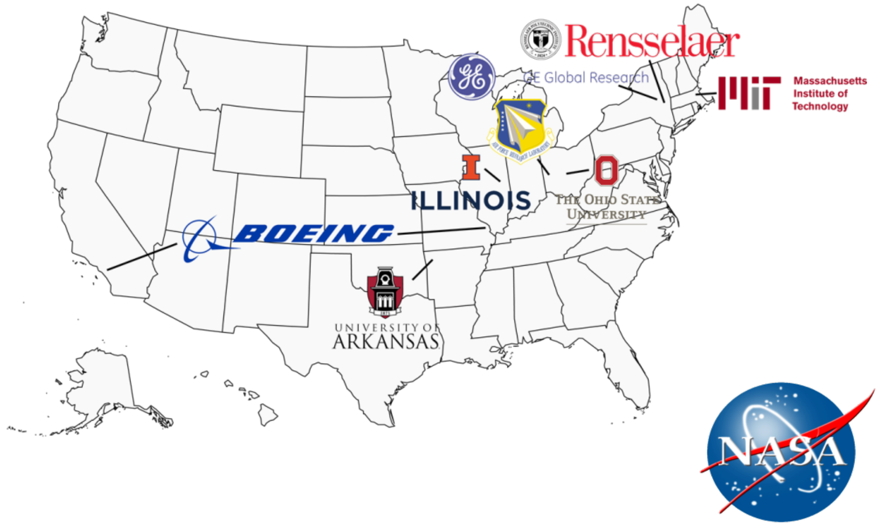
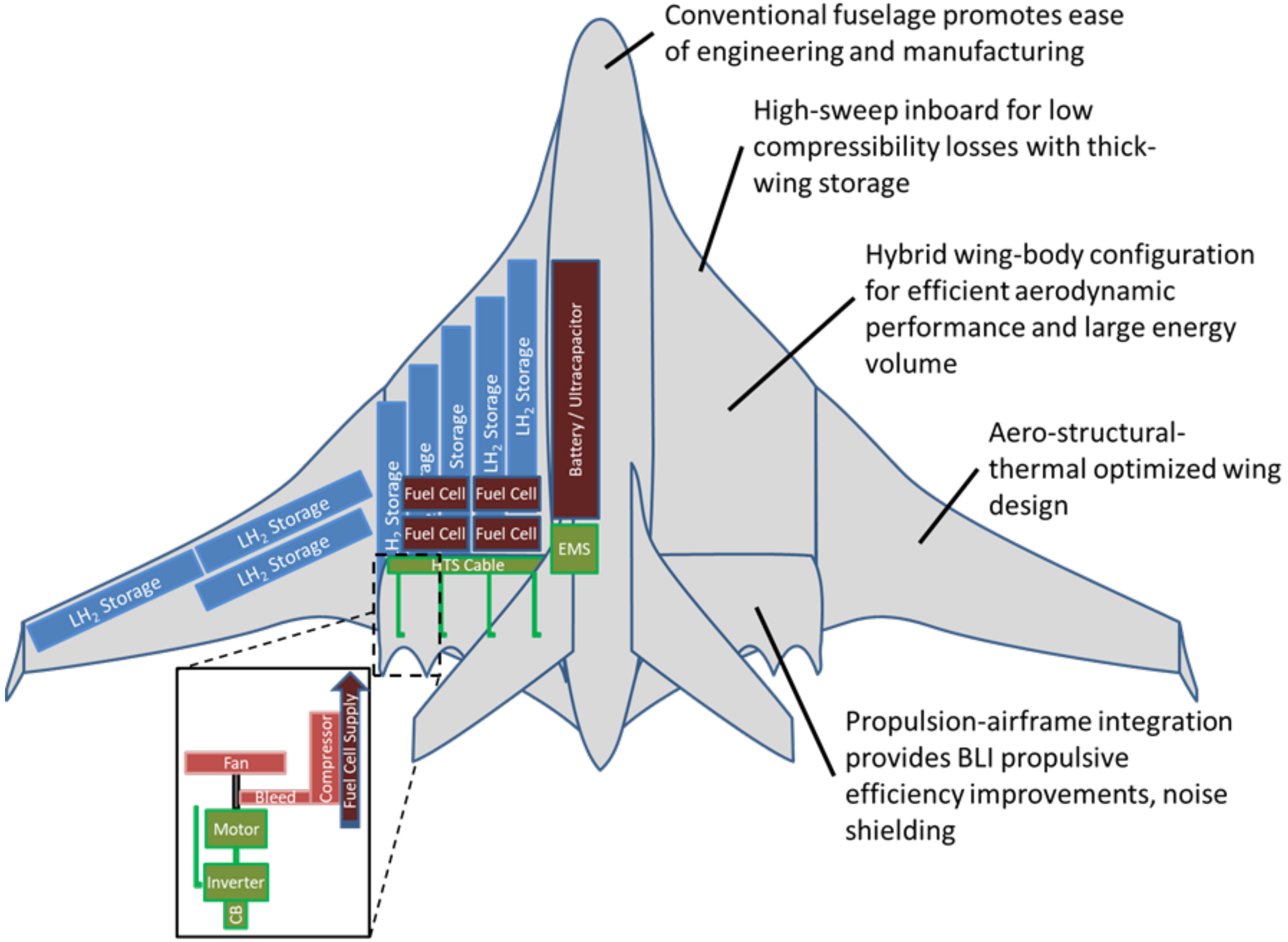
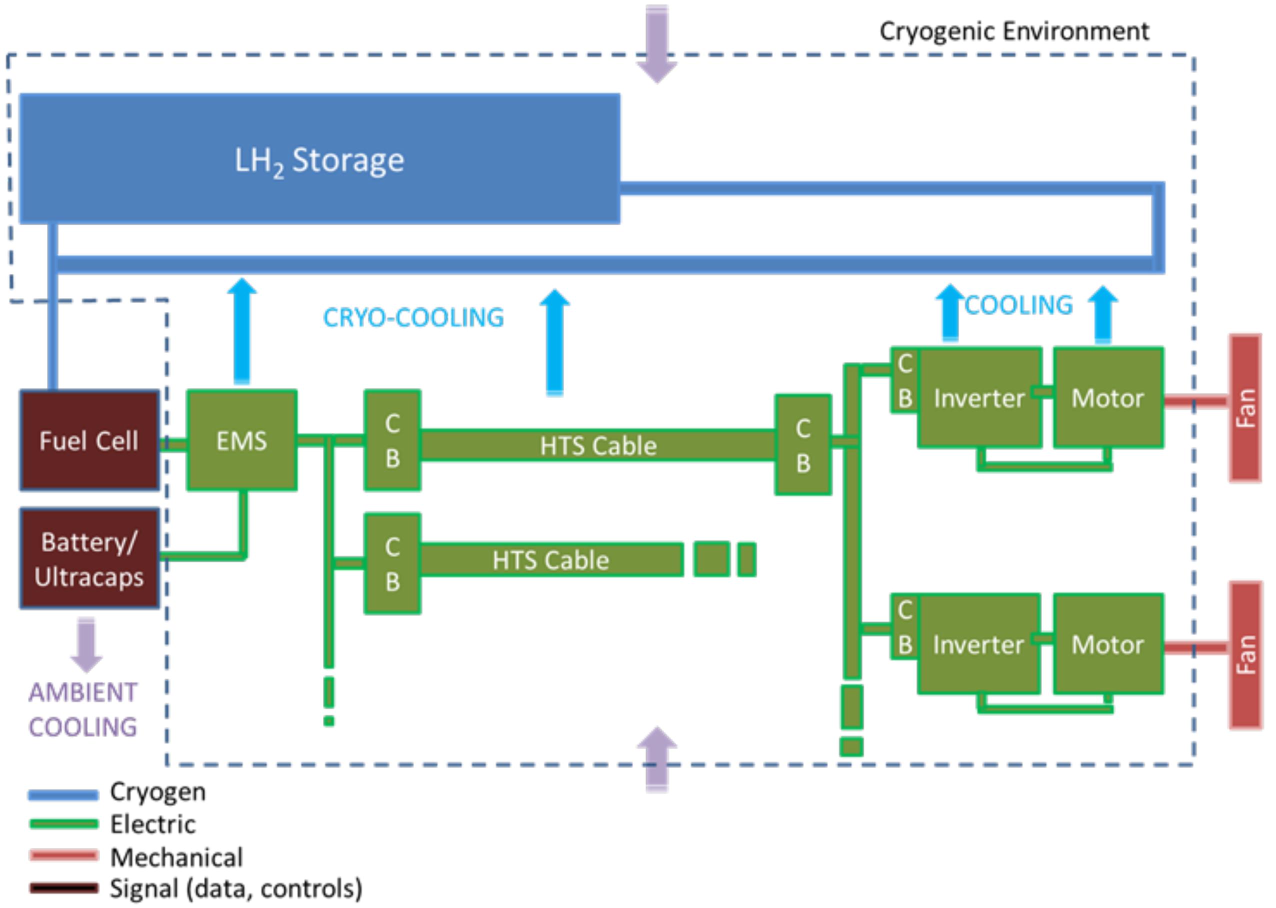
Cryogenic High-Efficiency Electric Technologies for Aircraft (CHEETA)

- LH2 energy storage with fuel cell system
  - Guaranteed energy availability
  - Doubled use as cryogen for superconducting electrical system
- Fully-electric propulsion system
  - Superconducting machines and cryogenic power electronics
  - Lightweight, low-voltage transmission system
  - Distributed, aero-integrated propulsion system
- No combustion and fan shielding reduce noise
- Zero CO_2 and NO_x emissions at vehicle level



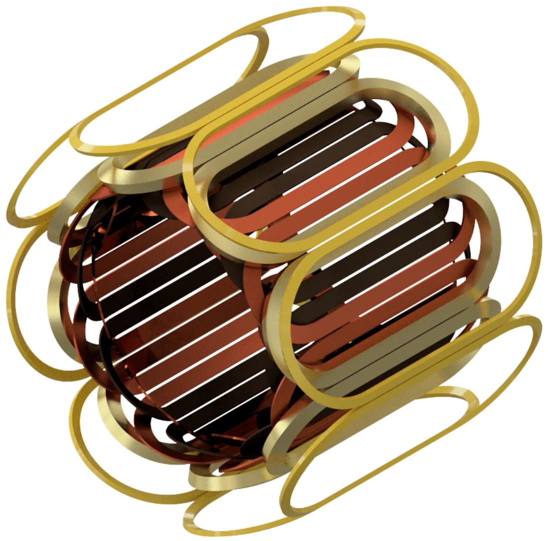
Key Features

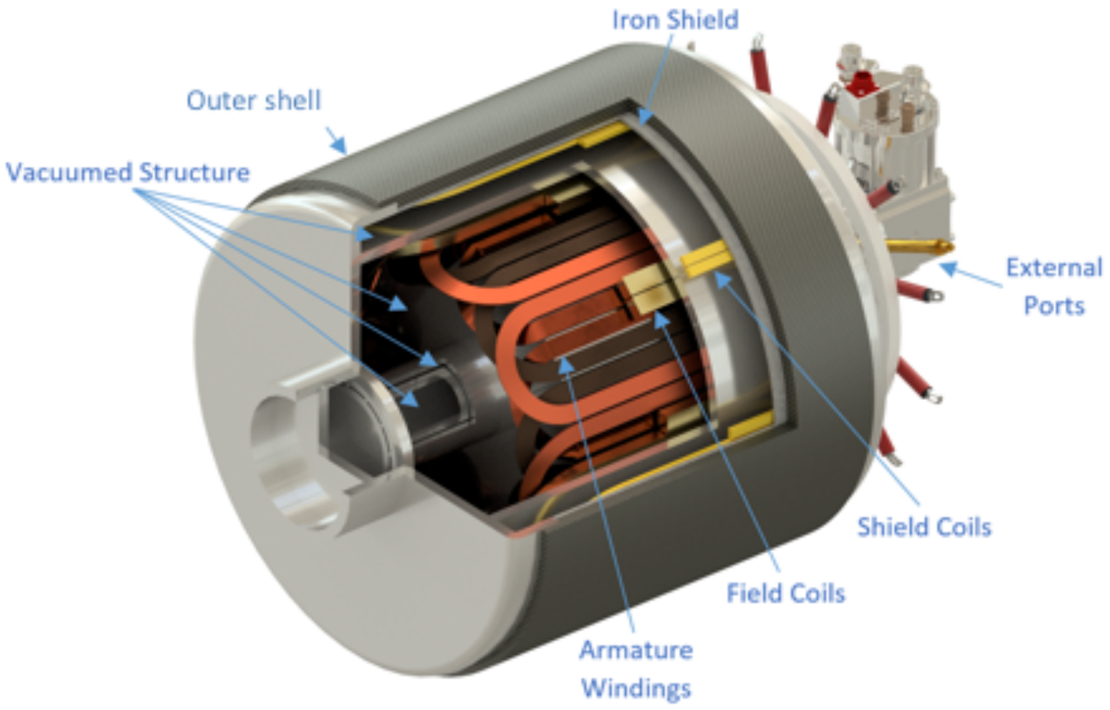




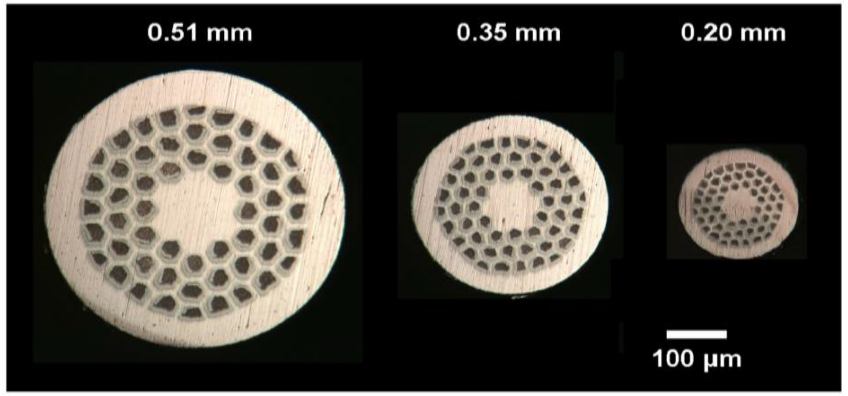
Fully Superconducting Machines

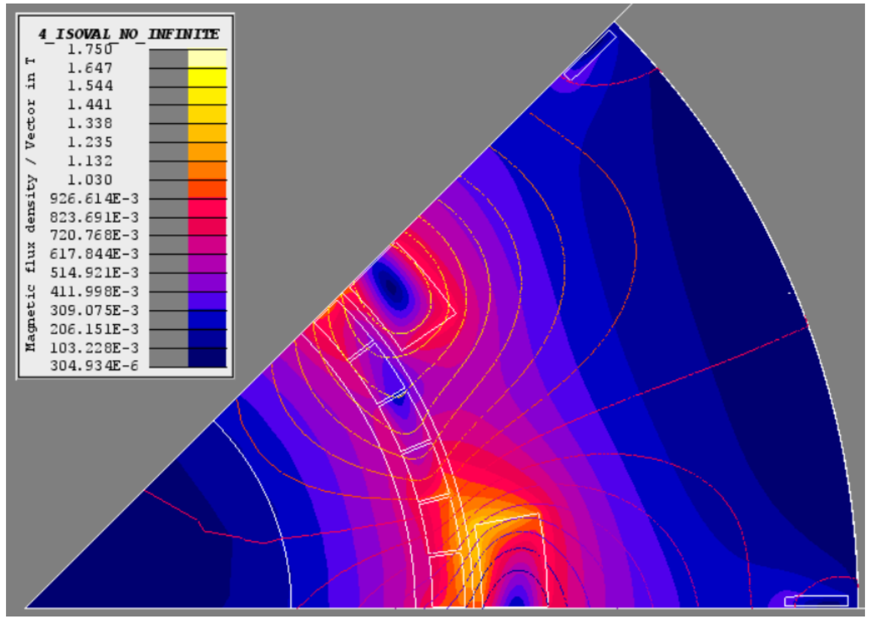
Low ac loss MgB_2 superconductors (HyperTech)





Fully Superconducting Motor for electric propulsion conceptual design





High Loss = 4158 W, Low weight = 18 kg

AC Losses

Penetration field

$$B_p = 0.4 * \mu_0 * J_c * d_f$$

Hysteresis loss

$$P_h = \left(\frac{8}{3 * pi}\right) * B_m * J_c * d_f * f$$

Eddy current loss

$$Pe = \left(\frac{\pi^2}{k * \rho_{eff}}\right) * (B_m * D_o * f)^2$$

Coupling loss

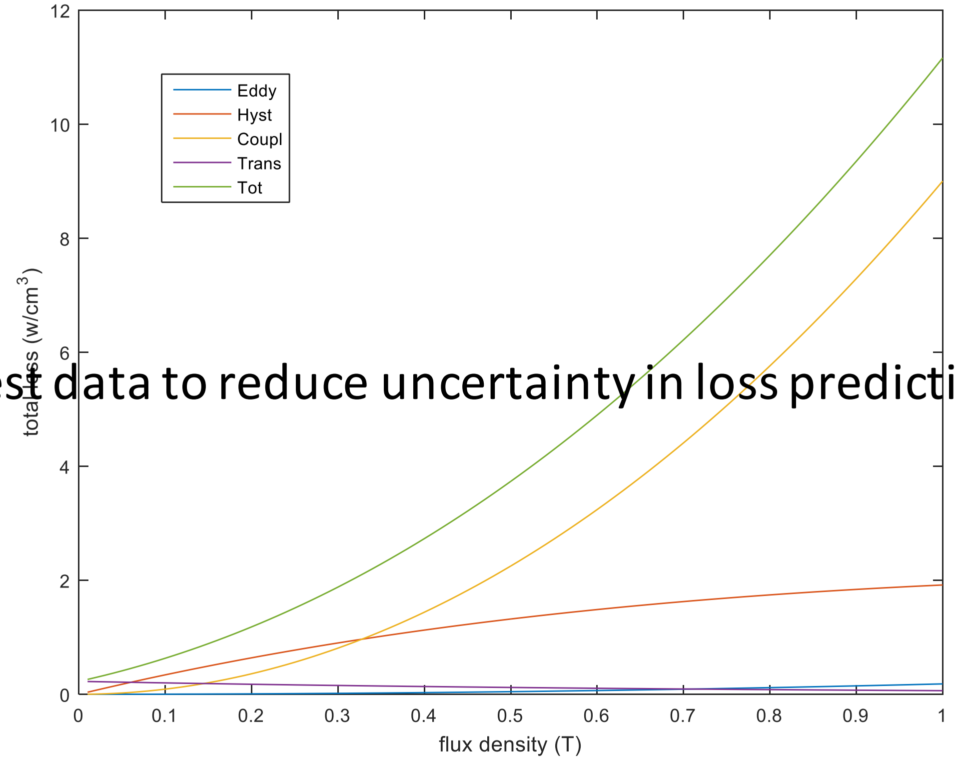
$$Pc = \left(\frac{1}{n * \rho_{eff}}\right) * (f * L_p * B_m)^2$$

Transport current loss

$$PI = \left(\mu_0 * \frac{f}{\pi}\right) * (Ic^2) * \frac{\left(1 - \left(\frac{I_0}{I_c}\right)\right) * log\left(1 - \left(\frac{I_0}{I_c}\right)\right) + \left(\frac{I_0}{I_c}\right) - .5 * \left(\frac{I_0}{I_c}\right)^2}{\pi * \left(\frac{D_o}{2}\right)^2}$$

K=4, n=2 constants

Symbol	Parameter	Conductor I 0.32/10/5
J_c	Critical current density at 0.4T at 20K [A/m^2]	6.6e9
D_0	SC diameter [mm]	0.32
d_f	Filament diameter [μm]	10
n	Number of filaments	114
λ	The area fraction of the wire that is SC	0.15
λ_{eff}	Effective fill factor	0.49
ρ_{eff}	Effective transverse resistivity [Ω-m]	12.5e-8
L	The twist pitch (mm)	5



Need test data to reduce uncertainty in loss prediction

Loss components at 300 Hz

Technology gaps & opportunities

- Thermal management – leveraging what's available in the vehicle system, better heat exchangers, phase change materials to tailor transient performance to application, high temperature magnets and insulation, cryogenic motors, etc.
- Functional integration of powertrain – fault tolerance, EMI mitigation,
- Advanced manufacturing techniques to attain full entitlement of new machine architectures e.g. slot-less windings, composite structures, superconducting coil assemblies.
- Health monitoring and prognostics to ensure safe reliable operation with high voltage, altitude conditions; low 'inertia' (electrical, thermal, mechanical).
- TRL advancement – system integration, ground tests and flight demos with new motors