

3rd International Workshop on Emissions Free Air Transport Through Superconductivity Applications of Cryogenic Superconducting Powertrains

Title: Benefit of cryo-fuels for thermal management of superconducting and aluminum conductors in motors, generators and cables for electric aircraft

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 **Hyper Tech**



Outline

- **Cyro-fuels – LH2 (20 -77K) and LNG (120 K plus)**
- **Drivetrain Cooling – Generator/Motor/Cable**
- **Motors- Ambient, and Cryo**
- **Induction Motors**
- **Conductors – Aluminum, Cu Clad Al**
- **Superconductors, and High Purity Aluminum**

Hydrogen

Holy Grail -DOE Hydrogen Production

DOE- Road Map (May 2023) Desired Cost

2026- \$2/kg (Possible?), 2030- \$1kg

Presently in U.S. Electricity, Wind and PV is being sold to utilities at \$0.02-0.04/kWh (Off-Take Agreements).

DOE target for electricity from electrolysis for \$2/kg is based on \$0.03/kWh by 2026.

Inflation Reduction Act offering

\$3.00/kg tax credit until 2030

Today-H2 from Electrolysis \$5-6/kg?- \$3/kg=\$2/kg?

Accelerate NASA Roadmap

Non-Cryo, Partial Superconducting, and All Cryogenic and High Purity Aluminum (HPAL) and Superconducting Drivetrain

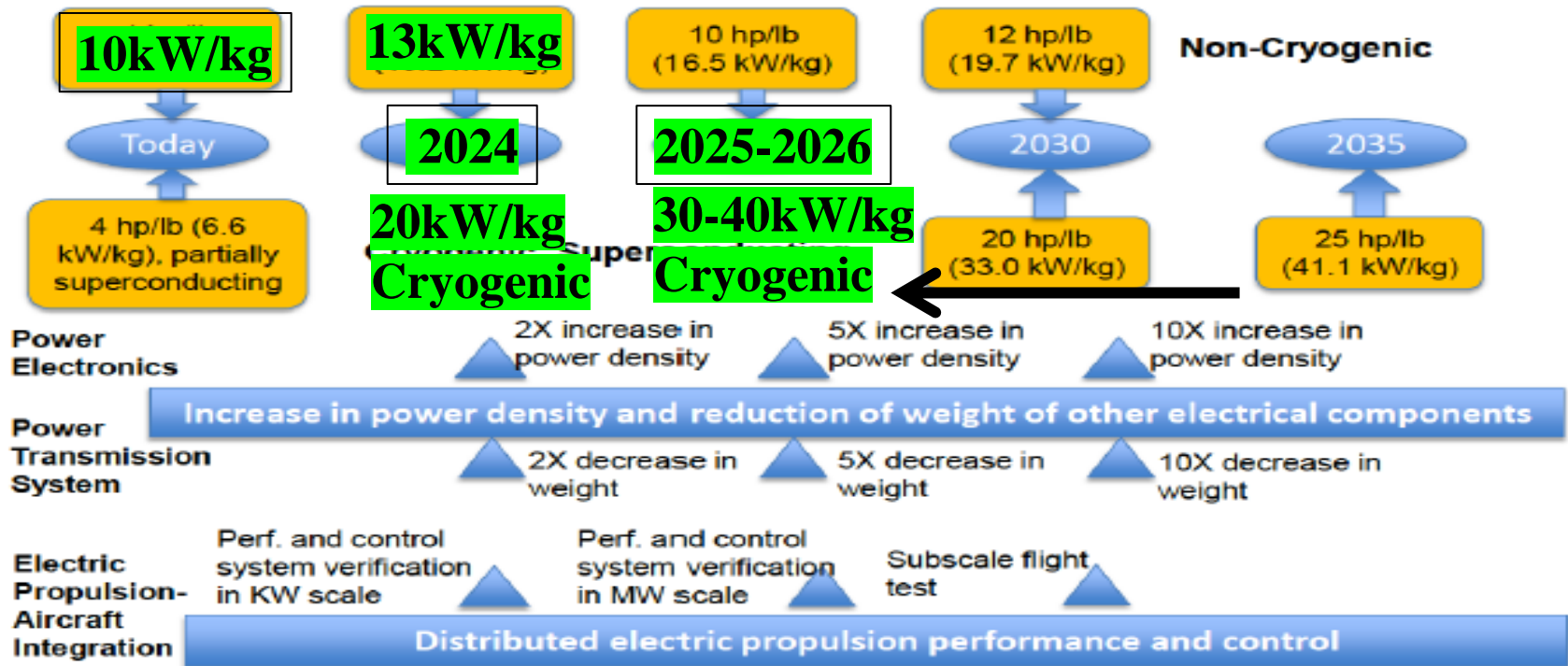
Accelerate NASA 2004 Road Map by 5 Years

The World needs to de-risking all the good options



NASA FW/AATT HEP Technology Roadmap

MW Size Motors



OPTIONS FOR TURBO-ELECTRIC DRIVE TRAIN

Comparison Non-Cryo, LNG and LH2 Motors and Drives

Non- Cryo fuel options for motors and generators. (SAF , Ammonia, or something else)

- Permanent Magnet 10-16 kW/kg motor not working on it because: a) Predicted shortages between now and at least 2035, b) increasing cost, c) RE-PM controlled by China, d) serious increase of CO2 when manufacturing RE-PM, serious environmental issues (new paper explaining the issues).
- Induction machine, ambient temperature, aluminum conductor, electrical steel–motor power density 10-16 kW/kg depends on MW size
- Partial superconductor rotor only, **cooled by rotating cryocooler**, stator ambient temperature, power density (16-30kW/kg) goes up as MW goes up.

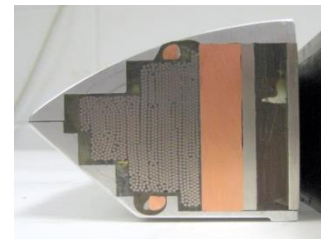
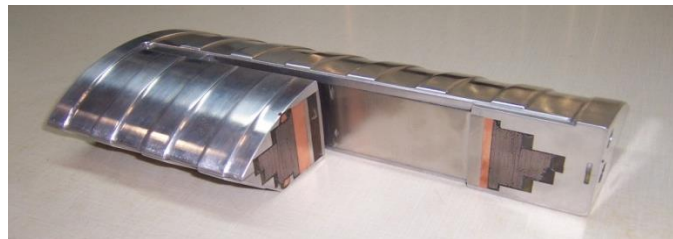
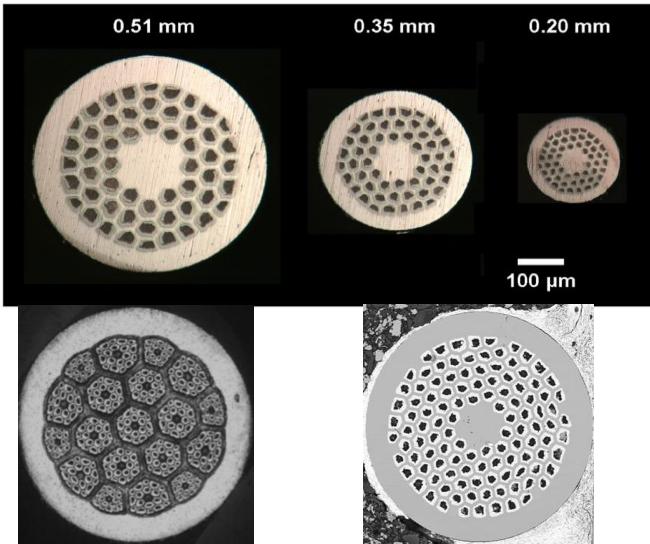
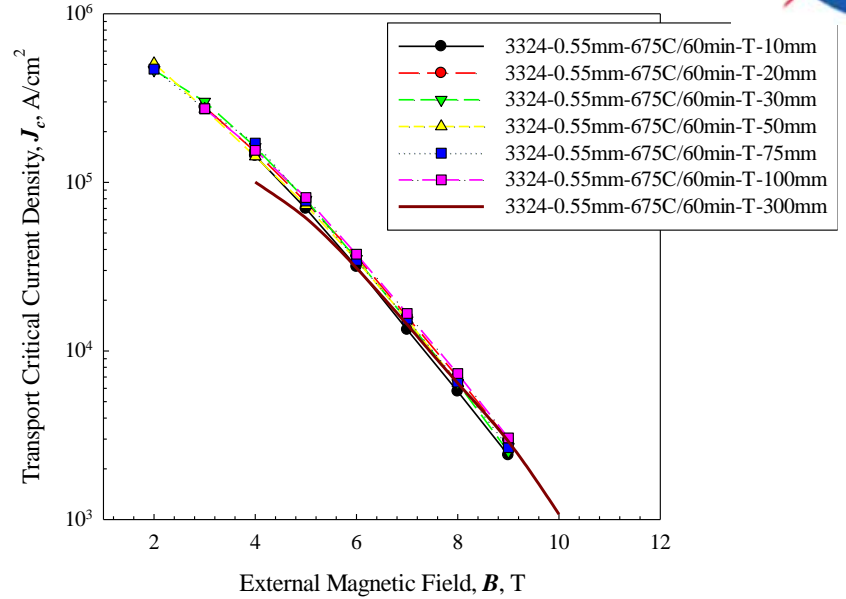
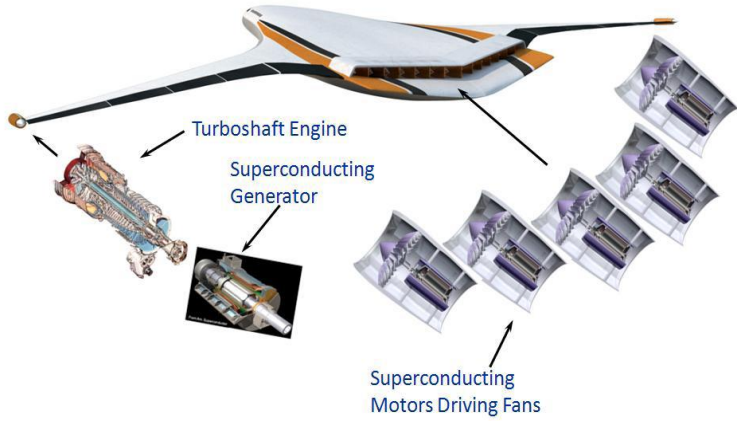
Cryogenic (LNG or LH2 fuels) use fuels for thermal management (can use inert secondary cooling loop

- Induction motor 2MW plus, fuel cooling or secondary non-flammable coolant), 77-120K, 20kW/kg
- Cryo-cooled. LH2, Induction motor, using the High Purity Aluminum or Superconductor, 30-50kW/kg, 20-30K Depends on MW size

High Power Density -Cables

- Ambient Temp, LNG temperature, LH2 temperature (or non-flammable secondary coolant)

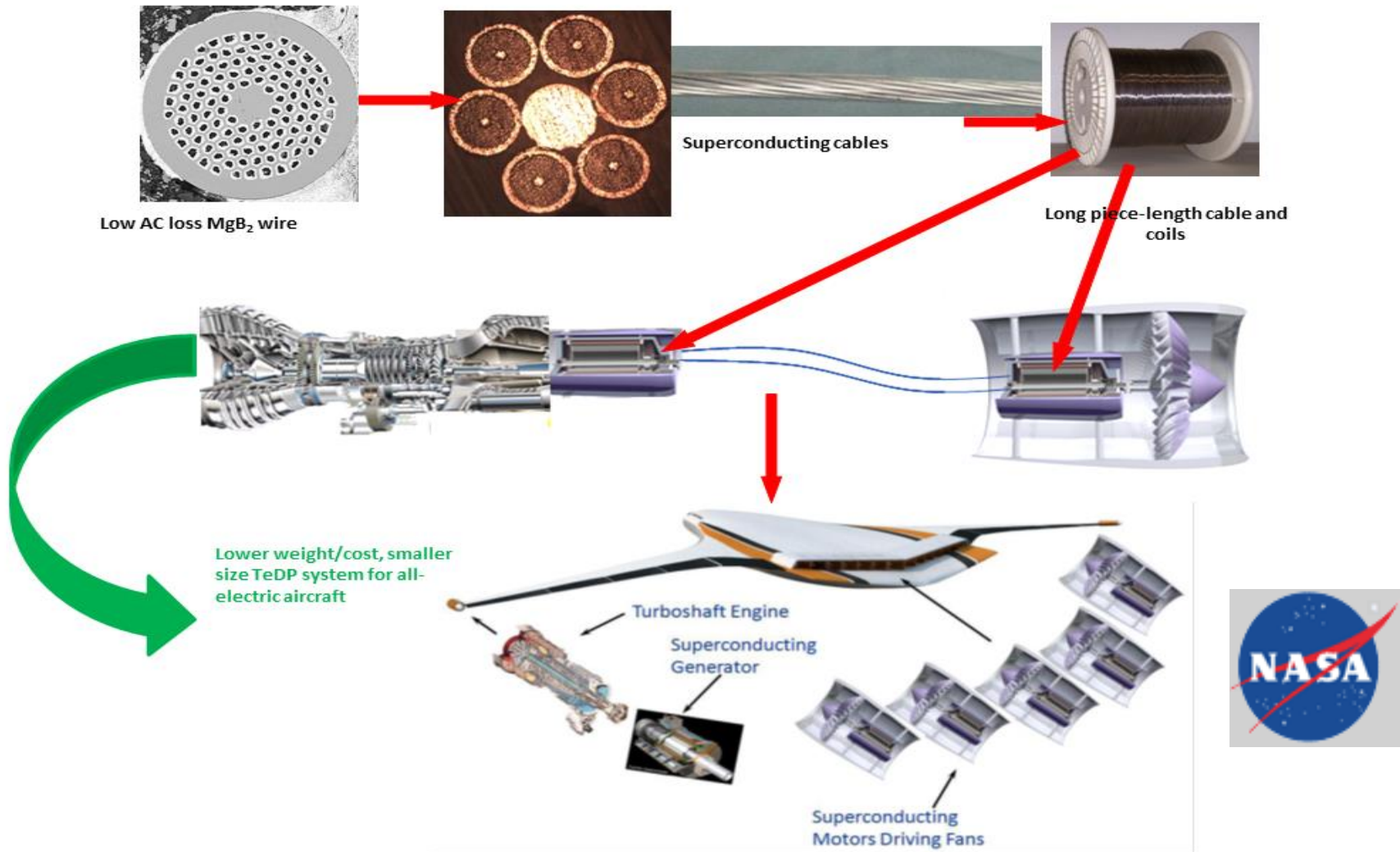
NASA All Electric Aircraft



NASA 2MW, 15000rpm Rotor coils.

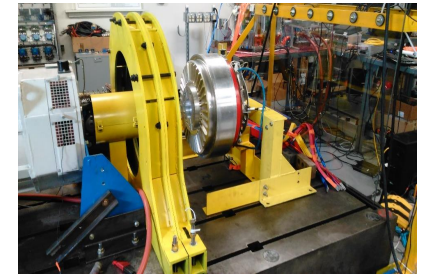
MgB₂: 10-20 micron filaments
5 and 10 mm twist pitches.

All-electric aircraft programs

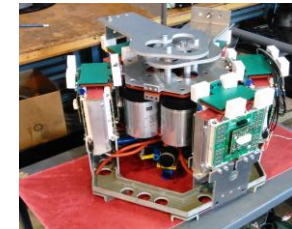


Hyper Tech's Comparison of Non-Cryo, Cryo 77-120K and 20K cooling for Motors, Generators and Drives

Hyper Tech/ OSU programs funded by NASA and ARPA-E



This Size approx. 100 kg
Ambient Temperature 1MW
Cryo 77-120 K cooled 2MW plus
Cryo 20K cooled 4MW plus



Commercial Power Electronics,

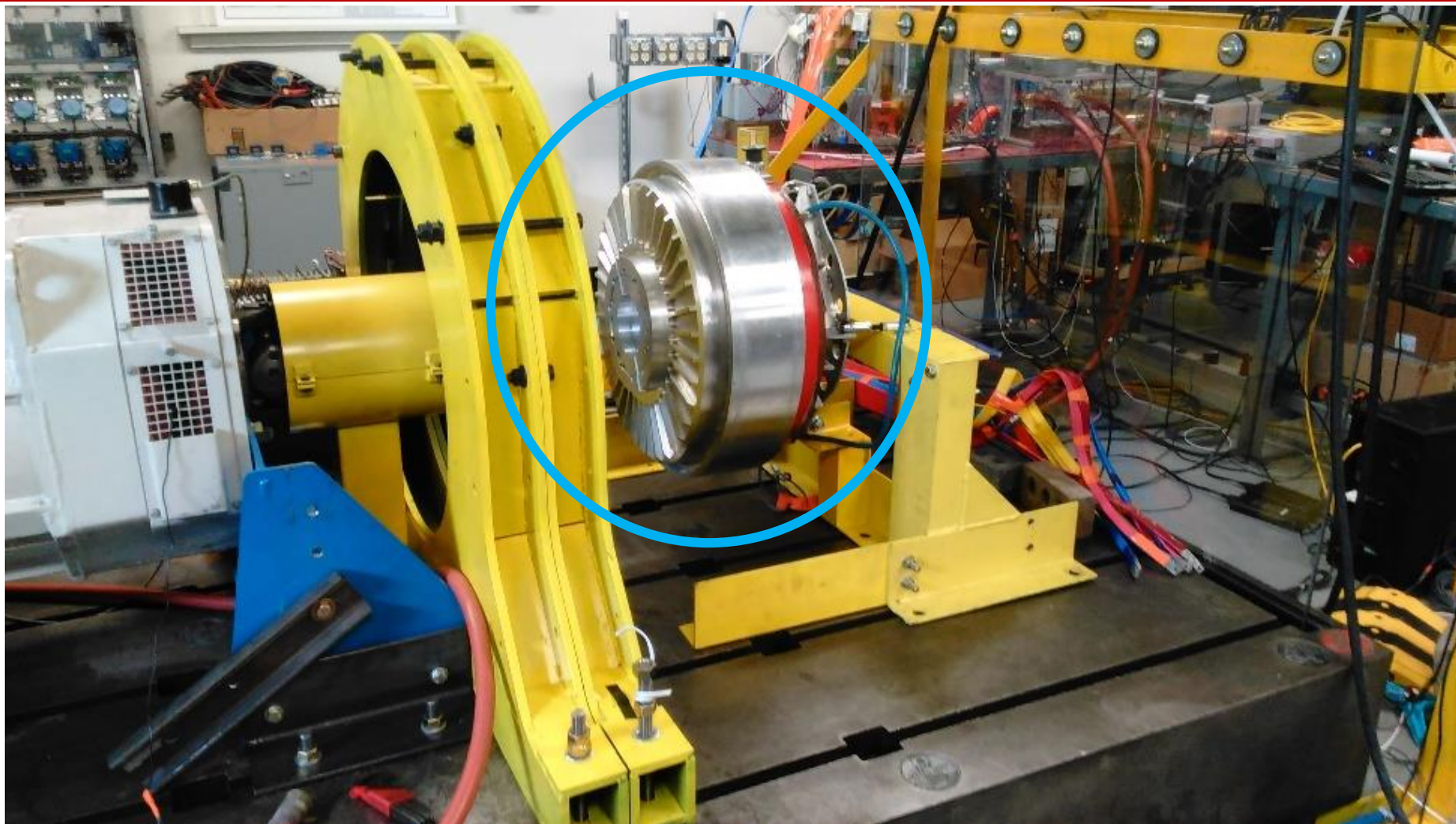
High Power Density, and Low Cost

System	Information based on 5000 RPM at takeoff	Non-cryo NASA Completed	Non-cryo NASA Funded 2024	ARPA-E Cryo Funded End 2024	Concept Cryo LH2 Design
Total-Thermal Management of Motor and Drive	System capacity Scalable 1-20 MW, MW	1	1.6-2.0	2.1 (2.4)	2-4
	Takeoff (motor, drive, TMS) kW/kg	8	13	18-22	32-45
Drive	TMS technology	Liquid cooling	Liquid cooling	223-273K	223-273K
	Power density (including TMS) at takeoff, kW/kg	60	100	127.5	130
Electric Motor	TMS technology	Liquid cooling	Liquid cooling	LNG< Bio-LNG, LN2 77-150K Can dump heat into LH2	LH2, 20K + (secondary cooling LHe)
	Power density kW/kg; Direct Drive, no gear box	10	14	20-24	Hyper conductor (HPAL) or Superconductor 35-50

THE MOTOR THAT HAS BEEN BUILT FOR NASA



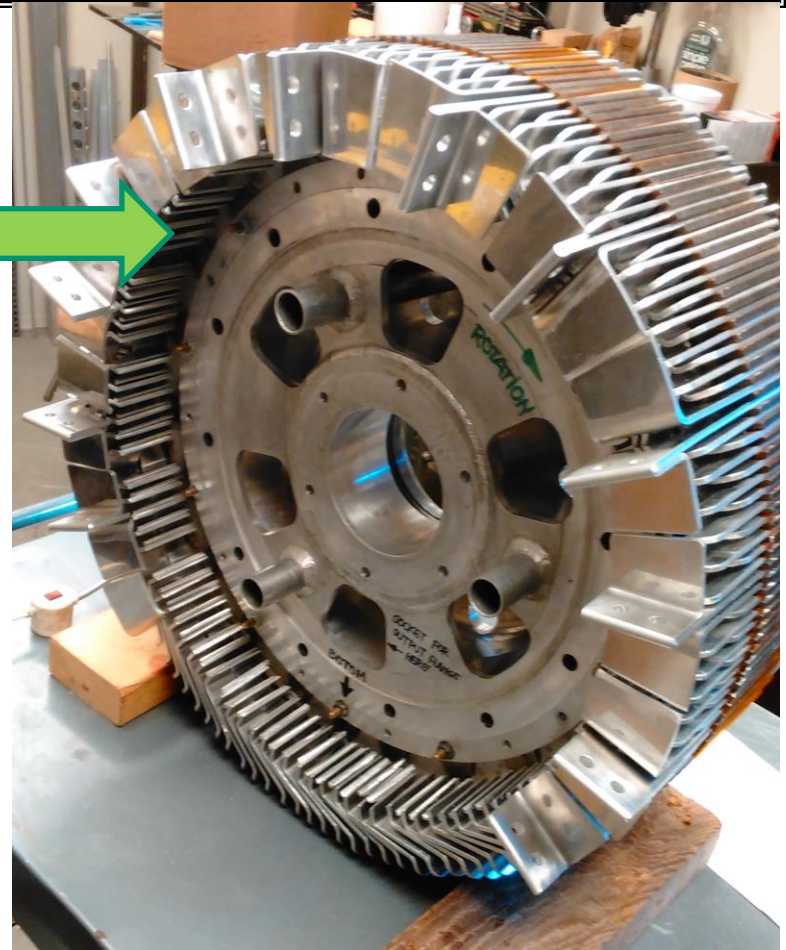
THE OHIO STATE UNIVERSITY
CENTER FOR AUTOMOTIVE RESEARCH



HT Hyper Tech

Basic specs (motor only): Continuous rating +1 MW

SIMPLE SHEET METAL JOB AND NOTHING ELSE



- All electric circuits are from aluminum and all magnetic circuits are from regular electric steel
- Coils do not have insulation per se and are wet all the way
- Semi-evaporative cooling

NO PERMANENT MAGNETS



Two different rotors have been tested successfully with different options for maximum speed and maximum torque

TUNED INDUCTION OUTRUNNER

TESTED TO DATE

- 4.7 kW/kg @ 1800 rpm – approx. 460 kW, 2430 Nm @ 1825 rpm
- 5.9 kW/kg @ 2500 rpm – approx. 576 kW, +2200 Nm
- **+7.25 kW/kg @ 3300 rpm** (bench test limited) , approx. 708 kW, 2050 Nm
- 2.6 W/kg*rpm @ 1800 rpm normalized continuous power density

RATED DESIGN

- 6 phases asymmetric at 30 degrees **2Y or 6 H** (12 terminals)
- No PMs, no Cu, and no conductor insulation
- Insulation to ground class IEC 350 (350 C) with operation below class H / IEC 180 (180 C)
- Maximum mechanical limitation (theoretical): 2500 kW peak
- Never exceed speed: 5800 rpm
- Efficiency: 0.96-0.965 at takeoff, at least. 0.975 cruise full power at -20C (temp. dependent)
- 2100-2450 Nm **CONTINUOUS**
- +10 kW/kg **CONTINUOUS**

Why should Aircraft Company what to use Hyper Tech Induction Motor Approach

Benefits of this induction motor and potential generator

- 1. Design can be used with ambient, LNG and LH2 fuel for propulsion and thermal management**
- 2. No permanent magnet! No need to worry about rising prices or availability of rare earth permanent magnets from China**
- 3. Induction motor are more fault tolerant**
- 4. Induction motor design with high continuous and take-off efficiency**
- 5. Uses low cost aluminum and electrical steel**
- 6. No electrical insulation uses dielectric liquids**
- 7. All materials can be made in the USA**

Benefits of this induction motor when using cryo-cooling

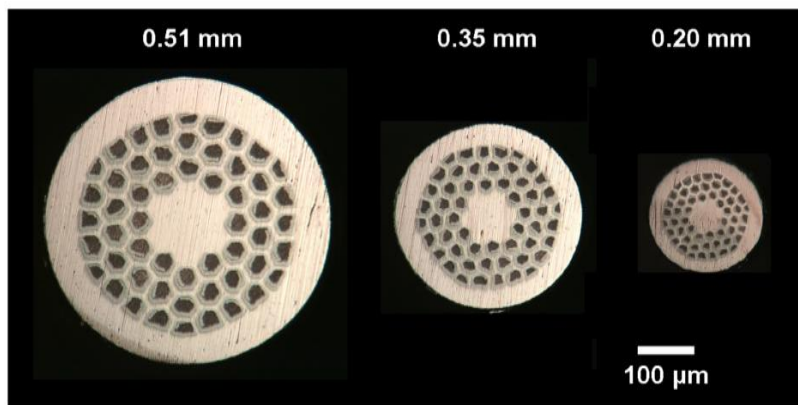
- 8. Can control temperature of operation of bearings**
- 9. Can control temperature of operation of power electronics**
- 10. Compatible with other cryogenic liquids by using a secondary cooling loop that can be used to transfer heat to cryogenic LNG or LH2 fuel**
- 11. LH2 motors- potential can use superconductors or High Purity Aluminum (HPAL)**
- 11. High power density for motors that are scalable to the multiple MW range.**
- 12. High power density generators that are scalable to the multiple MW range.**

Low AC loss MgB₂ conductor development

- Reducing strand diameter to reduce coupling loss and to reduce normal metal eddy current loss component.
- Successfully developed conductors with diameters as small as 0.2 mm, while maintaining J_c

$$P_e = \frac{\pi^2}{6\rho_n} [(\mu_0 H_m) wf]^2$$

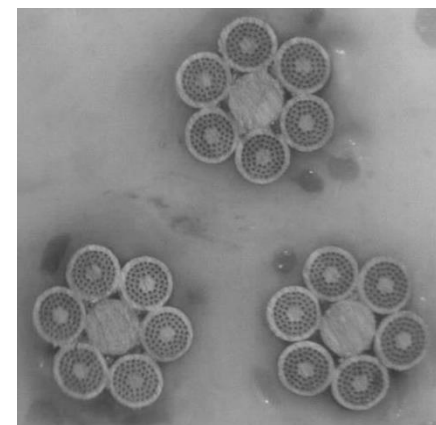
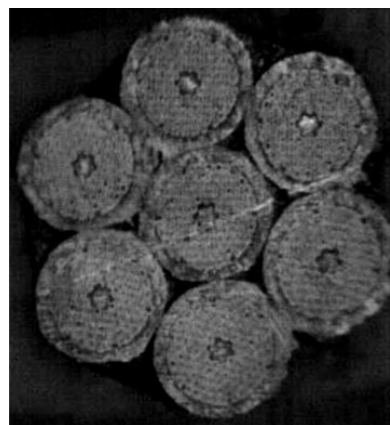
MgB₂ cable development



- I_c (therefore I_{op}) low with 0.2 mm – 0.3 mm strands
- Cables comprising of fine superconducting strands increase I_c to design specifications
- Need to account for cable pitch, inter-strand resistance, etc.



3 x [6+1] superconducting cable



AC MgB₂ conductors for coil development

In summary:

Superconductor strands and cables are engineered with features for reducing AC losses (e.g., small filaments, small twist pitches, resistive filamentary matrix, reduced magnetic content).

Hyper Tech has established long length fine-wire and cable manufacturing.

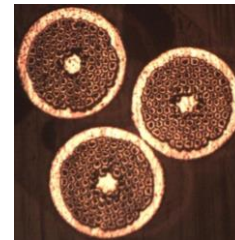
Thermal management considerations for coil design:

Solenoid & racetrack coils demonstrating direct cooling on superconducting windings.

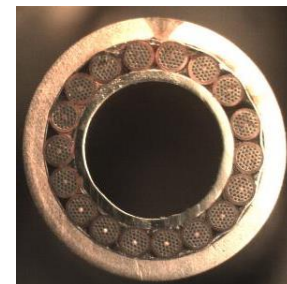
Losses from 200 m 3-strand MgB₂ cable cooled with GHe gas ~ 1 W/cm³.



- Epoxy impregnated coils; conduction cooled option
- Cabled and insulated with cryogen cooling directly on the cable

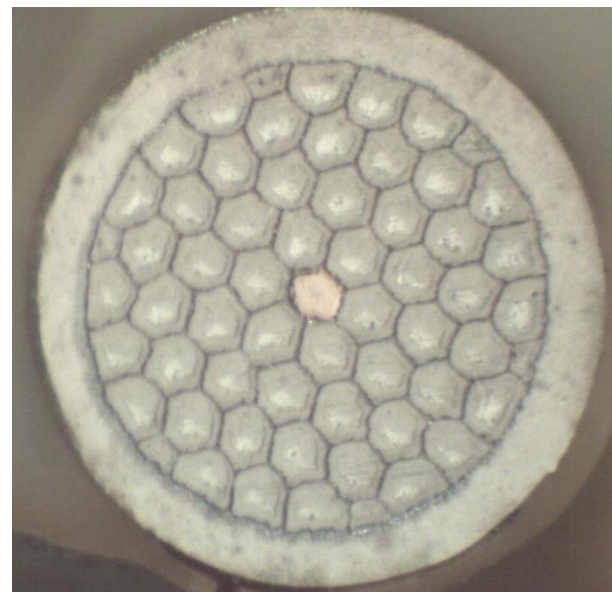


- Packaged in a cable form with liquid or gas cryogen down the center of the cable



Hyper Tech is manufacturing high purity multifilament aluminum wire for stators

Multifilamentary wires manufactured to minimize AC loss
61 filaments



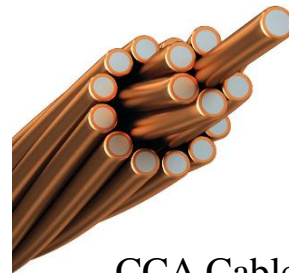
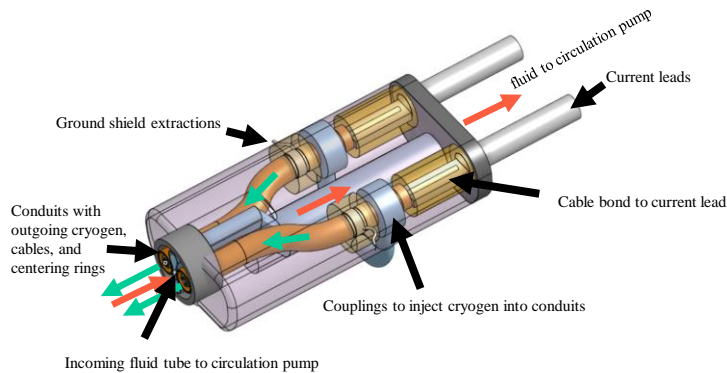
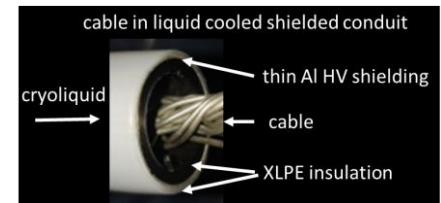
AC LOSS CONTRIBUTION 200 HZ | 500 HZ

Material	RT Cu <u>Litz</u>	Cryo Cu <u>Litz</u>	Cryo HPAL Multifilamentary	Cryo HPAL <u>Litz</u>
d_{subele} , mm	0.04	0.04	0.04	0.04
P_{Ohmic} , W/cm ³	1.00	1.00	1.00	1.00
P_{Eddy} , W/cm ³	0.0 0.01	0.12 0.75	1.04 9.35	0.77 4.87
P_{total} , W/cm ³	1.00 1.01	1.12 1.75	2.04 10.35	1.77 5.87
I_c , A	2.26	11.30	29.96	28.74

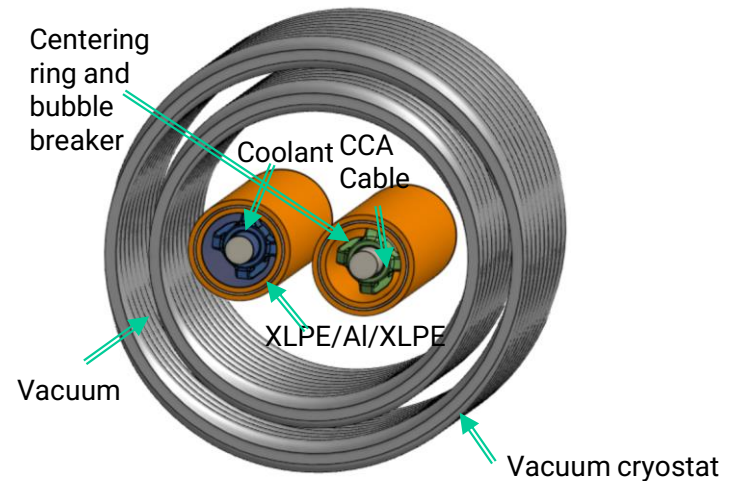
Power Transmission Cable for Electric Aircraft Using Bio-LNG for Cooling and Thermal Management (adaptable to other cryogenics and conductors from ambient temperature down to 20K)

Objective: We are creating lightweight, easily configurable, and highly robust aerospace power distribution using cryo-resistive (non-superconducting) cables which utilize cryogenic fuel to directly or indirectly cool the cable for increased ampacity.

- Our design is a 10s of meter long, ground-shielded, force-flow cooled, cryo-resistive cable with cryogenic coolant turn-around at terminations.
- Novel use of a XLPE-AI-XLPE cryogenic conduit with dielectrically compatible cable centering rings which double as bubble breakers.
- Low kg/m/kA compared to COTS power cables. At higher amperages, which permits lower voltages, cryo-resistive cables perform even better versus COTS cable.



CCA Cable



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Attention