Airplane Motors Employing Superconducting DC Field Windings and Conventional Conductor AC Windings

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COMPARE MOTORS WITH DIFFERENT STATOR COIL MATERIALS

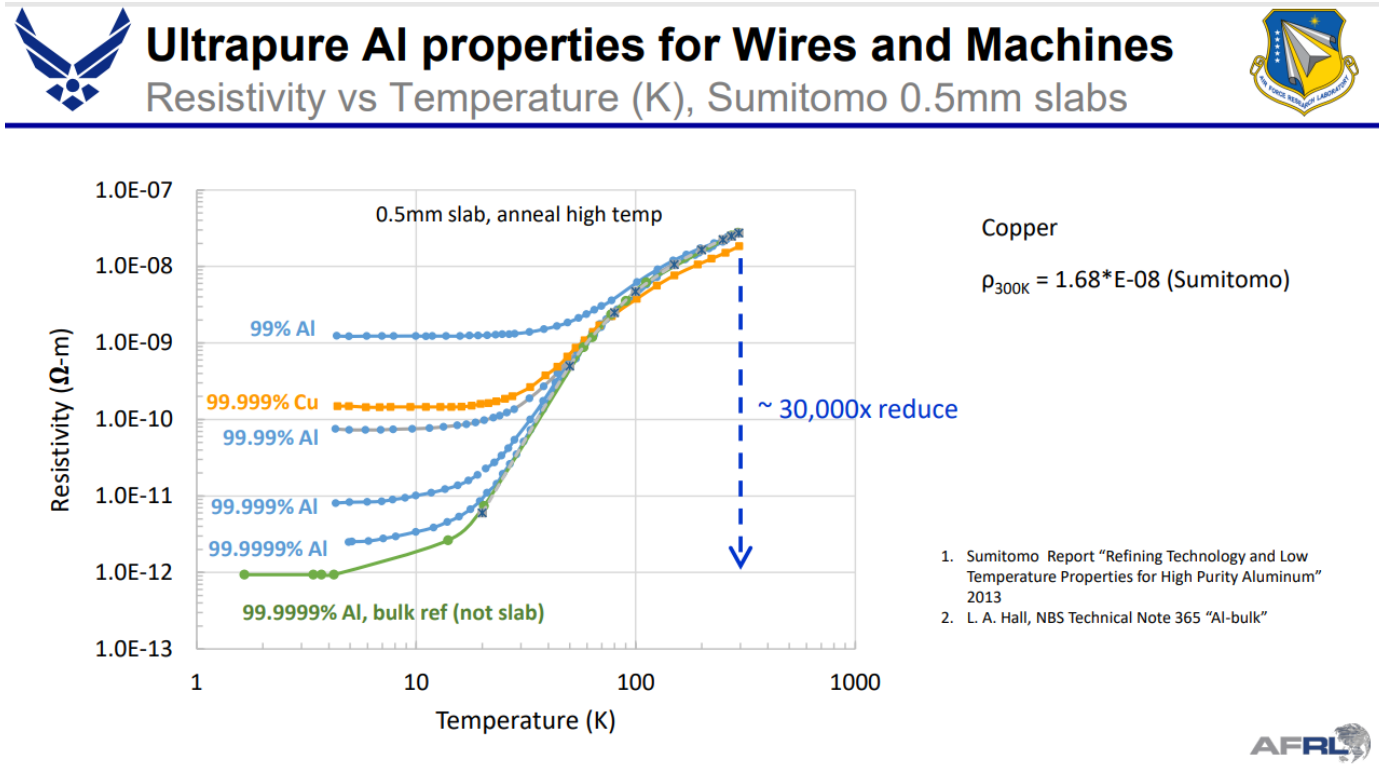
- Conceptual designs for 3 MW, 4500 RPM motors for Aircraft applications
- Features:
  - Field DC Excitation Coils on Rotor: employing REBCO CORC conductor
  - Stator AC Coils: Litz cable made of conventional conductors **cooled directly with LH2**
  - Stator conductor options: high-conductivity aluminum (Hyper-AL), aluminum and copper
  - Rotor and stator coils contained in separate cryostats
  - DC field excitation coils operating at 40-50 K to suite the brushless flux pump exciter
  - AC stator coils cooled directly with available LH2 for taking advantage of conventional conductors at cryogenic temperatures
  - AC stator winding voltage limited to about 1000 V
  - Motor size, mass and losses are compared for stator windings

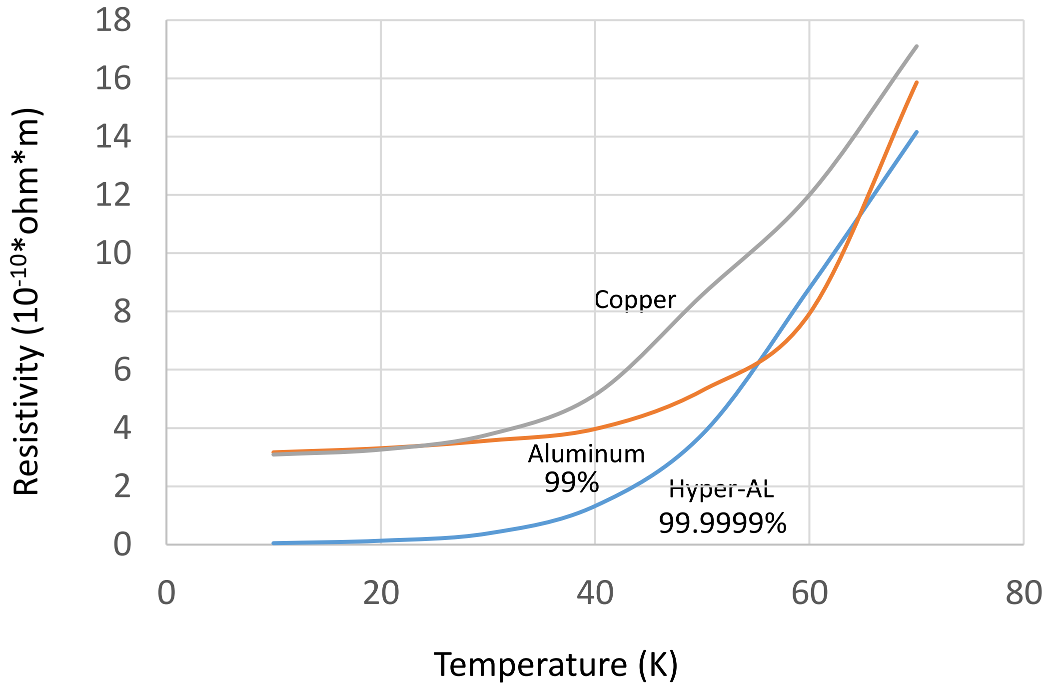
Reference Motor Specifications

- Motor design specification in the table selected based on the NASA study (Felder J L, Brown G V, Kim H D and Chu J 2011 Turboelectric distributed propulsion in a hybrid wing body aircraft Proc. 20th Int. Society for Airbreathing Engines (Gothenburg, Sweden, 12–16 Sept. 2011)
- Selected design baseline based on a 4-pole machine operating at nominal speed of 4500 RPM
- Field winding on the rotor operates at 40 K
- Stator AC winding operating at 20 K - cooled directly with liquid hydrogen (LH2)
- Based on these specifications, three motor designs are compared using stator coils made using the followings conductors,
  - **Hyper-AL 99.9999%**
  - **Conventional AL 99%**
  - **Copper**

MACHINE SPECIFICATIONS	Value
Rating, MW	3
Power factor	0.98
Number of phases	3
Desired DC voltage, V	1000
Number of poles	4
Rated rotational speed, RPM	4500
Rated frequency, Hz	150
Ambient coolant temp., K	300
Rotor operating temp., K	40
Stator operating temp., K	20
EM Shield operating temp., K	40

Resistivity Values of Selected Stator Coils

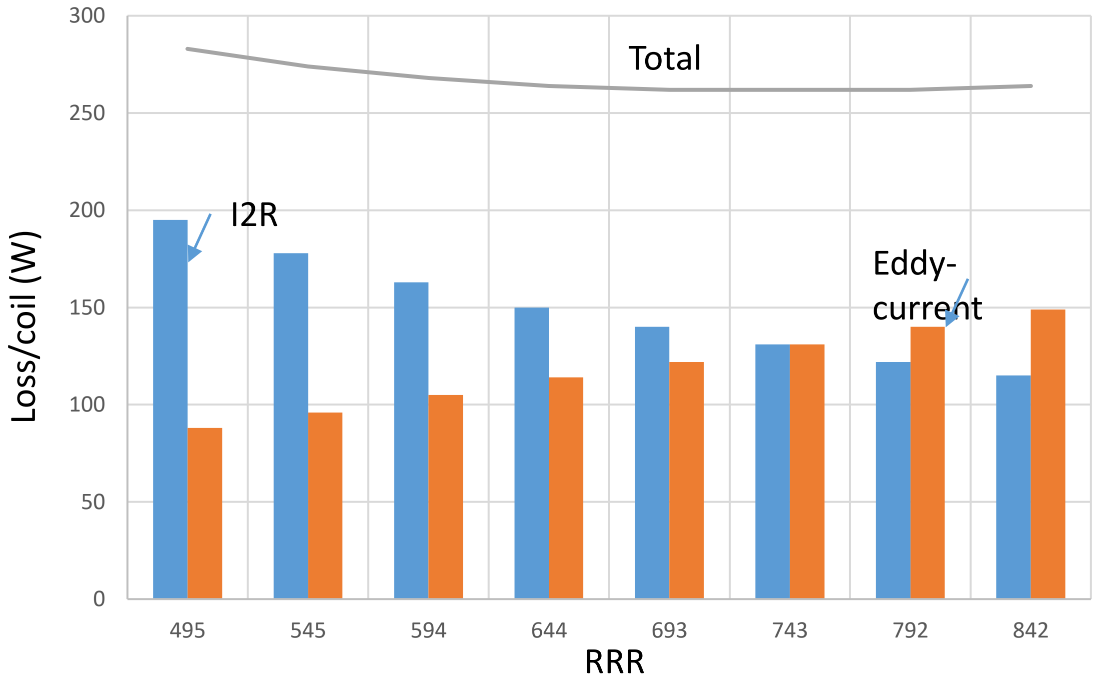




Very low resistivity requires judicial selection of purity level and strand diameter

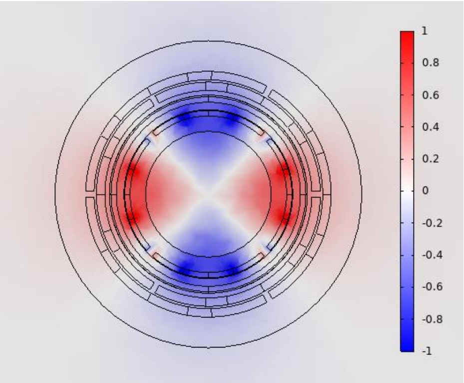
I2R and Eddy-Current Loss Comparison

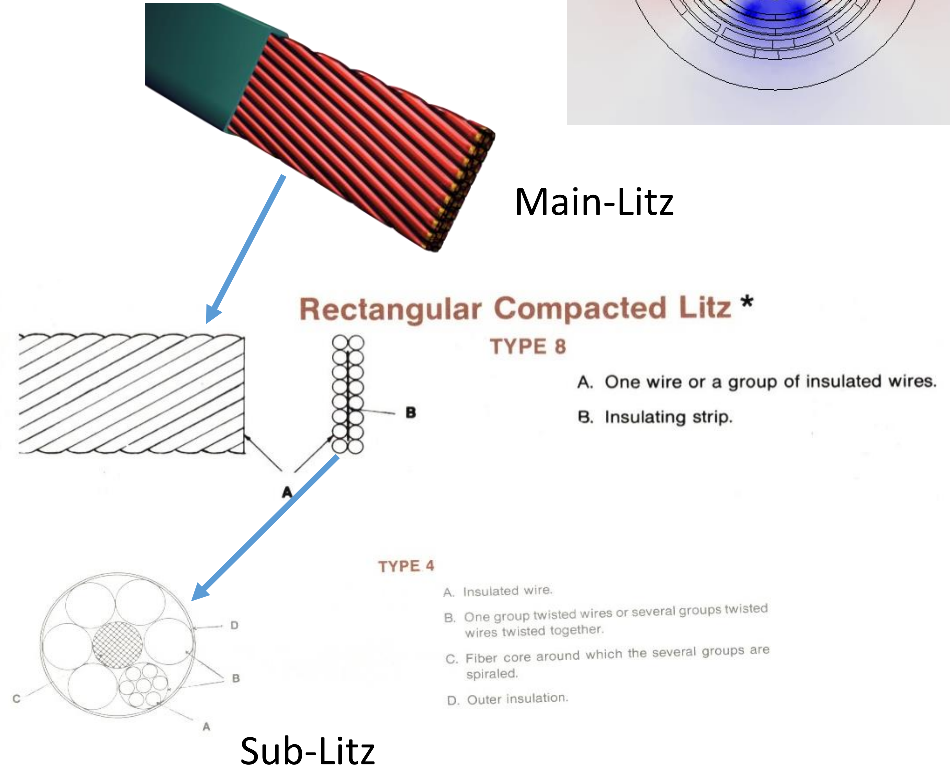
- High Conductivity Aluminum (Hyper-AL) could have large RRR (ratio of resistivity at 20K and 300K)
- RRR is both a function of magnetic field and temperature
- Total stator coil losses have 2 components – I2R loss to carry the desired current and eddy-current losses caused by the rotating rotor field
- At low values of RRR, I2R loss is larger than the eddy current loss
- At very large values of RRR, eddy-current loss exceeds the I2R loss
- For minimum total loss, select I2R loss equal to eddy-current loss
- For this motor design, lowest loss is at RRR ~ 740



Stator Coil Cable Configuration

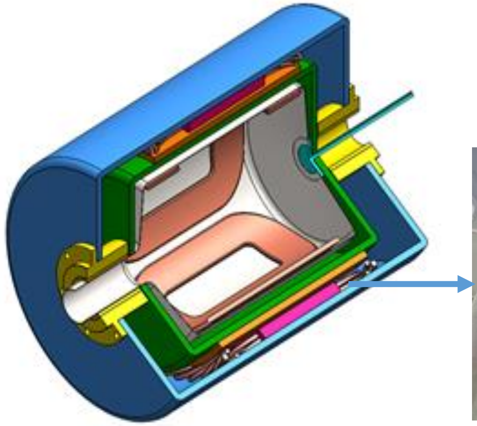
- Stator coils experience high rotating field of high-frequency from the excitation coils on the rotor
- Wire used in the stator coils have low electrical resistivity at the 20 K operating temperature
- To limit the excessive eddy-current heating, the wire size (diameter) and cable constructions are carefully selected
- Commercially available Litz wire configurations are utilized to define <u>hypothetical</u> cables for the stator coils
- Selected Main-Litz is a rectangular cable with specified number of round Sub-Litz cables
- Strand diameter of the sub-Litz cable is selected to suit eddy-current loss target
- Final cable configuration to be selected in consultation with manufacturers



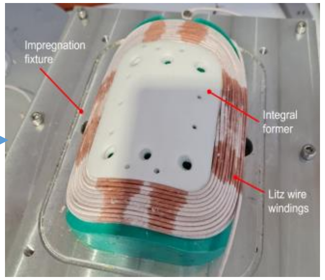


MOTOR CONFIGURATION

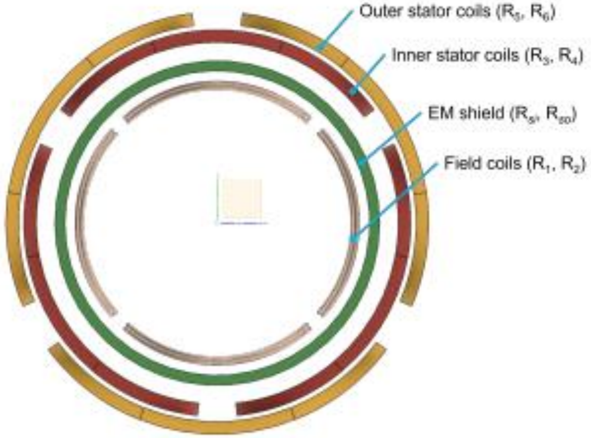
- Motors are sized using racetrack shaped saddle coils for rotor and stator windings
- Active length for all machines is the same (= 400 mm)
- Rotor EM shield forms a part of the rotor cryostat wall
- Clear airgap length (= 5mm) between the rotor and stator windings is identical for all motors
- Stator winding radial build (R3-R4 and R5-R6) sized to suit selected conductor for the coils
- All stator coils sized to remove the same heat flux (~0.7-0.8 W/cm2) by the chosen cooling approach
- Wall thickness for non-metallic motor case is 10 mm



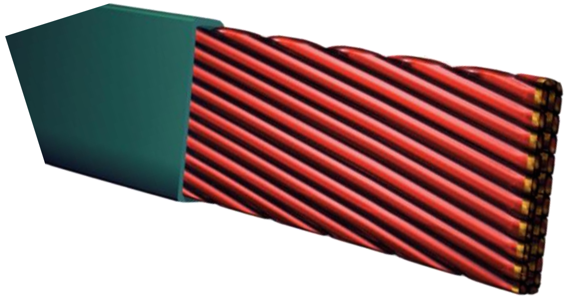
Motor Assembly



Stator Saddle Coil



Stator Cable Configuration



- Rectangular Main-Litz with round Sub-Litz cables – Table has details
- Nominal strand = 0.032 mm for Hyper AL, and 0.127 mm for AL and CU
- HyperAL designs has Litz strand size to make I2R loss = Eddy-current loss
- AL and CU designs are sized for the same coil heat flux (for cooling) as for the Hyper AL

	HyperAL	**AL**	**CU**
MAIN LITZ CHARACTERISTICS	Rectangular	Rectangular	Rectangular
Catalog number	4	10	10
Equivalent AWG	4	10	10
Cross-section, mm2	23.5	60.5	60.5
Number of strands	7	18	18
Strand AWG	12.0	12.0	12.0
Diameter of each strand (mm)	2.1	2.1	2.1
Nominalwidth of the cable (mm)	8.3	20.0	20.0
Nominal thickness of the cable (mm)	3.86	3.86	3.86
Weight (kg/m)	2.08E-01	5.37E-01	5.37E-01
Resistance (ohm/m)	8.60E-04	3.35E-04	3.35E-04
SUB-LITZ CHARACTERISTICS	Round	Round	Round
Catalog number	1,725	105	105
Equivalent AWG	16	28	28
Cross-section, mm2	1.35	1.33	1.33
Number of strands	1,725	105	105
Strand AWG	48	36	36
Diameter of each strand (mm)	0.032	0.127	0.127
Nominal dia of the cable (mm)	1.88	1.85	1.85
Weight (kg/m)	9.45E-03	1.31E-02	1.31E-02
Resistance (ohm/m)	1.52E-02	1.40E-02	1.40E-02

Stator Winding Details

- Table summarizes stator winding using Hyper-AL, AL and CU
- Stator winding consists of 6 race-track coils located in 2 radial locations
- Radial build of each race-track coil is 9 mm for HyperAL and 21 mm for AL and CU machines
- Maximum fields experienced by inner and outer coils are 0.6-0.7 T and 0.39-0.44 T, respectively
- Low resistance of HyperAL allows larger current (1100 A) than AL and CU coils (700A)
- Loss per meter length for HyperAL is 168 W compared to 363 W for AL and CU designs
- Heat flux (W/cm2) for cooling is about the same for all designs

STATOR WINDING DETAILS	HyperAL	AL	CU
Overall stator winding current density, A/mm^2	26	6.8	6.8
Number of stator coils	6	6	6
Coil span - center-to-center, deg	90	90	90
Coil cross-section span +/-, deg	29	29	29
Cross-section of a coil, mm^2	754	2078	2078
Radial build of the coil, mm	9	21	21
Mean-turn length of a coil, mm	1561	1715	1715
Overall axial length of coils, mm	651	697	697
Maximum radial field at winding, T	0.60	0.68	0.68
Maximum tangential field at winding, T	0.39	0.44	0.44
Maximum total field at winding, T	0.7	0.8	0.8
- Thickness of E-glass insulation, mm	0.20	0.2	0.2
- Thickness of Kapton tape, mm	0.05	0.05	0.05
- Total thickness of insulation on a turn, mm	0.50	0.50	0.50
- Outside width of insulated conductor, mm	9	21	21
- Cable current, A	1100	697	697
Width of coil cross-section, mm	84	99	99
Number of turns/coil_width	19	22	22
Number of pancakes/coil	1	1	1
Number of turns/coil	19	22	22
Number of turns/phase	38	44	44
Fill factor of the coil pack	1.0	0.9	0.9
Operating (phase) current, A	1100	697	697
Total length of cable used, m	178	226	226
Total resistive loss, kW	1.6	3.7	3.7
Coil resistive loss, W/m	168	363	362

Motor Mass Summary

- For HyperAL stator, dominant component of weight is the machine casing
- AL and CU machines, both stator windings and machine casing are dominant mass components
- HyperAL motor mass is lowest; 1/3rd lower than AL machine and ½ lower than CU machine
- In terms of power density, HyperAL machine power-density ~ 40 kW/kg, looks attractive

STATOR MASS SUMMARY	HyperAL	AL	CU
Stator winding, kg	3.6	16.2	53.3
Torque tube, kg	2.7	3.8	3.8
Machine case, kg	14.8	20.3	20.3
EM shield, kg	0.0	0.0	0.0
Machine end-flanges, kg	4.6	7.5	7.5
Misc. Fittings, kg	3.9	5.6	5.6
Total stator weight, kg	29.5	53.4	90.5
Total rotor weight, kg	50.6	65.4	65.4
Cryocoolers (rotor and stator), kg	3.3	3.6	3.6
Miscellaneous, kg	4.0	5.9	7.8
Weight of motor alone, kg	84.1	124.7	163.6
Weight of cryocooler, kg	3.3	3.6	3.6
Power density, without cryocooler, kW/kg	38.6	25.7	19.6
Power density, without cryocooler, MW/m^3	30.1	17.2	17.2

Conclusions

- Compared three superconducting synchronous motor options using Hyper-AL, Aluminum and Copper stator coils
- Hyper-AL motor looks attractive compared with the other two motors.
- The power density (~ 40 kW/kg) of the Hyper-AL motor looks attractive without concerns for stability of stator coils employing superconductors.
- Suggest Hyper-AL motor be studied more thoroughly and seek solutions for procuring Hyper-AL wire at acceptable cost.
- **Caution:** The power density estimate could be significantly lower if the LH2 cannot be used for direct cooling of stator coils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