Novel superconducting propulsor cooling method for All-Electric Aircraft

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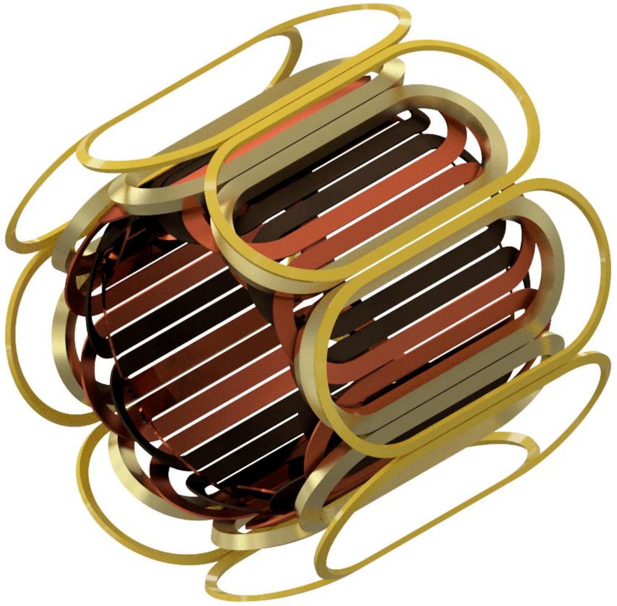

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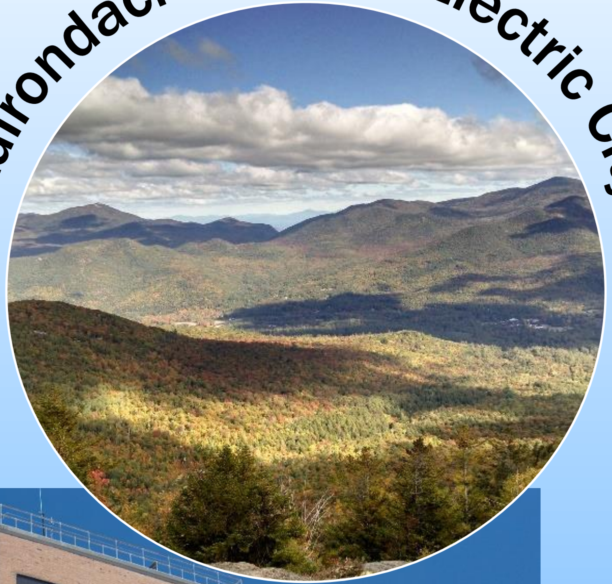
Adirondacks – NY – Electric City



GE Research
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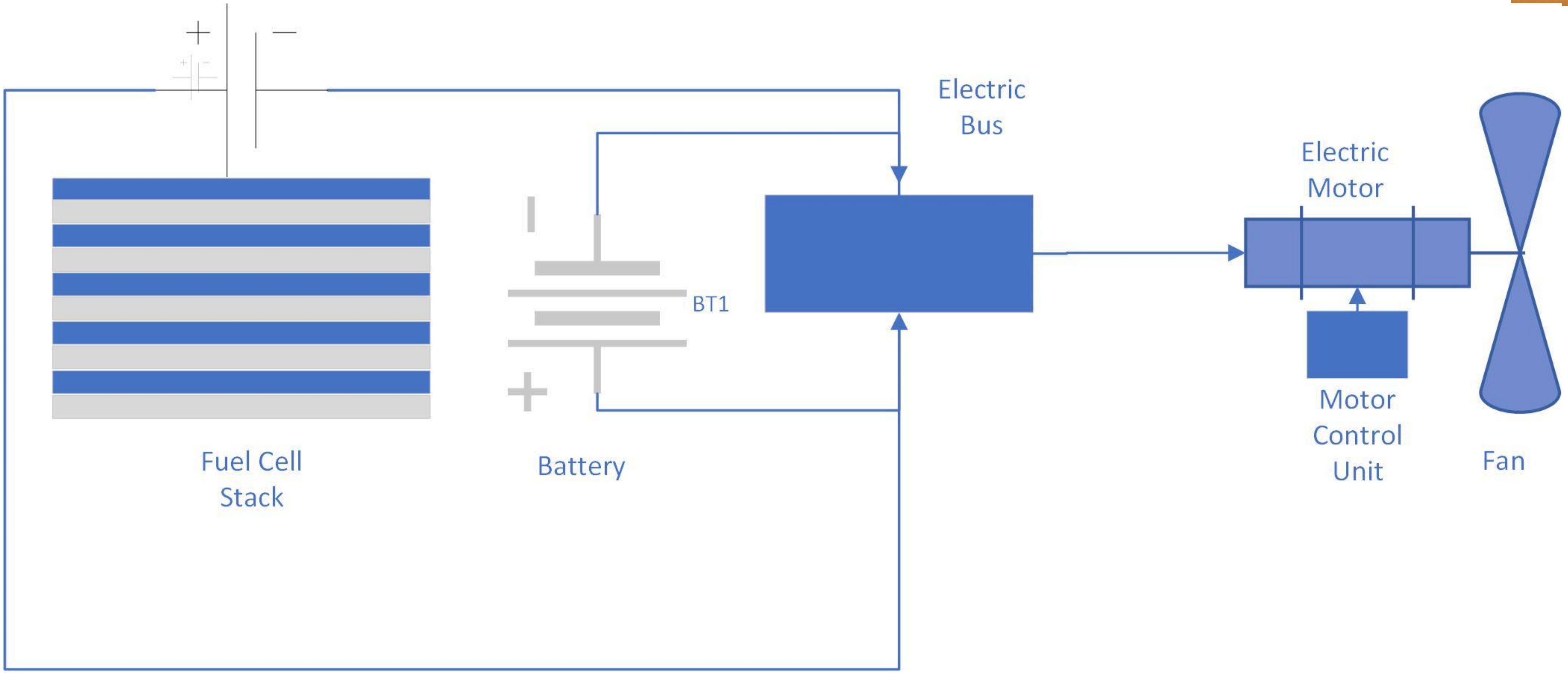
Niskayuna NY USA

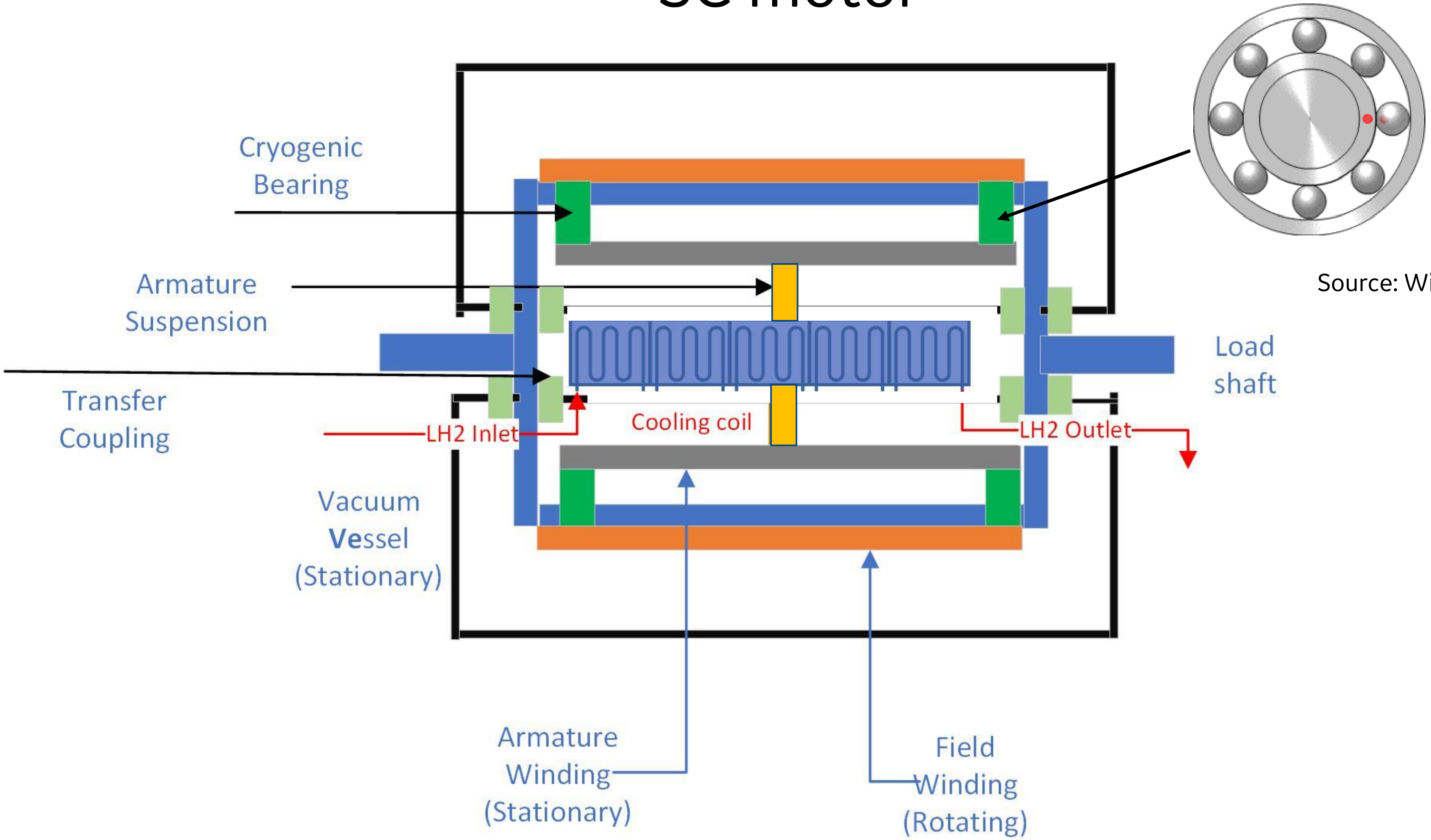
Overview

- Hydrogen-Electric aircraft technologies require electric propulsors to achieve the goal for zero emission. Those electric propulsors are preferably superconducting with high current density, resulting in an increased power density.
- We introduce a cryogenic cooling concept feasible for indirect cold mass cooling in the above 20 K or higher temperature range, depending on conductor choice.
- For a number of reasons, we would not bath-cool the propulsor (direct cooling) but prefer an indirect cooling approach where field and armature windings are not directly exposed to hydrogen.
- The stator of this motor is exposed to the rotating magnetic field of the field coils that rotate at e.g., 4500 rpm for the CHEETA design initiating eddy currents in the armature structure. Those AC losses need to be transferred to a cooling medium. In the proposed configuration a helical cooling coil is mounted on the inner surface of the stator. The cooling coil is configured such that liquid hydrogen can pass through the stator. We call that an armature winding cooled by highly efficient liquid hydrogen forced-flow boiling. The heat load generated from the armature due to those AC losses is quite substantial and may be around 2.3 kW.

Simplified Diagram of Electrified Aircraft



SC motor



Source: Wikipedia

Objective

- Develop cooling method that transfers heat from a stator to an outer rotating field winding (traditionally a tough task)
- Present heat transfer approaches are very limited:

Rotating cryocoolers ← Rotating Cryobearings → Thermal slip rings

Rotating cryocoolers fitted to the field winding – cooler MTBF, maintenance

Current research activities at:

- University of Illinois at Urbana-Champaign, Urbana, Illinois
- University of Auckland

SKF cryobearings, and other – No heat transfer possible

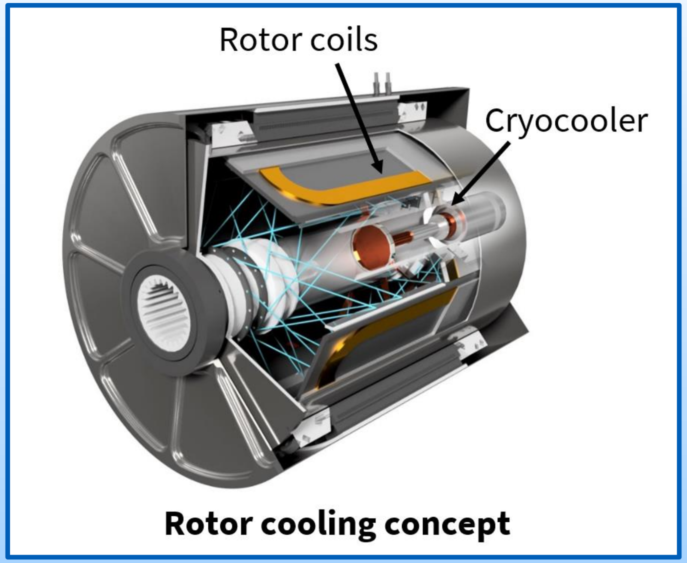
↓

Modify bearings ?

Preliminary designs discussed but need to be validated and tested

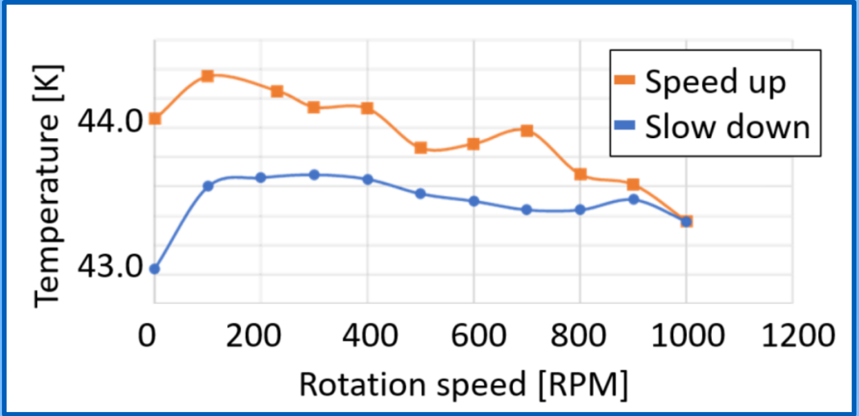
No direct use seen in Cryogenics yet – wear issues, little heat transfer only

Options



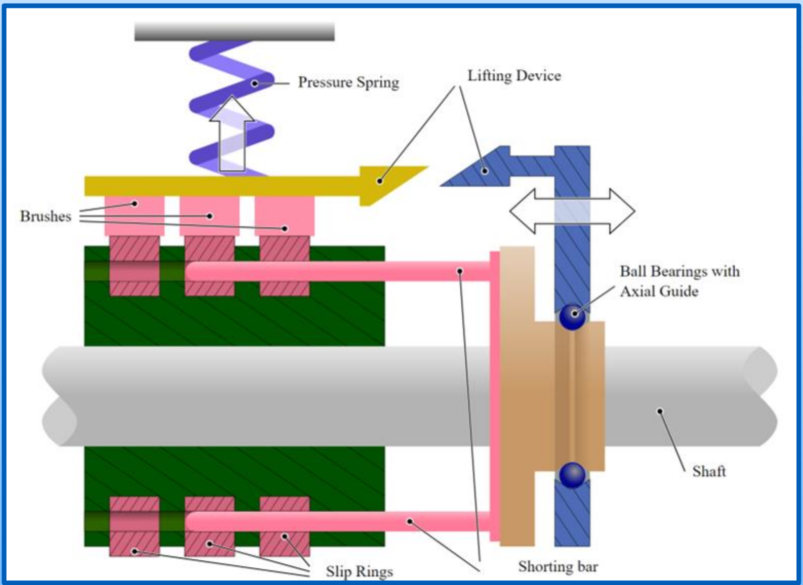
Rotating Cryocooler Test facility (ULI)

General Issues:
Operating temperature, MTBF



Cryogenic 6206 ABEC 3 with Si3N4 Ceramic Balls Bearing, Cage Peek

Application:
Cryogenic pumps e.g., SKF et al
Space mission cryogenic bearings e.g. RBCbearings



Thermal Slipring/brush design

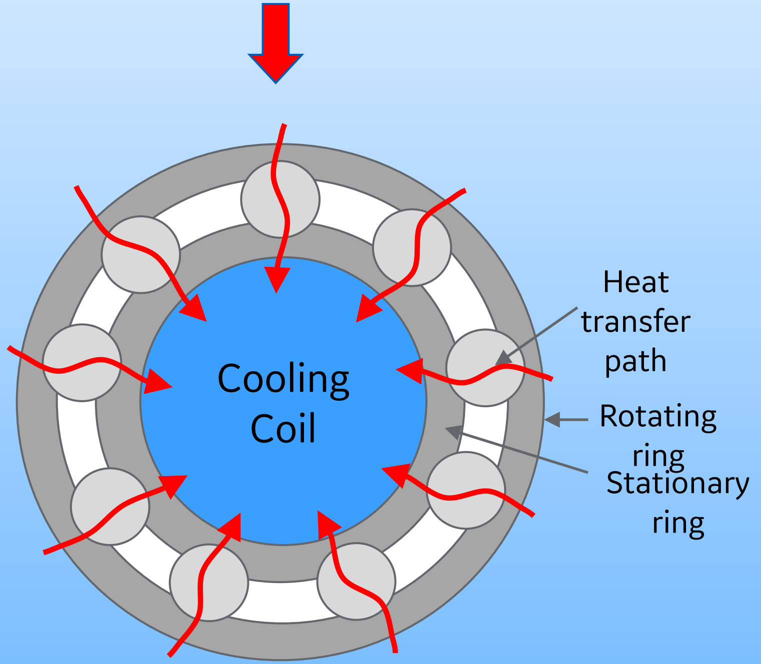
General Issues:
Operating temperature, Fatigue properties, vibration effects

Step 1: Material change

- The outer field coils need to be maintained at 23 K. Design a bearing that acts as a thermal link between rotating field coils and armature (heat removal approx. > 1 W)
- The Bearing rings are located at both ends, or at multiple locations along the length of the rotor.
- Material of bearing, high strength copper preferable (See NIST Monograph 177)
- Enhanced heat transfer with respect to stainless steel bearing

Thermal conductivity of materials:
316 steel @ 25 K 2 W/mK
Berylco 25 @ 25 K 75 W/mK,
other high strength CuNi materials similar
Factor 37.5 increase heat transfer

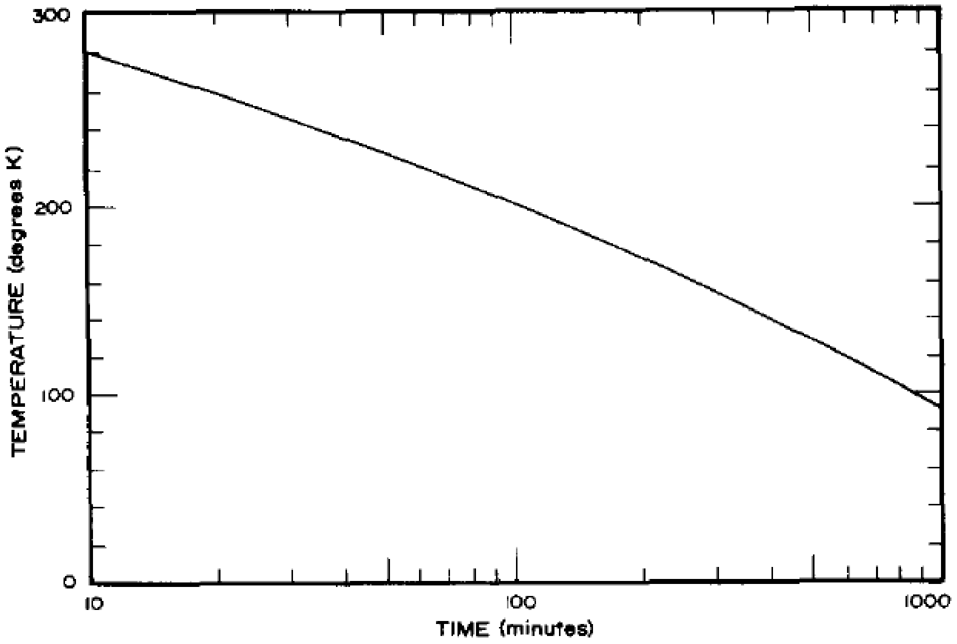
Stator and Rotating Field coils



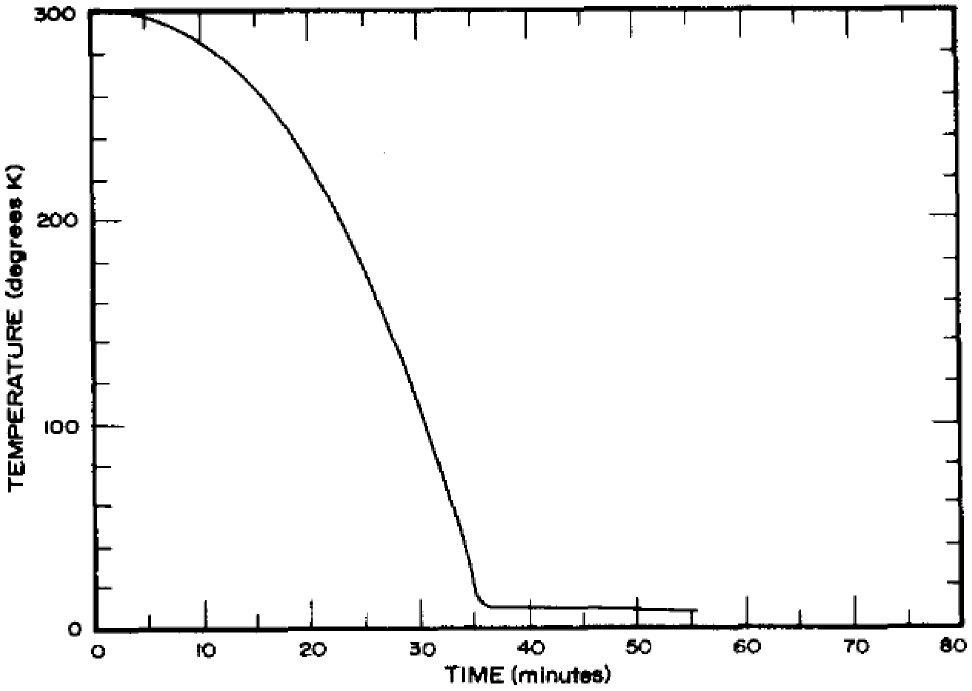
Stainless Steel bearing balls cannot be used:
K_{SS316} @ 25K =2 W/mK, R_{th}=750 K/W

Stainless Steel bearing housing cannot be used: thermal resistance too high

Example: Wyatt has shown that faster coldmass cooldown is possible, if copper bearings are chosen



Temperature history for the steel ball model



Temperature history of copper bearing.

Wyatt C L, Haycock R H 1974 **High thermal conductivity bearing for rotating devices at liquid helium Temperatures** Review of Scientific Instruments 45 pp 434-437

Step 1: Material change

For a 1 in Radius sphere (Rs), made of SS316L with a compressive pressure of 1 bar, the deformation a_1 and thermal resistance R_{c1} of:
Fa: Apparent Force P/piRs^2 E: Modulus of Elasticity

$$a_1 := 1.11 \cdot \left(F_a \cdot \frac{R_s}{E_{SS316}} \right)^{\frac{1}{3}} \qquad a_1 = 3.317 \times 10^{-4}\,m$$

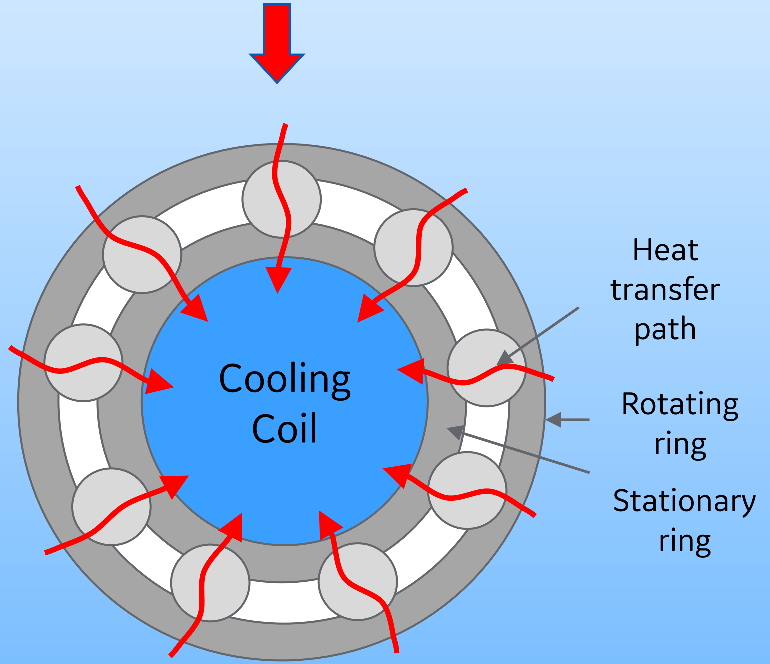
$$R_{c1} := \frac{1}{(2k_{SS316} \cdot a_1)} - \frac{\ln(2)}{\pi \cdot k_{SS316} \cdot R_s} \qquad R_{c1} = 749.45\,\frac{K}{W}$$

For a 1 in Radius sphere, made of Beryllium Copper C17200 with a compressive pressure of 1 bar, the deformation a_2 and thermal resistance R_{c2} of:

$$a_2 := 1.11 \cdot \left(F_a \cdot \frac{R_s}{E_{BeCu}} \right)^{\frac{1}{3}} \qquad a_2 = 3.833 \times 10^{-4}\,m$$

$$R_{c2} := \frac{1}{(2k_{BeCu} \cdot a_2)} - \frac{\ln(2)}{\pi \cdot k_{BeCu} \cdot R_s} \qquad R_{c2} = 17.276\,\frac{K}{W}$$

Stator and Rotating Field coils

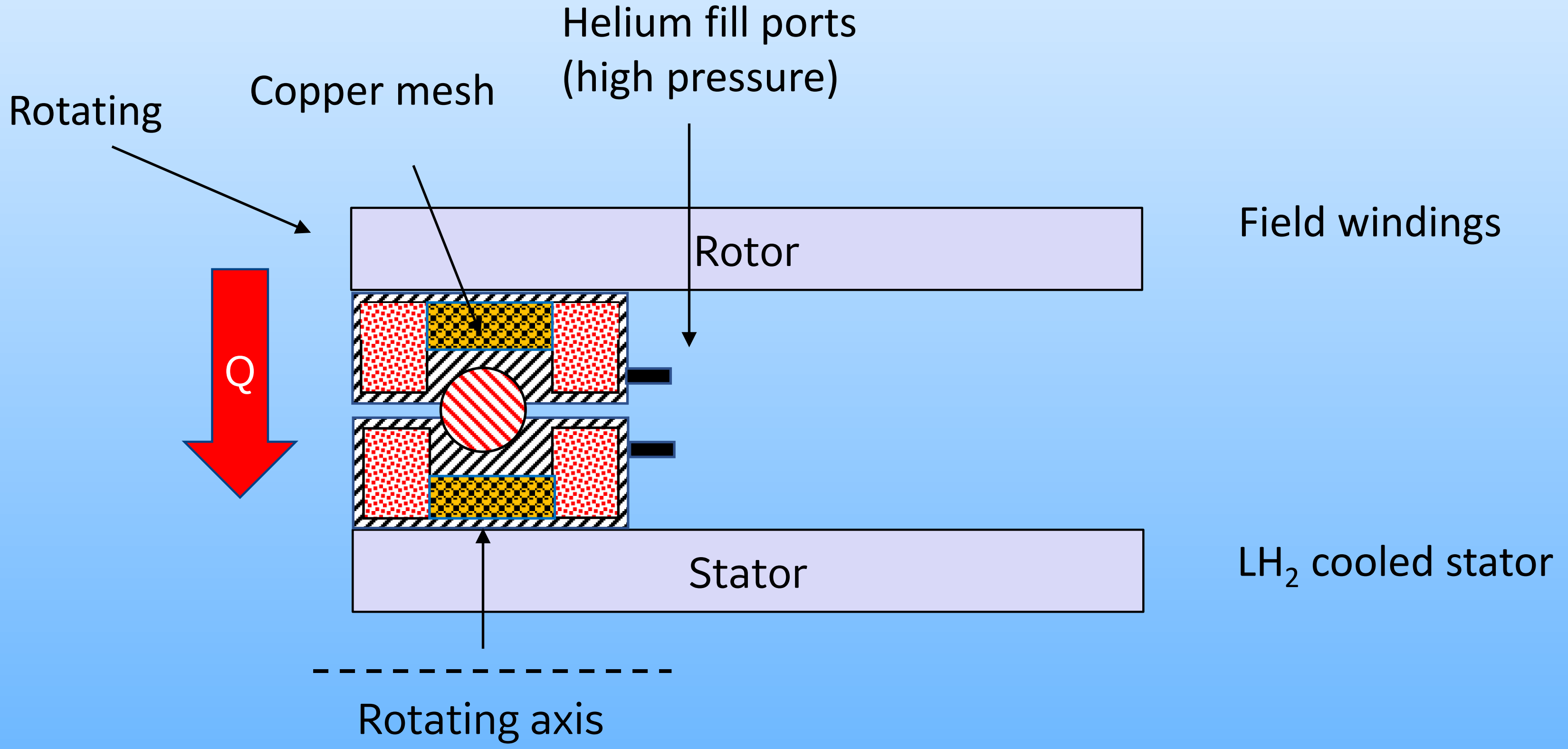


Stainless Steel bearing balls cannot be used:
K_{SS316} @ 25K =2 W/mK, R_{th}=750 K/W

Stainless Steel bearing housing cannot be used: thermal resistance too high

Step 2: Bearing housing change

Change housing and include helium filled heat exchangers in housing

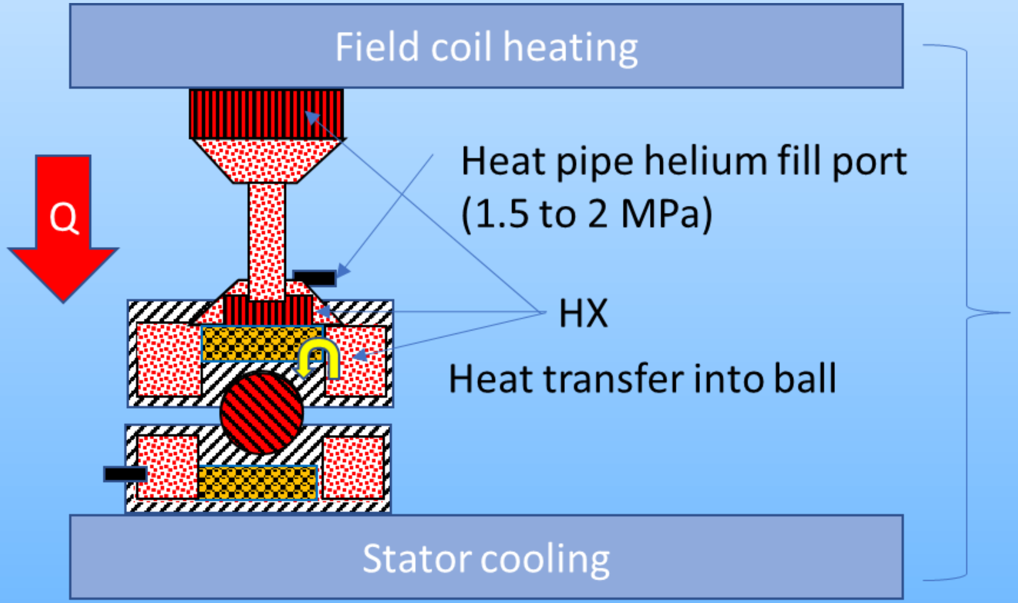


Several modifications possible

CuBe ball bearing in CuBe housing with rotating heat exchanger and with high pressure helium fill for heat transfer to copper interface structure to field coils

Step 3: Spoke ball bearing integration (heat pipe)

Improve thermal conductance of conductance outer and inner bearing housing with high conductivity material and helium filled chambers. Attached to those bearing chambers are gaseous helium filled heat pipe spokes transferring heat from balls to chambers and to the top of the heat pipe heat exchanger.



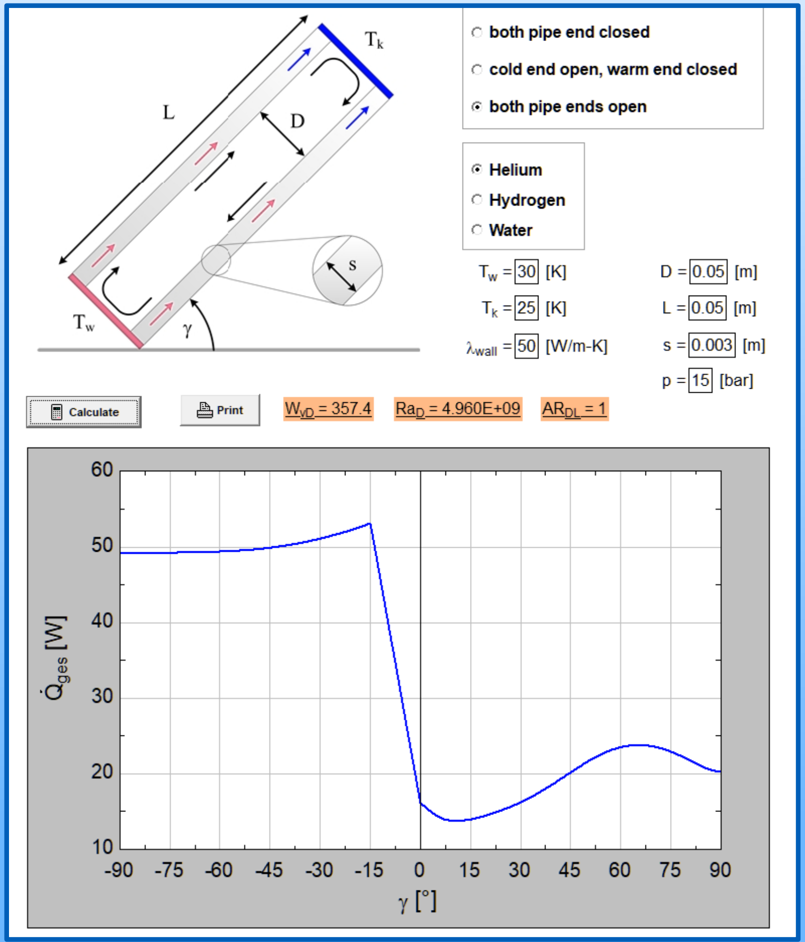
HEAT TRANSFER

Ball bearing with rotating heat pipe enclosure for cryogenic heat transfer and force balanced spokes

Bearing and heat pipe one reservoir for helium fill, both communicating

A simulation model based on CFD calculations for heat transfer in inclined tubes covers possible rotational angles under internal pressure (heat pipe). Results show that nearly 30 W can be transferred per housing spoke on average around the ball bearing circumference, at typical 4500 rpm.

Helium heat transfer in inclined tubes
Simulation model based on CFD calculations

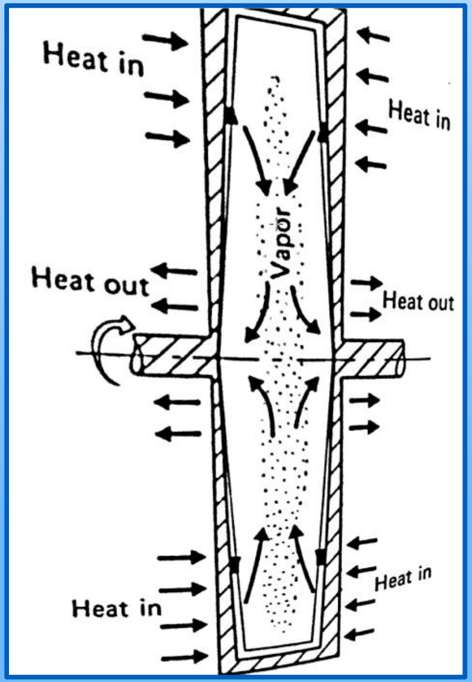


Courtesy of software used from Uni Dresden / Langebach

- Need to transfer heat of about 1 to 2 W from rotating field coils to stator (heat sink)
- Over the 360 rotational angle approx. 30 W / spoke on average can be transferred at 4500 rpm
- Rotating heat pipes are being used in different designs for motor rotors for room temperature applications

-90° = Tw on top
0° = Tw horizontal left side
90° = Tw at bottom

Berylco: 50 WmK



Dunn, Reay, Heat pipes, 4th edition, 94

Summary

- Rotating heat transfer between 2 surfaces is a very challenging task
- Our preliminary analysis shows us that heat transfer with a modified ball-bearing design may be feasible
- The ball bearing spoke design would allow us to use the bearings as a structural component
- Would eliminate and simplify SC motor cooling
- More research work is needed, combined with CFD modeling to further detail the respective design options

Literature

Dunn P D, Reay D A 1994 **Heat pipes** 4th Edition Pergamon

Morris W D 1981 **Heat transfer and fluid flow in rotating coolant channels** Research Studies Press Wiley

Wyatt C L, Haycock R H 1974 **High thermal conductivity bearing for rotating devices at liquid helium Temperatures** Review of Scientific Instruments 45 pp 434-437

Mikesell R P, Scott R B 1956 **Heat Conduction Through Insulating Supports In Very Low Temperature Equipment** Journal of Research of the National Bureau of Standards vol 57 No 6 Research Paper 2726

Feldman J Balachandran T Xiao J Stautner W Miljkovic N Haran K 2022 **Design of a Fully Superconducting Aircraft Propulsion Motor** EATS conference

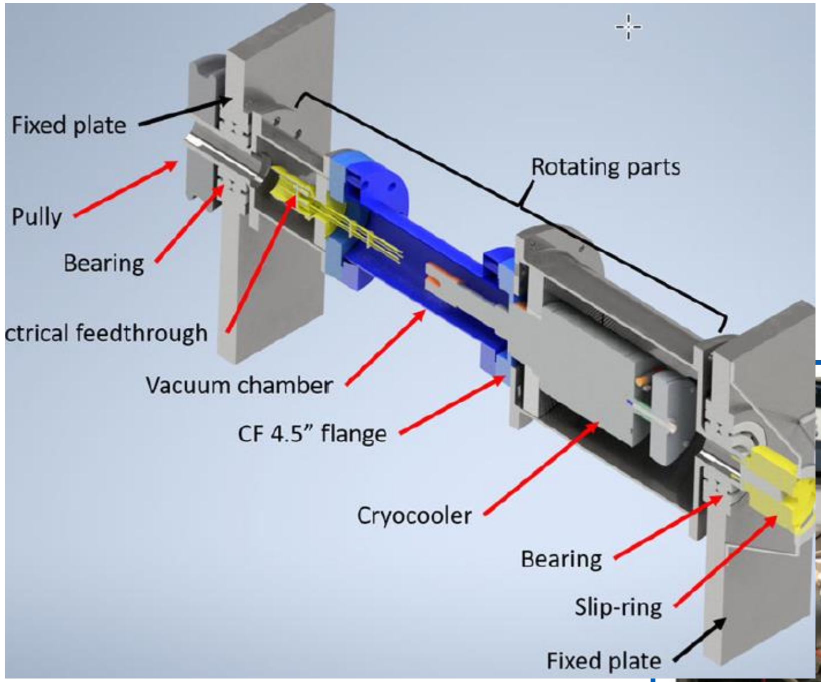
A. Hofmann paper rotating siphon and publications

Copper 0.324

Berylco and steel with nearly same CTE

Thermal expansion/contraction of technical materials (*Continued*)

Material	$\Delta L/L$ at 4 K [%]	$\Delta L/L$ at 40 K [%]	$\Delta L/L$ at 77 K [%]	$\Delta L/L$ at 100 K [%]	$\Delta L/L$ at 150 K [%]	$\Delta L/L$ at 200 K [%]	$\Delta L/L$ at 250 K [%]	α at 293 K [$10^{-6}K^{-1}$]
Cu–2%Be–0.3%Co (Beryllium copper, Berylco 25) [b]	0.316	0.315	0.298	0.277	0.219	0.151	0.074	18.1 [b]
Fe–9%Ni [a]	0.195	0.193	0.188	0.180	0.146	0.100	0.049	11.5
Hastelloy C [q]	0.218	0.216	0.204	0.193	0.150	0.105	0.047	10.9 [c]
Inconel 718 [a]	0.238	0.236	0.224	0.211	0.167	0.114	0.055	13.0 [k]
Invar (Fe–36%Ni) [a]	—	0.040	0.038	0.036	0.025	0.016	0.009	3.0 [k]
50%Pb–50%Sn solder [a]	0.514	0.510	0.480	0.447	0.343	0.229	0.108	23.4 [d]
Stainless steel (AISI 304) [b]	0.296	0.296	0.281	0.261	0.206	0.139	0.066	15.1 [l]
Stainless steel (AISI 310) [b]	—	—	—	0.237	0.187	0.127	0.061	14.5
Stainless steel (AISI 316) [b]	0.297	0.296	0.279	0.259	0.201	0.136	0.065	15.2 [l]
Ti–6%Al–4%V [a]	0.173	0.171	0.163	0.154	0.118	0.078	0.036	8.0 [m]


Fixed plate
Rotating parts
Pully
Bearing
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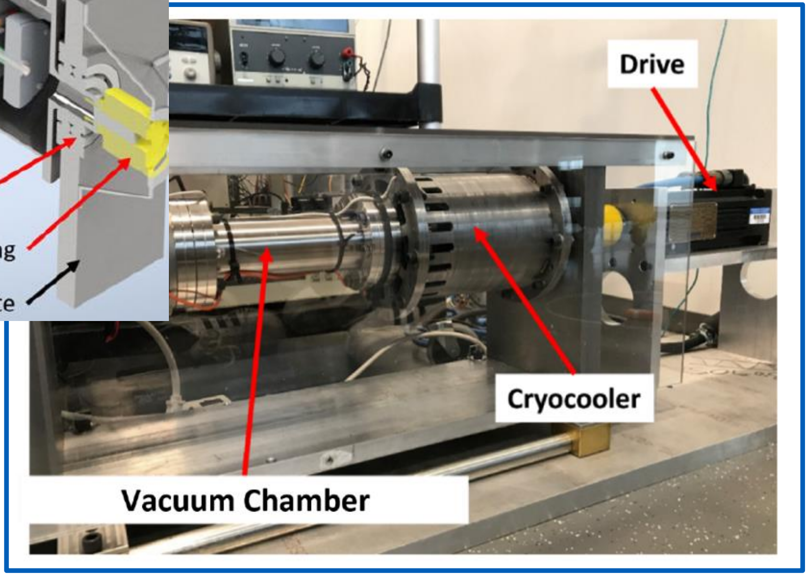
Vacuum chamber
CF 4.5” flange
Cryocooler
Bearing
Slip-ring
Fixed plate


Drive
Cryocooler
Vacuum Chamber