AC Loss of Superconducting Materials- loss estimates for motors and generators for hybrid-electric aircraft: MgB_2 wires, coated conductors

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Motivation

- Superconducting windings are enabling for high power density motors and generators for aircraft
- Motors with normal conductors can reach 20 kW/kg (future), but superconducting winding can double this, at 45 kW/kg
- Motors/generators with such higher power densities also hold great promise for revolutionary concepts including VTOL
- In particular, fully cryogenic superconducting stator and rotor generator design are promising
- Superconducting windings carry very large J (> 10 kA/mm^2) and can generate much higher B, but also losses
- Motors and Generators must be both higher power density while maintaining efficiency – which requires low loss
- Here we compare loss for best-of-class MgB_2 (wires) and YBCO (tape)
- Various loss contributions are considered, including applied fields, applied currents, and interaction terms

Summary Results: Details Follow

1. Superconducting windings are enabling for high power density motors and generators for aircraft use
2. It is shown that present day MgB_2 conductors with filament counts of 114 and wire in the 0.85 to 0.32 mm OD range could be in the 1-5 W/cm^3 range for f = 150-200 Hz.
3. Such conductors could be of interest for liquid hydrogen cooled machines -- Lower frequencies could allow windings to be conduction cooled
4. i.e., Present day MgB_2 conductors are usable for motors and generators
5. Filament numbers of 10-100 in a 2 mm wide YBCO tape will make coated conductors a viable candidates
6. Specific loss values are very dependent on rotational speed, number of poles, and conductor design, but detailed and specific losses are given for frequencies of 200-400 Hz and field amplitudes from 0.5-4 T, as well as scaling rules to extend these regimes.

What is a sensible loss target?

- Before we go into detail to calculate loss of SC, we should know what a sensible loss target is
- For conventional generators, windings are Cu, and J can be up to 8 A/mm^2 with no extraordinary cooling methods (i.e., extra size and weight)
- Up to J = 30 A/mm^2 can be achieved, but with very aggressive cooling that adds weight, and also reduces efficiency
- We will use J = 8 A/mm^2 as our comparison. At this J, loss per unit volume is about 1 W/cm^3 (for 30 A/mm^2, P = 16 W/cm^3!)
- Going much above this target leads to issues both in local heat removal, and in global heat removal (a lot of heat to be removed, and an efficiency reduction)
- If we want to lead to overall weight reduction with SC and no “free cooling”, we will see below that 1 W/cm^3 is an upper limit.
- If we can reject heat to a cooled fuel (as some conventional systems do), higher losses are OK, perhaps 1-5 W/cm^3

What's a useful criterion for SC in Aircraft motors and generators?

- Right now, motor/generator designs just have to "drop the SC in" and see what happens! Lots of design, and loss calculations detailed
- It would be better to have a metric
  - Power Loss?
  - Power Loss per meter?
  - Power loss per volume?
  - J ?
  - J/J_{cu}?
  - $(J/J_{cu})/(P_v/P_{cu,v})$?

Let's think about this as we go - see if we can get an answer

First off -- Aren't SC loss-less?

- SC with no flux inside with DC currents are lossless, but SC with AC current, and those with flux inside (Type II) and exposed to time changing fields experience loss
- Energy loss is due to work, which is force through a distance, W = F*d
- The force in this case is the Lorentz force,

$$F_{\text{per unit V}} = J \times B$$

This leads to the most fundamental kind of loss in a superconductor – so called "hysteresis loss"

This name is funny, since all loss is hysteretic by nature – but the name is traditional at this point

Such "hysteresis loss" is present for the simplest of superconductor configurations – a simple rod or slab – however, there are other losses too!

Loss Contributions

The total loss consists of

$$P_t = P_h + P_e + P_c + P_I + P_x$$

P_t is the total loss

P_h is the hysteretic loss

P_e is the normal metal eddy current loss

P_c is the coupling current loss

P_I is the transport loss term

P_x is an interaction term (positive or negative)

Hysteretic Losses (External Applied Fields)

For a cylinder in a time varying field applied in a fixed direction the power loss due to superconductor hysteresis is

$$P_h = (8/3\pi)B_m J_c d_f f$$

Where

P_h is power loss per unit volume (W/cm^3)

B_m is the maximum applied field amplitude (1/2 the peak to peak variation),
J_c is the superconductor critical current

d_f is the filament or monofilament diameter

f is the frequency of the time dependence of the applied field

If that cylinder is in a rotating field, as would be present in a motor or generator, the loss is given by

$$P_{rot} = \frac{\pi}{2} P_{time\ varying} = \frac{4}{3} B_m J_c d_f f$$

Thus the loss in a rotating field is larger by a factor of $\pi/2$

Normal Metal Eddy Current Losses

The second term is due a high conductivity outer sheath on superconducting wires, and leads to normal metal eddy currents generated by time varying applied fields according to

$$P_e = \frac{\pi}{k}\frac{1}{\rho}[(B_m)wf]^2$$

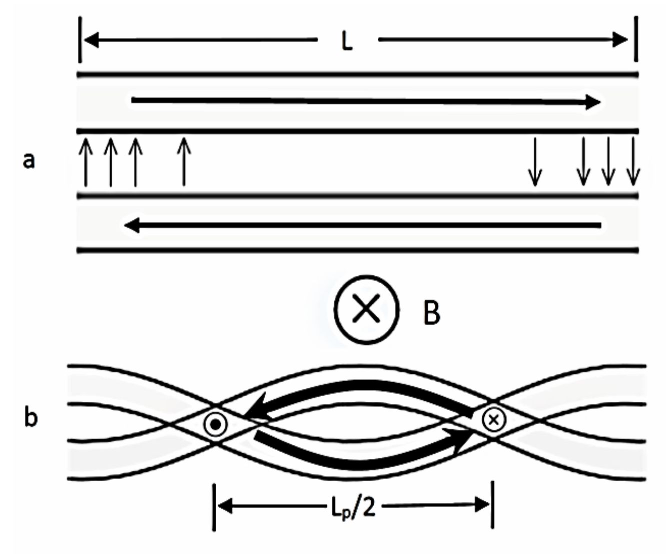
Where

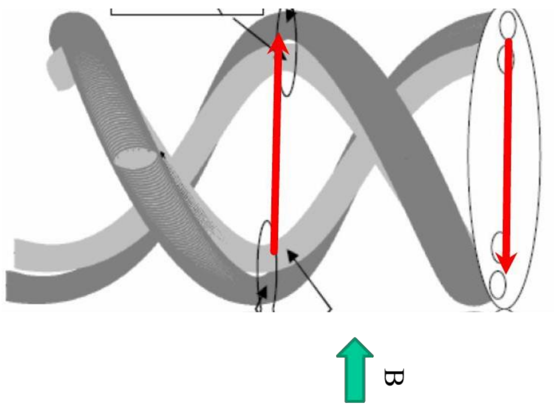
w is the diameter of the whole strand or the width of the tape $\perp$ B

k = 6 for a flat tape or 4 for a circular sheath

Coupling Current Losses

The third term is the coupling current term, which describes eddy currents which are "amplified" by current paths inside the SC





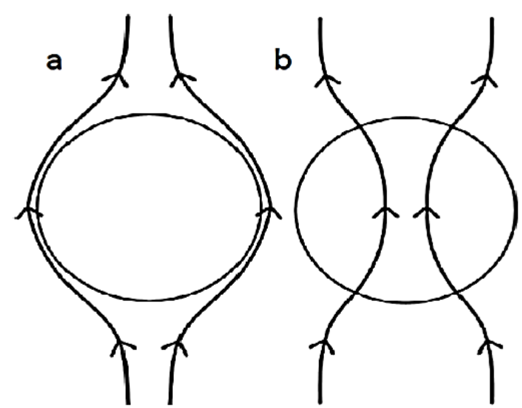
$$P_c = \frac{1}{n\rho_{eff}}\left[f L_p B_m\right]^2$$

Where n = 2 for a round MF strand and n = 4 for a striated flat tape

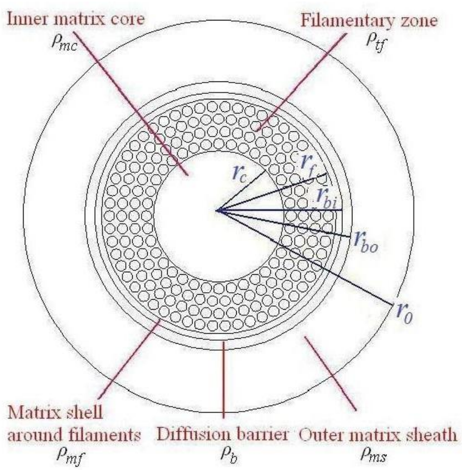
Depending upon whether the filament-matrix interface contact resistance is high or low, the filaments may act as barriers nt flow, leading to

$\rho_{eff} = \rho(1+\lambda)/(1-\lambda)$ for high interface resistance

$\rho_{eff} = \rho(1+\lambda)/(1-\lambda)$ for low interface resistance



Eddy and coupling Current Contributions in the Outer sheath and Effective Matrix resistivity



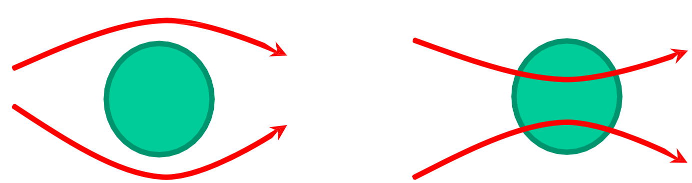
Main Points

1. Outer Sheath contributes less to coupling currents, based on geometry
2. Many SC strands have a central region which is lower in resistance, this complicates analysis, and result is given below, see Ref left

C. Zhou, Thesis, University of Twente
B. Turck, J. Appl. Phys. 50 (1979) 5397
B. Turck, Cryogenics 22 (1982) 466

$$P_{02} = \left(\frac{r_f}{r_0}\right)^2 \dot{B}^2 \left(\frac{L_p}{2\pi}\right)^2 \left(\frac{1}{\rho_{ms}} \frac{r_0^2 - r_f^2}{r_0^2 + r_f^2} + \frac{1}{\rho_{tf}} \frac{r_f^2 - r_c^2}{r_f^2} + \frac{1}{\rho_{mc}} \frac{r_c^2}{r_f^2}\right) + \frac{\dot{B}^2}{4\rho_{ms}} \left(\frac{r_0^4 - r_f^4}{r_0^2}\right).$$

The filament/matrix resistivity determines whether coupling currents flowing across the matrix use the filaments as short cuts or not, which can reduce or enhance resistivity by a factor
$(1-\lambda)/(1+\lambda)$
To
$(1+\lambda)/(1-\lambda)$



Such effects can easily change coupling loss by a factor of 5 or more

Transport Losses

The next term is a loss term for current transport

This term is typically much smaller than all of the others, and we include it here for round conductors, for comparison purposes.

In the self-field of an AC transport current of amplitude I_0 a round or elliptical strand experiences a power loss per unit length of

$$\frac{P}{L} = \frac{\mu_0 f}{\pi} I_c^2 \left[\left(1 - \frac{I_0}{I_c}\right) \ln\left(1 - \frac{I_0}{I_c}\right) + \frac{I_0}{I_c} - \frac{1}{2}\left(\frac{I_0}{I_c}\right)^2 \right]$$

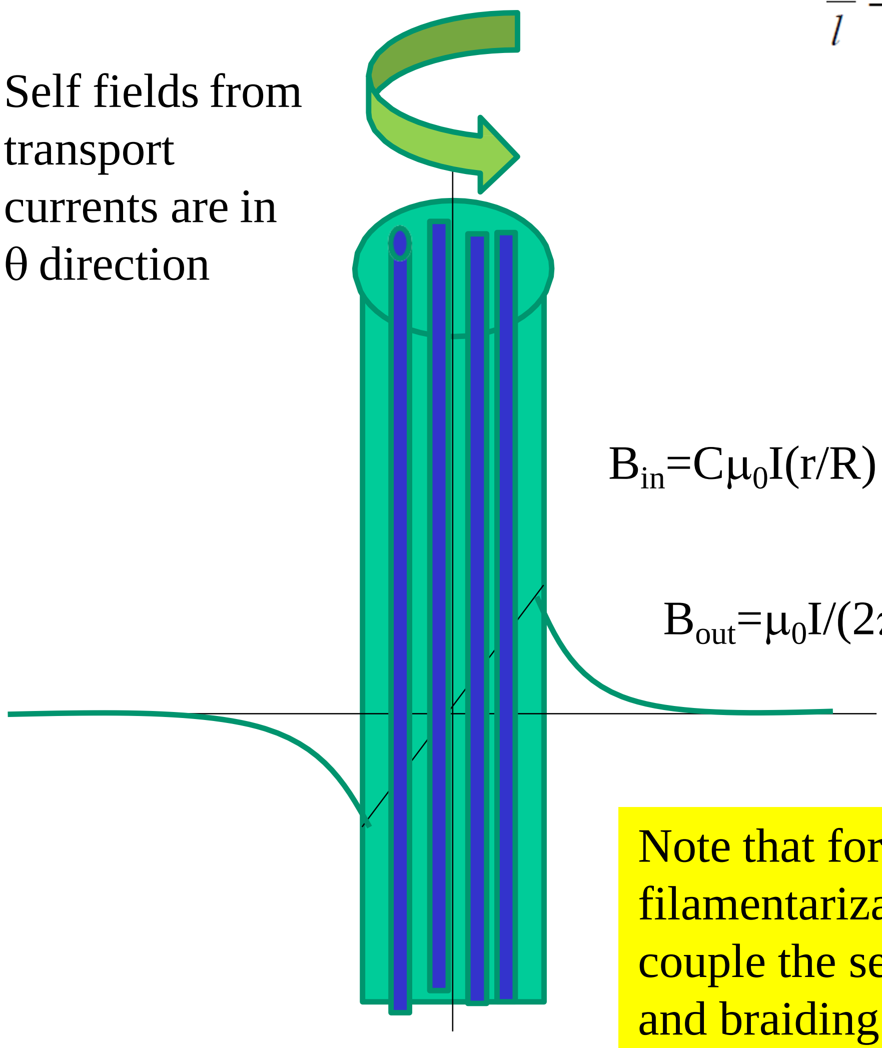
Where $i = I_0/I_c$ and there is no applied field

The expression is somewhat different for a strip

Transport loss in Multifilaments

$$\frac{P}{l} = \frac{\mu_o}{\pi} f\, I_c^2 \left[\left(1 - \frac{I_o}{I_c}\right) \ln\left(1 - \frac{I_o}{I_c}\right) + \frac{I_o}{I_c} - \frac{1}{2}\left(\frac{I_o}{I_c}\right)^2 \right]$$

Self fields from transport currents are in θ direction



Ellipse $\propto I_c^{\,2}(I/I_c)^3$

$P/L=C(J_cR^2)^2$

$P/V=(C/Pi)(RJ_c)^2$

Transport losses per unit volume go as R^2, $J_c^{\,2}$, f, and $(I/I_c)^3$

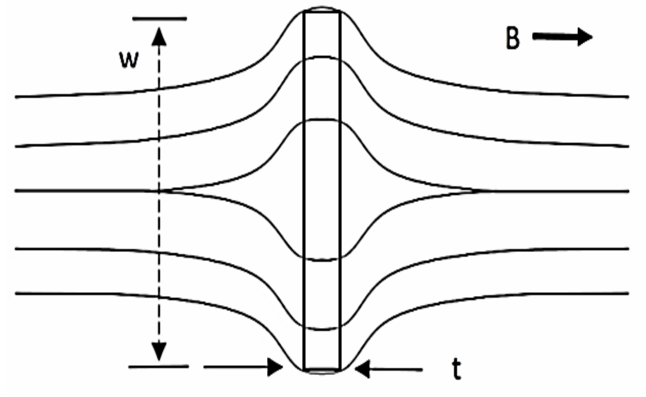
Transport losses per unit length as $I_c^{\,2}$, f, and $(I/I_c)^3$

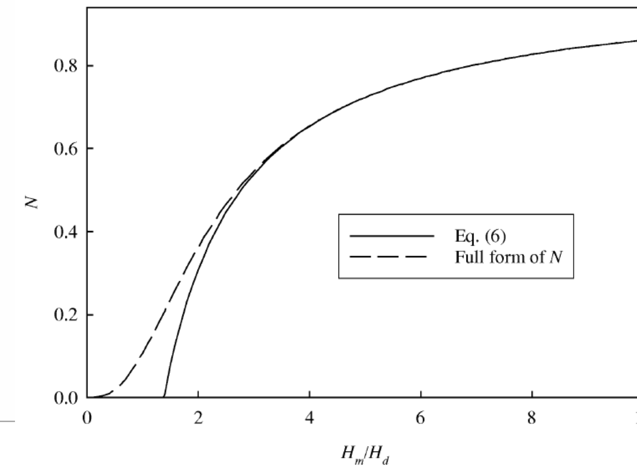
Note that for multis the transport losses are unaffected by filamentarization – this is because even a twist does not de-couple the self field since it is in θ direction. Separate wires and braiding is needed for that

Modifications for YBCO

- For YBCO tapes or CORC wires a the Hysteretic losses expression is modified by a prefactor *N*, approximated by

$$N \approx 1 - 2\left(\frac{B_d}{B_m}\right) Ln(2)$$





- where $B_d = 0.4\ \mu_0 J_c t$ is a characteristic field
- In order to calculate loss for the cable, we must correct by a factor of $\pi/2$ for samples with a sufficiently large twist pitch, and then multiply by the filling factor of the cable
- We can reduce the loss by a factor N_f, where N_f is the number of filaments if the coated conductor is striated

Combined Transport and Field Loss

$$\left.\begin{array}{l} I_{DC} + B_{AC} \\ I_{AC} + B_{DC} \end{array}\right\}$$

Leads to Dynamic Resistance

$$I_{AC} + B_{AC}$$

Combined external field and transport AC loss

Relative Phase

Relative Size

Additions of DC or AC B field onto SC with AC or DC transport in a **MULTI** tend to cause decoupling of the filament wrt transport loss, and thus loss **Reductions**. The dynamic resistance additions must also be added

Additions of DC or AC B field onto SC with AC or DC transport in a **MONO** tend to cause EXTRA loss, in the form of a dynamic resistance (power coming from current source)

In phase assumption

Other Combinations of *B* and *I*

This was DC current and AC field

How about AC current and DC field?

How about AC field and current?

N. Schonborg, J. Appl. Phys. 90 (2001) 2930 gives the result for AC field and current (field applied perpendicular, and in-phase). ***Expressions for arbitrary phase angles also exist***

$$C = \sqrt{(1+p_o)^2 - a_o^2} \qquad D = \sqrt{(1-p_o)^2 - a_o^2}$$

$a_o=2a/w$, $p_o=2p/w$ and $p = \frac{w}{2}\frac{I_o}{I_c}\tanh\left(\frac{H_o}{H_c}\right)$

$$\frac{P}{l} = \frac{\mu_o}{\pi} f I_c^2 \left[\begin{array}{l} 2\coth^{-1}\left(\frac{1-p_o^2+a_o^2}{CD}\right) - \frac{1}{4}\left((1+p_o)C + (1-p_o)D\right)\left\{\cosh^{-1}\left(\frac{1+p_o}{a_o}\right) + \cosh^{-1}\left(\frac{1-p_o}{a_o}\right)\right\} + \\ + \frac{1}{2}(C-D)\left\{(1+p_o)\cosh^{-1}\left(\frac{1+p_o}{a_o}\right) + (1-p_o)\cosh^{-1}\left(\frac{1-p_o}{a_o}\right)\right\} + \frac{1}{4}(C-D)^2 - \frac{1}{2}\left(C^2-D^2\right) \end{array} \right] \qquad (10)$$

$$a = \frac{w}{2}\frac{\sqrt{1-\left(\frac{I_o}{I_c}\right)^2}}{\cosh\left(\frac{H_o}{H_c}\right)}$$

Some Caveats

- **Magnetic Materials** (say Fe, Monel, or Cu-Ni, add ferromagnetic losses, but can also modify field lines, and thus both hysteretic and transport loss
- **Screening** (above 200 Hz or so, can have screening effects, depending on metal resistivity (Carr)
- **Field Profile Shape**: 10% influence on coupling and eddy current loss, none on hysteresis (Zenkovich)
- **Rotating vs oscillating fields:** Rotating fields can increase loss over oscillating fields by about 70% worst case
- **Variation of J_c with Field** – the simple hysteretic loss expressions assume J_c is field indepdendant –but this is very much not the case --see below!

Loss Comparison Table

OD/d_f/L_p (mm/μm/mm)	fil	Bar %	ρ_{matrix} μΩcm	λ, %	λ'	(1-λ')/(1+λ')	ρ_{eff}, μΩcm	NM (W/cm^3)	Hyst (W/cm^3)	Coup (W/cm^3)	Trans (W/cm^3)	Total (W/cm^3)
MgB_2 200 *Hz*, I_{op} = 50% of I_c, I_c = 560 A per strand, J_c = 66,0000 A/cm^2 at 0.4 T, 20K, losses per strand volume												
0.85/28/10	114	33%	36.5	15	49	0.342	12.5	0.091	1.88	2.56	1.26	5.79
MgB_2 200 *Hz*, I_{op} = 50% of I_c, I_c = 79 A per strand, J_c = 66,0000 A/cm^2 at 0.4 T, 20K, losses per strand volume												
0.32/10/5	114	33%	36.5	15	49	0.342	12.5	0.013	0.673	0.64	.180	1.50
***YBCO 200 Hz*, I_{op} = 50% of I_c, I_c = 200 A per strand, 2 mm width, J_e = 100,000 A/cm^2, at 0.4 T, 77K, losses per strand volume**												
2mm/2mm	1	--	0.214	2	1	1	0.214	19.6	160	0	--	180
2mm/0.2mm	10	--	.214	2	--	--	0.214	0.19	16	--*	--	16.2
2mm/.02 mm	100	--	0.214	2	1	1	0.214	0.0019	1.6	--*	--	1.6
OD/d_f/L_p (mm/μm/mm)	fil	Bar %	ρ_{matrix} μΩcm	λ, %	λ'	(1-λ')/(1+λ')	ρ_{eff}, μΩcm	NM (W/cm^3)	Hyst (W/cm^3)	Coup (W/cm^3)	Trans (W/cm^3)	Total (W/cm^3)
MgB_2 150 *Hz*, I_{op} = 50% of I_c, I_c = 560 A per strand, J_c = 66,0000 A/cm^2 at 0.4 T, 20K, losses per strand volume												
0.85/28/10	114	33%	36.5	15	49	0.342	12.5	0.051	1.41	1.44	0.948	3.85
MgB_2 150 *Hz*, I_{op} = 50% of I_c, I_c = 79 A per strand, J_c = 66,0000 A/cm^2 at 0.4 T, 20K, losses per strand volume												
0.32/10/5	114	33%	36.5	15	49	0.342	12.5	0.0073	0.504	0.36	0.0134	1.01
***YBCO 150 Hz*, I_{op} = 50% of I_c, I_c = 200 A per strand, 2 mm width, J_e = 100,000 A/cm^2, at 0.4 T, 77K, losses per strand volume**												
2mm/2mm	1	--	0.214	2	1	1	0.214	11.0	120	0	--	131
2mm/0.2mm	10	--	.214	2	--	--	0.214	0.11	12	--*	--	12.1
2mm/.02 mm	100	--	0.214	2	1	1	0.214	0.0011	1.2	--*	--	1.2

M.D. Sumption, “AC Loss of Superconducting Materials in Motors and Generators for Very High Density Motors and Generators for Hybrid-Electric Aircraft”, 2018 AIAA/IEEE Electric Aircraft Technologies Symposium, https://doi.org/10.2514/6.2018-5001

Newly Developed low Loss MgB_2 Strands

Table 1. MgB_2 Strand Specifications.

Strand Code	No. Fil.	$\rho_{interfil}$, μΩcm	ρ_{outer}, μΩcm	ρ_{core}, μΩcm	OD (mm)	MgB_2 (%)	Cu (%)	Nb (%)	Outer sheath (%)	Center (%)	Matrix (%)	λ'	Mult
3871	114	36	3.6	36	0.38	9.6	0.6	31.6	42.6	->	15.6‡	0.77	7.6
3786	54	36	36	36	0.48	15.3	0	30.9	33.1	7.0	13.7	0.69	5.5
3786	54	36	36	36	0.31	15.3	0	30.9	33.1	7.0	13.7	0.69	5.5
3799	114	36	36	11.7	0.31	12.0	0.9	33.4	36.8	3.3	13.6	0.73	6.4

‡ includes center, which is of the same material (center is 3.1%).

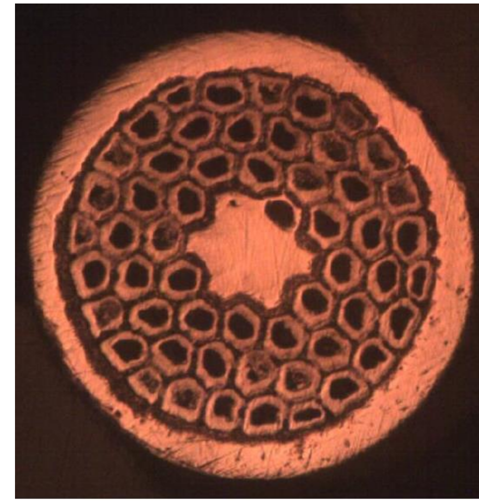
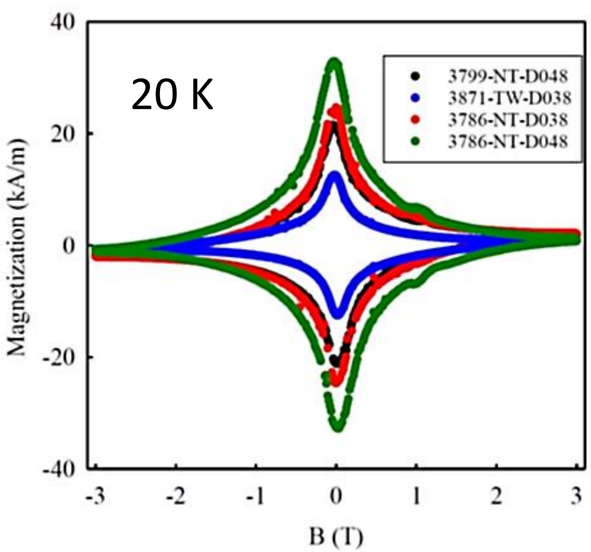
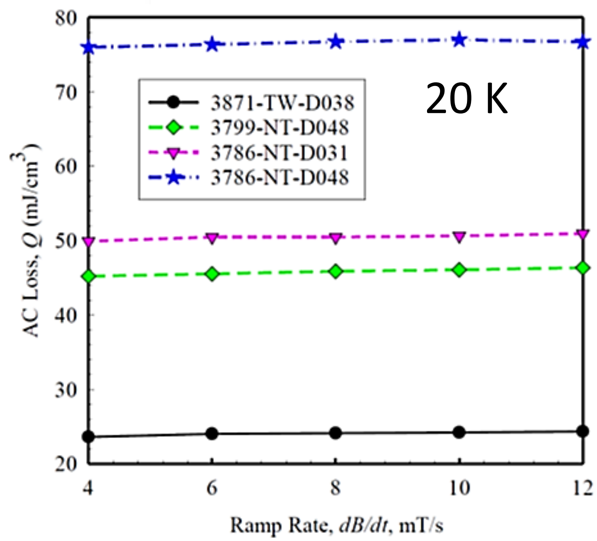


Table 2. Spiral Sample Specifications

Sample Name	L_{peff} (mm)	L_{spiral} (turns)	L_{wire} (mm)	OD (mm)	V_{strand} (10^{-3} cm^3)
3871-TW-0.38	69.1	7.5	64.78	0.38	7.347
3786-NT-0.31	145.6	10	72.81	0.31	5.496
3786-NT-0.48	182.5	10	91.25	0.48	16.512
3799-NT-0.48	182.5	10	91.25	0.48	16.512





Loss Analysis -- Hysteresis

Table 3. Spiral Sample Hysteretic and coupling loss Results for +-3 T M-H loops at 20 K (Fig 3)

Sample	d_f, μm	L_{peff} (mm)	Q_h (mJ/cm^3)	$\Delta Q/\Delta(dB/dt)$, 10^{-3} $Js/T{*}cm^3$	$\Delta Q/\Delta(dB/dt)$, $kJs/T{*}m^3$	ρ_{eff} ($\mu\Omega$cm)
3871-TW-038	10.7	69.1	23.4	83.3	83.3	2.14
3786-NT-031	15.6	145.6	49.9	110	110	7.17
3786-NT-048	24.3	182.5	75.7	105	105	11.8
3799-NT-048	14.9	182.5	44.7	142	142	8.75

$$\Delta M = \frac{4}{3\pi} j_c d \qquad \text{and} \qquad Q = \frac{8}{3\pi} J_c B_0 d$$

Fit of J_c from 3786 – NT-D031, leads to $J_c = y0 + A\exp(-bB)$, where $y_0 = 7.5 \times 10^3$ A/cm^2, $A = 4.07 \times 10^6$ A/cm^2, and b = 1.6. This leads to an average J_c over the 0-3 T sweep of 8.63 x 10^5 A/cm^2. Again, normalized to MgB_2 area. Also shown as dotted red line is J_c average over range from 0-to given B_0.

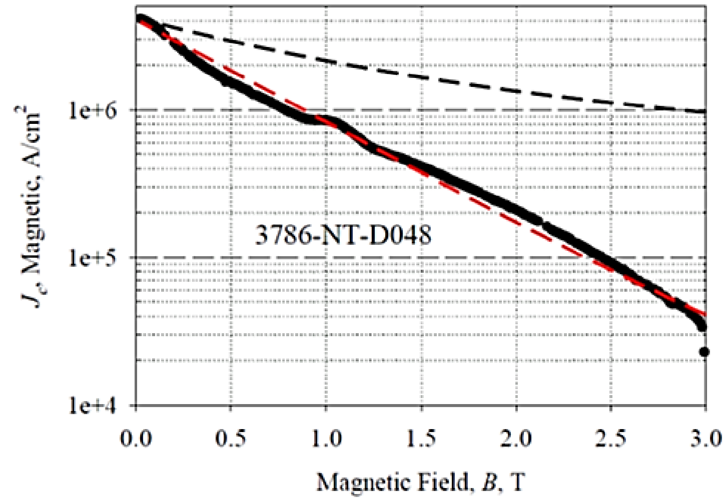


Table 4. Hysteresis loss analysis

Strand	d_{eff}, µm	Estimated $Q_{h,strand\text{-}V}$ mJ/cm^3	Estimated $Q_{h,\ SC\text{-}V}$, mJ/cm^3	Measured $Q_{h,strand\text{-}V}$ mJ/cm^3	Measured $Q_{h,\ SC\text{-}V}$, mJ/cm^3
3871-TW-0.38	10.7	22.6	236	23.4	243
3786-NT-D031	15.7	52.7	344	49.9	326
3786-NT-D048	24.2	81.6	533	75.7	494
3799-NT-D048	14.8	39.2	327	44.7	373

Loss Analysis -- Coupling

Table 3. Spiral Sample Hysteretic and coupling loss Results for +-3 T M-H loops at 20 K (Fig 3)

Sample	d_f, μm	L_{peff} (mm)	Q_h (mJ/cm^3)	$\Delta Q/\Delta(dB/dt)$, 10^{-3} $Js/T{*}cm^3$	$\Delta Q/\Delta(dB/dt)$, $kJs/T{*}m^3$	ρ_{eff} ($\mu\Omega$cm)
3871-TW-038	10.7	69.1	23.4	83.3	83.3	2.14
3786-NT-031	15.6	145.6	49.9	110	110	7.17
3786-NT-048	24.3	182.5	75.7	105	105	11.8
3799-NT-048	14.9	182.5	44.7	142	142	8.75

$$Q_t = Q_h + Q_e + Q_c + I$$

$$Q = \frac{L_p^2}{2\rho_{eff}} \frac{B_0}{4} \frac{dB}{dt}$$

$$P = \frac{1}{n\rho_{eff}} \left[f L_p B_0\right]^2$$

$$P_{coup} = \left(\frac{r_f}{r_o}\right)^2 \left(\frac{dB}{dt}\right)^2 \left(\frac{L_p}{2\pi}\right)^2 \left(\frac{1}{\rho_{ms}} \frac{r_0^2 - r_f^2}{r_0^2 + r_f^2} + \frac{1}{\rho_{tf}} \frac{r_f^2 - r_c^2}{r_f^2} + \frac{1}{\rho_{mc}} \frac{r_c^2}{r_f^2}\right) + \frac{1}{4\rho_{ms}} \left(\frac{dB}{dt}\right)^2 \left(\frac{r_0^4 - r_f^4}{r_0^2}\right)$$

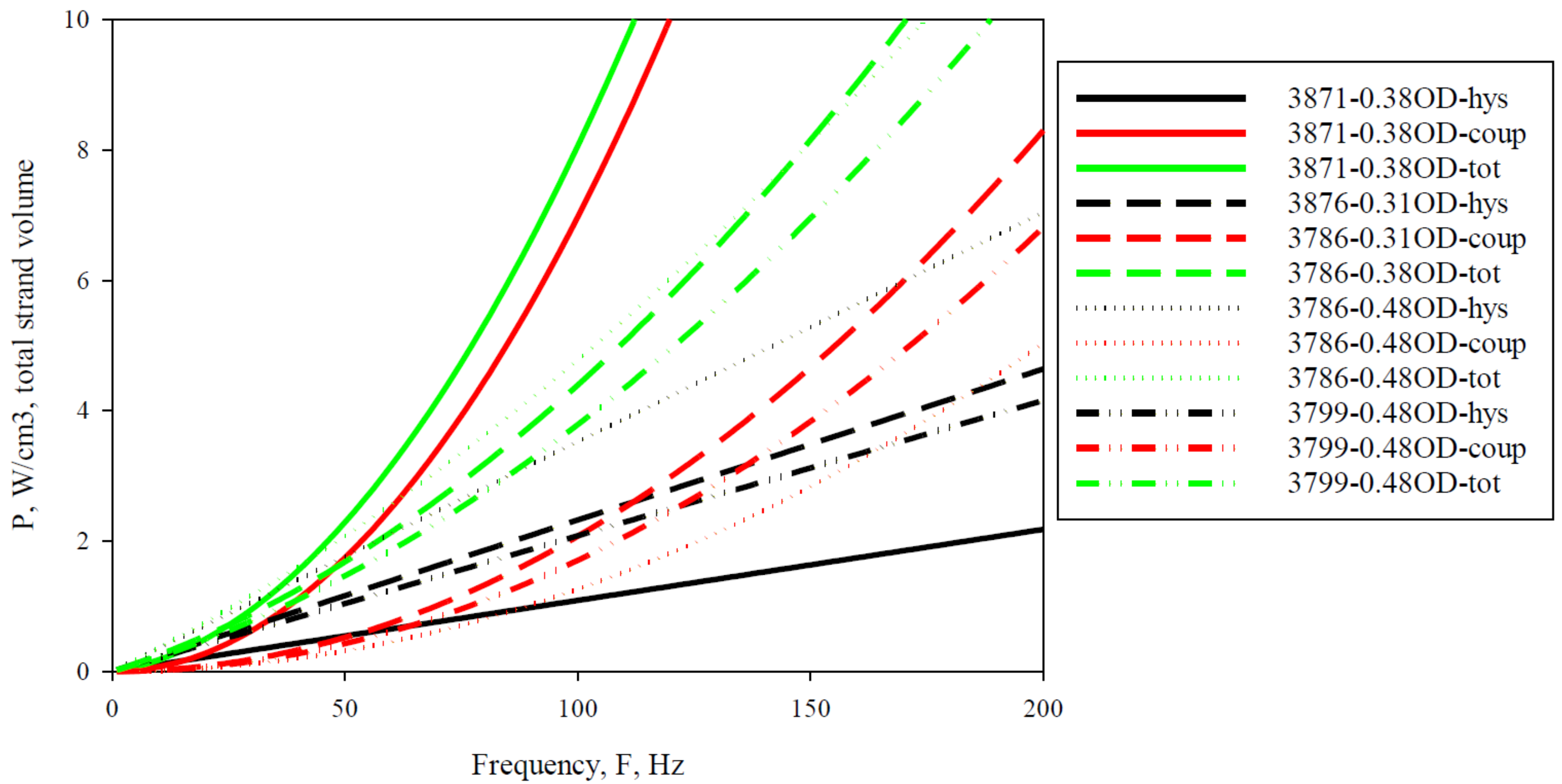
Table 5. More Detailed coupling loss analysis

Sample	L_{peff} (mm)	$\Delta Q/\Delta(dB/dt)$, $kJs/T{*}m^3$	Simple extracted ρ_{eff} ($\mu\Omega$cm)	r_o, mm	r_f, mm	r_c, mm	Full analysis extracted ρ_m, $\mu\Omega cm$
3871-TW-038	69.1	83.3	2.14	0.19	0.144	0.033	1.0
3786-NT-031	145.6	110	7.17	0.155	0.127	0.041	3.75
3786-NT-048	182.5	105	11.8	0.24	0.196	0.063	6.3
3799-NT-048	182.5	142	8.75	0.24	0.191	0.044	4.6

Extrapolations from Measured data

$$P_{coup} = \left[\frac{P_{coupK}}{1000}\right]\left(\frac{L_p'}{L_p}\right)^2 \frac{dB}{dt} f$$

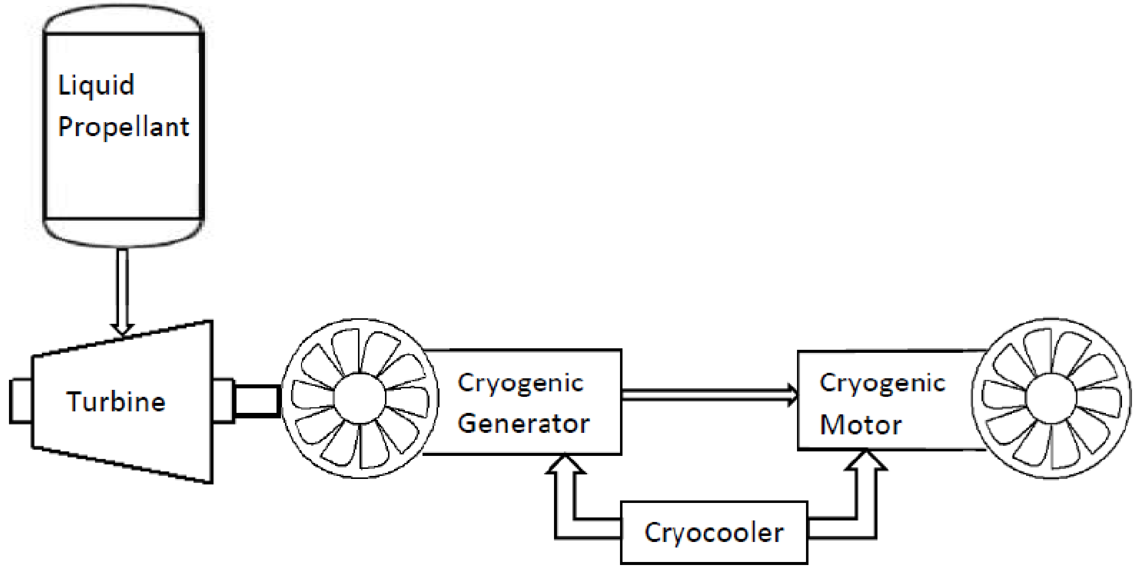
$$P_{hys} = \left[\frac{P_{hysK}}{1000}\right] f \left(\frac{B_0'}{B_0}\right) \frac{\langle J\rangle_{B_0'}}{\langle J\rangle_{B_0}}$$

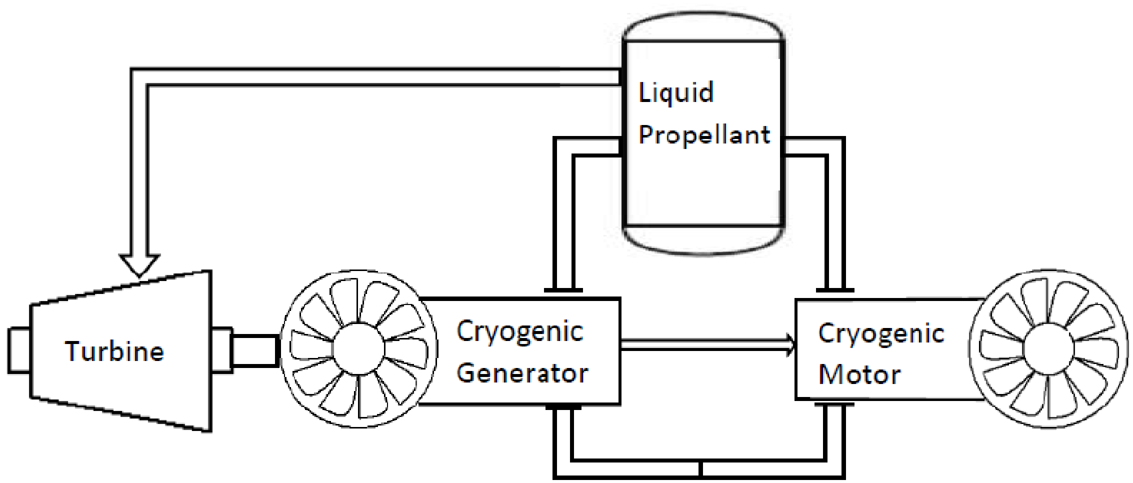


Transport loss, Rotating fields, Interaction effects

- We have not included transport loss --- because the strands are non-magnetic, transport losses are relatively low compared to the other components
- Less than 0.7 W/cm^3 for all strands at 200 Hz as long as I_{op}/I_c is 50% or less.
- The interaction term, ignored above, tends to suppress the transport loss, so this addition is expected to be lower than the 0.7 W/cm^3
- A more significant addition is the modification for a rotating aspect to the fields.
- The values given above assume magnetic fields along a direction perpendicular to the wire axis, and varying sinusoidally with time.
- On the other hand, if the strand is exposed to a field which instead rotates around the wire axis of symmetry, then as might be present in a motor or generator, the loss is given by
    - $Q_{rot} = \frac{\pi}{2} Q_{time\ varying} = \frac{4}{3} B_0 J_c d$
- If it was purely rotating, amounting to a roughly 57% loss increase. For a mixed case, the enhancement would lie between 0 and 57%

Two cases – cryocooler or heat rejection to fuel





Case I: No free lunch (cooling)

Unjustified here, I present the results of an analysis which estimates total machine reduction including cryocooler for a superconductor.

$$\Theta = \frac{\left[Y\left(1-\Gamma+\Gamma\left(\frac{J_{cu}}{J_{cc}}\right)\right)+\Lambda_v P_v \Gamma\left(\frac{J_{cu}}{J_{cc}}\right)Y\right]}{Y} = 1-\Gamma\left[1-\frac{1}{\alpha}\left(1+\Lambda_v P_v\right)\right]$$

$$\frac{J_{cc}}{J_{cu}}\gamma \geq \Lambda_m \frac{P_v}{D_{cc}} = \Lambda_m \frac{\psi(8/3\pi)B_m J_c d_f f}{D_{cc}}$$

The criterion that emerges is only a limit on filament size

$$d_f f \leq 0.844 \frac{D_{cc}}{J_{Cu} B_m}$$

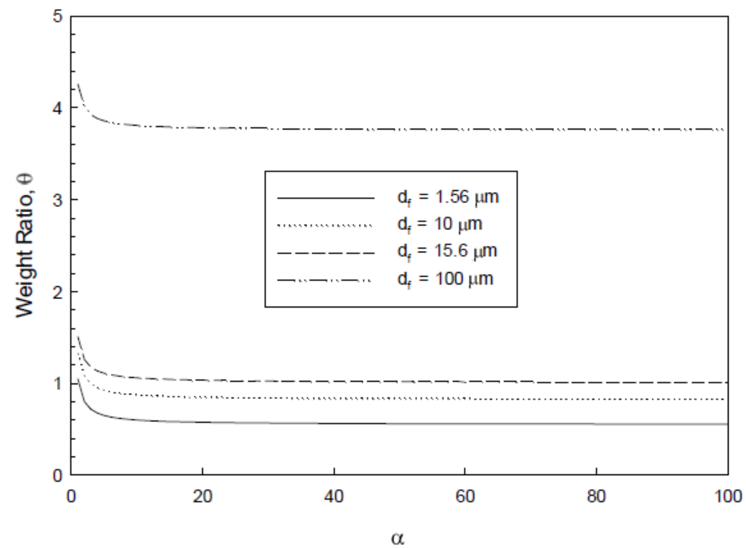


Figure 3. Weight ratio as a function of α for various values of d_f. Here $\psi = 1$ and $f = 150$ Hz. System temperature is embedded in the value of α.

1 W/cm3 gives breakeven, 10 X less gives large fraction of total effect – in between is regime of interest

Case II: Let's reject heat to the fuel!

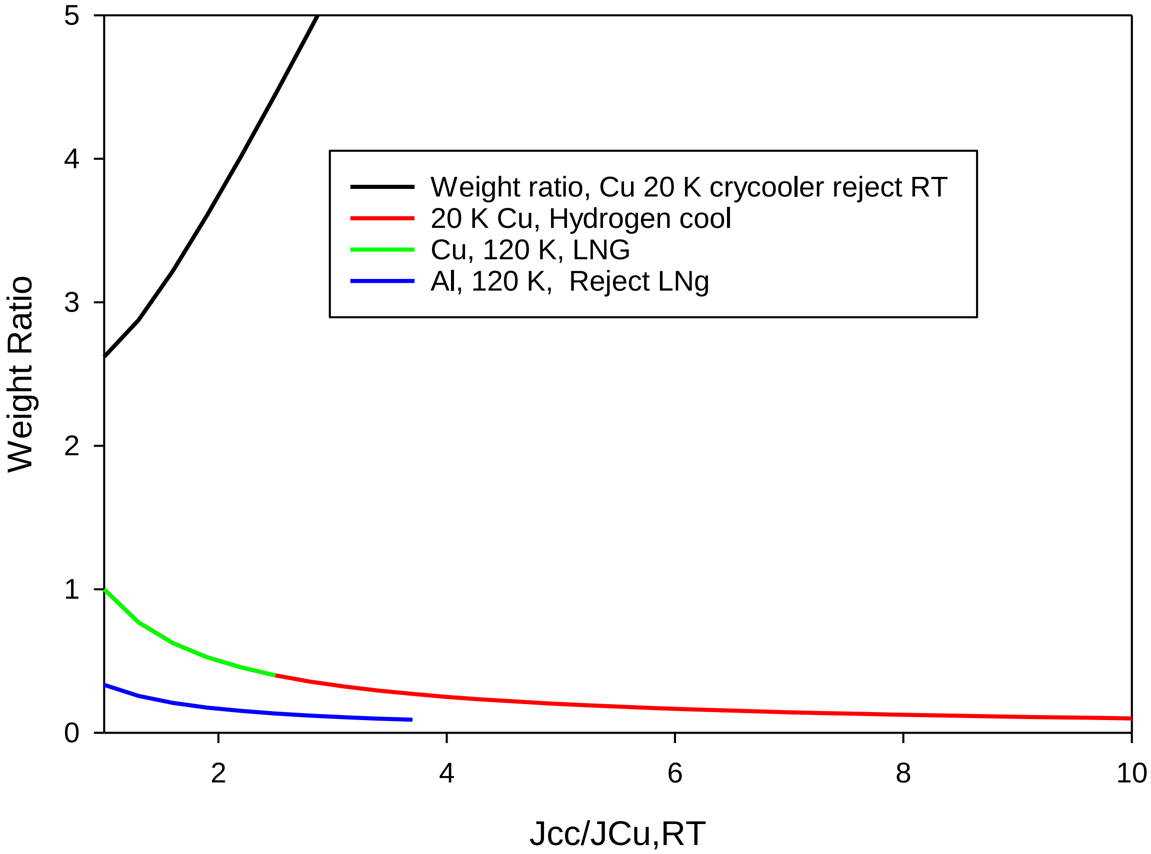
α = winding volume reduction

For rejection to fuel, much higher volume/Weight reduction

Also, cryogenic Cu and Al fare well!

	Cu	Al or HyperC	CNT		MgB_2	YBCO
RT, motor/generator winding DC						
J_{RT}, A/cm^2	800	632	243		--	--
α (J_X/J_{CuRT})	1	0.79	0.30		--	--
P_{RT}, W/cm^3	1.12	1.12	1.12		--	--
Fixed ΔT, direct liquid cryogen contact, 77 K DC[1]					***AC, B_m = 0.4 T/150 Hz***	
J_{cc}, A/cm^2	*[7390]*	*[5840]*	*[850]*		--	100,000
α (J_X/J_{CuRT})	*[9.24]*	*[7.3]*	*[1.06]*		--	125
P_{cc}, W/cm^3	*[13.7]*	*[13.7]*	*[13.7]*	d_f limit, µm	--	*[220]*
Fixed ΔT, direct liquid cryogen contact, 20 K[4] DC[1]					***AC, B_m = 0.4 T/150 Hz***	
J_{cc}, A/cm^2	*[164,000]*	*[274,000]*	*[4980]*		99,000	500,000
α (J_X/J_{CuRT})	*[205]*	*[343]*	*[6.22]*		124	625
P_{cc}, W/cm^3	*[468]*	*[468]*	*[468]*	d_f limit, µm	*[none]*	*[none]*
Fixed ΔT, Composite winding conduction, 77 K DC[2]					***AC, B_m = 0.4 T/150 Hz***	
J_{cc}, A/cm^2	5660	4480	650		--	100,000
α (J_X/J_{CuRT})	7.08	5.60	0.82		--	125
P_{cc}, W/cm^3	8	8	8		--	--
Fixed ΔT, Composite winding conduction, 20 K DC[2]					***AC, B_m = 0.4 T/150 Hz***	
J_{cc}, A/cm^2	11700	19600	356		99,000	500,000
α (J_X/J_{CuRT})	7.33	24.5	0.22		124	625
P_{cc}, W/cm^3	2.4	2.4	2.4	d_f limit, µm	21	--
Fixed Energy loss, 77 K DC					***AC, B_m = 0.4 T/150 Hz***	
J_{cc}, A/cm^2	2120	1680	243		--	100,000
α (J_X/J_{CuRT})	2.65	2.1	0.3		--	125
P_{cc}, W/cm^3	1.12	1.12	1.12	d_f limit, µm	--	18
Fixed Energy loss, 20 K DC					***AC, B_m = 0.4 T/150 Hz***	
J_{cc}, A/cm^2	8000	13,400	243		99,000	500,000
α (J_X/J_{CuRT})	10	16.8	0.3		124	625
P_{cc}, W/cm^3	1.12	1.12	1.12	d_f limit, µm	10	*[3.6]*

What about cryogenic Normal Conductors?



It seems that Aluminum, because of its lightness and also if used as a hyperconductor, can really have an excellent result – cryogenic but not SC engines

Discussion

- MgB_2 wire: the 0.32 mm OD wire has a small filament diameter which reduces hysteretic losses and a small L_p which reduces coupling losses
- The smaller OD also reduces both normal metal eddy currents and transport losses
- At 200 Hz, the total losses are 5.8 W/cm^3 and 1.5 W/cm^3 for the 0.85 and 0.32 mm OD wires respectively
- The YBCO results at the same 200 Hz were 180 W/cm^3, 16 W/cm^3, and 1.6 W/cm^3 for monofilament, 10 stripe filament, and 100 stripe filament, respectively
- Presently, only unstriated YBCO is commercially available, but work is ongoing for striated YBCO conductors
- Based on presently available conductors, MgB_2 losses can be significantly smaller than those of YBCO in external field conditions (about 100 X). However, the YBCO current density is higher, and if filament striation at the 100 filament level becomes available, they will be quite competitive
- Cryogenic normal state conductors worth re-thinking

So, what's a good metric for SC intended for Aircraft motor/generators?

Case I: No free cooling – include the cryocooler – Propose d_f/T_{op}) *as a metric (minimize this)*

Here we remember that the break even is

$$2x10^5 \ \frac{d_f f}{T_{op}} = 1$$

Case II: Free Cooling – remove heat by fuel cooling – Proposed J/J_{cu} at a fixed loss value, e.g. 1 W/cm^3. In that case we can find

J/J_{cu} = 125 for MgB2

Must reduce YBCO filament diameter or use a different loss baseline to get it's value

Summary Results

1. **Superconducting windings are enabling for high power density motors and generators for aircraft use**
2. **It is shown that present day MgB_2 conductors with filament counts of 114 and wire in the 0.85 to 0.32 mm OD range could be in the 1-5 W/cm^3 range for f = 150-200 Hz.**
3. **Such conductors could be of interest for liquid hydrogen cooled machines -- Lower frequencies could allow windings to be conduction cooled**
4. **Present day MgB_2 conductors are usable for motors and generators**
5. **Filament numbers of 10-100 in a 2 mm wide YBCO tape will make coated conductors a viable candidates**
6. **Loss values of about 1 W/cm^3 can lead to systems with overall weight reductions, even including cryocooler weight**
7. **IF we can reject heat to fuel, as some conventional systems do, the heat rejection can be kept reasonable, and J_c/J_{cu} ratios can reach 100, allowing a significant size/weight reduction**
8. **Cryogenic normal state conductors, particularly Al and hyperconducting Al worth re-thinking**