Contact Resistance and AC Loss for Coated Conductor Roebel Cables and CORC cables for HEP Applications

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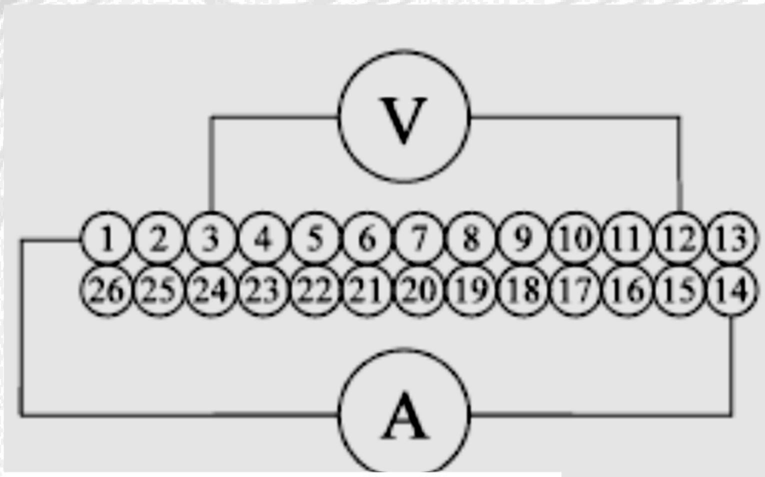
YBCO Cables in HEP Context

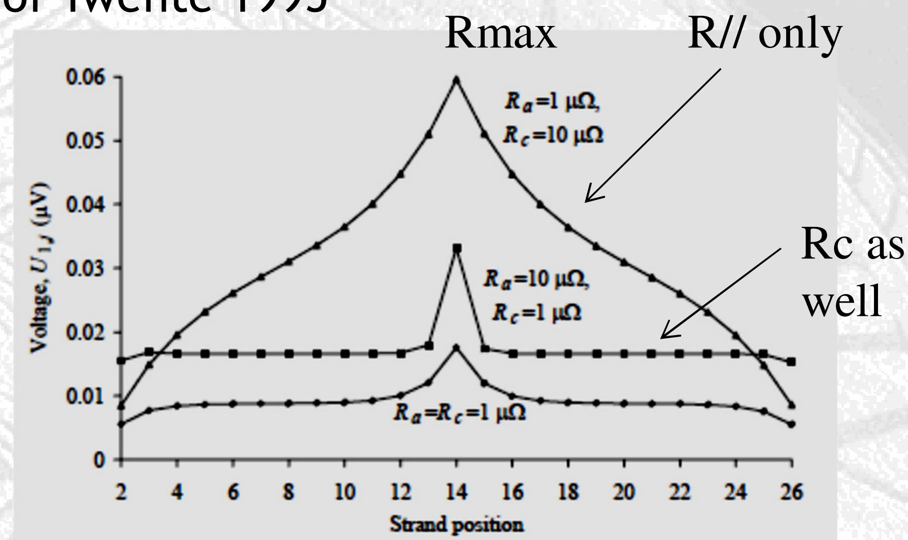
- It is useful to consider YBCO for HEP magnets for very high field devices – high field solenoids for muon colliders. Worth considering for other HEP magnets (very high field dipoles) as well
- Large magnets need cables, typically tens of kAs
- Cables need current sharing between the strands for stability and protection reasons in LTS, as well as current distribution uniformity considerations
- Strand to strand contacts must be low resistance enough to allow this, but high enough to keep low loss

Direct Contact Method for ICR

We can adopt the direct I-V technique used by Arian Verweij in his measurement of ICR in Rutherford cables, see “Electrodynamics of Superconducting cables in Accelerator Magnets, Thesis, University of Twente 1995

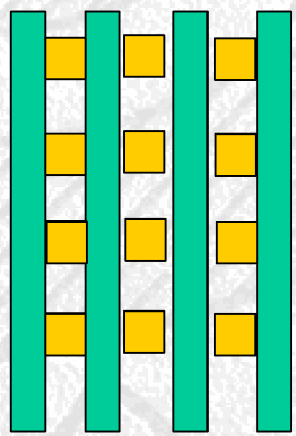


$$U_{ee} = \frac{L_{p,s} R_a}{2 l_{cab} \sqrt{N_s}} I \quad [V] \quad \text{for } R_a << R_c$$



Our case corresponds to his Eq 4.46 b, except that the Ra used there is slightly different, and given that our cable length is equal to Lp, we get

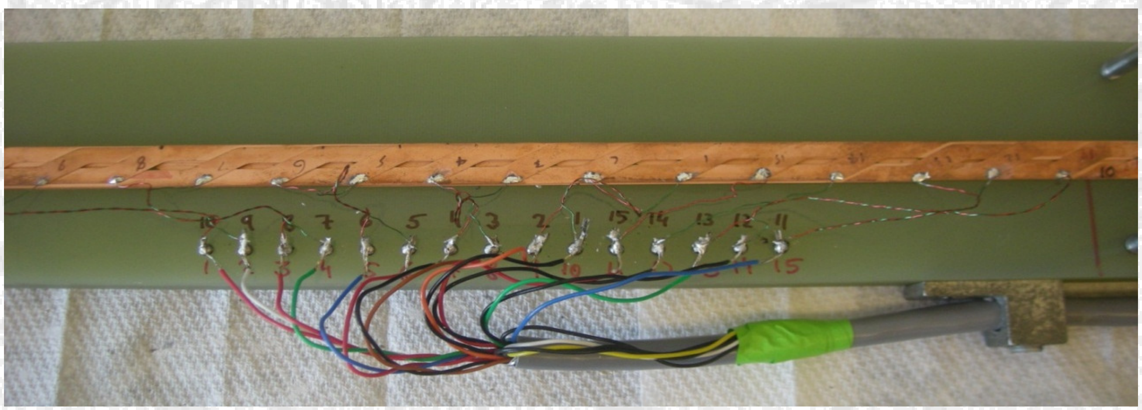
Ra = 2Rmax



Another way to see this is that we have N resistors in parallel, and N/2 series segments of these

Wiring of the cable

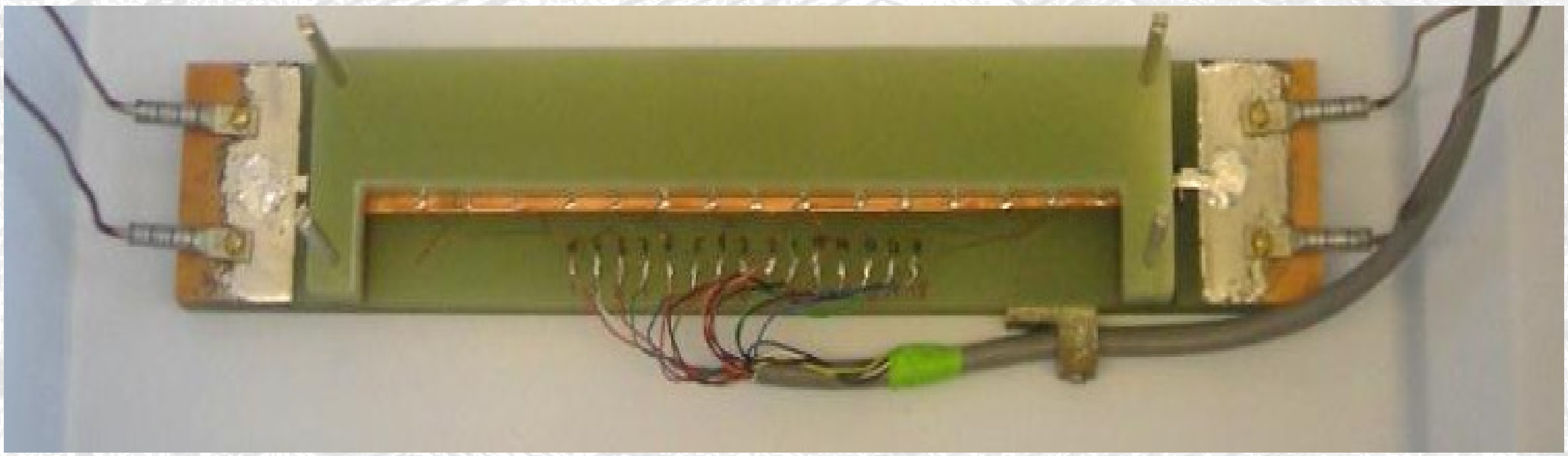
- Number of tapes: 15
- Current contact on one end of the cable – tape no. 2
- Current contact on the other end of the cable – tape no. 10
- DC power supply: HP6634 A (1 A – 100 V)
- Voltmeter: Keithley 2182A nanovoltmeter
- Pairs of the potential taps used for voltage measurements: 1-2, 1-3, 1-4, …. 1-15



Cable Provided by Industrial Research Limited, IRL

Pressure application

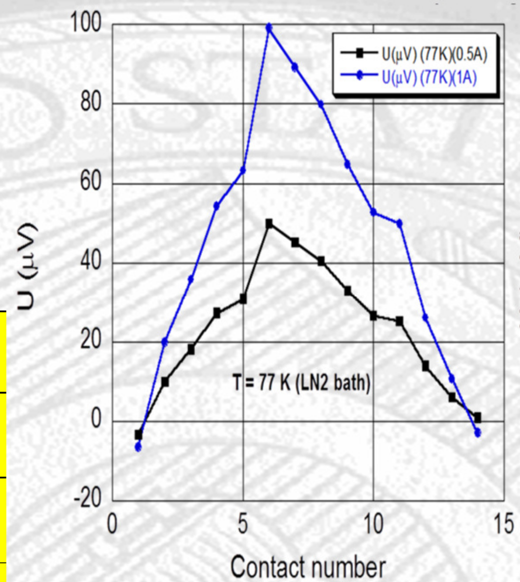
Pressure was applied by adding stainless steel plates on top of the G-10 top plate, both were free to move up and down but stabilized laterally by guide rods

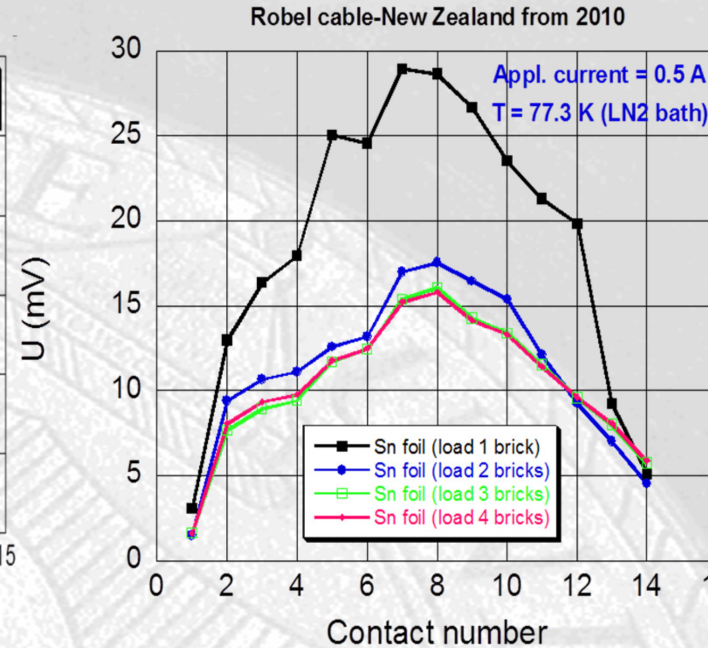


Direct I-V ICR Results

METHOD 2 (soft Metal)
METHOD 3 (Solder)

Condition	Rmax
77 K, zero Pressure	450 mΩ
77 K, 95 kPA	140 mΩ
77 K, Sn layer, no pressure	60 mΩ
77 K, Sn layer, 95 kPA	32 mΩ
solder	100 μΩ





Resistance of Solder contacts

$R = \rho L/A = 15\ \mu\Omega cm*10*10^{-4} cm/1cm^2 = 15\ n\Omega$

Resistance of 0.1 mm thick Cu strip (1cm sq)

$R = \rho L/A = (1.6\ \mu\Omega cm/RR(T))*1\ cm/0.01cm^2 =$

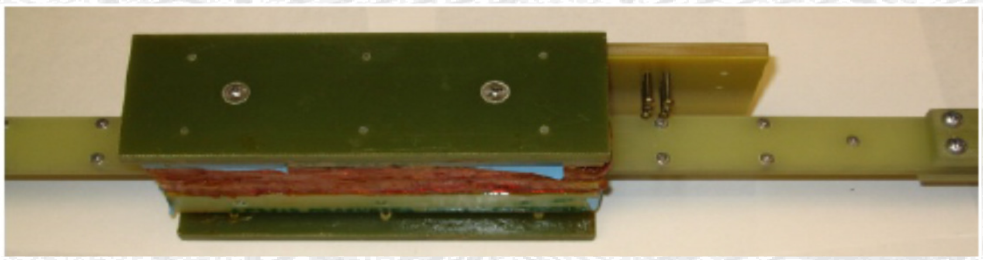
at 77 K, RR(T)=5, and R = 160 μΩ

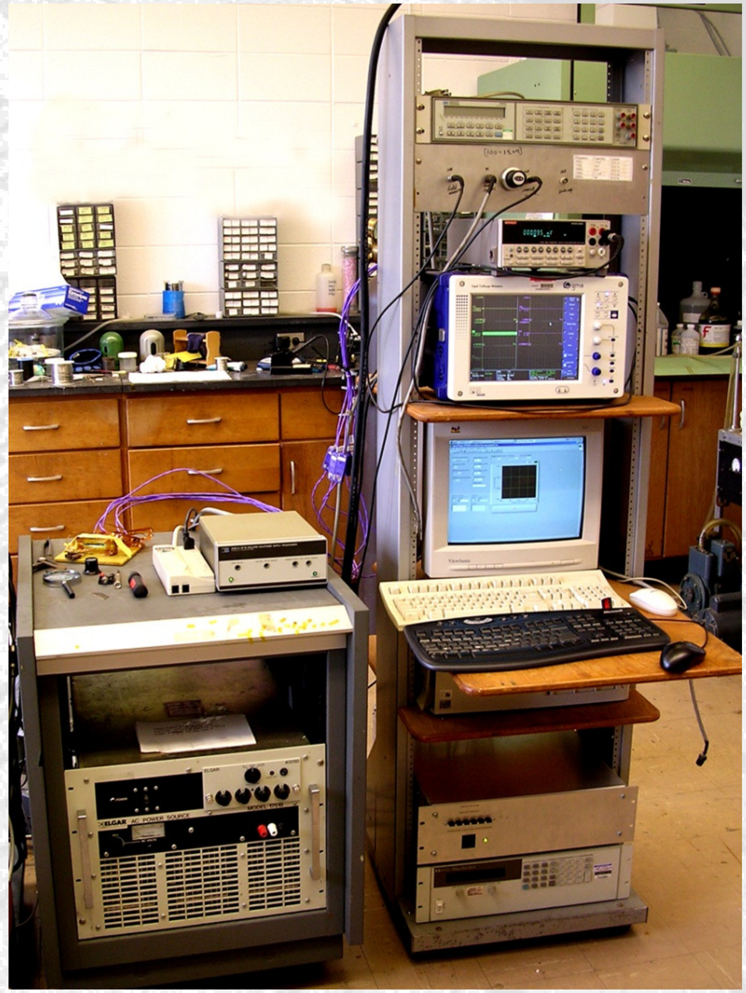
<u>Reasonable agreement with the direct ICR</u>

at 4 K, RR(T) = 100, and R = 8 μΩ

<u>Similar to what might be a target for a Rutherford accelerator strand</u>

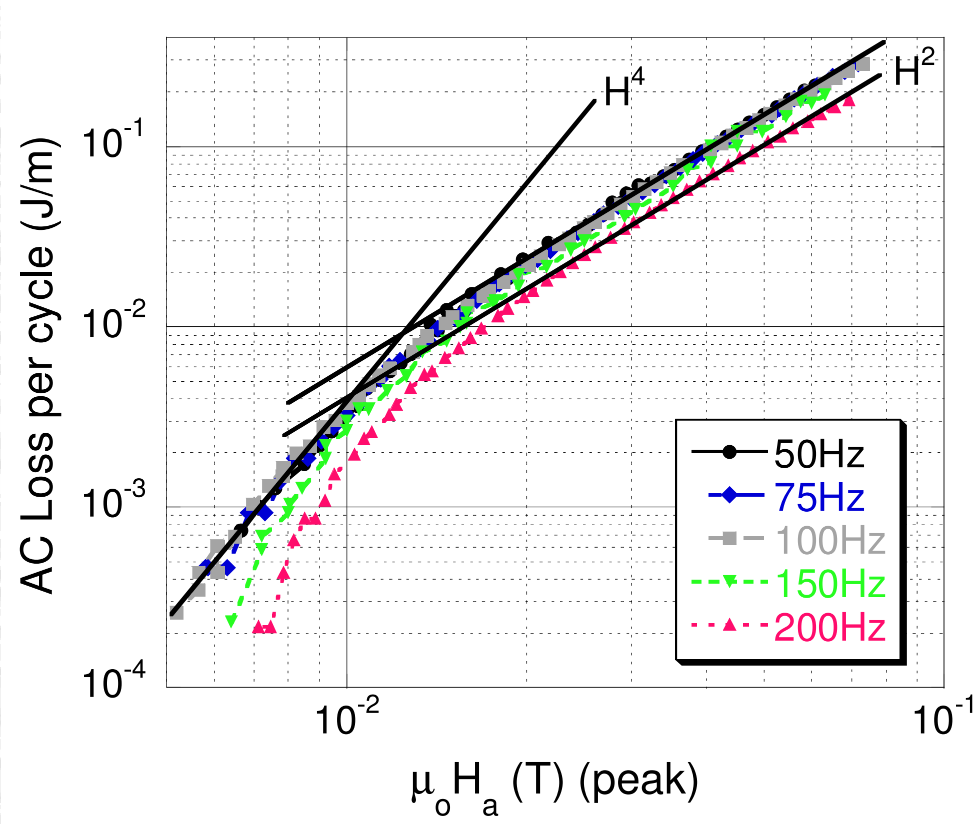
AC Loss Measurement





Roebel Cable AC Loss Measurement

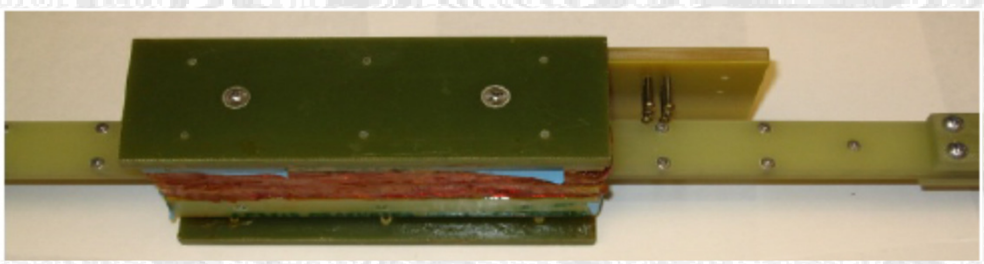
Roebel cable #2 (KIT)
width = 13 mm
thickness = 0.5 mm
twist pitch = 12.5 cm
Made of 9 tapes, each 5 mm wide
Cable Ic(77.3K, self field) = 922.5 A
Ic per tape = 92.5
Measured length of the cable = 14 cm

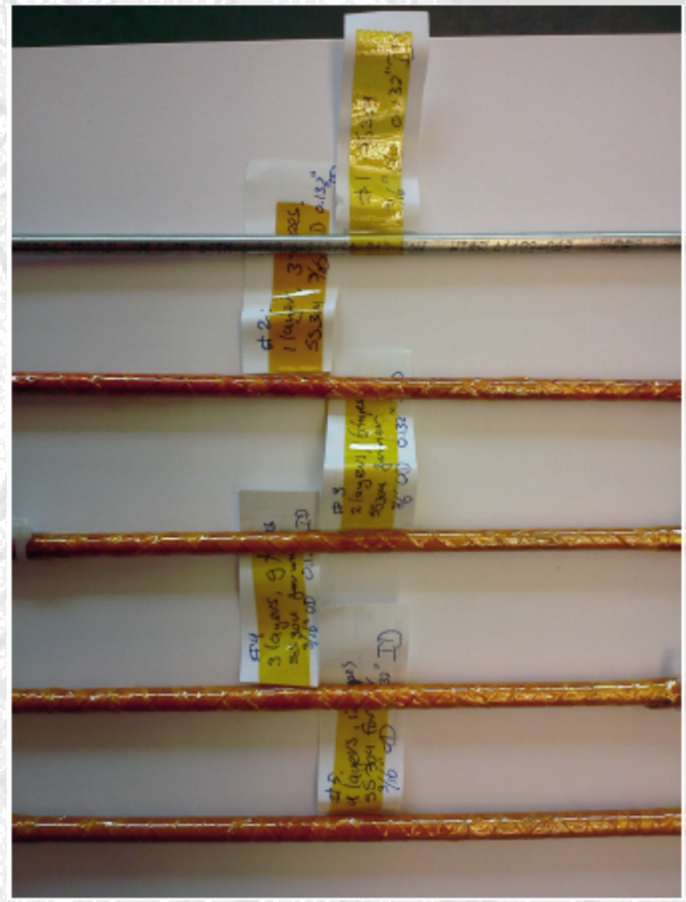


CORC Cable for AC Loss Measurement

Table 1. Samples for Ac Loss Measurements

Sample #	Number of tapes	Number of layers
1	0	0
2	3	1
3	6	2
4	9	3
5	12	4





CORC samples

- Samples had a stainless steel SS304 former with an outer diameter of 3/16” and a wall thickness of 0.032”.
- Each sample was about 20 cm in length and consisted of a different number of superconducting tapes in up to 4 layers.
- Tapes 4 mm wide, 77 K self field = 100 A

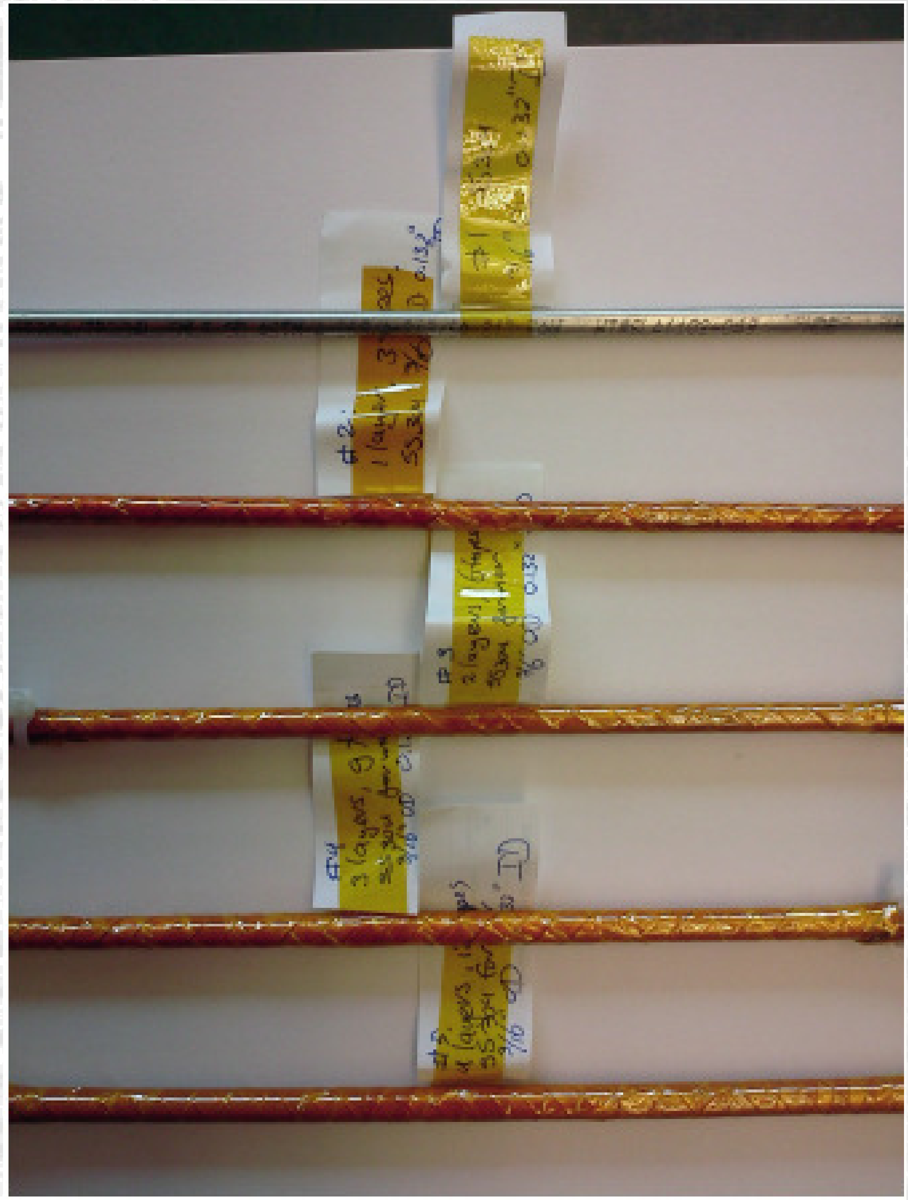


Table 1. Samples for Ac Loss Measurements

Sample #	Number of tapes	Number of layers
1	0	0
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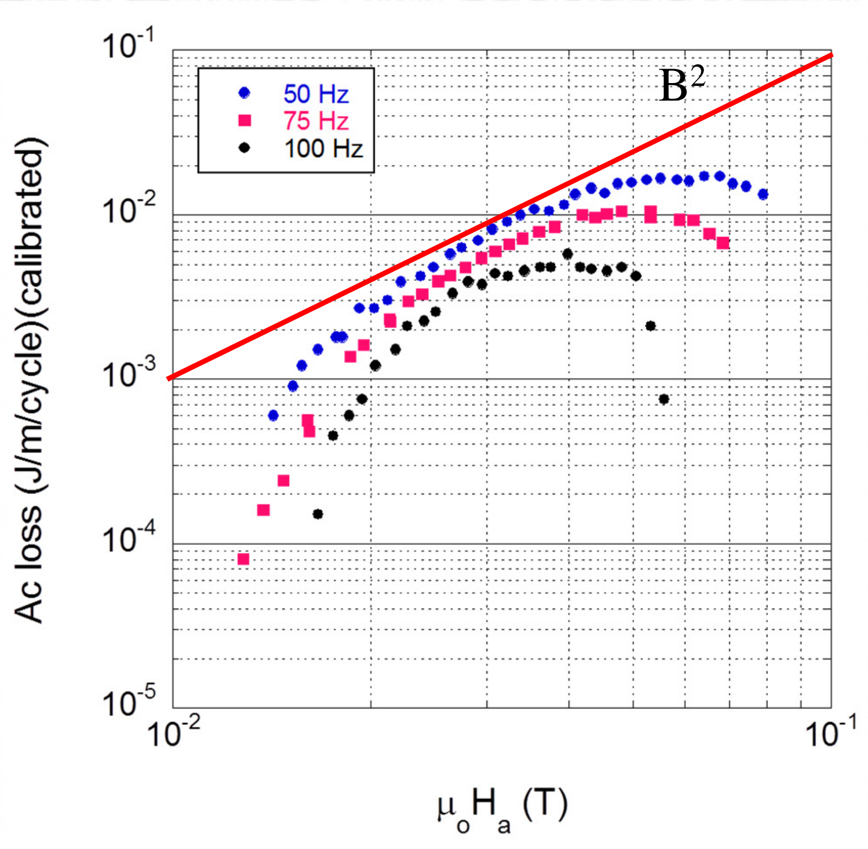
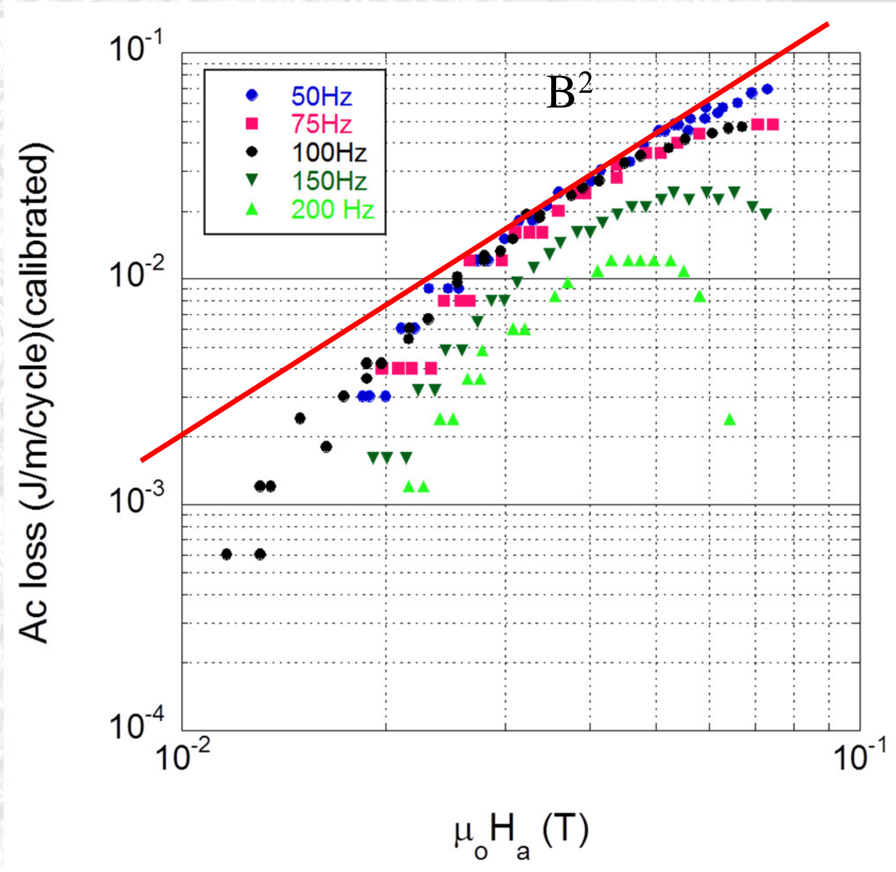
3	6	2
4	9	3
5	12	4

Loss per meter of cable per cycle CORC cable

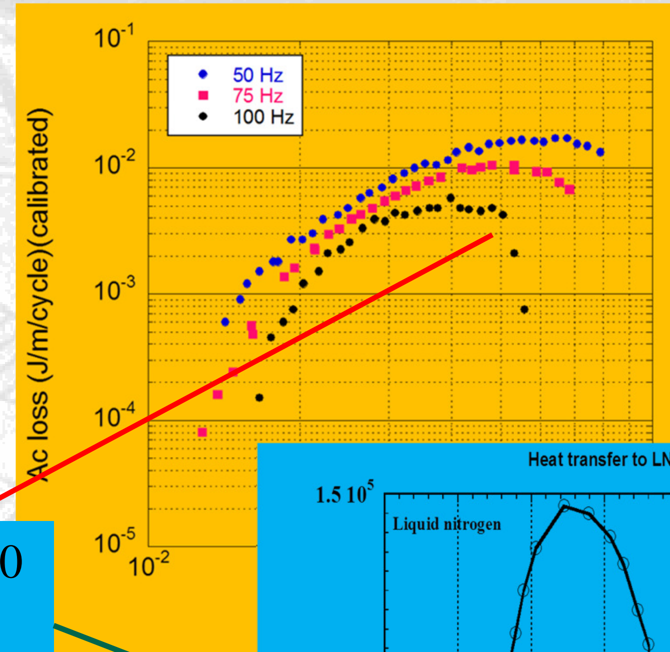
1 layer, 3 tapes

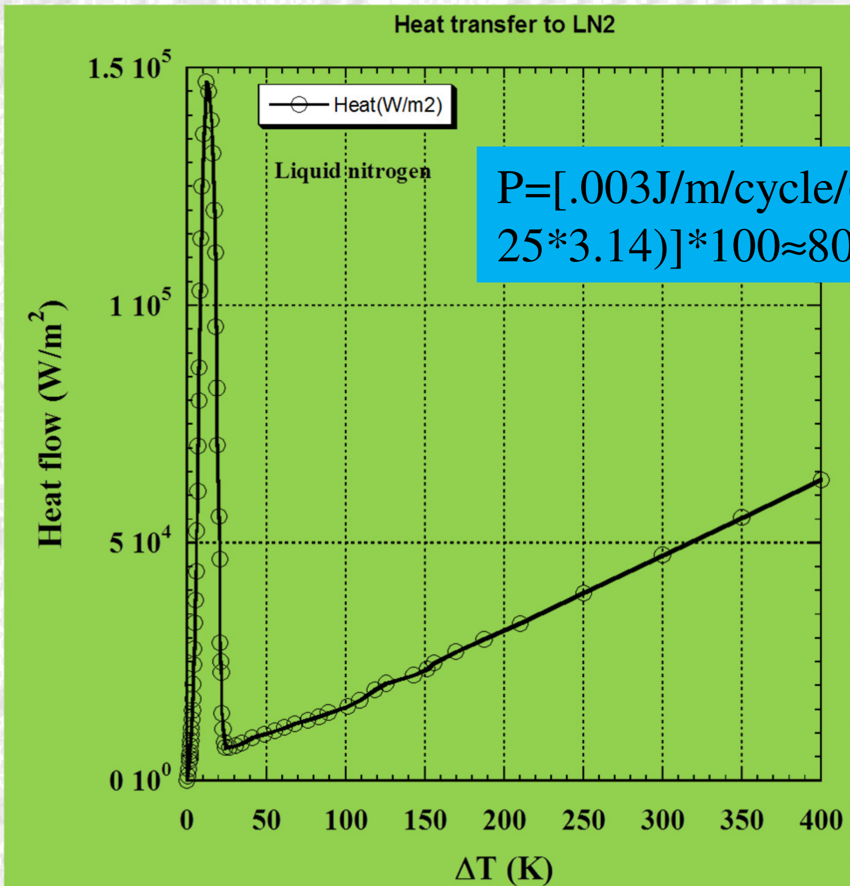


2 layer, 6 tapes

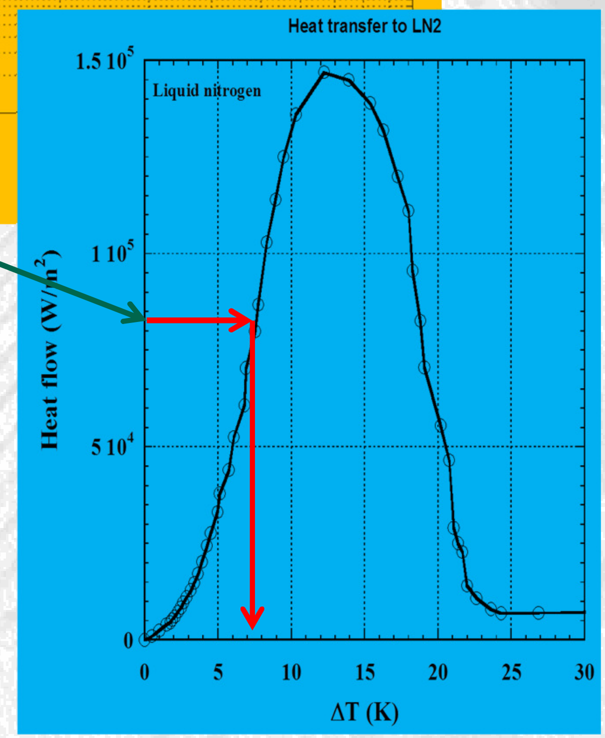


Influence of Heating



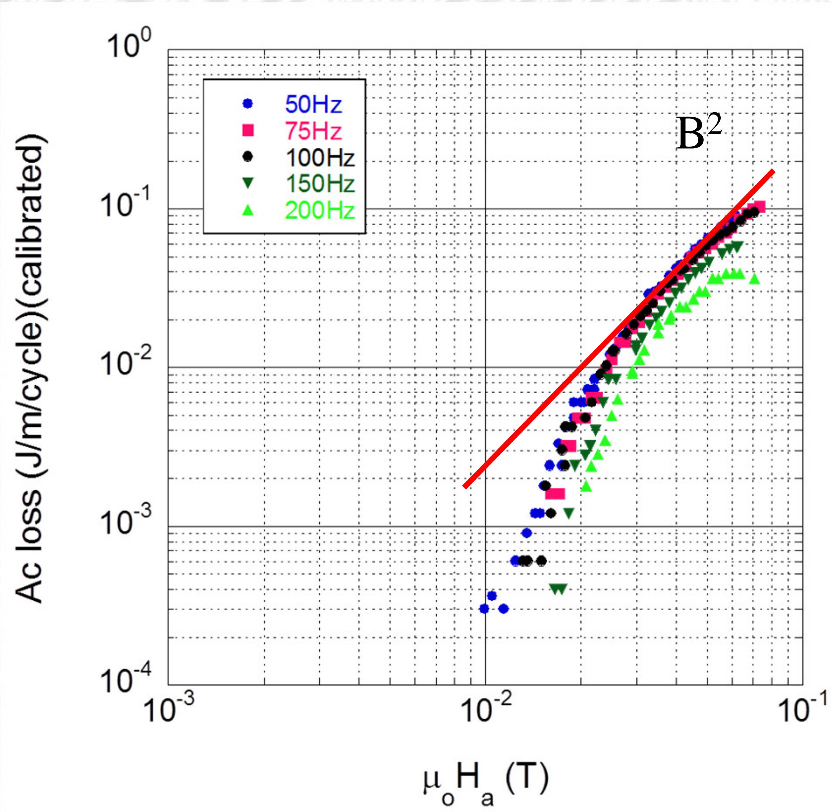


P=[.003J/m/cycle/(.2*.025*.025*3.14)]*100≈8000 W/m2

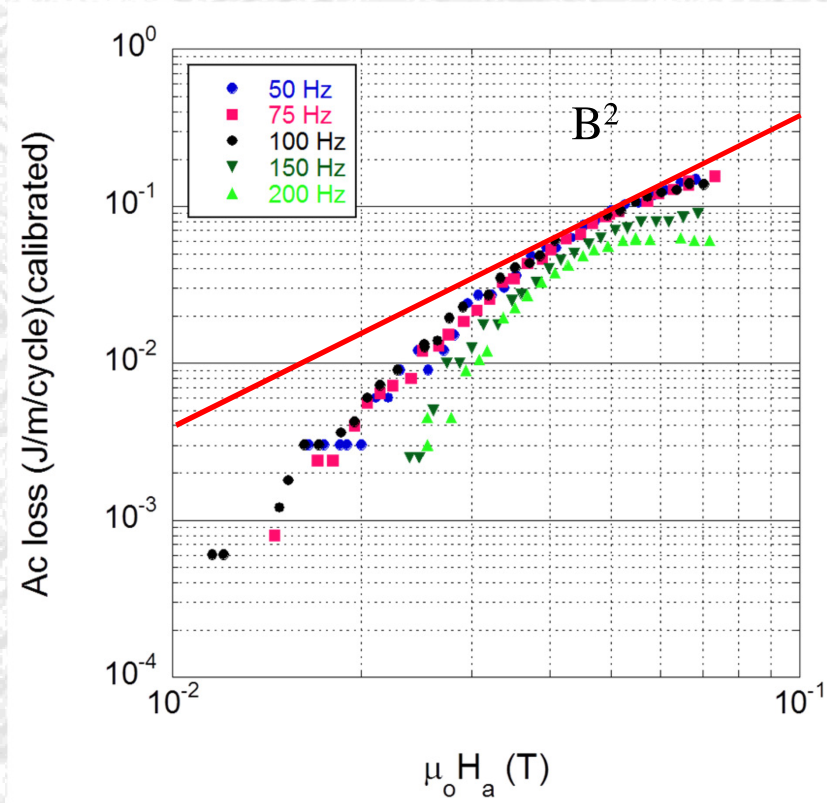


Loss per meter of cable per cycle CORC cable II

3 layer, 9 tapes

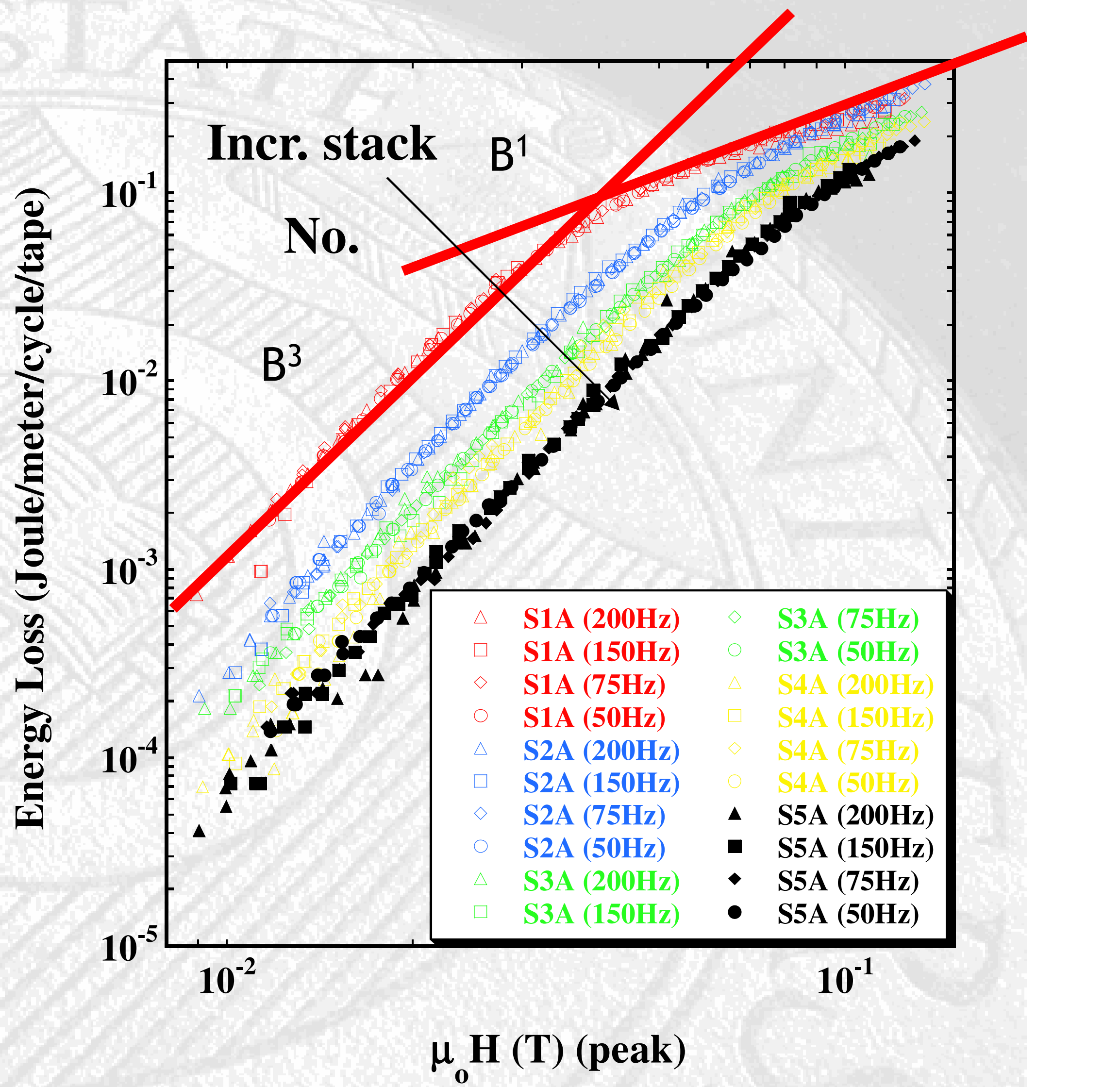


4 layer, 12 tapes



B^2 dependence?

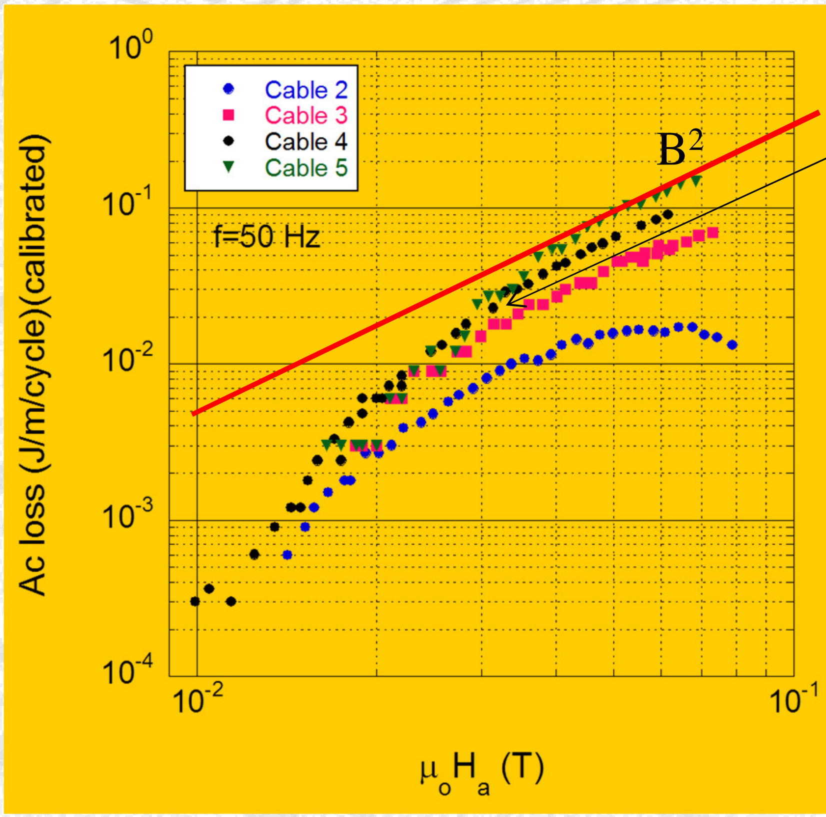
Increasing stack number causes a shift out in the penetration field, and causes apparent slope changes at lower excitation amplitudes



Comparison of CORC and Roebel

Table 1. Samples for Ac Loss Measurements

Sample #	Number of tapes	Number of layers
1	0	0
2	3	1
3	6	2
4	9	3
5	12	4



Cable	Number of Tapes	Loss per m cable, 40 mT, J/m	Loss per meter of Tape, 40 mT, J/m
Roebel	9	0.1	1.1×10^{-2}
CORC-1	3	10^{-2}	3.3×10^{-3}
CORC-2	6	3×10^{-2}	5×10^{-3}
CORC-3	9	4.5×10^{-2}	5×10^{-3}
CORC-4	12	6×10^{-2}	5×10^{-2}

4/5 correction + 0.63 (average of cosine) leads to agreement at 5 x 10-2 J/m

AC Loss Results ∝ magnetization

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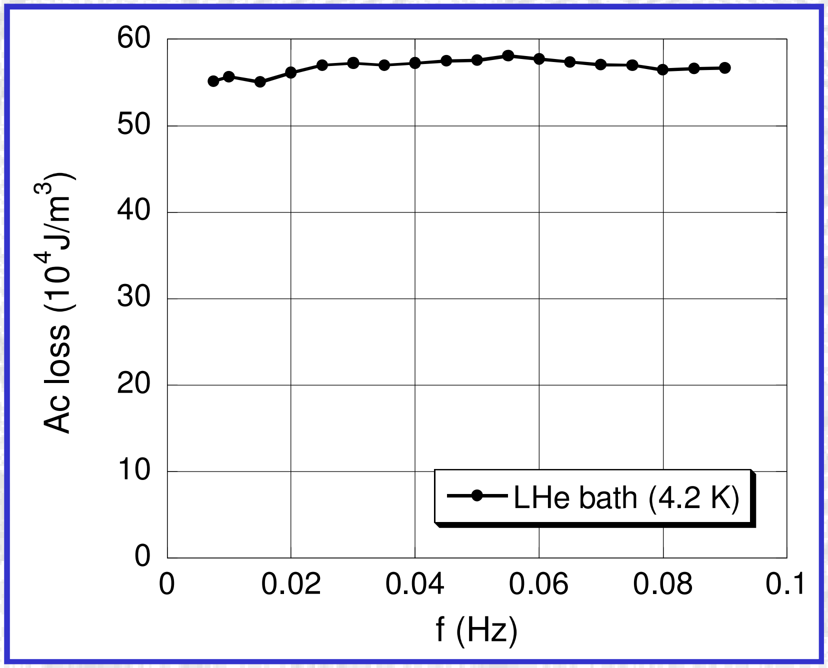
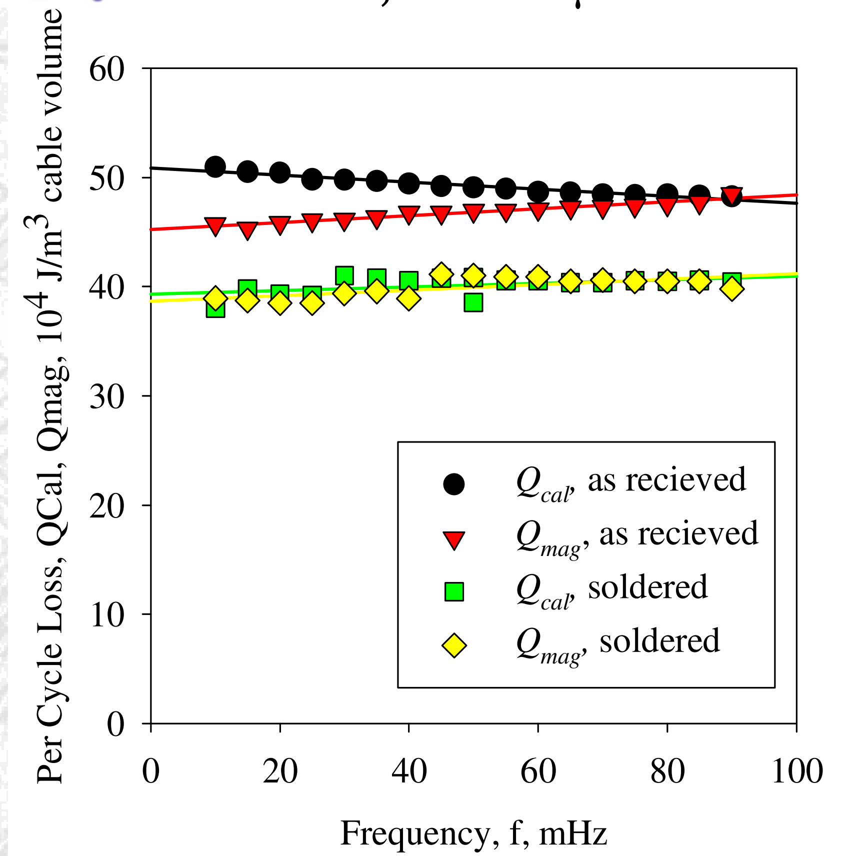
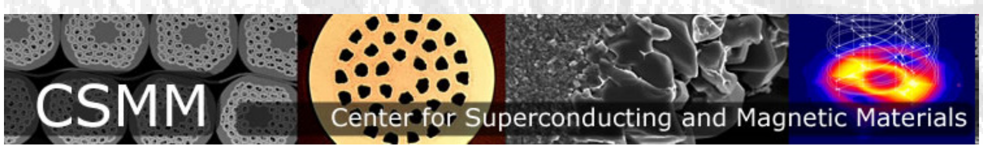
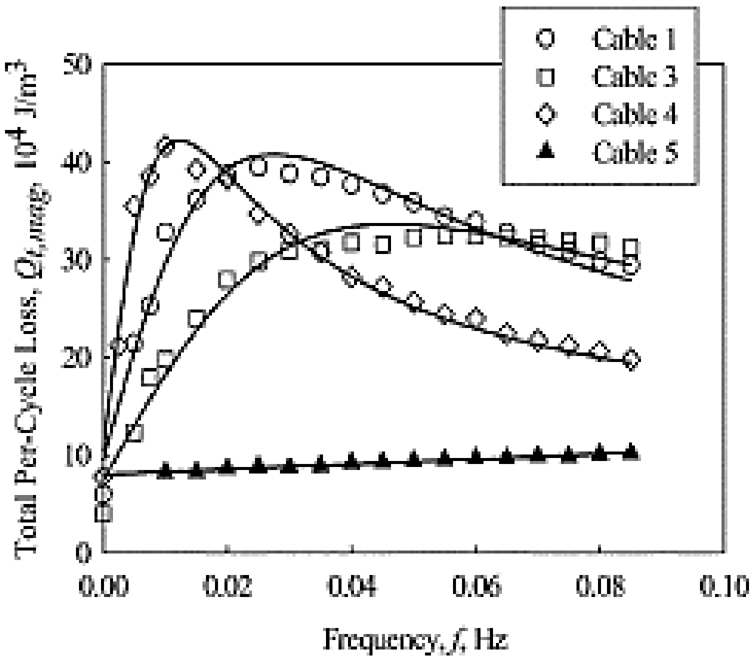


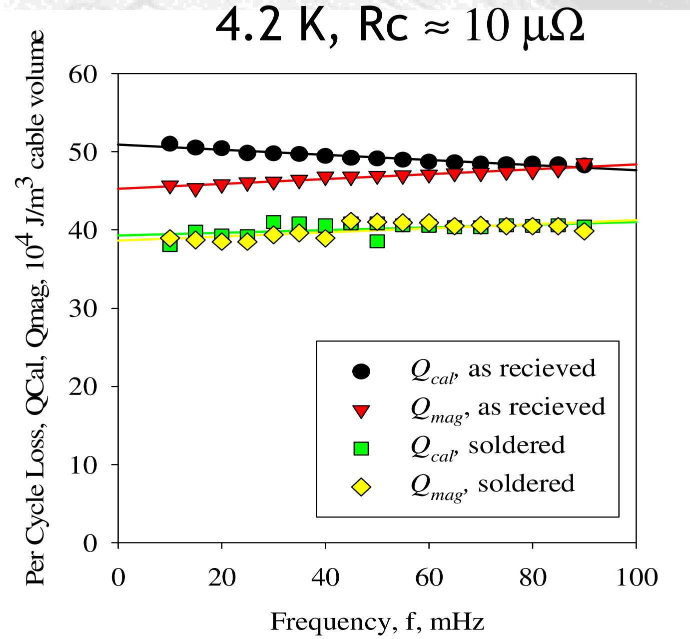
4.2 K, Rc ≈ 10 μΩ





Direct Nb_3Sn to YCBO Roebel Cable Comparison at 4.2K



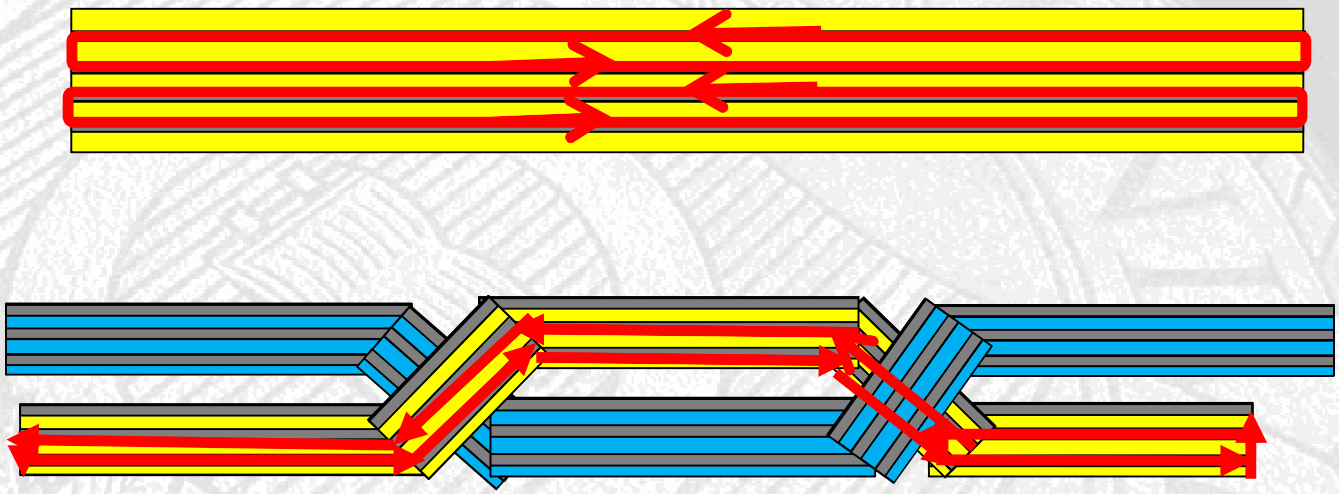


Assume 15 kA at operation for Nb-Sn, For YBCO about 1 kA at 20 T/4 K

So YBCO cable Magnetization normalized to performance about 4 * 15 =60 times worse -

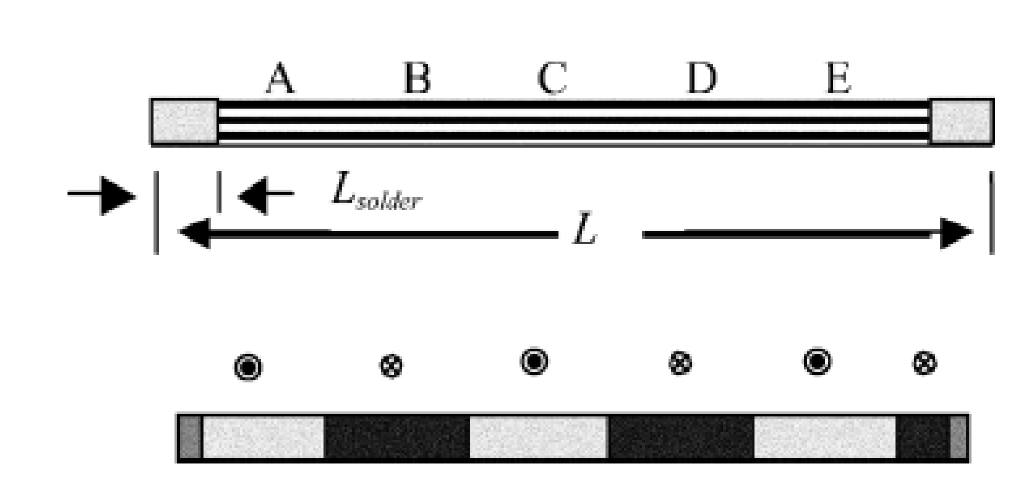
For NbSn, d_{eff} =60 μm, for Roebel, d_{eff} = 5 mm, ratio ≈ 100

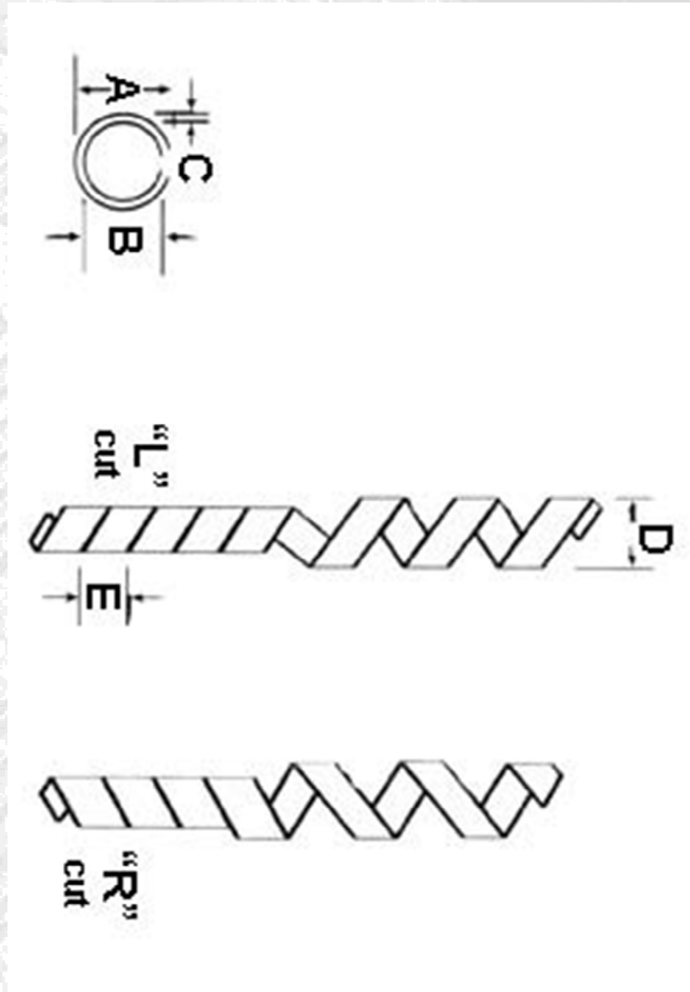
A low Magnetization YBCO Cable I ?



- Filamenting (striation) needed
- Transposition as well
- Does the Roebel cable transpose?
- No

CORC cable?





The helical wind introduces transposition

So– what's required for reaching acceptable magnetization?

100 filaments!

Summary and Conclusions

- Pressure and pressure with soft metal reduce ICR, but do not give great contact. Soldering reduces ICR, but does not induce much loss because flux coupling area is small
- Losses in Roebel and CORC cables are similar to the base strands, once the proper geometrical factors have been accounted for
- Losses (and thus magnetizations) on a rough “pound for pound basis” are about two orders of magnitude worse than Nb3Sn, as can be expected from geometric considerations
- If strands can be striated, the ability of CORC cables can be allow transposition, and possibly low losses
- 100 filaments would put YBCO on a similar magnetization level as Nb-Sn