Stability in Nb_3Sn -- Explicit Functional Dependence of J_s on d_{eff} and RRR, Local RRR Degradation, Adiabatic considerations

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Cable Stability and RRR

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Outline

- *Reminder* – Origins of J_s (stability current), influence of d_{eff} and RRR, postulated reasons for RRR influence
- Observation of localized RRR degradation in cables
- Analytic form of J_s and functional dependence on d_{eff} and RRR
- Origins of RRR Influence (K, τ, current sharing)

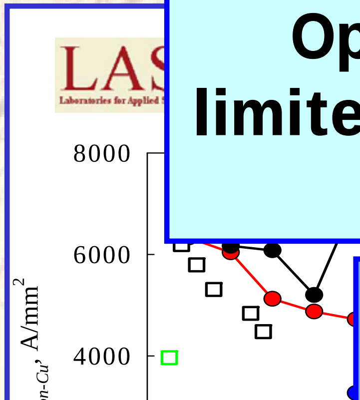
Finally, an attempt to answer the questions

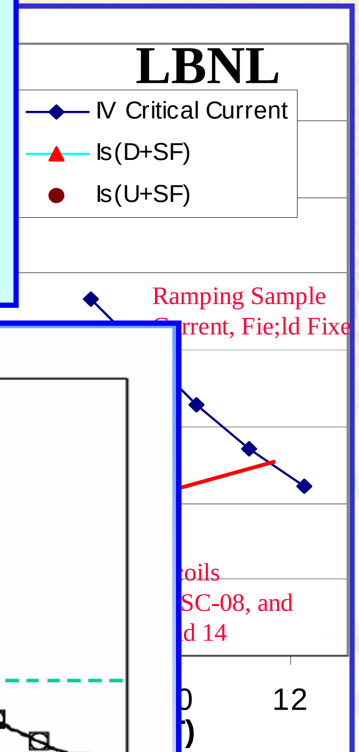
- Where (within the strand) does RRR have to be good?
- Can there be a d_{eff} small enough for full adiabatic stability for in-service strands/cables?

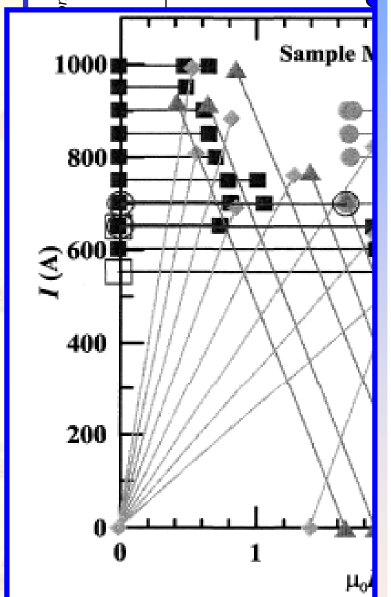
Origins of a defined J_s (Initial Observation of Problem)

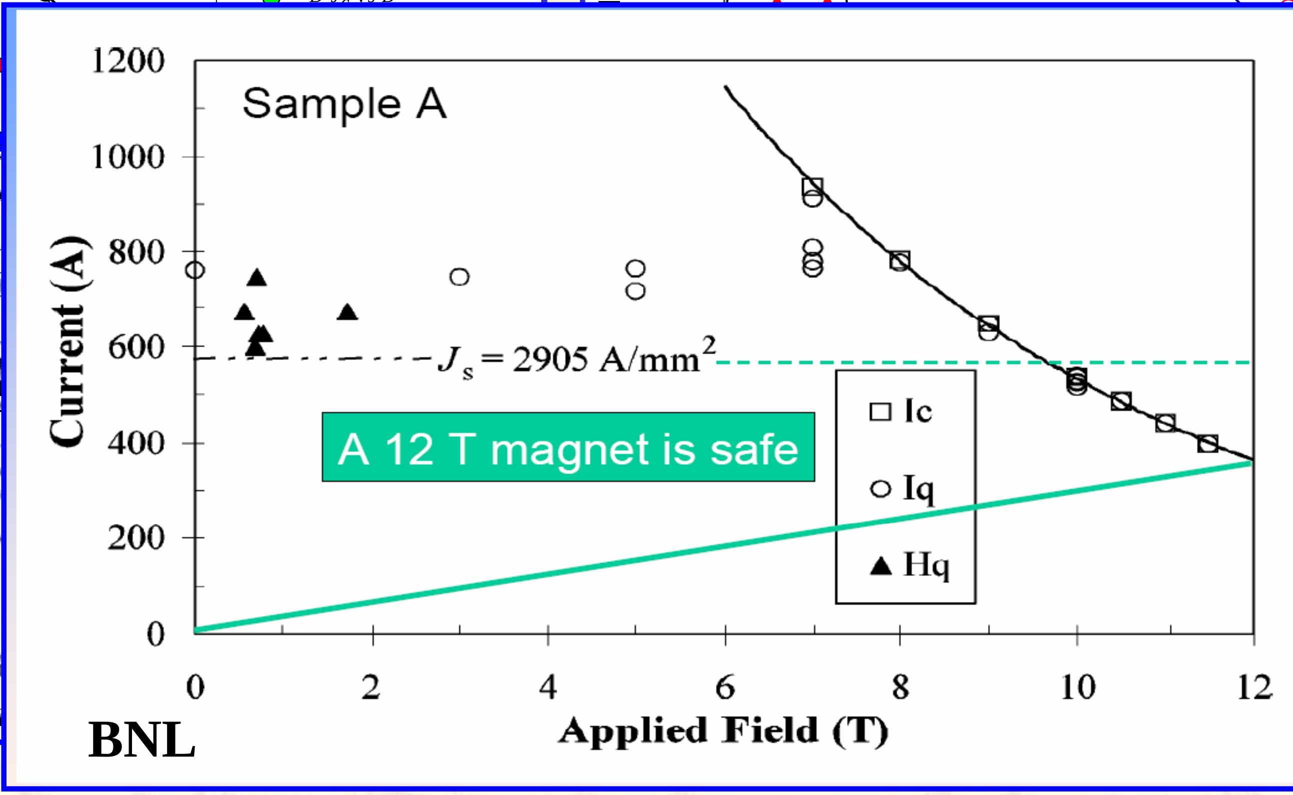
Obser

Experiments of many groups led to an Operational Definition of a stability-limited current, J_s, which was less than J_c at lower fields









Small d_{eff} improves adiabatic stability, high RRR improves dynamic stability

Questions

What is functional dependence on d_{eff}?

What is functional dependence on RRR?

What is specific origin of RRR influence?

RRR where? In the shell, near the filaments?

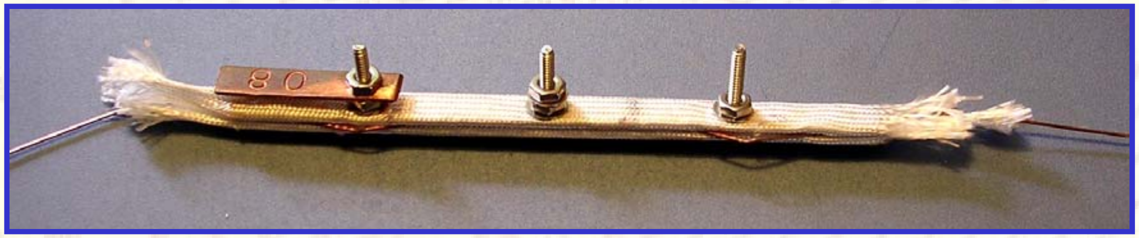
How will magnet potting influence things?

How will cabling strands affect d_{eff} and RRR?

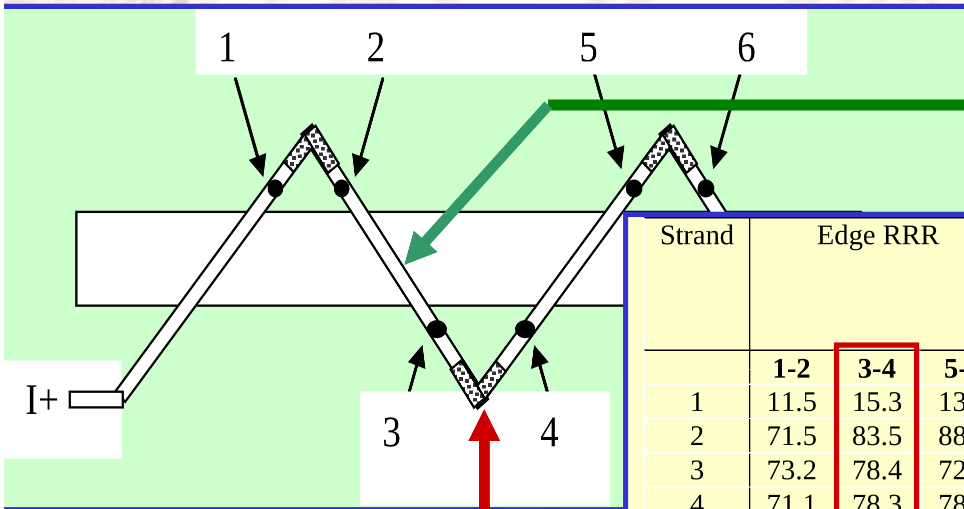
How will cabling strands affect d_{eff} and RRR?

FNAL

- **OSU/FNAL** Collaboration to Study Influence of Cabling on RRR –especially at Cable ends
- RRP strands were extracted from a set of 27- and 28- strand, mixed-strand cables with a variety of packing factors ranging from light (85% to heavier 9X%)
- Samples were HT, RRR was measured on the flats and bends



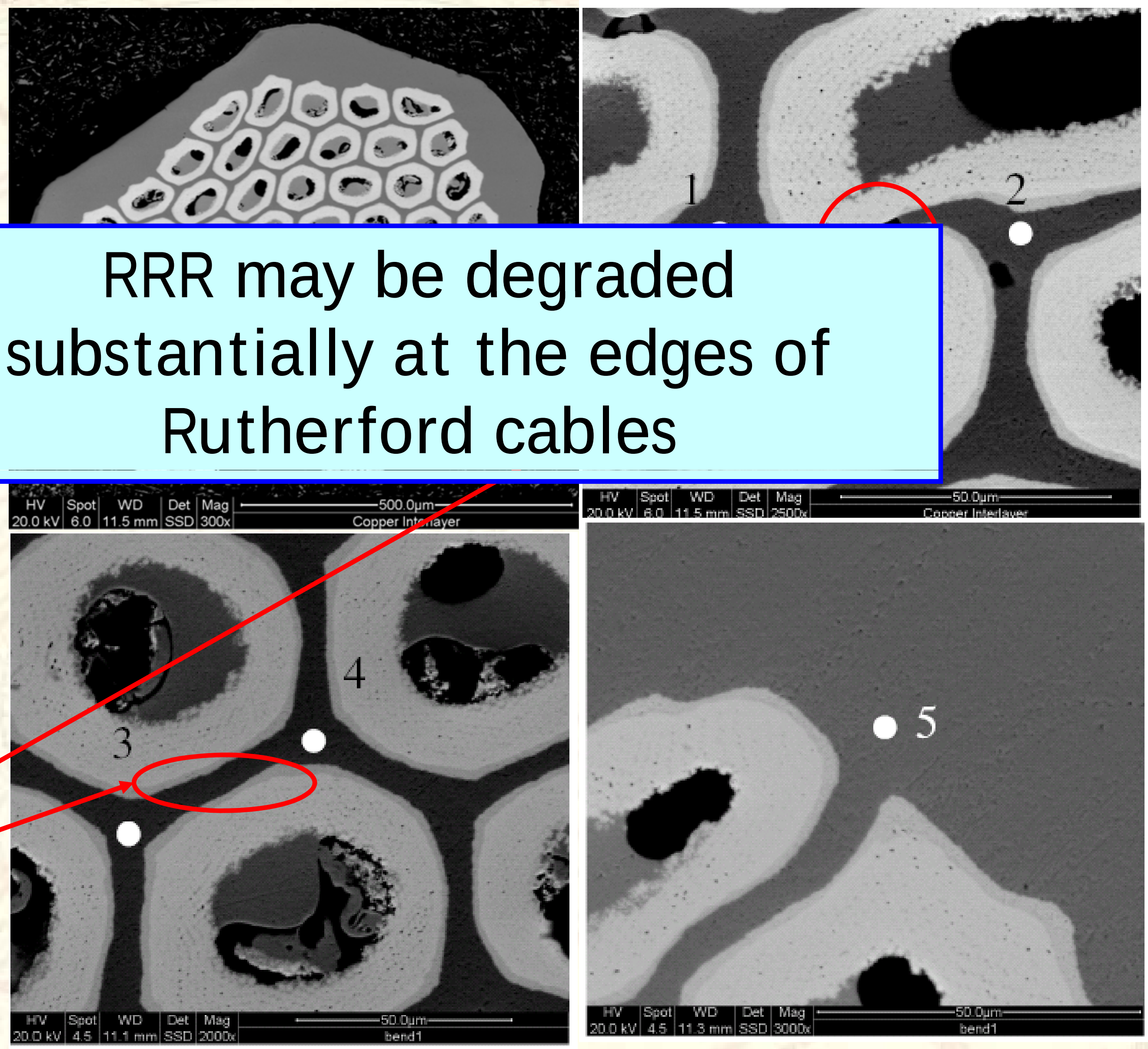
RRR Results on Cabled, Extracted, Reacted Strands



Strand	Edge RRR			Straight Seg. RRR		Whole RRR	Ave straight	Edge Contact Lengths, mm			Ave Local RRR est	Whole strand RRR Calc
	1-2	3-4	5-6	2-3	4-5	--	--	1-2	3-4	5-6	--	--
1	11.5	15.3	13.7	109	122	25.3	116	--	--	--	13.5	30.7
2	71.5	83.5	88.3	121	120	104	120	8	10	10	22.3	99.7
3	73.2	78.4	72.4	120	131	109	125	13	11	9	15.1	98.7
4	71.1	78.3	78.6	117	121	92.2	119	9	10	10	18.4	93.3
5	52.0	55.8	43.1	166	164	66.0	165	12	10	7	7.35	88.0
6	35.8	44.0	32.3	91.4	95.5	63.0	93.5	7	8	6	8.17	70.1
7	46.2	47.2	47.7	102	107	83.4	104	11	11	11	7.25	67.7
8	35.5	35.9	43.1	112	121	87.2	116	12	8	10	5.58	62.5
9	55.5	57.5	47.8	94.7	93.1	70.5	94.0	10	8	5	14.5	84.8
10	45.3	53.3	63.0	116	124	76.9	120	8	6	11	11.1	87.5
11	49.7	55.4	54.7	125	109	83.2	117	8	8	10	10.4	85.3
12	50.3	75.3	59.2	109	95.0	86.3	102	7	7	11	17.7	86.4
13	49.2	53.8	44.4	98.0	93.3	59.8	95.7	8	9	12	9.86	68.6
14	52.4	40.6	50.0	130	115	98.4	122	8	6	10	9.24	82.4
15	72.6	76.4	69.8	129	131	101	130	9	6	8	19.1	115
16	68.5	65.5	78.1	111	108	89.9	110	9	11	12	16.3	74.5

SEM / EDS

Location	% T
1	4.
2	3.83
3	0.45
4	0.40
5	0.39



RRR may be degraded substantially at the edges of Rutherford cables

Barrier thinning

No barrier thinning

What is the Origin of the RRR Influence

Options

Dynamic Stability Increases via heat transfer (increasing heat removal -- *K*)

Dynamic Stability via increasing heat deposition time (magnetic diffusion τ)

Current sharing Effects

Answering this question will also tell us where RRR needs to be high

Self Field vs Magnetization Instability

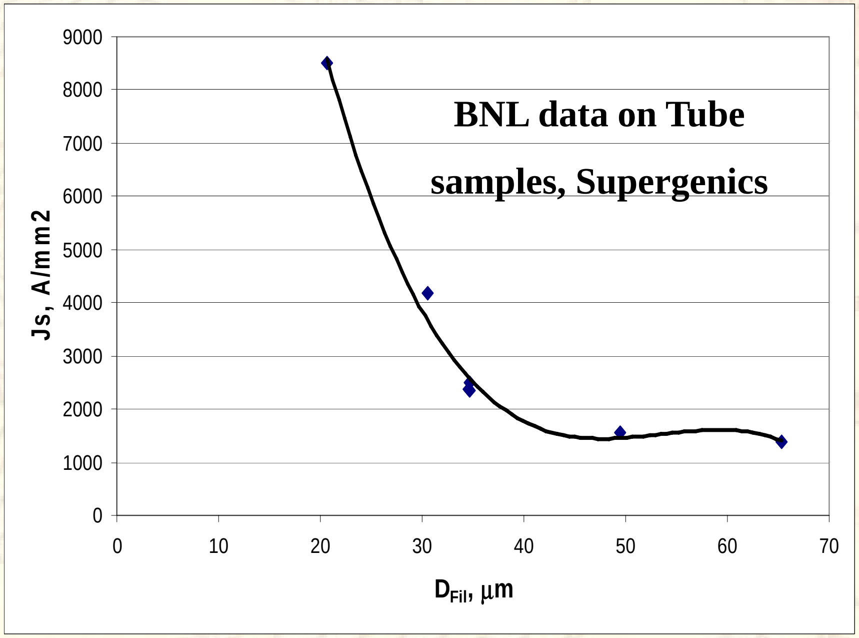
- Both individual filament and SF distributions will play into instabilities.
- SF Should be dominant near zero field
- At higher fields, magnetization instabilities seem to dominate (be controlling), but this may not be the case as d_{eff} continues to be reduced

Why Magnetization Instability

Reasons for interest in magnetization instability

1. More restrictive J_s criterion set by field ramping conditions
2. Increase of middle region stability (2-6 T plateau) with decreasing subelement d_{eff}

We will find that results seem to be in agreement with model



$$\beta = \frac{\mu_0 \lambda^2 J_c^2 a^2}{\gamma C \Delta T}$$

For typical parameters and a -> subelement size, results predictive. BUT, note that if we treat SF instability, while a grows by x 10, allowable β range much higher too.

SF effects may eventually be limiting

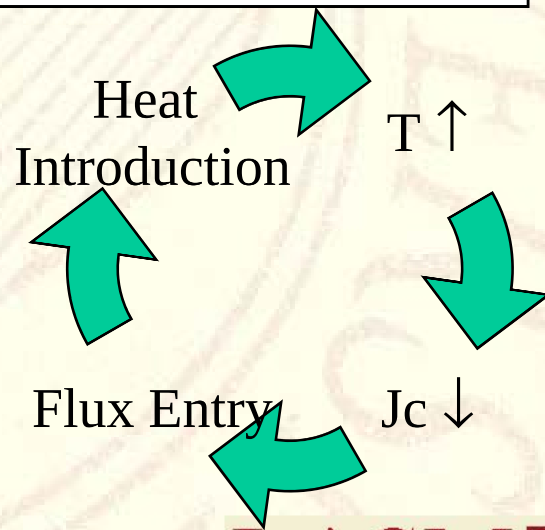
Sublement Magnetic Instability Model (I+B)

All stability calculations concerning the SC material (as opposed to cryostability, which focuses on the stabilizer), start from the following heat balance

Stimulating Heat Pulse [J/m^3]	+	Induced Heat Generation [J/m^3]	=	Volumetric Spec. Ht. *ΔT [J/m^{2}K * K]	+	Heat Transfer Coefficient * Surface Area per Unit Volume * time ***ΔT** [W/m^{2}K m^2/m^3*****sec]**[K]**

Slab model of Wilson

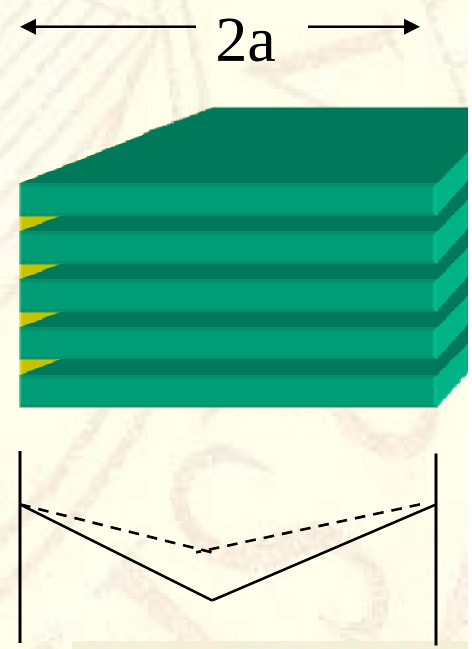
$$\Delta Q_s + \frac{\mu_0 \lambda J_c \lambda \Delta J_c a^2}{3} = \gamma C \Delta T + \frac{h \tau_J \Delta T}{a}$$



Results for Slab (Wilson)

$$\underset{1}{\Delta Q_s} + \underset{2}{\frac{\mu_0 \lambda J_c \lambda \Delta J_c a^2}{3}} = \underset{3}{\gamma C \Delta T} + \underset{4}{\frac{h \tau_J \Delta T}{a}}$$

1. Heat Perturbation
2. Heat Generated by Flux incursion
3. Heat absorbed by strand (delta T)
4. Heat removed by cryogen



ΔJ_c is the change in J_c due to the heat pulse

a is the slab width

γC = volumetric specific heat

h = heat transfer coefficient

τ_J = time constant for shielding current decay

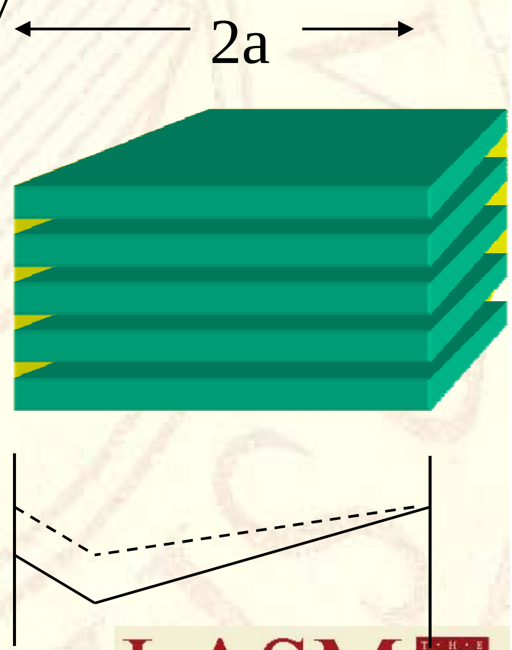
Results for Slab Conductor, with Cu stabilization layers and current

$$\beta_s = \frac{\mu_0 \lambda^2 J_c^2 \left(d_{eff} / 2\right)^2}{\gamma C \Delta T} = \frac{3}{(1+3i^2)} \left\{ 1 + \frac{4}{\pi^2}(1+i)^2 v \right\}$$

Here $i = I/I_c$, and v is a cooling parameter

Centerline shift (increases flux motion and energy

Time constant increase due to longer current decay



For Round Strands

For round strands, *Term 1* and *Term 3* OK

Term 2: needs modified for cylinder magnetization

Term 4: Heat removal from cylinder rather than slab

Ignoring for a moment the magnetization change (expect order of 20-30%) but changing the heat removal term, we get (very similar to Wilson)

$$\beta_S \equiv \frac{p\mu_0\lambda^2 J_c^2 d_{eff}^2 f^2}{\gamma C \Delta T_c} < \frac{3}{\left(1+3i^2\right)}\left\{1+\frac{8}{\pi^2}\nu\right\} \quad and \quad \upsilon = \frac{ha\mu_0\left(1-\lambda\right)}{\rho\gamma C}$$

What is J_{limit}?

So, starting with

$$\beta_S = \frac{p\mu_0\lambda^2 J_c^2 d_{eff}^2 f^2}{\gamma C \Delta T_c} < \frac{3}{\left(1+3i^2\right)}\left\{1+\frac{8}{\pi^2}\nu\right\} \qquad and \qquad \nu = \frac{ha\mu_0(1-\lambda)}{\rho\gamma C}$$

What $j = J/J_c$ can be reached before full instability occurs?
Setting $\beta = 1$, we find

$$\left(1+3i^2\right) < \frac{3\gamma C\Delta T_c}{\mu_0\lambda^2 J_c^2 a^2} F \qquad where \qquad F = 1 + \frac{8}{\pi^2}\upsilon$$

Setting $i = I/I_c = J/J_c = j$ we find

$$J < \sqrt{\frac{\gamma C\Delta T_c F}{\mu_0\lambda^2\left(d_{eff}{}^2/2\right)} - \frac{J_c^2}{3}}$$

Implicit expression for J_{limit}

Replacing $\gamma C \Delta T_c$ with the full heat capacity term H_v

$$H_v = \int_4^{Tc(B)} H_c(T) = \int_4^{Tc(B)} \gamma T + \delta T^3$$

Using $T_c = T_{c0}(1-b)^{1/1.52}$ [Godeke, Maki-De-Gennes], we find only the cubic term matters and $H_v \cong$

We integrate up to the current sharing ... nce $J_c = J_{c0}(1-T/T_c)$, we can set $T = T_{cs}$, an... $T_{cs} = T_c(1-j)$. Thus, also using $J_c = \frac{C}{b^{1/2}}(\ldots$

Note: If J_c goes up, at equal cooling (say by going from 4.2 K to 1.9 K – $J_{stability}$ may go down

$$J_{limit} < \sqrt{\frac{\delta\left(T_{c0}^{\ 4}(1-j)^4(1-b)^{2.63} - 4^4\right)}{4\mu_0\lambda^2\left(d_{eff}/2\right)^2}\left\{1+\frac{8}{\pi^2}\upsilon\right\} - \frac{J_c^{\ 2}}{3}\left(\frac{C(1-b)^2}{\Lambda + b^{1/2}}\right)^2}$$

Explicit form for J_{limit} --I

$$J_{\lim it} < \sqrt{\frac{\delta\left(T_{c0}{}^{4}(1-j)^{4}(1-b)^{2.63}-4^{4}\right)}{4\mu_0\lambda^2\left(d_{eff}/2\right)^2}\left\{1+\frac{8}{\pi^2}\upsilon\right\}-\frac{J_c{}^2}{3}\left(\frac{C(1-b)^2}{\Lambda+b^{1/2}}\right)^2}$$

Let $j = J/J_c$, then we can write above as $j^2=A+B(1-j)^4$

$$A=\frac{-4^4\delta}{J_c^2\mu_0\lambda^2(d_{eff}/2)^2}F-\frac{1}{3}\left[\frac{\left(1-b^2\right)}{\Lambda+b^{1/2}}\right]^2$$

$$F=1+\frac{8}{\pi^2}\nu$$

$$B=\frac{\delta T_{c0}^4(1-b)^{2.63}}{J_c^2 4\mu_0\lambda^2\left(d_{eff}/2\right)^2}\left\{1+\frac{8}{\pi^2}\nu\right\}$$

Let x=1-j

The we must solve

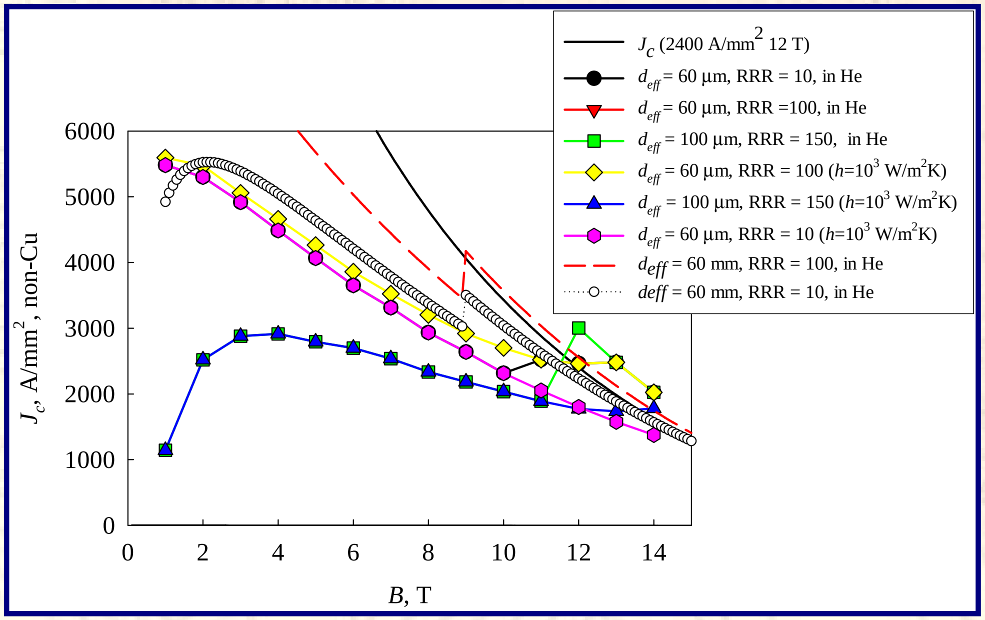
$(1-x)^2=A+Bx^4$

Explicit Form --II

The relevant root is

$$X = \sqrt{-\frac{1}{2B} + \frac{\sqrt{1+4B-4AB}}{2B}}$$

$$j = 1 - \sqrt{\frac{\sqrt{1+4B-4AB}-1}{2B}}$$



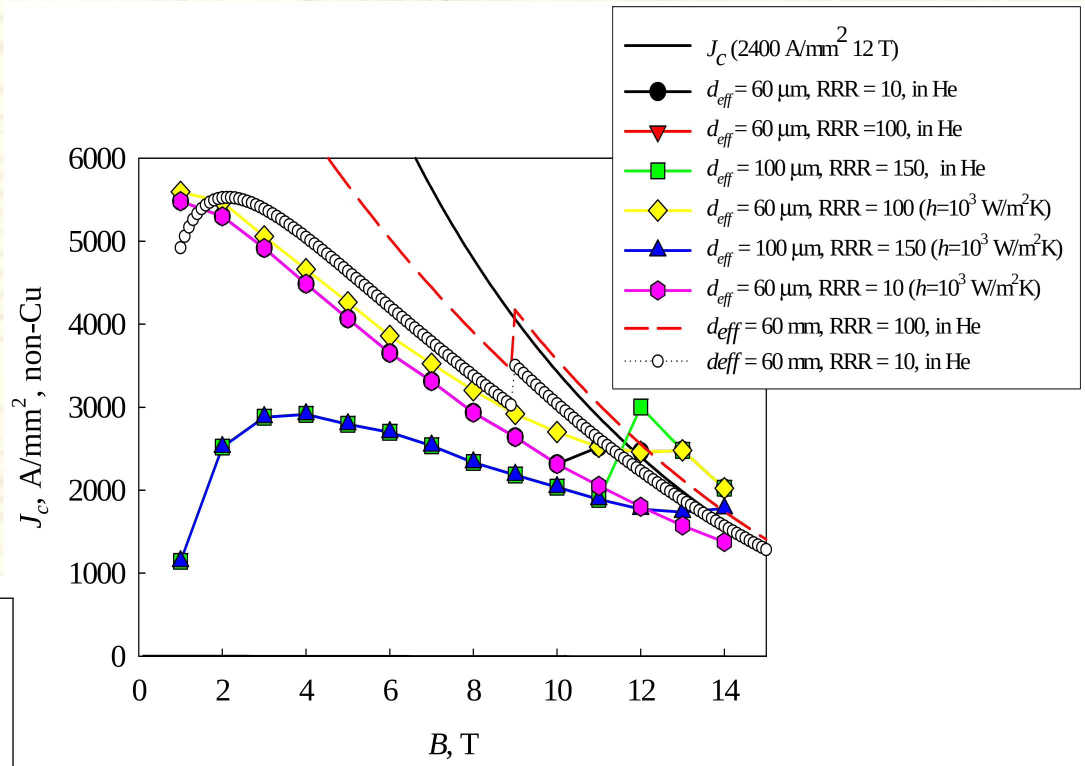
where

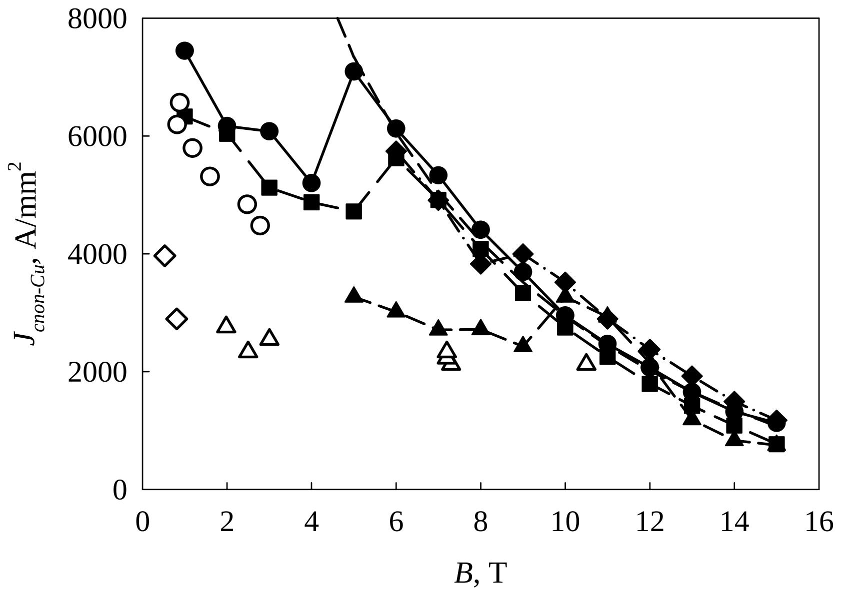
$$A = \frac{-4^4\delta}{J_c^2\mu_0\lambda^2(d_{eff}/2)^2}F - \frac{1}{3}\left[\frac{(1-b^2)}{\Lambda + b^{1/2}}\right]^2$$

$$F = 1 + \frac{8}{\pi^2}\nu$$

$$B = \frac{\delta T_{c0}^4(1-b)^{2.63}}{J_c^2 4\mu_0\lambda^2(d_{eff}/2)^2}\left\{1 + \frac{8}{\pi^2}\nu\right\}$$

Calculation Results





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Dependence on d_{eff}, RRR, and h

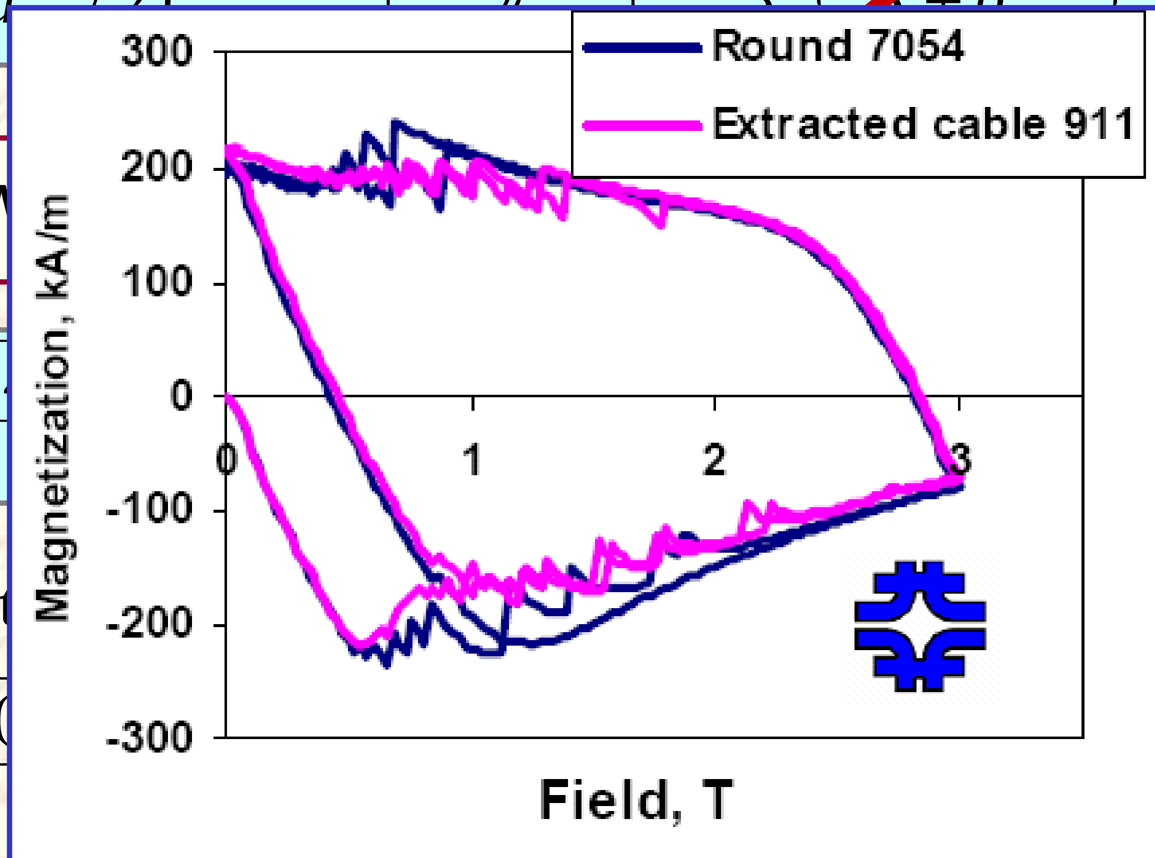
$$J_{limit} < \sqrt{\frac{\delta\left(T_{c0}{}^{4}(1-j)^{4}(1-b)^{2.63}-4^{4}\right)}{4\mu_0\lambda^2\left(d_{eff}/2\right)^2}\left\{1+\frac{8}{\pi^2}\upsilon\right\}-\frac{J_c{}^2}{3}\left(\frac{C(1-b)^2}{A+b^{1/2}}\right)^2}$$

If $j\rightarrow 0$, then w

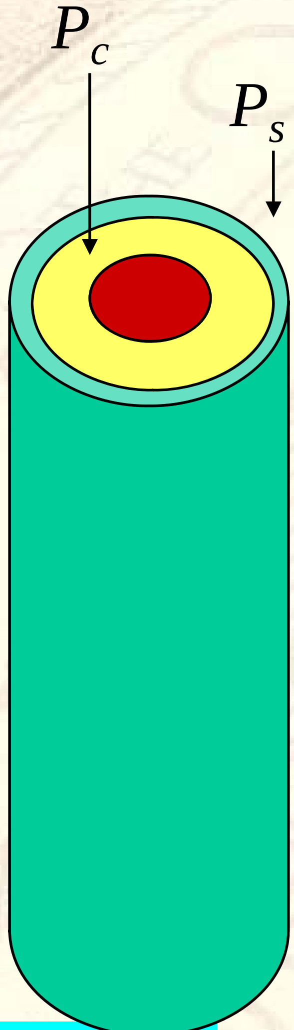
$$J_{limit} < \frac{1}{d_{eff}}\sqrt{\frac{\delta\left(T_{c0}{}^{4}(1-b)^{2.63}-\ldots\right)}{\mu_0\lambda^2}}$$

If dynamic component

$$J_{c,stab} = \frac{\sqrt{3C(\ldots}}{\ldots}$$



Influence of RRR – τ, not thermal Conductivity



Thermal Transport Inside Strand – radial, K-limited

Conduction through strand → $Q = (tA/D)K\Delta T$

Q = joules, t = time, A = heat flow area, D =heat flow distance,
K = thermal conductivity,W/Km, ΔT = temperature difference

If $A \approx 2\pi LR$, *and* $D \approx R$, $P_c = K\Delta TA/R = 2\pi LK\Delta T$ **[P]=W**

Heat Transfer into Liq He → $P_s = h2\pi RL\Delta T$

$$\frac{P_c}{P_s} = \frac{K\Delta T\, 2\pi L}{hL\Delta T\, 2\pi R} = \frac{K}{hR}$$

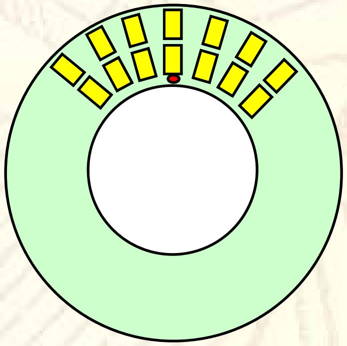
$$K = \frac{L_0 T}{\rho} = \frac{(2.45x10^{-8} W\Omega / K^2)(4K)RRR}{1.5*10^{-8}\,\Omega m} = 6RRR$$

$$\frac{P_c}{P_s}\left(h = 10^3\right) = \frac{6*RRR}{0.5*10^3 10^{-3}} = 12*RRR \qquad \frac{P_c}{P_s}\left(h = 5x10^4\right) = \frac{6}{25}RRR$$

But what about potted Magnets??

If not in direct contact with He, we are either transferring to neighboring regions, or out to the bath. In either case, the relevant parameter is <*K*>

$$P_c \approx \frac{2\pi RL\langle K\rangle \Delta T}{R} \quad \langle \kappa \rangle = l\left(\sum_i \frac{l_i}{\kappa_i}\right)^{-1}$$



Taking 125 μm as the insulation thickness, 1 mm as the strand OD, and 0.3 W/mK as the thermal conductivity of the insulation

$$\langle K\rangle = \frac{15*10^{-3}}{\left(\frac{15*10^{-3}}{600}+\frac{125x10^{-6}}{0.3}\right)} \approx \frac{15*10^{-3}}{\left(\frac{125x10^{-6}}{0.3}\right)} = \frac{15*1000}{375} = 45W/mK$$

Which is just the winding-pack-fraction normalized insulation K

Re-configuring Expressions for case of potted magnets-I

Equation for J_l has a factor ν which assumes cooling via pool boiling, and thus $\propto h$

Stimulating Heat Pulse [J/m^3]	+	Induced Heat Generation [J/m^3]	=	Volumetric Spec. Ht. *ΔT [J/m^{2}K * K]	+	Heat Transfer Coefficient * Surface Area per Unit Volume * time ***ΔT** [W/m^{2}K m^2/m^3 ***** sec] **[K]**

In Cryogen $$\frac{heat \quad rem}{m^3} = \frac{h\pi 2RL\Delta T\tau}{L\pi R^2} = \frac{2h\Delta T\tau}{R}$$

$$\frac{heat \quad removed}{m^3} = \frac{Power * time}{m^3}$$

In potted system $$\frac{heat \quad rem}{m^3} = \frac{\frac{2\pi RL}{\ell} K\Delta T\tau}{L\pi R^2} = \frac{2K\Delta T\tau}{\ell R}$$

Re-configuring Expressions for case of potted magnets-II

$\Rightarrow h \rightarrow K/\ell$

K_{magnet} is the average magnet thermal conductivity

L is the shortest distance to the cooling plane.

K = 45 W/mK, and L = 0.03 m, then $K/L \approx 10^3$, similar to the case of film boiling, as described above

$$\nu = \frac{hR\mu_0(1-\lambda)}{\rho\gamma C} \quad \rightarrow \quad \nu = \frac{K\mu_0(1-\lambda)}{\rho\gamma C}\left(\frac{R}{\ell}\right)$$

$$\nu = \frac{K(4\pi)10^{-7}(0.5)}{1.5x10^{-8}(10^3)}\left(\frac{R}{\ell}\right)RRR \approx \frac{RRR}{7}\left(\frac{R}{\ell}\right)$$

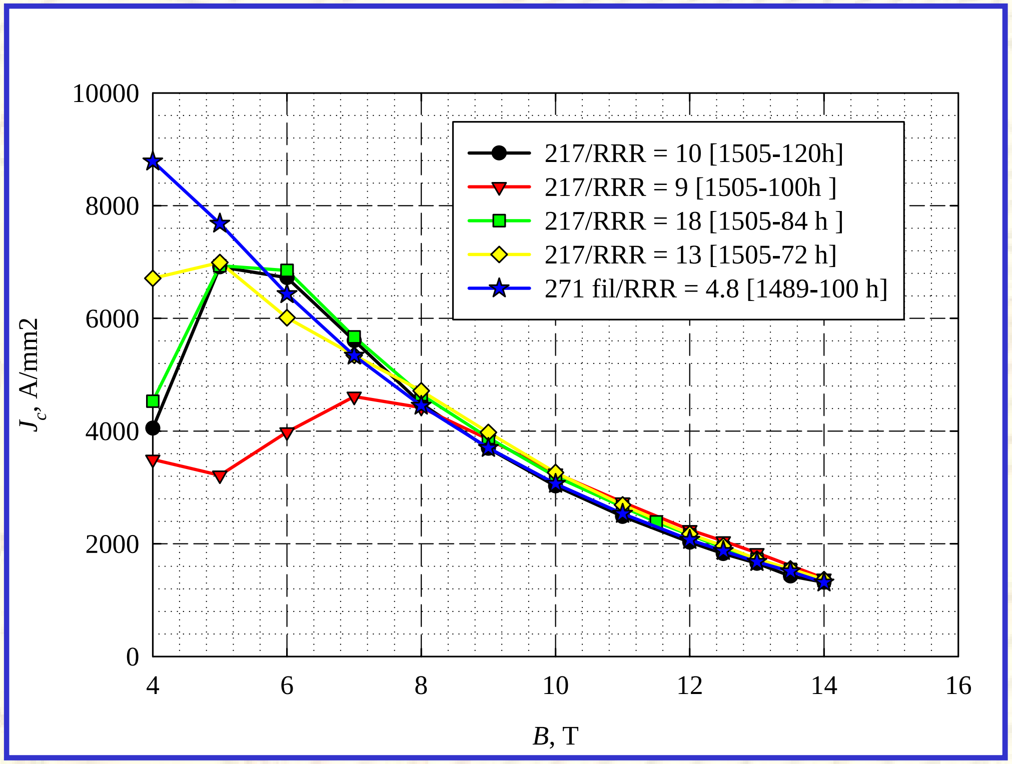
Is full "*full*" adiabatic Stability Possible?

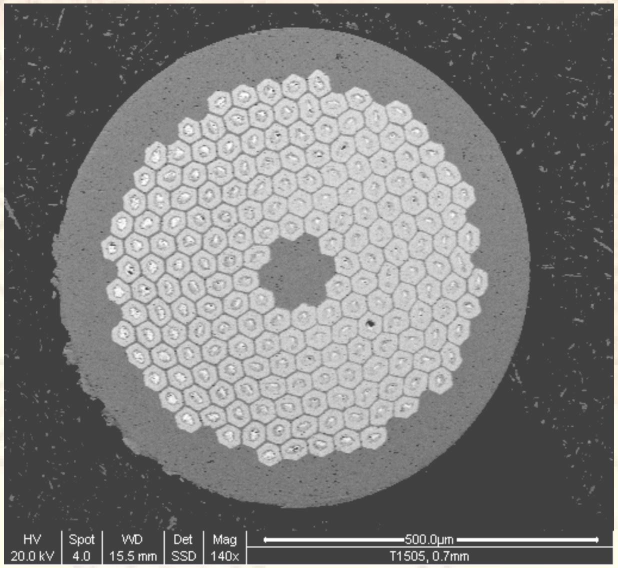
The magnetization limit for pure M-H flux jump is about 200 kA/m, corresponds to a d_{eff} of about 40 μm

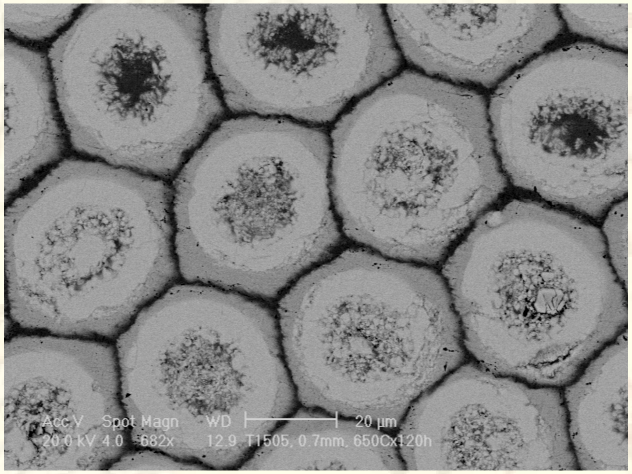
$$J_{c,stab} = \frac{\sqrt{3C(T)\Delta T/\mu_0}}{d_{eff}} \frac{1}{1+3i}$$

But, SF instability, *at the very least at zero field*, suggests that this happy result cannot really be achieved, so both low d_{eff} and high RRR are required

Supergenics Tube Conductor







2250 A/mm^2 12 T, 217 stack 0.7 mm OD

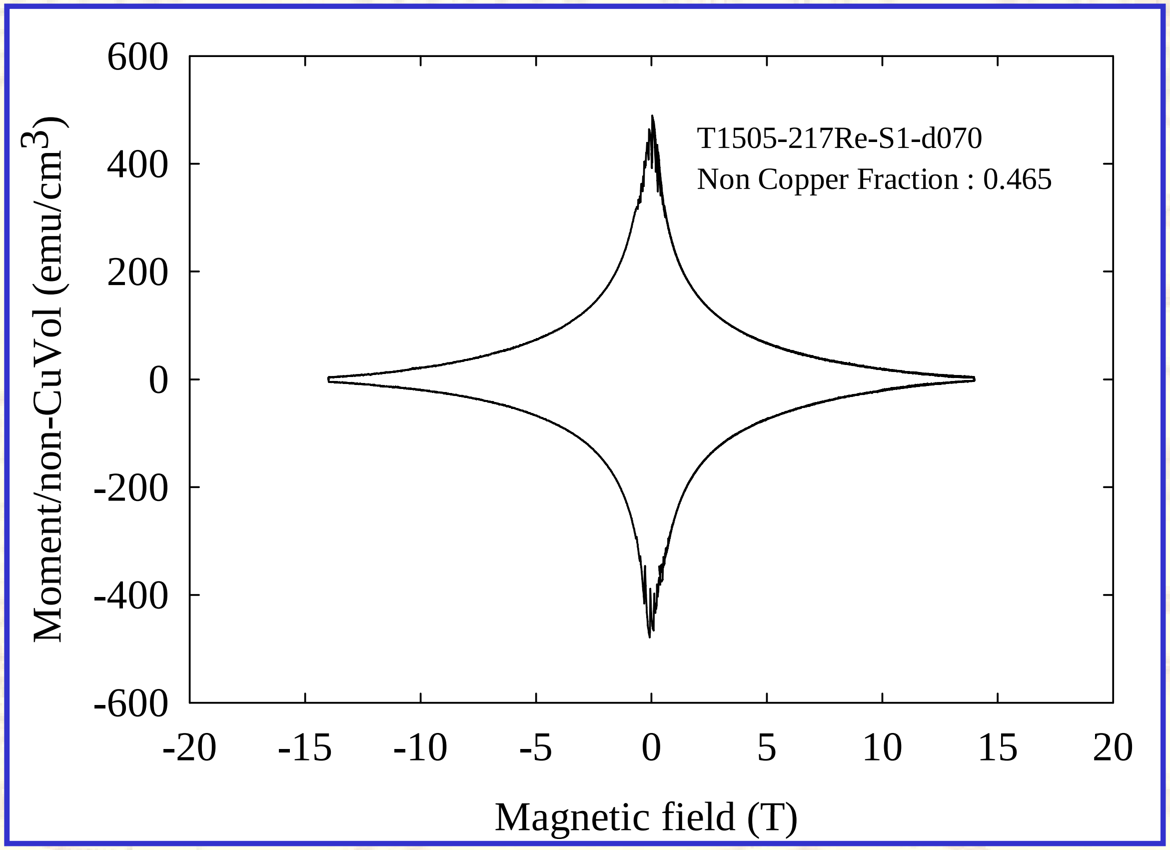
***D*$_{eff}$= 33 µm for 0.7 mm 217 stack**

***D*$_{eff}$ = 31 µm for 0.7 mm OD 271 stack**

***D*$_{eff}$ = 18 µm for 0.4mm OD 271 stack**

D_{eff} for 0.7 mm OD Tube-Sn

Conductor d_{eff} ≈20 μm because of reaction zone



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CONCLUSIONS

- In Nb_3Sn HEP conductors, instabilities not seen in *M-H* alone are generated by combined effects of magnetization and transport current induced field profiles
- Lowered d_{eff} and increased RRR known to improve things
- RRR Degradation seen at cable edges – could be important
- RRR improvement – main influence was not *K* but τ
- However, RRR values below 10 could begin to impede thermal transport
- In potted systems, some RRR influence possible even though the optimal solution would be reduced strand d_{eff}
- Dependence of J_{limit} on d_{eff}, RRR, and *h* explored
- BOTH small d_{eff} and high RRR seem to be required