Stability and Protection of CICC's An Updated Designer's View

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Focus on: **stability & protection of CICC's**

☞ new features:

cooling channel(s), hybrid cables

☞ new operating conditions:

superfluid helium

☞ new understanding and phenomena

helium *bath* temperature changes, RRL, THQB

Update consequently the design procedures and criteria

☞ **Stability**
- well-cooled regime
- recovery temperature
- current distribution
- hybrid cables
- cooling channel(s)
- superfluid helium

☞ **Protection**
- hot-spot temperature
- maximum pressure
- q-I diagram
- THQB
- normal voltage
- cooling channel(s)

☞ **An example**

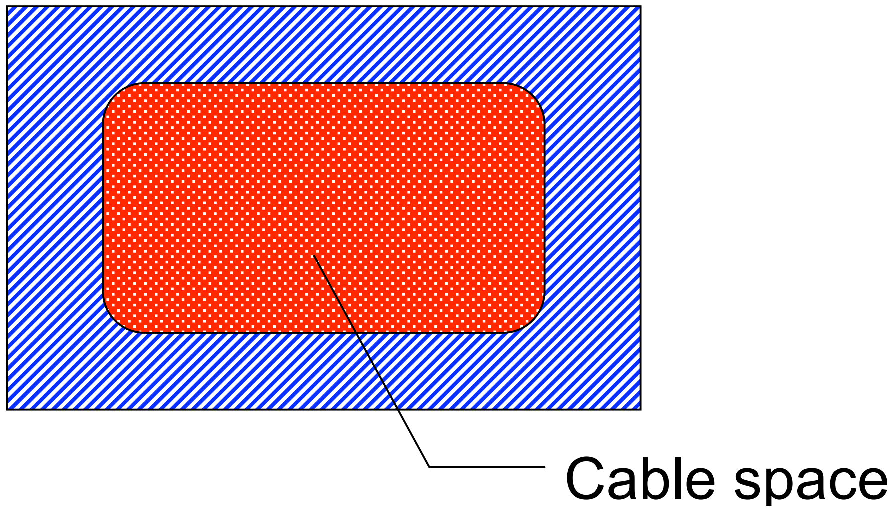
☞ cable space cross section A_{CS}

- ☝ helium A_{he} $f_{he} = A_{he}/A_{CS}$
- ✌ stabiliser A_{stab} $f_{stab} = A_{stab}/A_{CS}$
- 👌 superconductor A_{SC} $f_{SCe} = A_{SC}/A_{CS}$

$$f_{he} + f_{stab} + f_{SC} = 1$$

$$D_h = \frac{f_{he}}{K_p\left(f_{stab} + f_{SC}\right)} d$$

$$p_w = \frac{4K_p}{d}\left(f_{stab} + f_{SC}\right)A_{CS}$$

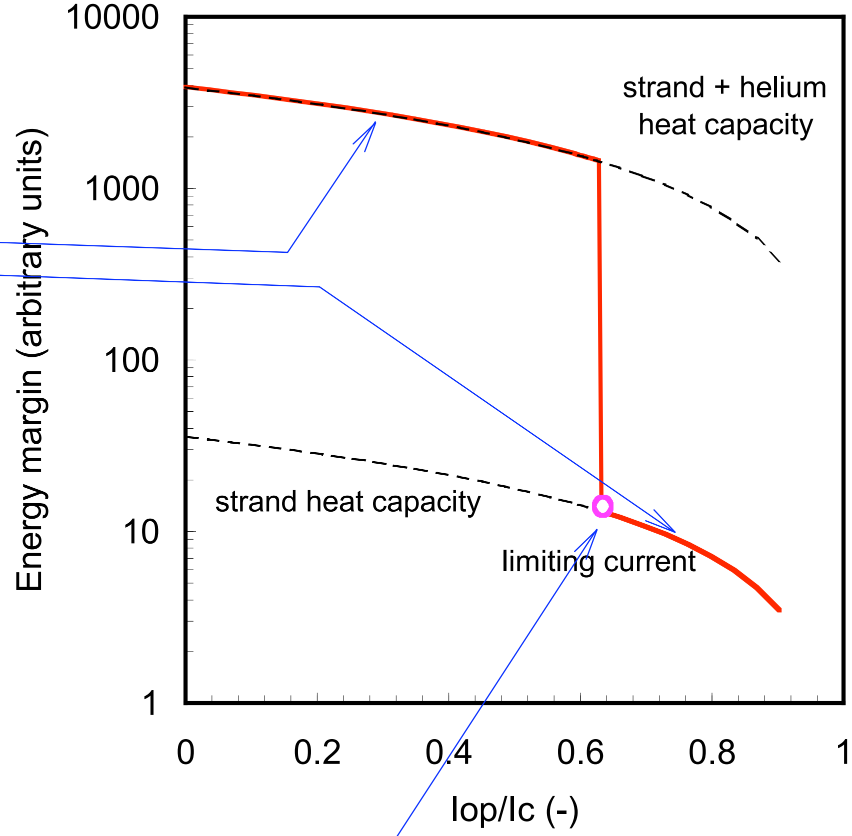


☞ limiting current and helium heat sink

$$\Delta E_{max} = \int_{T_{op}}^{T_{cs}} \frac{f_{stab} C_{stab} + f_{SC} C_{SC} + f_{he} C_{he}}{\left(f_{stab} + f_{SC}\right)} dT$$

$$\Delta E_{ic} \approx \int_{T_{op}}^{T_{cs}} \frac{f_{stab} C_{stab} + f_{SC} C_{SC}}{\left(f_{stab} + f_{SC}\right)} dT + \frac{4K_p}{d} \left(T_{cs} - T_{op}\right) \int_0^{\tau_e + \tau_r} h\, dt$$

$$I_{lim} = \sqrt{\frac{A_{stab} p_w h \left(T_c - T_{op}\right)}{\rho_{stab}}}$$

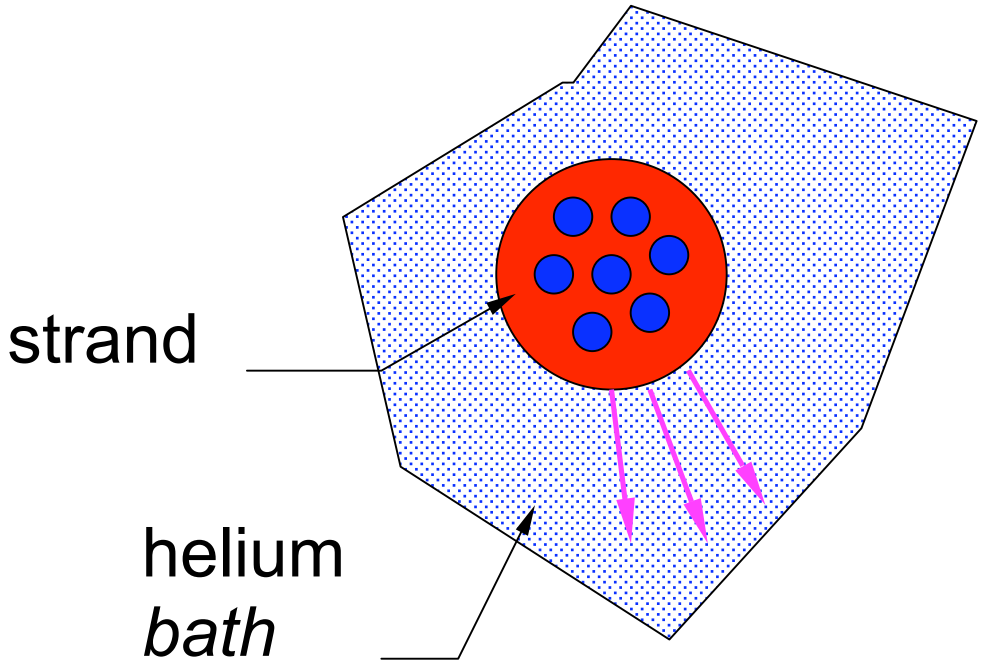


☞ recovery condition

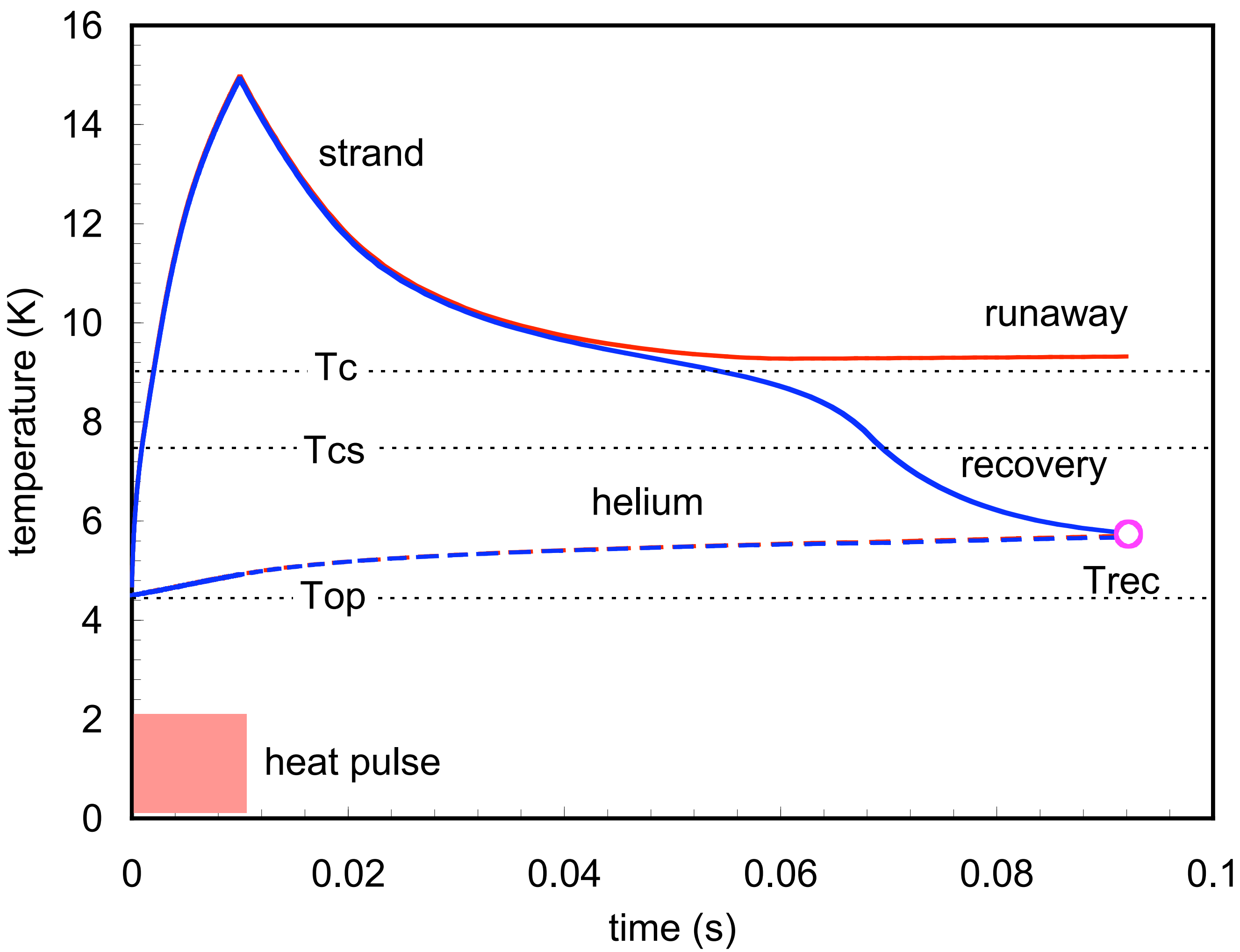
$$\frac{\rho_{stab} I_{\lim}^2}{A_{stab}} = p_w h\left(T_c - T_{op}\right)$$

$$\Downarrow$$

$$J_{op} = \cos(\theta)\sqrt{f_{stab}\left(f_{stab} + f_{SC}\right)\frac{4K_p h\left(T_c - T_{op}\right)}{\rho_{stab} d}}$$



Stability - recovery from a transient

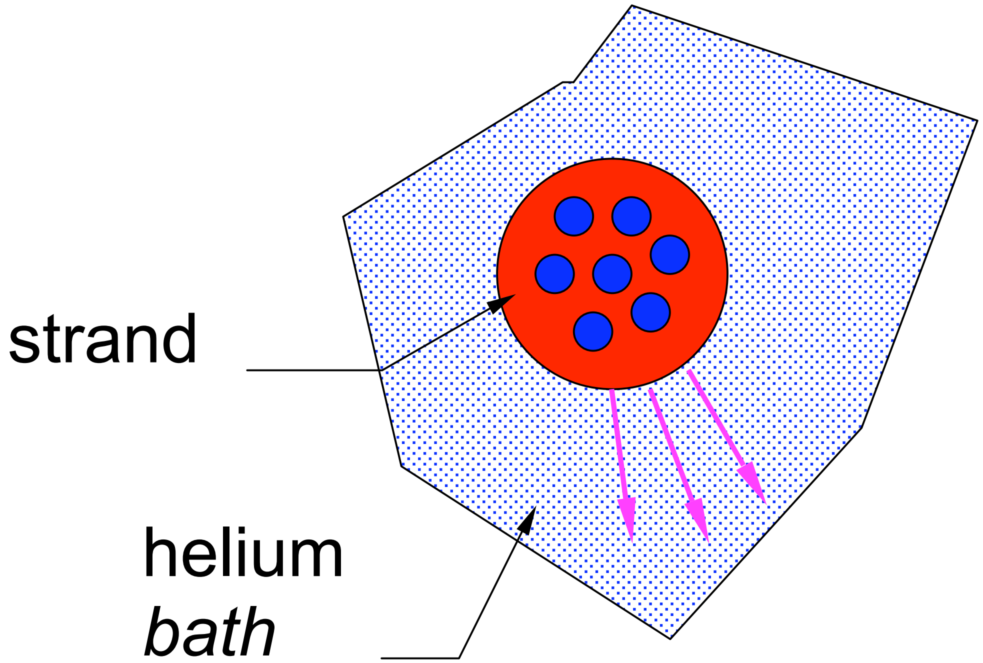


☞ recovery condition:

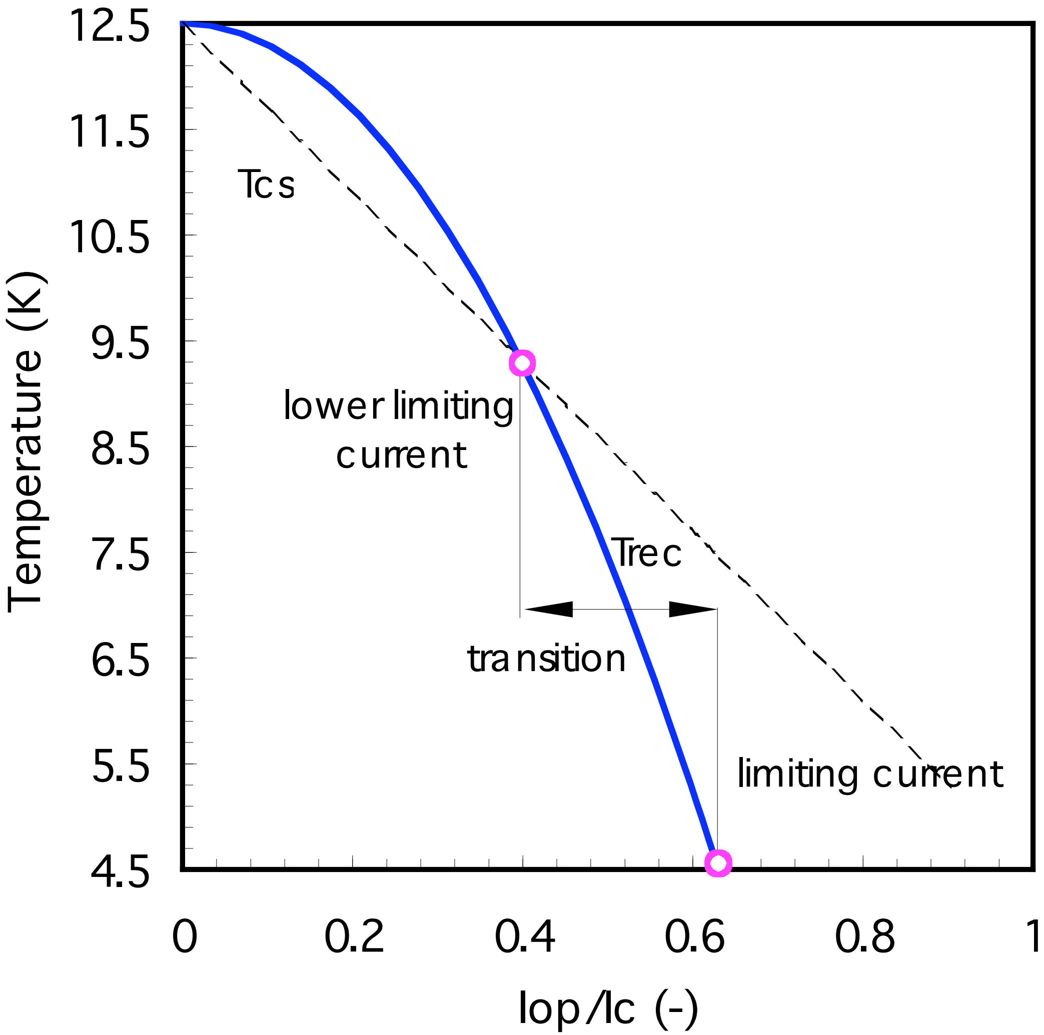
$$\frac{\rho_{stab} I_{op}^2}{A_{stab}} \leq p_w h \left(T_c - T_{rec} \right)$$

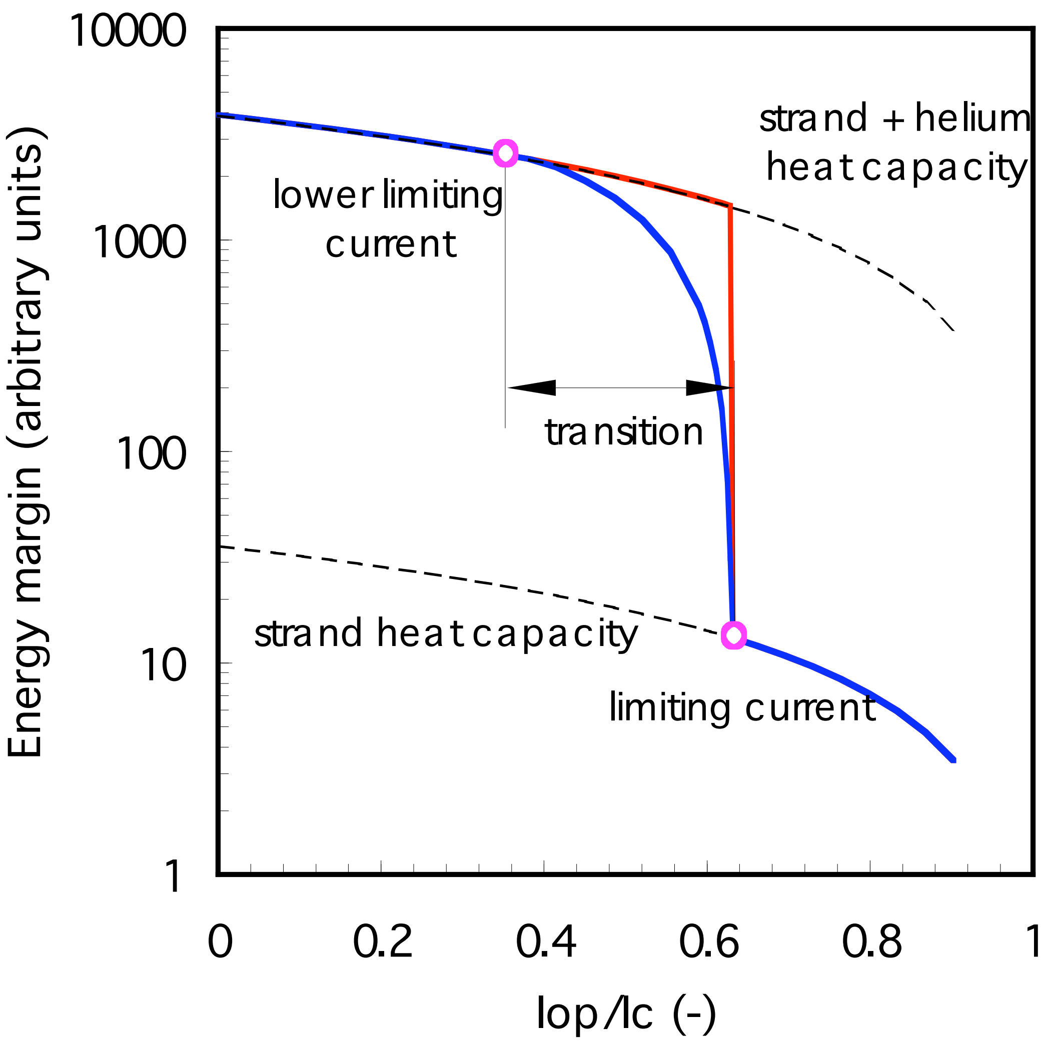
$$\Downarrow$$

$$T_{rec} = T_c - \frac{\rho_{stab} I_{op}^2}{p_w h A_{stab}}$$



Stability - recovery temperature




10000
1000
100
10
1
0
0.2
0.4
0.6
0.8
1
Energy margin (arbitrary units)
Iop/Ic (-)
strand + helium
heat capacity
lower limiting
current
transition
strand heat capacity
limiting current

☞ lower limiting current

$$I_{\lim}^{low} = \frac{A_{stab} p_w h \left(T_c - T_{op}\right)}{\rho_{stab} I_c}$$

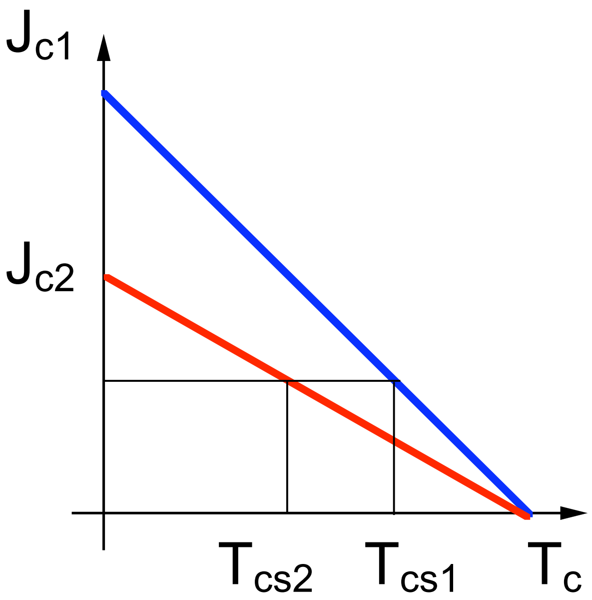
☞ lower limiting current density

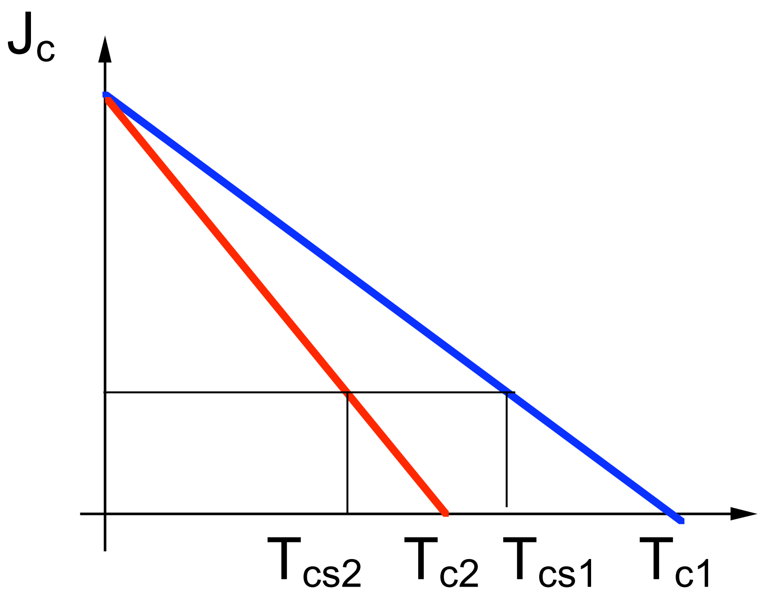
$$J_{op} = \cos(\theta) \frac{4 K_p h}{\rho_{stab} d} \frac{\left(T_c - T_{op}\right)}{J_c} \frac{f_{stab}}{f_{SC}} \left(f_{stab} + f_{SC}\right) \qquad (✿)$$

Recommendation: use (✿) for design: more stabilizer **BUT** less safety margin

$$J_{op} = \cos(\theta)\frac{4K_p h}{\rho_{stab} d}\frac{(T_c - T_{op})}{J_c}\frac{f_{stab}}{f_{SC}}(f_{stab} + f_{SC})$$

increases for Tc ⇑ and Jc ⇓





Stability - lower limiting current

Sample	Cu:NbTi
1	0.97
2	2.98
3	7.01

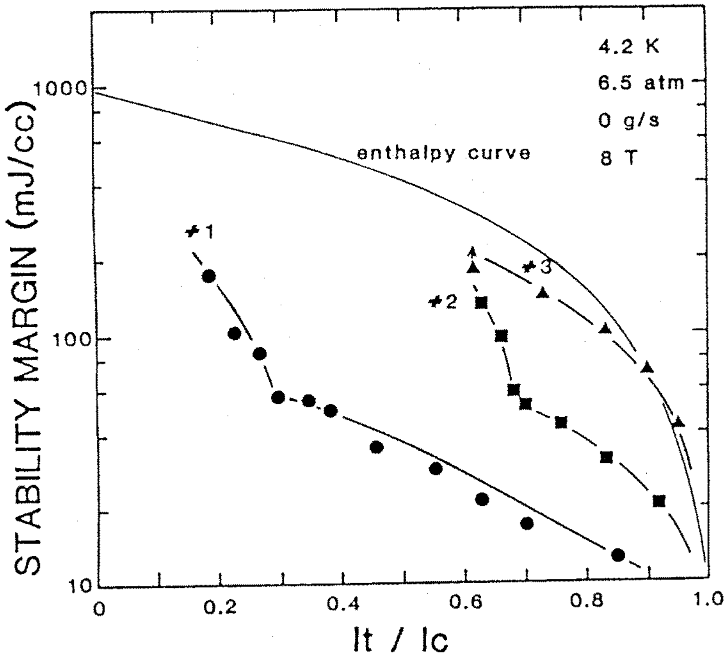
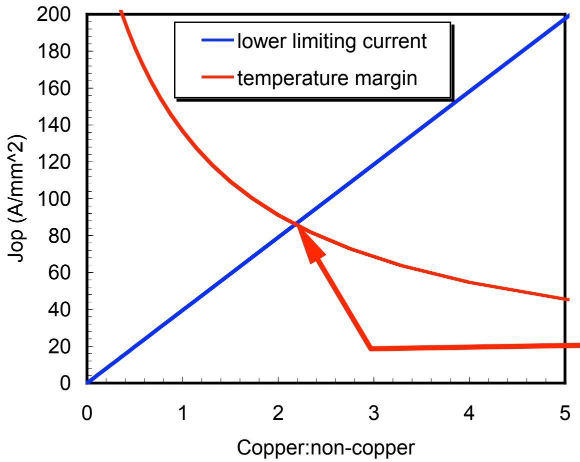


Fig. 6 Stability margin vs. fraction of critical current at different copper/NbTi rations.

T. Ando, et al., *Investigaton of Stability in Cable-in-Conduit Conductors with Heat Pulse Duration of 0.1 to 1 ms*, Proc. ICEC 11, 756-760, 1986

Stability - maximum useful Cu:non-Cu



$$\left.\frac{f_{stab}}{f_{SC}}\right|_{\max} = \frac{1}{2}\left[\sqrt{1+\frac{\rho_{stab} d J_c^2}{\cos(\theta) K_p h (T_c - T_{op})}\left(1-\frac{\Delta T}{(T_c - T_{op})}\right)} - 1\right]$$

Nb3Sn, ΔT = 2K, B = 13 T ☞ max useful Cu:non-Cu ≈ 2

NbTi, ΔT = 2K, B = 7 T ☞ max useful Cu:NbTi ≈ 5

Stability - superfluid helium

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☞ a second (superfluid) limiting current is present for $\Delta E \leq 200\ mJ/cm^3$

(J.C. Lottin, J.R. Miller, IEEE Trans. Mag., **19**, 3, 439, 1983)

Joule heat flux

fiducial (max) heat flux

$$q''_J << q''_*$$

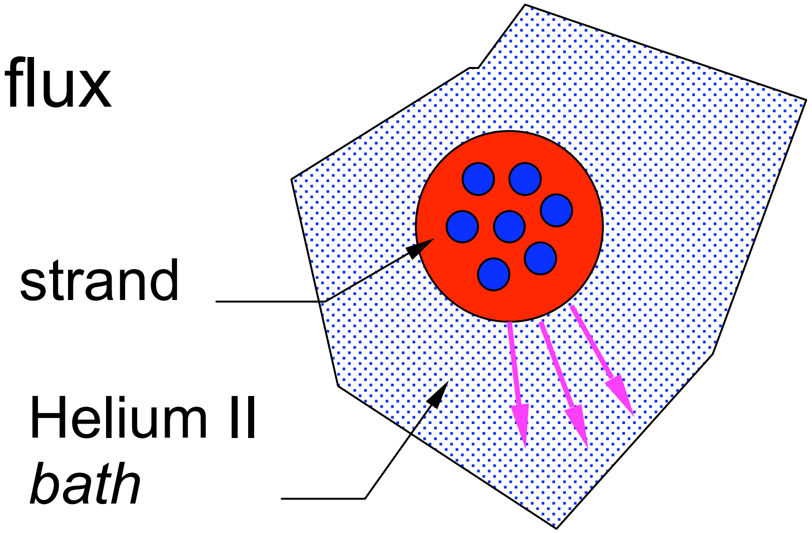
☞ superfluid well-cooled regime

$$q''_* \propto \left(\frac{K \left(T_\lambda - T_{op} \right)}{l} \right)^{1/3}$$

channel *length*

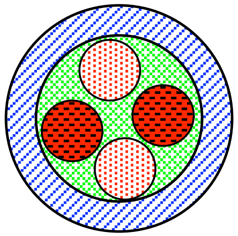
$$\Downarrow$$

$$J_{op} \approx \sqrt{ \frac{K^{1/3} \left(T_\lambda - T_{op} \right)^{1/3}}{\rho_{stab}} \left(\frac{K_p}{d} \right)^{4/3} \frac{f_{stab} \left(f_{SC} + f_{stab} \right)^{4/3}}{f_{he}^{1/3}} }$$



☞ cowound cables (hybrid cables)

added stabilizer is not (always) effective for stabilization

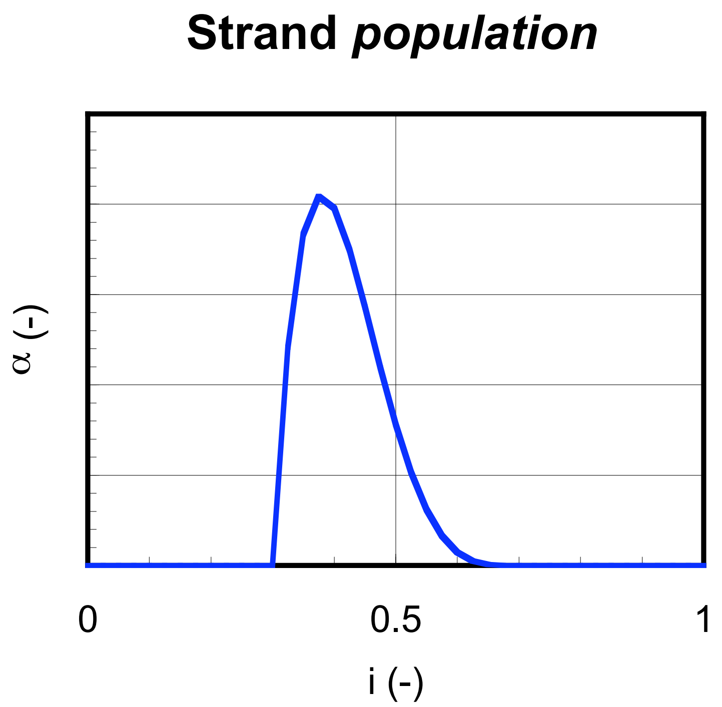


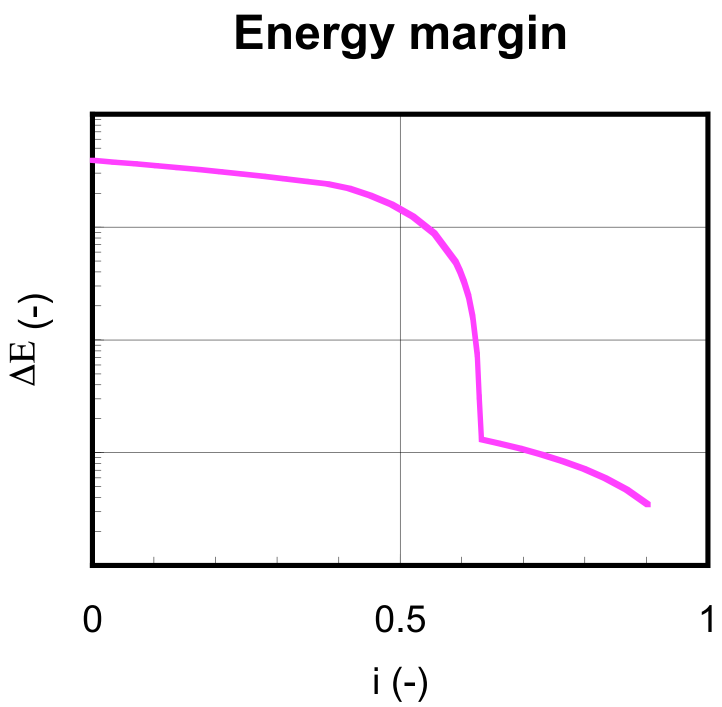
p (bar)	T (K)	Jlim meas (A/mm^2)	Jlim with xtra Cu (A/mm^2)	Jlim w/o xtra Cu (A/mm^2)
3	4.24	44.3	70.9	30.5
4		39.3	64.3	27.7
6		35.5	57.1	24.6

(J.R. Miller, Cryogenics, **25**, 552-557, 1985)

☞ central channel

stability ? (induced flow, mass transfer, heat transfer, ...)





- ☞ $\tau_i << \tau_r$ collective energy margin $\Delta E(i_{average})$
- ☞ $\tau_i >> \tau_r$ worst strand energy margin $\Delta E(i_{max})$

Stability - current distribution time and length

☞ current transfer time

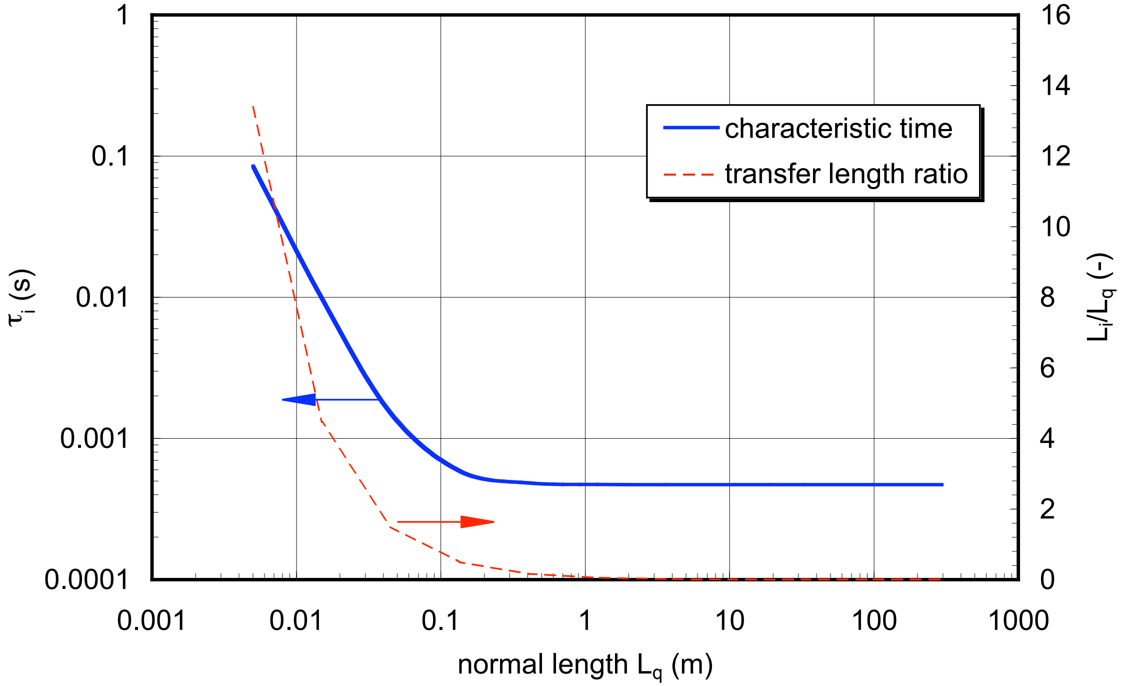
$$\tau_i \approx \begin{cases} \dfrac{L_i}{L_q}\dfrac{2L' - 2M'}{\pi R'} & L_q << L_i \\ \dfrac{2L' - 2M'}{\pi R'} & L_i << L_q \end{cases}$$

☞ current transfer length

$$L_i = \frac{1}{\sqrt{R'G'}}$$

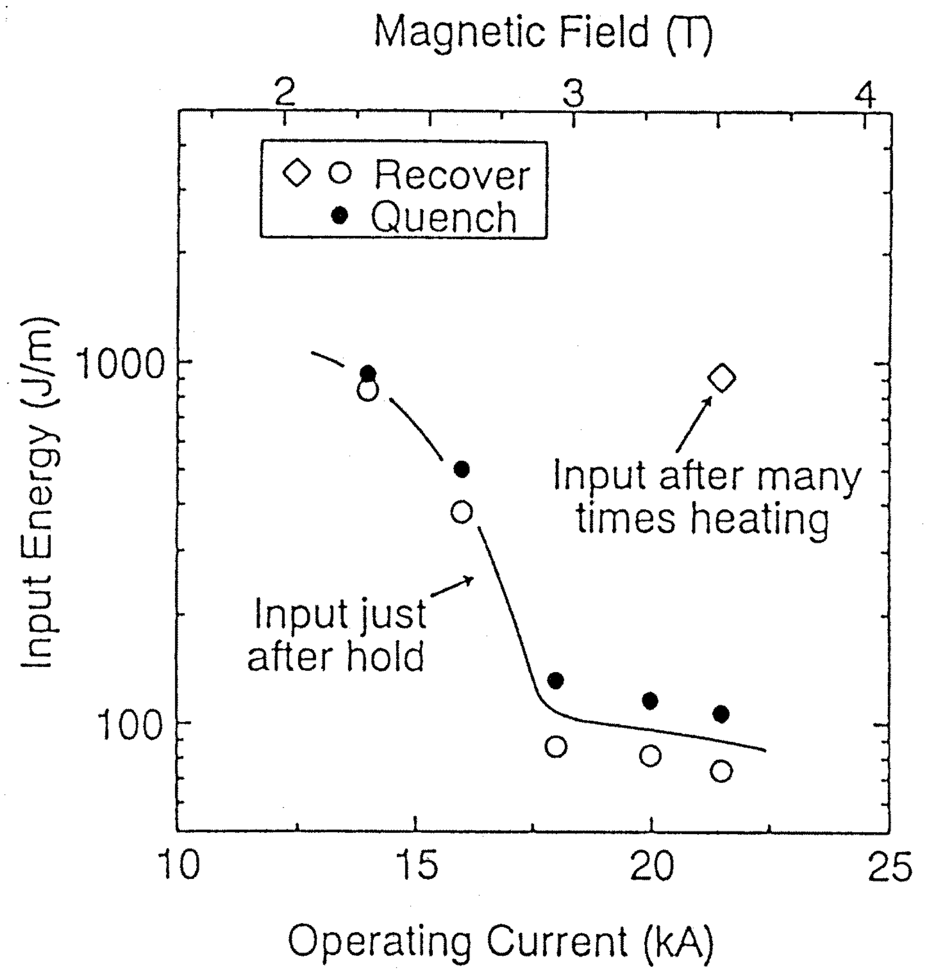
$$G' \geq \frac{1}{L_q^2 R'}$$

Current transfer chracteristic time and length
for a CICC with G' = 2099 + 214.7 * I * B

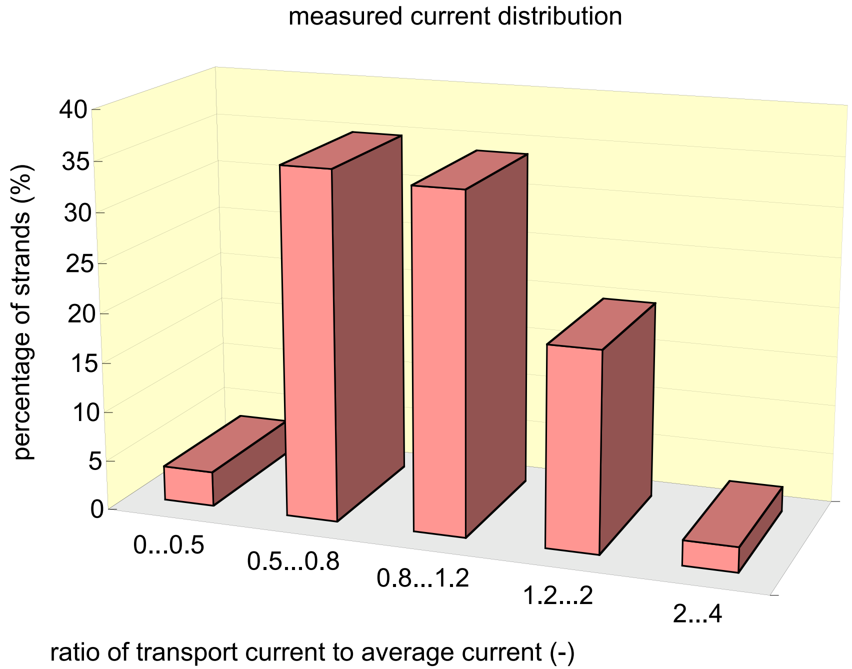


measurements of stability in the DPC-U coil

(formvar insulated strands)



N. Koizumi, et al., *Experimental Results of Stability and Current Sharing of Cable-in-Conduit Conductors for the Poloidal Field Coils*, IEEE Trans. Appl. Sup., **3**, 1, 610-613, 1993



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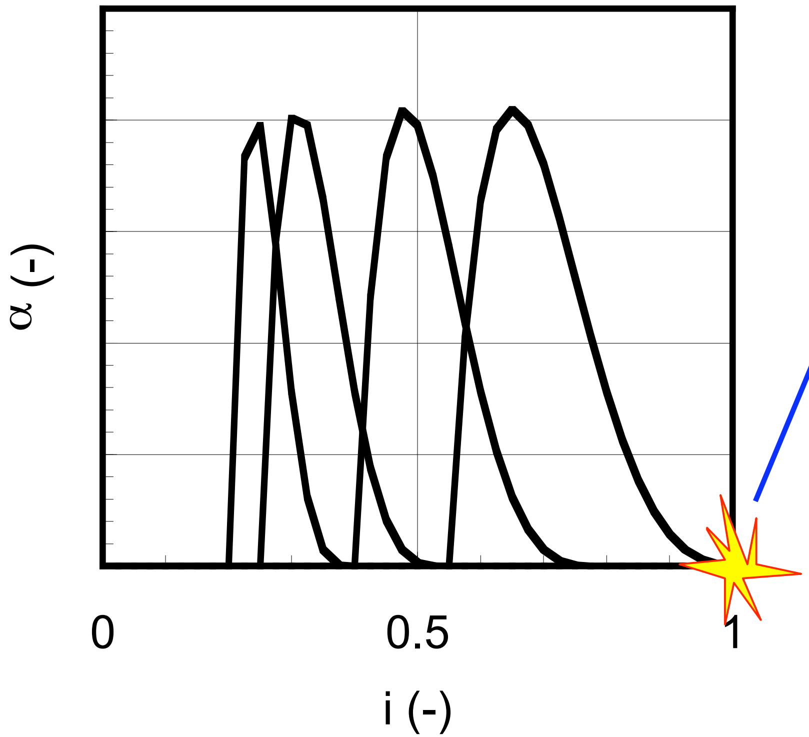
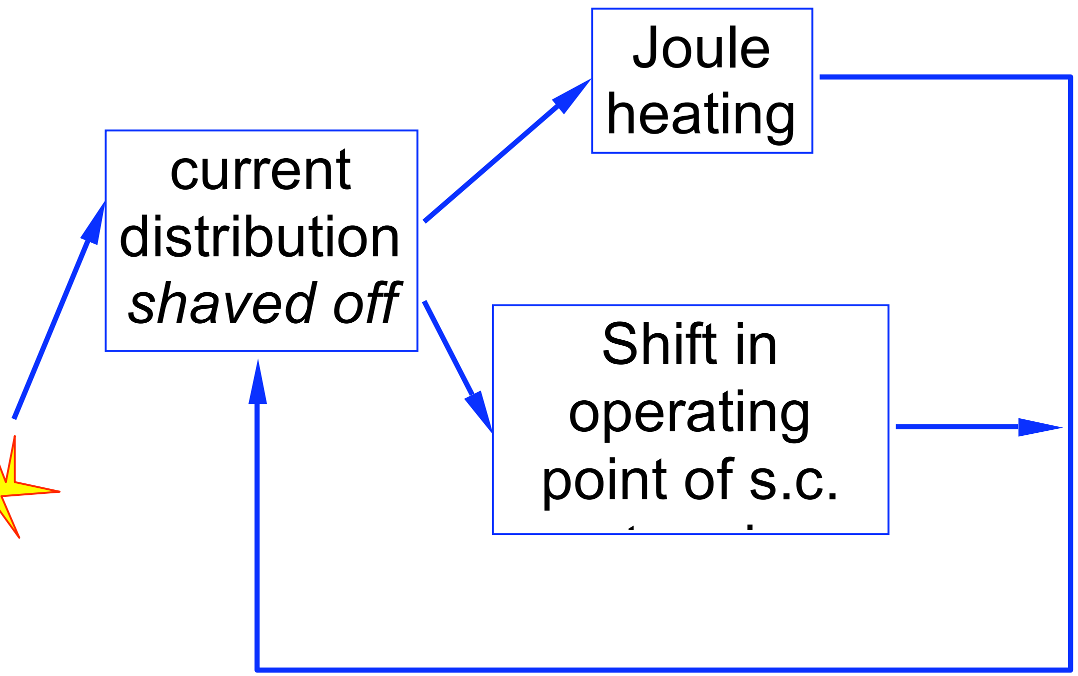
☞ strand population during ramps ($i = I_{op}/I_c$)



flux-jump like phenomenon



Recommendations:

- ☞ conductance G: large enough to guarantee *collective* behaviour

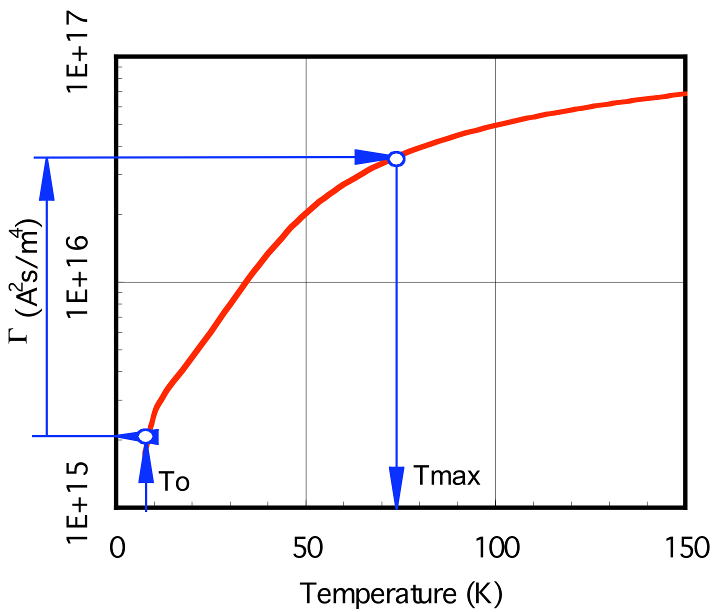
- ☞ operating current I_{op}: design below limiting current to prevent flux-jump like driven RRL

☞ adiabatic heat balance

$$T_m(t) \approx T_0 + \frac{J_{CS}^2}{f_{cu}\overline{\gamma}} t \qquad \gamma(T) = \frac{\sum_i f_i \rho_i C_i}{\rho_{cu}}$$

$$\int_{T_0}^{T_{max}} \gamma(T) dT = \Gamma(T_0, T_{max}) = \frac{1}{f_{cu}} \int_0^{\infty} J_{CS}^2 dt$$

Quell conductor characteristics



☞ q-l diagram for quench propagation

parameters defining the quench space:

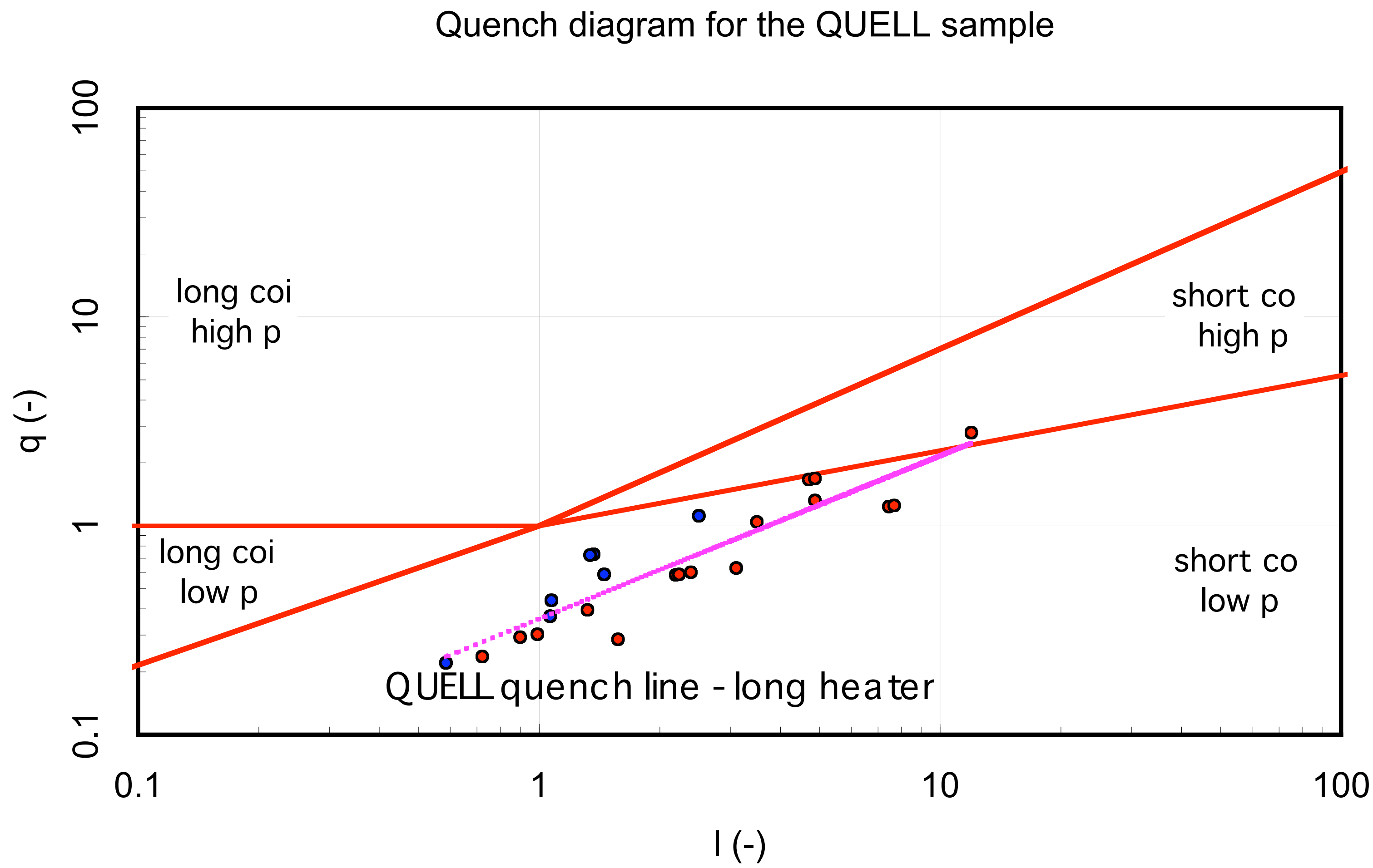
$$l = \frac{\lambda L_q}{L}$$ quench length

$$q = \frac{L_q J_{CS}^{4/3}}{\eta}$$ normal zone heating (quench strength)

definitions:

$$\lambda = 1.7\left(\frac{\rho_0 R T_{max}}{p_0}\right)\left(\frac{c_0^2 \rho_0}{p_0}\right) \qquad \eta = \frac{2.6}{R}\left(\frac{p_0^5}{c_0^2 \rho_0^5 T_{max}} \frac{D_h}{4f} f_{cu}^2 \gamma_0^2\right)^{\frac{1}{3}}$$

(Shajii, Freidberg & Chaniotakis, IEEE Trans. Appl. Sup. 5, 1995)


Quench diagram for the QUELL sample
q (-)
100
10
1
0.1
0.1
1
10
100
l (-)
long coi
high p
short co
high p
long coi
low p
short co
low p
QUELL quench line - long heater

Protection - quench propagation

long coil, high pressure rise

regime boundary	quenchback boundary
$q > 1$ $q > l^{5/6}$	$q > M^{5/3}$

$$v_q = 0.766\left(\frac{f_{he}d}{2K_p f\left(f_{stab}+f_{SC}\right)\tau_q}\right)^{\frac{1}{5}}\left(\frac{RL_q}{c_0}\,\frac{J_{op}^2}{f_{stab}\gamma_0}\right)^{\frac{2}{5}} \propto J_{op}^{4/5}$$

$$\Delta p = \frac{R\rho_0 L_q}{2v_q}\,\frac{J_{op}^2}{f_{stab}\gamma_0} \propto J_{op}^{6/5}$$

short coil, high pressure rise

regime boundary	quenchback boundary
$q > 1.2\, l^{1/3}$ $q < 1.1\, l^{5/6}$	$q > \frac{l^{1/3}}{2}\left[1+\sqrt{1+4(l-M)}\right]$

$$v_q = \left(\frac{f_{he}d}{2K_p f\left(f_{stab}+f_{SC}\right)}\,\frac{RL_q}{L}\,\frac{J_{op}^2}{f_{stab}\gamma_0}\right)^{\frac{1}{3}} \propto J_{op}^{2/3}$$

$$\Delta p = \frac{R\rho_0 L_q}{2v_q}\,\frac{J_{op}^2}{f_{stab}\gamma_0} \propto J_{op}^{4/3}$$

long coil, low pressure rise

regime boundary	quenchback boundary
$q < 0.8$ $q > l^{2/3}$	-

$$v_q = \frac{R\rho_0 L_q}{2p_0}\,\frac{J_{op}^2}{f_{stab}\gamma_0} \propto J_{op}^2$$

$$\Delta p = 1.36\,\rho_0 c_0\left(\frac{2K_p f\left(f_{stab}+f_{SC}\right)\tau_q v_q^3}{f_{he}d}\right)^{\frac{1}{2}} \propto J_{op}^3$$

short coil, low pressure rise

regime boundary	quenchback boundary
$q < 1.2\, l^{1/3}$ $q < l^{2/3}$	$q > M^{1/3}$

$$v_q = \frac{R\rho_0 L_q}{2p_0}\,\frac{J_{op}^2}{f_{stab}\gamma_0} \propto J_{op}^2$$

$$\Delta p = \left(\frac{K_p f\left(f_{stab}+f_{SC}\right)\rho_0 L}{f_{he}d}\right)v_q^2 \propto J_{op}^4$$

(Shajii, Freidberg & Chaniotakis, IEEE Trans. Appl. Sup. 5, 1995) condution at the front:

$$v_{ad} = \sqrt{\frac{J_{op}^2}{\gamma_0^2} \frac{K_{stab}}{\rho_{stab}} \frac{1}{T_{cs} - T_{op}}}$$

☜

(Bottura, Supercond. Sci. Technol., 9, 1996)

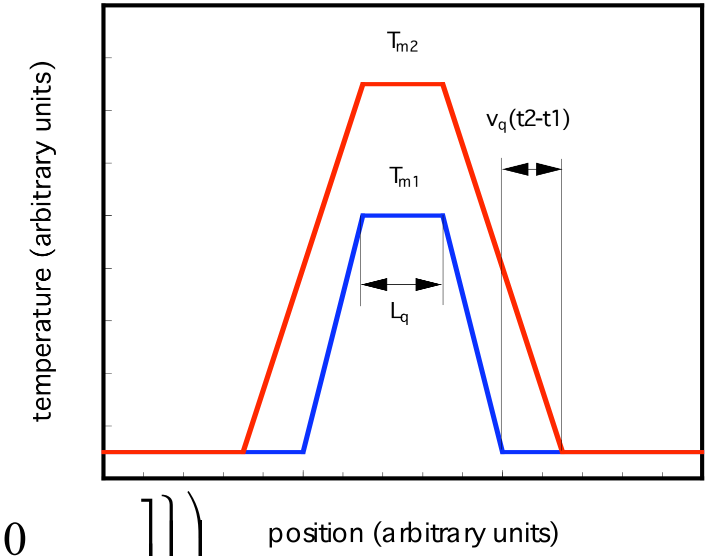
at THQB max pressure:

$$p_{\max} \approx 0.65 f^{0.36} \left(\frac{L^3 K_p}{d} \frac{f_{stab} + f_{SC}}{f_{stab}^2 f_{he}^3} \rho_{stab}^2 J_{op}^4 \right)^{0.36}$$

(J.R.Miller, L.Dresner, J.W.Lue, S.S.Shen, H.T.Yeh, Proc. of ICEC-8, Genova, 1980, 321-329)

☞ normal voltage

(approximate integration of copper resistivity, linear temperature profile)



$$V(t) \approx \frac{J_{CS}}{f_{cu}} \rho_{cu}(T_m) \left(L_q + 2 v_q t \left\{ 1 - 0.3 \left[1 + \frac{T_m - 47.0}{\sqrt{289. + (T_m - 47.0)^2}} \right] \right\} \right)$$