Stability of Cable-in-Conduit-Conductors in Rapidly Changing Magnetic Fields: Experiments and Model Calculations

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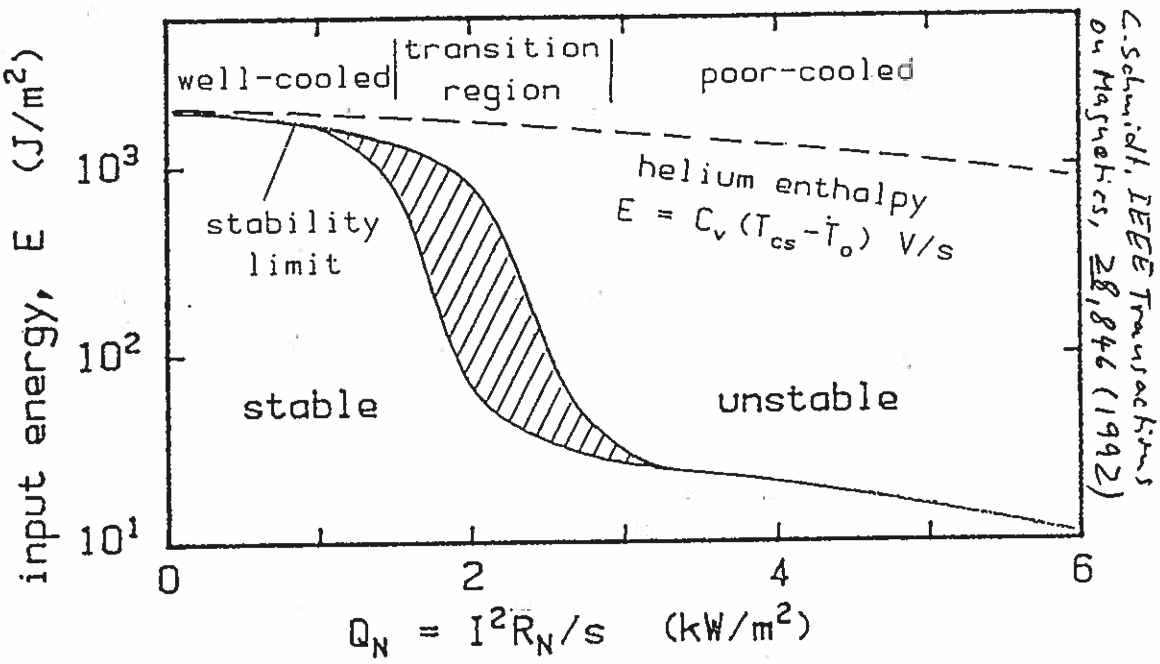
Definition of Problem:

-- Cable in conduit conductors for large sc magnets usually cooled by supercritical helium

-- Consider disturbances extended over large magnet volume, typical case: fast field and/or transport current change, on a time scale ~ 10 ms



Joule's heating in normal state

Stability limit in the poor cooled region:

Problem is easily treated, if these assumptions are fulfilled:

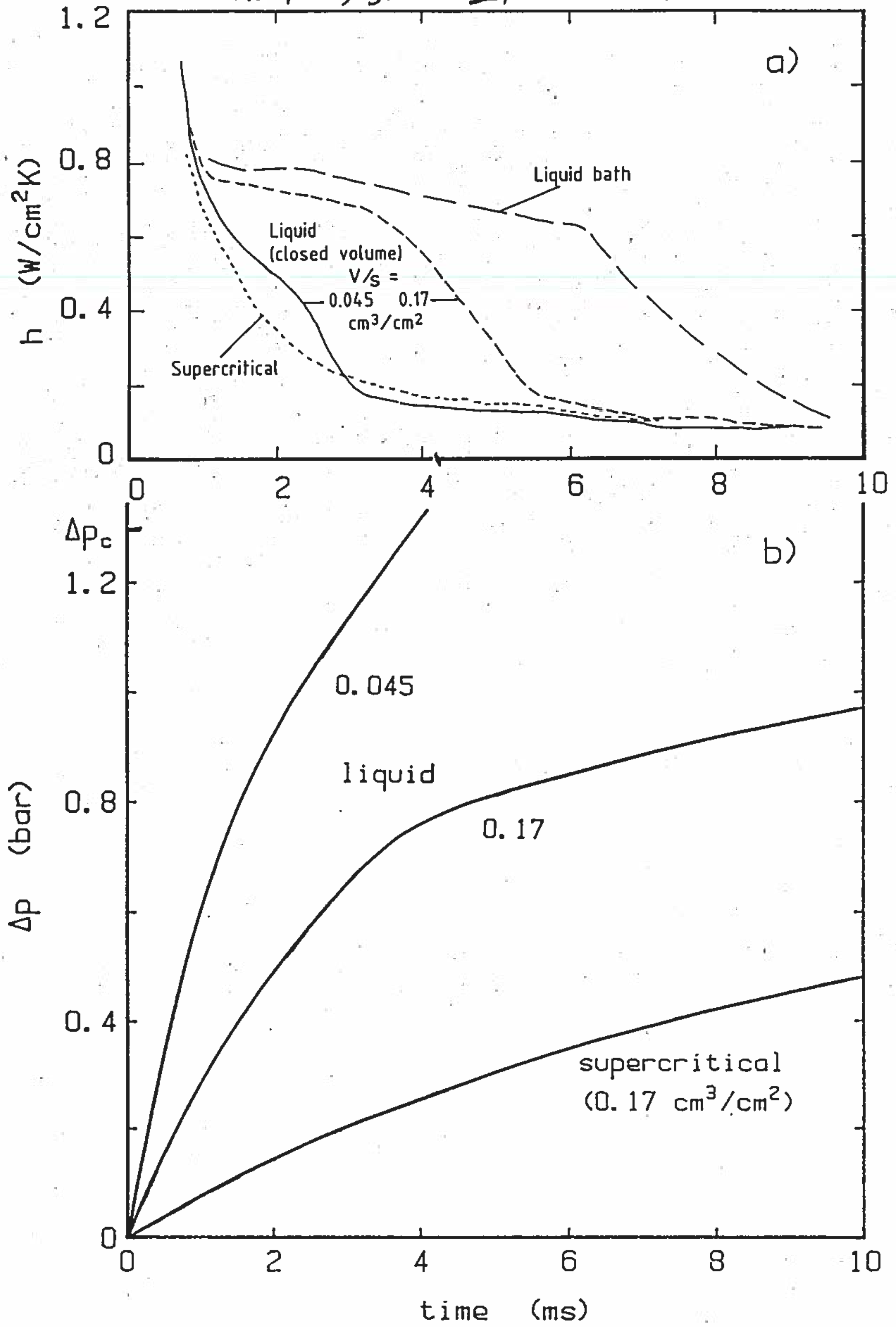
1.) Only extended disturbances considered, not localized (point) disturbances.

2.) Only heat diffusion plays a role, as it is the case for short disturbances (~ 10 ms). Convection is not considered.

3.) Induced flow effects are neglected. They are most important for point disturbances and on a longer time scale. (Transient heat transfer coefficient in the millisecond range does not depend much on mass flow).

4.) Heat capacity of conductor materials is neglected for convenience. Heat capacity of helium is usually much higher.

c. Schmidt, Cryogenics 31, 618 (1991)



INFLUENCE OF TRANSIENT HEAT TRANSFER ON STABILITY

External disturbances:

- localized (point) disturbances (e.g. mechanical origin)
- extended disturbances; energy input on a conductor length >> minimum propagation zone length (e.g. fast magnetic field change)

Here: Only second case considered. Problem easily treated quantitatively, calculation of stability limit directly used as a design criterion.

Liquid helium

Stability criterion is onset of film boiling, at time $t_f \propto Q^{-2}$
Total transferred energy per unit surface area, for constant heat flux

$$E \leq 0.083 \ [\mathrm{J\ cm^{-2}\ s^{-1/2}}] \sqrt{t_f} \qquad (1)$$

Closed volume of liquid helium

If transition to film boiling, same criterion as above (neglecting pressure dependence of heat of vaporization)
If the pressure rises to p_c before onset of film boiling, criterion is attainment of p_c.
p_c is reached after measured heat input per unit helium vol. of

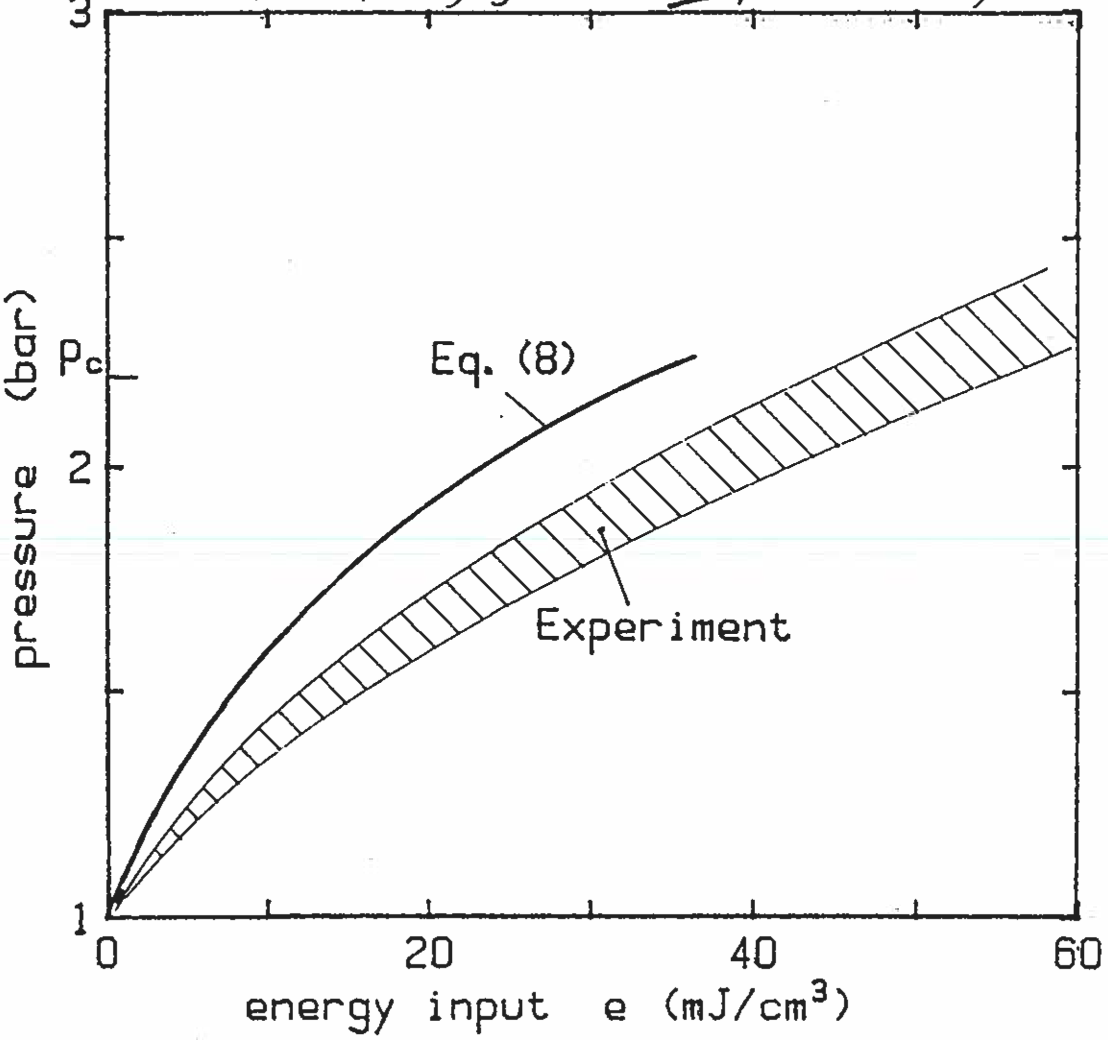
$$e = 0.053 \ \mathrm{J/cm^3}.$$

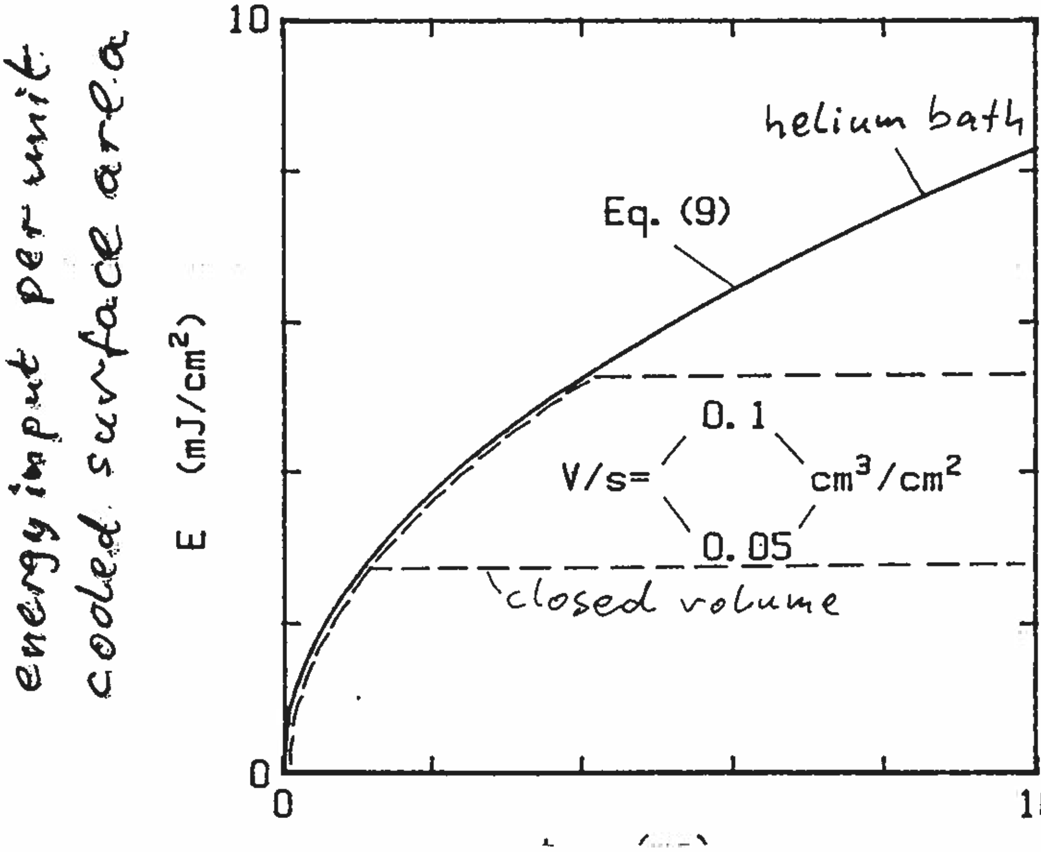
or multiplying by volume to surface ratio,

$$E \leq 0.053 \ [\mathrm{J\ cm^{-3}}] \ V/s \qquad (2)$$

The combination of Eq.(1) and Eq.(2) gives the stability limit as a function of the duration of disturbance

C. Schmidt, Cryogenics 31, 618 (1991)

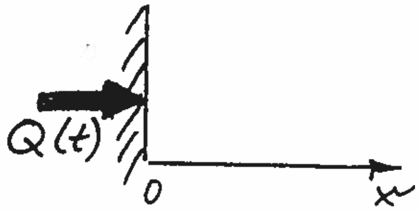




Solution of equation of linear heat flow

Consider a semi-infinite medium at $x > 0$,

and a heat flux per unit surface area $Q(t)$



Surface temperature at $x = 0$ becomes

$$T(t) = T_o + (\pi k C)^{-1/2} \int_0^t Q(t - \theta)\theta^{-1/2} d\theta$$

Three different types of heat load as examples:

$Q = Q_o$	for $t < t_o$	constant,
$Q = 2Q_o \cos^2 (\pi/t_o)t$	for $t < t_o$	cosine square
$Q = Q_o e^{-t/t_o}$		exponential

Total energy input: $E = \int_0^\infty Q\, dt = Q_o t_o$ (same for all cases)

Analytical solution only for case 1: $\Delta T(t) \propto \sqrt{t}$

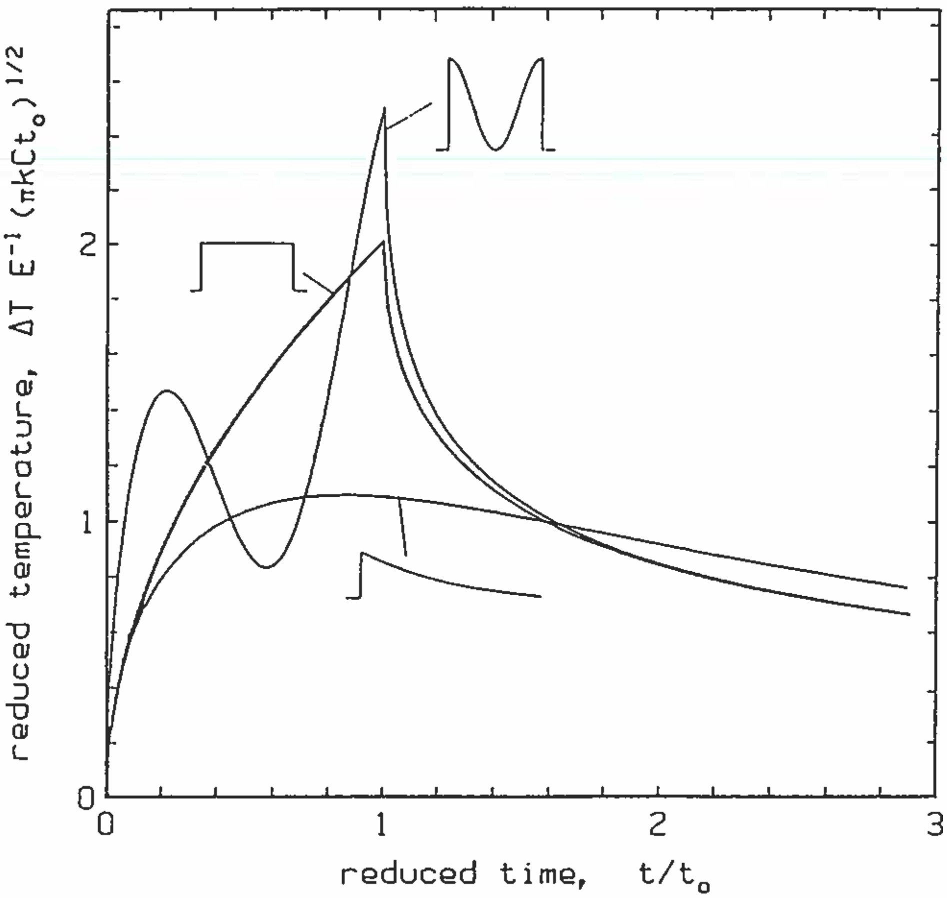
Case 2 is for sinusoidal magnetic field pulse

Case 3 for exponential magnetic field variation

$$B = B_o + \Delta B\, e^{-t/t_b}$$

Because of $Q \propto \dot{B}^2$, time constant of heat load is half of that of field variation, $t_o = t_b / 2$

Temperature traces of the solid surface for the three types of heat load:



The maximal temperatures are

$$\Delta T_m = \begin{matrix} 2 \\ 2.49 \\ 1.08 \end{matrix} \quad E\ (\pi\, k\, C\, t_0)^{-1/2} \qquad \begin{matrix} \text{for constant,} \\ \text{for cosine square,} \\ \text{for exp. heat load} \end{matrix}$$

The most simple **stability criterion** would be

$\Delta T_m < \Delta T_{cs}$ (current sharing temperature)

In this case the conductor never becomes normal. It is, however, a conservative criterion for constant and cosine square heat input. A small contribution of Joule's heating may not prevent recovery.

Up to here Joule's heating was not taken into account.

Summary of Stability Model

1 Calculate the recovery current using

$$I_R = [\, h\, [T_c(B) - T_o]\, s/R\,]^{1/2}$$

s:	cooled surface area
R:	normal state resistance
h:	heat transfer coefficient

According to the model, at transport currents below I_R the stability is only limited for the closed volume case by the available helium volume.

2 Above I_R, one has to distinguish between the cooling modes.

(a) ***Pool boiling helium***: The condition of stability gives as energy input per unit cooled surface area

$$E \leq 0.083\ [\mathrm{Jcm^{-2}\, s^{-1/2}}]\ t_d^{1/2}, \tag{1}$$

where t_d is duration of disturbance. E does not depend on I. The region near to I_c, where the stability limit approaches zero, is not considered here.

(b) ***Supercritical helium***: The stability limit is given by

$$E \leq 0.007\ [\mathrm{Jcm^{-2}\, s^{-1/2}\, K^{-1}}]\ t_d^{1/2}\ (T_1 - T_o) \tag{2}$$

where T_1 is a temperature between T_o and T_{cs}. Replace T_1 for a first approximation by the current sharing temperature, $T_{cs}\,(I,B)$.

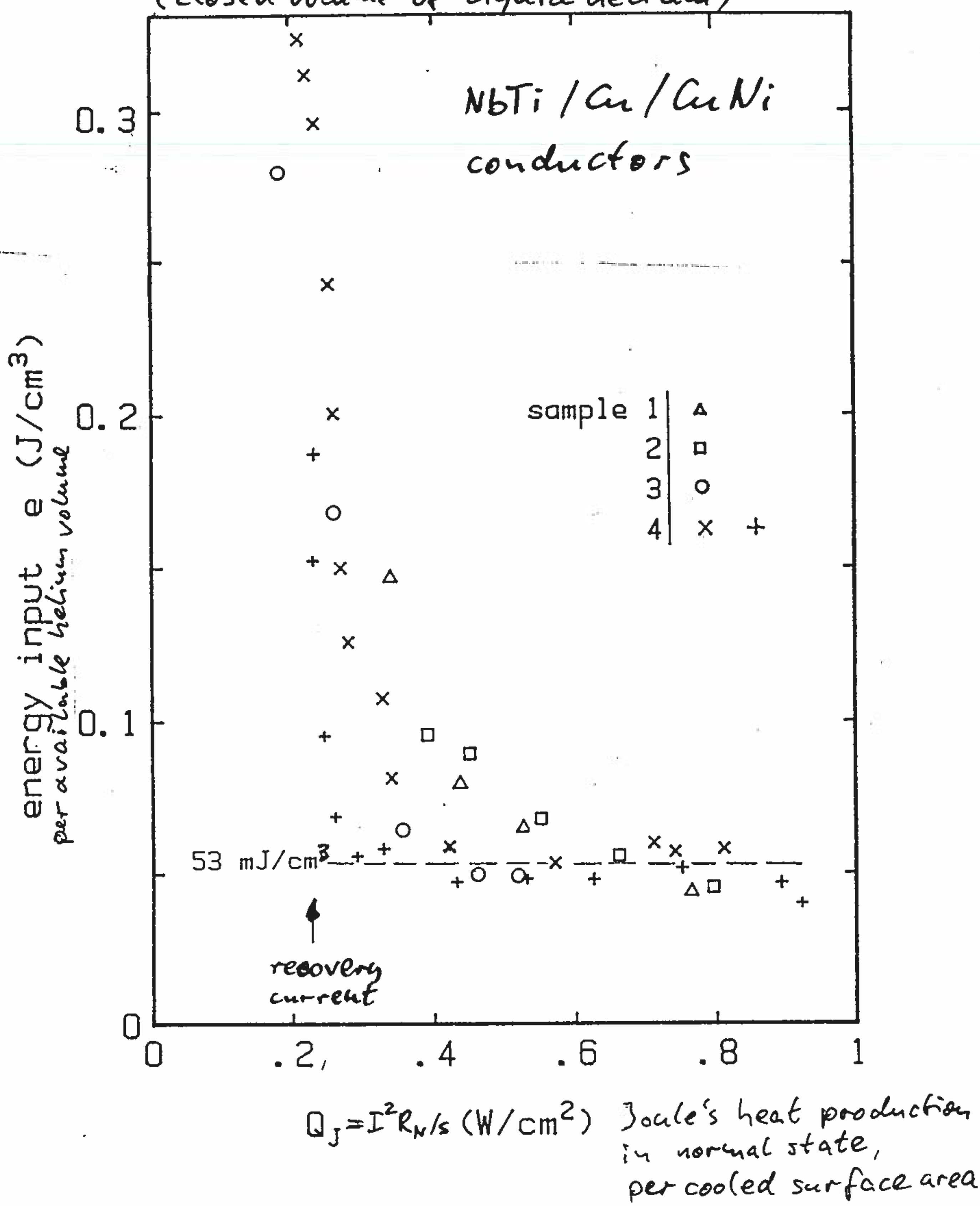
(c) ***Liquid helium in a closed volume***: The criterion here is that the disturbance energy does not lead to a pressure increase above critical pressure (2.2 bar). It depends only on the available helium volume. Energy input per unit helium *volume:*

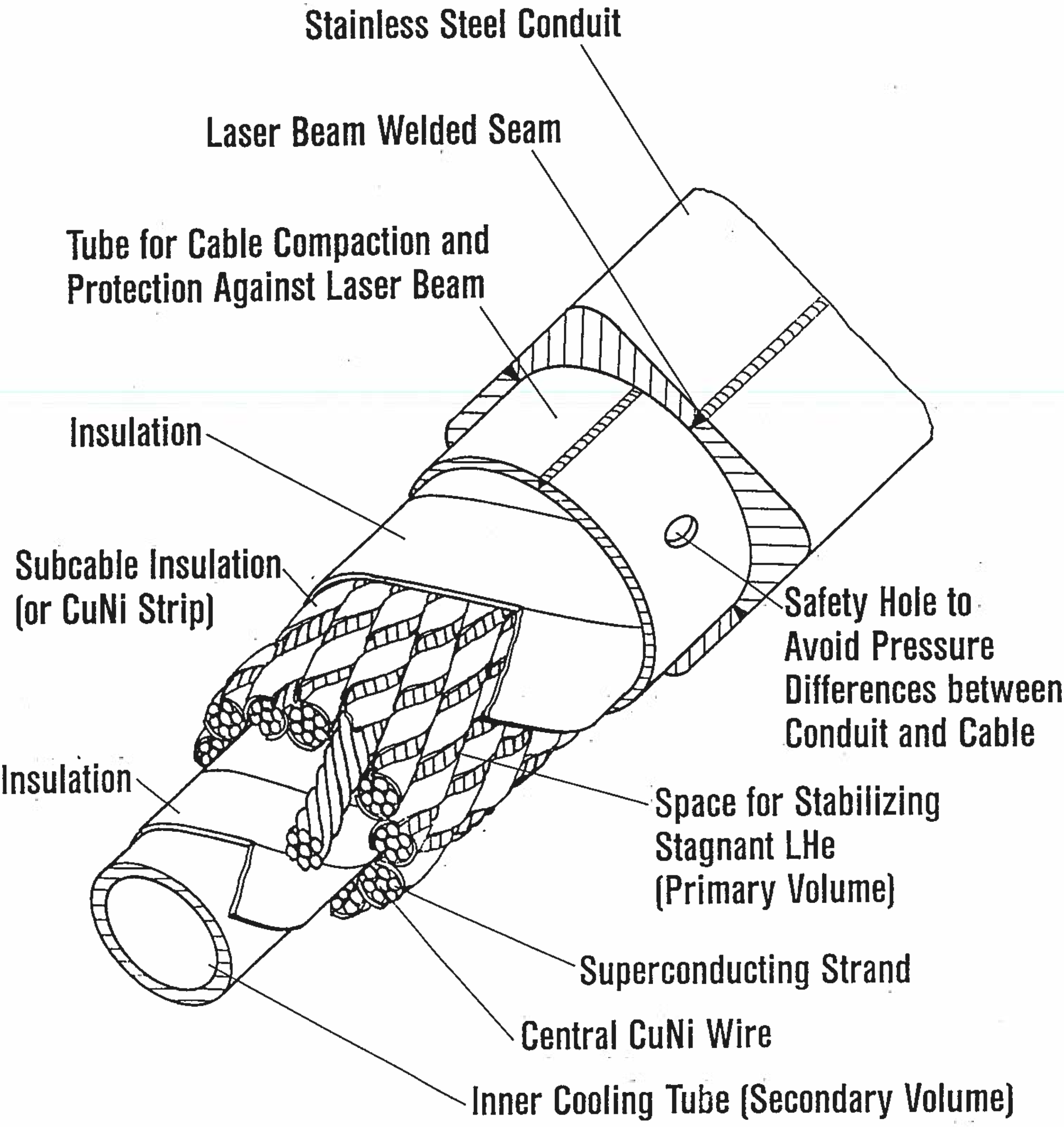
$$e \leq 53\ \mathrm{mJ/cm^3} \tag{3}$$

This approach is applicable if it gives higher values than that for supercritical helium (Eq. 2), and lower values than that for liquid bath cooling (Eq. (1)).

C. Schmidt, Cryogenics 30, 501 (1990)

Strand stability experiment
(closed volume of liquid helium)



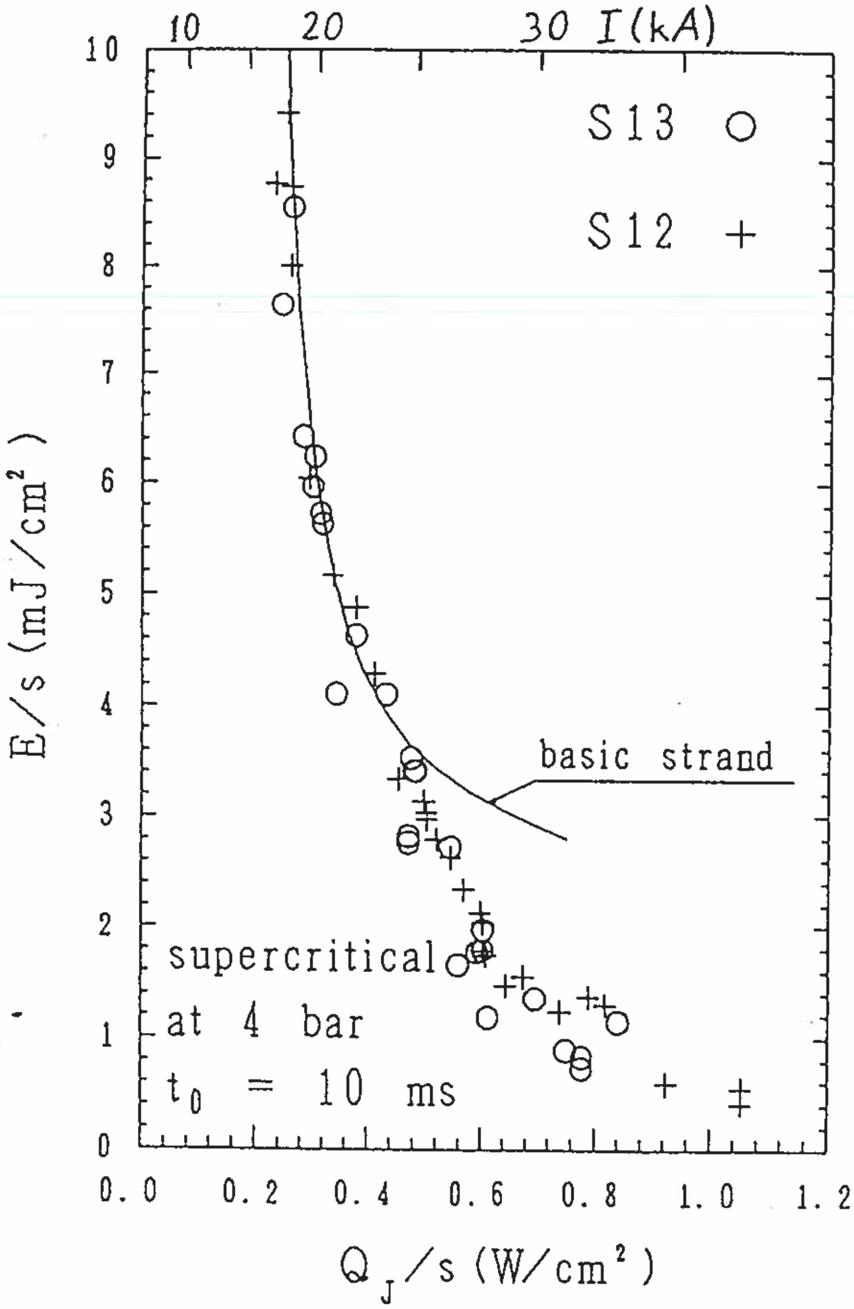


KfK

Polo Superconductor for Poloidal Field Coil Applications in Tokamaks

H.Tateishi, C. Schmidt, Cryogenics 33, 615 (1993)

Cable Stability Experiment



Stability limit in a half cycle sinusoidal external magnetic field pulse of 10 ms duration.

Comparison with strand experiment shows good agreement in the lower current range (below ~22 kA), but a sharp deviation in the upper current range.

Discussion of Reduced Stability in the Upper Current Range

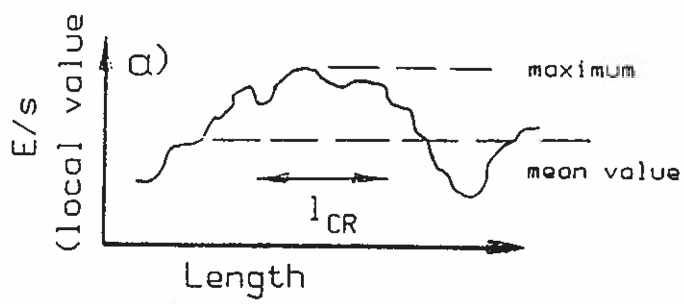
Two mechanisms may be responsible for reduced stability, but only a qualitative discussion can be given here

a) INHOMOGENEOUS DISTRIBUTION OF ENERGY DISSIPATION DURING FIELD PULSE:

In the model calculation a homogeneous energy flow across the cooled surface was tacitely assumed. This is not strictly true. Coupling losses between strands and between subcables occur locally, at the contacts.

Local loss values depend on contact resistances which show a large scattering.

Let us schematically trace the local energy dissipation over length:

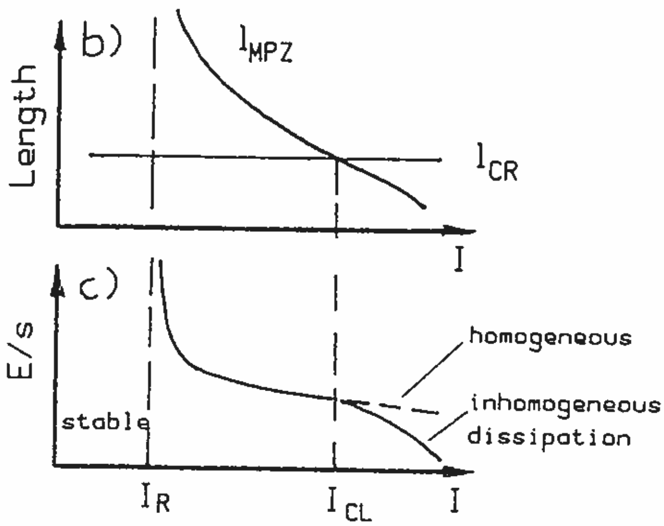


Let us assume that contact resistances and hence local dissipation fluctuate with some typical length ℓ_{CR}. Within ℓ_{CR}, the dissipation is supposed to be approximately constant. A typical value of ℓ_{CR} could be the subcable cabling length (~ 3.7 cm).

Now let us consider a minimum propagation zone length ℓ_{MPZ}, expressed, e.g., by the one dimensional correlation

$$\ell_{MPZ} = \sqrt{\frac{2\kappa\,(T_c - T_o)}{j^2 \rho}}.$$

It is a function of transport currents, while ℓ_{CR} is not.



If $\ell_{MPZ} > \ell_{CR}$, the <u>mean</u> energy dissipation determines stability.
For $\ell_{MPZ} < \ell_{CR}$, stability is determined by the <u>local</u> maximum of energy dissipation, which must not exceed the calculated limit.

<u>In summary</u>:
- Very high stability below I_e.
- Stability given by model calculation between I_R and I_{CL}.
- Reduced stability compared to stability model above I_{CL}.

b) INHOMOGENEOUS CURRENT DISTRIBUTION:

This leads, following a very similar argumentation, to a reduced stability margin in the upper current range:

– Current redistribution is possible if current is low enough.
– If current is too high, quench develops quicker than redistribution occurs.

Current distribution is determined by:
- Mutual inductances between strand/subcables.
- Contact resistances to the current leads at the ends.
- Geometry effects in case of not perfect transposition.

The current distribution during ramp-up of a magnet is mainly determined by inductances and geometry.
Thereafter the current distribution determined by the end resistances diffuses into the coil.

Quantitative description would require the knowledge of many parameter, which are usually not well known.

References:

C. Schmidt, "Stability of superconductors in rapidly changing magnetic fields", Cryogenics, 30, 501 (1990)

C. Schmidt, "Transient heat transfer to a closed volume of He I and its influence on superconductor stability", Cryogenics 31, 618 (1991)

C. Schmidt, "Stability of superconductors cooled by supercritical helium in rapidly changing fields", IEEE Trans. Magn. 28, 846 (1992)

H. Tateishi, C. Schmidt, "Experimental study of stability against magnetic pulse fields of the KFK poloidal field coil cable", Cryogenics 33, 615 (1993)