Luca Bottura
The NET Team

"Criteria for Stability-Based Design of CICC's"

Criteria for Stability Based Design of CICC's

L. Bottura

Introduction: Optimization

- Optimization is cost-effective

  Efficient use of material and margin

- Optimization spares analysis time aiming at the required performance.

  No trial-&-error required

How beautiful !

we are all looking for

- Design Criteria to be used to achieve the required performance in terms of stability margin.

3. Stability

ITER

☛ energy inputs:

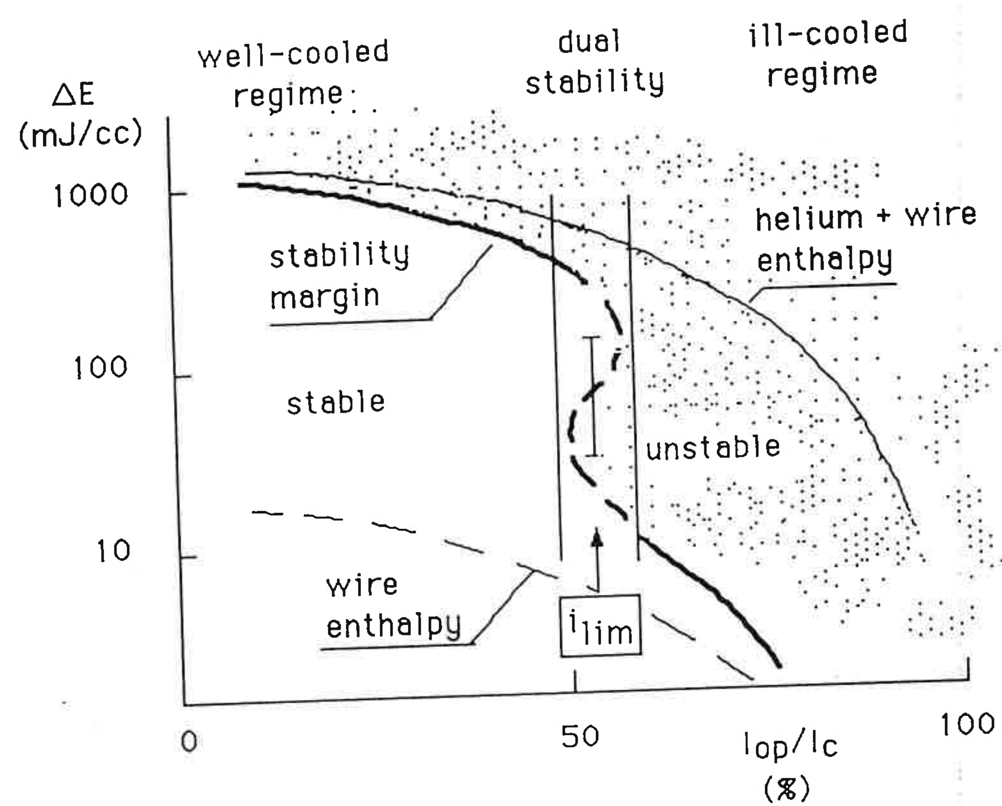
- AC Losses (transverse coupling loss) ≈ 150 (450) mJ/cc ($\dot{B} \approx 40 \frac{T}{s}$)
- mechanical energy release ≈ 50 mJ/cc

total ≈ 200 mJ/cc (500)

- copper enthalpy 4.5-6.5 K ≈ 3 mJ/cc of Cu
- helium enthalpy 4.5-6.5 K ≈ 2000 mJ/cc of He

Efficient use of the helium for stabilization is the fundamental characteristic of a CICC

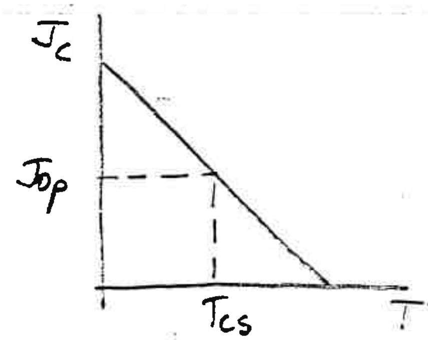
Schematic view of behaviour of the stability margin as a function of the operating current fraction



ENERGY MARGIN (0-th order approximation)

(*) $$\Delta E = \frac{A_{He}}{A_{cs}-A_{He}} \rho C_p (T_{cs}-T_{op})$$

(**) $$T_{cs} = (1-i)\,T_c + i\,T_{op}$$



$$i = \frac{I_{op}}{I_c} = \frac{J_{op}}{f_{nc}\,J_c}$$

use (**) in (*) to get:

(***) $$\Delta E = \frac{f_{He}}{1-f_{He}} \rho C_p (T_c-T_{op}) \left(1 - \frac{J_{op}}{f_{nc} J_c}\right)$$

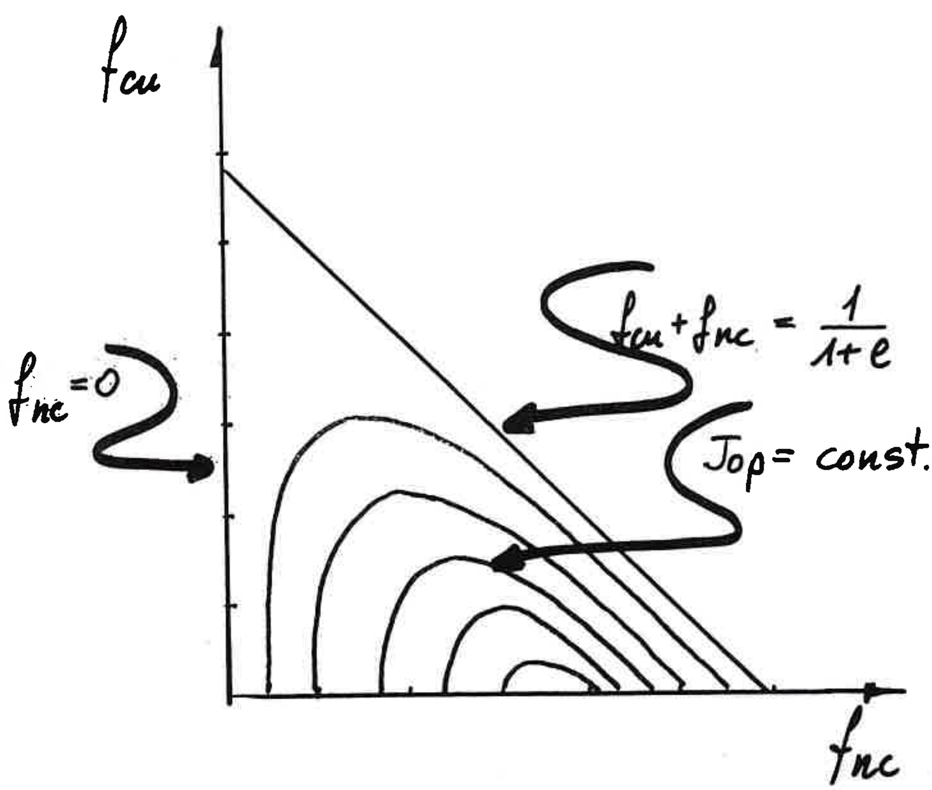
$$J_{op} = J_c\, f_{nc} \left[1 - \frac{f_{cu}+f_{nc}}{1-(f_{cu}+f_{nc})} \frac{\Delta E}{\rho C_p (T_c-T_{op})}\right]$$

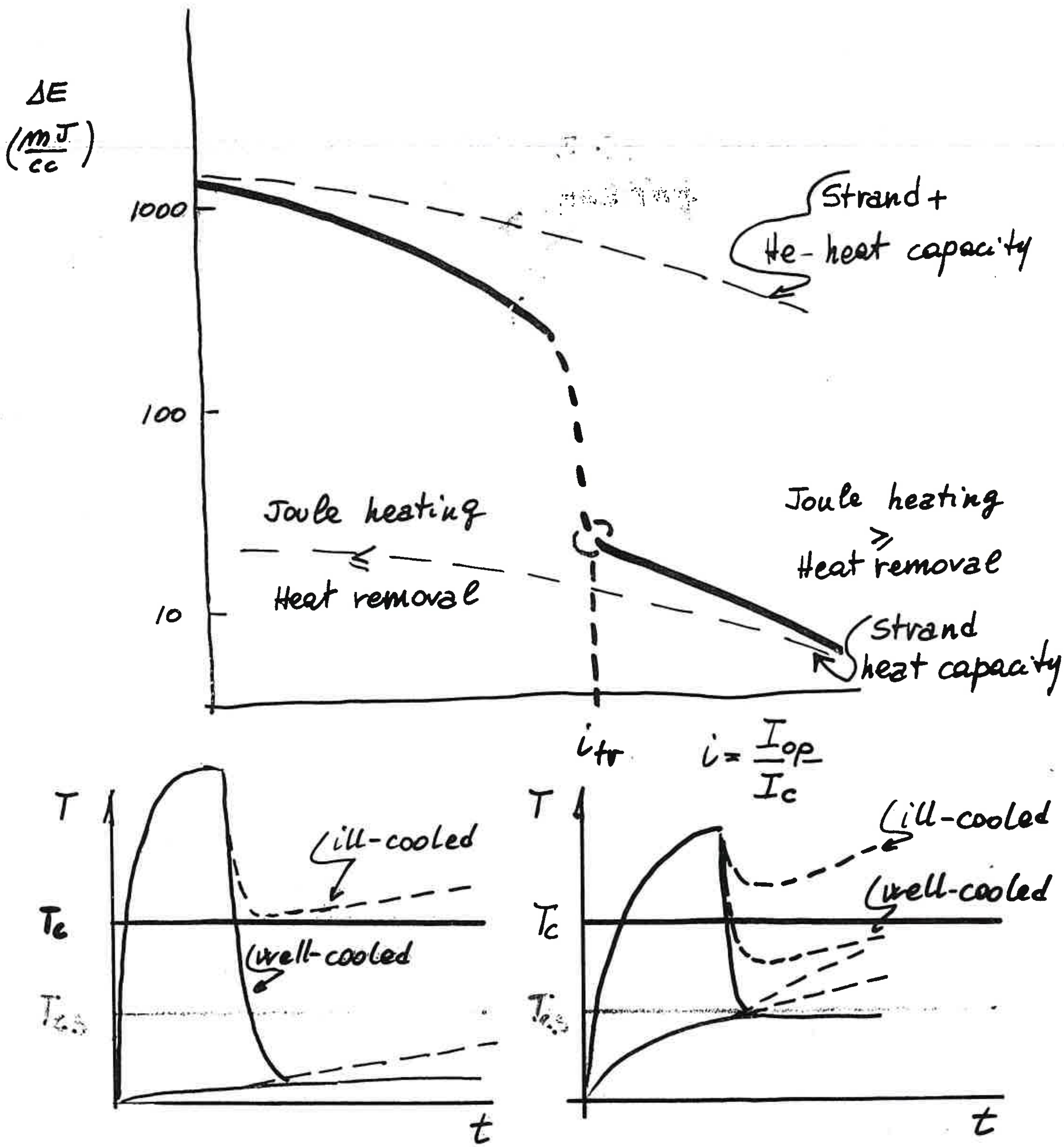
J_{op} is a surface in (f_{cu}, f_{uc}) plane

$J_{op} = 0$ for:

- $f_{uc} = 0$
- $f_{cu} + f_{uc} = \dfrac{1}{1+e}$

$$e = \frac{\Delta E}{\rho c_p (T_c - T_{op})}$$





ΔE
(mJ/cc)
1000
100
10
Strand + He-heat capacity
Joule heating ≤ Heat removal
Joule heating ≫ Heat removal
Strand heat capacity
i_tr
i = I_op / I_c
T
T_c
T_cs
ill-cooled
well-cooled
t
T
T_c
T_cs
ill-cooled
well-cooled
t

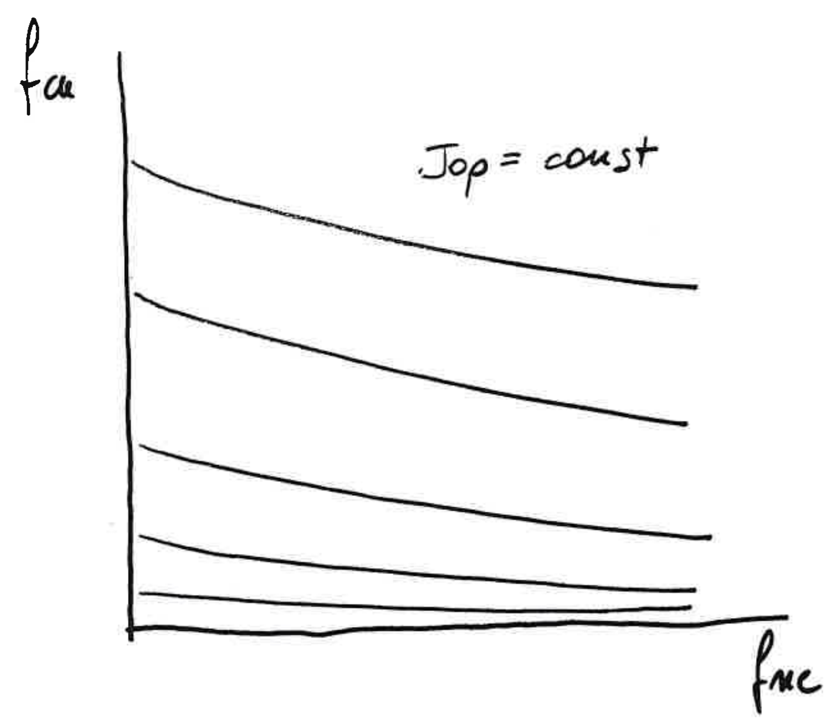
WELL-COOLED OPERATION

$$\eta \frac{J_{op}^2}{A_{cu}} = p\, h\, (T_c - T_{op})$$

$$p = k_p N_{st}\, \pi d = 4 \frac{k_p}{d} N_{st} \frac{\pi d^2}{4} = \frac{4 k_p}{d} (A_{cu} + A_{nc})$$

$$\boxed{J_{op} = \sqrt{\frac{4 k_p}{\eta d} h\, (T_c - T_{op})\, f_{cu} (f_{cu} + f_{nc})}}$$

$J_{op} = 0$ for $f_{cu} = 0$



SUPER-COOLED OPERATION

$$(*) \quad \eta \frac{I_{op}^2}{A_{cu}} = p h (T_c - T_{cs})$$

$$T_c - T_{cs} = i (T_c - T_{op}) = \frac{I_{op}}{A_{nc} J_c} (T_c - T_{op})$$

for $I_{op} \leq I_c$

$$(**) \quad \eta \frac{I_{op}}{A_{cu}} = p h \frac{T_c - T_{op}}{A_{nc} J_c}$$

from (**)

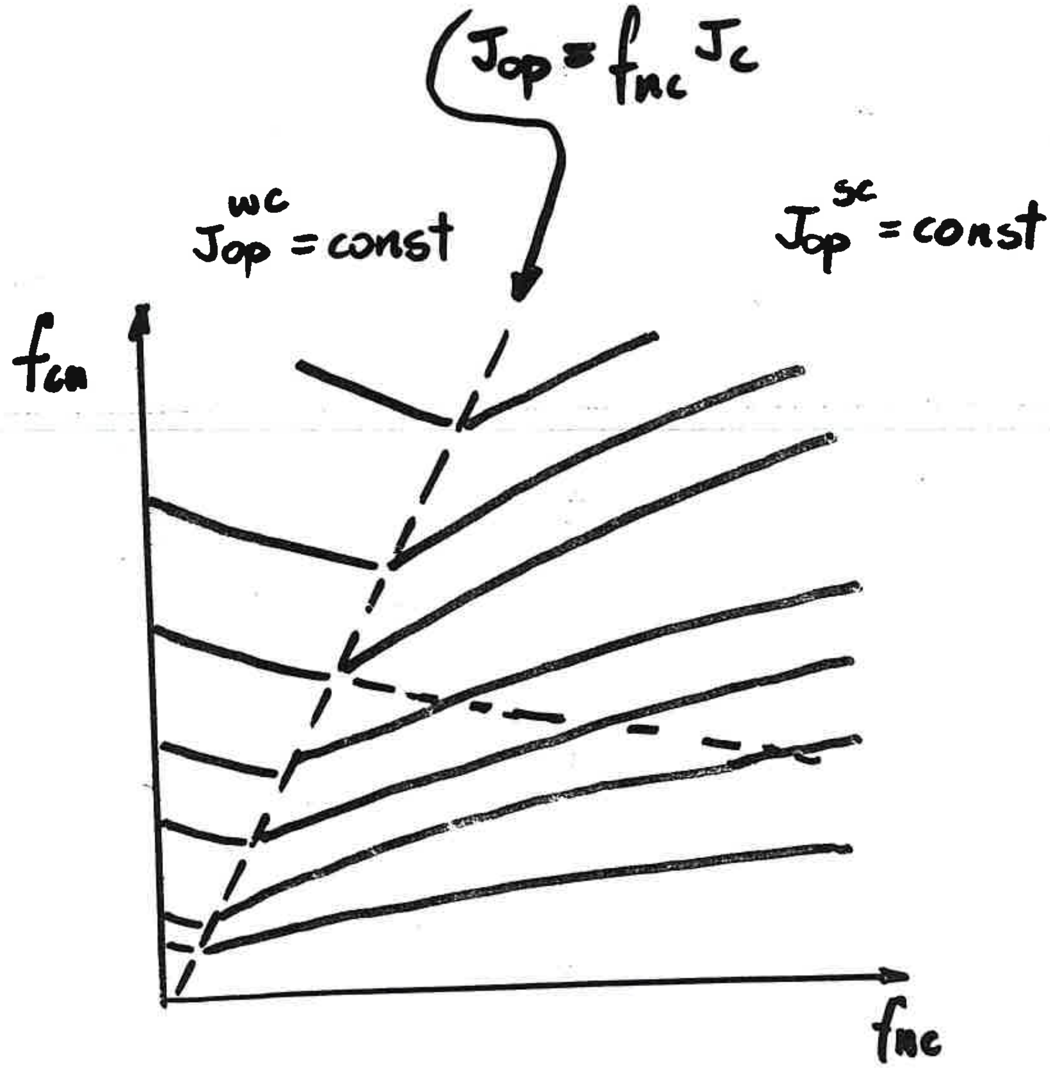
$$\boxed{J_{op} = \frac{4 k_p}{\eta d} h \frac{(T_c - T_{op})}{J_c} \frac{f_{cu} (f_{cu} + f_{nc})}{f_{nc}}}$$

with the conditions

$$f_{nc} J_c \geq \frac{4 k_p}{\eta d} h \frac{(T_c - T_{op})}{J_c} \frac{f_{cu} (f_{cu} + f_{nc})}{f_{nc}}$$

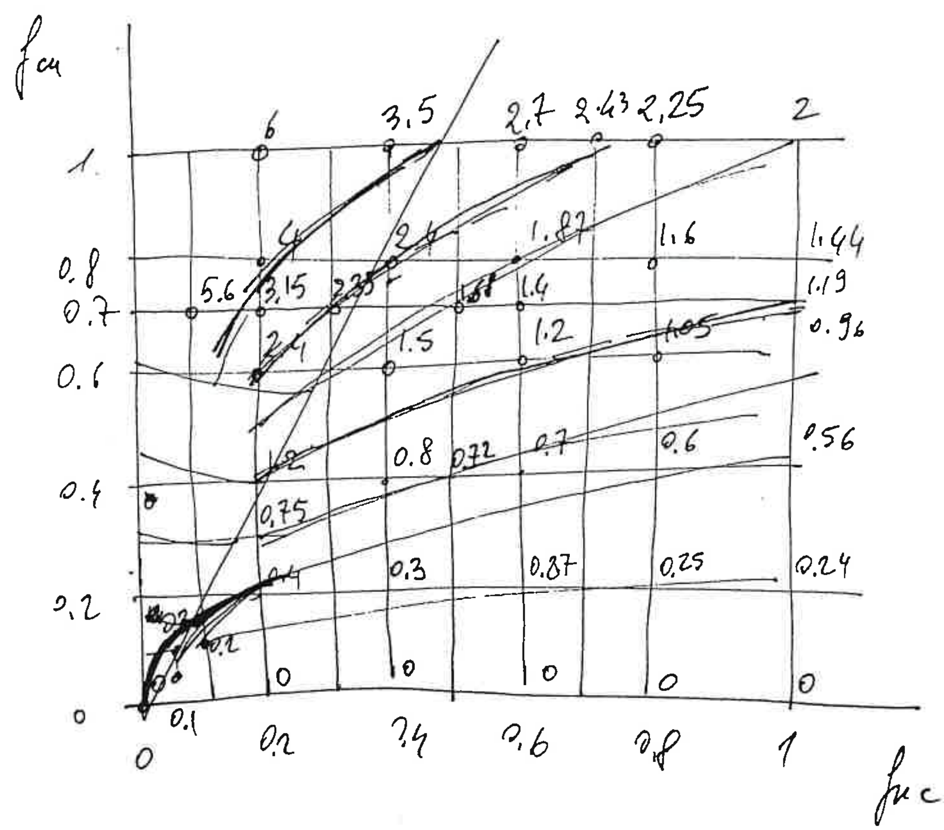
define $$\alpha_J = \frac{J_c^2}{\frac{4 k_p}{\eta d} h (T_c - T_{op})}$$

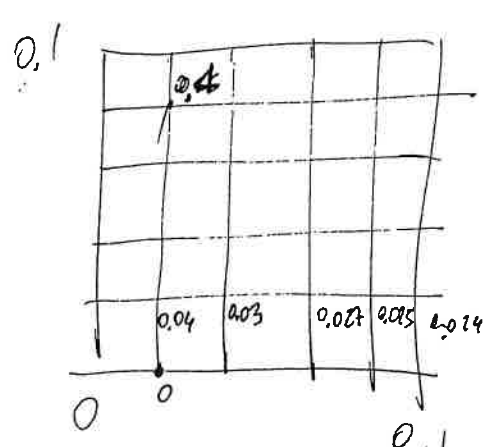
$$f_{cu} \leq \left(\sqrt{\frac{1}{4} + \alpha} - \frac{1}{2} \right) f_{nc}$$


$J_{op} = f_{nc} J_c$
$J_{op}^{wc} = const$
$J_{op}^{sc} = const$
f_{cn}
f_{nc}

$$J_{op} = \cos\theta \; \frac{4K_p}{\eta\, d} \; \frac{h\,(T_c - T_{op})}{J_c} \qquad \frac{\rho_{cu}\,(\rho_{cu} + \rho_{uc})}{\rho_{uc}}$$

$$J_{op} \propto \frac{\rho_{cu}\,(\rho_{cu} + \rho_{uc})}{\rho_{uc}}$$





Criteria Summary

Well-cooled operation

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

Super-cooled operation

$$J_{op} = \cos(\theta)\frac{4K_p}{\eta d}\frac{h\left(T_c - T_{op}\right)}{J_c}\frac{f_{cu}\left(f_{cu} + f_{nc}\right)}{f_{nc}}$$

Available heat capacity

$$J_{op} = \cos(\theta) J_c f_{nc}\left(1 - \frac{f_{cu} + f_{nc}}{1 - \left(f_{cu} + f_{nc}\right)}\frac{\Delta E}{\rho C_{He}\left(T_c - T_{op}\right)}\right)$$

Set of parameters used in the examples (cont'd)

Limits of operation

Required energy margin	500.0	(mJ/cm^3)
Hot-spot temperature	150.0	(K)
Quench pressure	250.0	(bar)
Dump time constant	10.0	(s)

Set of parameters used in the examples (cont'd)

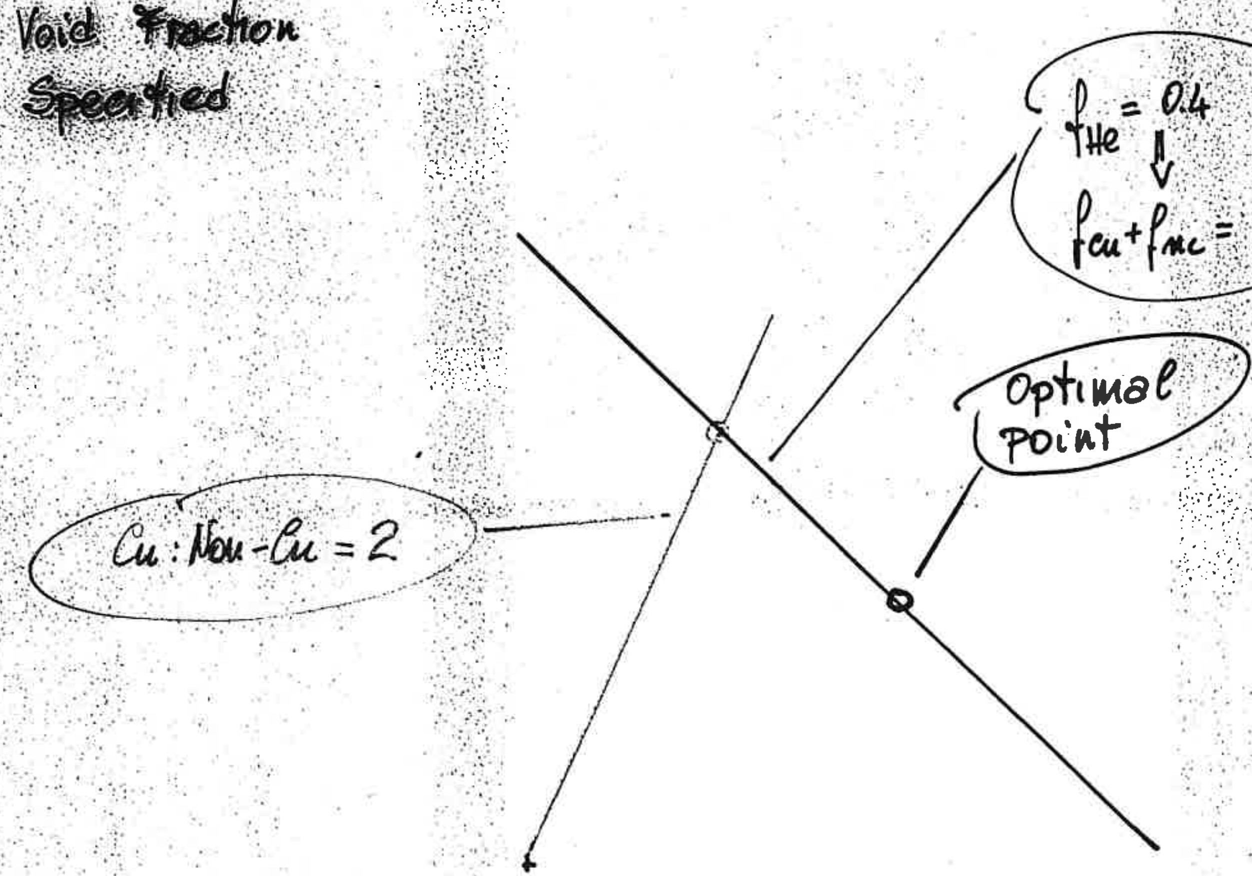
Operating conditions

Magnetic field	12.0	(T)
Helium temperature	4.5	(K)
Helium pressure	5.0	(bar)
Strain	-0.6	(%)
Average heat transfer coefficient	800.0	(W/m2K)
Average friction factor	0.01	(-)

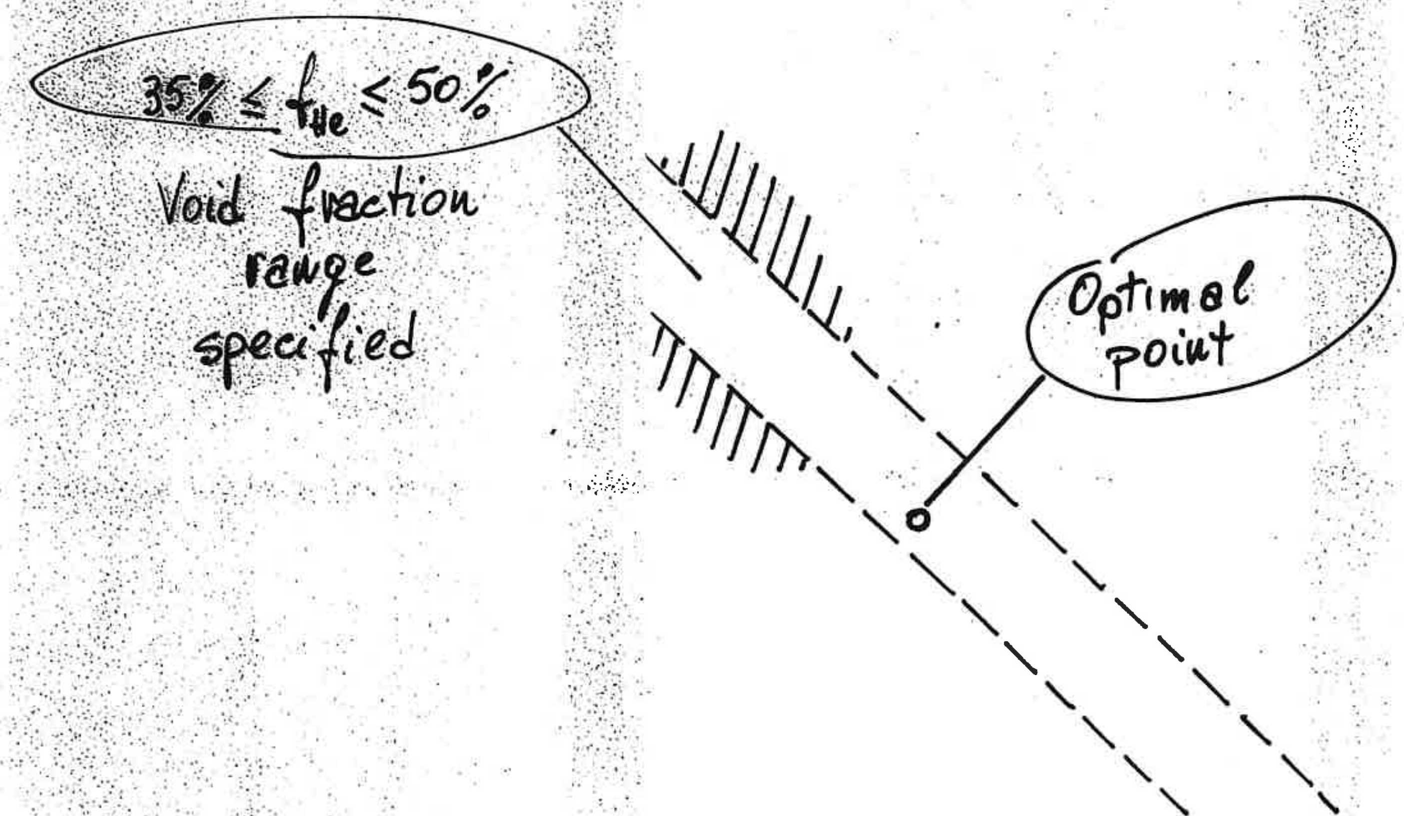
Set of parameters used in the examples

Conductor characteristics

Superconducting material	Nb_3Sn	
Critical current density	490	(A/mm^2)
Critical temperature	8.5	(K)
(both at B=12 (T), T= 4.5 (K), ε=-0.6 (%))		
Residual Resistivity Ratio (RRR)	100.0	(-)
Strand diameter	0.75	(mm)
Void fraction	40	(%)

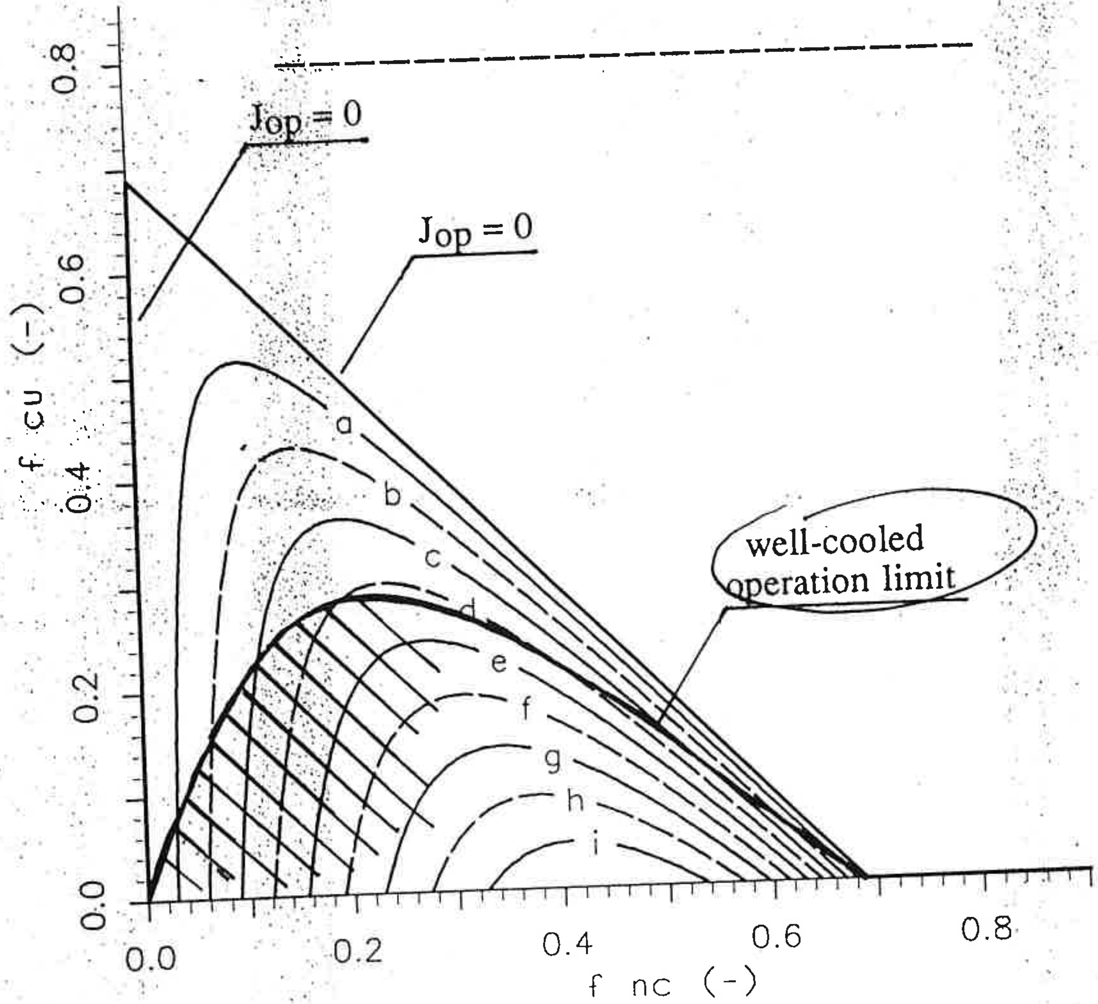


Void Fraction Specified
$f_{He} = 0.4$
$f_{cu} + f_{nc} = 0.6$
Optimal point
Cu : Non-Cu = 2



35% ≤ f_He ≤ 50%
Void fraction range specified
Optimal point

Maximum allowable cable space operating current density in the f_{cu}-f_{nc} plane



	J_{op} (A/mm^2)
a	13.8
b	27.6
c	41.4
d	55.2
e	69.0
f	82.8
g	96.6
h	124.2
i	138.0

1. @ f_{HE} = const.

$J_{op} \uparrow$ for $f_{CU} \downarrow$ / $f_{MC} \uparrow$

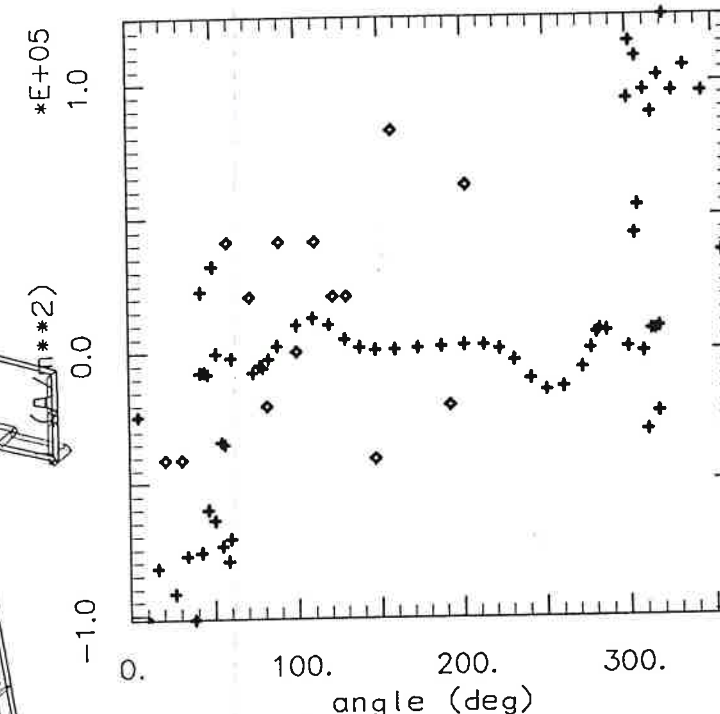
2. @ f_{MC} = const

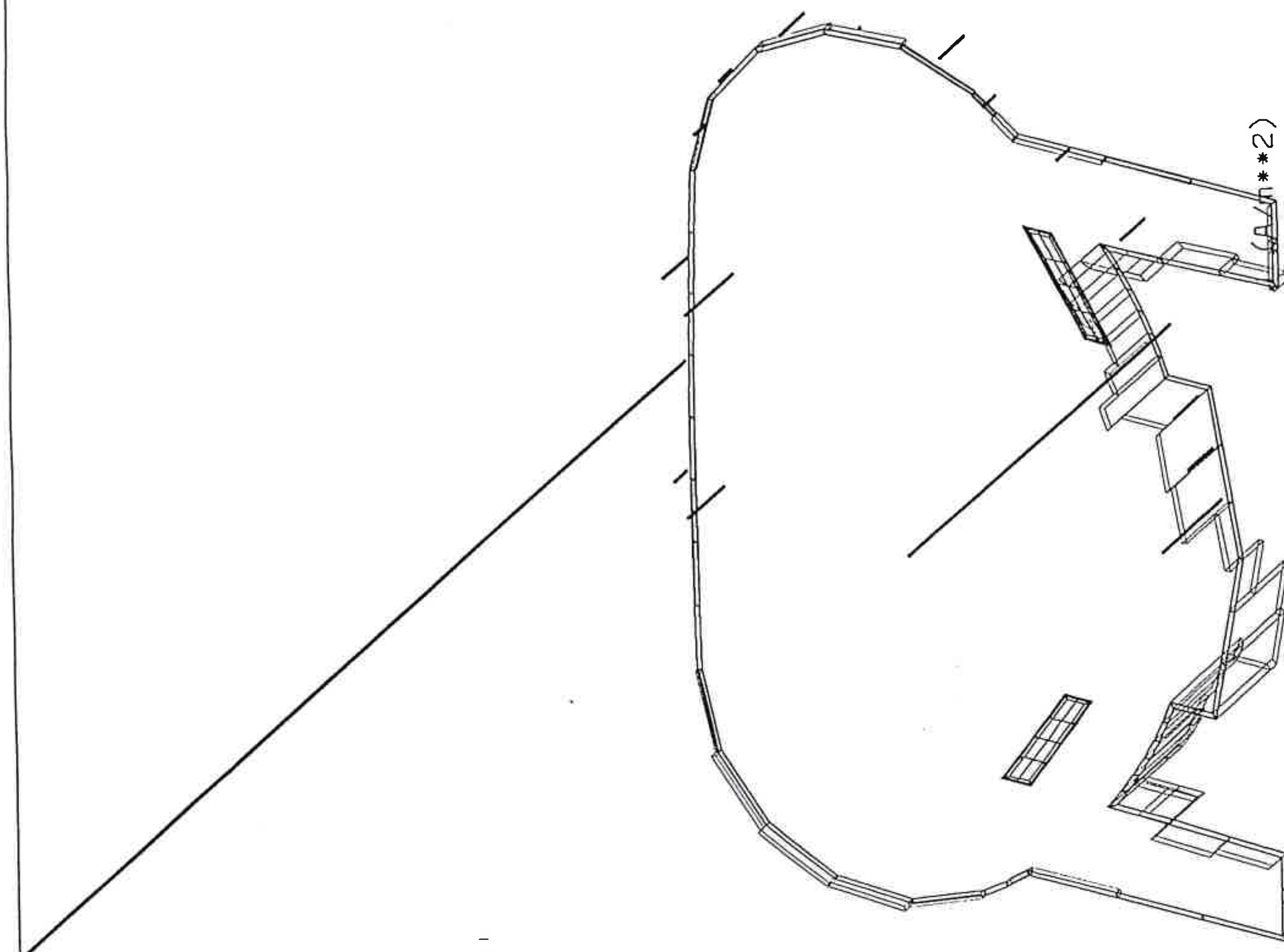
$J_{op} \uparrow$ for $f_{CU} \downarrow$

3. @ f_{CU} = const

$J_{op}(f_{NC})$ has a maximum

J_{op} is max when (1.+2.) f_{CU} is the min necessary





Cut number : 3 angle (deg) : 10.0000

Time : 4.40000E-02

constant ρ_{uc}

$J \uparrow$ at $\rho_{cu} \downarrow$ / $\rho_{uc} \uparrow$

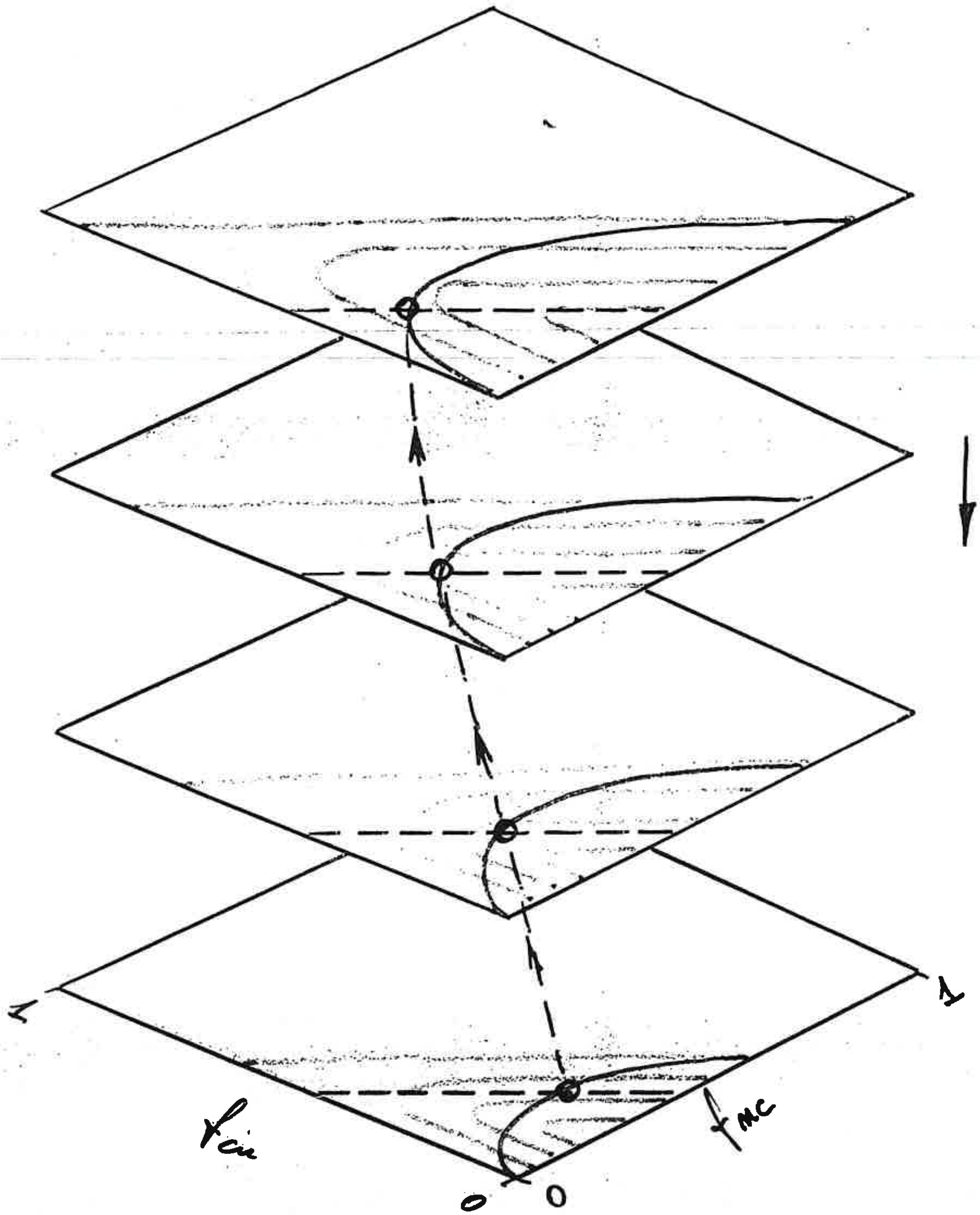
$\rho_{uc} = const$  $J \uparrow$ $\rho_{ca} \downarrow$

$\rho_{a} = const$

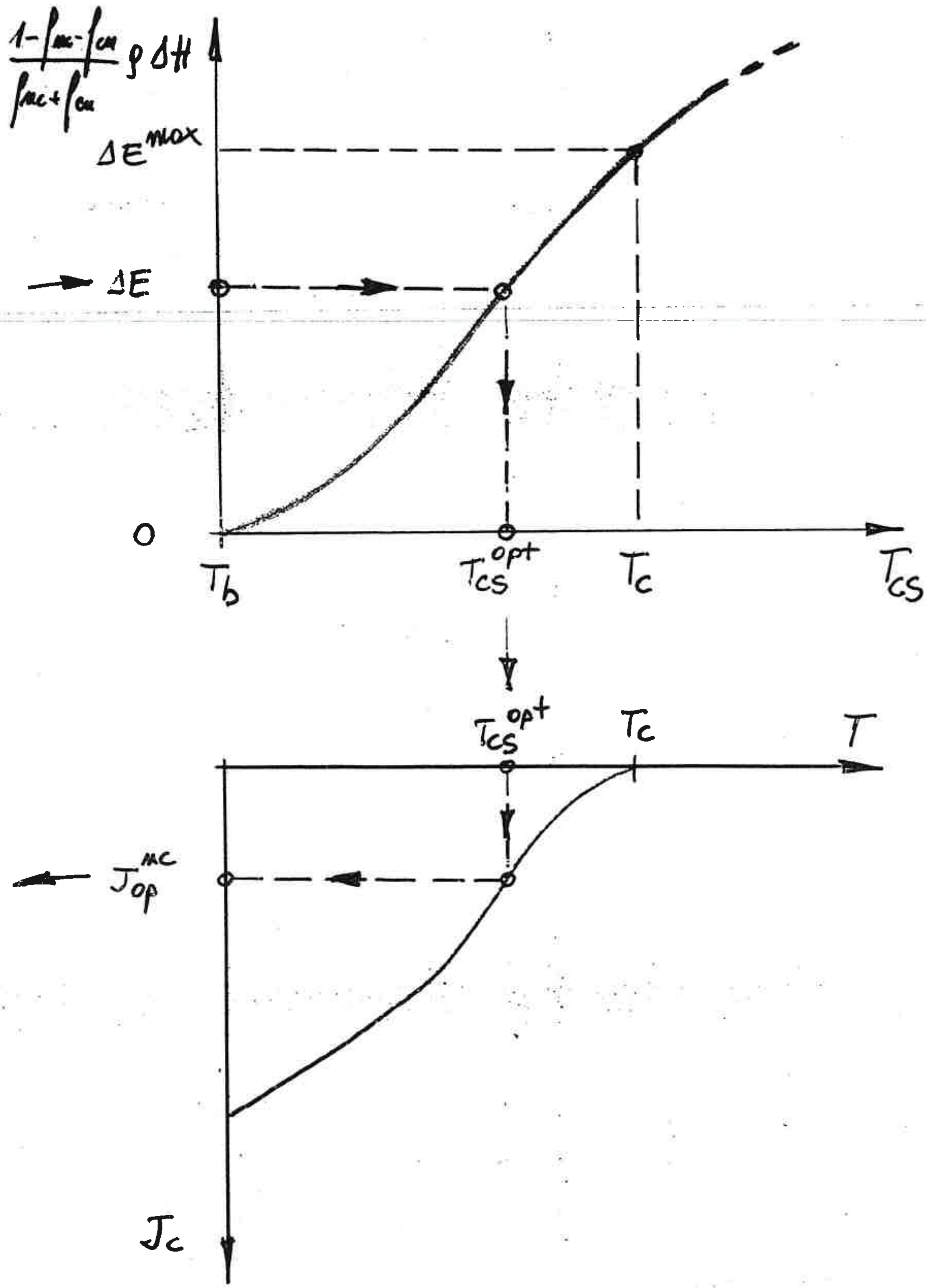
$J \uparrow$ ρ_{uc}) ρ_{os} 

4. Optimization (cont'd)

- the *surface search* in the non-linear case is not efficient
- non-linear optimization procedure for f_{cu} (f_{nc})
  - required energy margin -> compute T_{cs}
  - from T_{cs} compute optimal J_{nc}
  - satisfy all limits on J_{op} so to match the optimal J_{nc}
- non-linear optimization procedure for f_{he}
  - maximum search based on the optimum f_{cu}
- further optimization possible (material, J_c, ...)

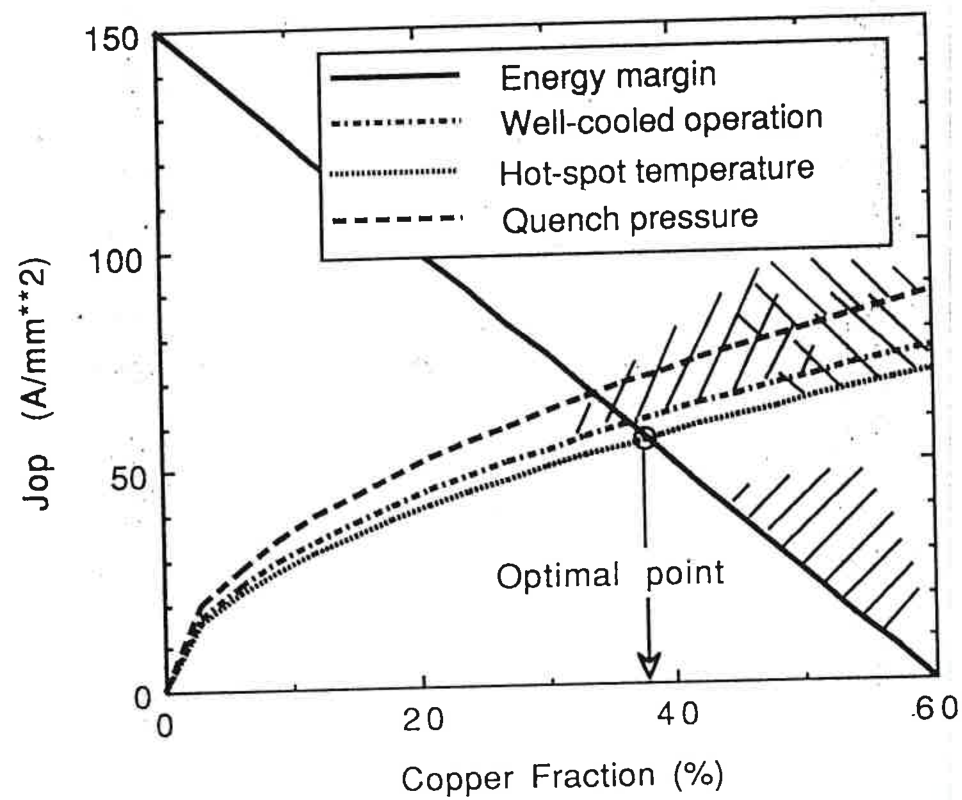


ΔE
1
1
0
0

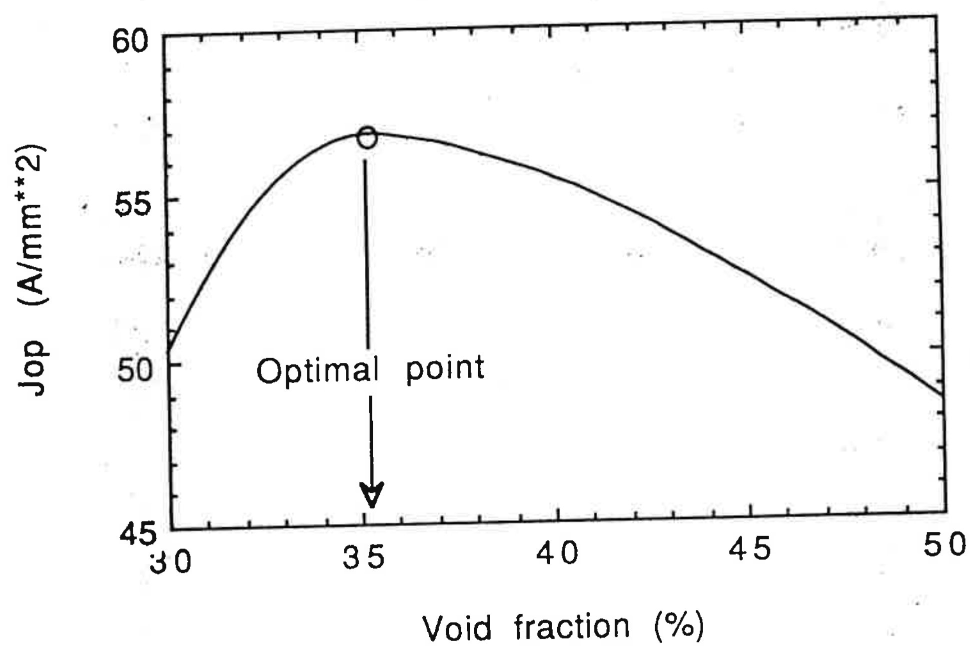


$\frac{1-f_{mc}-f_{cn}}{f_{mc}+f_{cn}}\rho\Delta H$
ΔE^{max}
ΔE
0
T_b
T_{cs}^{opt}
T_c
T_{cs}
T_{cs}^{opt}
T_c
T
J_{op}^{mc}
J_c

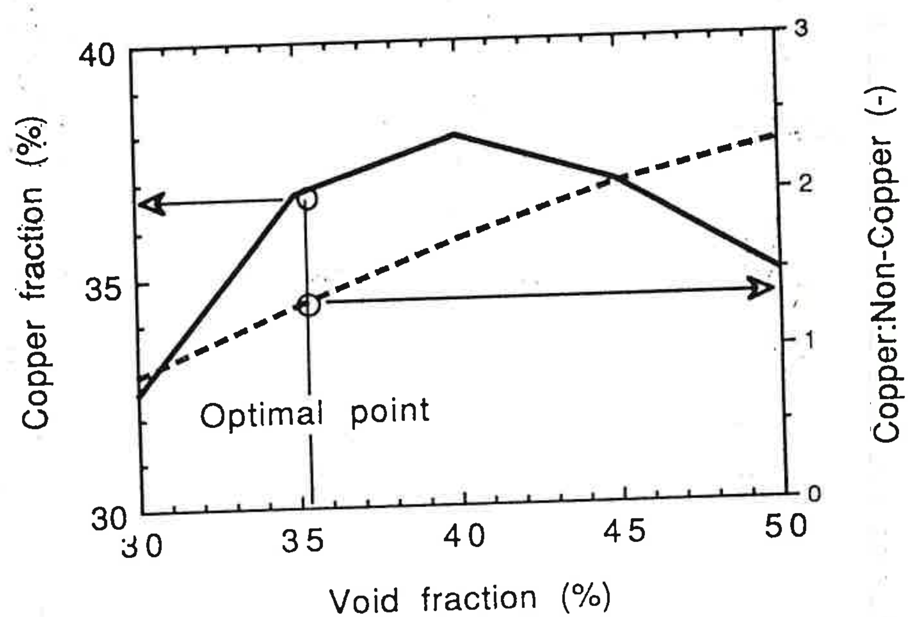
Search of the maximum allowable cable space operating current density at constant void fraction



Maximum allowable cable space operating current density with respect to void fraction (copper fraction maximized at each point)



Optimal copper fraction and Copper:Non-Copper ratio as a function of the void fraction



CONCLUSIONS

++ Parametric & Optimization Studies

− Estimate of ΔE

•) Validation Needed

⇓

Experiments

•) Improvements Needed

Super-cooled regime

Joule heating degradation of ΔE