A simple model for the prediction of the quench point in cable-in-conduit conductors

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General Frame

DC experiments (runs)

Current Sharing, CS

Critical Current, CC

CS run: fixed operating current, variable He temperature

CC run: fixed He temperature, variable operating current

Power-law conductor

$$E\left(I_{op}, T_{cond}, n\right) = E_c \left(\frac{I_{op}}{I_c\left(T_{cond}\right)} \right)^n$$

Critical current scaling by Sommers

Reference conductor CondA
(SECRETS & CONDOPT)

Thermal Equilibrium

1st Fact: CS and CC runs are steady state

- Temperature (CS) or current (CC) vary so slowly that at each instant of time the conductor and He are in thermal equilibrium
- The VTC or VAC are reversible

2nd Fact: The thermal equilibrium is broken at a certain location in the conductor indicating by

- the lost of reversibility
- accelerated increase of voltage and helium temperature

One speaks of: take-off or quench

Process

Two competitive effects:

Power generated in the conductor controlled by operating current and conductor temperature

$$W\left(I_{op},T_{cond},n\right)=E\left(I_{op},T_{cond}\right)I_{op}$$

- Change in I_c due to the Lorenz laoading
- Change of n with T and B
- Current redistribution

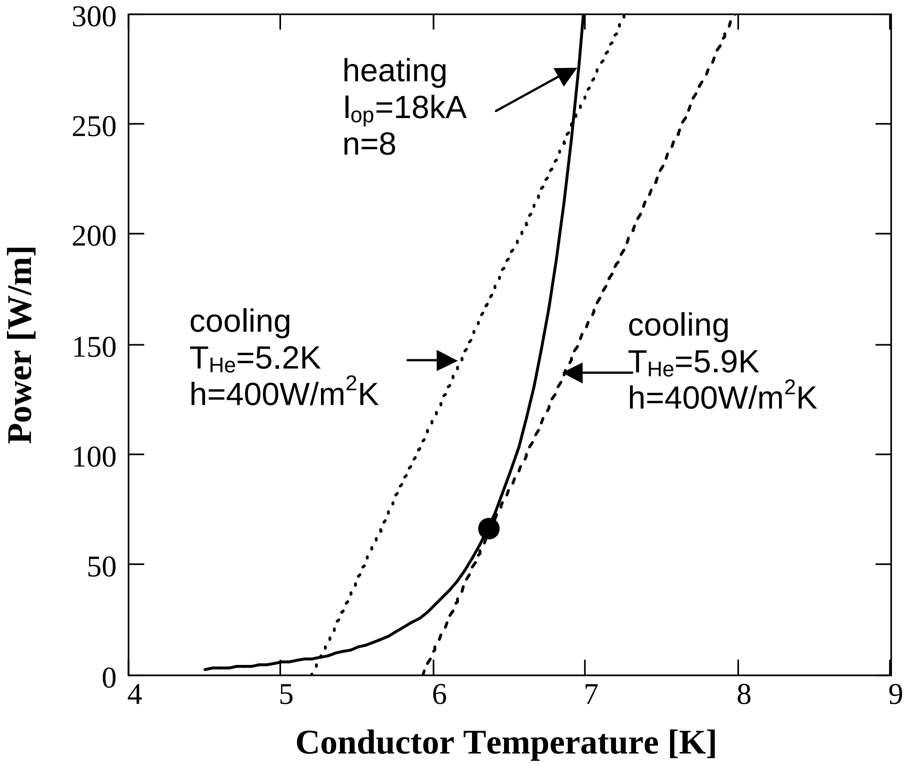
Cooling power controlled by heat exchange coefficient and temperature difference between He and conductor

$$G\left(T_{cond},T_{He},h\right)=hp_w\left(T_{cond}-T_{He}\right)$$

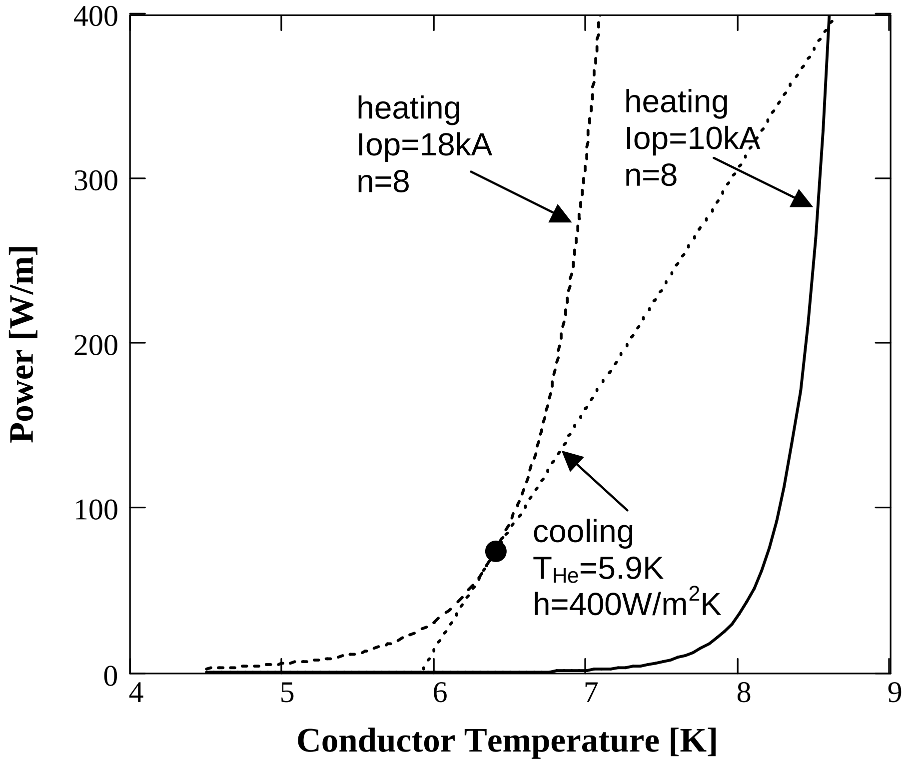
- Change in h due to Lorenz compaction
- Local variation of h due to cable geometry

Graphical Method

Current sharing



Critical current



The equation W=G has two solutions. A stable and an unstable one. Both converge to a unique point which is the contact point between the cooling and heating curves. Increasing T_{cond} beyond this point results in a breakdown of thermal equilibrium between conductor and helium. We have QUENCH

The Quench Point

We saw from the previous analysis that the quench point can be defined as the contact point between the heating and cooling power curves with the conductor temperature as a variable.

Based on the mathematical definition of a contact point between two curves we have

$$W = G$$

$$\left.\frac{\partial W}{\partial T_{cond}}\right|_{quench} = \left.\frac{\partial G}{\partial T_{cond}}\right|_{quench}$$

Warning!!
Highly
non-linear

Depending on how you pick the parameters, the output is

$$I_q = f\left(\cdot \middle| T_{op}\right) \qquad T_{q\_He} = f\left(\cdot \middle| I_{op}\right)$$

or

$$T_{q\_cond} = f\left(\cdot \middle| T_{op}\right) \qquad T_{q\_cond} = f\left(\cdot \middle| I_{op}\right)$$

A Simpler Method

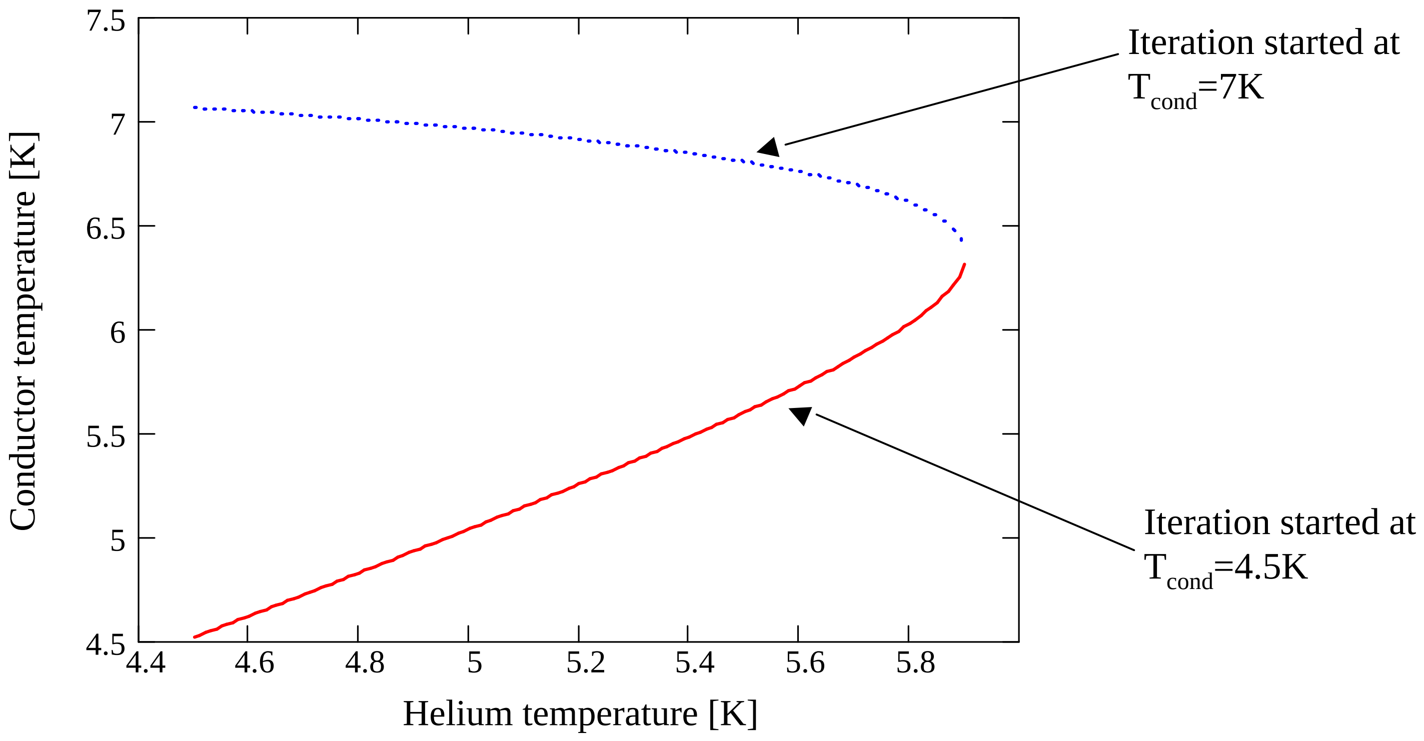
If you do not like derivatives (numerically any way not recomended) just take the first equation G=W but keep Sommers scaling (and any other non-linear stuff)

$$T_{cond}\left(I_{op},T_{He}\right) = T_{He} + \frac{E_c I_{op}^{n+1}}{hp_w}\left(\frac{1}{I_c\left(T_{cond}\right)}\right)^n$$

Iop=18kA

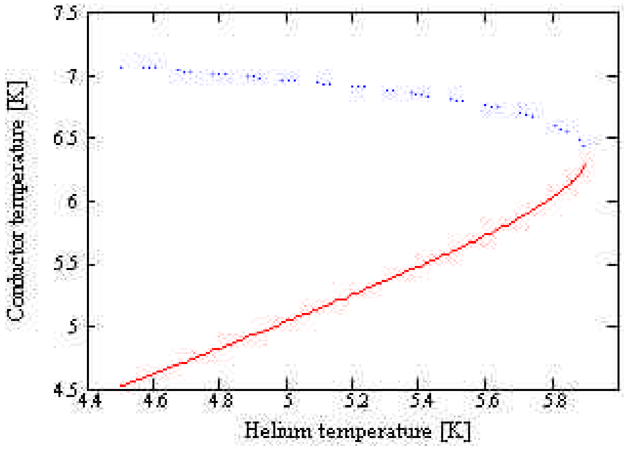
h=400W/m²K

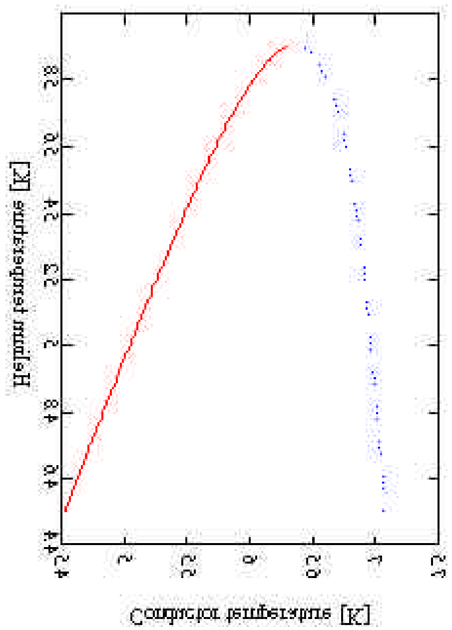
n=8



Avoid Convergence Problems

Rotate by 90° and fold



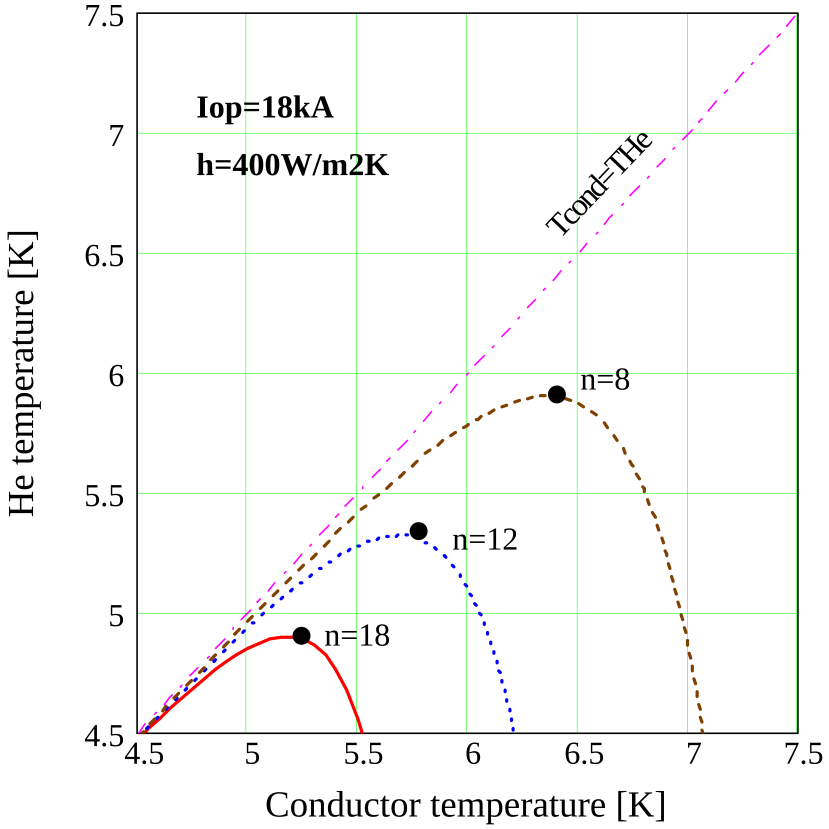


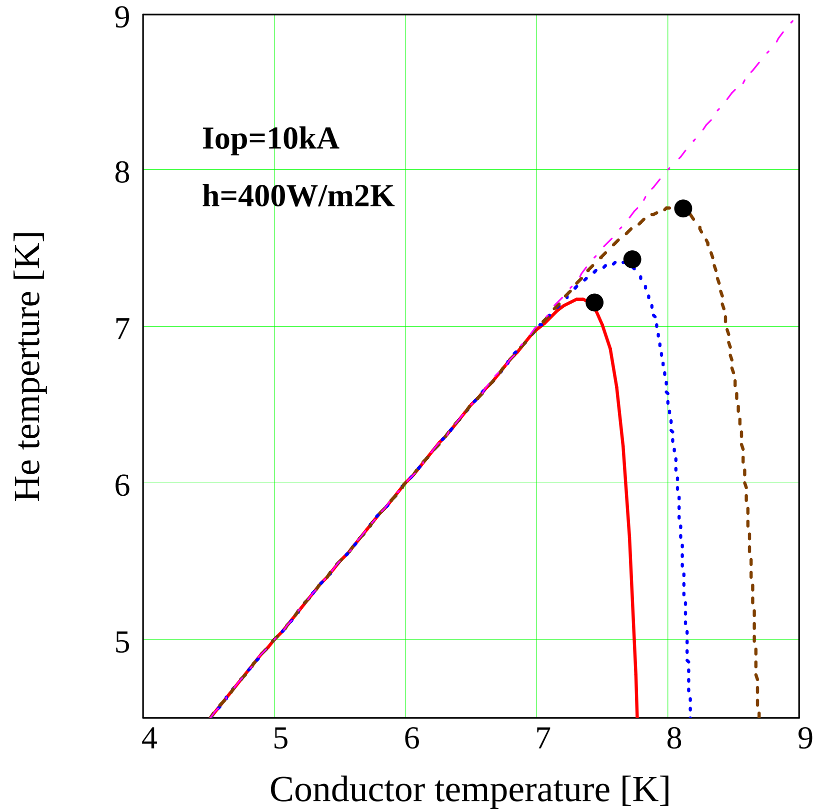
Now the quench point apears as the maximum of the function

$$T_{He}\left(I_{op},T_{cond}\right)=T_{cond}-\frac{E_c I_{op}^{n+1}}{hp_w}\left(\frac{1}{I_c\left(T_{cond}\right)}\right)^n$$

Everything is a matter of finding the maximum of a function

Effect of changing n and operating current

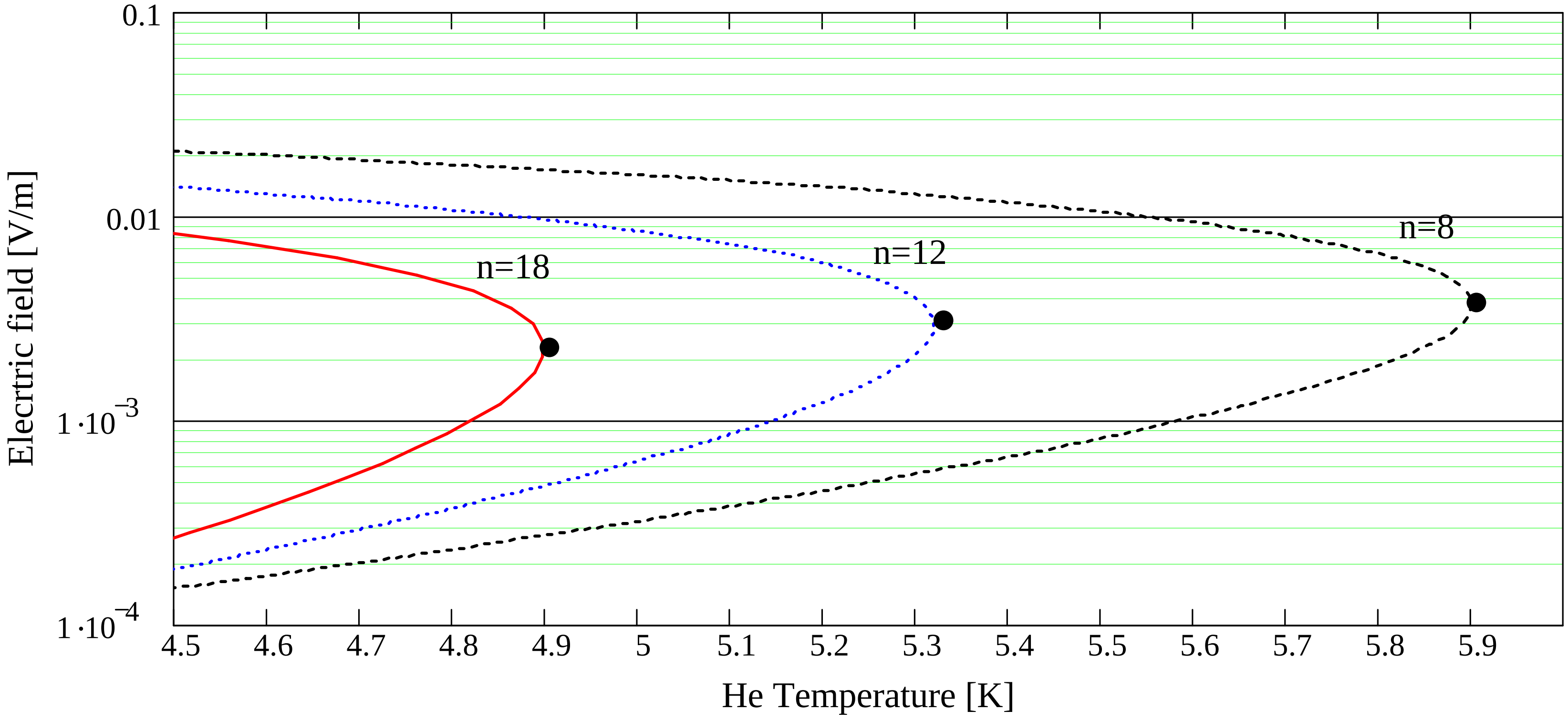




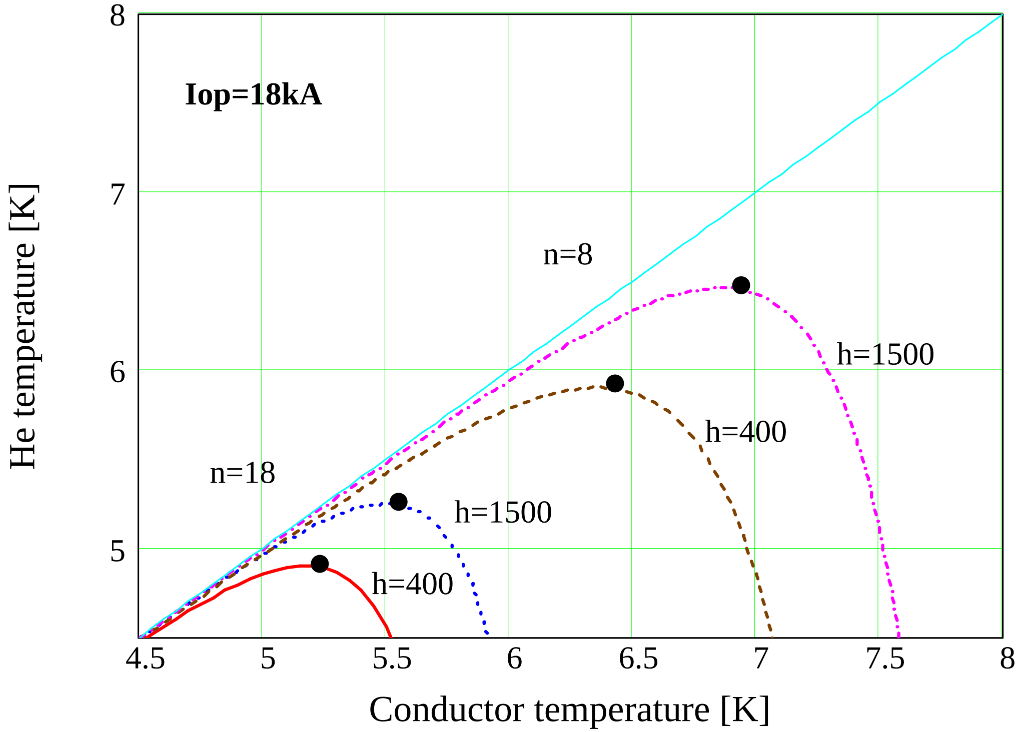
Effect of changing n on the electric field at quench

Once T_{q_cond} and I_q (or Iop for CS) are known E_q can be calculated with

$$E_q = E_c \left(\frac{I_q}{I_c\left(T_{q\_cond}\right)} \right)^n$$



Effect of heat exchange



Going Analytic

We learned that the basic equations defining the quench point are:

$$T_{He}\left(I_{op},T_{cond}\right)=T_{cond}-\frac{E_c I_{op}^{n+1}}{hp_w}\left(\frac{1}{I_c\left(T_{cond}\right)}\right)^n$$

$$\frac{\partial T_{He}}{\partial T_{cond}}=0$$

The second equation selects the maximum of $T_{He}(T_{cond})$ and if we neglect the temperature dependence of n

$$1-\frac{nE_c}{hp_w}\left(\frac{I}{I_c}\right)^{n+1}\left|\frac{\partial I_c}{\partial T_{cond}}\right|=0$$

But if $$I_c\left(T_{cond}\right)=I_{c0}\left(1-\frac{T_{cond}}{T_c}\right)$$

Everything is manageable analyticaly

A Collection of Analytical Results

$$T_{q\_cond} = T_c \left[1 - \frac{I_q}{I_{c0}} \left(\frac{nE_c I_{c0}}{hp_w T_c} \right)^{\frac{1}{n+1}} \right]$$

$$\Phi = \frac{hp_w T_c}{E_c I_{c0}}$$

Non-dimensional group:
Quench number ?

$$T_{q\_He} = T_c \left[1 - \frac{n+1}{n} \frac{I_q}{I_{c0}} \left(\frac{nE_c I_{c0}}{hp_w T_c} \right)^{\frac{1}{n+1}} \right]$$

$$T_{q\_He} = T_c \left(1 - \frac{n+1}{n} \frac{I_q}{I_{c0}} \frac{1}{\left(\frac{\Phi}{n} \right)^{\frac{1}{n+1}}} \right)$$

$$T_{q\_cond} = \left(\frac{n}{n+1} \right) T_{q\_He} + \frac{T_c}{n+1}$$

Linear relation !

$$T_{q\_cond} = T_c \left(1 - \frac{I_q}{I_{c0}} \frac{1}{\left(\frac{\Phi}{n} \right)^{\frac{1}{n+1}}} \right)$$

$$E_q = E_c \left(\frac{hp_w T_c}{nE_c I_{c0}} \right)^{\frac{n}{n+1}}$$

$$E_q = E_c \left(\frac{\Phi}{n} \right)^{\frac{n}{n+1}}$$

How to use Formulas

Current sharing

$$T_{q\_He} = T_c \left(1 - \frac{n+1}{n} \frac{I_{op}}{I_{c0}} \frac{1}{\left(\frac{\Phi}{n} \right)^{\frac{1}{n+1}}} \right)$$

$$T_{q\_cond} = T_c \left(1 - \frac{I_{op}}{I_{c0}} \frac{1}{\left(\frac{\Phi}{n} \right)^{\frac{1}{n+1}}} \right)$$

Critical current

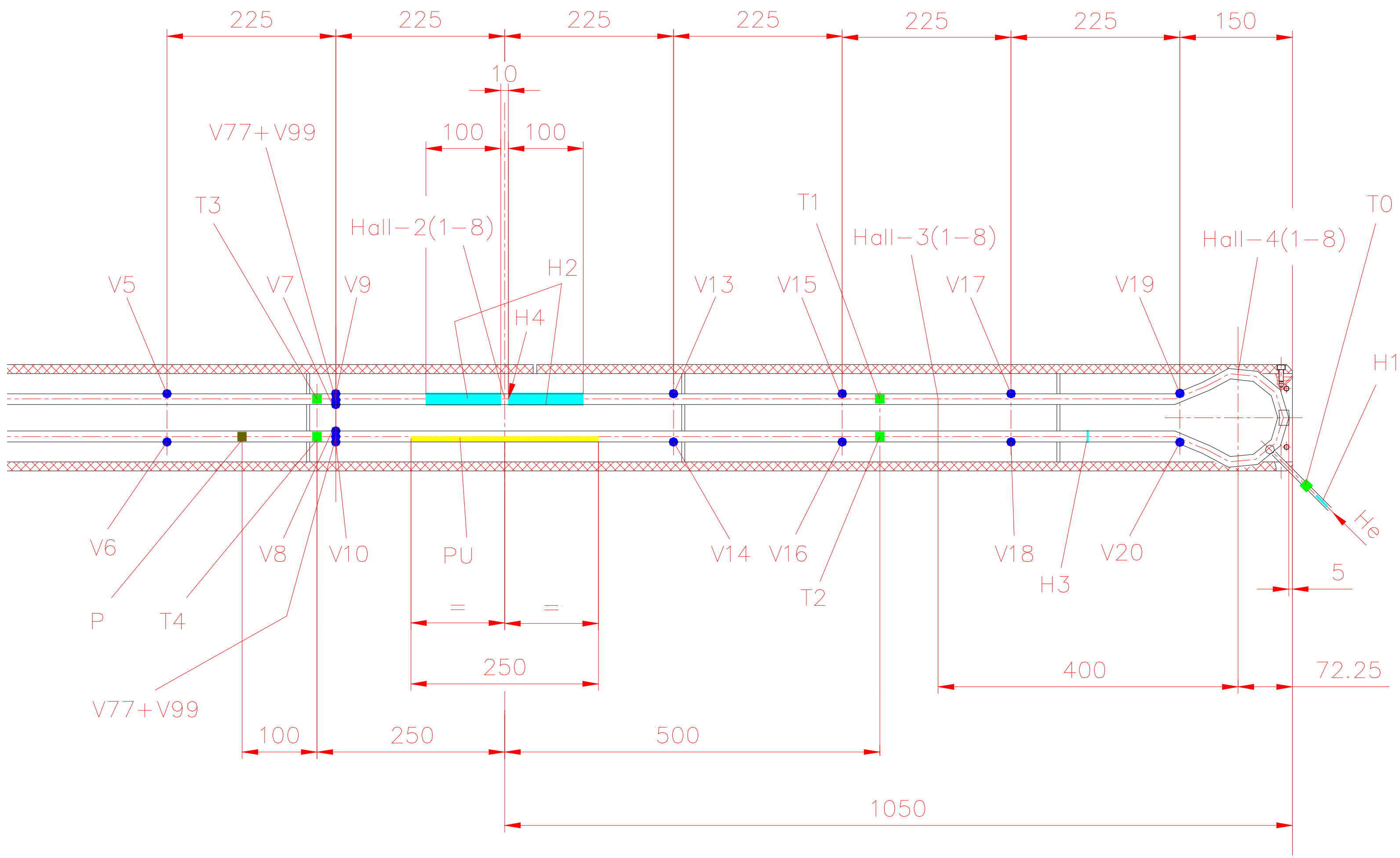
$$I_q = \frac{nI_{c0}}{n+1} \left(\frac{\Phi}{n} \right)^{\frac{1}{n+1}} \left(1 - \frac{T_{op}}{T_c} \right)$$

$$T_{q\_cond} = \frac{T_c}{n+1} \left(1 + n \frac{T_{op}}{T_c} \right)$$

$$E_q = E_c \left(\frac{\Phi}{n} \right)^{\frac{n}{n+1}} \sim \frac{hp_w T_c}{nI_{c0}}$$

Independent of current!!

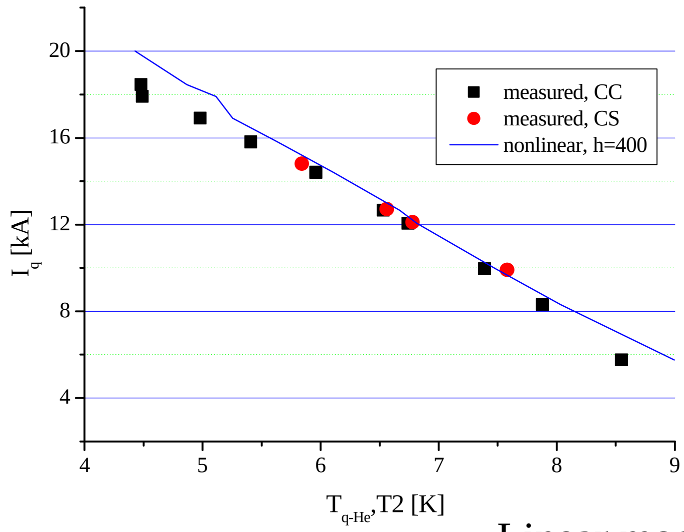
Condopt sample instrumentation

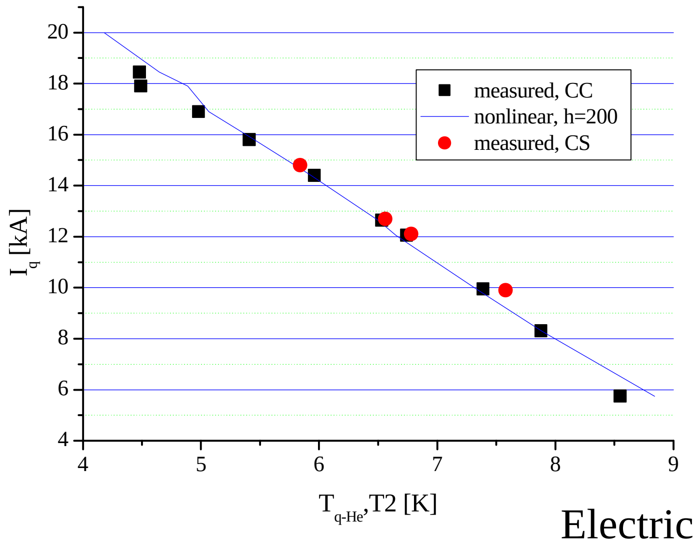


Theory vs. Experiment

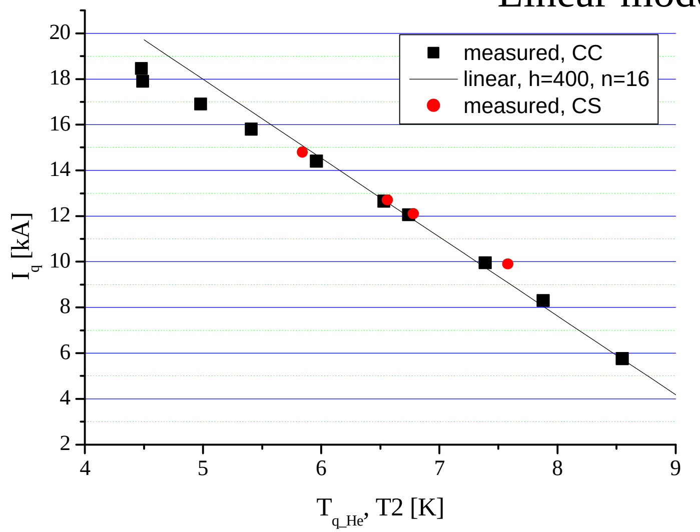
Condopt,B=10T

Nonlinear model

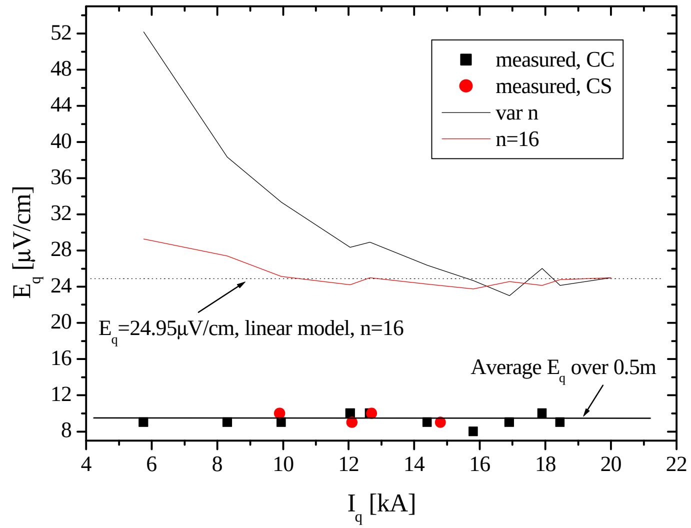




Linear model

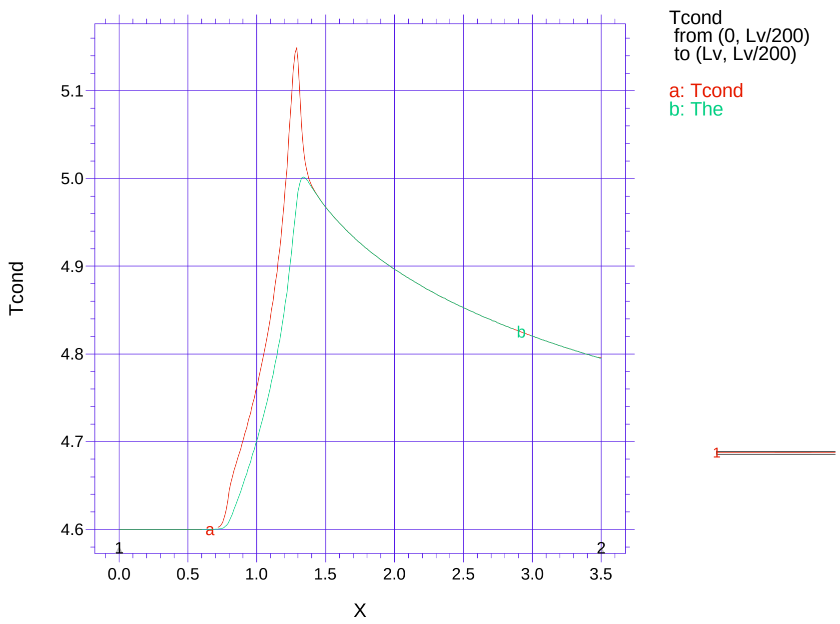


Electric field



1D simulation

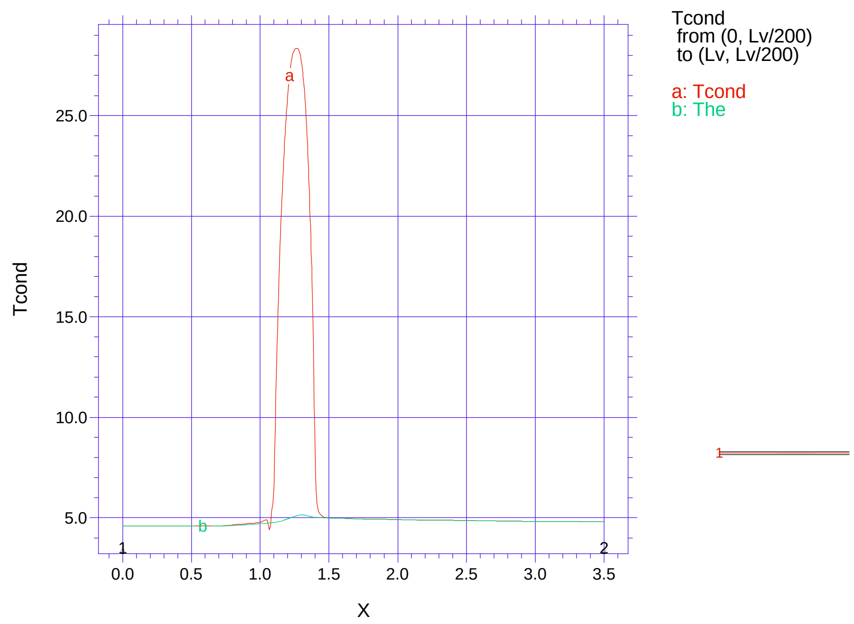
Ic-simulation



Ic-simulation: Cycle=247 Time= 235.00 dt= 0.2063 p2 Nodes=337 Cells=120 RMS Err= 1.3e-5
Integral(a)= 16.82361 Integral(b)= 16.77546

$\dot{m}$

Ic-simulation



Ic-simulation: Cycle=335 Time= 235.17 dt= 5.2853e-5 p2 Nodes=2488 Cells=1163 RMS Err= 3.2
Integral(a)= 22.12752 Integral(b)= 16.82122

Conductor and He temperature in the sample at take-off

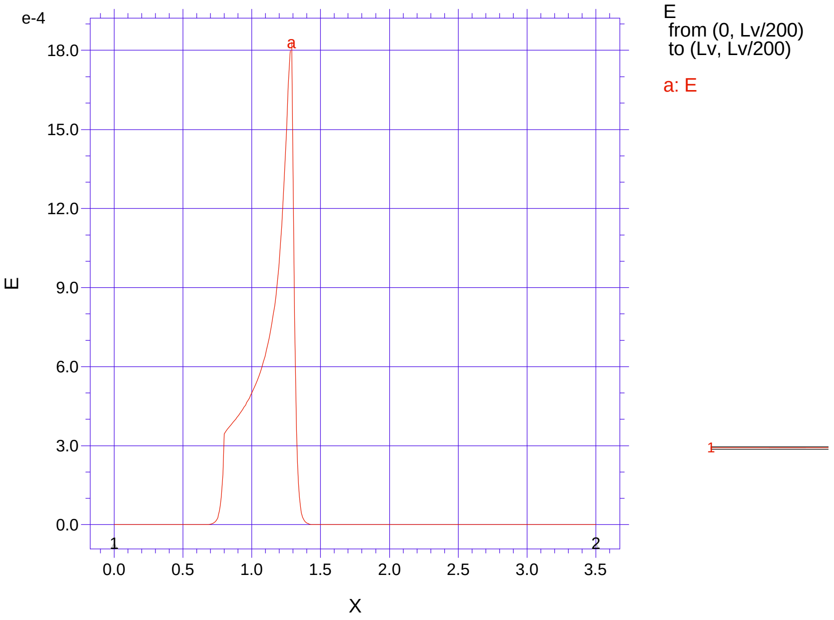
Conductor and He temperature in the sample after take-off (170ms)

h=400W/m^{2}K (from Tcs simulations in SECRETS), T$_{he}$ inlet=4.6K, =3g/s, n=16

1D electric field

n=16

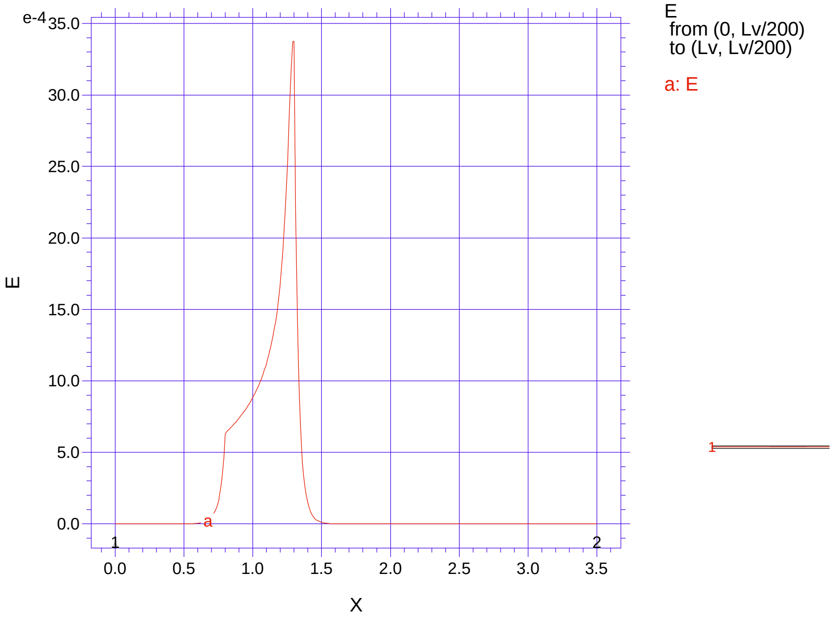
Ic-simulation



Ic-simulation: Cycle=247 Time= 235.00 dt= 0.2063 p2 Nodes=337 Cells=120 RMS Err= 1.3e-5
Integral= 3.996776e-4

n=8

Ic-simulation



Ic-simulation: Cycle=247 Time= 237.00 dt= 0.2730 p2 Nodes=337 Cells=120 RMS Err= 9.2e-6
Integral= 7.622767e-4

Electric field in the sample at take-off

Conclusions

•The method presented shows that it is possible to obtain a good estimate of the quench point parameters of CIC conductors

•This has been done by considering the thermal equilibrium of a conductor with power-law VAC and not assuming ab initio that the conductor and He have the same temperature.

•Calculation with fully non linear model show a good agreement with the experimental results

•For a linear dependence of the critical current on temperature, a fully analytic model can be developed.

•Usefull formulas for the calculation of the quench point parameters in the frame of the linear model are given and it was shown that they can be expressed with the help of a new nondimensional group called „quench number“

•The calculation with the linear model show also a good agreement with the experimental results.

•In the frame of the linear model it was shown that the electrical field at quench is independent on current. Experimental data can be used to asses the value of the heat exchange coefficient from DC experiments and offer an alternative to the assesment through stability.