Appearance of hot spots in coated conductors

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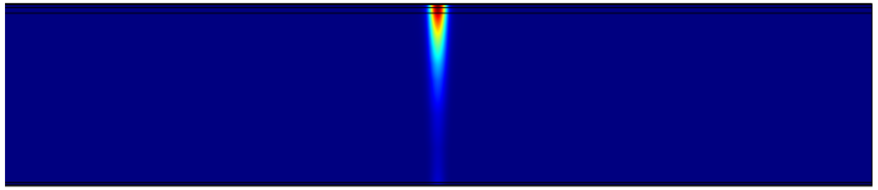


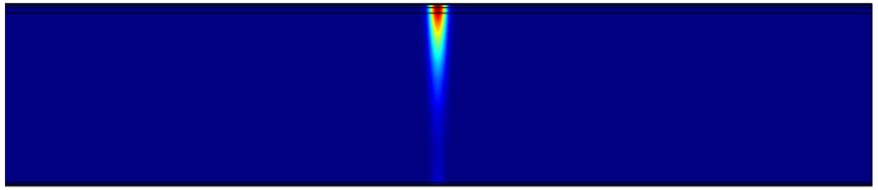
Outline

1) Introduction - coated conductor tape with locally reduced I_c

2) Characterization of I_c reduction

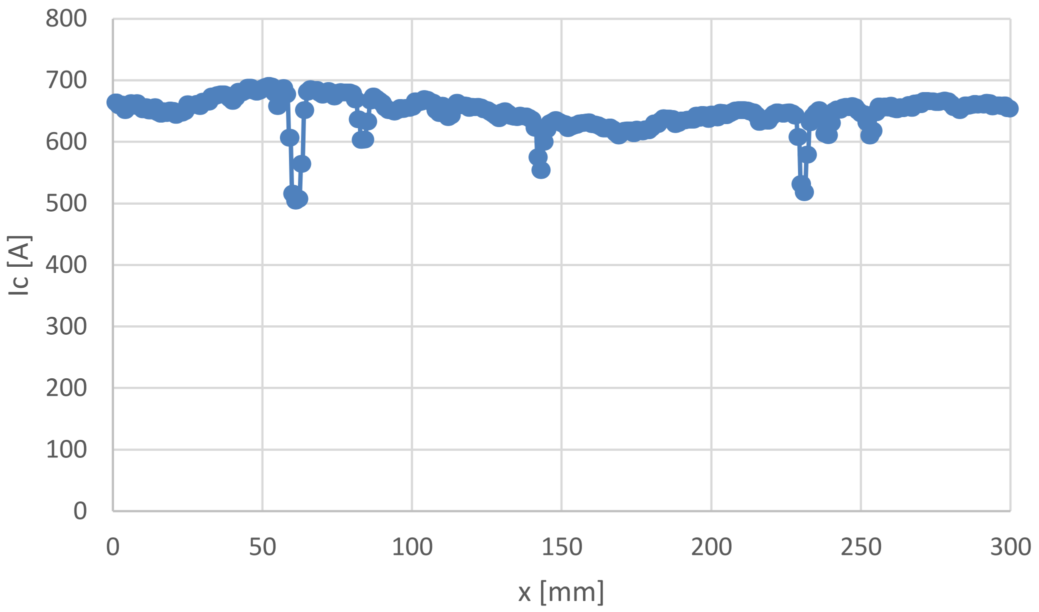
3) Analytic electro-thermal model

4) Conclusions



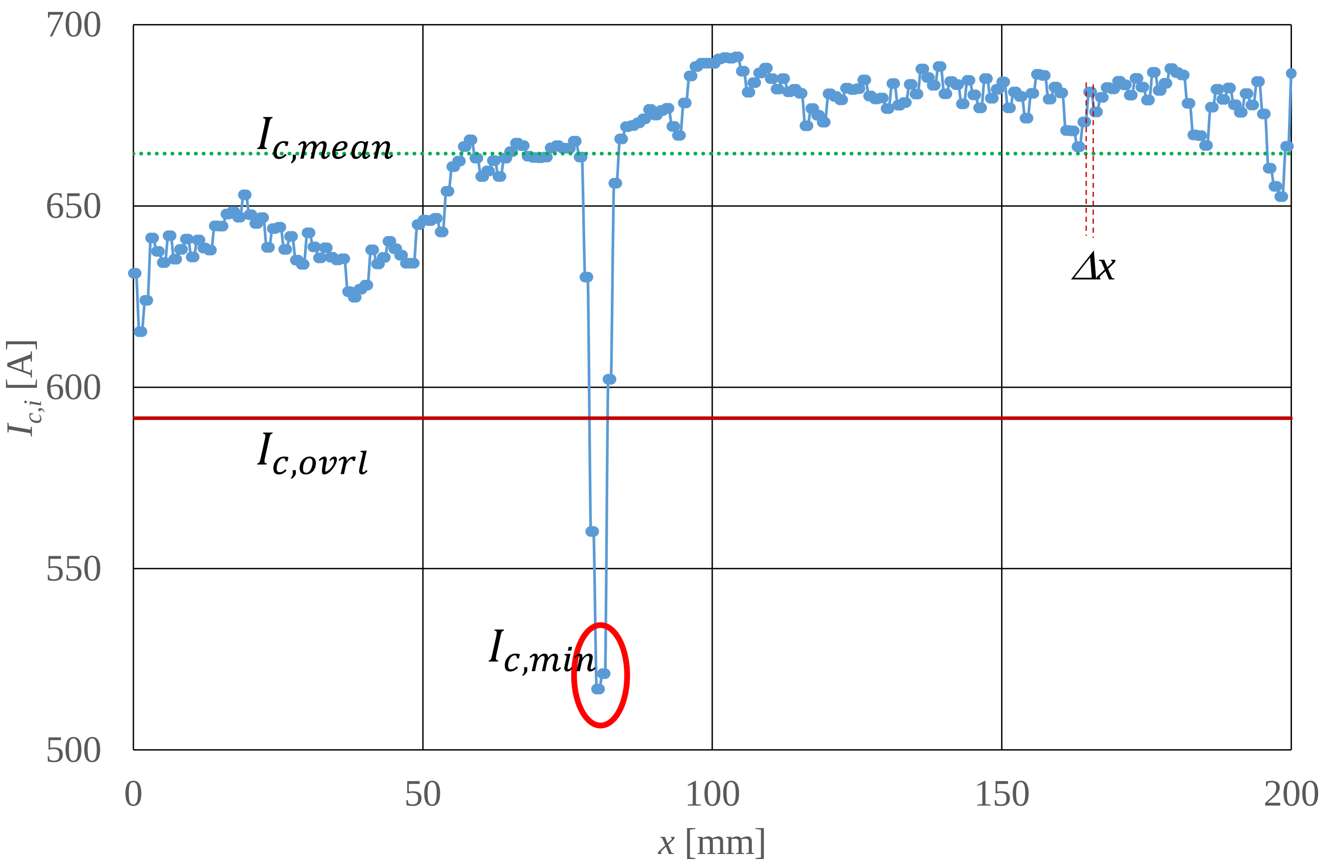
Motivation

Resistive Superconductivng Fault Current limiter for DC transmission:
superconducting device operating in DC regime – normally at $I < I_c$



At which DC current the device is safe?

Motivation



Tapestar data:

$$I_{c,i} = I_c\left(\left(i - \frac{1}{2}\right)\Delta x\right), i = 1..N$$

$$I_{c,mean} = \frac{\sum_{i=1}^{N} I_{c,i}}{N}$$

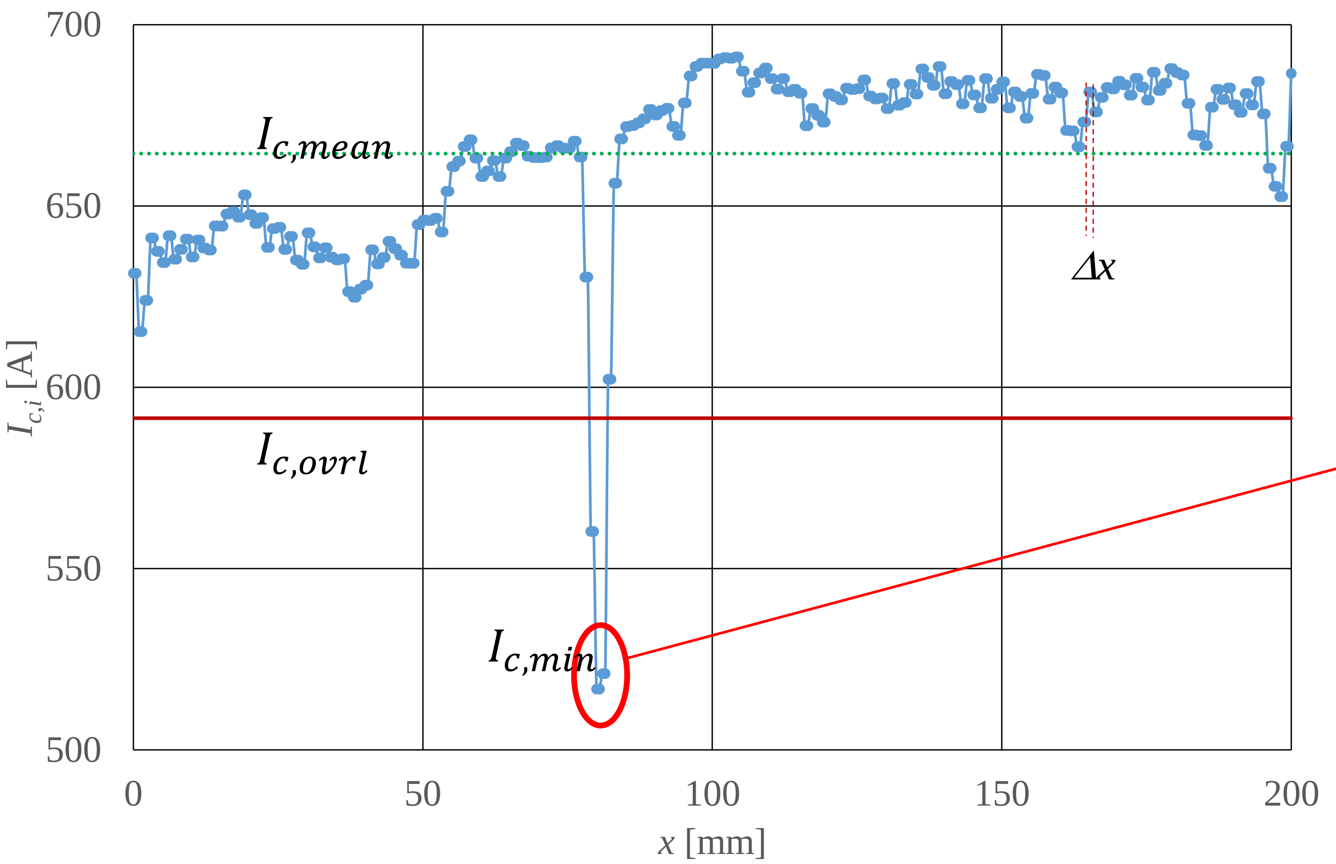
Overal critical current (1 µV/cm on 200 mm):

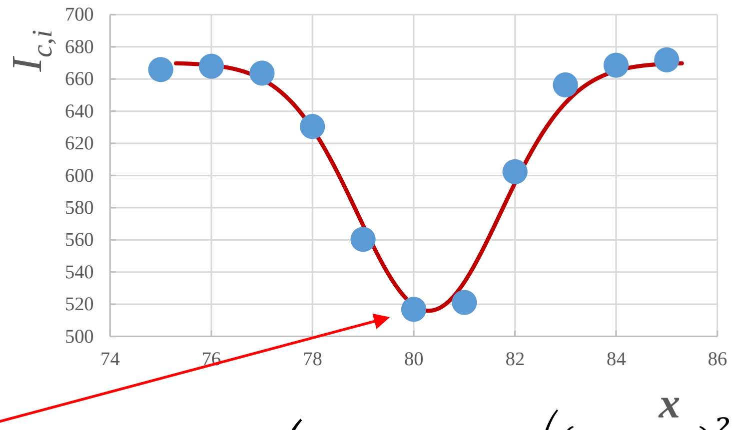
$$I_{c,ovrl} = \left[\frac{N}{\sum_{i=1}^{N}\left(\frac{1}{I_{c,i}}\right)^{n}}\right]^{\frac{1}{n}}$$

What happens if $I > I_{c,min}$?

Fee M, Fleshler S, Otto A, Malozemoff A P 2001 *IEEE. Trans. Appl. Supercond* **11** 3337-340
Wang Y, Xiao L, Lin L, Xu X, Lu Y, Teng Y 2003 *Cryogenics* **43** 71-77

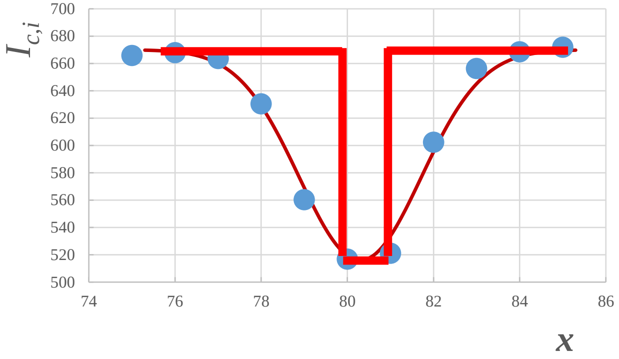
Characterization of I_c reduction





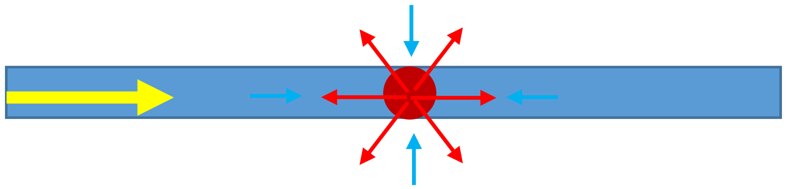
$$I_c(x) = I_{c0}\left(1 - D_{def}\, e^{-\left(\frac{(x-x_{def})^2}{R_{def}^2}\right)}\right)$$

For the analytical model:
defect is $I_{c,min}$ on Δx



Analytical model

electro-thermal model for checking the long-term stability



$$P(T) = IU(T) = I\Delta x E_c \left(\frac{I}{I_{c,min}(T)}\right)^n$$

$$I_{c,min}(T) = I_{c,min}(T_0)\frac{T_c - T}{T_c - T_0}$$

$$C\frac{\partial T}{\partial t} = P(T) - K(T - T_0)$$

heating cooling

$$P_0(I) = P(T_0, I) = I\Delta x E_c \left(\frac{I}{I_{c,min}(T_0)}\right)^n$$

$$K = K_0 + D(T - T_0)$$

$$\frac{\partial T}{\partial t} = \frac{1}{C}\left[P_0(I)\left(\frac{\theta}{\theta - \Delta T}\right)^n - K_0\Delta T - D(\Delta T)^2\right]$$

$$\Delta T = T - T_0$$
$$\theta = T_c - T_0$$

evolution of temperature in time easily found by iterative numerical computation

Analytical model - iterative solution

electro-thermal model for checking the long-term stability

$$\frac{\partial T}{\partial t} = \frac{1}{C}\left[P_0(I)\left(\frac{\theta}{\theta - \Delta T}\right)^n - K_0\Delta T - D(\Delta T)^2\right]$$

start

t	T	T-T0	P(T)	K(T-T0)	∂T/∂t	dP/dT	dCool/dT
[s]	[K]	[K]	[W]	[W]	[K/s]	[W/K]	[W/k]
0.00000	77.30000	0.00000	0.01069	0.00000	5.59173		
0.00100	77.30559	0.00559	0.01091	0.00059	5.39561	0.03899	0.10606
0.00300	77.31638	0.01638	0.01134	0.00174	5.02382	0.04019	0.10608
0.00500	77.32643	0.02643	0.01176	0.00280	4.68585	0.04178	0.10610
0.00700	77.33580	0.03580	0.01217	0.00380	4.37804	0.04332	0.10613
0.01000	77.34894	0.04894	0.01276	0.00519	3.95922	0.04517	0.10615
0.01300	77.36081	0.06081	0.01333	0.00645	3.59368	0.04733	0.10618
0.01600	77.37160	0.07160	0.01386	0.00760	3.27325	0.04937	0.10621
0.01900	77.38141	0.08141	0.01436	0.00864	2.99123	0.05131	0.10623
0.02500	77.39936	0.09936	0.01533	0.01055	2.50122	0.05406	0.10627

Analytical model - iterative solution

electro-thermal model for checking the long-term stability

$$\frac{\partial T}{\partial t} = \frac{1}{C}\left[P_0(I)\left(\frac{\theta}{\theta - \Delta T}\right)^n - K_0 \Delta T - D(\Delta T)^2\right]$$

end

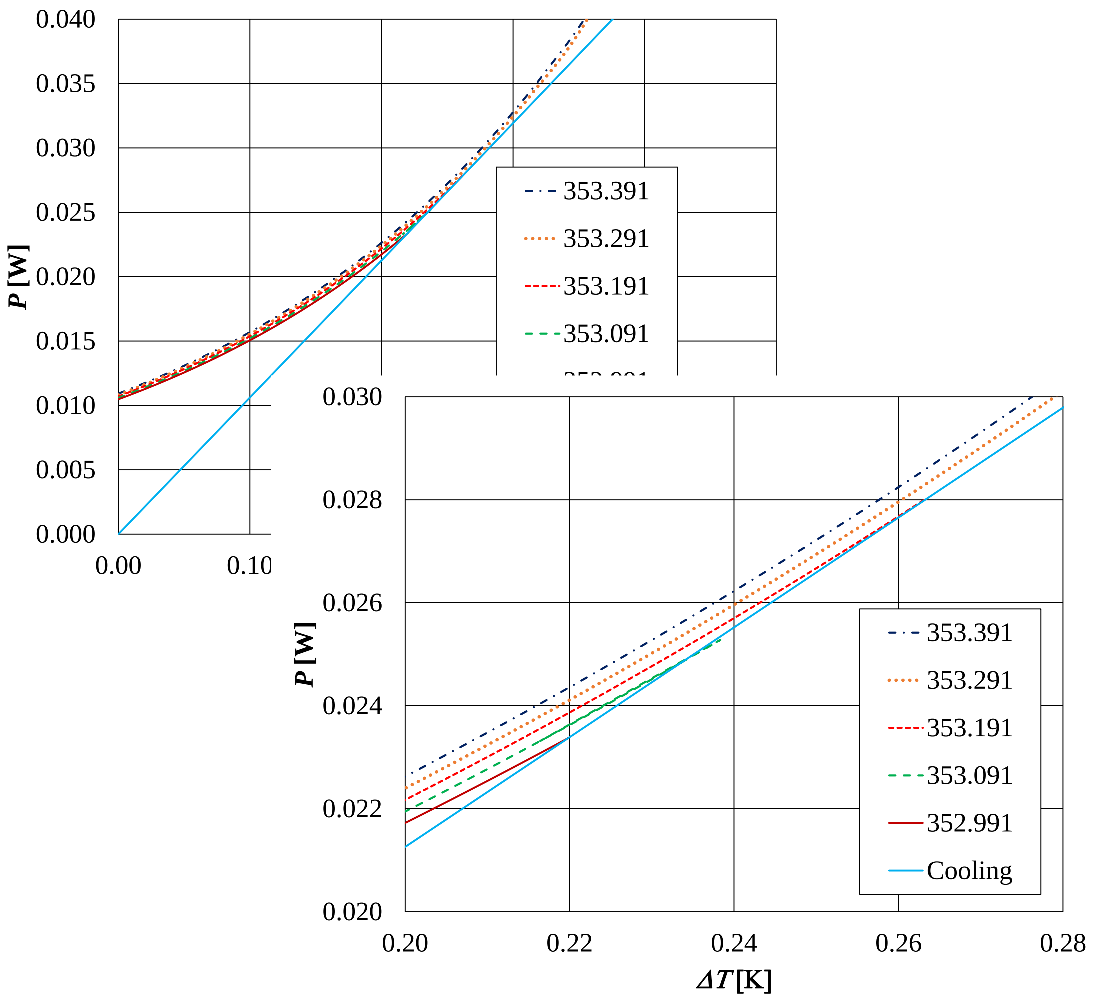
t [s]	T [K]	T-T0 [K]	P(T) [W]	K(T-T0) [W]	∂T/∂t [K/s]	dP/dT [W/K]	dCool/dT [W/k]
30.24000	77.56989	0.26989	0.02871	0.02871	0.00001	0.10656	0.10670
31.86000	77.56991	0.26991	0.02871	0.02871	0.00001	0.10656	0.10670
34.00000	77.56992	0.26992	0.02871	0.02871	0.00001	0.10656	0.10670
36.14000	77.56993	0.26993	0.02871	0.02871	0.00000	0.10657	0.10670
38.28000	77.56994	0.26994	0.02871	0.02871	0.00000	0.10657	0.10670
40.42000	77.56995	0.26995	0.02872	0.02872	0.00000	0.10658	0.10670
42.56000	77.56995	0.26995	0.02872	0.02872	0.00000	0.10658	0.10670
47.00000	77.56997	0.26997	0.02872	0.02872	0.00000	0.10658	0.10670
51.44000	77.56998	0.26998	0.02872	0.02872	0.00000	0.10659	0.10670
55.88000	77.56998	0.26998	0.02872	0.02872	0.00000	0.10659	0.10670
60.32000	77.56999	0.26999	0.02872	0.02872	0.00000	0.10659	0.10670
64.76000	77.56999	0.26999	0.02872	0.02872	0.00000	0.10660	0.10670

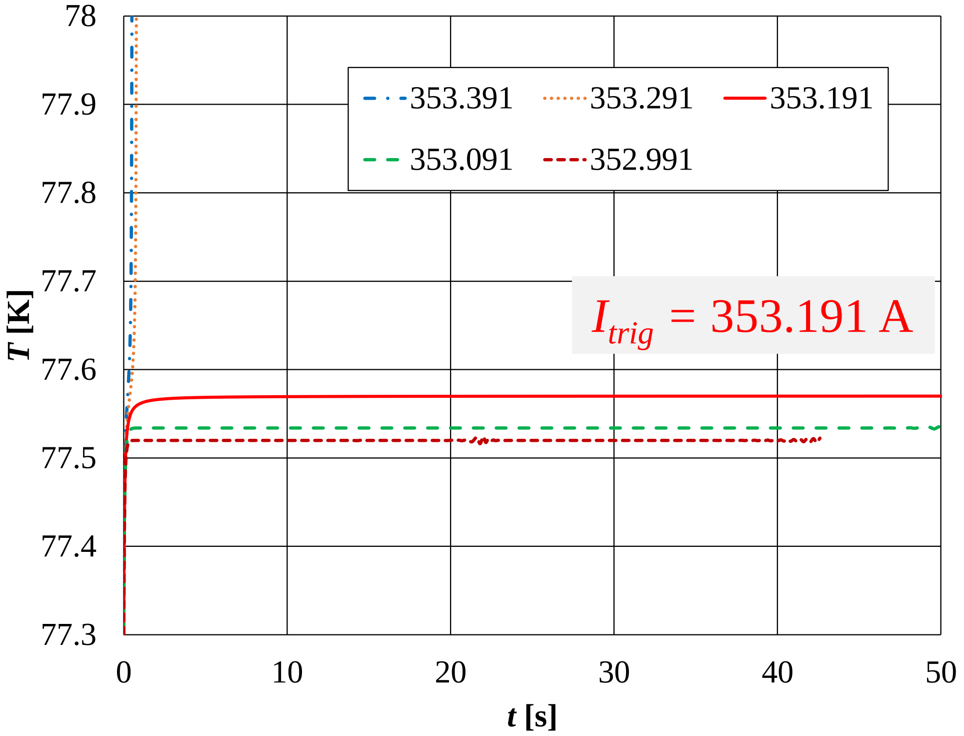
DC current triggering the hot-spot development

FCL tape: only 2x1 μm Ag stabilization

T_0 = 77.3 K, $I_{c,min}$ (T_0) = 517 A, n = 35, T_c = 87 K

$I_{c,min}$ = 300 A, Δx = 1 mm, K_0 = 0.106 W/K, D = 0.0012 W/K^2



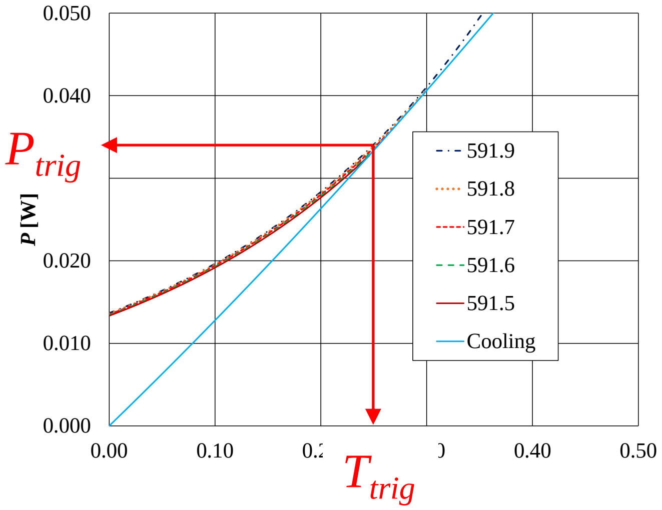


Rakhmanov A L, Vysotsky V S, Ilyin Yu A, Kiss T, Takeo M 2000 *Cryogenics* **40** 19-27

Analytic computation of the maximum stable temperature

at supplying the current I_{trig} , temperature will grow until reaching the maximum stable value, T_{trig} at the dissipation P_{trig}

$$P_{trig} = P_0(I_{trig})\left(\frac{\theta}{\theta - \Delta T_{trig}}\right)^n \qquad \Delta T_{trig} = T_{trig} - T_0$$



1) In the equilibrium, dissipation is exactly balanced by cooling

$$P_0(I_{trig})\left(\frac{\theta}{\theta - \Delta T_{trig}}\right)^n = K_0 \Delta T_{trig} + D\left(\Delta T_{trig}\right)^2$$

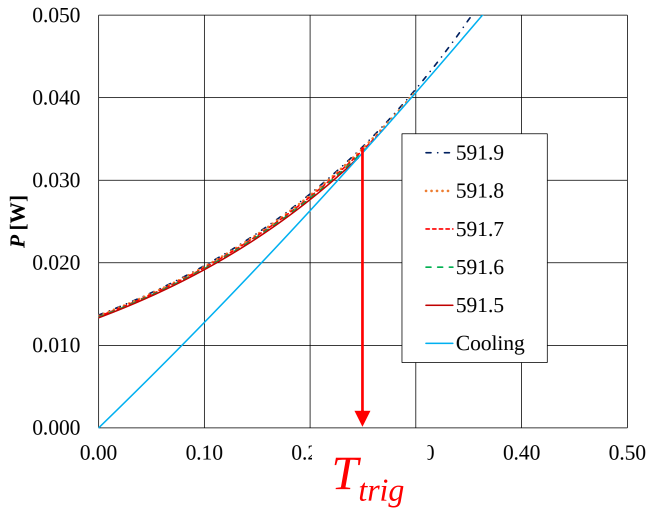
2) Also the derivatives with respect to temperature must be equal

$$P_0(I_{trig})\frac{n}{\theta - \Delta T_{trig}}\left(\frac{\theta}{\theta - \Delta T_{trig}}\right)^n = K_0 + 2D\Delta T_{trig}$$

Analytic computation of the maximum stable temperature

at supplying the current I_{trig} , temperature will grow until reaching the maximum stable value, T_{trig} at the dissipation P_{trig}

$\Delta T_{trig} = T_{trig} - T_0$



quadratic equation for unknown ΔT_{trig} :

$$\frac{n}{\theta - \Delta T_{trig}}\left[K_0 \Delta T_{trig} + D\left(\Delta T_{trig}\right)^2\right] = K_0 + 2D\Delta T_{trig}$$

solution: $$\Delta T_{trig} = \frac{\theta}{n+2}\left[1 - \frac{1}{\delta} + \sqrt{\frac{1}{\delta^2} + \frac{2}{\delta(n+1)} + 1}\right]$$ where $$\delta = \frac{2D\theta}{(n+1)K_0}$$

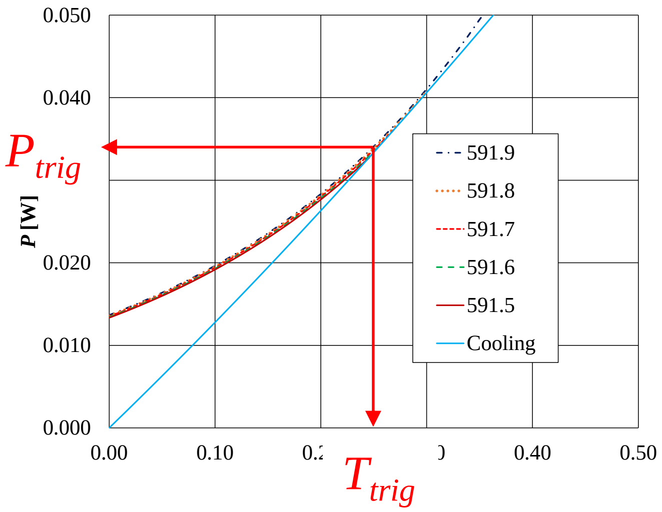
depends only on *n* and cooling !!!

simplified expression for $\delta << 1$: $$\Delta T_{trig} = \frac{\theta}{n+1}\left[1 + \frac{D\theta}{(n+2)K_0}\right]$$

Analytic computation of the maximum stable temperature and maximal dissipation

at supplying the current I_{trig} , temperature will grow until reaching the maximum stable value, T_{trig} at the dissipation P_{trig}

$$\Delta T_{trig} = T_{trig} - T_0$$



once knowing ΔT_{trig} we can compute:

$$P_{trig} = K_0 \Delta T_{trig} + D\left(\Delta T_{trig}\right)^2$$

but also true is:

$$P_{trig} = P_0\left(I_{trig}\right)\left(\frac{\theta}{\theta - \Delta T_{trig}}\right)^n$$

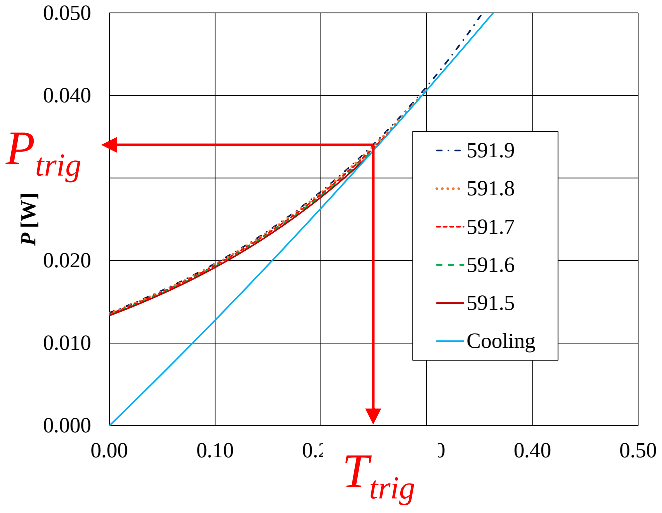
then the dissipation at the beginning:

$$\Rightarrow \quad P_0\left(I_{trig}\right) = P_{trig}\left(1 - \frac{\Delta T_{trig}}{\theta}\right)^n$$

Analytic computation of the maximum stable current

at supplying the current I_{trig} , temperature will grow until reaching the maximum stable value, T_{trig} at the dissipation P_{trig}

$$\Delta T_{trig} = T_{trig} - T_0$$



using another form of expression for $P_0(I_{trig})$:

$$P_0(I_{trig}) = I_{c,min}(T_0)\Delta x E_c \left(\frac{I_{trig}}{I_{c,min}(T_0)}\right)^{n+1}$$

we find:

$$\frac{I_{trig}}{I_{c,min}(T_0)} = \left[\frac{(K_0 + D\Delta T_{trig})\Delta T_{trig}\left(1 - \frac{\Delta T_{trig}}{\theta}\right)^n}{I_{c,min}(T_0)\Delta x E_c}\right]^{\frac{1}{n+1}}$$

or:

$$\frac{I_{trig}}{I_{c,min}(T_0)} = \left[\frac{I_1}{I_{c,min}(T_0)}\right]^{\frac{1}{n+1}}$$

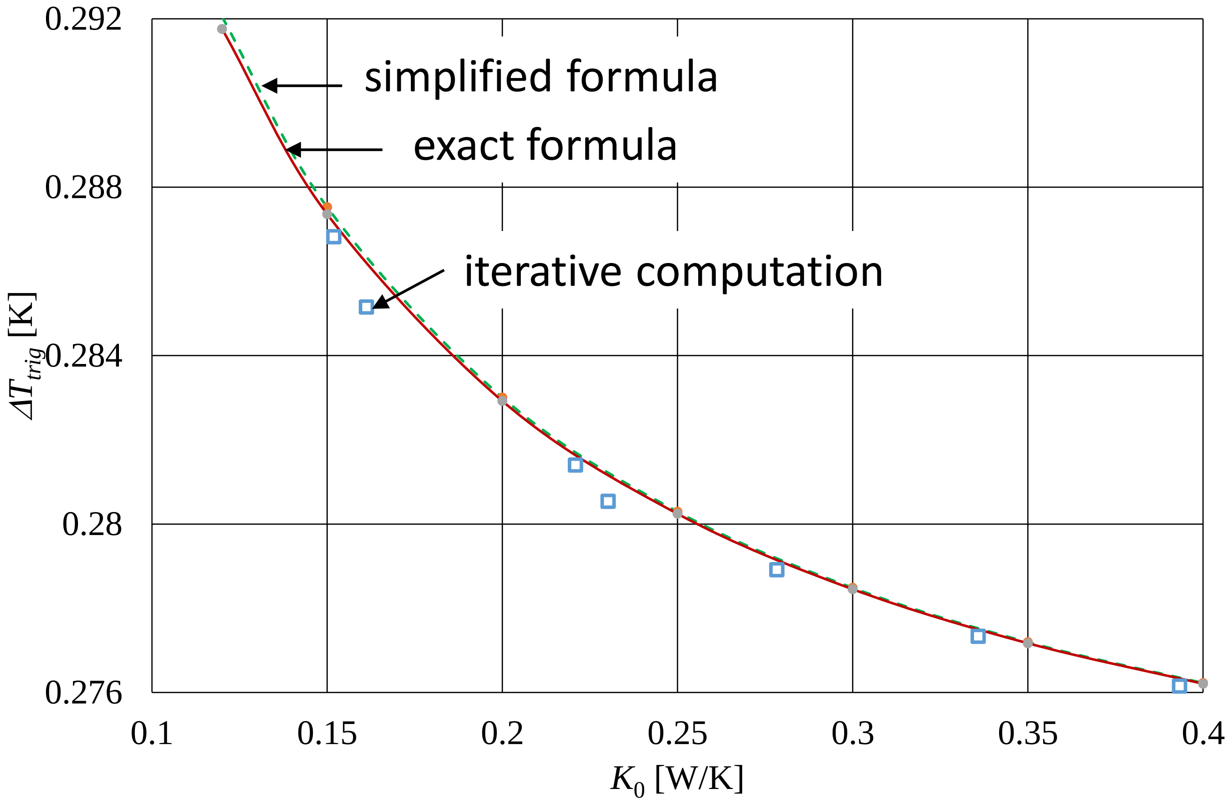
where

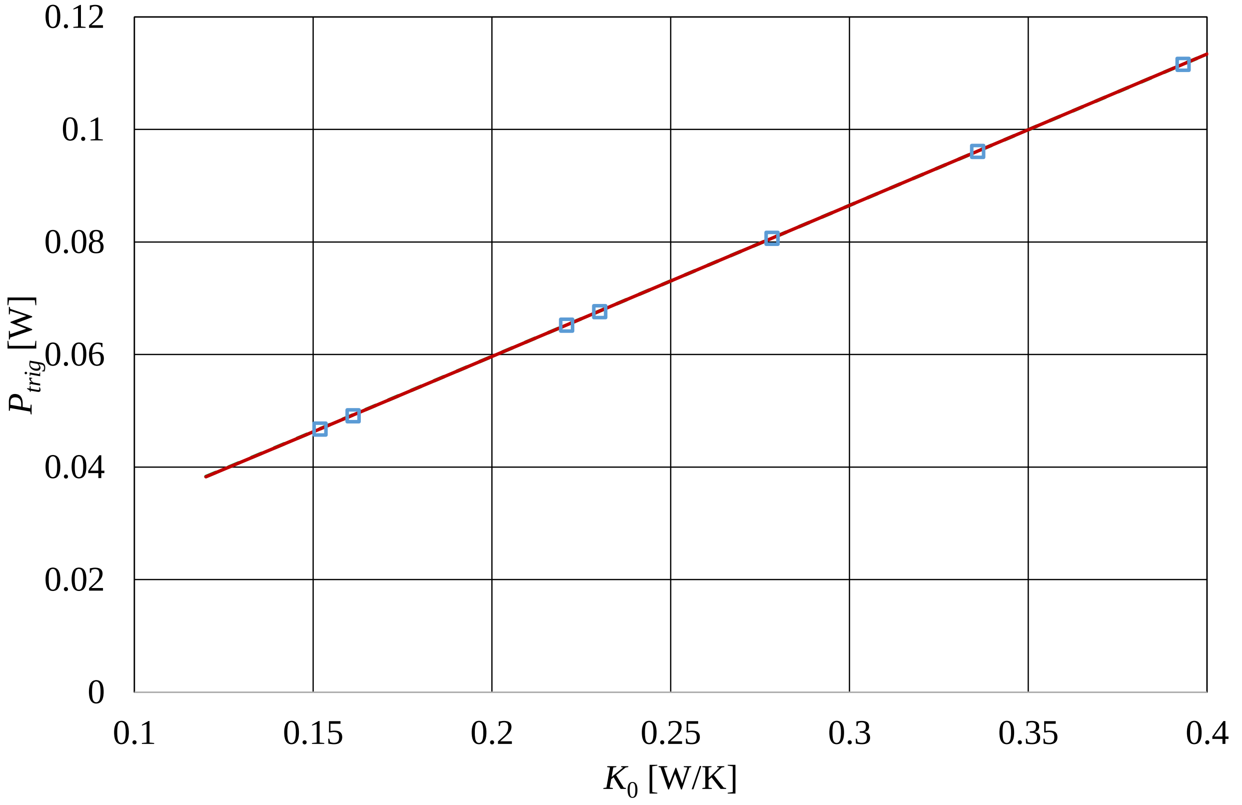
$$I_1 = \frac{(K_0 + D\Delta T_{trig})\Delta T_{trig}\left(1 - \frac{\Delta T_{trig}}{\theta}\right)^n}{\Delta x E_c}$$

is a constant that depends only on *n* and cooling !!!

DC current triggering the hot-spot development

FCL tape, single defect with dimension 2 mm, $n = 35$





DC current triggering the hot-spot development

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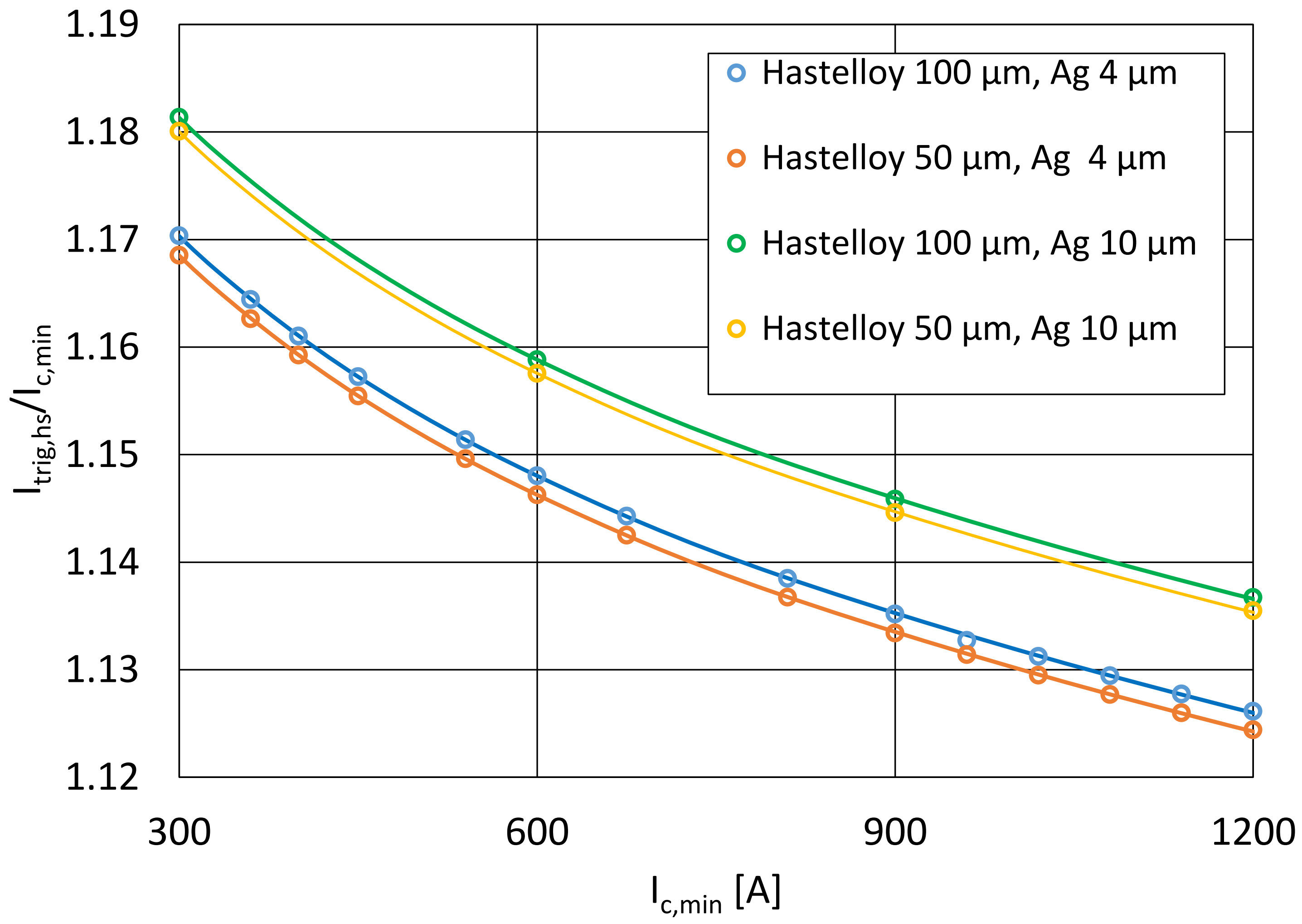
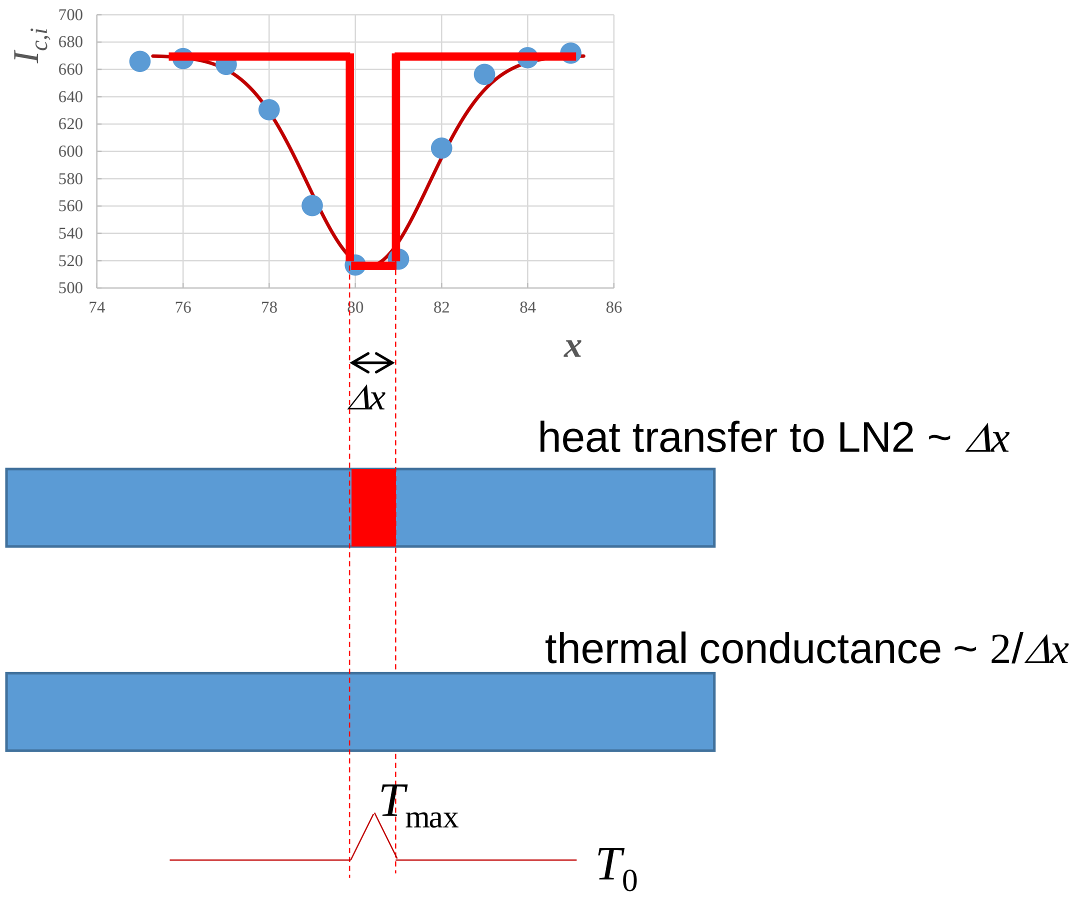
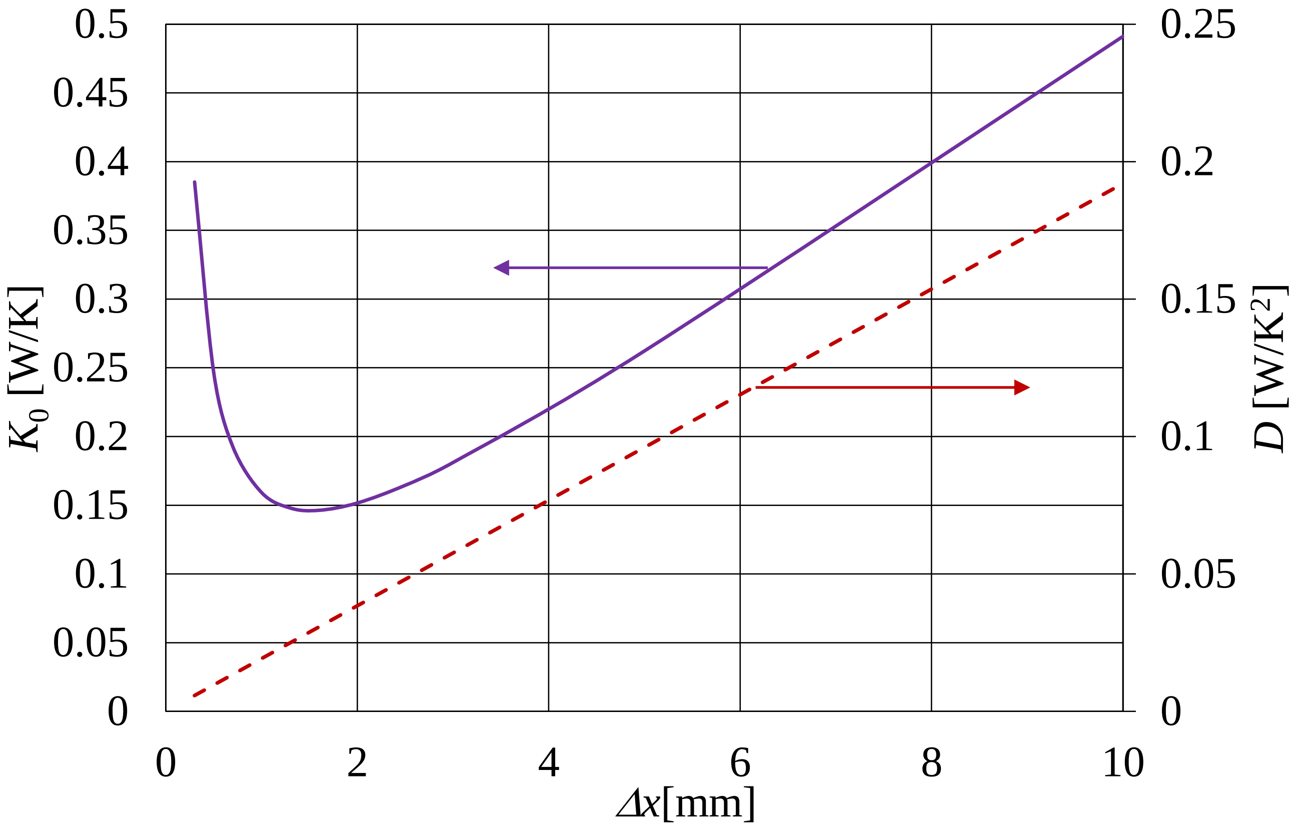


DC current triggering the hot-spot development

influence of defect dimension

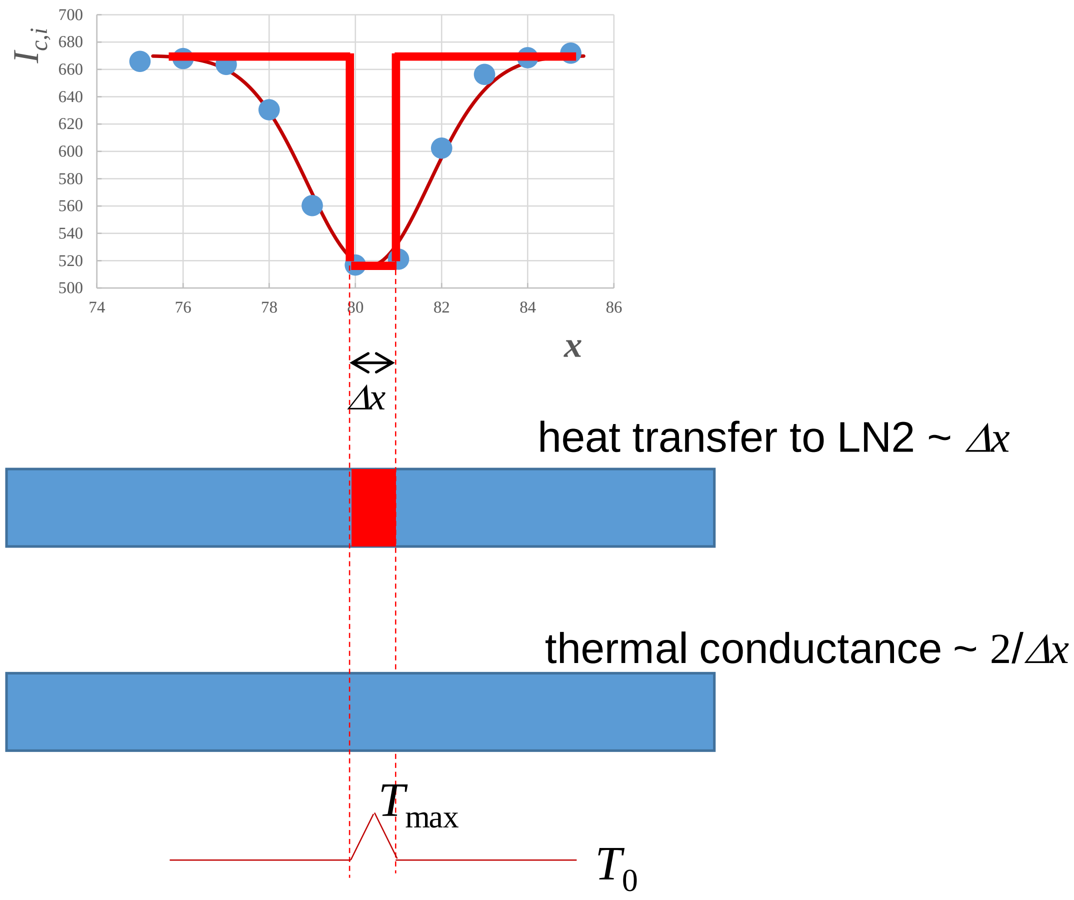


100 µm Hastelloy, 3 µmYBCO, 2 x 1.5 µmAg



DC current triggering the hot-spot development

influence of defect dimension



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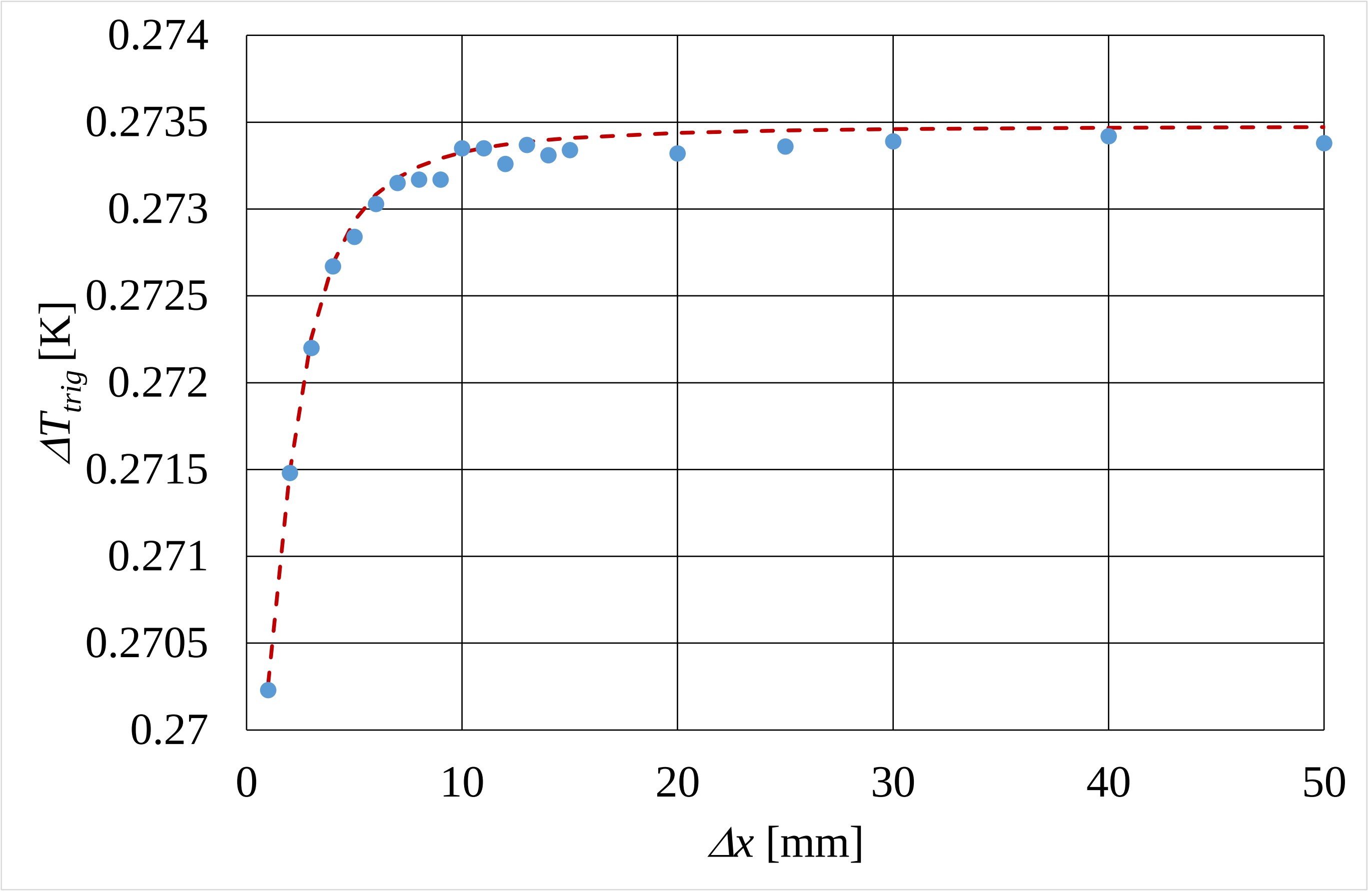

DC current triggering the hot-spot development

influence of defect dimension

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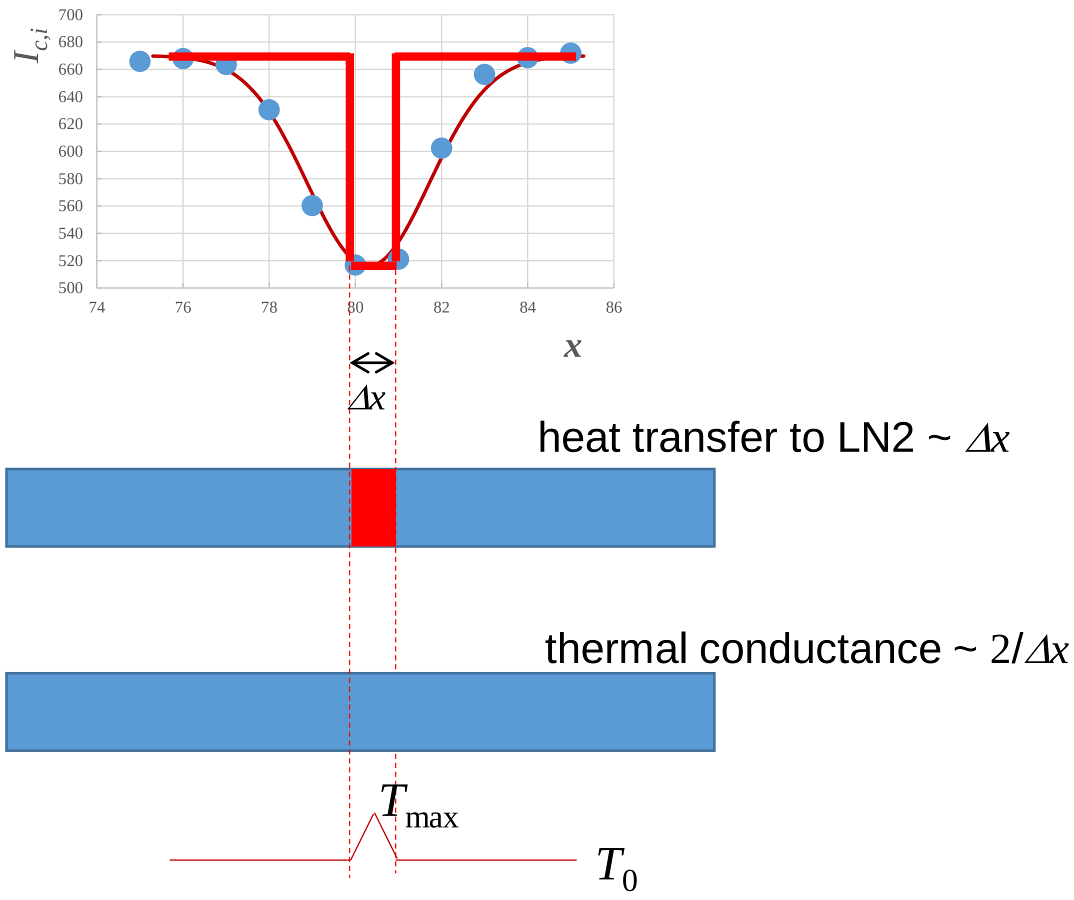
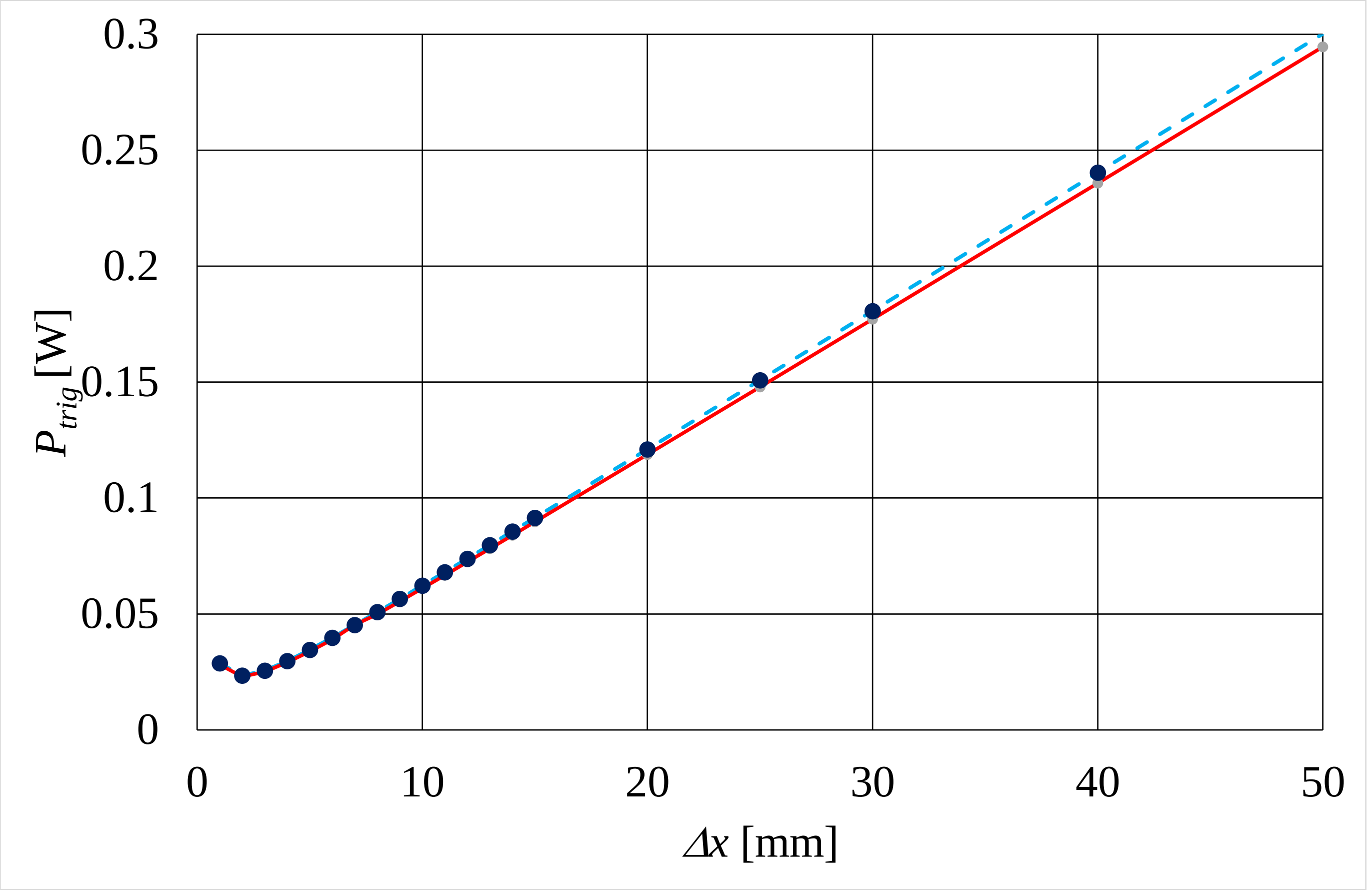
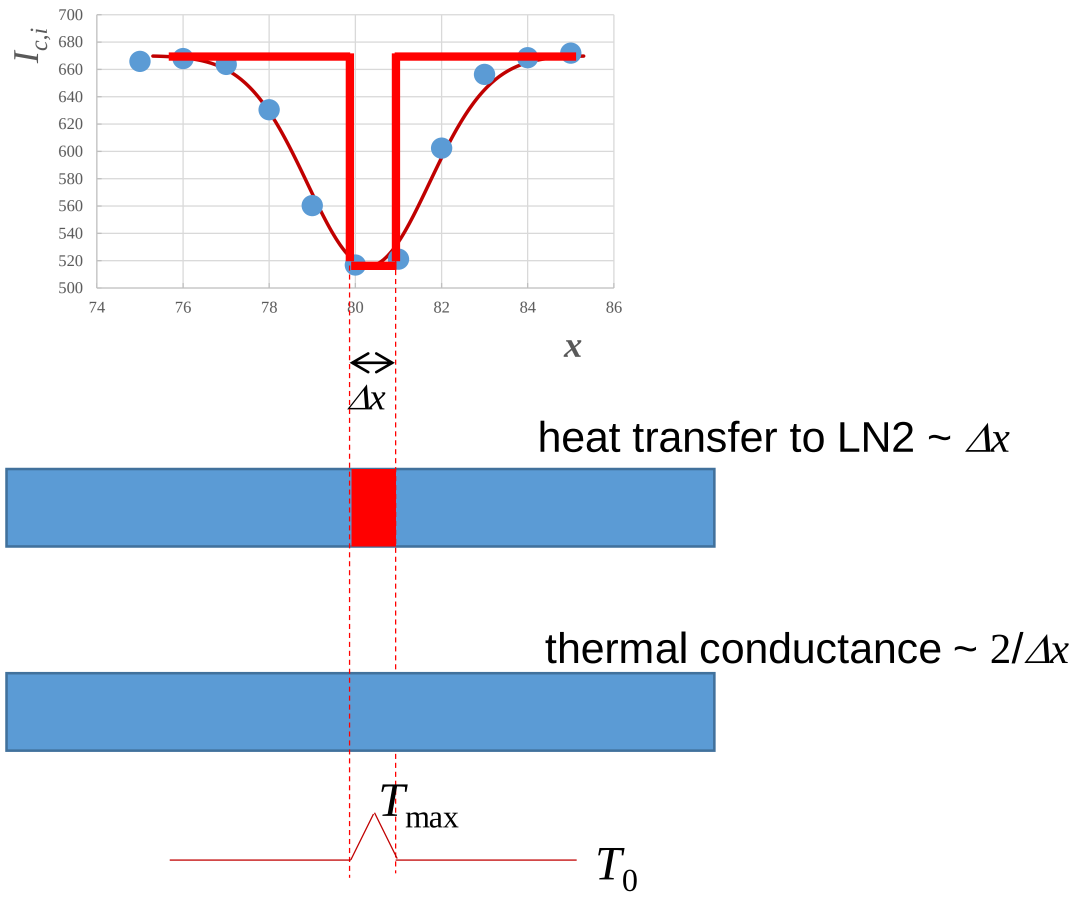




DC current triggering the hot-spot development

influence of defect dimension



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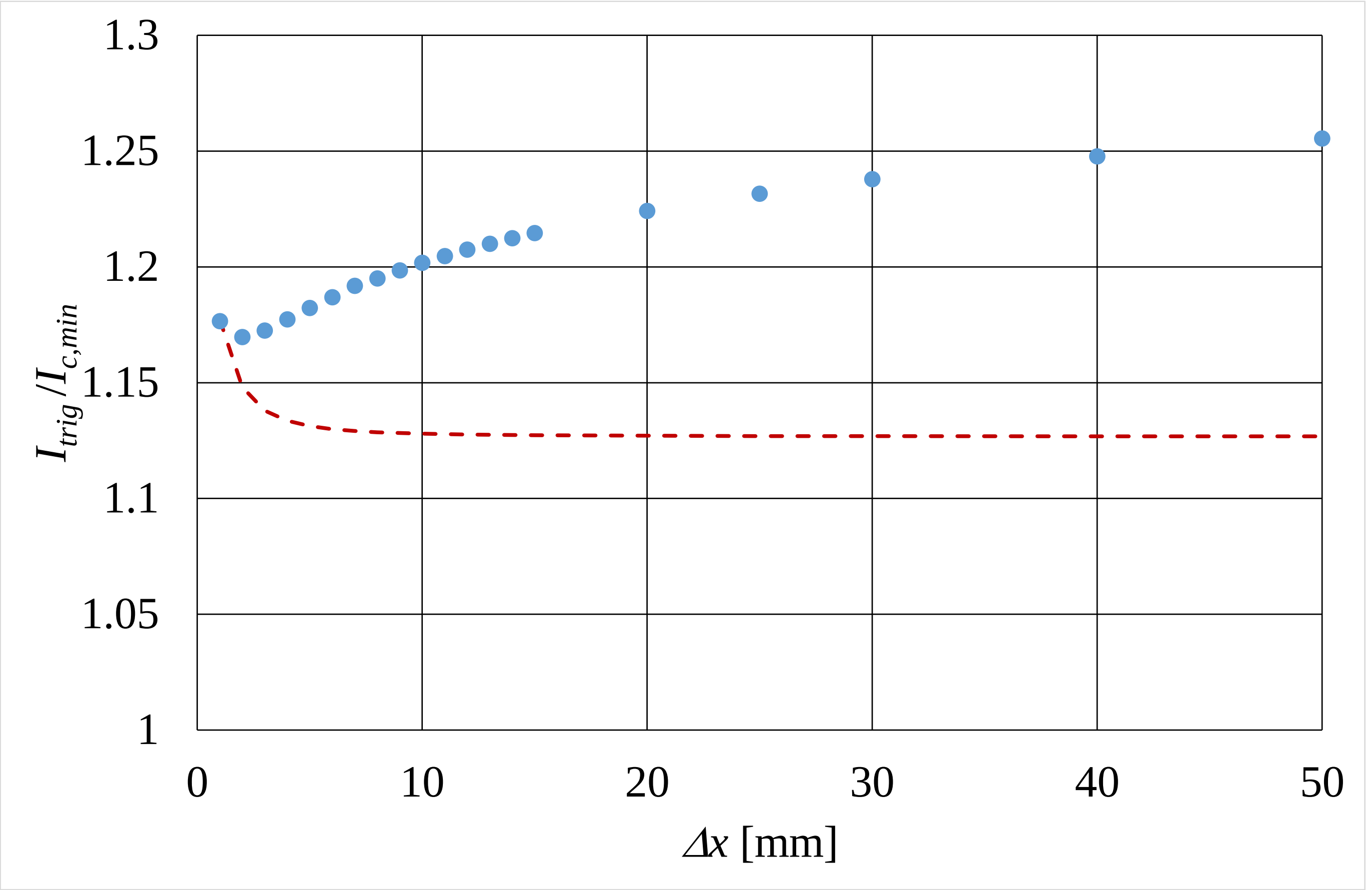
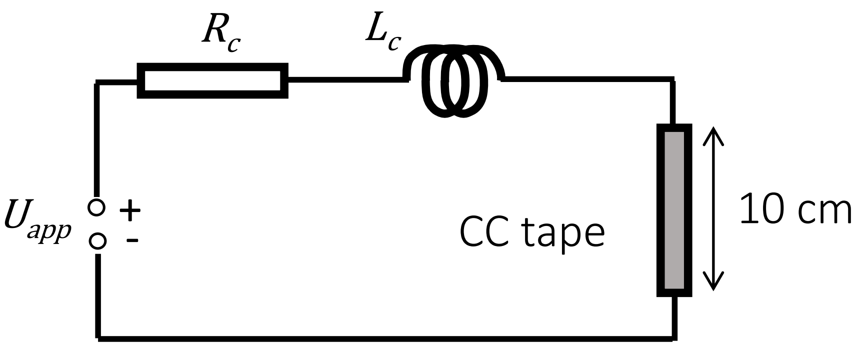
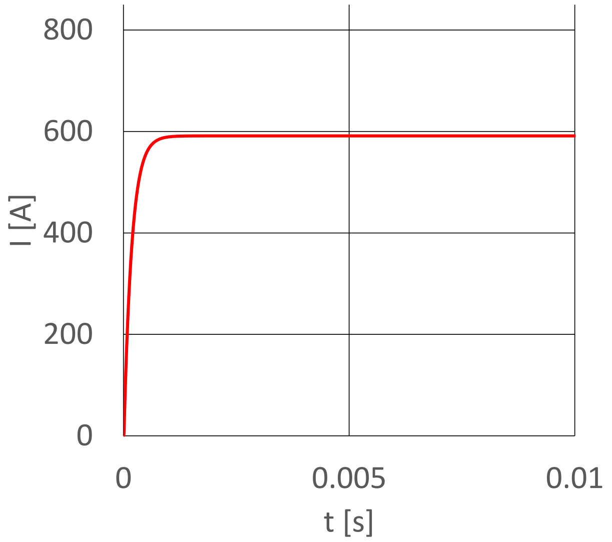


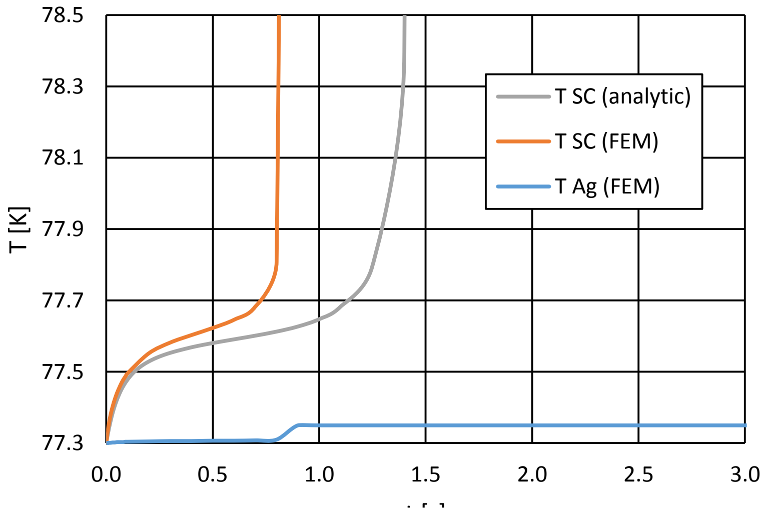
Remark on I_c determination

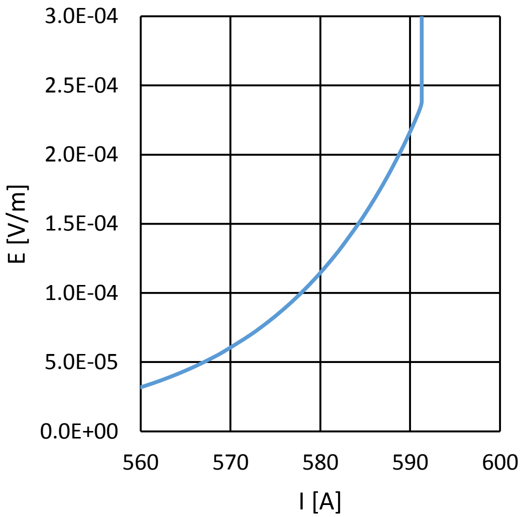
Computation for quasi-static testing current I

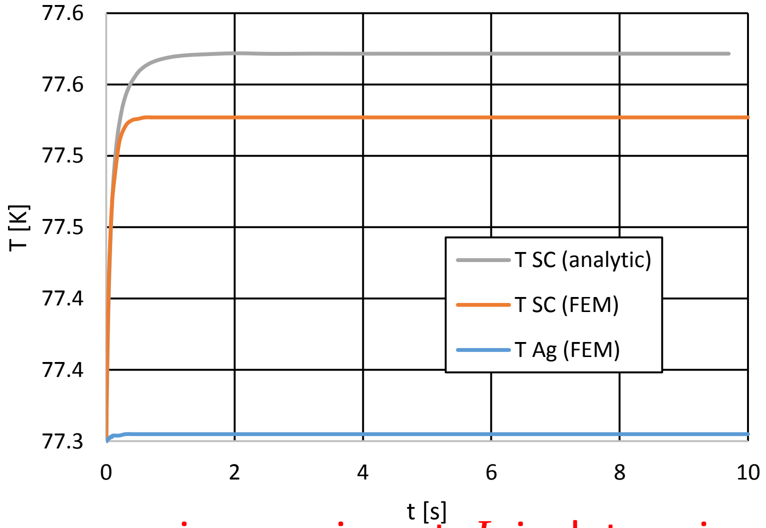


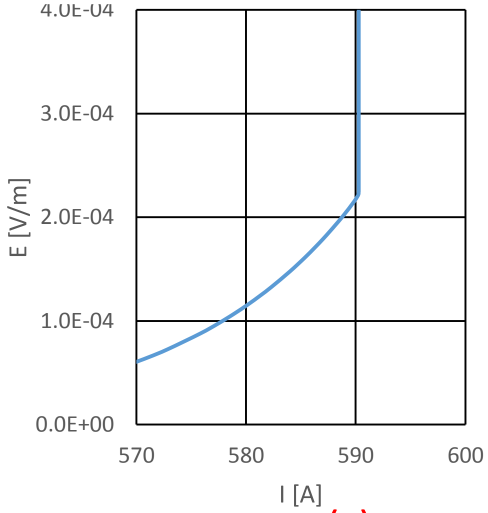
$U_{app} = 17$ V $L_c = 5$ μH R_c variable







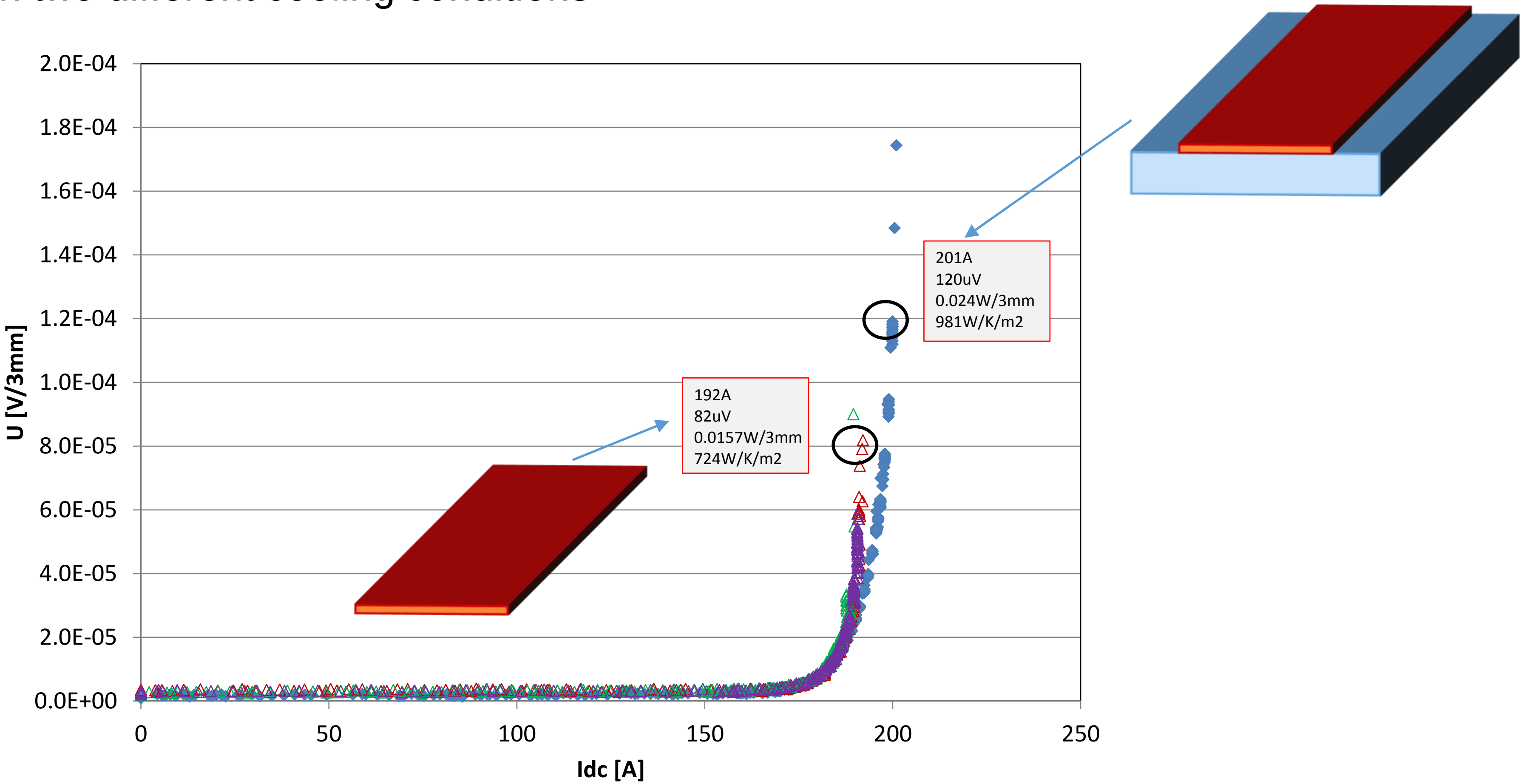




in experiment, I_c is determined at different temperature(s)

Remark on I_c determination

Tape with defect in two different cooling conditions



in experiment, I_c is determined at different temperature(s)

Conclusions

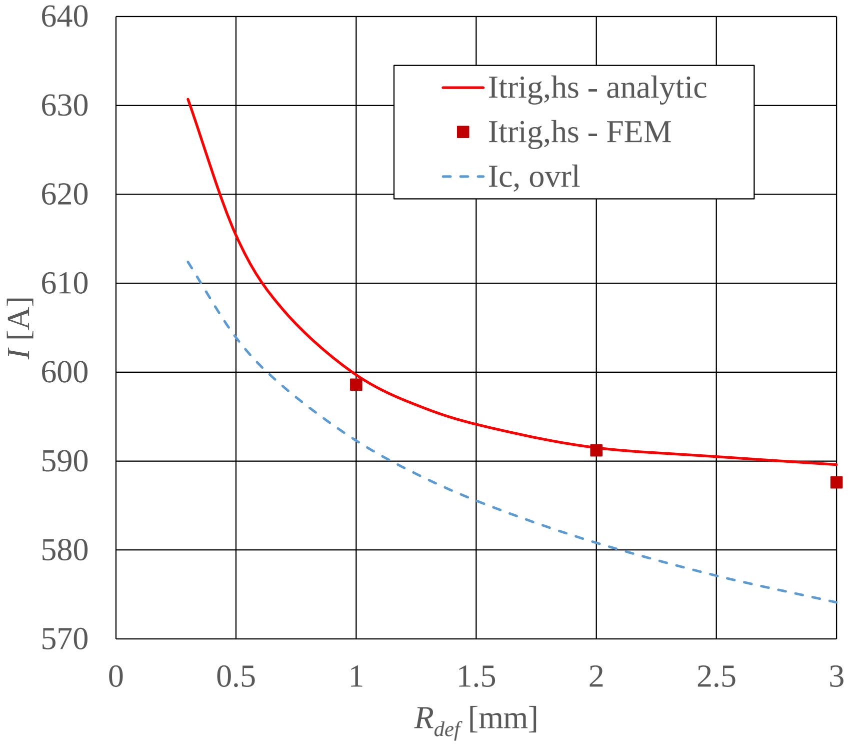
- Simple analytical model allows to predict the probability of hot spot creation in dependence on the value of transported DC current. It requires to know the value of minimum critical current, $I_{c,min}$, and the tape properties regarding the heat transfer.
- The length of tape section with reduced critical current has only minor influence on the value of current triggering the hot spot creation, I_{trig}
- In a long (>10 meters) tape, relevant for hot spot analysis is only the place with $I_{c,min}$
- Presence of spots with lowered I_c in combination with imperfect cooling leads to temperature increase resulting in lower determined I_c and increased n-power

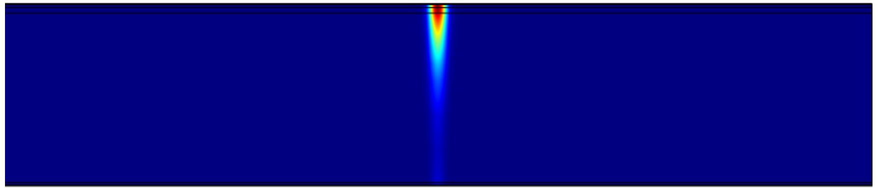
DC current triggering the hot-spot development

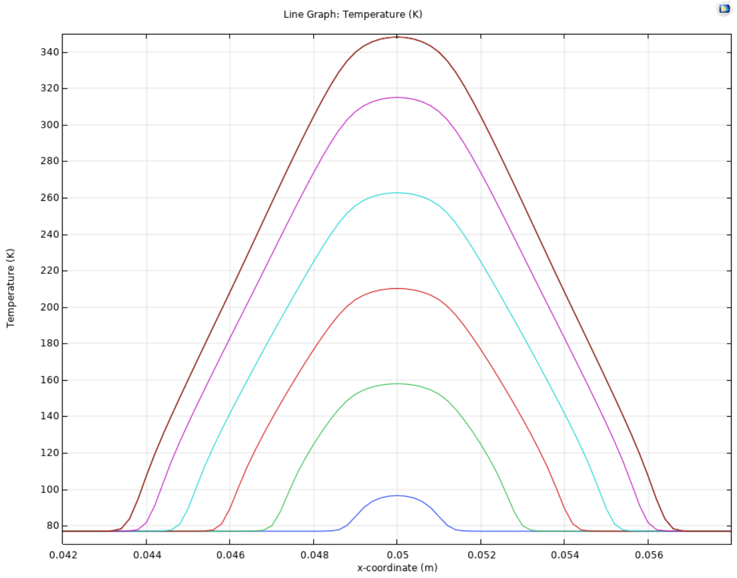
FCL tape, defect with dimension R_{def} in 10 cm long sample, I_{c0} = 670 A

FEM model : Comsol 5.4, 2D

D_{def} = 0.23 $\Rightarrow I_{c,min}/I_{c0}$ = 0.77







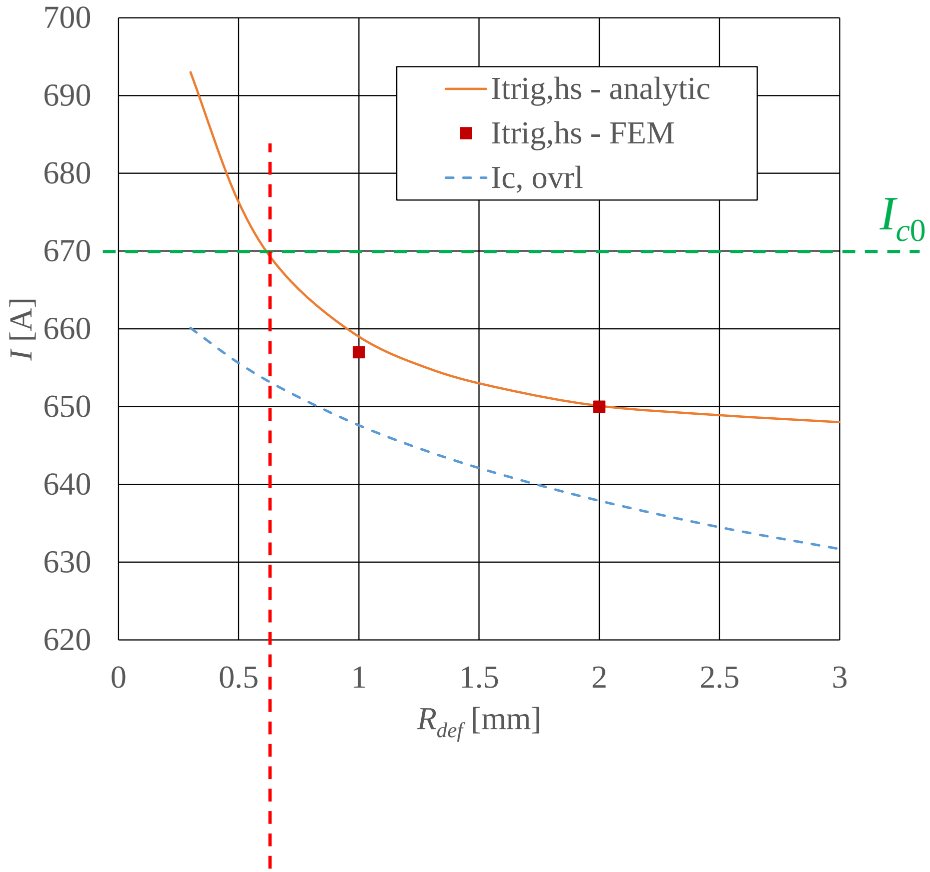
Surprisingly good prediction by simple analytic model

Lacroix C, Sirois F 2014 *Supercond. Sci.Technol.* **27** 035003

DC current triggering the hot-spot development

FCL tape, single defect with dimension R_{def} in 10 cm long sample, I_{c0} = 670 A

D_{def} = 0.15 $\Rightarrow I_{c,min}/I_{c0}$ = 0.85



Smaller defects do not evolve in a hot spot