Probability of premature quenching of HTS coil caused by a local reduction of critical current

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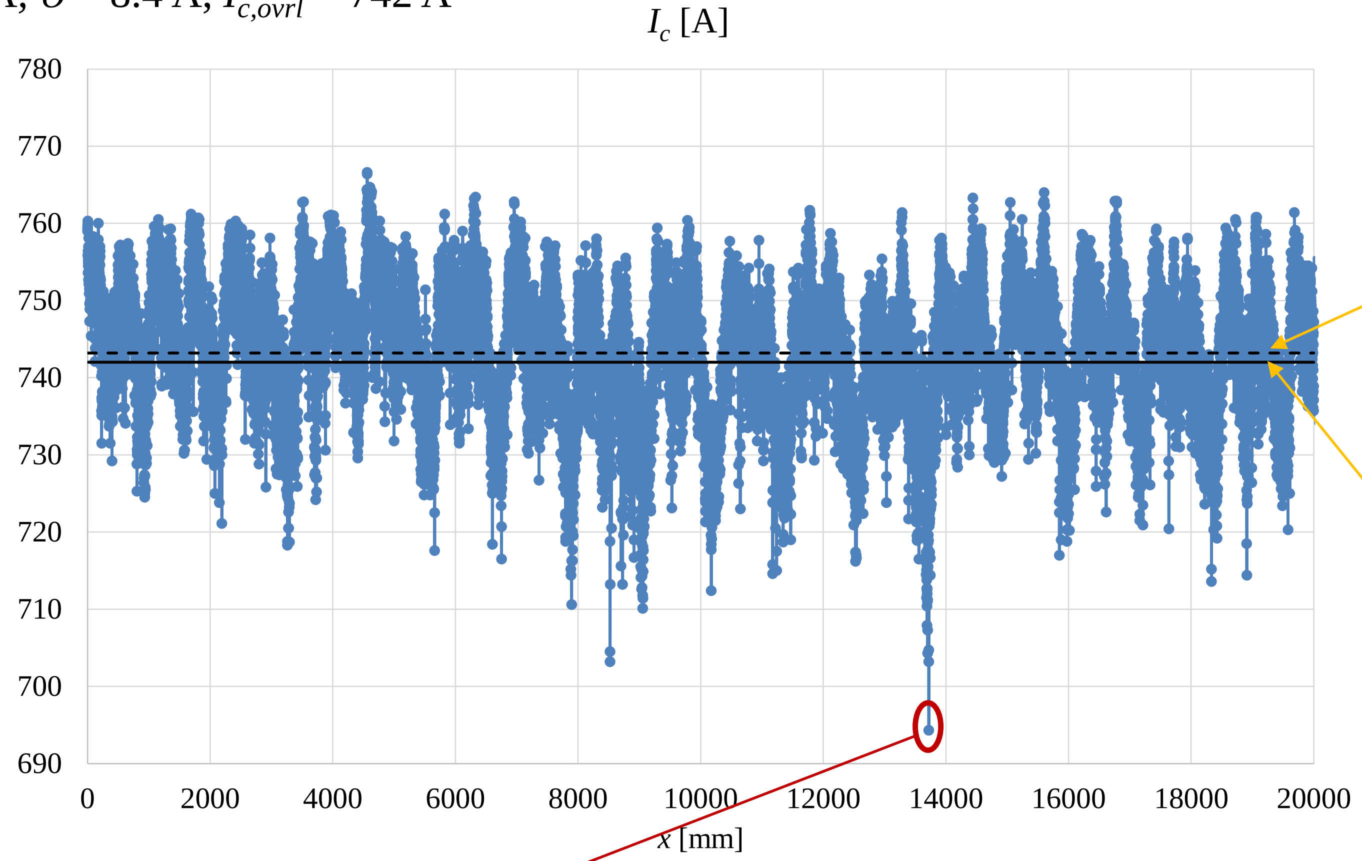
I_c (x) phenomenon: fluctuation of critical current, weak spot(s)

example: Tapestar data from 20 meters of commercial HTS tape 12 mm wide, 77 K self field

$I_{c,mean}$ = 743 A, σ = 8.4 A, $I_{c,ovrl}$ = 742 A



average value of critical current

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

overall critical current generating 1 µV/cm on all the tape length

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

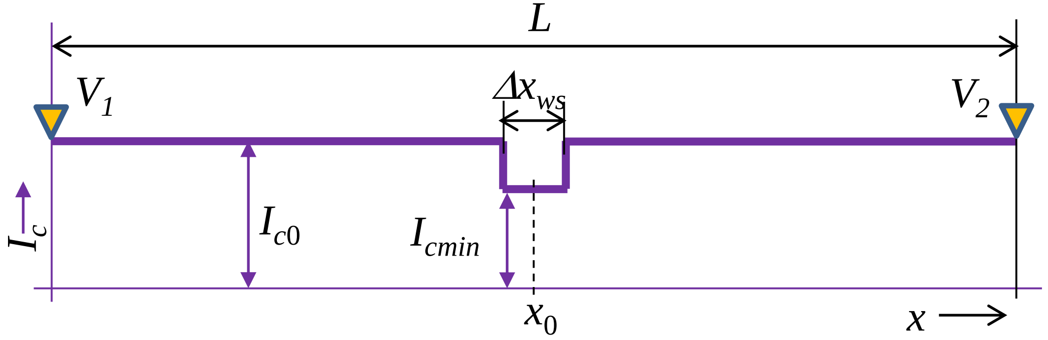
the weak spot with I_{cmin} = 694 A (i.e. 93.5% of $I_{c,ovrl}$)

how high is the probability that the weak spot will cause the tape to quench?

Outline

1) Simple model of the weak spot
2) Thermal runaway current vs. overall critical current
3) Weak spot length vs. the voltage taps distance
4) Influence of the electric field criterion
5) Conclusions

Simple model of the weak spot (stepwise approximation, 2 parameters)



critical current in the weak spot

length of the weak spot

$$I_c(x) = \begin{cases} I_{cmin} & if\,|x - x_0| \le \Delta x_{ws} \\ I_{c0} & elsewhere \end{cases}$$

assumption:

$$E(x) = E_c\left(\frac{I}{I_c(x)}\right)^n$$

voltage measured

power law exponent

overall critical current detected in DC testing, single weak spot between voltage taps V_1, V_2 :

Y Wang et al.: Cryogenics 43 (2003) 71-77 920030

$$U = LE_c\left(\frac{I}{I_{c,ovrl}}\right)^n$$

voltage criterion for determining I_c

$$I_{c,ovrl} = \left[\frac{N}{\sum_{i=1}^{N}\left(\frac{1}{I_{c,i}}\right)^n}\right]^{\frac{1}{n}} = \frac{1}{\left[\left(1 - \frac{\Delta x_{ws}}{L}\right)\frac{1}{I_{c0}^n} + \frac{\Delta x_{ws}}{L}\frac{1}{I_{cmin}^n}\right]^{\frac{1}{n}}}$$

tested length of tape

thermal conductance

thermal runaway current converts the weak spot into a hot spot:

F Gömöry and J Šouc: Supercond. Sci. Technol. 34 2021 025005

$$I_{tr} = I_{cmin}\left(\frac{K_0(T_c - T_0)}{I_{cmin}e\Delta x_{ws}E_c n}\right)^{\frac{1}{n+1}}$$

„critical temperature“

assumption: $I_{cmin}(T) = I_{cmin}\dfrac{T_c - T}{T_c - T_0}$

reference (bath) temperature

Influence of the weak spot length on removal of the dissipated heat

example: 12 mm wide tape

Hastelloy [µm]	50
SC [µm]	3
Ag [µm]	2
Cu [µm]	40
total [µm]	95

Tc [K]	85
T0 [K]	77.3
n	30

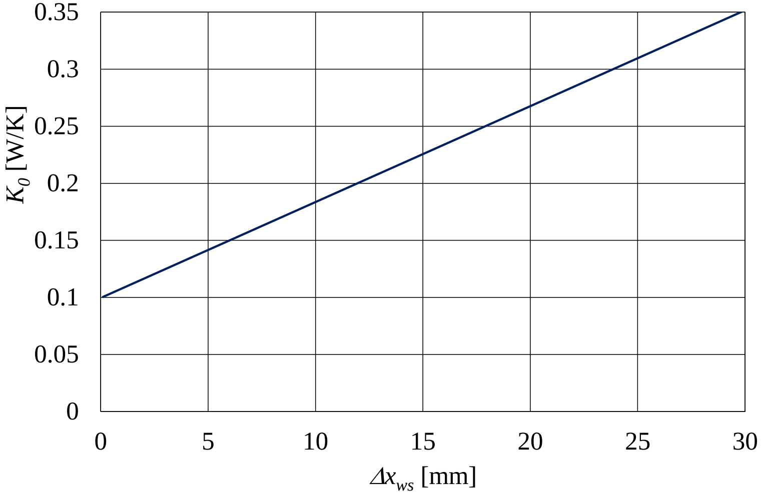
bath cooling = 350 Wm^{-2} K^{-1}

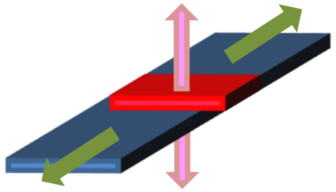
both sides wetted by LN

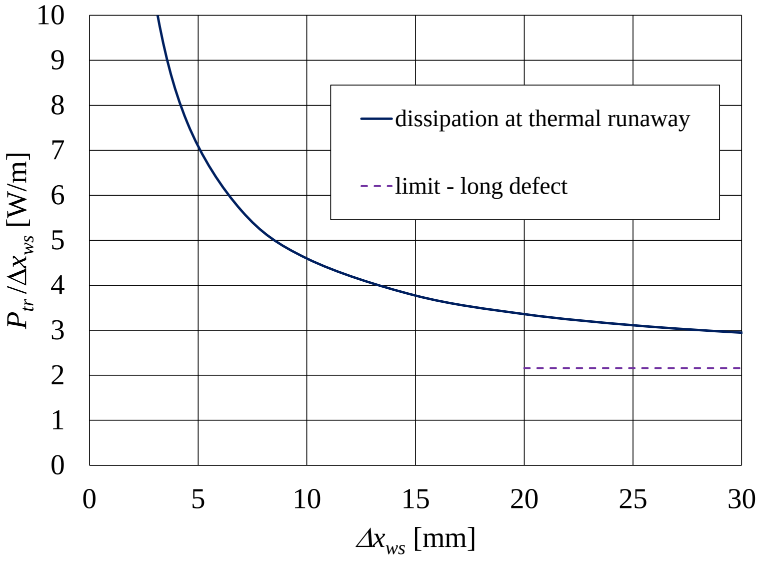
thermal conductivity = 259 Wm^{-1} K^{-1}

along the tape length

Thermal conductance from the weak spot to the surrounding







Smaller defect are cooled better
(because of longitudinal thermal conductivity)

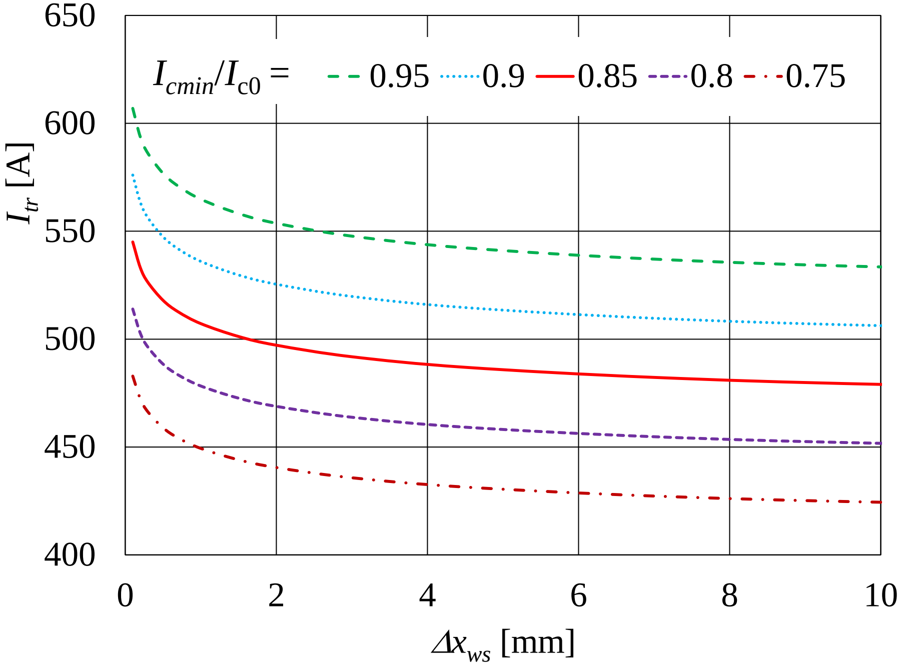
Influence of the weak spot length on the thermal runaway current and the overall critical current

example: 12 mm wide tape, $\boldsymbol{I_{c0}} = \mathbf{500\ A}$
(77.3 K, self field, $E_c = 1\ \mu V/cm$)

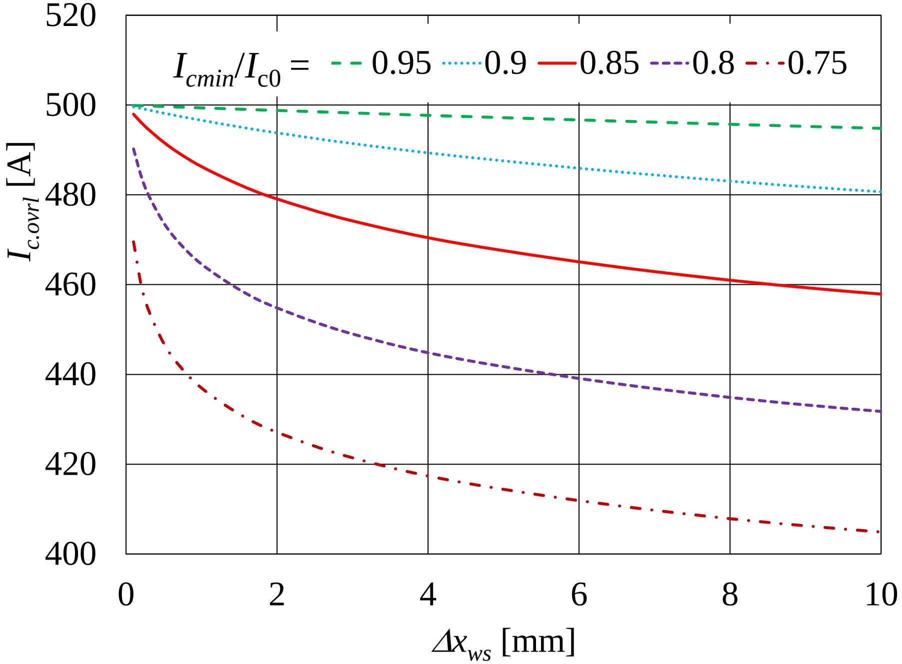
bath cooling = 350 $Wm^{-2}\ K^{-1}$
both sides wetted by LN

thermal conductivity = 259 $Wm^{-1}\ K^{-1}$
along the tape length

Thermal runaway current for 5 – 25% local reduction of critical current



Overall critical current determined on 10 cm long sample (with weak spot)



possible danger during conductor testing and/or operation close to the (overall) critical current, when $I_{tr} < I_{c,ovrl}$

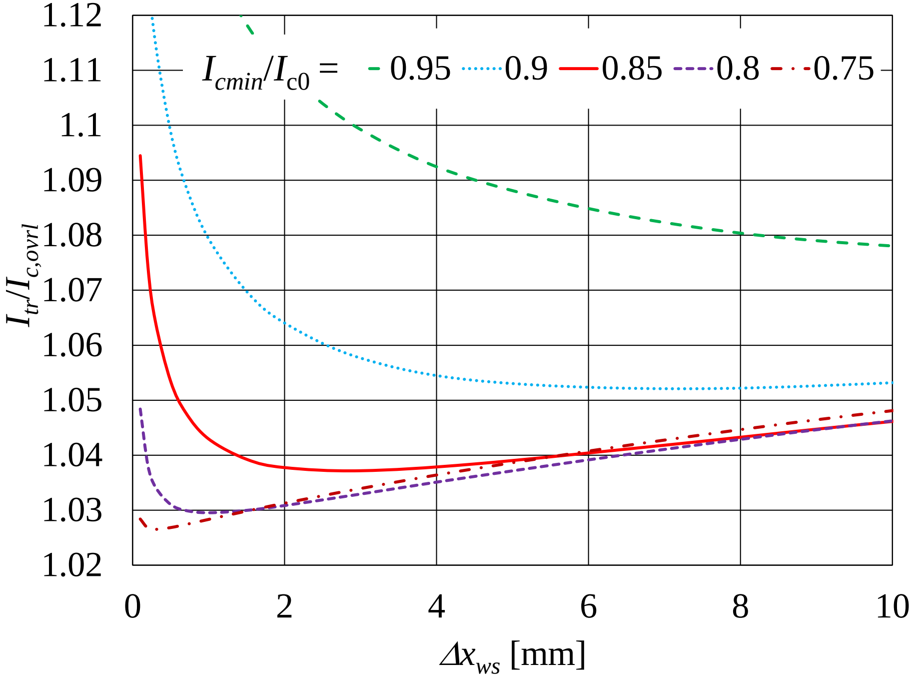
Ratio of thermal runaway current vs overall critical current, 500 A tape

example: 12 mm wide tape, I_{c0} = 500 A
(77.3 K, self field, E_c = 1 μV/cm)

bath cooling = 350 $Wm^{-2} K^{-1}$
both sides wetted by LN

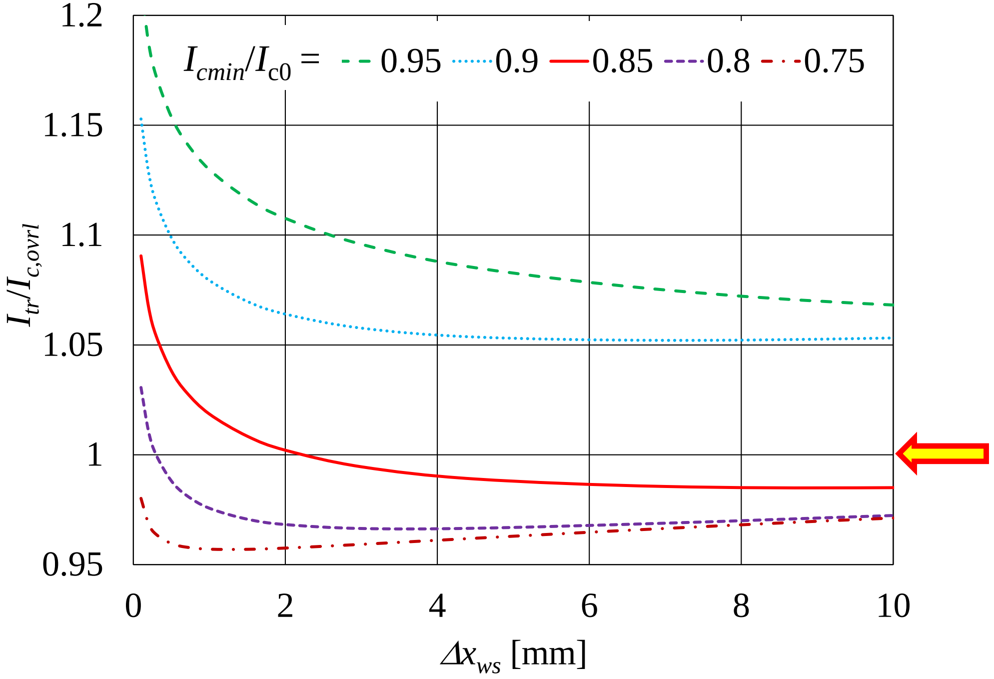
thermal conductivity = 259 $Wm^{-1} K^{-1}$
along the tape length

Distance of voltage taps: 10 cm



$I_{tr} > I_{c,ovrl}$ determined on 10 cm long sample
- no danger of entering the thermal runaway even at 25% local reduction of critical current

Distance of voltage taps: 1 meter



$I_{tr} < I_{c,ovrl}$ for the weak spot with 15% reduction if it were longer than ~2 mm

weak spot converted to hot spot before reaching the critical current $I_{c,ovrl}$

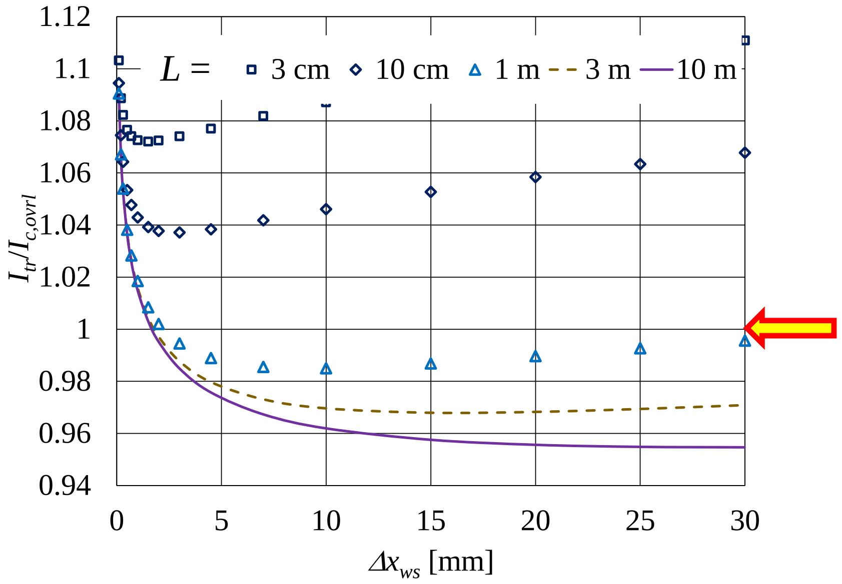
Ratio of thermal runaway current vs overall critical current, 500 A tape

example: 12 mm wide tape, I_{c0} = **500 A**
(77.3 K, self field, $E_c = 1\ \mu$V/cm)

bath cooling = 350 Wm^{-2} K^{-1}
both sides wetted by LN

thermal conductivity = 259 Wm^{-1} K^{-1}
along the tape length

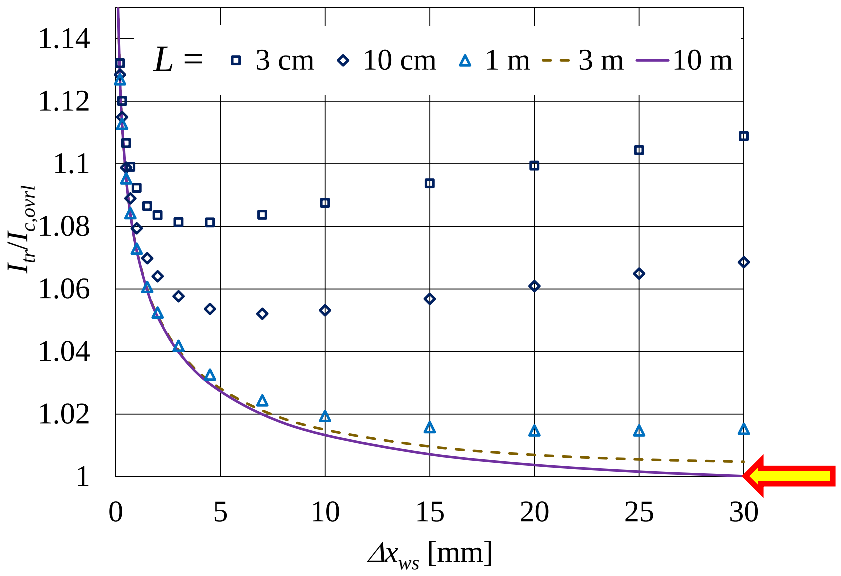
Weak spot with $I_{cmin} = 0.85\ I_{c0}$



$I_{tr} > I_{c,ovrl}$ on samples shorter than 10 cm,
but $I_{tr} < I_{c,ovrl}$ for the measurement on 1 m
(and longer)

weak spot with 15% reduction of critical current could escape detection
when the critical current is checked with 1 m resolution

Weak spot with $I_{cmin} = 0.9\ I_{c0}$



$I_{tr} > I_{c,ovrl}$ at any sample length
weak spot with 10% reduction O.K

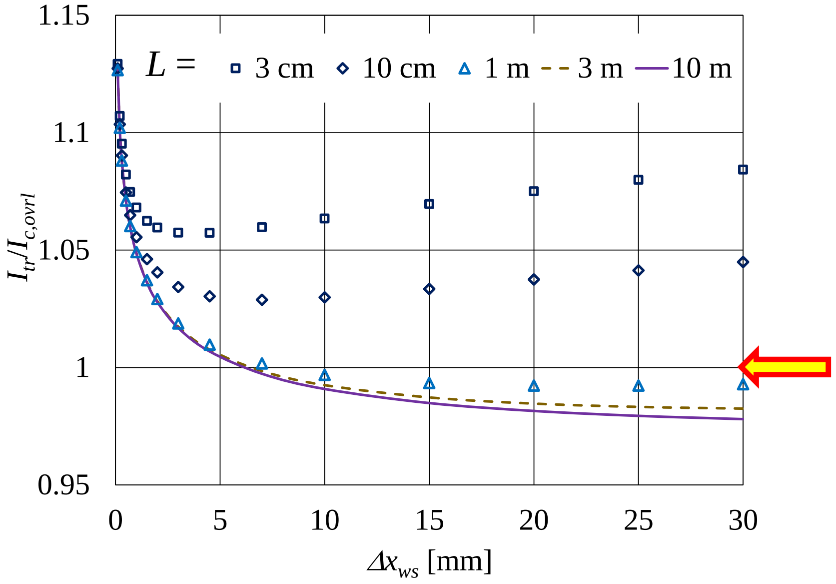
Ratio of thermal runaway current vs overall critical current, 1000 A tape

example: 12 mm wide tape, I_{c0} = **1000 A**
(77.3 K, self field, $E_c = 1\ \mu\mathrm{V/cm}$)

bath cooling = 350 $\mathrm{Wm^{-2}\,K^{-1}}$
both sides wetted by LN

thermal conductivity = 259 $\mathrm{Wm^{-1}\,K^{-1}}$
along the tape length

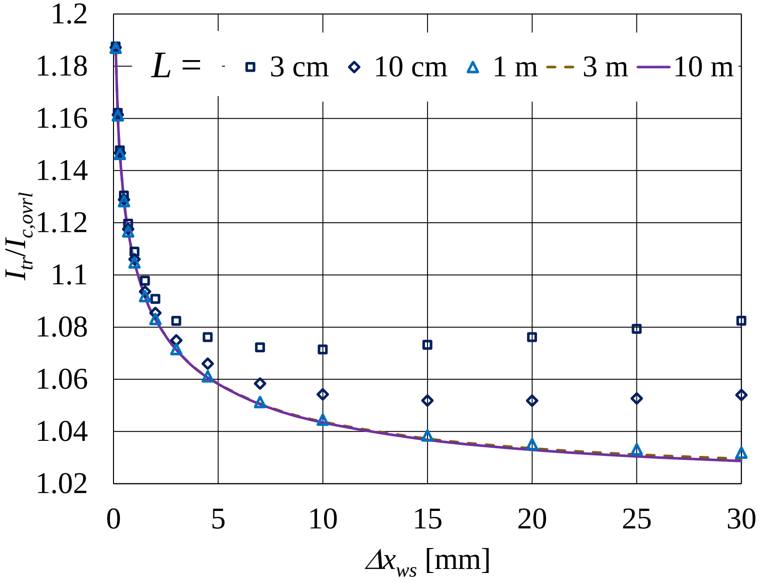
Weak spot with I_{cmin} = 0.9 I_{c0}



$I_{tr} > I_{c,ovrl}$ on samples shorter than 10 cm,
but $I_{tr} < I_{c,ovrl}$ for the measurement on 1 m
(and longer)

weak spot with 10% reduction of critical current could escape detection when the critical current is checked with 1 m resolution

Weak spot with I_{cmin} = 0.95 I_{c0}



$I_{tr} > I_{c,ovrl}$ at any sample length
the weak spot with 5% reduction O.K.

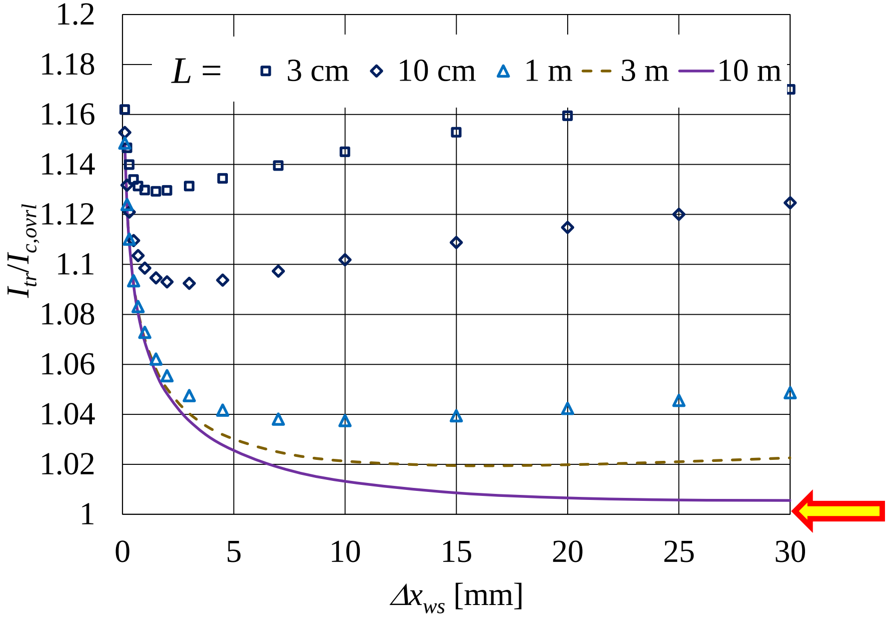
Possible remedy for high-current tapes: use of more sensitive I_c criterion

example: 12 mm wide tape, I_{c0} = **1000 A**
(77.3 K, self field, E_c = 0.1 μV/cm)

bath cooling = 350 Wm^{-2} K^{-1}
both sides wetted by LN

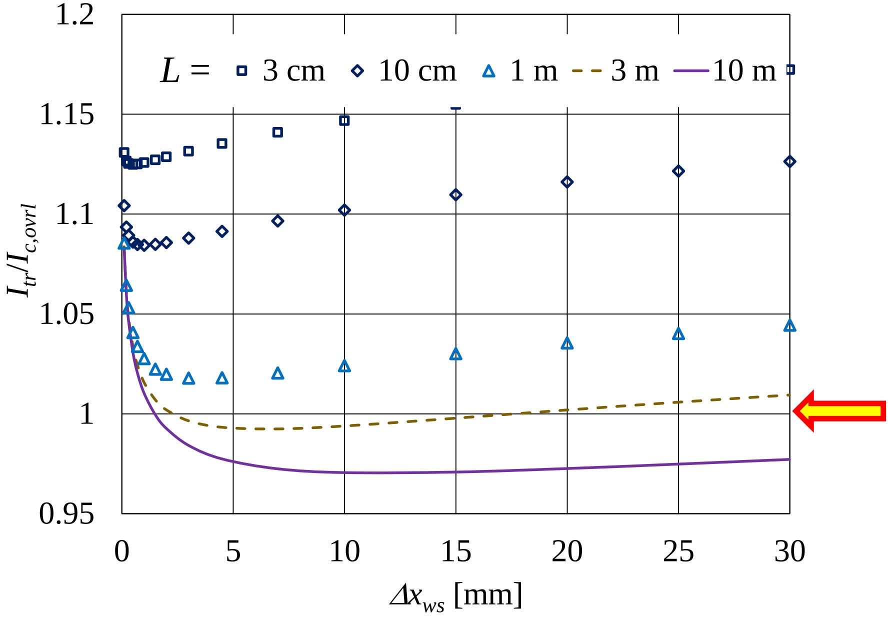
thermal conductivity = 259 Wm^{-1} K^{-1}
along the tape length

Weak spot with I_{cmin} = 0.85 I_{c0}



now the weak spot with 15% reduction of critical current does not represent a danger because $I_{tr} > I_{c,ovrl}$

Weak spot with I_{cmin} = 0.8 I_{c0}



…but at suspected 20% drop of critical current the 1 m resolution of I_c data would be necessary

Conclusions

Simple model allows to predict the relation between the thermal runaway current, I_{tr} , (converting the local weak spot into the hot spot) and the overall critical current, $I_{c,ovrl}$, detected at the electrical field criterion, E_c

When $I_{tr} < I_{c,ovrl}$ the conductor would quench before reaching the critical current

Very short weak spots are less dangerous, but $I_{tr} / I_{c,ovrl}$ dependence is rather complex

Conductors with higher critical current are more prone to premature quenching because of lower $I_{tr} / I_{c,ovrl}$

Using, instead of 1 µV/cm, a more sensitive criterion e.g. E_c = 0.1 µV/cm, offers more „reserve“ in $I_{tr} / I_{c,ovrl}$