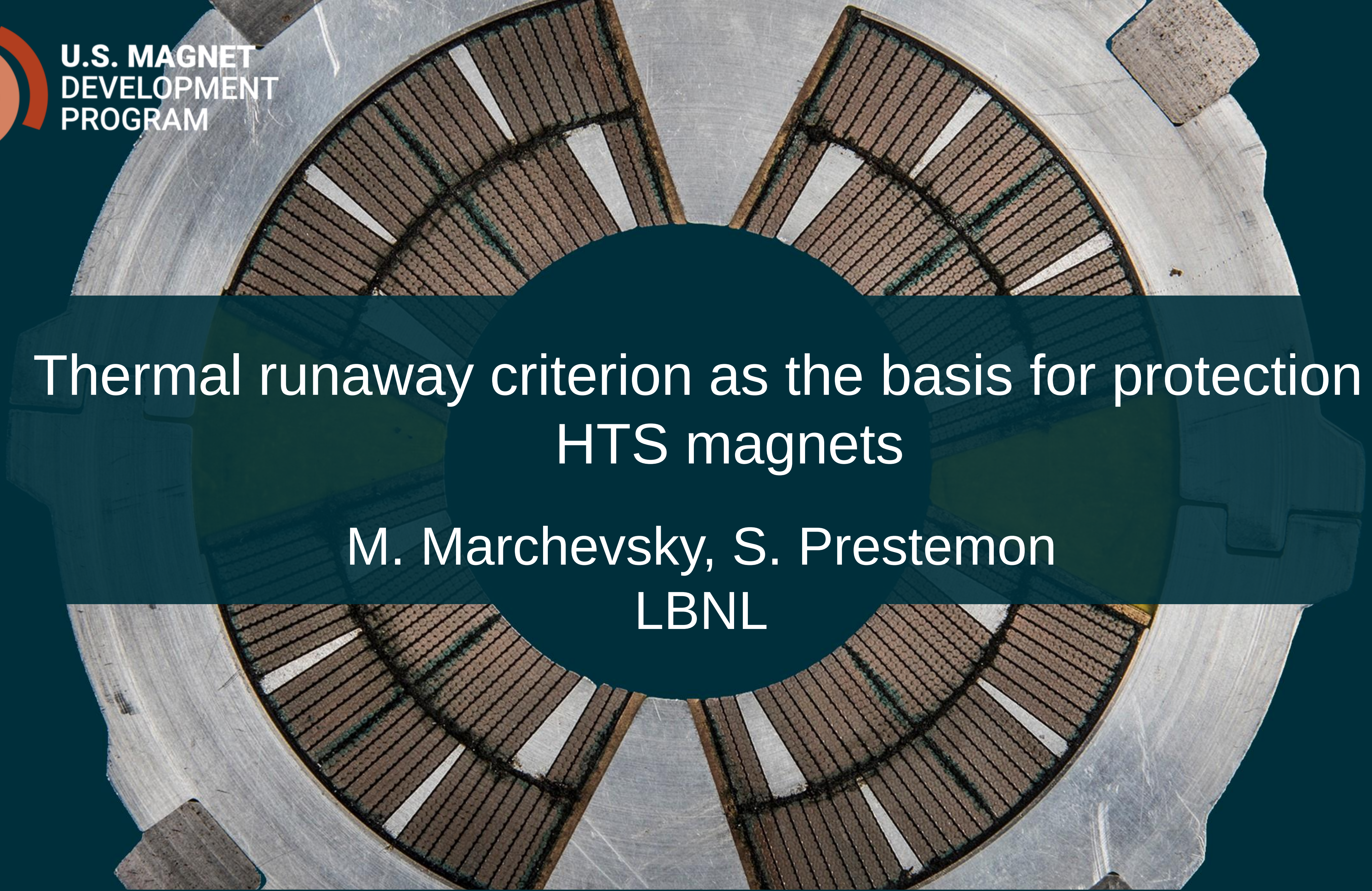
U.S. MAGNET DEVELOPMENT PROGRAM



Thermal runaway criterion as the basis for protection of HTS magnets

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A “no-quenching” protection paradigm for HTS magnets

- Quench protection of HTS-based magnets is difficult owing to a slow quench propagation velocity in HTS. A normal zone in an HTS magnet can be nearly stagnant and, thus, quickly heat up to high temperatures, destroying the conductor.

- At the same time, growing experimental evidence suggests that HTS conductors can operate in a stable dissipative flux flow regime for a substantial range of operational currents before entering an irreversible thermal runaway.

- Therefore, a new protection paradigm for HTS magnets has emerged, aiming to **prevent quenching altogether, using advanced diagnostics to detect the <u>onset of the dissipative regime</u> rather than quenching.**

“Classical” approach to quench protection in LTS magnets

The temperature of the quenching conductor can be evaluated using a well-established method by Wilson, equating the net Joule heating integrated over the quench propagation time τ to the thermal energy accumulated by the conductor when heated from T_0 to T_H, giving rise to the quench integral in the form:

$$\int_{T_0}^{T_H} \frac{c(T)}{\rho(T)} dT = \frac{1+r}{r} \int_{t_0}^{t_0+\tau} J^2(t) dt$$

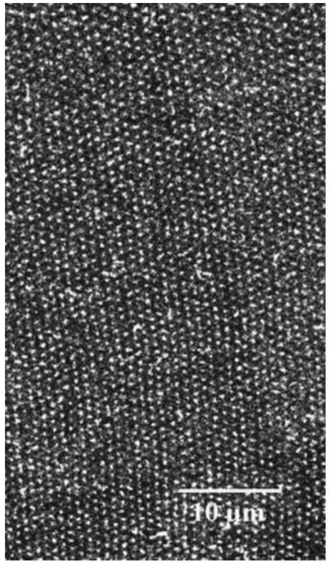
where $c(T)$ is the volumetric heat capacity of the conductor, $\rho(T)$ is its normal-state resistivity, r is the superconductor-to-normal stabilizer volumetric ratio, and $J(t)$ is the current density.

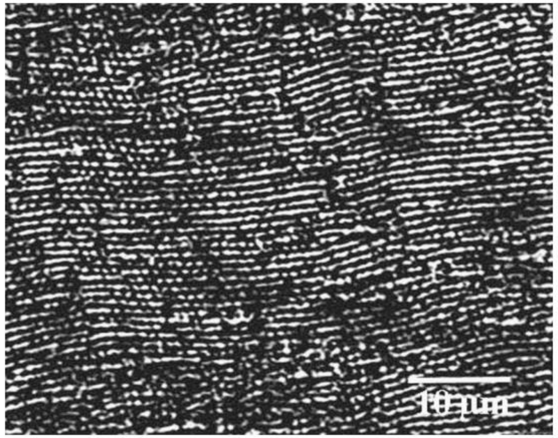
Adiabatic = heat transfer to the environment is neglected

The transition from superconducting (flux pinned) to normal state is assumed to be “abrupt” in time owing to the very low enthalpy of the normal zone formation in conventional (strongly pinning) superconductor conductors

I-V characteristics in the flux-flow regime

HTS conductors could be operated in a range of temperatures and magnetic fields in a flux-flow state, yet without quenching - owing to a significantly wider operational margin in the field-temperature plane.

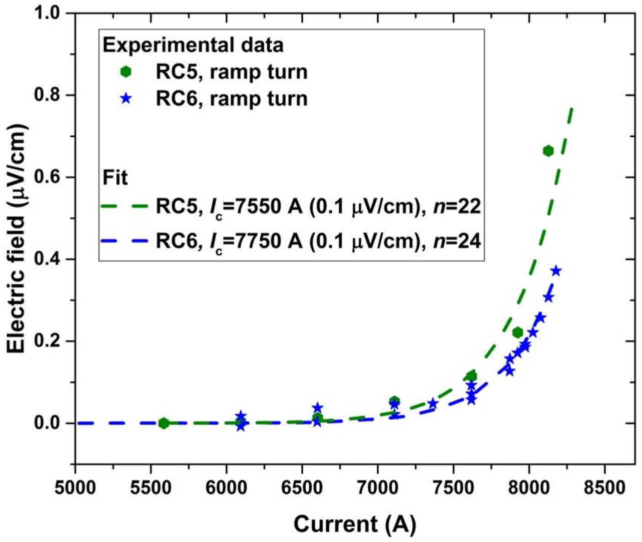




Flux flow can be sustained in low-pinning LTS and HTS

M. Marchevsky et al., Phys. Rev. B 60, pp 14601-14604 (1999)

$$U = U_0\left(\frac{I}{I_c(B,T)}\right)^n$$



T. Shen, E. Bosque, D. Davis et al. Sci Rep ***9****, 10170 (2019).*

The conductor is constantly dissipating heat in the flux flow regime. Yet, it may take many seconds to reach T^* where $I_c(T^*)$ = 0, invalidating the adiabatic approximation.

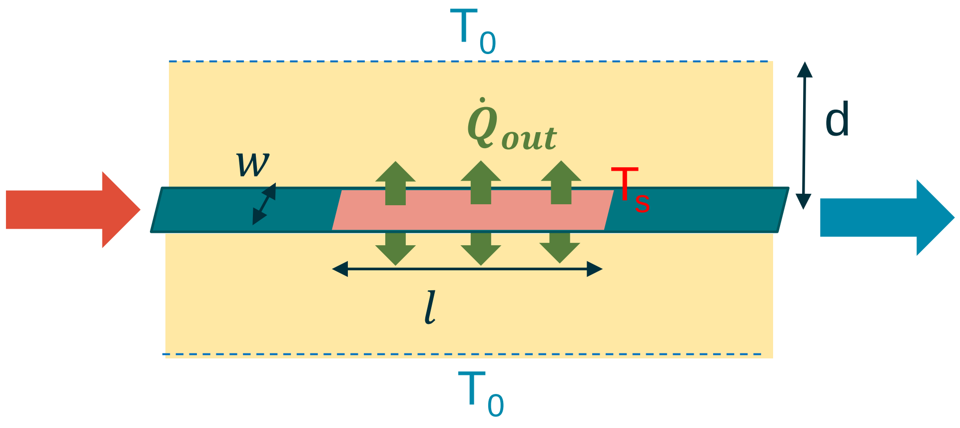
Quench integral approach cannot be used here...

An alternative approach

An alternative to using the quench integral is to define the upper boundary of a stable dissipative regime by considering a **dynamic thermal equilibrium** between the heat-dissipating HTS conductor and its environment.

A condition for the dynamic equilibrium: $\dot{Q}_{in}(I,B,T) = \dot{Q}_{out}(T)$

$$\dot{Q}_{in} = I^2 R(I,B,T)$$



$$\dot{Q}_{out} = \lambda(T)\frac{2lw}{d}(T - T_0)$$

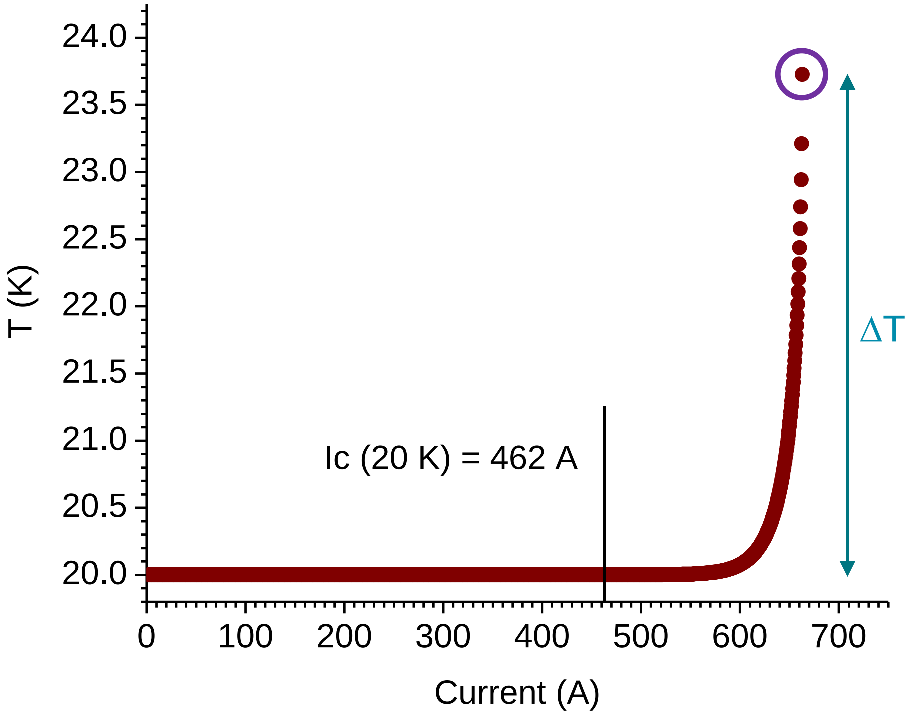
$$R_s = E_o l \frac{I^{n-1}}{I_c(B,T)^n} \qquad E_o = 1\mu\text{V/cm}$$

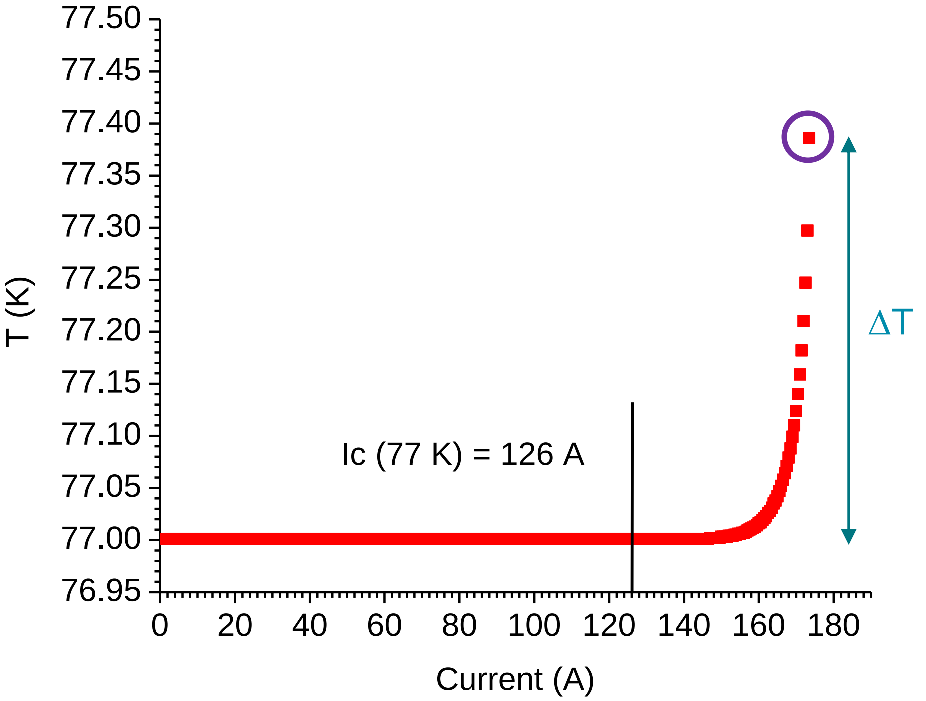
As long as this condition can be satisfied for some current I^* (and the corresponding $T^* > T_0$), the flux flow regime is **stable, and there is no thermal runaway**.

This is somewhat analogous to the cryo-stability condition in LTS, except here it describes a large-scale behavior of the conductor in a superconducting state, not a local normal-zone type of disturbance

Current-Temperature curves

λ =65 W / K m I_c (T=0) = 500 A n = 30





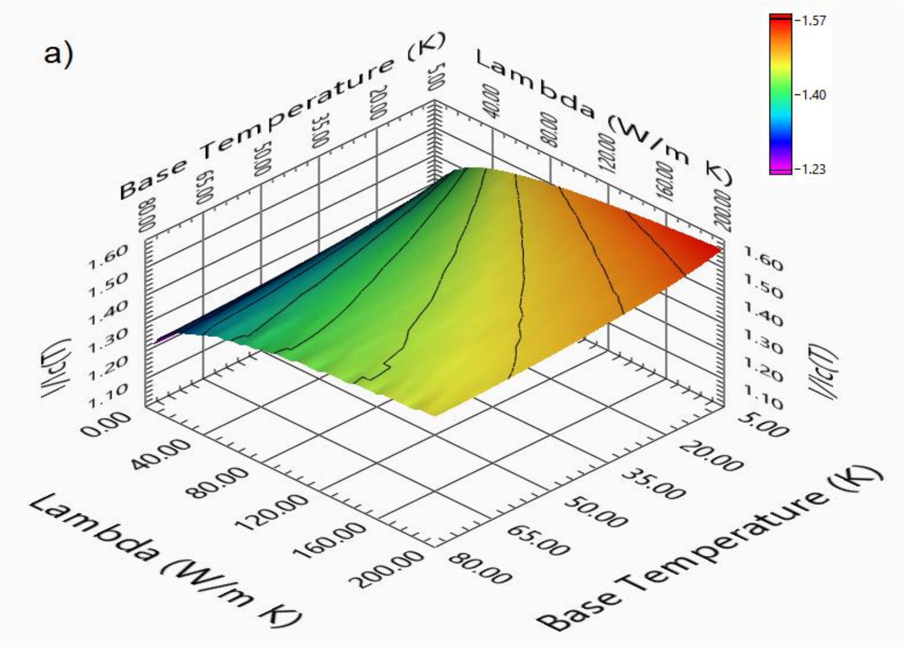
Current-temperature curves can be generated, where each point represents a dynamic equilibrium. The last point of each graph (encircled) defines the critical surface above which a thermal runaway will occur.

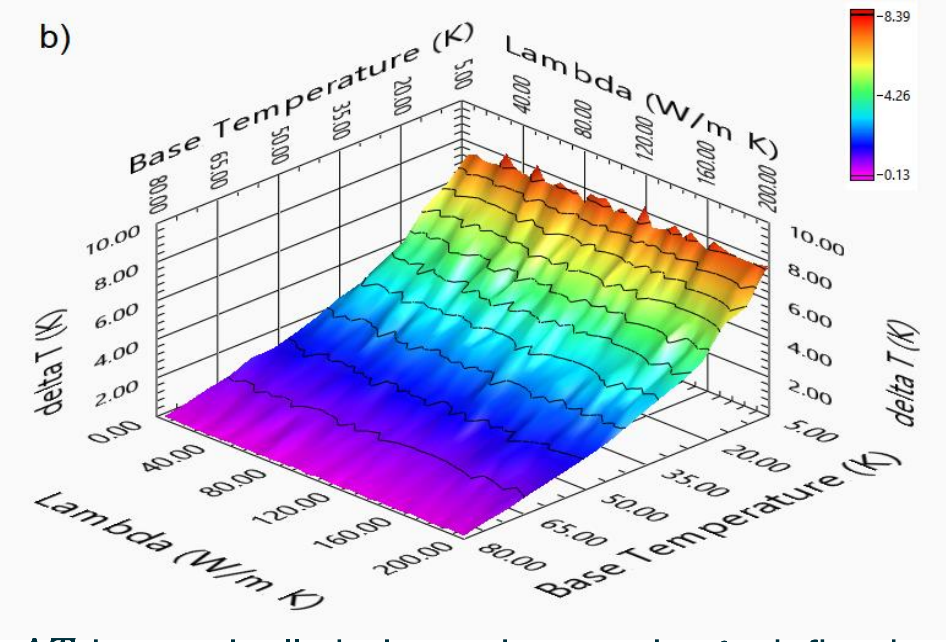
Thermal runaway surface
(bare HTS, temperature-independent heat transfer coefficient)

We assume the critical current of the HTS conductor to follow the empirical temperature dependence: $I_c(T) = I_{c0}\left(1 - \left({}^{T}/_{T_c}\right)^{1.7}\right)$
$T_c = 85$ K (irreversibility temperature).

The conductor has $I_{c0} = 500$ A, width $w = 0.004$ m (tape-shaped), and it is separated from thermal reservoir of constant temperature T_0 on both sides with a barrier of thickness of $d = 0.01$ m made of brass.

Solving the heat balance equation numerically for the current I^* and $\Delta T = T^* - T_0$, varying the base temperature T_0, heat transfer coefficient λ, and assuming $n = 20$





ΔT is practically independent on the λ, defined by the base temperature T_0

Case of a stabilized HTS conductor

In a practical HTS conductor, the superconducting layer can share current with the normal metal (usually copper) stabilizer and (to a smaller degree) with the metallic substrate (Hastelloy, stainless steel, or similar). As all layers (superconductor, copper stabilizer, substrate) are electrically connected in parallel, one can express the net resistance of the stabilized conductor as follows:

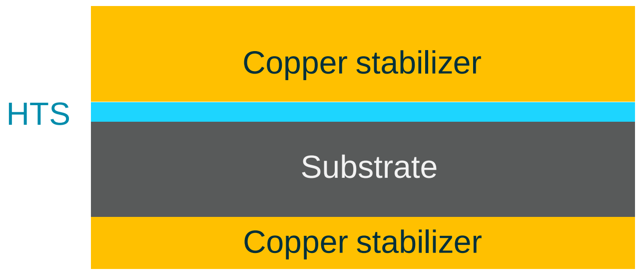
$$R(T) = \frac{R_s(I_x, T)\, R_{st}(T)}{R_s(I_x, T) + R_{st}(T)}$$

where $R_{st}(T) = \left(\frac{1}{R_{cu}(T)} + \frac{1}{R_{ss}(T)}\right)^{-1}$ is the net temperature-dependent resistance of the copper and substrate layers

We assume $R_{Cu}(T)$ to follow the known Gruneisen-Bloch dependence:

$$\rho(T) = A\left(\frac{T}{Q_R}\right)^n \int_0^{Q_R/T} \frac{t^n}{(e^t - 1)(1 - e^t)}$$

Where n =5 for simple metals, $Q_R \sim Q_D$ (Cu), and with the choice of free parameter *A* yielding the table room temperature resistivity value of $R_{Cu\,300K} =$ 1.6x10^{-8} W m and RRR ~24.



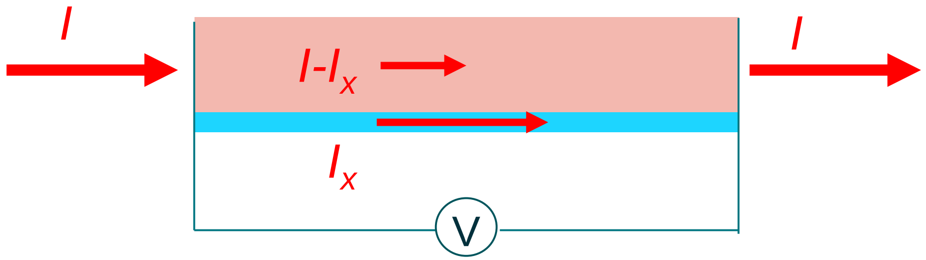
We assume the stabilized conductor cross-section is as follows:

- superconducting layer: 1.3 μm
- copper stabilizer: 50 μm (total)
- substrate: 50 μm

Calculating current balance

The resistance of the superconducting layer $R_s(I,T)$ can be calculated as $R_s = E_o l \frac{I_x^{n-1}}{I_c(T)^n}$ provided current I_x carried by the superconducting layer is known. To find I_x, one can equate voltage across the superconducting layer and the normal metal since they are electrically connected in parallel, leading to the equation:

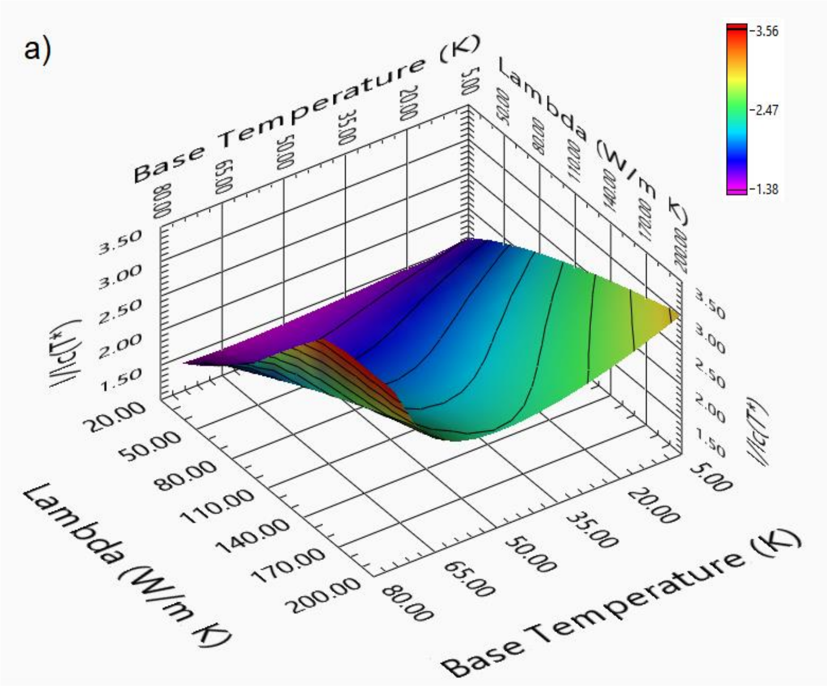
$$U_o \frac{I_x^n}{I_c(T)^n} = (I - I_x) R_{st}(T)$$

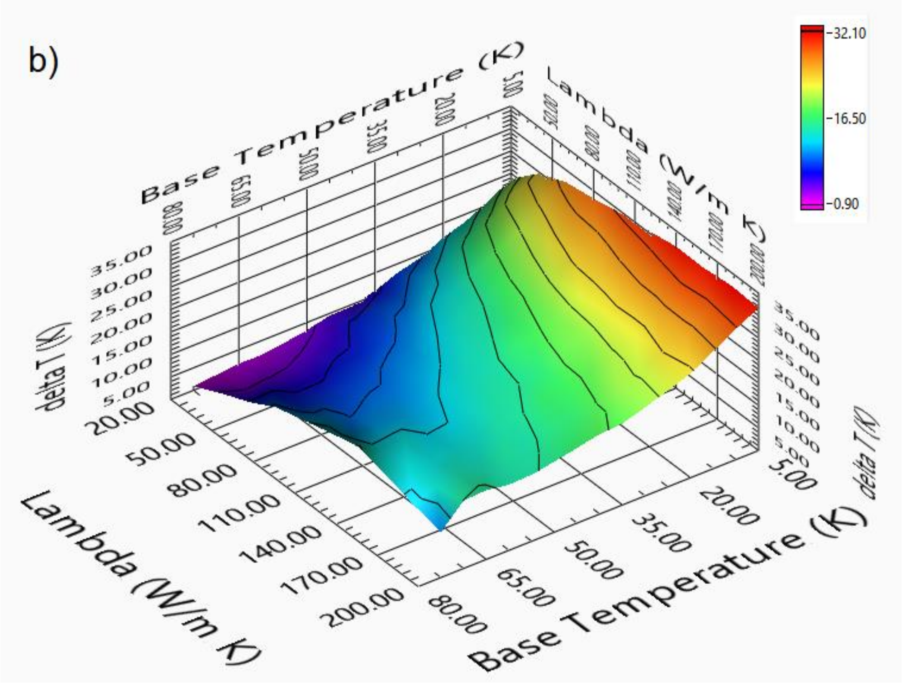


We use the Golden Section search algorithm to solve this equation recursively for each single-point calculation of $R_s(I,T)$.

Thermal runaway surface
(stabilized HTS, temperature-independent heat transfer coefficient)

The dependence of the runaway current ratio $I^*/I_c(T)$ and peak temperature difference $\Delta T = (T^* - T_0)$, plotted versus base temperature T_0 and varying (temperature-independent) heat transfer coefficient, assuming $n = 20$.

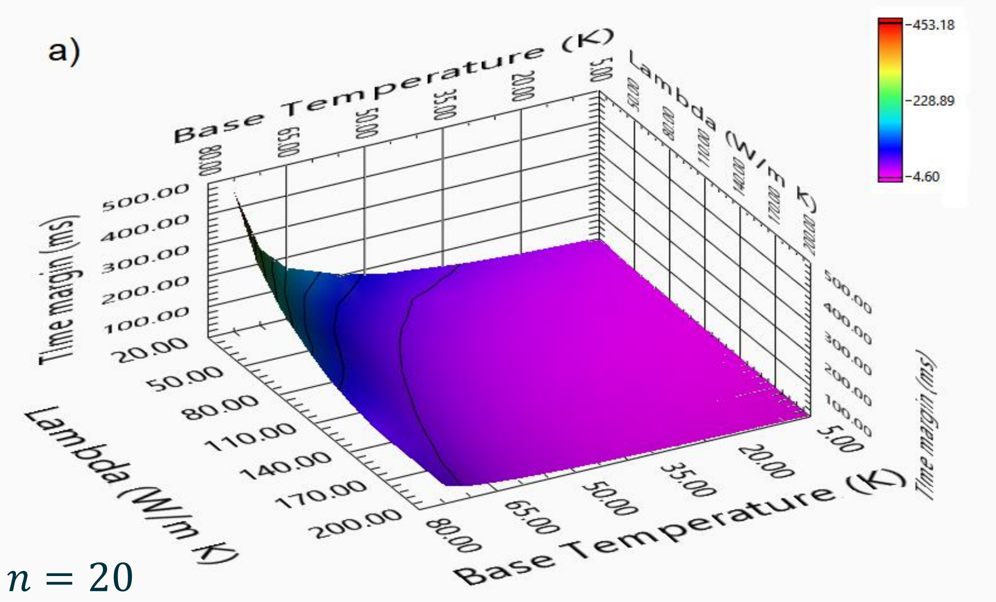


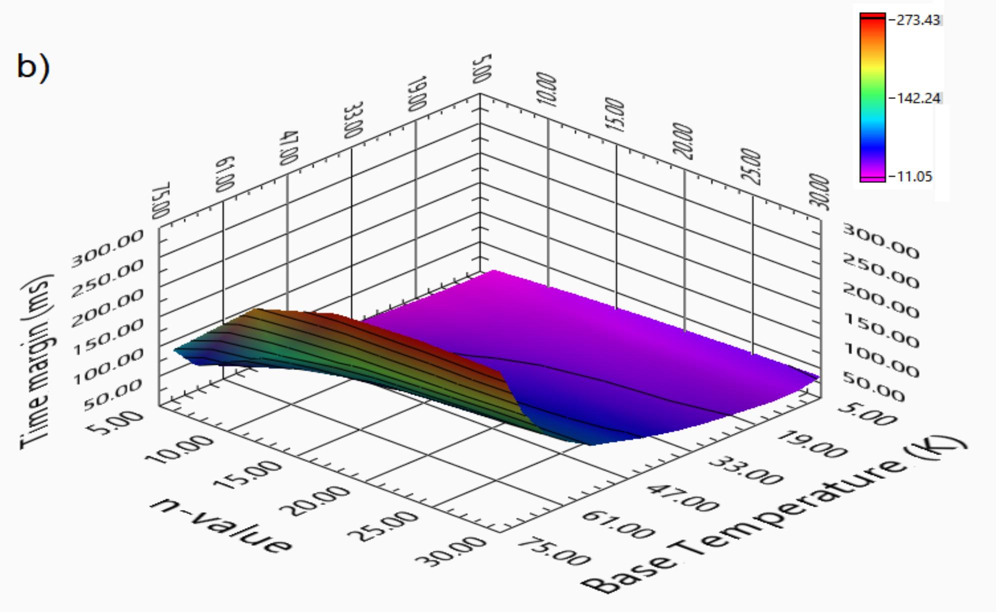


In the high-temperature range, where the current can now flow into the stabilizer as $I_c(T)$ drops, a steep up-turn of the overcurrent is seen.

Time margin

Above the thermal runaway surface, the conductor temperature will increase over time and **the quench integral method can be used** to estimate the upper boundary of the interval over which the conductor will heat up to a pre-defined "safe" temperature (assuming constant current flowing in the conductor, i.e. no current decay). The final "safe" temperature was taken as $T_f = 300$ K.





Having a higher current in the conductor when the thermal runaway criterion is reached translates into a shorter time needed to reach T_f, and vice versa. As this is an adiabatic approximation, the actual time margins can be longer due to heat leaking into the environment via the thermal barrier.

General approach: heat equation

The general approach to the problem which would include both the time-stable and time-varying solutions for the conductor temperature, can be attempted by implementing the heat equation with the heat source being the HTS conductor carrying constant current I, and iteratively calculating a time-resolved heat diffusion process. In 3D case, the equation has a form:

$$\frac{\partial T}{\partial t} - \alpha(T)\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) = \dot{Q}(\boldsymbol{r}, I, B\ T)$$

The heat source power $\dot{Q}$ is a function of current and temperature; $\dot{Q} = I^2 R(I, B, T), \boldsymbol{r} \in V_{\boldsymbol{c}}$ and $\dot{Q} = 0, \boldsymbol{r} \notin V_{\boldsymbol{c}}$, where $V_{\boldsymbol{c}}$ is the conductor volume, and $\alpha(T)$ is the temperature-dependent thermal diffusivity of the medium material surrounding the conductor.

Complex to solve; needs to be done in 3D

A simplified one-dimensional form of heat equation with no heat source and dimensionless time variable can be written as: $\frac{\partial T}{\partial(\alpha t/L^2)} = \frac{\partial^2 T}{\partial(x/L)^2}$ where $t_d = L^2/\alpha(T)$ is the *characteristic time* for the thermal diffusion across the medium barrier of length L.

By comparing t_d with the time margin calculated using the quench integral, one can verify if the adiabatic approximation is reasonable for calculating the temperature rise of the conductor above the thermal runaway boundary.

- *For the 1 cm-thick brass barrier considered in the model, t_d would vary between ~10 ms at 10 K to ~1 s at 300 K.*

How to apply this in practice?

1. Measure normal state resistivity $\rho(T)$ of the stabilizer
2. Measure heat transfer coefficient $\eta(T)$ $\left[\frac{W}{K\ m^2}\right]$
3. Measure $I_c(T,B)$ and $n(T,B)$ of the HTS conductor

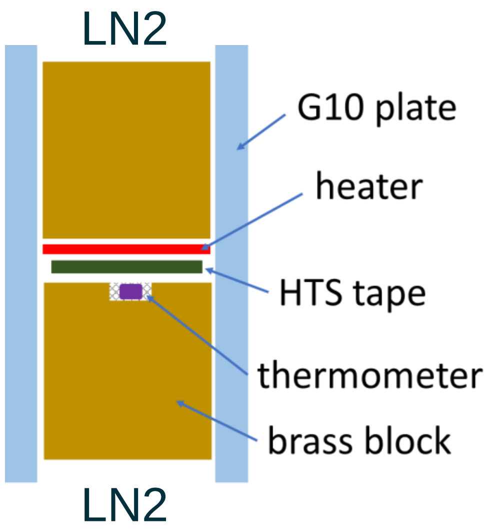
T_{base}

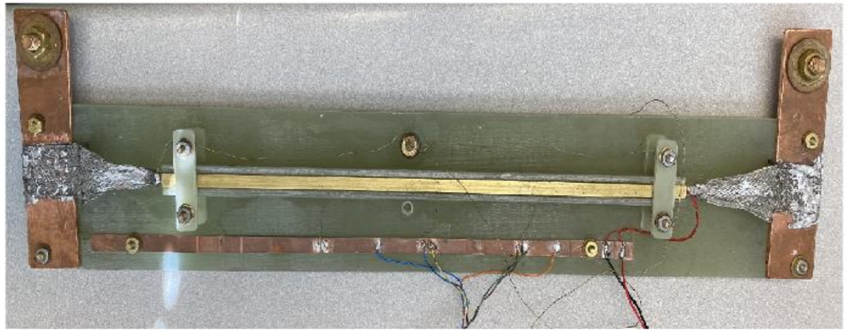
Thermal runaway model

$U(I), T(I)$

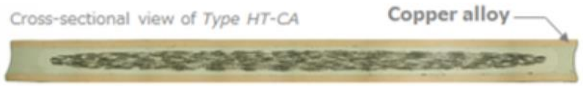
I^*, U^*, T^* – Runaway current, voltage and temperature

Experimental

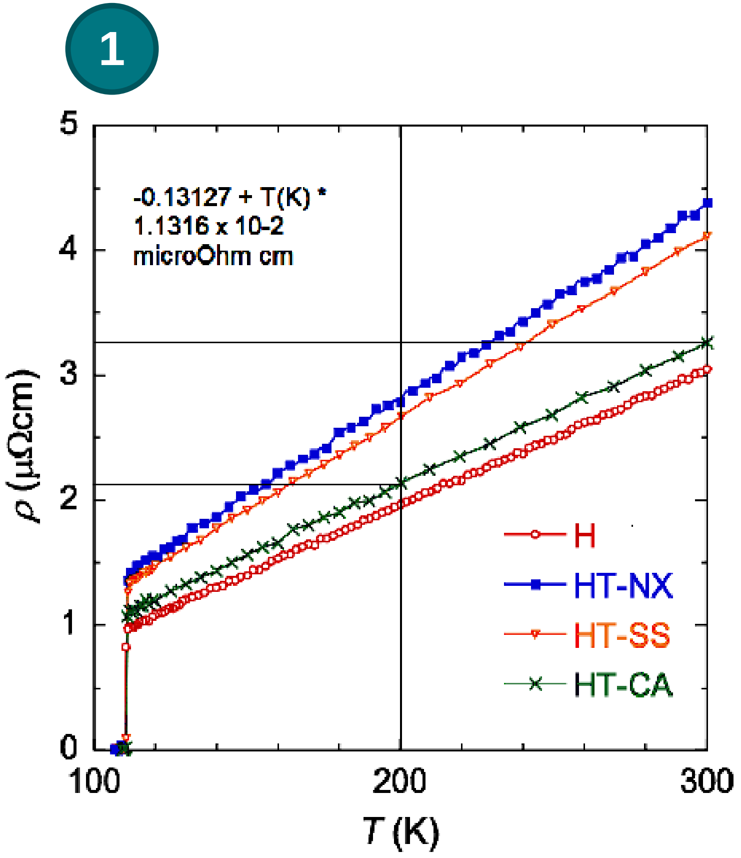




30 cm



Bi-2223 tape conductor (Sumitomo)



Type	Sheath and Lamination Materials	Cross Section (mm^2)	Width (w) (mm)	Total Thickness (t) (mm)	Thickness of Lamination (mm)
HT-CA	Ag + copper alloy	1.5	4.5	0.34*	0.05

IV-curves taken at different temperatures

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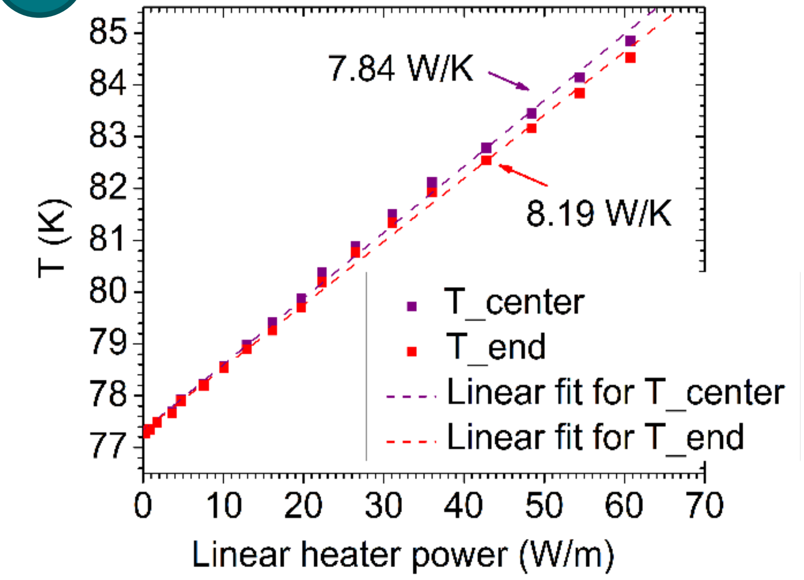
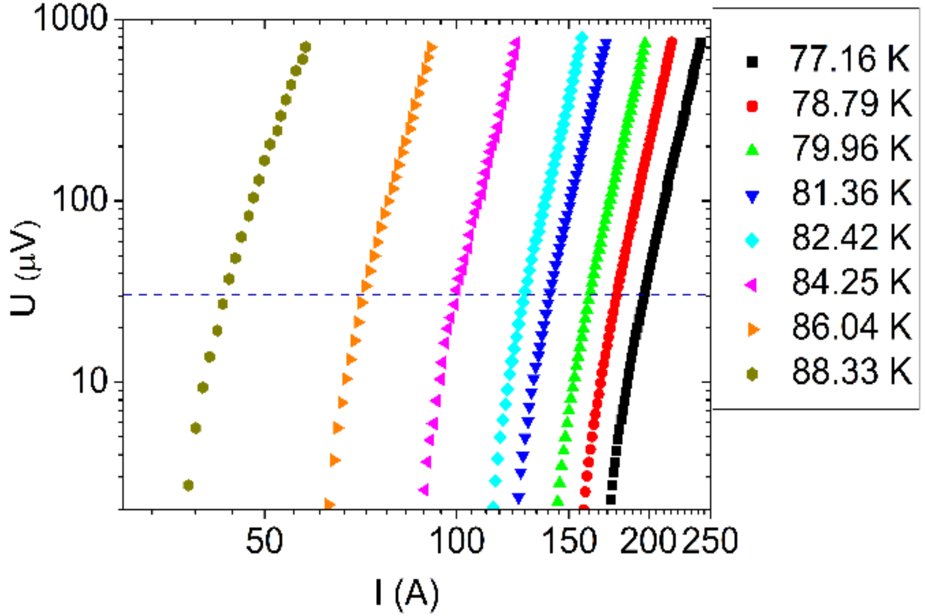
No current in the tape



Heat transfer coefficient can be estimated by powering the heater at no current in the tape conductor

IV curves



Experimental $I_c(T)$ and $n(T)$ dependences are then interpolated with a polynomial/liner dependences to be used by the model

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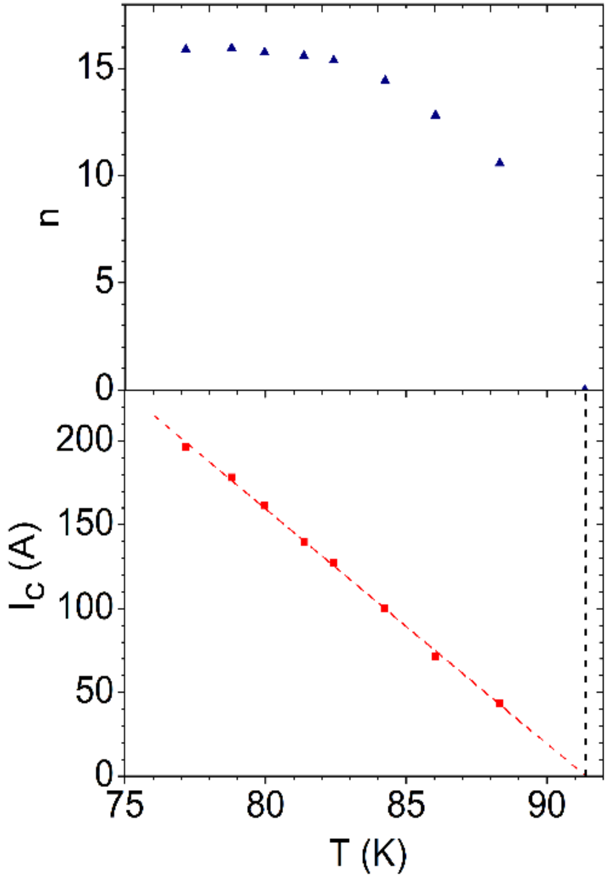
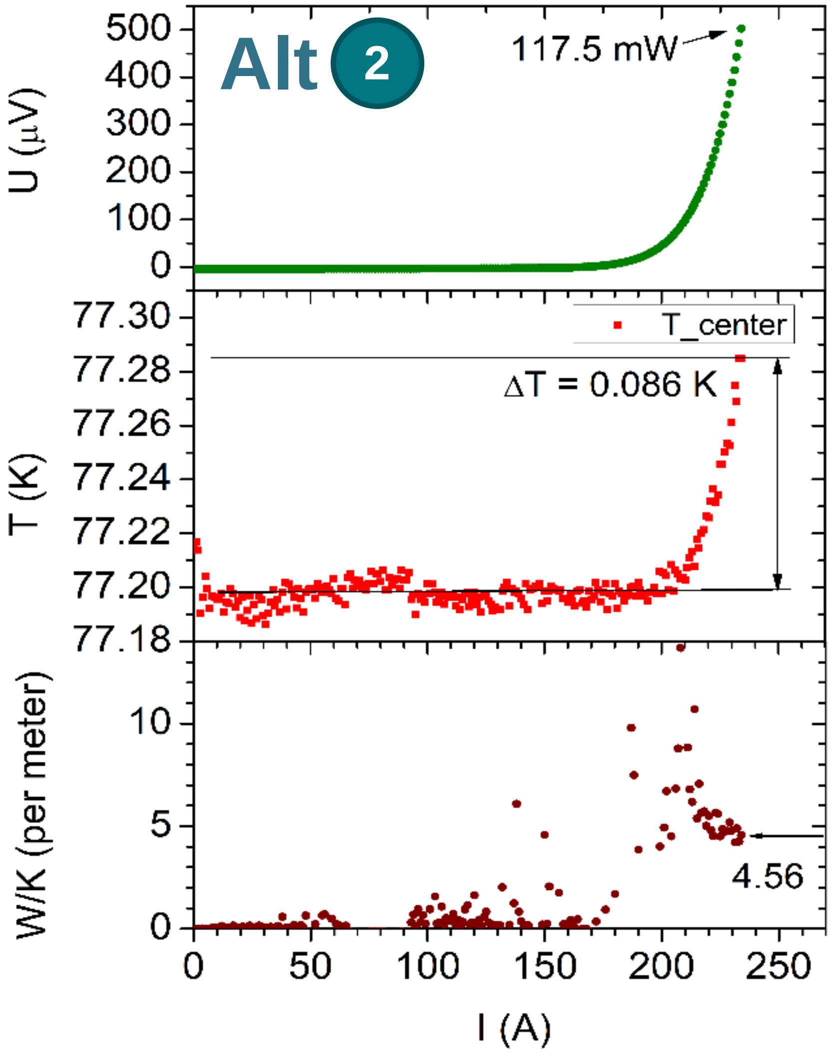
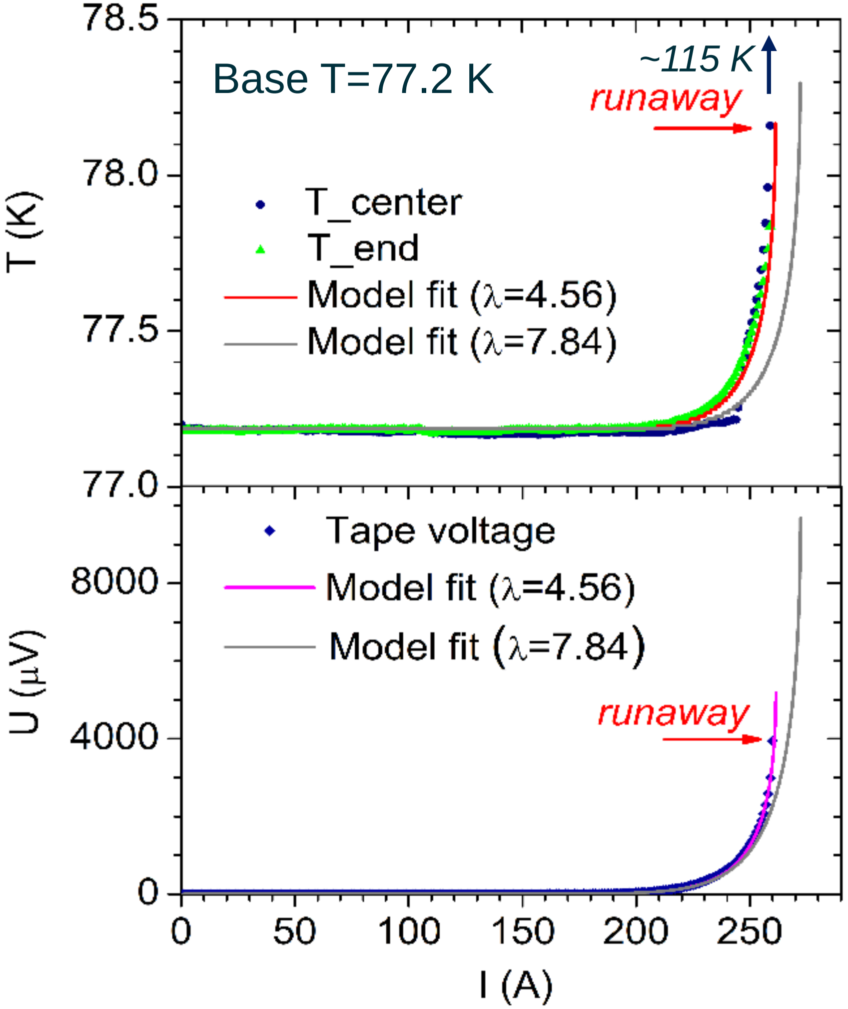
$I_c(T)$ and $n(T)$



Comparing the model and the experiment

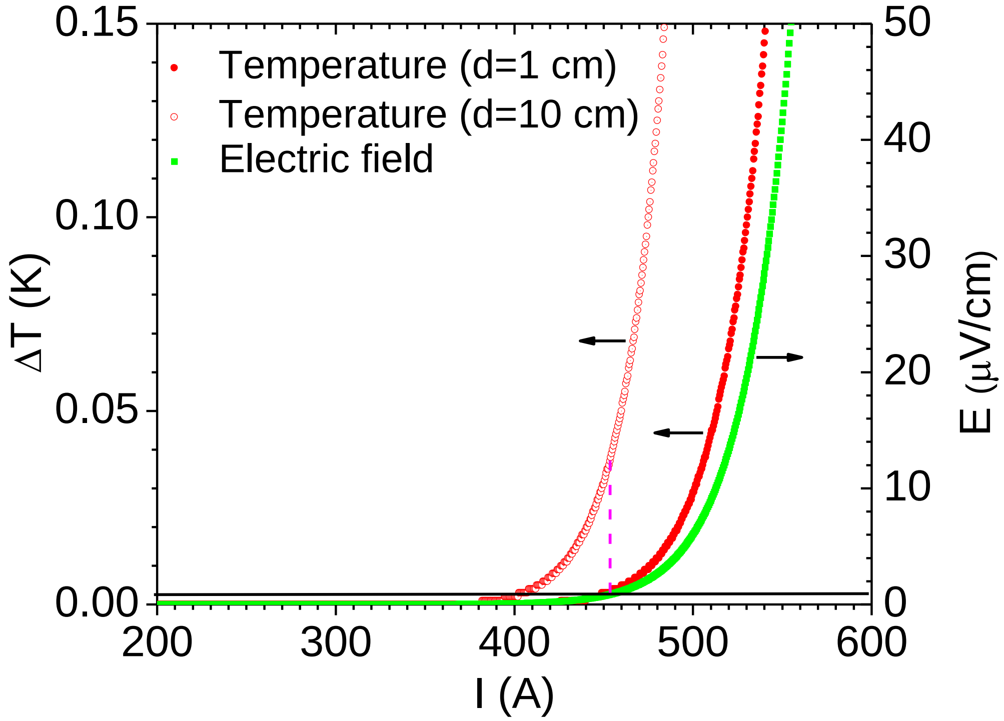




The runaways model implemented with the experimentally measured conductor parameters and heat transfer coefficient shows a very good agreement with the experiment.

Simulation can potentially run “on-the-fly” in the future to estimate the expected runaway value of the current while actually ramping the current up.

Comparing thermal and voltage diagnostics



Simulated current-voltage and current-temperature curves for a range of currents below thermal runaway threshold calculated for $n = 20$, $I_{c0} = 500$ A, base temperature $T_0 = 20$ K, and two thermal barrier thicknesses, $d = 1$ cm and $d = 10$ cm.

The voltage response of the conductor is practically the same for both cases, as the effect of such a small temperature rise on the critical current is negligible.

Yet, *the onset of the temperature rise* is very sensitive to the thermal barrier. If the barrier thermal conductivity is sufficiently low, temperature rise can become measurable earlier than the voltage.

Based on the present simulations, thermal sensitivity of the order of **0.1 K** or better may be required to reliably detect heating in the HTS conductor well below the thermal runaway threshold at liquid nitrogen temperature, while at temperatures of 5-20 K thermal sensitivity of the order of **0.5 - 1 K** should be sufficient given the larger expected ΔT.

Conclusions

- The thermal runaway criterion was explored as a potential basis for realizing the no-quench protection paradigm for HTS magnets. Basic principles of estimating the stability boundary for a practical HTS conductor were laid out.
- The temperature rise ΔT is only weakly dependent on the heat transfer coefficient or the n-value, and mainly defined by the base temperature T_0: lower T_0 leads to a larger ΔT.
- Low n-value conductors allow for a larger fraction of the over-critical current and a larger temperature increase of the normal zone without experiencing a thermal runaway
- A simple practical methodology for thermal runaway-based QD was proposed, and a successful experimental verification was conducted
- Monitoring conductor temperature instead of voltage can be a more reliable QD approach, especially where heat transfer between the conductor and the thermal bath is poor. We should go forward with developing more sensitive and practical distributed temperature monitoring techniques!