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# Analysis of stability and quench in HTS devices—New approaches

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## Abstract

R&D of HTS devices are in their full steam—more magnets and devices are developed with larger sizes. But analysis of their stability and quench was still old fashioned, based on normal zone determination, analysis of its appearance and propagation. Some peculiarities of HTS make this traditional, quite impractical and inconvenient approach to consideration of HTS devices stability and quench development using normal zone origination and propagation analysis. The novel approaches were developed that consider the HTS device as a cooled medium with non-linear parameters with no mentioning of "superconductivity" in the analysis. The approach showed its effectiveness and convenience to analyze the stability and quench development in HTS devices. In this paper the analysis of difference between HTS and LTS quench, dependent on index *n* and specific heat comparison, is followed by the short approach descriptions and by the consequences from it for the HTS devices design. The further development of the method is presented for the analysis of long HTS objects where "blow-up" regimes may happen. This is important for design and analysis of HTS power cables operations under overloading conditions.

*Keywords:* HTS superconducting devices; Stability; Quench

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## 1. Introduction

In recent years, the applications are more and more widening of devices using high temperature superconductors (HTS). HTS magnets, windings of HTS motors and generators, HTS transformers, HTS cables become usual items. Like their predecessors, made from low temperature superconductors (LTS), HTS devices have their operation limits, namely critical current, field and temperature. It means that at certain conditions HTS device may lose their stable superconducting state, heating may start with the temperature rise. For LTS devices such transition usually is called as a quench. For the HTS devices the study of stability and quench is a very important task also as such devices become more common and they are very prospective.

To describe the stability of LTS devices, usually the energy is analyzed that is necessary to initiate a normal zone in a superconductor while it carries current below its critical level. If due to some disturbance the normal zone appears in LTS, the normal zone propa-

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gation is studying to describe the quench development and heating of a LTS device. Thus, the LTS stability and quench description is based on the determination of the normal zone and analysis of the normal zone propagation. This approach was very fruitful and permitted to solve most stability and quench problems for LTS devices. It is not surprising that when HTS devices came to the scene, the same approaches were used for their stability and quench analysis [1]. In principle, this is fair because from the general, formal point of view there is no difference between HTS and LTS superconductivity except operating temperature. But just high operating temperature and, as a consequence, the sufficient difference in some material parameters make old fashioned description of HTS devices quite inconvenient. First of all it applies to the basic determination of the "normal zone" in HTS devices.

Besides that it is necessary to mention that the most prospective applications of HTS are power electrotechnical devices: power cables, transformers, generators, etc. All these devices must have one general feature—they must withstand fault currents dozens times more than their operating currents (if one not considers special current limiting devices). It is the standard for electric power grids. This situation is absolutely different from the quench of LTS devices, where the transport current is below or about the critical current during quench. In HTS power devices, the overload current forcibly becomes much more than the operating/critical current of a device. In this case the usual approaches to analyze quench and heating in superconducting devices are not valid. There is no normal zone and its propagation in the usual sense used for LTS devices.

That is why we believe that new approaches should be developed for more physically clear description of the stability and quench of HTS devices, especially at overload conditions. Below we present such approaches developed.

## 2. LTS versus HTS—the comparison

### 2.1. What is common?

In principle, the old approach to analyze HTS devices is fair, because for both LTS and HTS it is based on the same standard equation: the general, simplified, one-dimensional differential equation that governs the quenching process in any superconductor is given by [2,3]:

$$C(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right) + Q(T) - W(T) \qquad (1)$$

where $C(T)$ is the volumetrically averaged heat capacity, the first term on the right-hand side represents thermal conduction along the superconductors, $k(T)$ the volumetrically averaged thermal conductivity and $Q(T)$ represents the heat generation, particularly due to voltage–current characteristics (VCC). The last term represents the cooling, that is usually linear in temperature [1,4].

The traditional presentation of VCC of superconductors $E(I, T)$ is:

$$E(I, T) = E_0\left(\frac{I}{I_0(T)}\right)^n \qquad (2)$$

Here, $n$ is the parameter called index, $I_0(T)$ a current corresponding to the electric field level $E_0$ that is defined usually as 1 μV/cm or 0.1 μV/cm. The current $I_0(T)$ is what we usually call "critical current". In this case heat release term in (1) will look as:

$$Q(T, n) = IE = I_0E_0\left(\frac{I}{I_0(T)}\right)^{n+1} \qquad (3)$$

Eq. (1) is a basic heat balance equation to evaluate hot spot temperature in superconductors at a quench. This equation is the same for LTS and HTS superconductors. Generally, this equation should be solved numerically, because of non-linearity and complexity of all terms included. And exact results (if all parameters are known properly) could be obtained.

But for practical purposes some simplified models were developed permitting well-justified analysis of the quench development in superconducting devices, for example normal zone appearance and propagation analysis. We would like to offer another approach we consider more convenient for HTS devices.

### 2.2. What makes difference?

The major difference between HTS and LTS superconducting devices is the parameters' magnitude. Table 1 shows a comparison between the major material parameters for LTS and HTS superconductors.

Table 1
Comparison of LTS and HTS characteristic parameters

| LTS | HTS |
|---|---|
| High index value $n \geq 30$, $n \sim 50$—is a common value | Low index value $n < 30$, $n \sim 10$ or less—is a common value |
| Specific heat $C$ is low $C \sim 10^3$ J/m$^3$ K | Specific heat $C$ is high $C \sim 2 \times 10^6$ J/m$^3$ K |
| Matrix resistivity $\rho$—constant with temperature | Matrix resistivity $\rho$—non-linearly rises with temperature |
| Difference between the critical temperature and operating temperature $T_c - T < 1$–10 K | Difference between the critical temperature and operating temperature $T_c - T \gg 10$ K |
| Critical current criteria $\frac{I_c(1\,\mu\text{V/cm})}{I_c(0.1\,\mu\text{V/cm})} \sim 1.05$ | Critical current criteria $\frac{I_c(1\,\mu\text{V/cm})}{I_c(0.1\,\mu\text{V/cm})} \sim 1.25$ |

Strong differences in parameters and in their temperature dependencies do exist. It leads to the fact that for HTS it is difficult to distinguish properly normal and superconducting zones or just to determine which is superconducting and which is a normal part.

Another impact of parameters' difference is the determination of the critical current (see Table 1). For LTS only 5% difference for two critical current criteria (of 1 and 0.1 μV/cm) permits more or less precise determination of $I_c$. For HTS critical current is a very conditional parameter. For $n \sim 10$ there is no sense to be very serious with $I_c$ determination.

Most important difference between LTS and HTS parameters, is the very strong difference of characteristic times of the heat processes development $\tau_h = CA/Ph$. Here $A$ is a cross-section of a superconductor, $P$ its cooling perimeter and $h$ is the heat removal coefficient. Specific heat is about 2000 times more for HTS, $h$ is about 15 times (LN cooling) more for HTS, but much less for indirect cooling by cryocoolers. In any case, the specific heat development time $\tau_h$ is at least 200 times and more longer for HTS. The transition processes in HTS develop much more slowly.

Due to high $n$-values and low $C(T)$, fast thermal instability happens in LTS with the appearance of clearly determined and propagating normal zones. The model with the appearance of a normal zone and its propagation is well justified to analyze quench in LTS devices [1,4,5]. While for HTS devices other approaches should be found [3].

## 3. Novel approaches to describe stability and quench/heating development in HTS devices

### 3.1. The analytical model

The analytical model has been developed for stability and heating. The specific "thermal quench current" (TQC) $I_q$ has been introduced resembling the critical current for LTS devices. It was shown [6] that near the TQC, analytical expressions could be found for two cases. *If* $I < I_q$, *the temperature stabilizes* at some level $T_q - T_f$. *If* $I > I_q$, *the temperature rises with strong acceleration after the time* $t_q$ [3,4,8,13,19]. The following expressions have been found. Time evolution of temperature and the electric field in a HTS device:

$$\frac{T(t) - T_q}{T_f} = \frac{E(t) - E_q}{E_f} = \tan\frac{t - t_q}{t_f}, \qquad I > I_q; \tag{4}$$

Threshold thermal quench current:

$$I_q = I_c(T_0)\frac{n}{n+1}\left[\frac{hP(T_c - T_0)}{nE_0 I_c(T_0)}\right]^{1/(n+1)} \tag{5}$$

Characteristic time of the quench development:

$$t_q = t_h\left(\sqrt{\frac{2I_q}{|I - I_q|(n+1)}}\right) \times \arctan\left(\sqrt{\frac{I_q}{2|I - I_q|(n+1)}}\right) \tag{6}$$

Characteristic temperatures and voltages:

$$T_q = T_0 + \frac{T_c - T_0}{n+1},$$

$$T_f = (T_c - T_0)\sqrt{\frac{2|I - I_q|}{(n+1)I_q}}, \qquad E_q = \frac{hPT_c}{I_c(T_0)n},$$

$$E_f = nE_q\sqrt{\frac{2|I - I_q|}{(n+1)I_q}} \tag{7}$$

Characteristic time:

$$t_f = t_h\sqrt{\frac{2I_q}{|I - I_q|(n+1)}} \tag{8}$$

Here $T_0$ and $T_c$ are the ambient temperature and critical temperature of a superconductor, $T_q$ a characteristic temperature at which fast temperature rise starts

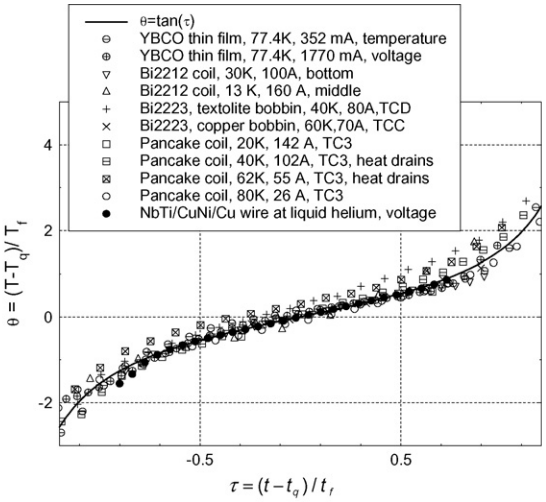

Fig. 1. Dimensionless temperature $\theta$ vs. dimensionless time $\tau$ for experiments with different superconducting objects.

at the time $t_q$, and $t_f$ is a time necessary to heat a sample to the equilibrium temperature $T_q - T_f$ at $I < I_q$ [1]. $t_h$ is the characteristic thermal time defined above. All the above expressions do not have adjusting parameters and were extensively verified by experiments [6–11]. It was also shown that expressions (5) for $I > I_q$ are universal and permit the scaling for the widest variety of superconducting devices. The parameters, describing the heat development of superconducting devices could be made dimensionless by dividing on the proper scaling factor and in this case one can obtain the universal dependence for different devices. In Fig. 1 such dependencies of dimensionless temperatures and voltages on dimensionless time are shown for different superconducting objects. One can see that the theory well coincides with the experimental data for quite different devices. It was shown also, that heating development time may be well scaled too [8].

Eq. (4) are quite universal and valid for any medium where heat release is sufficiently non-linear. One of the examples of such a behavior may be well known LTS superconductors. To illustrate this, in Fig. 1, we show the experimental results for the electric field trace measured during the quench of LTS superconductor. The sample is a typical multifilamentary NbTi/CuNi/Cu superconducting wire tested at the liquid helium. One can see in Fig. 1, the electric field rise in this wire obeys the universal curve calculated by Eq. (4). It means that heating process in the LTS wire has the same nature as for HTS superconductors. The only difference is the initial normal zone propagation in LTS wire (~50 m/s), which we never observed in the experiments with HTS objects. After normal zone filled entire LTS sample, the heating process for the LTS wire is similar to the heating for HTS devices.

### 3.2. *Inevitable consequences from the theory*

The major consequence from the implementation of this theory is the necessity of changing design criteria for HTS devices. LTS devices work if operating current is less then the critical current $I_c$ and this is the “critical current design criterion”. HTS devices may work if current is more than $I_c$, but may not work even at currents less than $I_c$, especially in large devices. This is illustrated in Fig. 2 where the TQC divided by the critical current (“relative TQC”) is shown versus characteristic parameter of total conductor length divided by the cooling perimeter. Because heat release is in the volume of a device while heat removal is from the surface their ratio reduces with sizes. In this case thermal quench or thermal runaway current may be less than the critical current. Thermal runaway current design criteria should be used [12].

The criteria of the heating temperature should be changed also. From the maximum heating temperature $T_{max}$ (LTS) used for LTS devices [1,4] to the temperature $T_q$, at which the slope of $T(t)$ is drastically changing for HTS devices (see Fig. 1).

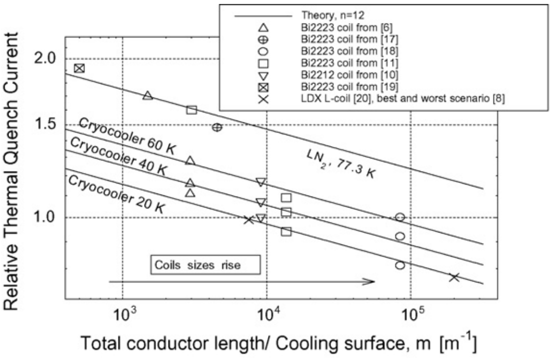

Fig. 2. Relative thermal quench current (TQC divided by the critical current) vs. inverse effective cooling perimeter [8]. Symbols are data from different HTS coils from literatures.

The change of the quench time criteria is: from the time necessary to heat a device up to $T_{\max}$ (LTS devices) to the time $t_q$, when the slope of $T(t)$ curve is changing (for HTS devices).

Both these criteria should be used because beyond $T_q$ the temperature rise is so fast that it could barely be controlled.

It is necessary to note that the low index $n$ while reducing the "critical current" or increasing "temperature of current sharing" may lead to better stability if good enough cooling is providing. It may be important for large CICC cables where the reduction of $n$ was observed [20]. The theory developed for HTS superconducting objects with the low index $n$ may be used for large CICC cables also.

In our opinion, the analytical model for quasi-uniform heating provides better, more convenient and more adequate understanding of HTS quench–heating development. Next step, is analysis of non-uniform heating for long objects.

## 4. Non-uniform cases and HTS device at overloading conditions

Non-uniform cases are important if characteristic heat length $l_h = \sqrt{Ak/Ph}$ is much less than the characteristic size of HTS devices. HTS power cables are the major examples of them. As we mentioned above, HTS cables being installed to a power grid may undergo overloading regimes, when current *forcibly* becomes much more than its operating value and critical current. In this case there is no way to talk about normal zone and its propagation!

Due to strong non-linearity with temperature of the heat release and material parameters of HTS devices some specific phenomena could happen: blow-up regimes with heat localization [13,14].

The study of these phenomena (beside the experiments) could be done by numerical analysis only. We performed such study with computer experiment [13–16]. The numerical solution of the standard Eq. (1) was performed with parameters as much as possible close to the reality. Depend on parameters combinations (current density, cooling, initial disturbance, etc.) different heating modes may appear [15,16].

In adiabatic cases, eventually, a fast temperature rise happens with heat localization (while may be after very long time). This is illustrated in Fig. 3.

In the presence of cooling, two modes do exist of the heat development, very similar to the analytical model—stable and unstable. This is illustrated in Fig. 4. In the stable mode the initial disturbances disappear. In the unstable mode the very fast, actually

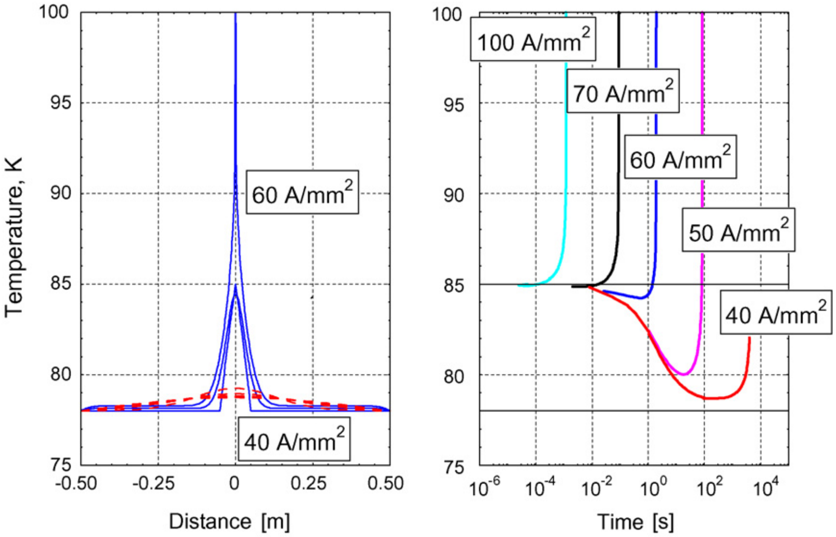

Fig. 3. Instability developments in the adiabatic cases. Slow decay eventually changes to the fast rise of the temperature [15].

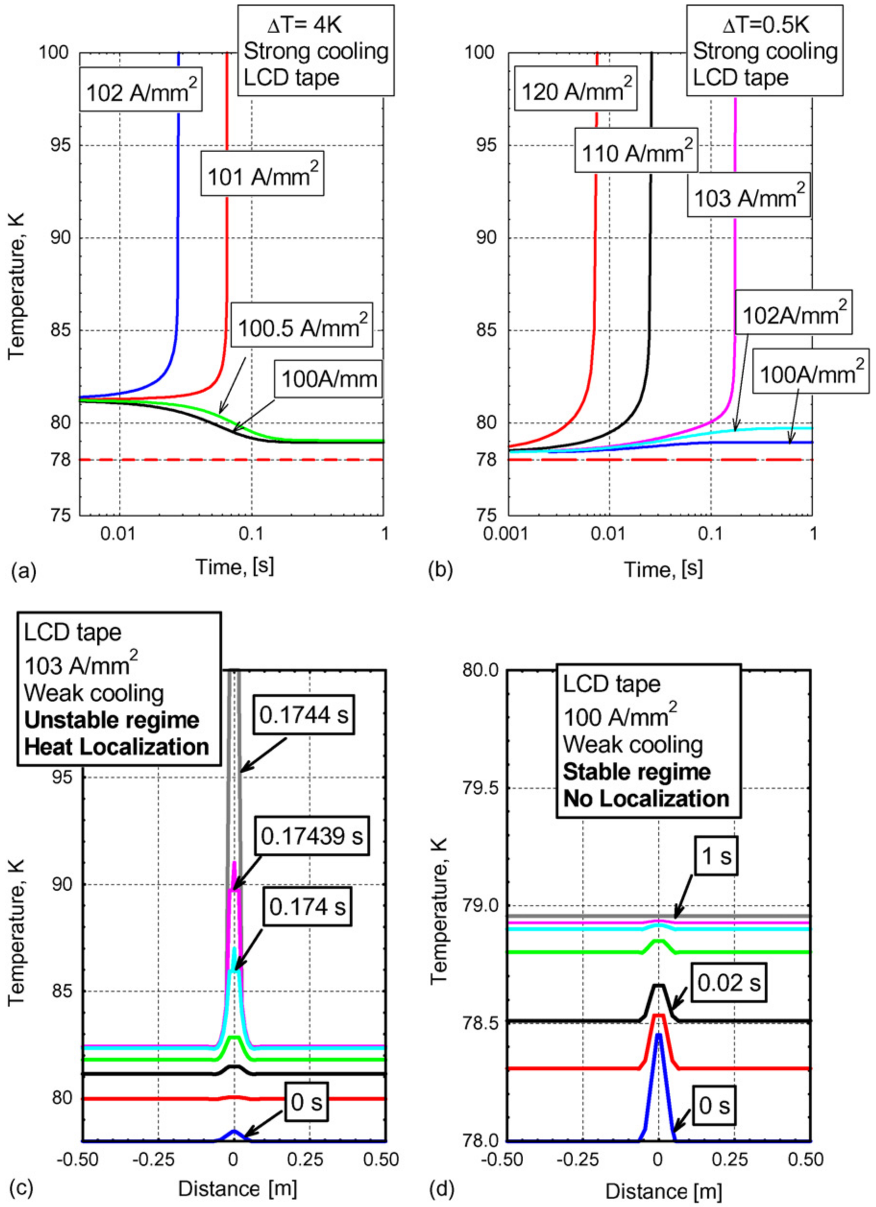

Fig. 4. The examples of the instability developments in the cases with cooling. LCD stays for "low current density sample"—the sample with the critical current at the self-field ∼40 A. Different initial disturbances levels and cooling are shown. (a and b) Time dependencies of the temperature. (c and d) Temperature profiles along samples. At currents above $I_q$—stable regimes switch to the regimes with the very fast temperature rise (a and b). (c) In the unstable mode the fast, actually a catastrophic temperature rise happens with the heat localization [15], no normal zone propagation observed. (d) In the stable mode the initial disturbances disappear.

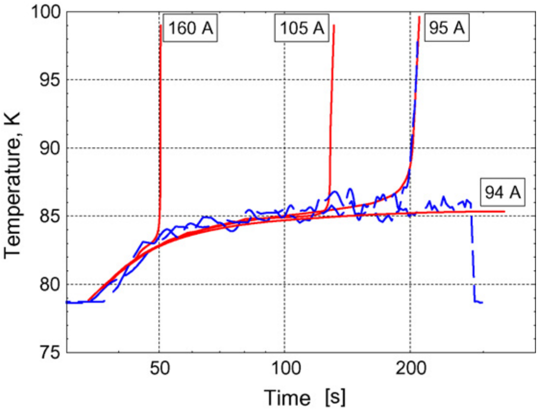

Fig. 5. Time depended traces of the temperature for the sample with critical current ∼40 A at the self-field in liquid nitrogen. Dashed lines, experiments; solid lines, calculations with the updated model [16].

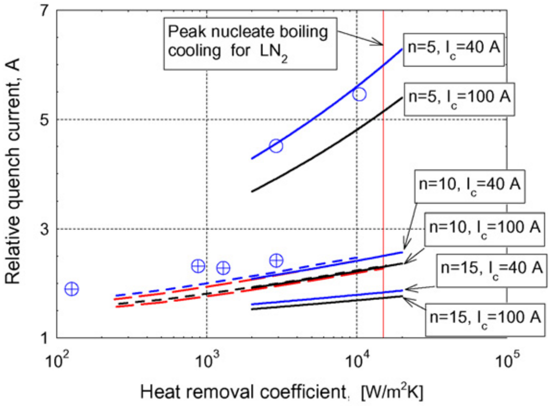

Fig. 6. Relative thermal runaway currents (transport current divided by the critical current) vs. the heat removal coefficient. Solid lines, analytical calculations by theory [6,8]. The upgraded model calculations [16] (short dashed lines), the experimental data [16] (symbols) and the data from calculations by the model [14] (long dashed lines) are shown also.

catastrophic temperature rise happens with the heat localization (see Fig. 4). The time till the temperature runaway starts in the unstable regime becomes rather short with a current density rise. Like in the analytical model this time can be considered as the safety parameter.

The numerical calculations were verified by the experiments [16]. Thermocouples were attached to the short samples of Bi-2223 HTS tape and overloading current has been applied with measuring of the temperature. The comparison of the numerical calculations and experiments are shown in Fig. 5. One can see the good coincidence of calculations and measurements. It confirm the model and accuracy of the parameters used for calculations.

In Fig. 6 the relative thermal runaway currents are shown in dependence on cooling for two types of HTS tapes mentioned. In Fig. 6 solid lines are calculations by the analytical model [6,8] (zero disturbance) and dashed lines are numerical calculations by the upgraded model [16] and by the model [15] with the temperature disturbances in the center of the sample ($\Delta T \sim 0.5$–$4$ K). In the model [15] the heat release was approximated for the simplicity by the power function, while in the upgraded model [16] we used the real heat release function described by Eq. (3). One can see the practical coincidence of calculations with different methods. Symbols shown in Fig. 6 are the experimental data. At low current, experiments coincide with calculations for $n$ close to 10 and at higher currents better coincidence is for $n$ close to 5. It is connected to the fact that at higher currents the effective value of $n$ usually reduces as it was observed in our experiments with HTS devices. The transition of the VCC from the power law with rather high $n$ at low currents to the linear dependence at currents much more than the critical one determines the presence of the VCC part with the reduced index $n$. It was shown in [6] that the thermal runaway current $I_q$ is proportional to the heat removal coefficient $h$ like $I_q \sim h^{1/n+1}$ [6]. That means very weak dependence on cooling at the high index $n$.

Thus, the behavior of the long HTS devices with non-uniform heating is quite close to the behavior of HTS devices with uniform (or quasi-uniform) heating. Both models are working and provide close results that are well coinciding with the experiments.

## 5. Conclusions

The novel approaches are offered to describe the stability and quench/heating development in HTS devices confirmed by the experiments. The models consider the instability development in HTS devices, while HTS device is considered not as a superconductor but the medium with non-linear material parameter.

*The analytical model* developed is scalable and it is good to use for the HTS devices with sizes less than characteristic heat length $l_\mathrm{h} = \sqrt{Ak/Ph}$. For liquid nitrogen temperatures $l_\mathrm{h}$ is about 2 m. This model may be used rather universally, even for LTS devices with low index $n$.

*The numerical model* has been developed for long HTS objects (for example, power cables at overloading conditions). It was shown that blow-up regimes with *heat localization* do exist in long HTS objects. Instability development time can be rather short (due to heat localization) in comparison with usual time of the heating development in HTS devices.

The threshold current $I_\mathrm{q}$ is weakly depending on cooling characterizes the stability of HTS devices. This current separates stable and unstable modes. Important safety parameter is the heating development time that quickly decays with the transport current rise.

The new approaches developed are useful to analyze HTS devices stability/quench/heating behavior, without using "superconducting" terms, like a normal zone and its propagation.

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