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Applied superconductivity: frustrations and hopes

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Contents

Abstract. The alternation of bright triumphs generating far-reaching expectations and subsequent deep disappointments is a characteristic feature of the development of applied superconductivity, associated with creating superconducting windings and winding wires. This, unfortunately, testifies to the inadequacy of scientific and technical foundations formed on the basis of several speculative hypotheses and a useful, but not quite accurate, model of the critical state. The protracted romantic period of evolution has been marked by a noticeable number of remarkable but overly costly advances in industrial physics. At the same time, the victim of the situation turned out to be commercial applications, without the development of which the huge economic potential of applied superconductivity will remain unrealized.

Keywords: superconducting winding, commercial applications, degradation, laminar winding

And enterprises of great pith and moment
With this regard their Currents turn away,
And lose the name of Action.
Shakespeare, *Hamlet*

1. Introduction

Almost 35 years have passed since the discovery of high-temperature superconductivity (HTSC). Although conferences and technical journals are filled with descriptions of numerous designs and layouts of windings made of HTSC materials, no significant commercial applications of HTSC have appeared. Bringing the initial promising forecasts [1, 2] to fruition has been delayed for decades, and enthusiastic expectations are increasingly poisoned by natural skepticism. Low-temperature superconductivity was not even 30 years old when HTSC enthusiasts announced that no commercial applications could be expected from it.

Although an attempt to draw attention to the history of the low-temperature period of applied superconductivity in our time of ongoing high-temperature hype may seem an annoying anachronism, there are several reasons to believe that such an attempt will not prove futile.

(1) Even a belated analysis of earlier mistakes can prevent new ones from being made. This is even truer, since the new period uncritically perceived what for a long time was mistakenly considered the foundations of applied superconductivity.

(2) The hope that the high heat capacity of materials at the temperature of liquid nitrogen would remove the difficulties of creating superconducting windings did not come true. On the contrary, new difficulties with the protection of such windings arose, which are still unresolved.

(3) The dependence of the critical current of a second-generation superconducting tape on the magnetic field and temperature, shown in Fig. 1, clearly demonstrates the advantages of its use at the temperature of liquid helium. Most likely, this testifies to the fact that the low-temperature period has not ended and there is no reason to ignore the accumulated experience, unless, of course, the helium produced by the Amur gas processing plant (60 mln m^3 per year) is not all exported [3].

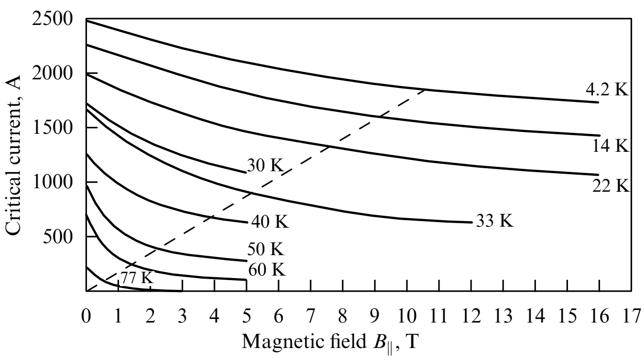

Figure 1. Critical currents of the tape (SCS12050) of the second generation produced by the SuperPower company depending on the magnetic field at different temperatures.

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The emergence of high-temperature superconductors was preceded by sluggish discussions about the reasons for the failure of attempts to commercialize applied superconductivity. The qualifications of the participants in the discussion did not allow them to come to conclusions other than trivial regrets about the low quality of superconducting wires and the excessively high price of liquid helium. However, the real reason was also quite trivial, but, unfortunately, inaccessible to most members of the community, since it demanded that the naive hypotheses proposed by authoritative scientists during the first two years after the birth of applied superconductivity, which formed the scientific and technical foundations of this field, be questioned.

Before abandoning the age-old dream of eliminating ohmic losses, it is necessary to figure out whether some fatal circumstances, allowing the widespread use of applied superconductivity in laboratory research and industrial science, categorically impede obtaining the desired economic effect, or it is due to the notorious human factor.

This article presents a version of the reasons for the dramatic wanderings of applied superconductivity in the 20th century. According to this version, the wanderings could and should already have a positive ending. However, three problems still do not allow stopping these wanderings: the lack of generally accepted electrodynamics of technical superconductors, the lack of a generally accepted opinion on the methods of designing superconducting windings, and an excess of specialists in applied superconductivity, which, according to the laws of sociology, does not allow reaching generally accepted opinions.

2. Situation with the electrodynamics of technical superconductors

The contribution of the superconductivity theory to applied science is undoubtedly significant; nevertheless, it is limited by the concepts of type-II superconductivity developed by Abrikosov and Zavaritsky [4]. The starting and fruitful point of the developed concepts was the assumption of a negative energy value at the boundary of the normal and superconducting phases. Using the Ginzburg–Landau phenomenological theory, Abrikosov demonstrated the inevitability of a mixed state, i.e., the decay of the magnetic flux in these materials into vortices containing one flux quantum. This is how physics encountered a new entity — an ensemble of quantum vortices — and the theory turned out to be unable to explain the observed properties of the emerging superconductors with high critical currents [5, 6], in particular, the gigantic hysteresis of the magnetic moment of these materials. Physicists were merely forced to return to medieval methodology and offer speculative hypotheses, trying to find approaches to solving the problems those arise.

It must be regretted that the exotic effect — insignificant for applications — of the formation of an ordered lattice of vortices in an *ideally homogeneous* superconductor [8] became known simultaneously with the mixed state of a type-II superconductor. This synchronicity led to identifying these two by no means equivalent phenomena in the minds of a significant proportion of specialists.

Several decades have been spent studying the properties of the lattice and making unsuccessful attempts to adapt it to the explanation of the high current-carrying capacity in technical superconductors. During these decades, the electrodynamics of superconductors was based on the speculative concept [9] formulated in the early 1960s about the motion of an ordered or slightly distorted lattice of vortices under the action of the Lorentz force, which numerically coincides with the pressure arising in a lattice with an inhomogeneous density. In the usually considered one-dimensional case, this inhomogeneity is uniquely equivalent to the flow of current in the bulk of the superconductor. Moreover, the inhomogeneity was assumed to be smooth with a characteristic length that coincides with the transverse dimensions of the wire. Based on these concepts, the stable term 'pinning force' arose as the strength of the lattice fixation on structural inhomogeneities, numerically equal to the critical Lorentz force, after exceeding which, the lattice moves in the form of a flow [10]. Note that such a flow regime is never observed in superconducting wires. This was explained by the fact that the thermal balance violation still occurs in the regime of the electric field exponentially increasing with an increase in the current. Within the concepts discussed, the latter regime, apparently, should be associated with some rearrangement in the lattice, which chooses the weak points of fixation.

Thus, it was assumed that the reasons for the superconducting current transition are fundamentally different from those for the temperature and field transitions. This is most likely why there were no known attempts to establish a relationship between the diffuseness parameters of these three transitions. The fundamental difference among the transition criteria forced a sacrifice of the concept of a three-dimensional critical surface, which was so clear when a jump-like transition served as a criterion.

The peculiarities of the nature of various pinning centers are still commonly associated with the position of the maximum of the dome-shaped dependence on the external field of the product of the magnitude of this field and the critical current [11]. At least three circumstances raise doubts about the adequacy of this method. First, the positions of the maxima of the product of the current and the external field ($I_c B$) and the product of the current density and the same field ($j_c B$) suitable for analysis coincide only in the case of a linear field dependence of the critical current. In the region of significant steepness of the field dependence of the critical current, the seemingly obvious equality $j_c(B) = I_c(B)/S$ is invalid [12]. Second, pinning in real wires is, as a rule, anisotropic, which strongly affects the shape of the dependence $I_c(B)$ in the region of low fields [13]. Finally, one cannot rule out the possibility of a combination of pinning centers of a different nature in the wire.

Meanwhile, one glance at the structure of the niobium–titanium alloy (Fig. 2) is enough to understand that no ordered lattice can exist in this material. Probably, the principal inhomogeneity of technical superconductors is responsible for the fact that numerous and, undoubtedly, important theoretical studies of type-II superconductors based on the Ginzburg–Landau theory have not led to conclusions that are essential for applied superconductivity. Within the framework of the mentioned methodology of previous centuries, it can be expected that the motion of a disordered ensemble of vortices in a medium with traps should be considered as the diffusion of vortex fragments that easily reconnect in traps containing several vortices.

Two circumstances contributed to the establishment of these initial hypotheses in the mind of the scientific community. First was the technique used by their authors to accompany the description of their hypotheses with handmade graphic illustrations [15, 16]. These illustrations were

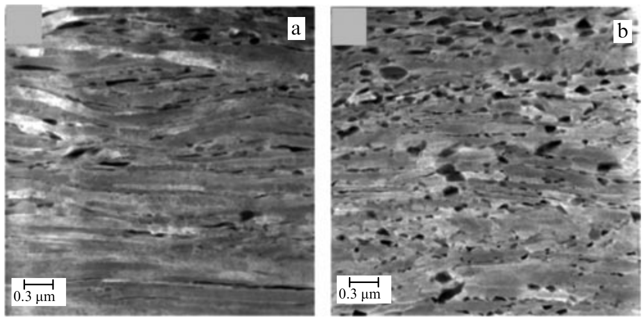

Figure 2. Examples of images of thermally processed Nb – Ti tape obtained using a transmission electron microscope (TEM) (a) along and (b) across the direction of rolling [14].

perceived by the community as the results of experiments that brilliantly confirm the stated hypotheses. Second was the collaboration of the authors with the well-known scientist Anderson, who made a significant contribution to the current chaos of ideas with his hypothesis [9] on the thermal activation of the motion of vortices in a superconductor with pinning centers. There is reason to believe that the author of the hypothesis quickly abandoned it. In any case, in the jubilee article [17], Anderson, listing his achievements, did not mention the thermal activation of the motion of vortices, claiming only the honor of introducing the critical role of the Lorentz force into use.

Nevertheless, for many members of the community, this hypothesis has become a dogma, which makes it necessary to give it some space in the present text. The hypothesis that arose in connection with the observation of an exponential increase in the current–voltage characteristics (CVCs), preceding the transition of the superconductor to the flow regime [10], introduces the idea of the existence of some potential relief in the superconductor. Potential wells fix groups (bundles) of vortices, preventing their free movement. The immobility of the magnetic flux in a material is equivalent to the absence of resistance. In a superconductor with a current, the potential relief is distorted, acquiring a tilt towards a lower value of the total magnetic field. This decreases the height of the potential well edge from the side towards which the Lorentz force is directed as the current increases, and the bundle, due to a small random perturbation, is able to go beyond the confining well to enter another well. Such an abrupt movement of the magnetic flux generates an electric field that grows exponentially with an increase in the transport current. Anderson described this process by an equation resembling the Arrhenius equation, which can be easily reduced to the following form:

$$E = E_0 \exp\left(-\frac{U_0 - j\Phi_0 d^2}{k_{\mathrm{B}} T}\right). \tag{1}$$

Here, E is the electric field, E_0 is a coefficient equal to the electric field value at which the exponent turns into zero, U_0 is the potential well depth, $j\Phi_0 d^2$ is the barrier lowering when the current flows, j is the current density, Φ_0 is the magnetic flux quantum, d is the transverse dimension of the bundle, k_{B} is the Boltzmann constant, and T is the temperature.

It is difficult to explain why exactly the exponential current–voltage characteristic described by Eqn (1) (describing the well-known experiment [15] rather than being predicted) was accepted by a large number of specialists as proof of the model's adequacy, despite the fact that in nature there are many processes described by the exponential function. In Ref. [18], which is considered an experimental test of the hypothesis, the process of decay of the magnetic moment in superconductors was scrupulously studied. However, the confirmation of the logarithmic dependence of the rate of this process on time predicted in [9] is not yet proof of the existence of thermal activation. This result is only a consequence of the exponential current–voltage characteristic. The study of the temperature dependence of the CVC slope is critical for the model. From Eqn (1), its strong dependence on temperature follows:

$$\frac{1}{\delta(T)} = \frac{\partial \ln (E/E_0)}{\partial j} = \frac{\Phi_0 d^2}{k_{\mathrm{B}} T}\,. \tag{2}$$

However, no such dependence is observed in experiments. Figure 3 shows the result of a detailed study [19] of transient characteristics of niobium–titanium and niobium–zirconium wire in the temperature range from 4.2 to 9 K. It can be seen that, in a very wide range of temperatures and fields, the value of δ does not decrease with decreasing temperature.

In 1986, Mitin [20] thoroughly studied the rate of magnetic moment decay in tubes of ternary molybdenum sulfide ($M_xMo_{15}S_{19}$) in the temperature range of 0.5–4.2 K and found that this rate very weakly depends on temperature, which categorically contradicts Anderson's hypothesis. Unfortunately, the author of Ref. [20] did not dare to declare the refutation of this hypothesis directly. We will not return to this inadequate model, although for a large number of specialists it has become a symbol of faith and still continues to fill the pages of journals. Perhaps infection with scholasticism is one of the reasons, although not the main one, for the wanderings mentioned above.

Meanwhile, practically simultaneously with the Anderson model, but in contrast to it, the idea [21] arose that the diffuseness of the superconducting transition is associated with the inhomogeneity of the samples. The current–voltage characteristic calculated using the one-dimensional model, taking into account the longitudinal inhomogeneity, was not exponential, and therefore the model did not interest the community. However, this model was reliably confirmed [22] when studying CVCs of early samples of multifilament wires, in which the inhomogeneity of superconducting filaments became evident when the copper matrix was etched away.

A simple numerical experiment [23] allowed extending the described approach to bulk-inhomogeneous superconductors consisting of grains of not quite constant composition differing, respectively, in critical temperature. In this experiment, the resistance was calculated for a multiply connected electrical circuit, consisting of elements that change the resistance from 1 to 0 at a critical temperature peculiar to each element. The calculation showed that this characteristic is described by a logistic curve, the shape of which in the region of low resistance values approaches exponential as the chain becomes more complex and the number of elements in it increases, provided that the distribution of individual critical temperatures is assumed to be normal (Gaussian).

Using only two resistance values, 1 and 0, of the elements that make up the circuit for the calculation is not critical. Of course, a real alloy consists of grains with a random scatter of sizes and shapes, as well as resistance values in the normal state, but this should not change the resulting exponential transition form, since the key assumption of the model about

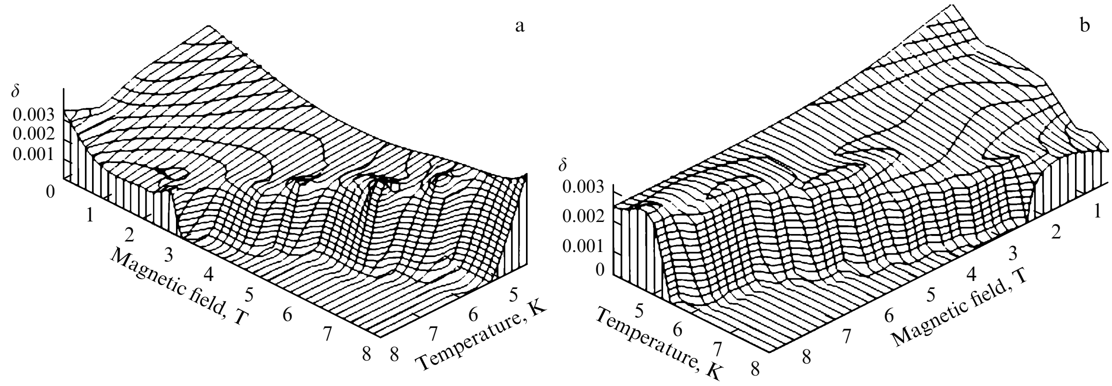

Figure 3. Values of parameter δ for (a) niobium–zirconium and (b) niobium–titanium wires.

a Gaussian distribution is preserved due to the central limit theorem [24]. Since the parameters of superconducting states are related by a smooth critical surface in the temperature, magnetic field, and current density coordinates, the conclusion obtained can be attributed to the form of the transition along any of these coordinates. The steepness of any of these transitions is determined by the dispersion of the distribution. There is no reason to believe that the dispersion is strongly dependent on temperature; therefore, the observed constancy of the parameter δ does not contradict the described simple model. The fact that, in the described representation, the current dependence of the resistance rather than of the electric field turns out to be exponential does not contradict experiment [25] and is easily explained by the great steepness of the CVC, within which the current varies very weakly.

The fate of the second long-lived idea, proposed in 1962 by C Bean, the critical state model (CSM) [26], is complex and ambiguous. The CSM was one of the first and most striking manifestations of common sense in the new science and explained the giant hysteresis of the magnetization curve unknown to physics at that time. It is formulated in a deliberately verbal form: ''the current flows through a superconductor with a critical current density.'' This form, although it looked exotic, described well the magnetic properties of a *hyperconductor*; the critical temperature usually attributed to it was supplemented with the critical current density.

Bean's breakthrough was a tacit rejection of the textbook concept of the fundamental difference between a superconductor and a hyperconductor. The idea of the CSM is based on the concept of a jump-like transition between two states of a material and is quite transparent. It was assumed that, at a critical value of the current, the material can be in only two states: either with zero resistance in the superconducting state or with a sufficiently high resistance in the normal state. With an arbitrarily small excess of the critical current density, the magnetic flux freely penetrates into the material. At the same time, for an arbitrarily small decrease in the current density, the *penetration* of the magnetic flux ceases. Already from this elementary description, the existence of two processes follows, namely, the fast process at high material resistance and coming to the steady distribution at zero resistance. The CSM allows the first of them to occur instantly, and the second does not develop in time.

The indisputable value of the CSM is that it allows calculating steady-state distributions of induction and current density in the cross section of a conductive wire, taking into account the dependence of this density on the local magnetic field, which is a vector sum of the external field and the current field. Such a problem can be easily solved numerically [12, 27, 28]. Some authors [29], using this model in a masterly way, successfully develop analytical methods. Their success convinces the community of the opinion that it is this particular model that universally describes the properties of technical superconductors. However, this is incorrect *since the CSM admits an unambiguous relationship between the distributions of induction and current density in the bulk of the superconductor and the instantaneous value of the magnetic field on its surface. This assumption violates the principle of locality and excludes the possibility of studying the processes of diffusion of fields and currents in a superconductor.* In particular, the model under consideration does not allow correctly assessing the stability of wires or the losses in rapidly changing fields.

Almost simultaneously with the CSM proposal, Kim et al. discovered that the current transition was in fact diffused [15]. Since then, there have been two opinions. One is that this diffuseness is an annoying deviation from the ideal; it may not be taken into account by the theory [30, 31] and should be eliminated whenever possible in the production of superconducting wires. Another opinion is that it is the transition diffuseness that ensures the operability of the superconducting wires [32, 33].

Simultaneously with the uncertain flux of the theory, the industry of producing superconducting wires and the construction of superconducting magnets developed. This development took place not without difficulties (a description of which is given in Section 3), but the practice of using a promising phenomenon has significantly outstripped scientific research, which rarely happens in our time.

Modern electrodynamics of isotropic superconductors with high current-carrying capacity is described in the traditional way as a combination of Maxwell's equations and material equations. It will not be possible to obtain material equations from the concepts of the dynamics of motion of a vortex ensemble in a medium with pinning centers until the community abandons the false model of thermal activation. Therefore, there remains a phenomenological way of forming material equations based on experimental data. The chosen model is based on the concept of the critical layer [34] in the temperature–magnetic field–current density coordinates. A uniform criterion has been introduced for all three coordinates: reaching a state with a resistivity equal to half the normal one. The critical surface is assumed to be flat. Any other resistance values correspond to planes parallel to the critical surface.

The basis for the construction of this model was the experimental observation of the current–voltage characteristics of superconducting niobium–titanium wires in a constant magnetic field and their voltage–field characteristics at constant current values. It turns out that both characteristics are exponential with the same increment values. In Refs [22, 35], based on the 'critical layer' concept, a model description of the materials under discussion was proposed as conductors (*hyperconductors*) with a strongly nonlinear conductivity that depends on temperature T, magnetic field $\mathbf{B}$, and current density $\mathbf{j}$, as well as on the angle between the vectors $\mathbf{j}$ and $\mathbf{B}$:

$$j_\alpha = \sigma_\alpha^\beta E^\beta \,. \tag{3}$$

In a magnetic field directed along the z-axis, the conductivity is described by a tensor whose matrix has the form

$$\begin{pmatrix} \sigma_\mathrm{t} & 0 & 0 \\ 0 & \sigma_\mathrm{t} & 0 \\ 0 & 0 & \sigma_\mathrm{l} \end{pmatrix}, \tag{4}$$

where σ_t and σ_l are the transverse and longitudinal conductivity with respect to the magnetic field,

$$\sigma_\mathrm{t} = \sigma_\mathrm{n}\left\{1 + \exp\left[\left(1 - \frac{T}{T_\mathrm{c}} - \frac{|\mathbf{B}|}{B_\mathrm{c2}} - \frac{j_\mathrm{t}}{j_{(\mathrm{c}/2)\,\mathrm{t}}}\right)\frac{1}{\delta}\right]\right\}, \tag{5}$$

$$\sigma_\mathrm{l} = \sigma_\mathrm{n}\left\{1 + \exp\left[\left(1 - \frac{T}{T_\mathrm{c}} - \frac{|\mathbf{B}|}{B_\mathrm{c2}} - \frac{j_\mathrm{l}}{j_{(\mathrm{c}/2)\,\mathrm{l}}}\right)\frac{1}{\delta}\right]\right\}, \tag{6}$$

$$j_{(c/2)\,\mathrm{l}} \geqslant j_{(\mathrm{c}/2)\,\mathrm{t}}\,,$$

where σ_n is the conductivity of the superconductor in the normal state, T_c is the critical temperature of the superconductor, B_c2 is the second critical field of the superconductor, and $j_{(\mathrm{c}/2)\,\mathrm{t}}$ and $j_{(\mathrm{c}/2)\,\mathrm{l}}$ are the current values at which the superconductor resistance would reach half of the normal resistance.

Transverse conductivity (5) is easily determined experimentally and turns out to describe well the properties of a superconductor such as solid solutions [19]. It has been successfully used in the modern theory of the stability of superconducting wires [32, 33]. Longitudinal superconductivity cannot be determined from direct experiment. The idea of a force-free flow, adopted from astronomy [36], in which the directions of the current and the field exactly coincide, is not justified in experiment. In any experiment, there is a contribution from the transverse component. Therefore, the value of $j_{(\mathrm{c}/2)\,\mathrm{l}}$ can only be chosen according to the results of the study of transient characteristics at small angles between the field and the current. In the exponent of the expression for the longitudinal conductivity, the last term may not appear at all, if Anderson's assumption about the role of the Lorentz force is universal.

The interested reader will find a detailed description of the constructed version of the electrodynamics of superconductors with strong pinning in Ref. [35]. Since in the material equation one of the arguments is temperature, the system of equations is supplemented with equations of local heat generation and heat conduction. The theory disregards the *reversible* part of the magnetic moment of the material $M_\mathrm{rev} = B_\mathrm{rev} - \mu_0 H$, which is valid for materials with a high value of the Ginzburg–Landau parameter. The reversible part of the magnetic moment of such materials is described by the expression [37]

$$M(B) = \frac{B_\mathrm{c2} - B}{(2\kappa^2 - 1)\beta_\mathrm{A}}\,, \quad \beta_\mathrm{A} = 1.16\,. \tag{7}$$

In the NT-50 alloy, the parameter $\kappa = 50$, and the magnetic moment is really small at inductions of technical interest: $M(B) = 3.45 \times 10^{-4}(B_\mathrm{c2} - B)$.

The solution to stationary problems has shown [35] that, in the tensor form, electrodynamics adequately reflect the generation of an electric field directed perpendicular to the magnetic field and the velocity of motion of magnetic flux quanta oriented along B arbitrary tilted to current.

The advantage of the developed theory is its closed nature: it allows formulating and numerically solving the problem of a dynamic three-dimensional distribution of currents and temperatures in a *structurally isotropic* superconductor with strong pinning under arbitrary boundary and initial conditions. In particular, it is possible to calculate in detail the dynamics of the penetration of the magnetic field into the superconducting wire and multifilament twisted cable, taking into account the appropriate heating. It is also possible to study the development of a short local perturbation in a three-dimensional version or a long local perturbation in a two-dimensional approximation with an arbitrary localization of the perturbation in the wire cross section.

The authors of Ref. [35] left a wide field of possibilities for the further development of electrodynamics by taking into account the pinning anisotropy in real superconductors [38].

3. Situation with the development of superconducting windings

The entire history of superconducting windings was marked by the mysterious phenomenon of degradation, which consisted in the fact that magnets did not manage to realize the high current-carrying capacity of short superconducting wires. The fact that pulsed heat release in a winding was the cause of the degradation was realized almost immediately after the discovery of the phenomenon [39], but the question of the nature of these perturbations is still of concern to the community. The alternative considered is to determine if they are due to the instability of the magnetic flux in the wire or mechanical phenomena in the winding. The first of these reasons immediately captured the attention of the community for 20 years. First, this choice was facilitated by the stunning success of the principle of stationary stabilization proposed by Z Stekly [40]. The principle declared that the operating current in the winding can be equal to the critical current I_c of the wire if there is enough copper in its cross section S_Cu, so that heating it up by current during a superconductor transition to the normal state would not exceed the critical temperature $T_\mathrm{c}(B)$ of the nucleate boiling of helium on the cooled perimeter P of the wire:

$$\alpha = \frac{\rho_\mathrm{Cu} I_\mathrm{c}^2}{S_\mathrm{Cu}\, hP(T_\mathrm{c} - T_\mathrm{b})} \leqslant 1\,,$$

where h is the heat-transfer coefficient, and T_b is the operating temperature of the superconducting wire.

Thanks to the implementation of this principle, the community for a short time came out of its depression associated with the failures in the construction of small

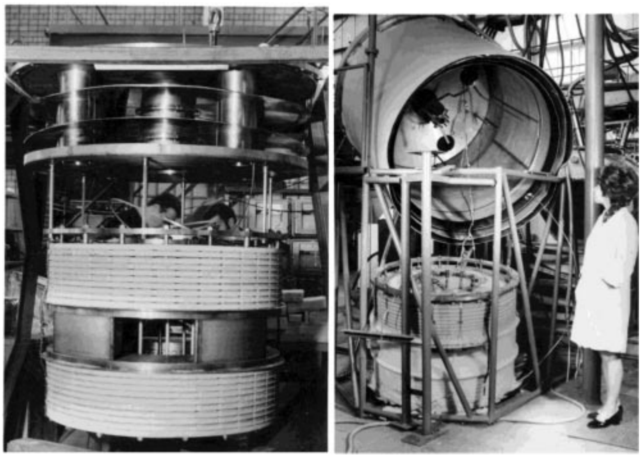

Figure 4. An incident at the Kurchatov Institute while testing a superconducting solenoid for MHDG IM-07 [41]. The cryostat was depressurized due to the release of 1 MJ energy in approximately 500 liters of liquid helium. At the same time, the magnet was not damaged and was successfully operated for the next 10 years at the State Research Center of the Russian Federation, Troitsk Institute for Innovative and Thermonuclear Research (TRINITI).

windings, and began the construction of large magnets for bubble chambers [41–43] and magnetohydrodynamic generators (MHDGs) [44, 45]. The absence of stable states at $\alpha > 1$ was considered a forgivable weakness of this model, which contradicted the practice of testing unstabilized wire samples. In these tests, a sufficiently long section of stable CVC is always observed.

The period of successful application of the Stekly principle ended rather quickly. Due to the large amount of copper in the wire, the windings turned out to be bulky; the constructive current density in them was disappointingly low. The very principle of stationary stabilization could be realized only in windings immersed in liquid helium, which was acceptable not for all devices, since it required a large amount of refrigerant and was fraught with explosions (Fig. 4). In addition, it turned out that the dogmatic application of the Stekly principle does not guarantee the operability of the winding [46, 47]. Initial successes were provided by the excess amount of copper in the wires, which was due to the applied technology of rolling or soldering superconducting wires into a copper substrate strip. The use of electrolytic technology [48], which ensures the literal fulfillment of the Stekly criterion $\alpha \leqslant 1$, as well as a modification of the model, which, according to calculations, can ensure stationary stability at $\alpha > 1$ by exceeding the critical current over the operating one and reducing the amount of copper, have shown that such windings do not preserve stability upon significant spontaneous heat release caused by the decay of screening currents in a cable with parallel superconducting wires. The advent of transposed wires, in particular the Rutherford wire [49], limited this kind of thermal perturbation.

The second reason for the enthusiasm concerning the stability of the magnetic flux distribution in a wire was the possibility of an analytical approach to the problems of applied superconductivity, which was rare for the 1970s. In a short time, several criteria for the stability of wires based on the critical state model appeared, taking into account the transverse thermal conductivity of the wire or its heat capacity, the resistance of the copper matrix, etc. A lot of these options [31] (internal stability, enthalpy, dynamic, etc.) had the common feature that they did not receive experimental confirmation and absolutely did not correspond to the practice of applied superconductivity, essentially underestimating the real operability range of wires.

The use of the material equation (5) of a real superconductor has made it possible to significantly improve the theory of stationary stability [32], extend it to arbitrary values of the Stekly parameter, and bring it into conformity with the practice of using superconducting wires. The criterion for stationary stability, e.g., for the case of a wire with a high thermal conductivity of the matrix, took the form [50]

$$\int jE\,\mathrm{d}S \leqslant hP\,\delta T_{\mathrm{c}}(B)\,.$$

This means that any wire remains stable until it overheats by its own current by the value $\delta T_{\mathrm{c}}(B)$. The most important consequence of this criterion — one not yet realized by the majority of the community — is that the wire remains stable in stronger electric fields as δ goes higher, i.e., the more diffused the transient response. The requirement for a high value of index n ($n \sim 1/\delta$), widespread in technical specifications for new wires, not only significantly complicates the technology and increases the price of the wire, but hopelessly destroys its stability.

Another costly prejudice that has existed since the fascination with the Stekly principle began is the requirement for high purity of the copper matrix in wires with a high factor of cross-section filling with a superconductor. Even with values of δ that reliably ensure the stability of the wire in the windings, critical overheating occurs at such a ratio of the conductivities of the superconductor and copper at which the current in the matrix remains negligible and has no effect on stability. The role of copper in the matrix is to provide a sufficiently high transverse thermal conductivity. Evaluations of the stability of wires in dynamic processes, in which the role of the heat capacity and conductivity of the matrix are important [33], in combination with convincing experimental confirmation [51–53] of the obtained criteria, in principle, settled the problem of low-temperature stability in applied superconductivity.

Deformation of the winding was thought to be another obvious cause of perturbation. The heat capacity of metals at the temperature of liquid helium is so small that even very small heat releases when the winding turns move can cause local temperature rises by one to two tens of kelvins [54]. Despite quite a large number of attempts to study this cause [55], it is difficult to find direct measurements of the magnitude, localization, and extent of perturbations.

The community waged a long struggle with perturbations. Compounding the windings eliminated the movement of individual turns, which removed the degradation of the winding on the scale of laboratory magnets. In larger-scale windings, in which significant forces and bending moments develop, the strength of the compound was found to be insufficient, and its failure increased the generation of heat. The very high strength of niobium–titanium wires provoked the use of wire not only to conduct current without heat loss but also as the main structural material that ensures the strength of the winding as a whole, as a result of which perturbations arose in the wire itself or in its immediate vicinity. This, as it has now become clear, delusion proved surprisingly tenacious. Ultimately, the community came to

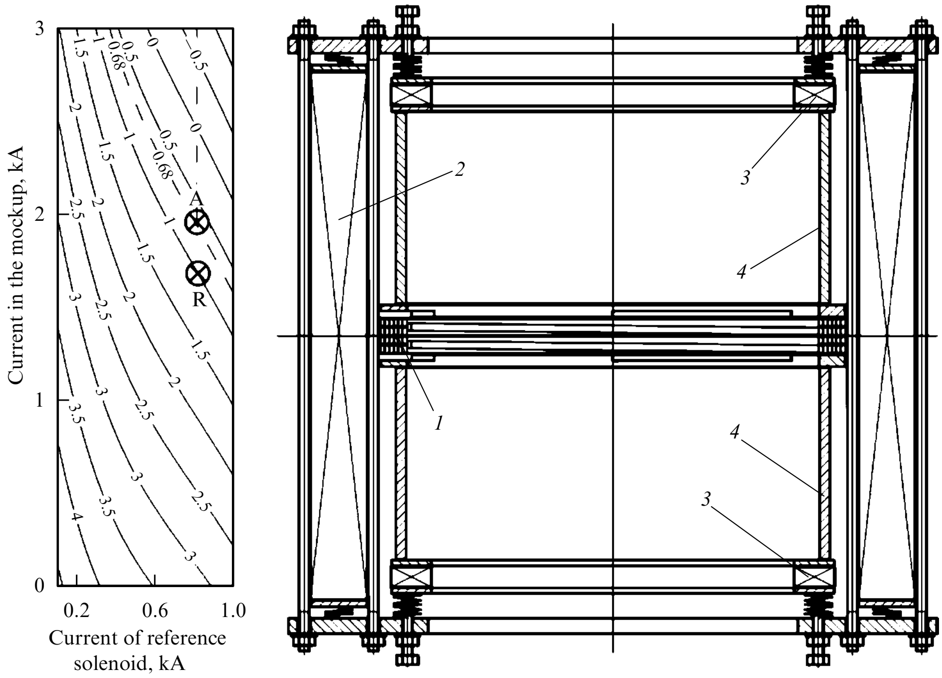

Figure 5. Testing setup for coils using a force generator. *1* — model block, *2* — solenoid of the reference field, *3* — radial windings of the force generator, *4* — cylinders transmitting force to the model block. Circles with X's mark the points of transition to the normal state: R — under the action of a radial force; A — under the action of an axial force.

terms with the fact that the operating currents of large windings are significantly lower than the critical currents of the winding material. To a certain extent, this humility was promoted by the widespread metaphor, apparently attributable to M Wilson: "Introducing a critical current of a short sample into the winding is like going up the stairs to the last floor of a skyscraper without splashing water from a glass filled to the brim." In this metaphor, namely, in the assumption that the glass is full to the brim, there is an unshakable conviction in the justice of the CSM. A bonus for this humility was a phenomenon called training: the current achieved in the winding could be increased by 10–20% after several tens of its transitions to the normal state.

A fortunate feature of superconducting windings, which made it possible to mitigate the shame of surrender, is that something less than the critical current of a short sample can always be injected from the superconducting winding to get, although not a calculated, a quite technically acceptable magnetic field in the winding. The comprehension of this feature has formed the following very popular paradigm for the design of superconducting windings [56]: *to prevent a transition of the winding to the normal state due to pulsed heat release of any nature, the superconducting wire temperature margin should be such that its heat capacity would allow taking up this heat release without exceeding by the local temperature of the wire the critical value, corresponding to the operating current and the maximum magnetic field on the winding*. The required temperature reserve is created at the expense of a significant increase in the superconductor expenditure. For example, in Ref. [56] it is recommended that the critical current of the wire exceed the operating current by 2.5 times.

It is funny that the development of the above paradigm was accompanied by a change in the content of the term 'degradation.' Instead of the initial distressing shortage of properties of the short wire sample, this term began to refer to the degradation of the characteristics of the winding over time. Such 'degradation' does not need to be overcome, since the aging of superconducting windings has not yet been observed. One would not have to regret the excessive consumption of a superconductor if we consider this paradigm to be the only and reliable possibility of constructing large superconducting windings. Of course, its implementation requires solving a number of scientific and technical problems, for example, ensuring a more or less uniform distribution of temperature and current over the cross section of the wire and redistribution of the current with local heat release somewhere in the section [57]. The greatest difficulty is the unpredictability of the parameters of the pulsed perturbation or at least the integral heat release in such a pulse. This is only found when testing a full-size winding.

Figure 5 shows one of the rare results of the experimental determination of the temperature margin in a mock-up of a real winding (Magneto-Cyclotron Ion Resonance, Isotope Separation (MCIRI) project) [58]. A four-pancake mock-up was tested in an external magnetic field. Isotherms of the temperature reserve in the current of the external magnet–current of the mock-up coordinates were plotted according to the results of the previously studied critical surface of the wire. A specific feature of the technique was that forces were reproduced on the winding of the mock-up, equal to the maximum design forces in the designed magnet. A radial force was created by the interaction of the prototype current with an axial external field equal to the maximum field in the designed magnet. The axial force was simulated using a superconducting magnetic press, due to the interaction of the current in the movable windings located near the ends of the external solenoid with the radial component of the field created by it. An increase in the axial force synchronous with an increase in the current in the mock-up reproduced the calculated situation in the designed magnet. The difference between the expected current of a short wire sample and the current of the transition of the winding of the mock-up to the normal state made it possible to determine the temperature rise during perturbations caused by the action of mechanical forces. As seen from Fig. 5, it appeared impossible to introduce the calculated current of 2.2 kA into the mock-up, while, at a smaller current, the amplitude of transition-inducing perturbations from the action of the radial force amounted to 1.0 K, and for the axial force it was 0.68 K.

The lack of confidence in achieving the rated current when using the version described above motivated the choice of the most conservative method of protecting the winding [58] by dissipating part of the energy stored in it into the external resistor. This method was successfully used in testing experimental magnets with a stored energy of the order of 1–10 MJ and allowed a significant reduction in refrigerant consumption for recooling the winding. As the stored energy of the project increases, to limit the maximum heating temperature of the winding during the current output after the appearance of the normal zone, it is necessary either to reduce the current density in the wire in inverse proportion to the square root of the energy stored in the winding or to increase the power output $(I_0 U(t=0))$ in proportion to the stored energy.

For the winding of the toroidal field of the International Thermonuclear Experimental Reactor (ITER) with a stored energy of 40 GJ, the required initial power output is of the order of 1 GW, which led to the choice of the operating current $I_0 = 68$ kA and the output voltage $U(t=0) \sim 20$ kV [59]. In our opinion, the choice of such parameters is beyond reason. Notably, it implies the construction of an extremely costly protection system for the magnetic system, the frequent and unpredictable triggering of which will make the entire thermonuclear device inoperative.

If the protection system is designed to rescue the winding in case of an unlikely emergency, when there is no need to think about saving the refrigerant, then its cost could be significantly less. For this purpose, care should be taken that the stored energy is evenly distributed in the winding and power structure. The author has already published in [60] the following maxim: *If the designer of a superconducting magnetic system does not guarantee a stable, reliable achievement of the operating current of a value that realizes the potential of the superconducting wire used, he should not undertake the project.*

If the operating current of the winding is below the design value, this is not always fatal for a device intended for a scientific experiment. For example, a scientific program was carried out in the first superconducting tokamak T7 [61], despite the fact that the operating current achieved was only 60% of the design one. If a similar situation had happened, for example, with a superconducting generator, it would lose 64% of its design power and would have lost its commercial attractiveness. In the case of the Large Hadron Collider, where obtaining the calculated operating current in all 1232 dipole magnets was critical, the number of manufactured dipole magnets was noticeably larger; they were all tested and trained up. Suitable dipoles were selected from their number. This high-cost approach has proven to be acceptable for a unique research facility. However, it is absolutely unsuitable for commercial windings.

Specialists who were directly involved in the creation of superconducting windings understood that the unpredictability of the operating current of the windings, the high price of superconducting wires, the possibly low yield of suitable windings, and the need for each magnet to have a cryogenic station to maintain the winding in operation did not allow commercial applications. They looked for ways to overcome these difficulties. Along with the specialists, there were enthusiasts who believed that zero resistance was the sole property of a superconducting wire, and they started headlong building mock-ups of various devices. Naturally, they failed, and if it was not possible to declare it a victory, they looked for excuses in external circumstances. Was it in this community of adventurers and losers that the idea of the inferiority of low-temperature superconductors arose? Unfortunately, some principals involved with the problem, shortsighted and not very responsible, have also concluded [62] that low-temperature superconductivity has proven unsuitable for commercial applications.

The problem of degradation of superconducting magnets was solved in the late 1980s. The answer to the question of how to deal with the degradation of wire properties in the winding in comparison with those in short samples is contained in the question itself: for the wire in the winding, it is necessary to provide the same conditions in which a short sample is tested, i.e., eliminate mechanical interaction between the turns of the wire.

Whereas, for a long time, winding designers struggled with the dilemma of whether critical disturbances occur in a wire or in a winding, the modern stability theory has clearly demonstrated that disturbances in a wire in slowly changing fields are easily eliminated. Excessive caution or fears of losing abstract objectivity still force us to use a vague formulation that is not filled with real content: "The reason for the disturbances in the winding is the peculiarities of its low-temperature abrupt deformation" [55].

The defining feature of a multi-turn winding is the anisotropy of its mechanical properties, and the obvious reason (or, to preserve the academism, one of the obvious reasons) for the generation of disturbances is the mutual friction of the turns at any deformation of the winding, during its bending or tension. This assumption does not contradict the known experimental facts, for example, the increase in the frequency and amplitude of acoustic noise observed by acoustic emission methods with increasing current, i.e., with an increase in the force factors acting in the winding. The pulsed nature of these noises can be easily attributed to the fact that the coefficient of static friction exceeds the coefficient of sliding friction. From the research alternative, we have either a thorough study of the causes and nature of perturbations in the winding or a radical elimination of the mutual movement of the turns: the second looks less academic, but quite pragmatic. Moreover, the method described below apparently eliminated other causes of degradation, for example, the longitudinal and transverse deformations affecting the critical current of niobium–tin wire, as well as possibly not yet identified reasons.

The proposed solution looks like this: the base of the magnet structure should be a steel or fiberglass frame, calculated by the methods of structural analysis so that its deformation by the forces acting in the winding never exceeds the value admissible for a superconducting wire. The wire must be rigidly fixed on this frame along its entire length, so that each turn of the winding transfers the force acting on it directly to the frame, without mechanically interacting with other turns.

To date, only one design option is known that satisfies this requirement — so-called laminar windings, the principle of

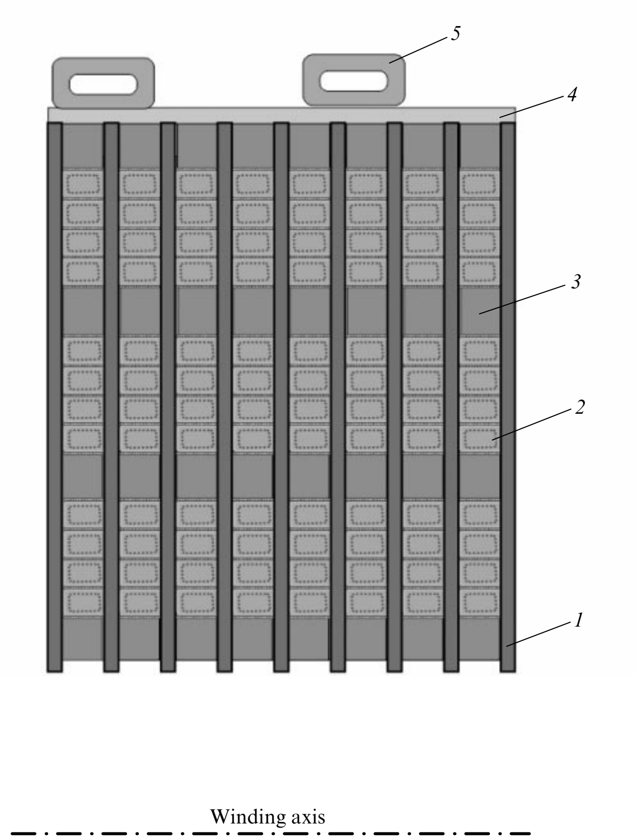

Figure 6. Portion of the laminar winding section: *1* — structural sheet, *2* — superconducting wire glued to the sheet, *3* — pieced axial support, *4* — cooling clamp, *5* — cooling channel.

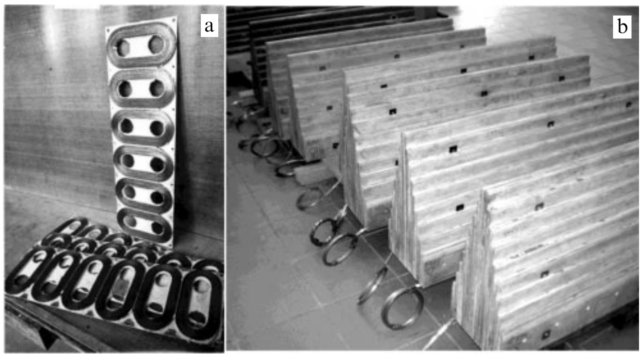

Figure 7. (a) Elements of a laminar winding of a magnetic separator [63]. (b) Sections of a toroidal superconducting energy storage device (SMES-8) with a glass-fiber laminate load-bearing structure [68].

which is explained in Fig. 6. It is unlikely that this option is the only possible one, but in view of its temporary uniqueness, we will consider it. The principle has been repeatedly implemented [63–66] and used in projects involving large superconducting magnets [57, 67, 68]. Examples of such an implementation are shown in Fig. 7.

Elimination of degradation is the main result of this method, but attention should also be paid to the simplicity of the design: it does not contain flanges or fasteners, which usually greatly increase the mass of the superconducting device. The role of the above-mentioned power frame is played by flat sheets glued to flat pancakes wound with a superconducting wire of a rectangular cross section. The use

Figure 8. Test section of the toroidal SMES-30 consisting of 36 pancakes wound with a continuous piece of wire with a cross section of 2×10 mm and a length of 800 m.

of high-strength film glue VK-36 [69], developed by the domestic aviation industry, turned out to be a success. The shear strength of this adhesive at a temperature of 4.2 K is about 10 MPa, which provides a 5–10-fold margin in the windings of large superconducting magnets with respect to the shear stresses acting on the wire. The use of VK-36 glue, in addition, radically improves the working conditions with epoxy compounds. Fixing the winding with glue makes it possible to manufacture multi-pancake windings from a continuous piece of wire, since there is no need for excessive tension on the wire during winding (Fig. 8).

This design fulfills for all wire lengths the conditions in which samples of short wires are tested, and there is no difference between the critical current of the winding and the critical current of a short sample that was called degradation.

The above statement itself is never criticized. Opponents usually doubt the possibility of implementing this principle, and also fear a significant decrease in the constructive current density. As for the constructive current density, its reduction in traditional windings due to degradation is 30–70%. If the frame actually takes up this space, then the obvious benefit will be in saving superconducting wire. In fact, the cross section of the required frame is not so large, since the magnitude of the deformation is determined not by the strength, but by the rigidity of the structure, i.e., not by the amount of material in the structure, but by its shape. From this point of view, used in a widespread class of windings consisting of flat pancakes of arbitrary shape, fixing the winding on flat sheets seems to be the best option.

With the proper choice of the material for the structural sheets, they will be able to provide cooling of the winding due to their thermal conductivity, as well as protection in emergency situations by forced transition of the entire winding [54] to its normal state when overheated by eddy currents induced in the sheets during the seed protective decrease in the current in the winding.

It cannot be argued that the success of a few windings is sufficient for immediate commercial implementation. The 1990s in our country were not favorable for carrying out detailed studies of low-temperature applications. Attempts at such research have been made in the framework of very rare contracts for the development of large superconducting windings. The most convincing results are from experiments carried out within the framework of the above-mentioned project [58] of the MCIRI superconducting magnet for a

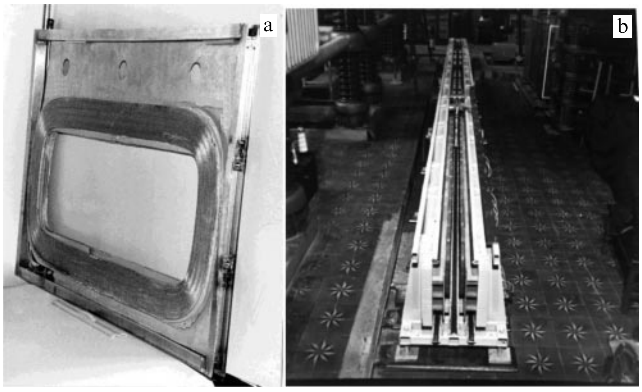

Figure 9. (a) Inductor winding and (b) mockup of electromagnetic catapult stator [68].

separator of gadolinium isotopes. In addition to the traditional winding described above, a laminar winding of the same wire was tested using the same method, in which the insulation was removed from the faces of the pancakes and stainless discs with a thickness of 1.0 mm were glued on. The critical current of this mock-up under the action of radial forces turned out to be equal to the critical current of a short sample. In the experiment with a magnetic press, a calculated operating current was introduced without the transition of the mock-up to the normal state. The unused temperature margin was 0.45 K. According to the test results, it was concluded that the purchased wire is not suitable for the manufacture of traditional windings but can be used in a laminar winding. This project, like many others, failed to be implemented.

The community, taught by the many failures of scaling designs that seemed promising, was wary of these developments. In the late 1980s, cooperation between teams from the Kurchatov Institute and the Kharkov Polytechnic Institute named after V I Lenin (KhPI) attempted a large-scale demonstration of the triumph of the new principles by applying them to the development of an electromagnetic catapult as an option for the heavy aircraft carrier Varyag [70], then under construction. A considerable part of the work was carried out [71]. One full-scale unit of the inductor was made of flat niobium–tin wire and tested at currents up to 95% of the critical current of a short sample. This current was frozen in the winding using a thermal switch. At KhPI, a mock-up of the stator of a linear DC motor with a semiconductor commutator was made. The mock-up had a full-scale cross section and a length of 14 m (Fig. 9) and was also successfully tested. However, well-known events led to the fact that funding for the electromagnetic catapult was stopped. Sold by Ukraine in 1998 as scrap metal, the Varyag hull was used to build the first Chinese aircraft carrier.

The use of laminar windings would allow mass production of a wide range of inexpensive commercial products. The absence of degradation would guarantee their performance, and the simplicity of the design would facilitate automation of the manufacturing. Products could have been shipped without costly cryogenic testing. It was reasonable to entrust random tests to a specialized oversight organization. Servicing of commercial devices was to be provided by a network of cryogenic firms. The excitement that gripped the world after the discovery of high-temperature superconductivity thwarted these plans.

4. Prospects of high-temperature wires in applied superconductivity

It would be difficult to justify ignoring in this article such a negatively fateful phenomenon for applied superconductivity, which turned out to be the discovery of high-temperature superconductors. The author is aware of how much his point of view contradicts the currently generally accepted opinion, but believes that in historical research the alternative point of view is acceptable and deserves attention, especially since in recent years there are clearly observed tendencies corresponding to his initial impression [72].

The author has no doubt about the importance of the discovery by Bednorz and Müller [73] for the physics of superconductivity. Nor is there any doubt that the high critical fields of new materials should eventually lead to the development of wires that would allow these advantages to be realized in high-field solenoids. Unfortunately, the senseless and merciless excitement inherent in revolutionary situations, which engulfed not only a highly specialized community but also associations of funders and government circles, led to a number of negative phenomena, some of which are listed below.

(1) The development of applied superconductivity itself stopped for at least 35 years. Achievements with a high probability of allowing the transition to the development of commercial applications have remained unrealized.

(2) The general level of applied superconductivity dropped sharply, as the army of enthusiastic neophytes could not navigate the sea of publications and became acquainted with the problems of this technical science, studying the monographs of the 1960s and absorbing the very prejudices that the previous generation had so hard refuted.

(3) Another reason for the decline in the level is that the previous generation thinned out due to natural reasons, the inability to continue work in a direction devoid of funding, or a change in the type of activity from technical to a funded chamber one.

(4) The ethical level of the community has dropped noticeably. In order to reorient so quickly to the high-temperature direction, it was necessary to radically compromise the low-temperature one: low-temperature superconductivity has practically exhausted the effect of eliminating ohmic resistance. For example, the power consumption for maintaining a superconducting solenoid with a field of 15 T in an opening with a diameter of 40 mm [74] was 0.003% of the power of a similar copper water-cooled solenoid (excluding the power of water pumps). A similar ratio for the magnet (3 T) of the Large Bubble Chamber [75] at CERN was 0.6%.

To compromise, arguments were used that were ridiculous for specialists, but, apparently, convincing for financiers. For example, cheap nitrogen was balanced against expensive helium. The manipulators kept silent about the obvious facts that the ratio of the effect price to the resource price is essential for a business and that no serious effect can be expected at the temperature of liquid nitrogen. Another argument of the same quality (at room temperature, the compensation for a heat flow of 1 W at the temperature level of liquid nitrogen requires 50 times less energy than the compensation for the same heat flow at the temperature level of liquid helium) was calculated for a layperson who does not know that liquid helium is always used with a nitrogen temperature shield, which reduces the heat flow to helium by

194 times, as a result of which the above ratio is reduced 25-fold. The energy costs associated with the use of helium are only twice as high as when working with nitrogen. This distinction has no significant economic significance.

The reader can see that the economic effect from the use of high-temperature and even room-temperature superconductivity in comparison with that using developed low-temperature superconductivity is negligible. Nevertheless, the manipulators succeeded in eliminating low-temperature superconductivity from the investors' field of vision, ascribing to HTSC the entire effect of zeroing the resistance.

What has been obtained after 35 years of unprecedented investment in the development of HTSC? Of course it should be noted first of all a series of manufactured combined solenoids with high-temperature inner sections with fields of 25–30 T and, in particular, an outstanding achievement — successful testing of a combined solenoid with a high-temperature insert with a magnetic field of 32 T [76] in liquid helium.

As for the rest, the conferences and journals are filled with promises, projects, and sometimes not very intelligible mock-ups. Among the promises are very impressive ones, for example, a plan for a high-field thermonuclear reactor [77]. Apparently, the trading of promises has remained a profitable item of superconductivity for more than 100 years.

An important result seems to be the consensus achieved in recent years regarding the choice of the operating temperature of HTSC windings. The community gradually came to appreciate the attractiveness of running windings at as low a temperature as possible. Now, options for the operation of windings in liquid hydrogen and liquid helium are mainly being considered. However, strict regulations on the use of flammable liquid hydrogen (Code of Rules (CR) 162.1330610.2014) will allow the use of such an operating temperature in devices where liquid hydrogen will play some other, more important, role, e.g., in aircraft with hydrogen engines. Other devices will work with tacitly rehabilitated liquid helium. This means that HTSC wires will have to compete with traditional niobium–titanium and niobium–tin wires, the design and technology of which are much more appropriate than those for a fragile tape with insufficiently studied electrophysical characteristics.

Hopefully, the community will overcome the stereotypes that have formed over 35 years and realize that, in the range of magnetic fields of $3-7-15$ T that is of interest for commercial applications, traditional materials, the technology of which has not yet been lost, are most suitable. Nothing hinders their commercial use. Experienced designs and technologies have been reliably tested. The theoretical foundations are solid enough. Ways to further improve them, consisting in the construction of material equations that take into account the real pinning anisotropy, are also well defined, at least for wires based on niobium–titanium. Experiments to determine the material equation of niobium–tin wires were planned in the 1990s, but these studies were not recognized as relevant. The technique developed since then allows executing them fairly quickly. There is no justification for damage from ignoring clearly defined commercial applications.

As for the prospects for the use of high-temperature superconductors, their application should be sought in the region of higher fields, as is now being done in the field of thermonuclear and accelerator technology [77, 78]. It is necessary to study the possibility of operating HTSC devices under conditions of significant external heat influx. By slightly lowering the operating current, it is possible to provide a temperature margin of 10–20 K and use windings with a nonuniform temperature distribution in the volume or provide a sufficiently intensive heat exchange with the refrigerant [77].

With the start-up of the Amur gas processing plant, helium will cease to be in short supply in Russia. Fascinated by exports, Gazprom has already planned to send almost all 60 million cubic meters a year along the Blagoveshchensk–Nakhodka–Singapore and Malaysia route [3] by caravans of tank trucks with a capacity of 45 tons of liquid helium each. Applied superconductivity will be able to develop in Russia if every 20th or 25th tank truck changes its destination to the European part of Russia.

5. Conclusion

The reason for the failure of attempts to commercialize superconducting windings in the 20th century was the inadequate scientific and technical foundations of applied superconductivity, proposed in the first two years after the emergence of this direction and dogmatically accepted by an overly large community of specialists. The conservatism inherent in large communities did not allow them to perceive the pragmatic changes in scientific and technical foundations developed in the penultimate decade of the 20th century, despite convincing experimental confirmation of the results of these changes in the electrodynamics of superconductors and the successful prototyping of laminar windings using the proposed principles. One can only regret the wasted time.

Despite the impressive advances in the technology of new high-temperature superconductors, the results of designing wires from these materials hardly meet expectations in terms of their electrodynamic and mechanical characteristics.

Relentless time has greatly reduced the size of the generation of developers of low-temperature superconducting windings. The success of the new generation can be attributed to the creation of HTSC sections of high-field magnets on a laboratory scale. Regarding the development of large-scale devices, despising the experience of the 20th century, it is carried away mainly by fantastic projects, the implementation of which is postponed due to the volume of production and quality and price of new winding materials. Not faced with the problems that developers had to solve in the last century, the new generation is content with a surrogate for scientific and technical foundations, gleaned from books published in the 1960s.

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