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Radiation treatment of the edges of a crack in a superconducting layer during restoration of HTSC tape

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Numerically, within the framework of the critical state model, the density of superconducting currents in a second-generation HTSC tape based on $GdBa_2Cu_3O_{7-x}$ is determined. It is shown that during the restoration of the transverse crack of the superconducting layer by shunting the crack with a piece of defect-free tape, the critical current of the restored area decreases by $\sim 8\%$. It is shown that preliminary i rradiation of the crack edges with ions of hydrogen, helium, neon, and oxygen makes it possible to restore the initial value of the critical current. The calculation of the effect of radiation on a superconducting tape was carried out using the SRIM software package.

Keywords: high temperature superconductor, irradiation, radiation defects, critical current.

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1. Introduction

Modern high-temperature superconducting (HTSC) composite bands of the second generation based on $YBa_2Cu_3O_{7-x}$ or GdBaCuO compounds have high critical currents, due to which are widely used in the field of electric power industry, when creating high-performance power lines, motors, generators, current limiters, etc. HTSC composites also have high critical current densities in strong magnetic fields, which makes them an extremely promising material for use in superconducting magnetic facilities of the MEGA-science class (Large Hadron Collider LHC, NIKA accelerator, ITER project, etc.). In these installations, HTSCs are exposed to strong radiation fields, which inevitably lead to a change in superconducting characteristics, primarily the critical current and critical temperature, due to the formation of radiation defects in the HTSC material. Depending on the type of superconductor and the nature of irradiation, radiation exposure can significantly affect the local critical current density, while the dose dependence of this quantity can be nonmonotonic. At a low dose, in some cases, an increase is observed; at a large dose, a drop in the critical current density is observed. For example, such nonmonotonicity is presented in the work [1], where a superconducting GdBaCuO film was irradiated with Zr ions, in the work [2], where HTSC films were subjected to neutron irradiation, or in the work [3], where a superconducting GdBaCuO film coated with the silver layer was irradiated with Ar, Xe, and Kr ions. The increase in the critical current density is associated with microscopic inhomogeneities in the distribution of radiation defects, which are pinning centers for Abrikosov vortices in a superconductor. The decrease in the critical current density during irradiation is associated with the disordering of the crystal structure of the superconductor.

The heterogeneity of the distribution of defects in a superconductor can also lead to local heterogeneity in the change in superconducting characteristics in the volume of the material. In turn, such heterogeneity can be accompanied by unusual physical phenomena, for example, the appearance of phase transitions in current, similar to those observed in granular superconductors $YBa_2Cu_3O_{7-x}$ [4].

This work shows the paradoxical situation, when the radiative decrease in the critical current density in the macroscopic region of a defective HTSC band can lead to an increase in the total critical transport current through this superconducting system.

Superconducting layer crack is studied as a defect of the HTSC band. Significant disadvantage of HTSC $YBa_2Cu_3O_{7-x}$ and $GdBa_2Cu_3O_{7-x}$ is the fragility of these materials. Excessive bending of the superconducting band leads to the appearance of transverse cracks in the band, which makes it unsuitable for use in current transport systems (see, for example, [5]). The simplest way to restore the current-carrying characteristics of the superconducting line based on the separate HTSC band is shunting the section with a transverse crack with the segment of similar defect-free band that has good electrical contact with the damaged band in the vicinity of the crack. Soldering of the HTSC bands is a common technique that provides good electrical contact when they are connected (see, for example, [6]).

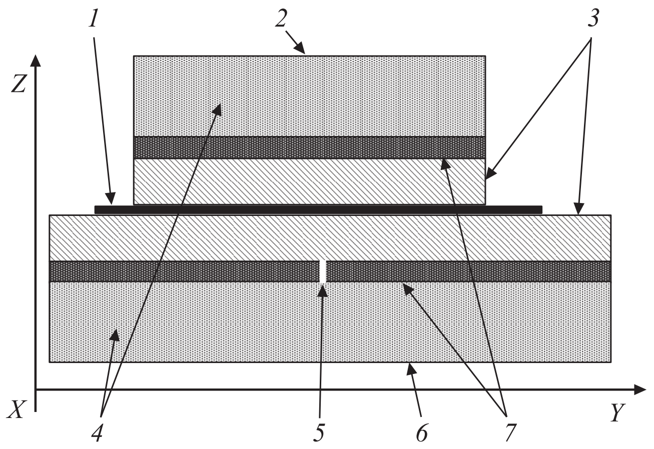

Figure 1. HTSC band with the transverse crack and the shunt soldered to it (side view). *1* — solder that provides electrical contact between the defective band and the shunt. *2* — shunt, *3* — protective coating of HTSC band and shunt, *4* — substrates of band and shunt, *5* — HTSC layer crack, *6* — HTSC band with the crack, *7* — superconducting layers bands and shunt.

Figure 1 shows the side view of composite HTSC band with the transverse crack, which is short-circuited by the segment of defect-free band of the similar type. Also in this figure, the Cartesian coordinate system (X, Y, Z) that coordinates the band is defined. In this work, we study the distribution of superconducting current density in this structure in cases where the region near the crack was not subjected to preliminary radiation exposure, and when this region was irradiated with fast ions before the shunt was attached to the band.

The article has the following structure: in Section 2, within the framework of the critical state model, the density of superconducting currents in a shunted HTSC band with a crack is determined without preliminary radiation treatment of the damaged area. In Section 3, for a certain inhomogeneous profile of radiation defects that arise during ion irradiation, the density of superconducting currents in the system under study is also determined. At the beginning of this section, the calculation of the irradiation regimes necessary for the formation of the concentration of radiation defects for the desired profile is given. The calculation of the radiation damage of an HTSC band is carried out using the SRIM software package (Stopping and Range of Ions in Matter [7]).

2. Superconducting currents in the absence of radiation treatment

2.1. Problem formulation

Determining the induced superconducting currents in the upper superconducting layer (USL) induced by the field of the magnetic bar is possible within the framework of various approaches. To describe critical currents in a thin superconducting film, one can use an approach based on solving the Ginzburg–Landau equations [8]. This approach makes it possible to determine in detail the structure of superconducting currents, including the structure of the individual superconducting vortex, but when solving macroscopic problems, it requires too high computer resources. More simplified approach to describing the system of currents operates with the system of Abrikosov vortices in the magnetic field, where vortices are considered as separate particles interacting with each other (see, for example, [9]), however, this approach also requires excessive computer resources.

The object under study, as well as in the works [10–12], is a HTSC band $GdBa_2Cu_3O_{7-x}$ manufactured by SuperOx. In the absence of the external magnetic field, the volume density of the critical current at liquid nitrogen temperature is $J_c = 2.77 \cdot 10^6\,\mathrm{A/cm^2}$ [13]. The width of the tape a is equal to 12 mm $(-a/2 < X < a/2)$. The thickness of the HTSC layer d (direction of the axis Z) in the band, as well as in the works [10–12], is equal to 1.5 μm. The relationship between the bulk density of the critical current J_c and the density of the two-dimensional critical current j_c of an HTSC band is determined by the following relation $j_c = J_c \cdot d$. In accordance with the data of the work [13] the band's protective coating consists of a 2 μm thick silver layer adjacent to the superconductor and a 20 μm thick copper layer covering it. The Hastelloy C-276 (Ni, Mo, Cr, Fe, W) alloy substrate is isolated from the superconductor by a thin layer of metal oxides. If necessary, the electrical resistance of the protective coating (Cu, Ag) between the band and the shunt can be reduced by removing the copper layer, and in this work we neglect this resistance. Within the framework of these assumptions and the two-exponential approximation of the dependence of the critical current on the magnitude of the magnetic field induction B [14], the density of the two-dimensional critical current j_c of the shunt−HTSC band system with a crack can be represented in the following form:

$$j_c(B, Y) = C(B) \cdot h(Y),$$

$$C(B) = \big(A_1 \cdot \exp(-|B|/\beta_1) + (A_2 \cdot \exp(-|B|/\beta_2)\big). \quad (1)$$

Approximation parameters $A_1 = 23665\,\mathrm{A/m}$, $A_2 = 17884\,\mathrm{A/m}$, $\beta_1 = 0.1175\,\mathrm{T}$ and $\beta_2 = 1.2238\,\mathrm{T}$ are determined by least-squares fitting to the experimental work-dependence [13]. In a separate band without the crack, dimensionless parameter $h = 1$. For the shunt−HTSC band system with the transverse crack at $Y = 0$ the parameter $h = 2$ at $Y \neq 0$ and $h = 1$ at $Y = 0$ (see Fig. 2).

The relation between the magnetic field $\mathbf{B}(x, Y, Z, t)$ and the electric field $\mathbf{E}(X, Y, Z, t)$ is determined by the induction law

$$\frac{\partial \mathbf{B}(X, Y, Z, t)}{\partial t} = -\nabla \times \mathbf{E}(X, Y, Z, t).$$

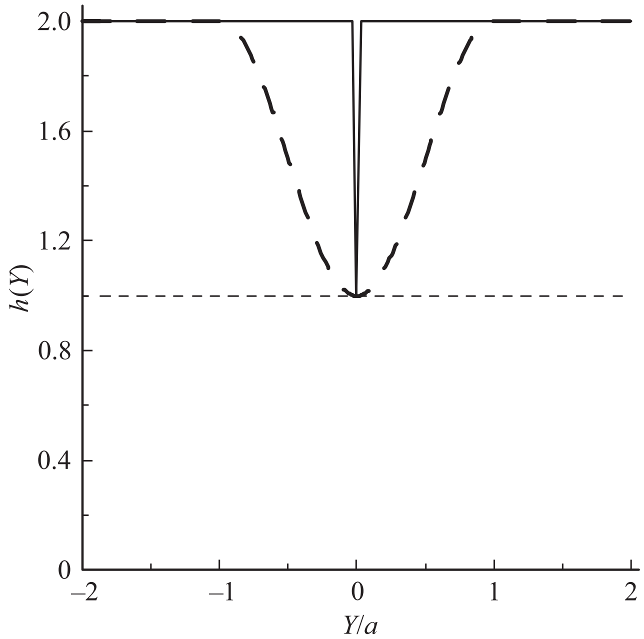

Figure 2. Dependence of the parameter h on the longitudinal coordinate Y. Thin dotted line — single HTSC band without crack. Solid thin line — shunt–band system with the crack in the absence of preliminary radiation treatment of the edges of the crack. Thick dotted line — shunt-band system with a crack after preliminary radiation treatment of crack edges.

On the two-dimensional structure (plane $Z = 0$):

$$\frac{\partial B_Z(X,Y,0,t)}{\partial t} = -\frac{\partial E_X(X,Y,0,t)}{\partial Y} + \frac{\partial E_Y(X,Y,0,t)}{\partial X}. \quad (2)$$

The system of equations is completed by the nonlinear Ohm's law for the HTSC film

$$\mathbf{E}(X,Y,0,t) = \rho\big(\mathbf{j}(X,Y,t), B(X,Y,0,t)\big) \cdot \mathbf{j}(X,Y,t). \quad (3)$$

The dependence of the two-dimensional resistivity $\rho(\mathbf{j}, B)$ is often chosen in the form

$$\rho(\mathbf{j}, B) = \rho_0[|\mathbf{j}|/j_c(B)]^n, \quad \mathbf{j} = \sqrt{j_X^2(X,Y,t) + j_Y^2(X,Y,t)} \quad (4)$$

(see, for example, [15,16]), where usually $n \sim 20{-}50$. In the present work, just as in [10–12,17,18], we choose the dependence $\rho(\mathbf{j}, B)$ as follows:

$$\rho(\mathbf{j}, B) = \begin{cases} 0, & |\mathbf{j}| < j_c(B) \\ \rho_0 \cdot [|\mathbf{j}| - j_c(B)]^2, & j_c(B) \le |\mathbf{j}|, \end{cases} \quad (5)$$

Detailed description of the algorithm for the numerical solution of this problem is presented in the works [17,18], and, due to cumbersomeness, is not given in this article. The presented model adequately (corresponding to experimental data) described the superconducting characteristics of HTSC wafers of various shapes.

2.2. Results and discussion

In the absence of dependence of the critical current density on the magnetic field at $j_c = A_1 + A_2 = 41549$ A/m (see expression (1)), the value of the critical transport current through the single defect-free HTSC band $I_c = 500$ A. Accounting for the field dependence of the critical current on the magnetic field when solving the problem (1–5) for the single defect-free HTSC band reduces this value to $I_c = 473$ A. The current density and the magnetic field induced by it in a defect-free HTSC band do not change in the longitudinal direction (Y axis). Figure 3 shows the distributions of the critical density of the superconducting current and the corresponding magnetic field in the transverse (X axis) direction. This figure shows that the critical current density is maximum at the center of the band, where the magnetic field is zero and decreases monotonically as one approaches the edges, near which the magnetic field is relatively strong and suppresses superconductivity.

The calculation of the critical transport current in the shunt–HTSC band structure with a crack gives the value $I_c = 437$ A — per $\sim 8\%$ less than in the original defect-free band. This drop occurs despite the

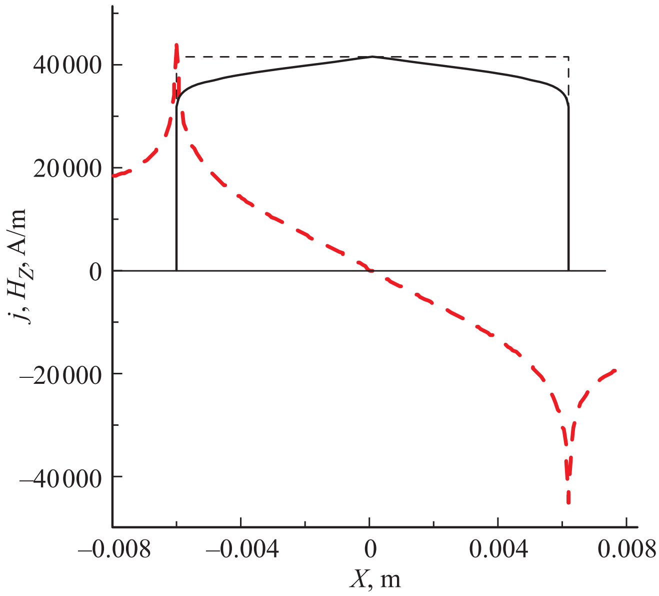

Figure 3. Dependence of the superconducting current density and the amplitude of the magnetic field induced by it in the single-layer defect-free HTSC band. The magnetic field component normal to the band surface $H_Z = B_Z/\mu_0$, μ_0 — magnetic constant. The thin black dotted line — the value of the critical current at zero magnetic field. The thin black solid line — the value of the critical current when taking into account the magnetic field dependence in the two-exponential approximation (2). Thick red dotted line — magnetic field amplitude.

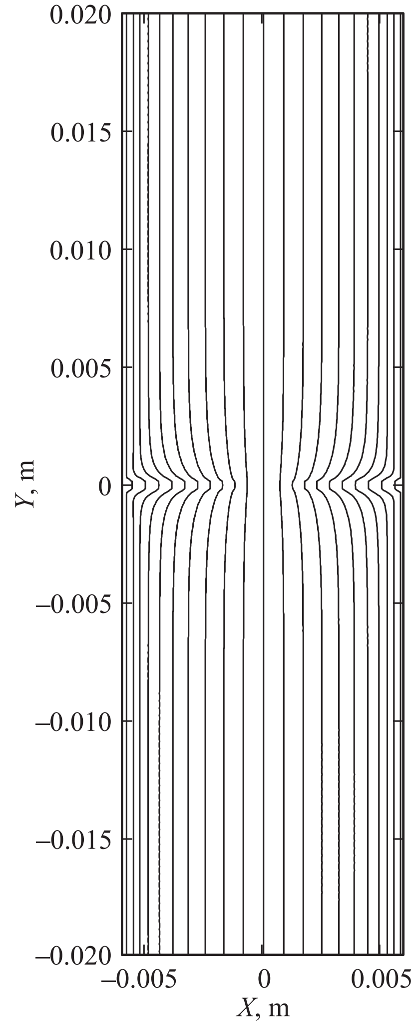

Figure 4. Current lines in the shunt–HTSC band system with a transverse crack in the region $Y = 0$ without preliminary radiation treatment. One line corresponds to the current of 20 A.

fact that the effective thickness of the superconducting layer in the two-layer structure almost everywhere exceeds the thickness of the single-layer band by a factor of 2, and these thicknesses coincide only at the crack (see Fig. 2). Such a strange situation at first glance is explained by the fact that the belt of the thinner HTSC film at $Y = 0$ is the magnetic field concentrator.

Near the crack, the amplitude of the magnetic field sharply increases, which leads to a decrease in the critical current density, and the total transport current through the system is determined precisely by the shunt region under the crack — „thin spot" of the superconducting line.

The effect of magnetic field concentration on the crack is illustrated and explained in Figs. 4 and 5. Figure 4 shows the calculated current lines in the shunt–defective HTSC band system. The current density in this figure is proportional to the density of the current lines. This figure shows that near the crack, the superconducting current has not only a j_Y component (the only nonzero current component in a defect-free band), but also a j_X component. The sign of the current components j_X after the crack $(Y > 0)$ is opposite to the sign of the current component j_X before the crack $(Y > 0)$, and this local circulation of the current significantly increases the amplitude of the magnetic field $H_Z(X, Y)$ over the crack.

The crack region is in the critical state, which can be seen in Fig. 5, which shows the level lines of the normal component of the magnetic field. Due to the symmetry of the band, the normal component of the magnetic field is antisymmetric in the transverse direction X, i.e. $H_Z(X, Y) = -H_Z(-X, Y)$ and $H_Z(0, Y) = 0$, i.e. in the central part of Fig. 5, where there are no level lines, there is also no magnetic field — the superconductor is in the Meissner state and completely shields the magnetic field on the surface of the structure.

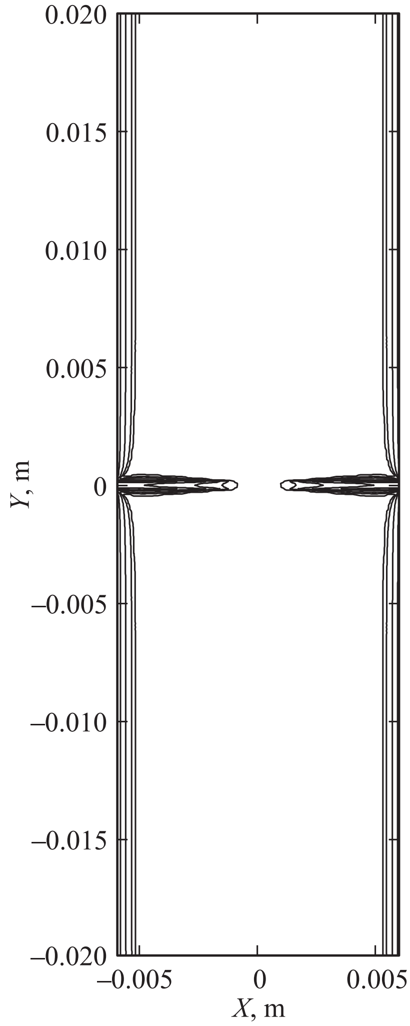

Figure 5. Level lines of the magnetic field amplitude in the shunt–HTSC band system with a transverse crack in the region $Y = 0$ without preliminary radiation treatment. The distance between the lines is 10000 A/m.

The magnetic field is non-zero only at the periphery of the band and in the region of the crack, where it suppresses the critical current flowing through the shunt. The effect of magnetic field concentration at the crack edges can be weakened by preliminary (before connection of the band and the shunt) radiation treatment of the crack edges, which leads to a smooth decrease in the critical current density near the superconductor fault line.

3. Superconducting currents of the band−shunt system after radiation treatment of a crack in an HTSC band

3.1. Possible irradiation modes

Smooth decrease in the critical current density in the defective band as it approaches a crack along the Y axis can be realized by irradiating the band through the shielding mask of variable thickness. The thickness of the mask above the crack is equal to zero and increases with distance from the defect to a thickness sufficient for complete absorption of incident fast particles. The destruction of the superconducting layer is possible by irradiation of various types. Prospects for the use of HTSC bands in accelerator and space technology have stimulated the study of the degradation of superconductors in radiation fields of various types — when irradiated with ions of various elements, neutrons, electrons and γ-quanta (see, for example, works [1–3,13,19–21]). However, among the numerous works on this topic, we did not find data on the irradiation regimes we need. For a preliminary assessment of the operating mode of the charged particle accelerator, we are interested in the minimum energies of hydrogen, helium and oxygen ions, which provide maximum damage in the middle of the superconducting layer of the HTSC band based on $GdBa_2Cu_3O_{7-x}$. In this case, irradiation is carried out from the side of the protective layer, which consists of copper ($20\,\mu$m) and silver ($2\,\mu$m, see Fig. 1). It is also necessary to determine the number of radiation vacancies created in the superconducting layer by these ions. We solved this problem using the SRIM [7] calculation package, which worked in the „Quick mode: Kinchen-Pease“. When selecting the calculated parameters introduced into this package, among others, it is required to determine the displacement threshold energy of atoms (E_d) in the HTSC layer. The authors of various works give different values of this quantity. In an experimental work [22] from the data on the irradiation of $YBa_2Cu_3O_{7-x}$ by fast electrons (0.1−2.4 MeV) for oxygen and copper, the values E_d equal to 10 and 15 eV, respectively, are obtained. In an experimental work [21] from the data on the irradiation of $YBa_2Cu_3O_{7-x}$ by fast electrons (20−120 keV) for oxygen in the CuO_2 planes and in chains, the values E_d are obtained equal to 8.4 and 2.8 eV, respectively. In a theoretical work [23], depending on the position of the oxygen atom and the direction of its motion, the value of Ed changes in the range of 5−20 eV. In the work [24] for the calculation in the SRIM package the values E_d for oxygen — 20 eV, for other atoms — 25 eV were taken. The most adequate values seem to us to be the experimental data of the work [21] — 8.4 and 2.8 eV for oxygen atoms in planes and oxygen chains, respectively. The displacement energies of other atoms are chosen by default, offered by the computational package (25 eV). The table shows the energies of fast particles and the number of vacancies created by one particle in the HTSC layer and adjacent layers. It follows from the data in the table that the complete disordering of the crystal structure of the HTSC layer with the thickness of $1.5\,\mu$m will occur at fluences $\sim 5\cdot10^{17}$, $5\cdot10^{16}$ and $4\cdot10^{15}$ ion/cm^2 for irradiating the HTSC band with hydrogen, helium, and oxygen ions, respectively. The highest uniformity of the distribution density of radiation vacancies over the thickness of the HTSC layer is observed when the band is irradiated with hydrogen ions.

The number of vacancies created by one fast particle in the protective layer (Cu, Ag), superconducting layer (GdBaCuO) and substrate of the HTSC band (Hastelloy) under irradiation

Particle type and its energy	Protective layer Cu, Ag	Superconductor GdBaCuO	Substrate Hastelloy
H 2.27 MeV	15.5	18	3.6
He 8.9 MeV	115	179	11
O 72.5 MeV	1057	2515	42

The deviations of the vacancy density from the average value of this quantity in the superconductor are equal to $\sim$ 5, 14, and 12% upon irradiation with hydrogen, helium, and oxygen ions, respectively. Better homogeneity can be expected when irradiated with particles of different energies, or when irradiated through different masks.

3.2. Formulation of the problem for calculating superconducting currents

Sharp change in the direction of the current density vector when passing through a crack, which determines the magnitude of the magnetic field above the crack, can be eliminated by preliminary radiation treatment of the edges of the crack before connecting the defective HTSC band and the shunt. Radiation defects suppress superconductivity and treatment consists in non-uniform irradiation of the crack region in such a way that the critical current density smoothly tends to zero at its boundaries (at $Y=0$). To illustrate the effect of a decrease in the magnitude of the magnetic field above the crack, we choose the dependence $h(Y)$ in expression (1) in the following form:

$$h(Y)=\begin{cases}1.5-0.5\cdot\cos(\pi Y/a); & |Y|\le a\\ 2; & |Y|\ge a\end{cases}. \quad (6)$$

Dependence (6) is shown in Fig. 2 by a dotted line.

3.3. Results and discussion

The calculation of the critical transport current of the shunt–HTSC band system with a crack after radiation treatment gives the value $I_c = 467\,\mathrm{A}$, which is closer to the current of the defect-free band $I_c = 473\,\mathrm{A}$ than to the current of the shunt–band system without radiation treatment ($I_c = 437\,\mathrm{A}$).

Figure 6 shows the current lines in the radiation-treated system. This figure shows the absence of a break in the direction of the current near the crack. Figure 7 shows the lines of the levels of the magnetic field $H_Z(X, Y)$. This figure shows the delocalization of the magnetic field in the region of the crack in comparison with the unirradiated sample (see Fig. 5). Figure 8 compares the amplitudes of the magnetic field $H_Z(X, Y)$ at $X = -3\,\mathrm{mm}$, $-20 < Y < 20\,\mathrm{mm}$ for a defect-free band and for a defect-free band, for the shunt–band system without radiation treatment and with treatment. This figure shows that the peak amplitude of the magnetic field near the crack is more than 4 times higher than the analogous value in the defect-free band, and the peak amplitude of the field in the treated system exceeds it only by $\sim 15\%$, which explains the weak degradation of the transport current in processed system.

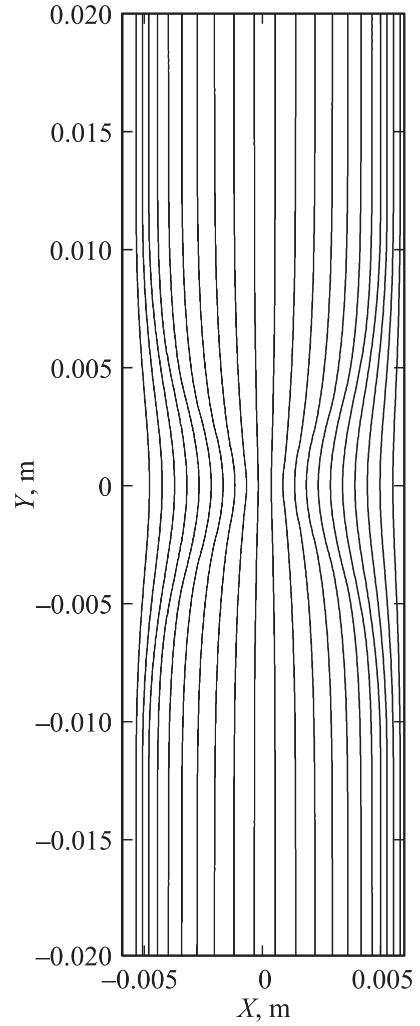

Figure 6. Current lines in the shunt–HTSC band system with a transverse crack in the region $Y = 0$ after preliminary radiation treatment. One line corresponds to the current of 20 A.

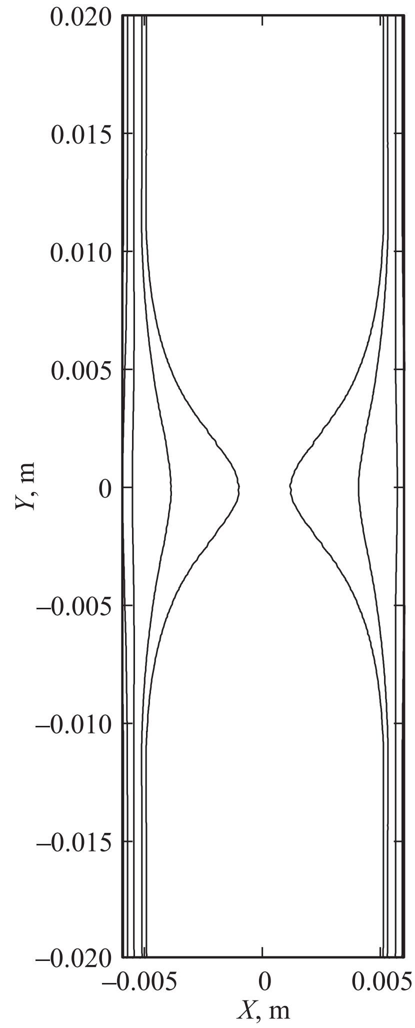

Figure 7. Level lines of the magnetic field amplitude in the shunt–HTSC tape system with a transverse crack in the region $Y = 0$ after preliminary radiation treatment. The distance between the lines is 10000 A/m.

4. Conclusion

It is shown that simple shunting of a section of an HTSC band with a crack does not allow one to completely restore the total transport current through the HTSC band–shunt system. To fully restore the transport characteristics of the system, a controlled decrease in the critical current density in the damaged band near the crack

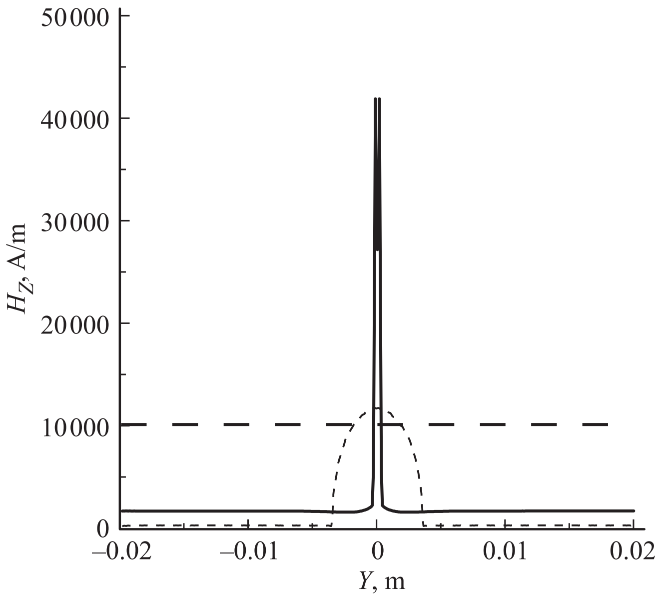

Figure 8. Dependence of the normal component of the magnetic field $H_Z(X = -3\,\text{mm}, Y)$ in the defect-free HTSC band (thick dotted line), in the shunt–HTSC band system with a crack without radiation treatment (thick solid line) and after radiation treatment (thin dotted line).

is necessary by means of radiation treatment. The simulation results presented in this work make it possible to formulate recommendations for restoring the current-carrying capacity of an HTSC band with a transverse crack. The width of the crack area, which must be subjected to inhomogeneous irradiation through a mask of variable thickness, must be greater than 24 mm. Hydrogen ion irradiation is most suitable for this purpose.

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Conflict of interest

The authors declare that they have no conflict of interest.

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