INFLUENCE OF FAST NEUTRONS IRRADIATION ON CRITICAL CURRENT EFFECTS IN HTc SUPERCONDUCTORS

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Abstract – Theoretical model of the critical current phenomena in fast neutrons irradiated HTc multi-layered superconductors is presented. The interaction of magnetic pancake type vortices with nano-sized defects caused by neutrons irradiation is considered. The potential barrier for flux creep process is determined and then current-voltage characteristics calculated in static magnetic field. Their behavior versus applied magnetic field is in accordance with experimental data measured on BiSrCaCuO doped Pb superconducting ceramic. For better recognition of the model have been performed calculations of the influence of the fast neutrons irradiationdose on critical current determined from the current-voltage characteristics in the function of applied magnetic field and size of nano-defects created by irradiation.

Keywords: magnetic flux penetration, current-voltage characteristics, critical current, HTc superconductivity

1. Introduction

Investigations of the interaction of fast neutrons with condensed matter bring new basic physical results on the atomic level. However important is also applied meaning of this interaction, considered in the present paper concerning the influence of fast neutrons irradiation on the macroscopic properties of HTc superconductors, to which belong their critical current properties. This topic is especially important for the functioning of superconducting accelerators as Nuclotron-NICA complex [1-4], in which just neutrons irradiation occurs and influences the work of superconducting electromagnets as well as functioning of future current leads constructed by using HTc superconductors. Nano-sized defects created by the fast neutrons irradiation influence also operationof other superconducting accelerators as LHC in CERN and will haveimportant meaning for the work of ITER nuclear reactor. It makes relevant topicdeeper understanding of the interaction nano-defects created in neutrons irradiation process with vortices.Assumed here individual mechanism of interaction makes analysis of this many body problem simpler and allows receive analytical results useful at understanding qualitatively tendencies in considered capturing model.

2. Influence of fast neutrons irradiation on superconductors

In the paper is presented model of the interaction of pancake type vortices appearing in HTc multilayered superconductors with nano-sized defects, created just by the fast neutrons irradiation, as it is shown in Fig. 1 for the system of ordered into square lattice defects. Previous phenomenological pinning models were proposed for instance in [5-6]. There are seen in Fig. 1vacancies generated by fast neutronsirradiation, it is defects of the atomic size, here called nano-defect, while free atoms are shifted then into inter-nodes positions. The scale of this phenomenon is dependent on the energy of neutronsand their concentration, while in the present model we have assumed that each neutron creates single nano-defect of the same nanometer sizein superconducting layer of multilayered structure of HTc materials.

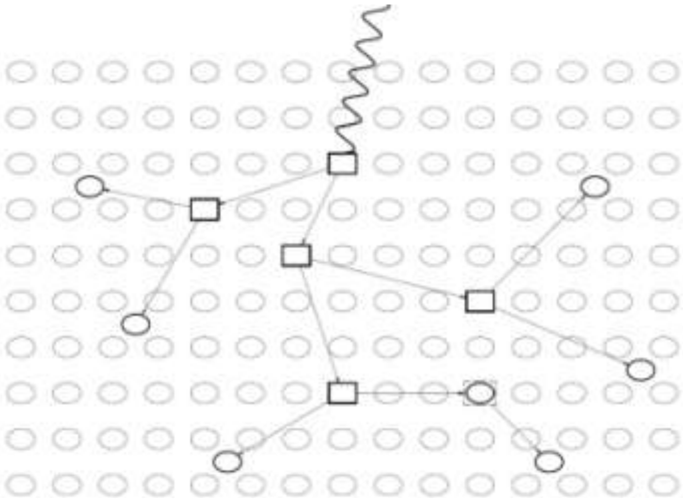

Fig. 1. Mechanism of creation nano-sized defects in the form of (□) vacancies and atomic inter-sitedefects (O) under the fast neutrons irradiation.

Fast neutrons irradiation influences especially properties of low dimensional superconducting materials as 2D type HTc multilayered superconductors but alsoA15 type materials as Nb_3Sn, whose superconducting properties are connected withlinear chains of the transition metals. These materials can be treated therefore as quasi-1D superconductors. Damaging of the chains by the neutrons irradiation, shown in Fig. 2 influences their superconducting properties. Materials crystalizing in this structure, as Nb_3Sn are used continuously in the technology of the superconducting wires and really their superconducting properties, especially critical temperature is sensitive to neutrons and heavy ions irradiation. From other side critical temperature of 3-dimensional type of conductivity NbTi materials is only slightly affected by punctual, irradiation induced defects.

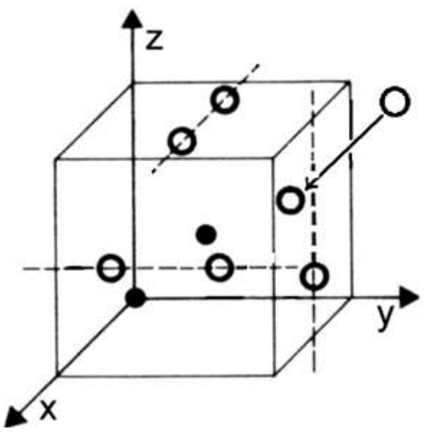

Fig. 2. Elementary cell of Nb_3Sn A15 type superconductor with shown positions of (●) Sn atoms and linear chains of transition metals(**O**), disturbed by the fast neutrons irradiation.

3. Model presentation and results

In the model it has been analyzed energy balance of the system of captured vortex on pinning nano-sized center created by neutrons irradiation [7]. The shift against the initial equilibrium position of the pancake type vortex during the vortex creep process under influence of Lorentz force has been considered taking into enhancement of elasticity energy of vortex lattice disturbed by anchoring process. Determined then energy barrierΔU brings the form:

$$\Delta U = \frac{\mu_o H_c^2 l \xi^2}{2}\left[-\arcsin\ i + \arcsin\frac{d}{2\xi} + \frac{d}{2\xi}\sqrt{1-\left(\frac{d}{2\xi}\right)^2} - i\sqrt{1-i^2}\right] + \alpha\xi^2\sqrt{1-i^2}\left(\sqrt{1-i^2}-2\right) \tag{1}$$

H_c denotes thermodynamic critical magnetic field, $\boldsymbol{\mu_0}$ is magnetic permeability, *d* width of the nano-sized defect. The radius of the vortex core has been approximated by the coherence lengthξ, while *l* is the thickness of the pancake type vortex, related to the thickness of superconducting layer in oxide HTc superconductor, coefficient α describes elasticity energy of the vortex lattice.During the transport current flow of the density *j*, the walls of the pinning potential well *U* described above are tilted by the Lorentz force and modified by elasticity energy of the vortex latticegiven by last term of Eq. 1, which is given in the reduced current representation $i=j/j_c$.j_c is critical current density expressing the transition between flux creep and flux flow states, described by Eq. 2.

$$j_c = \frac{\mu_0 H_c^2}{\pi\xi B}\cdot\frac{S(1-S/a^2)}{a^2} \tag{2}$$

S denotes the defect cross-section, while ***a*** lattice constant of regularly arranged defects, created by neutrons irradiation, B is magnetic induction.

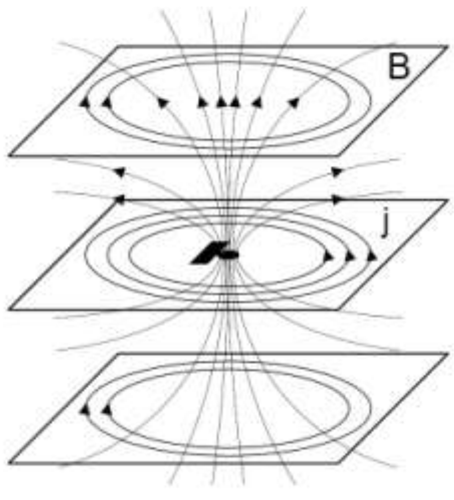

Fig. 3. Schematic structure of multilayered HTc superconductor with captured vortex and distribution of its magnetic flux lines as well asshielding currents in basic layer and surrounding layers.

In Fig. 3 is shown the vortex pinned on nano-defect created by neutrons irradiation in the middle plane and screening currents distribution circulating in the surrounding planes, as well as magnetic induction lines penetrating vortex core. It is seen heretoo electromagnetic coupling of adjacent layers in HTc superconductors, which structure allows to apply in the present paper an approximation of the visible here flat vortices shape. Theopposite direction of currents in nearest planes indicates that the vortices from the same plane repulse, while in surrounding planes attract. Potential barrier given by Eq. 1 allows to determine already the current-voltage characteristics of HTc nano-defected superconductors [8-9], according to the flux creep equation:

$$E = -B\omega a\left[\exp\left[-\frac{\Delta U(0)}{k_B T}\left(1+\frac{j}{j_C}\right)\right]-\exp\left(-\frac{\Delta U}{k_B T}\right)\right] \qquad (3)$$

E is electric field, while ω the flux creep frequency, k_B Boltzmann's constant, T temperature. Eq. 3 being the function of the current density, describes the forward and backward flux creep processes. In Fig. 4 is shown the comparison of the calculated current-voltage characteristics according to the present model with experimental data measured on BiSrCaCuO sample doped with Pb. Measured critical temperature for this sample reached 112 K. Good agreement has been observed in this comparison for various values of applied magnetic field.

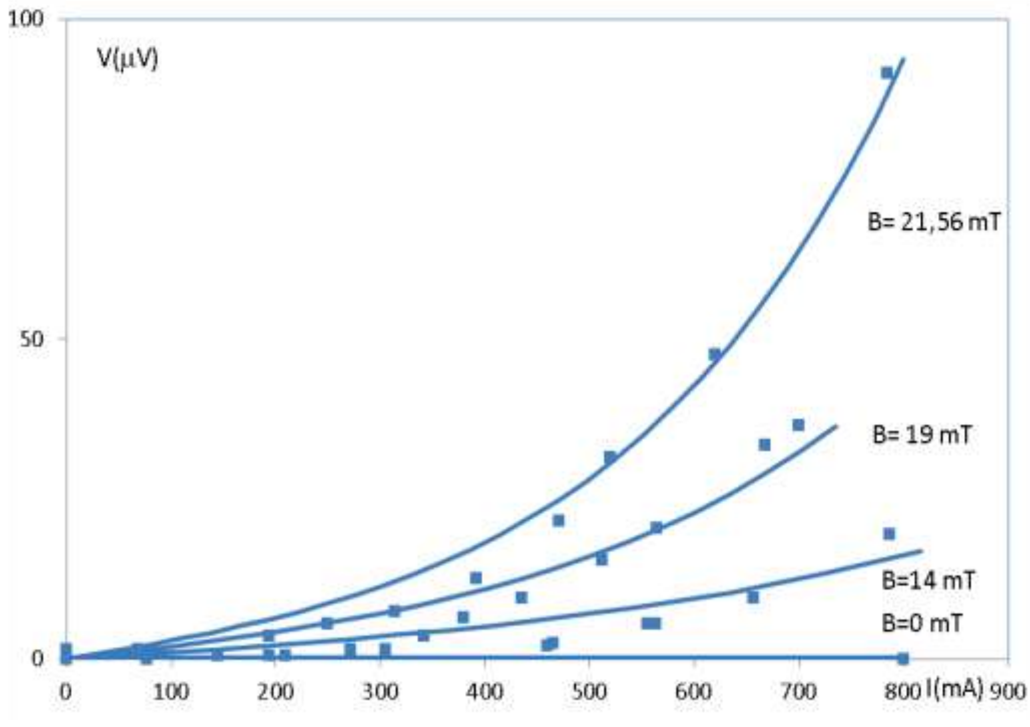

Fig. 4. Comparison of theoretical (lines) and experimental (squares) current-voltage characteristics for BiPbSrCaCuO superconductor at T=77K.

For better recognition of the influence of neutrons irradiation on current-voltage characteristics and then critical current the calculations have been performed in the function of magnetic fieldand sizes of defects. Selected results are shown in Fig. 5-6. Theoretical results presented here indicate strong influence of concentration of fast neutrons irradiation on critical current, initially increasing it which is confirmed by experimental results. Most effective from this point of view are fast neutrons or heavy ions of the energy loss 5-10 keV/nm, which produce the columnar effect, creating the tracks of diameter of 2-8 nm, which case was investigated in the Fig. 6.

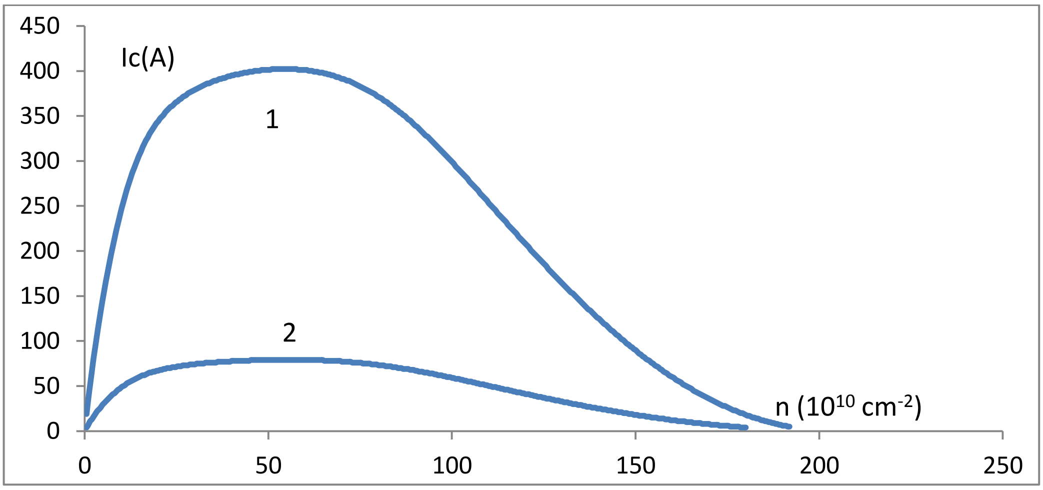

Fig. 5. Calculated dependence of the critical current on the neutrons irradiation concentration in HTc superconducting sample in the function of magnetic induction: (1) B=0.5 T, (2) B= 2T, for T=50 K.

Sometimes there are inserted even at this aim into HTc superconductors uranium atoms U^{235}, which undergo the fission process during neutrons irradiation.Such irradiation creates then new centers of capturing leading initially to enhancement of the critical current, as is shown in Fig. 6, while for higher irradiation intensity the material structure is damaged and critical

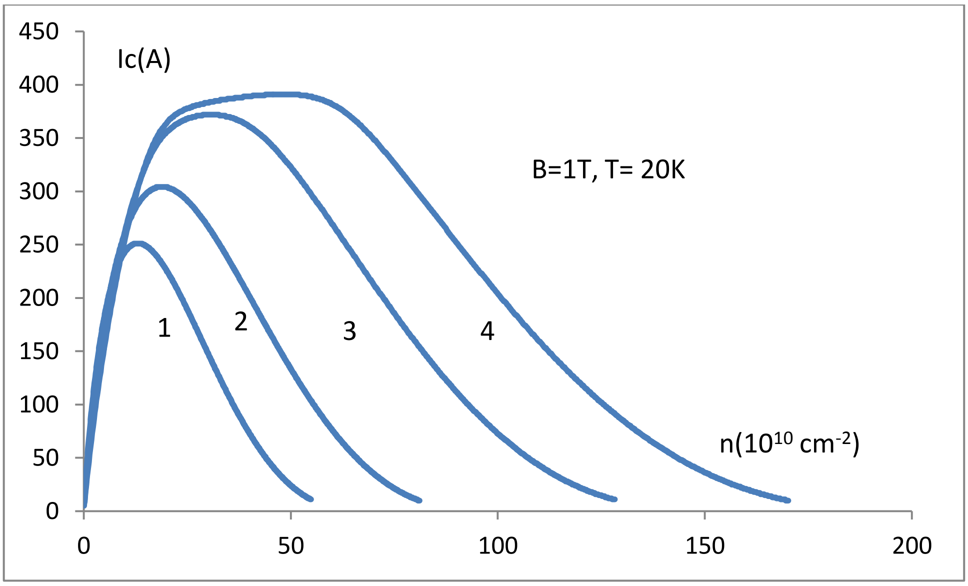

Fig. 6. Calculated influence of the neutrons irradiation dose, creating nano-defects of the dimensions: (1) d =12 nm, (2) 10, (3) 8, (4) 7 nm.

current decreases. Also heavy ions irradiation or gamma quanta should lead to the creation of similar tracks acting as pinning centers.

4. Conclusions

In the paper is performed analysis of the interaction of fast neutrons with HTc superconductors. Influence of the fast neutrons irradiation, creating nano-sized defects on the critical current phenomena in high temperature superconducting materials is considered. It is presented elaborated theoretical model of an interaction of pancake type vortices appearing in multi-layered HTc superconductors with nano-defects. Model is based on an energy balance analysis of the system of the vortex captured on the pinning centre in the function of the shift of the vortex against its equilibrium captured position.The potential barrier is determined, which is applied then for the calculation of the current-voltage characteristics. The influence of magnetic field on their shape is theoretically predicted, which corresponds well to the experimental data measured on the BiPbSrCaCuOHTc superconducting sample. From these characteristics the critical current is calculated in the present model according to the voltage criterion in the function of the fast neutrons irradiation dose versus static magnetic field and defects dimensions. The results of calculations indicate in which way the neutrons irradiation influences variation of critical currentfirstly increasing critical current for undefected initially superconductor, while for higher irradiation dose the sample structure is damaged leading to decrease of the critical current. Experimental situation is briefly described.

5. References

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