INFLUENCE OF FAST NEUTRONS ON CURRENT-VOLTAGE CHARACTERISTICS OF HTc MULTILAYERED SUPERCONDUCTORS

Sosnowski J.

Electrotechnical Institute, Pożaryskiego 28, Warsaw, Poland
sosnowski.jacek@wp.pl

Abstract

Influence of fast neutrons irradiation on the current carrying properties of multilayered HTc superconductors, especially current-voltage characteristics and critical current is analyzed. Genesis of the creation then nano-sized defects acting as capturing centers is given. It is presented detailed analysis of the pinning potential barrier formation caused by these defects in the function of size of the pinning centers for total vortex capturing inside them. The pinning potential is determined and the current-voltage characteristics calculated for current flow in a-b planes of the HTc multilayered superconductors. They are compared with experimental data measured on Bi-based HTc superconducting sample and materials parameters are detected then from fitting experiment with theoretical calculations. The results of the calculations of the critical current dependence on the fast neutrons irradiation is shown, as the function of temperature. Next it is analyzed important case of the influence neutrons irradiation on the current flow in the c-axis direction, determined by the Josephson's tunneling effects. It is shown how fast neutrons irradiation influences so called Swihart's velocity, modifying the Josephson's penetration depth λ_J. Then real velocity of vortex movement in the Josephson's junctions formed between superconducting layers is analyzed, as well as voltage generated by Josephson's current flow through long Josephson's junctions in magnetic field.

Keywords: fast neutrons irradiation, current-voltage characteristics, critical current, HTc superconductivity

1. Introduction

Impact of the fast neutrons irradiation on the current-voltage characteristics of HTc superconductors has important scientific meaning due to specific multilayered crystal structure of HTc superconductors. It has too technical significance because fast neutrons irradiation occurs in modern accelerators with superconducting windings as Nuclotron-NICA in JINR [1-2], acting on these windings. This problem has much wider meaning because it will concern too proper work of superconducting tokamaks, especially ITER, built presently in Cadarache. Neutrons irradiation appearing in superconducting accelerators leads to the generation of nano-sized defects, onto which are captured pancake vortices specific for multilayered structure of HTc superconductors as is shown in Fig. 1. Here are shown too profiles of magnetic field lines and shielding currents in the neighbouring planes. Direction of current lines shows that magnetic vortices in neighbouring planes attract, while in the same plane repulse, which effect indicates on the interlayers interaction, additionally influencing the current-voltage characteristics. Such capturing interaction leads then to creation of the pinning potential barrier, which should pass captured vortex in the flux creep process. Determination of the potential barrier, which is one of the key points of this paper has important meaning for the description of the current-voltage characteristics and then critical current of fast neutrons irradiated HTc superconductors.

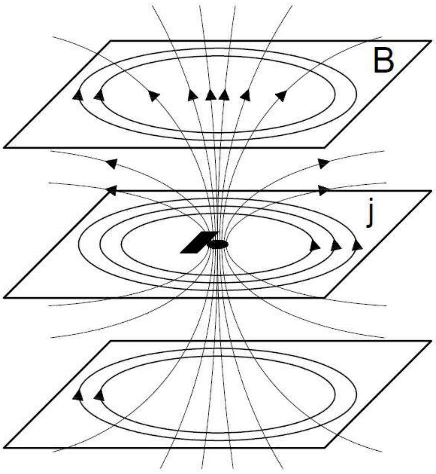

Fig. 1. Pancake vortex captured on nano-sized defect created by fast neutrons irradiation in multilayered HTc superconductor, with shown profiles of magnetic field lines and shielding currents in the neighbouring planes

Fast neutrons irradiation influences too properties of the classical superconductors as Nb_3Sn of A15 type structure, from which are produced windings of modern accelerators. Neutrons irradiation breaks then linear chains of transitions atoms responsible for 1D superconductivity in these materials [3-4].

2. Theoretical analysis of the pancake vortices interaction with nano-defects created by fast neutrons irradiation

In this clause is presented elaborated mathematical model of the formation potential barrier ΔU, determining the probability of occurrence of the flux creep processes forward and backward for currents flowing inside *a-b* planes of HTc multilayered superconductors. Considered geometry of fully pinned vortex is shown in Fig. 2. Symbol d is here nano-defect width, while symbol ξ denotes radius of pancake vortex core, equal to the coherence length, shifted on the distance x. S_4 is part of vortex core outside of nano-defect.

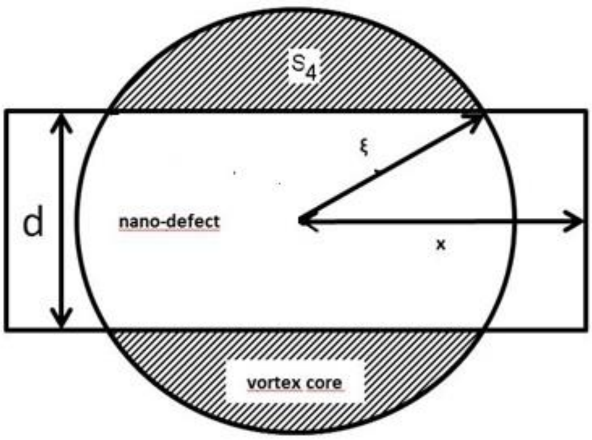

Fig. 2. Considered geometry of vortex captured on nano-defect and meaning of symbols

Total pinning interaction for the system of many captured vortices on created by fast neutrons irradiation nano-defects, is described by free energy F described in the form:

$$F(r_1, r_2, r_3, \dots r_N) = \sum_{i=1}^{N} U(r_i) + \frac{1}{2}\sum_{i\neq j}^{N} F_{inter}(r_i - r_j) - J\emptyset_0 \sum_{i=1}^{N} l_i\, \delta r_i - \sum_{i=1}^{N} \frac{C\delta {r_i}^2}{2} V_i \quad (1)$$

Parameter U is here pinning potential connected with individual interaction of nano-scaled defect, created by fast neutrons irradiation with magnetic pancake shape vortex, while F_{inter} energy of electromagnetic interaction between vortices at positions r_i and r_j. Summation concerns all vortices, each of them transports flux $\emptyset_0$. Third term on right side of Eq. 1 is connected with Lorentz force acting on the length l_i and shifting vortex initially being in the position r_i on the distance δr_i in the flux creep process, J is transport current density. Last term describes energy connected with the elasticity forces of the pancake vortices lattice. V_i is volume of deformed lattice during capturing of i-th vortex, while C elastic spring constant of vortex lattice.

In an approximation of individual interaction vortex-pinning center and applying scaling law of vanishing pinning potential outside of vortex core the energy of the initial state for fully captured pancake vortex, shown in Fig. 2 is given by following relation for $d<2\xi$:

$$U(0) = \frac{-\mu_0 H_c^2 l}{2}\left[2\xi^2 \arcsin\frac{d}{2\xi} + d\sqrt{\xi^2 - \frac{d^2}{4}}\right] \quad (2)$$

During the shift of the pancake vortex core outside of the nano-sized defect limited by the following range of the vortex deflection:

$$-\xi \le x \le -\xi\sqrt{1-\left(\frac{d}{2\xi}\right)^2} \quad (3)$$

pinning potential $U(x)$ changes according to the expression:

$$U(x) = \frac{\mu_0 H_c^2 l}{2}\left[\begin{array}{l} -2\xi^2 \arcsin\frac{d}{2\xi} + \\ \xi^2 \arcsin\frac{\sqrt{\xi^2 - x^2}}{\xi} - d\sqrt{\xi^2 - \frac{d^2}{4}} \\ + x\sqrt{\xi^2 - x^2} \end{array}\right] \quad (4)$$

H_c denotes here the thermodynamic critical magnetic field, l is thickness of superconducting layer, d width of nano-defect, ξ coherence length. Potential barrier ΔU arises then, which taking into account the Lorentz forces potential, in the current representation brings the form:

$$\Delta U(i) = \frac{\mu_0 H_c^2}{2} l\xi^2 \left(\begin{array}{c} -\arcsin(i) + 2arcsin\left(\frac{d}{2\xi}\right) + \frac{d}{\xi}\sqrt{1-\left(\frac{d}{2\xi}\right)^2} \\ +i\left(\frac{\pi}{2} - 2arcsin\left(\frac{d}{2\xi}\right) - \frac{d}{\xi}\sqrt{1-\left(\frac{d}{2\xi}\right)^2} - \sqrt{1-i^2}\right) \end{array}\right) \quad (5)$$

$i=j/j_C$ is reduced transport current density j, to j_C critical current density. In derivation of Eq. 5 the renormalization procedure has been applied, similar to used in the collective flux creep theory, assuring the vanishing potential barrier at critical current density.

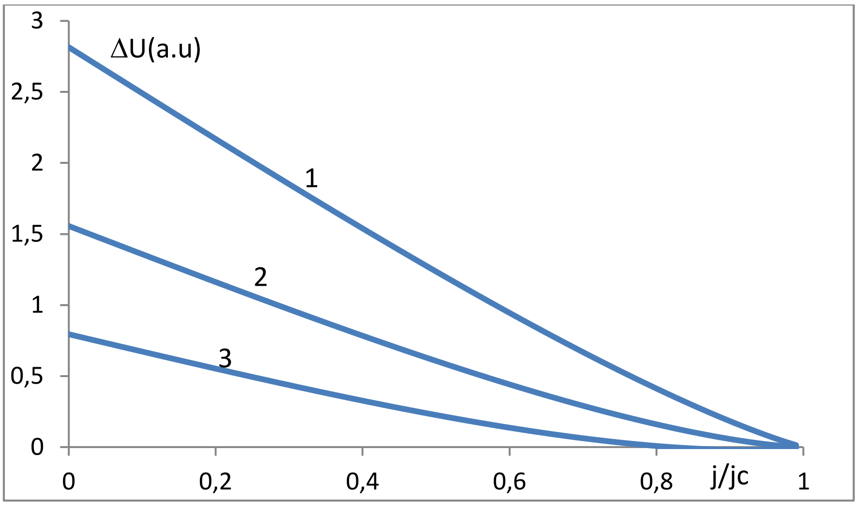

Fig. 3. The dependence of the potential barrier ΔU on reduced current density j/j_C as the function of the reduced size of nanoscale defect: (1) $d/2\xi = 0{,}8$, (2) 0,4, (3) 0,2

In Fig. 3 are presented the results of calculations according to this model potential barrier ΔU in arbitrary units in the function of reduced current density for various dimensions of pinning centers, which correspond to various energies of irradiating fast neutrons and heavy ions in superconducting accelerators.

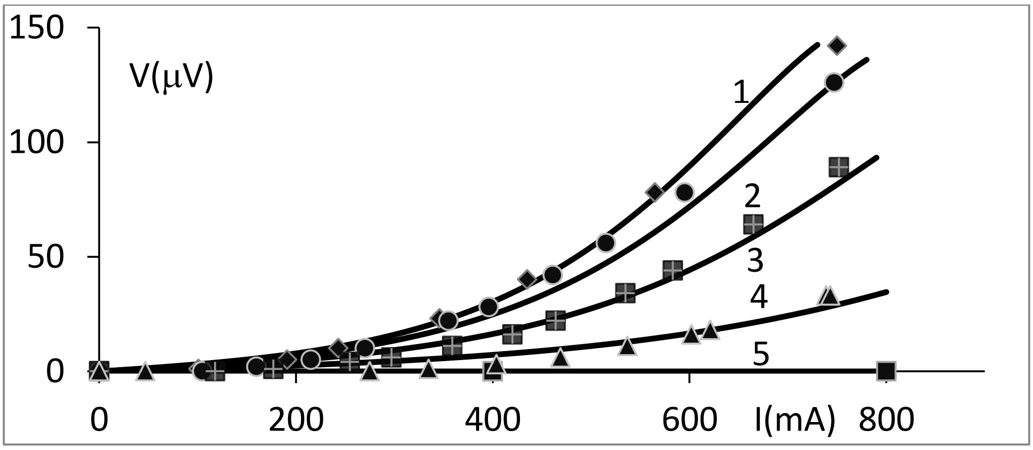

Fig. 4. Comparison of theoretical and experimentally measured current-voltage characteristics for $Bi_{1.6}Pb_{0.3}Sr_2Ca_2Cu_{3.06}O_8$ ceramic superconductor at liquid nitrogen temperature for various magnetic fields: (1) B=0, (2) 13,5 mT, (3) 24 mT, (4) 33 mT, (5) 35 mT.

3. Analysis of current-voltage characteristics and influence of irradiation on critical current

Height of the potential barrier determines the frequency of the flux creep processes in which during current flow perpendicular to magnetic field magnetic vortices are jumping over this barrier and generate electric field. It means that current-voltage characteristics are then created. Calculations of them have been performed as the function of magnetic field and compared with experimental data measured at liquid nitrogen temperature on $Bi_{1.6}Pb_{0.3}Sr_2Ca_2Cu_{3.06}O_8$ ceramic superconductor. The results shown in Fig. 4 indicate on good agreement between model and experiment. In the calculation procedure have been used as fitting parameters average size of the intrinsic defects acting as the pinning centers and their concentration. For data shown in Fig. 4 the values of these parameters were equal: size of defect $d = 12\ nm$ and inherent concentration of defects in the sample $n = 3\cdot 10^{10}\ cm^{-2}$.

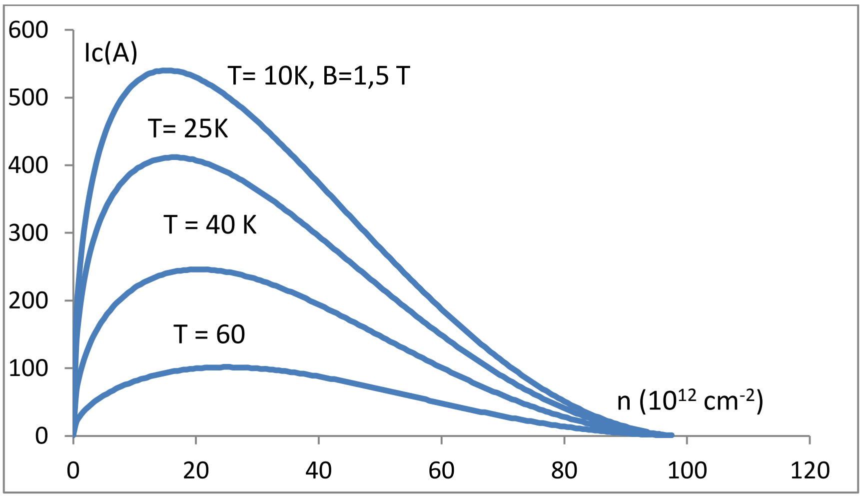

Fig. 5. Theoretical dependence of critical current on fast neutrons irradiation dose versus temperature

In Fig. 5 are shown on the other hand the results of calculations the influence of temperature on critical current versus neutrons irradiation concentration. Theoretically predicted initial increase of critical current with irradiation dose is in qualitative agreement with experimental

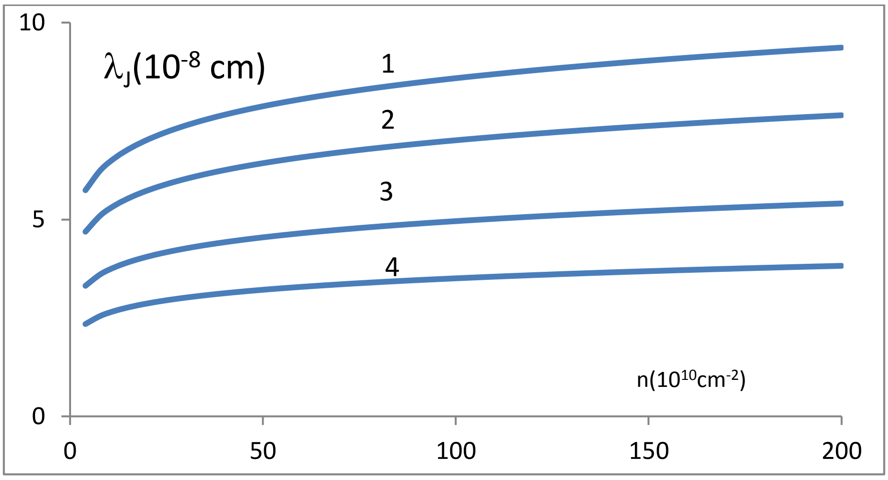

Fig. 6. Calculated dependence of Josephson's penetration depth λ_J on fast neutrons irradiation dose versus λ_L London's penetration depth in pure limit: (1) $\lambda_L = 10^{-5}$ cm, (2) $\lambda_L = 2\cdot 10^{-5}$ cm, (3) $\lambda_L = 4\cdot 10^{-5}$ cm, (4) $\lambda_L = 6\cdot 10^{-5}$ cm

data concerning the influence of protons irradiation on critical current of Nb_3Sn low temperature wires [5]. The decrease of critical current in high regime of neutrons irradiation dose is connected with damaging the crystal structure of the superconductor, which effect plays then essential function. For lower irradiation dose increase of flux pinning is dominating.

As it will be shown now neutrons irradiation influences too the inter-plane Josephson's current-voltage characteristics. Then the movement of the magnetic vortex arising between the covers of Josephson's junction appears and electric field is generated. Velocity of this movement is dependent on so called Swihart velocity: $\lambda_J \cdot \omega_p$. ω_p is here Josephson's plasma frequency, while λ_J Josephson's penetration depth in multilayered HTc superconductor

$$\lambda_J = \sqrt{\frac{\phi_0}{2\pi\mu_0(d_i+2\lambda_d \,\mathrm{cth}\frac{d_s}{\lambda_d})j_c}} \qquad (6)$$

related to London's penetration depth in the dirty limit λ_d given by the formula $\lambda_d = 0{,}615\lambda_L\sqrt{\frac{\xi_0}{a}}$. Φ_0 is flux quantum, d_i thickness of buffer layer, d_s thickness of superconducting layer. λ_d for dirty superconductors is function of mean free electron path, approximated here as lattice constant $a = 1/\sqrt{n}$ of regularly ordered nano-defects, while n is neutrons irradiation dose surface concentration. Results of calculations the influence of neutrons irradiation dose on Josephson's penetration depth λ_J in the function of London's penetration depth in pure case λ_L is presented in Fig. 6. This relation according to previous considerations influences the real vortex velocity and in this way the current-voltage characteristics for perpendicular direction of current to superconducting layers.

4. References

[1] N.N. Agapov, J. Sosnowski, Y.A. Mitrofanova, Cryogenic Sources of Irradiation, Electrotechnical Institute Works, 256, p. 369-377, 2012

[2] H. Khodzhibagiyan, A. Bazanov et al, Experimental Study of Superconducting Magnets for the NICA Accelerator Complex, The 12-th Cryogenics Conference Proceedings, Dresden, p. 53-58, 2012

[3] J. Sosnowski, *Superconducting materials: modelling and properties*, Electrotechnical Institute Book Publisher, Warsaw, p. 1-200, 2008 (in polish)

[4] J. Sosnowski, *Superconductivity: properties and applications*, Electrotechnical Institute Book Publisher, Warsaw, p. 1-208, 2003 (in polish)

[5] T. Spina, C. Scheuerlein, D. Richter, L. Bottura, A. Ballarino, R. Flükiger, IEEE/CSC & *ESAS Superconductivity News Forum (global edition)*, January (2014)