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INFLUENCE OF THE BEAM INDUCED IRRADIATION ON THE CRITICAL CURRENT PHENOMENA IN SUPERCONDUCTING ELEMENTS

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Abstract

In the constructions of the modern accelerators, of free electrons as is in the case of FEL-s or ionized particles as in LHC working in CERN, the ionized beam is guided by the magnetic field generated in electromagnets, more and more frequently wound up using superconducting wires. The beam's induced irradiation arises in these accelerators, which influences the properties of the superconducting elements, as wires, current leads or shields, which issue is discussed in the present paper. It is shown in which way the irradiation damages the subtle structure of superconducting materials, leading to columnar defects formation in 2D HTc superconductors. It is analysed theoretically how these nano-structural defects influence the critical current properties of the superconducting materials. In the paper is developed energetic approach, of the Ginzburg-Landau type in lowest order approximation, to the process of capturing of the magnetic pancake vortices in HTc superconductors. Various initial positions of the captured vortices are analysed, movement of them through the potential barrier leads to electric field generation. The dependence of the potential barrier on transport current is analysed. Influence of the irradiation effects on the current-voltage characteristics of superconductors are investigated then and critical current values detected, as the function of irradiation intensity, size of created then nano-defects and physical parameters such as critical temperature and elasticity forces. This analysis has therefore physical meaning and should be useful also for prediction the proper work conditions of accelerators with superconducting elements.

INTRODUCTION

Nowadays it is intensively developed nuclear accelerators technology, to which belong also linear constructions of the FEL-s type. In these facilities more and more frequently there are applied superconducting materials [1], including the HTc superconductors too. They are used in solenoids generating magnetic field, forming the electron beam at FEL-s facilities but also as current leads, resonant cavities, shields and various correctional coils, guiding the beam along the appropriate track. Before applying these new materials in accelerating machines, we should therefore to establish the sensitivity of their properties to irradiation, which appears especially in nuclear accelerators. This issue is just the subject of paper.

In the paper is discussed how irradiation arising in modern accelerating devices, caused by primary beam of ionized particles circulating in synchrotrons or electrons beam in linear FEL-s machines, will influence the current carrying properties of superconducting elements. For the case of FEL-s linear accelerators beside primary beam, in which irradiation is created by moving electrons, occur too the secondary beams, composed beside all from neutrons, γ-rays, positrons and photonic bunches. They are created during collisions of electrons with walls of accelerators.

These investigations are especially relevant for HTc superconductors, which are characterised by the subtle planar structure of 2D type, very sensitive therefore to the defects concentration. These defects are created just by the irradiation caused by the ionic or electrons beam guided in accelerators lines. For that 2D structure the ionic bombardment can lead to the columnar defect creation. At an aim of describing mathematically the influence of the irradiation, creating the nano-sized defects on superconducting elements, it has been developed the model oriented on the energy variation analysis during the dynamic interaction of nano-defects with the magnetic vortices. They are generated by external magnetic field or current flow. This general model has been applied to the defects induced by irradiation as well as mechanically formed defects, such as dislocations arising especially during the winding procedure of the superconducting coils.

BEAM IRRADIATON EFFECTS IN SUPERCONDUCTORS

Irradiation in superconducting accelerators although caused by rather small volume of ionized beam has significant influence on superconducting elements just because the superconductivity is very subtle effect. It is second order effect in perturbation range, which for many years was not explained theoretically therefore by scientists. So it can be expected that irradiation of the superconducting materials will have large influence on their properties, which concerns especially the low dimensional superconductors as two-dimensional HTc superconductors based on CuO_2 planes but also will apply to the quasi one–dimensional A15 type superconductors. This class of materials is characterized by three linear, perpendicular chains of the atoms of the transition metals. Beam irradiation of these materials, for instance Nb_3Sn wires, will lead to damage of the chains responsible for their superconducting properties. Critical temperature is then really decreasing. Also HTc superconductors, reaching already room temperature are more and more attractive from the point of view of application them in nuclear physics devices. World record of the critical temperature belongs now to the hydrogen sulphide and exceeds already room temperature. T_c = 14 °C at H_2S + CH_4, unfortunately under very high pressure at 267 GPa. But this world record for highest T_c should be still confirmed. Second on this list is lanthanum - hydrogen compound of the composition LaH_{10} at pressure of the 170 GPa, with critical temperature of -23 °C [2]. To the

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power applications of the superconductors in nuclear physics, belong nuclear accelerators, as FEL-s linear free electron laser, including built now in Poland PolFEL, in which construction appears the direct exposition of the superconducting elements to the ionizing beam irradiation. It is primary ionic beam or as in the case of FEL-s facilities beside initial electrons beam arise too the secondary beams composed from neutrons, ions, positrons, γ-rays, interacting with the superconducting elements creating nano-defects. Defects of the dislocation type are created too during winding up of the superconducting coils, leading to bending strain, this is shown in the chapter about I-V characteristics. The nano-defects act as the pinning centers capturing the pancake type vortices as is shown in Fig. 1 for layered superconductors or linear flux lines for usual low temperature superconductors. This interaction vortices with nano-sized defects is described by the system energy F, described by the following formula:

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

Equation (1) describes the energy of N magnetic pancake type vortices, specific for layered superconductors, captured on the pinning centers at positions $r_1,..r_N$. U is pinning potential of the captured pancake vortices, shown in Fig. 1, while summation runs over N captured magnetic vortices, each of them is transporting quantized magnetic flux $\Phi_0 = 2{,}07\cdot 10^{-15}$ Wb. Second term in Eq. (1) describes the contribution to system energy of the inter-vortices interaction, while third expression is connected with Lorentz force, where J is electric current density. Last part in Eq. (1) determines the increase of the elasticity energy of the vortices lattice, during the shift of the vortex from equilibrium position at the process of the magnetic flux capturing. V_i describes connected with this deformation volume, while C is spring constant of the vortices lattice.

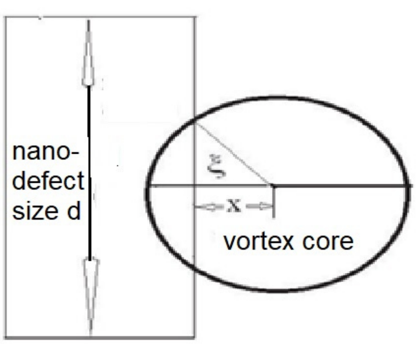

Figure 1: Schematic view of the capturing of magnetic pancake vortex on nano-sized defect of the width d>2ξ.

In Fig. 1 is shown the capturing of magnetic pancake vortex by nano-sized defect of the width d > 2ξ, where ξ is the coherence length. The movement of the vortex against capturing forces, caused by the Lorentz force leads to the potential energy U(x) of the system increase according to the relation (2), while parameter x here denotes the shift of the vortex against its initial position:

$$U(x) = \frac{\mu_0 H_c^2}{2} l\xi^2 \langle arcsin\frac{x}{\xi} - \frac{\pi}{2} + \frac{x}{\xi}\cdot\sqrt{1-\left(\frac{x}{\xi}\right)^2}\rangle - jB\pi\xi^2 lx \quad (2)$$

In Eq. (2) H_c is thermodynamic critical magnetic field, μ_0 magnetic permeability of vacuum, while l the thickness of the superconducting layer. Existence of the potential energy U(x) varying with the vortex deflection from the initial position against the capturing center, according to the Lorentz force leads to the potential barrier ΔU uprise, which should pass vortex in the flux creep process. The potential barrier arising then reaches the maximum for the vortex deflection $x = x_m$, where x_m is given by the relation joining the cartesian units with current representation:

$$x_m = \xi\sqrt{1-\left(\frac{I}{I_c}\right)^2} \quad (3)$$

The transformation to the current representation brings new expressions for single vortex potential barrier ΔU:

$$\Delta U(i) = \frac{\mu_0 H_c^2}{2} l\xi^2 \langle arcsin\frac{d}{2\xi} - arcsin i + \frac{d}{2\xi}\cdot \sqrt{1-\left(\frac{d}{2\xi}\right)^2} - i\left[\sqrt{1-i^2} + arcsin\frac{d}{2\xi} - \frac{\pi}{2} + \frac{d}{2\xi}\cdot \sqrt{1-\left(\frac{d}{2\xi}\right)^2}\right]\rangle + \propto \xi^2\left(\sqrt{1-i^2}-2\right)\cdot\sqrt{1-i^2} \quad (4)$$

$$\Delta U(i) = \frac{\mu_0 H_c^2}{2} l\xi^2 \langle arcsin\frac{d}{2\xi} - arcsin\, i + \frac{d}{2\xi}\cdot\left(1+\sqrt{1-\left(\frac{d}{2\xi}\right)^2}\right) + i\left[-\sqrt{1-i^2} - arcsin\frac{d}{2\xi} + \frac{\pi}{2} - d/2\xi\cdot\left(1+\sqrt{1-\left(\frac{d}{2\xi}\right)^2}\right)\right]\rangle \quad (5)$$

$$\Delta U(i) = \frac{\mu_0 H_c^2}{2} l\xi^2 \langle 2arcsin\frac{d}{2\xi} - arcsin\, i + \frac{d}{2\xi}\cdot\sqrt{1-\left(\frac{d}{2\xi}\right)^2} + i\left[-\sqrt{1-i^2} - 2arcsin\frac{d}{2\xi} + \frac{\pi}{2} - d/\xi\cdot\sqrt{1-\left(\frac{d}{2\xi}\right)^2}\right]\rangle \quad (6)$$

In Eq. (4) $i = I/I_c$ is reduced transport current and has been considered here case of half-captured initially vortex on beam's irradiation created nano-defect. As well as it has been included too term describing the elasticity forces described by parameter α proportional to spring constant C from Eq. (1). In Eq. (5) is given case of temporary initially captured vortices, while in Eq. (6) of totally captured, respectively. In half captured vortex is still kept the structure of the circulating currents in the vortex, while fully captured vortex configuration is most favourable energetically [3]. Figure 2 presents the variation with current height of the potential barrier, which should pass vortex in the flux creep process movement for these cases, it is for totally captured initially vortex, temporary and half pinned respectively, on beam's irradiation created nano-defects.

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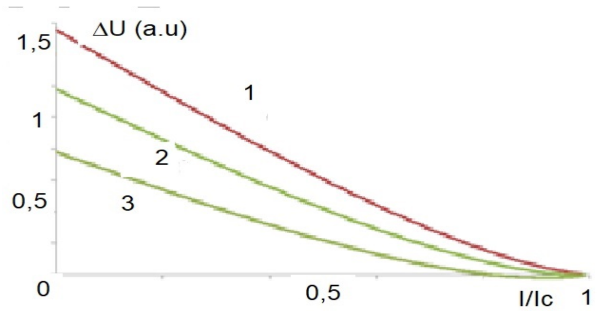

Figure 2: Dependence of the potential barrier ΔU on reduced to critical, transport current, for various initial captured vortex positions: (1) $x_0 = -\xi$ (fully captured), (2) $x_0 = -\xi/2$ (partly captured), (3) $x_0 = 0$ (half captured).

ANALYSIS OF SUPERCONDUCTING I-V CHARACTERISTICS

Discussed in the previous point potential barrier height ΔU has crucial meaning for determining the I-V characteristics and then critical current I_c of the superconducting materials. Useful at that aim is the general relation (7), describing the generated electric field E for the forward and backward flux creep processes, as the function of $i = I/Ic$, the reduced to critical transport current:

$$E = B\omega\, a \left(e^{\frac{-\Delta U(0)(1+i)}{k_B T}} - e^{\frac{-\Delta U(i)}{k_B T}} \right) \quad (7)$$

B is here applied magnetic induction, a distance between nearest capturing pinning centers, ω flux creep process frequency, k_B Boltzmann's constant, T temperature.

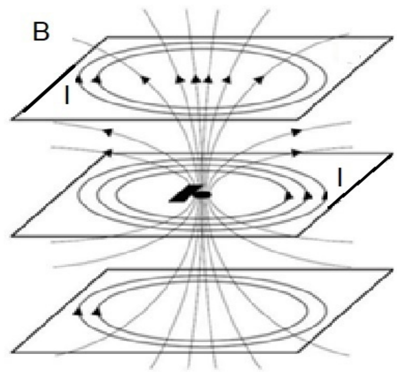

Figure 3: View of the vortex - pinning center interaction in the multi-layered superconductors.

It should be noticed that for some especial structures, as for instance 2D high temperature superconductors it can be taken into account too the interlayered vortex – pinning center interaction, as it shows Fig. 3, giving additional contribution to system energy, described by Eq. (1). From Fig. 3 follows that circulating currents in neighbouring layers have opposite direction, which means that interlayered vortices attract. In the same layer the vortices generate parallel magnetic field which results in the repulsion effect and forming the hexagonal vortex lattice.

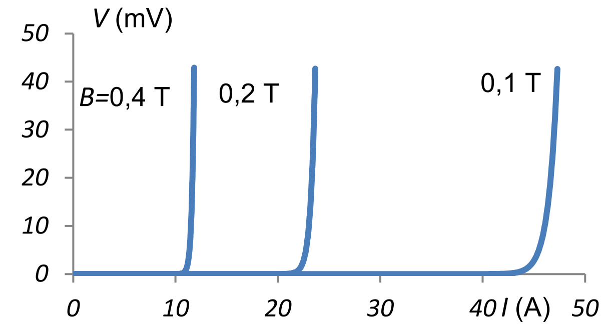

Figure 4: Calculated the current-voltage characteristics of subjected to bending strain HTc superconductor, as the function of the static, external magnetic induction.

The results of the calculations influence on the current-voltage characteristics of bent HTc superconductors, of the static magnetic field are shown in Fig. 4 and predict rapid decrease critical current, as is really observed. It should be noticed also that above model allows too predict current-voltage characteristics in dynamic case, as it shows Fig. 5.

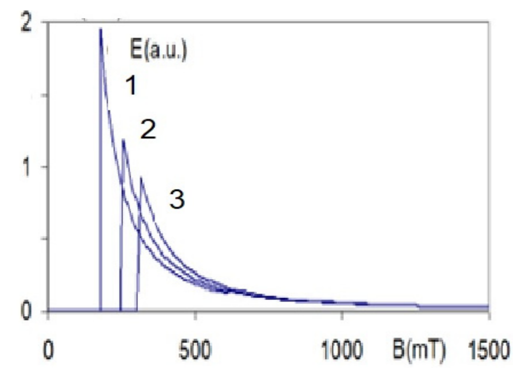

Figure 5: Theoretically calculated influence of the magnetic field sweep rate on the dynamic current-voltage characteristics anomalies in varying magnetic field: (1) 20 mT/s, (2) 30 mT/s, (3) 45 mT/s.

In Fig. 5 are presented calculated dynamical anomalies of the current-voltage characteristics in HTc superconducting slab in the slowly varying magnetic field. These anomalies observed us previously on various HTc superconductors as YBaCuO, HoBaCuO, BiSrCaCuO ceramics are sensitive to the magnetic field sweep rate, current amplitude, temperature. Generally they depend on sample quality and velocity of the magnetic flux diffusion into superconductors, so can be used in principle as superconducting sensor for measuring the electromagnetic properties of superconducting materials.

Presented in previous part static model allows also to determine the materials parameters of the investigated superconductors. At that purpose [3] fitting procedure of experimental and calculated I-V characteristics has been performed and the surface concentration of the inherent defects established as equal to $3{\cdot}10^{10}$ cm^{-2}, for sintered PbBiSrCaCuO superconductor. Such comparison can be used as new method of superconductors characterisation, allowing just to determine this way their state of purity.

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INFLUENCE OF BEAM RADIATION ON Ic

Discussed potential barrier ΔU has crucial meaning for determining the current-voltage (I-V) characteristics and then critical current I_c of the superconducting materials, because height of ΔU determines the probability of the flux creep process. In this process captured vortex under influence of the Lorentz force and current flow should pass just this potential barrier, generating electric field. For better understanding of this effect the critical current has been determined as function of various physical parameters. In Fig. 6 is presented the influence on critical current of the nano-defect size *d* as the function of the nano-defects concentration. It is observed here that for low irradiation generating nano-defects the critical current initially increases, reaches the maximum, while then starts to decrease. This dependence is in agreement with physical interpretation, in which initially created defects act as new pinning centers, while for higher irradiation intensity nano-defects begin above all to damage the structure of superconductors. Similar course appears at the dependence of the critical current as the function of the irradiation intensity versus the critical temperature of superconductors shown in Fig. 7. In Fig. 8 is presented the dependence of the critical current on the nano-defects concentration, proportional to beam's irradiation intensity. It is shown here the influence of the elasticity constant of vortex lattice on the critical current.

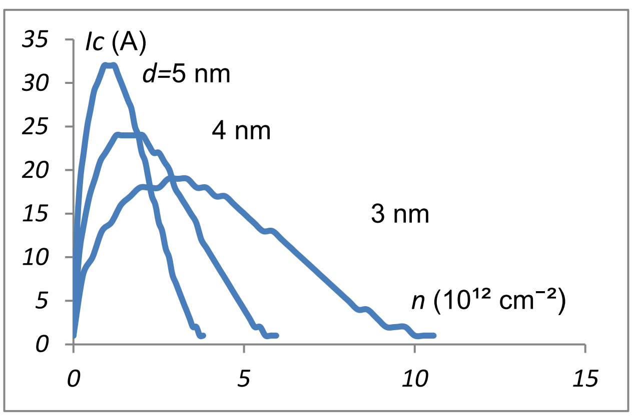

Figure 6: The influence of the nano-defect size on the dependence of the critical current versus beam's created irradiation defects surface concentration.

As it follows from runs shown in Fig. 8 the elasticity constant determining the stiffness of vortices lattice α has negative influence on the critical current. It is in agreement with physical interpretation of this phenomenon, indicating that for rigid lattice the vortices are strongly kept in regular hexagonal vortices array, so their capturing will be weak and therefore critical current appropriately smaller.

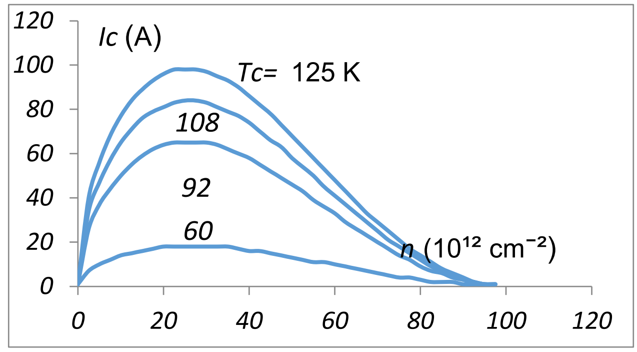

Figure 7: The influence of the critical temperature on the dependence of the critical current as the function of the beam's irradiation created defects surface concentration.

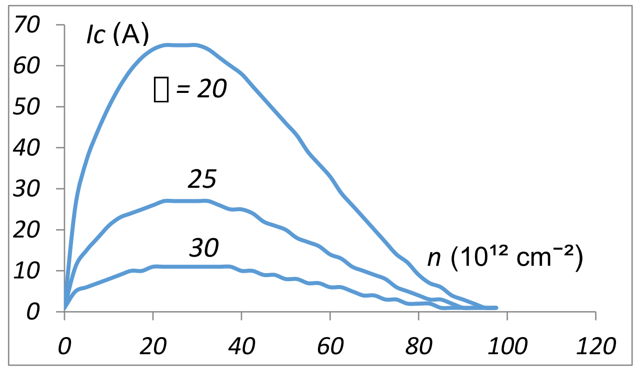

Figure 8: The influence of the vortex lattice elasticity constant α (10^{-5} eV/m^2), proportional to spring constant C, on dependence of the critical current, versus beam's created irradiation defects surface concentration.

CONCLUSIONS

In the paper is discussed important from scientific and applied point of view effect of influence beam's irradiation on the current carrying properties of the superconducting elements, more and more frequently used in modern accelerators. The creation of the nano-sized defects has been then considered and their influence on the critical current of superconductors. The energetic approach has been performed, which allowed to determine the height of potential barrier and critical current of irradiated samples.

REFERENCES

[1] J. Sosnowski, *Superconducting cryocables*, Book Publisher of Electrotechnical Institute, in Polish, pp. 1-100, 2012.

[2] M.I. Eremets *et al.,* "High-Temperature Superconductivity in Hydrides: Experimental Evidence and Details", *J. Supercond. Novel Magn.,* vol. 35, pp. 965–977, 2022. doi:10.1007/s10948-022-06148-1

[3] J. Sosnowski, "Analysis of electric current flow through the HTc multilayered superconductors", *IOP Conf. Ser.: Mater. Sci. Eng.,* vol. 113, p. 012019, 2016. doi:10.1088/1757-899X/113/1/012019