Interaction of Fast Neutrons with HTc Superconductors – Critical Current Effects

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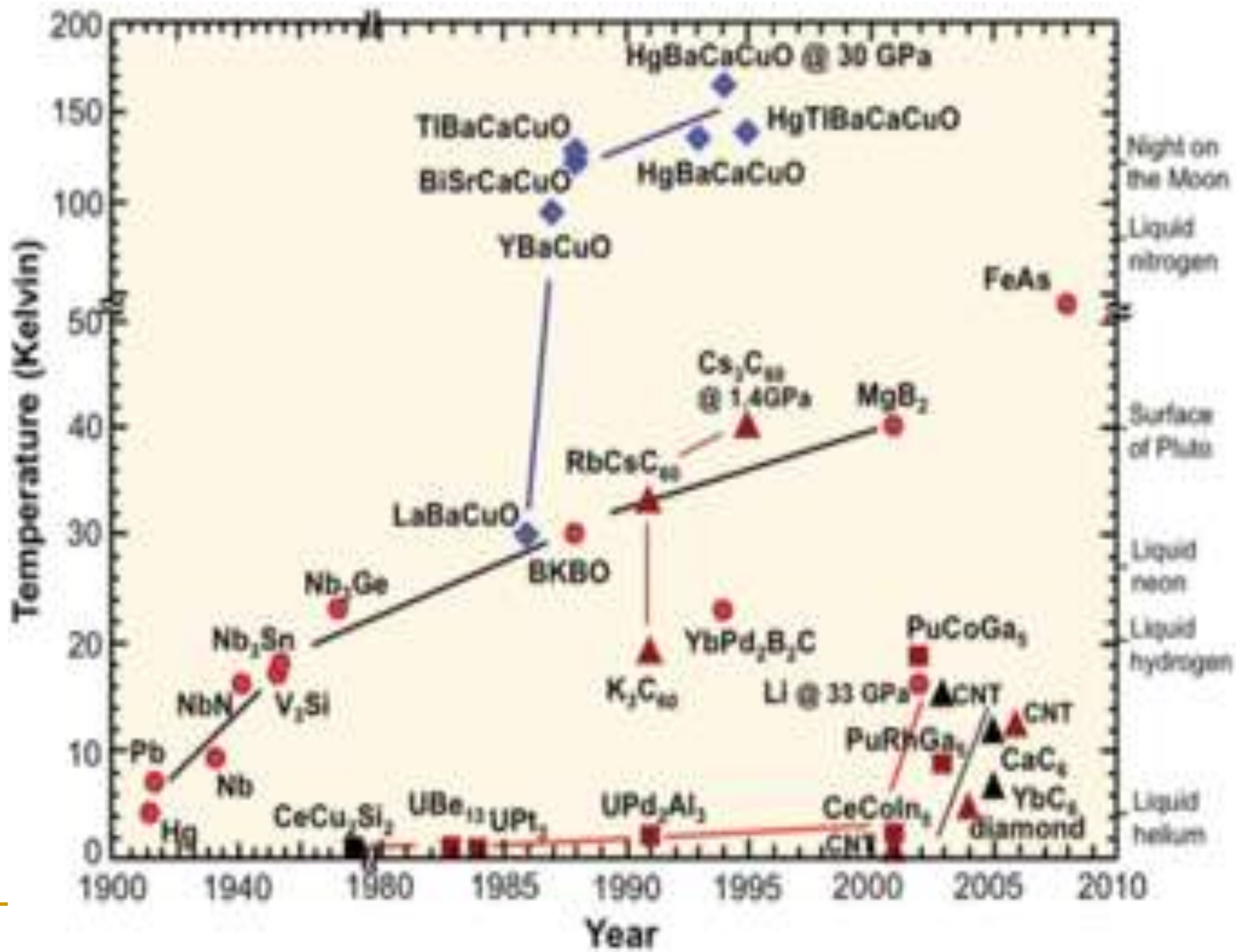
Summary

- Investigations of the **interaction of fast neutrons** with the condensed matter brings new basic physical results on an atomic level. However important is also applied meaning of this interaction, it is influence neutrons irradiation on the critical current phenomena in HTc superconductors, used for instance in nuclear acelerators. Theoretical model of the critical current phenomena under this irradiation is proposed based on an analysis of the interaction of nano-defects created by fast neutrons irradiation with pancake vortices appearing in HTc multi-layered superconductors. The static and dynamic magnetic field cases have been regarded and current-voltage characteristics calculated then. Influence of fast neutrons irradiation on the pinning forces and flux trapping is also considered in paper.

Introduction

- Superconductors, including HTc materials are more and more widely applied in experimental devices, especially of modern, nuclear physics. During the work of nuclear accelerators arises however the irradiation of fast neutrons, which falling on the superconducting windings, creates nano-sized defects, influencing their properties, including critical current in magnetic field.

Timeline of superconducting materials



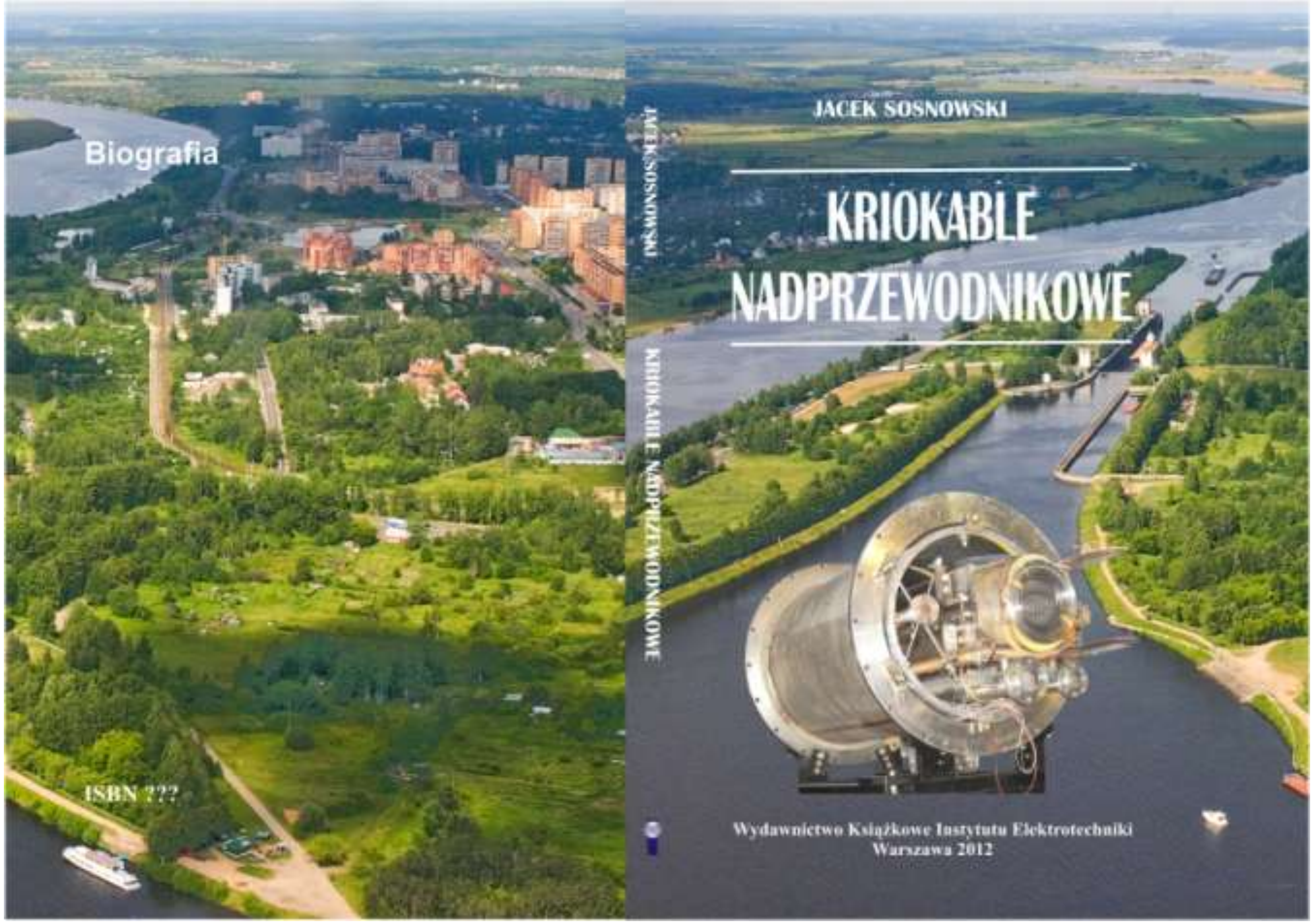
Odolanów near Wrocław – largest resources of gas helium in EU

Helium liquefier

Electrotechnical Institute main building in Warsaw

Model of cryocable and superconducting fault current limiter holder

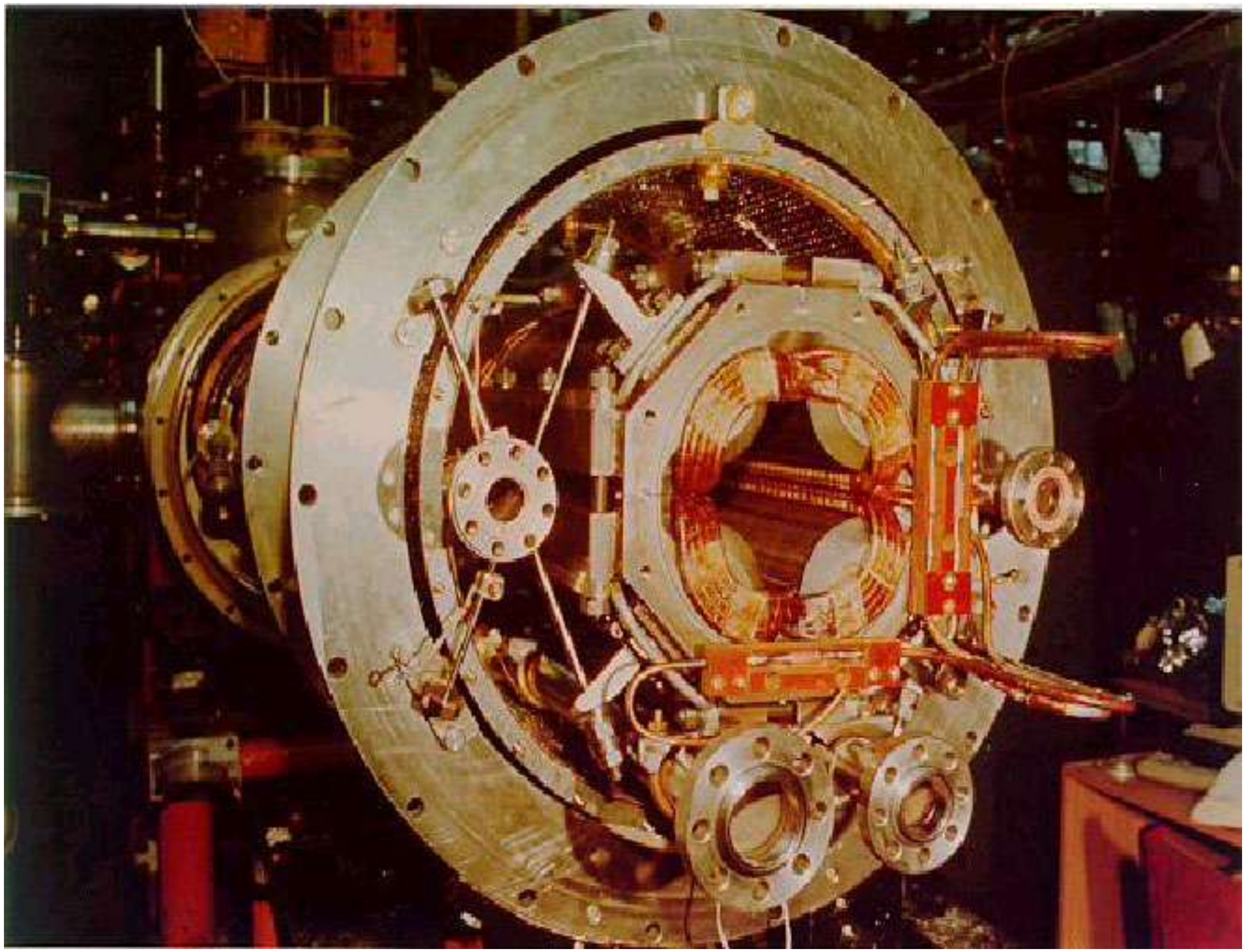
Book „Superconducting cryocables” prepared during my stay in JINR



In JINR superconductors are applied mainly in accelerator Nuclotron and in starting project NICA, and in current leads

Dipole type Nuclotron electromagnet

Quadrupole type Nuclotron electromagnet



The scheme of the interaction of the fast neutrons with the crystal lattice leading to the nano-defects creation

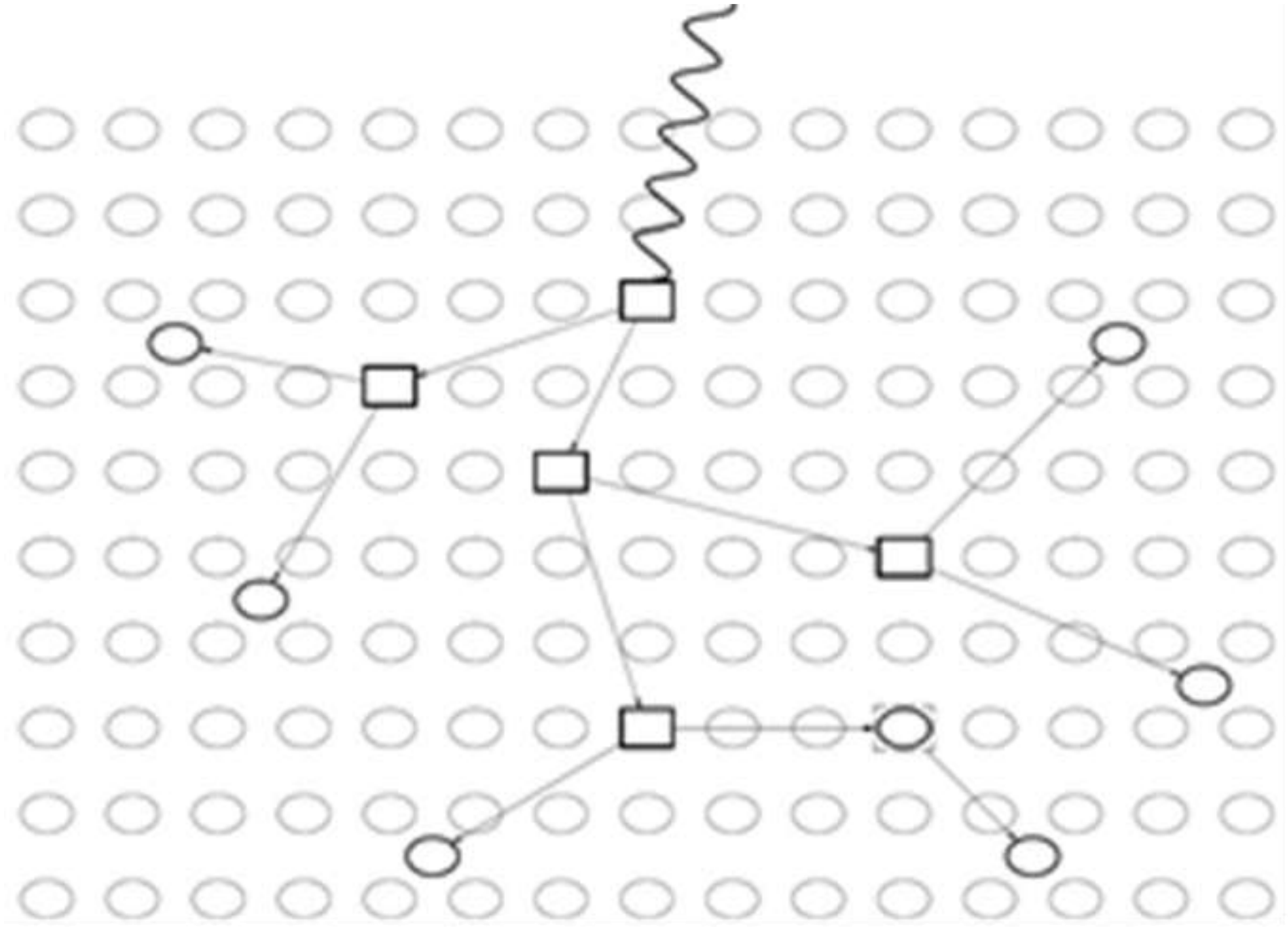
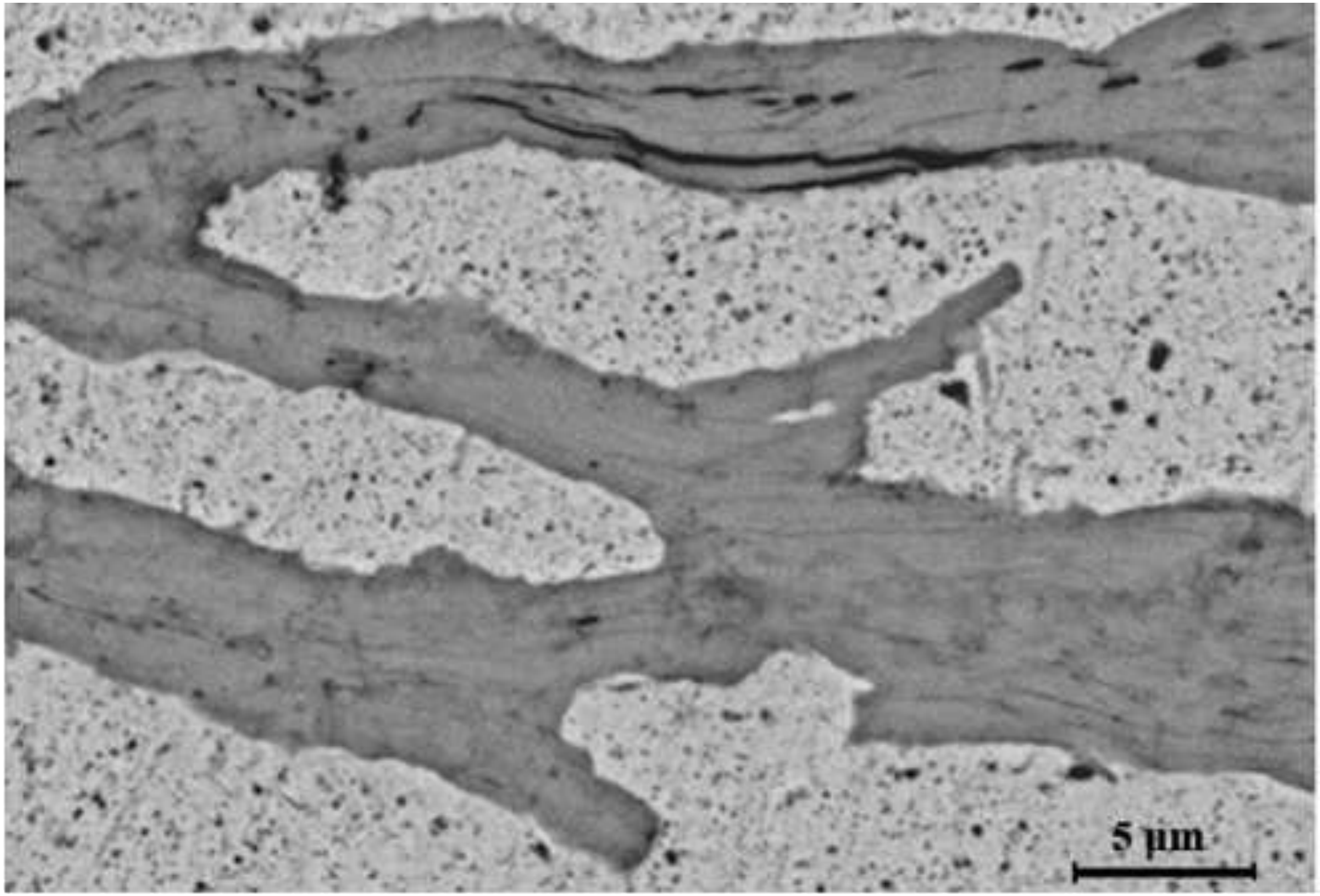
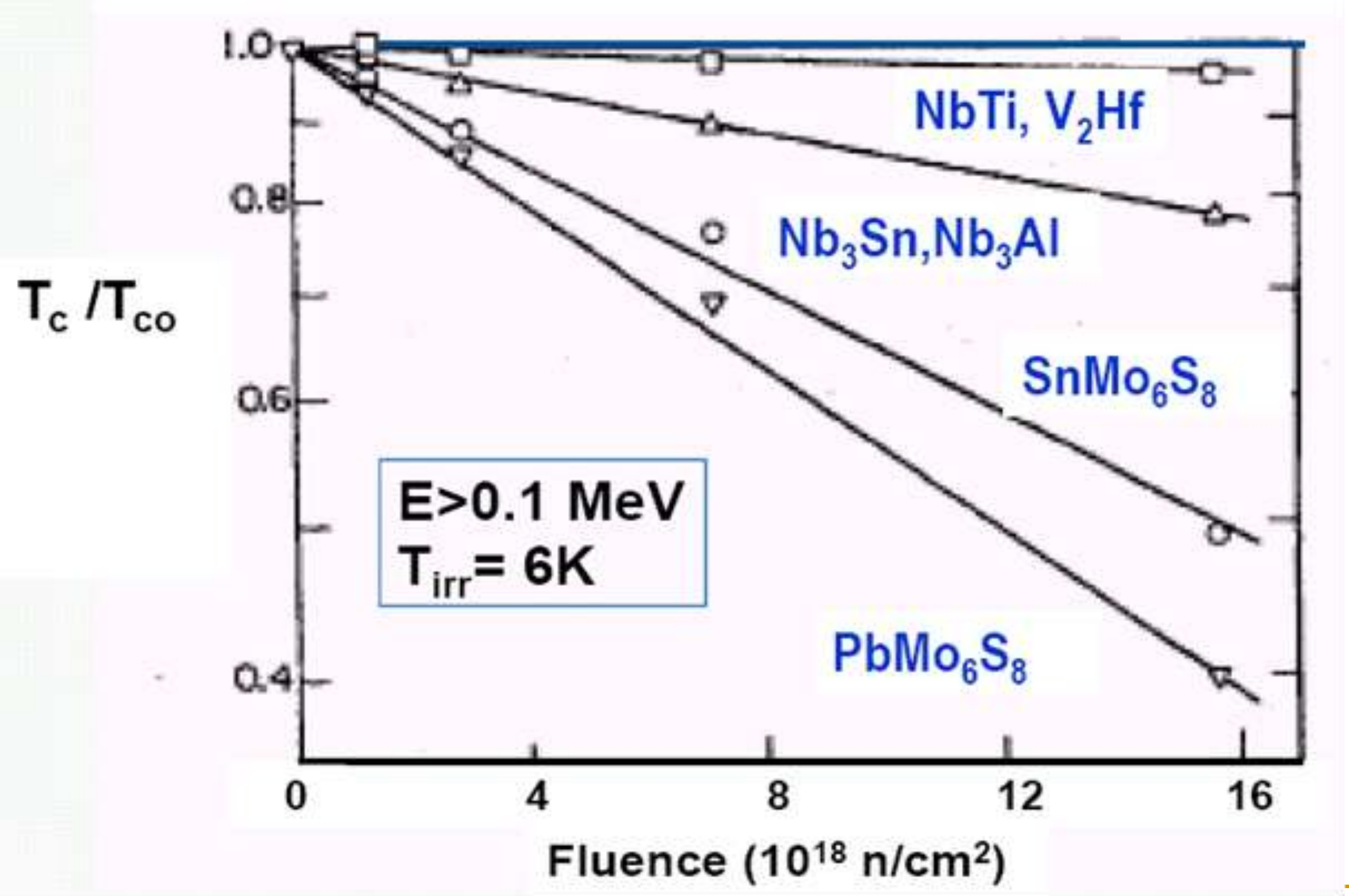
- 

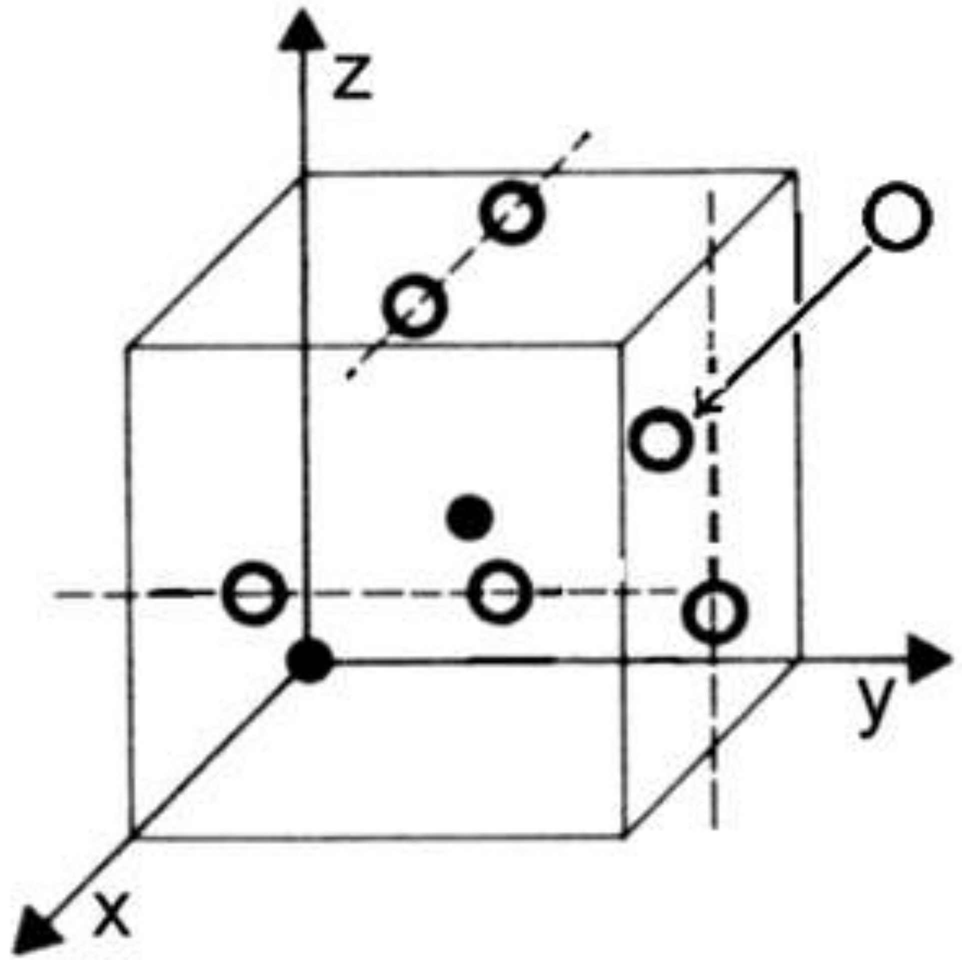
Image of scanning electron microscopy (SEM) of the cross-section of the HTc superconducting Bi-based tape I generation, indicating the existence of the nano-sized defects (black points).



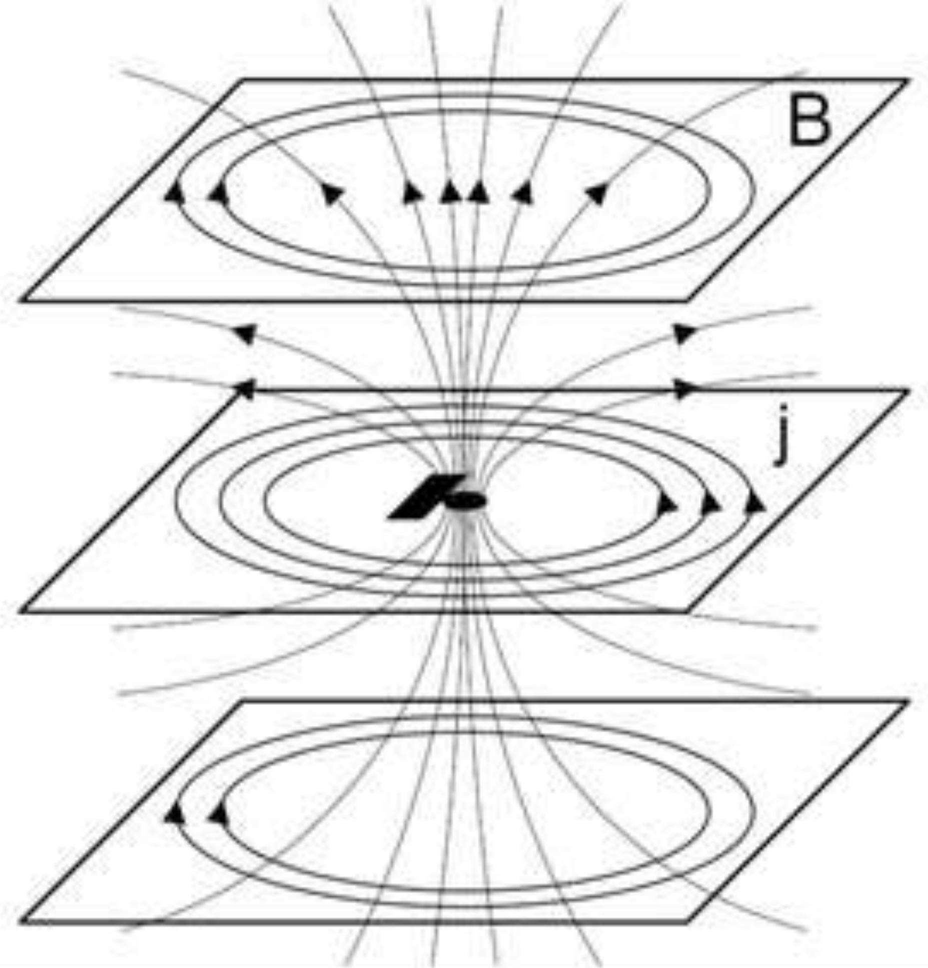
Influence of fast neutrons irradiation on critical temperature Tc



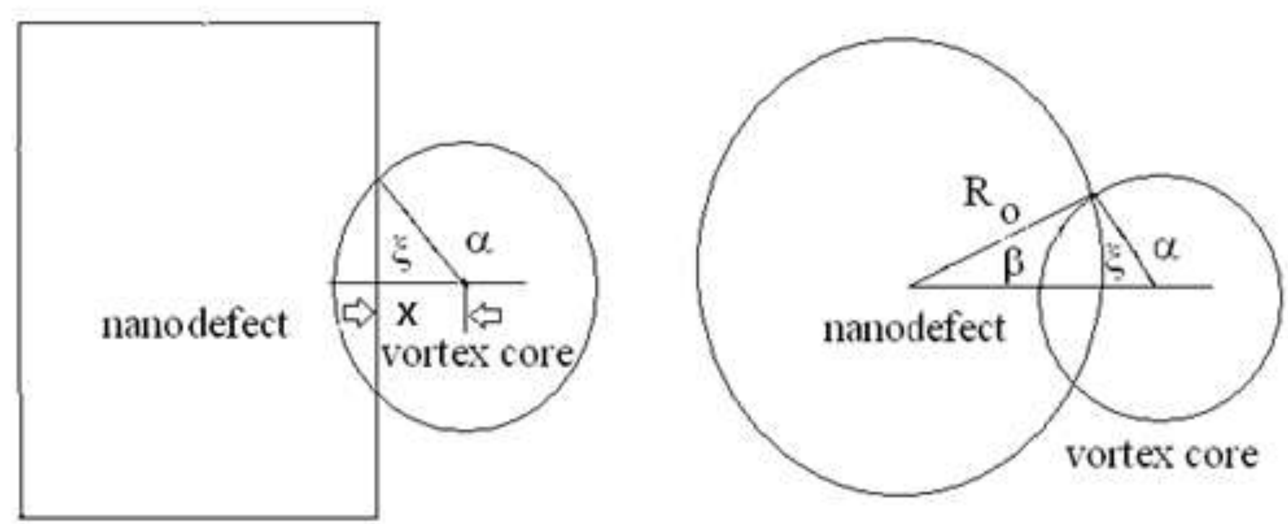
Crystal structure of an A15 type superconductor indicating an existence of linear chains of transition metals responsible for superconductivity exposed to the fast neutron irradiation, knocking out the transition atoms from linear chain.



Captured on radiational defect pancake type magnetic vortex in multi-layered structure of HTc superconductors B is magnetic induction, j circular currents density



Schematic geometry of the interaction of the vortex of the core radius equal to coherence length ξ captured on flat and cylindrical radiational defect



Potential energy wells for pinning interaction on radiational defect

$$U = \frac{\mu_0 H_c^2 l \xi^2}{2}(\alpha - \pi - \frac{\sin 2\alpha}{2})$$

$$U = \frac{\mu_0 H_c^2 l}{2}[\xi^2(\alpha - \pi - \frac{\sin 2\alpha}{2}) - R_0^2(\beta - \frac{\sin 2\beta}{2})]$$

$$U(x) = \frac{\mu_o H_c^2 l \xi^2}{2}\left[-\frac{\pi}{2} + \arcsin\frac{x}{\xi} + \frac{x}{\xi}\sqrt{1 - \left(\frac{x}{\xi}\right)^2}\right] - jB\pi\xi^2 lx$$

$$\Delta U(x) = \frac{\mu_o H_c{}^2 l \xi^2}{2}\left[\arcsin\frac{x}{\xi} + \frac{x}{\xi}\sqrt{1-\left(\frac{x}{\xi}\right)^2}\right] - jB\pi\xi^2 lx$$

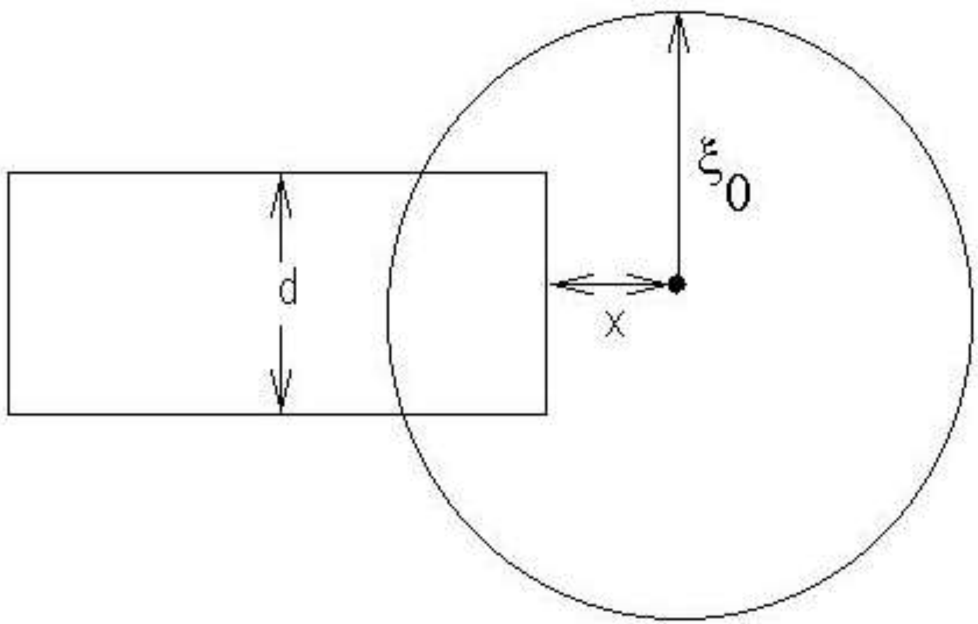
$$x_m = \xi\sqrt{1-\left(\frac{j}{j_c}\right)^2}$$

$$\Delta U = \frac{\mu_0 H_c^2}{2} l\xi^2\left[-\arcsin\left(\frac{j}{j_c}\right) + \frac{\pi}{2} - \frac{j}{j_c}\sqrt{1-\left(\frac{j}{j_c}\right)^2}\right]$$

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

i = j/jc

View of the vortex core of the radius equal to the coherence length (ξ_0) captured on nano-sized radiational defect of width (d) smaller than ξ_0



$$U_1(\xi) = \frac{\mu_o H_c^2 l}{2}\left[\pi\xi^2 - \xi^2 \arcsin\frac{d}{2\xi} - \frac{d\xi}{2}\sqrt{1-\left(\frac{d}{2\xi}\right)^2}\right]$$

$$U_2(x) = \frac{\mu_o H_c^2 l}{2}\left[\pi\xi^2 + dx - \xi^2 \arcsin\frac{d}{2\xi} - \frac{d\xi}{2}\sqrt{1-\left(\frac{d}{2\xi}\right)^2}\right]$$

$$x_c = \xi\sqrt{1-\left(\frac{d}{2\xi}\right)^2}$$

$$U_3(x) = \frac{\mu_o H_c^2 l \xi^2}{2}\left[\frac{\pi}{2} + \arcsin\frac{x}{\xi} + \frac{x}{\xi}\sqrt{1-\left(\frac{x}{\xi}\right)^2}\right]$$

$$\Delta U_2(x) = \frac{\mu_o H_c^2 l dx}{2}$$

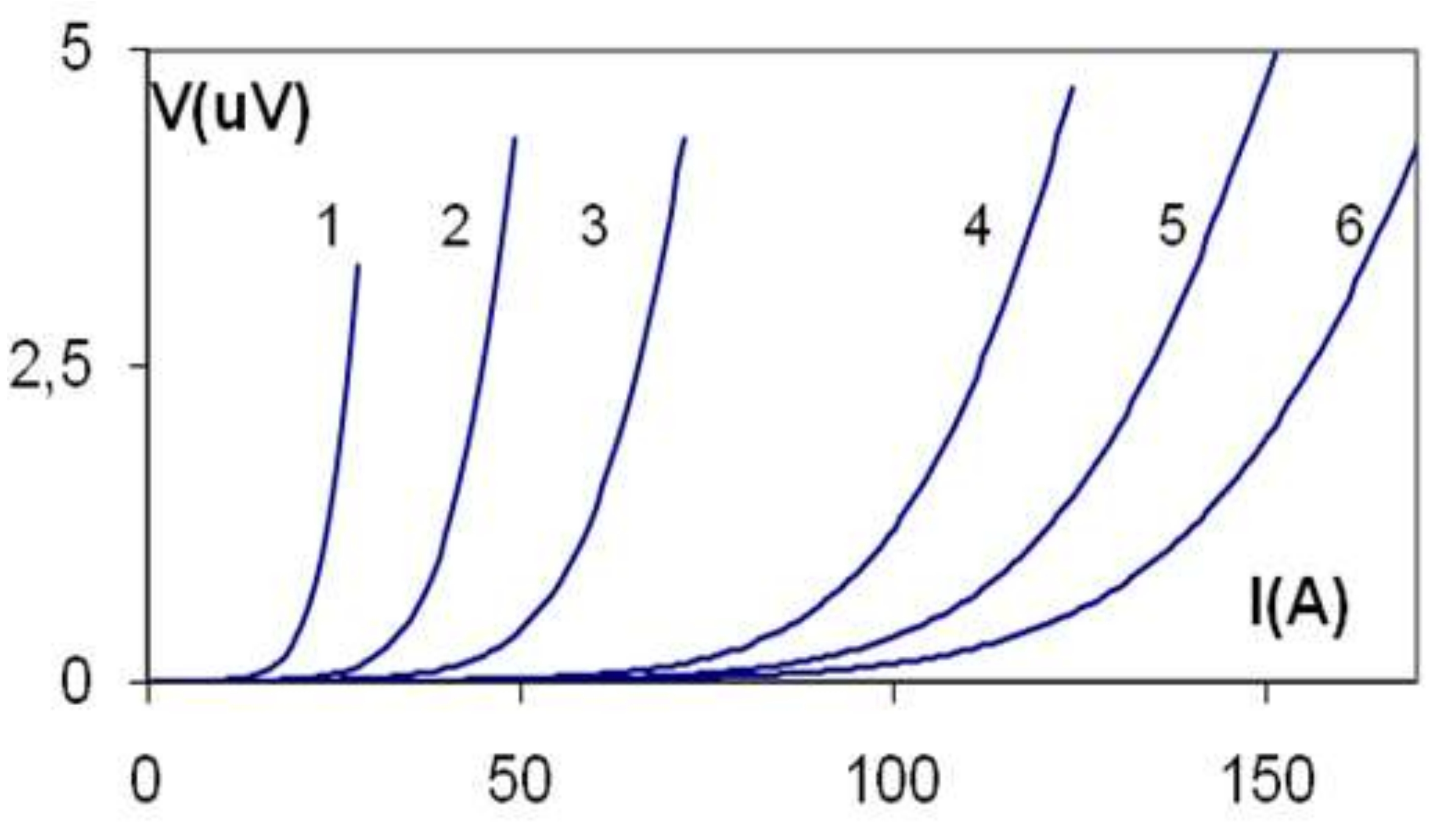
$$\Delta U_3(x) = \frac{\mu_o H_c^2 l \xi^2}{2}\left[\arcsin\frac{x}{\xi} - \frac{\pi}{2} + \arcsin\frac{d}{2\xi} + \frac{x}{\xi}\sqrt{1-\left(\frac{x}{\xi}\right)^2} + \frac{d}{2\xi}\sqrt{1-\left(\frac{d}{2\xi}\right)^2}\right]$$

$$\Delta U_3 = \frac{\mu_o H_c^2 l \xi^2}{2}\left[-\arcsin i + \arcsin\frac{d}{2\xi} + \frac{d}{2\xi}\sqrt{1-\left(\frac{d}{2\xi}\right)^2} - i\sqrt{1-i^2}\right] + \alpha\xi^2\sqrt{1-i^2}\left(\sqrt{1-i^2} - 2\right)$$

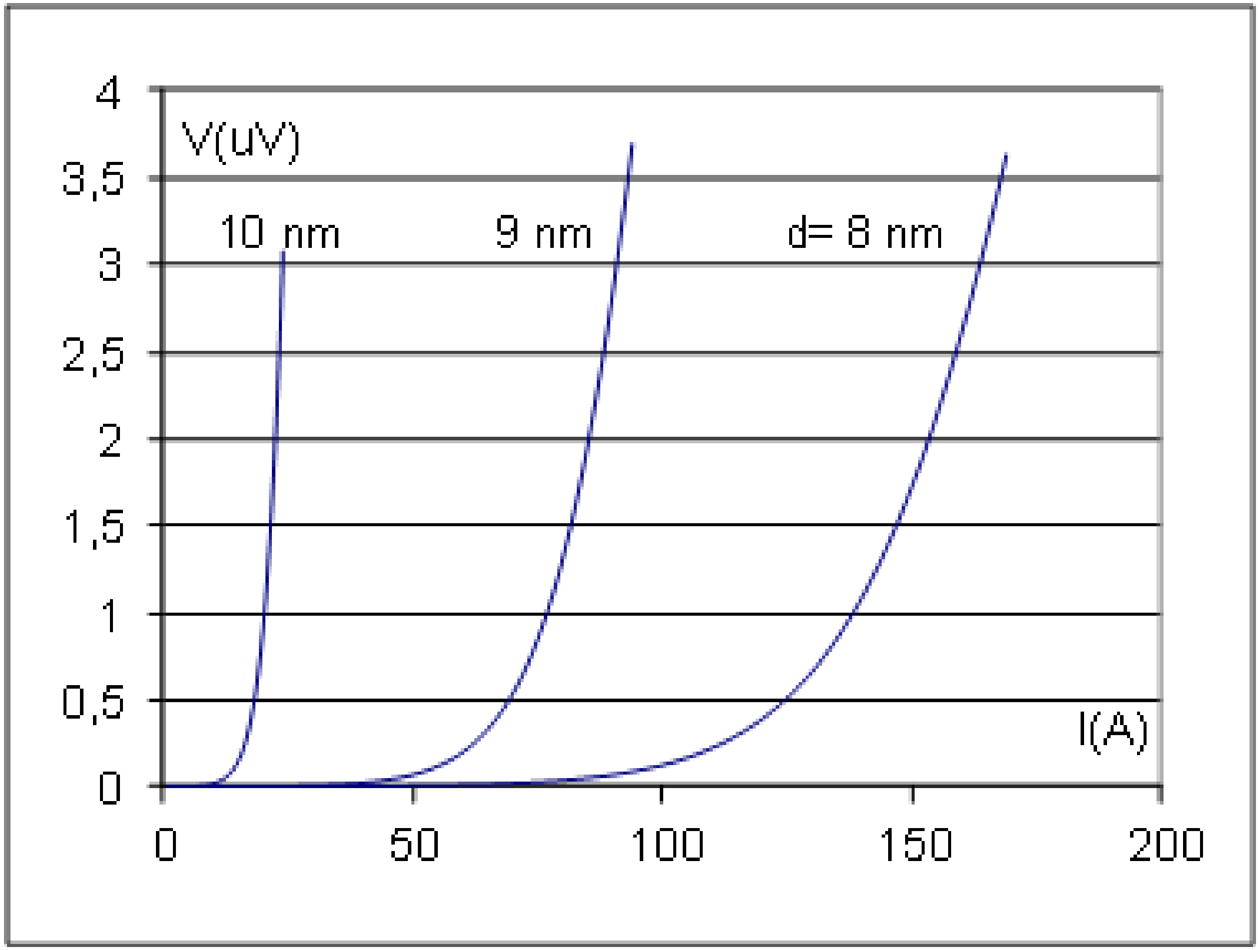
$$U_{el} = \frac{2 c_s \pi \xi^2 (\xi - x)^2}{l_a} = \alpha(\xi - x)^2$$

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

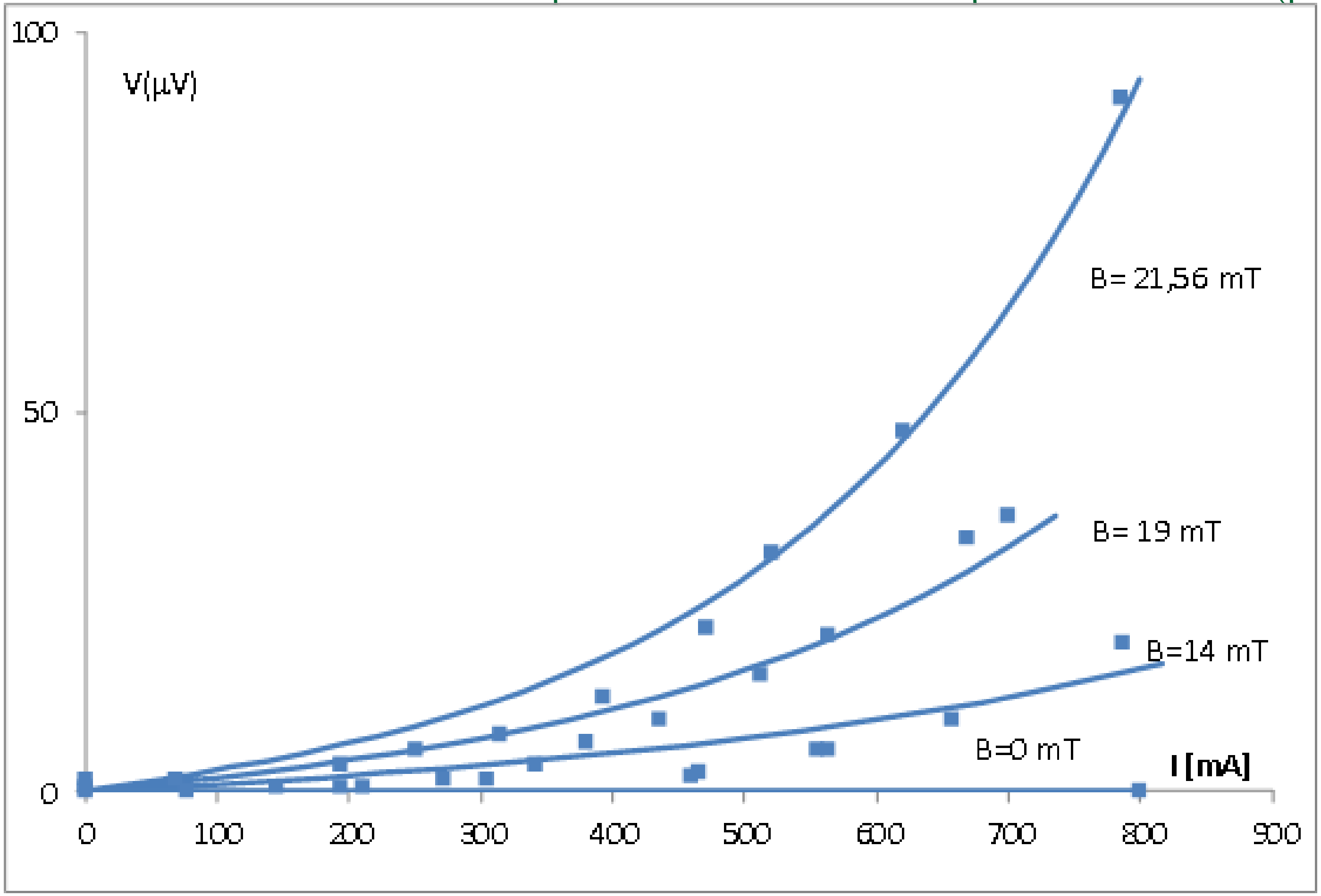
Influence of nano-defects on I-V characteristic for HTc superconductor and surface concentration of the fast neutrons dose equal to: (1) $105 \cdot 10^{10}$ cm^{-2}, (2) $99 \cdot 10^{10}$ cm^{-2}, (3) $92,5 \cdot 10^{10}$ cm^{-2}, (4) $80 \cdot 10^{10}$ cm^{-2}, (5) $74 \cdot 10^{10}$ cm^{-2}, (6) $68 \cdot 10^{10}$ cm^{-2}.



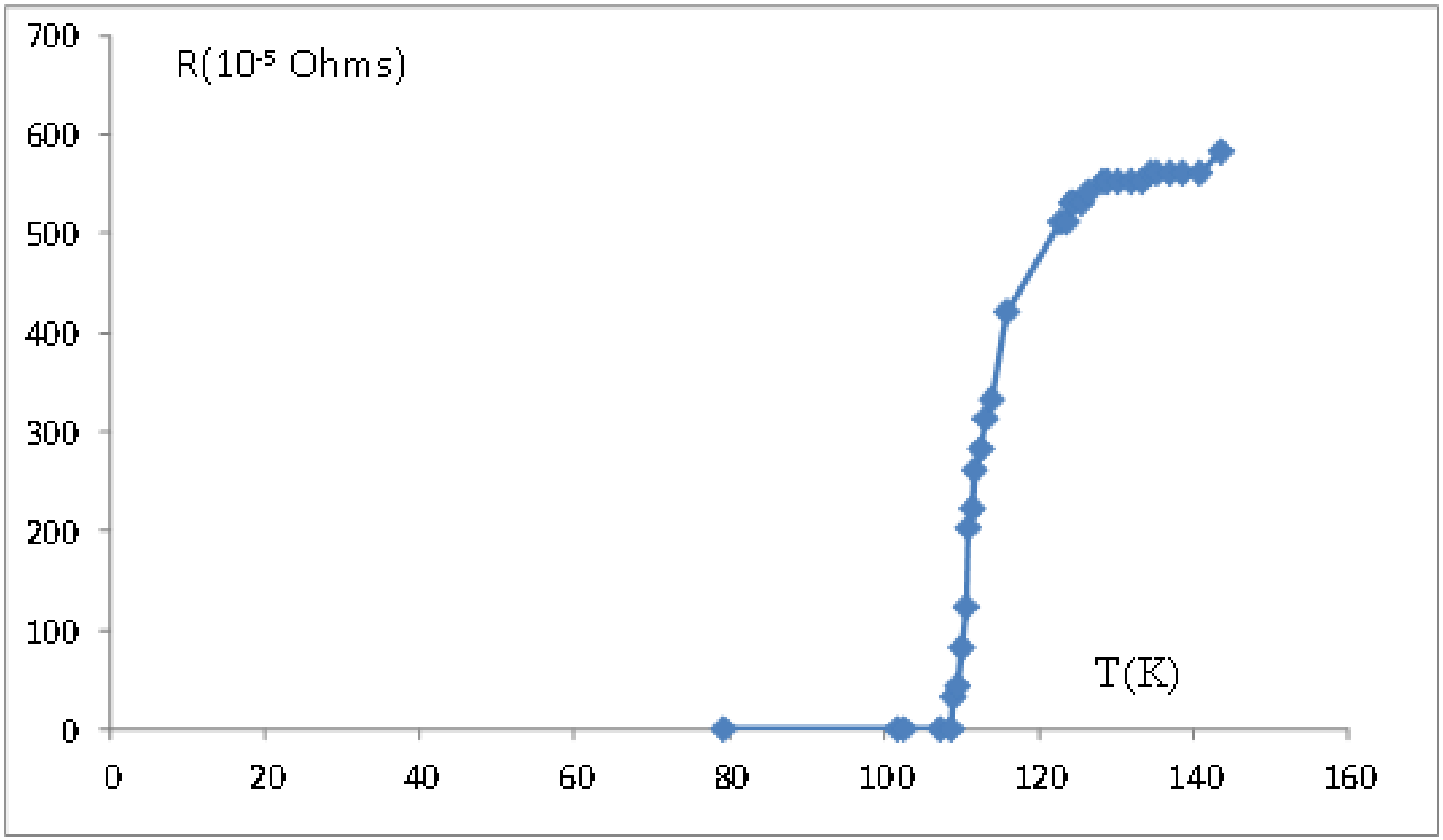
Influence of size of fast neutrons radiational defect on the current-voltage characteristic



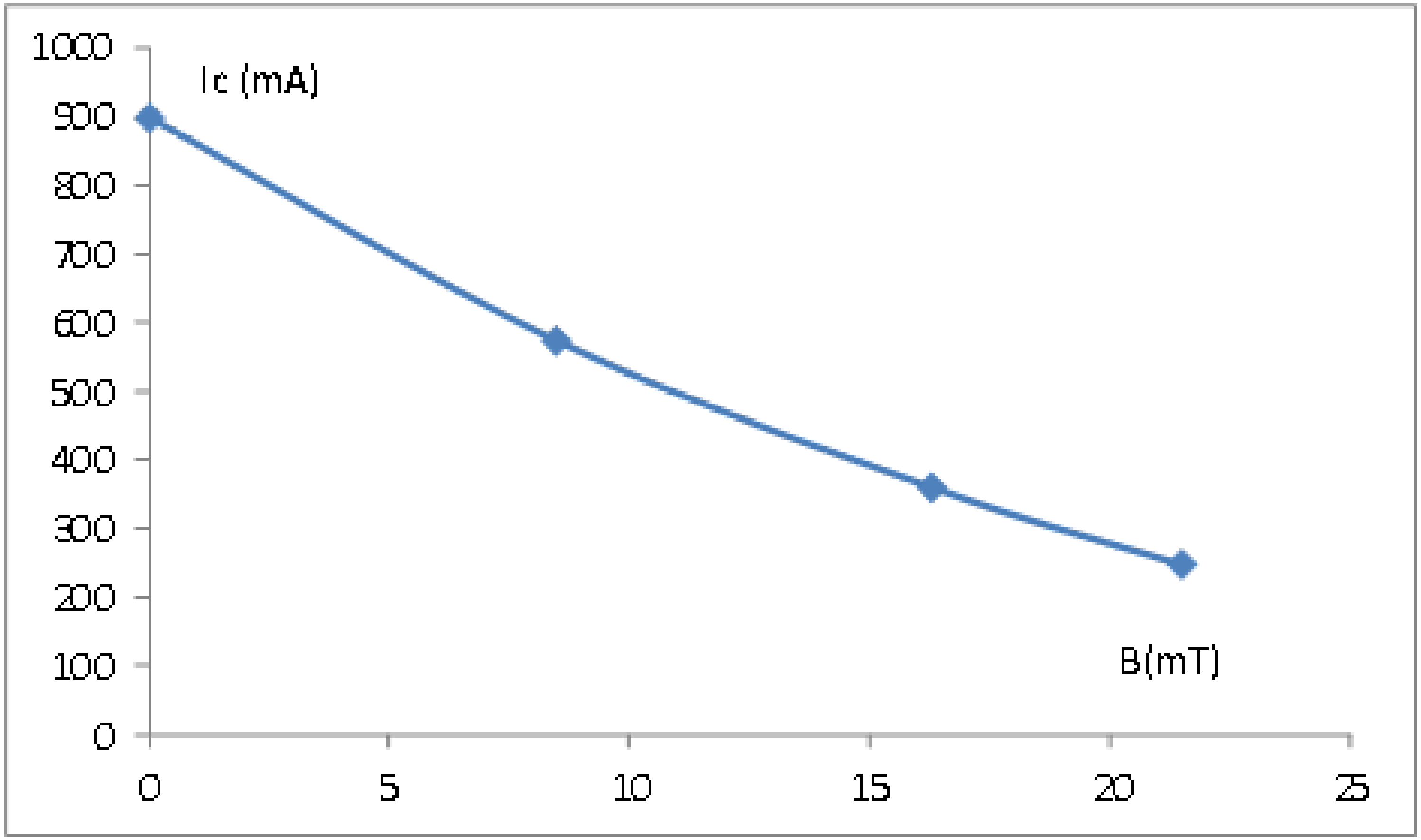
Comparison of the calculated current-voltage characteristics of the HTc $Bi_{1.6}Pb_{0.3}Sr_2Ca_2Cu_{3.06}O_8$ superconductor (solid line) in static magnetic field perpendicular to the surface of superconductor with experimental data(points).



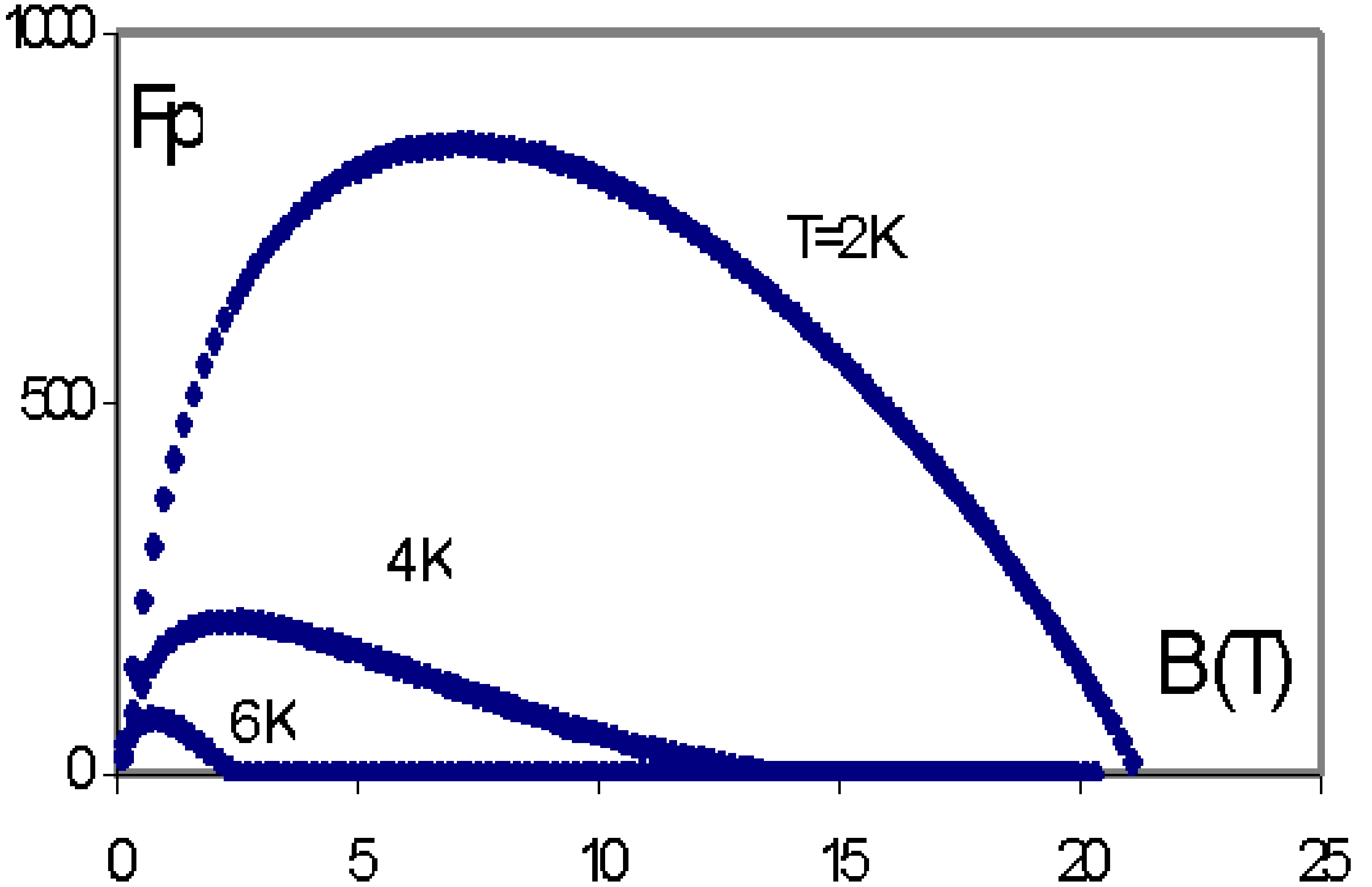
Measured superconducting transition curve of $Bi_{1.6}Pb_{0.3}Sr_2Ca_2Cu_{3.06}O_8$ HTc sample



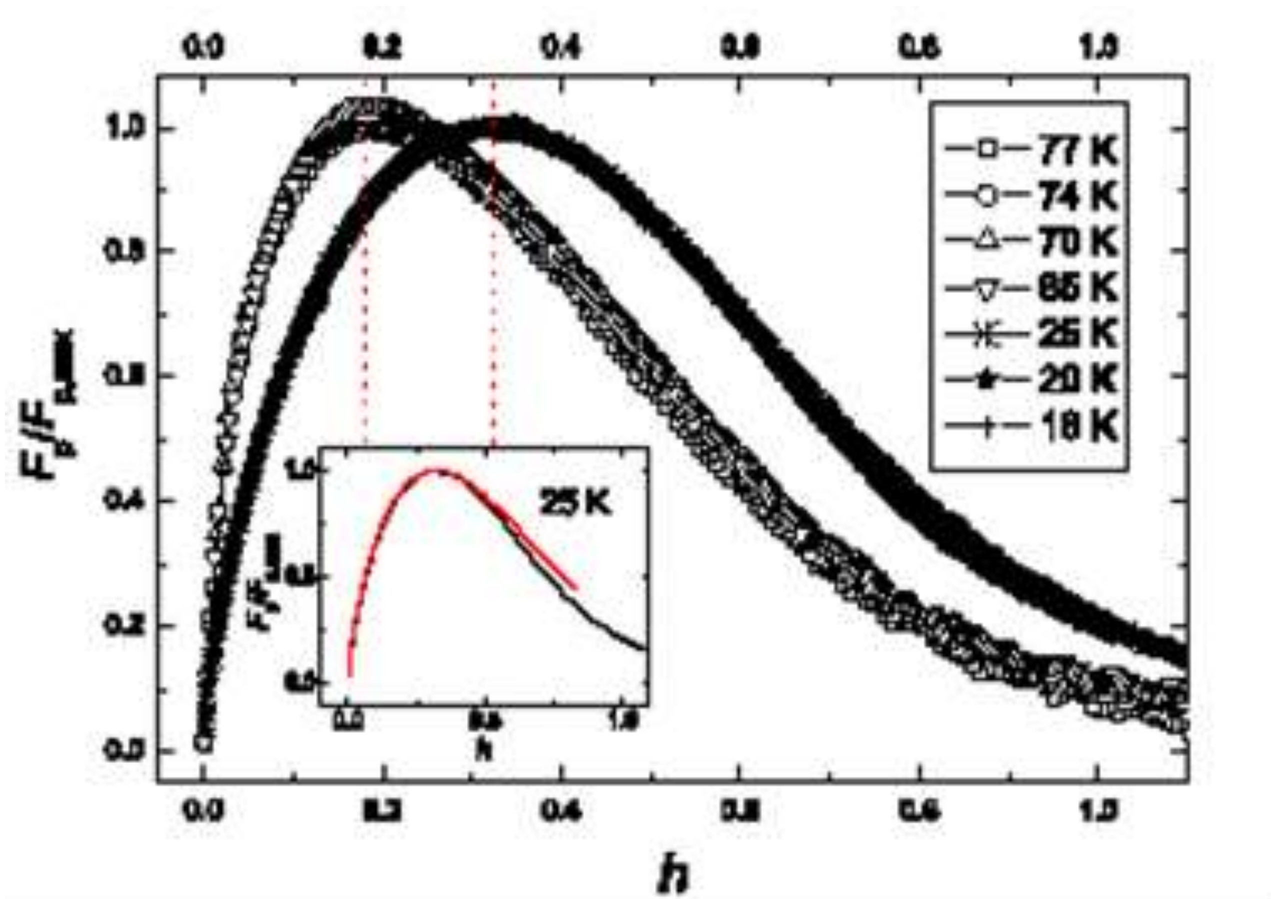
Critical current magnetic field dependence for $Bi_{1.6}Pb_{0.3}Sr_2Ca_2Cu_{3.06}O_8$ ceramic at 77K



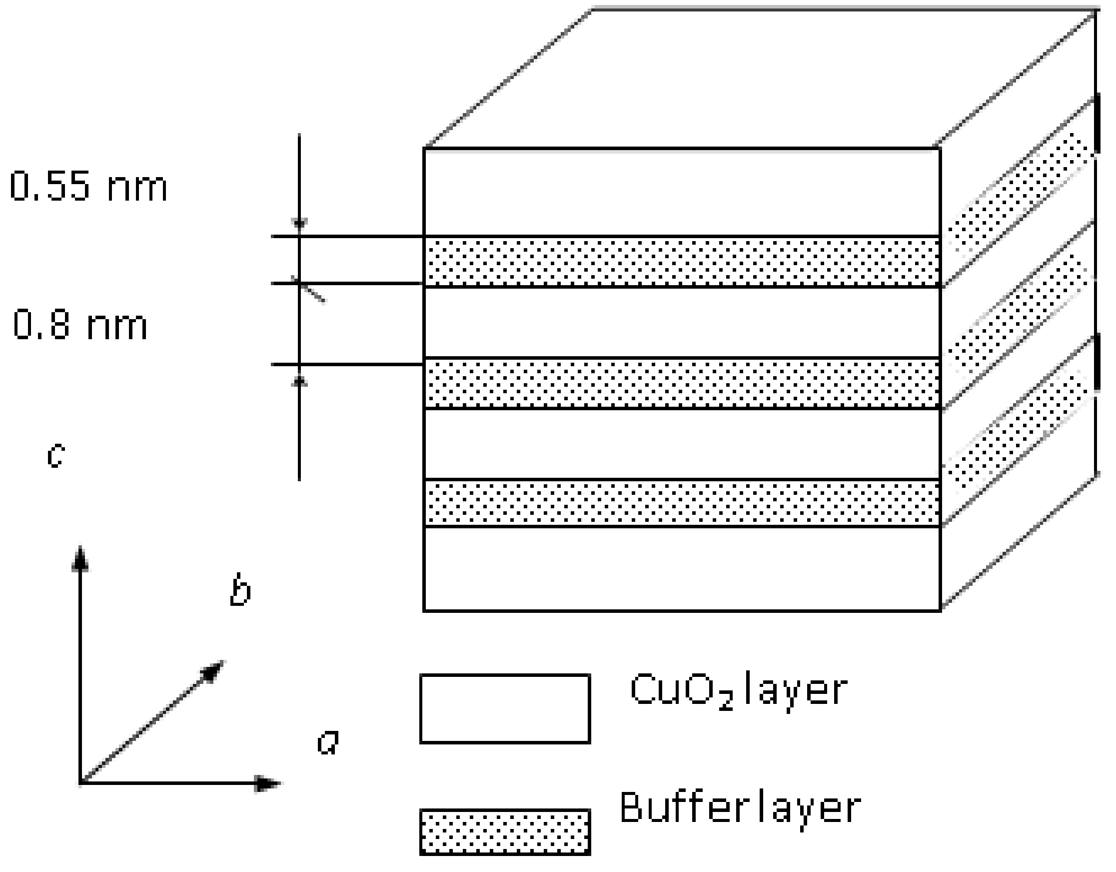
Theoretical dependence of the flux pinning on the magnetic induction for various temperatures



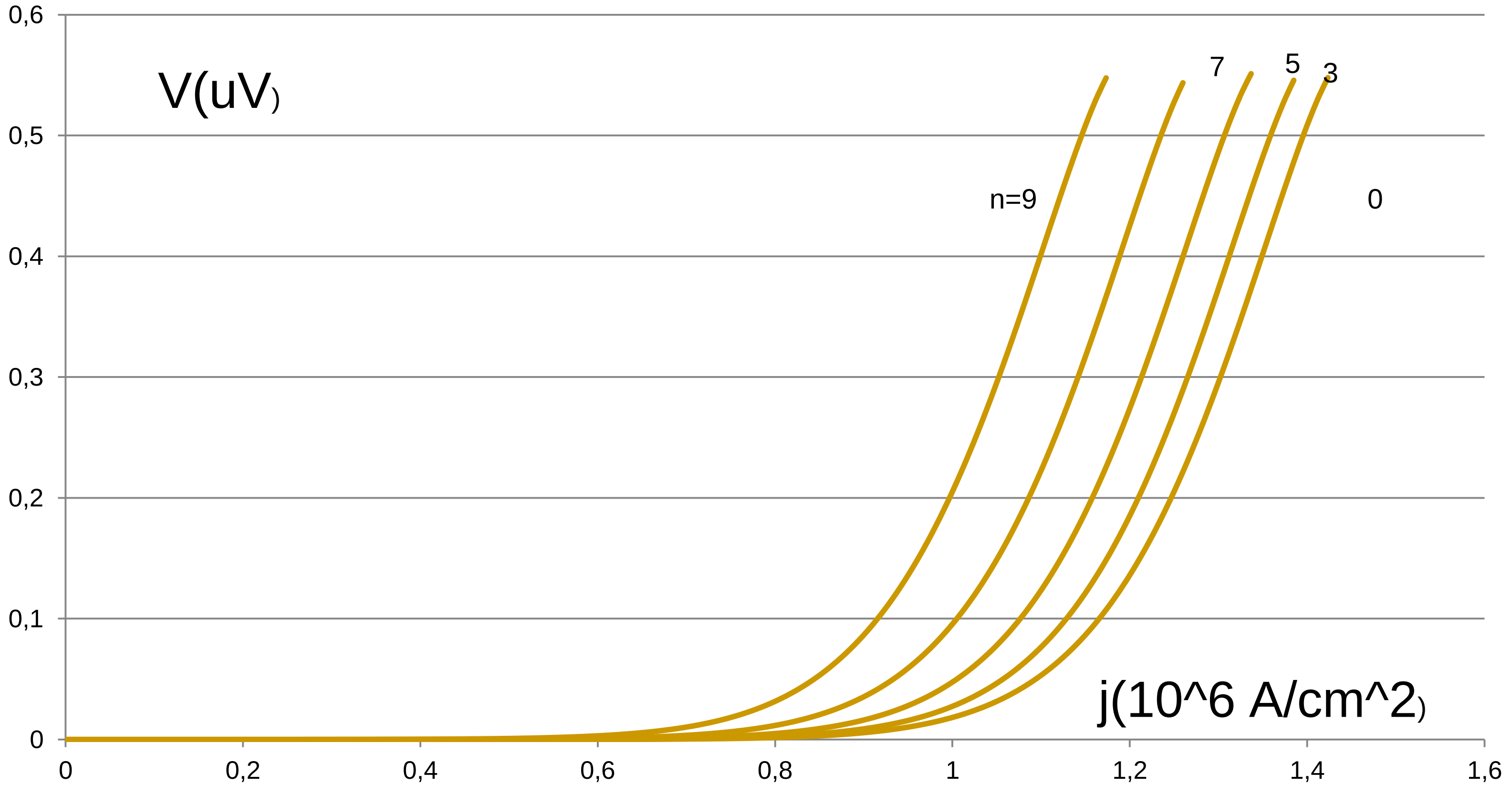
Experimental dependence of the normalized flux pinning force F_p for Bi-2223 tape on magnetic induction, for various temperatures



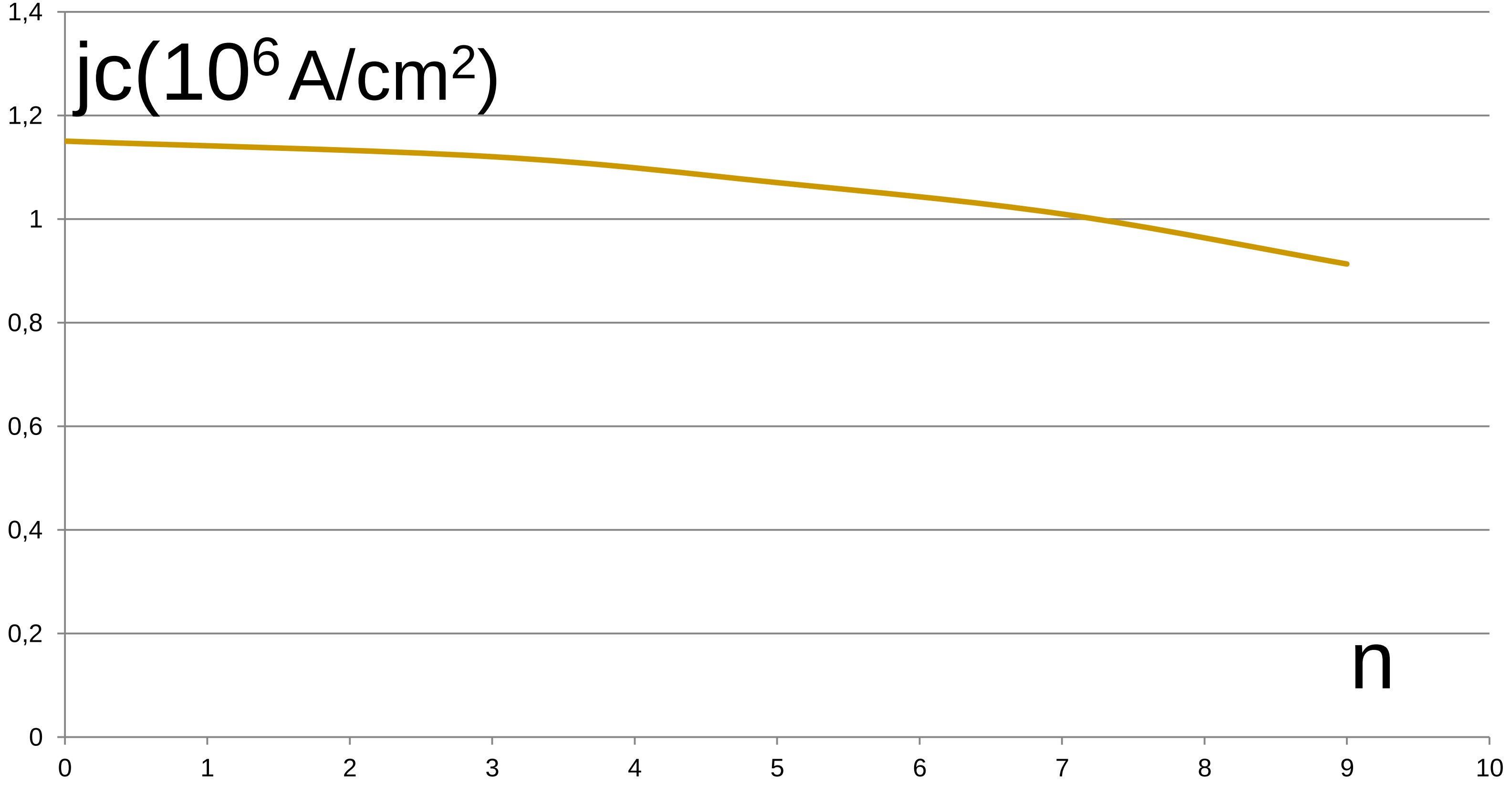
Scheme of the multilayered structure of the Bi:2212 high temperature superconductor



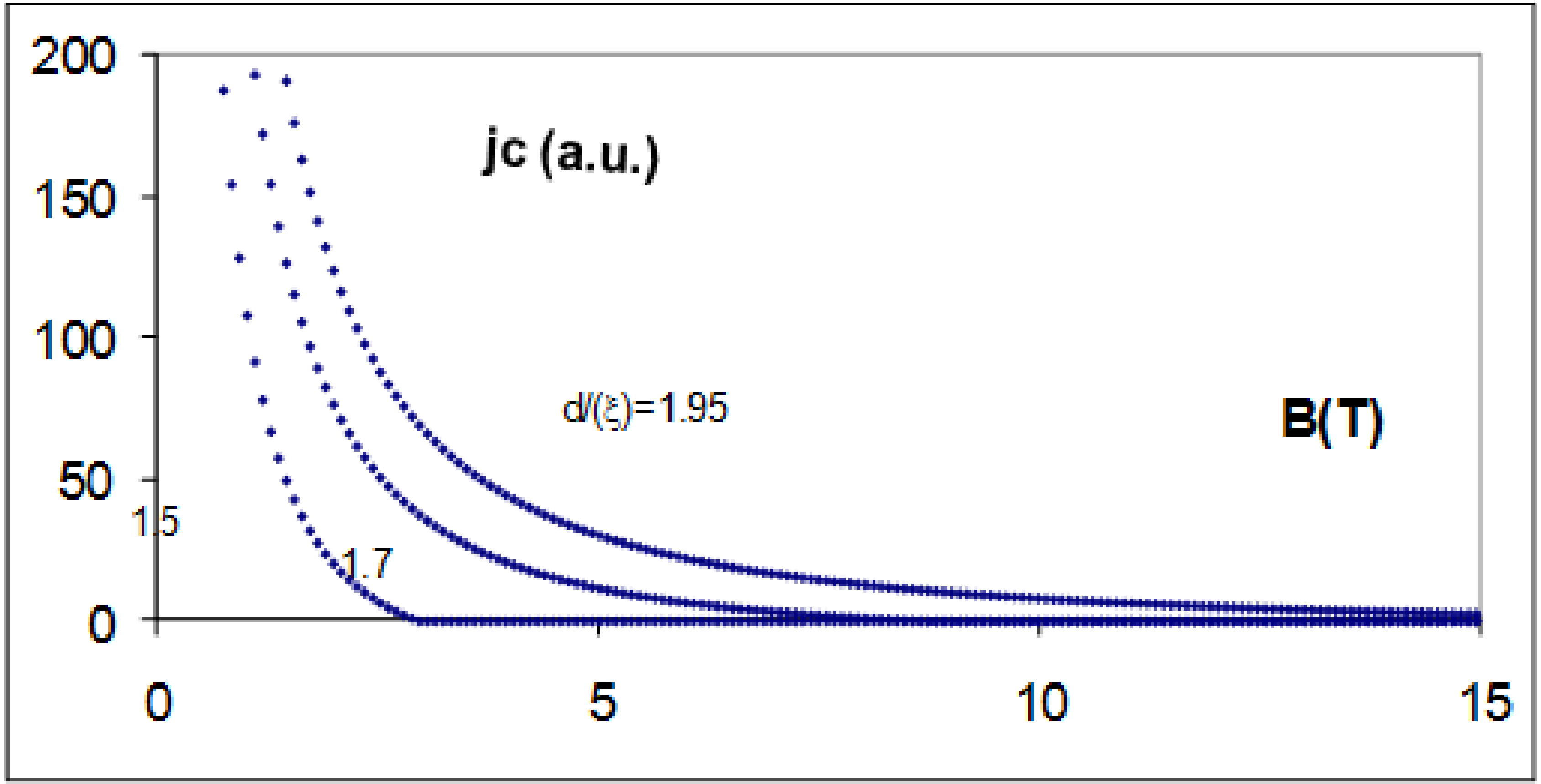
Influence of the number of interacting planes (***n***) in HTc multilayered superconductor on the current-voltage characteristics of the neutrons irradiation defected sample n=0, 1, 3, 7, 9.



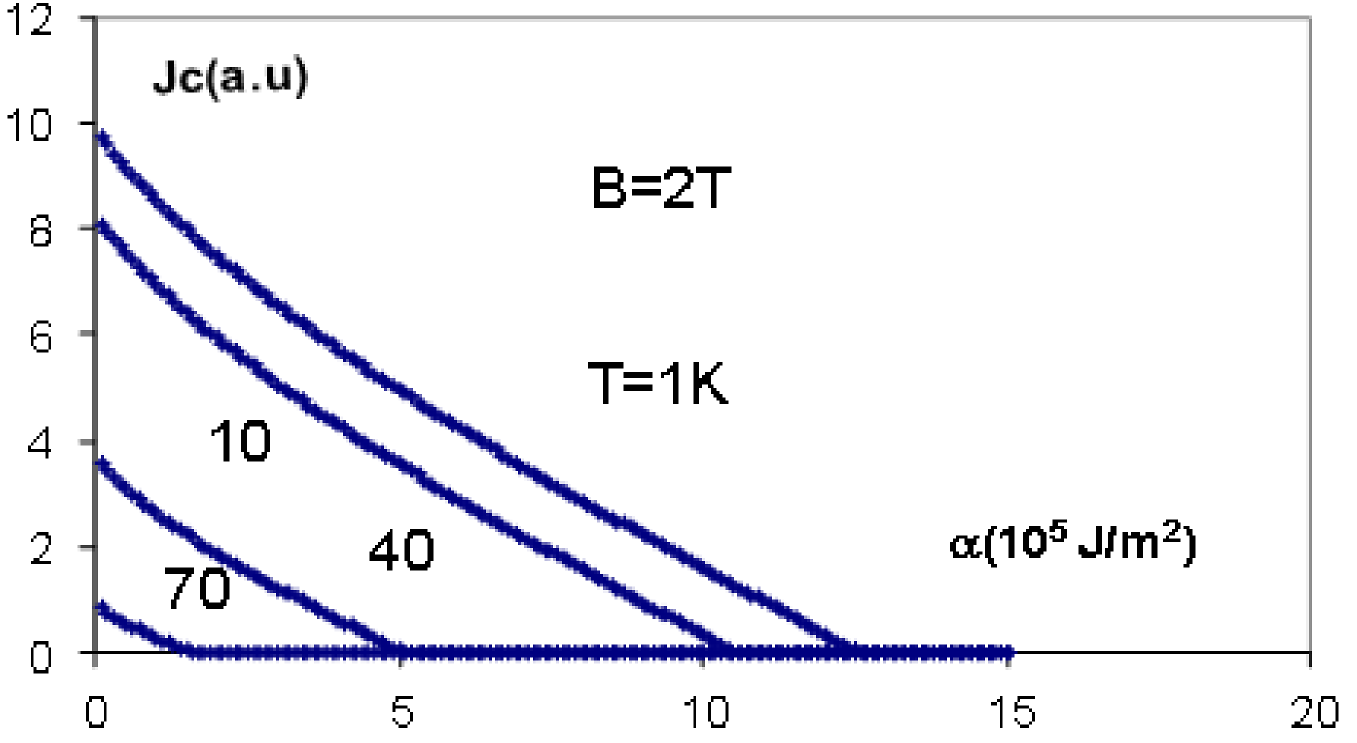
Critical current dependence on the number of interacting layers



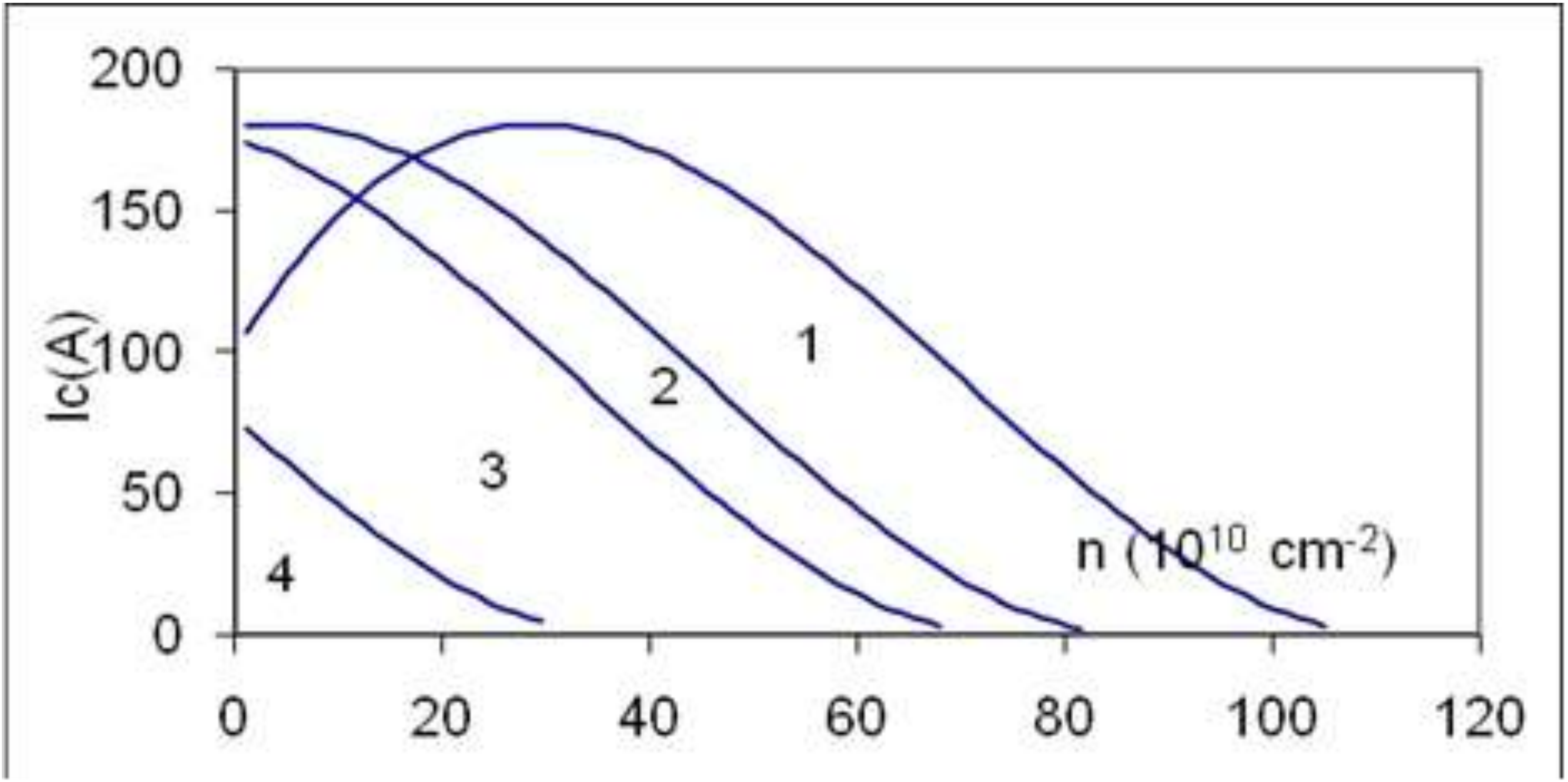
Influence of the fast neutrons irradiation creating nano-sized pinning centers of dimensions (d) on the critical current density magnetic field dependence



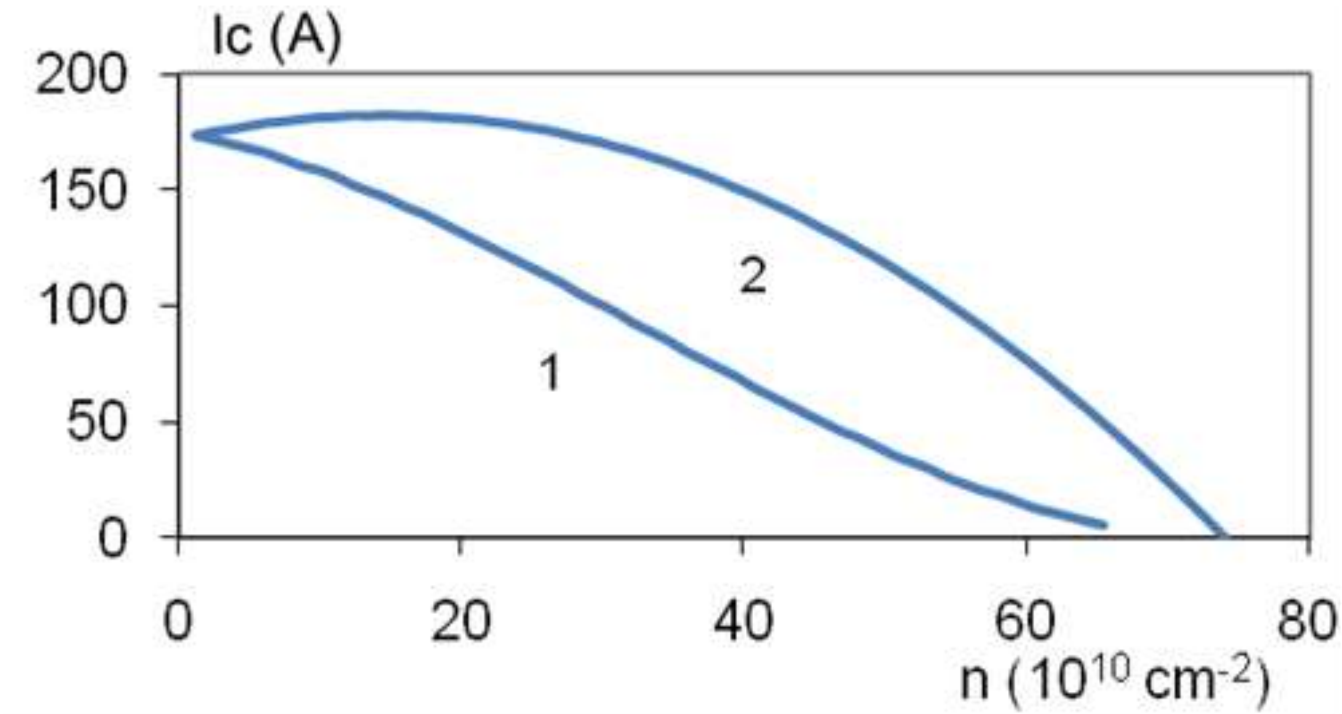
Influence of elastic properties of the vortex lattice, expressed by parameter α, on the critical current density, versus temperature.



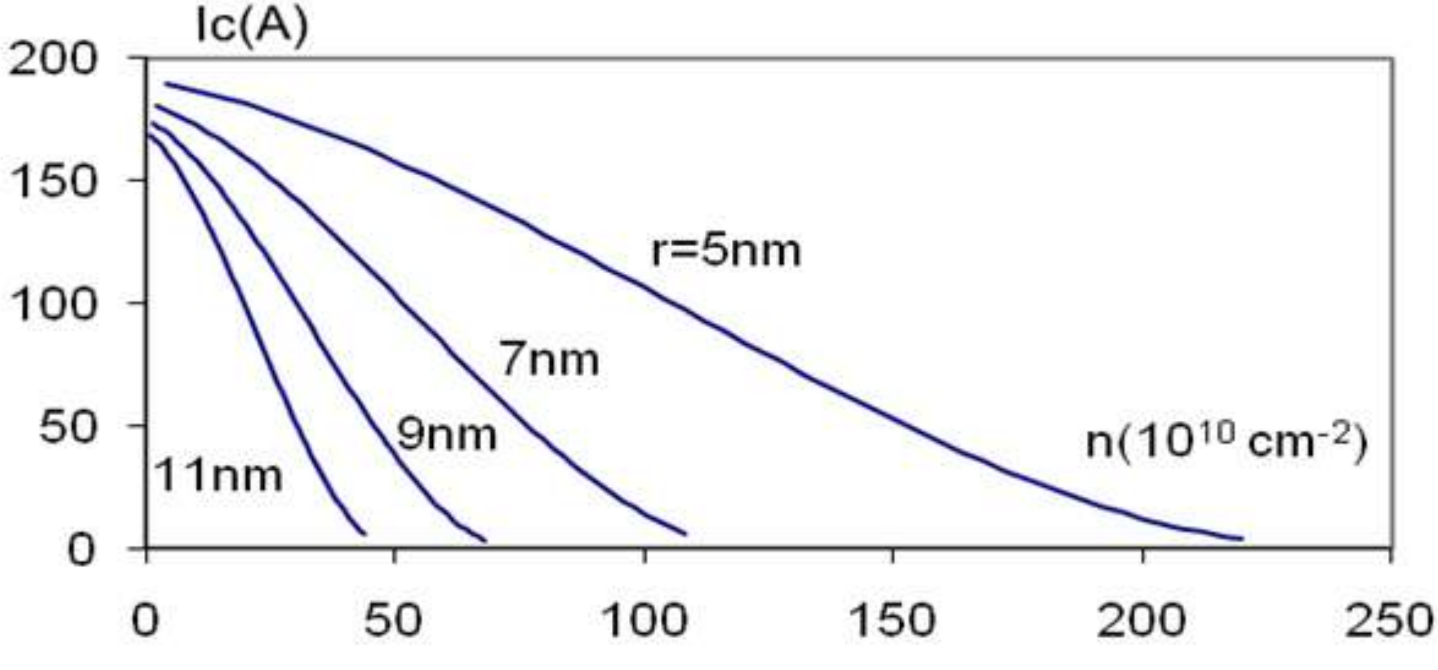
Variation of the critical current in the function of fast neutrons irradiation dose for various initial states of superconducting tapes, in the respect to inner defects concentration: 1 – low defected tape, 2 – optimal internal defects concentration, 3 – slightly over-defected tape, 4 – strongly over-defected tape



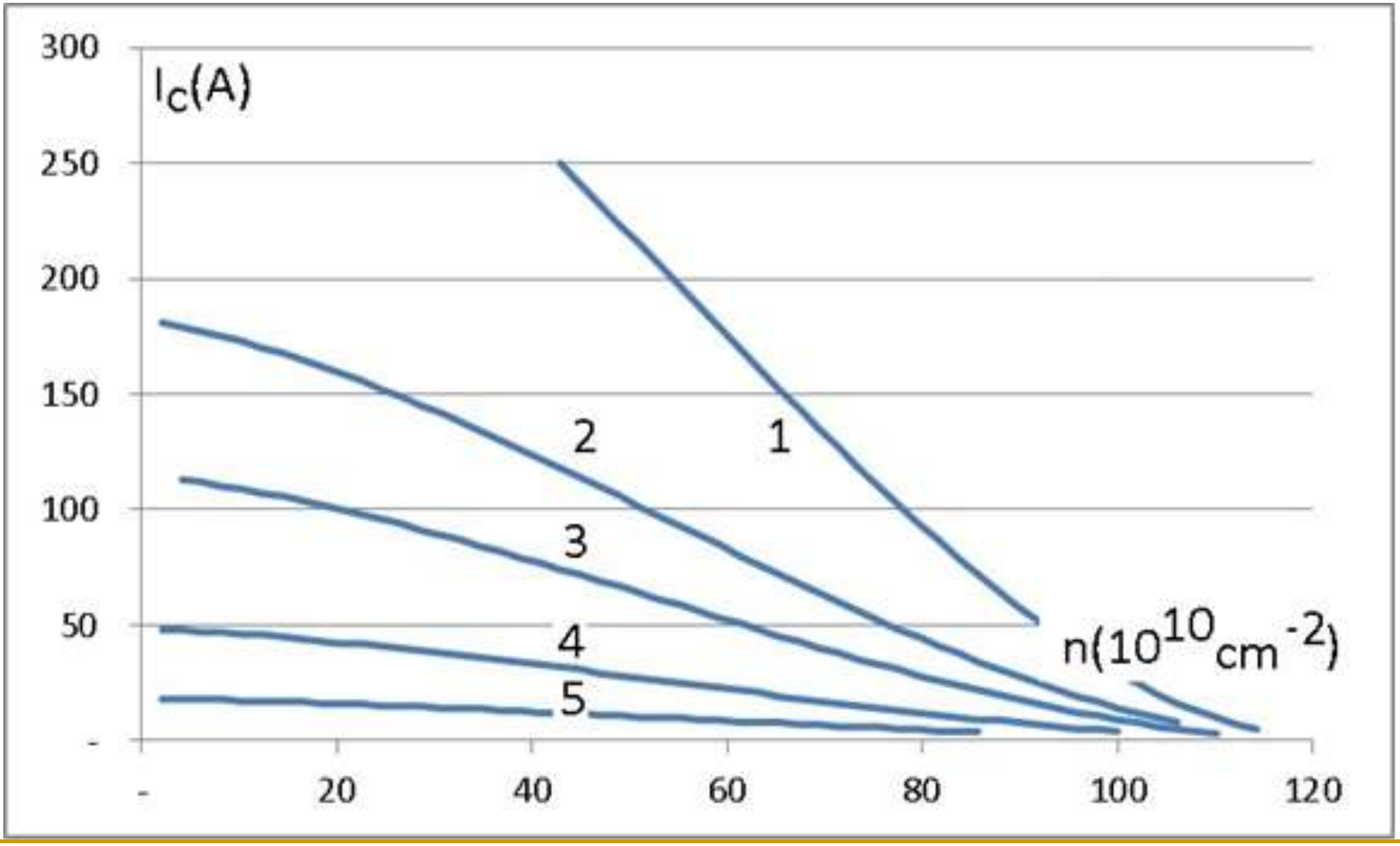
Theoretically predicted influence of the fast neutrons irradiation on the critical current of HTc superconducting tape for the model: (1) of connected in raw regions and (2) basing on simplified relation.



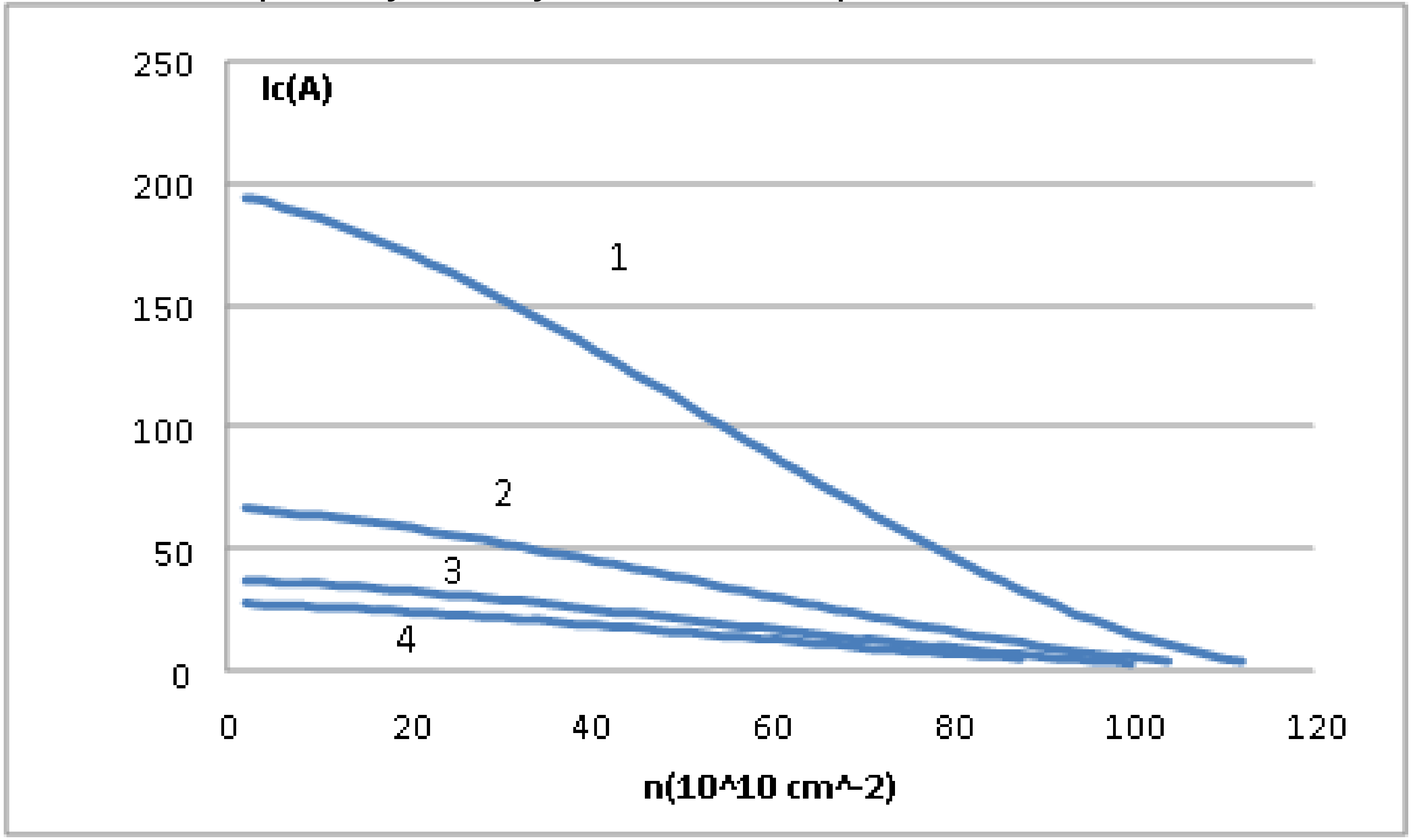
Calculated influence of the fast neutrons irradiation dose, creating nano-defects of the dimensions given at each curve, on the critical current of HTc superconducting tape optimally defected innertly



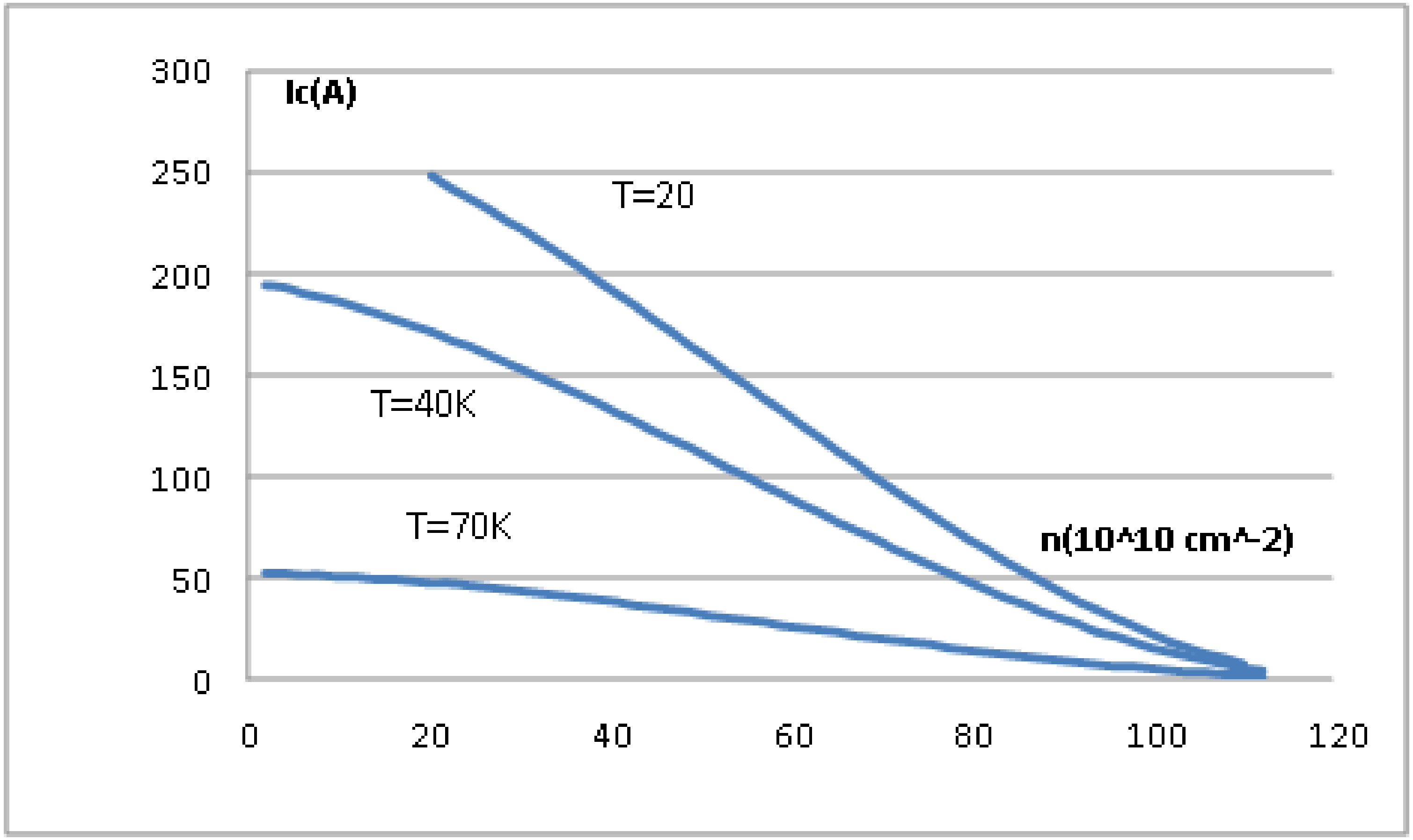
Calculated influence of the neutrons irradiation dose, creating nano-defects on the critical current of HTc superconducting tape optimally defected, in the function of the coherence length ξ determining vortex core radius: 1- ξ = 2 nm, 2 - 2,57 nm, 3 - 3 nm, 4 - 4 nm, 5 – 5,57 nm.



Calculated influence of the neutrons irradiation dose, creating nano-defects on the critical current of HTc superconducting tape, in the function of the magnetic induction: 1- 2T, 2 - 5T, 3 - 8T, 4- 10 T at T=40K for optimally initially defected sample.



Calculated influence of the irradiation dose, creating nano-defects on the critical current of HTc superconducting tape, in the function of temperature for magnetic induction equal to 2T for optimal innertly defected sample.



Influence of initial vortex position versus irradiated defect on I-V curves

$$U(-\xi) = \frac{\mu_0 H_c^2 l_p}{2}\left[\pi\xi^2 - 2\xi^2 \arcsin\frac{d}{2\xi} - d\sqrt{\xi^2 - \frac{d^2}{4}}\right]$$

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

$$U_1(x) = \frac{\mu_0 H_c^2 l_p}{2}\left[\begin{array}{l} \pi\xi^2 - 2\xi^2 \arcsin\frac{d}{2\xi} + \\ \xi^2 \arcsin\frac{\sqrt{\xi^2 - x^2}}{\xi} - d\sqrt{\xi^2 - \frac{d^2}{4}} \\ + x\sqrt{\xi^2 - x^2} \end{array}\right]$$

Capturing potential for various vortex positions

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

$$U_2(x) = \frac{\mu_0 H_c^2 l_p \xi^2}{2}\left[\pi - \arcsin\frac{d}{2\xi} - \frac{d}{2\xi}\sqrt{1-\left(\frac{d}{2\xi}\right)^2} + dx\right]$$

$$U_3(x) = \frac{\mu_0 H_c^2 l_p \xi^2}{2}\left[\frac{\pi}{2} + \arcsin\frac{x}{\xi} + \frac{x}{\xi}\sqrt{1-\left(\frac{x}{\xi}\right)^2}\right]$$

$$\Delta U_1(x) = \frac{\mu_0 H_c^2 l_p}{2}\left[\xi^2 \arcsin\frac{\sqrt{\xi^2 - x^2}}{\xi} + x\sqrt{\xi^2 - x^2}\right]$$

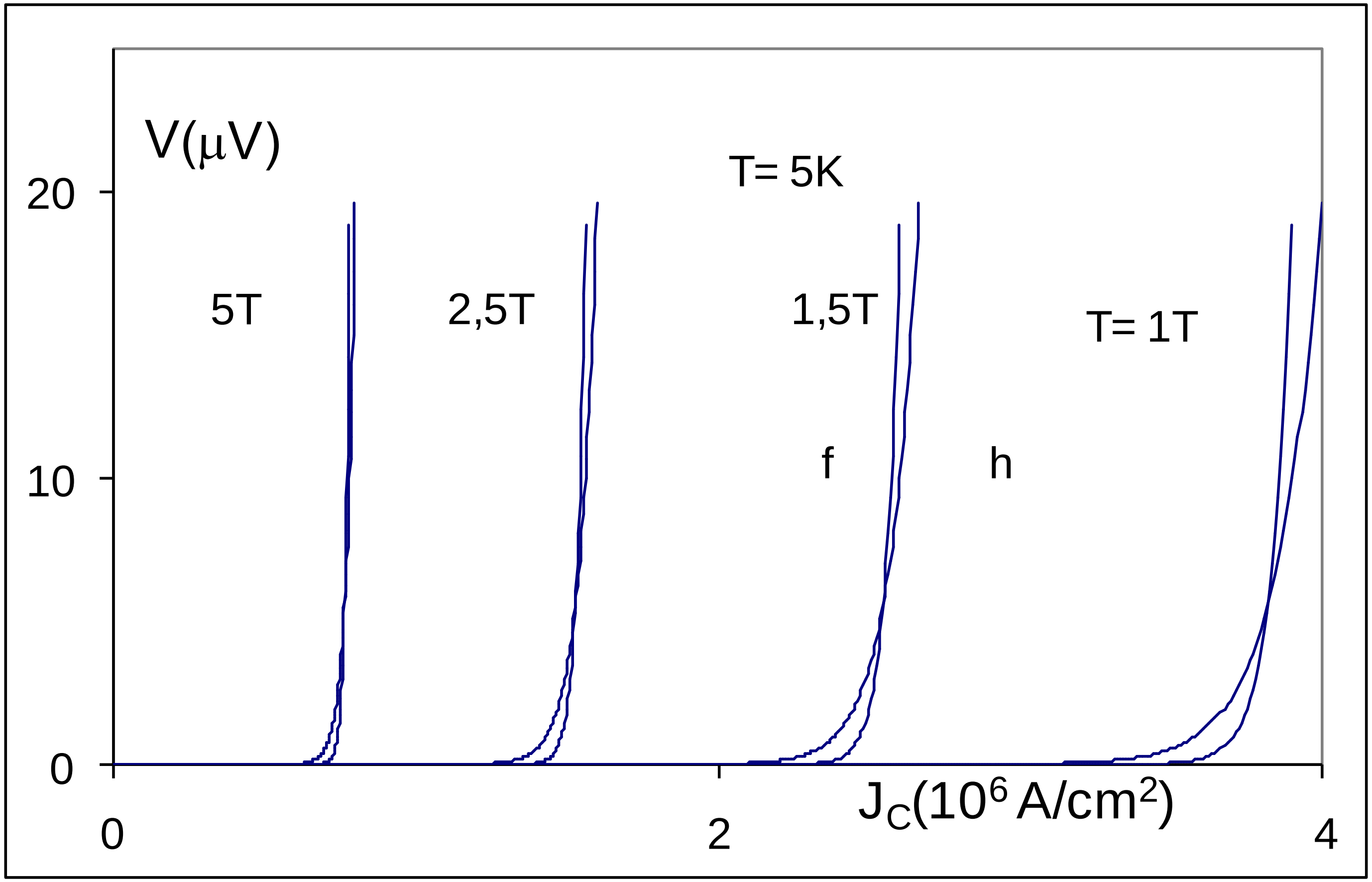
Potential barrier height

$$\Delta U_2(x) = \frac{\mu_0 H_c^2 l_p}{2}\left[\xi^2 \arcsin\frac{d}{2\xi} + \frac{d}{2\xi}\sqrt{\xi^2 - \frac{d^2}{4}} + dx\right]$$

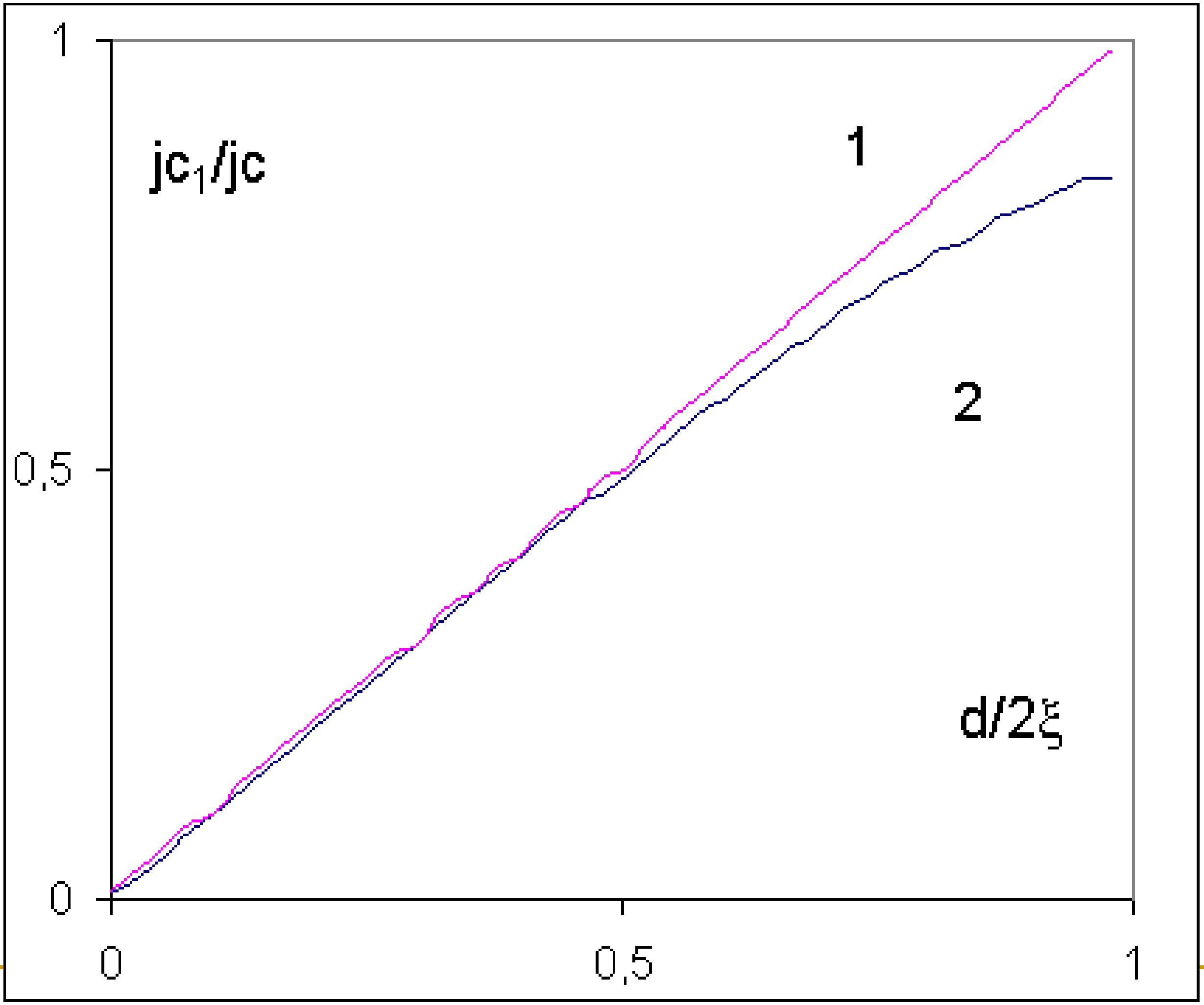
$$\Delta U_3(x) = \frac{\mu_0 H_c^2 l_p}{2}\left[\begin{array}{l} -\frac{\pi\xi^2}{2} + \xi^2 \arcsin\frac{x}{\xi} + \\ x\xi\sqrt{1-\left(\frac{x}{\xi}\right)^2} + 2\xi^2 \arcsin\frac{d}{2\xi} \\ + d\sqrt{\xi^2 - \left(\frac{d}{2}\right)^2} \end{array}\right]$$

$$\Delta U_3(i) = \frac{\mu_0 H_c^2 l_p \xi^2}{2}\left[\begin{array}{l} -\arcsin(i) - i(2+\sqrt{1-i^2}) + \\ 2\arcsin\frac{d}{2\xi} + \frac{d}{\xi}\sqrt{1-\left(\frac{d}{2\xi}\right)^2} \end{array}\right]$$

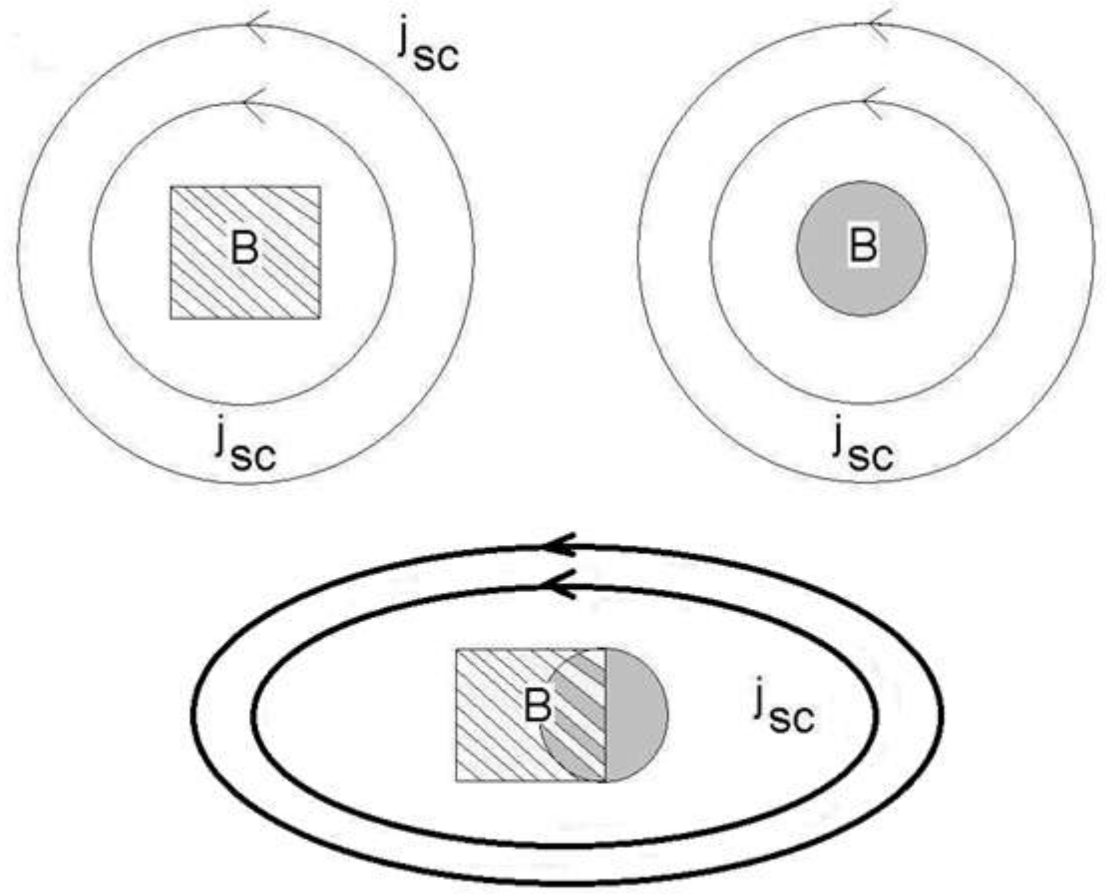
Current-voltage characteristics of HTc superconductor for $d/2\xi=0,4$ with (h) halfly captured vortex in the initial state and (f) fully pinned, versus applied external magnetic field



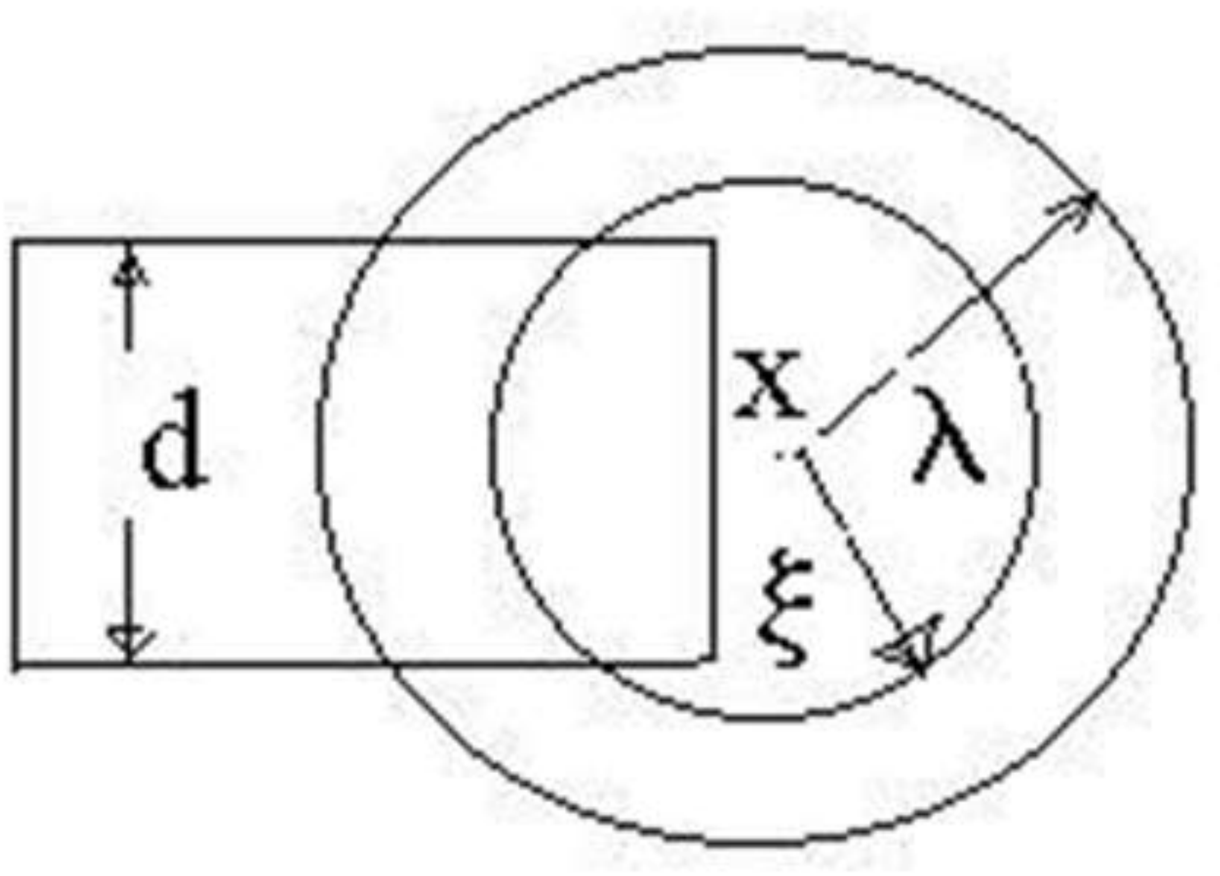
Impact of the pinning centers size, created in irradiation process on reduced critical current density for two initial positions of the vortex: 1 – half captured, 2 – fully captured.



Schematic comparison of the shielding currents distribution and magnetic induction penetration into the vortex core for isolated nano-sized defect (up) created by fast neutron irradiation and for captured on this radiational defect vortex (down) in HTc superconductor



Scheme of the capturing vortex on the nano-sized neutrons irradiation induced pinning center, of the core radius approximated by parameter ξ coherence length, while full vortex has size of the penetration depth λ



Magnetic flux crossing captured vortex

$$B(r) = B(0)\exp(-\frac{r}{\lambda})$$

$$\Phi_0 = 2\pi\int_0^\infty B(0)\exp(-\frac{r}{\lambda})r\,dr = 2\pi\lambda^2 B(0)$$

$$B(0) = \frac{\Phi_0}{2\pi\lambda^2}$$

$$\frac{\Phi_1}{\Phi_0} = 1 + \frac{B_e\lambda^2}{\Phi_0}\left[\arcsin\frac{d}{2\lambda} + \frac{d}{2\lambda}\sqrt{1-\left(\frac{d}{2\lambda}\right)^2}\right]$$

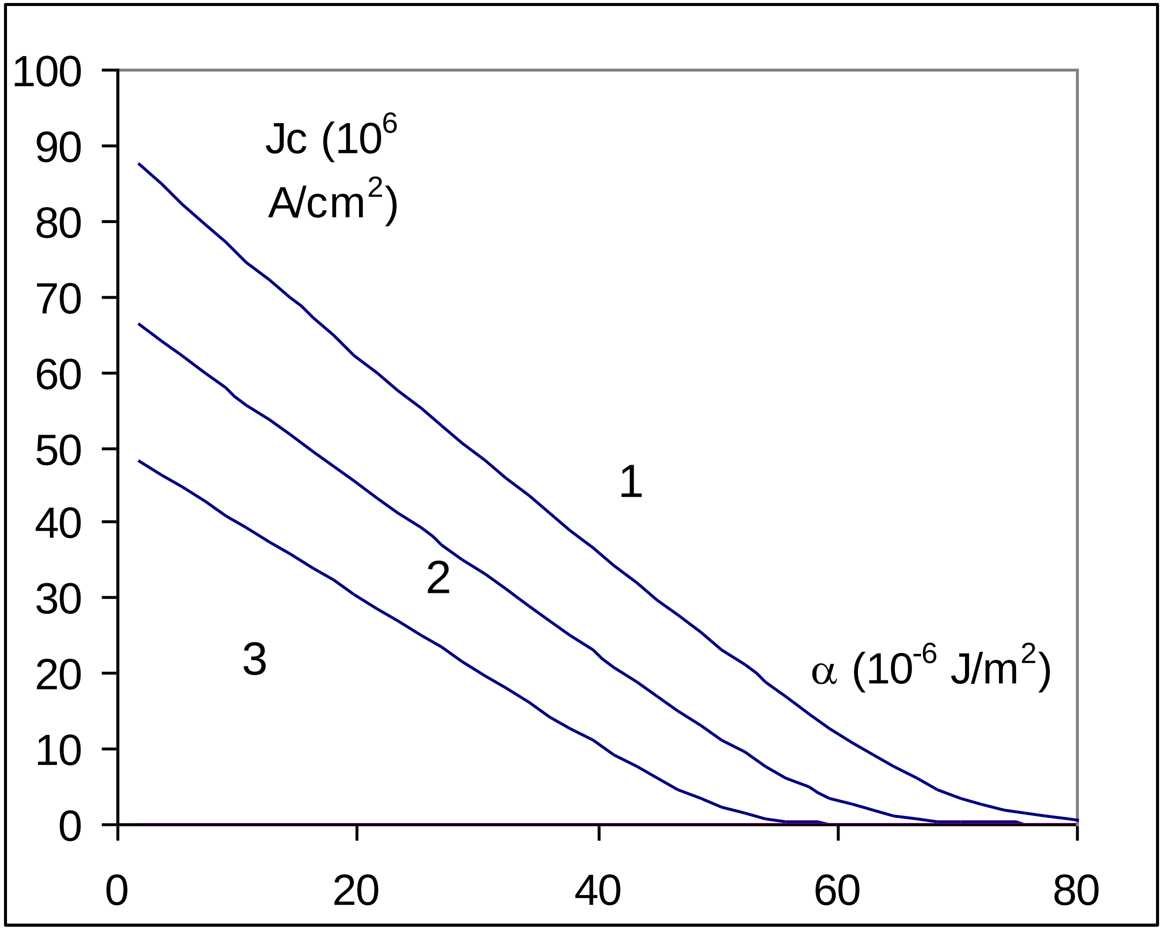
Calculations of renormalized vortex core size in captured vortex

$$\frac{\Phi_1}{\Phi_0} = 1 + \frac{B_e \lambda^2}{\Phi_0} \left[\arcsin\frac{d}{2\lambda} + \frac{d}{2\lambda}\sqrt{1 - \left(\frac{d}{2\lambda}\right)^2} - \frac{d}{\lambda}\cdot\frac{x}{\lambda} \right]$$

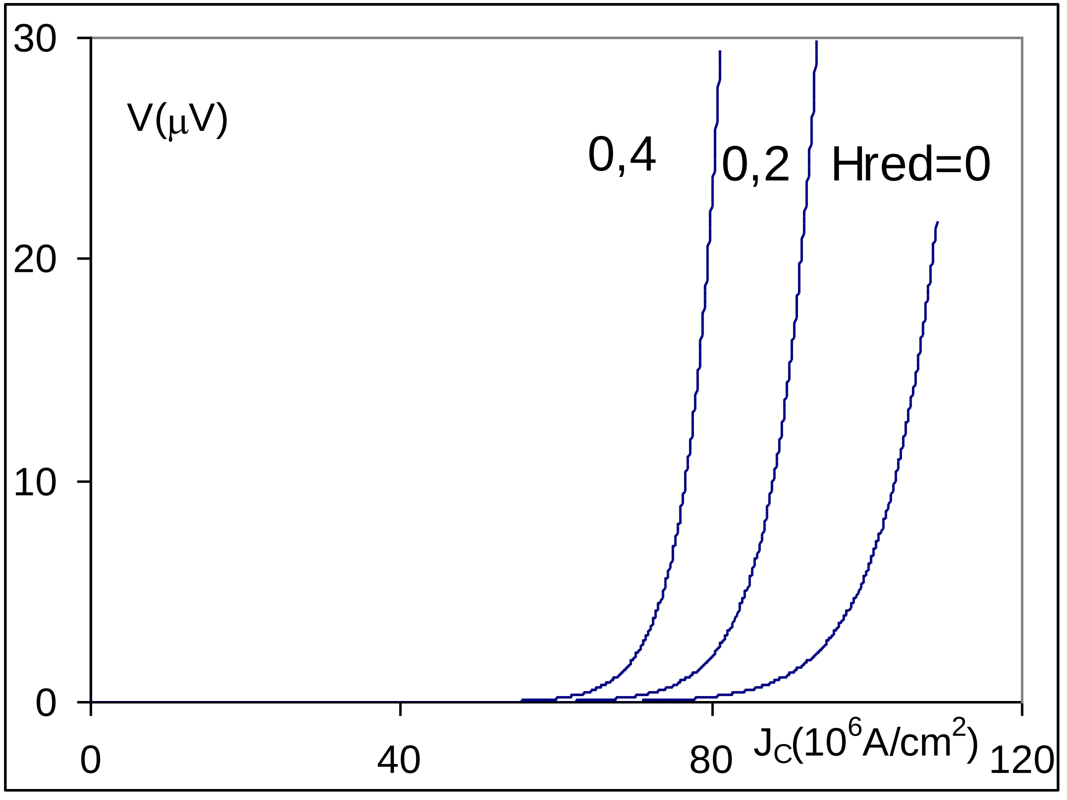
$$\frac{\Phi_1}{\Phi_0} = 1 + \frac{B_e \lambda^2}{\Phi_0} \left[\frac{\pi}{2} - \arcsin\frac{x}{\lambda} - \frac{x}{\lambda}\sqrt{1 - \left(\frac{x}{\lambda}\right)^2} \right] \quad x_{c1} = \lambda\sqrt{1 - \left(\frac{d}{2\lambda}\right)^2}$$

$$\mu_0 H_c = \frac{\Phi_1}{2\pi\lambda^2} \exp\left(-\frac{\xi_1}{\lambda}\right) \quad \mu_0 H_c = \frac{\Phi_0}{2\pi\lambda^2} \exp\left(-\frac{\xi_0}{\lambda}\right) \quad \frac{\xi_1}{\xi_0} = 1 + \kappa \ln\frac{\Phi_1}{\Phi_0}$$

The dependence of the critical current on the rigidity of the vortex lattice, expressed by the parameter α in the function of the magnetic flux Φ_1: (1) $\Phi_1 = \Phi_0$ (2) $\Phi_1 > \Phi_0$ (3) $\Phi_2 > \Phi_1$

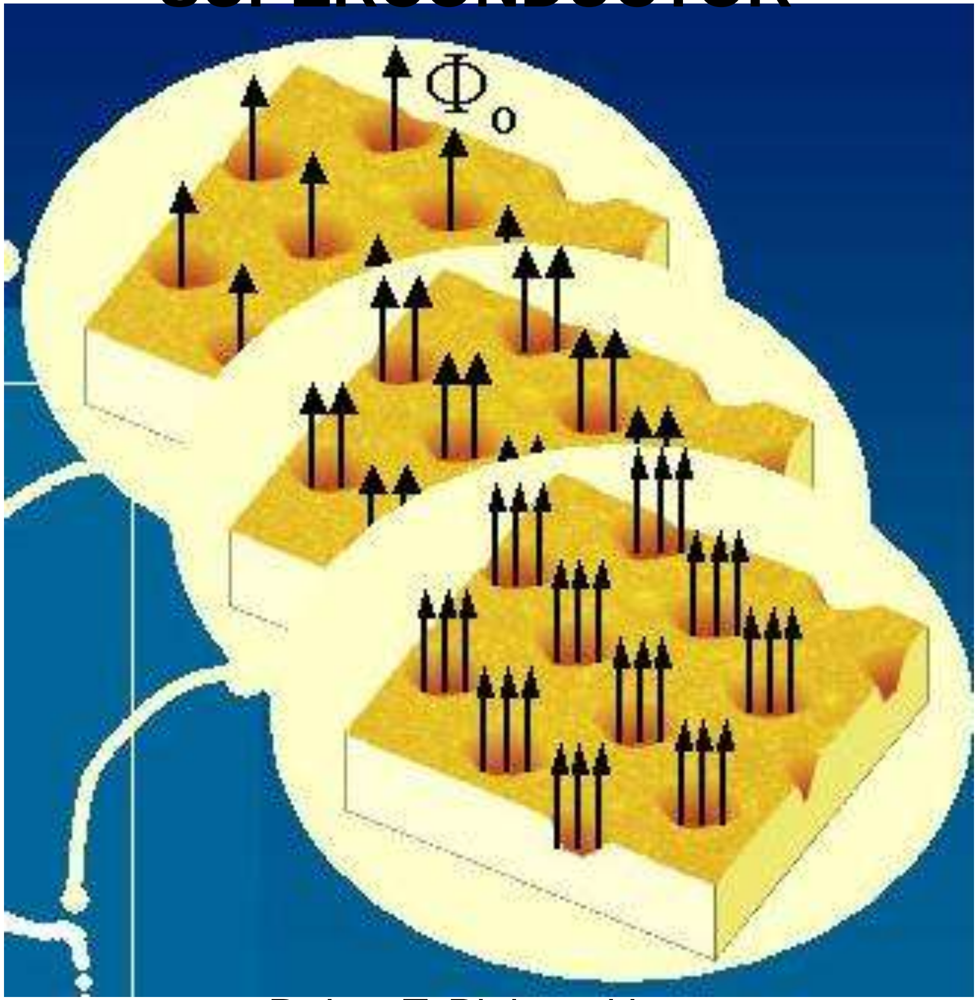


Influence of reduced magnetic field on I-V characteristics



Program wizualizacji dynamiki wirów w nadprzewodnikach

SUPERCONDUCTOR



Dr inż. T. Binkowski

Doc dr. hab. J. Sosnowski

$$\frac{dB}{dt} \propto a \cdot B \cdot p$$

$$p = p_0 \exp\left(-\frac{\Delta U}{k_B T}\right)$$

$$\frac{dB_{av}}{dt} = \frac{2}{k(1+\eta)} a\mu_0 H p_0 \exp\left(-\frac{\Delta U}{k_B T}\right)$$

$$\frac{dM}{dt} = \frac{2}{k(1+\eta)} aHp_0 \exp\left(-\frac{\Delta U}{k_B T}\right)$$

$$\frac{\partial U}{\partial t} = \frac{2aHp_0}{k(1+\eta)\partial M / \partial U} * \exp\left(-\frac{\Delta U}{k_B T}\right)$$

$$\frac{\partial M}{\partial t} = \frac{\partial M}{\partial U} * \frac{\partial U}{\partial t}$$

$$\frac{1}{t_1} = \frac{2aHp_0}{k(1+\eta)k_B T \cdot \partial M / \partial U}$$

$$\Delta U = k_B T \ln(1 + \frac{t}{t_1})$$

$$\Delta U = \frac{\theta\pi}{2} - 2\theta \frac{j}{j_c} \qquad \Theta = \frac{\mu_0 H_c^2}{2} l \xi_a \xi_b$$

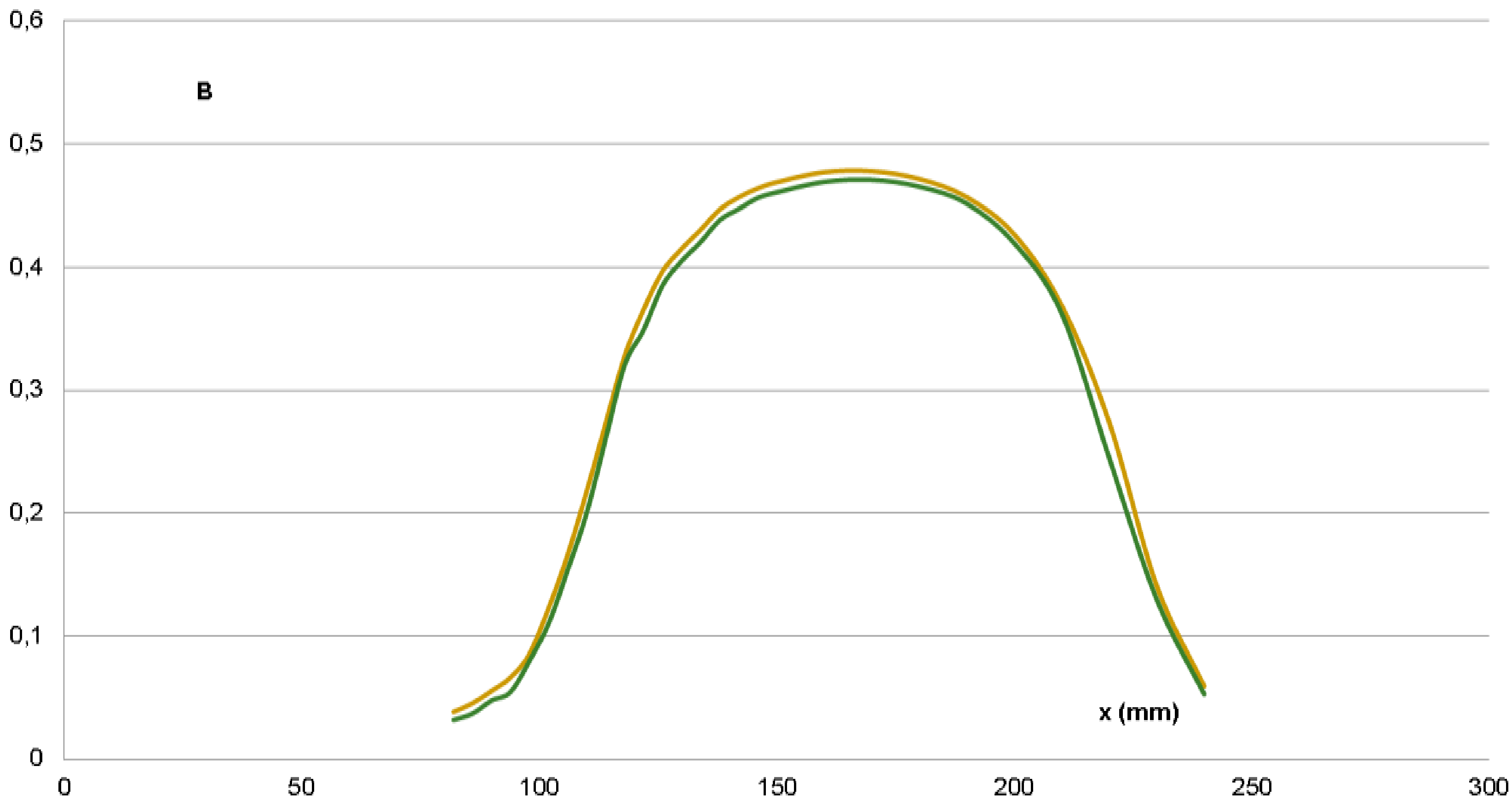
$$M = \frac{jk}{4(1+\eta)}$$

$$M(t) = \frac{kj_c}{8(1+\eta)}\left(\frac{\pi}{2} - \frac{k_B T}{\Theta}\ln(1+\frac{t}{t_1})\right)$$

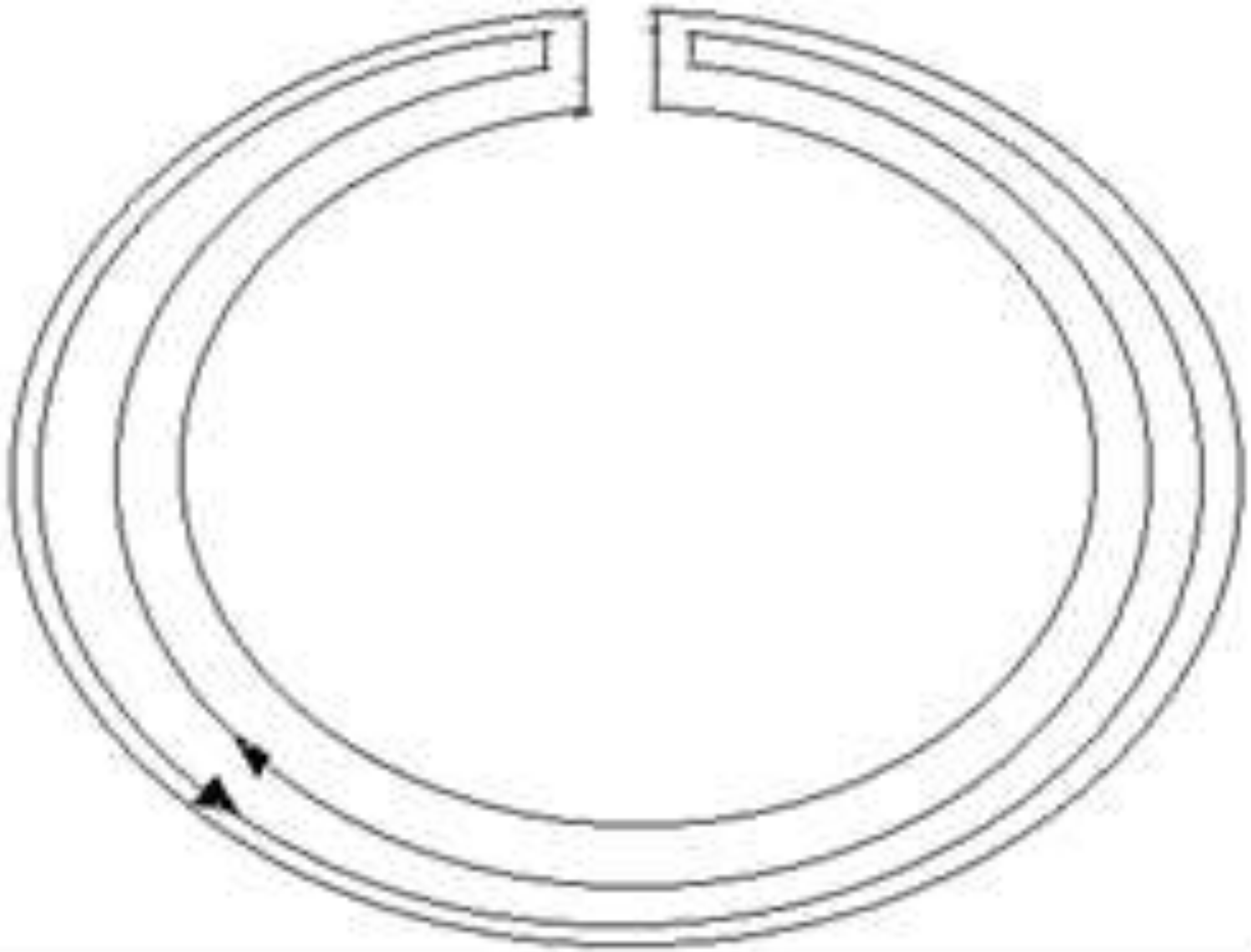
$$j(t)/j(0) = M(t)/M(0) = 1 - \Theta_1 \ln(1+\frac{t}{t_1})$$

$$\Theta_1 = \frac{2k_B T}{\pi\Theta}$$

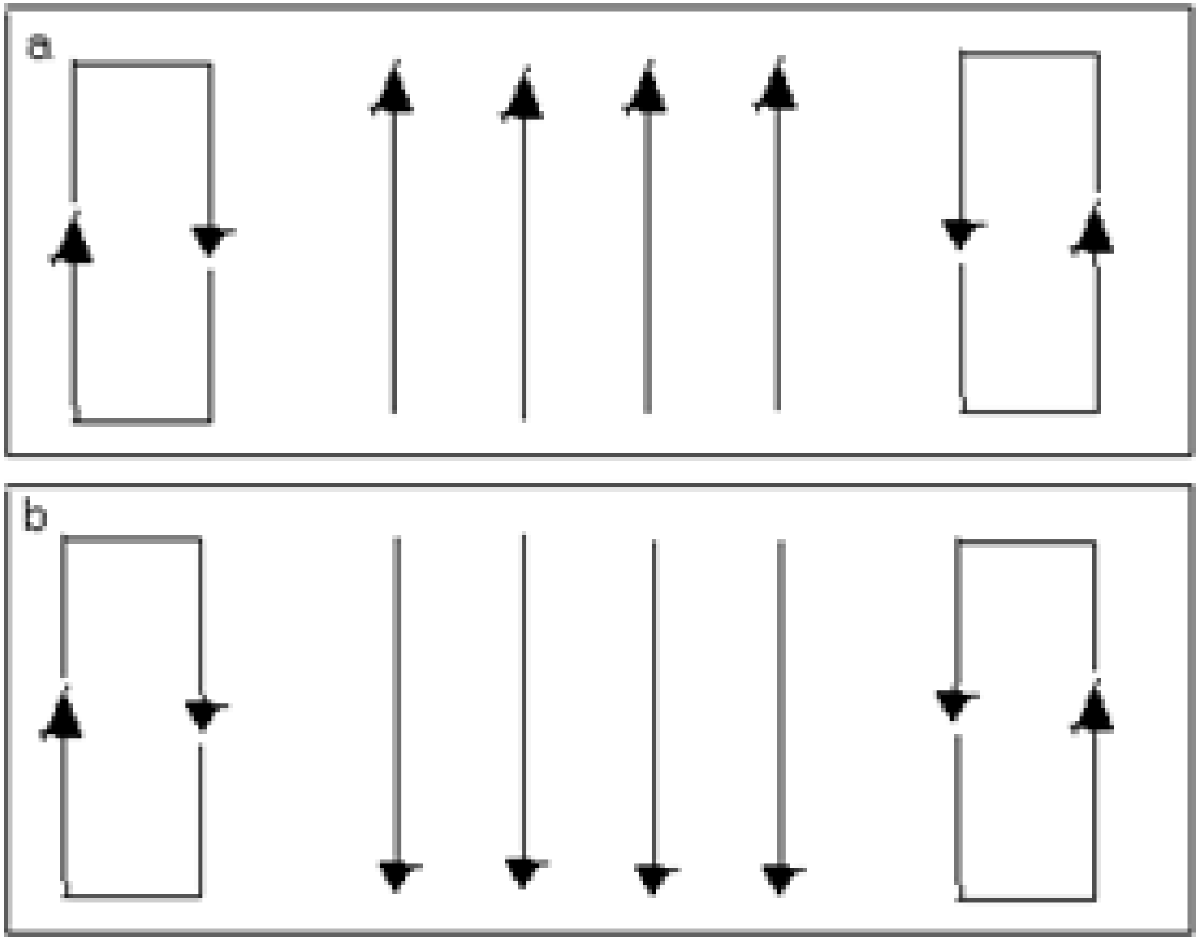
Magnetic induction distribution in coil



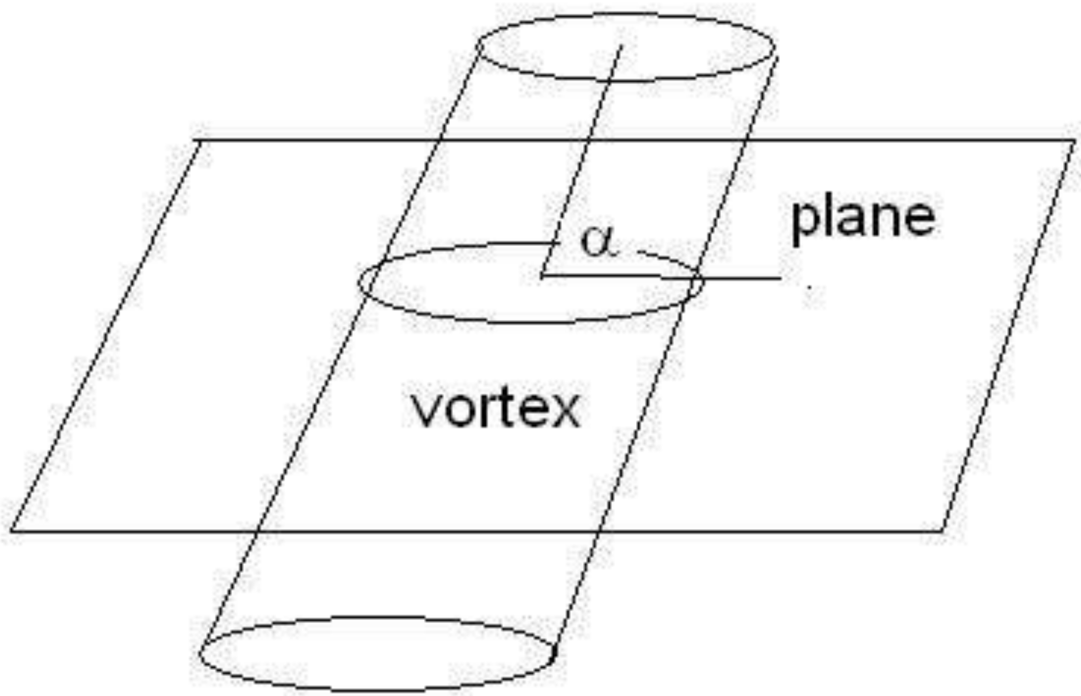
Cross-section of the opened superconducting shield, with screening current of the direction indicated by arrows



Shielding current distribution in the upper (a) and bottom (b) cover of the superconducting opened shield



Tilted magnetic field and radiational defects leading to vortex anisotropy



Dynamic penetration of vortices

$$\frac{\partial B}{\partial t} = \frac{1}{D}\frac{\partial^2 B}{\partial x^2}$$

$$B(x,t) = \frac{D\dot{B}}{2}x^2 + bx + B(t)$$

$$\partial B / \partial x = D\dot{B}x + b \qquad b = -\alpha D\dot{B} / B$$

$$t_1 = \frac{-(0{,}5D\dot{B}x_{\text{м}}^2 + \Delta B) + \sqrt{\left(\frac{D\dot{B}x_{\text{м}}^2}{2} + \Delta B\right)^2 + 4D\dot{B}\alpha x_{\text{м}}}}{2\dot{B}}$$

Time t of transition to saturated case

$$x_1 = \frac{\alpha}{B} - \frac{1}{\dot{B}}\sqrt{\left(\frac{\alpha}{f}\right)^2 - \frac{2\dot{B}}{D}(B + \Delta B)}$$

$$x_c = x_m + \frac{\Delta B}{D\left(\frac{\alpha}{f} - \dot{B}x_m\right)}$$

$$D\left(x_m + \frac{\Delta B t_2}{D\alpha - x_m \dot{B} t_2}\right)\left(\dot{B}\left(x_m + \frac{\Delta B t_2}{D\alpha - x_m \dot{B} t_2}\right) - \frac{2\alpha}{t_2}\right) + 2\left(\dot{B}t_2 + \Delta B\right) = 0$$

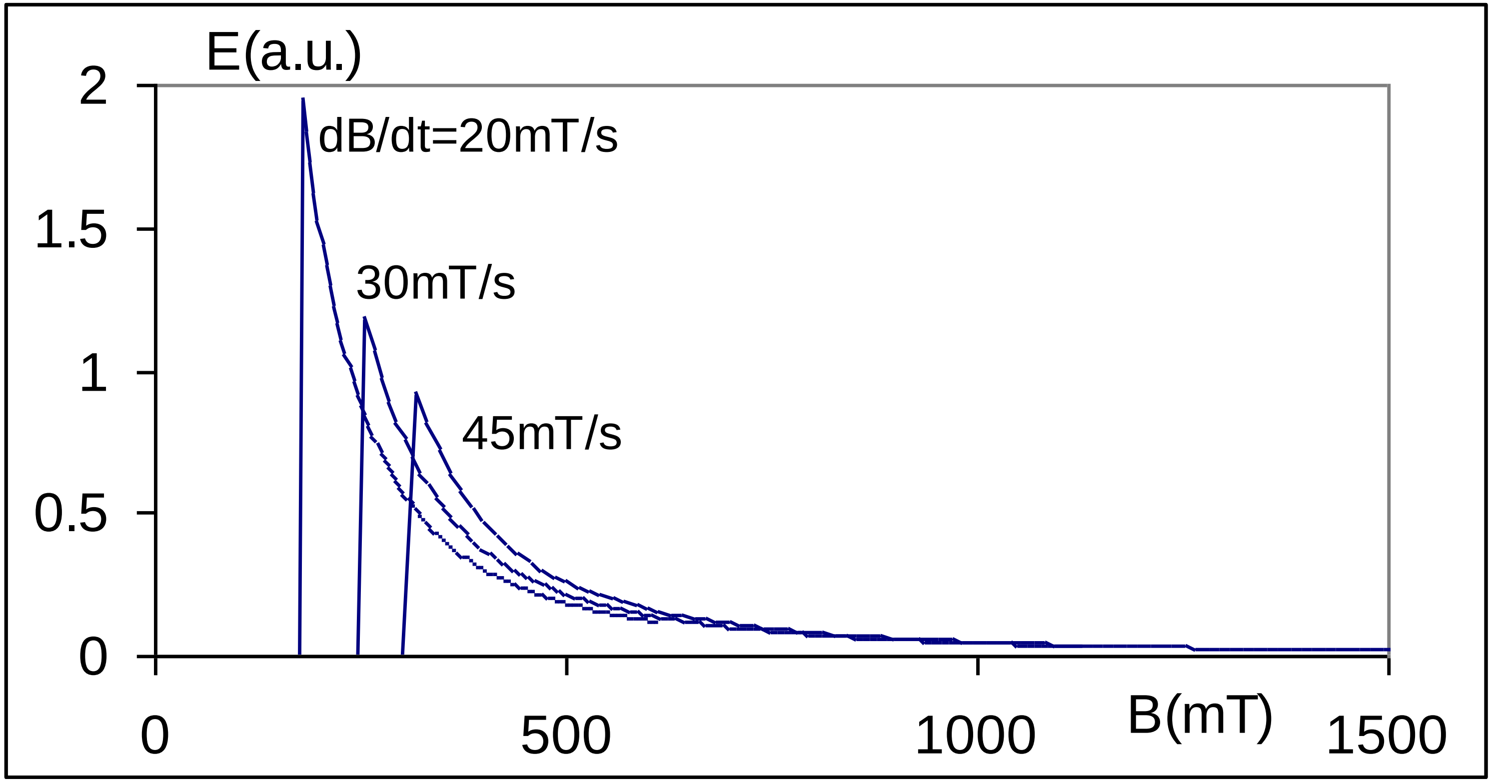
Dynamical electric fields in non-saturated and saturated cases

$$E = \frac{1}{(\dot{B}t)^4}\left[\dot{B}^3 x_m t^4 + \frac{\dot{B}^2 D\alpha x_m^2 t^2}{2} + \dot{B}\alpha\Delta B t^2 - D\alpha^3 + (\dot{B}^2 t^3 + D\alpha^2)\sqrt{\frac{D\alpha^2 - 2\dot{B}^2 t^3 - 2\dot{B}\Delta B t^2}{D}}\right]$$

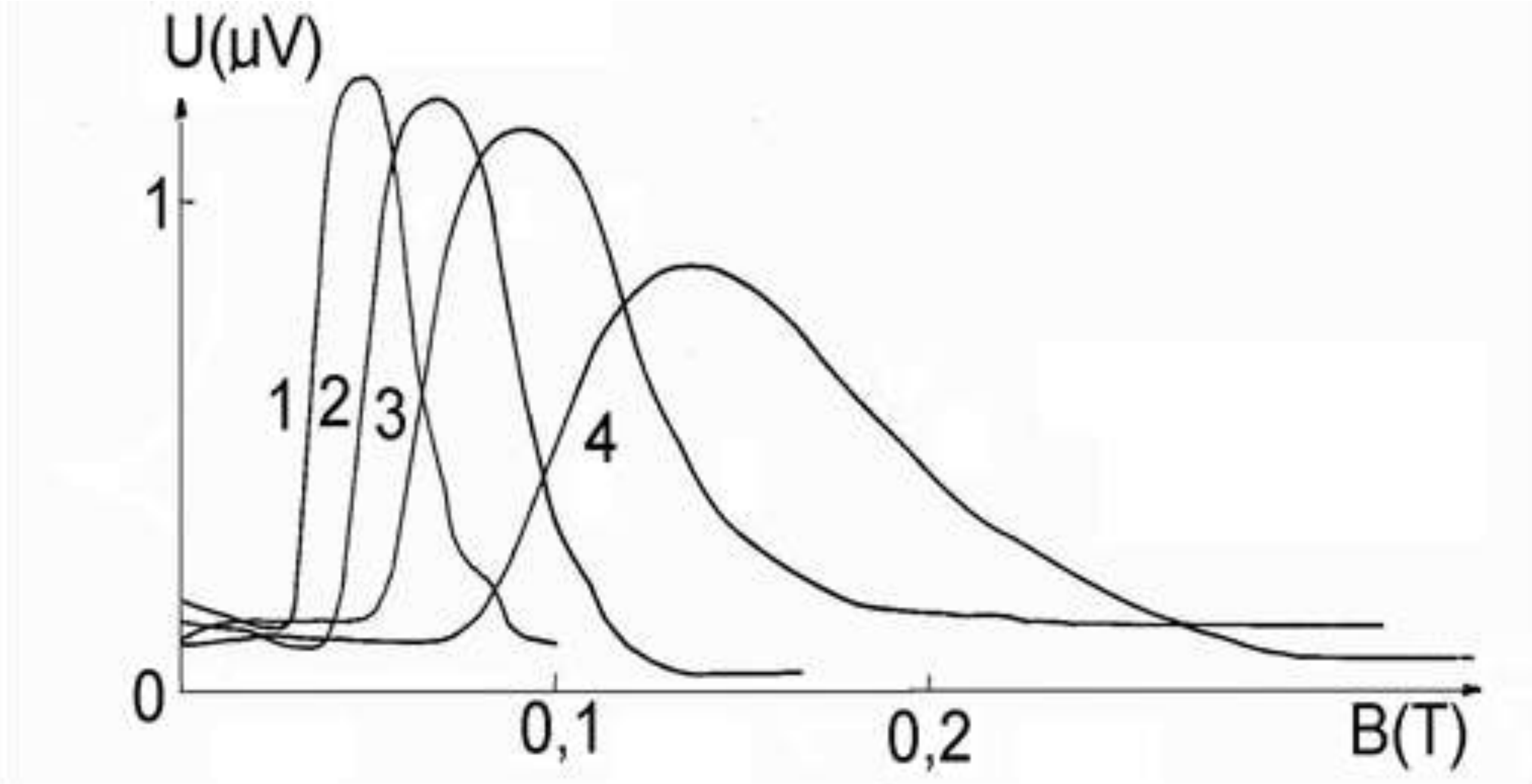
$$E = \frac{\alpha\Delta B}{2D^2 x_m (Bx_m \dot{t} - \alpha)^4}\left\langle \begin{array}{l} B^3 D^2 x_m^5 t^2 - B^2 D x_m^2 t(2D\alpha x_m^2 + \dot{t}(2\alpha + \Delta B x_m) + \\ Bx_m\left[D^2\alpha^2 x_m^2 + 2D\alpha t(2\alpha + \Delta B x_m) - (\Delta B t)^2\right] - D\alpha^2(2\alpha + \Delta B x_m) \end{array} \right\rangle$$

$$+ \frac{\Delta B}{Dx_m}$$

Influence of magnetic field sweep rate on I-V curves defected sample



Measured dynamical anomalies of the I-V curves on YBaCuO superconductor for various values of the linearly sweeping magnetic field: (1) 1 mT/s, (2) 5 mT/s, (3) 10 mT/s, (4) 15 mT/s.



$$\mu_0 j_c = \pm \frac{\alpha}{\left(B(x) + B^0\right)^{\gamma}}$$

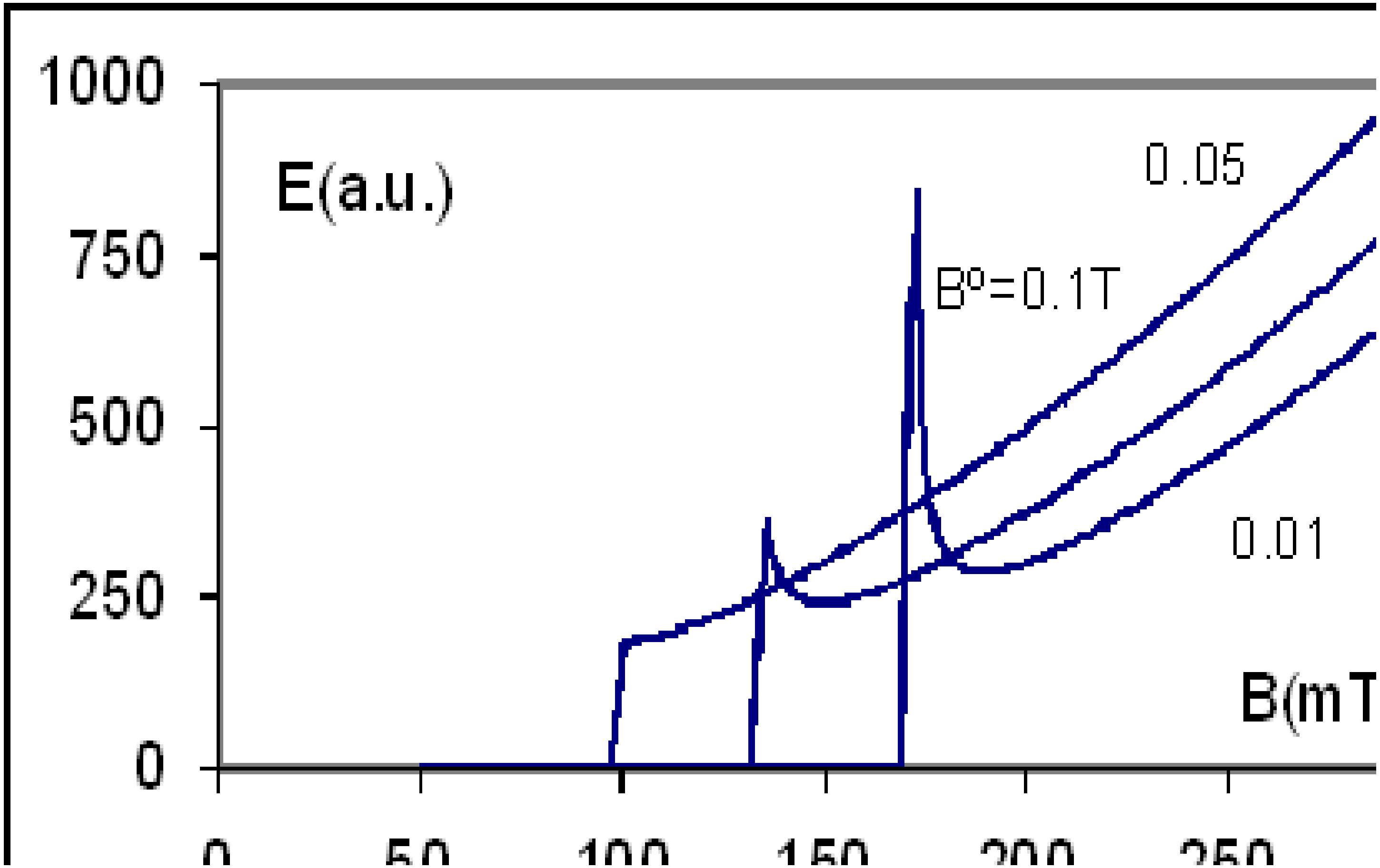
$$E = \frac{\dot{B}}{\alpha}\left(B + \Delta B + B^0\right)^{\gamma} \cdot \left\langle \left[\left(B + \Delta B + B^0\right)^{1+\gamma} - \alpha(1+\gamma)x_1\right]^{\frac{1}{1+\gamma}} - B^0 \right\rangle$$

$$E = \frac{\dot{B}}{\alpha}\left\langle \left(B + \Delta B + B^0\right)^{\gamma} \cdot \left(\left[\left(B + \Delta B + B^0\right)^{1+\gamma} - \alpha(1+\gamma)x_1\right]^{\frac{1}{1+\gamma}} - B_{av}(x_m)\right) + B^{\otimes}\left(B_{av}(x_m) - B^0\right)\right\rangle$$

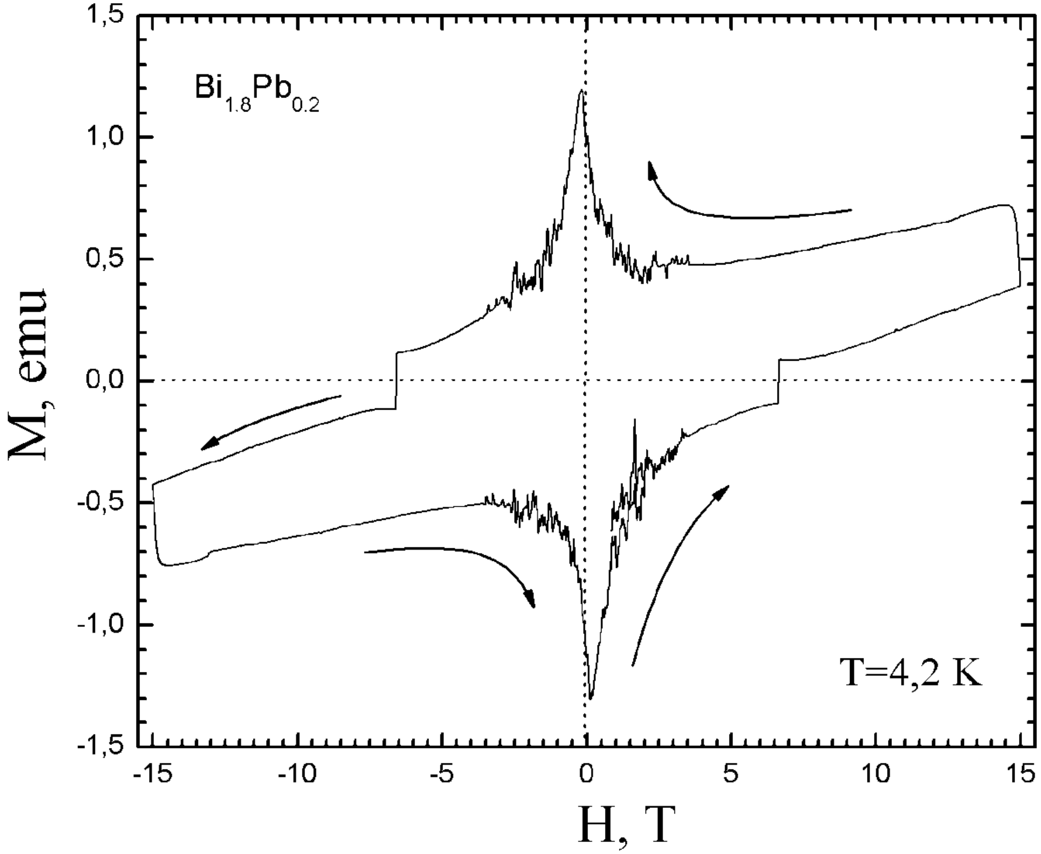
$$B^{\otimes} = \frac{\left(B + \Delta B + B^0\right)^{\gamma} - \left(B - \Delta B + B^0\right)^{\gamma}}{2}$$

$$B_{av}(x_m) = \left[\frac{\left(B + \Delta B + B^0\right)^{1+\gamma} + \left(B - \Delta B + B^0\right)^{1+\gamma}}{2} - \alpha(1+\gamma)x_m\right]^{\frac{1}{1+\gamma}}$$

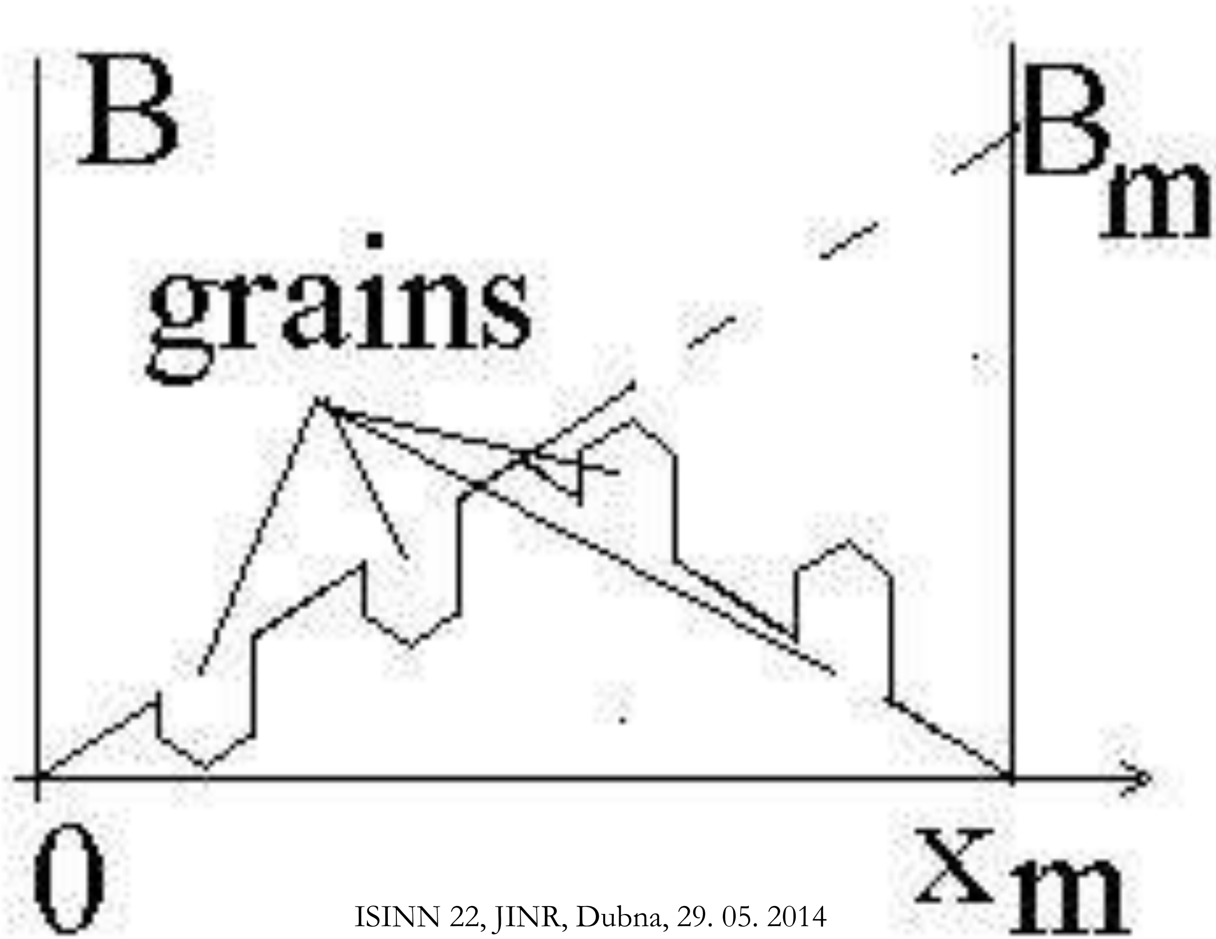
Influence of material, magnetic parameter B0 on dynamic I-V curves anomalies in slowly varying magnetic field.



Experimental magnetization curve for prepared $Bi_{1,8}Pb_{0,2}$ SCCO



Influence of inhomogeneous structure in irradiated superconductor on induction profiles



Flux trapping Ftr for cylindrical sample

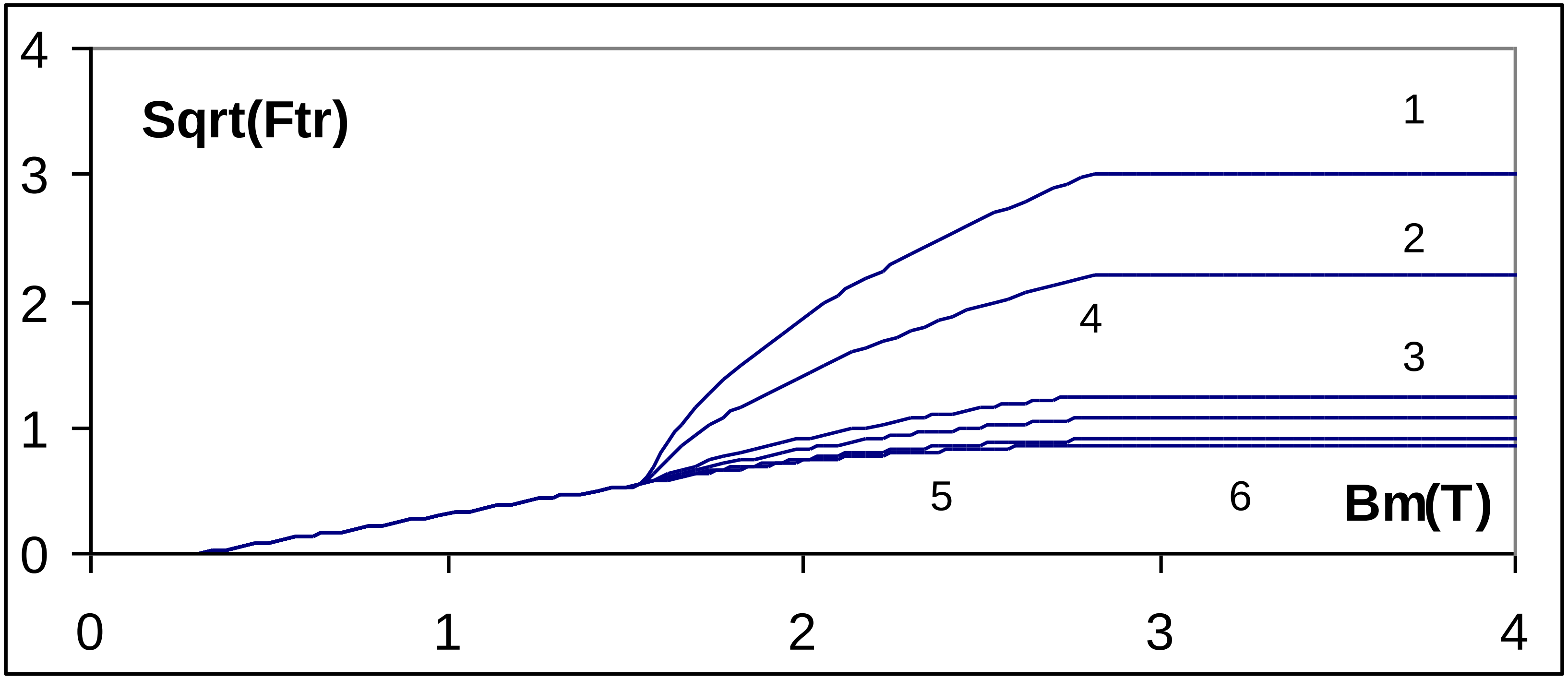
- $$F_{tr} = \frac{B_m^{1^2}}{2\xi^2}\left[\xi - \frac{B_m^1}{2} + nB_{sg}\right]$$

$$\xi = \mu_0 j_c R \qquad B_{sg} = Bc_{1g} + \frac{\xi g}{3} \qquad 2\xi \geq B_e^1 \geq \xi$$

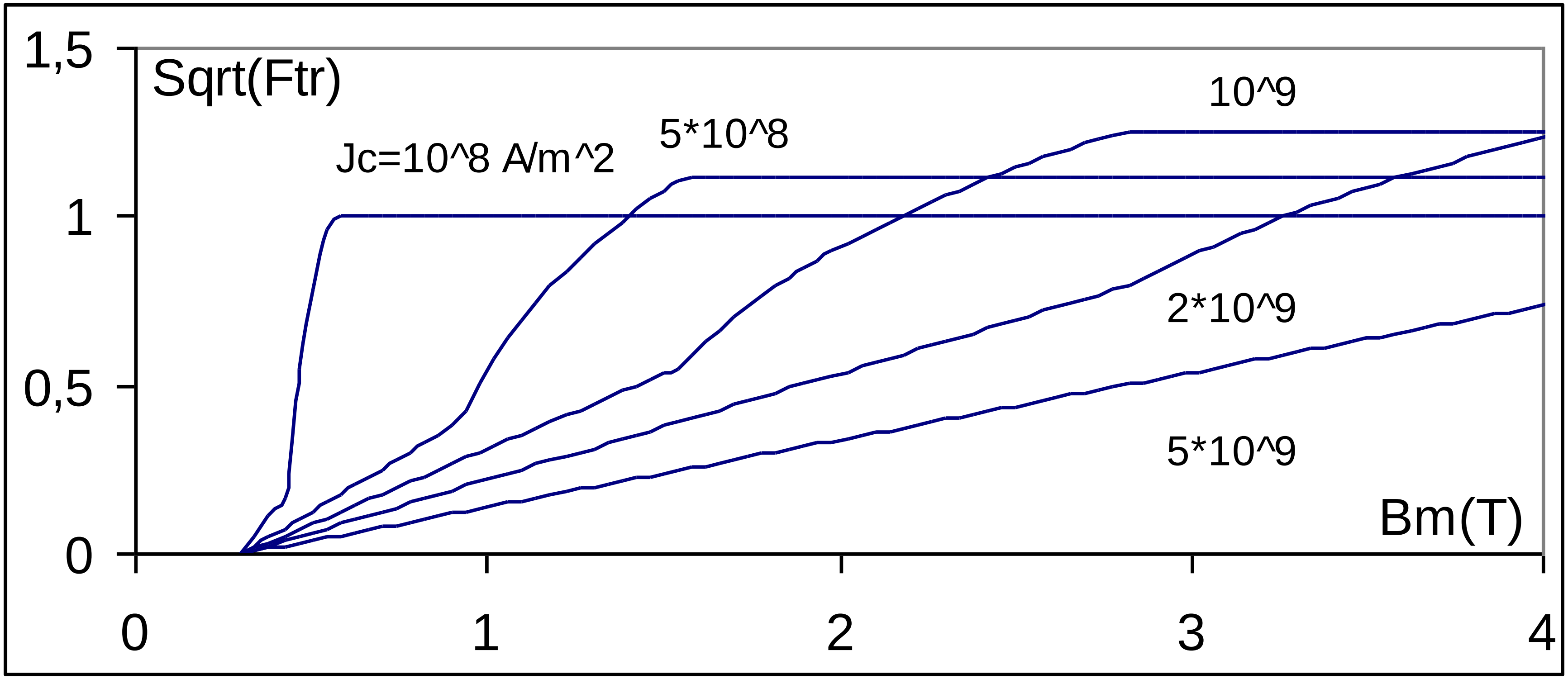
$$F_{tr} = \frac{2nB_{\lambda g}}{\xi^2}\left(B_e^1\xi - \frac{\xi^2}{2} - \frac{B_e^1}{4}\right) + \frac{2\xi}{3}\left(\frac{1}{2} - \left(1 - \frac{B_e^1}{2\xi}\right)^3\right)$$

$$B_e^1 \geq 2\xi \qquad F_{tr} = \frac{\xi}{3} + nB_{1g}$$

Dependence of the flux trapping in superconducting plate on maximal magnetic induction in the cycle for various critical current density inside the irradiated regions Subsequent curves refer to the following current densities: (1) $j_{cq} = 10^{12}$, (2) $5*10^{11}$, (3) 10^{11}, (4) $5*10^{10}$, (5) 10^{10}, (6) $5* 10^{9}$ A/m^2



Dependence of the square root of the flux trapping in superconducting plate on maximal magnetic induction in the cycle Ftr for various critical current density inside the superconducting matrix.



Ftr taking into account surface barrier

$$B_{c1} + 2\Delta B \le B_{\max} \le j_c R + B_{c1} + \Delta B$$

$$B_{c1} + \Delta B \le B_{\max} \le B_{c1} + 2\Delta B \qquad B = B_{\max} - B_{c1} - \Delta B$$

$$F_{tr} = \frac{j_c}{R^2}\left[\frac{\left(R + \frac{B}{j_c}\right)^3}{3} + R^2\left(\frac{B}{j_c} - \frac{R}{3}\right)\right] \qquad B_{c1} + \Delta B + j_c R \le B_{\max} \le B_{c1} + \Delta B + 2 j_c R$$

$$F_{tr} = \frac{1}{6R^2 j_c}\left[3R\left(B^2 - \Delta B^2 + 2\Delta B\right) - \frac{\Delta B^3 + 3B\left(B\Delta B + B^2 - \Delta B^2\right)}{2 j_c}\right]$$

Experimental situation

It was experimentally stated that critical current of HTc superconductors is dependent on the availability of defects created among other by fast neutrons or swift heavy ions tracks of the energy loss larger than 5-10 keV/nm. These tracks arise as the result of direct bombarding HTc superconductors by the fast neutrons or in the indirect process of collision neutrons with introduced into HTc superconductor uranium atoms or their mixture $U^{235, 238}$ leading to the fission. Length of the tracks called sometimes columnar defects, is of 4-7 μm, while diameter 2-8 nm. In nuclear accelerators not only emitted fast neutrons interact with superconductors.

- Generated electrons of energy larger than 0,1 MeV and light ions penetrating with linear energy loss $dE/dx \approx$ 2-5 keV/nm lead to creation of nano-defects influencing critical current, without fission of nuclei. Also heavy ions of energy loss 5-10 keV/nm with optimal dose in the range 10^{11} - 10^{12} cm^{-2}, create such tracks acting as pinning centers. For HTc doped with U^{235} atoms, neutrons bombardment leads to fission effect. Cross-section is 582 barns (1 barn = 10^{-24} cm^2), optimal irradiation dose 1-12 10^{16} cm^{-2}. Neutrons of energy larger than 1,4 MeV, bombarding U^{238} atoms, of cross-section 0,6 barns are most effective for fluencies larger than 10^{18} cm^{-2}.

- Also other radiation, as gamma quanta, of energy larger than 15 MeV produce tracks in the process of fission of U^{238} atoms. Cross-section of this process is 0,15 barn. Radiation of very fast particles, as protons, deuterons of energy 200-1000 MeV may lead to fission of heavy metals being intrinsic component of HTc superconductors: Bi, Pb, Tl, Hg. The cross-section of this process is 0,1 – 0,15 barn, while optimal fluence 10^{17} cm^{-2}. There are some experimental data on influence of thermal neutrons on optimal critical current and flux trapped in YBaCuO samples polycrystalline and melt-textured uranium doped. The mixture of U^{235} and U^{238} was used. Under thermal neutrons bombardment the fission of atoms U^{235} arises.

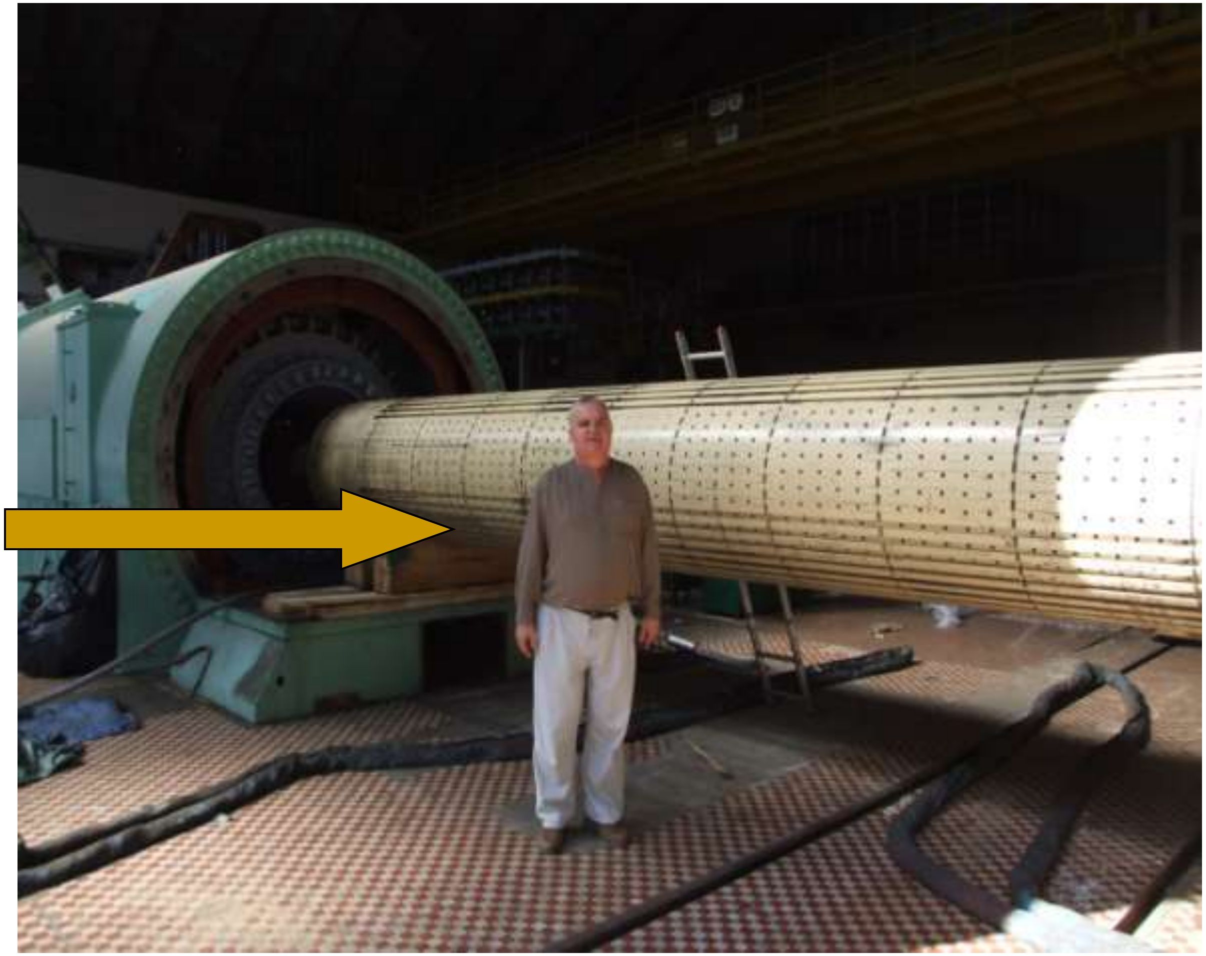
- **The problem is radioactivity of the irradiated samples.**
- Only the heavy ions of the energy lower than Coulomb barrier don't lead to radioactivity. Other forms of irradiations produces isotopes which may emit gamma rays of energy 0,1 – 2,5 MeV, while in fission process arise also new isotopes of various times of decay. Neutrons irradiation of HTc superconducting tapes of the YBaCuO/Ag composition, as it has the place in the second generation tapes, leads to the generation of the radioactivity from the ^{133}Ba atoms, of the concentration 15-25 %, time of decay is 10,5 years of the intensity for the mass of one gram 500 decays/second = 0,5 kBq/g.

- Doping with Uranium^{235} atoms increases radioactivity level, which is in agreement with experimental data observing radioactivity of such sample on the level of 7,4 kBq/g, after half year. HTc superconducting tapes obviously are covered or immersed into Ag matrix. This matrix also can lead to radioactivity effect during neutrons irradiation. In combined thermal neutrons and gamma radiation effect the ^{109}Ag atoms which occur in 49% of natural silver are transformed into ^{110}Ag radioactive atoms with time of half-decay 250 days. For Bi:2223 tape doped with 0,3 wg. % uranium it was experimentally observed radiation of 9000 kBq/g from Ag matrix, 80 kBq/g from Bi:2223 and 18 kBq/g from fission elements. Using fast neutrons instead of thermal is one method of increasing number of nano-defects and critical current, reducing too the radioactivity, because fast neutrons do not produce radioactive isotope ^{110}Ag.

To avoid such problems as below of quench in superconducting devices, as accelerators our knowledge on the influence of fast neutrons and heavy ions irradiation on HTc superconductors should be also accelereted

Заключение

It has been analyzed the influence of nanodefects caused by fast neutrons irradiation on the critical current of superconduc-tors.Too large concen-tration of irradiation defects decreases critical current, while generally irradiation influences current capability of superconductors. Understanding of function of nano-sized defects created by ineutrons rradiation is very important for using HTc in nuclear devices.



- Optimal parameters of thermal neutrons irradiation are $2x10^{18}$ cm^{-2} for polycrystalline sample doped U and 10^{17} cm^{-2} for melt-textured sample U doped. The fission of U atoms intensity which is created then reaches $2,5x10^{14}$ cm^{-2} for polycrystalline sample leading to increase of critical current. For melt textured YBaCuO sample optimal thermal neutron concentration is of the order 10^{17} cm^{-2}, which leads to the fission of the uranium atoms of the range 10^{15} cm^{-2} , while maximal critical current density increases in irradiated samples and remanent magnetic moment increases about five times.