Effect of anisotropy on the current-voltage characteristics of layered high-temperature superconductors with internal ferromagnetic defects

V.A. Kashurnikov, A.N. Maksimova, I.A. Rudnev, D.S. Odintsov
National Research Nuclear University MEPhI (Moscow Engineering Physics Institute)
115409, Kashirskoe shosse, 31, Moscow, Russia

Abstract. Dynamic of the three-dimensional vortex system in layered high-temperature superconductors with internal nanosized ferromagnetic defects has been studied by using Monte Carlo simulations. Magnetization processes in the array of ferromagnetic defects under the field of Abrikosov vortices have been taken into account. The current-voltage characteristics under applying of external dc magnetic field have been obtained. It has been shown that S-type nonlinearity of E(J) curve which have been obtained previously for two-dimensional vortex system also appears in this more realistic anisotropic three-dimensional case. The effect of vortex-vortex inter-layer coupling on the S-nonlinearity has been analyzed.

1. Introduction
The effect of nanosized particles as pinning centers on magnetic and transport properties of high-temperature superconductors has been widely analyzed till recent time. To improve the transport properties, the ferromagnetic nanoparticles as pinning centers can be used due to additional interaction energy between vortex and magnetic moment of the nanoparticle [1-3]. The superconductor-ferromagnet multilayers are also fabricated to study the mutual influence of vortices and domain walls and to analyze the transport properties of such structures [4-7]. Spherical and ellipsoidal magnetic particles have been used as pinning centers in [1-2]. In the frame of London approximation the interaction energy between vortex and nanoparticle was obtained and the increase in critical current (estimated from the width of magnetization loop) was demonstrated. The authors of Ref. [3] considered the ensemble of ferromagnetic particles inside superconductor and the vortex lattice as a self-consistent system and numerically demonstrated some new effects, such as S-type nonlinearity on current-voltage characteristic, due to magnetization reversal of nanoparticles and the enhancement of critical current under certain conditions. Superconductor-ferromagnet multilayers are also widely studied. Formation of domain structure in ferromagnetic layer and interaction of vortex lattice with domain walls give additional opportunities for vortex pinning and tuning superconductive properties. The effect of magnetic-domain geometry on vortex pinning and, therefore, magnetic flux penetration and critical current was studied [4], the hysteretic vortex pinning in superconductor-ferromagnet multilayer was demonstrated [5]. The effect of domain wall width was also analyzed [6,7]. Thus, the study of ferromagnetic inclusions in the superconductor and superconductor-ferromagnet hybrid structures are subject of a sufficient practical interest. Since it seems difficult to fabricate
superconductive samples with ferromagnetic inclusions of given parameters, the numerical simulations might be useful. A macroscopic magnetic inclusion can be represented by an ensemble of nanosized ferromagnetic particle with a magnetic moment or by effective potential profile for vortices. In this paper, we perform Monte Carlo simulations for three-dimensional layered high-temperature superconductor with nanosized ferromagnetic defects magnetized with self field of transport current in presence of external dc magnetic field.

2. Model and simulation results

We performed our simulations within three-dimensional model of layered high-temperature superconductor [8] by using Monte Carlo method. This model represents a vortex line as a stack of interacting planar vortices (pancakes). The Gibbs thermodynamic potential incorporates various types of in-plane interaction and inter-plane interaction. The details of simulation method for one superconducting layer have been previously reported in [9-11].

To provide artificial pinning centers, we used nanosized ferromagnetic particles as internal defects. The size of individual nanoparticle is much less than the average size of ferromagnetic domain so that such a particle can be described as a magnetic moment with a constant absolute value and variable direction. The direction of each moment depends on local magnetic field and so that is related to local vortex configuration near magnetic defect. For simulations, we describe superconductor and ferromagnetic particles as a self-consistent system and introduce an additional process – reorientation of magnetic moment – into Monte Carlo algorithm which was previously reported by us in [12,13].

We calculated current-voltage characteristics using method developed in [11] for three-dimensional Bi$_2$Sr$_2$CaCu$_2$O$_{8-\delta}$ slab at temperature range 1-10 K. Ferromagnetic nanoparticles have a size about several $\xi$, the magnetic moments of the particles are of order of $10^3$ - $10^4$ Bohr magnetons, which is typical for ferromagnetic materials. We suggest that the direction and absolute value of the magnetization of the particles change within the magnetization process depending on local field of Abrikosov vortices. The superconducting slab has a finite size $L$ in $x$ direction and periodic boundary conditions with period $b$ in $y$ direction and with period $N_L d$, where $d=2.7$ nm is a thickness of a superconducting layer, in $z$ direction. In our simulations $L=5$ $\mu$m and $b=3$ $\mu$m that is much larger than characteristic distances at which vortices interact. We considered a three-dimensional superconducting slab which contains $N_L \sim 10$ superconducting CuO$_2$ layers. In our algorithm, the production of vortex line containing less than $N_L$ pancakes is allowed.

Let us consider a superconducting slab with internal ferromagnetic defects.

Fig.1. Current-voltage characteristics of anisotropic layered superconductor with internal ferromagnetic defects under applying external dc magnetic field. $\mu$ is magnetic moment if individual particle, $\mu_b$ is Bohr magneton, $\gamma$ is anisotropy parameter.
Fig. 1 represents the current-voltage characteristics in the presence of external dc magnetic field at different anisotropy parameters. One can easily see that in the case of high anisotropy ($\gamma=250$) the $j(E)$ curves at magnetic field $H>200$ Gs have S-type nonlinearity reported by us in [13]. However, in the case of low anisotropy the nonlinearity is less pronounced. To explain qualitatively this fact, we consider a periodic lattice of point ferromagnetic defects with variable period in the $x$ direction (which is perpendicular to the direction in which vortices penetrate into the slab, fig. 2(a)). The vortex which appears at the boundary interacts approximately with two nearest magnetic defects and two vortices pinned by them. The resulting interaction potentials at three different periods $a$ in $x$ direction (magnetic particles are fully magnetized) are plotted in fig. 2(b). It is easy to see that for $a=220$ nm and $a=250$ nm there is a potential barrier for the vortex and for $a=300$ nm the barrier is absent and vortices easily penetrates deep into the slab. Due to our quantitative explanation [13], the barrier is essential for S-type nonlinearity. $j(E)$ curves in fig. 1 were obtained for $a=300$ nm. The nonlinearity at $\gamma=250$ appears in this case is due to additional pinning of incomplete vortex lines on the boundary. In fig. 3 the current-voltage characteristics at $a=250$ nm are shown.

![Diagram of a vortex moving from the boundary](image1)

**Fig. 2.** The plot of interaction potential for vortex moving between two magnetic defects with pinned vortices. Vortex moves antiparallel to $x$-axis.

![Comparison of $j(E)$ curves](image2)

**Fig. 3.** Current-voltage characteristics for superconductor with high anisotropy ($a=250$ nm).
3. Conclusion
In conclusion, a description of ferromagnetic nanoparticles with variable magnetization as internal pinning centers was introduced into three-dimensional model of layered high-temperature superconductor. The magnetization of such a superconductor with self-field of transport current under application of dc magnetic field was considered, the current-voltage characteristics were obtained. It was shown that the S-type nonlinearity obtained previously in two-dimensional model remains in more realistic three-dimensional case.

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