Vortex clusters in intertype and ferromagnetic superconductors in Monte Carlo approach

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В настоящее время представляет интерес изучение магнитных свойств ВТСП на мезоскопическом уровне. Одним из лучших методов численного моделирования в таких случаях является метод Монте-Карло. В нашей работе предпринята попытка применить этот алгоритм к некоторым необычным сверхпроводникам. Проведено исследование с 2 различными потенциалами взаимодействия вихрь-вихрь. Первый может представлять интертипный ВТСП, а второй соответствует ферромагнитным сверхпроводникам. Были смоделированы распределение магнитного поля и кривые намагничивания. Кроме того, проведено исследование поведения вихревых кластеров с различными конфигурациями дефектов. Что касается ферромагнитных сверхпроводников, то исследована зависимость распределения поля от магнитной восприимчивости.

Currently, it is of interest to study the magnetic properties of HTSC at the mesoscopic level. One of the best methods of numerical modeling in such cases is the Monte Carlo method. In our work, an attempt is made to apply this algorithm to some unconventional superconductors. The survey with 2 different vortex-vortex interaction potentials was carried out. The first one can represent intertype HTSC, and the second one corresponds to ferromagnetic superconductors. Magnetic field distribution and magnetization curves were modeled. Moreover, the study of behavior of vortex clusters with various configurations of defects was conducted. As for ferromagnetic superconductors, the dependence of the field distribution on magnetic susceptibility has been investigated.

PACS: 44.25.+f; 44.90.+c

Introduction

At present, the development and study of the properties of unusual superconductors is actively underway. Of particular interest are, firstly, the so-called intertype superconductors (Ginzburg-Landau parameter $\kappa \sim \frac{1}{\sqrt{2}}$), in which the partial overlap of the vortex cores, which promotes attraction, competes with repulsion due to the screening supercurrents they create. All this leads to the complication of phase diagrams and the appearance of clusters, chains of vortices. It is known that the superconducting and magnetic subsystems conflict and suppress each other. Nevertheless, it turns out that unusual effects can be obtained locally. In studies of ferromagnetic superconductors [1–3] vortex clusters were also obtained. Such clustering processes occur in such intertype and ferromagnetic HTSCs as MgB_2, LuB_{12}, ZrB_{12} [4, 5]. In the last few years, attempts have been made to develop a

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general theory for the data obtained, but the submicron level [6], the formation of a single cluster or a chain of several vortices, were mainly considered, which does not allow us to reconcile or compare the predictions of modeling and experiment. At the same time, these superconductors are increasingly used in experimental studies, since they have prospects in microelectronics and spintronics. An effective method for studying such systems with complex phase diagrams, especially in the presence of pinning centers, is the Monte Carlo method. This work is devoted to the application of this method to unusual superconductors and the study of their magnetic properties.

Model and Results

In our work we model a two-dimensional plate, which is an approximation of the behavior of the system under high anisotropy.(See, for instance, [7]) Interactions of point vortices are considered in pairs, as well as interactions of vortices with defects (Fig. 1). To eliminate the influence of the boundary, the simulation region has periodic boundary conditions along both coordinate axes. The construction of the free energy system is based on the Lawrence-Doniac model [8], and its minimization is carried out using the Monte Carlo algorithm [9, 10] The Gibbs free energy of the system:

$$G = \sum_i \left(\frac{1}{2}\sum_{j\neq i} U_{ij} + \varepsilon + U_h + U_p\right). \tag{1}$$

$\varepsilon = \delta\left(\frac{\Phi_0}{4\pi\lambda}\right)^2 \ln\left(\frac{\lambda}{\xi}+0.52\right)$ is vortex self-energy(δ is the thickness of superconducting layer), under the conditions of this geometry, the third term corresponding to the additional vortex energy associated with the external magnetic field, has the form $U_h = -\frac{\Phi_0 H}{4\pi}\delta$, $U_p = -\alpha|U_0(T)|\frac{1}{\frac{r}{\xi}+1}e^{-\frac{r}{2\xi}}$ is the energy of interaction of a single vortex with a defect. The first term reflects the contribution of the vortex-vortex interaction; for an intertype superconductor, the model dependence is taken [11]:

$$U_{ij}\left(r\right) = \left(-q\right)\left(\ln\frac{r}{r+\lambda} + k\exp\left(-\frac{r}{\lambda}\right)\right) \tag{2}$$

, r is the distance between vortex centers, q, k - model parameters, which were selected in such a way that at large distances the interaction potential coincided with that usual for type II HTSC. For ferromagnetic HTS the interaction potential is as follows [2]:

$$U_{ij}(r) = \frac{\Phi_0^2\delta}{8\pi^2\lambda_e^2}K_0\left(\frac{r}{\lambda_e}\right) + \frac{\Phi_0^2}{8\pi\Lambda}\left[H_0\left(\frac{r}{\Lambda}\right) - Y_0\left(\frac{r}{\Lambda}\right)\right] - \frac{\delta\Phi_0^2\chi_0 r}{4\pi\left(1+4\pi\chi_0\right)\lambda_e^3}K_1\left(\frac{r}{\lambda_e}\right)$$

(3), $\Lambda = 2\lambda_e coth\left(\frac{\delta}{\lambda_e}\right)$ is the modified Pearl length, $\lambda_e = \frac{\lambda}{\sqrt{1+4\pi\chi_0}}$ is the magnetic field penetration depth after renormalization, χ_0 is the magnetic susceptibility of the material.

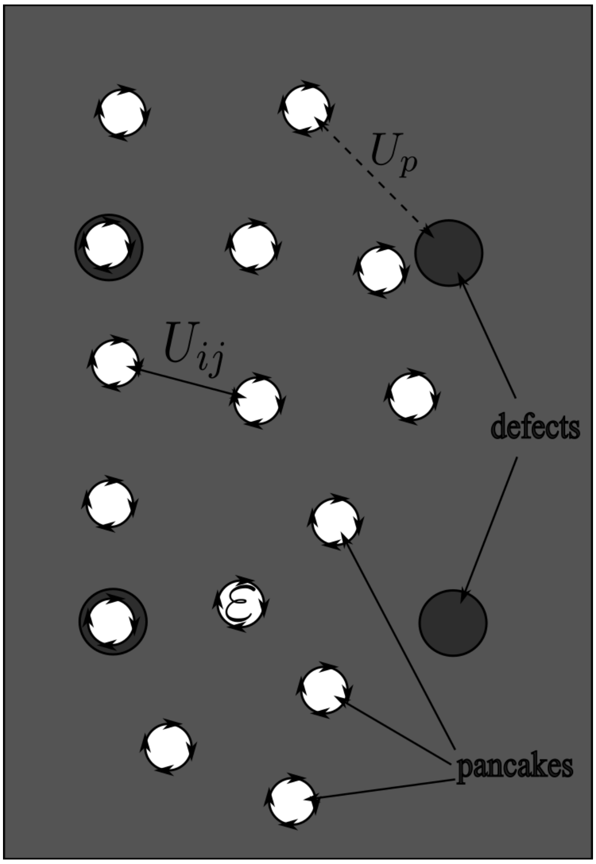

Fig. 1. The geometry of the model

As for the results, the field distribution in the superconductor was obtained depending on its magnetic susceptibility. At a low value of ξ_0 the field coincides with a conventional HTSC, in the case of a pure ferromagnet, bands are visible, which is confirmed by the experiment.

In the case of intertype SC magnetization curves were obtained (Fig. 2) which, when compared with conventional SC, clearly indicated greater stability of the cluster lattice, which was also confirmed by the field distribution (Fig. 3). When defects were added, pinning could be observed in low fields, and at high field values the cluster lattice changed to the shape of triangles and rhombuses, which was also observed in the absence of pinning centers (Fig. 4).

In conclusion, we can say about ferromagnetic superconductors that although the magnetic subsystem as a whole does not contribute to better magnetic flux creep, local effects may be interesting for further research (Fig. 5). With regard to intertype superconductors, the results obtained indicate the stability of vortex structures, which is of interest for practical applications.

Funding

The research was carried out with the support of the MEPhI Program Priority-2030.

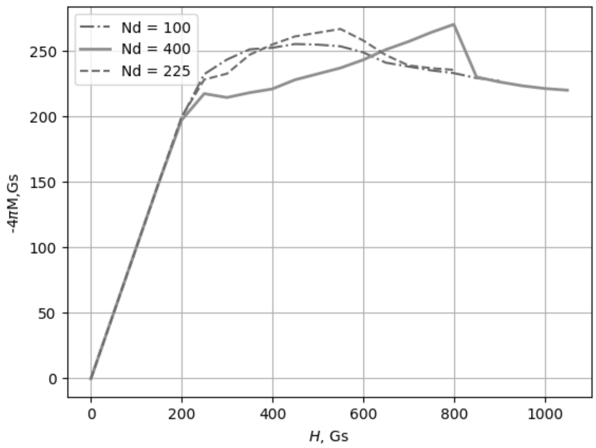

Fig. 2. Magnetization curves at different number of defects Nd

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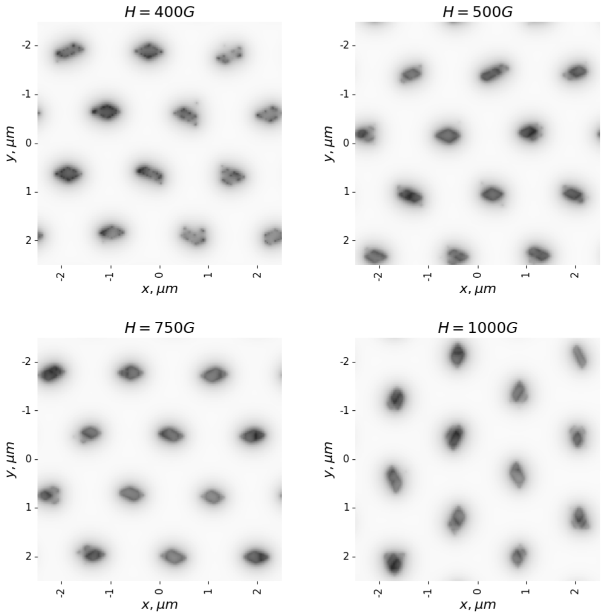

Fig. 3. The field distribution at different values of the external field

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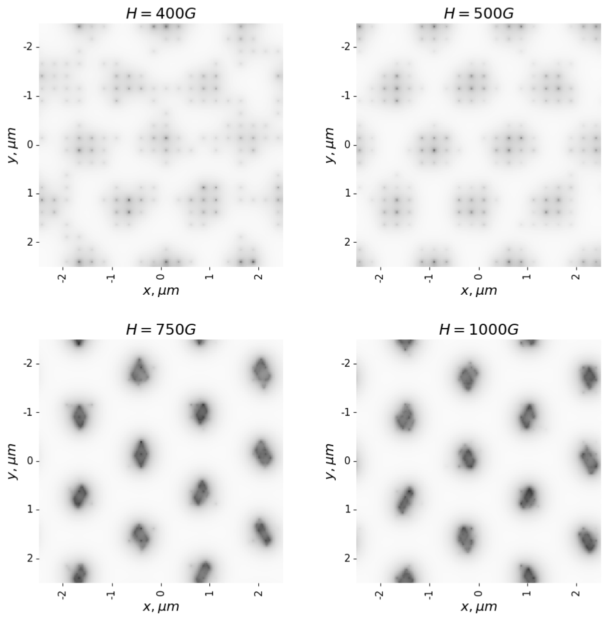

Fig. 4. The field distribution at different values of the external field in the presence of pinning centers (square lattice 20x20)

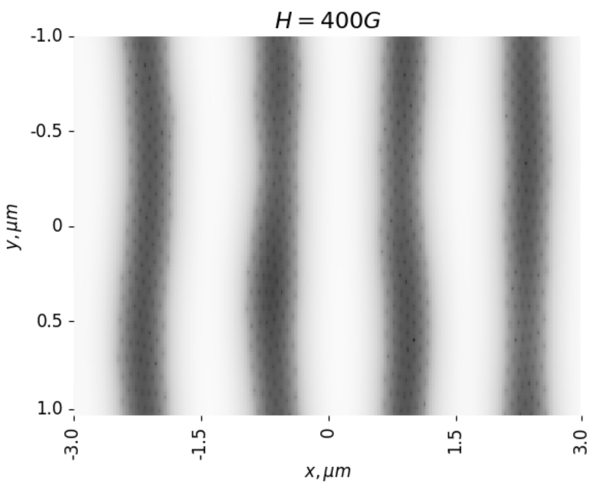

Fig. 5. The field distribution in ferromagnetic superconductor, $\chi = 1.0$