Monte Carlo simulations of vortex dynamics in high-temperature superconductors under pulsed-field magnetization

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***Abstract*—The influence of pulsed-field magnetization on a high-temperature superconductor has been numerically studied using the Monte Carlo method. Calculations have been done for a broad range of pulse parameters, such as amplitude and shape, and the sample parameters, such as temperature and the concentration and type of distribution of defects. The dependences of penetrated magnetic field on the calculation time have been obtained and jump-like features have been observed. Trapped field profiles have been calculated for various conditions and the optimal pulse and sample parameters have been determined.**

Keywords—HTS, pinning, pulsed-field magnetization, Monte Carlo, vortex dynamics

I. Introduction

Lately, great attention has been dedicated to the development of the pulsed-field magnetization (PFM) technique because of the possibility of using high-temperature superconductors (HTSCs) as trapped-field magnets [1–6]. The PFM methods, having a relatively low cost, small size, and higher magnetization speed than the conventional static methods [1] (field cooling and zero-field cooling), have nonetheless an important disadvantage: due to the non-equilibrium vortex motion caused by the rapidly increasing magnetic field, local heating of the sample occurs reducing the trapped field [2–3]. To minimize this effect, great effort is put into finding the optimal parameters of samples and pulses [4–5], and for these purposes, numerical modeling is a very powerful tool. The Monte Carlo method can be a good choice allowing to consider the magnetization processes from the point of view of the vortex dynamics and take into account all the necessary parameters. In the present study, a set of Monte Carlo calculations of pulsed-field magnetization of HTS samples has been done.

II. The Model

The main idea of the Monte Carlo (MC) method lies in the minimization of the thermodynamic Gibbs potential of a system through the randomly chosen processes of creation, annihilation and movement of a random single vortex over the calculation time (~10^6-10^7 MC steps). The potential for a 2D system of N vortices per unit thickness can be written as (1) where, in their respective order, the interaction energies of vortices with one another, the sample surface, Meissner current and pinning centers, as well as their own energies, are represented. A more detailed description of the model can be found in our previous works [7–8].

$$G = \sum_{i<j} U_{\mathrm{vv}}(\boldsymbol{r}_{ij}) + \sum_{i,j} U_{\mathrm{surf}}\left(\left|\boldsymbol{r}_i - \boldsymbol{r}_j^{\mathrm{img}}\right|\right) + \sum_i U_{\mathrm{m}}(\boldsymbol{r}_i) + \sum_{i,j} U_{\mathrm{pin}}\left(\left|\boldsymbol{r}_i - \boldsymbol{r}_j^{\mathrm{def}}\right|\right) + N\varepsilon \qquad (1)$$

To simulate the magnetic field pulses in our calculations, the external field H was increased by a certain value every 10^4 MC steps. This period was chosen as the smallest time slice in which the system reaches dynamic equilibrium. The triangular, trapezoid and exponential pulses of various amplitudes from 600 to 2100 Oe have been considered. Additionally, the resulting magnetization and vortex behavior have been compared for the cases of previously magnetized samples and samples with no initial trapped flux.

The square 5 μm-sized samples of a $Bi_2Sr_2CaCu_2O_{8+x}$ superconductor have been modeled at temperatures of 1 to 40 K. The samples contained various numbers of defects (from 0 to 1000) located in 3 different ways (random distribution, triangular and conformal triangular lattice).

III. Results

For all the above-mentioned parameters, the dependences of averaged magnetic field inside the samples (determined as the amount of penetrated flux divided by the sample area) on the calculation time (i.e. the number of MC steps) were calculated. An example of such dependences is presented in Fig. 1 for a case of exponential 900 Oe pulses acting on samples with different numbers of defects aligned in a triangular lattice. Many of the obtained dependences demonstrated features in the form of jumps of magnetic field (i.e. the number of vortices) inside the samples. It was shown that these features had been caused by the formation of a potential barrier by the vortices pinned near the sample border, and the height of this jump and the value of the external magnetic field at which the jump occurs (the threshold field) depended on the temperature as well as the number of defects and the shape of their distribution across the sample. The calculations also allowed to determine the

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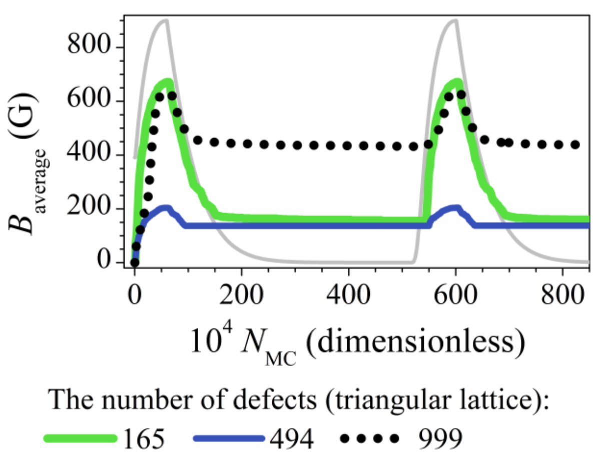

Fig. 1. Time-dependences of the magnetic field inside 3 different samples. The thin grey line demonstrates the magnetic field pulse.

values of saturation field – the field at which the trapped flux ceases to increase with *H*.

Furthermore, the profiles of magnetic field distribution inside the sample averaged over the sample height were calculated. In the case of a regular pinning distribution (the triangular lattice), given the external magnetic field was greater than the threshold value, these profiles had a symmetrical dome-like shape with a maximum in the sample center which corresponded with the experimentally observed profiles (e.g. in [6]). If the external magnetic field was less than the threshold value, the profiles had an “M-like” shape which also corresponded with the experimental results of [6].

Comparing the profiles of trapped field (i.e. the residual field after the external field had been switched off) for different pulse amplitudes and shapes, temperatures, and the defect concentrations and distributions has allowed to determine the optimal parameters of pulses and pinning potential of samples to obtain the maximum value of trapped field and its most homogeneous distribution. The calculation results also included the instant vortex configurations obtained at different points of calculation time which clearly demonstrated the features of the behavior of vortex system for different sample and pulse parameters.

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