Thermoactivated flux creep in high-temperature-superconducting rings in a low-frequency magnetic field

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The effect of ac/dc magnetic fields and temperature on the trapped flux has been studied on superconducting rings, in which a random net of Josephson junctions has been established. Using the obtained experimental data, the dependences of the flux relaxation rate on temperature and magnetic field have been derived, and the flux-creep activation barrier has been evaluated. The electrodynamic properties of the samples have been calculated under three models of voltage-current characteristics under the assumption of a thin ring. When placed in an ac magnetic field and in the critical state, the ring displays a quasi-Meissner behavior, which has been verified by experiments. If ac/dc magnetic fields and temperature produce vortex density gradients throughout the ring, the flux locks up in the ring hole and stays invariable, while elsewhere in the ring creep continues. A peculiar graded decrease in the magnitude of the trapped flux has been observed under the action of ac field and has been supported by theoretical calculations; we suppose that this rapid dropoff can be accounted for by a change in effective time scale in the logarithmic creep law. [S0163-1829(99)09813-6]

I. INTRODUCTION

As is known, vortices in a Josephson medium can leave the pinning centers due to heat and viscous motion under the Lorentz force. As a result, a resistance to the current and the respective electric field develops. This causes energy dissipation, which, in turn, accounts for a special electrodynamic feature, namely a thermoactivated creep of the magnetic flux.[1–6]

In this paper we consider the electrodynamic behavior of a superconducting ring, in which a chaotic Josephson medium has been established,[5,6] and compare our experimental data with theoretical calculations. We demonstrate how external conditions (magnetic field, temperature) affect flux creep in the ring, and measure the main parameters which determine the electrodynamic properties of the Josephson medium in our ceramics. Under the assumption of a thin ring, its electrodynamic behavior is given by a first-order differential equation[7]

$$2\pi Rl(dj/dt)+2\pi RE-\mu_0\pi R^2(dH^e/dt)=0, \tag{1}$$

where j is the current density; R is the average radius of the ring; $l=sL/(2\pi R)=\mu_0 RW/2$ is the reduced inductance of the ring (s is the cross section, W is the ring width), $E=E_c\exp\{-U/T\}$ is the electric field in the ring; U is the effective activation barrier; H^e is the external magnetic field applied along the ring axis; μ_0 is a magnetic constant; t is the time. The dependence of E on j is determined by the properties of vortex motion. At present, the most popular creep models that include current-voltage (I-V) characteristics are

$$E=E_c\left(\frac{j}{j_c}\right)^n,\quad U=U_0\ln\left(\frac{j}{j_c}\right),\quad U_0=nT, \tag{2a}$$

$$E=E_c\exp\left\{-\frac{U_0}{T}\left[\left(\frac{j_c}{j}\right)^\beta-1\right]\right\}, \tag{2b}$$

$$U=U_0\left[\left(\frac{j_c}{j}\right)^\beta-1\right],$$

$$E=E_c\exp\left\{-\frac{U_0-\alpha j}{T}\right\}, \tag{2c}$$

$$U=U_0(1-\alpha j/U_0),\quad U_0=\alpha j_c.$$

Here Eq. (2a) is a generalized model,[3] Eq. (2b) is the glass state (or collective creep) model,[1] Eq. (2c) is the Anderson-Kim model;[8] U_0 is the activation barrier parameter, j_c is the critical (depinning) current density, n and β are exponents $(n\gg 1)$, α is the coefficient, which allows a barrier reduction due to the Lorentz force to be taken into account in Eq. (2c).

The time dependence of the current density j, the field E, and the relaxation of the magnetic flux trapped in the ring under the action of the ac field $H^e(t)$ after the external dc field H^e has linearly increased and linearly removed derives from Eqs. (1) and (2). The relaxation $j(t)$ [or $E(t)$] at $(dH^e/dt)=0$ derives Eq. (1) with the last term cancelled out. The initial magnitude of the field $E(0)=E_0$ [or current density $j(0)=j_0$] can be approximately derived from Eq. (1) with the first term cancelled out, at $(dH^e/dt)=dH^e(0)/dt=a=\text{const}$ (i.e., to obtain $E_0=\mu_0 Ra/2$), the onset of relaxation is the instant at which the dc component of the field H^e stabilizes. Thus, if $H^e=\pm at$ (linearly increased and then linearly removed) is applied during the time interval $2\Delta t$ to the ring with no trapped flux in it, then for $n\gg 1$, $T/U_0\ll 1$ the following equations hold true:

$$j(t)=\frac{j_0}{(1+t/\tau_0)^{1/(n-1)}}, \tag{3a}$$

where $j_0=j_c(E_0/E_c)^{1/n}, \tau_0=j_0 l/[(n-1)E_0]$;

$$j(t)=j_c\left[1+\frac{T}{U_0}\ln\left\{\frac{E_c}{E_0}\left(1+\frac{t}{\tau_0}\right)\right\}\right]^{-1/\beta}, \tag{3b}$$

where $\tau_0 = j_c l T/(E_0 \beta U_0)$;

$$j(t) = j_0\left[1 - \frac{T}{U_0}\frac{j_c}{j_0}\ln\left(1 + \frac{t}{\tau_0}\right)\right], \tag{3c}$$

where $U_0 = \alpha j_c$, $j_0 = j_c[1 + (T/U_0)\ln(2E_0/E_c)]$, $\tau_0 = lT/(\alpha E_0)$.

Note that the estimate $E(0)$ can be derived from solving completely Eq. (1), in which $E(j)$ has been substituted (assuming linear switch on/off of the external field H^e over $2\Delta t$ before the onset of relaxation). The accurate estimate only changes the value of $E_0 = \mu_0 Ra/2$ in formulas (3) into $E_0 = E_c/[2e^{U_0/T} + 4E_c(e^{C\Delta t} - 1)/(\mu_0 Ra)]$, where $C = U_0 a/(TWj_c)$.

The time dependence of the experimentally measured field $B(t)$ during relaxation is described by the same formulas (3), given that $B(t) = j(t)/(2R)$, $S' = T/U_0$. Then, for example, Eqs. (3b) and (3c) can be written as

$$B = B_0/[1 + S' \ln(1 + t/\tau_0)]^{1/\beta},$$

$$B = B_0[1 - S' \ln(1 + t/\tau_0)], \tag{4}$$

assuming $j_0 \sim j_c$.

Equation (1) can be solved analytically if the applied field is harmonic: $H^e = H^0 \sin(\omega t)$. Suppose that the ac field amplitude H^0 is high enough for the field to penetrate into the ring hole (i.e., $H^0 > H_{cj}$, where H_{cj} is the penetration field), then the electrodynamic behavior of the ring, assuming the initial conditions $j(t=0) = j_0 \sim j_c$ and the model I-V characteristics as in Eq. (2), is described by the formulas below. If the I-V characteristic is as in Eq. (2a) then

$$\frac{j(t)}{j_c} = \frac{j_0}{j_c}\left[1 + \frac{E(0)}{\omega\mu_0 R H^0/2}\frac{j_c}{j_0}C\left\{\omega t - C\exp(-C\sin\omega t) \times \int_0^{\omega t}\eta\cos\eta\exp(C\sin\eta)d\eta\right\}\right]^{1/(1-n)}, \tag{5}$$

where $E(0) = \mu_0 R H^0 \omega/2$, $j_0 = j_c(E(0)/E_c)^{1/n}$, for $n \gg 1$.

Under the collective-creep model, which describes the I-V characteristic by Eq. (2b), the time dependence of the current density is

$$j(t) = j_0\left[1 - \beta H^0/(Wj_0)\sin\omega t + (T/U_0) \times \ln\left\{1 + \beta C\int_0^{\omega t}\exp(\beta C\sin\eta)d\eta\right\}\right]^{-1/\beta}. \tag{6}$$

For the I-V characteristic Eq. (2c), the solution is

$$j(t) = j_0\left[1 + H^0/(Wj_0)\sin\omega t - \frac{T}{\alpha j_0} \times \ln\left\{1 + C\int_0^{\omega t}\exp(C\sin\eta)d\eta\right\}\right]. \tag{7}$$

Averaging expression (7) over the period and assuming $j_0 \sim j_c$, we obtain

$$\langle j(t)\rangle = j_0[1 - (T/U_0)\ln(1 + G(H^0)\omega t)], \tag{8}$$

where

$$G(H^0) = \left[C\int_0^{\omega t}\exp(C\sin\eta)d\eta\right]\Big/(\omega t).$$

In formulas (6)–(8), $C = (U_0/T)H^0/(j_c W)$.

II. EXPERIMENTAL

To compare the results of measurements with the solutions to Eqs. (5)–(8) given an applied ac field, flux-creep experiments were run under the same conditions as stipulated for Eq. (1). In approximating the experimental dependences by Eqs. (3), (4) we assume B_0, S', and β to be the fitting parameters.

Samples of fine-granulated (~ 1 μm) $Bi_{1.6}Pb_{0.4}Sr_2Ca_2Cu_3O_y$ ceramics were prepared in the form of tablets after a routine technique. Rings were made with the following dimensions: outer radius $R_1 \sim 4.6$–5 mm, inner radius $R_2 \sim 3$–3.4 mm, width $W = R_1 - R_2 \sim 1.2$–2 mm, height $d \sim 1.4$–2 mm. The critical current density was $j_c \sim 1$ kA/cm^2 at 4.2 K, the superconducting transition temperature was $T_c \approx 105$–107 K. The first critical field for the granules was $H_{c1}^{\text{gr}} > 250$ Oe; the second critical field for the Josephson medium was 100 Oe at 40 K, and the first critical field for the Josephson medium was $H_{c1} < 100$ mOe. The penetration field was $H_{cj} \sim 25$ Oe.

The measurements were carried out in a solenoid with two additional internal coils forming a Helmholz system, the coils being coaxial with the solenoid. A high-temperature superconducting ring was placed between these additional coils. A Hall probe and a thermocouple were placed at the center of the ring. The solenoid generated a dc magnetic field of up to 200 Oe. Low-inductance coils were employed to generate an additional ac field of up to 20 Oe and a frequency of up to 20 kHz. The sample was cooled by either liquid nitrogen or liquid helium.

The measurements of the magnetic-field magnitude at the ring center as a function of the external field H^e, temperature T and time t has been performed using a software program; the field measurement accuracy was 0.02 Oe; the temperature of the sample was measured within an error of 5×10^{-2} K.

The following experimental results have been obtained. The temperature dependence of the relaxation rate $S = -(1/2R)dj(t)/d\ln(1+t/\tau_0)$ has a domelike shape, and the reduced rate $S' = -(1/j_0)\partial j/\partial\ln(1+t/\tau_0)$ grows with the average slope $S'/T = 1.9\times 10^{-5}$ K^{-1} (Fig. 1). Thus the activation energy is $U_0 = 5.3\times 10^3$ K.

The relaxation dependences of the trapped field, $B(t)$ were obtained at $T = 78$ K, when the external field H^e was linearly increased and then quickly decreased (see Fig. 2). Curve 1 (relaxation without applied ac field) behaves otherwise than curves 2 and 3 plotted for the case when a harmonic ac magnetic field is applied to the sample after removal of the dc field H^e. The relaxation curve in the absence of ac field is described as

$$B(t) = B_0[1 - S' \ln(1 + t/\tau_0)], \tag{9}$$

where $S' = 0.0133$, $B_0 = 8.77$ Oe, $\tau_0 = 1$ (curve 1). Note that this dependence is in fact the limit of the function (3b) at $1/\beta \to 1$ and $S' \ll 1$. If the amplitude of the applied ac field is

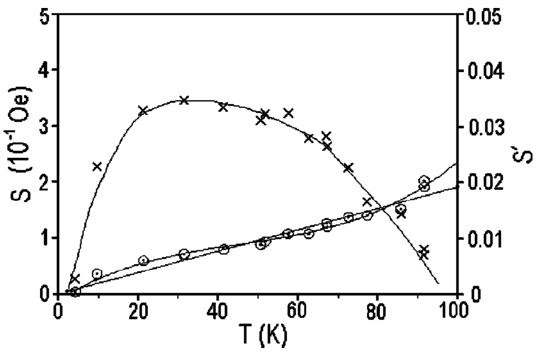

FIG. 1. Temperature dependences, S and S', of the relaxation parameters. Experimental values of S are marked by crosses, reduced values of S' are marked by circles. The solid line for S was derived by the best cubic spline, the straight line and the cubic polynomial approximation for the dependence $S'(T)$ were derived by the least-squares fit.

2.9 Oe and the frequency $\nu=1100$ Hz, the relaxation dependence $B(t)$, averaged over the period, is described by function (3b) at $S'=9.48\times10^{-3}$, $B_0=7.18$ Oe,$1/\beta=1.83$ (curve 2). At 100 Hz (curve 3), the parameter values are $S'=1.48\times10^{-2}$, $B_0=7.31$ Oe, and $1/\beta=1.26$. The time scale $\tau_0=S'j_cW/(dH^e(0)/dt)$, calculated by formula (3c), is equal to 0.06 s. As can be seen from Fig. 2, applying the ac field changes the dependence $\langle B(t)\rangle$ as by curve 1 to that as by curve 2.

The effect of the toggling ac field on the relaxation of the averaged field trapped in the ring is demonstrated in Fig. 3. At times up to t_1 the relaxation rate of $\langle B\rangle$ is $S'=0.015$. At t_1 the ac field ($H^0=1$ Oe, $\nu=7$ kHz) is applied and $\langle B\rangle$ drops off abruptly. Relaxation runs on at $S'=0.017$ until t_2 (t_1 is assumed to be the onset of relaxation).

An interesting effect of trapped flux lockup within the ring hole was observed in these experiments. We achieved such a special field distribution in the ring body that the trapped field in the ring hole does not change in the absence of external field. Such a distribution as this can be obtained

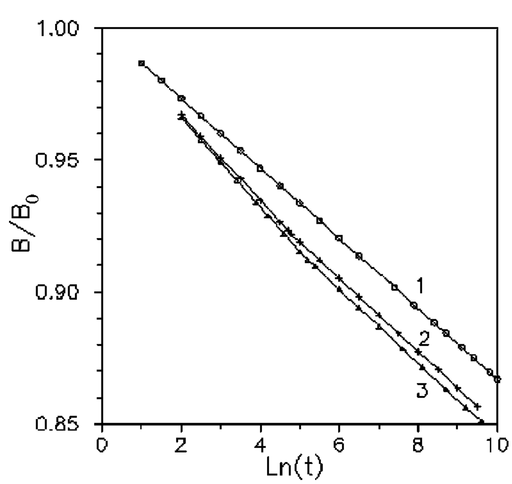

FIG. 2. Relaxation of the trapped field B as the ac magnetic field was switched on, after dc field H^e switchoff at 77.3 K. (1) no ac field applied; (2) ac field $H^0=2.0$ Oe,$\nu=1100$ Hz, the initial value of H^e is the same as for the curve 1; (3) $H^0=2.9$ Oe,$\nu=100$ Hz, H^e is as for curve 1.

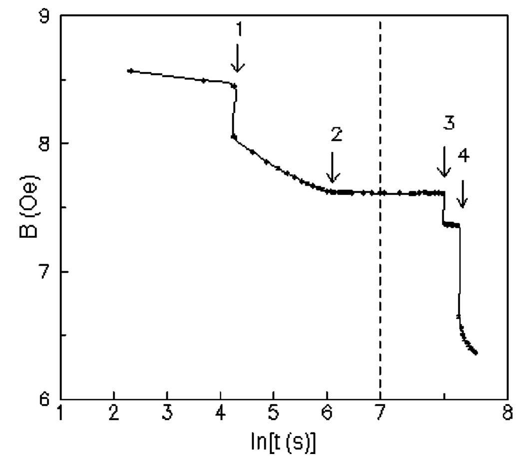

FIG. 3. Effect of ac field application on the relaxation process of the dc component of the trapped field B at 77.3 K. H^e is switched off, times are indicated by arrows: t_1 is the ac field on, $H^0=1$ Oe,$\nu=7$ kHz; t_2 is the ac field off; t_3 is the ac field on, $H^0=2.5$ Oe,$\nu=7$ kHz; t_4 is the amplitude increased up to $H^0=3.11$ Oe. The dotted line is where the time-axis scale changes.

threefold. First, increase H^e to a value ranging between $H_{cj}<H^e<1.8H_{cj}$ and then switch it off. Second, at a constant temperature, apply the external field H^e to the ring until trapped, remove the external field, cool the ring promptly (see Fig. 4). As a result of such cooling, the time dependence of the trapped field is as presented in Fig. 5. As can be seen, as soon as the temperature stabilizes, the relaxation process first stops, then resumes (curve a). The time interval over which the trapped field remains constant depends on the difference between the initial temperature (the one at which the field was trapped in the hole) and the final temperature (the one to which the ring was cooled). The time interval can be large enough (curve b). Third, (see Fig. 3) turn off the ac field at t_2 and ensure it is removed within $\sim$0.5–1 s. Thereafter, within the Hall probe sensitivity in our measurements ($\delta B\sim0.004$ Oe), the trapped field remains stable for at least a few hours. When the ac field with $H^0=2.5$ Oe,$\nu=7$ kHz is switched on again at t_3, the trapped flux drops abruptly and the relaxation process resumes explicitly (Fig.

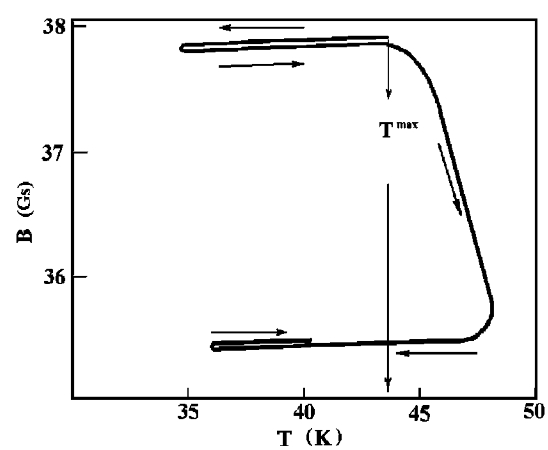

FIG. 4. The temperature dependence of the trapped field magnitude in the ring hole. Arrows show the direction of changes in temperature. T^{max} stand for the initial temperature at which the strongest field B was trapped.

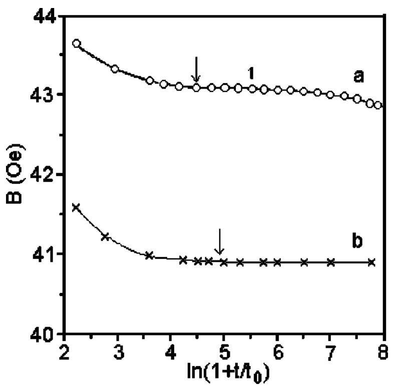

FIG. 5. The stoppage of the relaxation of the field B at the ring center by cooling to a constant $T=34.4$ K ($t_0=1$ s). The onset of relaxation stoppage and the instant at which the temperature reaches the constant $T=34.4$ K are indicated by arrows. Trapping temperatures were: ○ indicates $T=37.0$ K, × indicates $T=40.1$ K, the external dc field being $H^e=87$ Oe in both cases. Relaxation starts at the time when the dc field H^e is switched off (at the corresponding initial temperature). On curve a, relaxation spontaneously resumes at time 1, as compared to curve b where relaxation is not resumed for hours.

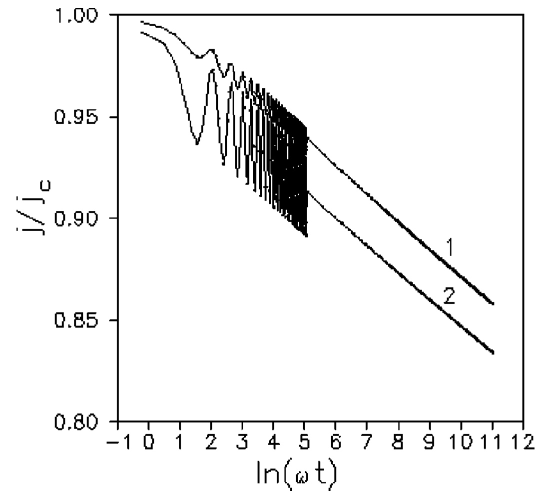

FIG. 7. Relaxation of the transport current density under an applied ac field. Calculations were performed by Eq. (5) for model (2a) with $n=67$ at a frequency of 100 Hz and the amplitudes H^0 equal to 0.5 and 2 Oe (curves 1 and 2, respectively). For $t \leqslant 0.25$ s the extrema of the wavelike relaxation are shown, and at $t>0.25$ s the same curves averaged over time are shown. In doing calculation, it was assumed that $j_0=j_c$.

3). Increasing the ac field amplitude to $H^0=3.11$ Oe at t_4, we observe a further abrupt decrease in $\langle B(t)\rangle$ and the continuation of relaxation with $S'=0.017$.

The characteristic dependence of the dc component of the remanent trapped field B on the amplitude and frequency of the applied ac field in all the rings dealt with are shown in reduced units in Fig. 6 [the lowermost values of the remanent trapped field magnitude after ac field $H(t)$ switchon, Fig. 3]. As can be seen, the same curve results for all amplitudes and frequencies assumed. Note, however, that the dependence of the derivative $d\langle B(t)\rangle/dH^0$ on the frequency is somewhat weak (see inset to Fig. 6).

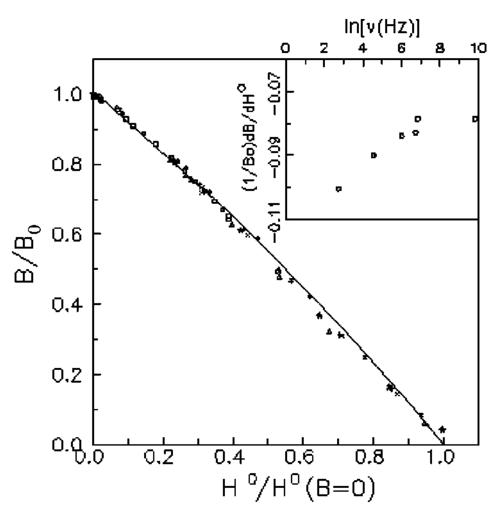

FIG. 6. The dependence of field B trapped in the ring after H^e switchoff at the ac field amplitude H^0. B_0 is the field trapped at $H^0=0$; $H^0(B=0)$ is the ac field amplitude at which the trapped field becomes zero. The solid line is the curve calculated by formula (10). The experimental points for six frequencies (10 Hz$<\nu<20$ kHz) lie in the calculated curve at the corresponding values of $H^0(B=0)$ for each frequency. Inset: the dependence of the average derivative $d(B/B_0)/dH^0$ on $\ln(\nu)$ for $0.5<H^0/H^0(B=0)<1$.

III. DISCUSSION

To explain the effect of ac field on the evolution of the trapped flux, we have described our experiments in terms of models (2) using Eqs. (6)–(8). As follows from these equations, if the ac field applied to the ring is moderate enough, the current generating the trapped flux decreases logarithmically and the same rate as in the case of regular creep. The value of τ_0, however, is governed by the integral in Eqs. (6)–(8), e.g., Eq. (8) yields $\tau_0=[G(H^0)\omega]^{-1}$. Figure 7 presents solutions to Eq. (5) at $\nu=100$ Hz and H^0 equal to 0.5 Oe and 2 Oe. Here we assume $j_0\sim j_c=3.4\times10^6$ A/m^2 and $n=67$, which corresponds to the observed value of $S'=0.015$. Calculations were made at $0<t<100$ s. Note that while relaxation is under way, the ac component of $j(t)$ has a quasi-Meissner behavior, its amplitude being little dependent on time, and the higher H^0, the lower the averaged $\langle j(t)\rangle$. Our experiments (Fig. 2) provide further support to this conclusion by the fact that the relaxation rate remains the same at long times, whether with or without applied ac field. In their work,[3] Gurevich and Brandt came to the same conclusions.

The observed drops (abrupt decreases) in the trapped flux following ac field application (see Fig. 3), can be formally described as an acceleration of the relaxation process. Increasing H^0 decreases τ_0 abruptly, which is due to an exponential growth of $G(H^0)$, and a striking change in effective time scale takes place. One real-time second is now equivalent to τ_0^{-1} seconds in the course of relaxation, which is in the form of a drop in the trapped field magnitude. The relaxation curve presented in Fig. 8 was plotted by numerical calculation of Eq. (7), where $\nu=100$ Hz and the initial amplitude $H^0=0.5$ Oe rises up to 2 Oe at $t=10$ s. In the case of a real ring (which are, e.g., for a Bi-based ring: $T/U_0=1.6\times10^{-2}$, $W=2\times10^{-3}$ m, $j_0=3.4\times10^6$ A/m^2 at 77 K), the calculations by expression (7) were performed with $G(H^0=11.4$ Oe), which was integrated numerically with

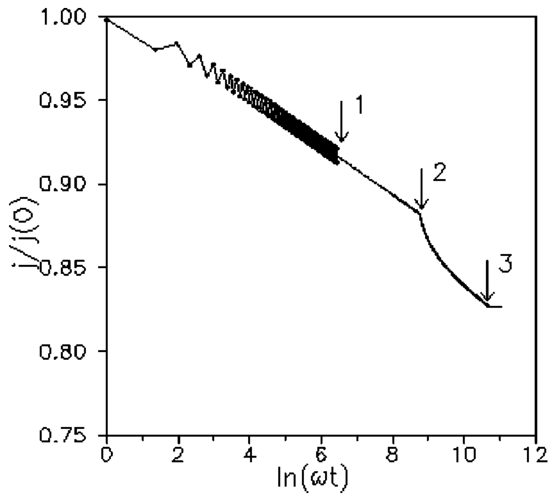

FIG. 8. The current relaxation calculated at $T/U_0=0.015$ and $j_c=3.4\cdot 10^6$ A/m^2 [Eq. (7)] for the Anderson-Kim model where the amplitude H^0 of the ac field of $\nu=100$ Hz changes at $t=10$ s and $t=70$ s. Times denoted by arrows: (1) for $t<1$ s all the extrema of solution (7) are plotted and connected by straight lines, for $t>1$ s the solution was averaged over the period; (2) at $t=10$ s H^0 was enlarged from 0.5 Oe ($0<t<10$ s) to 2 Oe (10 s$<t<70$ s); (3) at $t=70$ s H^0 was reduced from 2 Oe to 0.02 Oe (70 $s<t<100$ s). A change in the slope of the relaxation curve at the times (2) and (3) could be interpreted as a change in the effective time scale following a change in H^0 (a change in $\tau_0=[G(H^0)\omega]^{-1}$). The abrupt fall at time (2) and a weak change after the instant (3) are in a good agreement with experimental data [see Fig. 3 after times (1) (fall) and (2) (the relaxation stoppage)].

the above parameters, which yielded a drop from 8.63 Oe to 6.86 Oe in ~ 1 s. Theoretically, the trapped field totally releases from the hole in a few seconds at $H^0=76$ Oe owing to an almost exponential growth of the function $G(H^0)$. Experimentally, applying an ac field of $H^0\approx H_{cj}=11.4$ Oe and $\nu=100$ Hz warrants total release in less than a second. Applying the ac field decreases the trapped flux magnitude promptly (within the ac field rise time, ~ 1–2 s), see Fig. 3. Calculations by Eq. (8) shows that this step in the relaxation curve at t_1 (Fig. 3) could be accounted for by applying an ac field of $H^0=0.04$ Oe and $\nu=7$ kHz, while the actual amplitude was $H^0=1$ Oe. Although the experimental and theoretical data disagree, the qualitative description is nevertheless quite satisfactory, because the calculations were performed on the thin ring [see Eq. (1)], in which finite width is neglected. The curves derived under the collective-creep model under the above assumptions behave very similarly to those just discussed [see Eq. (6)].

Noteworthy, the solution (7) for the thin ring involves a term with a constant amplitude [it is proportional to $\sin(\omega t)$], which results in that the ac field of any amplitude penetrates into the hole. However, this conclusion cannot be extended to any real ring of width W, in which case only the external layers accessed by the ac field are of influence to the field in the ring center.

Thus, a better agreement with the experimental data can be achieved via taking into account the finite size of samples and the corresponding current and field distributions. Return to Fig. 6. To explain this dependence, we presume that according to the critical state condition requirements, a weak ac field penetrates the ring of finite width radial from the outside to a depth. In the layers accessed by the ac field the trapped field distribution becomes uniform. Thus, if H^0 does not exceed H_{cj} (penetration field), there is a layer of thickness ΔR with zero average transport current and, consequently, the trapped field is lower than it is when the average current runs throughout the entire ring body. In this case, the dependence of the dc component of the field B in the ring center on H^0 is given by

$$\frac{B(H^0)}{B_0}=\frac{\ln\{1+(W/R_1)[1-H^0/H^0(B=0)]\}}{\ln(1+W/R_1)}, \quad (10)$$

where $B(H^0)$ is the lowermost value of the remanent field amplitude in the ring center due to the ac field; $H^0(B=0)$ is the ac field amplitude at which the trapped flux is frustrated throughout the entire ring; $B_0=B(H^0=0)$ is the initial field in the center of the ring. Experimental data (in Fig. 6) are well approximated by dependence (10) (solid line). Within the experimental frequency range, $B(H^0)$ is little dependent on ν (see inset to Fig. 6). In this case, $H^0(B=0)$ grows with frequency. Consequently, the proposed dependence (10) gives a good qualitative description to the observed behavior of the derivative $(1/B_0)dB/dH^0$. A weak dependence of this derivative on frequency also follows from Eq. (7), because $(1/j_0)(dj/dH^0)\sim(1/B_0)(dB/dH^0)$ deduced from Eq. (7), is nearly frequency independent. Gurevich and Brandt[3] reported similar conclusions.

The observed graded changes in B (Fig. 3) match the dependence $B(H^0)$ in Eq. (10), and flux lockup following removal of the ac field is similar to relaxation stoppage in the ring hole when an external $H_{cj}-1.8H_{cj}$ dc field provided flux trapping and then was removed.

The relaxation, stopped by the first and second methods, can be explained if the finite width of the ring and the field distribution in it are taken into account. As is known,[1,9] in a Josephson medium the trapped flux relaxation takes place due to viscous motion of the Josephson vortices with the diffusion coefficient D and their drift under the field gradient. It is assumed that an opposite field gradient is produced by the above methods, which prevents vortices from escape and is responsible for the relaxation stoppage in the ring hole. The reason for the gradients being opposite in sign in terms of the two methods[10] obviously follows from the Bean theory and the critical state equation.[11]

However, the relaxation stoppage following removal of the ac field is explained in a more complicated way. The vortex diffusion coefficient little depends on field frequency (20 Hz–20 kHz in our experiments). For a change in D to be significant, the field frequency should be comparable with the frequency of vortex jump attempts ($\Omega\sim 10^6$–10^{10} s^{-1}). Thus, the change in the flux relaxation rate must be due to the field gradients. We assume that the flux lockup, achieved by this third way, is caused by the field structure modulated along the radius which freezes after an applied low-frequency field has been removed.[12] This remanent structure has oppositely directed gradients, and we assume that there is no average gradient in this modulated structure, and, therefore, no average trapped flux. We suggest that the vortices are pushed outwards by a constant field gradient which occurs in the innermost layer in the course of relaxation in the ac field of an amplitude smaller than $H^0(B=0)$. In the external layers of the ring accessed by the ac field, the field distribution is oscillating with zero average gradient which does not prevent vortices from coming out, but only disturbs the logarithmic shape of the relaxation curve (see Fig. 2). When the ac field is removed, the modulated structure freezes, the field gradients in it are directed so that coming out is hampered; the flux freezes and the relaxation stops (Fig. 3, between t_2 and t_3).

The shape of the modulated structure is determined by the critical state conditions, and the phenomenon of the self-organized maintenance of critical state[1] provides its stability. This phenomenon implies that a spontaneous decrease in field gradient in a part of the sample causes a decrease in current density, which causes an increase in the effective pinning energy, and vice versa. Thus, this feedback provides the field gradient stabilization. Batkin and Savtchenko[12] report observing a modulated structure such as this, which allows us to consider the proposed model as adequate to the experiment.

Noteworthy, when the flux is locked within the ring hole, the relaxation of the total flux does not stop. At that the field gradient, which pushes the vortices outward, exists in the outer layers of the ring. While the vortices are coming out, the counter-gradient decreases and after long locking the relaxation resumes (Fig. 5).

IV. CONCLUSION

Investigation of various effects on the trapped flux relaxation process has been carried out for rings, in which the chaotic Josephson net was established. In particular, effects of variation in temperature and the ac magnetic field have been studied.

The electrodynamic behavior of a thin ring has been evaluated acted on by for a low-frequency ac magnetic field using three models of I-V characteristics. Quick energy dissipation following application of the ac field and a drop in trapped flux magnitude have been demonstrated. The value of the drop depends on the ac field amplitude, the relaxation rate is invariable, only the effective time scale is affected by the external ac field. Thus, the amplitude of the ac component of a shielding current remains almost invariable during relaxation. In other words, when an ac field is applied, the shielding of the ring hole from the ac field displays a quasi-Meissner behavior. Experiments confirm the calculations and reveal a number of new phenomena.

The external conditions under which the flux freezes have been specified and analyzed. This is valid in the cases where the action of either magnetic field or temperature results in the formation of vortex density gradients in the ring body, which prevent the trapped flux from escape. It has been established that the ac magnetic field has a minor effect on the shape of the relaxation curve, so that it looks like the one under the collective-creep model.

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[1] G. Blatter *et al.*, Rev. Mod. Phys. **66**, 1125 (1994).
[2] E. H. Brandt, Phys. Rev. B **54**, 4246 (1996).
[3] A. Gurevich and E. H. Brandt, Phys. Rev. Lett. **73**, 178 (1994); Phys. Rev. B **55**, 12 706 (1997).
[4] E. Zeldov, J. R. Clem, M. McElfrest, and M. Darvin, Phys. Rev. B **49**, 9802 (1994).
[5] I. R. Clem, Physica C **153-155**, 55 (1988).
[6] S. L. Ginzburg *et al.*, Physica C **174**, 109 (1994); S. L. Ginzburg, Zh. Eksp. Teor. Fiz. **106**, 607 (1994).
[7] A. A. Zhukov, Supercond., Phys. Chem. Technol. **5**, 260 (1992).
[8] P. W. Anderson, Phys. Rev. Lett. **9**, 309 (1962); P. W. Anderson and Y. B. Kim, Rev. Mod. Phys. **36**, 39 (1964).
[9] E. H. Brandt, Int. J. Mod. Phys. B **5**, 751 (1991).
[10] E. V. Matizen *et al.*, Supercond., Phys. Chem. Technol. **7**, 1398 (1994); E. V. Matizen, P. P. Bezverkhy, and V. G. Martynets, JETP **84**, 578 (1997).
[11] C. P. Bean, Phys. Rev. Lett. **8**, 250 (1962); Rev. Mod. Phys. **36**, 31 (1964).
[12] V. I. Batkin and O. Ia. Savtchenko, Pis'ma Zh. Tekh. Fiz. **19**, 29 (1993).