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Magnetic instabilities in high-temperature superconductors under rapidly varying magnetic fields

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The irreversible magnetization of single-crystalline samples of the high-temperature superconducting compounds $\text{LaSr}_2\text{CuO}_4$ and $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}$ has been studied under rapidly varying magnetic fields. Three types of behavior can be identified for increasing rates of the field variation: first, a stable regime close to the critical state; magnetic instabilities or jumps for intermediate ramp rates; and a second stable regime with a strongly suppressed magnetization for high sweep rates. The conditions for breaking the critical state and the dynamics of the flux penetration at the instability are discussed.

INTRODUCTION

The behavior of superconductors in the presence of a magnetic field has been a subject of much scientific and practical interest over the past few decades. The discovery of high-temperature superconductors has triggered a significant reexamination of this subject. A variety of experiments on both the static and the dynamic properties of vortices and flux-line lattices in the mixed state has been performed. The main experimental efforts have focused on either the imaging of the magnetic-flux pattern by magnetic decoration and neutron scattering, or on experiments that explore the dynamics of vortices through the resistivity or magnetic relaxation in a constant applied field. We present here another aspect of the dynamical processes occurring in superconductors under rapidly varying magnetic field, giving rise to dramatic effects and yet being poorly understood.

A magnetic instability or a flux jump is a phenomenon associated with hard superconductors whereby magnetic flux suddenly rushes into the sample. If a hard superconductor is exposed to a changing magnetic field, shielding supercurrents are induced near the surface.¹ When the shielding field exceeds some critical value, the supercurrents become unstable and magnetic flux abruptly penetrates into the sample.^{2,3} This phenomenon is of paramount importance for technical applications and attracted much attention in the late sixties. The successful construction of multifilament high-field superconducting magnets⁴ is a direct result of these efforts. The detailed understanding of the underlying mechanism, however, is far from being reached. The investigation of magnetic instabilities in high-temperature superconductors is challenging in view of either potential applications or fundamental understanding of the phenomenon. In this report, we wish to demonstrate that high-temperature superconductors are intrinsically unstable under varying magnetic fields, and to highlight the main characteristic properties of the instabilities.

EXPERIMENTAL TECHNIQUES

All experiments reported here have been performed on single-crystalline samples of $\text{LaSr}_2\text{CuO}_4$ and

$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}$ that have been prepared by using a traveling-solvent-floating-zone technique.⁵ The $\text{LaSr}_2\text{CuO}_4$ sample has a disk-shaped form with a radius of about 1 mm and a thickness of 1 mm. The $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}$ sample is an as-grown piece of material containing a pile of *c*-oriented single-crystalline slabs. For both samples the field is oriented along the *c* axis.

The main part of the measurements has been performed in the 40-T semicontinuous field facility at the University of Amsterdam. This installation can produce any pulse shape that is compatible with the thermal and mechanical constraints.⁶ The field sweep rate can be regulated within the interval from 0.1 up to 60 T/sec after an initial rapid field increase to 1 T. The magnetization is measured by integration of the output voltage of a carefully compensated coil system.⁷ Complementary magnetization measurements have been performed at constant fields up to 7 T by a two-coil extraction technique.

EXPERIMENTAL RESULTS AND DISCUSSION

The magnetic instabilities manifest themselves in the magnetization curves presented in Fig. 1. The irreversible magnetization loop of the single-crystalline sample of $\text{LaSr}_2\text{CuO}_4$ is shown as measured under different conditions of the field variation at 4.2 K: (a) $dH/dt=0$, the field is stabilized and the measurement is performed 30 sec later; the field is swept with constant rates of 5, 10, and 42 T/sec in (b), (c) and (d), respectively. The difference between the results in these cases is dramatic and demonstrates a general tendency of the magnetization modulation that depends on the rate of the field change. The smooth curve in case (a), which is usually observed, is replaced by a sharp sawtooth structure (b), (c), which in turn is replaced by a stable but strongly suppressed magnetization loop in (d). The pattern remains highly reproducible under the same experimental conditions after numerous reheatings of the samples up to the room temperature. It justifies an attempt to find and characterize the systematics of the observed instabilities.

FIG. 1. Irreversible magnetization loops measured in the single-crystalline sample of $\text{LaSr}_2\text{CuO}_4$ at 4.2 K at different applied field-sweeping rates: (a) $dH/dt=0$; (b) $dH/dt=5$ T/sec; (c) $dH/dt=10$ T/sec; (d) $dH/dt=42$ T/sec.

PERIODICITY OF THE JUMPS

The repetition of the magnetization jumps [Figs. 1(b) and 1(c)] can be described as semiperiodic. Although one also finds a number of randomly distributed partial jumps, the periodicity of the main jumps is found to be well defined by the field-sweeping rate dH/dt . We show in Fig. 2 the repetition period of the jumps as a function of the sweep rate. Two regimes are found: (1) a “low” sweep-rate regime with $dH/dt < 5$ T/sec in which the oscillation period decreases with increasing sweep rate and can be approximated by $\Delta H = A - \ln dH/dt$; (2) a “high” sweep-rate regime with $5 \text{ T/sec} < dH/dt < 20 \text{ T/sec}$ in which the period becomes independent of the sweep rate and saturates to the limit of about 0.4 T. For still higher sweep rates, i.e., $dH/dt > 20 \text{ T/sec}$, no jumps are observed [see Fig. 1(d)].

A description of the magnetization jumps can be given⁸ by an extension of the critical-state model¹ by including the effects of heating when magnetic flux enters or leaves the bulk of the superconductor. The physics of the situation lies in the fact that the impediments to flux motion are, in general, decreased by increasing temperature. Each element of volume that is exposed to an increment

of field receives a thermal pulse. This pulse, in turn, lowers the barriers to flux motion, giving rise to a further impulse. In the adiabatic limit of a semi-infinite sample, the problem can be solved analytically. The critical field at which the instability occurs, H_{fj} (flux-jump field), is

FIG. 2. Magnetization jump periods as a function of the field-sweeping rate for the single-crystalline sample of $\text{LaSr}_2\text{CuO}_4$ at 4.2 K.

given by

$$H_{\text{fj}} = \left[-\alpha \pi^3 C_v \frac{J_c}{\partial J_c / \partial T} \right]^{1/2}, \quad (1)$$

where C_v is the specific heat per unit of volume, J_c is the critical current density, and α a coefficient of the order of unity.^{9,10}

Assuming that $C_v = \beta T^3$ and $J_c = J_c(0)(1 - T/T_c)$, Eq. (1) gives the temperature dependence of the flux-jump field as

$$H_{\text{fj}} = [\alpha \pi^3 \beta T_c T^3 (1 - T/T_c)]^{1/2}. \quad (2)$$

This equation passes a maximum for $T = 0.75T_c$ and falls to zero at both $T = 0$ and $T = T_c$. For the $\text{LaSr}_2\text{CuO}_4$ sample with $T_c = 34$ K and $C_v = 17T^3$,¹¹ this equation gives a maximum value for H_{fj} of about 8.6 kOe at 25 K and a value of 1.1 kOe at 4.2 K.

The condition that an excess or shielding field H_s is larger than H_{fj} is expected to be a necessary and sufficient condition for a flux jump when an additional small field increment is applied adiabatically to the sample. It is important to note that H_s represents the shielding field rather than the absolute magnitude of the field. There is no difference, therefore, between the value of the first flux-jump field H_{fj} and the period between the full jumps ΔH . The adiabatic concept requires that no heat leave the volume of the flux front during the instability. The fulfillment of this condition is usually estimated by comparing the thermal τ_{th} and magnetic τ_{mag} diffusion time; both are inversely proportional to the corresponding diffusion coefficients D_{th} and D_{mag} . D_{th} can be calculated as $D_{\text{th}} = K/C_v$, where K is the thermal conductivity. Taking for $\text{LaSr}_2\text{CuO}_4$ the values $K = 0.002$ W/cm K and $C_v = 17T^3$ (erg/cm³ K) (Ref. 11) we get $D_{\text{th}} = 10$ cm²/sec at 4.2 K. On the other hand, the magnetic diffusivity related to the viscous motion of vortices D_{mag} can be expressed in terms of the flux-flow resistivity¹² as $D_{\text{mag}} = \rho_f / \mu_0 = \rho_n B / B_{c2}$, where ρ_n is the normal-state resistivity. Assuming this result to be applicable also for high-temperature superconductors and extrapolating the normal-state resistivity of single-crystalline $\text{LaSr}_2\text{CuO}_4$ at 4.2 K to 200 $\mu\Omega$ cm, we obtain D_{mag} of the order of 10⁴ cm²/sec under the field of 1 T. A simple comparison between D_{th} and D_{mag} implies that the adiabatic conditions are automatically met in this material and the model is expected to be valid. However, the flux-jump field H_{fj} given by Eq. (1) depends only on the intrinsic material parameters: specific heat, critical-current density, and its temperature derivative, and not on the external conditions such as the field sweep rate, which is found to influence strongly the jump periodicity (Fig. 2). The situation described here is very similar to that previously reported for the conventional superconducting alloys. The ratio between the magnetic and thermal diffusion constants in these superconductors can be as high as 10³, which implies that magnetic flux moves much faster than the heat wave. However, the flux-jump field is found to decrease as $\ln dH/dt$ in Nb_3Sn ,¹³ NbZr ,¹⁴ and to saturate asymptotically at high sweep rates¹⁵ in the same way as

we find in $\text{LaSr}_2\text{CuO}_4$. The adiabatic model fails to explain the ramp dependence of the jump periodicity and, as has been pointed out by McHenry *et al.*,¹¹ the predicted period value does not correspond to the observed ones.

A nonadiabatic approach to the instability problem⁹ is based on the solution of the flux-lattice-motion equation. In the shielding layer in equilibrium, the Lorentz force is balanced by pinning and viscous forces,

$$F_L = F_p + \eta v. \quad (3)$$

On exceeding the stability limit, the Lorentz force becomes larger than the pinning force and the vortex lattice will accelerate. The time derivative of Eq. (3) gives an equation of motion for the flux structure,

$$\frac{\partial F_L}{\partial t} - \frac{\partial F_p}{\partial t} = \eta \frac{\partial v}{\partial t} + v \frac{\partial \eta}{\partial t}. \quad (4)$$

This equation has to be valid for all x and t , together with the flux-conservation condition

$$-\frac{\partial B}{\partial t} = \frac{\partial B v}{\partial x} = B \frac{\partial v}{\partial x} + v \frac{\partial B}{\partial x} \quad (5)$$

An exact solution of Eqs. (4) and (5) remains an unresolved problem; its solution depends upon the exact nature of the disturbance that initiates the instability. One can, however, get an impression of the parameter dH/dt . The acceleration of vortices will take some time during which thermal conduction drops and the temperature rise restores, to a certain extent, the pinning strength of the material. The vortices will reach their maximum velocity, decelerate, and stop. The size of this limited instability will depend on the relative growth of the shielding layer (assuming a semi-infinite sample), or the maximum velocity reached by the vortices, the last in turn depending on the initial velocity. For low values of dH/dt [and assuming $\partial v \partial x = 0$, Eq. (5)], the initial velocity v_{in} on the sample's surface is given by

$$v_{\text{in}} = \frac{dH/dt}{\partial B / \partial x|_{x=0}} = \frac{dH/dt}{4\pi J_c (B = H)}. \quad (6)$$

Using a number of general assumptions, Wipf⁹ has shown that for small dH/dt the maximum velocity v_{max} and the relative increase of the shielding layer $\Delta x_0/x_0$ will be proportional to

$$v_{\text{max}} \propto \frac{\Delta x_0}{x_0} \propto \frac{dH}{dt} e^H. \quad (7)$$

This would imply

$$H_{\text{fj}} \propto \text{const} - \ln \frac{dH}{dt}. \quad (8)$$

A straightforward application of this result for finite-dimension superconductors in the vicinity of their critical state is, however, questionable.

SIZE OF THE JUMP

One of the most important conclusions of our work is that the magnetization curve of superconductors depends not only on the value of the applied magnetic field but

also on the rate of its variation. In the instability regime, the maximal magnetization level reached between the jumps (the external magnetization envelope), the minimum magnetization limiting the jump (the internal magnetization envelope), and, therefore, the size of the jump, all depend on the sweeping rate. We show in Fig. 3 three sequences of the jumps corresponding to a variation of the applied field with the rates 0.5, 1, and 2 T/sec. These values of the sweeping rates were stabilized after an initial rapid increase ($dH/dt = 150$ T/sec) of the field up to 2 T. An abrupt change of the sweeping rate from 150 to about 1 T/sec provokes a complete jump (to be discussed later) and the magnetization drops to zero in all three experiments. When the applied field is increased at the given lower sweep rate, the magnetization amplitude is being rebuilt. It is important to note that after the jump the sample's magnetization depends only on the change of the field and shows no correlation to the time passed after the jump. For each value of the sweeping rate, the next jump occurs when the shielding field reaches a well-defined value. The corresponding maximum value of the magnetization decreases for higher sweeping rates. The internal magnetization envelope (minimum magnetization at which the jump is stabilized) shows an opposite tendency: its value increases for higher sweeping rates. As a result, the size of the jumps decreases with an increasing sweeping rate. This is summarized in Fig. 4 in which we show the maximum and minimum magnetization values (the starting and final jump points) as a function of the sweeping rate for single-crystalline $\text{LaSr}_2\text{CuO}_4$ in fields in the vicinity of 3 T. The size of the jumps monotonically decreases and the jumps are totally suppressed for the sweeping rates exceeding 20 T/sec.

One can distinguish three types of magnetic instabilities: limited, large-scale runaway jump and full jumps. The duration of the limited instability is short enough that the shielding layer has not grown noticeably compared to the original thickness x_0 . The runaway jumps are often preceded by these limited instabilities like those

FIG. 3. Magnetization of the $\text{LaSr}_2\text{CuO}_4$ sample as a function of the applied magnetic field for the sweeping rates of: (·) — 0.5 T/sec; (+) — 1 T/sec; (x) — 2.5 T/sec. The jumps at 2 T are provoked by a sharp reduction of the initial sweeping rate.

FIG. 4. The maximum and minimum magnetization values (the starting and final jump points) as a function of the sweeping rate for single-crystalline $\text{LaSr}_2\text{CuO}_4$ in fields in the vicinity of 3 T.

shown in Fig. 5. They are usually observed under “slow” variation of the magnetic field when magnetization approaches its critical-state level between the jumps.

A large-scale runaway jump can be defined as a full flux jump if the magnetization of the sample falls to zero and the sample is driven to the normal state. Following Wipf and Lubell,¹⁵ the necessary condition for a full flux jump at a temperature T_0 is determined by equating the decrease in magnetic energy of complete penetration to the energy necessary to heat the sample to a higher temperature T_u at which it is not superconducting under the given field. The full flux-jump field H_{fj} has to satisfy the conditions

$$\frac{1}{8\pi} H_{fj}^2(T_0) = \int_{T_0}^{T_u} C(T) dT \quad (9)$$

and

$$H_{fj}(T_0) = H_{c2}(T_u) \quad (10)$$

If the superconductor was initially cooled in a field H_0 Eq. (10) has to be replaced by

FIG. 5. The limited (marked) and large-scale runaway instabilities in $\text{LaSr}_2\text{CuO}_4$ sample.

$$H_{\text{ff}}(T_0) + H_0 = H_{c2}(T_u) . \quad (11)$$

For high-temperature superconductors the transition to the normal state is not necessary and $H_{c2}(T)$ should be replaced by the irreversibility field $H_{\text{irr}}(T)$. The field-dependent irreversibility temperature is a strongly decreasing function of field; therefore, if the sample has passed a full jump and was cooled back to the ambient temperature, the next full flux jump has to occur under lower shielding field, i.e., the repetition step will decrease for each jump. The periodic sequence of complete jumps, where the magnetization drops to zero within the experimental resolution, like that in the descending branch of curve (b) in Fig. 1, does not satisfy this condition. These jumps cannot be considered as full.

TIME DURATION OF INSTABILITY

Magnetic instabilities are usually visualized in the form of the jumps, during which the magnetization changes within a fraction of a millisecond.^{2,16} Flux penetrates or leaves the sample within the time determined by the magnetic diffusion time τ_{mag} . It is therefore surprising to find that in high-temperature superconductors, especially in single-crystalline $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}$, the time duration of the instability can be orders of magnitude longer than expected. We show in Fig. 6 three magnetization curves measured under the sweeping rates of 1, 2.5, and 5 T/sec. The time interval between the measuring points is 3 msec. One does not observe a quick break of the magnetization which we have called a jump. Instead, the process of magnetization change can take as long as ten milliseconds for $dH/dt = 1$ T/sec, up to hundreds of milliseconds for $dH/dt = 5$ T/sec. As a result, the magnetization curve becomes oscillatory.

This contradicts, to a certain extent, the adopted model of magnetic instabilities based on the competition between the magnetic flux flow and the heat flow. The necessary condition for a self-accelerating instability is that it develops faster than the thermal diffusion time. In $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}$ we find instabilities that develop much more slowly than this criterion.

Variation of the magnetization as a function of time provides a straightforward mapping of the flux penetration dynamics into the bulk of the superconductor. The vortices's acceleration, maximum velocity, and deceleration can be estimated by assuming that each magnetization value during the instability corresponds to the coordinate of the flux front moving from the perimeter to the center of the sample. More accurate calculations have to take into account the sample's geometry and the fact that the recovery of the critical state on the surface can start before the flux rush is stopped inside the bulk.

We come here to another important point of our report: the development of the magnetization curve under rapidly varying magnetic field. The loss of the critical-state magnetization in high-temperature superconductors is generally explained by the giant flux creep.¹⁷ Intuitively, one expects that by increasing the field sweeping rate on asymptotically approaches the maximum magnetization of the critical state. Indeed, this effect has been recently calculated and observed.¹⁸ We find, however, that

in the limit of very high sweeping rates, the description of superconductors in the framework of standard models is misleading. We show in Fig. 7 a set of irreversible magnetization loops observed in a $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}$ sample under the sweeping rates of 5, 10, 20, and 42 T/sec. Apparently, the magnetization level at a given field above 2 T decreases for higher sweeping rates.

The development of this surprising result can be followed by and seems to be intimately connected to the in-

FIG. 6. Magnetic instabilities in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}$ sample measured under the sweeping rates of (a) 1 T/sec; (b) 2.5 T/sec; (c) 5 T/sec. The time interval between the measuring points is 3 msec.

FIG. 7. Irreversible magnetization loops observed in a $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}$ sample under the sweeping rates of (a) 5 T/sec; (b) 10 T/sec; (c) 20 T/sec; (d) 42 T/sec.

intrinsic magnetic instability of a superconductor under varying magnetic field. When the external field is increased from zero, the critical state is being built and for shielding fields below the critical field H_{fj} , the magnetization does not depend on the sweeping rate (one can neglect the creep in these conditions). The stability is broken at a field of about 1.8 T. The magnetization is partially recovered (oscillatory curve) for $dH/dt=5$ T/sec, but is not recovered for higher sweeping rates. The change of the magnetization due to the instability decreases and the time duration of the instability increases when the instability is initiated at a lower level of magnetization (see Fig. 6). In its turn, for relatively low sweeping rates, the instability is initiated at a lower level of magnetization when the field sweeping rate is higher (see Fig. 6). On the other hand, for high sweeping rates ($dH/dt > 10$ T/sec for $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}$ sample) the instability is initiated at the same magnetization level (see Fig. 7) and the change of magnetization is larger for higher sweeping rates. As a result, the irreversible magnetization amplitude decreases for higher sweeping rates.

HEAT DISSIPATION

Ascribing the modifications of the magnetization to an intrinsic instability under varying field, one has to take into account that at least part of the effects observed can be caused by the overall heating of the sample. In our experiments the samples are immersed in the liquid helium bath. A direct measurement of the sample's temperature during a pulse by an attached RhO thermometer shows only a minor variation of the order of 0.1 K. The validity of this result is questionable, since the thermal contact between the thermometer and the helium bath can be better than to the sample.

The power p dissipated locally in a superconductor due to the change of the magnetic induction is equal to $J_c E$, where E is the induced electric field, and to a first approximation proportional to dB/dt . For the superconductor in the critical state $dB/dt = dH/dt$ and the total dissipat-

ed power for the cylindrical sample can be estimated as

$$P = \frac{\pi}{3} 10^{-8} L R^3 J_c \frac{dH}{dt}, \quad (12)$$

where P is measured in Watts; L (length) and R (radius) in cm; J_c in A/cm^2 and H in gauss. Taking $R, L = 1$ mm, $dH/dt = 10^5$ G/sec and the reasonable value for J_c of 10^5 A/cm^2 , one obtains P of the order of 10^{-2} W, which is a few times below the helium film boiling heat transfer value.¹⁹

In addition, several arguments indicate that the ramp heating alone cannot explain the whole variety of the phenomena described. First, the typical behavior is not modified when the helium bath temperature is lowered below the superfluidity point where the heat transfer to the bath is strongly improved. Second, an onset of the magnetization decrease (Fig. 7) does not depend on the ramp rate between 0.1 and 50 T/sec. Third, in an adiabatic model of magnetic instabilities the flux-jump field H_{fj} is expected to increase with temperature as follows from Eqs. (1) and (2). Indeed, an increase of the jump repetition period with temperature has been observed in $\text{LaSr}_2\text{CuO}_4$,¹¹ as well as in $\text{YBa}_x\text{CuO}_{1-x}$ samples.^{20,21} In spite of the increased power dissipation, we find a strong decrease of the jump period when the sweeping rate is increased from 0.5 to 5 T/sec (Fig. 2).

Superconductors are heated during the jump when an excess of magnetic energy is suddenly converted into heat. Spikes in temperature, which occur simultaneously with the magnetization jumps, have been recorded in different systems in quasiadiabatic conditions.^{3,21,22} In order to recover its prejump magnetization, the sample has to be cooled down to the ambient temperature and the applied field has to be changed. In Fig. 3 we have shown the dynamics of the jumps and the magnetization recovery when the jumps were initiated by a sudden change in the sweeping conditions and the magnetization was recovered under different field change rates. Surprisingly, one does not observe any effect of the cooling process. The magnetization is found to depend only on the change in the applied field and not on the time passed after the jump.

Finally, the development of nonmonotonic oscillatory magnetization with very long time periodicity of the order of 1 sec cannot be explained by heating alone and implies other mechanisms.

ARTIFICIALLY INITIATED INSTABILITIES

The magnetic stability of the superconductors to the well-defined excitations can be tested experimentally. We show in Fig. 8 one of the possible field pulses and the corresponding time variation of the magnetization monitored in a $\text{LaSr}_2\text{CuO}_4$ crystal. One can distinguish four types of instabilities in this experiment, two artificial and two intrinsic: (1) an artificially initiated complete jump (from a to b) when the field-sweep rate is suddenly decreased from 150 to 0.3 T/sec; (2) an artificially provoked limited instability due to a small discontinuity in the field variation; (3) intrinsic limited instabilities; and (4) intrinsic runaway jumps whose periodicity is determined by the

FIG. 8. One of the possible field pulses and the corresponding time variation of the magnetization monitored in the $\text{LaSr}_2\text{CuO}_4$ sample.

field-sweeping rate.

The break of magnetization and the size of the jump depend on the relative change of the sweeping rate and the magnetization level at which the instability is provoked. This type of experiment can test explicitly the models of magnetic instabilities in superconductors.

CONCLUSIONS

High-temperature as well as conventional low-temperature superconductors are intrinsically unstable under varying magnetic fields. After its breakdown, the critical or quasicritical state can be periodically recovered when the applied field-sweeping rate does not exceed a certain limit, which is of the order of 1–10 T/sec for the studied single-crystalline samples of

$\text{LaSr}_2\text{CuO}_4$ and $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}$. For higher sweeping rates, no periodic instabilities are observed and magnetization is stabilized at the corresponding lower level. This strongly suggests a development of an equilibrium distribution of the magnetic field inside the superconductor, whose profile depends not only on the intrinsic bulk parameter $J_c(T, B)$, but also on the rate of the flux variation when the vortices enter or leave the body of the superconductor. In this regime, magnetization curves are totally modified and their interpretation based on the standard isothermal^{1,23} as well as adiabatic⁸ models is doubtful. We are not aware of theoretical attempts to describe the field distribution in the hard superconductors under rapidly varying field.

The mechanism of the magnetic instabilities and the dynamics of a nonequilibrium flux penetration into a superconductor also await detailed studies. A number of basic questions have to be clarified, among them the role of the field-sweeping rate, the role of the surface layer, the dynamics of the flux runaway, its stabilization, etc.

Magnetic instabilities in superconductors seem to be closely related to problems of simultaneous magnetic-domain-wall motion observed in such magnetic systems as single-crystalline $\text{Sm}_x\text{Co}_{1-x}\text{Cu}$.²⁴ We find ourselves at the opening of a vast and interesting field of study. Its theoretical development is necessary to suggest more informative experiments.

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