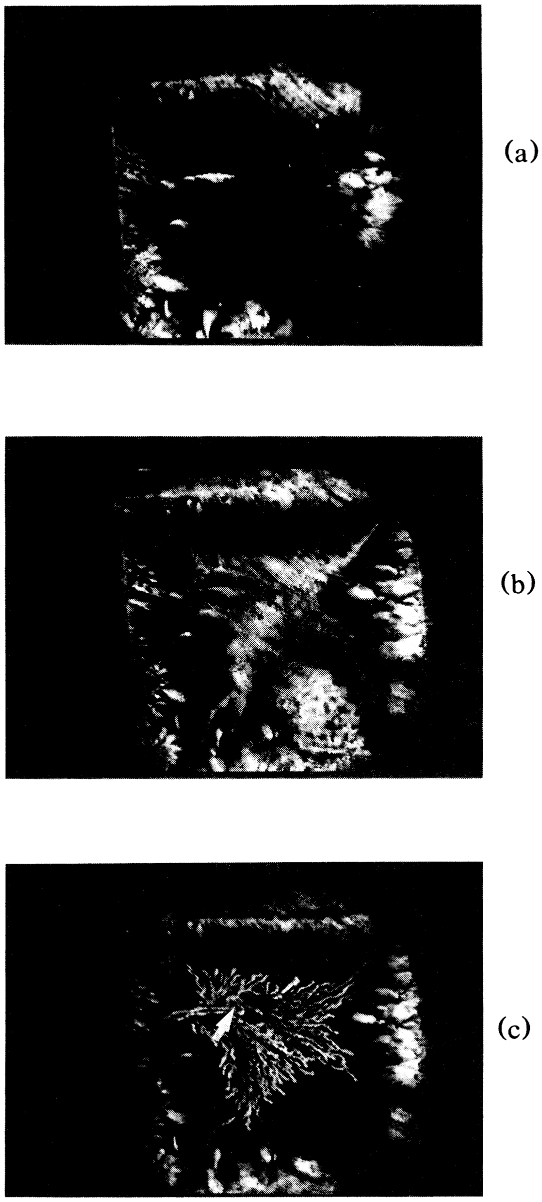

FIG. 1. Laser-induced changes in the magnetic flux distribution of a thin $YBa_2Cu_3O_{7-x}$ film. Bright regions correspond to the Shubnikov phase and dark regions to the Meissner phase. The sample size is 1×1 cm^2. (a) Flux distribution before the laser pulse ($T=1.8$ K, $B_{ext}=60$ mT). A major part of the sample is in the Meissner phase. (b) Change of the flux distribution after laser heating a spot in the sample center. (c) Change of the flux distribution after laser heating a spot (position indicated by the white arrow) close to a weak region, where some flux had already penetrated.

fore [7]. It should be pointed out that due to the small film thickness comparable to the London penetration depth (~150 nm), large shielding currents with current densities close to the critical current density j_c of about 2×10^7 A/cm^2 flow even in the Meissner phase [8,9]. Figure 1(b) shows the same film after laser heating a spot approximately at the sample center. Although somewhat difficult to discern, a rather large portion of the former Meissner region now displays an increased, nearly constant light intensity—and hence the presence of a perpendicular magnetic field—indicating that the laser pulse has nucleated a large scale redistribution of magnetic flux.

Next we started again from a field distribution as depicted in Fig. 1(a)—after heating the sample above T_c, zero field cooling and applying $B_{ext}=60$ mT—but now the laser focus was adjusted near the sample edge, close to a "weak spot" where flux had already entered the film. Although the overall contour of the resulting laser-induced flux distribution, as seen in Fig. 1(c), is similar to the one in Fig. 1(b), the fine structure is obviously completely different. Instead of the more or less spatially constant flux density in Fig. 1(b) one now observes pronounced, branchlike structures with an average spacing of 0.3 mm and a width of the branches of 0.1 mm. On closer inspection one can also distinguish in Fig. 1(c) an area of about 0.5 mm radius around the nucleation spot with a structureless flux distribution without branches. This is a first hint that flux motion triggered by the laser pulse actually develops in two steps [10]: (i) First, a perturbation grows in the Meissner phase around the nucleation spot in a roughly isotropic way, forming a region where flux, accumulated at some weak parts of the film before, is afterwards distributed homogeneously within the perturbed area; (ii) as soon as this region makes contact with the surrounding externally applied field at some point, massive avalanchelike penetration of external flux sets in, and branches start to spread out from the rim of the homogeneous area.

More conclusive evidence for the hypothesis of such a two-step process comes from the time-resolved measurements to be discussed now. Figure 2 displays a sequence of pictures taken before (2a), 56 ns after (2b), and a few seconds after (2c) the Nd:YAG pulse. Figure 2(b) thus represents a transient state, whereas 2(a) and 2(c) are steady distributions. A comparison of Figs. 2(b) and 2(c) shows that already after $t=56$ ns the flux structure has nearly reached its final size. Nevertheless, some of the branches are not yet fully developed and apparently still are to grow a few tenths of a mm. A series of such recordings with variable delay times has been used to investigate the growth dynamics of the flux structures in more detail. These studies reveal that the spatially homogeneous field distributions like in Fig. 1(b) develop extremely fast on a time scale which is not even accessible with our temporal resolution of 10 ns. We therefore can only estimate that the speed at which the front of this phase propagates is larger than 2×10^5 m/s. The propagation speed of the branches, on the other hand, was small enough that it could be determined with our technique. In Fig. 3 we have plotted results for the mean velocity, $\langle v\rangle=l/\tau$, where l is the length of the flux branches

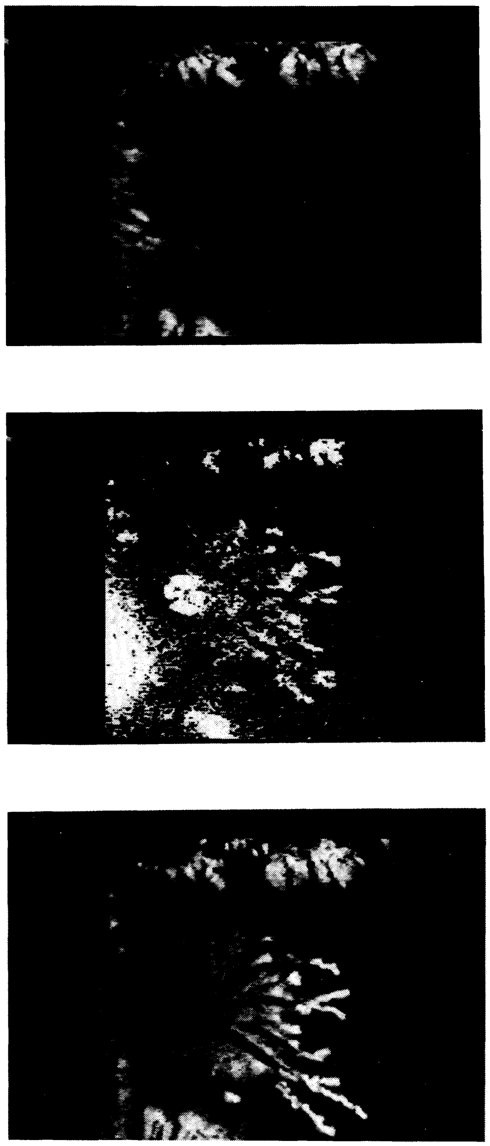

FIG. 2. Time evolution of the instability in the magnetic field distribution. The frames correspond to a 4×4 mm^2 section of the superconductor ($T=1.8$ K, $B_{\mathrm{ext}}=25$ mT). (a) Before the laser pulse, (b) 56 ns after the laser pulse, and (c) final flux distribution. The width of the branches is similar as in Fig. 1(c) (≈ 100 μm).

and τ is the delay time. The data yield $\langle v\rangle=(5\pm2)\times10^4$ m/s, which, for comparison, is an order of magnitude higher than the velocity of sound in $YBa_2Cu_3O_{7-x}$ [11].

We now turn to possible interpretations of the observed phenomenon. As a superconducting spot carrying large shielding currents is heated up to temperatures where j_c has dropped considerably or is even zero, dissipation and a redistribution of the shielding currents will take place. We concentrate here on the second step of the instability,

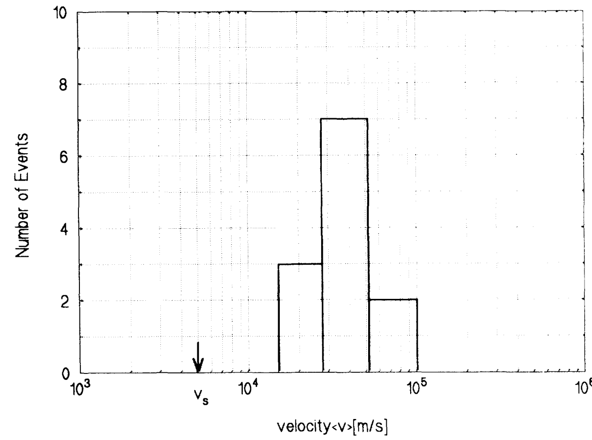

FIG. 3. Histogram of the average spreading velocity $\langle v\rangle$ of flux branches, derived from several recordings [as in Fig. 2(b)] at different delay times τ. The quoted values were obtained from $\langle v\rangle=l/\tau$ (where l is the length of the branch pattern at this time τ), and therefore only represent a lower limit for the actual spreading velocity. The arrow marks the velocity of sound v_s in $YBa_2Cu_3O_{7-x}$ [11].

where more experimental information is available. Regarding the high propagation speed of the flux branches, a theoretical description of the phenomenon has to rest on the interaction of the supercurrents with the electromagnetic field, in contrast to theories based on primarily thermal quench fronts [2,12].

Our approach is similar to the one used by Pippard [13] to study the dynamics of the quench front in bulk superconductors. We start combining Maxwell's and London's equations to the equation of motion,

$$(\Delta-\partial_{tt}/c^2-l/\lambda^2-\mu\sigma\partial_t)\Phi=0\,, \qquad (1)$$

where Δ is the Laplace operator, ∂_{tt} indicates the second derivative with respect to time, λ is the London penetration depth, μ the magnetic permeability, and σ the normal conductivity of the material. Φ stands for either the electric or the magnetic field. The field equations for the normal conducting state are obtained by setting $l/\lambda^2=0$. As a simple model, we consider a straight quench front moving with the velocity v. A straightforward calculation yields the decay lengths l of the fields into the superconducting (l_{sc}) and into the normal region (l_{nc}). We obtain $l_{\mathrm{sc}}\approx\lambda$ and $l_{\mathrm{nc}}\approx\sqrt{Rd}$, where R is the lateral sample dimension and d the sample thickness. Inserting typical sample dimensions yields $l_{\mathrm{nc}}\approx 40$ μm. Thus the minimum width of any structure in the normal region must be at least $2l_{\mathrm{nc}}\approx 80$ μm which agrees very well with the observed branch width of 100 μm. In order to shed light on the formation mechanism of the branches we have also carried out a linear stability analysis of a straight quench front [14]. As the calculations show, the front is stable with respect to small perturbations, as in the case of bulk superconductors [15]. This suggests that the branches do not evolve from a soft mode of the straight front. In fact, it seems that the branch number grows during the whole quench process by repeated splitting of individual branches, in contrast to a soft mode mechanism which would produce a large number of evenly spaced branches from the start. Apparently, the rather uniform spacing in Fig. 1(c) originates from the statistics of the splitting process. For a quantitative prediction of the front (or growth) velocity, detailed information about the magnetic field distribution would be required [13]. In addition, eddy currents in the aluminum mirror adjacent to the superconducting film would have to be taken into account [4].

In summary, we have studied the evolution of a novel instability nucleated by a laser pulse in thin superconducting films exposed to a static magnetic field. We find two regimes: first, a process where the perturbation leads to a homogeneous redistribution of flux over a certain part of the sample on a time scale less than 10 ns, and a second step, where flux entering the sample from the outside penetrates the Meissner phase in the form of branches which propagate at a speed of about 5×10^4 m/s. Some of the characteristics of this instability follows directly from a combination of Maxwell's and London's equations; others, like the origin of the branching, require further investigations. The experiments have been performed with a high-T_c superconductor, but we expect similar phenomena to occur also for conventional hard type II superconductors.

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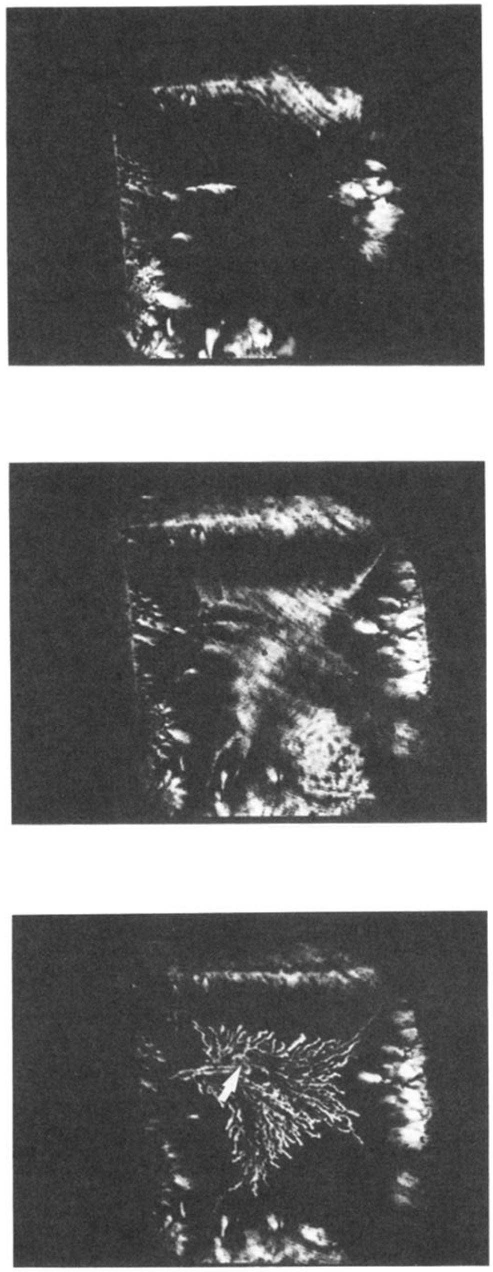

(a)

(b)

(c)

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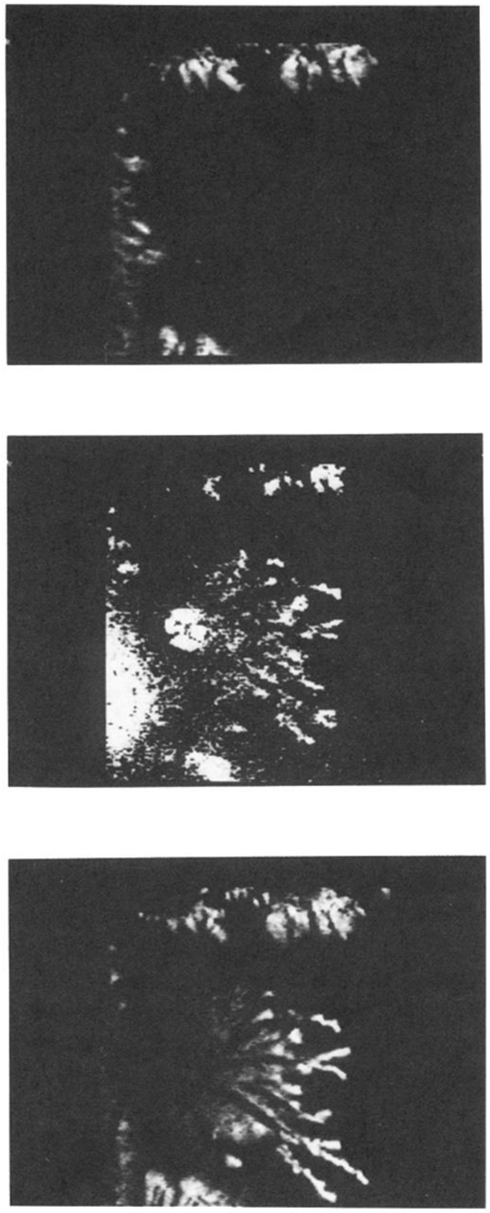

(a)

(b)

(c)

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