Temporal Behavior of the Breakdown of Superconductivity

Wolfgang Buck

Physikalisch-Technische Bundesanstalt, Institut Berlin *

Jürgen Parisi

Physikalisches Institut, Lehrstuhl für Experimentalphysik II, Universität Tübingen

Z. Naturforsch. **44a,** 247–256 (1989); received January 4, 1989

On a very short time scale, breakdown of superconductivity with increasing transport current turns out to be a highly dynamical process, called "current-induced resistive state". Magnetic flux domains rapidly move perpendicular to the direction of the transport current applied, with increasing velocity as the current is further increased. At sufficiently high currents, superconductivity is completely destroyed, and the sample ends up in the normal state. In this paper, the first time-resolved measurements of voltage signals induced by the motion of single flux domains are reported. A stability analysis of the superconducting state based on the "Gibbs free energy barrier model" describes the temporal voltage profile generated by a single flux domain, which is solitarily moving across the sample cross-section, as well as the superimposed signals of a series of competing domains, existing simultaneously in the sample. In the latter case, the interaction among the flux domains is taken into account by a monopole ansatz. Studying the onset of the breakdown of superconductivity in type I materials, an oscillatory behavior of the domain size was found. After a few periods, these transients change into a stationary number of flux quanta per domain.

1. Introduction

Superconductivity is a well-known physical state, which was already discovered in 1911. Very recently, superconductivity has been pushed again into public interest, since a new class of ceramic materials has been found to show superconductivity at exceptionally high transition temperatures, promising a large variety of unexpected technical applications. But there are still a lot of problems with the "classical" superconducting materials remaining unsolved up to now. Among them, the solution of certain problems appears to be important for the understanding and the application of the high-T_c superconductors, as well. This is particularly true for the breakdown of superconductivity in current-carrying samples.

In the following, we report on the results of experimental investigations performed during the last decade, which for the first time show the temporal development of the current-induced breakdown of superconductivity in great detail. Furthermore, we present a theoretical interpretation of these results on the basis of a stability analysis of the superconducting state. The results of our study are relevant to all cases where the capability of transporting electrical currents in superconducting materials is of major interest.

Our experiments have been designed to reveal the temporal aspect of the breakdown of superconductivity. Therefore, local sample inhomogeneities or special sample geometries projected for high current densities were not in the center of interest. The samples were designed as simple as possible in order to compare the results with a simple model and to simplify the physical interpretation. The samples have been prepared as evaporated strips of type I superconducting material (about 100 μm wide and a few μm thick) with a geometrical constriction, acting as a well-defined nucleation center [1] for the breakdown of superconductivity (see upper part of Figure 1).

If the voltage drop across this geometrical constriction is measured as a function of the current applied, the result is a current-voltage characteristic similar to that of a "microbridge". Below a certain critical value of the transport current, there is no voltage drop observed. Above the critical current, a sudden voltage jump appears to a finite value, followed by a further increase of the voltage that smoothly bends into a straight line with ohmic behavior. Then, superconductivity is completely destroyed. The critical current and the voltage jump are, of course, larger than in the

* Abbestr. 2–12, D-1000 Berlin 10.

Reprint requests to J. Parisi, Physikalisches Institut, Lehrstuhl II, Universität Tübingen, Auf der Morgenstelle 14, D-7400 Tübingen 1, FRG.

0932-0784 / 89 / 0300-0247 $ 01.30/0. – Please order a reprint rather than making your own copy.

Dieses Werk wurde im Jahr 2013 vom Verlag Zeitschrift für Naturforschung in Zusammenarbeit mit der Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. digitalisiert und unter folgender Lizenz veröffentlicht: Creative Commons Namensnennung-Keine Bearbeitung 3.0 Deutschland Lizenz.

Zum 01.01.2015 ist eine Anpassung der Lizenzbedingungen (Entfall der Creative Commons Lizenzbedingung „Keine Bearbeitung") beabsichtigt, um eine Nachnutzung auch im Rahmen zukünftiger wissenschaftlicher Nutzungsformen zu ermöglichen.

This work has been digitalized and published in 2013 by Verlag Zeitschrift für Naturforschung in cooperation with the Max Planck Society for the Advancement of Science under a Creative Commons Attribution-NoDerivs 3.0 Germany License.

On 01.01.2015 it is planned to change the License Conditions (the removal of the Creative Commons License condition "no derivative works"). This is to allow reuse in the area of future scientific usage.

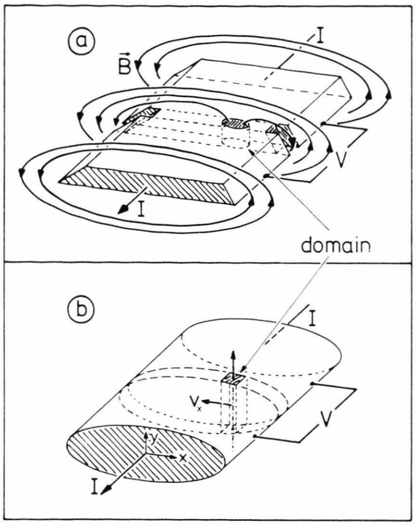

Fig. 1. Sample geometry; (a) schematic representation of the real sample; (b) ideal sample shape used for model calculations.

case of a microbridge, according to the large geometry and capability of carrying transport current.

Our investigations concentrated on the transition region between the undisturbed superconducting state and the ohmic state, which is called "current-induced resistive state" (CIRS) [2], this being the regime where the system decides between stability or breakdown of superconductivity.

It is well-known from magnetooptical experiments with stroboscopic illumination [3] that a superconducting sample does not immediately become a normal conductor when driven just beyond the critical current. Instead, magnetic flux domains have been observed, that are nucleated at one sample edge and annihilated at the opposite one, after having crossed the sample perpendicular to the direction of the transport current. This means that the CIRS represented by the voltage jump in the current-voltage diagram has to be characterized as a highly dynamical state. By evaluation of the magnetooptical photographs, which show the magnetic domains via the Faraday effect in an additionally deposited, optically active layer, the average velocities of magnetic domains could be determined in the order of some meters per second. This imaging method, however, is only capable of investigating stationary and well periodic states of the CIRS and the motion of domains away from the sample edge. Note that one requires the superposition of a few thousand single illumination events to obtain sufficient optical contrast. Therefore it can not at all be expected to observe the nucleation of the initial domains generated at the very beginning of the breakdown of superconductivity.

During the magnetooptical experiments, it was a striking fact that there exist wide ranges of experimental parameters, like temperature or current, where no predicative picture of flux domains could be extracted by superposition of the single stroboscopic snapshots. The reason for that seemed to be the lack of sufficient periodicity of the flux-flow motion, even when it was stimulated periodically. This result led to the conclusion that the normal case of CIRS is unperiodic or, at least, not sufficiently periodic. Imagine the parameter space where a few single islands of strong periodicity exist within a sea of possibly chaotic behavior. This assumption was the motivation for extended investigations on the nucleation frequency of flux domains [4]. For this purpose, a narrow and thin superconducting strip was evaporated onto the sample, separated by a thin isolating layer. This test strip was oriented parallel to the current direction and, therefore, perpendicular to the path of flux domains. A domain crossing the sample switched the superconducting test strip into the normal state and generated a voltage pulse, which was measured on the test strip using a four-probe arrangement. Since the normal resistance of the test strip has been chosen to be sufficiently large, the voltage pulse could easily be detected. Now the passing flux domains could be counted in a similar way as, e.g., people passing a photoelectrical barrier. With the same arrangement, the temporal distances between consecutive domains, their nucleation frequency, and the fluctuations of both quantities could be determined. The results again confirmed the existence of highly periodic modes of flux-tube nucleation among completely aperiodic behavior within large parameter ranges. Sometimes the transition from one periodic mode with a certain nucleation frequency to another mode with a different frequency could be observed. During such a transition, the fluctuations of the first nucleation frequency started to increase, until the mode has completely disappeared. But already before that, the fluctuating frequency of the second mode could be detected. Thus, the nucleation process switched between both frequencies, until the second mode survived eventually. The limitations of these experiments resulted from the fixed position of the test strip on top of the sample. Therefore, only locally restricted information – and definitely no information on the dynamics at the sample edge where nucleation and annihilation of domains take place – could be gained.

Consequently, a new method had to be developed, if the total life of a flux domain, ranging from its nucleation up to its annihilation, and, especially, the very onset of the breakdown of superconductivity should be investigated. The physical quantity containing all information needed was well-known, but difficult to measure: the tiny flux-flow voltage recorded with extreme temporal resolution along the superconducting sample, i. e., across the path of moving flux domains. Indeed, the temporal resolution required had to be large compared to the life time of a flux domain. Therefore, a recording bandwidth of 25 megahertz was neccessary. The voltage signals were estimated to be of the order of hundred nanovolts. The voltage resolution should be better by at least one order of magnitude. The disturbing electrical noise could only be reduced down to the order of 1 microvolt by the help of different steps of shielding. Even then it remained larger than the expected voltage signals by one order of magnitude. Consequently, the signal-to-noise ratio (SNR) had to be improved by at least a factor of hundred, demanding a signal-averaging procedure. Finally, for the samples to be investigated type I superconducting material was selected. Then flux domains having a typical size of about hundred flux quanta are created, which generate accordingly larger voltage signals (by almost the same factor) compared to single-quantum flux domains in type II superconductors. With this arrangement [5], which is described in more detail in the next chapter, we were able to detect voltage signals of flux domains even containing down to 5 flux quanta [6]. Moreover, we have recorded signals ranging from the very beginning of the flux-flow state up to the transition into the stationary state of periodically migrating flux domains. The experimental parameters could be controlled in such a way that, in one case, only a single domain existed in the total sample cross-section. Then the voltage profile of a single domain could be registered. In the other case, a series of simultaneously existing domains moved across the sample like a one-dimensional chain, successively nucleated at one sample edge and annihilated at the opposite. In this case, the mutual interaction between the domains could be studied and compared with model predictions.

2. The Experimental Details

The average velocity of a flux domain in a superconducting strip, having a width of 40 μm and a thickness of 2 μm, is about 20 m/s, if the transport current is kept closely above the critical current [7]. This results in a life time of the domain of 2 μs. If the domain contains, e. g., 50 flux quanta, its total magnetic flux is 10^{-13} Vs. Then, the domain generates an averaged voltage signal of 50 nV.

From these estimates, we can derive the specifications of the detection system, which should allow to record the time-resolved flux-flow voltage. In order to resolve the steep slopes of the expected voltage peaks, the time scale should be chosen to record two hundred voltage points during the 2 μs life time of a single domain. Therefore a sampling time of 10 ns is required. According to the sampling theorem, the pre-amplifiers and filters have to be selected with an appropriate bandwidth of 25 MHz in order to provide the neccessary temporal resolution and, at the same time, to avoid the "aliasing effect" due to electrical noise of higher frequencies.

Although the sample was shielded inside the cryostat by a niobium can, and the cryostat including the pre-amplifiers was located inside a radiofrequency shielded room made from copper foil, the input noise could not be reduced below 3 μV, as a consequence of the large bandwidth needed for the temporal resolution. Accordingly, the noise was larger than the expected signal by a factor of 60. Therefore, the signal-averaging method [8] was chosen to improve the SNR considerably. Here, the noisy signal is digitized by a transient recorder during short subsequent time steps. Each voltage data point is stored in a separate memory cell. When the memory of the transient recorder is full, the stored string of data points is transmitted to the memory of a computer. The acquisition of data in the transient recorder has to be started within a precisely defined temporal distance from a trigger pulse, which should be as noiseless as possible. Such a measurement cycle is repeated many times and added to the sum of the previous cycles in the computer memory. Thus, the amplitude of the desired signal, which is coherent to the trigger pulse, is increased proportional to the number of measurement cycles added. Note, however, that the amplitude of statistical noise is increased only proportional to the square root of the number of measurements. Accordingly, the SNR itself is increased proportional to the square root of the number of measurements. For our experimental situation, one can easily estimate that some 100 000 measurement cycles are needed in order to achieve an acceptable SNR of about 10.

The signal-averaging method cannot discriminate against disturbing signals, which appear at a fixed phase difference to the desired signal, like, e. g., pick-up signals. We call such kind of disturbances "coherent noise". To eliminate these signals, a differential method was used. There were two types of voltage strings measured. The first type was recorded in the usual way, with a transport current exceeding the critical current and, therefore, containing the signals generated by flux domains. The other type was registered with the transport current kept closely below the critical current, so that no domain is nucleated. However, due to the similar electrical conditions, pick-up signals appear in the same way as before. The first type of data is added in the computer memory, whereas the second type is subtracted. Certainly, a factor of two is lost in the measuring time, but disturbing signals coherent to the desired signal are eliminated completely.

Figure 2 shows a schematic representation of the experimental apparatus [5]. The sample strip is biased with a constant dc current smaller than the critical current. To this dc current, a trapezoidal current pulse is added periodically. The total current exceeds the critical current during the width of the pulse, and flux domains are generated. The voltage drop across the domain path is amplified by a series of low-noise amplifiers by 95 dB in the frequency band from 6 kHz to 100 MHz and transferred afterwards to the input of a transient recorder (BIOMATION 8100). The transient recorder is triggered synchronously to the current pulse. In order to reduce the measuring time determined by the large number of measurement cycles, a fast data transfer system between the transient recorder and the PDP 11/04 computer was developed using a CAMAC I/O interface. The positive or negative superposition of the single measurement cycles was performed by the computer program as well as a digital filtering procedure, if required.

To characterize the features of the experimental set-up, a voltage resolution of 10 nV (with 2048 measured data points) and a temporal resolution of 10 ns (i. e., a bandwidth of 25 MHz) could be achieved by superposition of a few 100 000 measurement cycles. If the measurement cycle was reduced to 10 data points, the voltage resolution could accordingly be improved to almost 1 nV. Note that in the former case, using the total memory of the transient recorder, a product of rise time and voltage resolution of 10^{-17} Vs is available, which is much smaller than the size of one flux quantum (2×10^{-15} Vs).

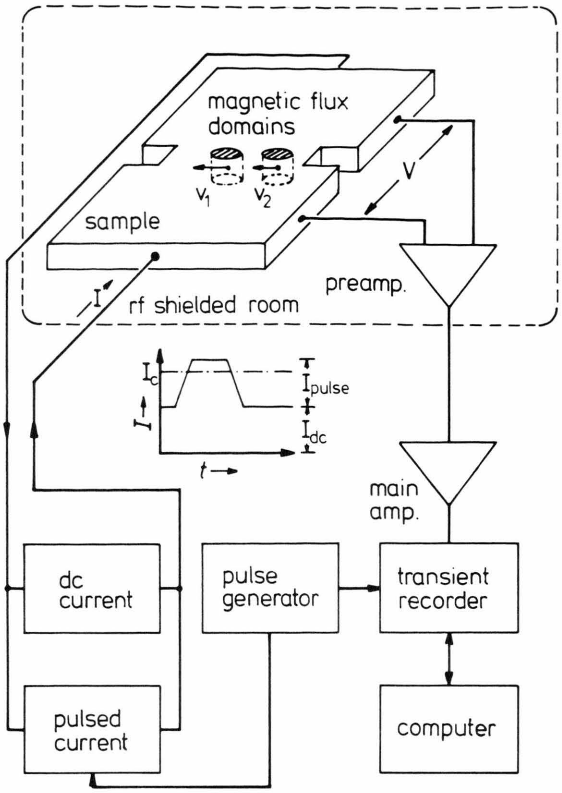

Fig. 2. Block diagram of the experimental set-up.

3. Experimental Results

The result of a typical experiment is collected in Figure 3 [7]. The measurements were performed with an indium sample of 43 µm width and 2 µm thickness at a temperature of 3.0 K (critical temperature of indium: 3.4 K). Figure 3 a shows a conventional current-voltage characteristic with a zero-voltage state up to the critical current of 58 mA. Beyond that, nucleation of flux domains starts and generates a voltage jump of almost 200 nV. At higher currents the voltage increases further with the current. At much higher current values the sample becomes completely normal,

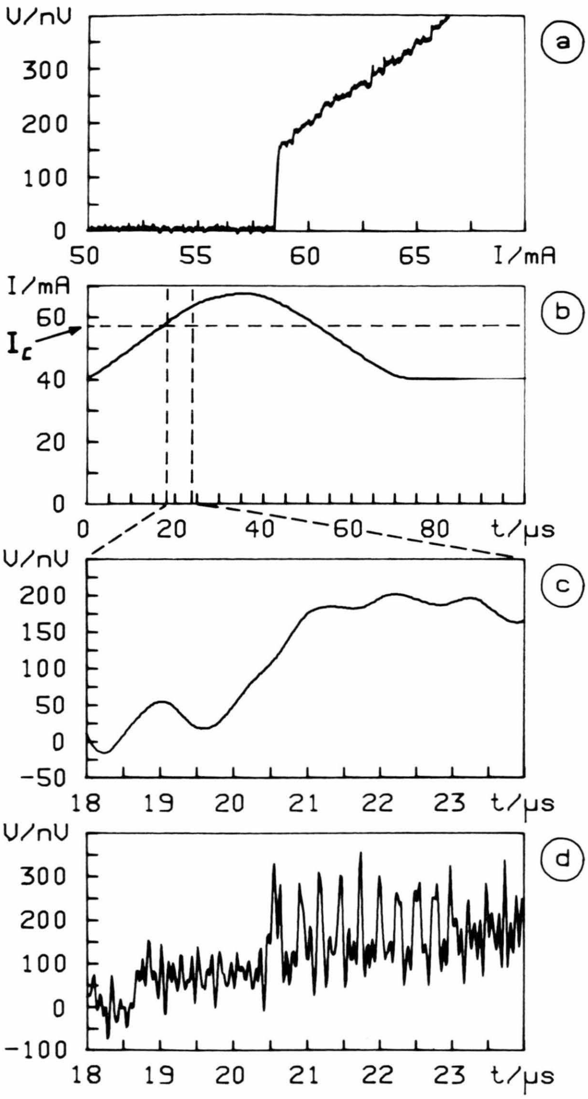

Fig. 3. Voltage signals of migrating flux domains; (a) conventional current-voltage characteristic; (b) applied transport current as a function of time; (c) time dependent flux-flow voltage with reduced, and (d) with high resolution; note the extended time scale of (c) and (d) compared to (b).

resulting in an ohmic characteristic which is outside the frame of Figure 3a.

If the transport current is not increased continuously, like in Fig. 3a, but exceeds the critical current in a trapezoidal shape, as shown in Fig. 3b, then the CIRS can be switched on and off periodically, and the time-resolved voltage signal can be extracted from the noisy background by the signal-averaging procedure. In Fig. 3c such a signal is represented, which is measured during a small number of repeated measurement cycles (about 1000) using a small bandwidth (6–800 kHz). First, the voltage oscillates around the zero level. Then, there are two increasing steps. The first one is small and coincides with the crossing of the current pulse and the critical current. The second one goes up to 200 nV and will be interpreted later on. Much clearer is the message of Figure 3d. There, the bandwidth is enlarged from 6 kHz to 12 MHz, and the number of measurement cycles is extended to 9000. Now, there is no more doubt about the small voltage step at 18.7 μs, which is due to the nucleation of the first flux domain. Later on, we will demonstrate that the voltage needles starting at 20.5 μs result from the annihilation of flux domains. The life time of the first domain can be determined to be about 1.8 μs. Due to the changed time scale, Fig. 3c and 3d represent only a small part of the rising edge of the current pulse in Figure 3b. With sufficiently short current pulses, the voltage needles can be observed during the whole time, while the transport current exceeds the critical current. With longer current pulses, this structure is wiped out towards the end of the pulse due to the long-term instability of the flux nucleation process. From the average distances of the voltage needles, $t_0 = 250$ ns (from Fig. 3d), and from the average voltage level, $V = 190$ nV (taken from the according part of Fig. 3c), the number of flux quanta per domain can be estimated to be $N = 23$, based on the equation

$$V = N\, \varphi_0 / t_0, \tag{1}$$

where φ_0 represents the flux quantum.

A series of experimental checks has been performed in order to clearly identify the voltage signals generated by moving flux domains. First of all, the dc bias current was reduced in such a way that the superimposed current pulse could not exceed the critical current any more. Immediately, the voltage needles disappeared, as expected.

On the other hand, the increase of the underlying dc current with unchanged current pulse resulted in an onset of flux tube nucleation occurring earlier than before. The reason for such behavior is obvious from the trapezoidal shape of the current pulse. Shifting the total current to higher values means to shift the crossover with the critical current to earlier times.

Furthermore, the reproducibility of the characteristic voltage profile was tested by the help of repeated measurements performed under constant external parameters. These experiments were successful up to time differences of 30 minutes between two measurements. Over longer periods, problems arose from the critical dependence of the periodic CIRS modes on instabilities of the experimental control parameters (like, e. g., the temperature), as mentioned above.

If the distances between the voltage needles in Fig. 3 d are analyzed in more detail, a change of the annihilation frequency is observed, which is clearly related to the rising current of the trailing edge of the current pulse. This result is expected as a matter of course, since the averaged migration velocity of the flux domains follows the value of the transport current.

Since all experimental indications point out that we have directly observed the tiny voltage signals generated from rapidly moving flux domains in a superconducting strip, these results call for an interpretation in terms of a plausible physical model, to be given in the following sections.

4. The Model

In order to simplify the model consideration, the sample is assumed to be of an ideal shape, as shown in Figure 1 b [9]. On one hand, the calculation of magnetic field distributions is easily performed using a cylindrical geometry. This formulation can be directly transformed to an elliptically shaped sample, without trouble by conformal mapping. On the other hand, an elliptical cross-section represents an acceptable approach to the real sample (Fig. 1 a), if it is very flat having a width much larger than its thickness. This is not true, of course, for sample regions very close to the edges. There, the sample thickness grows much faster with the distance from the edge for the elliptical shape than for the real cross-section having a flat shadowed slope due to the evaporation process. This generally results in larger critical currents (typically by a factor of 2) predicted from the model calculations, compared to the experimental results. For this reason, the critical current has to be used as a fit parameter, although it can be calculated in principle from the model equations, as we will show later on. Note, however, that the critical current is the only fit parameter used in the model. In order to retain clarity, inhomogeneities of the superconducting material like, e. g., grain boundaries are not regarded within the momentary version of the model. That means that the spatial dimensions of such phenomena should be smaller than the diameter of the flux domains, if the model is applied.

As shown in Fig. 1 b, a magnetic domain is regarded as a normal conducting volume surrounded by superconducting phase. Since for type I superconductors the magnetic penetration depth is smaller than the coherence length, we assume the domain wall to be sharp. Nevertheless, the model can also be applied to type II superconductors without difficulties if the distance between domains is kept large enough, such that no interference can take place inside the superconducting part of the sample (e. g., via screening currents).

A normal conducting domain containing the magnetic flux Φ perceives a Lorentz force F_T, if a transport current I_T is applied to the sample. F_T is proportional to the product $\Phi \times I_T$ and is directed from the nucleation site of the domain towards the sample center or to the opposite sample edge, respectively. To be more precise, the local distribution of the current density $j(x)$ has to be applied, which shows strong peaks near both sample edges. Thus, F_T would continuously accelerate the domain away from its nucleation site if a dissipative friction force F_d would not prevent this purpose. F_d is proportional to the velocity of the domain and is mainly caused by eddy-current damping of the screening currents, partly passing through the normal conducting area of the domain. If we do not take care of other forces acting on the magnetic domain, the equation of motion can be derived from the balance of the Lorentz force and the friction force. From the solution of this differential equation, the temporal profile of the domain velocity $v(t)$ can be calculated. Since the desired voltage signal $V(t)$ is proportional to the domain velocity except a geometrical factor [10], we have gained a simple theoretical ansatz to interprete the experimental results. Curve (b) in Fig. 4 represents this theoretical result, with a current applied as shown in curve (a) and shaped according to the experimental conditions [11]. The result gives an ideally symmetric shape of the voltage profile, containing sharp peaks at the beginning and at the end of the domain life and a structureless part in between.

The equation of motion can be solved only by numerical methods, since the differential equation is strongly nonlinear. This is in agreement with the experimental fact mentioned above, that there are limited parameter ranges with highly periodic modes of the domain nucleation among wide aperiodic areas (reminiscent of periodic islands in a sea of chaos).

However, comparison of curve (b) in Fig. 4 with the experimental result in Fig. 3 d clearly indicates differ-

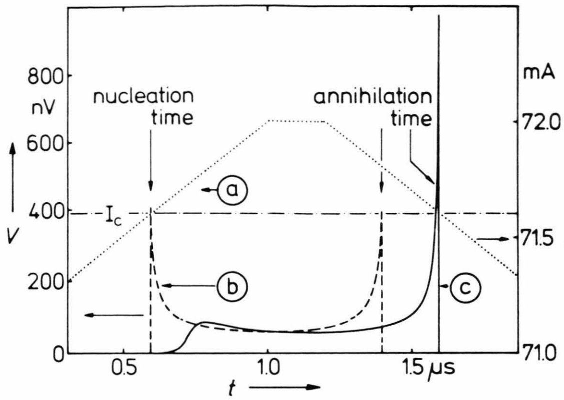

Fig. 4. Calculated time dependent voltage profiles of a single flux domain; (a) applied transport current as a function of time; (b) time dependent voltage without, and (c) including the barrier forces.

ent shapes of the voltage profile. It is a matter of fact that the experiment shows voltage needles caused only by domain annihilation, but no voltage peak is observed at the nucleation of a flux domain. As a consequence, additional forces acting on the domain have to be taken into account, which are not yet included in our simple model. Moreover, the model at the momentary stage does not predict the existence of a critical current, that gives a threshold above which superconductivity becomes instable, and the CIRS sets in. Therefore, forces are necessary which are directed against the penetration of magnetic flux into the superconducting sample volume (caused, e.g., by the Meissner effect), and which had to be overcome by the Lorentz force in order to nucleate flux domains. In a more detailed consideration, three different phenomena have to be taken into account. Two of them are confined to the interior of the sample or rather the flux domain itself. If a magnetic domain is created, its volume has to change from superconductivity to normal conductivity. For this change in phase, the condensation energy of the Cooper pairs inside the domain volume must be provided. Furthermore, the domain volume of normal conducting phase also contains a magnetic field of the critical strength which gives the corresponding magnetic field energy. Both energy contributions are proportional to the critical magnetic field strength and to the domain volume. After differentiation we obtain a force F_{in} which is directed versus the edges on both sides of the sample. This force component strongly increases towards the sample edges. The third phenomenon takes place in the space outside of the sample. If the distribution of the magnetic field lines surrounding the sample is compared for the case with a magnetic domain existing in the sample and the case without domain, the former state (including a domain) shows strong distortions of the field lines with regard to the almost elliptical profile of the latter state (without domain). The distorted field distribution costs energy, which again results in a repulsive force F_{out} acting in the same direction as F_{in}. Both forces are called barrier forces. Accordingly, the underlying model is called "Gibbs free energy barrier model" [12], since these barrier forces build up a threshold against the Lorentz force and thus determine the critical current by balancing F_T. If the barrier forces are taken into account in the equation of motion, the resulting voltage profile has the form of curve (c) in Figure 4. The nucleation peak predicted by the simple ansatz disappears, because the domain now starts at the barrier with an arbitrarily small velocity. After nucleation, the flux domain is accelerated following the inhomogeneous current density, which is concentrated at the sample edge. The result is a pronounced voltage step which does not coincide with the nucleation event, but follows about hundred nanoseconds later. Then, the unchanged central part of the voltage trace is again observed without any structure. The annihilation peak, however, is strongly amplified, since here the barrier forces support the Lorentz force and, hence, increase the acceleration of the domain. Due to the reduced velocity during the starting period, the life time of the domain is extended by about 20 percent. As shown in [11], curve (c) in Fig. 4 is in excellent agreement with the measured voltage profile of a single flux domain.

5. Interpretation of the Experimental Results

In order to compare the theoretical results shown in Fig. 4 with experimental reality, a particular situation has to be arranged, where only one single domain is nucleated and moving across the sample. The nucleation of the following domain has to be delayed until the previous one is annihilated. Such behavior can be accomplished by reducing the transport current below the critical current immediately after the birth of a domain. However, this is very difficult to perform experimentally. But we were supported by the effect that the existing domain prevents the nucleation of a successor via increasing the barrier, if the transport cur-

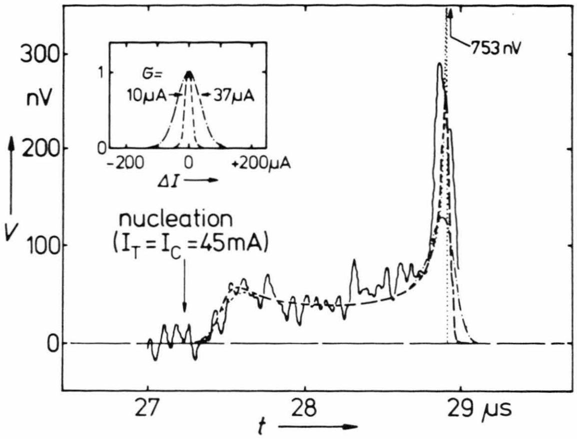

Fig. 5. Comparison between a measured time dependent voltage profile of a single flux domain and a computer simulation (details see text).

rent is kept close enough to the critical current. Figure 5 gives the result of such an experiment (solid curve), which has been averaged 160000 times to improve the SNR. On the same figure, the result of a model calculation is shown (dotted curve), based on parameters taken from the experiment. If the theoretical value of the critical current is reduced by a factor of 1.6 for fitting purposes, there remains only a disagreement in the height and the width of the annihilation peak. From the time integral of the voltage, the number of flux quanta in the domain can be determined to be about 50.

Up to now, always ideal conditions without any fluctuation have been assumed for the experimental parameters. Note that fluctuations of different experimental parameters can be simulated by, e.g., the fluctuations of only the transport current. The result of two fluctuation strengths (see inset of Fig. 5) is shown in Fig. 5 as dashed and dash-dotted curve. Obviously, the current noise does not affect the global structure of the voltage profile. The main effect is a decrease and broadening of the annihilation peak, which almost disappears at current fluctuations of 37 μA (relative amplitude of 5×10^{-4} with respect to the total current of 72 mA). As a consequence, the reproducibility of the domain dynamics must be better than 10^{-4}, if the signals can be detected by the help of signal-averaging procedures. The same restriction holds for the stability of the experimental parameters. From Fig. 5 we extract the message that the electrical "fingerprint" of a single flux domain can even quantitatively be interpreted by the aid of the Gibbs free energy barrier model that includes tiny fluctuations of the experimental parameters.

6. Interaction between Flux Domains

So far, we have seen that the particular situation of the temporal voltage profile generated by a single flux domain can be both prepared experimentally and reproduced quantitatively by model calculations. But now, a theoretical description of the usually observed voltage traces like that shown in Fig. 3 d remains to be derived from the model equations [13]. From the relatively long temporal distance between the first nucleation and the first annihilation event in Fig. 3 d, on the one side, and the relatively short distances between the subsequent annihilation peaks, on the other side, we have to conclude that the life times of several domains have been overlapping. Since all domains nucleated on the same sample edge have the same polarity of their magnetic field, they generally perceive a repulsive force from each other due to the field in the space outside the sample. The preceding domains, therefore, tend to slow down a certain domain, whereas the succeeding ones tend to push it forward.

If the distance between two domains is not too small, we can assume the intervening superconducting phase to be an ideal magnetic shielding. Then, each domain can be represented by two magnetic monopoles of opposite sign, located at the site where the domain axis penetrates the upper and lower surface of the sample (see Figure 1 b). As a consequence of symmetry, our consideration can be restricted to one half space above or below the sample, and the other half space can be taken into account by doubling the result. The interaction of two domains can now be modelled via the interaction of two magnetic monopoles in one half space, which is proportional to the amount of flux in each domain and inversely proportional to their distance squared. We want to emphasize again that this approach is only valid if any interaction inside the sample can be neglected. This condition, however, should certainly be fulfilled during the onset of the breakdown of superconductivity, where only a few domains are nucleated. And just this moment of the beginning instability is the aim of our investigations.

If we use the monopole ansatz for the domain interaction introduced above and permit the simultaneous existence of several domains, the original single equation of motion changes into a set of differential equations which are coupled via the interaction force F_{int}. Each equation describes the motion of one domain. Although it becomes more complicated, this system of coupled equations can be solved using the same standard numerical methods as before.

The success of this approach, however, is very poor. Voltage traces like in Fig. 3d cannot be reproduced if a set of parameters according to the experimental values is applied. In any case, the nucleation of the next domain is prevented until the previous one is annihilated at the opposite sample edge. The interaction energy between flux domains assumed in our model is obviously so large that the simultaneous existence of two domains is excluded. Even if the interaction strength is reduced to about 10 percent of its original ansatz, no sufficient agreement with the experiment can be obtained.

During the above considerations we have supposed that flux domains of equal size (i.e., flux domains containing an equal number of flux quanta) are generated at any time. This assumption seemed to be obvious from the results of all previous experiments where only the stationary state of flux flow could be investigated. Here, domains are created and annihilated in regular time intervals. The evaluation of those experiments always gave equal numbers of flux quanta for consecutive domains.

There are, however, a lot of physical systems in nature which do not occupy the final stationary state immediately after having started, but begin with oscillating around it (transient behavior). Therefore we introduced the number of flux quanta per domain as a free parameter into the calculations. This can be performed in two different ways. Either the computer may vary all possible numbers of flux quanta following a preselected scheme and calculate the minimum height of the free energy barrier with respect to the domain size. The existence of such a minimum was shown earlier [12]. Then, the computing time will increase considerably. Or a more empirical procedure is applied. The number of flux quanta of the first domain can be estimated from the experiment with the solitarily existing domain using identical experimental adjustments. The size of the domains in the final stationary state can be estimated from the temporal distances between the annihilation peaks, observed well beyond the starting period such that the transients have died out. Thus, only the oscillatory transition region remains, where the domain size can be determined by comparison of test calculations with the experimental result. It is true that this procedure needs many test calculations, but it converges more rapidly than expected. Figure 6 shows the agreement between a typical experimental trace and a calculation based on the following numbers of flux quanta for consecutive domains: 50, 4, 14, 9, 12, 11, ..., 12, 11, ... The agreement of the annihilation peak positions on the time scale is quantitative if the critical current is adjusted using the nucleation and annihilation time of the first domain, as described above.

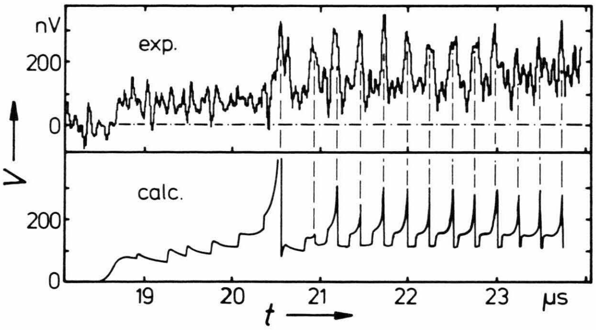

Fig. 6. *Upper part*: typical time dependent voltage trace of many flux domains; *lower part*: computer simulation of the experiment above including domain interaction.

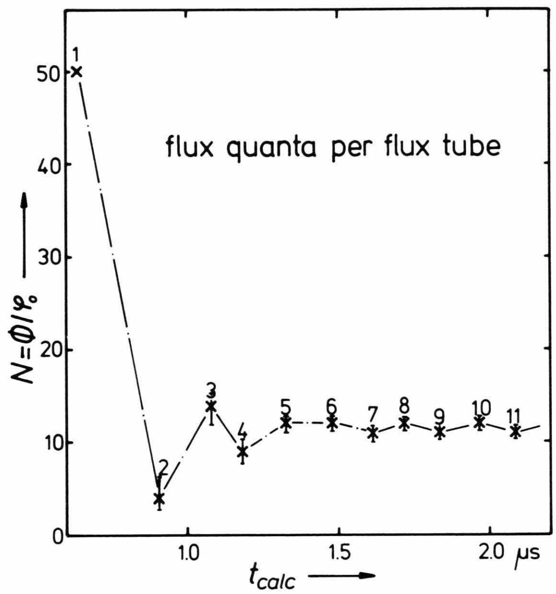

Fig. 7. Oscillation of the number of flux quanta per domain during the onset of the breakdown of superconductivity.

If the numbers of flux quanta per domain are plotted as a function of their nucleation time (Fig. 7), a damped oscillation of the flux-domain size is clearly recognized [14]. The succeeding domains react on the existence of any precursor not by waiting on its annihilation, intending to stick to the previous size, but by nucleation with a reduced size already during the life time of the preceding domains. Due to the same argument, just the other way round, a larger domain is favored after a small one. During the course of simulation calculations, it became obvious that even a change of the domain size by only 1 or 2 flux quanta would shift the position of the annihilation peaks in such a way that the fine structure in the voltage trace would have been averaged away due to the signal-averaging procedure applied. This finding is an additional indication for the existence of highly periodic modes with stable numbers of flux quanta per domain in the flux-flow state of superconductors.

7. Conclusions

The temporal behavior of the breakdown of superconductivity during the current-induced transition to the dissipative state could be studied by a simultaneous improvement of both the temporal and the voltage resolution. For this prupose, the time dependent voltage drop across the flux-flow region of a superconducting strip was measured in great detail. Using signal-averaging techniques, strongly periodic modes have been found at distinct parameter constellations among large regions of probably chaotic behavior. This result is typical for a system governed by a strongly nonlinear equation of motion. By application of the Gibbs free energy barrier model, which is based on a stability analysis of the superconducting state against a penetrating magnetic field, the voltage profile of a single flux domain could be simulated as well as the superimposed voltage pattern of many domains existing simultaneously in the sample. In the latter case, where the interaction of domains has to be taken into account, an oscillatory behavior of the number of flux quanta per domain was found, which ends up in a stationary state after a few oscillation cycles.

Acknowledgements

The authors would like to thank R. P. Huebener and B. Mühlemeier for fruitful collaboration. Part of this work was supported by a grant of the Deutsche Forschungsgemeinschaft. – Elaboration of an invited paper presented at the Spring Conferece of the German Physical Society held in Karlsruhe, March 1988.

[1] D. E. Chimenti, H L. Watson, and R. P. Huebener, J. Low Temp. Phys. **23**, 303 (1976).
[2] R. P. Huebener, Magnetic Flux Structures in Superconductors, Springer, Berlin 1979, p. 215.
[3] D. E. Chimenti and J. R. Clem, Phil. Mag. B **38**, 635, (1978).
[4] K.-P. Selig, D. E. Chimenti, and R. P. Huebener, Z. Phys. B – Condensed Matter **29**, 33 (1978); V. Hurm, K.-P. Selig, and R. P. Huebener, Z. Phys. B – Condensed Matter **32**, 175 (1979).
[5] J. Parisi, B. Mühlemeier, and W. Buck, Rev. Sci. Instrum. **57**, 1196 (1986).
[6] B. Mühlemeier, Dissertation, Tübingen 1986.
[7] B. Mühlemeier, J. Parisi, R. P. Huebener, and W. Buck, J. Low Temp. Phys. **64**, 131 (1986).
[8] J. Parisi, Rep. Prog. Phys. **48**, 709 (1985).
[9] W. Buck, J. Parisi, and B. Mühlemeier, J. Low Temp. Phys. **55**, 51 (1984).
[10] J. R. Clem, J. Low Temp. Phys. **42**, 363 (1981).
[11] W. Buck and J. Parisi, Phys. Lett. **116A**, 77 (1986).
[12] W. Buck, K.-P. Selig, and J. Parisi, J. Low Temp. Phys. **45**, 21 (1981).
[13] W. Buck and J. Parisi, Proc. 18th Int. Conf. on Low Temperature Physics, Kyoto 1987, Japan J. Appl. Phys. **26**, 1491 (1987).
[14] W. Buck and J. Parisi, Phys. Lett. **133A**, 342 (1988).

Nachdruck — auch auszugsweise — nur mit schriftlicher Genehmigung des Verlages gestattet
Verantwortlich für den Inhalt: A. KLEMM
Satz und Druck: Konrad Triltsch, Würzburg