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FLUX-TRANSPORT NOISE IN SUPERCONDUCTORS

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Résumé. — En conséquence du caractère quantifié du flux magnétique dans les supraconducteurs, les appareils utilisant le transport de flux présentent un bruit intrinsèque dû à ce transport.

On discute les spectres de puissance de ce bruit, mesuré sur des rubans supraconducteurs de deuxième et de première espèce, parcourus par un courant électrique. Le niveau du bruit peut être élevé parce que le flux se meut comme un système de faisceaux de lignes de tourbillons. Le nombre de ces lignes dans un faisceau est plus grand pour température, densité de flux ou densité de courant plus basses et pour un plus fort blocage des lignes de tourbillons.

Les spectres mesurés peuvent être expliqués par diverses fonctions de distribution du temps de transit des lignes à travers le ruban.

Les fluctuations de température causent un bruit extrinsèque, mais ce bruit peut être écarté.

Abstract. — Due to the quantized nature of flux in superconductors, devices making use of transport of flux exhibit intrinsic flux-transport noise. In this paper, a discussion will be given of power spectra of this noise, as measured on current-carrying ribbons of type II and type I superconductors. The noise level may be high in these ribbons because the flux moves as bundles of vortex lines, the number of flux quanta per bundle being greater for lower temperature, flux density and current density and stronger vortex-pinning. The measured power spectra can be accounted for by various distribution functions for the transit time of the vortex lines across the ribbon.

Temperature fluctuations give rise to extrinsic noise, but this can be removed.

Introduction. — In this paper, a description is given of a type of noise that arises in superconductors when there is motion of magnetic flux, if this is an incoherent flow of discrete flux entities. This noise may in some cases set a limit to the sensitivity of superconducting magnetometers. The experiments were not done on magnetometers but on superconducting ribbons which carried a transport current in the presence of a perpendicular magnetic field. The flux motion was caused by a Lorentz force on vortex lines in type II superconductors or normal domains in type I superconductors.

A type II superconductor in the mixed state contains vortex lines which are ordered as a two-dimensional triangular lattice. A type I superconductor contains superconducting and normal domains, one or two orders of magnitude bigger than the vortex lines. In our experiments the temperature, magnetic field and current were held constant. The amount of flux in the superconductor was also constant.

FIG. 1.

The vortex lines move across the ribbon in a direction perpendicular to current and field, as shown in figure 1, thereby generating a d.c. voltage in the direction of the current :

$$V = N\Phi/c \quad (1)$$

where N is the number of flux entities Φ which cross the ribbon per unit time. Each flux Φ generates a voltage pulse $V(t)$ such that :

$$\int_0^\tau V(t) dt = \Phi/c \quad (2)$$

where τ is the transit time across the ribbon.

If the flow of vortices with velocity v is coherent, so that the vortex lattice is conserved during the

FIG. 2. — Power spectra of flux-flow noise for various pulse shapes.

motion [1], each voltage pulse is followed by a subsequent one at a fixed time interval and the d.c. voltage is accompanied by an a.c. component with line spectrum $V(\omega) \sim \cos k\omega t$ where k is an integer, $\omega = v/d$. V and d is the vortex-lattice spacing.

If the flow is incoherent, i.e. if separate entities are generated at random times, one should expect to find a continuous shot-noise spectrum, which can be shown to be given by Carson's theorem :

$$\langle \delta V_f^2 \rangle = 2N |F(f, \tau)|^2 df = W(f) df \quad (3)$$

where $\langle \delta V_f^2 \rangle$ is the mean squared noise voltage in a frequency range between f and $f + df$, $F(f, \tau)$ is the Fourier transform of an elementary voltage pulse $V(t)$ and $W(f)$ is the power spectrum. The spectrum thus depends on the shape of the voltage pulses. If these pulses are identical, the spectrum is as shown in figure 2. This figure shows that the spectrum is little dependent on the actual pulse-shape. The value of the power spectrum at zero frequency is given by $2\Phi V/c$.

Power spectra. — Figures 3 and 4 show some experimental power spectra taken on vanadium foils for various values of current and field, compared with the theoretical spectrum for sinusoidal voltage pulses.

FIG. 3. — Power spectra measured on cold-rolled vanadium at $T = 4.21^\circ\text{K}$.

FIG. 4. — As for figure 3 at $T = 2.09^\circ\text{K}$.

The agreement between experimental and theoretical spectra is reasonable, except for a high-frequency tail at low temperatures. The size Φ of the moving flux entities (bundles of vortex lines) is seen to be dependent on current, field and temperature and may be much greater than the flux quantum ϕ_0 . The transit time is of the order of a few ms. The measured spectra permit the determination of both Φ and τ . The transit time can also be found from d.c. experiments, as the d.c. voltage is given by $V = lvB/c$ and $\tau = v/w$, where l is the distance between the potential probes, w is the width of the ribbon and B is the induction in the specimen. These values for τ agree reasonably well with the values from noise measurements, if it is taken into account that a fraction p of the flux is not flowing but is pinned to inhomogeneities.

The high-frequency tail can be accounted for qualitatively in terms of a distribution of transit times $g(\tau)$. The spectrum is then :

$$W(f) = \int_{\tau'}^{\tau''} 2N |F(f, \tau)|^2 g(\tau) d\tau \quad (4)$$

if τ varies between τ' and τ'' .

Such a distribution can come about if the velocity v is not the same everywhere in the specimen because the interaction of lattice defects with the vortices (pinning) is not the same everywhere. We have calculated the power spectrum for a rectangular distribution function $g(\tau)$. At high frequencies the spectrum falls off approximately as $1/f^2$.

A different case is that where the pinning is so inhomogeneous that the vortices move in a jerky manner, jumping from one place to the other. The pulses have a length τ_i that is shorter than τ . If it is assumed that

FIG. 5. — Power spectra measured on cold-rolled vanadium V2c and on annealed vanadium V2a.

the time, during which the vortices are halted, is negligible and the total transit time is τ , the spectrum can be shown to follow a $1/f$ frequency dependence at high frequencies, for various distribution functions $g(\tau_i)$.

Experiments confirm qualitatively these models, as can be seen in figure 5 for two specimens. Specimen V2c is a cold-worked foil where the inhomogeneities are on a microscopic scale (dislocation tangles). Specimen V2a is an annealed foil where a small number of grain boundaries are effective as pinning centres, at which the flux bundles may be halted for short times. At high frequencies the spectra vary as about $1/f^2$ for specimen V2c and $1/f$ for specimen V2a.

Noise level. — We calculated the value of Φ from the noise level at low frequencies and the d.c. voltage V and studied its dependence on temperature, current and pinning conditions. The results are shown in figure 6, where Φ/ϕ_0 for a constant reduced field is

FIG. 6. — Bundle size determined from noise level as a function of current density for various temperatures.

shown as a function of transport current density J . The bundle size is reduced by increasing the current or the temperature. It can further be seen that there is a big difference between cold-worked and annealed material. All these effects are different aspects of one mechanism: pinning of vortex lines to inhomogeneities. The driving force on a vortex line is given by $(J - J_c) \phi_0/c$, where J_c is a critical current density, which is greater for more pinning. Since J_c decreases with increasing temperature, an increase in both

current density and temperature means a greater driving force. Annealing of a cold-worked material also results in reduced pinning.

The experiments thus show that strong pinning results in larger bundles Φ and thus a high noise level. These pinning effects at low temperatures and currents are likely to be present also in thin films.

The mechanism by which the bundles are formed is not completely clear. It is not sure whether the bundle formation is determined by bulk properties or also by the edge of the ribbon, where they are generated.

In type I superconductors the situation is more complicated because there are two mechanisms of voltage generation, viz. flux-flow and ohmic loss in immobile regions and only the flux-flow voltage exhibits flux-flow noise. This noise exhibits more or less the same behaviour as in type II superconductors.

Evidence for bundle formation in flux-flow was also presented by Zimmerman and Silver [2] who found in Josephson point contacts that the fundamental oscillation frequency was a submultiple of the Josephson frequency.

Current induced transitions. — If the external magnetic field is absent, flux can be generated by passing a current through a superconductor. The resulting fluctuations have been discussed by Thiene and Zimmerman [3] who assumed that the current generates vortex lines which are anti-parallel on either side of a superconducting film, move inward with constant velocity and are annihilated in the centre. The magnetic field of the current is, however, directed all along the circumference of the film so that it is likely that oval vortex rings are formed, rather than vortex lines. When moving inward these rings shrink and move with increasing velocity. The noise level at zero frequency is still given by $2\Phi V/c$, if the motion is incoherent. If the motion is periodic, as was earlier suggested by Gorter and Potters [4], the spectrum should exhibit peaks at certain frequencies.

FIG. 7. — Power spectra measured on In-2 % Pb and $T = 3.28$ °K and various values of the magnetic field. In the inset: the d.c. voltage transition.

We have not made measurements in zero magnetic field but at temperatures close to the critical value the external field necessary for flux-flow was rather low, so that the current-induced field can no longer be neglected. In a type I superconducting In-Pb ribbon we found a spectrum as shown in figure 7. The peaks in the spectrum disappeared at lower temperatures, where the external field was much higher. It seems that the phenomenon of voltage generation is partly periodic.

Temperature fluctuations (flicker noise). — Since in a superconductor the resistance is a strong function

of temperature, temperature fluctuations give rise to voltage fluctuations. This type of noise is shown in figure 8. The points are experimental. The curves were calculated assuming temperature pulses with shape as found in the nucleate boiling regime in other liquids and caused by formation and flow of gas bubbles. This noise is high even for rather low dissipation levels. This flicker noise can be removed by putting the specimen in an exchange gas or by cooling the liquid helium through the λ point. There is then no boiling. One should be aware, however, of another possible temperature variation : that caused by pressure variations in the pumping line.

FIG. 8. — Flicker-noise power spectra for various values of power dissipation P and temperature T . In the inset : the elementary temperature pulse.

Flux penetration and expulsion. — Flux-transport noise is also present if there is no transport current, but the field is varied. This causes flux penetration or expulsion and the fluctuations due to this process have been studied by a number of authors [5]. It was found in these experiments that the noise was caused by the flow of bundles containing from 10 to 10^4 vortex lines. The noise is higher at low temperatures, due to more effective pinning. Heiden showed that the bundle size (and thus the noise level) decreased by Ni-plating the surface so that the surface barrier decreased.

A phenomenon often found is that flux expulsion causes more noise than flux penetration. This can be understood qualitatively by surface irregularities and end effects which cause a lower surface barrier for flux penetration but a higher barrier for flux expulsion [6], so that in the latter case the bundles are bigger.

Conclusions. — The experiments have shown that flux-flow in superconductors is a more or less random process, giving rise to noise. The spectrum is determined by the transit time of the vortex lines and is affected by pinning. The noise level is higher when pinning effects are more pronounced.

Our experiments were not carried out on weak links or point-contacts. However, Eck [7] has found similar noise spectra in the same frequency range due to flux-flow in superconducting point contacts. It should therefore be expected that our results are also applicable to other configurations where flux-flow takes place.

Details of this work can be found elsewhere [8].

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