I. INTRODUCTION

The rapid development of nanostructuring methods in the last decade has enabled highly precise fabrication of artificial pinning centers (APC’s) for vortices in superconductors. It has already been proved that pointlike inclusions in a superconducting film, such as perforating holes, structural defects, and magnetic dots, can pin vortices. A regular two-dimensional array of APC’s stabilizes the vortex lattice against external driving forces, and results also in commensurability effects which scale with a matching magnetic field $B_M = \phi_0 / S$, where $S$ is the area of the array unit cell and $\phi_0$ the magnetic flux quantum. At a magnetic field $B > B_M$ vortices fill in the interstitial positions as well, where they are subject to intrinsic pinning originating from the structural defects. In a certain $B$ range above $B_M$ they may even form a commensurate multiple-flux-quanta lattice, as revealed from magnetization measurements. A less symmetrical APC landscape, such as a rectangular array or a set of parallel continuous lines of a magnetic material, introduces anisotropies to the vortex transport. So far the effects of APC’s have been found to be important at temperatures $T$ rather close to $T_c$, typically at reduced temperatures $t = T / T_c > 0.9$, whereas at lower temperatures the intrinsic pinning dominated. Moreover, APC’s invariably decreased the dissipation, apart from in a recent report.

The simplest APC is a small perforating hole in a superconductor, having magnetic permeability larger than its diamagnetic surroundings. The most efficient pinning is obtained if the hole diameter is comparable to the magnetic-field penetration depth $\lambda$ rather than the coherence length $\xi$, as one may expect at first sight. This was predicted by virtue of the Ginzburg-Landau (GL) theory for a single hole and observed experimentally for two-dimensional arrays of holes. The relevance of $\lambda$ for the artificial pinning potential is a consequence of the comparatively small supercurrent kinetic energy required for preserving the flux-quantization condition around a hole not smaller than $\lambda$.

Local interactions of vortices with holes in the presence of a driving current have not yet been studied in detail experimentally. These go beyond the cited matching phenomena and are important for understanding the function of holes in an arbitrary arrangement, which may have implications for possible design of future devices based on manipulation of artificially pinned vortices. In this report we present such an investigation facilitated by arranging the holes in a line centered along the main axis of a superconducting microbridge [lower inset to Fig. 1(a)], which eliminates the matching phenomena but still provides a sufficient signal arising from the presence of the holes. In addition, we have minimized the influence of the intrinsic pinning by using the amorphous superconductor Nb$_{0.7}$Ge$_{0.3}$, which is known for its very low background pinning. Another property of this material is its relatively large $\lambda$ and small superconducting condensation energy $U_c$. This results in weak vortex-vortex correlations, the strength of which decreases with decreasing $U_c$ and $\lambda^{-2}$, and thus permits using simplified, essentially single-vortex models in analyzing the vortex-motion phenomena.

The vortex motion was detected by recording the electric field vs current density characteristics $E(J)$ at constant $(B, T)$, in three different temperature regimes, over a wide range of applied currents and $B$ up to the upper critical magnetic field $B_{c2}$. Close to $T_c$ we observed a clear increase of the power dissipation by the holes over the whole range of $B$ and $J$. This result can be explained plausibly by taking into account a local enhancement of the vortex driving force due to a spatial modulation of the driving-current density around the holes. To our knowledge such current-modulation effects have so far been disregarded in the interpretation of previous experiments carried out on perforated superconductors. Well below $T_c$ the holes pin the vortices and reduce the dissipation, which shows that their usefulness as APC’s may extend to low temperatures if the intrinsic pinning is weak. Our results imply that the interplay of hole pinning and inhomogeneous current drive determines whether the holes enhance or reduce the dissipation in the vortex transport.

II. EXPERIMENT AND RESULTS

Two 210 $\mu$m long, 5 $\mu$m wide, and 20 nm thick microbridges between two large contact pads were sputtered onto the Nb$_{0.7}$Ge$_{0.3}$ amorphous superconductor. Each sample contained a line of perforating holes patterned along the sample axis. The power dissipation in the perforated sample exhibits a crossover, being reduced at temperatures well below the superconducting transition temperature $T_c$, and unexpectedly enhanced close to $T_c$. At low temperatures the holes are efficient artificial pinning centers and reduce the average vortex velocity. We argue that the dissipation enhancement close to $T_c$ is a consequence of a combination of the weakened pinning by the holes and an inhomogeneous driving-current distribution in their vicinity, which results in an increased average vortex velocity as well as in a channeling of the vortex motion through the holes.

We measured and compared the electric field vs current density characteristics in the vortex state of two amorphous Nb$_{0.7}$Ge$_{0.3}$ microbridges, with and without a line of submicron holes patterned along the sample axis. The power dissipation in the perforated sample exhibits a crossover, being reduced at temperatures well below the superconducting transition temperature $T_c$ and unexpectedly enhanced close to $T_c$. At low temperatures the holes are efficient artificial pinning centers and reduce the average vortex velocity. We argue that the dissipation enhancement close to $T_c$ is a consequence of a combination of the weakened pinning by the holes and an inhomogeneous driving-current distribution in their vicinity, which results in an increased average vortex velocity as well as in a channeling of the vortex motion through the holes.

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the same Si/SiO₂ substrate as described in Ref. 10. One of the samples (sample P) was perforated with a line of equi-
distant holes along the central axis of the microbridge (des-
ignated as x direction) as sketched in the lower inset to Fig.
1(a). The holes had a diameter of 800 nm [slightly smaller
than \( \lambda (0) \)] and their center-to-center distance was 1.2 µm.
Both samples had the same \( T_c = 2.75 \) K and the same overall
normal-state and superconducting properties. Throughout the
paper we use the nonperforated sample (sample N) as a re-
ference for identifying the effects of holes. Its transport prop-
erties were analyzed in detail in Ref. 11, and its GL param-
eters \( \xi (0) = 6.8 \) nm and \( \lambda (0) = 1.15 \) µm are taken as represen-
tative of both samples.

The measurements were carried out in a \(^3\)He system
equipped with a commercial calibrated superconducting
magnet and homemade rf filtering of measurement leads. A
magnetic field was applied perpendicularly to the film plane
and a dc current was passed in the x direction, so that the
vortices traversed the sample in the y direction. The applied-
current sweep rate was found not to affect the measured \( E(J) \)
up to at least 50 nA/s, and the rate used in the presented
measurements was 10 nA/s. The applied current is for sample P converted into the average current density \( J_p \) by
calculating the (uniform) current density \( J_N \) for sample N and
taking the ratio of the normal-state resistances to determine
\( J_p = 1.23 J_N \). We use this notation, together with \( E_N \), \( E_P \) for
electric field in samples N and P, respectively, when refer-
ning to the \( E(J) \) of the two samples specifically. At high
\( J \) the \( E(J) \) exhibit nonlinearities due to the flux-flow insta-
bilities that are related to the nonequilibrium changes of vor-
tex cores.\(^{11}\) Here we concentrate on the close-to-equilibrium
regime where these effects have not yet been developed and
the vortex cores maintain their equilibrium properties.

In order to investigate whether the differences in the \( E(J) \)
of the two samples could originate from, e.g., small vari-
tions of \( T \) and/or \( B \), at several \( (B,T) \) points we checked re-
producibility of our measurements. In all cases the repro-
ducibility of the measured voltage was within 0.5%, which
allowed us to identify the differences between \( E_N (J_N) \) and
\( E_P (J_P) \) reliably. Moreover, the behavior presented below was
also found in a less detailed set of measurements on another
pair of samples, of which one was nonperforated and one
with a less dense line of (not equidistant) holes of the same
diameter.

In Fig. 1 we plot typical \( E(J) \) representative of three tem-
perature regimes: (a) \( T \) well below \( T_c \) (1.1 K, \( \tau = 0.4 \)), (b)
intermediate \( \tau \) (2.0 K, \( \tau = 0.7 \)), (c) \( T \) close to \( T_c \) (2.5 K, \( \tau = 0.91 \)). The open circles show \( E_N (J_N) \), solid circles \( E_P (J_P) \),
and the lines different theoretical predictions of the Larkin-
Ovchinnikov (LO) flux flow (FF) theory,\(^{12}\) as discussed be-
low. The scaled magnetic field \( b = B / B_c \) corresponds to
0.30–0.38, the \( B_c \) values being (a) 3.0, (b) 2.0, and (c) 0.65 T, with the uncertainty of around 5%. At low \( T \) [Fig.
1(a)] the \( E(J) \) of both samples reveal two different dynamic
regimes: thermally activated magnetoresistance at \( T \rightarrow 0 \),
followed at larger \( J \) by an \( \alpha = (J - J_1) \) behavior that implies FF
against a background pinning potential with a depinning
threshold \( J_c \).\(^{10}\) The solid line is a plot of the latter depen-
dence, with the slope \( dE/dJ = \rho_p / 0.9 \) equal to the low-\( T \) LO
FF resistivity \( \rho_f \) (\( \rho_p \) is the normal-state resistivity), and \( J_c \)
chosen to obtain a fit to \( E_N (J_N) \). The LO theory describes this
part of \( E(J) \) reasonably well until the out-of-equilibrium nonlin-
earities in \( E(J) \) start to take place at large \( J \).\(^{11}\) As can be
seen, the power dissipation in sample P is lower for \( \sim 10\% \)
throughout the whole current-density range, suggesting an
efficient pinning by the holes even far below \( T_c \). In Fig. 1(b)
we show the \( E(J) \) at \( T = 2.0 \) K (\( \tau = 0.7 \)), just at the boundary
of the low-\( \tau \) and high-\( \tau \) regimes, displaying a weaker reduc-
tion of \( E_P \) below \( E_N \). Close to \( T_c \) [Fig. 1(c)] the theoretical
high-\( \tau \) LO \( \rho_f \) (see Ref. 11 for details), shown by the dashed
line, describes \( E_N (J_N) \) excellently starting from \( J = 0 \) and up
to the appearance of the nonlinearities mentioned before.
However, over the entire current-density range the dissipa-
tion in sample P is larger than in sample N, unexpectedly and
in contrast to the result at lower temperatures. The reason for
this peculiar behavior cannot be found in the pinning prop-
erties of holes.
The magnetic field range over which $E_p \neq E_r$ is wide at all three characteristic temperatures. This is demonstrated in Fig. 2, where we plot the ratio $p = P_p/P_N$ of the power dissipated in samples $P$ and $N$, integrated up to the appearance of the flux flow instabilities, vs $b = B/B_{c2}$. Sufficiently below $T_c$, the holes reduce the dissipation ($p < 1$) whereas close to $T_c$ the situation is opposite.

The magnetic field range over which $E_p \neq E_r$ is wide at all three characteristic temperatures. This is demonstrated in Fig. 2, where we plot the ratio $p = P_p/P_N$ of the power dissipated in samples $P$ and $N$ vs $b = B/B_{c2}$. The integration $P_{N,f} = \int E_{N,f} dI_{N,f}$ is for each curve performed over the maximum region where the dissipation is not affected by the FF instabilities. We checked whether $p$ depends on the upper limit of integration, and we found minor numerical differences of the order of 10–15% of the values shown in Fig. 2, with no change in the general shape of $p(b)$. As can be anticipated from the $E(J)$ shown in Figs. 1(a) and 1(b), for $t = 0.4$ and $t = 0.7$ we find $p < 1$, i.e., the holes are active pinning sites and decrease the dissipation. Their relative contribution to the pinning becomes smaller as $t$ and $b$ increase, which is expected qualitatively and discussed in the next Section. Close to $T_c$ the dissipation in sample $P$ is always larger, thus $p > 1$ with a maximum around $b \approx 0.4$. This enhancement implies a suppression of the artificial pinning by another effect which is fully manifested close to $T_c$.

III. DISCUSSION

In order to understand the above results one has to address the equation of motion for the vortices

$$m \ddot{u} = F_d - \eta \dot{u} + F_h + \sum_n F_n,$$

where $\dot{u}$ is the vortex velocity, $\eta$ the vortex-motion viscosity, $m$ the effective vortex mass per unit length,$13$ $F_d = \phi_0 J \times \dot{z}$ the driving force ($\dot{z}$ is the unit vector in the direction of the applied magnetic field), $F_h$ the repulsive force between the mobile vortices and those pinned by the holes, and $F_n$ representing other relevant forces (e.g., the interaction of mobile vortices with each other or with intrinsic pinning potential). The spatial dependence of the $i$th component of the vortex acceleration $\ddot{u}$ is given by $\ddot{u}_i = u_i - \nabla u_i$. By solving Eq. (1) one finds the vortex-velocity profile $u(r)$. The generated electric field, the $x$ component of which contributes to measured $E_p$, is calculated as $E(r) = u(r) \times B(r)$, where $B(r)$ is related to the local vortex density $n(r) = B(r)/\phi_0$.

The procedure just outlined in principle requires a knowledge of the details of $F_h$ and $F_n$—which depend on the superconducting properties, as well as the inhomogeneous profile of $J$. However, for qualitative reasoning one can take into account the known characteristics of the vortex state in a particular $(B,T)$ point to simplify the right-hand side of Eq. (1) by keeping the most relevant terms only.

In the spirit of such an approach we first discuss the role of $F_h$. When confining a pinned vortex each hole acts as a source of repulsion to other vortices, with $F_h$ pointing radially from the center of the hole. The repulsive force between two vortices separated by $r < \lambda$ is proportional to $\lambda^2 \ln(\lambda/r)$ and therefore weakens as $\lambda \to \infty$. Furthermore, the probability of a vortex being pinned by a hole becomes progressively smaller as $\lambda$ grows much larger than the hole diameter.$^8$ Hence it is reasonable to assume that $F_h$ decreases monotonically with increasing $\lambda$ and eventually becomes irrelevant in the limit of diverging $\lambda$ at $T \to T_c$. This leads to a plausible assumption that close to $T_c$, even a very weak $J$ may result in $F_d \approx F_h$.

Of the terms $F_n$ the dominant ones are most likely those which account for the vortex interaction with the background pinning, and for the stiffness of the vortex lattice expressed through the shear-stress modulus $C_{66}$. The former contribution vanishes at the irreversibility field $B_{ir}$, irrespective of its nature (i.e., vortex-lattice melting or depinning), whereas $C_{66}$ drops discontinuously to zero at the melting field $B_m$. It is known that $B_{ir}$ in amorphous Nb–Ge films is rather low,$10,11,14$ and that it may be close to the melting field calculated theoretically.$15$ The agreement of $p_{t}$ and $E_{t} / (n J)$ at $t = 0.91$ [Fig. 1(c); see also Ref. 11] down to the lowest $B$ under consideration implies $B_{ir}(t=0.91) \approx \Phi_b$ for these results. Although the $B_{ir}$ cannot be interpreted with certainty as the $B_m$, since $C_{66} \approx U_i(t)$ is close to $T_c$, small,$16$ $F_d$ can easily overcome the long-range vortex-vortex interactions. Together with the smallness of $F_h$, only the term $F_d$ on the right-hand side of Eq. (1) remains relevant in the limit $T \approx T_c$. Thus we use this (independent-vortex) approximation to discuss the dissipation enhancement by the perforation close to $T_c$, as follows.

The driving force $F_d$ is not uniform around the holes because the supercurrent density $J$ is spatially modulated. A schematic of the modulation of $J$, and consequently of $F_d$, around the holes is shown in Figs. 3(a) and 3(b) by the dashed lines. In the regions denoted by $H$ the driving force is larger than far from the holes, while in the regions denoted by $L$ the situation is the reverse. Assuming negligible $F_h$ and $F_n$ in the vicinity of $T_c$, as discussed above, the vortices are accelerated parallel to $F_d$ (perpendicular to $J$), thus the vortex trajectories accumulate in regions $H$ as sketched in Fig. 3(a) by the solid lines. The second effect of the current modulation is that in regions $H$ the vortices move faster than in the sample bulk and produce a larger local electric field, while in regions $L$ the opposite happens. Although the holes themselves shorten the distance the fast vortices travel in regions $H$, a sufficient imbalance in favor of the number of these vortices, together with their large acceleration, may result in the total dissipation in sample $P$ being larger than in sample $N$. Therefore if a highly dense two-dimensional array...
of holes is intended to be used for enhancing the pinning of a sample there is no guarantee that this will work close to $T_c$ in the presence of a transport current, although the magnetization loops may widen up. Moreover, the current-induced vortex-velocity enhancement strengthens with increasing $J_v$ around the holes at $B \approx B_c$ of the volume filled with the vortices they can all easily be channeled through regions $H$, which excludes $\Delta E$ and in turn results in a nonmonotonic $p(b)$. As temperature is lowered $\lambda$ becomes smaller and the holes start to pin more efficiently, which explains qualitatively the stronger reduction of the dissipation at lower temperatures (Fig. 2). The vortices trapped by the holes now repel the incoming vortices and change the vortex trajectories depicted in Fig. 3(a) to those shown in Fig. 3(b). The repulsive force $F_h$ is indicated by the dotted arrows. In a simple model of pinning by the holes in dynamic conditions a vortex remains pinned by a hole for some time until it is replaced by an incoming vortex. At low vortex density almost all vortices in the vicinity of holes are either pinned by them or scattered to pass through regions $L$ of low current density. Hence the holes cause a noticeable reduction of the dissipation. As $B$ increases the incoming vortices exert more force upon those pinned at the holes, reduce the pinning time, and the overall suppression of the dissipation decreases. This qualitative picture may explain the behavior of $p(b)$ at low temperatures.

We note, however, that the above explanation is still based on the single-vortex approximation, which disregards the enhanced stiffness of the vortex lattice far below $T_c$. The primary consequence of such a collective effect is expected to be an increase of $J_1$ by the holes. Indeed, for $J > J_1$ in Fig. 1(a) $\rho_p(J_P)$ is essentially shifted with respect to $\rho_p(J_B)$, having nearly the same slope, which supports this expectation. Thus, although the single-vortex approximation of Eq. (1) suffices for a qualitative explanation of the low-temperature pinning by the holes, a more quantitative approach should include the long-range vortex-vortex correlations as well.

### IV. SUMMARY AND CONCLUSIONS

In conclusion, we have patterned a line of holes with a diameter close to $\lambda(0)$ along an amorphous Nb$_{0.7}$Ge$_{0.3}$ microbridge. A comparison of the measured $E(J)$ curves of the samples with and without perforation reveals an unusual crossover in the power dissipation close to and well below $T_c$. Close to $T_c$ the artificial pinning is weak and an unexpected rise of the dissipation is observed. This is attributed to the inhomogeneous current distribution around the holes leading to a significant increase of the local vortex velocity. As temperature is lowered the pinning by the holes becomes stronger and eventually suppress the vortex velocity enhancement. In addition, our weak background pinning has permitted, to our knowledge, the first observation the pinning properties of holes as artificial pinning centers far below $T_c$.

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