Experimental phase diagram of moving vortices

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In the mixed state of type II superconductors, vortices penetrate the sample and form a correlated system due to the screening of supercurrents around them. Interestingly, we can study this correlated system as a function of density and driving force. The density, for instance, is controlled by the magnetic field, B, whereas a current density j acts as a driving force F = j × B on all vortices. The free motion of vortices is inhibited by the presence of an underlying potential, which tends to pin the vortices. Hence, to minimize the pinning strength we studied a superconducting glass in which the depinning current is 10 to 1000 times smaller than in previous studies, which enables us to map out the complete phase diagram in this new regime. The diagram is obtained as a function of B, driving current and temperature and led a remarkable set of new results, which includes a huge peak effect, an additional reentrant depinning phase and a driving force induced pinning phase.

The Peak effect (PE), which is one of the most intriguing consequences of the motion of vortices in superconductors, is a peak in the critical current as a function of B and typically occurs below, but near, the critical field (Bc2) in some strong type II conventional superconductors [1, 2, 3, 4, 5]. In high temperature superconductors the PE is also observed but usually appears well below Bc2 as inferred from magneto-transport measurements. The PE can lead to a reentrant superconducting phase as a function of B or T when a current slightly below the maximum critical current is applied. Above the critical current, vortices experience a force strong enough to be depinned and they start moving, which leads to a non-zero electrical field (E = v × B) and hence to a non-zero resistance, where v is the average vortex velocity. At the PE the vortices are pinned again, which decreases the resistance and enhances the critical current. While the exact mechanism of the PE is not fully understood, recent experiments on Nb have correlated the PE with the disappearance of neutron scattering Bragg peaks from the vortex structure. This was attributed to the transition from a long-range ordered phase to a short-ranged disordered phase, which in turn is pinned more efficiently [5, 6]. This transition can be induced either by increasing disorder or equivalently by increasing B, since the disorder potential couples to all vortices, hence effectively increasing with B. However, recent experiments on NbSe2 have questioned the amorphous nature of the phase in the PE regime [6].

In this work we investigate the vortex dynamics in a system with the weakest possible pinning potential. It is well known that amorphous superconductors have a lower critical current than crystals because of the absence of long-range order, which implies weaker collective pinning. The remaining pinning is then mainly governed by impurities. We therefore used high purity Fe – Ni – Zr based superconducting glasses, which have a similar critical temperature (Tc) and Bc2 as the widely studied crystalline 2H – NbSe2 system [1] and others [3, 4, 7, 8, 9], but our amorphous samples exhibit a critical current density, (Jc ≤ 0.4A/cm²), just below the PE, which is typically 100 to 1000 times smaller. In comparison to earlier studies on the PE in amorphous films, our samples still have a Jc 10 times smaller [2, 5, 10, 11], which reflects the high level of purity of our samples.

We obtained these high purity superconducting glasses by melt spinning [12] Fe2xNi1−xZr2 with different values of x. Although we only present results for x=0.3, qualitatively very similar features were obtained for x=0, 0.1 and 0.2, which suggests that these effects are inherent to these types of materials and do not depend critically on composition. The transition temperature (Tc) for x=0.3 is 2.30 ± 0.02K as extracted from three different samples. The sharpness of the transition region is quite remarkable, with a transition temperature width (10-90% value) ranging between 5 and 20mK for all three samples, indicative of very homogenous samples. The absence of crystallinity is confirmed by the absence of Bragg peaks in X-ray diffraction. The samples have the following typical sizes (thickness=21μm, width=1.15mm, and length between indium contacts=8mm). Using standard expressions for superconductors in the dirty limit [3], we can estimate the different length scales in our system. The zero temperature penetration depth is λ = 1.05 × 10−3(ρN/Tc)1/2 ≃ 0.9μm, the BCS coherence length is ξ ≃ 7.3nm (or 8.3nm using GL), the Ginzburg-Landau (GL) parameter κ ≃ 76 and Bc1 ≃ 29mT. Relevant experimental quantities are Tc = (2.30 ± 0.02)K, Bc2(T = 0) = (4.8 ± 0.1)T, ρN = (1.7 ± 0.2)μΩm (normal resistivity) and dB2/dT|Tc = (−2.7 ± 0.2)T/K. These numbers are typical for a strong type II low-Tc material.

Since moving vortices give rise to a non-zero resistance in a superconductor, we measured the B-dependence of the magneto-resistance for different currents to probe the dynamics of the vortices. The results are presented in figure 1. The most striking feature is the B-induced reentrant superconducting phase for currents above 0.07mA. Such a strong reentrant superconductor was never observed before in any amorphous superconductor. However, because we observed a similarly strong reentrant behavior for different concentrations of Fe (x=0, 0.1, and 0.2), we believe that this effect is very general for high purity and weakly pinned amorphous superconductors.
Indeed, when comparing our results to previous studies on the $PE$ in amorphous superconductors \cite{2, 3, 10, 11}, the most notable difference is the critical current, which is a measure of the pinning strength and is at least 10 times smaller in our samples, indicating that weak pinning enhances the reentrant behavior. The reentrant behavior is the most dramatic signature of the $PE$, which disappears below 0.07 mA and implies a peak in the critical current in the region of the reentrant superconductor.

![Graph](image1)

**FIG. 1:** Lower curves: Resistances as function of $B$ for up and down $B$-sweeps. The left curves expand the high field region. The different curves are for different currents, ranging from 0.01 mA to 3 mA (0.01, 0.02, 0.04, 0.07, 0.1, 0.15, 0.2, 0.3, 0.4, 0.6, 0.8, 1, 1.5, 2.1, 3) mA. The upper curve, which is the resistance for the down sweep with 1 mA, illustrates how we determine the different transition points. The resistances were measured using an AC resistance bridge at 17 Hz and $T = 450$ mK.

We map-out the phase diagram of the moving vortices using the dissipative transport in figure 1 and illustrated by the top figure with the help of the 1 mA down-sweep curve. The results of the diagram are presented in figure 2. At low fields we have the first depinning transition defined when the resistance exceeds 0.5 mΩ, which is our experimental resolution. The choice of this cut-off is not critical since close to the depinning transition the dependence of the resistance on $B$ is stronger than exponential. When increasing $B$ further, the system becomes more and more resistive for currents above 0.07 mA. In this region, which we denote *depinning 1*, the vortices start moving. At even higher $B$, the moving vortices are pinned again in the *pinning* region, which leads to the reentrant superconducting phase inside this *pinning* region. The pinning transition is defined when $dR/dB = 0$. Inside the *pinning* region, the resistance eventually vanishes within our experimental resolution (0.5 mΩ). Finally, at high enough $B$ we cross $B_{c2}$ and the system becomes *normal*. $B_{c2}$ is defined as the point of strongest negative curvature just before reaching the normal state. At higher driving currents we observe another region, labelled *depinning 2*, which corresponds to a sudden increase of resistance after the *pinning* or *depinning 1* regions, indicative of another depinning transition, before reaching $B_{c2}$, which is defined as the point of highest positive curvature.

![Graph](image2)

**FIG. 2:** Phase diagram of vortex dynamics as extracted from fig. 1. The solid lines are obtained when sweeping $B$ up and the dotted lines when $B$ is swept down. The lower half is an enlargement of the high $B$ region. Overall, the diagram is consistent with three distinct phases (*depinning 1*, *pinning* and *depinning 2*) connected by a strongly hysteretic triple point at the end of the thick dashed line.

A striking feature of the phase diagram is the huge $PE$ at 4.3 T. Indeed, the critical current, which delimits the
superconductor (shaded in dark blue in figure 2) from the non-zero resistance depinned phases, jumps from 0.07mA to 1.5mA close to 4.3T. This PE is associated with the depinning 1 - to - pinning transition of the vortices.

Quite generally, the depinning 1 region is characterized by weakly pinned vortices, which move beyond a B-dependent activated threshold. Giamarchi and co-workers argued that this phase is a long-range ordered moving Bragg glass (MBG), consistent with a recent experiment showing algebraic neutron scattering Bragg peaks in this region with measurements performed on \((K, Ba)BiO_3\). Our results support this picture since the dependence of the voltage \((V)\) on current \((I)\) below the PE for B-fields between 0.25 and 3.75T, (as illustrated in the inset of figure 3), is well fitted by the activated creep expression \(V \sim e^{-U/(T\gamma)}\). \(U\) reflects the pinning strength and the expression was derived directly from the equation of motion and assumes a long-range ordered phase, such as a Bragg glass. The long-range nature of this phase can be inferred from the geometry dependent transition point. Indeed, when tilting the field so that \(B\) is aligned along the wide axis of the sample (instead of perpendicular to it), the transition is shifted upwards between 1.5T and 2.5T depending on the current. Since the sample is amorphous and 1mm wide but only 20\(\mu\)m thick this implies long range order above 20\(\mu\)m. This transition is the only one, which is significantly affected by the tilted field below 1.5mA, suggesting that the remaining phases have short-ranged order.

![Depinning curve](image)

**FIG. 3:** Dependence of the resistance as a function of excitation voltage for increasing field. Inset: dependence of the voltage on driving current for decreasing field.

At higher \(B\) the pinning increases in the PE region. In this region the inter-vortex distance is close to \(\xi\), which is the size of the vortex core and implies strong inter-vortex correlations. The exact nature of this pinning transition is still under debate, but is commonly associated with an order-disorder transition, the melting of the vortex structure or the anomalous friction close to \(B_{c2}\). Experimentally, the reentrant superconductor is nonetheless the most spectacular demonstration for the existence of a depinning - to - pinning transition. In figure 2, the reentrant superconductor is shaded in dark blue, which is included in the pinning region delimited by the light blue line. We mapped out the pinning regions for both \(B\)-sweep directions up (solid lines) and down (dotted lines) and observed an increasing hysteresis as a function of driving current, which is the region shaded in light blue. The region of hysteresis does not depend on the sweeping rate and is stable once reached. The left inset of figure 1 shows details of the region of hysteresis and the \(B\)-sweep direction is labelled with corresponding arrows. The hysteresis is particularly striking, when coming from the low \(B\) region into the pinning region. Indeed, at a fixed \(B = 4.3T\) and \(I = 1mA\), the sample is superconducting, then we can either increase the current to 2mA and back or sweep \(B\) to 4.5T and back, or increase \(T\) to 1K and back, and the sample is no longer superconducting and remains dissipative on time scales beyond our experiment. Sweeping \(B\) to 3.5T and back recovers a highly stable superconducting phase. Hence, for the same \(B\) and \(I\) we can have two different phases, which are stable over very long time scales. Moreover, when increasing the temperature, the size of the region of hysteresis decreases and eventually vanishes as illustrated in figure 4 (the light blue shaded region). Since the dependence on temperature is non-critical, this transition is strongly suggestive of a first order phase transition inside the region of hysteresis, which we indicated as a thick dashed line in figure 2. This is in agreement with earlier experiments on crystals, but in our system this first order transition is not associated with the formation of the pinning region but rather with the transition to the depinning 2 phase at \(B\)-fields above the PE.

This additional depinning 2 phase between the PE and the normal phase is only seen at sufficiently high driving currents (figure 2) and is masked by the hysteresis at low \(T\) and becomes more apparent at higher \(T\) as seen in figure 4. This hints to a much richer transition region between the PE and the normal state than previously expected and constitutes an important new experimental finding for the theoretical understanding of these systems.

At even higher currents the depinning 2 region can be reached directly from the depinning 1 region, which corresponds to a sudden delocalization of the vortices identified by a jump in the resistance. This region is not an inhomogeneous mix of normal and superconducting regions because at low currents the superconducting - to - normal transition is extremely sharp, i.e., less than 50mT wide for the 10-90%, which excludes any large scale inhomogeneities in the sample. This type of transition is consistent with several theoretical and numerical results...
FIG. 4: Phase diagram as a function of temperature. The data was rescaled to $B_C$ and taken for $B$ applied parallel to the wide axis of the sample.

Summarizing, we have studied a new class of superconductors in relation to the peak effect, in which the depinning threshold is extremely weak and where there is no underlying crystalline order. In our system the $PE$ region is huge, with an increase by more than an order of magnitude of the critical current in the $PE$ region, indicating that very low pinning tends to enhance the peak effect. In addition, after mapping out the entire phase diagram of our system, while many similarities with previous studies on the $PE$ have been found, we also observed two striking differences. Indeed, we observed an additional transition between the $PE$ and the normal state as well as a dynamical pinning transition at constant vortex density. These results have important implications on our understanding of the dynamics of vortices in very weakly pinned systems.

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