The strengthening of reentrant pinning by collective interactions in the peak effect

J. Lefebvre, M. Hilke, and Z. Aloutnian

Department of Physics, McGill University, Montréal, Canada H3A 2T8.

Since it was first observed about 40 years ago [1], the peak effect has been the subject of numerous research mainly impelled by the desire to determine its exact mechanisms. Despite these efforts, a consensus on this question has yet to be reached. Experimentally, the peak effect indicates a transition from a depinned vortex phase to a reentrant pinning phase at high magnetic field. To study the effects of intrinsic pinning on the peak effect, we consider Fe$_x$Ni$_{1-x}$Zr$_2$ superconducting metallic glasses in which the vortex pinning force varies depending on the Fe content and in which a huge peak effect is seen as a function of magnetic field. The results are mapped out as a phase diagram in which it is readily seen that the peak effect becomes broader with decreasing pinning force. Typically, pinning can be understood by increased pinning centers, but here, we show that reentrant pinning is due to the strengthening of interactions (while decreasing pinning strength). Our results demonstrate the strengthening of the peak effect by collective effects.

Vortices in type II superconductors form a correlated system of interacting particles which can be studied as a function of particle density or driving force by simply tuning the external magnetic field or driving current. While elastic vortex-vortex interactions tend to order the system, vortex-pin interactions result in disorder. An ever intriguing phenomena resulting from this competition between elastic and plastic interactions is the peak effect (PE): an anomalous peak in the critical current $J_c$ (or dip in resistance) appearing with increasing temperature or magnetic field just below the transition to the normal state in some conventional superconductors [1, 2, 3, 4, 5, 6], and at lower field below $B_{c2}$ in high $T_c$ superconductors [7]. In type II superconductors, vortices will depin under the action of a driving force larger than the critical force. As a result of vortex motion, a dissipative voltage proportional to $E = \bar{v} \times B$ where $\bar{v}$ is the average vortex velocity will be induced and a non-zero resistance will be measured. In the PE, some or all (reentrant superconducting phase) the vortices are pinned again, resulting in a decrease of the resistance or an increase of the critical current. The origin of the PE is still under debate. Early, it was suggested to arise due to the softening of the elastic moduli of the vortex lattice [1] and to a decrease of correlation volume $V_c$ in the collective pinning theory of Larkin and Ovchinnikov [8]. It has also been proposed to be the signature of a disorder-induced or a thermally-induced order-disorder transition [9, 10, 11, 12]. However, it has equally been said to occur naturally at the crossover between a weak to strong vortex pinning regime [13]. It could also simply appear depending on the strength and density of pinning centers, and their competing action depending on magnetic field and temperature [14, 15, 16]. In general, the dependence of the PE on disorder is strongly dependent on the pinning mechanism: single vortex pinning, or collective.

In this work, we investigate how the PE depends on pinning strength by using a series of Fe$_x$Ni$_{1-x}$Zr$_2$ metallic glasses with $x$ from 0 to 0.6, since changing $x$ modifies the pinning properties. The extreme purity and absence of long range order due to the amorphous nature of these glasses confers them extremely weak pinning properties ($J_c \leq 0.4$ A/cm$^2$) which make it an ideal system to study vortex phases and vortex motion. Pinning in these glasses is collective. In Ref. [6], a huge PE, larger than in other weakly-pinned amorphous systems [2, 4, 17, 18], was observed in a sample of Fe$_{0.3}$Ni$_{0.7}$Zr$_2$. Since the critical current density in these alloys is at least ten times smaller than seen in other amorphous alloys [2, 4, 17, 18], this provides an ideal case study in the weak-pinning limit.

The Fe$_x$Ni$_{1-x}$Zr$_2$ superconducting glasses are obtained by melt-spinning, as described in Ref. [19]. Resistance measurements are performed in the standard four-probe technique through soldered indium contacts using a resistance bridge providing ac current at 15.9 Hz in a $^3$He refrigerator and a dilution refrigerator.

![FIG. 1: GL coherence length $\xi_{GL}(0)$ and penetration depth $\lambda(0)$ as a function of the pinning force density $f_p$. Inset: $f_p$ as a function of Fe content $x$ in Fe$_x$Ni$_{1-x}$Zr$_2$.](image-url)
expressions for superconductors in the dirty limit \[4\], in increase substantially in these alloys. As calculated from the fact that with increasing \( f \) is about a factor of five smaller in \( \xi_{GL}(0) = 8.1 \) nm and \( \lambda(0) = 0.87 \) \( \mu \)m, which which is close to our experimental resolution. As can be seen, increasing the Fe content in these glasses results in an important decrease of the pinning force density; \( f_p \) is about a factor of five smaller in \( x = 0.5 \) and \( 0.6 \) than it is in \( x = 0.1 \). This dependence can be related to the fact that with increasing \( x \), vortex core and size increase substantially in these alloys. As calculated from expressions for superconductors in the dirty limit \[4\], in \( x = 0, \xi_{GL}(0) = 8.1 \) nm and \( \lambda(0) = 0.87 \) \( \mu \)m, which respectively almost doubles and triples in \( x = 0.6 \) \[20\]. This yields the relationship between \( \xi_{GL}(0) \) and \( \lambda(0) \), and \( f_p \), shown in Fig. 1. A strong decrease of the pinning force density with increasing coherence length was also predicted by Larkin and Ovchinnikov \[8\] (LO) for 3D collective pinning, with dependence:

\[
f_p = \frac{n^2 \langle f^2 \rangle^2}{10B^2C_{66}^3 \xi^4},
\]

where \( n \) and \( f \) are the density and strength of pins respectively, and \( C_{66} \) is the shear modulus which describes the elasticity of the vortices. The decrease of \( f_p \) with increasing \( \xi \) is readily understood considering that, for identical vortex number density, vortex overlap is enhanced for large \( \xi \) and \( \lambda \), thereby increasing collective interactions between vortices which tend to order the system and reduce pinning. Indeed, according to the LO collective pinning theory \[8\], the scale of vortex interactions can be described by a correlation volume \( V_c = R_c^3L_c \), where \( R_c \) and \( L_c \) are the correlation radius and length respectively. \( R_c \) increases with \( \xi \) according to \( R_c = 4\pi^{1/2}BC_{66}^3\xi^2/n \langle f^2 \rangle \), which then results in a decrease of the pinning force:

\[
f_p = \left( \frac{n \langle f^2 \rangle}{V_c} \right)^{1/2}.
\]

According to the LO collective pinning theory, in the weak pinning limit and for high magnetic fields where the number of vortices greatly surpasses the number of defects, reentrant pinning in the peak effect results from the pinning of mobile vortices through collective interactions with pinned vortices. Hence, enhanced collective interactions strengthen the peak effect.

The evolution of pinning strength and collective vortex interactions with Fe content in \( Fe_xNi_{1-x}Zr_2 \) evidenced above allows us to study how the peak effect depends on collective effects. As seen in resistance as a function of magnetic field measurements on samples with \( x = 0, 0.3 \)

![FIG. 2: Resistance vs magnetic field for different driving currents as shown at T=0.33 K measured on different metallic glasses of varying pinning properties. a) NiZr2 (more strongly pinned) b) Fe0.3Ni0.7Zr2 c) Fe0.5Ni0.5Zr2 (more weakly pinned).](image1)

![FIG. 3: Lowest resistance reached in the resistance dip (PE) (left axis) and width of the peak effect (right axis) as measured in temperature sweeps in a fixed B field of 2 T with I = 0.1 mA.](image2)
and 0.5 in Fig. 2, the dip in resistance characterizing this B-induced re-entrant pinning phase changes from thin and shallow in the more strongly pinned NiZr$_2$ to very broad and deep in the more weakly pinned Fe$_{0.5}$Ni$_{0.5}$Zr$_2$. In the later case, the resistance even decreases back to zero in the peak effect and a large re-entrant superconducting phase is seen. In crystals of 2H-NbSe$_2$ and 0.0 0.1 0.2 0.3 0.4 0.5 0.0 0.2 0.4 0.6 0.8 1.0 0.0 0.2 0.4 0.6 0.8 1.0 5000 10000 15000 20000 25000 0 1 2 3 4 5 6 $B/B_c^2$ $f_p [N/m^3]$ superconducting normal depinning 1 depinning 2 Pinning $B$ [T] $R$ [Ω]

FIG. 4: a) R vs B trace measured at T=0.35 K on Fe$_{0.1}$Ni$_{0.9}$Zr$_2$ with I = 1 mA showing how different vortex phases are defined. b) Phase diagram of vortex dynamics as a function of pinning force density. The phase boundaries are defined as described in the text and extracted from R vs B data measured with $J = 1.8$ A/cm$^2$ for each alloy composition. The solid lines represent phase boundaries obtained in increasing B field sweeps while the dotted lines are for decreasing field sweeps. In this manner, we can identify regions of hysteresis (hatched areas).

Having established that the characteristics of the PE as a function of $x$ are equivalently observed in B field and temperature sweeps, we complete our analysis from measurements performed as a function of B field because these results are more readily obtained. A typical $R$ vs B trace is shown in Fig. 3(a). Following the naming scheme of Ref. [3] to identify vortex phases, we distinguish the superconducting phase where $R = 0$ at low B field, followed at higher field by a depinned vortex phase called depinning 1, the onset of which is defined when the resistance reaches 0.5 mΩ. In Refs. [24, 25], we have demonstrated that the depinning 1 phase is characterized by the long range ordered moving Bragg glass phase (MBG) [26]. At still higher B field, a re-entrant pinning phase is seen; the onset of this phase is defined when $dR/dB = 0$, and its termination is defined at the position in B where the resistance reaches the same value as at the onset of the pinning phase. The end of the pinning phase marks the onset of the depinning 2 phase, which we have shown in Ref. [24] exists even in the lowest driving current regime. This phase has smectic order characteristic of the moving transverse glass (MTG) [28] in which the orientation of channels in which vortices flow can vary suddenly depending on the driving force and vortex density. Finally $B_{c2}$ is defined at the point of strongest negative curvature before reaching the normal state.

Extracting the boundaries of vortex phases according to the definitions above from $R$ vs B traces measured at constant current density $J=1.8$ A/cm$^2$, we obtain the phase diagram of Fig. 3(b). For all alloys, this current density corresponds to a regime in which we observe a peak effect, and never a direct transition from the depin-
ning 1 to the depinning 2 phase as visible for example in the \( I = 10 \text{ mA} \) trace in Fig. 2a). In the diagram, the superconducting and peak effect phases are represented by filled green areas. These two phases merge in the most weakly pinned sample \((x = 0.6)\) in which no PE is visible and the vortices remain pinned up to the depinning 2 phase. A downward bending of the pinning phase toward lower reduced field \( b = B / B_\text{c} \) with decreasing pinning force is observed. In the PE, an amorphization of the vortex lattice with collapse of \( V_c \) occurs\[^{[8]}\] due to a softening of the elastic moduli\[^{[1]}\], which increases pinning. In the high \( B \) field range where the PE appears, the size of the correlation radius \( \xi \) becomes comparable to \( \xi \) and to the inter-vortex distance \( a \). In the large coherence length limit, where \( R_c \) is also largest, the onset of the peak effect can occur at lower magnetic field where \( \lambda \) is larger, which explains this downward bending of the pinning phase toward lower \( b \) in this limit. In the most weakly pinned sample, \( V_c \) presumably becomes so large due to the large \( \xi \) and \( \lambda \) that, even at very low \( B \), coherent pinning of these large vortex bundles does not permit depinning. As a result, the sample remains in the pinning phase up to the transition to the depinning 2 phase. The broadening of the PE phase with decreasing \( f_p \) (or increasing \( V_c \)) is readily seen from the phase diagram and confirms that reentrant pinning is strengthened by collective vortex interactions. This also infers that collective vortex interactions cause the PE in these materials.

In the phase diagram of Fig. 4b), the solid and dotted lines represent transitions obtained in increasing and decreasing magnetic field sweeps respectively. As a result, regions of hysteresis become visible, as highlighted by the orange hatched areas in the weak pinning range. These hysteresis regions are not stable and depend on the \( B \) field sweep rate. They arise due to the inhomogeneous distribution of vortices resulting from structural inhomogeneities discussed earlier. However, even ignoring the hysteresis regions, the broadening of the PE with decreasing pinning force is obvious. A large broadening of the depinning 2 phase is also visible in the low pinning force region of the phase diagram of Fig. 4b). This broadening is partly due to the increasingly two-phase character of these alloys. An increase of the \( B_c \) transition width is common in inhomogeneous superconductors. At this stage, it is not known how the intrinsic pinning force and collective vortex interactions affect the smectic order characteristic of the depinning 2 phase and if it could cause its widening.

In summary, we have presented the pinning force dependence of the peak effect based on measurements in the metallic glasses \( \text{Fe}_2\text{Ni}_{1-x}\text{Zr}_2 \). It was shown that in this metallic glass series, the intrinsic pinning force decreases with Fe content as the coherence length and penetration depth increase, as well as collective vortex interactions. Then, a strengthening of the peak effect, which broadens to eventually fill the whole space below the transition to the depinning 2 phase in the most weakly pinned sample, was seen with decreasing pinning force. These observations confirm that collective vortex interactions are at the origin of the peak effect phenomenon in these weakly-pinned metallic glasses.

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