Tunable critical current for a vortex pinned by a magnetic dipole

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Abstract. – A simple model for a superconductor with tunable critical current is studied theoretically. The model consists of a thin superconducting film with one vortex interacting with one magnetic dipole, whose magnetic moment is free to rotate, in the presence of a magnetic field applied parallel to the film surfaces. The pinning potential for the vortex is calculated exactly in the London limit. It is found that, due to the dipole freedom to rotate, the dependence of the pinning potential on the applied field is non-trivial, and allows both the spatial dependence and strength of the pinning potential to be changed by the field. As a consequence, the critical current can be tuned by the applied field. The critical current is obtained numerically as a function of the applied field. Order-of-magnitude changes in the critical current resulting from changes in the direction and magnitude of the applied field are reported, with discontinuous changes taking place in some cases. Possible application to vortices in low-$T_c$ superconducting films pinned by arrays of magnetic dots are briefly considered.

The pinning of vortices in superconducting films by arrays of magnetic dipoles placed in the vicinity of the film is a topic that has received a great deal of attention lately. Most of the experimental [1] and theoretical [2–7] work carried out so far deals with arrays of permanent dipoles, that is, dipoles with magnetic moments fixed both in magnitude and direction. A related topic that has received little attention is vortex pinning by arrays of dipoles with magnetic moments free to rotate. The feasibility of fabricating such arrays has been demonstrated recently by Cowburn et al. [8]. These authors reported on the magnetic properties of arrays of nanomagnets made of Supermalloy, each nanomagnet being a thin circular disk of radius $R$. They found that for $R \sim 50–100$ nm the magnetic state of each nanomagnet is a single domain one with the magnetization parallel to the disk plane, and that the magnetization can be reoriented by small applied fields. One possible source of interest in vortex pinning by freely rotating dipoles is, as demonstrated in this paper, that the critical current may be tuned by an applied field. This paper studies theoretically in the London limit the interaction between one vortex in a thin superconducting film with one dipole, located outside the film, in the presence of a magnetic field parallel to the film surfaces. The magnetic dipole moment is assumed to be parallel to the film surfaces, to have constant magnitude and freedom to rotate. Tuning of the critical current is this model results because the interaction between the vortex and the dipole...
Fig. 1 – Superconducting film with one vortex at \( r \), a magnetic dipole, \( m \), at \( r_0 = (0, 0, z_0) \), and an applied magnetic field, \( H \), parallel to the film surfaces.

depends on the dipole orientation which, in turn, depends on the applied field. Besides, in a thin film, a magnetic field parallel to the film surfaces has no effect on the vortex in the absence of the dipole. As shown here, this mechanism allows the pinning potential to be changed by the applied field over a wide range. When a transport current is applied to the film, the magnetic field created by it is parallel to the film surfaces and also contributes to the dipole orientation. This makes the pinning potential dependent on the transport current, and has important consequences for the critical current, as shown here. The main new results reported in this paper are: i) the exact analytic calculation of the pinning potential for one vortex interacting with a freely rotating dipole, and its dependence on the applied field and transport current; ii) the numerical calculation of the critical current for one vortex pinned by the dipole, and its dependence on the magnitude and direction of the applied field. This paper argues that these results are relevant for vortex pinning by arrays of nanomagnets, similar to those reported in ref. [8], placed on top of superconducting films made of homogeneous materials, like most low-\( T_c \) ones. The model is not applicable to layered high-\( T_c \) superconducting films.

The calculation of the pinning potential proceeds as follows. The superconductor film is assumed to be planar, with surfaces parallel to each other and to the \( x-y \) plane, isotropic, characterized by the penetration depth \( \lambda \), and of thickness \( d \ll \lambda \). A vortex with vorticity \( q \) is located at position \( r \), and the dipole is at \( r_0 = (0, 0, z_0 > 0) \). The dipole moment \( m \), has constant magnitude, \( m \), and is oriented parallel to the film surfaces, and is free to rotate in the \( x-y \) plane. A uniform magnetic field \( H \) is applied parallel to the film surfaces. The vortex-dipole system is shown in fig. 1. The total energy in the London limit, neglecting pinning by random material defects, can be written as \([7]\)

\[
E_T = -m \cdot (b^s_\perp + H) + mH,
\]

(1)

where \( b^s_\perp \) is the component parallel to the film surfaces of the field generated by the vortex at the dipole position. The energy \( E_T \) does not include the vortex self-energy nor the interaction energy of the dipole with the field of the screening current generated by it in the film, because both are independent of the vortex position and dipole orientation. The constant \( mH \) is added for future convenience. The parallel component of the vortex field is given in the thin-film limit \((d \ll \lambda)\) by \([9]\)

\[
b^s_\perp = -q \frac{\phi_0 d}{4\pi \lambda^2} \frac{r}{r^2} \left( 1 - \frac{z_0}{\sqrt{r^2 + z_0^2}} \right).
\]

(2)

This expression is exact for a thin film provided that \( r \ll \Lambda = 2\lambda^2/d \), which is the region of interest here. The total energy, \( E_T \), depends both on the vortex position \( r \) and on the dipole orientation. The pinning potential for the vortex at zero temperature, denoted by \( U_{vm} \), is the total energy for the equilibrium dipole orientation, that is, for \( m \) which minimizes \( E_T \), with the vortex held fixed at \( r \). Thus, according to eq. (1), the equilibrium \( m \) is parallel to
b^s_\perp + H$, and the pinning potential is given by

\[ U_{vm} = -m |b^s_\perp + H| + mH. \]  \tag{3}

Note that, by definition, $U_{vm}$ vanishes in the absence of a vortex. According to eqs. (3) and (2), the spatial dependence of $U_{vm}$ is anisotropic. It depends both on $r$ and on the angle between $r$ and $H$. An important consequence of the dipole freedom to rotate is the non-trivial dependence of $U_{vm}$ on $H$ obtained in eq. (3). According to it, $H$ plays the role of a handle that controls the strength and spatial dependence of $U_{vm}$, as will be discussed shortly. The scale for $H$ in eq. (3) is the vortex field, which is bound by $b^s_\perp \leq b^s_{max} = 0.3d/4\pi z_0 \times (\phi_0/\lambda^2)$. It is convenient to use the following natural scales for physical quantities. Energy: $\epsilon_0 d$, where $\epsilon_0 = (\phi_0/4\pi\lambda)^2$ is the basic scale for energy/length of the superconductor. Magnetic moment: $\phi_0 z_0$. Magnetic field: $\phi_0/\lambda^2$.

For $H \gg b^s_{max}$ the dipole equilibrium orientation is parallel to $H$, and $U_{vm}$ reduces to the pinning potential for a vortex interacting with a permanent dipole. Assuming that $H$ is along the $x$-direction, $U_{vm} = -mb^s_x$, which, according to eq. (2), coincides with the expression obtained in refs. [3, 4, 6, 7]. In this case $U_{vm}$ is anti-symmetric with respect to both an inversion of the vortex position ($r \rightarrow -r \Rightarrow U_{vm} \rightarrow -U_{vm}$), and to a change in the sign of the vorticity ($q \rightarrow -q$). For a vortex ($q > 0$), $U_{vm}$ has a minimum (maximum) on the $x$-axis at $x = -(+)1.3z_0$, with minimum (maximum) value $U_{vm} = -(+)0.3 \times 4\pi\epsilon_0 d(m/\phi_0 z_0)$, as shown in fig. 2a. In general, for $H \neq 0$ the minimum of $U_{vm}$ occurs when $b^s_\perp$ is parallel to $H$, that is when the vortex (anti-vortex) is on the negative (positive) $x$-axis. In this case, according to eq. (3), $U_{vm} = -mb^s_x$. As a consequence, the minimum of $U_{vm}$ for $H \neq 0$ is identical to that for a permanent dipole. However, the spatial dependence of $U_{vm}$ is strongly dependent on $H$, as shown in fig. 2 for some values of $H < b^s_{max}$ ($b^s_{max} = 0.024\phi_0/\lambda^2$ for the parameters in fig. 2). For $H = 0$, $U_{vm}$ is given by $U_{vm} = -m |b^s_\perp|$. In this case, according to eq. (2), $U_{vm}$ is the same for vortices and anti-vortices, has circular symmetry, and is attractive with a repulsive core, as shown in fig. 2d. The minimum of $U_{vm}$ is degenerate on a circle of radius $r = 1.3z_0$, and has the same minimum value as a permanent dipole ($U_{vm} = -0.3 \times 4\pi\epsilon_0 d(m/\phi_0 z_0)$).
Now the critical current, $J_c$, for a single vortex with vorticity $q = 1$ is considered. The effect of a transport current density, $J$, applied to the film is twofold: it exerts on the vortex a force $F_L = q(\phi_0d/c)J \times \hat{z}$ and creates a field at the dipole position $H_J = (2\pi d/c)J \times \hat{z}$, which adds to the external field and modifies the vortex pinning potential, because $U_{vm}$ is now given by eq. (3) with $H$ replaced by the total field $H_T = H + H_J$. The critical current depends on the relative orientation of $J$ and $H$. Here it is assumed that $J$ is fixed in the positive $y$-direction, so that both $F_L$ and $H_J$ are along the positive $x$-direction, and have magnitudes $H_J = 2\pi J/c$ and $F_L = \phi_0dJ/c$, and that $H$ points in a direction that makes an angle $\alpha$ with the positive $x$-axis, that is with $\hat{F_L}$. In this paper $J_c$ is obtained by solving numerically the equations of motion for the vortex. It is assumed that for $J = 0$ the vortex is pinned at the absolute minimum of $U_{vm}$, and that $J$ increases very slowly with time. These assumptions ensure that the vortex follows the position of the minimum of $U_{vm} - F_L x$ as $J$ increase, until $J$ reaches a value for which the minimum becomes unstable, and the vortex depins. As $J$ increases further, the vortex velocity also increases. The $J_c$ obtained here corresponds to $J$ for which the vortex velocity reaches a small value chosen for numerical convenience. The obtained $J_c$ is slightly larger than the $J$ for which the minimum becomes unstable. This is analogous to the voltage criterion in $J_c$ measurements. The values of $J$ are, of course, limited to $J < J_d$, where $J_d = \phi_0/((12\sqrt{3}\pi^2\lambda^2\xi)$ is the depairing current, $\xi$ being the vortex core radius. In the results reported next, regions where $J_c > J_d$ are discussed for the sake of completeness. Now there are two scales for $H$ in $U_{vm}$: $b_{max}$ as discussed above, and $H_J$. The maximum $H_J$ occurs for $J = J_c$, and can be written as $H_{J_c} = 0.031d/(\xi(J_c/J_d)(\phi_0/\lambda^2))$. For $d \sim z_0 \sim \xi$, these two scales are comparable if $J_c \sim J_d$.

For $H \gg (b_{max}, H_J)$, $U_{vm}$ reduces to that for a permanent dipole oriented parallel to $H$, that is, with $m$ making an angle $\alpha$ with the $x$-axis. In this case, $U_{vm}$ is independent of $H$ and $J$ and has a spatial dependence like that shown in fig. 2a rotated by $\alpha$ with respect to the $x$-axis. For $J = 0$, the vortex is pinned at the absolute minimum of $U_{vm}$, located at a point in the $x$-$y$ plane defined in polar coordinates, $(\rho, \theta)$, by ($\rho = 1.3z_0$, $\theta = \alpha + \pi$). The critical current depends on $\alpha$ and $m$, being a linear function of $m$, since $U_{vm}$ is linear in $m$. It is found that $J_c$ depends strongly on $\alpha$, being largest for $\alpha = 0^\circ$, and decreasing smoothly with $\alpha$, as shown in fig. 3a and b) (curves labeled permanent dipole). This results from the spatial dependence of $U_{vm}$, as can be seen for $\alpha = 0^\circ$, $180^\circ$, where the critical current can be estimated analytically, because the vortex moves only along the $x$-direction as $J$ increases. The result is $J_c/J_d \simeq 4m/\phi_0z_0$ for $\alpha = 0^\circ$, and $J_c/J_d \simeq 0.4m/\phi_0z_0$ for $\alpha = 180^\circ$. The origin of this tenfold difference can be seen in the plot of $U_{vm}$ shown fig. 2a. The driving force is parallel to the $x$-axis in fig. 2a for $\alpha = 0^\circ$, and antiparallel for $\alpha = 180^\circ$. As can be seen in fig. 2a, the slope of potential barrier is much steeper in the positive $x$-direction than in the negative one. For other values of $\alpha$ the depinning process is more complicated, because the vortex motion as $J$ increases is not confined to the direction of drive.

For $H$ comparable to or less than $b_{max}$ and $H_J$, the equilibrium orientation of $m$ is no longer fixed, and $J_c$ depends, besides on $\alpha$ and $m$, also on $H$. Typical results for $\lambda = 10.0\xi$ and $d = z_0 = 2.0\xi$ are shown in fig. 3. The $J_c$ vs. $\alpha$ curves are shown in fig. 3a for $m = 0.25\phi_0z_0$, and in fig. 3b for $m = 0.5\phi_0z_0$, for characteristic values of $H$. In both cases the $J_c$ vs. $\alpha$ curves differ considerably from those for a permanent dipole for small $H$, being strongly dependent on $H$, and showing sharp changes in $J_c$ close to $\alpha = 180^\circ$, like those for $m = 0.25\phi_0z_0$, $H = 0.001\phi_0/\lambda^2$ (fig. 3a) and $m = 0.5\phi_0z_0$, $H = 0.01\phi_0/\lambda^2$ (fig. 3b). The curve labeled $H = 0$ in fig. 3a is the limit of the $J_c$ vs. $\alpha$ curve as $H \to 0$ with $\alpha$ fixed. The strong dependence of $J_c$ on $H$ is even more evident if $J_c$ is plotted as a function of $H$ for fixed $\alpha$, as shown in fig. 3c for $m = 0.5\phi_0z_0$. In this case it is found that for $\alpha \geq 146.25^\circ$ the $J_c$ vs. $H$ curves have discontinuities at $H = H_d$, jumping from $J_c > J_d$ for $H < H_d$ to $J_c \sim 0.2J_d$ for $H > H_d$. For
Fig. 3 – Single vortex \((q = 1)\) critical current for \(\lambda = 10\xi, d = z_0 = 2\xi\): a) and b) \(J_c\) vs. \(\alpha\); c) \(J_c\) vs. \(H\) for constant \(\alpha\), indicated in the boxes; d) discontinuity field \(H_d\) vs. \(m\). Labels: \(m\) in units of \(\phi_0 z_0\), \(H\) in units of \(\phi_0/\lambda^2\).

\(\alpha < 146.25^\circ\), the dependence of \(J_c\) on \(H\) is continuous, as illustrated by the curves for \(\alpha = 135^\circ\) and \(\alpha = 90^\circ\). For \(\alpha = 135^\circ\), \(J_c\) undergoes a rapid change with \(H\) around \(H_d = 0.014\phi_0/\lambda^2\), whereas for \(\alpha = 90^\circ\) the change in \(J_c\) with \(H\) is much slower. It is found that the \(J_c\) vs. \(H\) curves have no discontinuities if \(m\) is smaller than a minimum value which depends on \(\alpha\). As shown in fig. 3d, \(H_d\) vanishes at the minimum \(m\), and increases above it essentially linearly with \(m\).

This complex behavior results from the dependence of \(U_{vm}\) on \(J\), through \(H_T = H + H_J\), as can be seen by examining how the position the minimum of \(U_{vm} - F_Lx\), which coincides with the vortex position, changes as \(J\) increases (fig. 4). For \(\alpha = 157.5^\circ\); \(H = 0.011\phi_0/\lambda^2 < H_d\), and

Fig. 4 – Vortex positions with increasing \(J\) for \(m = 0.5\phi_0 z_0\), \(\lambda = 10.0\xi, d = z_0 = 2.0\xi\). A: vortex initial position for \(J = 0\). C: positions where the vortex depins. a) and c) vortex trajectories. Dot indicates dipole location. b) and d) \(x\) and \(y\) coordinates vs. \(J\) corresponding to trajectories in a) and c). In d) top curves represent \(x/\xi\), bottom curves \(y/\xi\). Labels: \(H\) in units of \(\phi_0/\lambda^2\).
\[ \alpha = 135^{\circ}; \ H = 0.011 \phi_0/\lambda^2, \ 0.013 \phi_0/\lambda^2, \text{ when there are large enhancements in } J_c \text{ with respect to the permanent dipole value, the position of the minimum undergoes a large displacement, from the initial one on the right side of the dipole (A in figs. 4a and c) to the final one, where the minimum becomes unstable, on the left side of the dipole (C in figs. 4a and c). This is accompanied by a flip in the direction of } \mathbf{H}_T \text{ from near the negative } x\text{-axis at } J = 0 \text{ to one near the positive } x\text{-axis when the minimum becomes unstable. The enhancement in } J_c \text{ results because the vortex is effectively pinned by a permanent dipole oriented at a small angle with the positive } x\text{-axis. This can be seen for } \alpha = 157.5^{\circ}; \ H = 0.011 \phi_0/\lambda^2 \text{ (fig. 4b), which shows that most of the vortex displacement from A to C takes place for } 0 < J < 0.5 J_d. \text{ In this interval the direction of } \mathbf{H}_T \text{ rotates from } 157.5^{\circ} \text{ to } 12^{\circ} \text{ with the } x\text{-axis. When the vortex depins, at } J = 1.35 J_d, \mathbf{H}_T \text{ points at } 3^{\circ} \text{ with the } x\text{-axis and has magnitude } \mathbf{H}_T = 0.074 \phi_0/\lambda^2. \text{ When there is little or no enhancement in } J_c \text{ with } (\alpha = 157.5^{\circ}; \ H = 0.0115 \phi_0/\lambda^2, \text{ and } \alpha = 135^{\circ}; \ H = 0.015 \phi_0/\lambda^2) \text{ the position of the minimum undergoes only a small displacement, from A to B in figs. 4a and c, and } \mathbf{H}_T \text{ points in a direction away from the } x\text{-axis.} \]

The reason for the discontinuous jumps in \(J_c\) is related to the way that the stability of the minimum of \(U_{vm} - F_L x\) changes as \(J\) increases. It is found that for \(H > H_d\) the minimum becomes unstable twice, whereas for \(H < H_d\) it becomes unstable only once. For \(H > H_d\) (\(\alpha = 157.5^{\circ}; \ H = 0.0115 \phi_0/\lambda^2\) in fig. 4a) the minimum becomes unstable at B, where \(J = 0.25 J_d\). A stable minimum, not shown in fig. 4a, reappears again at a slightly larger value of \(J\), and follows a trajectory close to the A-C curve. However, the vortex depins when the minimum becomes unstable for the first time at point B. For \(H = 0.0115 \phi_0/\lambda^2 > H_d\) in fig. 4, the minimum only becomes unstable once at point C.

The \(J_c\) results described above are believed to be representative of low-\(T_c\) superconducting films. First, the particular set of parameters used, \(d \sim z_0 \sim \xi\), are typical ones for superconducting films with magnetic dots placed on top. For instance, in the experiments with arrays of magnetic dots with permanent magnetization placed on top of superconducting Nb films, reported in ref. [10], \(d = 20 \text{ nm} \sim \xi\). The magnetic dots are separated from the film by a thin protective layer of thickness \(\sim 20 \text{ nm}\), so that the distance from the magnetic dipole to the film is \(z_0 \sim \xi\). Second, since the dependence of \(J_c/J_d\) on the model parameters \(d, z_0, m, \lambda, \xi, \) and \(H\) is, according to eqs. (3), and (2), only through the scaled variables \(d/z_0, m/\phi_0 z_0, \) and \(H \lambda^2/\phi_0, \) many superconducting film-dipole systems are equivalent.

The London limit is valid for vortices in low-\(T_c\) films. However, when a magnetic dipole is placed close to the film, it certainly breaks down if the dipole field destroys superconductivity locally in the film. Roughly speaking, London theory is valid as long as the maximum dipole field at the film is less than the upper critical field, that is, \(m/z_0^3 < \phi_0/(2\pi \xi^2), \) or \(m/(\phi_0 z_0) < (z_0/\xi)^2/2\pi. \) For the values used in the above calculations (\(z_0 = 2 \xi\)) this gives \(m/(\phi_0 z_0) < 0.64, \) which is larger than the values used in this paper. The London limit would be a better approximation if the present calculations were carried out for larger values of \(z_0/\xi\). However, the results for \(J_c/J_d\) would be identical to those described above if \(m\) and \(d\) were scaled by the same factor as \(z_0/\xi. \) For instance, if \(z_0 \rightarrow 2z_0, \) \(J_c/J_d\) would remain the same if \(d \rightarrow 2d\) and \(m \rightarrow 2m, \) but the upper limit of \(m/\phi_0 z_0\) for the validity of the London approximation would increase by a factor of 4. The present model also breaks down if \(m\) is sufficiently large to create vortices in the film. The threshold value of \(m\) for spontaneous vortex creation, estimated as \(m \sim 0.7 \phi_0 z_0\) using the results of ref. [7], is larger than \(m\) used here.

The simple model discussed here is relevant to vortex pinning by arrays of magnetic dots, providing that: i) the dots are sufficiently far apart to neglect dipole-dipole interactions between them, ii) the number of vortices per dot is small enough, so that each dot pins at most one vortex, and the vortices are far enough apart to neglect vortex-vortex interactions. Unfortunately, there are no experimental results on vortex pinning by magnetic dots with freely
rotating magnetic moments to compare the model predictions with. Instead, consider under which conditions the results described above apply to a system consisting of a typical array of nanomagnets reported in ref. [8] on top of a thin superconducting film. Assuming that $\xi = 20\, \text{nm}$, it follows that for $d = z_0 = 2\xi$, $\lambda = 10\xi$ (as above), $d = z_0 = 40\, \text{nm}$, $\lambda = 200\, \text{nm}$, and $\phi_0/\lambda^2 = 500\, \text{G}$. The value $m = 0.5\phi_0 z_0$ follows if the disk radius and thickness are chosen, respectively, as $R \sim 50\, \text{nm}$ and $t \sim 10\, \text{nm}$, and the disk magnetization is taken as $M \sim 10^2 \mu_B/(\text{nm})^3$. If the distance between disks in the array is $a \sim 1\, \mu\text{m}$, the dipole-dipole interaction energy, $E_{dd} \sim m^2/a^3$, is small compared with the vortex pinning potential, $U_{vm} \sim -mb_{max}^6$, since $E_{dd}/U_{vm} \sim 10^{-2}$. The values chosen for the disk radius and thickness, for the magnetization, and for the distance between disks are typical of those of ref. [8]. The results reported above (fig. 3) predict that for $H < b_{max}^6 = 12\, \text{G}$, $J_c$ depends strongly on $H$, as in fig. 3c, whereas for $H > b_{max}^6 = 12\, \text{G}$, $J_c$ is that for a permanent dipole, and depends only on $\alpha$.

In conclusion then, this paper demonstrates that the critical current for a vortex in a thin superconducting film pinned by a freely rotating dipole can be tuned by a magnetic field applied parallel to the film surfaces. It is found that tuning takes place for a wide range of fields. For large fields, when the dipole moment is stuck in the field direction, the critical current changes continuously by one order of magnitude when the field is rotated by 180°, from the direction parallel to the driving force to the direction opposite to it. For fields comparable to the vortex field the critical current is very sensitive to field variations, showing very rapid and even discontinuous changes by as much as one order of magnitude. It is suggested that the results apply to experiments on magnetic dot arrays on top of clean superconducting films.

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