Theory and simulations on strong pinning of vortex lines by nanoparticles

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The pinning of vortex lines by an array of nanoparticles embedded inside superconductors has become the most efficient practical way to achieve high critical currents. In this situation pinning occurs via trapping of the vortex-line segments and the critical current is determined by the typical length of the trapped segments. To verify analytical estimates and develop a quantitative description of strong pinning, we numerically simulated isolated vortex lines driven through an array of nanoparticles. We found that the critical force grows roughly as the square root of the pin density and it is strongly suppressed by thermal noise. The configurations of pinned lines are strongly anisotropic, displacements in the drive directions are much larger than in the transverse direction. Moreover, we found that the roughening index for the longitudinal displacements exceeds one. This indicates that the local stresses in the critical region increase with the total line length and the elastic description breaks down in the thermodynamic limit. Thermal noise reduces the anisotropy of displacements in the critical regions and straightens the lines.

I. INTRODUCTION

The introduction of large-size nanoparticles of different shapes has emerged as the best practical way to improve the current performance of high-temperature superconductors. While in the first superconducting cables the critical currents were limited by weak links, in the second-generation superconducting wires based on aligned YBa$_2$Cu$_3$O$_7$ (YBCO) films this problem has been mostly resolved and critical currents are determined by vortex pinning. Impressive progress has been made to enhance critical currents in these films using both isotropic and columnar inclusions. In spite of this progress, our understanding of strong pinning mechanisms is far from satisfactory. Theoretical estimates describing the pinning of vortex lines by an array of strong pins at low temperatures were elaborated by Ovchinnikov and Ivlev. This theory was applied to describe the behavior of the critical currents in the real YBCO films in Refs. 12 and 13. In particular, frequently observed power-law decay of the critical current as a function of the magnetic field with a power slightly larger than 1/2 is naturally explained by this theory. More recently, it was also argued that strong pins of unknown origin determine critical currents at low magnetic fields in several iron pnictide compounds. It is not clear, however, to what extent available qualitative estimates describe the real situation. Due to the obvious importance of strong pinning by large-size inclusions for real superconducting materials, it is desirable to elaborate a quantitative theory describing pinning in such situations. Moreover, the very important issue of pinning suppression by thermal fluctuations does not have any theoretical description in the strong-pinning regime.

In this paper we consider the pinning of vortex lines in a superconductor containing insulating inclusions with lateral sizes larger than the coherence length. We focus on the pinning of individual vortex lines corresponding to small magnetic fields. Pinning occurs via the trapping of finite-size segments of a vortex line with a typical length $L$, as illustrated in Fig. 1. The critical current is determined by the length of the trapped segment $L$ and the pin-breaking force $F_p$,

$$\frac{\Phi_0}{c \cdot j_c} \approx \frac{F_p}{L}. \quad (1)$$

Therefore, in the strong-pinning regime the critical-current problem is mostly reduced to evaluation of the trapped-segment length $L$. In general, trapping of the vortex lines is a complicated dynamic process controlled by the competition between the pinning energy, line tension, and intervortex interactions. Different approaches may be used to evaluate the trapped-segment length. One can assume that the pinning center always grabs a piece of the vortex line when it is energetically favorable. This assumption implies that thermal fluctuations facilitate local equilibration. In this case the parameters of the trapped configurations can be obtained from the energy-
balance estimates. We will call this type of trapping the
equilibrium regime. This energy-balance consideration
determines trapped configurations of static vortex lines
prepared by cooling in finite magnetic field. However,
such consideration is not applicable to the more typical
dynamic scenario when moving lines are trapped after the
driving force is slowly reduced down to the critical value.
In this case the line motion close to the critical force is
a continuous trapping-detrapping process limited by lo-
cal instabilities. The driven vortex can be captured when
the line either directly collides with a strong pin or passes
sufficiently close to it. In the second case trapping may
occur due to the long-range pin-vortex interaction as a re-
result of local instability. The line remains trapped until
the force acting from the pin does not exceed the pin-
breaking force. When the line finally stops, the pinned
configuration is expected to be very anisotropic because
the transverse pin-to-pin displacements which are de-
determined by trapping events are much smaller than the lon-
gitudinal displacements limited by the pin-breaking cri-
teria.

To develop a quantitative picture and verify analyt-
ical estimates, we explore in this paper the pinning of
the vortex lines by nanoparticles with extensive numeri-
cal simulations. We study the dependence of the critical
force on the density of pins, the statistical properties of
trapped lines including average values, and the distri-
butions of trapping length and pin-to-pin displacements.
We study long-range behavior of line displacements in
the direction of the driving force and in the transverse
direction. We also study in detail the suppression of the
apparent critical force by thermal fluctuations and the tem-
perature dependence of the trapping parameters.

The paper is organized as follows. In Section II we de-
scribe parameters characterizing the interaction between
a vortex line and large-size pinning centers. In Section
III we present analytical estimates. This includes the
formulation of general conditions for stable trapped
configurations in subsection IIIA making estimates for pa-
rameters of trapped line in equilibrium, subsection IIIB
and in the case of dynamic trapping, subsection IIIC.
In the Section IV we describe the model used in our nu-
merical simulations. In the Section V we present our
numerical results including the zero-temperature case in
subsection VA and the finite temperature in subsection
VB. In Section VI we discuss our results and make pre-
liminary comparisons with experiments.

II. INTERACTION BETWEEN VORTEX LINE
AND PINNING CENTER

We consider first the essential parameters describing
the interaction of vortex lines with large-size pinning cen-
ters. The vortex pinning energy by an insulating spheroid
inclusion with the axes \( b \) and \( b_2 \) is given by

\[
U_p \approx 2b_2 \varepsilon_0 \mathcal{L}_p, \quad \mathcal{L}_p = \ln(b/\xi_{ab})
\]

with \( \varepsilon_0 = \Phi_0^2/(4\pi\lambda_{ab})^2 \). A very important parameter is
the pin-breaking force, the maximum force with which
the pinning center can attract the vortex line. In con-
trast to small defects, the pin-breaking force for large-
size defects is limited by the line tension of the vortices.
With increasing external force, the tips of the vortex line
slide along the surface of the insulating inclusion until
they meet near the equator and reconnect leading to the
depinning of the vortex. For the in-plane current in the
anisotropic layered material, the upper estimate for such
a line-tension-limited force can be obtained by consider-
ing the simple geometry of equally spaced pins aligned
along the \( c \) axis and neglecting the interaction between
vortex tips at the pin surface. In this case, evaluating
the external force at which the tips meet, we obtain the
following estimate

\[
F_p \lesssim (2\xi_0/\gamma) \ln(b_2/\xi_{\text{pin}}),
\]

where \( \gamma \) is the anisotropy factor, \( \xi_{\text{pin}} = \max(\xi_c, s) \), \( \xi_c \)
is the \( c \)-axis coherence length, and \( s \) is the interlayer pe-
riod of a layered superconductor. This force only weakly
depends on the size and shape of the pinning center.

The interaction of the vortex line with a remote pin is
long ranged, due to the perturbation of the supercurrent
flow around the vortex by the pin,

\[
U_i(r) \approx -\frac{\varepsilon_0 V_p}{\pi(1 - n_y/r)^2}, \quad \text{for } b \ll r \ll \lambda_{ab},
\]

where \( V_p = (4\pi/3)b_2 b_2^2 \) is the volume of the pinning cen-
ter and \( n_i \) are “depolarization factors”, which depend on
the parameter \( \gamma b_2/b \). In particular, in the case \( b_2 > b/\gamma \)
which includes close-to-spherical inclusions,

\[
n_z = \frac{1 - \zeta^2}{\zeta^3} (\tanh^{-1} \zeta - \zeta), \quad \text{with } \zeta = \sqrt{1 - \frac{b^2}{\gamma^2 b_2^2}}
\]

and \( n_x = n_y = (1 - n_z)/2 \).

Recently, it was demonstrated that magnetic force mi-
croscopy can be effectively used not only for imaging but
also for the manipulation of individual vortices\cite{10}. This
technique gives principal possibility to measure the in-
teraction between a vortex line and an individual pinning
center and extract the relevant interaction parameters
described in this section.

III. ANALYTICAL ESTIMATES FOR THE
TRAPPING OF A VORTEX LINE

A. General conditions for a static pinned line

Consider a general vortex-line configuration trapped
at the points \( (u_n, z_n) \). For simplicity, we assume that
the forces from the pins are applied locally at the points
\( z = z_n \). In between the trapped points, \( z_n < z < z_{n+1} \),
the displacement obeys the following equation

\[
\varepsilon_0 \frac{\partial^2 u}{\partial z^2} + f e_x = 0,
\]
where \( f \) is the driving force applied along the \( x \) axis and 
\( \varepsilon_1 = (\varepsilon_0/\gamma^2) L_1 \) is the line tension with \( L_1 \) being the logarithmic factor \( L_1 = \ln(r_{\text{max}}/r_{\text{min}}) \). The displacement can be found as 
\[
\mathbf{u}(z) = \mathbf{u}_n + (\mathbf{u}_{n+1} - \mathbf{u}_n) \frac{z - z_n}{z_{n+1} - z_n} - \frac{\mathbf{e}_x f(z-z_n)(z-z_{n+1})}{2\varepsilon_1}.
\] (6)  
The force acting from the pin on the vortex line at \( z = z_n \) is given by 
\[
\mathbf{F}_n = -\varepsilon_1 \left[ \frac{\partial \mathbf{u}}{\partial z}(z_n + 0) - \frac{\partial \mathbf{u}}{\partial z}(z_n - 0) \right]
\] and can be evaluated as 
\[
\mathbf{F}_n = -\frac{\mathbf{e}_x f(z_{n+1} - z_{n-1})}{2} - \varepsilon_1 \left( \frac{\mathbf{u}_{n+1} - \mathbf{u}_n}{z_{n+1} - z_n} - \frac{\mathbf{u}_n - \mathbf{u}_{n-1}}{z_n - z_{n-1}} \right). \] (7)  
The stability condition for the trapped line is given by 
\[
F_n < F_p \quad \text{for all} \ n,
\] (8)  
while the critical state corresponds to the condition that at least one local force reaches the pin-breaking force 
\[
\max_n (F_n) = F_p. \] (9)  
One simple consequence of Eqs. (7) and (8) is that for “behind” sites, \( u_{x,n} < u_{x,n-1}, u_{x,n+1} \), the line-tension force adds to the external force meaning that they, in average, have shorter trapping segments \( z_{n+1} - z_n, z_n - z_{n-1} \).  

B. Equilibrium trapping  

Consider the trapping of a single vortex line by strong-pinning centers with concentration \( n_p \) and pinning energy \( U_p \). Assuming local equilibrium, the typical trapping length \( L \) and transverse displacement \( u \) are determined by the energy-balance condition \[\] 
\[
\varepsilon_1 u^2 L = U_p
\] and by the condition that the average number of impurities in the trapping volume should be of the order of one, 
\[
n_p u^2 L = 1.
\]  
These equations give 
\[
L_{eq} = \frac{\varepsilon_1}{n_p U_p}, \quad u_{eq} = \sqrt{\frac{U_p}{n_p \varepsilon_1}}. \] (10)  
Strictly speaking, the above conditions are obtained for zero current. Assuming that the trapping length does not change much when current is applied, we obtain an estimate for the critical current for the equilibrium trapping 
\[
\Phi_0 \frac{c_{j,c,eq}}{L_c} \approx \frac{F_p}{L_c} \approx F_p \sqrt{\frac{n_p U_p}{\varepsilon_1}}. \] (11)  
It is expected to increase with the pin density as \( \sqrt{n_p} \).  

C. Dynamic trapping  

The equilibrium estimates for the trapping parameters \[\] are definitely valid for the line configurations prepared by cooling at fixed field and at zero transport current. However, it is clear that they cannot be applied to the vortex lines in the critical state at low temperatures when moving lines are trapped after the driving force drops below the critical value and equilibration does not take place. The critical current in such a dynamic regime
has been estimated in Ref. [11] for high fields when the intervortex interactions are essential. These estimates can be directly generalized to the trapping of individual vortex lines at small fields. When the vortex line moves close to the pinning center, it may be trapped and the line remains trapped until the force acting from the pin on the vortex line does not exceed the pin-breaking force. In this regime two typical trapping distances, in the direction of motion, \( u_t \), and in the transverse direction, \( u_t \), are very different and have very different origins, see Fig. 2. These distances and the trapped-segment length \( L \) are connected by the geometric relation

\[ n_p L u_t u_t = 1. \tag{12} \]

The longitudinal trapping distance, \( u_t \), is determined by the pin-breaking condition,

\[ \varepsilon_1 \frac{u_t}{L} = F_p. \tag{13} \]

This condition can be obtained from the \( x \) component of Eq. (7) assuming that the two terms on the right-hand side are of the order of the pin-breaking force.

The transverse displacement between the pins, \( u_t \), is determined by the trapping events. The simplest assumption is that in most cases trapping occurs when the lines directly collide with the pins meaning that \( u_t \approx b \). This immediately gives estimates for other trapping parameters,

\[ u_t = \sqrt{\frac{F_p}{n_p \varepsilon_1 b}}, \quad L = \sqrt{\frac{\varepsilon_1}{n_p b}}. \tag{14} \]

This corresponds to the following result for the critical current

\[ \Phi_0 c \frac{J_{c, tr}}{L} = F_p^{3/2} \sqrt{\frac{n_p b}{\varepsilon_1}}. \tag{15} \]

Note that in this situation the estimate is somewhat similar to the result for the equilibrium case, Eq. (11), and has the same dependence on the pin density, \( \sqrt{n_p} \). The physical assumptions behind the two estimates, however, are completely different.

The above simple assumption, however, may underestimate \( u_t \). Due to the long-range pin-vortex interaction [4] a pinning center may capture the vortex line even without direct collisions. When the line passes sufficiently close to the pinning center it may be trapped by this center due to instability. To estimate the maximum transverse trapping distance \( u_t \), we consider the interaction energy of a segment of length \( L \) with a pinning center located at a distance \( R \gg b/11 \) see Fig. 3

\[ E(u) = \varepsilon_1 \frac{2u^2}{L} - \frac{A \varepsilon_0 V_p}{(R - u)^2} \]

with \( A = 1/\pi(1 - n_p) \). This gives the interaction force

\[ F(u) = \varepsilon_1 \frac{4u}{L} - \frac{2A \varepsilon_0 V_p}{(R - u)^3} \]

Introducing the reduced variables

\[ x = \frac{u}{R}, \quad W = \frac{A \varepsilon_0 L V_p}{2 \varepsilon_1 R^2}, \]

we rewrite the energy and force as

\[ E = \varepsilon_1 \frac{2R^2}{L} \left[ x^2 - \frac{W}{(1 - x)^2} \right], \]

\[ F(x) = -\varepsilon_1 \frac{4R}{L} \left( x - \frac{W}{(1 - x)^3} \right). \]

The equilibrium points are determined by

\[ x(1 - x)^3 = W. \]

The instability point corresponds to the value of \( W \) when the equilibrium points vanish which happens at \( W > W_{\text{max}} = \max[x(1 - x)^3] = 3^3/4^4 \). Therefore the condition for the instability can be written as

\[ \frac{A \varepsilon_0 L V_p}{2 \varepsilon_1 u_t^2} = \frac{3^3}{4^4}, \]

which determines the maximum trapping distance \( u_t \) as

\[ u_t = 4 \left( \frac{A \varepsilon_0 L V_p}{54 \varepsilon_1} \right)^{1/4}. \tag{16} \]

The vortex line will be trapped by the pinning centers located closer than this distance in the direction perpendicular to the driving force. Note that the numerical coefficient in this equation should not be taken too literally because it is only correct for the simplest geometry illustrated in Fig. 3. Using this result, we find from Eqs.
force which the vortex segment remains pinned and that the average line velocity can be estimated as in the crossover region consists of segment jumps, mean-

ing that the trapped segments are typically released from pins. At finite temperatures this gives us the following relation for $F_p$

\[ \frac{\tau_0}{\eta} \exp \left[ \frac{a_F U_p}{T} \left( 1 - \frac{F_p}{F_p} \right)^{3/2} \right] \approx u_t \frac{C_f \tau_0}{C_f \tau_0} \]

Using the estimate $f_c \approx \tilde{F}_p/L_t$, the geometric relation (13) and assuming for simplicity that $u_t \approx b$, we obtain

\[ \tilde{F}_p(T) \approx F_p \left[ 1 - \left( \frac{T}{a_F U_p} \ln \frac{\eta}{C_f \tau_0 F_p n_p b} \right)^{-2/3} \right] \]

We expect that at low temperatures the effective critical force and trapping parameters can be roughly evaluated using the simple replacement $F_p \to \tilde{F}_p(T)$.

IV. MODEL FOR NUMERICAL SIMULATIONS

To develop a quantitative understanding of the strong pinning by the array of inclusions, we numerically simulated motion of the vortex line described by the dynamic equation

\[ \eta \frac{\partial u}{\partial t} = \varepsilon_1 \frac{\partial^2 u}{\partial z^2} + \sum_j F(u - R_j) \delta(z - z_j) + e_x f + F_T(z, t) \]

Here $f$ is the driving force along the $x$ direction from the current, $(R_j, z_j)$ are the random pin coordinates, $F_T(z, t)$ is the Langevin thermal force

\[ \langle F_{T,\alpha}(z, t) F_{T,\alpha'}(z', t') \rangle = 2\eta T \delta_{\alpha \alpha'} \delta(t - t') \delta(z - z') \]

and

\[ F(u) = -\frac{\partial U(u)}{\partial u} \]

is the interacting force with a strong pin. We model the interaction potential by the function

\[ U(u) = -\frac{U_p b^2 G_{cut}(u)}{u^2 + b^2} \]

where the cutoff function $G_{cut}(u)$ is introduced for numerical convenience, $G_{cut}(u) = (1 - u^2/R_{cut}^2)^2$ for $u < R_{cut}$ and $G_{cut}(u) = 0$ for $u > R_{cut}$ with $R_{cut} \gg b$. An important feature that was not taken into account in modeling before is the long $1/u^2$ tail in the interaction potential. However, this model does not describe the line-tension limited pin-breaking force. In our model the pin-breaking force from an isolated pin is given by
the increasing the system sizes by a rare, nontypical configuration of pins. As a consequence, the maximum pinning force slowly grows with the increasing the system sizes $L_x$ and $L_y$, meaning that it is not a self-averaging parameter for a fixed line length $L_z$. To avoid this, a carefully chosen (anisotropic) thermodynamic limit in all directions was proposed for $d + 1$ dimensions. The maximum pinning force of a very large system is also very difficult to compute. Simulations of Eq. (24) at zero temperature are not very suitable for this purpose, because when the external force is close to the critical value, the vortex line traps forever in the first metastable state it finds. It is not clear how representative this state is and how close the corresponding critical force is to the maximum value. In addition, neither the maximum critical force nor depinning forces for a few accidental metastable states are very interesting quantities from a practical point of view. The maximum critical force is essentially a property of an isolated vortex line. A more interesting quantity is the typical pinning force for the finite density of the vortex lines. Indeed, even at low densities when vortex-vortex interactions can be neglected, we expect a typical pinning force rather than an extreme non-self-averaging force value to determine the observable critical current.

To evaluate a typical pinning force at zero temperature, instead of the fixed-force approach, we employ fixed-velocity simulations using approach suggested in Ref. 21. Namely, we replaced the fixed external force $\mathbf{f}$ in Eq. (24) with a slowly moving parabolic potential,

$$f \to K [W(t) - u_x(z, t)], \quad W(t) = W_0 + V t$$

Such a potential forces the vortex line to move with the average velocity $V$. Every time the line finds a metastable pinned state and stops, the dragging force starts to increase with time until it exceeds the critical force for this state and the line resumes motion. This trick allows us to explore many metastable states and to avoid the extreme value statistics of the sample-dependent critical force. The typical critical force is then evaluated as the average force acting on the vortex line in the critical configurations,

$$f_c = \langle (K [W(t) - u_x(z, t)]) \rangle_t$$

where $\langle \ldots \rangle_t$ implies averaging over the local maxima of the instantaneous force. The spring constant $K$ and the drag velocity $V$ have to be taken sufficiently small so that they do not influence the calculation of the critical force. We typically use $K \sim 10^{-5} - 10^{-4}$ and $V = 0.001 - 0.002$. The spring constants satisfy $K \sim L_z^{-2}$ in each case, assuring a proper thermodynamic limit for the critical force and associated critical configuration. The velocities are small enough to assure a quasistatic stick-slip motion. Figure 4(left) illustrates the typical dependences of the force acting on the line on the displacement of its center of mass for different pin densities $n_p$ and line lengths $L_z$.

We also explore the velocity-force dependences at finite temperatures using the direct fixed-force simulations described by Eq. (24). Even though the term "critical force" is widely used in the experimental community, at
finite temperatures the concept of the critical force does not have an exact meaning because the velocity is finite at all forces due to the thermal creep. Nevertheless, one can still introduce the characteristic force describing crossover between the flux-flow and flux-creep regimes using some average-velocity criterion. At low temperatures near such critical force the line motion becomes very uneven, see Fig. 4(right). It spends considerable time in metastable traps waiting for a strong fluctuation which allows it to continue motion. Such line motion is illustrated by animation. As a consequence, a proper averaging over such events requires huge simulation times and/or averaging over many realizations of the random potential. In addition to the critical force, we explore statistical parameters of trapping which allow us to understand better the pinning mechanism. We evaluated the average length of a trapped segment \( L_t \) and typical displacements along the motion direction \( u_l \) and in the perpendicular direction \( u_t \). We studied the distribution of these parameters and their evolution with temperature and force. We also studied the long-range wandering of the line in the direction of motion and in the transverse direction.

For a numerical solution the reduced equation has to be discretized both in time and in the \( z \) coordinate. We typically used \( dt = 0.05-0.1 \) and \( dz = 1 \) for the discretization steps. To study finite-size effects, the equation was solved for different numbers of \( z \)-axis slices, \( N_z \equiv L_z/dz \), ranging from 512 to 2048.

V. NUMERICAL RESULTS

A. Behavior at zero temperature

FIG. 5. The dependence of the critical force on the pin density. The plot contains data obtained for different system sizes, and the legend shows \( N_z/L_x/L_y \). The finite-size effects in the critical force are weak.

FIG. 6. Summary of the pin-density dependences of the trapping parameters for different system sizes. As in the previous plot, the legend shows \( N_z/L_x/L_y \). \textit{Upper plot}: The dependences of the average trapped-segment length \( L_t \). For comparison, we show the expected trapping length extracted from the critical force. \textit{Lower plot}: The pin-density dependences of the average pin-to-pin displacements in the direction of the force (longitudinal) and in the perpendicular direction (transverse). The longitudinal displacement, \( \langle u_l \rangle \), has a considerable finite-size effect with respect to the line length \( N_z \).
We systematically studied the behavior of the critical force and the properties of trapped line configurations within a pin-density range spanning two orders of magnitude, from $2.7 \cdot 10^{-3}$ to $2.7 \cdot 10^{-5}$. Figure 2 presents the dependences of the critical force $f_c$ on the pin density $n_p$ for different system sizes $N_z$. We found that $f_c$ increases with $n_p$ according to the power law $f_c = f_{0n_p^\alpha}$. The fit gives for the power index a value slightly smaller than $1/2$, $\alpha \approx 0.48$ and the coefficient $f_0 \approx 0.61$. In fact, the square-root dependence $f_c \approx 0.71 \sqrt{n_p}$ also provides a reasonable description of the data. The power is, however, clearly larger than the value 0.44 suggested by the dynamic-trapping estimates in the case when trapping occurs due to instabilities. For the used line lengths $N_z \geq 512$ a noticeable finite-size effect becomes visible only for small pin densities $n_p < 3 \cdot 10^{-4}$.

To understand the statistical properties of trapped configurations, we plot in Fig. 3 the pin-density dependences of the average trapping parameters defined in Fig. 2, the trapping length $L_t$, and the pin-to-pin displacements along the direction of force, $u_t$, and in the transverse direction, $u_l$. In the plot $L_t(n_p)$ we show the expected value of the typical trapped segment extracted from the value of the critical force $L_{t,f} = F_p/f_c$. We can see that the real trapping segments extracted from the configurations indeed closely follow the expected values. We also see that the average trapping segments are systematically smaller than the segments which determine the critical force. This is a natural behavior because one can expect that the critical force is determined by “weak spots” where the trapping segments are longer than average along the line. The difference, however, is not very significant. The trapping length shows a weak but unexpected size effect, it slightly decreases with increasing total line length. We found that the product $n_pL_tu_lu_t$, which on general ground is expected to be of the order of unity is, in fact, slowly decreases with $n_p$ from $\sim 0.18$ to $\sim 0.14$.

From the plots of the pin-to-pin displacements, we can see that the pinned configurations are strongly anisotropic, the average displacement along the direction of the driving force $u_t$ significantly exceeds the displacement in the transverse direction $u_l$. This is consistent with the dynamic-trapping picture described in Sec. III C. The difference grows with decreasing pin density $n_p$. In addition, the longitudinal displacement shows a significant size effect, it grows with an increasing system size $N_z$. Further analysis shows that this is an indication of growing local stresses with increasing line length and suggests the destruction of the vortex lines by the pinning potential in the critical state for sufficiently large systems. This behavior is not anticipated by the simple estimates. It is interesting to note, however, that this size effect in $u_t$ does not lead to a significant size dependence of the critical force. On the other hand, the average transverse displacement $u_l$ does not show any size effect. It slowly grows with decreasing $n_p$ from 1.24 at $n_p = 0.0027$ to 2.54 at $n_p = 2.7 \cdot 10^{-5}$. As $u_l$ remains comparable with the defect size, the regime in which the transverse trapping is determined by the long $1/r^2$ tail of the pin-vortex interaction is not quite realized. This explains why the power index in the force--pin-density dependence is larger than suggested by the metastable-regime estimates which assume $u_t \gg 1$. To obtain further insight into the properties of trapped lines we show in Fig. 7 examples of the distribution functions of trapping parameters for a fixed density $n_p = 2.67 \cdot 10^{-4}$ and different system sizes. One can see that these distributions are characterized by long exponential tails. There is a noticeable probability to find segments with very large $u_t$ and $L_t$. Note that the tails have opposite size effects for these parameters, the probability to find a large $u_t$ increases with $N_z$ while the probability to find a large $L_t$ decreases with $N_z$. The last trend is opposite to naive expectations.

To characterize the long-range displacements of the line, we studied behavior of the structure factors, the Fourier transforms of the displacement correlation functions,

$$S_{l,t}(q) = \frac{1}{N_z} \Bigg\langle \sum_{z=1}^{N_z} u_{x,y}(z) \exp(-iqz) \Bigg\rangle^2. \quad (27)$$
Examples of these quantities are presented in Fig. 8 (left) for two pin densities. Similar to local quantities, the long-range displacements are also strongly anisotropic. Such anisotropic scaling of the displacements is a general property of the driven lines in the critical regime independent of the pinning mechanism. For both components we clearly observe two regions of $q$ characterized by different power-law dependences $S_{l,t}(q) \propto q^{1+2\zeta_l,t}$. For the smallest $q$’s we found the roughness exponents $\zeta_l \approx 1.14$ and $\zeta_t \approx 0.45$. The value of $\zeta_l < 1$ for the transverse direction corresponds to the line displacements increasing as $\langle (u_y(z) - u_y(0))^2 \rangle \propto z^{2\zeta_l}$ at large $z$. On the other hand, the value of $\zeta_t > 1$ found for the longitudinal displacements implies that the assumed elastic approximation is not self-consistent in the thermodynamic limit, the average local stress $\langle (du_l/dz)^2 \rangle$ increases with the line length $L_z$ as $L_z^{2(\zeta_l-1)}$. In this case the longitudinal line displacements grow quadratically as $\langle (u_l(z) - u_l(0))^2 \rangle \propto C_l z^2$ with the coefficient increasing with the line length as $C_l \propto L_z^{2(\zeta_l-1)}$. This provides a natural explanation for the strong size dependence of the longitudinal pin-to-pin displacement $u_l$ in the lower plot of Fig. 8. The negative size effects for the trapping lengths in the upper plot of the same figure can also be understood. Growing local stress with increasing $N_z$ forces the line to travel longer distances in the longitudinal direction which increases the probability of finding a pin separated by a smaller distance in the $z$ direction.

The found exponents are slightly different from the values $\zeta_l = 1$ and $\zeta_t = 0.5$ obtained in Ref. 23 from the approximate functional renormalization group calculations. However, a similar situation was found for elastic lines in a plane where the numerically computed index $\zeta = 1.25 \pm 0.05$ also exceed the predicted value $\zeta = 0.45$. We see that the transverse displacements somewhat reduce the exponent value in the 3D case. Since the small-$q$ exponents are expected to be universal, i.e., independent of the pinning mechanism, our results suggest that the elastic description will also break down for the weak pinning case. Although we have considered the linear approximation for the elastic forces, this conclusion is expected to hold for the full non-quadratic energy of the deformed vortex line.

At larger $q$’s we observe the regime where both components behave as $S_{l,t}(q) \propto q^{-\alpha_l,t}$ giving the short-scale indices $\zeta_l = \zeta_t = 3/2$. This corresponds to displacements induced by a short-range-correlated random force, and such behavior is actually similar to the static Larkin regime for weak pinning. However, the random forces in our case clearly have a very different origin.

The crossover between different regimes occurs at a wave vector that scales approximately as $\sqrt{n_p}$. This allows us to approximately collapse the structure factors at different pin densities into a single curve using the scaling $S_{l,t}(q) = n_p^{-\alpha_l,t} C_{l,t}(q n_p^{-1/2})$. We found $\alpha_l \approx 1.32$ and $\alpha_t \approx 0.9$. These scaled dependencies are shown on the right-hand side of Fig. 8. Scaling works better for the longitudinal structure factor. This scaling is consistent with the identification of the trapping parameter $L_t(u_p)$ as a geometric crossover length at $q L_t \sim 1$, between a short-distance roughness regime with exponents $\zeta_l = \zeta_t = 3/2$ and a large-distance universal regime with exponents $\zeta_l \approx 0.45$ and $\zeta_t \approx 1.14$. This behavior is again very similar to the crossover between the Larkin regime and the random-manifold regime established for the case of weak collective pinning even though disorder is not weak in the present case.

We can also see from Fig. 8 (left) that both structure factors increase with the pin density for all wave vectors. This means that, in contrast to elemental pin-to-pin displacements $u_{l,t}$ plotted in Fig. 6, the line displacements at fixed $z$ grow with increasing pin density. This behavior can be easily understood. The displacements at small distances are determined not only by the behavior of $u_{l,t}$
but also by the behavior of the trapping length $L_t$. All these parameters decrease with increasing pin density, meaning that smaller displacements occur on a smaller length scale. The net increase of the line displacements at fixed $z$ coordinate with increasing $n_p$ is a consequence of a faster $L_t(n_p)$ decrease than that of $u_{l,t}(n_p)$, as can be seen from Fig. 9.

**B. Dynamics at finite temperatures**

In this section we consider the influence of thermal noise on the dynamic response and configurations of vortex lines interacting with strong pins. Figure 10 presents the temperature evolution of the velocity-force dependences and trapping parameters in the critical region for two very different pin densities, $n_p = 5.33 \times 10^{-5}$ and $n_p = 1.33 \times 10^{-3}$. We remind that we use the pinning energy of a single pin as the temperature unit. At finite temperatures the critical force does not have an exact meaning, because the line velocity is finite at all forces due to the thermal creep. Nevertheless, we can introduce a typical force corresponding to the crossover between the flow and creep regimes, similar to the voltage dependence of the critical force in real units.

As we found approximately $f_c \propto \sqrt{n_p}$ at $T = 0$, according to the estimate of Eq. (15) we also expect the relation $f_c \propto F_p^{3/2}$. This means that, according to Eq. (21), we expect the dependence $\left( f_c(T)/c(0) \right)^{2/3} = 1 - (\beta dp T)^{2/3}$ with $\beta dp = (1/a_F) \ln(n_p / n_0)$. This is directly verified in Fig. 10(c) where we observe the approximate linear dependencies of $\left( f_c(T)/c(0) \right)^{2/3}$ versus $T^{2/3}$. Moreover, as shown in the inset, the coefficient $\beta dp$ found from the linear fits for different pin densities indeed has a logarithmic dependence on $n_p$, $\beta dp \approx 1.6 \ln(0.115/n_p)$. These observations provide justification for our assumption that the reduction of the typical pin-breaking force is the main source of thermal suppression of the effective critical force.

We consider now the influence of thermal noise on the long-range behavior of the line displacements. Figures 11(a,c) present the evolution of the structure factor with increasing temperature for the pin density $n_p = 1.33 \times 10^{-4}$. We can see that the slope of the small-$q$ dependences does not change indicating that the roughening indices $\zeta$ and $\zeta_t$ are temperature independent. However, the coefficient is significantly reduced for the longitudinal displacements and is enlarged for the transverse displacements. Correspondingly, as one can see from the line wandering plots shown in Fig. 11(b,d), the components of displacements in the critical region have opposite tendencies: the longitudinal displacements decrease and the transverse displacements increase with increasing temperature. As the longitudinal displacements dominate, the lines become more straight in the critical region. Another important observation is that the random-force regime $S_{l,t} \propto q^{-4}$ at large $q$ is rapidly washed out by thermal noise for both components and is replaced by the isotropic fluctuational line wandering $S_{l,t} = T^2/\zeta^2$.

**VI. DISCUSSION AND COMPARISON WITH EXPERIMENT**

Using the square-root fit of the pin-density dependence of critical force in Fig. 5, we can restore the $n_p$ dependence of the critical force in real units

$$f_c = 1.9 F_p^{3/2} \frac{1}{\sqrt{\frac{n_p b}{\varepsilon_1}}} \quad (28)$$

This coincides with the estimate [15] which is obtained assuming that the transverse trapping distance $u_t$ is on the order of the pin size $b$. This does not contradict too much our numerical results, because our average values of $u_t$ only slightly exceed the pin size. Note that in our simulations the pin-breaking force $F_p$ is fixed by interaction with the pin while in real superconductors for large-size inclusions it is determined by the in-plane line energy, see Eq. 5. Substituting this estimate, our result leads

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FIG. 9. Temperature evolution of the velocity-force dependences (bottom plots), lengths of trapped segments (top plots, right axes), and pin-to-pin displacements (middle plots) for two very different pin densities, \( n_p = 5.33 \times 10^{-5} \) (left) and \( 1.33 \times 10^{-3} \) (right) in the regions corresponding to crossover between flow and creep.

FIG. 10. (a) Temperature dependences of the effective critical forces for different pin densities and line lengths. (b) Relative suppression of effective critical forces by thermal fluctuations for selected pin densities/line lengths. (c) Plots of \( \frac{f_c(T)}{f_c(0)} \) vs \( T^{2/3} \) showing approximately linear dependences in agreement with Eq. (21). The inset shows the pin-density dependence of the coefficient \( \beta_{dp} \) with the logarithmic fit. Legends in the plots (b) and (c) imply \( n_p/N_z \). The top axes in the plots (a) and (b) provide the approximate real temperature scales computed for spherical particles with radius \( b = 5 \) nm assuming \( \lambda_{ab} = (140 \text{ nm})/\sqrt{1 - (T/T_c)^2} \) with \( T_c = 90 \text{ K} \).

to the following estimate for the critical force

\[
f_c = A_c \varepsilon_0 \sqrt{n_p b/\gamma},
\]

where, assuming \( \xi_c < s \), we estimated \( A_c \lesssim 5.4[\ln(b/s)]^{3/2} [\ln(L_z/s)]^{-1/2} \).

For preliminary comparison with experiment we use results of the recent paper [7] in which approximately spherical (Y-Gd)\(_2\)O\(_3\) particles with radii \( \sim 4 \) nm were embedded into the YBCO films. The typical concentration of particles was \( 5 \times 10^{16} \text{ cm}^{-3} \). For estimates, we assume the temperature-dependent London penetration depth as \( \lambda_{ab} = 140 \text{ nm}/\sqrt{1 - (T/T_c)^2} \) with \( T_c = 90 \text{ K} \).
and the anisotropy $\gamma = 5$. Such parameters correspond to the reduced concentration $\tilde{n}_p = 1.3 \times 10^{-4}$. From the above zero-temperature result, we estimate $A_c \approx 3.9$ and the critical current $j_c \approx 1.7 \times 10^7$ amp/cm$^2$ which is close to the low-field experimental value at $5K$, $2.08 \times 10^7$ amp/cm$^2$. The reduced temperature can be evaluated as $\tilde{T} \approx (T/5.3 \times 10^4 K)/(1 - (T/T_0)^{2})$. At 55 K this gives $\tilde{T} \approx 0.017$. According to Fig. 10(b), at this temperature thermal suppression of the critical current is expected to be around 50%. Taking this factor and the temperature dependence of the parameters into account, we expect a critical current $j_c \approx 5.2 \times 10^6$ amp/cm$^2$, which again is quite close to the experimental value of $6.22 \times 10^6$ amp/cm$^2$. We can conclude that the our strong-pinning result for the critical current is in reasonable agreement with experiment.

Our results show that the wandering of dynamically pinned lines is strongly anisotropic, displacements in the direction of motion are much larger than displacements in the transverse direction. In principle, experimentally this can be directly demonstrated using flux visualization techniques, such as a scanning SQUID or Hall probes. With these techniques individual vortices can only be resolved at small fields. Usually statically pinned vortices are visualized after cooling in fixed magnetic field. Nevertheless, it should also be possible to visualize shapes of the dynamically-pinned vortices near the boundary of the Bean profile, which is formed when the magnetic field is applied after cooling of a superconducting sample in zero field. We expect the vortex field profiles to be strongly elongated along the direction of motion. The elongation length along the direction of motion is given by the longitudinal displacement $u_l$ at a distance on the order of the London penetration depth. This length is expected to decrease with increasing temperature.

In conclusion, we developed a quantitative description of individual vortex lines pinned by an array of nanoparticles. We found that the critical force grows roughly as the square root of the pin density. This result is consistent with qualitative estimates assuming that for our pin-density range trapping events mostly occur as a result of direct collisions with pinning centers. The apparent critical force is strongly suppressed by thermal noise. The relative suppression reduces with increasing pin density. The configurations of pinned lines are strongly anisotropic, displacements in the drive directions are much larger than those in the transverse direction. The displacement anisotropy is rapidly reduced by thermal noise mostly due to the rapid reduction of the longitudinal displacements. This leads to straightening of the lines in the critical region. Analyzing the behavior of the structure factors at small wave vectors, we found that the roughening index for the longitudinal displacements exceeds one. This means that the local stresses in the critical region increase with the line length indicating a breakdown of the elastic description in the thermodynamic limit. The behavior of the structure factor at large wave vectors for both directions is typical for the displacement induced by random force. At finite temperatures this random-force regime is rapidly replaced by the thermal displacements.

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The cutoff lengths $r_{\text{max}}$ and $r_{\text{min}}$ depend on microscopic details. Typically, $r_{\text{max}}$ is determined by the length scale of line deformation in the $z$ direction, which in our case is given by the trapping length $L_t$. The lower bound for $r_{\text{max}}$ is given by the c-axis coherence length $\xi_c$. However, in layered superconductors more accurately $r_{\text{min}}$ can be estimated as the typical distance between the pancake vortices in the neighboring layers divided by the anisotropy factor $\gamma$.

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Near depinning threshold, the pin-vortex potential as a function of the pinned-point displacement $u$ can be expanded as $V(u) = (F_p - F)(u - u_c) - (b/6)(u - u_c)^3$ where $F \approx f L_t$ and $u = u_c$ is the marginal equilibrium point. Below threshold this yields the barrier $U(F) = [4\sqrt{2}/(3\sqrt{b})](F_p - F)^{3/2}$.

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