# Vortex structures in tilted field in layered superconductors

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**The intervortex interaction is investigated in very anisotropic layered superconductors in tilted magnetic field. In such a case, the crossing lattice of Abrikosov vortices (AVs) and Josephson vortices (JVs) appears. The interaction between pancakes vortices (PVs), forming the AVs, and JVs produces the deformation of the AV line. It is demonstrated that in the result of this deformation a long range attraction between AVs is induced. This phenomenon is responsible for the dense vortex chains formation. The vortex structure in weak perpendicular magnetic field is the vortex chain phase, when only a small part of JVs is occupied by AVs.**

Vortex physics in layered superconductors occurred to be extremely rich and interesting. In moderately anisotropic superconductors, the tilted magnetic field leads to the formation of the vortices inclined towards the superconducting layers. The interaction between such tilted vortices happens to be quite unusual.

In the plane defined by the vortex line direction and the **c**-axis (normal to the superconducting planes), the interaction between tilted vortices is attractive at long distances. Such attractive intervortex interaction is quite unexpected and leads to the formation of the vortex chains where the intervortex distance is governed by the balance between the long range attraction and the short range repulsion. The existence of these vortex chains in tilted field in layered superconductors has been predicted in [1, 2], and subsequently confirmed by the decoration technique [3], and the scanning-tunneling microscopy [4], measurements in $YBa_2Cu_3O_7$ and $NbSe_2$ crystals respectively. Recently the vortex chains were observed in an unconventional superconductor $Sr_2Ru0_4$ by the µSQUID force microscopy [5]. The systems studied in [3-5], are characterized by the moderate anisotropy. The theoretical approach [1, 2] is completely applicable to this case and gives a good qualitative and quantitative description of this phenomenon.

On the other hand, in the much more anisotropic $Bi_2Sr_2CaCu_2O_x$ (BSCCO) single crystals in [6-7], a more complicated mixed vortex chain-vortex lattice phase has been observed. As it has been demonstrated in [8] in strongly anisotropic layered superconductors in tilted magnetic field, a crossing lattice of Abrikosov and Josephson vortices (JVs), a combined lattice, must exist. Abrikosov vortex is in fact a line of pancake vortices (PVs) interacting with JVs. Following [9], the perpendicular vortex line formed by the PVs is deformed and attracted by JVs, so the JVs stacks accumulate additional PVs, creating vortex row with enhanced density [6-7]. This scenario has been proposed in [9] to explain the mixed chain-lattice state formation. Very recently, the detailed Hall probe and magneto-optic studies of vortex chains in BSCCO have been performed and revealed the stability of the dense vortex chains state even in the absence of lattice and in a very weak perpendicular magnetic field [10, 11].

Here we discuss the proposed in [12] mechanism of the formation of such dense vortex chain due to the attraction between the deformed lines of pancakes vortices. The deformation, responsible for a long range attraction, appears due to the interaction with JVs. In the result, the mechanism of vortex chains formation, in tilted field, in strongly anisotropic superconductors, appears to be quite similar to the case of moderately anisotropic superconductors [1, 2],

Keeping in mind BSCCO, let us consider the layered superconductor with high anisotropy ratio $\gamma = \lambda_c \backslash \lambda_{ab} \sim 200\text{-}500$, where $\lambda_c$ is the penetration depth for currents along **c**-axis (perpendicular to the layers), and $\lambda_{ab}$ is the penetration depth for currents in the **ab** plane (parallel to the layers). The in-plane field $B_x = B\cos\theta$ penetrates inside the superconductor in the form of JVs, while the perpendicular field $B_z = B\sin\theta$ creates the PVs which interact with JVs via the Josephson coupling [9]. We consider the case of the very weak coupling of the layers when the Josephson's core radius $\lambda_J = \gamma s$, (s is the interlayer spacing) is larger than an in-plane penetration depth, i.e. $\lambda_J >> \lambda_{ab}$. The interaction between JVs and PV produces a zigzag displacement of PVs along the **x**-axis, see Fig.1.

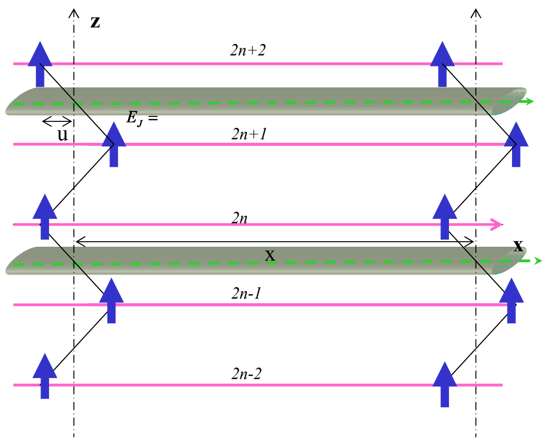


Fig. 1. Zigzag deformation of the pancake vortex stacks in the presence of parallel Josephson vortices.

In the limit of weak Josephson coupling, the interaction which stabilizes the straight PVs line is mainly of an electromagnetic origin. Then we may use the general expression for the energy of an arbitrary configuration of pancakes in the framework of the electromagnetic model to calculate the energy increase due to the line deformation [12].

Let us consider the limit of weak parallel field, when the Josephson vortices are well separated and the distance D between them along **z**-axis strongly exceeds the interlayer distance s, i.e. $B_x \ll H_0=\Phi_0/\gamma s^2$, see Fig. 2.

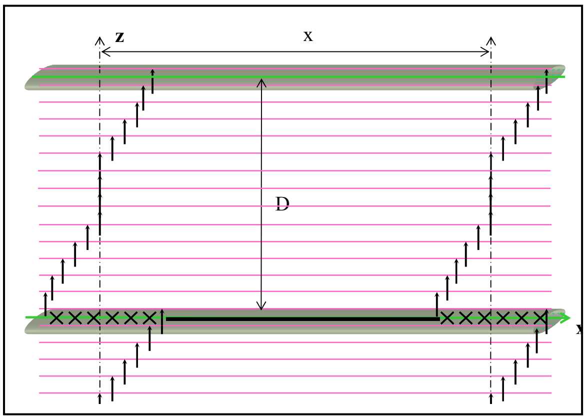


Fig. 2. Schematic picture of deformed vortex line.

As it has been demonstrated in [9], if the JV is located between the layers 0 and 1, the pancake displacements $u_n$ on the n-th layer in the case of the single Abrikosov vortex is

$$u_n \approx \frac{\lambda^2_{ab}}{\left(n-\frac{1}{2}\right)\lambda_J \ln\left(\frac{\lambda_J}{\lambda_{ab}}\right)}.$$

To consider the interaction of these deformed vortices, it is convenient to add the fictive pair of pancake vortex and antivortex at the central line of the Abrikosov vortex. Then the obtained configuration will be equivalent to two straight Abrikosov vortices and to two vortex-antivortex pairs at the distance x in each layers. Vortex and antivortex are separated by the distance $u_n$, and we are coming to the problem of an interaction of such magnetic dipoles. Firstly note that the interaction between dipoles in the same layer is attractive, and it may be directly calculated:

$$E^d{}_{n,n}(x) \approx -\frac{s\Phi_0^2}{8\pi^2\lambda^2_{ab}}\frac{u_n^2}{x^2}.$$

It is much larger then the interaction between dipoles from different layers n and m, which may be attractive or repulsive. The main contribution to the dipole interaction energy is coming from the interaction in the same layer, and it may estimated (per period D of the modulation of PVs line along z- axis) as

$$E_{att}(x) \approx -\frac{s\Phi_0^2}{8\pi^2\lambda^2_{ab}}\frac{u_1^2}{x^2}.$$

The main contribution to the repulsion energy is coming from the straight Abrikosov vortices interaction, and per period D at distances $x \gg \lambda_{ab}$ it is

$$E_{rep}(x) \approx \frac{D\Phi_0^2}{8\pi^2\lambda^2_{ab}}\sqrt{\frac{\pi\lambda_{ab}}{2x}}\exp\left(-\frac{x}{\lambda_{ab}}\right).$$

The prevailing interaction between Abrikosov vortices at long distances is attraction, and it will lead to the vortex chain creation. However, the relative strength of attraction is much smaller, as the attraction is coming only from the PVs near JVs , and other PVs contribute to the repulsion. In the result, the distance between Abrikosov vortices in the chain may be estimated as

$$x_{\min} \approx 2\lambda_{ab}\ln\left[\frac{\lambda_{ab}}{u_1}\sqrt{\frac{D}{s}}\right].$$

Then the perpendicular vortices also appear as the vortex chains, and when the perpendicular field increases it will lead firstly to the increase of the number of these chains, each chain located at JVs. The distance between the chains will be the integer number of the distance between JVs along **y**- axis. Finally, when all JVs will contain chains, then the formation of the usual Abrikosov lattice will start. Namely this case corresponds to a mixed vortex chain-vortex lattice observed in [6-7].

The distance between Abrikosov vortices in chain is always around $\lambda_{ab}$ and slightly varies with $B_x$. On the other hand, the energy of vortex coupling in chain is maximal at $B_x \sim H_0$, and then they are more stable at this conditions. At low or high $B_x$ limits, we may expect the melting of vortex lines. The detailed analysis of different crossing lattices has been recently performed in [13].


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