

## Unusual dc electric fields induced by a high frequency alternating current in superconducting Nb films under a perpendicular magnetic field

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2009 New J. Phys. 11 063033

(<http://iopscience.iop.org/1367-2630/11/6/063033>)

[The Table of Contents](#) and [more related content](#) is available

Download details:

IP Address: 150.244.118.6

The article was downloaded on 11/01/2010 at 14:27

Please note that [terms and conditions apply](#).

## Unusual dc electric fields induced by a high frequency alternating current in superconducting Nb films under a perpendicular magnetic field

F G Aliev<sup>1</sup>, A P Levanyuk<sup>1</sup>, R Villar<sup>1,3</sup>, J F Sierra<sup>1</sup>, V V Pryadun<sup>1</sup>,  
A Awad<sup>1</sup> and V V Moshchalkov<sup>2</sup>

<sup>1</sup> Departamento de Física de la Materia Condensada, Instituto Nicolás Cabrera de Ciencia de Materiales, Universidad Autónoma de Madrid, 28049 Madrid, Spain

<sup>2</sup> Nanoscale Superconductivity and Magnetism Group, LVSM, Katholieke Universiteit Leuven, Celestijnenlaan 200 D, B-3001 Leuven, Belgium

E-mail: [raul.villar@uam.es](mailto:raul.villar@uam.es)

*New Journal of Physics* **11** (2009) 063033 (19pp)

Received 11 December 2008

Published 16 June 2009

Online at <http://www.njp.org/>

doi:10.1088/1367-2630/11/6/063033

**Abstract.** We report a systematic study of dc electric fields produced by sinusoidal high frequency ac currents in Nb superconducting films subject to a constant magnetic field perpendicular to the film plane. At frequencies in the 100 kHz to MHz range appears a new rectification effect which has not been previously observed at lower frequencies. We have observed the dc electric field generated in this regime in films without intentionally created anisotropic pinning centres, i.e. plain films, both in strip geometry as in cross-shape geometry, and also in films with symmetric periodic pinning centres. The electric field appears in both directions along and transverse to the alternating current and is essentially different at opposite film sides. It depends strongly on the intensity of the magnetic field and may exceed by nearly an order of magnitude the rectified electric fields recently reported at lower frequencies (few kHz) in systems with artificially induced anisotropic vortex pinning. The effect has a non-monotonic dependence on the drive current frequency, being maximum around a few 100 kHz to MHz, and shows a complicated temperature dependence. It is found to be different in long strips and cross shape samples. In the case of films with symmetric periodic pinning centres the rectified voltage

<sup>3</sup> Author to whom any correspondence should be addressed.

shows a lower magnitude than in plain films, and shows an interesting structure when the applied magnetic field crosses the matching fields. We are only able to put forward tentative ideas to explain this phenomenon, which irrespective of its explanation should be taken into account in experimental studies of rectification effects in superconductors.

## Contents

|                                     |           |
|-------------------------------------|-----------|
| <b>1. Introduction</b>              | <b>2</b>  |
| <b>2. Experimental details</b>      | <b>3</b>  |
| <b>3. Results and discussion</b>    | <b>5</b>  |
| 3.1. Plain films . . . . .          | 5         |
| 3.2. Nanostructured films . . . . . | 12        |
| 3.3. Discussion . . . . .           | 13        |
| <b>Acknowledgments</b>              | <b>18</b> |
| <b>References</b>                   | <b>18</b> |

## 1. Introduction

Ideal superconductors (type I) are perfectly diamagnetic. An applied magnetic field gives rise to screening currents in the surface of the sample which completely shield the field in the bulk. This is the Meissner effect. Above a certain critical field ( $H_c$ ) superconductivity is destroyed. Type II superconductors only show this ideal behaviour up to a certain lower critical field ( $H_{c1}$ ). At higher fields up to the upper critical field ( $H_{c2}$ ) the magnetic field enters the superconductor in the form of flux quanta or vortices of magnitude  $\Phi_0$  ( $2.07 \times 10^{15}$  Wb). An electric current  $J$  in the superconductor gives rise to a Lorentz force on each vortex  $F_L = J \times n\Phi_0$ , with  $n$  a unit vector in the direction of the applied field. The force acts in a direction perpendicular to the current and to the vortex axis. If the vortices are not sufficiently pinned in the material, a relaxation of the vortex system is produced. This is, in effect, a redistribution of the magnetic flux and, therefore, leads to the appearance of an electric field according to the Faraday induction law. Since there are many influences on the vortex movement: local inhomogeneities (pinning centres), barriers either due to surfaces or to specific features of geometrical form of the sample, vortex–vortex interactions as well as various dynamic factors, this relaxation is a complicated, strongly nonlinear process and is accompanied often by fairly unusual phenomena. If in this situation the applied magnetic field, the electric current or both change with time, the electric field produced by the flux flow will also change in time.

The first hints on rectification effects in superconductors were reported in the 1960s and early 1970s, using dc transport currents, as an unexpected asymmetry in the critical current of vortex depinning and the  $IV$  characteristics when changing the polarity of the current. These experiments were performed in thin type II superconducting films subject to an external applied magnetic field parallel to the surface of the films. The first observation by Swartz and Rose [1] was ascribed to the different surface properties of the film, namely the surface in contact with the substrate and the one open to vacuum. Morrison and Rose [2, 3] obtained similar effects in films with intentionally patterned microgrooves to direct vortex motion. Lobb and co-workers [4] generalized these experiments in the 1990s, also with a parallel magnetic field, explaining their results in terms of surface barriers and inhomogeneous pinning centres.

Also in the 1990s several groups observed rectifying effects in thin film superconductors as the appearance of ohmic resistance in a type II superconductor subject to a permanent applied magnetic field and with a dc current flowing in it, if an additional alternating magnetic field was externally applied [5, 6].

Other type of rectification effects in superconductors have recently attracted much attention due to simulations which studied the movement of vortices, in samples with artificially nanostructured non-symmetric pinning centres [7]–[10]. This rectification has been observed for alternating currents in the range of kHz frequencies [11]–[13]. A rectification is also possible without any other asymmetry than a time asymmetry in the ac drive [14] and was observed experimentally [15, 16].

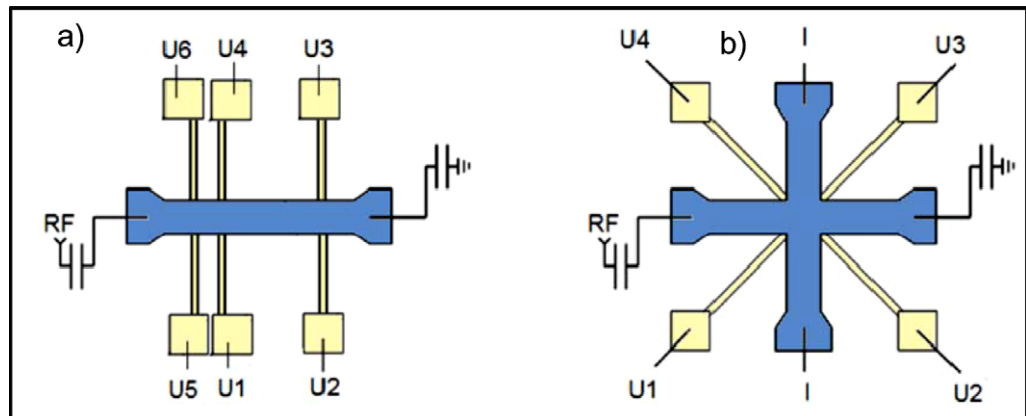
In two previous papers [17, 18] some of the present authors have reported the existence of a new kind of rectification effect in superconductors, observed in samples without non-symmetric pinning centres and under a harmonic, i.e. time symmetric, ac drive. This rectification has a higher magnitude near and within the MHz frequency range. The new characteristics of this effect, in contrast to previous reports, are the following. Firstly, the dc component of the electric field is completely different close to the opposite transverse and longitudinal borders of the sample, relative to the current direction. Secondly, its values are much higher in plain samples than in those with artificial pinning centres for similar current densities and ac drive frequencies. Thirdly, the dc voltages exhibit very complicated temperature dependences. Fourthly, the frequency dependence of the voltages is non-monotonic and there is a frequency of maximal effect at a given applied magnetic field. Fifthly, the dependence of the effect on the applied magnetic field is also non-monotonic.

In this paper, we present a systematic experimental study of these rectification effects with a detailed description of the dependence of the dc voltage on several parameters: frequency and intensity of the ac current, temperature and applied magnetic field ( $H$ ). We acknowledge having only tentative ideas about the possible mechanisms of the reported rectification. We discuss them in the final part of the paper. But irrespective of the possible explanations, since in experiments on rectification in superconductors this electric field adds to the one due to anisotropic vortex pinning, or to time asymmetry of the ac drive, one has to take it into account when interpreting rectification experiments in superconductors, especially if an increase of the frequencies to the MHz range is involved.

## 2. Experimental details

The experiments were performed on plain and nanostructured Nb films with thickness ( $d$ ) of 100 nm. In both cases the Nb was deposited on silicon substrates by dc magnetron sputtering. In our thin films  $T_C$  ranged from 8.35 to 8.75 K.

The plain films were optically patterned to strip shape, of width  $40\ \mu\text{m}$  (figure 1), or alternatively to cross shape with a cross area of  $40 \times 40\ \mu\text{m}^2$ . In the case of the strip, the alternating current is injected from the ends. On the sides of the strip six contacts allow voltages to be measured in longitudinal direction at two different distances (40 and  $320\ \mu\text{m}$ ), and also in the direction perpendicular to the current (transverse voltage). The voltage could also be measured at opposite sides of the strip. In the case of the cross shape, the alternating current was injected through opposite arms of the cross (RF in figure 1). The capacitors (see figure 1) prevent the existence of a dc current in the experimental set-up used to measure the rectified voltages. Only in the control experiments shown in figures 4 and 9, was a dc current used.

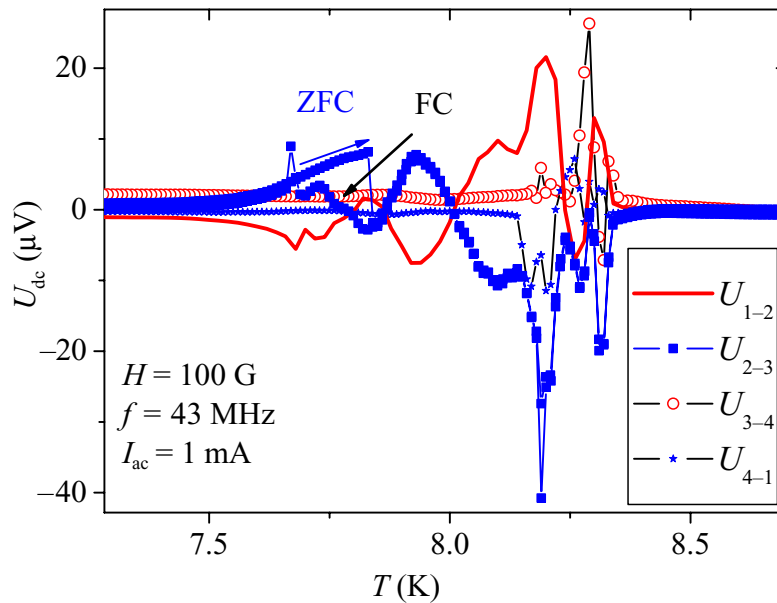


**Figure 1.** Geometries of samples with contacts for the experiments. (a) The strip configuration has two ac current contacts (RF) at opposite ends of the strip, and six voltage contacts ( $U_1$ ,  $U_2$ ,  $U_3$ ,  $U_4$ ,  $U_5$  and  $U_6$ ), which allow to measure voltage at different distances along both sides of the strip, as well as in the direction transverse to the strip. The figure shows that two capacitors isolate the ac line from direct currents. (b) The cross shape configuration has four voltage contacts ( $U_1$ ,  $U_2$ ,  $U_3$  and  $U_4$ ) in the corners of the cross and two contacts for the ac current (RF) at opposite ends of one arm of the cross. The two contacts for dc current ( $I$ ) at the opposite ends of the other arm of the cross were only used in control experiments (see text).

This dc current ( $I$  in figure 1(b)) was injected through the other two perpendicular arms. Four voltage contacts ( $U_1$ ,  $U_2$ ,  $U_3$  and  $U_4$ ) are situated in the corners of the middle square of the cross.

The nanostructured sample was prepared by patterning a regular rectangular array of Ni dots by e-beam lithography and dc magnetron sputtering. On top of these dots a 100 nm thick Nb film was sputtered. By means of optical lithography the sample was patterned in cross shape geometry with a cross area of  $40 \times 40 \mu\text{m}^2$ . The dimensions of the Ni dots were 250 nm diameter and 40 nm height. It is known that these dots have in-plane magnetization and act as strong pinning centres of the vortices. The size of each rectangle was  $0.4 \times 0.5 \mu\text{m}^2$ . Further information about film growth and characterization can be found in [17, 19].

The alternating current was injected with a Rohde and Schwarz Signal Generator SM 300. The signal was nearly perfectly sinusoidal, being the amplitudes of higher harmonics of order  $10^{-5}$  of the main harmonic. We have used frequencies in the range of 10 kHz to 150 MHz. The current was applied through two capacitors placed on opposite sides of the sample to avoid any possible dc component from the drive current. It may be noted that with the geometry of our samples a current of 1 mA corresponds to a current density of  $25 \text{ kA cm}^{-2}$ . For frequencies below 300 kHz, the ac current was measured directly by a Keithley 2400 multimeter. For drive currents in the MHz range, the ac current value was obtained by dividing the applied ac voltage by the effective impedance of the circuit. In our experiments a dc voltage, which we shall call rectified voltage ( $U_{\text{dc}}$ ), is detected in the superconducting sample when an ac current is injected along the sample and simultaneously a magnetic field is applied perpendicularly to the film. This voltage was measured with a Keithley 2182 nanovoltmeter, and has been detected along and transverse to the ac drive current direction. The dispersion of the rectified dc signal was typically



**Figure 2.** Temperature dependence of the longitudinal ( $U_{1-2}$  and  $U_{3-4}$ ) and transverse ( $U_{2-3}$  and  $U_{4-1}$ ) dc voltage generated in a long strip ( $40 \times 320 \mu\text{m}^2$ ) with an applied magnetic field of 100 G (0.01 T), a drive ac current of frequency 43 MHz and intensity of 1 mA. The transverse voltage  $U_{2-3}$  data correspond to two measurements carried out with different magnetic history and marked by arrows: field cooled (FC) and zero field cooled (ZFC) conditions.

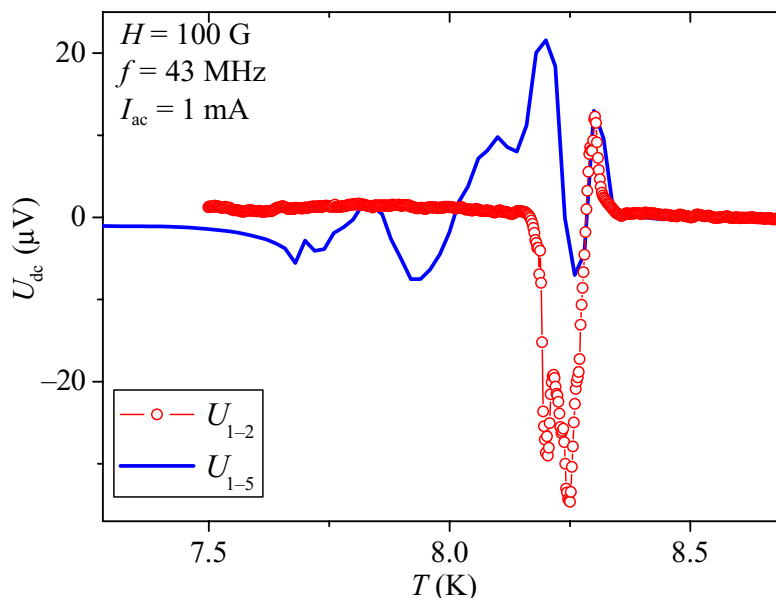
of order 100 nV, far below the reported magnitudes of the rectifying effect. The magnetic field was applied with a superconducting magnet in persistent mode. The measurements have been performed in a Janis cryostat, which allows for a two-loop temperature control with temperature stability better than 1 mK for several hours.

### 3. Results and discussion

#### 3.1. Plain films

**3.1.1. Strip shape samples.** We present first our results on the plain film with strip shape. In all cases a permanent magnetic field was applied perpendicular to the film surface, and a sinusoidal drive current was injected along the film. With the voltage contacts which may be seen in the scheme of figure 1(a), the dc rectified voltages could be measured between pairs of points along the strip, i.e. along the current, and also perpendicular to the current (longitudinal and transverse voltages).

In figure 2 we plot the rectified dc voltage obtained with an ac current of 43 MHz as a function of temperature, both in transverse and in longitudinal directions, in a  $40 \mu\text{m}$  wide and 100 nm thick strip, with a distance between longitudinal contacts of  $320 \mu\text{m}$ . The geometry of the voltage contacts is shown in figure 1(a). It may be seen in the figure that the voltages between the pairs of contacts on opposite longitudinal sides of the film ( $U_{1-2}$  and  $U_{3-4}$ ) and on opposite transverse probes ( $U_{4-1}$  and  $U_{2-3}$ ) have opposite signs just close to the transition



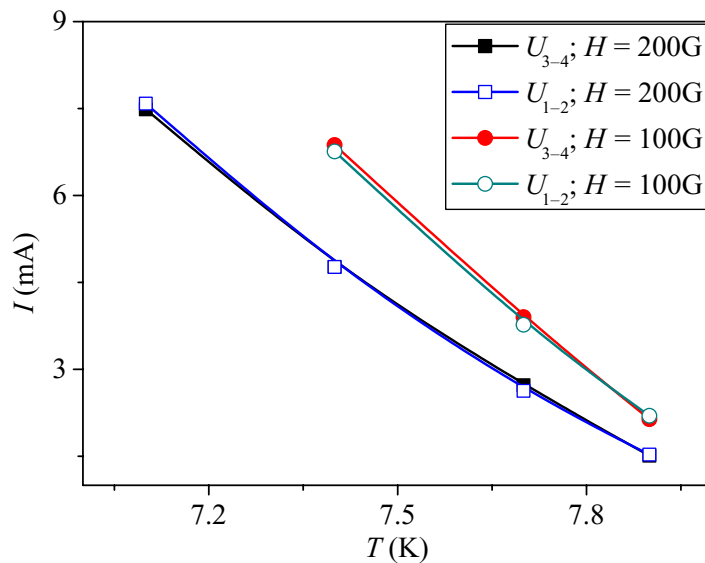
**Figure 3.** Dependence of the longitudinal rectified dc voltage on the distance between contacts and on temperature.  $U_{1-5}$  ( $L = 40 \mu\text{m}$ ) and  $U_{1-2}$  ( $8L$ ) measured in the same border of the strip with an applied magnetic field of 100 G (0.01 T), an ac current intensity of 1 mA and drive frequency of 43 MHz.

and comparable magnitudes. However, at lower temperatures (for example at 7.8 K) there is a strong asymmetry between the opposite borders:  $U_{1-2} \ll U_{3-4}$  and  $U_{4-1} \ll U_{2-3}$ . The maximum magnitude of the rectified voltage is  $40 \mu\text{V}$ .

We have examined the influence of magnetic history on these data, which has proved to be negligible, except at the lowest temperatures where rectification is observed. Indeed, the data in figure 2 corresponding to the transverse geometry ( $U_{2-3}$ ) consist of two curves measured in the same conditions, except that one is taken on heating after ZFC, and then applying the external magnetic field, and the other one with the temperature decreasing under FC conditions. The difference between both curves is very small, except in the low temperature region highlighted by the arrows.

Important new information can be seen in figure 3, where we plot the temperature dependence of the rectified longitudinal voltages at two different distances along the same border of the strip. The pairs of nearby contacts are  $U_5$  and  $U_1$  at a distance of  $40 \mu\text{m}$  and the distant ones are  $U_1$  and  $U_2$  at  $320 \mu\text{m}$ . Close to the phase transition temperature  $U_{5-1} \approx U_{1-2}$ . This is already significant: the distance between the contacts  $U_1$  and  $U_2$  is eight times the distance between the contacts  $U_5$  and  $U_1$ , i.e. the electric field is strongly inhomogeneous along the border. At lower temperatures  $U_{5-1}$  and  $U_{1-2}$  have opposite signs, what implies that the electric field is not only inhomogeneous but can even change its sign. We shall return to this observation when discussing the experimental data.

A rectifying effect due to the anisotropy of the sample may be obtained if the critical current is different when measured at opposite sides of the strip. We have measured this critical current anisotropy, using dc currents and the usual  $10 \mu\text{V}$  criterion, under applied fields of 100 G (0.01 T) and 200 G (0.02 T). The results are plotted in figure 4 and it may be seen that the



**Figure 4.** Critical current versus temperature measured at opposite longitudinal sides of the strip, with the criterion of a critical voltage of  $10\ \mu\text{V}$ . The measurements have been performed with applied magnetic fields of 100 G (0.01 T) and 200 G (0.02 T). It may be seen that for each applied field the critical currents measured at opposite sides of the strip are practically equal.

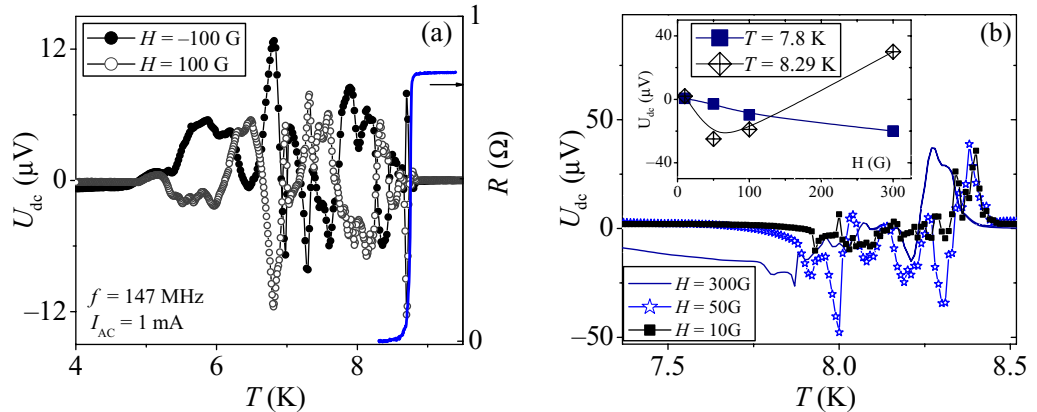
measured currents practically coincide. Therefore, the reported voltages are not associated with the anisotropy of the sample.

*3.1.2. Cross-shape samples.* Now we present our results in plain films with cross configuration. This configuration has been used by several authors in previous reports at lower frequencies and with intentionally created anisotropy (see, for example, [12, 13]). Therefore, we are able to compare their results with our data in similar samples. Besides, thanks to the cross geometry, we have been able to measure the transition temperature under dc current, while a high frequency ac current was injected in the perpendicular direction, and an external magnetic field was applied to the sample (see below).

Rectification at high frequencies with this configuration proves to be a very intricate phenomenon. In order to have as much information about it as possible, we have studied the dependence of the voltages on the drive current intensity  $I_{ac}$ , by using several currents from 0 to 2 mA, and on the frequency of the ac current. The measurements have been performed in a wide temperature range below the superconducting phase transition. The temperature was varied by steps of 50 mK. We have also studied the effect of reversing the applied magnetic field and of changing its magnitude. Finally, we have measured the voltage drops along a closed contour on the film plane.

To control that we are studying effects specific for the superconducting phase we have measured the dc resistance of the sample through the normal–superconducting transition with the same set of external parameters as in a measurement of the rectification voltage. This could be done thanks to the cross shape geometry with two perpendicular current probes (see figure 1(b)). A dc current of 1 mA was superimposed onto the ac current in the perpendicular

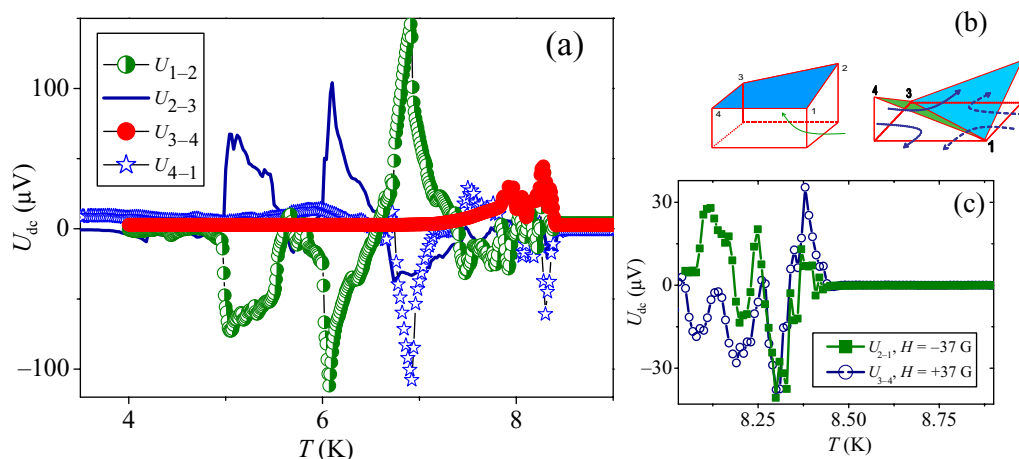




**Figure 5.** (a) Measured dc voltage (left axis) transversal to the applied ac current, as a function of temperature, with two applied magnetic fields of opposite polarity:  $\pm 100$  G ( $\pm 0.01$  T). The ac current intensity was  $I_{ac} = 1$  mA (rms) and its frequency  $f = 147$  MHz. To demonstrate that the rectification is a specific feature of the superconducting phase we show the temperature dependence of the dc resistance (right axis) through the superconducting transition. The resistance was measured between  $U_2$  and  $U_3$  with a dc current  $I = 1$  mA perpendicular to the same applied ac current and in the presence of the same magnetic field of 100 G (0.01 T). (b) Temperature dependences of the rectified longitudinal dc voltage with different applied perpendicular magnetic fields from 10 G (0.001 T) to 300 G (0.03 T). The ac current intensity was  $I_{ac} = 1.17$  mA and its frequency  $f = 43$  MHz. The inset shows the field dependence of the rectified voltage ( $U_{dc}$ ) at two different temperatures.

direction. The voltage between contacts  $U_2$  and  $U_3$  has been measured with both polarities of the dc current, with the aim of compensating possible thermoelectric effects. The difference between these two voltages has been used to calculate the dc resistance of the sample in the presence of the ac current and of the applied magnetic field. The dc current resistance is presented on the right axis of figure 5(a). It may be noted that the superconducting resistive transition is localized at the same temperature (8.35 K) where the rectified voltages cease to appear. This proves that the rectified voltages are specific to the superconducting phase.

Now we turn to the description of the observed rectified voltages. The main features of the MHz frequency range rectification are shown in figures 5 and 6. In figure 5(a), we represent the voltage measured between contacts  $U_2$  and  $U_3$  (i.e. in the direction perpendicular to the applied ac current) as a function of temperature, and for two applied fields of the same magnitude [100 G (0.01 T)] and opposite directions. Each curve shows several peaks and sign inversions of the voltage in the temperature range from about 5 K up to  $T_C$ . The measurements showed highly reproducible temperature dependence. The measured rectified voltage ( $U_{dc}$ ) was independent of the magnetic history of the sample. Only at temperatures far below  $T_C$  have we detected a weak dependence. It may be noted that the change in sign of the applied magnetic field leads, in general, to a change of sign of the rectified voltage, with approximately the same absolute value, especially not far from  $T_C$ . When the magnetic field is close to zero (within the precision of about 1 G ( $10^{-4}$  T), determined by the field trapped in the magnet and the resolution of the

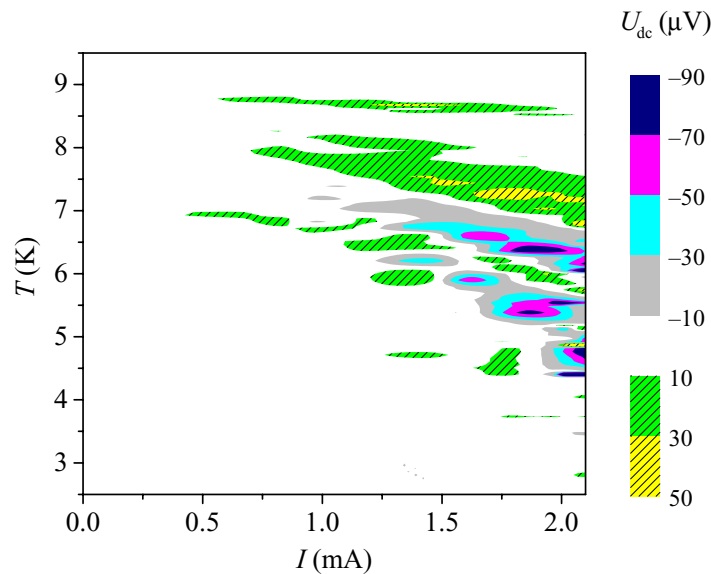


**Figure 6.** Temperature dependence of the rectified voltage ( $U_{dc}$ ) in four pairs of contacts around the cross area ( $U_{1-2}$ ,  $U_{2-3}$ ,  $U_{3-4}$  and  $U_{4-1}$ ).  $H = 100$  G (0.01 T),  $I_{ac} = 1.2$  mA,  $f = 43$  MHz. (b) The electric potential profiles around the cross area are schematically sketched for temperatures close to  $T_C$  ( $T \approx 8$  K, right sketch) and far below  $T_C$  ( $T \approx 5$  K or 6 K, left sketch). The dominant vortex flows in each situation are shown by arrows. (c) The longitudinal rectified voltage measured at opposite sides of the cross area and in magnetic fields of opposite polarity [ $\pm 37$  G ( $\pm 0.0037$  T)].

magnet current supply), the representative dc signals drop by more than one order of magnitude in comparison with the data obtained at 100 G (0.01 T).

In figure 5(b), we show the temperature dependences of the voltage measured in the longitudinal direction (i.e. parallel to the ac current) for three different magnetic fields of the same sign. It is seen that the voltage at a given temperature may be a non-monotonic function of the magnetic field. This is illustrated in the inset to figure 5(b) where the rectified voltage at two selected temperatures is plotted as a function of the applied magnetic field. These temperatures correspond to the highest negative peak (7.80 K) and highest positive peak (8.29 K) of rectified voltage under a field of 300 G (0.03 T). At 7.80 K, the signal is very sensitive to the field and its dependence on the field is fairly monotonic while at 8.29 K this dependence is non-monotonic and the signal even changes sign with increasing field.

In figure 6(a) we show the temperature dependence of the rectified voltages measured at the four contacts at the corners of the cross shown in figure 1. The measurements were performed successively in neighbouring pairs of contacts in anti-clockwise sense. It may be noted that close to  $T_C$  the dc voltage has nearly the same absolute values but different signs for opposite sides of the cross area. The situation is different at temperatures  $T < 0.8 T_C$  where rectification is dominant on two neighbouring sides of the cross area. Since the voltages between different pairs of contacts were measured in different experimental runs, we have checked that for a given temperature the sum of the four voltages was zero, which assures that there is a net zero flow of vortices through the entire contour of the cross area. Figure 6(b) shows another symmetry property of the phenomenon close to  $T_C$ : the electric fields at opposite sides of the cross area interchange when inverting the magnetic field direction.



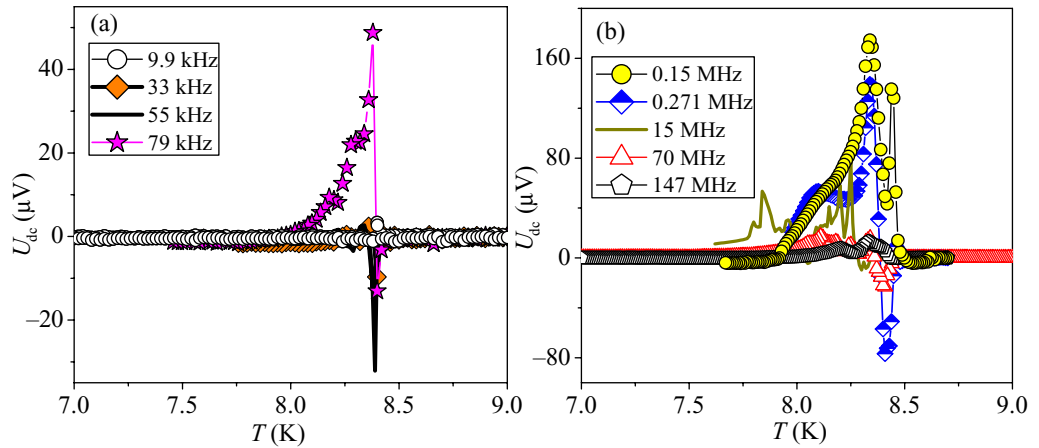
**Figure 7.** 3D contour plot of the dependence of the transverse rectified dc voltage ( $U_{2-3}$ ) on temperature and ac current intensity, with  $f = 50$  MHz and  $H = 100$  G (0.01 T). The increase of the maximum magnitude of the (positive or negative) rectified voltage with increasing ac current intensity is clearly observed. Some displacement of the maximum to lower temperatures with increasing ac current is also visible.

We have found that the above data are reproducible for two identical plain samples in the temperature region close to  $T_C$ . Further below  $T_C$ , the dc voltage showed some differences between both samples. This seems to indicate that in the latter case the effect is mainly due to uncontrolled asymmetry of the borders or to an inhomogeneous density of pinning centres. These two samples were patterned for the measuring contacts in two different zones of the same film.

We have studied in some detail the dependence of the rectified voltage on the intensity and frequency of the ac current and on temperature. These dependences proved to be fairly similar for longitudinal and transverse rectified voltages. For this reason we present some data for transverse voltages and some others for longitudinal ones.

In figure 7, the dependence of the transverse rectified voltage  $U_{dc}$  on temperature and ac current intensity is displayed in a three-dimensional (3D) contour plot. In this case the drive frequency was 50 MHz and the applied magnetic field 100 G (0.01 T).

One may see that the temperature dependence of the voltage is very complex, with several changes of sign. Besides, the rectification effect is not limited to the close proximity of  $T_C$ , but is observed down to  $T_C/2$ , with current intensities above 1 mA. The magnitude of the rectified voltage reaches values ( $90 \mu\text{V}$ ) which are nearly an order of magnitude higher than those reported previously [12] for comparable ac currents and magnetic fields but for frequencies in the low kHz range ( $10 \mu\text{V}$ ). The maximum magnitude is also much higher than the rectified voltages measured in the same MHz frequency range in the nanostructured samples which we report below in this paper. The magnitude of the voltage maxima scales with the ac current intensity and their positions shift in temperature with the change of current. It may be noted that



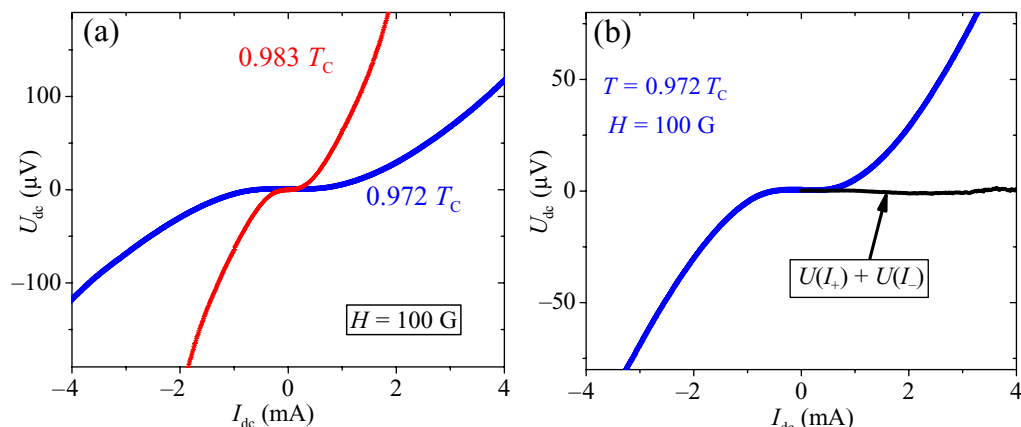
**Figure 8.** Dependence of the rectified longitudinal ( $U_{1-2}$ ) dc voltage on the frequency of the ac current and on temperature. (a) Measured frequencies in the kHz regime from 9.9 to 79 kHz. (b) Measured frequencies in the MHz regime from 0.15 to 147 MHz. In both regimes  $I_{ac} = 1.2$  mA and  $H = 100$  G (0.01 T). Note the different vertical scales.

this shift is not related to any heating effect, because it is at least one order of magnitude larger than the reduction of  $T_C$  induced by the ac current. This reduction of  $T_C$  may be observed in the figure as a smooth decrease of the highest value of temperature where rectification shows up when increasing the drive current (the upper ‘island’ on the map). With  $I_{ac} = 2.1$  mA, the data were obtained both decreasing and increasing the temperature, with no noticeable difference.

Next, we present data on the dependence of the longitudinal rectified voltage on the frequency of the ac current and on temperature keeping constant the applied magnetic field (100 G (0.01 T)) and the current (1.2 mA). Nine different drive frequencies have been used in the interval between 9.9 kHz and 147 MHz.

In figure 8, we show the temperature dependence of the rectified voltage at different drive frequencies in the range between 9.9 kHz and 147 MHz. Note that panels (a) and (b) have different vertical scales in order to highlight the change in magnitude of maximum rectified voltages. For the lowest frequency, 9.9 kHz, the generated dc voltage appears only close to the critical temperature, and does not exceed a few  $\mu\text{V}$ . On the other hand, for ac drives close to and in the MHz range, we observe a dramatic enhancement of the measured dc voltage, accompanied by a very non-monotonic dependence on temperature with a noticeable effect quite far below the critical temperature.

We have shown above, for the case of plain strip samples, that the current anisotropy in opposite sides of the strip was negligible to explain the rectification effect. We now present for the cross samples another method to evaluate the possible anisotropy of the critical current magnitudes when the polarity of the current is changed, as was reported to be the cause of other rectification phenomena, as for example in figure 10 of [1] or figure 1 of [4]. Indeed, the superconducting films under study are almost perfectly symmetrical and present no substantial difference between their dc critical currents with a change of their polarity, within an error of less than 3%. In figure 9(a) we show the electron transport characteristics of the cross-shaped film measured in the dc regime near  $T_C$ .



**Figure 9.** (a)  $I$ – $V$  curves measured in a plain film in cross configuration with  $H = 100$  G (0.01 T), at two different temperatures close to  $T_C$ . (b) Analysis of the asymmetry of the  $I$ – $V$  characteristic for one of the curves from panel (a) (for  $T/T_C = 0.972$ ): the solid line plots the sum of the left and right branches  $U(I_+) + U(I_-)$  of the  $I$ – $V$  characteristic, and shows that the asymmetry is nearly negligible, below 3%.

The data show clearly that the  $I$ – $V$  curves are almost perfectly symmetric, and that the rectified voltage due to the dc current asymmetry for currents up to 2 mA is below some few  $\mu$ V. This is demonstrated by the horizontal curve in figure 9(b), which presents the sum of the left and right branches of the  $I$ – $V$  curve for a selected temperature, namely for  $T/T_C = 0.972$ . In a magnified scale (not shown) it could be observed that the values of the voltage registered by this curve are always within a few  $\mu$ V. This is between one or two orders of magnitude smaller than the rectified voltages which we have reported above near and within MHz frequencies, and with similar current intensities.

### 3.2. Nanostructured films

We have also looked for high frequency rectification effects in an artificially nanostructured Nb film with *symmetric* periodic pinning centres (PPCs), made up of Ni dots. The idea was to study how the enhanced vortex pinning could influence the effect studied in plain films. It is well known that in nanostructured films the pinning force is stronger and obviously better controlled than in plain films [19, 20]. In these films one defines the matching field  $H_1$  as the applied magnetic field that produces a total flux through the sample equal to the flux of one flux quantum  $\Phi_0$  in each pinning centre. It is assumed that when the applied field is equal to the matching field there is a single vortex pinned in each artificial pinning centre. The integer multiples of  $H_1$  are called second, third matching fields, and so on. It is clear that the value of the matching field may be calculated by knowing the surface density of pinning centres in the sample. In our case,  $H_1 = \Phi_0/(p q) = 103$  G ( $103 \times 10^{-4}$  T),  $p$  and  $q$  being the unit distances of the rectangular cell of Ni dots. This value is in good agreement with the measured value  $H_1 = 105$  G ( $105 \times 10^{-4}$  T) [21]. The critical temperature of the sample is  $T_C = 8.73$  K. The choice of studying a sample with symmetrical pinning centres was directed to avoid the rectification effects which have been previously reported in nanostructures with asymmetric

pinning centres [12]. The nanostructured samples were patterned to the same cross shape as the plain films previously described.

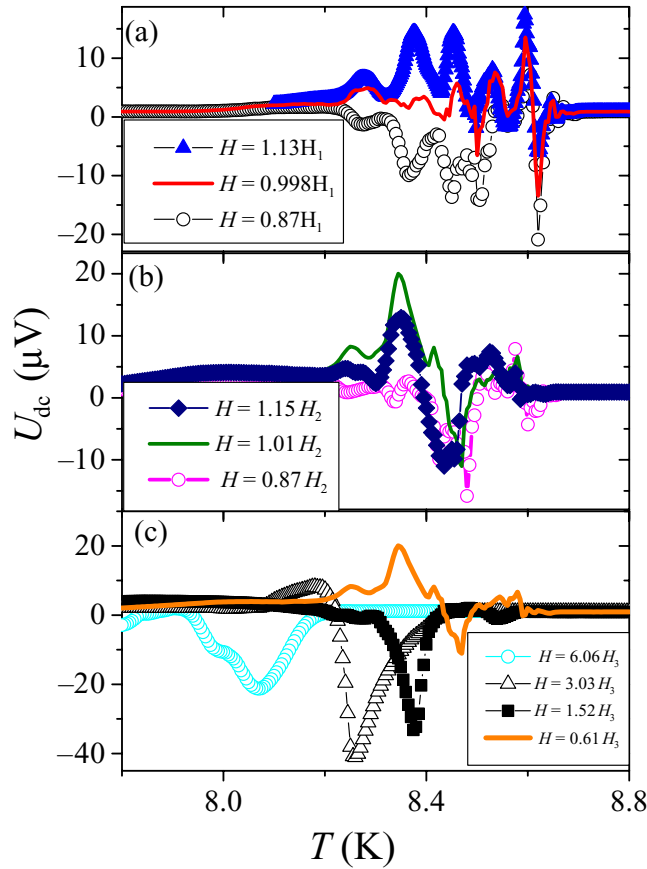
Our measurements of ac current rectification in superconductors with PPCs reveal at least two main differences in comparison with plain films. First of all, the magnitude of the rectified dc voltage is lower for the same ac current intensity and frequency, magnitude of the applied magnetic field and temperature. Second, at temperatures far below  $T_C$ , the rectified dc voltage changes polarity not only when the magnetic field changes its sign, as in plain films, but also when the magnetic field intensity changes and crosses the matching fields.

In figure 10(a) we present the values of high frequency (43.4 MHz) transverse rectified voltage as a function of temperature for three applied fields close to  $H_1$ . It may be noted that the form of the curve is very well reproduced for different values of the field, but the rectified voltages change sign when crossing the first matching field. We also find that the maximum magnitude of rectified voltage (around  $20 \mu\text{V}$ ) is nearly an order of magnitude smaller than in a plain Nb film with similar geometry and external parameters (see figure 8 showing up to  $150 \mu\text{V}$  of rectified signal). In panel (b) we show similar data as in panel (a), but in this case crossing the second matching field  $H_2$ . The influence of crossing the matching field can be identified, but is weaker than when crossing  $H_1$ . In panel (c) we show results for fields near and above  $H_3$ . The influence of crossing this third matching field is completely smeared out. However, we note that at high fields the rectification peak is visibly shifted to lower temperatures with increasing field, while the magnitude of the peak does not show a monotonic variation, reaching a maximum in the region of 1000 G (0.1 T).

In this case we have also performed a detailed experimental study, sweeping the field at small intervals with an ac current intensity of 0.94 mA and a drive frequency of 147 MHz. The data have been represented in figure 11, as 3D contour plots. One clearly observes the vertical lines without dc rectified signal which correspond to zero field and to the first matching field.

### 3.3. Discussion

As we have already mentioned in the introduction there are, in principle, several reasons for the appearance of dc electric fields when ac current is applied in the presence of magnetic field. Asymmetry of pseudo-dc  $I$ - $V$  curves with different critical currents for opposite current directions has been known since 1960s [1]–[4]. We have taken special care to check if it is relevant to our case and found that it is not (see figure 9). More recently other types of rectification began to be studied which cannot be revealed through studies of the dc-current behaviour. This is first of all rectification due to non-symmetric pinning centres. Experimentally, it has been observed in samples with artificially nanostructured non-symmetric pinning centres for alternating currents in the range of kHz frequencies [11]–[13] as well as, probably, in samples without artificially created anisotropic pinning centres in the same frequency range [18]. This mechanism is also irrelevant to our observations because we should accept the unrealistic assumptions that close to opposite borders of the sample there is uncontrollable asymmetric pinning of opposite asymmetry. Moreover, the qualitatively different character of the lower (kHz) and the higher (MHz) frequency ranges studied in this paper has been shown in [18] for the same sample with only the low-frequency rectification ascribable to the asymmetric pinning centres or to asymmetric  $I$ - $V$  curves. Recently, it has been shown that a rectification is also possible without any other asymmetry than a time asymmetry in the ac drive [14] and it was observed experimentally [15, 16]. This mechanism is irrelevant to our

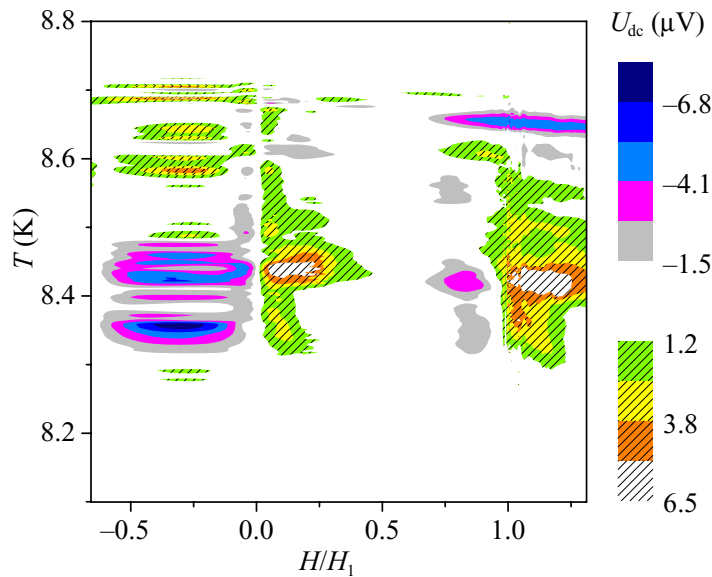


**Figure 10.** Transverse rectified dc voltage  $U_{2-3}$  in a nanostructured sample as a function of temperature for several magnetic fields. The data have been obtained with magnetic fields (a) close to the first matching field  $H_1 = 105$  G ( $105 \times 10^{-4}$  T), (b) to the second matching field  $2H_1$  and (c) to the third matching field  $3H_1$ , in all cases with  $f = 43.4$  MHz and  $I_{ac} = 0.94$  mA.

experiments because in our case the ac drive was highly sinusoidal (time symmetric), being the amplitudes of higher harmonics of order  $10^{-5}$  of the main harmonic (see section 2). Below we propose several hints for a qualitative explanation of our findings.

Let us recall first of all that a type II superconductor is not an ideal superconductor, because it permits the appearance of an electric field in the transport current direction because of vortex movement provoked by the current [4]. In a real sample this movement is hampered for several reasons: pinning centres, electrodynamic barriers associated with the geometry of the sample and with the vortex–vortex interaction. As a result it may take considerable time for the stationary state of the vortex movement corresponding to a fixed value of the transport current to be achieved after a complicated, strongly nonlinear relaxation process.

Having this in mind we shall try to rationalize our observations close to the phase transition temperature where the presence of the dc electric fields do not change the symmetry of the supposedly ideal system: the fields at the opposite borders are equal, have opposite directions and change directions to the opposite when the magnetic field is switched. Let us consider a strip as in figure 12. If a transversal magnetic field is applied in the superconductor phase there

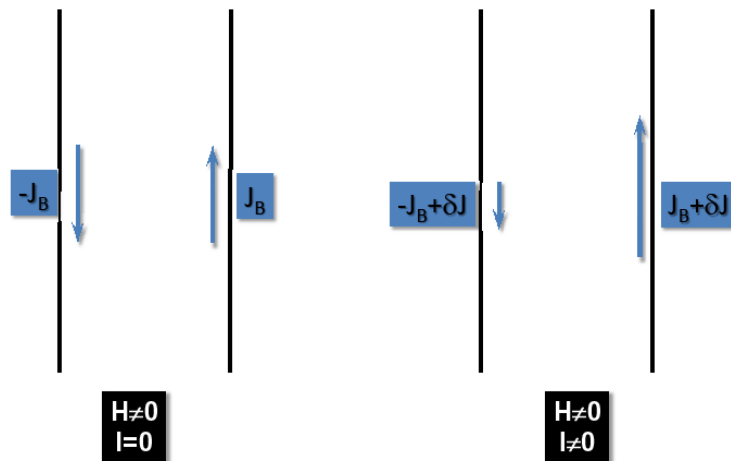


**Figure 11.** 3D contour plot of the transverse rectified dc voltage  $U_{2-3}$  in a nanostructured sample as a function of temperature and applied magnetic field, measured with  $I_{ac} = 0.94$  mA and  $f = 147$  MHz. The matching field  $H_1$  is 105 G ( $105 \times 10^{-4}$  T). It may be seen that the rectification effects are quite similar, when crossing zero field from negative to positive fields, to the effects observed when crossing the matching field.

is an eddy current in the strip with the current density  $J_B$  higher near the lateral boundaries of the strip than in the centre and with opposite directions at the two boundaries. This conclusion can be derived both from a theory [22] and from the direct experimental study of the current distribution [23]. Let us now apply an external current  $\delta J$  along the strip. Suppose first that this current is just added to the eddy current, i.e. close to the left side of the strip the current density  $J_1 = -J_B + \delta J$  is lower, while close to the other side  $J_2 = J_B + \delta J$  is higher than the boundary current density  $J_B$ . Then the generated electric field close to the right side of the strip is higher than that (of opposite direction) close to the left one, i.e.  $|E_2| > |E_1|$ . This is possible, of course, in a transitional regime only because  $\text{curl } \vec{E} \neq 0$ . For the opposite applied current a dominant electric field of opposite direction appears for some time close to the other side of the strip  $|E_1| > |E_2|$ . This situation is somewhat similar to that considered in [24] in a different context.

To obtain a nonzero average voltage when an ac current is applied it is necessary that the relaxation of the vortex flow be different for increase and decrease of the transport current. This is naturally realized in our case since the obstacles for the vortex ‘entrance’ and ‘exit’ are different, which is a general feature of the geometric electrodynamic barriers. There is evident difficulty with our arguments for an infinite strip: if the current density does not change along the strip, as we have supposed, the transversal voltage increases without a limit when one moves to infinity along the strip. This makes no sense, of course, and one has to suppose that in an infinite strip only a transversal voltage survives or the current density becomes inhomogeneous along the strip. Anyway, for a finite strip the voltage will be both longitudinal and transversal.





**Figure 12.** Sketch of currents and fields in the strip as discussed in the text. Left: without ac drive, and right with ac drive of intensity  $I$ , in both cases with the applied magnetic field  $H$  perpendicular to the strip surface.

Let us now make a rough estimation of the inhomogeneity in the current density within our model. At  $T = 0.972T_c$ , with  $H = 100$  G (0.01 T) and  $I_{ac} = 1.2$  mA, the longitudinal voltage was about  $10 \mu\text{V}$ . From the measured  $I$ - $V$  characteristics for the dc current (figure 9), this voltage corresponds to a current of 1.4 mA. According to the model, this means that the local voltage (which is nonzero only during half period) is about twice the mean voltage, if we neglect the relaxation during the half period. This corresponds to a local current density about 1.5 times the global current density averaged over cross section. This sounds reasonable. Further below  $T_c$  the same current density would provide a much lower voltage (see figure 9). However, due to the inhomogeneity of the current distribution, the local current density near the borders may be high enough to provide the observed dc voltage.

The slow current relaxation implied in our model has been, in fact, considered repeatedly. Gurevich *et al* [25] argued that in systems with vortices the duration of the first stage of relaxation of field and current distribution is a macroscopic quantity which can be expressed via directly measured parameters. Despite considering a different geometry (slab of width  $a$  in parallel magnetic field and relaxation after the magnetic field change), nevertheless, their estimation of the characteristic time:  $\tau \approx \mu_0(\partial j/\partial E)a^2$  can be applied as a rough estimation to our case. Indeed this time has, in any case, the physical meaning of the characteristic time which a vortex needs to cross the sample. If we take  $\partial j/\partial E$  about its value in the normal phase and  $a^2$  about the cross area, we get  $\tau \sim 10^{-7}$ - $10^{-8}$  s. This is in reasonable agreement with the frequencies for which the effect becomes clearly observable. In the case considered in [25],  $\tau$  was proportional to the characteristic time of change of the external magnetic field. Similar behaviour in our case could explain the weak frequency dependence of the rectification effect.

The above arguments imply that the sign of the voltage between the same lateral contacts should change sign if the direction of permanent field is changed. This is, indeed, the case (see figure 5(a)). Another natural conclusion is that the electric fields at the opposite lateral sides are of the same value and of opposite signs. This is not exactly the case experimentally. Near  $T_c$  the signs are, indeed, opposite but the absolute values are not equal (see figure 6(c)). Quite spectacular is the change of the value and even of the sign of the effect with the change of

temperature. At the moment we have no explanation of this phenomenon, though it may be related to the above suspected phenomenon that the distribution of ac current in a long strip subject to a perpendicular magnetic field becomes inhomogeneous along the strip. We also mention that in the case of superconductors with PPCs, ramping the field through the matching fields also changes the sign of the rectified voltage. This suggests that the dependence of the critical current on the field is important for the phenomenon because it is just the sign of the derivative  $dJ_c/dH$ , which changes when crossing a matching field [26].

Finally, we compare the dc electric fields in cross structures observed here with those reported before for similar Nb cross-like structures with nearly the same film thickness, but with intentionally induced anisotropy in the form of Ni triangles [12]. For similar conditions (current density about  $2\text{--}4 \times 10^4 \text{ A cm}^{-2}$ , magnetic flux density of 100 G (0.01 T) and temperature range with  $T/T_c$  about 0.97–0.99), the dc electric fields observed here have the same order of magnitude as those generated by the triangular ratchet potential at lower (kHz) ac drive frequencies [12]. This means that future experiments on vortex ratchets to be made at high current drive frequencies should take into account the generation reported here of a new type of dc electric field, in addition to the one created by intentional vortex rectification.

The above interpretation is far from being exhaustive even qualitatively, not to mention the quantitative aspect of the phenomenon. Unfortunately, it would not be an easy task to get a more detailed and specific interpretation. To understand the situation better it makes sense to have a better idea about parameters defining properties of our films. The magnetic field penetration length,  $\lambda(T)$ , is important for what follows. For bulk Nb it was found in [27] that  $\lambda(0) = 47 \text{ nm}$ . The transition temperature of bulk Nb is about 9.2–9.3 K. In thin films the transition temperature is lower and the magnetic field penetration length is larger because of the decrease in electron mean path with the film thickness. Recently the value of  $\lambda(0)$  in thin Nb films prepared as in our case on the Si substrate by magnetron sputtering has been determined in [28, 29]. Both groups report  $\lambda(0) \approx 100 \text{ nm}$  for film thickness  $d$  about 100 nm. It is worth mentioning that in their samples the transition temperature  $T_c$  was about 9 K, what is considerably higher than in our samples (8.45 K). For the Nb films used in our group other authors [30] have estimated  $\lambda(0)$  as 340 nm, from Gorkov's theory, using experimental values of  $T_c$  and the resistivity of the normal phase. In any case, one concludes that the value of  $\lambda(0)$  is larger than  $d$  even at  $T = 0$ , the more this is valid for the vicinity of the phase transition temperature, so that the conditions of our experiments correspond to the so-called thin film limit, where the characteristic magnetic length  $\Lambda = \lambda^2/d$  and  $\Lambda \gg \lambda$ .

Therefore, we have a system of pancake vortices whose interaction is a long-range one (see [31, 32]) and the electrodynamic effects should strongly depend on the geometry of the system.

Recently several electrodynamic problems for thin films in perpendicular magnetic field have been discussed by Zeldov *et al* [33], as delay of vortex penetration due to a geometrical barrier, and by Brandt [34], taking into account the finite value of the magnetic field penetration depth. Time-dependent transport currents have been included, in principle, into consideration. However, no specific problem with alternating transport current in perpendicular magnetic field has been solved. Moreover, in the problem for a thin strip, integration over the strip length has been performed at the first stage of the treatment, so that an important effect of inhomogeneity of the electric field along the strip observed in our experiments and mentioned below has been lost in the calculation. Unfortunately, we were unable to find any other theoretical papers concerning our case even for strip geometry, not to mention the cross one.

In conclusion, we have shown that a high frequency ac current gives rise to dc electric fields in plain continuous superconducting films under a magnetic field perpendicular to the film plane. The spatial distribution of the electric field is qualitatively different from all previously reported cases where a dc electric field has been observed in superconductors. Close to  $T_C$ , the dc component of the electric field is of opposite sign and of roughly the same magnitude close to opposite borders. The values of the rectified dc voltage are much higher in plain samples than in those with artificial pinning centres for similar current densities. The dc voltages exhibit a quite complicated dependence on temperature and magnetic field. Finally, the frequency dependence of the effect is non-monotonic, being maximal around a few MHz with the sample dimensions that we have studied.

### Acknowledgments

We thank V Vinokur, F Guinea, Y M Galperin, J Palacios, D Golubovic, A Silhanek, M Alieva, J L Vicent and E M González for useful discussions and technical assistance. The experimental work was supported by Comunidad de Madrid (S-505/MAT0194), Spanish MEC (MAT2006-07196, Consolider ‘Molecular Nanoscience’ CSD2007-00010) and ESF VORTEX and AQDJs programmes. This work, as a part of the European Science Foundation EUROCORES Programme 05-FONE-FP-010-SPINTRA, was also supported by funds from the Spanish MEC (MAT2006-28183-E) and the EC Sixth Framework Programme, under contract no. ERAS-CT-2003–980409.

### References

- [1] Swartz P S and Hart H R Jr 1965 *Phys. Rev. A* **137** 818
- [2] Morrison D D and Rose R M 1970 *Phys. Rev. Lett.* **25** 356
- [3] Huebener R P 1979 *Magnetic Flux Structures in Superconductor* (Berlin: Springer) p 191
- [4] Jiang X, Connolly P J, Hagen S J and Lobb C J 1994 *Phys. Rev. B* **49** 9244
- [5] Andrianov V V, Zenkevic V B, Kurgozov V V, Sychev V V and Ternokski F F 1969 *Sov. Phys.—JETP* **31** 815
- [6] Huebener R P and Rove V A 1969 *Solid State Commun.* **7** 1763
- [7] Lee C S, Janko Derenyi I and Barabasi A L 1999 *Nature* **400** 337
- [8] Wambaugh J F, Reichhardt C, Olson C J, Marchesoni F and Nori F 1999 *Phys. Rev. Lett.* **83** 5106
- [9] Zapata I, Bartussek R, Sols F and Hänggi P 1996 *Phys. Rev. Lett.* **77** 2292
- [10] Savel'ev S and Nori F 2002 *Nat. Mater.* **1** 179
- [11] Wördenweber R and Dymashevski P 2004 *Physica C* **404** 421
- [12] Villegas J E, Savel'ev S, Nori F, González E M, Anguita J V, García R and Vicent J L 2003 *Science* **302** 1188
- [13] Van de Vondel J, de Souza Silva C C, Zhu B Y, Morelle M and Moshchalkov V V 2005 *Phys. Rev. Lett.* **94** 057003
- [14] Reimann P 2002 *Phys. Rep.* **361** 57
- [15] Ustinov A V, Coqui C, Kemp A, Zolotaryuk Y and Salerno M 2004 *Phys. Rev. Lett.* **93** 087001
- [16] Cole D, Bending S, Savel'ev S, Grigorenko A, Tamegai T and Nori F 2006 *Nat. Mater.* **5** 305
- [17] Aliev F G 2006 *Physica C* **437–438** 1
- [18] Pryadun V V, Sierra J F, Aliev F G, Golubovic D S and Moshchalkov V V 2006 *Appl. Phys. Lett.* **88** 062517
- [19] Martin J I, Vélez M, Hoffmann A, Schuller I K and Vicent J L 1999 *Phys. Rev. Lett.* **83** 1022
- [20] Baert M, Metlushko V V, Jonckheere R, Moshchalkov V V and Bruynserade Y 1995 *Phys. Rev. Lett.* **74** 3269

- [21] Villar R, Pryadun V V, Sierra J F, Aliev F G, González E, Vicent J L, Golubovic D S and Moshchalkov V V 2006 *Physica C* **437–438** 345
- [22] Brandt E H, Indenbom M V and Forkl A 1993 *Europhys. Lett.* **22** 735
- [23] Bobyl A V, Shantsev D V, Galperin Y M, Johansen T H, Baziljevich M and Karmanenko S F 2002 *Supercond. Sci. Technol.* **15** 82
- [24] Delrieu J M 1973 *Solid State Commun.* **12** 881
- [25] Gurevich A, Küpfer H, Runtsch B, Meire-Hirmer R, Lee D and Salama K 1991 *Phys. Rev. B* **44** 12090
- [26] Van Bael M J, Van Look L, Lange M, Temst K, Güntherodt G, Moshchalkov V V and Bruynseraede 2000 *Physica C* **341–348** 965
- [27] Maxfield B W and McLean W L 1965 *Phys. Rev.* **139** A1515
- [28] Gauzzi A, Le Coche J, Lamura G, Jönsson B J and Gasparov V A 2000 *Rev. Sci. Instrum.* **71** 2147
- [29] Gubin A I, Il'in K S, Vitusevich S A, Siegel M and Klein N 2005 *Phys. Rev. B* **72** 064503
- [30] Villegas J E and Vicent J L 2005 *Phys. Rev. B* **71** 144522
- [31] Pearl J 1964 *Appl. Phys. Lett.* **5** 65
- [32] Clem J R 1991 *Phys. Rev. B* **43** 7837
- [33] Zeldov E, Larkin A I, Geshkenbein V B, Konczykowski M, Majer D, Khaykovich B, Vinokur V M and Shtrikman H 1994 *Phys. Rev. Lett.* **73** 1428
- [34] Brandt E H 1999 *Phys. Rev. B* **59** 3369