Non-Josephson Emission from Intrinsic Junctions in $Bi_2Sr_2CaCu_2O_{8+y}$: Cherenkov Radiation by Josephson Vortices

G. Hechtfischer, R. Kleiner, A. V. Ustinov, and P. Müller
Physikalisches Institut III, Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany
(Received 25 March 1997)

We have investigated Josephson vortex flow in intrinsic junctions in $Bi_2Sr_2CaCu_2O_{8+y}$. In addition to the Josephson radiation we find a strong broadband non-Josephson microwave emission which is not expected for conventional junctions. We explain this non-Josephson signal by Cherenkov radiation occurring when the vortex velocity exceeds the lowest of the N possible mode velocities for electromagnetic waves in an N junction stack. [S0031-9007(97)03867-2]

PACS numbers: 74.50.+r, 41.60.Bq, 74.80.Dm, 85.25.Cp

Because of the strong modulation of the superconducting order parameter in the c axis direction, highly anisotropic materials like $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO) act as stacks of hysteretic Josephson junctions [1–3]. The superconducting electrodes are formed by the copper oxide bilayers as thin as 3 Å and are separated by the nonsuperconducting BiO layers. It has been demonstrated experimentally that single crystals of BSCCO show properties expected for stacks of Josephson junctions. Among these properties are magnetic field dependence of the c axis critical current [4], multihysteretic switching to the individual tunnel junction gap voltages [1,2], and Josephson-like radiation emission detected in several frequency bands [5,6].

In this Letter we present new experimental data on radiation from intrinsic stacks. In addition to already reported Josephson-like emission, we observe broadband radiation which is not expected for conventional Josephson junctions. Based on its magnetic field dependence and our numerical simulations, we suggest that this non-Josephson emission is due to Cherenkov radiation by Josephson vortices moving in the multilayered stack.

As the superconducting electrodes in BSCCO are vanishingly thin compared to the London penetration depth λ, the mutual inductive coupling is extremely strong. The characteristic length scale for Josephson vortices, the Josephson penetration depth λ_J, is given for this case by

$$\lambda_J = \sqrt{\frac{\Phi_0}{2\pi \mu_0 j_c (t_{\rm eff} + 2\lambda^2/d_{\rm eff})}}, \tag{1}$$

with the effective thicknesses $d_{\rm eff} = \lambda \sinh(d/\lambda)$ and $t_{\rm eff} = t + 2\lambda \tanh[d/(2\lambda)]$. Here, the electrode thickness $d = 3$ Å and the barrier thickness $t = 12$ Å [7]. Φ_0 is the magnetic flux quantum, and j_c the Josephson critical current density. In BSCCO λ_J is typically between 0.5 and 1 μm.

The samples were prepared by cleaving from a single crystal. Mesas were patterned by evaporating gold through a shadow mask on one side of the crystal. The other side of the crystal was completely covered with gold. These crystals were chemically etched using a HNO_3 dilution. Various parameters of the samples used for this work are listed in Table I. Samples were mounted on the inner conductor of a microwave coaxial (SMA) plug, with a flexible tip of 25 μm Au/Ni wire as bias contact on top of the mesa. The magnetic field was generated by a 5 T split coil magnet with horizontal field. Sample bias and microwave emission signals were guided by a low loss coaxial cable. The microwave detection system consisting of a low noise preamplifier and a spectrum analyzer for the frequency range from 6 to 18 GHz allows the detection of 3×10^{-17} W in a 3 MHz bandwith. The magnetic field was aligned parallel to the copper oxide layers to prevent pinning of the vortex lattice by pancake vortices [8]. The experimental setup and the procedure to find the parallel orientation was described elsewhere [6].

In zero magnetic field, the I-V characteristic of an intrinsic junction stack with N junctions consists of $N + 1$ branches, depending on how many junctions are switched to the gap state (no junction or between one and N). By carefully sweeping the bias current up and down, all these states can be found in the experiment. A set of I-V characteristics for four magnetic field values from 20 to 35 kOe is shown in Fig. 1. The magnetic field primarily increases the slope of the branch where no junction is switched to the gap [3,6]. As can be seen from Fig. 1, the slope of this leftmost branch is approximately linear for low fields, and develops a slight upturn at higher fields. The hysteresis is due to states with a different number of junctions switched to the gap state. As the critical current is reduced with increasing field the hysteresis becomes

TABLE I. Geometric and electrical parameters of the samples.

Sample No.	Mesa size (μm^2)	N	j_c 25 K (A/cm^2)	T_c (K)
z4c	18 × 18	95	680	87
z4f	18 × 18	50	1100	85
z4h	18 × 18	90	800	86

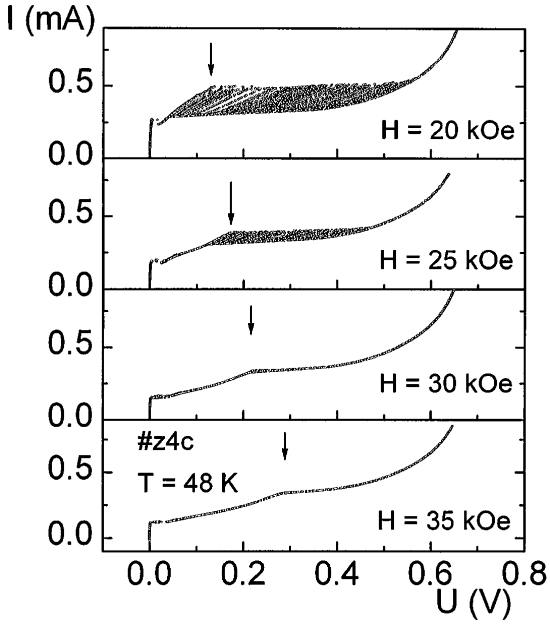

FIG. 1. I-V characteristics for sample No. z4c at various magnetic fields. The arrow denotes the top of the flux-flow branch, i.e., the point of maximum vortex velocity. For the two higher field values, the up-turned flux-flow step can clearly be seen.

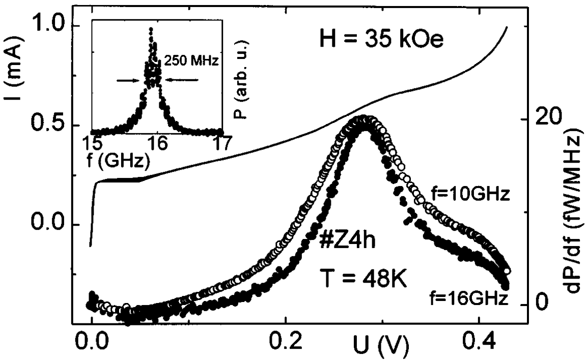

FIG. 2. I-V characteristic and non-Josephson microwave emission signals at 10 GHz (open circles) and 16 GHz (solid circles) for a magnetic field of 35 kOe. The curves were normalized to account for different coupling losses. Note that the form of the peak is almost the same for the two frequencies, showing that the non-Josephson signal is extremely broadband. The inset shows a typical spectrum of the Josephson signal, taken at 3 mV bias, which has a linewidth of only 250 MHz.

smaller for higher magnetic fields and vanishes at about 30 kOe. The curves for the two higher magnetic fields look similar to flux-flow steps known from conventional single Josephson junctions. The maximum voltage of the flux-flow branch at 35 kOe is about 290 mV. As the mesa consists of about 95 Josephson junctions this corresponds to a Josephson frequency of 1.5 THz. Note that the position of the total gap voltage at about 0.65 V remains unaffected by the magnetic field, as expected for Josephson junctions.

In all experiments, in addition to the I-V characteristics, microwave emission signals were recorded. The Josephson signal from the collective motion of Josephson vortices appeared at a voltage U_J given by

$$U_J = N\Phi_0 f\,. \tag{2}$$

Here N is the number of intrinsic Josephson junctions and f is the detected frequency. Equation (2) results from the second Josephson relation for a series connection of N junctions. In sample No. z4h the Josephson radiation peak was detected at a voltage of 1.88 mV for $H =$ 24 kOe and $f = 10$ GHz, giving $N = 91$ junctions. By counting the number of branches on the I-V characteristic we found that the sample contains about 90 junctions. This shows that nearly all junctions in the stack contribute to the flux flow. The inset of Fig. 2 shows a typical spectrum of the Josephson signal for 3 mV bias voltage. Emission occurs at 16 GHz with a linewidth of only 250 MHz. At the higher magnetic fields an additional microwave emission signal was found at voltages much higher than the voltage of the Josephson signal. The intensity of this signal was increasing towards the top of the flux-flow branch and was by almost 1 order of magnitude higher than that of the Josephson signal. We recorded the signal for several fixed receiver frequencies from 7 to 16 GHz. The data are qualitatively the same for different frequencies, suggesting that the spectrum of the non-Josephson signal is extremely broadband. Accordingly, the spectrum recorded at a fixed voltage showed an overall increase of the intensity but no peak. Figure 2 shows the detected power at 10 and 16 GHz together with the I-V characteristic for a magnetic field of 35 kOe. As can be seen, the maximum of the emission signal occurred at the end of the flux-flow branch at a voltage by 2 orders of magnitude larger than that of a Josephson signal.

The maximum voltage of a flux-flow step in a single long Josephson junction (LJJ) is given by

$$U_{\mathrm{FFS}} = \Phi_0 f = \overline{c} H \Lambda\,, \tag{3}$$

where $\overline{c}$ is the standard Swihart velocity, H the magnetic field, and Λ the magnetic thickness. For a stack of N intrinsic junctions, this relation can be modified to

$$U_{\mathrm{FFS}} = N\Phi_0 f = N c_{\mathrm{eff}} H(t + d)\,, \tag{4}$$

with an effective maximum vortex velocity c_{eff} and $(t + d)$ being the thickness of one intrinsic junction, i.e., 15 Å [6]. In Fig. 3, the maximum voltage of the flux-flow branch is plotted versus the magnetic field. As can be seen, the slope U/H is constant for low fields below about 17 kOe and corresponds to an effective mode velocity of 2.7×10^5 m/s according to Eq. (4). At the crossover field $H_{\mathrm{cr}} \approx 17$ kOe the value of U/H

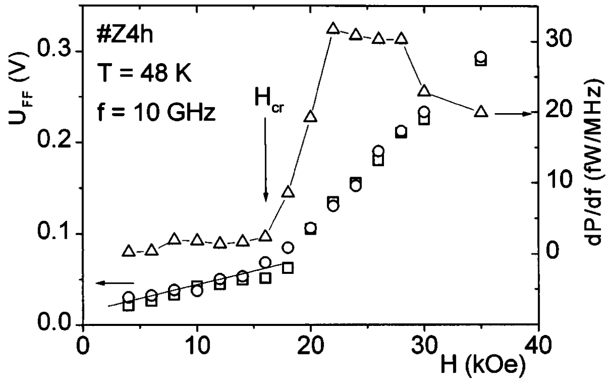

FIG. 3. Maximum voltage reached on the flux-flow branch versus the magnetic field (left axis). The voltage corresponds to the position of the arrow in Fig. 1. Squares are for positive bias current, circles for negative. Note that the voltage-field relation is different for fields below and above about 17 kOe. Right axis: intensity of the non-Josephson signal (triangles) at 10 GHz versus the magnetic field. The lines are a guide to the eye.

and thus the highest vortex velocity increase over this value. This behavior was observed for both polarities of the external field and the sample bias current in all investigated samples. The increase of U_{FFS} cannot be due to an increase in the number of junctions because nearly all junctions in the sample contribute to the flux flow at $H < H_{\mathrm{cr}}$. Also the position of the total gap voltage is the same for fields below and above H_{cr}.

To find the physical meaning of the observed field value of 17 kOe, we calculate the mean distance a between two vortex cores by $H_{\mathrm{cr}} = \Phi_0/(\mu_0 \cdot 15\ \text{Å} \cdot a)$ and get $a = 0.81\ \mu\text{m}$. We compare this to the diameter of a Josephson vortex $2\lambda_J$ given by Eq. (1). With a typical Josephson current density of 800 A/cm^2 and a typical value of 2000 Å for the London penetration depth [9], we get $2\lambda_J = 0.70\ \mu\text{m}$. The coincidence of these two values is striking. A distance between two vortices equal to the diameter of a vortex corresponds to the formation of a dense vortex lattice. We note that the observed value of H_{cr} is just about half the value of $H_0 = \Phi_0/\gamma s^2$ given in Ref. [10] as an order of magnitude estimate of field where a regular, triangular vortex lattice exists.

The intensity of the non-Josephson emission signal is also strongly dependent on the magnetic field. In fact, this signal shows a sharp onset at the same value H_{cr} of the magnetic field where the increase of the maximum vortex velocity is observed [cf. Fig. 3].

Non-Josephson microwave emission from single junctions has been observed earlier and was explained by subharmonics of the Josephson signal due to vortex bunching or by coupling of Josephson oscillations to a resonator [11,12]. We note that, in our case, the frequency of the observed non-Josephson radiation is by 2 orders of magnitude lower than the Josephson frequency. This difference and the fact that the power of our non-Josephson signal is even higher than the Josephson emission makes subharmonics to be an unlikely explanation. Vortex bunching [12] can be relevant low fluxon densities, whereas our non-Josephson signal occurs only for a dense vortex lattice. In the high fields we expect the order of the Fiske resonances to be between 50 or 100, and thus we are well above the fundamental cavity resonance. Any resonator-dominated behavior is expected to be accompanied by low-frequency resonances at low fields. Such resonances were not found in these measurements.

None of the above mechanisms can explain the non-Josephson emission and the observed increase in the maximum vortex velocity. We consider the model of coupled sine-Gordon equations for vertical stacks of LJJ with thicknesses of the superconducting electrodes of the order of the London penetration depth λ or smaller that has been derived and investigated in the past years [7,13,14]. This model accounts for the inductive coupling of stacked Josephson junctions caused by the screening currents. An important consequence of the inductive coupling is the existence of different mode velocities for electromagnetic waves [14–16]. As the system of coupled sine-Gordon equations is not invariant under a Lorentz transformation, the velocity of a moving fluxon may exceed some of these velocities. This may give rise to qualitatively new effects like the motion of a soliton at a velocity matching the phase velocity of a lower lying electromagnetic mode.

In the simple case of a two junction stack, two mode velocities are possible and form the limiting velocities of the so-called in-phase and out-of-phase mode for vortex motion. For a stack with N junctions, N different mode velocities exist, where the lowest mode velocity corresponds to a complete out-of-phase motion of the vortices, i.e., a moving triangular vortex lattice. For strong coupling, this velocity is about $\bar{c}/\sqrt{2}$, where $\bar{c}$ is the standard Swihart velocity for uncoupled junctions [6]. The highest of the N velocities corresponds to a complete in-phase motion of vortices and can exceed the standard Swihart velocity by far. The rest of the spectrum of mode velocities lies between these values with a strong accumulation near the lowest mode velocity.

For the low field regime, the effective maximum vortex velocity from Eq. (4) has been identified with the lowest mode velocity c_N of the layered stack [6]. From the experimental observation of an increasing maximum vortex velocity for fields above H_{cr}, we conclude that vortex motion with higher mode velocities is excited in the case of dense vortex lattice.

It is known that a particle moving at the phase velocity of an electromagnetic wave emits radiation via the Cherenkov effect. As an N junction stack has many modes lying close to the lowest one, exceeding the lowest mode velocity by the vortex should allow Cherenkov coupling for many modes, and a strong effect at many close frequencies is expected. Thus we believe that the non-Josephson signal is caused by Cherenkov radiation of vortices.

Cherenkov radiation was discussed in the case of a nonlocal Josephson junction [17] and was predicted for the case of two coupled junctions with different Swihart velocities [18]. For the case of a Nb-Al-AlO-Nb two junction stack, Cherenkov radiation was observed recently by Goldobin *et al.* when the fluxon velocity exceeds the lower mode velocity $\overline{c}_-$ [19]. In our case of a stack of 50 or 100 strongly coupled Josephson junctions, most of the mode velocities lie close to the lowest mode velocity. Exceeding the lowest mode velocity will easily allow for matching many of the modes. The generation of broadband Cherenkov radiation should be even stronger in this case.

In order to illustrate the existence of vortex Cherenkov radiation in a system of stacked Josephson junctions, we performed numerical simulations based on the coupled sine-Gordon equations as described in [6,15]. We considered a stack of 7 junctions with coupling parameters that are typical for BSCCO. To eliminate the influence of the boundaries, periodic boundary conditions were used. The seven mode velocities are given in units of $\overline{c}$ as 0.721, 0.765, 0.850, 1.00, 1.27, 1.85, and 3.62 [14,15]. In Fig. 4, the supercurrent distributions in the seven junctions are shown for a single vortex steadily moving in the middle junction with a velocity of 0.816 $\overline{c}$, which means that the vortex is faster than the lowest two mode velocities. The waves trailing the vortex and the waves induced in the other vortex-free junctions are caused by Cherenkov radiation as they are only observed when the lowest mode velocity of 0.721 $\overline{c}$ is exceeded.

In summary, we have shown that in magnetic fields higher than a crossover field H_{cr} the maximum velocity of Josephson vortices moving in a stack of intrinsic Josephson junctions increases over its low field value.

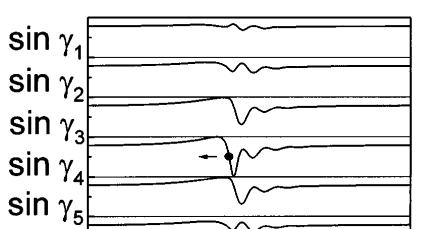

FIG. 4. Spatial distribution of the supercurrents in a strongly coupled stack of seven Josephson junctions with periodic boundary conditions. A circumference of 40 μm and a McCumber parameter of 20 was used. A single vortex is moving in the middle junction at a velocity of 0.816 $\overline{c}$. The center of the vortex is indicated by a circle. The velocity of the vortex is higher than the lowest two mode velocities, 0.721 $\overline{c}$ and 0.765 $\overline{c}$. Cherenkov radiation in the form of a trailing wave and waves induced in the neighboring junctions can clearly be seen.

We identified H_{cr} with the magnetic field where the vortex lattice becomes dense. The increase of the fluxon velocity is accompanied by a broadband, non-Josephson microwave emission signal. We suggest that this signal is due to Cherenkov radiation which is emitted when the vortex velocity matches the lowest mode velocities for electromagnetic waves in the stack. The existence of Cherenkov radiation is strongly supported by our simulations using coupled sine-Gordon equations.

We wish to thank W. Gerhäuser for supplying the BSCCO crystals and E. Goldobin for useful discussions.

[1] R. Kleiner, F. Steinmeyer, G. Kunkel, and P. Müller, Phys. Rev. Lett. **68**, 2394 (1992); R. Kleiner and P. Müller, Phys. Rev. B **49**, 1327 (1994).
[2] A. Yurgens, D. Winkler, N. Zavaritsky, and T. Claeson, Phys. Rev. B **53**, R8887 (1996).
[3] J. U. Lee, J. E. Nordman, and G. Hohenwarter, Appl. Phys. Lett. **67**, 1471 (1995).
[4] Yu. I. Latyshev, J. E. Nevelskaya, and P. Monceau, Phys. Rev. Lett. **77**, 932 (1996).
[5] G. Hechtfischer, K. Schlenga, W. Walkenhorst, P. Müller, A. Murk, W. Prusseit, M. Veith, W. Brodkorb, and E. Steinbeiß, in *Proceedings of the 5th International Superconductive Electronics Conference, Nagoya, 1995*, edited by H. Hayakawa (Institute of Physics Pub., Bristol, U.K., 1996), p. 52.
[6] G. Hechtfischer, R. Kleiner, K. Schlenga, W. Walkenhorst, P. Müller, and H. L. Johnson, Phys. Rev. B **55**, 14 638 (1997).
[7] R. Kleiner, P. Müller, H. Kohlstedt, N. F. Pedersen, and S. Sakai, Phys. Rev. B **50**, 3942 (1994).
[8] L. N. Bulaevskii, M. Maley, H. Safar, and D. Dominguez, Phys. Rev. B **53**, 6634 (1996).
[9] O. Waldmann, F. Steinmeyer, P. Müller, J. J. Neumeier, F. X. Régi, H. Savary, and J. Schneck, Phys. Rev. B **53**, 11 825 (1996).
[10] L. Bulaevskii and J. R. Clem, Phys. Rev. B **44**, 10 234 (1991).
[11] J. T. Chen and D. N. Langenberg, in *Low Temperature Physics LT 13,* edited by K. D. Timmerhaus, W. J. O'Sullivan, and E. F. Hammel (Plenum, New York, 1974), Vol. 3, p. 289.
[12] B. Dueholm, O. A. Levring, J. Mygind, N. F. Pedersen, O. H. Soerensen, and M. Cirillo, Phys. Rev. Lett. **46**, 1299 (1981).
[13] S. Sakai, P. Bodin, and N. F. Pedersen, J. Appl. Phys. **73**, 2411 (1993).
[14] S. Sakai, A. V. Ustinov, H. Kohlstedt, A. Petraglia, and N. F. Pedersen, Phys. Rev. B **50**, 12 905 (1994).
[15] R. Kleiner, Phys. Rev. B **50**, 6919 (1994).
[16] K. L. Ngai, Phys. Rev. **182**, 555 (1969).
[17] R. G. Mints and I. B. Snapiro, Phys. Rev. B **52**, 9691 (1995).
[18] Yu. S. Kivshar and B. A. Malomed, Phys. Rev. B **37**, 9325 (1988).
[19] E. Goldobin, A. Wallraff, N. Thyssen, and A. V. Ustinov (to be published).