Noise suppression and stabilization of an ion beam extracted from dense plasma

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(Received 22 May 2007; accepted 14 July 2007; published online 6 September 2007)

The dynamics of an ion beam formed in a two-electrode extraction system with a long puller is studied. The dependence of the extracted beam current on the plasma density is investigated numerically and experimentally. It is found that the dependence is weak (the "plateau regime"), when the density greatly exceeds the optimal value corresponding to the maximum current that can be extracted. Beam formation in the plateau regime ensures noise suppression, as well as stability of the extracted current, even at appreciable density fluctuations in the emitting plasma; it also significantly enhances the brightness of the beam. The proposed technique of noise suppression and ion beam stabilization using the two-electrode extraction system may find application in sources with dense plasmas (MEVVA, laser sources, etc.). The efficiency of the technique was demonstrated in experiments with gas-dynamic electron cyclotron resonance source of multicharged ions SMIS 37. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2776000]

I. INTRODUCTION

Plasma ion sources are widely used for generation of intense high-current ion beams for accelerators and heavy ion fusion applications.[1–3] However, fluctuations of plasma parameters, typical for the existing sources, cause noise in the extracted beam current. Beam current stability is extremely important for many applications. Therefore, high emphasis is placed on methods of noise suppression.[1,4–7]

Ion beams can be formed by using a variety of extraction systems. A standard, widely used two-electrode extraction system works as follows (Fig. 1). Positive voltage U is applied to the plasma-containing chamber. A plasma electrode with aperture diameter $2r_0$ is inserted into the plasma, separating it from the extraction system. An accelerating electrode (puller) of length L is maintained at zero potential $U_p=0$ and placed at distance d from the plasma electrode. The quality of ion beam extraction strongly depends on the shape of the plasma boundary. The boundary can be either convex or concave (Fig. 1), depending on the ratio of the current density of the ions leaving the quasineutral plasma with the Bohm velocity, $j_B=0.61Z_i e n_p V_s$, to the space-charge limited current density determined by the Child–Langmuir law, $j_{CL}=\sqrt{2Z_i e/m_i}U^{3/2}/(9\pi d^2)$. Here, m_i and Z_i are ion mass and charge, respectively, n_p is the emitting plasma number density, and e is electron charge. For one-component plasma with cold ions, ion sound velocity V_s, is defined as $V_s=\sqrt{Z_i T_e/m_i}$. For low-density plasma, $j_B<j_{CL}$, plasma boundary is concave [Fig. 1(a)], which leads to initial beam focusing. In the case of dense plasma, $j_B>j_{CL}$, the meniscus is convex [Fig. 1(b)] and the beam diverges.[1–3] It is evident that time variation of plasma density results not only in changes of beam current density but also in changes of the initial convergence angle.

Some of the available methods of ion beam current noise suppression involve complication of the extraction system.[4,6,7] However, it was noticed[1,5,6] that even a simple two-electrode system possesses the property of self-stabilization. A noise in extracted beam current was studied in Refs. 1 and 5 for a MEVVA plasma source. The extracted current, I_{FC}, was measured at the exit of the accelerating electrode (puller) by the Faraday cylinder (Fig. 1). It was demonstrated[1,5] that the noise decreases with increasing plasma density and may attain a rather low level at an optimal value of plasma density, n_p^{opt}, when the extracted beam current, I_{FC}, is maximum. Moreover, it was noticed that with a further increase of plasma density, noise level continued to decrease.[5,6] The following qualitative explanation of beam noise suppression for the extraction from dense plasma was

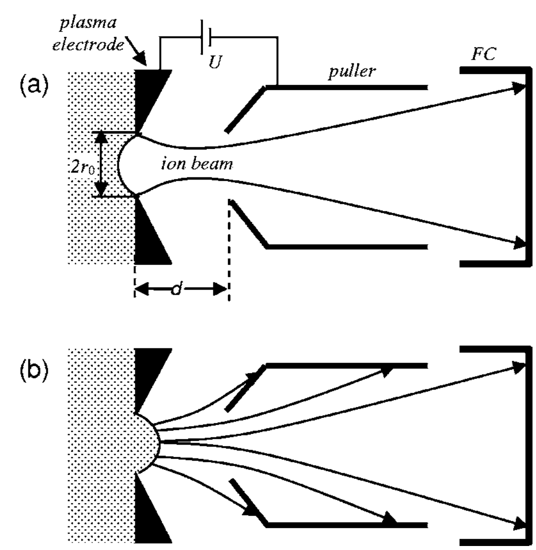

FIG. 1. A two-electrode extraction system: (a) ion beam extraction from low-density plasma, $j_B<j_{CL}$ and (b) ion beam extraction from dense plasma, $j_B>j_{CL}$.

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proposed in Refs. 5 and 6. An increase in plasma density provides a larger ion beam current at the plasma boundary. However, due to an enlarged initial divergence and increased subsequent space-charge beam spreading more ions are absorbed by the puller. Mutual compensation of the earlier effects may diminish the dependence of the beam current at the output of the extraction system, I_{FC}, on plasma density and, therefore, significantly reduce the noise caused by plasma density fluctuations.

In previous works, plasma ion sources were operated at plasma densities, n_p, that did not significantly exceed the optimal value and despite the noticed tendency to noise reduction, extracted beam current, I_{FC}, still depended significantly on plasma density.[5] In the present work, the extracted beam current dependence on n_p is investigated in a broad range, including plasma densities much higher than the optimal value, by means of numerical simulations, analytical estimates, and experimentally. It is shown that for n_p that is several times higher than n_p^{opt}, the dependence of the extracted beam current on plasma density almost vanishes, thus resulting in stable beam extraction in this regime, in spite of large density fluctuations of emitting plasma.

The article is organized as follows. Results of numerical simulations and analytical analysis of ion beam extraction are presented in Sec. II. Simulations show that in the case of extraction at optimal plasma density (maximum beam current at the puller exit) large fluctuations in n_p of about tens of percent lead to significant changes in the extracted beam current, I_{FC}, and such a regime of source operation may be unsatisfactory for certain applications. It is found that, with a further increase of plasma density, the magnitude of beam current at the puller exit, I_{FC}, first drops down and then almost ceases to depend on plasma density (plateau regime) providing stable source operation. The dependence of the magnitude of the extracted beam current in the plateau regime on extraction voltage and puller length is investigated. Ion beam emittance at the puller entrance and exit as a function of plasma density is also studied. It is revealed that in the plateau regime beam emittance at the puller exit is much less than at the entrance, which leads to enhancement of ion beam brightness by more than an order of magnitude.

Results of experimental studies of ion beam extraction from gas-dynamic electron cyclotron resonance (ECR)-source SMIS 37 are presented in Sec. III. An axisymmetric magnetic trap employed in SMIS 37 for plasma confinement gives rise to a number of instabilities that may lead to large plasma density oscillations. It is shown that operation of the source at optimal plasma density does not ensure sufficient stability, unlike the case of extraction from very dense plasma (plateau regime) when even large fluctuations in plasma density do not change beam current at the output of the extraction system.

II. NUMERICAL SIMULATIONS OF ION BEAM EXTRACTION FROM PLASMA

The process of ion beam extraction from plasma was studied numerically using the WARP electrostatic particle-in-cell code.[8] The computations neglected the effect of space-charge compensation due to secondary electrons knocked out of the puller surface by an ion beam. It can be shown that for the two-electrode extraction system secondary electrons rapidly return to the plasma and no noticeable compensation occurs. Simple estimates also show that the influence of residual gas ionization and charge-exchange processes are negligible. Testing of the code demonstrated not only qualitative but also good quantitative agreement with results of experiments. Extracted ion beam current, I_{FC}, dependence on the plasma density obtained in the numerical simulations is shown in Fig. 2. One can see that the curve in Fig. 2 has a maximum corresponding to the optimal value of plasma density. The initial growth of the current is caused by increasing density of the ion beam at the plasma boundary. The subsequent decrease is caused by an increase in space-charge spreading and by initial defocusing due to extraction from dense plasma. As a result, the beam spreads out and part of the ions is absorbed by the puller. A characteristic feature of the obtained dependence is the presence of a plateau with a further increase of plasma density. Formation of the plateau means that changes in plasma density do not lead to changes in the beam current at the output of the extraction system. The extracted beam current, I_{FC} , versus plasma density for different values of extraction voltage and puller length is plotted in Figs. 3(a) and 3(b). The figures demonstrate that as the voltage increases or puller length decreases the stable value of I_{FC} increases and the plateau shifts to the region of higher plasma density. Such a dependence on the extraction voltage can be explained by an increase of the Child–Langmuir space-charge limited current as the voltage increases. Some details of plateau position as a function of both plasma and extraction system parameters, as well as the fact of plateau formation may be elucidated by means of analytical estimates given later in this section.

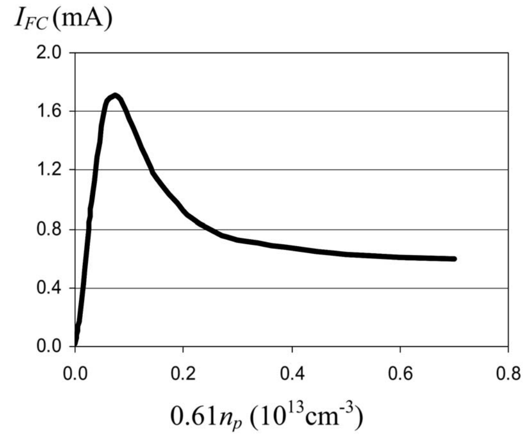

FIG. 2. The extracted ion beam current dependence on plasma density. Extraction voltage $U=40$ kV, puller length $L=33$ cm, the distance between electrodes $d=5$ mm, diameter of the aperture in the plasma electrode $2r_0=1$ mm, and electron temperature $T_e=70$ eV. Results are obtained using the WARP code.

Of considerable interest is the dependence of beam transverse emittances ε_x and ε_y and brightness $B=I/(\varepsilon_x\varepsilon_y)$ on plasma density. Here, $\varepsilon_x=4(\langle x^2\rangle\langle x'^2\rangle-\langle xx'\rangle^2)^{1/2}$, $x'=v_x/v_z$; x, v_x, and v_z are the coordinate, the transverse, and the longitudinal ion velocities, respectively, and I is total beam current. The magnitude of ε_y is determined similarly to

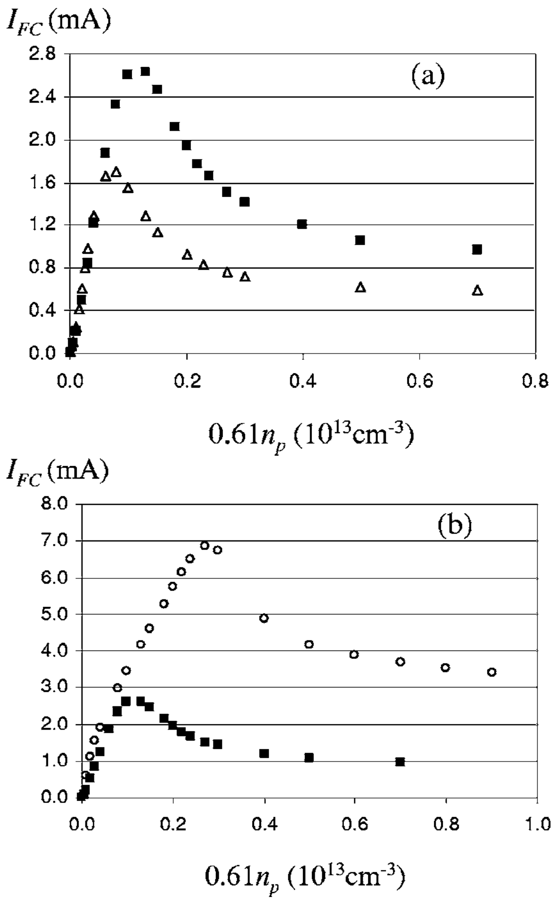

FIG. 3. The extracted ion beam current dependence on plasma density obtained for different values of extraction voltage and puller length. (a) Black squares correspond to U=53 kV and white triangles correspond to U =40 kV; L=33 cm. (b) Black squares correspond to L=33 cm and white circles correspond to L=18 cm; U=53 kV. Results are obtained using the WARP code for d=5 mm, $2r_0$=1 mm, and T_e=70 eV.

ε_x. The emittance at the puller entrance and exit as a function of plasma density is plotted in Fig. 4. The figure shows that in the case of extraction from dense plasma, in the plateau regime, the emittance significantly decreases as the beam propagates through the puller. This decrease can be attributed to strong space-charge spreading that causes the particles with high transverse energies to be absorbed by the puller,

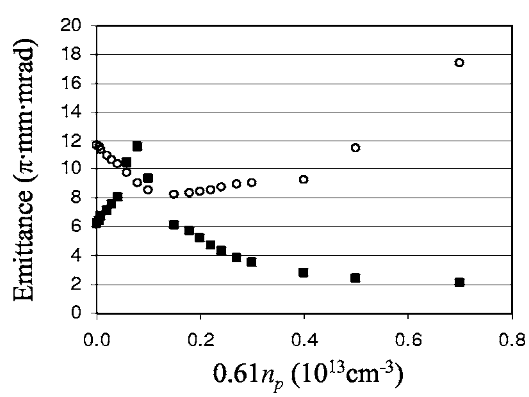

FIG. 4. The transverse beam emittance, ε, measured at the puller entrance (circles) and exit (black squares) vs plasma density. L=33 cm, U=53 kV, d=5 mm, $2r_0$=1 mm, and T_e=70 eV. Results are obtained using the WARP code.

thus decreasing effective beam temperature and the transverse emittance. Although the extracted ion beam current, I_{FC}, in the plateau regime is 2.5 times less than in the optimal regime [Fig. 3(a)], more significant reduction of the emittance provides a much higher (by almost 14 times) brightness of the extracted beam.

Note that in contrast to the plateau regime, extraction at optimal plasma density leads to certain emittance growth as the beam propagates through the puller. This growth occurs because the fraction of ions absorbed by the puller is not large in the optimal regime of extraction and nonlinear mechanisms stipulated by inhomogeneity of beam density profile provide the increase of the emittance.

The results of the numerical simulations presented earlier show that, if the plasma density appreciably exceeds the optimal value, n_{opt}, the possible increase of the extracted current due to the growth of ion beam density at the plasma boundary is fully compensated by the increase of the beam fraction absorbed by the puller due to spreading. This results in formation of a plateau. We propose a simplified theoretical model which also demonstrates the appearance of a plateau with increasing beam density. The influence of initial beam divergence at the plasma boundary is neglected in this model, only space-charge spreading is taken into account.

For the sake of simplicity we consider an infinitely long cylindrical ion beam moving with velocity V_b in the longitudinal direction. Initially, ions have zero transverse velocity and the beam density, n_0, is uniform across the beam cross section. We can now find the final ion beam density, n_f, at time $T=L/V_b$ corresponding to the time of ion flight through the puller of length L. Considering azimuthal symmetry, it is clear that during the spreading process, time evolution of the beam density inside the circular puller is the same as it would be if spreading occurred in vacuum. Therefore, we can now consider beam spreading in the absence of the radius-limiting puller and readily obtain the following equation:

$$m_i d^2R_b/dt^2 = 2\pi Z_i^2 e^2 n_0 r_0^2/R_b, \qquad (1)$$

where R_b is the beam radius and n_0 is the initial beam number density. Integration of Eq. (1) yields an implicit expression for the final beam radius $r_f=R(T)$ at time T,

$$\omega_p^0 L/V_b = \int_1^{r_f/r_0} dx/\sqrt{\ln(x)}. \qquad (2)$$

Here $\omega_p^0=4\pi Z_i^2 e^2 n_0/m_i$ is the initial plasma frequency of the beam. In the case of appreciable beam spreading, $r_f/r_0 \gg 1$, provided by large values of parameter $\omega_p^0 L/V_b$, the value of the integral on the right-hand side of Eq. (2) is approximately proportional to the ratio of the final to initial beam radius, $\int_1^{r_f/r_0} dx/\sqrt{\ln(x)} \propto r_f/r_0$. Furthermore, it can be readily shown that the beam density profile stays uniform during the spreading. This gives the following expression for the final beam density

$$n_f = n_0 r_0^2/r_f^2 \propto n_0 V_b^2/(L\omega_p^0)^2 \propto V_b^2/L^2. \qquad (3)$$

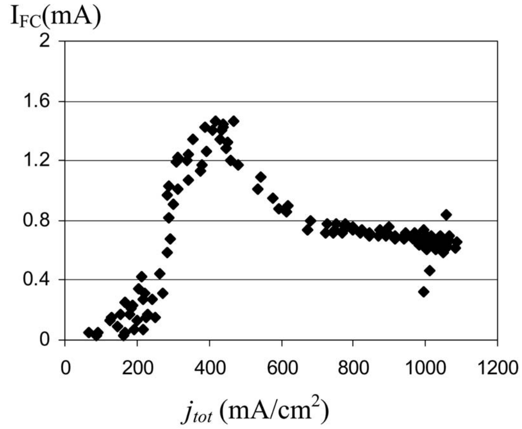

FIG. 5. The dependence of beam current at the output of the extraction system, I_{FC}, on the total current density extracted from plasma. Extraction voltage $U=40$ kV, puller length $L=33$ cm, the distance between electrodes $d=5$ mm, diameter of the aperture in the plasma electrode $2r_0=1$ mm, and electron temperature $T_e=70$ eV. Results are obtained on the SMIS 37 stand.

Beam current at the puller exit is given by $I_{FC}=Z_i e n_f V_b S$, where S is the cross-section area of the puller. Using Eq. (3) for the final beam density, n_f, we obtain

$$I_{FC} \propto V_b^3/L^2. \tag{4}$$

One can see that expression (4) obtained for I_{FC} under the assumption of strong beam spreading, $r_f/r_0 \gg 1$, is independent of the initial beam density, n_0. This result may be a plausible explanation of the plateau appearance in the dependence of the extracted beam current, I_{FC}, on plasma density. According to the earlier analytical model, the plateau is formed when the condition

$$\omega_p^0 L/V_b \gg 1 \tag{5}$$

is fulfilled, hence, as the puller length decreases, the plateau will be observed at higher plasma densities and the stable value of I_{FC} will grow [see expression (4)]. This coincides well with the results of the numerical simulations.

III. RESULTS OF EXPERIMENTS

Experimental study of ion beam extraction from plasma was carried out on the SMIS 37 stand (simple mirror ion source).[9–12] ECR gas breakdown in the magnetic trap was produced by high-power (≈ 100 kW) pulsed ($\tau \approx 1.5$ ms) microwave radiation. An ion beam was formed in a two-electrode extraction system with long puller described earlier (see Fig. 1). A 37.5 GHz gyrotron used as a source of microwave pumping provided high plasma concentration ($n_p \sim 10^{13}$ cm^{-3}) in the magnetic trap and quasi-gas-dynamic regime of confinement.[13] By moving the extraction system away from the magnetic plug toward the plasma spreading region, ion beam current density, j_{PE}, at the location of the plasma electrode (PE) was controlled. It should be noted that the experimental design allowed one to vary ion beam current density in a very wide range, from 70 to 1100 mA/cm^2, and perform experiments in the regime of optimal extraction as well as in the plateau regime.

Figure 5 shows the dependency of the extracted ion beam current, I_{FC}, measured by the Faraday cylinder on the

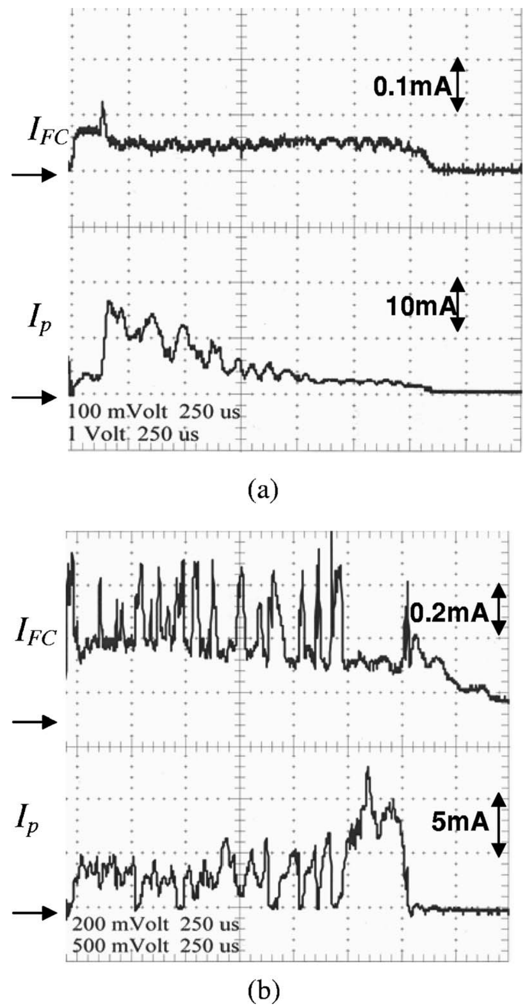

FIG. 6. Oscillograms of the beam current to the Faraday cylinder (upper trace) and to the puller (lower trace). (a) Extraction from dense plasma with $\langle j_{tot}\rangle \sim 100$ mA/cm^2, $j_{CL} \sim 50$ mA/cm^2. (b) Plasma density value lies between the optimal and "plateau" values, $\langle j_{tot}\rangle \sim 400$ mA/cm^2, $j_{CL} \sim 365$ mA/cm^2. Small arrows denote zero values of corresponding currents. Results are obtained on the SMIS 37 stand.

total current density extracted from plasma, $j_{tot}=(I_{FC}+I_P)/(\pi r_0^2)$. Here, I_P is the current to the puller. Note that the secondary electrons knocked out from the puller surface by the beam ions also contribute to the I_P value, hence, j_{tot} is larger than the ion current density emitted from the plasma. Experimental measurements and the numerical simulations (see Figs. 2 and 5) were performed at extraction voltage $U=40$ kV and puller length $L=33$ cm. The distance between the electrodes was $d=5$ mm, and the plasma electrode aperture was $2r_0=1$ mm. The electron temperature and the plasma potential were close to 70 eV and 350 V, respectively. Note that such a high value of the plasma potential, compared to that in the classical ECR ion sources, is a result of the quasi-gas-dynamic regime of plasma confinement in a magnetic trap.[9] Figures 2 and 5 demonstrate a good agreement between the numerical simulations and the experimental results in terms of the maximum and stable values of the extracted beam current. Note that in the case of optimal regime of extraction (I_{FC} is a maximum) $j_{tot} \sim 350$ mA/cm^2, and the Child–Langmuir current density is $j_{CL}=560$ mA/cm^2.

Oscillograms of ion beam current to the puller and the Faraday cylinder are presented in Fig. 6. In the case of extraction from dense plasma [Fig. 6(a)], when the total beam current density averaged over duration of microwave pulse is twice as large as the Child–Langmuir current density, $\langle j_{\mathrm{tot}}\rangle \sim 2j_{\mathrm{CL}}$, the extracted beam current, I_{FC}, is stable despite significant plasma density variations (the current to the puller, I_P, changes appreciably during the pulse). However, as plasma density decreases and the extraction regime approaches the optimal one, beam current measured by the Faraday cylinder becomes highly unstable [Fig. 6(b)]. The oscillogram shown in Fig. 6(b) corresponds to extraction in the case of $\langle j_{\mathrm{tot}}\rangle \sim j_{\mathrm{CL}}$. The time dependence of the extracted beam current is represented by a set of peaks (fluctuation current increase) above some constant value (plateau). This behavior can be explained by the presence of large fluctuations in the emitting plasma density providing the extracted beam current variations from the optimal (maximum) value to the stable value in the plateau regime.

IV. CONCLUSIONS

Analytical estimates, numerical simulations, and experimental studies have been used to investigate the phenomenon of ion beam current noise suppression in the case of extraction form dense plasma. It was demonstrated that with the increase of the emitting plasma density, the extracted beam current almost ceases to depend on plasma density (plateau regime), resulting in stable extraction. Dependence of stable value of ion beam current on extraction voltage and puller length was investigated. It was shown that despite a moderate extracted current decrease, the brightness of the beam is much higher in the case of the plateau regime extraction, compared to that in the optimal regime. High-density plasma can be produced without particular difficulties for quite a number of ion plasma sources, such as MEVVA, laser, or ECR sources with gas dynamic plasma confinement (SMIS 37). For these sources, extraction from a dense plasma can be an efficient method for suppressing large-amplitude noise and for stabilizing the magnitude of the extracted ion beam.

AKNOWLEDGMENTS

The authors greatly appreciate the assistance of D. Grote in implementation of the WARP code, P. Spädtke's fruitful discussions, and S. V. Golubev's interest in our work and his useful comments. They are also grateful to M. Yu. Kazakov for his expert technical support of the experiments. The work was supported by the Russian Foundation for Basic Research, Grant No. 05-02-17187, and by the International Science and Technology Center, Grant No. 2753.

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