CONTAINMENT OF A CYLINDRICAL PLASMA STREAM BY A STRONG MICROWAVE FIELD

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We report here experiments on the containment of a transparent plasma ($\omega_{Le} \ll \omega$) in an axisymmetric quasipotential well produced in a round waveguide by the field of a traveling H_{01} wave [1,2].

Experiments on the focusing of electrons in quasipotential configurations were reported in [3,4]. The pinching of the plasma by a microwave field, which was observed earlier in [5], has no relation to the containment of a plasma by a microwave barrier, as pointed out in [6], since the condition of the applicability of the quasipotential theory [1] was not satisfied there.

The distribution of the quasipotential in the field of a H_{01} wave with $r/R \leq 0.2$ is close to a parabola:

$$\Phi(r) \approx 10{,}8\,\Phi_0 (r/R)^2, \tag{1}$$

where $\Phi_0 = eE^2_{\varphi\ \max}/4m\omega^2$ (height of the quasipotential barrier at $r/R = 0.48$), e and m are the charge and mass of the electron, E_φ is the amplitude of the electric field intensity, and ω is the field frequency.

For a stationary filling of the quasipotential well (1) with plasma having $kT/e = (k/e)(T_e + T_i) \leq 0.2\ \Phi_0$, the following distribution of the density n should be established [7]:

$$n/n_0 \approx \exp\{-10{,}8 \frac{e\Phi_0}{kT} (r/R)^2\}. \tag{2}$$

We neglect here the perturbation of the microwave-field distribution by the plasma. In the case of nonequilibrium filling of the well with plasma, within the region $\rho/R \leq 0.2$, when $\Phi(\rho) \gg kT/e$ (ρ - initial boundary of the plasma), the plasma pinch should execute radial harmonic oscillations about r = 0 with frequency

$$F = 7{,}25 \cdot 10^3 \frac{1}{R} \sqrt{\frac{Ze\Phi_0}{A}}, \tag{3}$$

where Z and A are the multiplicity of charge and the mass number of the ion. The experimental setup (Fig. 1) consisted of a round waveguide, in which a converter [8] was used to excite a H_{01} wave with VWSR < 1.1. The plasma was produced by a spark source with a discharge over a Plexiglas surface (C = 0.15 μF, U ~ 2 kV) and was injected in the form of a directed diverging stream into the region of the stationary microwave field through a metallic tube terminated with a diaphragm. The relative diameter of the diaphragm, which was located at a distance of 58 cm from the source, was d/2R = 0.1. A generator operating in the 10-cm band produced a pulse with duration up to 40 μsec, with a value $\Phi_0 < 100$ V. The residual pressure was (5 - 9) x 10^{-7} Torr.

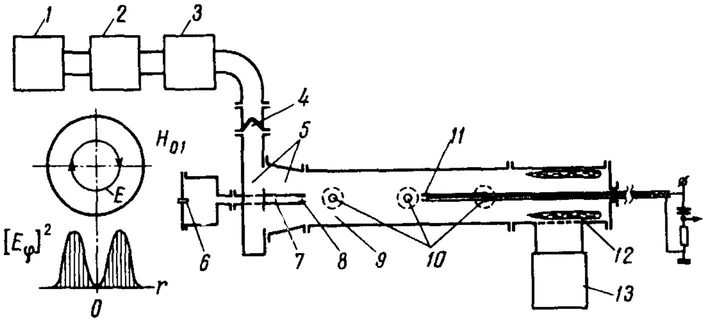

Fig. 1. Diagram of apparatus with H_{01} wave. 1 - Microwave generator, 2 - adjustable attenuator, 3 - ferrite valve, 4 - microwave vacuum window, 5 - exciter for H_{01} mode, 6 - spark plasma source, 7 - tube, 8 - diaphragm, 9 round waveguide, 10 - side stubs, 11 - screened plasma probe, 12 - microwave load, 13 - vacuum pump.

We investigated first the radial confinement of the plasma as it is injected in the stationary microwave field (stationary filling). To this end, a screened plasma probe was introduced through the end of the waveguide and registered a small fraction of the plasma current (relative probe aperture $\delta/2R = 2 \times 10^{-2}$). The probe was moved along the axis of the installation over a length $l = 0 - 70$ cm, measured from the entrance diaphragm. In the experiment we measured the integral of the ion-current pulse in the probe collector circuit $N = \int_0^\infty I_i dt$, with the microwave field turned on. From the integrals we could determine whether the number of particles striking the probe as the latter was moved away from the diaphragm remained constant or decreased. Figure 2 shows typical oscillograms of the ion current, obtained with the probe near the diaphragm (a, b) and with the probe 70 cm away (c, d) (in case c the signal was amplified by an additional factor 4.4). The maximum plasma density, determined from oscillogram a, corresponded to $\omega_{Le}^2/\omega^2 = 0.04$. From a comparison of c and a we see that in the absence of a microwave field the plasma diverges and the number of particles registered by the probe located far from the diaphragm greatly decreases. When the plasma is injected in the microwave field with a barrier $\Phi_0 = 65$ V, the ion current of the probe located 70 cm from the diaphragm increases strongly (d) and the integral of the ion-current pulse tends to the integral of the current pulse measured under the same conditions near the entrance diaphragm (b). The pulses in b and d have a similar form. From the integrals of the ion current N, measured at different distances from the probe to the diaphragm for two values of Φ_0, respectively 0 (no microwave field) and 65 V, we plotted N/N_0 vs. l (see Fig. 3a). We took N_0 to be in each case the ion-current integral measured near the entrance diaphragm. The experimental points obtained for $\Phi_0 = 65$ V lie near the straight line $N/N_0 = 1.0$, which, by comparison with the plot for $\Phi_0 = 0$, demonstrates the containment of the plasma current by the microwave field. The deviation of the values of N/N_0 from 1.0 can be attributed either to the random measurement error (the error was calculated with reliability 0.9), or the possible fluctuations of the plasma density due to a certain disparity between the radial distribution of the plasma current at the entrance diaphragm and the distribution (2).

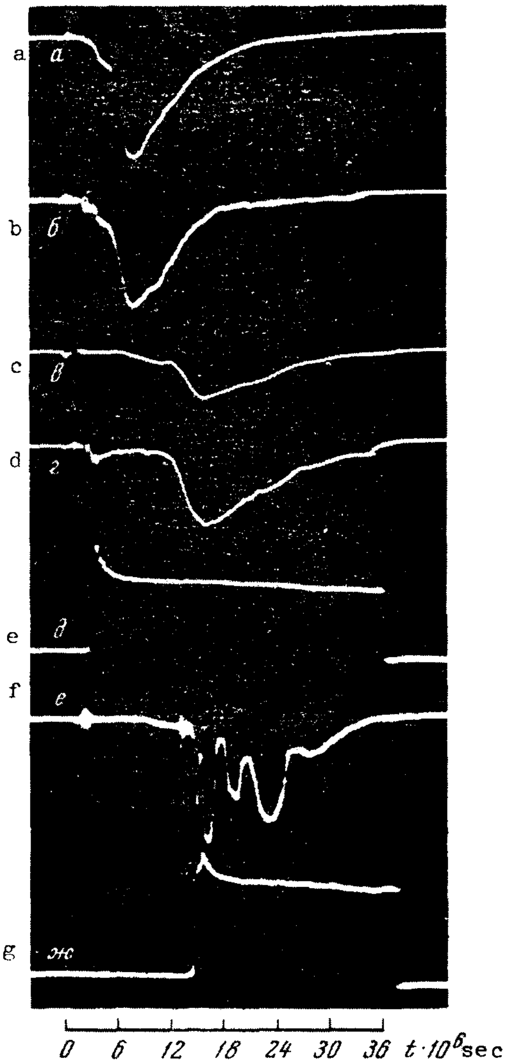

Fig. 2. Oscillograms of ion current in plasma probe: a - $l = 0$, $\Phi_0 = 0$; b - $l = 0$, $\Phi_0 = 65$ V; c - $l = 70$ cm, $\Phi_0 = 0$ (amplified 4.4 times); d - $l = 70$ cm, $\Phi_0 = 65$ V; e - envelope of microwave pulse (for b and d); f - $l = 70$ cm, $\Phi_0 \neq 0$; g - envelope of microwave pulse (for f).

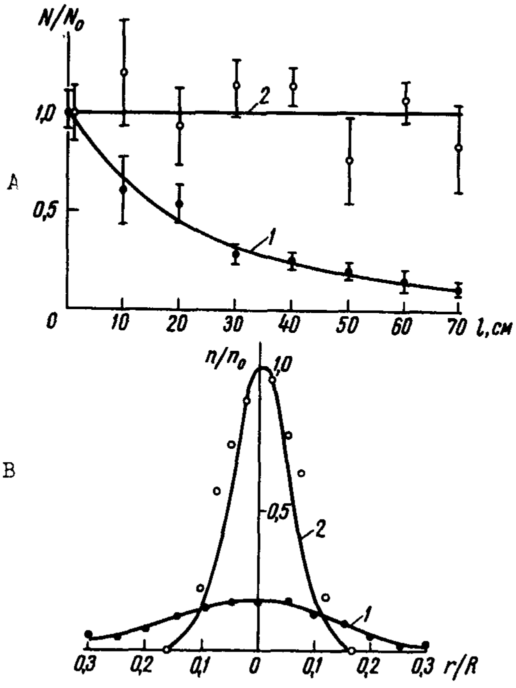

Fig. 3. Plots showing plasma containment. A - Variation of relative value of the ion-current integral along the waveguide: 1 - $\Phi_0 = 0$, 2 - $\Phi_0 = 65$ V; B - radial distribution of plasma density ($l = 92$ cm): 1 - $\Phi_0 = 0$, 2 - $\Phi_0 = 65$ V.

To investigate the radial distribution of the contained plasma current, a screened plasma probe with relative diameter $\delta/2R = 10^{-2}$ was introduced through lateral stubs, at a distance 92 cm from the diaphragm, and was moved along the waveguide radius. The maximum plasma density at the entrance diaphragm was in this experiment higher and corresponded to $\omega_{Le}^2/\omega^2 = 0.2$. The probe was used to plot N/N_0 against r/R for Φ_0 equal to 0 and 65 V (Fig. 3b). N_0 was taken to be the ion-current integral at $r/R = 0$ and $\Phi_0 = 65$ V. These plots are essentially the distributions of the particle density, $n/n_0 = f(r/R)$, as follows in this case from the geometrical similarity of the oscillograms. The transverse energies of the ions were negligibly small compared with the electron temperature. (The maximum transverse ion energies were ~0.1 eV, whereas the electron temperature kT_e/e, as measured with a Langmuir probe, was 4 eV.) Therefore the experimental points of the plot of n/n_0 vs. r/R were compared with the calculated plot obtained from (2) for $\Phi_0 = 65$ V and $kT/e = 4$ eV (curve 2, Fig. 3b). We see from curves 1 and 2 that the plasma is confined in the microwave field within a diameter smaller by a factor 2.5 than the stream diameter measured in the same section without the microwave field (judging from the half-width of the distribution). The plasma becomes channeled, and maintains a radial concentration distribution which is close to the initial value (at the diaphragm). The fact that the integrals $2\pi\int_0^\infty (n/n_0) r\,dr$ calculated from the experimental curves 1 and 2 of Fig. 3b agree within 20%, also indicates that practically the entire plasma injected in the microwave field is contained without noticeable loss.

When the instant of turning on the microwave pulse was delayed relative to the instant of emission from the plasma source in such a way that this instant corresponded to the appearance of ion current in the probe, modulation of the ion-current amplitude was observed (Figs. 2f, g).* The modulation periods were different at the beginning and at the end of the ion-current pulse, this being due to the presence in the plasma of ions of different sorts, which move in different longitudinal parts of the current. The characteristic modulation frequencies of the ion-current pulse lie in the interval (0.2 - 1.0) x 10^6 Hz; calculation of F for H^+ and C^+ for the same value of Φ_0 respectively gives 0.25 x 10^6 Hz and 0.83 x 10^6 Hz.

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* The case of nonequilibrium filling, when the boundary of the plasma content broadens to the corresponding value of ρ.