Generation of steady-state currents and transfer control in a toroidal magnetic trap due to Alfvén heating

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Quasi-steady-state, rf-driven currents with $\langle j \rangle \approx 30\ \mathrm{A \cdot cm^{-2}}$ ($J_p = 1.2$ kA, $q \approx 2.2$) were generated in the Alfvén heating mode in a P-0 stellarator. The transfer of particles and of plasma energy along the minor radius decreases as a result of propagation of the wave in the direction of diamagnetic electron drift.

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The feasibility of generating steady-state currents in toroidal systems without a magnetic field by means of low-frequency ($\omega = 10^6 - 10^7\ \mathrm{sec}^{-1}$), traveling electromagnetic fields has been demonstrated experimentally.[1,2] At present, the experiments on generation of rf-driven currents are performed primarily in the region of higher frequencies (lower hybrid resonance[3–5]). At the same time, the use of radio waves in the lower-frequency Alfvén range ($\omega < \omega_{ci}$) to excite steady-state currents in magnetic traps has a number of advantages.[6,7] Moreover, a conversion to lower frequencies makes it possible to control the transfer of plasma along the minor radius.[7,8] Previously, we have investigated the heating of plasma by Alfvén waves[9] and the radial structure of rf fields induced in the plasma.[10] We present in this paper the results of experiments on excitation of rf-driven currents by Alfvén waves and on the transfer control of plasma across the magnetic field.

The helical rf circuit of the device excited helical standing or traveling waves in the plasma that were propagated simultaneously in the toroidal and azimuthal directions at the phase velocity

$$\mathbf{v}_{\mathrm{ph}} = \mathbf{v}_\phi + \mathbf{v}_z = \pm\left(\frac{\omega a}{m}\frac{\mathbf{B}_\phi}{B_\phi} - \frac{\omega R}{n}\frac{\mathbf{B}_z}{B_z}\right),$$

where $m = 2$ and $n = 2$ are the azimuthal and toroidal wave numbers, respectively, $R = 50$ cm, $a = 3.5$ cm is the major and the minor radius of the plasma, and $\omega = 5 \times 10^6$

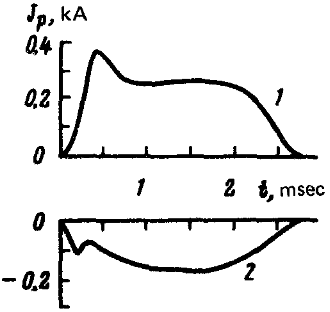

FIG. 1. Oscillograms of the rf-driven current in the plasma for different directions of propagation of the rf wave. $B_z = 5.4$ kG, $\iota_0 = 0.2$, $p = 1.5 \times 10^{-3}$ Torr of helium: 1, "diamagnetic" rotation; 2, "paramagnetic" rotation.

sec^{-1}. The plus "+" sign corresponds to the wave rotation in the direction of diamagnetic electron drift ("diamagnetic" rotation) and the minus (-) sign corresponds to "paramagnetic" rotation. The experiments were performed using hydrogen and helium at pressures $p = 10^{-4} - 10^{-3}$ Torr. The use of high-power rf generators made it possible for us to maintain the operating modes without ohmic heating and to monitor the rf-driven current in a pure form. Because of relatively low temperature ($T_e = 10$-20 eV) and high plasma density ($n_e \leqslant 10^{14}$ cm^{-3}), the time constant of the plasma column $\tau_p = L_p/R_p \approx 10^{-4}$ sec was smaller than the pulse duration of the rf field $\tau_{\text{rf}} = 2.5 \times 10^{-3}$ sec.

The experiments showed that an Alfvén wave with $\tilde{E}_z/\tilde{E}_\phi \ll 1$ (Ref. 10) is launched in the plasma and the rf power in it is intensely absorbed if the condition $\omega = k_{\parallel} c_A$ is satisfied. In the absence of a current produced by ohmic heating, the plasma was heated and the quasi-steady-state current with a duration equal to that of the rf pulse was excited by turning on the rf field [the absorbed power $P \approx 150$–200 kW (Fig. 1)]. The sign of the current was changed by changing the direction of the wave propagation. It is characteristic that the plasma density and the power lifetime were larger when the wave propagated in the direction of diamagnetic electron drift rather than in the "paramagnetic" direction.

The maximum rf-driven currents, which were attained when the rf field propagated in the "diamagnetic" direction, were $J_p \approx 1.2$ kA ($\langle j \rangle \approx 30\,A \cdot \text{cm}^{-2}$) at $\tilde{P} = 380$ kW, $n_e \approx 10^{14}$ cm^{-3}, and $T_e = 15$–20 eV when hydrogen was used. Under these conditions the rf-driven current increased the angle of rotational conversion and the safety factor

$$q = \frac{1}{\iota_0 + \iota_J}$$

reached the value $q \approx 2.2$, $\beta_p = 8\pi \langle nT \rangle / (B_{\phi 0} + B_{\phi J})^2 \approx 2.5$.

The average current density coincides within a factor of 2 with that calculated according to the formula

$$j = \frac{\sigma_{\parallel}}{\sigma_{\perp}} \frac{e}{m_c \nu_c} \frac{k_{\parallel}}{\omega} \tilde{Q}$$

(Ref. 8) ($\tilde{Q}$ is the power absorbed per unit volume). However, a number of effects,

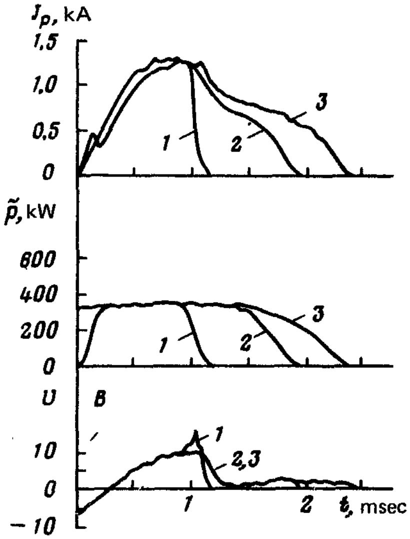

FIG. 2. Oscillograms of the current in the plasma, of the absorbed rf power and of the bypass voltage obtained for different durations of the rf pulse (1, 2, and 3). $B_z = 4$ kG, $l_0 = 0.2$, $p = 1.5 \times 10^{-3}$ Torr of hydrogen, "diamagnetic" rotation of the rf wave.

which cannot be explained by the current theory, require further investigation. They are, for example, the excitation of appreciable, steady-state currents by an electromagnetic standing wave and the decrease of currents induced when the wave propagates in the paramagnetic direction as the toroidal magnetic field is increased.

Figure 2 shows oscillograms of discharges in which the plasma current was maintained by means of an air-core transformer and by driving it by a traveling rf field. We can see that first the current decreases by 20–30% after completion of the voltage pulse in the circuit and then remains the same while the rf power is supplied to the plasma (curves 2 and 3 in Fig. 2).

The dependence of the radial plasma-density profile on the direction of wave rotation is shown in Fig. 3. It follows from these experiments that the transfer of plasma along the minor radius decreases appreciably when the rf wave rotates in the

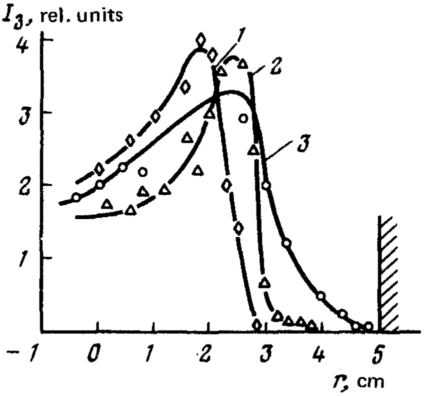

FIG. 3. Radial distribution of the ion saturation current in a probe for different directions of rotation of the wave. $B_z = 3.6$ kG, $l_0 = 0.4$, $p = 1.3 \times 10^{-3}$ Torr of helium: 1, "diamagnetic" rotation, $\langle \tilde{B}_\phi (r = 5 \text{ cm}) \rangle \approx 30$ G; 2, standing wave, $\langle \tilde{B}_\phi (r = 5 \text{ cm}) \rangle \approx 30$ G; 3, "paramagnetic" rotation, $\langle \tilde{B}_\phi (r = 5 \text{ cm}) \rangle \approx 45$ G.

diamagnetic direction and it increases when the rf wave rotates in the paramagnetic direction. In fact, a comparison with theory[7,8] shows that the influence of a rotating rf field on diffusion under these conditions must be appreciable, since the radial velocity v_{r1} of plasma induced by an rf wave, which was calculated according to the formula

$$v_{r1} \approx \frac{k_\phi \tilde{Q}}{\omega e n_e B_z}$$

(Ref. 8), is close to the diffusion rate v_{r2}, which was estimated from the decay time τ_n of the density after the rf pulse was quickly turned off ($\tau_{\text{off}} \ll \tau_n$) and from the characteristic inhomogeneity Δ, $v_{r2} \sim \Delta/\tau_n$. These results qualitatively explain the decrease of the power lifetime of plasma in the wave-heating mode in which the wave rotates in the paramagnetic direction.

Thus, the conducted experiments show that the Alfvén method of generating current, which is sufficiently efficient, can maintain the current after the induced electric field vanishes. Moreover, the transfer of plasma across the magnetic field can be substantially modified by changing the direction of wave propagation along the azimuth.

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