Observation of a bootstrap current in the Uragan-3 torsatron

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A study of the plasma produced and heated through the absorption of rf power at frequencies $\omega \lesssim \omega_{Hi}$ in the Uragan-3 torsatron has revealed a unidirectional current, which flows parallel to the confining magnetic field. The direction and the functional dependence of this current on the parameters of the plasma and the magnet system are the same as the predictions of the neoclassical theory for stellarators. The magnitude of the current is approximately the same as that of the bootstrap current predicted by that theory.

An important conclusion of the theory of plasma transport to toroidal magnetic confinement systems is the assertion that the diffusion of particles is accompanied by the appearance of a unipolar "bootstrap" current.[1,2] According to the theory, the magnitude of this current should increase with increasing values of the plasma parameters, exerting an important influence on the equilibrium and stability of the plasma. Although several experiments have been carried out to observe a bootstrap current,[3,4] the nature of the observed currents has not yet been clarified.

In the present letter we report the observation of a unipolar current during rf heating of the plasma in the Uragan-3 torsatron. The behavior of this current is consistent with the predictions of the neoclassical theory describing the bootstrap current in a stellarator.

The experiments were carried out at the Uragan-3 torsatron in the regime of rf heating[5] at magnetic fields $B_0 \cong 0.5$ and 4.5 kG, with an rf power $W = 200$–600 kW radiated by the antenna. Figure 1 shows the time evolution of the plasma parameter

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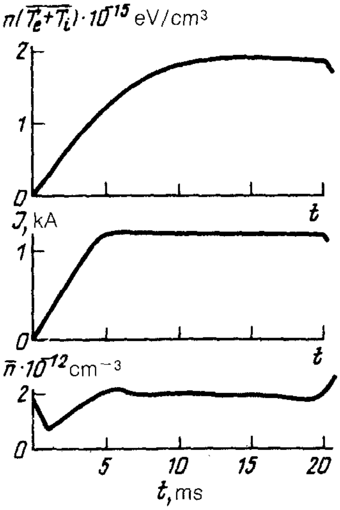

FIG. 1. Time evolution of the average plasma energy $\overline{n(T_e + T_i)}$, the plasma current J (measured by a Rogowski loop), and the average electron density $\bar{n}$.

values at the magnetic field value $B_0 \cong 4.5$ kG. The plasma parameter values $[n \lesssim 4\times 10^{12}$ cm^{-3}, $T_e(O) < 250$ eV, $T_i(O) \leqslant 900$ eV$]$ were such that the electron and ion collision rates satisfied the condition $\nu_j < v_{Tj} \iota r^{3/2}/R^{5/2}$, over the greater part of the cross section of the plasma column. In other words, we were dealing with a regime of collisionless transport.[1] Here v_{Tj} is the thermal velocity of plasma component j, r and R are the major and minor radii of the plasma, and ι is the rotational transform. The reader is directed to Ref. 6 for a detailed description of the experimental conditions, the heating methods, the diagnostic apparatus, and the behavior of the various plasma parameters.

In the experiments we observed a unipolar plasma current, detected by a Rogowski loop, which reached a magnitude $J \leqslant 2$ kA at an average plasma energy $n(T_e + T_i) \lesssim 3\times 10^{15}$ eV/cm^3. The ratio J/ψ [the magnetic flux of the dipole equilibrium currents $j_{\rm ps}$ (the Pfirsch-Schlüter currents) across the surface defined by the saddle-shaped measuring winding] was found to vary only slightly with the discharge parameters (Figs. 2 and 3). It was shown in Ref. 5 that the flux measured by the saddle-shaped winding, ψ, is quite accurately the same as the magnetic flux of a dipole equilibrium current

$$j_{\rm ps} = -\frac{2c}{}\frac{\nabla P}{B\iota}\cos\theta, \tag{1}$$

where P is the plasma pressure, and θ is the poloidal angle.

Figures 2 and 3 show results of the current measurements in the steady stage of the discharge (at $t > \tau_{\rm sk} \cong 10$ ms, where $\tau_{\rm sk}$ is the skin time); the measurements were carried out in this stage of the discharge in order to avoid effects of the currents which arise during rapid heating of the plasma. It can be seen from these figures that the ratio J/ψ varies only slightly as the parameters of the plasma and the magnet system of the Uragan-3 torsatron are varied over broad ranges.

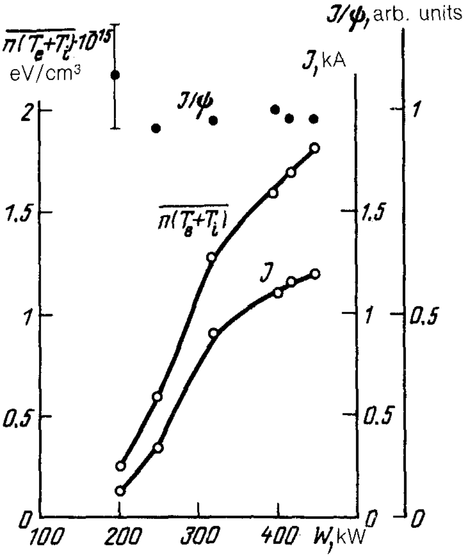

FIG. 2. The aveage plasma energy $\overline{n(T_e + T_i)}$, the plasma current J, and the ratio J/ψ versus the power of the rf field radiated by the antenna.

The plasma current flowed in the direction such that the magnetic field that it produced increased the rotational transform in the device. The direction of this current was determined by the direction of the longitudinal magnetic field. When the direction of the magnetic field was changed, the change in the sign of the current J was accompanied by a simultaneous change in the direction of the field of the dipole

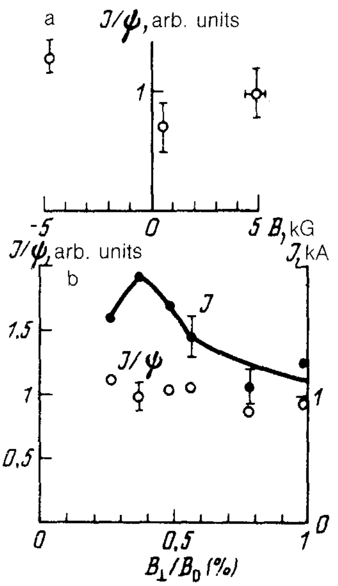

FIG. 3. a—J/ψ versus the magnetic field B; b—the plasma current J and the ratio J/ψ versus the magnitude of the transverse field, $B_\perp/B_0$, in the vacuum magnetic configuration.

currents, while the sign of the ratio J/ψ remained the same (Fig. 3a). It can be seen from these experimental facts that we have

$$J \propto \psi = C\,\frac{\overline{n(T_e + T_i)}}{B\ell}. \tag{2}$$

The coefficient C depends on the radial profiles of the plasma parameters and the rotational transform.

The expression for the bootstrap current density in the collisionless region can be written[8]

$$j = -\frac{A(r)\nabla P}{(r/R)^{1/2}\,B\ell}, \tag{3}$$

where the coefficient $A(r)$ is different for tokamaks and stellarators.

Using expression (3), we can write the bootstrap current as

$$J = \frac{\bar{A}\,\overline{n(T_e + T_i)}}{(a/R)^{1/2}\,B\ell}, \tag{4}$$

where a is the radius of the plasma column. It follows from expressions (2) and (4) that the functional dependence of the current observed in this experiment is the same as the predictions of the theory.

Our estimates show that the use of the expression given in Ref. 7 for the bootstrap current in a stellarator leads to a current smaller by a factor of 1.5–2 than that found experimentally. The transport theory for tokamaks[1] predicts a bootstrap current nearly 3–5 times greater than that found experimentally.

In summary, a longitudinal current has been observed during rf heating of the plasma under the condition $\beta = 8\pi P/B^2 \lesssim 0.5\%$ in the Uragan-3 torsatron. The direction of this current and its functional dependence on the parameters of the plasma and the magnet system of the device are the same as those predicted for the bootstrap current by the neoclassical theory for toroidal magnetic confinement systems, in particular for stellarators. The magnitude of this current is approximately the same as that predicted by this theory.

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