Plasma heating in a magnetic cusp confinement system without injection

M. S. Ioffe, B. I. Kanaev, V. P. Pastukhov, V. V. Piterskiĭ, and
E. E. Yushmanov

(Submitted 6 October 1981)

Pis'ma Zh. Eksp. Teor. Fiz. **34**, No. 11, 594–597 (5 December 1981)

A high-vacuum discharge with certain distinctive properties has been produced in a ring magnetic cusp confinement system with electrostatically plugged apertures. This discharge can provide ohmic heating of the plasma.

PACS numbers: 52.50.Gj, 52.55.Ke

The magnetoelectric confinement system is a magnet cusp system in which the loss through the cusps is blocked by electrostatic barriers produced by narrow apertures (with a width on the order of the Debye length) with grounded walls, backed up by negative cutoff electrodes ("reflectors"). The simplest way to heat the plasma in a magnetoelectric confinement system is to inject an electron beam from the reflector region.[1] Microwave heating is also being used.[2] The electron and ion temperatures achieved in the corresponding experiments are typically in the range 50–100 eV at a density $\approx 10^{11}$–10^{12} cm^{-3} (Ref. 3).

A new mechanism for pumping energy into the plasma has been developed for the ATOLL device. This new mechanism has no analog among the other methods which are used for heating in magnetoelectric confinement systems or in confinement systems of other types. The experimental arrangement is shown in Fig. 1; some details of the magnet aperture are shown in Fig. 2. The electron gun 4 is a hot emitter, which occupies a small fraction of the area of one of the reflectors. The auxiliary electrodes 3 (Fig. 2) suppress secondary emission from the reflectors and the emission current of the gun. In "ordinary" operation, a hydrogen plasma is produced and sustained partially by the electron current from the gun but primarily by the current of secondary-emission electrons which are ejected from the reflectors by the incident ions and then drawn into the confinement system by the potential of the reflectors, which is usually about 2 kV. The plasma itself assumes a negative potential on the order of 1 kV. The application to the auxiliary electrons of a negative potential greater than that applied to the reflectors stops the electron injection and leads to a decay of the plasma. If the magnetic field is sufficiently strong (stronger than 15 kG in the small apertures), however, conditions may be arranged such that a plasma with ordinary parameters ($\approx 10^{12}$ cm^{-3}, $T_e \approx 30$ eV, $T_i \approx 50$–100 eV, $P \approx 10^{-6}$ Torr) sustains itself in the confinement system, without any sort of external injection of electrons. This state corresponds to a special type of high-vacuum discharge (between the reflectors and ground) with a current of 10 A or more, in which electrode processes are not involved. The plasma is heated by the currents which flow within the plasma itself, between regions with different potentials. The mass balance of the plasma is sustained through the ionization of neutral hydrogen.

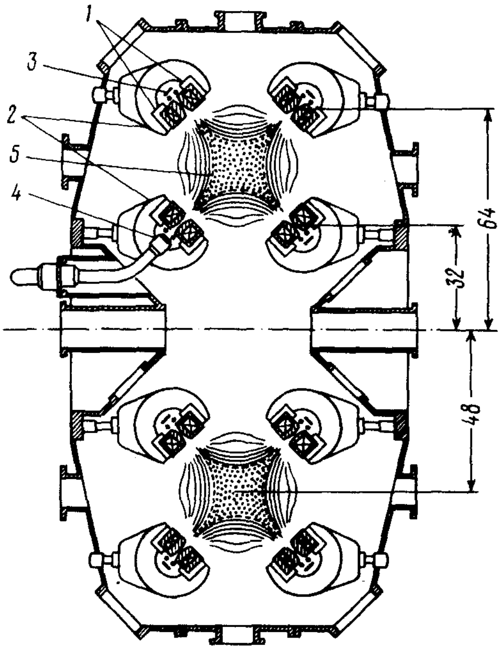

FIG. 1. The ATOLL confinement system. 1—Magnetic field coils; 2—yoke holders; 3—reflectors; 4—electron gun; 5—plasma. The dimensions are in centimeters.

What mechanisms could lead to such a state? The specific features of these mechanisms are determined by the geometry of the system. The escape of electrons from the system along the magnetic field is blocked by the electrostatic barriers between the apertures and the reflectors, but there is a rapid transport of electrons across the magnetic field to the walls of the apertures (we will not take up the nature of this transport). This loss must be balanced by an equal loss of ions. The ions cannot reach the walls, as the electrons do, since the ions are in a deep potential well with respect to the walls, but they can escape freely along the magnetic field to the reflectors. The rate of this ion loss is adjusted by the plasma potential to match the electron loss. If the plasma potential were zero, the ions would pass freely through the entire width of the

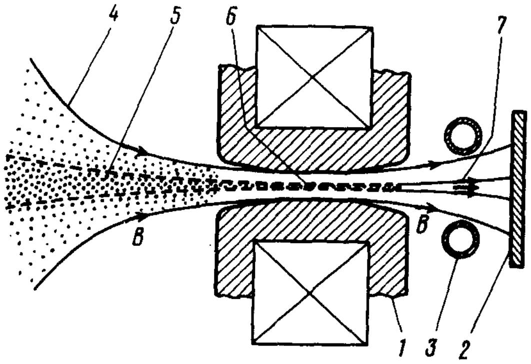

FIG. 2. The magnetic aperture. 1—Body of the coil which forms the aperture; 2—reflector; 3—auxiliary electrode; 4—line of force bounding the volume of the confinement system; 5—central part of the plasma with the highest negative potential; 6—ion loss corridor; 7—flux of escaping ions.

magnetic aperture, and this loss would exceed the electron loss. To reduce this loss, the plasma assumes the negative potential mentioned above, so that the ions can escape only through a narrow corridor at the center of the aperture (Fig. 2). Elsewhere in the aperture, the escape of ions is blocked by the electrostatic barrier produced by the field of the grounded walls of the aperture.

This is the reason for the appearance of the negative plasma potential. Direct observations have shown that the absolute value of this potential falls off significantly in the transverse direction toward the periphery, even within the confinement system, so that a substantial electric field, on the order of 50 V/cm, exists inside the plasma. This field is the primary factor in the "self-heating": As the electrons diffuse outward and cross a potential difference, they acquire energy; some of this energy is transferred to the central parts of the system by inverse heat conduction and replenishes the energy expended on ionization, radiation, etc. In other words, this energy sustains the plasma. The ions acquire their energy from the same electric field, whose accelerating effect is greater than the deflecting effect of the relatively weak magnetic field (about 300 *G* at the plasma boundary). As a result, an ion produced at the periphery "slides down" to the bottom of the potential well, i.e., to the center of the plasma, and then begins a periodic, cycloidal-type motion. Coulomb collisions do not play a role here, since the times τ_{ii} and τ_{ie} are much longer than the ion lifetime in the system.

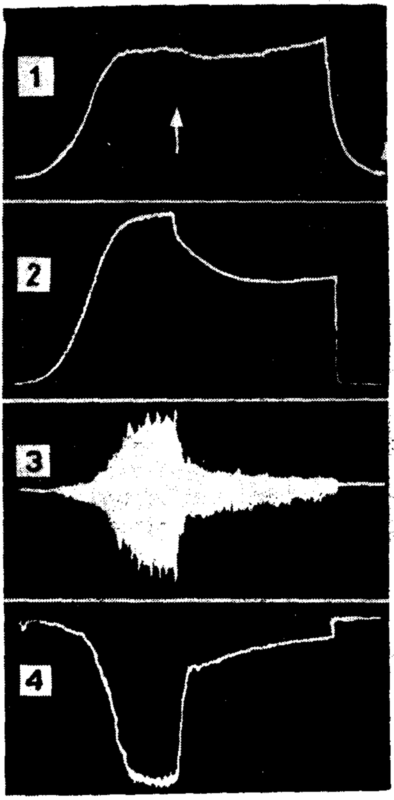

FIG. 3. Operation with and without injection at $B > 15$ kG. The sweep time is 8 ms. The arrow shows the time at which injection is cut off. 1—Signal from rf interferometer; 2—ion current drawn by the reflectors; 3—noise signal from probe; 4—electron current drawn by an electrode outside the plasma boundary.

These mechanisms are operating in the ATOLL in the case of a self-sustaining plasma. This heating can be described somewhat arbitrarily as "transverse ohmic heating," by which we mean that the heating is caused by currents which flow in transverse electric fields. As mentioned earlier, one condition for this self-sustained operation is that the magnetic field be quite strong. The role played by the magnetic field can apparently be described as follows: With increasing B, there is a decrease in the intensity of the transverse electron transport, so that there must also be a reduction in the loss of ions. For this reason, the plasma increases its negative potential. This potential increase in turn amplifies the ohmic heating, making self-sustained operation possible. Another condition is that the hydrogen be pure: If impurities (N_2, for example) are present in a concentration of about 5%, this type of discharge begins to be extinguished. The apparent reason is that the impurities increase the radiative energy loss, and they also reduce the negative plasma potential, since the heavier ions leave the system at a lower velocity, so that the corridor in the aperture must be broader.

An advantage of this injection-free heating is its obvious technical simplicity, which may in fact be labeled "ideal," since the heating requires nothing beyond those electric and magnetic fields which form the confinement system itself. Another advantage is of a physical nature: There are no electron beams, which would generally drive instabilities. In this case, therefore, we can expect a better confinement, as has been confirmed qualitatively by experiments in the ATOLL. It can be seen from Fig. 3 that at the transition to injection-free operation the plasma density in the system remains essentially constant, while the ion-loss current becomes smaller. We also see a decrease in the noise level and a decrease in the intensity of the electron transport across the magnetic field.

[1] Yu. S. Azovskiĭ, V. I. Karpukhin, O. A. Lavrent'ev *et al.*, Fiz. Plazmy **6**, 256 (1980) [Sov. J. Plasma Phys. **6**, 142 (1980)].
[2] Yu. G. Zalesskiĭ, A. D. Komarov, O. A. Lavrent'ev *et al.*, Fiz. Plazmy **5**, 954 (1979) [Sov. J. Plasma Phys. **5**, 532 (1980)].
[3] C. Gormerano, Nucl. Fusion **19**, 1094 (1979).

Translated by Dave Parsons
Edited by S. J. Amoretty