TURBULENT HEATING OF PLASMA IN A TORUS

PHYSICS

1968

SovietRxiv

Abstract

Full Text

UDC 533.951.7

PHYSICS

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TURBULENT HEATING OF PLASMA IN A TORUS

(Presented by Academician E. K. Zavoiskii, March 21, 1968)

The general principle of turbulent plasma heating consists in the conversion of the ordered motion of particles into disordered motion by means of turbulent pulsations excited in the plasma by the ordered motion itself. Turbulent heating was first carried out by E. K. Zavoiskii in 1961 (^{1}), with strong magnetohydrodynamic waves used in that case as the ordered motion.

Another type of ordered particle motion suitable for carrying out turbulent heating is the directed motion of charged particles when a current flows in a strong electric field. If the current velocity of the electrons exceeds a certain threshold value, the electron stream must excite in the plasma a Buneman or ion-acoustic instability.

In 1963 we discovered an anomalously large dissipation of the energy of an electric current flowing parallel to the magnetic field in an electrodeless toroidal discharge with a strong electric field. During the flow of current in a plasma with density 10^{12} cm^{-3}, a temperature $T_e \sim 10^2 \div 10^3$ eV was observed, and a high level of turbulent pulsations was detected in the ranges of the Langmuir and ion-acoustic frequencies, capable of explaining the anomalous resistance of the plasma ($^{2-4}$).* According to the theory used in (^{2}), a simple toroidal magnetic field cannot provide equilibrium of the plasma in a torus. Subsequently, experiments of this kind were described by several authors ($^{9-11}$), who obtained, during the flow of current, temperatures $T_e \sim 10^3 \div 10^4$ eV with practically complete absence of plasma confinement after the heating was stopped, although stellarator (^{10}) and high-frequency (^{9}) confinement variants were also used.

The present work was undertaken in order to test the fundamental possibility of confining turbulently heated plasma of toroidal configuration after the heating current is stopped.

Twenty titanium-hydride plasma injectors 2 could prepare in the discharge chamber of the Vikhr-2 installation (Fig. 1) a plasma with density 10^{11} cm^{-3} < $n < 5 \cdot 10^{13}$ cm^{-3}. Magnetic coils 3 provided the production of a strongly corrugated quasi-stationary magnetic field (^{3}), which had the configuration of a

Fig. 1

Figure 1: Fig. 1

corrugated torus near the magnetic axis and a cusped geometry at the chamber walls. The corrugation of the magnetic field in the paraxial region was $(B_{\text{max}}/B_{\text{min}}) = 20$, which is much greater than that achieved previously ($^{12-14}$). The toroidal plasma cord constituted the secondary winding of an h.f. transformer, whose primary winding consisted of 4 parallel annular conductors 10, connected through a spark gap to a capacitor bank of capacitance 0.1 μF at a voltage of 100 kV. This system was used to create on the torus circumference of an electric field up to 250 V/cm, which greatly exceeded the Dreicer "runaway" limit ($E_{\text{Dr}} \sim 10$ V/cm at $n \sim 10^{13}$ cm^{-3} and $T_{e0} \sim 1$ eV). The electric field at a frequency of 1 MHz was interrupted after 1 μs by means of a special nonlinear resistance in the primary circuit of the rf transformer.

The current in the plasma was also measured by means of internal and external Rogowski belts. The measurements showed, first, that the current flows mainly within the internal region of the magnetic field (the region of the "corrugated torus," hatched in Fig. 1); second, that the plasma resistance was strongly anomalous (as in (2-4)); third, that the current was interrupted after 1 μs (together with the electric field).

Fig. 1. Schematic of the Vikhr-2 experimental setup. 1—quartz discharge chamber; 2—titanium-hydride plasma injector; 3—coil of the quasi-stationary magnetic field, one of 20; 4—internal Rogowski belt; 5—external Rogowski belt; 6, 11—antennas for microwave diagnostics; 7—five-turn internal diamagnetic probe; 8—double Langmuir probe for determining T_{e0}; 9—external diamagnetic probe; 10—turns producing the circumferential electric field. The dashed lines denote magnetic field lines; the hatched region is the region where the field has the configuration of a corrugated torus. The maximum strength of the quasi-stationary magnetic field is 15 kOe.

The plasma pressure nT was determined by means of internal and external diamagnetic probes.

Figure 2 presents one of the oscillograms of the readings of the internal diamagnetic probe a and, simultaneously, the oscillogram b of the current in the plasma. During the flow of current, oscillogram a shows a paramagnetic signal at twice the current frequency. Then a purely diamagnetic signal is observed (with an initial nT up to $5 \div 7 \cdot 10^{15}$ eV $\cdot$ cm^{-3}), which is maintained for several

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* Analogous phenomena were later observed in a pinch-type discharge (^{5}) and in direct discharges, where the current flowed between electrodes ($^{6-8}$).

Fig. 2

Figure 2: Fig. 2

microseconds after interruption of the current. Microwave diagnostic methods at wavelengths of 4 mm, 8 mm, and 3 cm were used to determine the behavior of the plasma column and the time dependence of the plasma density. It was shown that the density changed by no more than a factor of 2 during the heating stage, which lasted 1 μs, while T increased by a factor of 10^2.

A high level of small-scale longitudinal plasma oscillations*, inevitable under the conditions of turbulent heating by its very definition, must lead both to an increase in the rate of dissipation of the current energy and to an increase in the rate of diffusion. The final result of heating depends on the ratio of these two effects. The data presented above apparently may serve as direct experimental proof that, under suitable conditions, the first effect predominates. Therefore it may be considered proven that turbulent heating is in principle suitable for obtaining high-temperature plasma in toroidal magnetic systems.

Fig. 2. *a*—oscillogram of the diamagnetic signal; *b*—electric field around the torus circumference; *v*—current I in the plasma; *g*—calibration trace $f = 1$ MHz. Plasma density $2 \cdot 10^{13}$ cm^{-3}; $nT = 5 \div 7 \cdot 10^{15}$ eV $\cdot$ cm^{-3}; $E_0 = 250$ V/cm; $I_0 = 1.5$ kA.

In conclusion, two further remarks.

1. The experimental confinement time nT indicated above exceeds by at least an order of magnitude the calculated time of toroidal drift in our apparatus. This confirms the original idea of B. B. Kadomtsev (15) and the conclusions of later works (12-14) on the possibility of ensuring plasma equilibrium in a torus by a corrugated magnetic field.
2. The data on the confinement time nT may perhaps give only a lower limit of the true plasma confinement time. Since $T_e \sim 10^2$ eV, and in the volume of the discharge chamber there were $5 \cdot 10^{13}$ atoms of neutral gas per 1 cm^3, cooling of the plasma could occur during an ionization time of $\sim 10^{-5}$ s.

The authors express their gratitude to E. K. Zavoisky for his constant advice and support, to D. D. Ryutov for valuable theoretical discussions, and also to V. D. Shafranov for numerical estimates of the conditions of plasma equilibrium in our particular magnetic configuration.

Received
11 XII 1968

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* The energy density of the oscillation background, measured in work (4), proved to be 7 orders of magnitude higher than the equilibrium thermal level.

Note: Figure translations are in progress. See original paper for figures.

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