INVESTIGATION OF DIFFUSION OF A DENSE DECAYING PLASMA IN A STELLARATOR

R. A. DEMIRKHANOV, D. G. BARATOV, N. I. MALYKH, V. G. MEREZHKIN, M. A. STOTLAND, Yu. TEN, and Sh. V. KHIL'

Sukhumi Physicotechnical Institute

Submitted February 24, 1970

Zh. Eksp. Teor. Fiz. 60, 569–578 (February, 1971)

Diffusion of a helium plasma in a double-screw stellarator is investigated experimentally for magnetic field strengths between 6 and 12 kOe. The density and temperature of the plasma were 1×10^{14} cm^{-3} and 0.6 eV. It is shown that the dependences of the plasma diffusion time on the magnetic field intensity and on the angle of rotational transformation of the force lines is in agreement with the hydrodynamic model of classical diffusion of a plasma in a toroidal helical magnetic field.

1. INTRODUCTION

THE mechanism of classical plasma diffusion in a toroidal magnetic trap with rotational transformation of the force lines, due to paired electron-ion collisions, was first qualitatively considered by Budker[1], who predicted an increase of the diffusion coefficient in such a system owing to the drift mixing of the particles. This problem was then investigated more rigorously by Pfirsch and Schluter[2] and by others[3-6] in the hydrodynamic approximation, when the electron mean free path λ_{ei} is much shorter than the "coupling length" L—the distance along the force line corresponding to one turn of the line around the "minor axis" of the torus. In particular, it is shown in[6] that in a stellarator with a circular magnetic axis, the coefficient of collision diffusion of a plasma is expressed in the form $D_c = \rho_e^2 \nu_{ei}(1 + 8\pi^2/\vartheta^2)$, and consequently an estimate of the diffusion lifetime of the plasma can be obtained from the expression

$$\tau_c = \frac{a^2}{(2{,}4)^2 \rho_e^2 \nu_{ei}(1 + 8\pi^2/\vartheta^2)}. \qquad (1)$$

Here ρ_e is the Larmor radius of the electrons, ν_{ei} the frequency of the electron-ion collisions, a the radius of the plasma, and ϑ the angle of rotational transformation when the torus is traversed.

By now, many experiments have been performed on plasma containment in stellarators, under conditions $\lambda_{ei} \ll L$[7-13], but in most of them[7-10] (with the exception of the investigations with the Wandelstein stellarator[11,12] and the experiments with a weakly-ionized plasma on the stellarator of the Novisibirsk Institute of Nuclear Physics[13]), the processes of the transport of a current-free plasma were determined by instabilities, and the plasma analysis exceeded by several orders of magnitude those expected assuming classical diffusion. Thus, the theory of classical diffusion of a plasma with $\lambda_{ei} \ll L$ in toroidal traps with rotational transformation of the force lines was not fully confirmed experimentally, and further investigations are needed under the indicated experimental conditions.

In this connection, from the point of view of verifying the main conclusions of the theory, interest attaches to the following formulation of the experiment. A study of the diffusion of a currentless plasma in a stellarator magnetic field is carried out under conditions when the estimate of the classical diffusion time τ_c with the aid of expression (1) gives a value much smaller than the time of the turbulent diffusion, corresponding, for example, to the reciprocal of the increment of the drift-dissipative instability and equal in order of magnitude to the Bohm diffusion time $\tau_B = a^2/(2,4)^2 D_B$ (D_B = ckT/16eH—Bohm diffusion coefficient). With such a formulation of the experiment, one can expect a relative decrease of the contribution of the turbulent plasma-transport processes, and the main laws of classical diffusion should become manifest more clearly. It should be noted that in this case the effects of increased diffusion losses, connected with rotation of the plasma and predicted by Stringer[14], are certainly negligible.

We present below results of an investigation of the diffusion of a dense and sufficiently cold plasma in an accelerator, when $\tau_c < \tau_B$. Unlike in the experiments of[15 16], the decay time of the plasma density is dependent on the magnetic field and on the angle of rotational transformation.

2. EXPERIMENTAL SETUP AND METHOD OF PLASMA PRODUCTION

The experiments were performed with the RT-2 installation, comprising a circular two-screw stellarator with a quartz discharge chamber. Figure 1 shows a diagram of the RT-2 setup. We present its basic parameters:

Major radius of torus	65 cm
Minor radius of helical winding	10 cm
Number of helices of helical winding	2
Number of periods of the field	12
Inside radius of quartz discharge chamber	4 cm
Maximum intensity of toroidal magnetic field H_0	20 kOe
Maximum value of current in the helical winding, I	100 kA
Duration of magnetic-field pulse	12 msec
Parameter of modulation of helical magnetic field, ϵ	0.07 I/H_0
Maximum calculated value of the angle of rotational conversion on the outermost magnetic surface, ϑ	4π
Maximum value of average shear of force lines, θ	~ 0.02
Depth of magnetic well at $\epsilon \lesssim 0.25$	1–2%

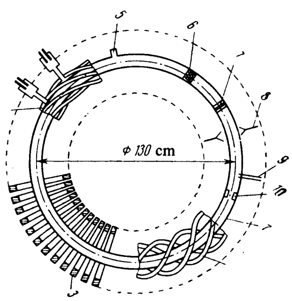

FIG. 1. Schematic diagram of the RT-2 setup: 1—quartz discharge chamber, 2—helical-field winding, 3—coils of toroidal magnetic field, 4—high-frequency circuit, 5—tube for optical measurements, 6—Rogowski loop, 7—diamagnetic pickup, 8—microwave antennas, 9—double electric probe, 10—bolometers.

The RT-2 apparatus provides for interchangeable sets of two-helix and three-helix windings, consisting of standard-construction single-turn elements. The existence of magnetic surfaces on the installation with the three-helix winding was verified earlier with the aid of the method of multiple passage of an electron beam, described in[17]. Depending on the position of the electron gun, the number of beam revolutions registered ranged from ~ 100 to ~ 300, in agreement with the estimate of the loss of electrons at the gun and at the receiving probe. Such numbers of revolutions are typical for measurements of this type performed with other stellarators whose windings are made multiturn.

The experiments described below were made after the triple-helix winding was replaced by a double-helix winding, this being done mainly in an effort to increase the equilibrium margin of the plasma, and also because in the case of a double-helix winding it becomes easier to compare the experimental results with theory, since the angle of rotational conversion ϑ changes little over the radius.

In the case of a double-helix winding, no second study of the "quality" of the helical magnetic field was made with the aid of an electron beam, but one can expect with sufficient justification that the replacement of the windings with retention of their standard structural elements and precision of manufacture did not bring about any additional defects in the magnetic field. The accuracy of the toroidal magnetic field was checked independently with the aid of an electron beam making one turn along the torus. The integral accuracy of the magnetic field $\delta B/B$, determined from the deflection of the electron beam, was not worse than 1.5×10^{-3}. We note that the requirements with respect to the number of turns of the force lines prior to their leaving the system, in the case of experiments with a cold plasma, are much less stringent because of the lower rate of drift of the charged particles along the force lines.

The plasma was produced by an induction high-frequency field excited by a toroidal system of turns with in-phase currents at a frequency 2 MHz. The longitudinal HF field in the plasma could be varied in the range 0.5–2 kA. The initial pressure of the gas (helium) ranged from 1×10^{-3} to 7×10^{-3} mm Hg. The lower pressure limit of the working gas was determined by the threshold for the ignition of the discharge. The degree of ionization of the plasma was determined from the relative intensity of the helium lines (HeII 4686 Å/HeI5047 Å) and was very close to 100% at a high-frequency current ≥ 1.5 kA. The high-frequency field was turned on for ~ 1.5 msec close to the attainment of the maximum of the quasiconstant magnetic field. The study of the plasma decay was carried out after abrupt termination of the high-frequency voltage (the time of complete disappearance of the high-frequency current from the plasma was ~ 5 μsec).

The electron density n in the plasma was measured with the aid of microwave interferometers operating at wavelengths 1.5 and 2.2 mm. The value of n determined from the measurements agreed with the density value averaged over the length of the microwave beam in the plasma. With the aid of a measuring coil installed in one of the sections of the chamber and surrounding it, we measured the diamagnetism of the plasma. The transverse plasma temperature $(T_e + T_i)_\perp$ was determined from measurements of the diamagnetism and the density of the plasma. A monochromator and a photoelectron multiplier were used to register the glow of the helium lines in the visible region of the spectrum.

The values of the density and temperature of the plasma measured during the active stage of the discharge were respectively 3×10^{13}–3×10^{14} cm^{-3} and 10–20 eV. Probe measurements have shown that in the active stage the density and the temperature of the plasma have strongly pronounced maxima near the surface of the plasma, owing to the skin effect of the high-frequency field.

Microwave sounding of the cross section of the plasma at a wavelength 2.2 mm in two orthogonal directions has established that the dimension of the plasma column is determined in the employed range of variation of the magnetic-field modulation parameter ϵ by the dimension of the outermost magnetic surface—the last magnetic surface inscribed in the minor cross section of the chamber. The effect of localization of the plasma by the helical magnetic field was also confirmed by probe and optical measurements. A two-channel microwave sounding of the plasma cross section has shown that the ratio of the major dimension of the plasma cross section to the minor one, both in the active stage of the discharge and in the decay phase, agrees with the geometry of the magnetic surfaces obtained by numerical integration with an electronic computer. In the calculation, we used an expression for the scalar magnetic potential[18] in which five harmonics of the expansion of the surface helical current were taken into account. The results of the measurements and typical cross sections of the calculated magnetic surfaces are shown in Fig. 2. The data given in Fig. 2 concerning the profile of the plasma cross section were used by us in the reduction of the results of the diamagnetic and microwave measurements, and also in the choice of the calculated diffusion dimension of the plasma a, which enters in expression (1).

The intensity of the toroidal magnetic field H_0 in the discussed experiments ranged from 6 to 12 kOe.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The decay of the plasma in the afterglow stage was investigated not immediately after the termination of the high-frequency voltage, but 100–200 μsec later,

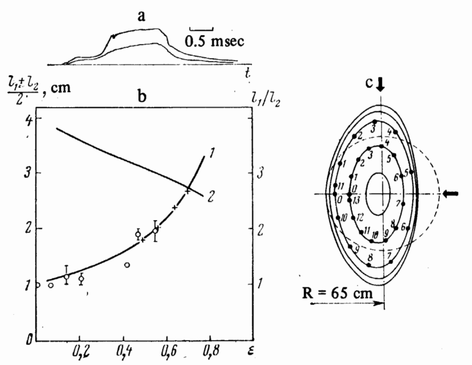

FIG. 2. a—Oscillograms of microwave signals. The signal is proportional to $\int_0^l$ ndx, where l is the length of the microwave beam in the plasma. Upper oscillogram—sounding by transmissions through the major dimension of the plasma, lower—through the minor dimension. ϵ = 0.49. b—Dependence of the calculated ratio of the maximal dimension l_1 of the magnetic surface inscribed in the chamber to the minimum dimension of l_2 on the value of ϵ(curve 1). The points + were obtained as a result of a numerical integration in the toroidal case. The points O represent the ratio of the microwave signals passing through the plasma along its major and minor dimensions. Curve 2—dependence of the calculated average dimension of the magnetic surface inscribed in the chamber on ϵ. Curves 1 and 2 were obtained from calculation in the cylindrical approximation [22]. c—Cross section of magnetic surfaces at ϵ = 0.49, obtained as a result of numerical integration in the toroidal case. The numbers indicate the representative points of the force lines, obtained during each period of the magnetic field. The angle of the rotational conversion on the magnetic surface inscribed in the chamber lies in the interval $^{12}/_{13}\cdot 2\pi \leqslant \vartheta \leqslant {}^{12}/_{11}\cdot 2\pi$ (the number of periods of the field on the perimeter of the torus is equal to 12). Dashed circle—cross section of discharge chamber. The arrows indicate the directions of sounding of the plasma by the microwaves in the given section of the magnetic surfaces.

when the decrease of the density became quiescent and, as shown by controlled measurements with the aid of electric probes, the singularities in the spatial distribution of the density and of the temperature, connected with the skin effect of the high frequency field during the active stage of the discharge, disappeared. At the instant of the measurements, the plasma temperature dropped to a value ≤ 1 eV, and a flash of recombination radiation of the helium appeared. Typical time plots of the plasma density, its temperature, and the recombination-glow intensity of the He HeI 5875 Å line are shown in Fig. 3.

Under the experimental conditions, the time of equalization of the electron and ion temperatures was much shorter than the containment time, and therefore the plasma could be regarded as isothermal with a temperature $T_e = T_i = \frac{3}{4}(T_e + T_i)_\perp$.

The assumed requirement $\tau_c < \tau_B$, in conjunction with the necessary condition that the plasma be magnetized, leads to the inequality

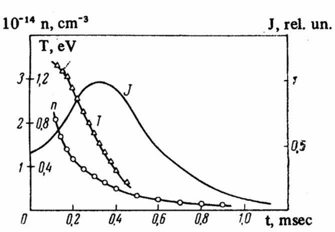

FIG. 3. Time dependences of the plasma density n, of the temperature T, and of the glow intensity J of the He 5875Å line. H_0 = 10 kOe, ϵ = 0.49.

$$1 < \omega_{He}/\nu_{ei} < 16(1 + 8\pi^2/\vartheta^2), \tag{2}$$

where ω_{He} is the electron cyclotron frequency. The experimental relations presented below were obtained in a range of magnetic fields 6 kOe $\leq H_0 \leq$ 12 kOe, when the inequality (2) was satisfied. In practice the condition (2) was satisfied (in a certain time interval) by choosing the initial values of the plasma density and temperature. We note that the right-hand side of the inequality (2) at $\vartheta \sim 2\pi$ and H_0 = 6–12 kOe gives rise to $\nu_{ei} > 4 \times 10^9$ sec^{-1}, i.e., an experiment of this type can actually be carried out only with a dense and sufficiently cold plasma.

The decrease in the plasma density was close to exponential (this was verified by plotting n(t) in a semilogarithmic scale).

Figures 4 and 5 show plots of the time τ_n necessary for the plasma density to decay by a factor e, against the magnetic field intensity and the square of the modulation of the helical field ϵ^2, which is proportional to the twist angle of the force line ϑ. In plotting these relations we chose from the aggregate of experimental points τ_n for a given ϵ or for a given H_0 the points corresponding to identical values of n and T_0 (within limits of ~20%).

In the range of variation of the initial plasma density 1×10^{14}–3×10^{14} cm^{-3} and at an initial temperature $T_e \approx 0.6$ eV, the plots of $\tau_n(H_0)$ have a nearly linear character, and an increase of the decay time with decreasing plasma density is observed (see Fig. 4).

In the range of variation of the parameter ϵ^2 from 5×10^{-2} to 2×10^{-1}, the value of τ_n increases with increasing ϵ_2, and the $\tau_n(\epsilon^2)$ dependence is somewhat stronger than linear. With further increase of ϵ, a minimum is observed in the $\tau_n(\epsilon^2)$ dependence at a value $\epsilon \approx 0.5$, corresponding, as follows from Fig. 2c, to a rotational-conversion angle $\vartheta \approx 2\pi$ on the magnetic surface inscribed in the chamber. Similar minima in the dependence of the lifetime of the plasma on

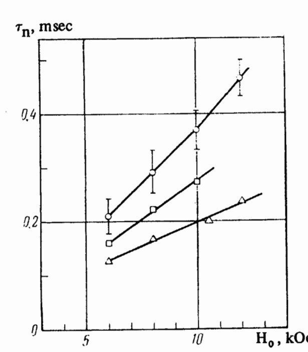

FIG. 4

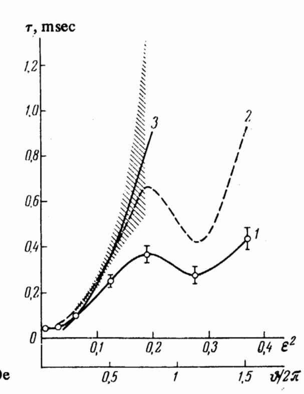

FIG. 5

FIG. 4. Dependence of the plasma density decay time τ_n on the magnetic field. ϵ = 0.49, T ≈ 0.6 eV. O—n = 1×10^{14} cm^{-3}, □—n = 1.4×10^{14} cm^{-3}, Δ—n = 3×10^{14} cm^{-3}.

FIG. 5. Dependence of the plasma density decay time τ_n(curve 1) and of the diffusion time τ_d(curve 2) on the parameter $\epsilon^2 \propto \vartheta$. Curve 2 was obtained with the aid of expression (4), and curve 3 is theoretically calculated from expression (1). The shading denotes the field of errors in the quantity τ_d. H_0 = 8 kOe, n = 1×10^{14} cm^{-3}, T = 0.6 eV.

ϵ at rational values of $\vartheta/2\pi$ were observed earlier in[12,19] and were attributed to the destruction or else to the splitting of the magnetic surfaces as a result of resonant perturbation of the magnetic field. Integer values of $\vartheta/2\pi$, from this point of view, as is well known, are the most dangerous. It should be noted that the minimum at $\epsilon \approx 0.5$ was also observed in the dependence of the energy lifetime of the plasma on ϵ during the active stage of the discharge, when the plasma parameters and their spatial distribution were essentially different from those during the decay stage. This fact, in our opinion, confirms independently the explanation of the observed minimum as being due to perturbation of the structure of the magnetic field, and not to some other effect.

If we compare the plasma decay times shown in Figs. 4 and 5 with the theoretical estimate of the classical-diffusion time (1), then it turns out that they agree within a factor on the order of 2–4. The experimental density decay times actually turned out to be much shorter than the Bohm diffusion time. These results, together with the observed growth of the plasma decay time with increasing magnetic field and with increasing angle of rotational conversion, point to an important role played by classical diffusion in the transport of the plasma particles in the stellerator under our experimental conditions.

In spite of the quantitative agreement, in order of magnitude, between the experimental density decay time and the estimate that follows from the classical diffusion theory, there is an appreciable deviation in the functional dependences of τ_n on the magnetic field and on the angle of rotational conversion. This difference may be due to the fact that the rate of plasma loss is influenced not only by the diffusion but also by some other mechanism whereby the charged particles are removed from the volume. The most probable cause of the additional plasma loss, as follows from the sequel, is collision-radiative recombination.

We observed the dependence of the time τ_n on the magnetic field only for an initial value $T_e \gtrsim 0.6$ eV. Thus, for example, at $T_e \approx 0.4$ eV and at an initial value $n = 1.4 \times 10^{14}$ cm^{-3}, the value of τ_n was independent of the magnetic field if its intensity exceeded ~8 kOe, and was equal to 0.2 msec (Fig. 6). The independence of the decay time of a dense and cold plasma ($n \sim 10^{13}$–10^{14} cm^{-3}, $T_e < 0.4$ eV) of the magnetic field was observed earlier in experiments with the B-1 stellarator[15,16], and was also attributed to the competing process of volume recombination elimination of particles.

The characteristic recombination time can be determined from the expression

$$\tau_r = (1.2\alpha n)^{-1}, \tag{3}$$

which, as indicated in[20], is valid for $\alpha n a^2/D < 5$, i.e., in a sufficiently wide range of ratios of the recombination time to the diffusion time (α is the recombination coefficient). Expression (3) will be used by us henceforth to determine the recombination time for known $\alpha(T)$ and n.

The functional dependence of the recombination coefficient on the plasma temperature in the range T = 0.2–0.6 eV is shown in Fig. 7. It was obtained

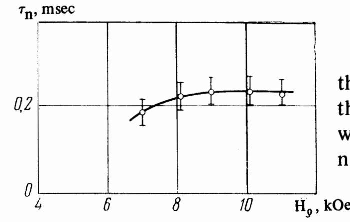

FIG. 6. Typical dependence of the plasma density decay time on the magnetic field under conditions when recombination predominates. $n \approx 1.4 \times 10^{14}$ cm^{-3}, $T \approx 0.4$ eV.

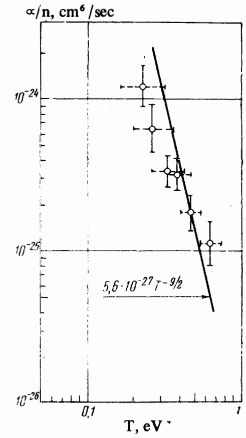

FIG. 7. Dependence of the recombination coefficient of a helium plasma on the temperature. Points—experimental values, solid curve—theoretical dependence of the three-particle recombination coefficient [16]. $H_0 = 11$ kOe; $\epsilon = 0.49$; $6 \times 10^{13} \leqslant n \leqslant 2 \times 10^{14}$ cm^{-3}.

from the experimental curves n(t) and T(t) with the aid of the expression $dn/dt = -\alpha n^2$ under conditions of significant predominance of recombination, which was monitored against the absence of a dependence of τ_n on the magnetic field. It is seen from Fig. 7 that at $T < 0.3$ eV the experimental dependence of α/n on T is in satisfactory agreement with the theory of collisional three-particle recombination developed in[16]. At higher temperatures, the dependence of the recombination coefficient on the temperature turns out to be weaker, and this agrees qualitatively with the results of careful calculations of the coefficient of radiative-collision recombination of a hydrogenlike plasma carried out by Bates et al.[21]. The estimates of the recombination time that can be obtained with the aid of the dependence shown in Fig. 7 and with the aid of (3), show that the recombination time in our experiments is comparable with the plasma decay time τ_n. Thus, to separate the diffusion time τ_d it is necessary to introduce a correction that takes the recombination loss of the plasma into account. We note that ionization during the stage of plasma decay can be neglected, for when $T_e \leq 0.6$ eV the ionization coefficient is smaller by many orders of magnitude than the recombination coefficient[21].

The dependences of the plasma diffusion time in a magnetic field on H_0 and ϵ^2 were determined by us on the basis of the reciprocal quantities

$$\frac{1}{\tau_n} = \frac{1}{\tau_d} + \frac{1}{\tau_r} \tag{4}$$

at chosen initial plasma parameters $T_e \approx 0.6$ eV and $n \approx 1 \times 10^{14}$ cm^{-3}, where a distinct dependence of τ_n on the magnetic field intensity was observed, is shown by curve 1 in Fig. 8. Each experimental point is the mean value of three measurements at the indicated plasma parameters, and the values of the plasma density and of the temperature for all the experimental

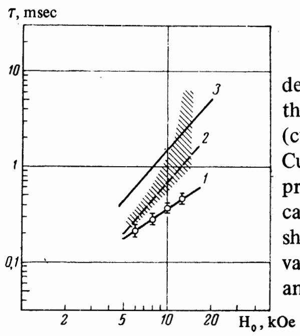

FIG. 8. Dependence of the plasma density decay time τ_n (curve 1) and of the diffusion times τ_d (curve 2) and τ_c (curve 3) on the magnetic field intensity. Curve 2 was obtained with the aid of expression (4), curve 3 is theoretical and calculated from expression (1). The shading denotes the field of errors in the value of τ_d. $\epsilon = 0.49$, $n = 1 \times 10^{14}$ cm^{-3}, and T = 0.6 eV.

points of curve 1, as already noted above, were the same within about 20%.

The experimental value $\alpha/n \approx 1 \times 10^{-25}$ cm^6 sec^{-1} obtained at T_e = 0.6 eV (Fig. 7) corresponds to a recombination time, determined from (3), of $\tau_r \approx 0.8$ msec for a plasma density $n \approx 1 \times 10^{14}$ cm^{-3}. The $\tau_d(H_0)$ dependence calculated with the aid of (4) is close to quadratic (curve 2 of Fig. 8) and coincides quantitatively, apart from a factor ~ 2, with the theoretical estimate (1) (curve 3). In expression (1) we substituted for a the average dimension of the outermost magnetic surface inscribed in the chamber, equal to ~ 3 cm.

The $\tau_d(\epsilon^2)$ dependence (curve 2 on Fig. 5) obtained with allowance for recombination losses in the manner indicated above turns out to be much stronger than $\tau_n(\epsilon^2)$ (curve 1), and is functionally in satisfactory agreement with the theoretical relation (1) (curve 3). Expression (1), obtained in the approximation of rounded magnetic surfaces, is not perfectly adequate in the case of pronounced ellipticity of the plasma cross section. Allowance for the ellipticity of the plasma cross section was expressed by the fact that the diffusion dimension a was chosen to be the dimension of the outermost magnetic surface; we used in this case the dependence of the average dimension of the magnetic surface on the value of ϵ, as shown in Fig. 2b. The rotational transformation angle was assumed to be its average value $\vartheta = (\vartheta_1 + \vartheta_2)/2$, where the calculated values of ϑ_1 and ϑ_2 were determined respectively near the magnetic axis and on the outermost surface.

The error in the determination of τ_d is mainly due to the inaccuracy in the value of τ_r substituted in (4). The relative error in the determination of τ_r from (3) can be represented in the form

$$\frac{\Delta\tau_r}{\tau_r} \approx \frac{\Delta\alpha}{\alpha} + \frac{2\Delta n}{n}$$

(it is recognized here that the experimental recombination-coefficient points shown in Fig. 7 are normalized with respect to density). The error in the determination of the coefficient α, owing to its strong dependence on the plasma temperature, is due mainly to the error in the determination of the temperature, which in individual measurements could reach $\Delta T/T \approx 0.2$; the probable error (the number of measurements was not less than 3) is estimated at $\lesssim 0.1$. The probable relative error in the determination of the density is estimated at $\lesssim 0.05$. If it is recognized that near $T \approx 0.6$ eV, as follows from[21], the recombination coefficient is approximately proportional to T^{-3}, then the probable relative error is $|\Delta\tau_r/\tau_r| \le 0.4$.

Figures 5 and 8 show the error fields of the quantity τ_d, obtained when account is taken of the probable relative errors of $\Delta\tau_r/\tau_r = 0.4$ and $\Delta\tau_n/\tau_n = 0.1$ (in Fig. 5 the error field is shown only in the region where the experimental dependence is compared with the theoretical one). We see that the primary experimental relations $\tau_n(\epsilon^2)$ and $\tau_n(H_0)$ do not intersect the error field. The theoretical relation $\tau_c(\epsilon^2)$ lies within the error field in its entirety and the $\tau_c(H_0)$ relation partly. The poorer approximation of the $\tau_d(H_0)$ relation to $\tau_c(H_0)$ in Fig. 8 is probably due to the fact that the experimental dependence was obtained at $\epsilon \approx 0.5$ ($\vartheta \approx 2\pi$ on the magnetic surface inscribed in the chamber), when a decrease of the diffusion dimension of the plasma due to the resonant perturbations of the magnetic field is to be expected. From Figs. 5 and 8 we can conclude that the relations $\tau_d(\epsilon^2)$ and $\tau_d(H_0)$ agree quantitatively with the theoretical ones, at any rate with accuracy not worse than by a factor of ~ 2.

4. CONCLUSION

The results and their discussion lead to the conclusion that in the case of a relatively small contribution of the turbulence to the transport processes, the main experimental dependences of the plasma diffusion time on the magnetic field and on the angle of rotational transformation, in a two-helix stellarator under the condition $\lambda_{ei} \ll L$ are in satisfactory agreement functionally (and with allowance for the measurement errors, also quantitatively) with the hydrodynamic model of classical diffusion of a plasma in a toroidal helical magnetic field. An estimate of the time of diffusion from the Bohm relation, at $T_e \le 0.6$ eV, gives a value that exceeds the observed one by more than one order of magnitude, thereby confirming both the correctness of the choice of the experimental conditions and the main conclusion of the present paper. We note also that during the measurement time, the density and the energy of the plasma decayed monotonically without visible symptoms of instability, at signals up to frequencies $\sim 1 \times 10^6$ Hz, determined by the bandwidths of the measuring channels.

The authors are grateful to V. A. Zhdanov, S. E. Il'inskiĭ, and I. S. Furs for help with the experiments.

[1] G. I. Budker, in: Fizika plazmy i problema upravlyaemykh termoyadernykh reaktsiĭ (Plasma Physics and the Problem of Controlled Thermonuclear Reactions). V. 1, AN SSSR, 1958, p. 66.

[2] D. Pfirsch and A. Schlüter, Report of the Max-Planck-Institute, Münich, MPI/PA/7/, 62, 1962.

[3] G. Knorr, Phys. of Fluids, 8, 1334 (1965).

[4] B. B. Kadomtsev and V. D. Shafranov, Dokl. Akad. Nauk SSSR 167, 65 (1966) [Sov. Phys.-Dokl. 11, 205 (1966)].

[5] V. D. Shafranov, Atomnaya énergiya 19, 120 (1965).

[6] V. D. Shafranov, in: Voprosy teorii plazmy (Problems of Plasma Theory), No. 5, Gosatomizdat, 1967.

[7] I. G. Gorman and L. H. Th. Pietjens, Phys. of Fluids, 9, 2504 (1966).

[8] W. Stodiek, D. T. Grove, and I. O. Kessler, Plasma Physics and Controlled Nuclear Fusion Research 2, IAEA, Vienna, 1966, p. 687.
[9] A. S. Bishop and E. Hinnov, Plasma Physics and Controlled Nuclear Fusion Research 2, IAEA, Vienna, 1966, p. 673.
[10] P. Ya. Burchenko, B. T. Vasilenko, E. D. Volkov, O. S. Pavlichenko, V. A. Potapenko, V. A. Rudakov, F. F. Tereshchenko, V. T. Tolok, V. M. Zalkind, V. G. Zykov, V. I. Karpukhin, and N. I. Rudnev, Plasma Physics and Controlled Nuclear Fusion Research, 1, IAEA, Vienna, 1969, p. 543.
[11] D. Eckhart, G. v Gierke, and G. Grieger, Plasma Physics and Controlled Nuclear Fusion Research, 2, IAEA, Vienna, 1966, p. 719.
[12] E. Berkl. D. Eckhart, G. v. Gierke, G. Grieger, E. Hinnov, K. N. v., Hagenow, and W. Ohlendorf. Plasma Physics and Controlled Nuclear Fusion Research, 1, IAEA, Vienna, 1969, p. 513.
[13] V. N. Bocharov, V. I. Volosov, A. V. Komin, V. M. Panasyuk, and Yu. N. Yudin, Plasma Physics and Controlled Nuclear Fusion Research, 1, IAEA, Vienna, 1969, p. 561.
[14] T. E. Stringer, Phys. Rev. Lett., 22, 770 (1969).
[15] R. W. Mottley, and A. F. Kuckes, Proc. of the Fifth Intern. Conference on Ionization Phenomena in Gases, 1, Munich, 1961, North-Holland Publishing Company. Amsterdam, 1962, p. 651.
[16] E. Hinnov and J. G. Hirschberg, Phys. Rev., 125, 795 (1962).
[17] G. I. Batanov, M. S. Berezhetskiĭ, S. E. Grebenshchikov, N. M. Zverev, A. P. Popryadukhin, M. S. Rabinovich, I. S. Sbitnikova, and I. S. Shpigel', Dokl. Akad. Nauk SSSR 160, 1293 (1965) [Sov. Phys.-Dokl. 10, 144 (1965)].
[18] L. M. Kovrizhnykh, Zh. Tekh. Fiz. 33, 377 (1963) [Sov. Phys.-Tech. Phys. 8, 281 (1963)].
[19] M. S. Berezhetskiĭ, S. E. Grebenshchikov, I. A. Kossyi, Yu. I. Nechaev, M. S. Rabinovich, I. S. Sbitnikova, and I. S. Shpigel', Plasma Physics and Controlled Nuclear Fusion Research, 1, IAEA, Vienna, 1969, p. 529.
[20] V. E. Golant, Usp. Fiz. Nauk 79, 377 (1963) [Sov. Phys.-Usp. 6, 161 (1963)].
[21] D. R. Bates, A. E. Kingston, and R. W. P. Whirter, Proc. Roy. Soc., Ser. A, 267, 297 (1962).
[22] A. I. Moroz and L. S. Solov'ev, in: Voprosy teorii plazmy (Problems of Plasma Theory), No. 2, Gosatomizdat, 1963.

Translated by J. G. Adashko
63