energiya"). Therefore the transformation of a barely "trapped" particle into a transiting particle changes its position relative to the magnetic surface by a finite amount.

When account is taken of the collisions between the "trapped" and transiting particles, a transition layer is produced in phase space. In the transition layer itself, the effective collision frequency turns out to be of the order of the frequency of revolution in the "banana" in the transverse plane of the toroidal tube ω_E, and the diffusion calculated in the approximation of a finite random step, has the Bohm coefficient as its scale. However, since the number of particles in the transition layer decreases with increasing collision frequency, the total diffusion coefficient also decreases[2]:

$$\left.\begin{aligned} &D \sim \left(\frac{\nu\Lambda}{\varepsilon_h\omega_E}\right)^{1/2}\varepsilon_h^{1/2}\varepsilon_t^2\frac{cT}{eB_0}\left(\frac{\omega_*}{\omega_E}-1\right),\\ &\varepsilon_t/\varepsilon_h < (\nu/\varepsilon_h\Lambda\omega_E)^{1/2} < 1,\\ &\omega_* = \frac{cT}{eB_0 r}\frac{d(\ln n)}{dr},\quad \Lambda = \frac{1}{2}\ln\left(\frac{\omega_E\varepsilon_h}{\nu}\right),\quad \omega_E = \frac{c}{rB_0}\frac{d\Phi}{dr};\end{aligned}\right\} \qquad (2)$$

here ν is the collision frequency, $\Phi(r)$ is the potential of the electric field, and $n(r)$ and T are the densities and temperature of the particle.

In the case of less frequency collisions, it is necessary to take into account the fact that there exists an intermediate class of banana-like trajectories, which go over into transiting trajectories (see Fig. 2). For such particles, the deviation from the magnetic surface is the smaller, the smaller the fraction of the trajectory on which they are "trapped" in the region of the weak helical field. For these particles, a small change in velocity, due to collisions, leads to a small change in the deviation. Consequently, the diffusion coefficient, just as in axially-symmetrical systems, turns out to be proportional to the collision frequency:

$$D \sim \frac{\nu}{\omega_E\varepsilon_t}\varepsilon_h^{1/2}\varepsilon_t^2\frac{cT}{eB_0}\left(\frac{\omega_*}{\omega_E}-1\right), \qquad (3)$$

where the thickness of the boundary layer is assumed to be smaller than the width of the region of intermediate trajectories:

$$(\nu/\omega_E\varepsilon_h\Lambda_*)^{1/2} < \varepsilon_t/\varepsilon_h,\quad \Lambda_* = \ln(\varepsilon_h/\varepsilon_t).$$

[1]A. A. Galeev and R. Z. Sagdeev, Zh. Eksp. Teor. Fiz. 53, 348 (1967) [Soviet Phys. 26, 233 (1968)].
[2]A. A. Galeev, R. Z. Sagdeev, H. P. Furth, and M. N. Rosenbluth, Phys. Rev. Lett. **22**, 511 (1969).

M. S. Rabinovich and I. S. Shpigel'. Plasma Containment in the Stellarator "Liven'-1" of the Physics Institute of the USSR Academy of Sciences.

In light of modern concepts, the most promising magnetic traps in which prolonged plasma containment can be realized are closed toroidal traps. These include the Tokamak, the stellarator, and many other systems.

Unlike open systems with magnetic-field force lines that emerge to the outside, in toroidal systems the force lines constitutes a helix that winds around the magnetic axis of the system, forming the so-called magnetic surface. As the force lines makes one turn around the principal axis of the torus, it rotates relative to the magnetic axis by a certain angle i, called the conversion turning angle. In stellarators, the turning conversion and the magnetic surfaces are produced with the aid of external currents, whereas in the Tokamak they are produced by currents flowing in the plasma pinch. The slanting of the force lines, i.e., the dependence of the angle of transformation i on the small radius of the torus, is called the "shear" θ. If $\theta \neq 0$, then it is possible in principle to obtain an almost stable plasma, and the stabilization of the different instabilities depends essentially both on the parameters of the plasma itself (large or small mean free path of the particles), and on the form of the instabilities that develop in it.

For many years, plasma containment in stellarators has been under study at the Physics Institute of the USSR Academy of Sciences (FIAN). The investigations have been carried out with a specially constructed strictly circular stellarator "Liven'-1" (L-1) with a double helical winding. Such a scheme has made it possible to avoid a number of disturbances inherent in other stellarators, which use linear sections of a homogeneous field, and by the same token to improve greatly the quality of the magnetic field of our setup.

An original procedure was used to demonstrate experimentally, for the first time, the existence of magnetic surfaces and their destruction at resonant values of the twist angle ($i/2\pi = l/m$, where l and m are integers) under the influence of the corresponding harmonics of the perturbations.

The vacuum chamber was filled with plasma by injection. The plasma temperature ($T_e \approx 5-10$ eV, $T_i \approx 20-30$ eV) and its density ($n \approx 10^{10}-10^{11}$) were such as to ensure smallness of the collision frequencies and accordingly large mean free paths $\lambda > L = 2\pi R$ (R is the radius of the torus). As is well known, a similar condition ($\lambda > L$) must be realized for the containment of a plasma having thermonuclear parameters ($n \approx 10^{15}$, $T_e \approx T_i \approx 10^4$ eV) in a hypothetical reactor ($R \sim 10^3$ cm). In this sense, our experiments are a definite approximation in the simulation of a thermonuclear plasma.

A study of plasma containment, carried out with the stellarators of the Princeton University, has shown that under conditions when the collision frequencies are high and the mean free path of the particles is small ($\lambda < L$), the diffusion is described by the following empirical formula, proposed by Bohm: $D \approx cT_e/16eH$. Our experiments have shown that under conditions of a large mean free path of the particles ($\lambda > L$) the diffusion coefficient decreases and the time of plasma containment exceeds the Bohm value by approximately one order of magnitude. However, even this containment time turns out to be sufficiently small, and until recently no theoretical model has been proposed describing such a plasma behavior. In 1968, papers were published by Galeev, Sagdeev, and Furth and also by Kovrizhnykh, in which attention was called to the significant role played by the special group of particles, the presence of which is due to the toroidal character and satisfying the condition $v_\parallel/v_\perp < (r/R)^{1/2}$ (where r is the minor radius of the torus and $v_\parallel$ and $v_\perp$ are the longitudinal and transverse particle velocities relative to the magnetic field direction). These particles are "trapped" between regions of large containing-field intensities, due to the toroidal geometry. In stellarators there is one more group of particles "trapped" between the "mirrors" produced by the helical field. The displacement of the "trapped" particles relative to the magnetic surfaces is much larger than that of the particles that pass through, and in the case of a weak-collision plasma this leads to an appreciable increase of the diffusion.

In the collision-diffusion theory in which the toroidal geometry is taken into account, the rate of departure of particles of various kinds (ions or electrons) is different, and by virtue of the ambipolar character of the losses this leads to the appearance of an equilibrium electric field equalizing the diffusion drifts of the ions and electrons.

The comparison of the characteristics of plasma containment in the stellarator "Liven'-1" with the results of Kovrizhnykh has shown that the electric field and the functional dependences of the field and the containment time on the magnetic-field intensity agree quite well. The difference between the calculated containment time and the experimentally observed value is due, in particular, to the fact that the theory is used at the borderline of its validity.

Another mechanism capable of determining the plasma containment time is the turbulent loss due to the low-frequency oscillations. Measurements have shown that in the plasma of the stellarator L-1 there exist in the region of the density gradient oscillations whose frequency is 20—100 kHz. The region of their localization is ~1 cm, the azimuthal wavelength is ~3—5 cm, and its mode is determined by the conversion angle. Thus, the second and fourth modes are observed at a conversion angle $i = \pi/2$, the third mode is observed at $i = 4\pi/3$, etc.

To estimate the role played by these oscillations in the observed containment time, measurements were made of the flux $\Gamma = cH^{-}\langle \tilde{E}\tilde{n} \rangle$, where $\tilde{E}$ and $\tilde{n}$ are the oscillations of the electric field and of the plasma density, and $\langle \dots \rangle$ denotes time averaging. Preliminary results show that in spite of the fact that the "shear" present in the setup ($\theta \sim 10^{-2}$) is insufficient to stabilize the drift oscillations, the particle flux amounts to ~0.1 of the total diffusion flux, i.e., the particle escape is not determined by the observed oscillations.

Thus, the results of an experimental investigation of the containment of a plasma with a large mean free path in the "Liven'-1" stellarator allow us to assume that one of the main mechanisms of loss is the diffusion due to paired collisions. The contribution of the turbulent diffusion to the plasma loss is small.

Of course, it is impossible to assume that the conclusions drawn here make it possible to extrapolate our results to the conditions under which a much more dense and hotter plasma is contained. At the present time these conclusions can serve only as a working hypothesis. Indeed, simulation of the containment of a thermonuclear plasma has been reduced only to satisfaction of the condition $\lambda > L$, i.e., turned out to be very limited. To verify this hypothesis concerning the classical character of the diffusion, it is necessary to perform experiments with a denser and hotter plasma using a number of other installations of similar type.

The experiments on the L-1 stellarator were performed by D. K. Akulina, M. S. Berezhetskiĭ, S. E. Grebenshchikov, I. A. Kossyĭ, Yu. I. Nechaev, A. P. Popryadukhin, I. S. Sbitnikova, and the authors of this paper.

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