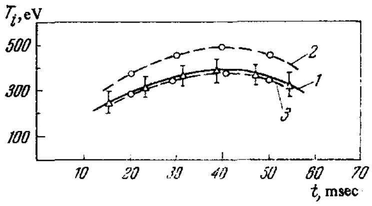
servations. It is possible to explain the second-class periods of the pulsars, either by foregoing the hypothesis wherein the pulsar pulsates as a whole, or by finding other equations of state for the neutron stars.

L. A. Artsimovich. Heating of Ions in "Tokamak" Machines.

Results are reported of experiments on heating of ions in a toroidal plasma pinch with the "Tokamak" machine. It was shown earlier that by choosing the necessary ratios of the longitudinal and transverse magnetic fields it is possible to obtain a stabilized plasma pinch with a lifetime on the order of 5×10^{-2} sec. The heating of the electrons is due to the Joule loss of the current in the plasma. It is shown that heating of the ions in the plasma at relatively high concentrations ($\sim 3 \times 10^{13}$ cm^{-3}) occurs mainly as a result of Coulomb collisions with hot electrons, whereas at lower plasma density the heating of the ions calls for the presence of specific plasma processes connected with development of instabilities.

One of the most important experimental problems with the "Tokamak" is the determination of the ion temperature T_i. For many years T_i was determined from the energy spectrum of the neutral atoms emerging from the plasma pinch. Such atoms result from charge exchange of the plasma ions with the atoms of the neutral gas, and contain information concerning the energy of the plasma ions. This method was developed at the Physico-technical Institute of the USSR Academy of Sciences (Leningrad). For an independent estimate of T_i at an ion temperature exceeding 300 eV, use was also made of registration of the neutron emission from the volume of the toroidal chamber as a result of the D-D reaction. Although the intensity of the neutron emission is small ($\sim 10^6$ neutrons per pulse), the sensitivity of the apparatus makes it possible to measure T_i for ~ 30–40 msec.

The $T_i(t)$ curves obtained from an analysis of the spectrum of the neutral atoms (curve 1) and the intensity of the neutron radiation (curves 2 and 3, assuming different forms of the $T_i(t)$ distribution inside the plasma pinch) are shown in the figure, from which we see that measurements of $T_i(t)$ by two independent methods give satisfactory agreement. The ion temperature turns out to lie within 300–400 eV for the entire measurement interval.



A. A. Galeev and R. Z. Sagdeev. Paradoxes of Classical Diffusion of Plasma in Toroidal Magnetic Traps.[1,2]

The authors consider of the increase of classical plasma diffusion, due to the presence of particles locked in the region of a weak toroidal magnetic field. It is assumed that the larger classical diffusion[1] compared with that in straight systems) has already been observed in the simplest traps having axial symmetry ("Tokamak"). Therefore particular attention is paid to the distinguishing features of this effect in traps that do not have actual symmetry. By way of a concrete example, a model of a triple-loop stellarator with small toroid ratio is considered. The magnetic field near the magnetic axis z (which is aligned with the minor axis of the torus) is of the form

$$B_z = B_0 \{1 - \varepsilon_h \cos [3 (\vartheta - \alpha z)] - \varepsilon_t \cos \vartheta\} \qquad (\varepsilon_t \ll \varepsilon_h \ll 1). \tag{1}$$

It is noted that in an axially-symmetrical magnetic field ($\epsilon_h \equiv 0$) the trajectories of the "trapped" and transiting particles differ in their topology, but each changes over continuously into the other (Fig. 1). Consequently, a small change of the particle velocity along the field can transform the particle from a "trapped" one into a particle that passes through, but changes the inclination of the particle to the magnetic surface also by a small amount.

On the other hand, particles that are "trapped" in the region of a weak helical field in a stellarator ("banana") are capable of moving under the influence of the toroidal drift by a finite amount, while those that pass through follow the magnetic surface strictly (Fig. 2 shows the trajectory of a "trapped" particle which goes over into the region of the weak toroidal field into a particle that passes through; the figure is borrowed from the article of A. Komin et al. ("Atomnaya

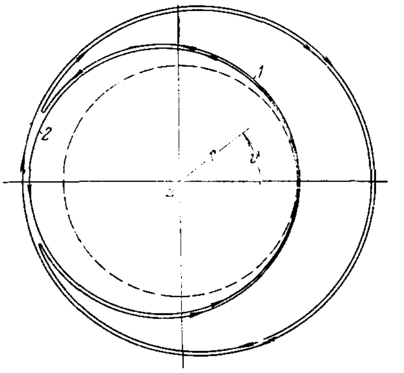


FIG. 1. Trajectories of "trapped" (1) and transiting (2, 2′) particles in a magnetic field with axial symmetry.

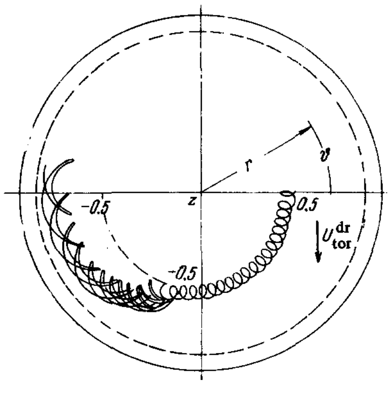


FIG. 2. Trajectory of a particle changed from a "trapped" one into a transiting one by the inhomogenities of the helical field.

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 ωE, 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]:

$$\left.\begin{aligned} &D \sim \left(\frac{\nu\Lambda}{\varepsilon_h\omega_E}\right)^{1/2}\varepsilon_h^{1/2}\varepsilon_t^2\frac{cT}{eB_0}\left(\frac{\omega_*}{\omega_E}-1\right),\\ &\varepsilon_t/\varepsilon_h < (\nu/\varepsilon_h\Lambda\omega_E)^{1/2} < 1,\\ &\omega_* = \frac{cT}{eB_0r}\frac{d(\ln n)}{dr},\ \Lambda = \frac{1}{2}\ln\left(\frac{\omega_E\varepsilon_h}{\nu}\right),\ \omega_E = \frac{c}{rB_0}\frac{d\Phi}{dr};\end{aligned}\right\} \qquad (2)$$

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:

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

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[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