EXCITATION AND THERMALIZATION OF PLASMA OSCILLATIONS IN A STELLARATOR

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Numerous experiments with electric discharges, carried out in a variety of installations, demonstrate convincingly the need for taking into account the collective processes that take place in a plasma in the presence of a group of accelerated particles. From an analysis of the available data we can conclude that these processes are manifest in almost any case when the plasma is heated directly in a trap and the electron temperature T_e is at the same time higher than or of the same order as the ion temperature [1-4].

The present investigation was devoted to a study of the influence of collective processes on the behavior of a plasma in a stellarator. The experiments were made with the closed magnetic trap "Sirius," which comprises a racetrack with two trifilar helical windings placed on the toroidal sections. The "Sirius" stellarator has a vacuum chamber with axial length l = 600 cm and minor diameter d = 10 cm, a maximum retaining field $H_0 = 2 \times 10^4$ Oe, and

$$\beta_c = \frac{nkT}{H_0^2/8\pi} = 75 \times 10^{-4}.$$

To excite intense collective oscillations, a longitudinal electric field of large amplitude, $E \geq E_k = 1.58 \times 10^{-8}\, n/T_e$ [5], was applied, by discharging a 0.8 μF capacitor bank charged to 5.15 kV, to a plasma produced in the stellarator chamber by a pre-ionization generator. All the experiments were made at initial neutral-helium pressures 5×10^{-5} - 8×10^{-4} mm Hg.

During the course of the experiments we measured the plasma current and the loop voltage in the chamber, the plasma density, the x-radiation from the diaphragm limiting the dimensions of the plasma pinch and from the chamber walls, the microwave radiation from the plasma, and the integral amount of light.

When the discharge was produced at an electric field intensity lower than the critical Dreicer field E_k, the current signal was sinusoidal in form. With increse in field, the signal waveform became distorted, and at $E > E_k$ the current decreased, after build-up of the oscillations, to a value I = 100 - 200 A, at which level it remained for 10 - 20 μsec, although a rather large electric field was applied to the plasma (Fig. 1a).

A study of the dependence of the plasma impedance Z on the electric field has shown that Z increases with increasing E. Whereas the plasma impedance changes insignificantly in fields $E/E_k < 2$, it increases from 1 to 8 ohms (Fig. 2) when a field from $E = 2E_k$ to $E = 10E_k$ is applied.

In all the intervals of the investigated neutral gas pressure and electric and magnetic field intensities the discharge was accompanied by microwave emission from the plasma. At an electric field intensity $E < E_k$ the microwave radiation was most intense at wavelengths

λ = 2 - 4 cm, i.e., in the immediate vicinity of the Langmuir frequency. It must be noted that no radiation was observed at the Langmuir frequency itself, although apparatus with sensitivity one order of magnitude higher was used for its detection. With increasing electric field, the power radiated in the wavelength range λ = 2 - 4 cm increases and becomes maximal at E/E_k = 2 - 4. Further increase in E/E_k leads to weakening of the radiation. At the same time, when the electric field intensity is $E \geq E_k$ a broad spectrum of oscillations is excited in the plasma at wavelengths λ = 4.6 - 600 cm (Fig. 1, b - e), with the maximum radiated power in the interval λ = 12 - 15 cm, corresponding in our case to a Buneman frequency $\omega = \omega_0(m/M)^{1/3}$.

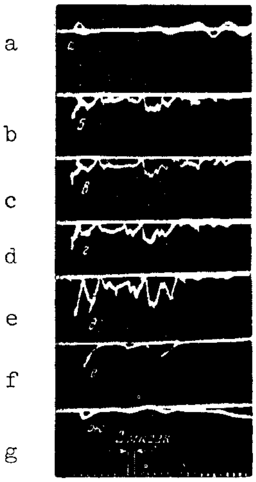

Fig. 1. Variation of plasma parameters with time: a) current, b - e) microwave radiation at the following wavelengths (λ): 7.5 - 10 cm (b), 10 - 15 cm (c), 12 - 600 cm (d), 15 - 600 cm (e); f) x-radiation; g) integral light.

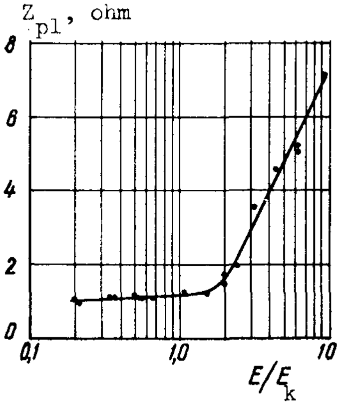

Fig. 2. Plasma impedance vs. electric field intensity.

In electric fields stronger than critical, the plasma emits intense x-rays (Fig. 1, f), which are registered at the instant of occurrence of instability both from the diaphragms bounding the dimensions of the plasma column and from the walls of the chamber and of the x-ray probe located in the chamber at the plasma boundary. If a beam of energy ranging from 100 to 200 keV is incident on the plasma, corresponding to electron acceleration in a field E = 10 V/cm with a time t = 1 μsec ($W = (eEt)^2/2m$), then it can be concluded from the absorption spectra of the x-rays from the chamber walls that the plasma contains a group of electrons with almost-Maxwellian velocity distribution, and with a temperature that ranges from 4 to 9 keV as the capacitors are charged to 10 - 15 kV.

It is interesting to note that measurements of the integral amount of light have shown that at the instant of excitation of the collective processes and appearance of x-radiation from the chamber walls the intensity of plasma glow decreases abruptly (Fig. 1, g), thus confirming indirectly the fact that the electrons become heated.

In conclusion, we consider it our pleasant duty to thank K. D. Sinel'nikov for interest in the work and valuable discussions.

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HIGH-FREQUENCY INSTABILITY OF A PLASMA IN A RADIAL ELECTRIC AND LONGITUDINAL MAGNETIC FIELD

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Ioffe et al. [1] realized a plasma with hot ions by applying a potential between an axial ion beam (serving as an internal electrode) and the walls, thus producing a radial electric field in the plasma. The potential difference was increased to its maximum value within times on the order of 2 μsec and maintained constant for 25 - 30 μsec, after which it dropped to zero in a time of the order of 0.2 μsec. All these characteristic times greatly exceed the time of ion cyclotron rotation ($\omega_{Bi}^{-1} = e_iB/M_ic \sim 10^{-2}$ μsec). The switching of the field on and off thus satisfies the adiabatic-approximation requirement ($\partial \ln E_r/\partial t \ll \omega_{Bi}$), and from the point of view of the adiabatic theory the ion energy should have approximately the same value after the field is switched off as before its application, i.e., several electron volts. However, an appreciable number of ions with energy of the order of hundreds of electron volts were observed in the experiment. This indicates that irreversible processes, which are beyond the scope of adiabatic theory, have taken place in the plasma.

It is therefore natural, when attempting to interpret the ion heating in these experiments, to ascertain which high-frequency instabilities ($\omega \gtrsim \omega_{Bi}$) are possible in a plasma situated in superimposed magnetic and radial electric fields.

To this end we consider the following idealized problem. Let a plasma with negligibly low particle temperature be situated in a magnetic field $\vec{B} \parallel \vec{z}$ and an electric field $\vec{E}$ ($\vec{E}_r$, 0, 0). (As is well known, in the presence of a magnetic field a quasistationary electric field perpendicular to it is capable of penetrating the plasma.) The fields $\vec{B}$ and $\vec{E}$ are assumed to be static. We consider the perturbation of such a system, assuming that the perturbation of the electric field is potential, $\vec{E} = -\nabla\psi$. Choosing the space-time dependence of the perturbed quantities in the form $f = f(r)\exp(im\varphi + ik_z z - i\omega t)$ and putting $\omega_{Be} \gg \omega \gg \omega_{Bi}$ and $f(r) \sim \exp(i\int k_r dr)$, we obtain from the equations of two-fluid hydrodynamics the equation

$$k_1^2\left\{1 + \frac{\omega_{Pe}^2}{\omega_{Be}^2} - \frac{\omega_{Pi}^2}{[\Omega - \frac{m}{r}(v_i - v_o)]^2}\right\} - \left(k_z\frac{\omega_{Pe}}{\Omega}\right)^2 - \frac{m}{r}\frac{\frac{\partial\omega_{Pe}^2}{\partial r}}{\omega_{Be}\Omega} = 0, \qquad (1)$$

where

$$\Omega = \omega - \frac{m}{r}v_o, \quad k_1^2 = k_r^2 + \left(\frac{m}{r}\right)^2, \quad \omega_{P_\alpha}^2 = \frac{4\pi e_\alpha^2 n}{M_\alpha}, \quad \omega_{B_\alpha} = \frac{e_\alpha B}{M_\alpha c}, \quad v_o = -\frac{cE_r}{B},$$

$$v_i = r\omega_{Bi}[-\tfrac{1}{2} + \sqrt{\tfrac{1}{4} + (v_o/r\omega_{Bi})}],$$

n is the plasma density, e_α and M_α are the charge and mass of the particles, and the subscripts