was confirmed in the very first measurements that the wave attenuates strongly in a collisionless plasma. The dissipation of the energy was in this case practically independent of the plasma concentration which was varied from 10^{11} to 10^{14} cm^{-3}. The experiments showed that almost 50% of the energy of the magnetic field of the wave, $\tilde{H}^2/8\pi$ went into heating the electrons and ions of the plasma. This was the first direct proof of the role of the collective processes in the propagation of strong magnetosonic waves in a plasma. As is well known, these experiments stimulated the development of a new field of plasma physics—the physics of collisionless shock waves. This plasma-heating effect was given the name of turbulent heating.

Subsequently, the instability of the current flowing along the magnetic field was discovered at our Institute. This instability also led to intense heating of the electrons and ions of the plasma. Experiments were set up in open as well as in closed magnetic traps. These experiments will be described here in detail.

Well-known methods as well as spectroscopic polarization Stark-effect measurements using image-converter tubes, UHF-radiation magnetic analyzers, and some others, were used to investigate the mechanism underlying turbulent heating.

The first experiments showed that to within 10^{-3}–10^{-5} of the number of the current electrons, no electrons escaped during turbulent heating when the plasma density did not exceed 10^{12}–10^{13} cm^{-3}. It was established with the aid of measurements of plasma concentration, current, diamagnetism, and the temperature of the electrons and ions, that the current velocity u_D of the electrons is, during turbulent heating, close to the velocity of ion sound $c_s = T_e/M$. These measurements established beyond doubt the ion-acoustic type of current instability. The spectrum of the plasma oscillations was measured with the aid of electric and magnetic probes. It turns out that the frequencies ω_{pi} appear at the beginning of the excitation of an instability ($\sim 10^{-8}$ sec), but later on the spectrum rapidly broadens on both sides of ω_{pi}. This effect should, apparently, be considered as a nonlinear interaction between the ion-acoustic oscillations. A theory of the Stark effect was worked out specially for the measurement of the ion-acoustic fields in a plasma, and measurements were made of the microfields in a plasma at the moment of turbulent heating. Strong anisotropy of the electric microfields in a turbulent plasma has been experimentally established. The ratio of the intensity E_z along the magnetic field to $E_x = E_y$ is, according to measurements, equal to 3, and this corresponds to an energy ratio of nearly 10.

The magnitude of the anomalous resistance of a plasma at the moment of the development of an instability turns out to be larger by many orders of magnitude than the normal plasma resistance. As follows from measurements, the anomalous resistance does not depend on the intensity of the electric field in the plasma.

The heating of the ions during turbulent plasma heating was studied on the TN-5 and "Ogra-2" facilities. The measurements showed that the temperature of the ions reach 3–5 keV. The energy distribution curve of the ions has a kink. It is possible that acceleration of part of the ions by the Landau mechanism on the ion-acoustic oscillations is responsible for this discontinuity.

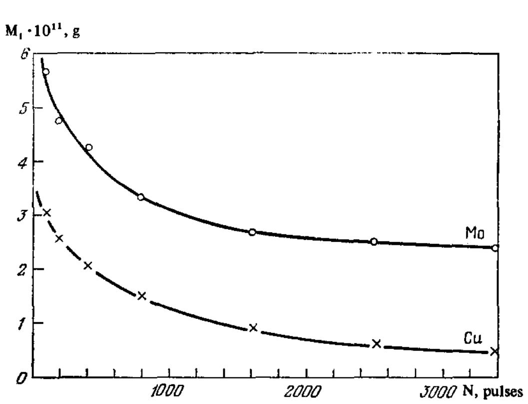
Experiments were carried out at the IAE on turbulent plasma heating in the "Tokamak" system. It follows from these experiments that turbulent heating can be used in traps with current confinement.

We should, in view of this, consider the question of the use of turbulent heating in traps of large dimensions. It is known that the depth of the skin effect of the current during turbulent heating is of the order of magnitude $\Delta = (c/\omega_{pi})\beta_{\varphi}^{-1/2}$, where c is the velocity of light, $\beta_{\varphi} = 8\pi nT/H_{\psi}^2$, H_{φ} being the magnetic field of the current giving rise to the turbulent heating. An estimate of the quantity Δ shows that $\Delta/r \ll 1$ for a plasma radius $r \approx 1$ m and $n > 10^{12}$ cm^{-3}. However, the concentration of the current at the surface could prove to be practically convenient if we could achieve turbulent heating of the core of the plasma cord as a result of the excitation of an additional spectrum of oscillations in the plasma and the transport of heat from the skin layer into the plasma. But the solution of this problem is possible only in experiments with traps which can confine hot plasmas well.

The solution of the formulated problem of plasma heating in traps, which was in the beginning a purely practical problem, led to the discovery of a fundamental property of plasmas: if the current density in a plasma attains a critical value, then an ion-acoustic instability is excited in the plasma as a result of which the plasma acquires an anomalously high resistance and the electron and ion components of the plasma are rapidly heated up. Thus, ordinary Joule heating of a plasma automatically develops into turbulent heating at the critical current value. The final temperature of the plasma is then determined by the value of the critical current and the density of the plasma.

V. P. Silin. Anomalous Nonlinear Dissipation of UHF Waves in a Plasma

About seven years ago theoretical investigations were undertaken at the FIAN in connection with the problems of radiative plasma acceleration formulated by V. I. Veksler. The theoretical ideas which emerged from these investigations led to the setting up experi-



Dependence of the mass of metal carried away from a needle per pulse on the number of pulses. The duration of a pulse is 10 nsec, the amplitude is 30 kV, d = 1 mm, the angle of the tip of the needle is 24°, and the radius of the tip after N > 1000, is about 8–10μ.

mental investigations into the properties of a plasma in a strong electromagnetic field. Theorems on the parametric resonance of a plasma in the electric field of a wave and initial theorems on the parametric action of a high-power radiation on a plasma were formulated in 1965. It was shown[1] that under the conditions when the oscillation speed of the electrons in the electric field of a wave exceeds their thermal velocity, a rapid buildup of the perturbations of the longitudinal field in the plasma takes place, the maximum increment in the vicinity of the resonances $n\omega_0 = \omega_{Le} = \sqrt{4\pi e^2 n_e / m_e}$ being of the order of magnitude $\omega_{Le}(m_e/m_i)^{1/3}$, while for $\omega_0 < \omega_{Le}$ outside the region $|n\omega_0 - \omega_{Le}| \sim \omega_{Le}(m_e/m_i)^{1/3}$ the increment has the value $\gamma \sim \omega_{Le}(m_e/m_i)^{1/3}$. The perturbations of wave length comparable with the amplitude of oscillation of an electron in the electric field of the pumping wave then grow with the maximum rate. In leading to the growth of the perturbations of the longitudinal field, the parametric resonance leads to an increase in the energy of the plasma particles. Thus, for the 2n-th harmonic of the distribution function (the electron distribution function itself will, on the development of a parametric instability in the plasma, contain a rapidly-varying part), we have

$$\frac{vt_p}{d} \ll 1, \qquad \frac{4{,}3\cdot 10^5 d^2}{RSU^{1/2}} = 1.$$

For times not very much exceeding $1/2\gamma$, the electron energy, which increases owing to the resonance in the n-th overtone of the external frequency, then turns out to be commensurable with the energy of the external field.

Allowance for thermal motion showed[2] that if $T_e \gg T_i$, then parametric effects of the plasma instability with respect to a buildup in the plasma of potential oscillations are possible when the electron Langmuir frequency is considerably smaller than the frequency of the external field; and when this happens the low-frequency ion-acoustic vibrations as well as the high-frequency waves will grow. A quasilinear theory[3], which was constructed for such an instability, made it possible to show the possibility of the appearance of an anomalously large high-frequency conductivity of a plasma. And what is more, it proved possible to estimate such a conductivity under the conditions of a strong field and the development of the instability in the immediate neighborhood of a resonance, when such a conductivity can attain values $\sim(m_e/m_i)^{1/3}\omega_{Le}$.

In the vicinity of the resonance $\omega_0 = \omega_{Le}$ the threshold values at which the instability appears are smaller[4]. For one of the cases when the parametric instability is similar to forced combination scattering (or, in a different terminology, when it pertains to the decay type of instabilities), a nonlinear theory of the stationary turbulence spectrum was constructed which made it possible to find the effective collision frequency. Under real conditions this frequency considerably exceeds the electron-ion collision frequency[5].

These theoretical investigations, which were carried out in the USSR, were confirmed and developed in a number of theoretical investigations carried out abroad and, in particular, in a number of numerical experiments carried out in the USA on electronic computers. Such experiments confirmed the ideas of the theory of the parametric effect of radiation on a plasma, and made possible a better understanding of the laws governing the development of parametric instabilities[6].

It is to be emphasized that, due mainly to theoretical investigations carried out at FIAN, a large number of laws has now been discovered which characterizes the parametric instabilities of a plasma under the action of an intense radiation that are connected with the possibility of the development of perturbations of the nonpotential field[7], as well as with the effect of such factors as the presence of a strong constant magnetic field[8] and spatial inhomogeneity of the plasma[9].

Experimental investigations have shown that under the conditions of the development of the theoretically predicted parametric instabilities, there occurs a development of increased drift of the plasma[10], an anomalous absorption by the plasma of the energy of the high-power radiation[11], and of a strong energy transfer to the plasma, which leads to a rise in temperature and the appearance of a large number of fast particles[12]. The effective collision frequency, by which such processes can be characterized, then turns out to be by many orders of magnitude higher than the frequency of the Coulomb collisions. The quantitative laws, characterizing the results of the experimental investigations, are, in quite a number of important cases, in agreement with theory.

We can assert that at the present time a sufficiently large number of theoretical and experimental results have been accumulated which allow us to speak of a qualitatively new picture of the action of an intense high-frequency radiation on a plasma, for which the decisive thing is the development of plasma instabilities capable of manifesting themselves as a frequency transformation of the pumping radiation and as the onset of a turbulent state of the plasma. The development of a turbulent state qualitatively changes the high-frequency properties of the plasma, which, in particular, manifests itself in the conductivity of the plasma. In conclusion, we should emphasize that such a picture makes sense in the microwave, as well as in the optical region of laser frequencies.

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V. E. Golant. Ultrahigh-frequency Methods of Plasma Heating

As is well known, one of the main problems of controlled thermonuclear fusion is the heating of a plasma to "thermonuclear" temperatures. Interest in the search for suitable methods of heating has particularly deepened in connection with the advances made in the confinement of plasma for prolonged periods in quasi-stationary toroidal magnetic traps. We discuss in this report the possibility of the application in such systems of high-frequency methods of heating. In order to reduce the influence of these methods on the confinement of the plasma to a minimum, it is desirable to accomplish them at the smallest possible values of the power fed into the plasma, and to employ linear absorption mechanisms.

As is shown by analysis (see[1,2]), the most effective conditions for linear absorption of high-frequency waves can be realized if we excite in the plasma longitudinal waves with a large refractive index (the so-called plasma waves). A direct excitation of longitudinal waves is difficult to accomplish. However, an effective mechanism exists in a nonuniform plasma for the conversion of externally introduced transverse waves into longitudinal plasma waves. Such a conversion in a plasma, confined by a magnetic field can occur in the regions of the upper hybrid frequencies $\omega = \sqrt{\omega_p^2 + \omega_{He}^2}$ and lower hybrid frequencies

$$\omega = \left[\omega_{He}\omega_{Hi}\,\frac{\omega_p^2 + \omega_{He}\omega_{Hi}}{\omega_p^2 + \omega_{He}^2}\right]^{1/2}$$

(ω_{He} and ω_{Hi} are the electron and ion cyclotron frequencies, and ω_p is the plasma frequency)*. A theoretical analysis shows that the efficiency of the linear conversion can, under suitable conditions, be fairly high[1-3]. It is important that the efficiency then turns out to be practically independent, under a wide range of conditions, of the plasma temperature and the collision frequency of the charged particles[4]. Thus, the conversion of transverse waves into plasma waves may result in their efficient absorption.

Wide-ranging experimental investigations of the absorption of high-frequency waves, directed towards the establishment of the absorption mechanism, have been carried out at the A. F. Ioffe Physico-technical Institute of the USSR Academy of Sciences (a review of the principal experiments on the absorption is given in[2]). These investigations were carried out in the frequency range 9–10 GHz, 3–4 GHz, and 100–200 MHz at powers of from 1 mW to 20 kW for a wide range of plasma parameters (plasma in H_2, He, and Ar at pressures of 10^{-5}–10^{-1} mm Hg, charged-particle concentrations of 10^{10}–10^{13} cm^{-3}, electron temperatures of 3–10 eV, in specific experiments up to 1000 eV, and magnetic fields of up to 5 kOe; the radius of the plasma was 1–5 cm).

The experiments showed, first and foremost, that effective absorption can be observed within the limits of sharply bounded frequency bands[5-8]. The boundaries of these bands practically coincide with the theoretical boundaries of the frequency regions in which wave conversion is possible.

Further, measurements were made of the high-frequency field distribution (with the aid of probes and from the Stark broadening of the spectral lines), and the localization of the absorption region (with the aid of electrostatic probes)[9,10]. The data obtained as a result of these measurements, are in good agreement with the proposition that the absorption is connected with the conversion of the waves fed into the plasma into slow, strongly-damped plasma waves. In particular, the measurements of the amplitudes of the high-frequency field intensity in the conversion region and the measurements of the attenuation distance of the plasma waves are in agreement with theory.

Finally, we must mention the measurements of the efficiency of absorption of UHF waves and of plasma heating within the limits of the conversion regions[5-8]. In conformity with theoretical predictions, the efficiency of absorption turned out to be weakly dependent on the collision frequency and the energy of the charged particles when these quantities were varied by several orders of magnitude. It also changed little when the

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*For the parameters of quasi-stationary thermonuclear installations, both of these regions fall in the ultrahigh-frequency region.