centers on its surface. Multineedle cathodes and cathodes with a dielectric are examples of such cathodes. If the explosion time of the emitting needles $t_d \ll t_f$, the mean distance between the emitting centers $a \ll d$, and the surface area of the cathode $s \gg d^2$ (t_f is the rise time of the front of a pulse, while d is the distance between the anode and the cathode), then for such a diode the "(3/2)-power" law is obeyed. The conditions for maximum efficiency of such a diode are

$$\int d\mathbf{p} \frac{p^2}{2m_e} F_e^{(2n)} \sim \frac{\varkappa T_e}{r_E^3} e^{2\gamma t}.$$

where R is the wave impedance of the line, and t_p is the pulse duration.

Controlled cathodes with a dielectric allow us, on account of an initial input of a master pulse, to fill a diode with a plasma and increase the beam perveance by a factor of 10 or more[10].

Two types of accelerators using the explosive emission of electrons have been developed: one with a controlled cathode which operates at a voltage of 500 keV and a current of 10 kA[10]; the second type—with multineedle cathodes, which operate at a voltage of 1000 keV and a current of 50 kA[11].

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E. K. Zavoĭskiĭ. Turbulent Plasma Heating

In a paper on the problem of controlled thermonuclear fusion presented at a recent session of our division by L. A. Artsimovich, only the problem of the confinement of a plasma in closed magnetic traps, mainly in Tokamaks, were considered. However, there is in the thermonuclear problem a no less important aspect—the production of a hot plasma. And this can be seen on the example of the same Tokamaks, for which the problem of plasma heating is still an unsolved problem. A hot plasma is necessary not only for filling traps. Its production is important in its own right, since it is possible to construct a thermonuclear reactor without confinement—thermonuclear mini-explosions. This way of solving the problem has in a number of cases advantages and, undoubtedly, its regions of applicability. Such a detonation of a DT mixture by an electron beam or by a laser may produce the effect of detonation of a relatively large block. In this case the question of the efficiency of the device initiating the detonation does not practically arise, and this is important. However, I shll not touch upon this side of the matter.

Why does the problem of plasma heating arise at all? It seems natural to pass a current through the plasma and Joule heating will lead to the desired result. However, as is well known, the Coulomb cross section, which determines the resistance of the plasma, decreases as v^3, i.e., as $T_e^{3/2}$. Therefore, at thermonuclear temperatures (~10 keV), the resistance of the plasma is about one-hundredth of the resistance of copper and huge current densities are required to heat up the plasma. Of course, we could heat the plasma with a low current but for a long time. This is impossible, since, in the first place, a hot plasma radiates, and, on the other hand, energy losses due to diffusion across the magnetic field is fairly high. Obviously, the current cannot be severely reduced, for then equilibrium between heating and losses will set in at a low temperature of the plasma.

In the early Sixties, when physicists were perplexed by newer and newer plasma instabilities in different magnetic traps, suggestions were made at the Institute of Atomic Energy (IAE) and experiments were begun on the use of certain types of instabilities for plasma heating. Certain types of instabilities, such as the beam, the Budker-Buneman, and the ion-acoustic instabilities, were known at that time. Beam instability arises when the velocity of the electrons in a beam penetrating a plasma greatly exceeds the thermal velocity of the electrons of the plasma. The Budker-Buneman instability is excited when the ordered velocity of the electrons is somewhat higher than the thermal velocity of the plasma electrons. The ion-acoustic instability appears when the directed velocity of the electrons is of the order of the velocity of ion sound. However, the state of the theory of these instabilities was such that it was impossible to predict the effectiveness of the heating of the electrons and ions of a plasma on the appearance of these instabilities. It was also not certain that the excitation of these instabilities would not lead to a strong drift of the plasma from the traps. The first experiments were set up at the IAE with the object of detecting the collective effects in a plasma when the current flows across the magnetic field. In these experiments a high-intensity magnetosonic wave, propagating across the constant magnetic field, was produced in the cold plasma. It 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.

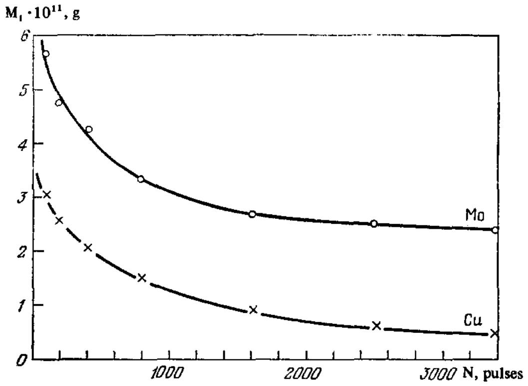
Experiments were carried out at the IAE on turbulent plasma heating in the "Tokamak" system. It follows from these experiments that turbulent heating can be used in traps with current confinement.

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.