responding exactly to the positions of the most intense lines of the stabilized structure from the doublet (±1/2), predicted by A. M. Afanas'ev and Yu. M. Kagan. An important fact in this case is also that the entire spectrum as a whole becomes sharper and more distinct. This greatly facilitates its interpretation.

The results show that the distances between the external lines of the spectra correspond to a hyperfine field 548 ± 3 kOe at the nucleus, and that the quadrupole interaction is $e^2qQ = 4P \approx 0.09$ cm/sec. These values agree well with the data of [3].

In connection with the great advantages afforded by this method of investigating the hfs in paramagnets when a stabilizing field is applied, we are now carrying out such investigations in a wide interval of temperatures, for the purpose of revealing the character of the spin-lattice relaxation, and also in a wide interval of Fe^{3+} impurity ion concentrations, for the study of the spin-spin relaxation.

Great interest attaches also to an investigation of single-crystal samples, which would make it possible to obtain detailed information on the structure of the crystalline environment (in particular, to sense very small deviations from axial symmetry), and also to verify the effect of the dependence of the positions of the lines of the stabilized spectrum on the direction of the external magnetic field relative to the crystal-symmetry axis.

The authors thank A. M. Afanas'ev and Yu. M. Kagan for the opportunity of reading [2] prior to publication, which stimulated the organization of this experiment, and are also grateful to M. L. Mel'man for preparing the samples.

[1] A. M. Afanas'ev and Yu. M. Kagan, Zh. Eksp. Teor. Fiz. 45, 1660 (1963) [Sov. Phys.-JETP 18, 1139 (1964)].
[2] A. M. Afanas'ev and Yu. M. Kagan, ZhETF Pis. Red. 8, 620 (1968) [JETP Lett. 8, 382 (1968)].
[3] G. K. Wertheim and J. P. Remeika, Phys. Lett. 10, 14 (1964).

HEATING OF PLASMA IONS BY AN EXTERNAL STOCHASTIC FIELD

O. M. Shvets, S. S. Kalinichenko, V. I. Kurilko, and G. A. Miroshinchenko
Physico-technical Institute, Ukrainian Academy of Sciences
Submitted 23 September 1968
ZhETF Pis. Red. 8, No. 11, 629-632 (5 December 1968)

High-frequency heating is regarded as one of the effective methods of heating ions in a plasma. This method was used to heat ions to energies 1 - 2 keV at particle densities $10^{13} - 10^{14}$ cm^{-3} in a volume of several liters [1]. Inasmuch as in high-frequency heating the ion energy is contained initially in the form of regular motion of the ions in the field of the wave, so that there are no particle collisions, a process leading to randomization of this motion is essential in order to ensure the fusion reaction.

When particles are accelerated in a stochastic field, there is no need for a special thermalization process, since the thermalization is ensured by the field itself. The possibility of heating particles by a stochastic field was first indicated in [2]. Heating of the electronic plasma component by a stochastic field was considered in [3]. To ensure stochastic heating of the plasma ions, it is necessary to ensure penetration of the field into the dense plasma, and simultaneous satisfaction of the condition $\tau_c \ll t$, where τ is the correlation time of the stochastic field and t is the particle lifetime in the trap. The expression for the average particle energy is [3]

$$\bar{\epsilon} = \frac{1}{4M} \frac{e^2 E^2}{(\omega - \omega_{ci})^2 + \tau_c^{-2}} \frac{t}{\tau_c},$$

where $\bar{\epsilon}$ - average particle energy, M - particle mass, E - electric field intensity in the plasma, e - electron charge, ω - generator frequency, and ω_{ci} - ion cyclotron frequency of the particle.

The experimental investigations of the stochastic heating of the ions were made with the "Vikhr'" setup [4], with a glass chamber. The plasma was produced by the same stochastic HF field used for the heating. The initial noise source was a gas-filled SG3P ballast tube, the noise spectrum of which lies in the frequency range 0 - 1.5 MHz. This spectrum was transformed with the aid of a ring-type balanced modulator into the employed frequency range, was amplified, and was fed to the output power amplifier (OPA). The OPA load was a resonant circuit loaded by the introduced plasma resistance. The operating frequency band was regulated both at the input and output of the OPA by decreasing the coupling of the output resonant circuit with the plasma. The band was measured in the continuous mode by means of an S4-8 spectrum analyzer, with a resistance equal to the equivalent plasma resistance connected to the resonant circuit. When working with the plasma, the OPA was used in the pulsed mode. The experiments were performed at operating bandwidthes $\Delta f = 200$ kHz and $\Delta f = 80$ kHz in the 2 MHz region, corresponding to the condition of excitation of ion-cyclotron waves ($\omega \leq \omega_{ci}$). The power introduced into the plasma was measured by the equivalent-resistance method, and the HF voltage by the square-law detector.

The experiments were performed far from the "magnetic edge," in order to be sure that the effect of its randomization is decreased. Under these conditions, differences between the ion energy distribution functions resulting from the action of stochastic and regular signals on the plasma were to be expected. The energy spectrum of the ions was determined with the aid of a transverse-energy probe operating on the blocking-potential principle [4]. An estimate of the density of the charged particles was by the method of cutting off the signal of a 3-cm generator. At a hydrogen pressure $P = 5 \times 10^{-3}$ mm Hg in the working chamber and at an output power 700 W, a plasma of density 10^{12} cm^{-3} was produced in a volume of 2 liters. Under these conditions, the ion lifetime was determined essentially by the collisions with the molecules of the neutral gas and amounted to $t = 100$ μsec. Consequently, the condition $\tau_c \ll t$ was satisfied for the signal with $\Delta f = 200$ kHz.

To observe differences in the energy spectrum in the case of action by means of a stochastic and a sinusoidal signal, a series of probe characteristics was plotted for different values of the external magnetic field intensity H. When the voltage at the input to the high-frequency working chamber was constant, the collector current of the probe at a blocking voltage $U_{bl} = 0$ was also constant.

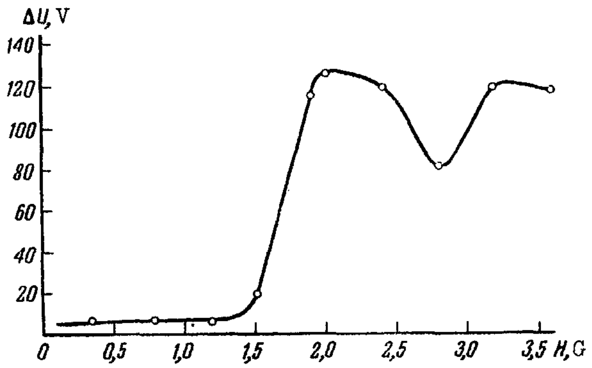

Fig. 1. Difference of the blocking voltages $\Delta V = U_{bl}^{stoch} - U_{bl}^{reg}$ vs. the intensity of the external magnetic field.

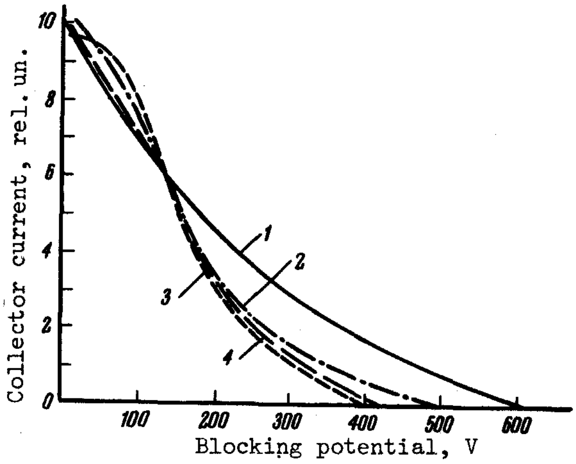

Fig. 2. Probe characteristics plotted for different signals ($H = 2.0$ kG, $P = 5.5 \times 10^{-3}$ mm Hg): 1) $\Delta f = 200$ kHz, 2) $\Delta f = 80$ kHz, 3) regular signal ($\Delta f = 0$), 4) regular signal modulated at a frequency $F = 40$ kHz and modulation depth $m = 80\%$.

The measurement results are shown in Fig. 1. It follows from the figure that the difference between the spectra is observed in that magnetic-field intensity region where ion-cyclotron waves are excited.

The probe characteristics obtained by applying to the plasma stochastic and regular signals (Fig. 2) show that the energy spectrum broadens when the bandwidth of the noise signal broadens. The energy distribution of the ions, determined from the dependence of the logarithm of the probe current on the blocking potential, approaches a Maxwellian distribution with increasing width of the signal band. However, the energy spectrum remains the same as in the case of a regular signal if a modulation signal with frequency $F = 40$ kHz and depth of modulation $m = 80\%$ is applied to the latter. This confirms once more the need for a stochastic field to ensure heating.

Thus, the use of a stochastic high-frequency field makes it possible to realize heating of a dense plasma in traps without using special thermalization processes, leading to a number of advantages compared with heating by means of regular fields.

[1] O. M. Shvets, V. F. Tarasenko, S. S. Ovichinnikov, and V. T. Tolok, in: Vysokochastotnye svoistva plazmy (High Frequency Properties of Plasma), Naukova dumka, 1967.
[2] V. I. Veksler, A. A. Kolomenskii, and E. L. Burshtein, in: Nekotorye voprosy teorii uskoritelei (Certain Promblems of Accelerator Theory), AN SSSR, 1955.
[3] F. G. Bass, Ya. B. Fainberg, and V. D. Shapiro, Zh. Eksp. Teor. Fiz. 49, 7 (1965) [Sov. Phys.-JETP 22, 4 (1966)].
[4] O. M. Shvets, V. F. Tarasenko, S. S. Ovchinnikov, and V. T. Tolok, in: Fizika plazmy i problemy upravlyaemogo termoyadernogo sinteza (Plasma Physics and Problems of Controlled Thermonuclear Fusion), AN UkrSSR, No. 3, 1963.