A CALIBRATED MULTICHANNEL ANALYZER OF NEUTRAL CHARGE-EXCHANGE PARTICLES FOR THE STUDY OF PULSED PROCESSES IN A PLASMA

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The construction and calibration of a multichannel neutral particle-energy analyzer applicable for the study of the heating of the ion component of a plasma in processes of brief duration are described. The analyzer allows one to obtain nine points in the energy distribution under study in one cycle of operation of the experimental apparatus, which makes it possible to exclude the effect of nonduplication of the process on the results obtained. The instrument consists of a gas stripping chamber and a nine-channel electrostatic ion-energy analyzer based on a flat capacitor with the angle of entrance of the particles into the analyzing field $\theta = 45°$. Results are given on the calibration of the stripping chamber for hydrogen atoms H° in the energy range $\varepsilon = (0.3\text{-}10)$ keV and for He° atoms in the range $\varepsilon = (1\text{-}10)$ keV. Air, hydrogen, and helium were used as the conversion target gases.

1. The method of energy analysis of neutral charge-exchange atoms which freely depart from plasma traps [1] is used for the study of the characteristics of the ion component of a plasma which is in a magnetic field. An instrument consisting usually of a gas stripping chamber and an ion-energy analyzer serves for this purpose. Single-channel electrostatic ion analyzers have received wide distribution [1-3]. In the study of pulsed processes of brief duration, where the use of rapidly changing analyzing fields is impossible in practice, a single-channel instrument allows one to obtain one point in the energy distribution under study after one cycle of operation of the apparatus. In this case the instability of operation of the plasma apparatus can strongly affect the ion spectrum obtained. Gross statistics are required to obtain reliable results, which greatly complicates the experiment.

This can be avoided if the ions emitted by the plasma in a brief time are sent into a constant analyzing field which deviates the particles of different energies through different angles. For this purpose it is convenient to use the electrostatic field of a flat capacitor in conjunction with a multichannel system for recording the ions [4-6]. In this case the instrument's time resolution Δt, determined by the finite energy resolution of the analyzer and the flight length of the particles, also cannot be made as small as desired, which for processes with a duration $\tau < \Delta t$ leads to time averaging of the ion-distribution function.

2. A diagram of the neutral particle analyzer is presented in Fig. 1, in which 1 is the deflecting capacitor, 2 is a channel for the creation of a pressure drop, 3 is the stripping chamber, 4 is a needle valve, 5 is the plate containing slits, 6 is the analyzing plate, 7 is the ion-energy analyzer, and 8 is the recording system. The instrument consists of three main units: the gas stripping chamber 3, the multichannel ion-energy analyzer 7, and the recording system 8.

The stripping chamber 3 is made of Armco iron to shield the beam of charged particles from the effect of the quasistationary magnetic field of the plasma apparatus. The chamber length L = 25 cm was chosen so that at the working pressure $p = (1\text{-}5)\cdot 10^{-4}$ mm Hg the condition that the fast neutral atoms make single collisions with the particles of the target

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gas was satisfied. Such a choice is conditioned by the fact that without the use of an additional pump for differential evacuation it is easy to achieve a pressure drop in the range of two orders of magnitude using the two channels 2 with a diameter of 8 mm and a length of 70 mm mounted at the two ends of the chamber. Gas is admitted to the chamber with the precision needle valve 4. The deflecting capacitor 1 is mounted at the entrance end of the chamber, filtering out all charged particles if they are present in the flux being analyzed.

The ion-energy analyzer 7 consists of a flat capacitor formed by the plate 6 to which the analyzing voltage U is applied and the plate 5 which is at zero potential. The ions enter the retarding analyzing field at an angle $\theta = 45°$ through an entrance slit in plate 5. The ions return to plate 5 at different distances from the entrance slit as a function of the energy. The nine exit slits behind which the detectors of the recording system are located are made in this plate at equal intervals $\Delta x = 3$ cm. A fine-mesh grid is fastened to plate 6 to absorb the ions whose energy allows them to overcome the retarding analyzing potential. In the presence of reflection from the surface of the plate these ions can give false signals which distort the distribution function.

With a fixed voltage U on the analyzing plate one can find the energy of the ions arriving at the i-th channel of the analyzer

$$\varepsilon_i = x_i ZeU / 2d$$

where x_i is the distance between the entrance slit and the i-th exit slit, Ze is the ion charge, and d is the distance between the analyzer plates.

The time resolution Δt_i of the i-th analyzer channel can be determined from the equation

$$\Delta t_i = \frac{l_i (2\varepsilon_i / M)^{-1/2}}{2} \frac{\Delta\varepsilon_i}{\varepsilon_i}$$

where l_i is the flight length of the ions from the radiation source to the i-th exit slit, M is the ion mass, and $\Delta\varepsilon_i/\varepsilon_i$ is the energy resolution of the analyzer.

The ion recording system 8 consists of nine identical detectors mounted behind the exit slits of the analyzer. The ions passing through an exit slit are accelerated to an energy $\varepsilon \simeq 10$ keV onto the target of the ion-electron converter made in the form of a stainless steel plate with a polished surface. The secondary electrons knocked out of the target are accelerated to the same energy and enter a scintillator joined to a photomultiplier which records the light quanta formed. An opaque silver coating deposited on the scintillator maintains a zero potential on its surface and shields the photomultiplier from the light radiation of the plasma. The special arrangement of the targets of the ion-electron converters made it possible to use powerful FÉU-16B photomultipliers having a gain of $\sim 10^6$ as the detecting elements, which assured the high sensitivity of the instrument.

The channel for the passage of the ions into the analyzer was shielded from the effect of external quasistationary magnetic fields. The photomultipliers were placed in a special compartment additionally shielded from the high-frequency electromagnetic interference produced during the operation of the apparatus.

3. The calibration of the stripping chamber of the analyzer was carried out on an instrument for which a diagram is shown in Fig. 2. An ion beam of fixed energy, formed by the high-frequency ion source 1, was passed through the magnetic mass analyzer 2 to isolate the desired H^+ or He^+ component and entered the gas charge-exchange chamber 3. To prevent the entry of a foreign gas into the stripping chamber the neutralization of the ion beam took place on the same gases as the stripping. Upon departing the charge-exchange chamber the beam passed through the deflecting capacitor 5 which removed all the charged particles from it. The pure beam of fast neutral atoms thus obtained fell on the entrance of the stripping chamber 7 which was connected to the measuring space 8 in such a way that the geometry adopted in the neutral particle analyzer was preserved.

The equivalent current of the neutral particles was measured with the secondary-emission detector 6 placed at the exit of the stripping chamber. The detector consisted of a stainless steel target with a polished surface mounted at a 90° angle to the incident beam and a cylindrical electrode surrounding it to collect all the secondary electrons knocked out of the target.

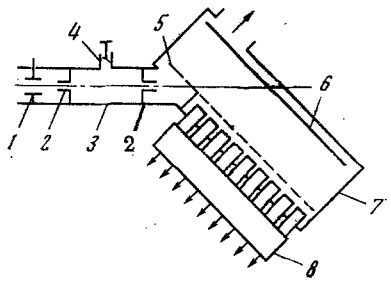

Fig. 1

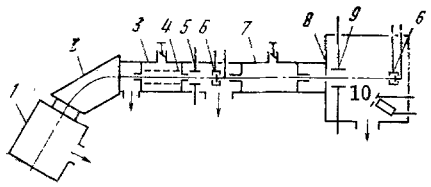

Fig. 2

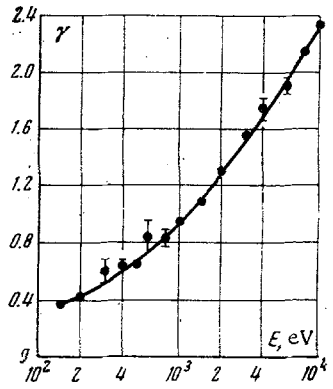

Fig. 3

The absolute intensity of the beam of neutral particles was determined from the current of secondary electrons on the basis of the assumption of the equality of the secondary-emission coefficients γ for charged (γ^+) and neutral (γ°) particles having the same energies. This assumption was tested on hydrogen ions and atoms in the energy range from 1 to 10 keV. For this purpose the secondary-emission detector 6 was placed at the exit from the charge-exchange chamber. The secondary-electron-emission coefficient γ was measured as the ratio of the current of electrons formed to the current of particles striking the target.

In the measurement of γ° the intensity of the beam of atoms was determined from the current of slow charged particles formed in the charge-exchange chamber [7] and taken from the plates of the sectioned capacitor 4.

The dependence of the ion-electron-emission coefficient γ^+ on the energy of the incident H^+ particles in the energy range from 0.3 to 1 keV is given in Fig. 3. The values of the coefficient γ° in the measured energy range ε = (1-10) keV lie on the same curve within the limits of the measurement error.

The current I^+ of positive ions formed at a given pressure in the stripping chamber was measured with the Faraday cylinder 10 to which the beam was deflected with the capacitor 9 placed behind the entrance slit of the measuring space. The capacitor also filtered from the beam the negative ions and electrons coming from the stripping chamber together with the positive ions. The ratio of the current I^+ to the equivalent current I° of neutral particles measured with the stripping chamber pumped out to the limiting vacuum gave the value of the coefficient α of conversion of neutral particles into charged particles.

4. The coefficient α was measured for different pressures of the gases in the stripping chamber in the range from $1\cdot10^{-4}$ to $6\cdot10^{-4}$ mm Hg. The dependences of the conversion coefficient α on the energy of H° atoms obtained for two target gases are presented in Fig. 4. It is seen from the graphs that the conversion efficiency is higher on air (curve 1, P = 10^{-4} mm Hg) than on hydrogen (curve 2, P = $2\cdot10^{-4}$ mm Hg), which makes the use of air as the stripping target preferable. The use of hydrogen can prove necessary in cases where one must exclude the danger of contaminating the hydrogen plasma with admixtures.

A comparison of the results obtained with the data of [8] (curve 3, stripping gas hydrogen) shows that the geometry of the stripping chamber does not strongly affect the conversion coefficient α for the given energy range.

Helium in the pressure range from $2\cdot10^{-4}$ to $6\cdot10^{-4}$ mm Hg was used as the stripping gas for the conversion of the fast He° atoms into ions. The dependence of α on the energy of the He° atoms at the pressure P = $2\cdot10^{-4}$ mm Hg is given in Fig. 5. As the measurements showed, the efficiency of conversion of atoms into ions is low ($\alpha = 2\cdot10^{-5}$ at ε = 1 keV), and at the maximum beam intensity which the source could provide reliable data were obtained only for energies $\varepsilon > 1$ keV.

The calibration of the sensitivity of the recording channels of the analyzer was conducted on the same instrument. A beam of ions with energies in the range of (0.3-10) keV and a current $I^+ = 10^{-12}$ A was sent, in turn, into all the channels by varying the voltage U and the output currents of the photomultipliers were measured. The dependence of the

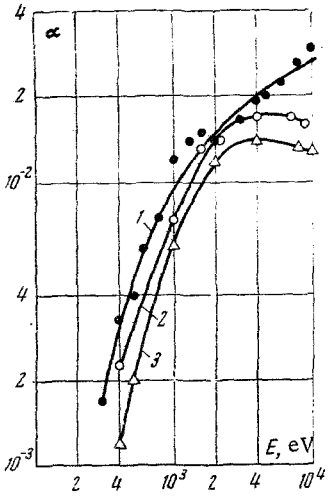

Fig. 4

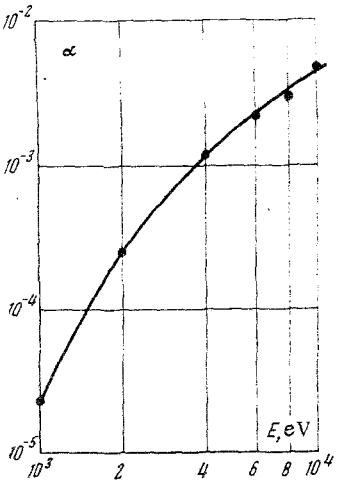

Fig. 5

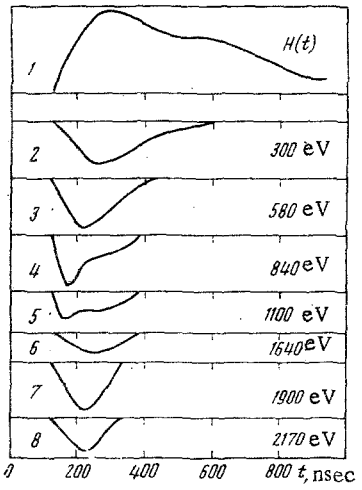

Fig. 6

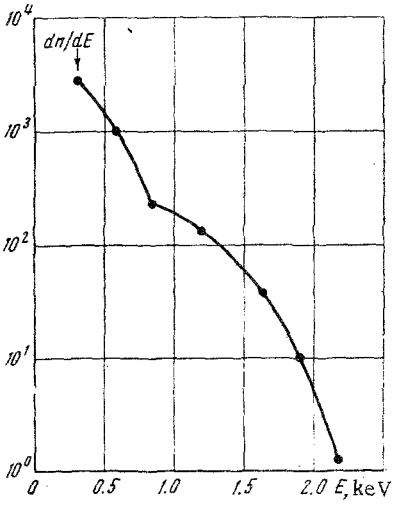

Fig. 7

gain of each channel on the energy of the recorded ions was plotted. The measurements gave values of the gains of the different channels in the range of $5 \cdot 10^6$–10^7 and a weak dependence on the ion energy.

The calibrated analyzer was used to measure the energy of ions in a fast theta pinch in a UN-4 apparatus [9]. A hydrogen plasma with a concentration of $(3\text{–}5) \cdot 10^{13}$ cm^{-3} and a temperature of (1–5) eV preliminarily created without a magnetic field in a cylindrical glass volume 16 cm in diameter was subjected to rapid compression by a magnetic piston ($H \approx 1500$ Oe, $T/4 = 500$ nsec). The velocity of the disturbance thus produced, moving toward the center of the system, was measured with two magnetic probes having open loops 3 mm in diameter and located at different distances $r_1 = 25$ mm and $r_2 = 35$ mm from the axis. The flux of fast neutral charge-exchange atoms traveling along the radius of the volume was studied. For this purpose the analyzer was joined to the plasma volume in the central cross section of the shock coil. The neutral particles were led out along a ceramic tube 5 mm in diameter mounted along a radius of the volume and advanced beyond the axis by a distance $r_1 = 25$ mm to exclude cumulation effects from the investigation.

In Fig. 6 we present typical oscillograms of the signals from the detectors of the recording system of the analyzer obtained with the magnetic probe ($r_2 = 25$ mm, sensitivity 450 Oe/div.) (1) and with the analyzer detectors (2–8) in one cycle of operation of the apparatus. Using the method of analysis described in [2] and the instrument calibration data one can reconstruct from these signals the distribution function of the ions formed during the movement of the magnetic disturbance (Fig. 7, where $n_0 = 5 \cdot 10^{13}$ cm^{-3} and $H_0 = 0$).

It can be concluded from the form of the distribution function that the acceleration of some of the ions occurs in the plasma stream such that their velocity exceeds the velocity of movement of the magnetic disturbance. In the case under consideration the velocity of the disturbance is $V = 2.5 \cdot 10^7$ cm/sec (the value $MV^2/2$ is marked by an arrow on the graph of Fig. 7), while the energy of the ions reaches values exceeding $MV^2/2$ by several times. Ions of higher energies were detected in an experimental arrangement analogous to that of [10] on the escape of neutrons formed at the moment of cumulation of the plasma streams at the axis of the system.

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