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Dynamic Behavior of Turbulent Heating of Plasmas

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To investigate mass dependence of ion heating, a mixture gas was filled in the chamber at a pressure of 2×10^{-4} Torr. The mixture gas consisted of 84 % of helium and four kinds of gases as test ions (neon, argon, krpton and xenon) of 4 % each. The plasma produced by the titanium washer gun was also injected into the chamber to preionize the gas before the heating current started. Ion velocity destribution perpendicular to the magnetic field has been measured from Doppler broadening of ion spectral lines of each species. The measurement was made along central chord with 2 cm in length of the plasma column.

Results were as follows: The line width started to broaden at about 0.3 - 0.5 μs after the onset of the current and increased in the next 0.5 μs and reached its maximum value. At this time the velocity distribution function seemed to consist of two components with different temperatures (see Fig. 7). The temperature of the cold component of each test species were about 100 eV, while those for the hot component were several 100 eV, and the heavier ions reached higer temperature. Doppler shift for those ion lines were also observed, and it suggested that existence of mass motions of the ions in the plasma with a velocity of about 10^6 cm/s for all species of the ions.

3. DISCUSSIONS

The noise with frequencies more than 20 MHz (see Fig.3(d)) just after the onset of the heating current seems to be responsible for the electron heating , that is, the plasma energy content grows rapidly during this stage. The noise , however, is not accompanied by rapid ion heating. The high energy ions were observed during the course of resistive hump[5].

The low frequency, high intensity potential oscillation during the resistive hump is clearly responsible for the ion heatig. It seems to be an electrostatic ion cyclotron wave (ESICW). The observed frequency at which the intensity is peaked is about 5 MHz and the estimated frequency of ESICW is about 7 MHz. A theoretically estimated growth rate is proportional to both the density gradient and the collision frequency ν. When ν is replaced with an effective one estimated from an observed plasma resistance R = 1 Ω (the one just before the onset of the high intensity oscillation, see Figs.(3-c,d)) the growth rate is of the order of 0.1 μs and is consistent with the experimental result.

As to the formation of the low energy component a stochastic model[9,10] is employed for THE MACH II experiment. Then we have

$$\frac{dT_i}{dt} = \frac{e^2}{m_i} \frac{\tau^{-1}}{\omega^2} \langle E^2 \rangle .$$

where τ is the auto-correlation time of the wave. The fact that the amplitude is about 100 V/2 mm gives E being 500 V/cm. Using $\omega = 2\pi\times5\times10^6$ rad/μs, and $\omega\tau$ = 12 obtained by spectral analysis of the measured potential oscillation, we have dT_i/dt = 650 eV/μs, which is a reasonable value compared with the observed one.

For the creation of the high energy component, we present a plausible explanation as follows. The tail of the low energy component which has been formed by the process described above is accelerated by the wave potential of ESICW to form a bump. Then the bump breaks down in a time $t_b = (1/\omega)(n/\delta n)$ [11] and forms a high energy tail, where $\delta n/n$ is the ion density perturbation. The t_b is $1.4 \times 10^{-8} (n/\delta n)$ second for $\omega = \Omega_i$, the ion cyclotron frequency. If we choose $\delta n/n = 0.03$, which is probable in the present experimental condition, we have $t_b = 5 \times 10^{-7}$ s , close to the observed value. The phase velocity v_p can be estimated by referring to Fig.5. Taking $m_i v_p^2/2 =$ 3.5 keV, we get $v_p = 8.2 \times 10^7$ cm/s. On the other hand, if we assume $k = 1$ cm^{-1} the phase velocity of ESICW is in this case 7×10^7 cm/s.

As to the spikes of high energy neutrals in THE OCU II it is probably claimed that they are produced by a sequently created, strong electrostatic potentials.

Simultaneous heating of different ion species was observed in both BSG II and THE MACH II devices. There will be two ways of thinking about heating of the test ions. One is that different species are heated simultaneously by strong, long lived potentials. The other is that an anomalously fast energy transfer between different species occurs and equipartitionof energy takes place as soon as one species out of the others is heated.

ACKNOWLEDGEMENT

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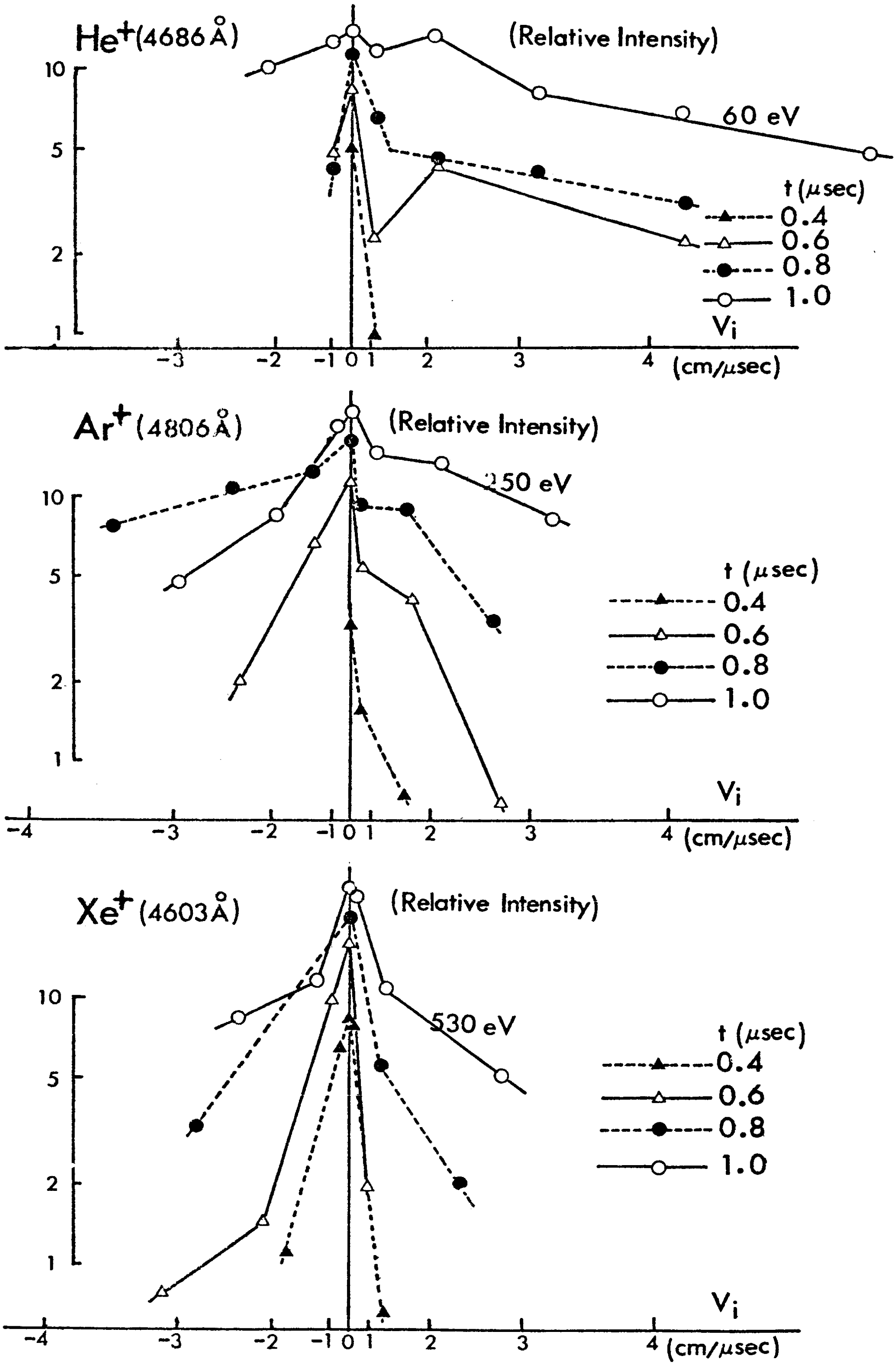

Fig. 7 Temporal variation of the velocity distribution functions of the ions with different masses, relative to the major mass motion in the plasma. V_c = 33 kV, B = 4.5 kG.

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ABSTRACT

Dynamical behaviors of turbulently heated plasma have been studied experimentally in three linear machines by using a particle energy analyzer, spectrometer and ruby laser. Parameters of the plasma were covered in ranges $10^{12} \sim 10^{15}/cm^3$ in density, $3 \sim 17$ kG in strength of the magnetic field and $1 \sim 40$ in mass number of the ions. Special attentions were paid to the dependencies of ion heating on the species of ions, strength of the magnetic field and the density of the plasma.

Measurement of ion energy distribution by charge exchanged neutrals showed that a bump was observed in the high energy component during the course of resistive hump in the discharge current for the heating. In the experiment in density range of $10^{14}/cm^3$, the temperature of the low energy component became lower as the plasma density increased, while those of the high energy component didn't change. Fluctuation measurement indicated that intense electric potential oscillations with frequencies around 10 MHz appeared in the period of resistive hump, which was considered to be responsible for heating and accerelations of ions. The oscillation seems to have a character of the wave whose phase velocity is the ion acoustic one. The heating of the low energy component is reasonably explained by a stochastic model, in which ions diffuse in velocity space by the above oscillating potential field. The high energy component is considered to be formed due to strong resonant acceleration by this potential.

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1. INTRODUCTION

It is the main object of this study to understand the physical mechanism of the turbulent heating of the plasma in order to obtain high ion temperature with high efficiency. Turbulent heating experiments have been always suffered from rather poor reproducibility. Almost all results, so far obtained, have been provided by averaging experimental data of many discharge shots under the identical condition of experiment. In order to improve the situation, we have made measurements of temporal evolutions, shot by shot, of energy spectra of the ions as well as the electrons and of excited oscillations in the linear turbulent heating experiments, by using eight-channel detector systems for simultaneous measurement.

Dependence of the ion heating on the plasma density and on the strength of magnetic field were investigated and the heating of impurity ions was also studied. The experiments have been carried out by using three linear machines, BSG II, THE MACH II and THE OCU II. The first machine has large diameter, the second provides a high magnetic field, and the third is devoted for heating of a high density plasma.

2. EXPERIMENTS

The schematics of the devices are shown in Fig.1 (a) and (b) and the parameters of the plasmas and devices are summarized in Table I.

2.1. BSG II [1]

Observation of Doppler shift and broadening in ion lines (He II: 4686 Å) showed that the "resistive hump" on the heating current trace was accompanied by a macroscopic deformation of a plasma column as well as an increase in the ion temperature as shown in Fig.2, on which the line profiles are plotted at an interval of 10 ns. The current path was measured by multi-head magnetic probes and was found to fluctuate around the center of the plasma column. From the Doppler broadening measurement, it was also shown that argon ions mixed as test ions in the dominant helium ions were heated almost simultaneously to 20 eV, same as helium ions [2].

2.2. THE MACH II

Typical behavior of the heating discharge and the plasma parameters is summarized in Fig.3 (a) ∿ (e). Those characteristics were similar to the case in BSG II [3] except that the current penetration is faster in THE MACH II.

Magnetic field dependence of the anomalous resistance at the resistive hump, power input, the maximum energy content and its decay time are shown in Fig.4 (a) ∿ (d). The anomalous resistance decreased with the strength of the magnetic field, while the energy input and the resultant energy content showed rather unchanged. The decay time of the energy content in the mirror field (mirror ratio is 1.8) was found to be about 2 ∿ 5 μs and to increase with the strength of the magnetic field.

Fluctuations picked up by floating double probes (3 mm in length, 2 mm in separation of two wires of 0.3 mm in diameter) in a frequency region up to several 100 MHz is shown in Fig.3(d). Oscillations with frequencies about 20 MHz appeared when the current started and became weak at about 1 μs. Then oscillations of large amplitude (100 V) and low frequency (2 ∿ 20 MHz) appeared suddenly on the axis of the discharge with a duration of about 2 μs. Then as the intensity of the large amplitude oscillations decreased, fluctuations with higher frequency components up to several 100 MHz were superimposed on them. Those natures of the fluctuations were similar in both cases either when the probes were oriented to pick up electric field parallel ($E_{//}$) or perpendicular ($E_{\perp}$) to the direction of the axis of the device. Observations of the sattelite of forbidden lines of neutral helium in the plasma showed that occurence of a high frequency component (around ω_{pe}) of the fluctuations appeared at the time of resistive hump, and that the field strength of this component went up to 3 kV/cm.

Temporal behaviors of the electron temperature are measured by ruby laser light scattering and X-ray spectroscopy. Electron temperature was observed to increase up to 70 eV till about 0.8 μs. At 0.9 μs, the distribution function initially Maxwellian shape changed into rather flat top, then the scattered light signal disappeared. X-ray bursts were observed from the carbon target in the plasma at the time of the resistive hump, when the electron temperature became maximum (10 ∿ 20 keV). This maximum electron temperature is the same as the one measured from the diamagnetic signals.

Averaged ion energy has been measured by means of S.E.D. (secondary emission detector) [4]. It showed that the ion temperature for the hot component was 2 to 3 keV corresponding to the heating voltage of 30 to 36 kV. By S.E.D. the movement of the plasma column was also observed, which went upward with a velocity of about 10^6 cm/s and the velocity was lower in a higher magnetic field. Detailed temporal change of the energy distribution was measured by ion line profiles and by charge exchange fast neutrals in which temporal resolution of the detector was 0.1 μs for the ion with an energy of 2 keV. Ion energy profile was found to have two components with different temperatures. The low energy component had a temperature of a few 100 eV. Typical result in an energy range of 1 to 8 keV was shown in Fig.5. At about 1 μs after the current started, fast neutral signals started to be observed. Then the intensity of the high energy tail started to increase, and after 0.4 μs a bump at about 4 ∿ 6 keV was observed. The bump smeared out before the resistive hump disappeared.

2.3. THE OCU II

Heating current, 230 kA maximum, showed a weak resistive dip during the first quarter cycle (Fig.6(a)). When the initial density of filling hydrogen is $5 \times 10^{14}/cm^3$ (case h), magnetic probe measurement showed that the current did not flow on the axis even 1 μs after the resistive dip, showing the skin-like current density profile.

The high energy neutral particles, ejected perpendicularly to the magnetic field, were observed during about 0.5 μs, for the case h, around the instant of resistive dip, and the intensity of 1 keV particles showed a train of a few spikes (Fig.6(a)). It was checked that a spike of the signal was composed of more than twenty neutral atoms. At the 'spikes' irregular oscillations of $E_{\parallel}$ as well as $E_{\perp}$ about 15 MHz were observed to be intensive, with equal intensities for both components, on the axis and also at a position 1 cm from the axis. When the density was decreased to $2 \times 10^{14}/cm^3$ (case ℓ), high energy neutrals (composed of a train of successive spikes) appeared for more than 1.5 μs, starting from the onset of heating current. The irregular oscillations with the same characteristics as those described above were also observed for corresponding duration.

Ion energy spectra were obtained by integrating over observing times of about 0.4 μs for case h and about 1 μs for case ℓ, shown in Fig.6(b). In case h, the temperature of the low energy component was lower than in case ℓ, while those of the high energy components were same.

3. DISCUSSIONS

The noise with frequencies about 20 MHz (see Fig.3(d)) just after the onset of the heating current does not seem to be responsible for the ion heating, since the high energy ions were observed during the course of resistive hump[5]. This contrasts with the discussion given by Kalinin et al.[6].

The low frequency, high intensity potential oscillations during the resistive hump have not been identified yet but is clearly responsible for the ion heating. They could be an ion acoustic wave. It is, however, hard to ascribe to a drift current instability in a collisionless plasma[7,8] because its growth rate is maximum at about the ion plasma frequency (250 MHz).

A clear result of the experiments is the observation of a bump in ion energy spectrum (Fig.5). This is not inconsistent with the observation of the two-temperature Maxwellians, so far reported[9 ∿ 11]. Because the energy at the bump in the spectrum was observed to fluctuate shot by shot between 3 and 6 keV, so one could not detect the bump if spectrum is obtained by averaging data of many discharge shots.

As to the formation of the low energy component a stochastic model[12,13] is employed for THE MACH II experiment. Since the oscillations are rather coherent (Fig.3(d)), we assume they are quasi-monochromatic with frequency ω or $\omega\tau > 1$, τ being the auto-correlation time of the oscillation, and we have

$$\frac{dT_i}{dt} = \frac{e^2}{m_i}\frac{\tau^{-1}}{\omega^2}<E^2>.$$

The fact that the amplitude is 100 V/2 mm gives E being 500 V/cm. Spectral analysis of the measured potential oscilltion gives dominant frequency $\omega = 2\pi f = 60$ rad/μs and $\omega\tau = 12$. Thus we get $dT_i/dt = 300$ eV/μs, which is consistent with the observed value. In THE OCU II, the plasma parameters are quite different from those of THE MACH II and the heating mechanism may be different.

We note that the distribution of the high energy component have a bump or in another word it shows a population inversion as shown in Fig.5 (t = 1.45 μs and 1.65 μs). This fact leads to a following model for the creation of the high energy component. Suppose that the oscillation has wave characters with a definite phase velocity v_p and assume that the correlation time τ of the wave is nearly equal to the bounce period τ_b of ions in the potential trough. Hence the tail of the low energy component which is formed by the process described above is then accelerated by the potential wave and in a bounce period the accelerated particles diffuse in velocity space. We estimate $\tau_b \equiv 2\pi(m_i/ekE)^{1/2}$ by using E = 500 V/cm and by assuming $k = 1.5$ cm^{-1} since the oscillation is macroscopic. Then we get $\tau_b = 0.3\ \mu s$, while $\tau = 12/\omega = 0.3\ \mu s$, and consequently these values justify the assumption $\tau \sim \tau_b$.

The phase veloctiy v_p can be estimated by reffering to Fig.5. Taking $m_i v_p^2/2 = 4$ keV, we get $v_p = 9 \times 10^7$ cm/s which is equal to the ion acoustic velocity provided $T_e = 8$ keV, while Alfvèn velocity is 3×10^9 cm/s. Then the observed oscillation in THE MACH II possibly has characters like the ion acoustic wave.

As to the spikes of high energy neutrals in THE OCU II it is probably claimed that they are produced by a sequently created, strong electrostatic potentials.

Simultaneous heating of different ion species was observed in BSG II device. This phenomenon has been observed recently in some turbulent heating experiments[14,15] while the mechanism have not been made clear yet. There will be two ways of thinking about heating of the test ions (Ar^+). One is that He^+ and Ar^+ are heated simultaneously by strong, long lived potentials. The other is that an anomalously fast energy transfer between He^+ and Ar^+ ions occurs and equipartition of energy takes place as soon as He^+ is heated. These two possibilities are being investigated theoretically and experimentally.

4. CONCLUSION

In conclusion the high intensity oscillations of several MHz during the resistive hump was found to be responsible for the heating of the bulk ions as well as of the high energy component. The heating, expecially of the high energy component, is not ascribed to a simple diffusion process in velocity space, but due to some processes composing of large acceleration and randomization.

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The authors wish to acknowledge Prof. Y. Matsukawa, Prof. T. Yokota and Mr. K. Kawasaki for their collaborations with the experiments. The works related with the devices BSG II and THE MACH II were performed under the collaborating research program at the Institute of Plasma Physics of Nagoya University.

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FIGURE CAPTIONS

Fig.1 Schematic drawings of (a) THE MACH II and (b) THE OCU II.

Fig.2 Temporal evolution of the line profile of He II (4686Å) during the resistive hump. The heating current is 7.4 kA at the maximum value and the charging voltage of the capacitor for heating is 36 kV.

Fig.3 (a) The heating voltage between the electrodes, V_H.
(b) The current of heating discharge, I_H.
(c) Resistance of the heated plasma column calculated from V_H, I_H and the inductance of the heating circuit.
(d) The floating potential difference between two proves set 2 mm apart each other along the axis of the machine.
(e) The electron temperature on the axis of the machine. Here, ruby laser scattering with an 8 channel detector system being used.

Fig.4 Magnetic field dependence of (a) the resistance of the heated plasma column, (b) the power input to the plasma column, (c) the thermal energy density of the plasma, $p_\perp$ and (d) the decay time of $p_\perp$. In (a) ∿ (c), the maximum values in time are plotted for each quantity. The initial plasma density is a few times $10^{12}/cm^3$ (•) or roughly its half (o) and the heating voltage between the electrodes is about 15 kV (•) or 20 ∿25 kV (o).

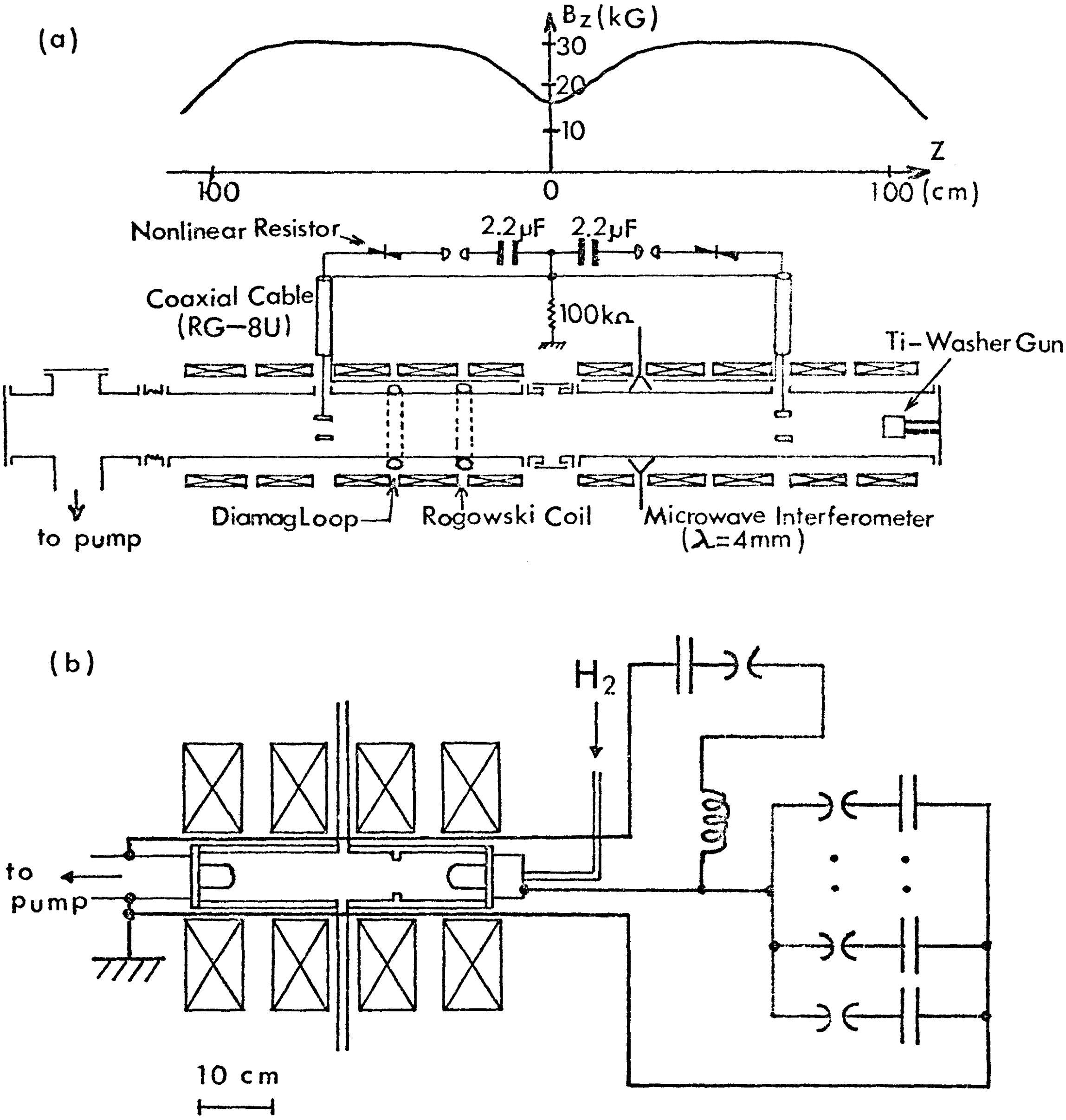
Fig.5 Temporal evolution of the high energy part of the ion energy spectrum. The charging voltage of the capacitor for heating V_c is 30 kV.

Fig.6 (a) The wave form of the heating current (upper trace) and the intensity of 1 keV particles (lower trace). The time difference between two arrows on the axes corresponds to the time of flight of the detected particles. (b) Comparison of the energy spectra for the two cases of low (o) and high (•) filling gas pressure (2×10^{14} $/cm^3$ and $5 \times 10^{14}/cm^3$, respectively).

TABLE I PARAMETERS OF PLASMAS AND DEVICES USED IN THE EXPERIMENTS

	Name	Plasma Source	Species of Ions	Plasma Density	Initial Temperature
(1)	BSG II	Theta pinch	He^+	2×10^{13} cm^{-3}	2 eV
(2)	THE MACH II	Ti washer gun	H^+	5×10^{12}	10
(3)	THE OCU II	rf pre heat	H^+	5×10^{14}	---

	Magnetic Field	Heating Voltage	Maximum Current	Rise Time	Electrode Distance	Vessel Diameter	Plasma Diameter
(1)	2 kG	36 kV	10 kA	2-3μs	120 cm	50 cm	6 cm
(2)	3 - 14	36	20	2	135	18	4
(3)	17	25	240	2	30	7	---



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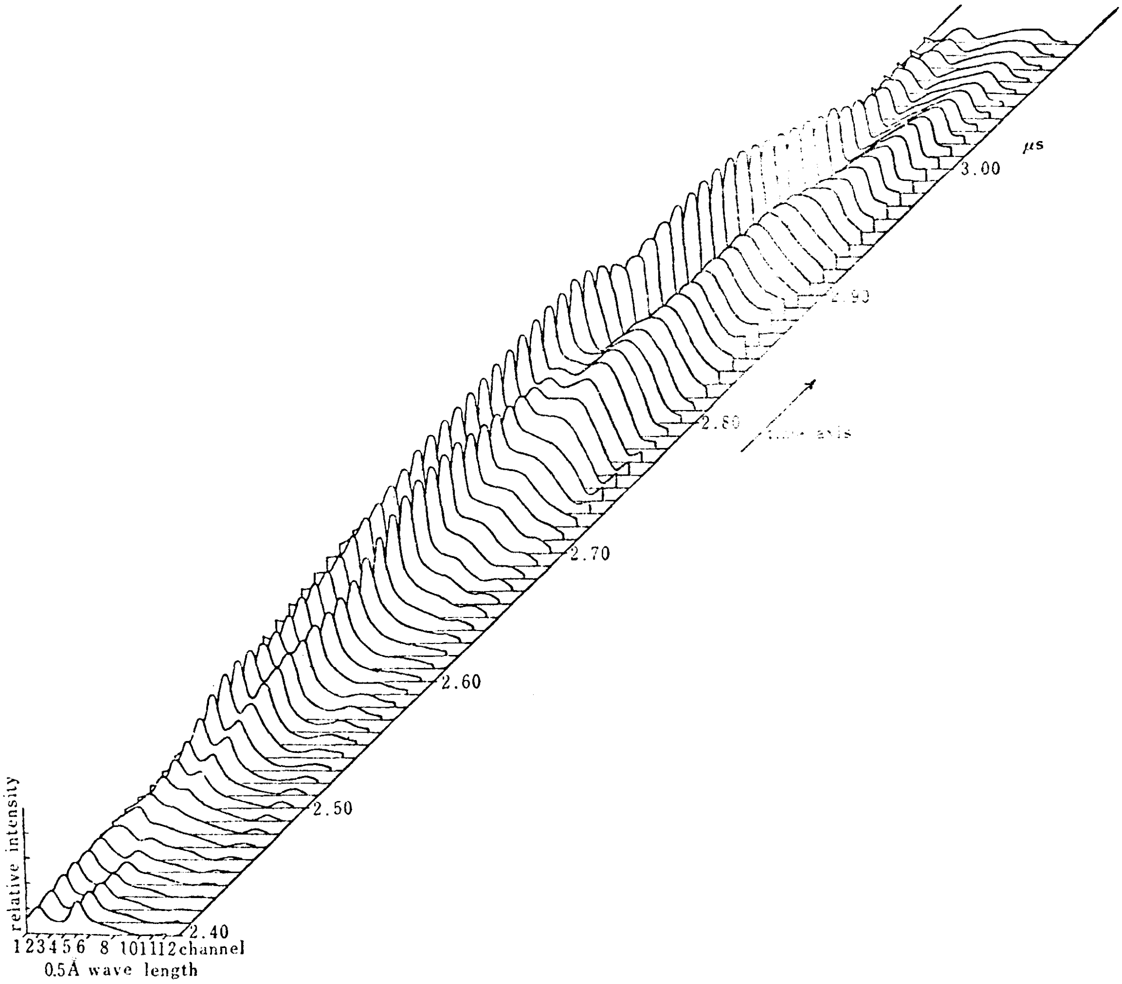

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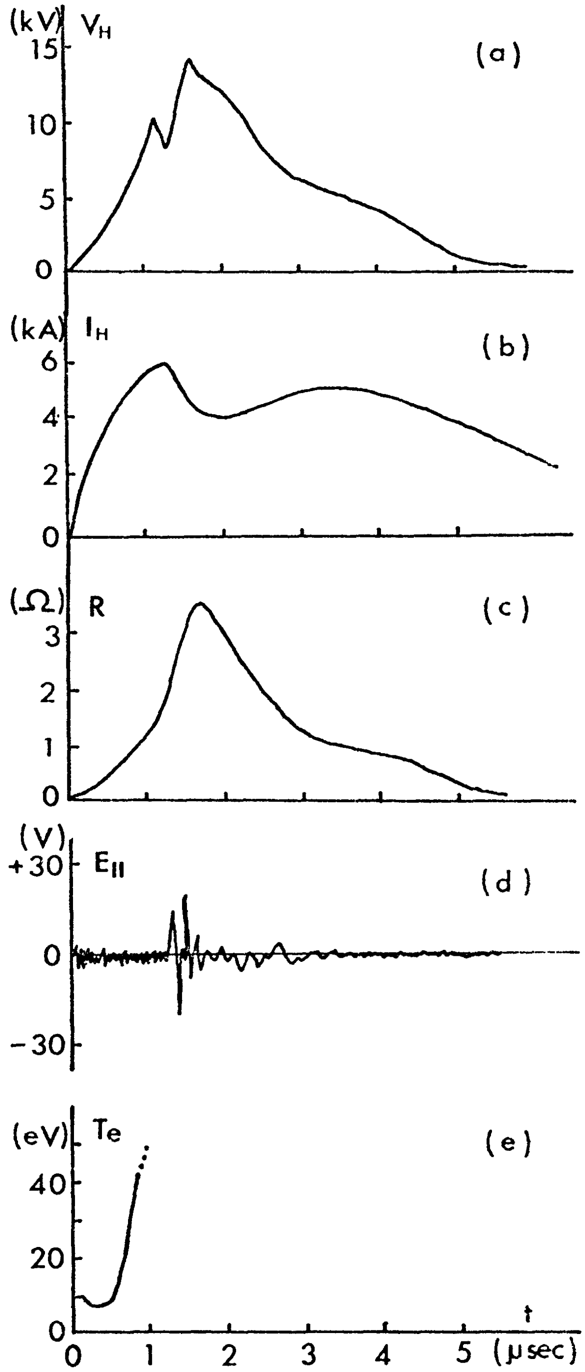

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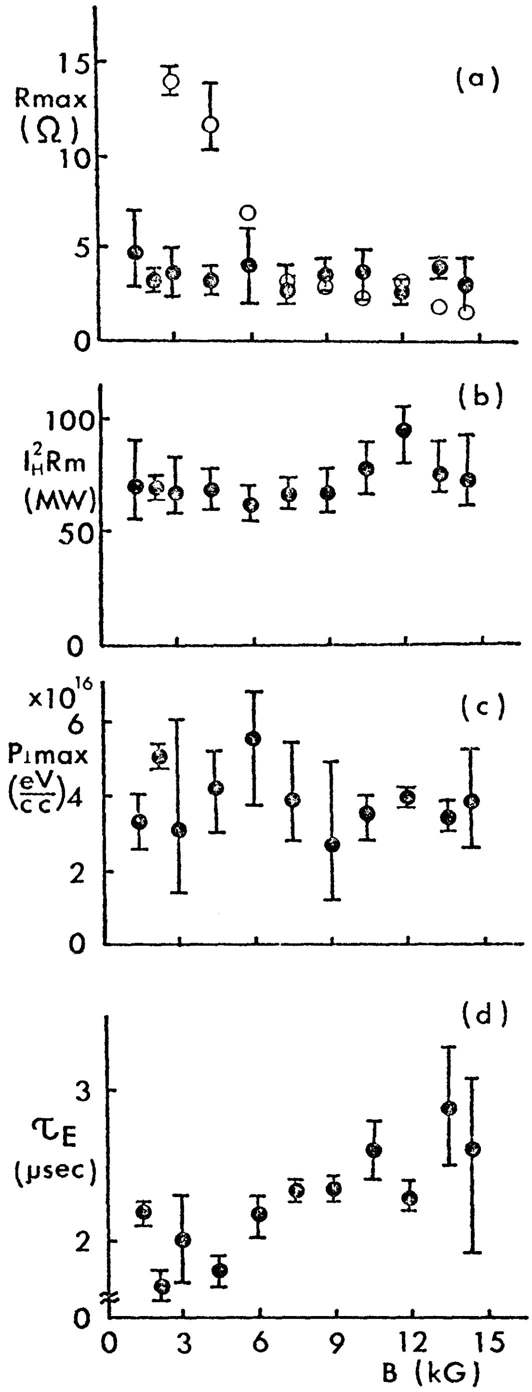

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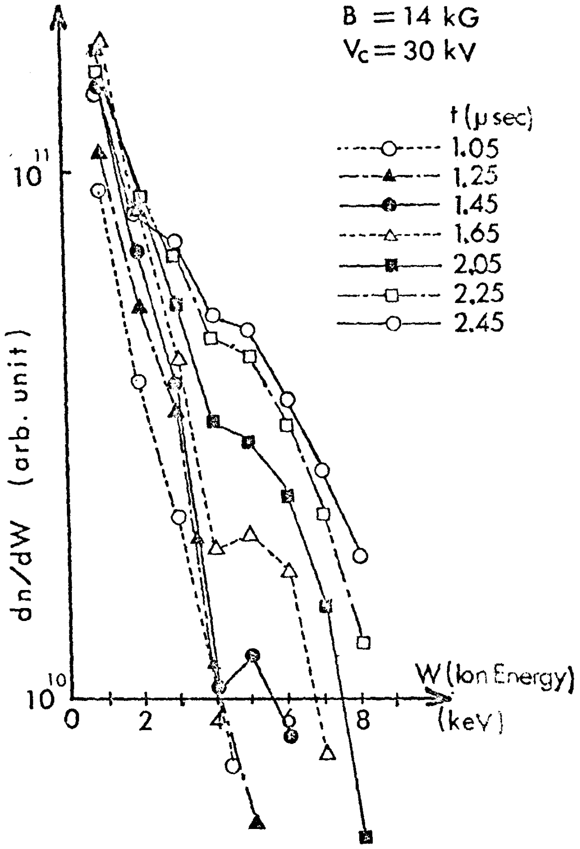

Fig.5 Temporal evolution of the high energy part of the ion energy spectrum. The charging voltage of the capacitor for heating V_c is 30 kV.

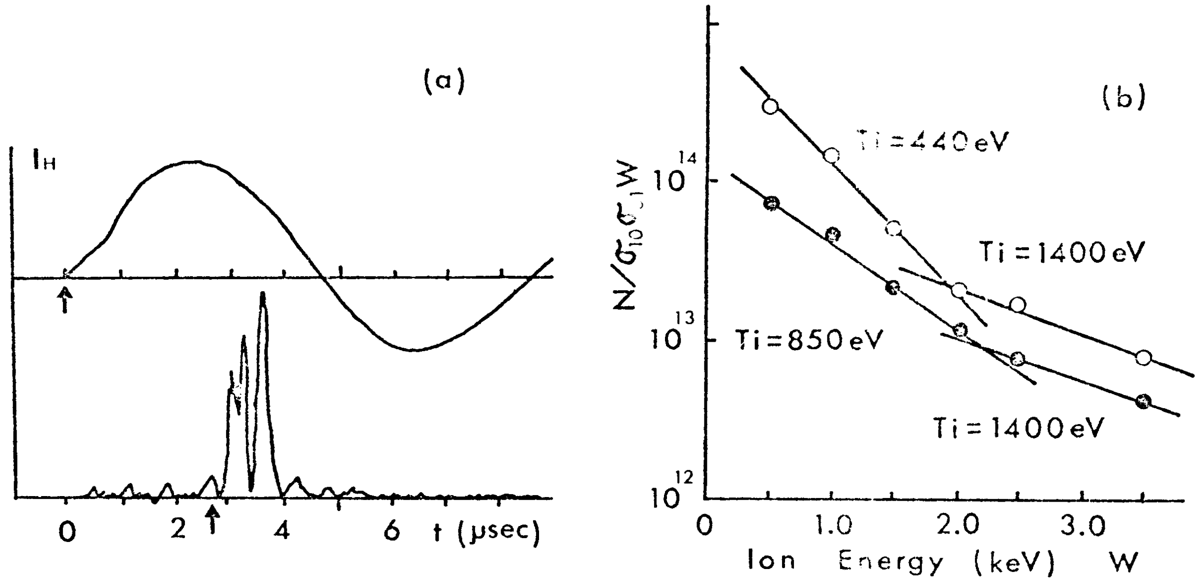

Fig.6 (a) The wave form of the heating current (upper trace) and the intensity of 1 keV particles (lower trace). The time difference between two arrows on the axes corresponds to the time of flight of the detected particles. (b) Comparison of the energy spectra for the two cases of low (o) and high (●) filling gas pressure (2×10^{14} /cm^3 and 5×10^{14}/cm^3, respectively).