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GENERATION OF ENERGETIC ELECTRONS BY ELECTRON CYCLOTRON HEATING IN A MAGNETIC MIRROR FIELD

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RESEARCH REPORT

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Further communication about this report is to be sent to the Research Information Center, Institute of Plasma Physics, Nagoya University, Nagoya, Japan.

Abstract

Electron cyclotron heating that generates hot-electron plasma in a magnetic mirror trap by microwaves is studied experimentally. Evolution of energy distribution functions for the high energy electron is observed in each successive 1 msec during a 200 msec of heating period from the initial stage at the microwave power input until the stationary, final state. According to the proposed statistical model for the cyclotron heating, heating rates are estimated to be 10 MeV/sec typically, under three characteristic cases of the mirror field configuration with the heating microwave power as a parameter. Some problems associated with the stochastic cyclotron heating are discussed in the experimental light.

1. Introduction

It has been well known from numerous experiments[1-4] that microwave discharge plasma in a magnetic trap supports a significant fraction of energetic electrons and that the plasma can be confined stably without showing predicted flute instabilities. Because of those energetic electrons that sustain most of the plasma energy, the plasma is generically known as hot electron plasma. The stabilization of flute instabilities in the hot electron plasma is understood to be due to the existence of those energetic electrons that have large Larmor radii and ionize ambient neutral gases continuously.

Recently the hot electron plasmas have attracted strong interests in the program of the controlled thermonuclear fusion. Quite interesting idea is to use their high β effect in order to realize a stable bumpy torus confinement.[5,6] Hot electron plasmas can be an ideal target plasma[7,8] for trapping injected beams of energetic neutral atoms. Idea of using hot electron plasmas as an energetic medium[9] to heat a confined plasma by thermal relaxation was an old one proposed by N. C. Christofilos.

Mechanism of generating hot electron plasmas by the introduction of microwave power has been generally accepted as a stochastic heating, since the hot electron plasmas are generated mostly in a mirror trap, which is characterized by better confinement for energetic particles, in other words, it takes much longer time than any characteristic times of the electrons before a significant amount of energetic electrons are generated to establish the hot electron plasma.

The microwave power for generating the hot electron plasma is normally with a single frequency, so that if no random forces are introduced, the particle motion should be adiabatic. However, the interaction of the electrons with the applied electromagnetic field in a mirror trap is quite complicated. The electron cyclotron frequency is approximately equal to the applied frequency only when the electron happens to be at a particular point in the mirror field. As the electron moves along a flux tube of the mirror field, its cyclotron frequency changes with the position of its guiding center. Strong interaction with the microwave field could be expected when the electron satisfies the cyclotron resonance condition, $\omega - kv_{\parallel} - \Omega = 0$, where Ω is the electron cyclotron frequency and $v_{\parallel}$ is the electron velocity parallel to the static magnetic field. When the electron gains its perpendicular kinetic energy, it simultaneously reflects on the longitudinal velocity $v_{\parallel}$ as the result of which both resonance point and reflection point are shifted. Furthermore, experimentally one cannot specify the direction of the microwave propagation, so that the microwave power in the actual configuration has a narrow ω-spectrum with a diffused k-spectrum when observed by the electron.

Stochastic heating in a magnetic trap has been subjected to theoretical analysis often in terms of electron cyclotron heating. There are two main subjects to be discussed: First is the adiabaticity of the electron interacting with the electromagnetic field in a mirror trap. It will be reasonably accepted that the electron cyclotron heating is a slow statistical process which is made possible by some randomizing process.[10,11] Numerical studies[12] on the cyclotron heating in a magnetic mirror show that the phase plane consists of a complicated structure of islands characterized as an adiabatic barrier embedded in a stochastic sea even without random forces. Secondly, the mechanism that determines the ultimate energy distribution function has been discussed in various ways.[13,14] The distribution function in the stochastic process obeys a Fokker-Planck equation. It appears that stochastic heating theories in one dimension limit the maximum particle energy by the maximum phase velocity in the wave spectrum. In order to circumvent this restriction, sudden random phase changes are introduced.[15] To the authors, however, a spread in k-spectrum in the actual system seems the most important factor to be taken into consideration. In a three-dimensional, cyclotron heating, one problem is what limits the maximum attainable temperature. From our experimental results, it is more likely that the restriction is first brought about by the confinement time rather than by a relativistic effect.[16]

In the present paper, the electron cyclotron heating that generates hot-electron plasmas is studied experimentally. Evolutions of the electron energy distribution function during the heating is measured from the initial stage at the microwave power input to the stationary, final state.

The model of cyclotron heating makes us possible to estimate the heating rate which is examined under various conditions with the heating microwave power as a parameter. Some problems associated with the stochastic heating will be discussed in the experimental light.

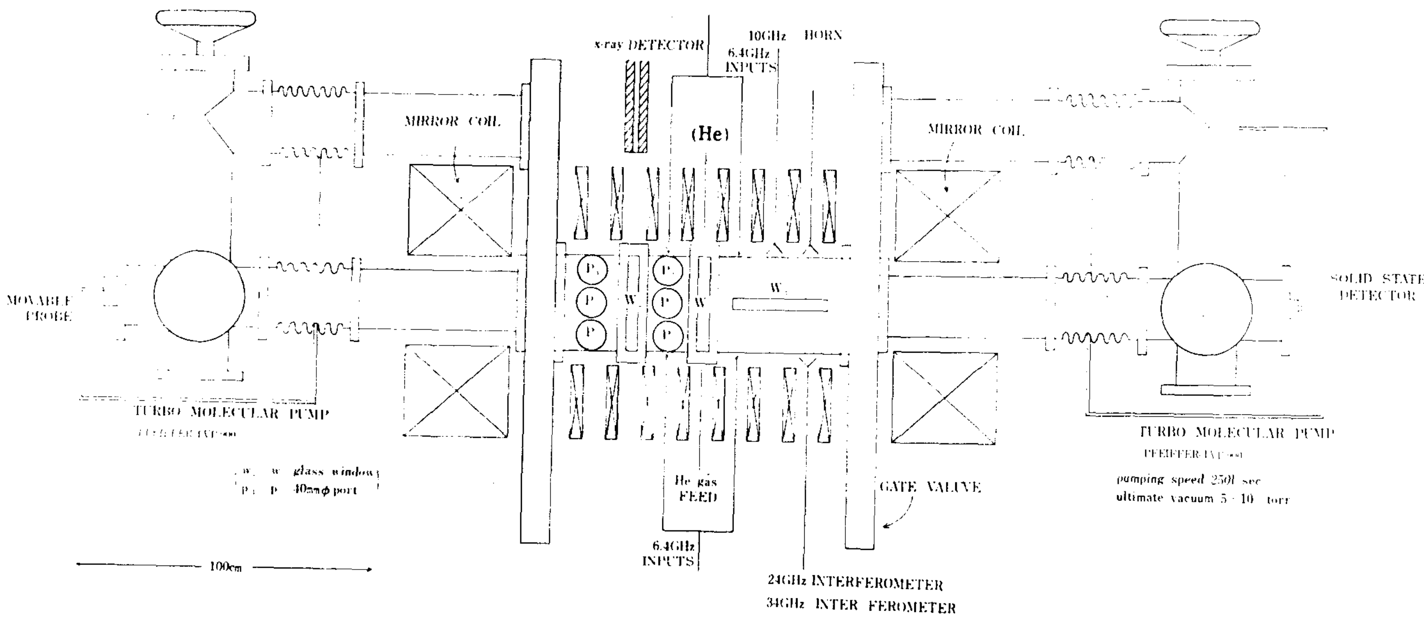

Fig.1. Schematic layout of the apparatus (TPM) for the hot electron plasma experiment.

2. Experimental Apparatus

The hot electron plasma is generated in a stainless steel cylinder 25 cm in diameter and 98 cm long, which is evacuated through openings of 12 cm in diameter on the end walls. The base pressure of 1×10^{-7} Torr is achieved by using turbo-molecular pumps to get rid of impurities of heavy atoms. Six rectangular, glass windows (2 cm × 25 cm) are equipped for monitoring x-ray and visible light. The device is shown in a schematic form in Fig.1.

The magnetic coil assembly consists of 18 air-core coils: 8 coils in the middle produce uniform magnetic field, and the other 10 coils constitute the magnetic mirror and control the mirror ratio. The magnetic lines of force for the case of mirror ratio, R = 5.8 is shown in Fig.2.

The microwave power for generating the hot electron plasma is introduced from 4 ports on the cylindrical wall as indicated in Fig.1. The wave frequency is fixed at 6.4 GHz with a dispersion of less than 50 kHz. The microwave power is obtained from a klystron amplifier with three cavities, which operates at the power up to 5 kW, cw. Typically the microwave is modulated into a pulse of 200 msec duration at the repetition rate of 1 pps.

The rectangular waveguide to the input ports is so arranged as the microwave electric field is almost perpendicular to the static magnetic field and propagates across the magnetic lines of force, that is, in the extraordinary mode.[17] The plasma chamber could functionate as a multimode

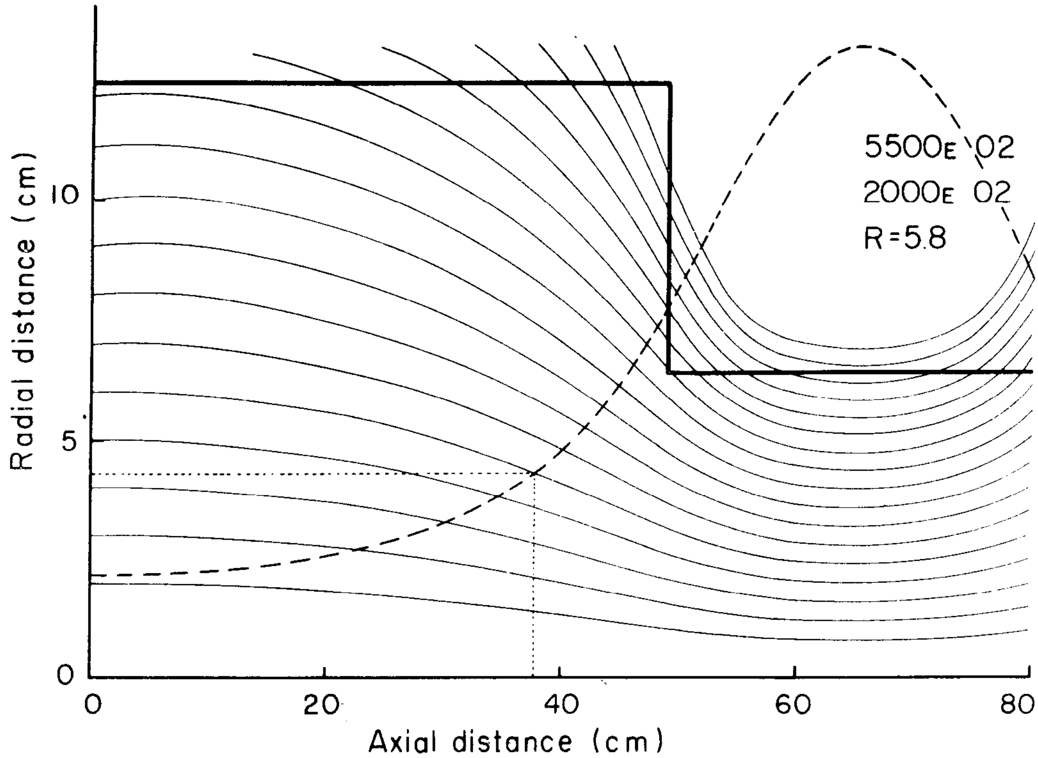

Fig.2. Magnetic mirror field configuration with the mirror ratio R = 5.8. In this case the magnetic field at the midplane gives rise to the second electron cyclotron harmonic resonance associated with the microwave frequency 6.4 GHz. The dotted line indicates the location of the fundamental cyclotron resonance on the axis. The vacuum chamber is so designed that the magnetic flux, which is just tangential to the inner wall surface at the midplane, does not intersect the chamber wall.

cavity without plasmas. However, with the plasma present, the microwave will propagate into various directions, that is, making a variety of angles with respect to the static magnetic field. The discharge takes place within the first 2 μsec of the power input. In most of the electron cyclotron heating experiments, the fundamental cyclotron resonance, associated with the microwave frequency, is necessary to be located within the discharge chamber to ignite and produce plasmas, but is not necessary to generate energetic electrons. Moreover, non-resonant microwave power, whose frequency does not find any corresponding electron cyclotron resonance region, is reported to be remarkably effective in generating hot electron plasma.[18]

In the present experiment, typical hot electron plasmas consist of cold electrons (T_c = 10 eV, n_c = 10^{12} cm^{-3}), cold helium ions, and hot electrons (T_h = 2 × 10^5 eV, n_h = 2 × 10^{11} cm^{-3}). The plasma density is determined with use of a 34 GHz microwave interferometer, and the hot electron temperature and density are estimated from the x-ray bremsstrahlung of the hot electron by using a 400 channel pulse height analyzer.

The hot electron density, immediately after the removal of the microwave power is typically 2 × 10^{11} cm^{-3} and decays exponentially with a time constant of several hundreds of msec at a helium pressure of 3 × 10^{-5} Torr. On the other hand, the cold electron density decreases to about 1/3 of the initial value within a few msec after the removal of the microwave pulse, being followed by a slight increase in density, and thereafter decays with the same decay constant as that of the hot electron.

It is interesting to consider how the balance is maintained between the cold electron and the hot electron. The hot electron is assumed to obey the following equation,

$$\frac{dn_h}{dt} = \frac{n_c}{\tau} - \frac{n_h}{\tau_h} \qquad (1)$$

where τ_h is the decay constant of the hot electron, that is, the velocity-space diffusion time for the electron to be lost into the loss cone characterized by the magnetic trap, and n_c/τ is the production rate of hot electrons as a result of heating the cold electrons by microwaves. Corresponding equation for the cold electrons may be given by

$$\frac{dn_c}{dt} = q + \frac{n_h}{\tau_i} - \frac{n_c}{\tau_c} - \frac{n_c}{\tau} \qquad (2)$$

where q is the production rate by microwave discharge, τ_i is the mean ionization time of neutral atoms by the hot electron, and τ_c is the decay constant of cold electrons.

During the steady-state microwave discharge, one obtaines from eq.1,

$$n_h = \frac{\tau_h}{\tau} n_c \, . \qquad (3)$$

Experimentally, $\tau_h \simeq \tau$ is a good approximation and $n_h \simeq n_c$ is roughly established. The relative density of the two groups depends on the heating rates and loss rates, and no complete prediction is available. After the removal of the microwave power ($q = 0$, $\tau \to \infty$), we get the following equation for the cold electron from eq.2,

$$n_c = \frac{\tau_c}{\tau_i} n_{ho} \exp(-t/\tau_h) + (n_{co} - \frac{\tau_c}{\tau_i} n_{ho}) \exp(-t/\tau_c) \qquad (4)$$

where n_{ho} and n_{co} is the initial density of the hot and cold electron, respectively. In deriving eq.4, $\tau_h >> \tau_c$ is assumed, and for $t >> \tau_c$ we get

$$n_c = \frac{\tau_c}{\tau_i} n_h \ . \qquad (5)$$

Under a typical experimental condition, $\tau_c/\tau_i > 1$ is satisfied, and this is the main reason why the hot electron plasma in a mirror trap is stable against flute instabilities, that is, the stabilization is attributed to a short circuiting effect by the cold electron which are continuously generated by the hot electrons ionizing ambient neutral atoms during the late afterglow. The decay time τ_c is roughly determined by the cold ions escaping from the mirror trap at their thermal velocity for which $\tau_c \sim 1$ msec. For the ionization cross section $\sigma_{ion} \sim 10^{-16}$ cm^2, one obtains the ambient gas pressure greater than 10^{-5} Torr necessary for the stabilization.

Transient state just after the removal of the microwave power has been observed to support various kinds of instability[19]: interchange modes in simple mirror traps,[20] electrostatic velocity space mode,[21] and electromagnetic, whistler mode.[22] During the heating period with the microwave power input, the stability aspect of the plasma is similar to that during the transient state, and the life time of the hot electron is supposed to be much shorter than it is during the stable, late afterglow. The fact is not only attributed to those various instabilities, but also to the stochastic heating process itself in the sense that the diffusion in velocity space inevitably accompanies simultaneously the diffusion in the coordinate space. During the heating period, a copious amount of x-ray emission is detected, which is obviously radiated by numbers of hot electrons colliding with the cylindrical wall of the vacuum chamber.

In order to determine the density and temperature of the hot electrons, x-ray photons are taken through a 0.1-mm-thick Mylar window onto a 3" dia. × 3" long NaI scintillator being collimated by an x-ray telescope. The solid angle subtended by the crystal through the collimator is about 10^{-5} sr and it collects photons from a cylindrical volume of plasma approximately 10 cm long with a cross section of 2 cm^2. The collimation system excludes any reception from the chamber walls. When the x-ray telescope is moved along the vertical slit (see Fig.1), it is possible to calculate the radial distribution of x-ray emission by using Abel's transformation. The intensity distribution is directly proportional to that of the hot electron density. The hot electrons are thus observed to be bunched in a shell structure[3] both during the microwave discharge and in the afterglow of the plasma as seen in Fig.3. The radius of the shell is observed to increase with the magnetic field. The shell structure is a peculiar feature of this microwave-produced hot-electron plasma in a mirror trap.

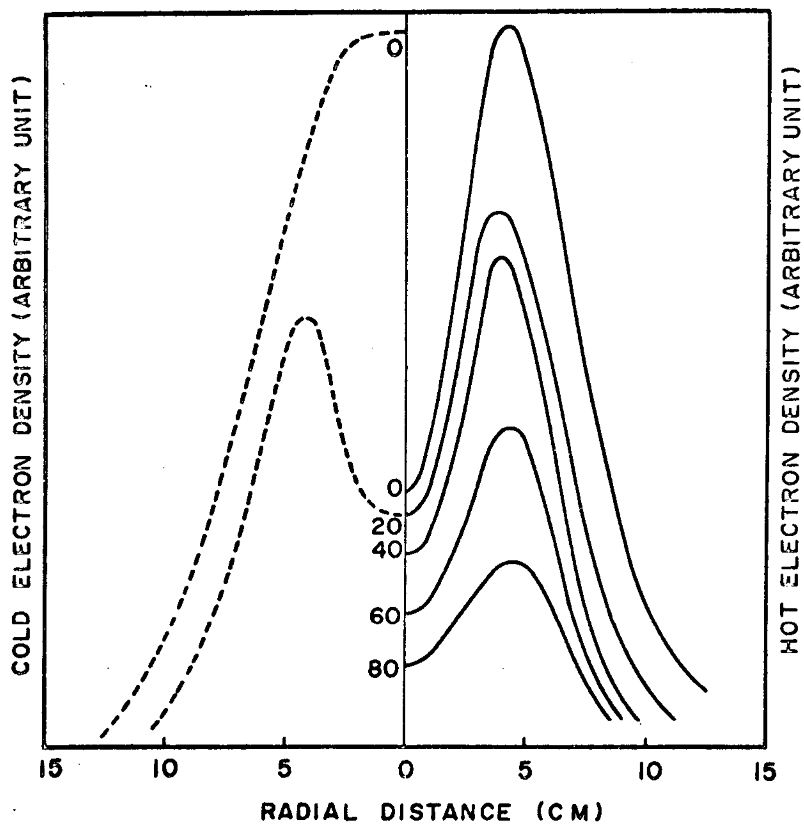

Fig.3. Plot of the radial density distribution of the electrons, after Abel's transformation. The dashed curves in the left half are related to the cold electrons and solid curves in the right half to the hot electrons. Parameters are the times (msec) after the front of the heating microwave pulse, of 20-msec duration. Each observation is made for 20 msec.

3. Energy Distribution Function

Spectral distribution of the x-ray bremsstrahlung is normally used to determine the hot electron temperature, for which a typical spectral distribution is shown in Fig.4. If we assume the hot electrons to have the Maxwellian energy distribution and adopt the quasi-classical approximation

(Weiche-Näherrung formula)[23] for the total cross-section for the emission of a photon with energy k, the photon number $n(k)$ within the energy interval $(k, k+\Delta k)$ is given by

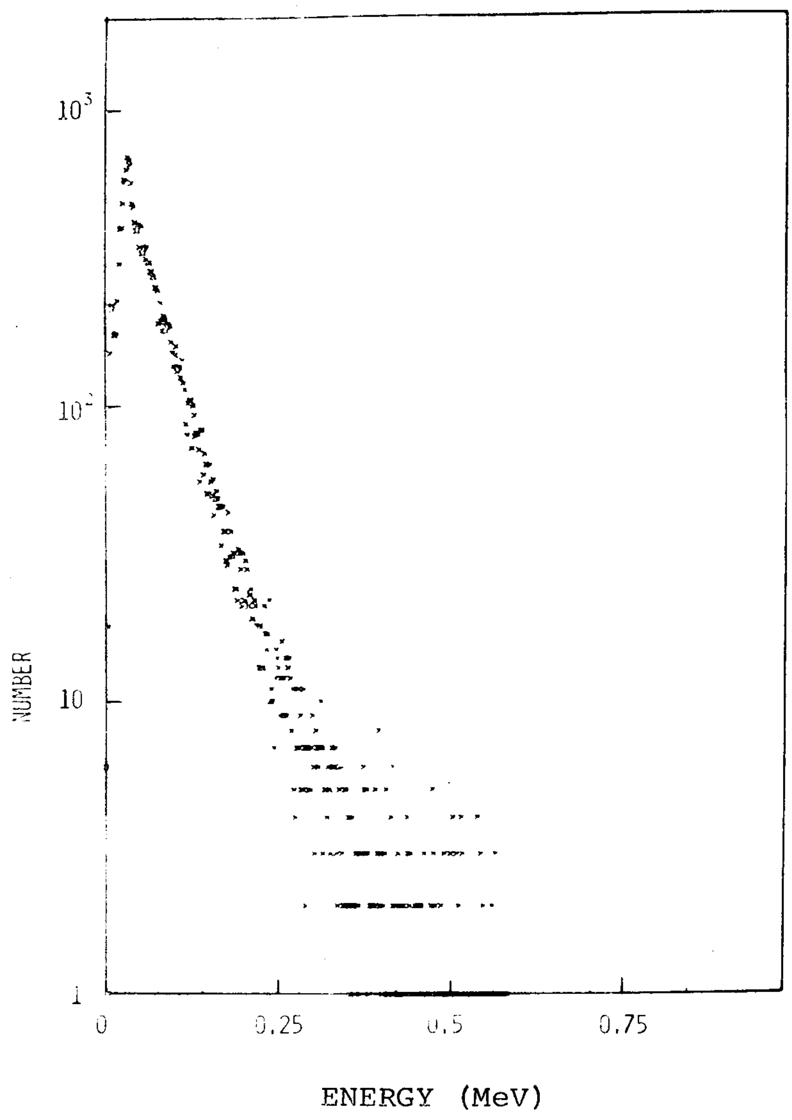

Fig.4. Typical energy spectrum of the x-ray bremsstrahlung. The ordinate is the photon number obtained with the use of a 400-channel pulse-height analyzer.

$$\eta(k) = 3.38 \times 10^{-15} Z^2 N n T^{-1/2} k^{-1} \exp(-k/T) \quad (6)$$

$$(\text{photons/sec}\cdot\text{cm}^3\cdot\text{keV})$$

where N is the density of atoms with the atomic number Z, n is the hot-electron density, and T is the hot-electron temperature in keV. The electron temperature can be roughly estimated from the slope of log $k\eta(k)$ vs. k. However, the quasi-classical approximation valid only for the condition $2\pi Ze^2/hv >> 1$, to which corresponding critical energy of the electron for the hydrogen atom is as low as 700 eV. For the hot electron plasma in the present experiment, Born's approximation is preferable, whose applicability is based on the condition $2\pi Ze^2/hv << 1$. With the Born approximation, we get

$$\eta(k) = 1.69 \times 10^{-15} Z^2 N n T^{-1/2} k^{-1} \exp(-k/2T) K_0(k/2T) \quad (7)$$

$$(\text{photons/sec}\cdot\text{cm}^3\cdot\text{keV})$$

where $K_0(Z)$ is the modified Bessel function.

In Fig.5, the hot-electron temperature is estimated with the use of eq.6, which is more tractable than eq.7. With the input peak power of 5 kW, the heating rate dT/dt is evaluated to be of the order of MeV/sec. The heating process is so slow that it takes several tens of milliseconds until the temperature saturates.

Such behavior of so-called temperature in time presents us only limited information. The energy distribution

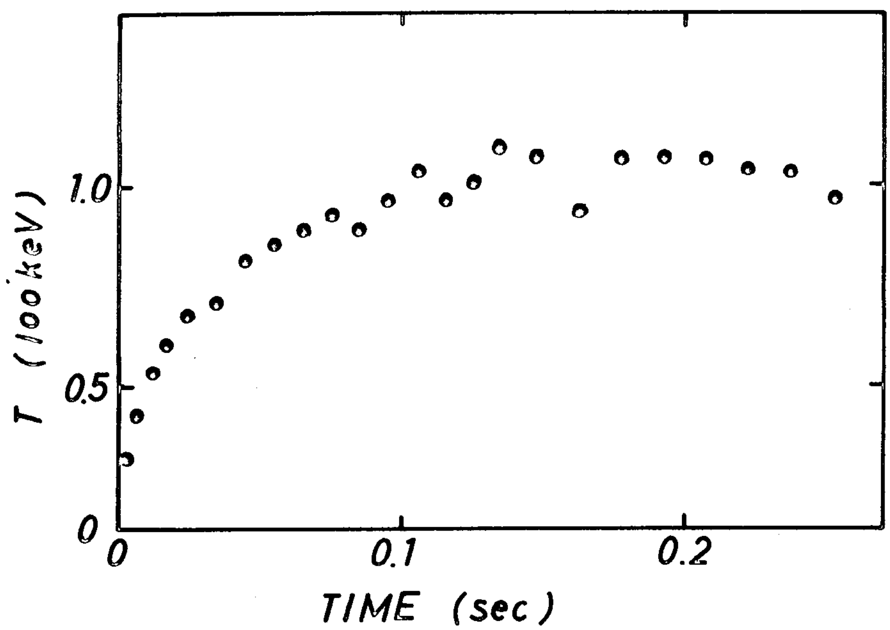

Fig.5. Time development of the electron temperature estimated from the slope of $\ell n\ k\eta(k)$ vs. k. Input microwave pulse is of 0.2-sec duration at the peak power 3 kW. Gas is helium at 4×10^{-5} Torr.

function is then calculated from the Volterra's integral equation given by

$$\eta(k) = \frac{16}{3}\phi\mu N k^{-1}\int_k^\infty \sqrt{2E/m}\ G(E,k)E^{-1}f(E)dE \qquad (8)$$

where $\phi = Z^2 r_0^2/137$, $\mu = mc^2$, f(E) is the energy distribution function of the electron, and

$$G(E,k) = \ell n\{(\sqrt{E} + \sqrt{E-k})^2/k\} \qquad (9)$$