INSTITUTE OF PLASMA PHYSICS

NAGOYA UNIVERSITY

RESEARCH REPORT

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Dense Relativistic Electron Plasma by Electron Cyclotron Heating and Adiabatic Compression

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Abstract

The hot-electron plasma produced by resonant electron cyclotron heating was successfully used as a well-controlled initial phase for a subsequent slow compression experiment. The plasma electron temperature increased almost linearally with an increase of magnetic field up to a compression ratio of over 10:1. The initial value was about 10 keV, and the final value was about 110 keV. An important observation was that the compressed plasma appeared to be stable, even when the cold background plasma density decreased dramatically.

1. Introduction

The production of ulta-relativistic ($\approx$ 10 MeV), dense ($\approx 10^{16}$ cm^{-3}) plasma is of interest, both as a basic physics problem and for many engineering applications. Concerning basic physics, we could study the confinement, behavior, and radiation of plasma in a region never before accessible. Concerning engineering applications, the plasma could be used as a gas-free target plasma for neutral injection in controlled nuclear fusion, an intense x-ray source, a cloud of hot electrons for a "collective ion accelerator", and a source of highly stripped ions for a high-Z nuclear accelerator.

Attempts at producing dense, ultra-relativistic plasma have been under way for over ten years, at the Institute of Plasma Physics in Nagoya,[1),2)] Oak Ridge National Laboratory,[3),4)] and Lawrence Radiation Laboratory in Livermore,[5)] and other locations.[6)] The three main approaches at these laboratories have been electron cyclotron resonant heating, electron-beam interaction, and adiabatic compression. The basic result of these experiments is that the temperature and density of the hot electrons have both been limited in practice to $\approx$ 100 keV and $\approx 10^{11}$ cm^{-3} respectively, in spite of intensive and expensive research efforts.

The basic limitations appear to be as follows. Concerning temperature, at temperatures above 100 keV, the average electron is beginning to experience a relativistic mass change (rest mass = 500 keV), and the electron cyclotron resonance frequency is becoming poorly defined. Thus, both electron cyclotron resonant heating, and beam plasma interaction (which appears to use electron cyclotron resonance as an intermediate step) do not work well. An additional form of "off resonance"[7] or "stochastic" heating[2] can raise some of the electrons to a temperature of ≈ 1 MeV, but the microwave power supplies are difficult to use.

Concerning the density limit of hot electrons around $10^{11}/cm^3$, the problem may be that to produce electron cyclotron heating in dense plasmas requires large amounts of microwave power in the sub-centimeter range, and such power supplies are not readily available. (In the case of stochastic heating described above, the frequency of the power supply must be above the electron cyclotron resonance frequency, so power-supply problems are even more severe.)

In the case of beam-plasma interaction, the problem may be due to the growth length for the required plasma heating instability becoming so short that the radio-frequency energy is lost near the plasma surface.

Thus, in practice, we find a barrier to producing relativistic dense plasmas of about $T_e \approx 100$ keV, and $N_e \approx 10^{11}/cm^3$, respectively. In view of the intense research effort expended on this work over the past ten years, prospects of producing a major improvement by the past techniques appear to be poor. However, we now wish to demonstrate that the plasma described above is an excellent initial state for further heating and density increase by means of slow adiabatic compression. The reasons for this are that at the temperature and density described above, the plasma is well confined against scattering loss through the mirrors ($\tau \approx 1$ second) and the plasma experimentally seems to be very stable for reasons not completely understood. Thus, the plasma can be well contained while a strong compression magnetic field is slowly increased. The fact that the risetime of the magnetic field can be slow means that the expensive fast compression apparatus such as is used in theta-pinch experiments is not required.

Two kinds of magnetic compression can be applied to a hot electron plasma. In the first case, the magnetic field is simply increased while preserving its shape. In this case, it is easy to demonstrate that both the electron temperature and the density increase directly as the magnetic field. Thus, the plasma value of $\beta = 8NKT/B^2$ is a constant under such a compression.

If we compute the final state of such a plasma, using as an initial magnetic field the value of 1 kgauss, and a final magnetic field the easily-reached (for a pulsed magnetic field) the value of 300 kgauss, we find the final temperature T_f and density n_f to be $T_f = 300\ T_e = 30$ MeV, and $n_f = 300\ n_e = 3 \times 10^{13}\ cm^{-3}$. In this case, the final electron temperature and density are becoming very interesting in themselves. Also, if the initial temperature were 1 MeV, as can be produced by "stochastic" heating, T_f would be 300 MeV! As an additional good feature, the plasma lifetime τ for mirror scattering increases as $T_e^{3/2} n_e^{-1}$, so this lifetime increases as the square root of the magnetic field increase. In the case described above, $\tau = (300)^{1/2}\tau_o$, or ≈ 14 seconds! Thus, the resultant plasma exists in almost a steady-state as far as mirror scattering is concerned.

A second, even more interesting kind of compression experiment is possible if the magnetic field is allowed to change its shape during the compression process. The basic idea is to take advantage of the fact that electron cyclotron resonance heating can produce a hot electron cloud in which the velocity of most hot electrons is perpendicular to the initial magnetic field. In this case, the magnetic mirrors can be moved together, causing axial as well as radial compression. This axial compression results in the axial electron energy component being increased, and eventually electrons reach the loss cone. The combination of both axial and radial compression could possibly give a density increase scaling as high as the square of the increase in the magnetic field. This would produce a final density, $n_f = (300)^2 \, n_o = 10^{16} \text{ cm}^{-3}$. By using such a combination of radial and axial compression, the density can be improved to very interesting values, and the axial electron distribution can be spread to produce a more stable plasma. A disadvantage of this axial compression is that the lifetime against mirror scattering scales less rapidly than the square root of the magnetic field increase. At large plasma density increases, the plasma lifetime could even become shorter!

2. Experimental Results

The above discussion concerning the possible production of ultra-relativistic, dense plasma, is very interesting, but the calculations need to be supported by experiments. Unforseen results, such as a compression-induced plasma instability might cause severe plasma losses. Therefore, an experiment is required to verify the above computed results.

Such an experiment has been performed at the Institute of Plasma Physics, Nagoya, and will be described in detail later. The basic observations can be summarized as follows. The experiment is quite successful. A hot electron plasma was generated in a simple student-constructed mirror machine. The initial electron temperature was 10 keV, a value that is rather low because of the simplicity of the apparatus. The density was not measured; but was estimated from previous experiments to be $\approx 10^{10}/cm^3$. To compress this plasma, a slow-compression with a rise time of $\approx$ 1 msec, and a crowbarred decay with a time of $\approx$ 10 msec was used. Under the proper compression conditions the electron temperature was observed to rise a bit more slowly than the magnetic field, and to reach a maximum value $\approx$ 110 keV, as computed from the x-ray spectrum. No evidence of instabilities was observed, and the electron temperature decayed smoothly as the pulsed magnetic field dropped with its time constant of 10 msec. The total x-ray photon count also appeared to increase as expected with the compression magnetic field, and a large x-ray pulse was observed.

The experimental device, shown in Fig. 1, is made of a pyrex glass tube which is 10 cm indiameter, the inside of which is fabricated with stainless steel mesh with a cut in the axial direction to avoid induction currents caused by the pulsed magnetic field. For discharge, steady gas flow of argon is fed at 3×10^{-5} Torr. The microwave of 2.45 GHz at 800 W is pulsed for 106 msec and is introduced along the axis through the waveguide into the mirror field, which is 670 G at the midplane. The pulsed magnetic field rises to its maximum value of 11 kG at the midplane in 1.5 msec and decays with a time constant of 5 msec. Its mirror ratio is the same as that of the static mirror field, and with a distance between the mirror points 24 cm. In the direction perpendicular to the magnetic field, bremsstrahlung x-ray from hot electrons is detected through a mailar window (2 cm dia.) on a NaI(Tℓ) scintillator followed by the photomultiplier, and the energy spectrum is displayed on a 400-channel pulse height analyser.

The photo-diode and the Langmuir probe are also used to obtain information on the cold electrons. The synchrotron radiation is observed by a 10 GHz radiometer system in the direction perpendicular to the magnetic field. To get the most reliable results from the compression experiment, we had to turn off the electron cyclotron heating power immediately before compression, under which condition, cold plasma production certainly decreased. Of course, some cold plasma is always produced by the hot electrons, but this is experimentally shown to be much smaller than that produced by the electron cyclotron resonance heating. Time sequences of the microwave power for discharge, the compression field, and the output of photo diode which is regarded as a main signal from the cold electron component are shown in Fig. 2. The temperature of the primary hot electron plasma produced by microwave at the electron cyclotron resonance is estimated to be 10 keV from the energy spectrum displayed on the pulse height analyser.

When the pulsed magneticfield (11 kG peak) is applied to the after-glow plasma, the hot electron temperature is observed to increase up to 110 keV in accordance with the compression ratio (Fig. 3). Change in the hot electron density can be estimated from the total photon number with the pulse height analyser operated in the scaler mode. With Born approximation, the photon number η emitted by the hot electron with energy E(eV) and density $n(cm^{-3})$ is given[2)] by

$$\eta = 1.69 \times 10^{-15}\ NnGT^{-1/2}\int_{E_o}^{\infty} \frac{e^{-E/2T}K_o(E/2T)}{E}dE \qquad (1)$$

where N is the density of neutral atoms, G is a geometrical factor, K_o is the modified Bessel function, and the electron energy distribution is assumed to be Maxwellian. Using this equation, we can estimated the hot electron density by measuring T, N and η.

For the adiabatic magnetic compression, the dependence of temperature, T_e, and density, n_e, on the magnetic field strength B is given by

$$n_e/n_{eo} = T_e/T_{eo} = B/B_o \qquad (2)$$

where subscript "o" represents the values before the compression. Typical data obtained in the experiment are shown in Fig. 4 and Fig. 5 and compared with the value calculated from Eq. (2).

As seen in Fig. 4, the hot electron temperature increases adiabatically to eleven times in accordance with the compression ratio without any instabilities. While the density increases linearly but by a factor of ~ 1.7 more rapidly. In Fig. 5, it is shown that the time constant of the magnetic field is equal to that of the hot electron temperature. The fact confirms the adiabaticity of the hot electrons in the compression process.

One interesting observation is that the hot-electron plasma is stable even though the cold-plasma density in the machine during compression was quite small. The reason that cold plasma is not present, is that under compression, the electron cyclotron resonance cannot occur. And also because of so-called plasma pumping, the base pressure still remains too low to make ionization by hot electrons effective. Consequently, under compression, cold plasma production decreases. Experimental observations supporting this fact are that under compression a cold plasma probe in the mirror throat detects a dramatic drop in the cold plasma flow. Also, the light output from the plasma decreases dramatically when the compression pulse is applied. However, when the compression is made during the microwave duration, the electron temperature shows a peak at the earlier compression stage ($\lesssim 4$), as seen in Fig. 6, and consequently the photon number goes up sharply. This phenomenon may be considered to be due to certain instabilities. In this case, the second harmonic cyclotron resonance exists somewhere in the plasma, and the effect of electron cyclotron resonance heating and adiabatic heating is superimposed. To summarize the experimental observations, the compression appeared to heat the plasma, as expected and no strong instabilities were detected during the compression phase of $\approx$ 10 msec.

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Figure Captions

Fig. 1 Schematic structure of the experimental device.

Fig. 2 In the upper photograph the magnetic compression field is applied to the microwave durated plasma. In the lower photograph, the same magnetic field is applied to the after glow plasma. The upper trace is the pattern of the microwave input power, the second one is that of the compression field, and the lowest one is the signal from the photo diode.

Fig. 3 The energy spectrum of hot electrons before the compression (B_{max} = 1 kG) and after the 11 times compression (B_{max} = 11 kG). ($p = 3.2 \times 10^{-5}$ Torr, ;B_{max} = 11 kG, x;B_{max} = 1 kG)

Fig. 4 The density (n_e) and temperature (T_e) of hot electrons of the after glow plasma in changing the compression ratios. The subscript "0" represents the value before the compression. (●;T_e, x;n_e)

Fig. 5 The time dependence of the hot electron temperature in changing the compression field. The subscript "0" represents the value before the compression. The real line represents the behavior of hot electron temperature and the dashed one is that of the magnetic field.

Fig. 6 The density (n_e) and temperature (T_e) of hot electrons during the microwave duration in changing the compression ratios. The subscript "0" represents the value before the compression (●;T_e, x;n_e).

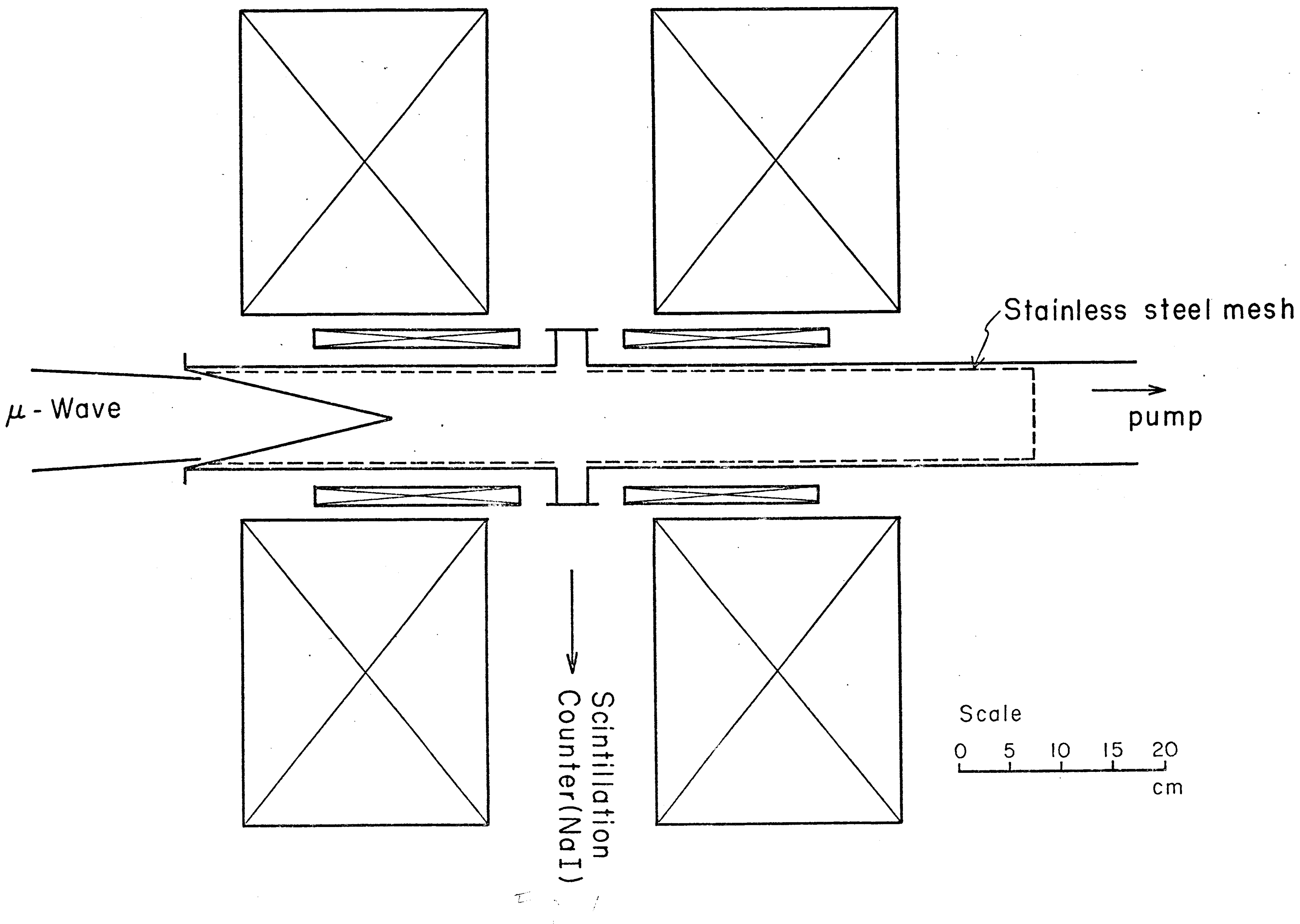

Stainless steel mesh
μ - Wave
pump
Scintillation
Counter(NaI)
Scale
0 5 10 15 20
cm

Fig. 1

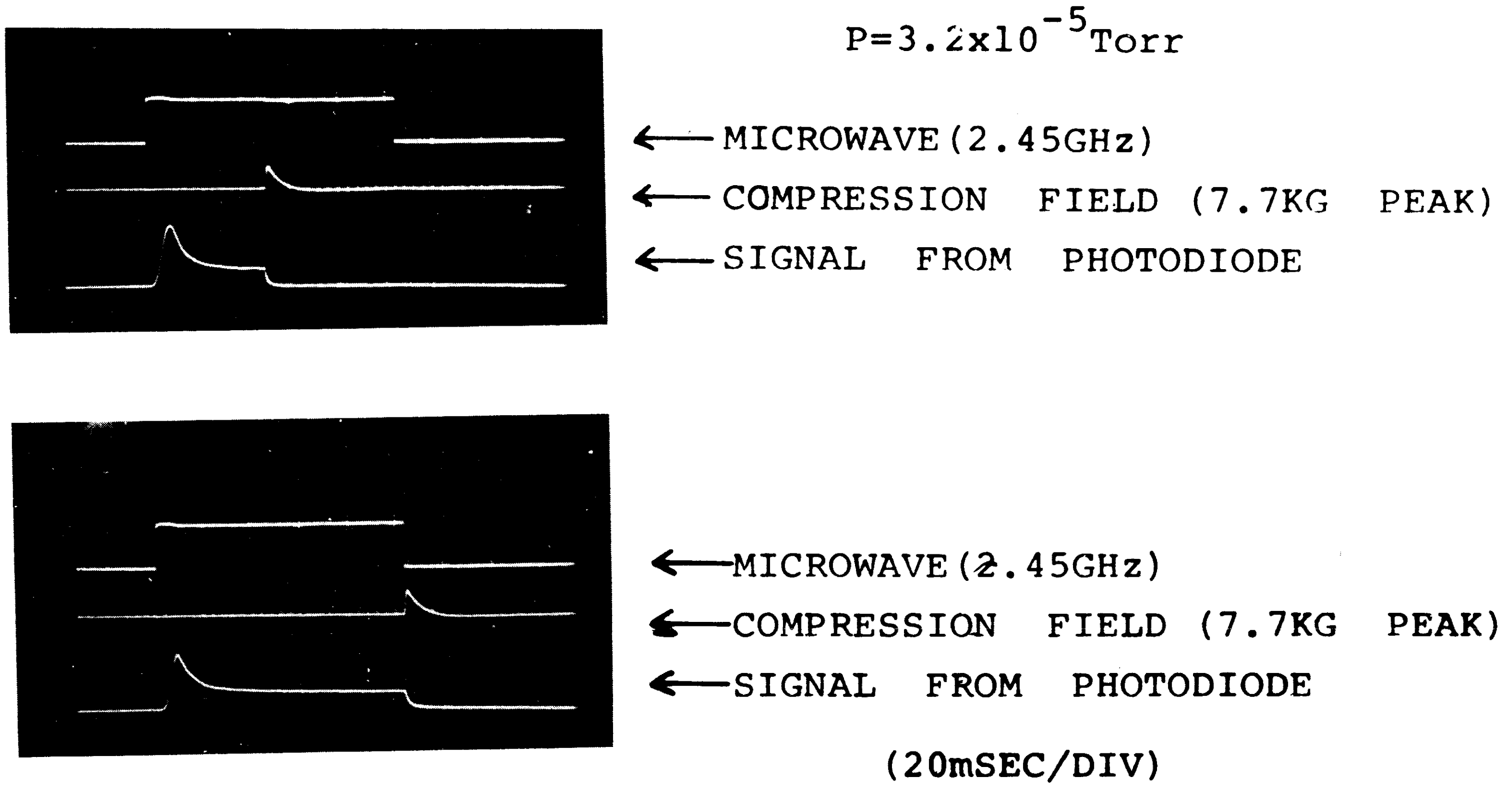
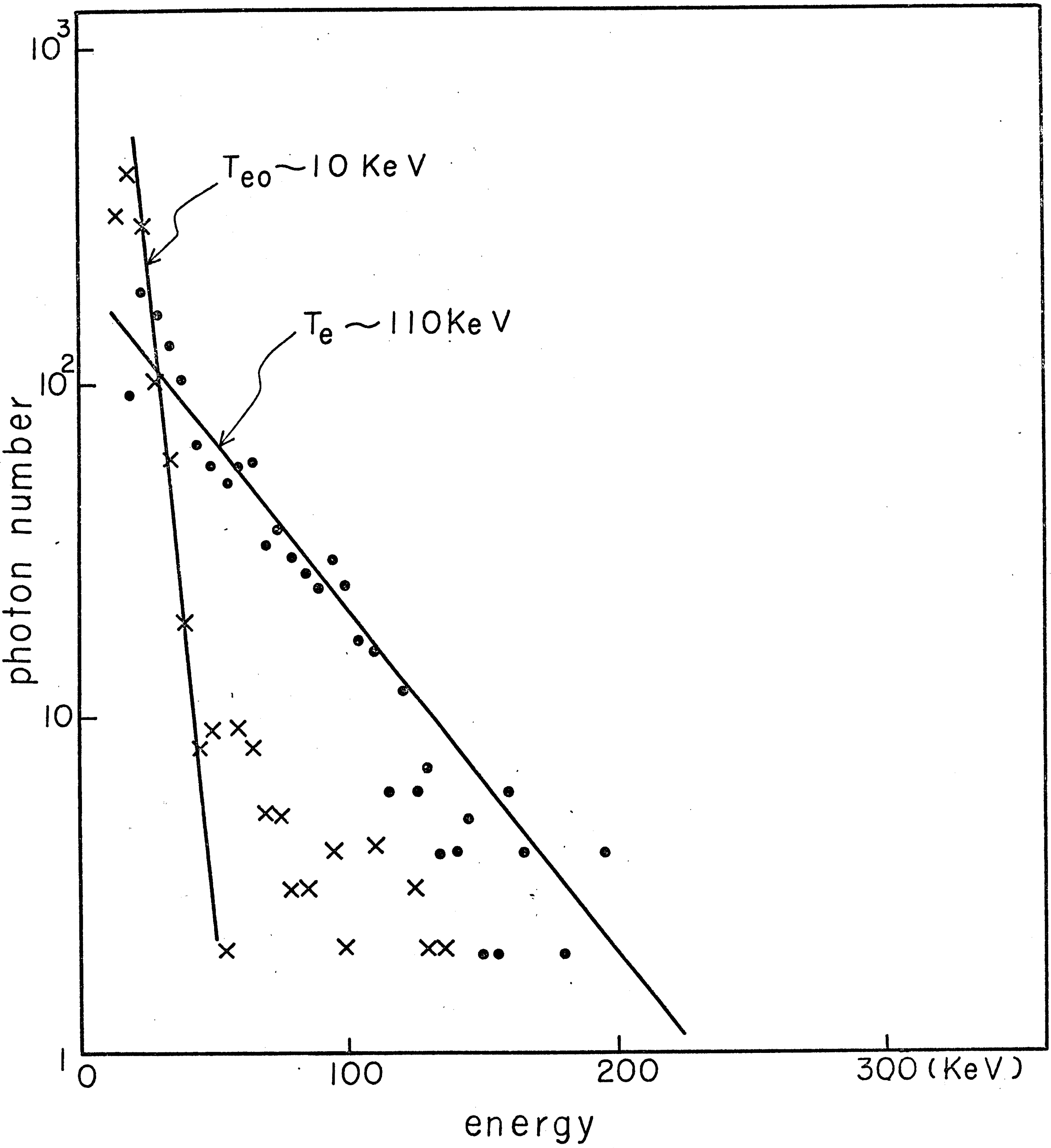

P=3.2x10^-5 Torr
MICROWAVE (2.45GHz)
COMPRESSION FIELD (7.7KG PEAK)
SIGNAL FROM PHOTODIODE
MICROWAVE (2.45GHz)
COMPRESSION FIELD (7.7KG PEAK)
SIGNAL FROM PHOTODIODE
(20mSEC/DIV)

FIG. 2



$T_{eo} \sim 10$ KeV
$T_e \sim 110$KeV
photon number
10^3
10^2
10
1
0
100
200
300 (KeV)
energy

Fig. 3

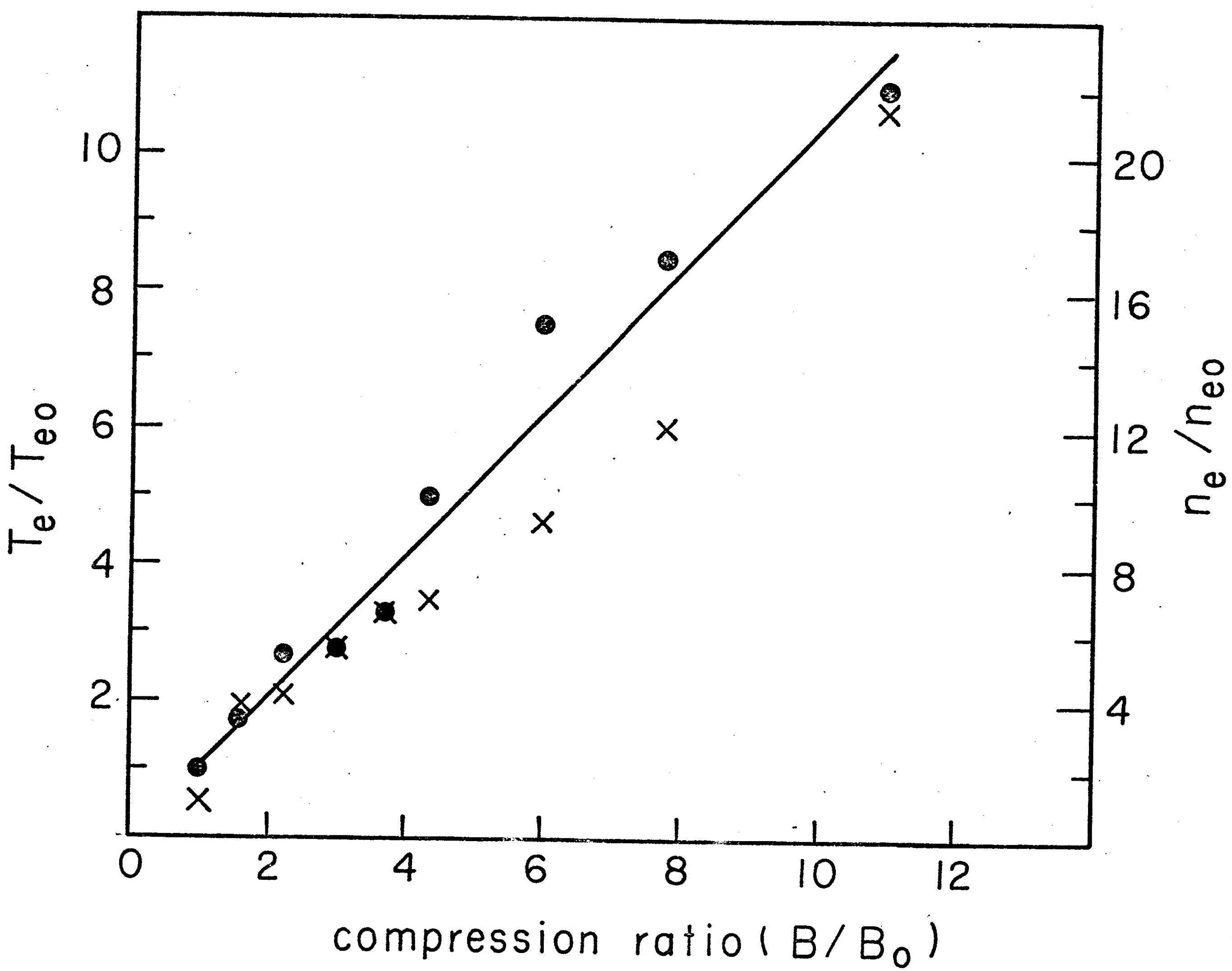


Fig. 4

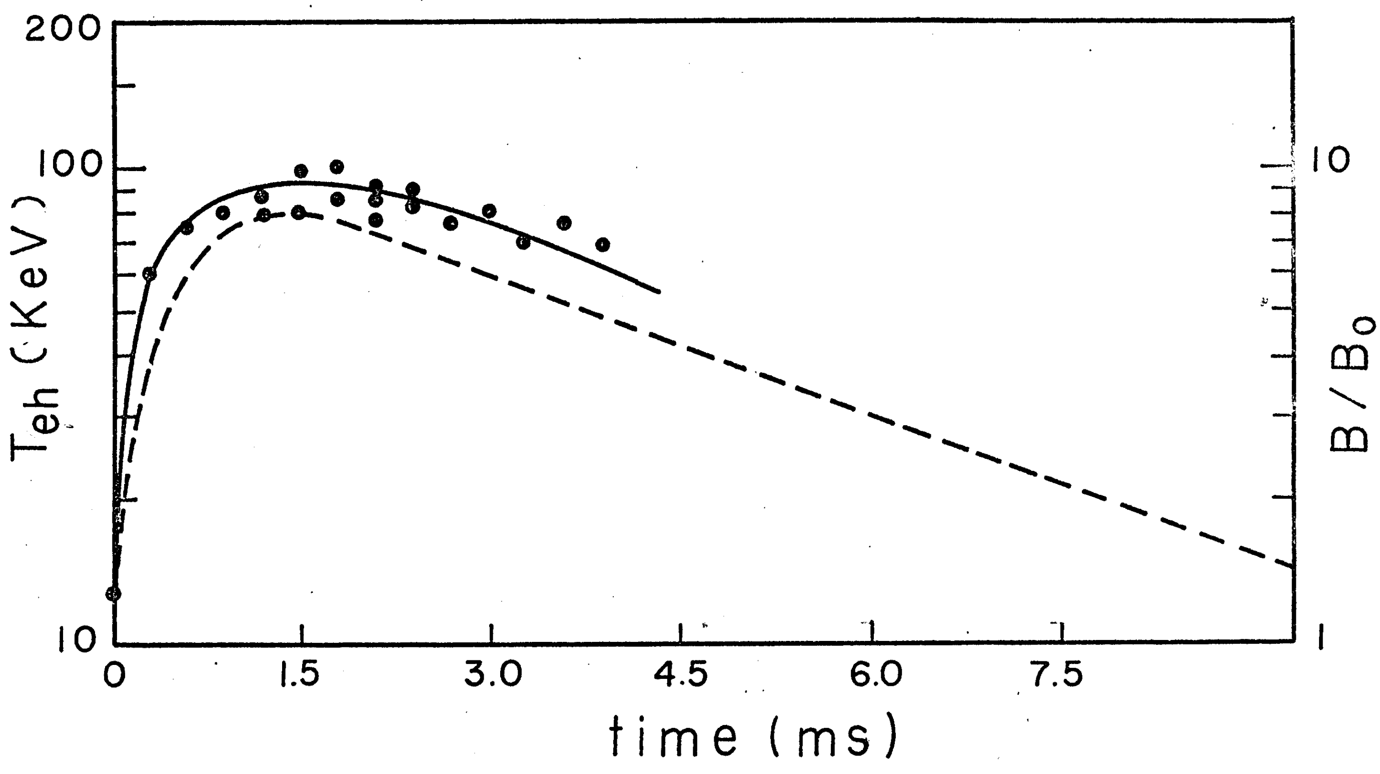


Fig. 5

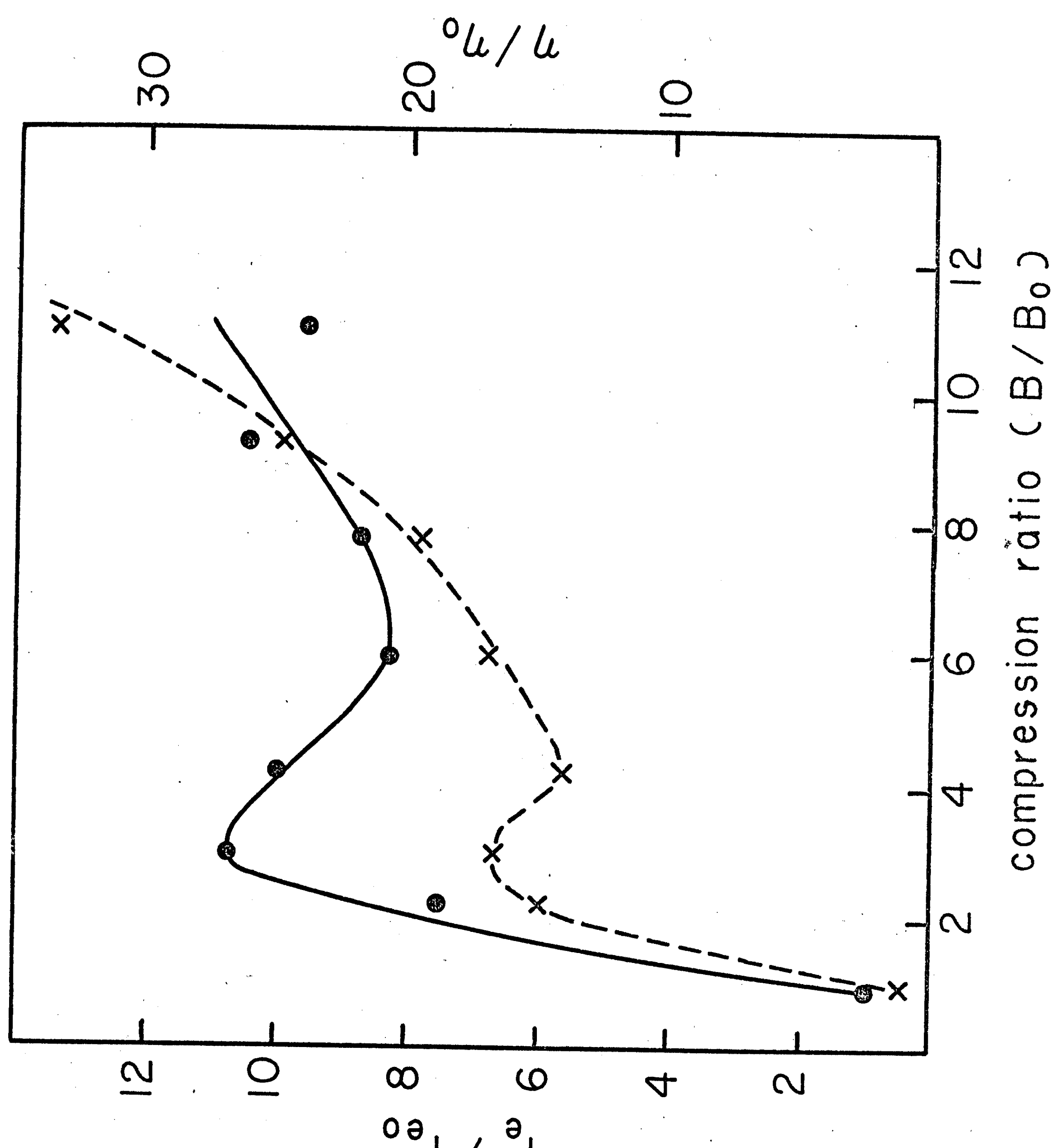


Fig. 6