PFC/JA-87-38

Time-of-flight analyzer for ion endloss of a mirror plasma

Petty, C.C.; Smith, D.K.; Smatlak, D.L.

October 1987

Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139 USA

Submitted for publication in: Review of Scientific Instruments

Supported by the U.S. Department of Energy Contract No.
DE-AC02-78ET51013

Abstract

A time-of-flight analyzer has successfully been used to measure the extracted charge-state distribution and impurity level of an ECRH mirror plasma. Endloss temperatures for each ion species have been determined from the rise time of the analyzer output pulses. Ions entering the line-of-sight device are first accelerated by a two aperture lens and are then focused with an einzel lens. Electrostatic deflection plates chop the ion beam into short pulses which travel down a 1.20m tube to an electron multiplier. Ion spectra are summed at a rate of 1kHz using a hardware signal averager.

Introduction

In a mirror plasma, a plasma potential (V_p) develops which confines electrons and expels ions. An ion leaving the plasma as endloss therefore has a total energy equal to the sum of its kinetic energy (E_i) plus its potential energy ($q_i V_p$). If the ion is then accelerated through an externally applied potential (V_b), the time required for it to transverse a distance L is

$$t = L\sqrt{\frac{m_i}{2[q_i(V_p + V_b) + E_i]}}. \tag{1}$$

For the condition $E_i \ll q_i(V_p + V_b)$, this becomes

$$t = L\sqrt{\frac{m_i}{2q_i(V_p + V_b)}}\left[1 - \frac{E_i}{2q_i(V_p + V_b)}\right]. \tag{2}$$

Thus the time-of-flight (TOF) of an ion is proportional to the square root of its mass-to-charge ratio. The endloss temperature of each ion species can be determined from the rise time of its pulse. From Eqn. 2, the difference in arrival times (Δt) between an ion with initial kinetic energy E_i and an ion with no initial kinetic energy is

$$\Delta t = -\frac{L m_i^{1/2} E_i}{[2q_i(V_p + V_b)]^{3/2}}. \tag{3}$$

If the ion endloss current is assumed to have a one-dimensional Maxwellian distribution of energies, $I \propto exp(-E_i/T_i)$, then substituting for E_i from Eqn. 3 gives

$$I \propto exp\left\{\frac{[2q_i(V_p + V_b)]^{3/2}}{L m_i^{1/2} T_i}\Delta t\right\}. \tag{4}$$

Thus by fitting an exponential to the rising edge of the analyzer output pulse, the endloss temperature of that ion species can be determined.

A TOF analyzer is presently being used to study ion endloss from the Constance B quadrupole-mirror experiment. The main function of the analyzer is to measure the extracted charge-state distribution and ion endloss temperature of non-hydrogen plasmas. A secondary function is to identify and monitor impurity levels in the plasma. Knowing the extracted charge-state distribution allows the total ion particle current to be found from the electrical current collected by a faraday cup. For hydrogen plasmas, the TOF analyzer can find the H_2^+ to H^+ ratio in order to determine the correct number of ionizations per H_α photon for source measurements. The Constance experiment is described in detail elsewhere.[1,2] Briefly it uses several kilowatts of ECRH to create a hot electron plasma ($\beta \sim 20\%$) with $n_{eh} = 2 \times 10^{11}\text{cm}^{-3}$ and $T_{eh} = 400\text{keV}$. The hot electrons are responsible for stripping heavy atoms to high charge states. There is also a cold population of electrons with $n_{ec} = 1 \times 10^{11}\text{cm}^{-3}$ and $T_{ec} = 50\text{eV}$. The ion endloss current-density is typically $5\mu\text{A/cm}^2$. Pulse lengths for Constance are 1–2 seconds.

TOF analyzers have previously been used as mass spectrometers in chemical ionization sources[3] and other apparatus.[4,5] As mass spectrometers, they are designed to achieve high mass resolution by minimizing the thermal spread of the ions. More recently, TOF analyzers have been used to determine the charge state distribution of ion sources.[6] The TOF analyzer

described here differs from these because it combines m_i/q_i resolution and sensitivity with the ability to measure ion temperatures. It also operates at low ion current densities and on fast time scales.

I. Analyzer design

There are four sections to the time-of-flight analyzer: 1) the accelerating/focusing lens, 2) the deflection plates, 3) the time-of-flight length and 4) the ion detector. A drawing of the first two sections is shown in Fig. 1. For simplicity the analyzer was designed to be a line-of-sight device. If potential is measured relative to the plasma, then the entrance aperture is negative by the plasma potential (V_p). The second aperture is biased at a high negative voltage (V_b) to accelerate the ions to 2–3kV. It is important that this bias voltage be much greater than the ion temperature, otherwise the TOF will depend more on temperature then on $\sqrt{m_i/q_i}$. These two accelerating apertures make up a convergent lens with a focal length approximately equal to three times the distance between them.[7] Thus after several centimeters the ion beam becomes strongly unfocused and the ion current density starts to decline. An einzel lens is therefore placed after the accelerating lens in order to refocus the beam and thus increase the amount of current reaching the ion detector. The einzel lens does not change the ion's energy because the entrance and exit apertures are at the same potential. The middle aperture is biased with a second power supply at a less negative potential (V_f).

The ions exit the accelerating/focusing lens with paths parallel to the axis when the sum of the mid-focal lengths of the two lenses equals the distance between their reference planes. The current at the ion detector is typically increased by a factor of fifteen when the einzel lens is used. The optimal focusing voltage for the einzel lens depends on both the bias voltage and the plasma potential, and thus can change by several hundred volts as plasma conditions change.

After leaving the accelerating/focusing lens, the ion beam is collimated and passes between two electrostatic deflection plates. Normally one plate is biased relative to the other, creating an electric field which deflects the ions. The angle of deflection (θ) is given by

$$\tan\theta = \frac{lV_d}{2d(V_p + V_b)}, \tag{5}$$

where l is the deflection plate length, d is the separation between plates, and V_d is the potential difference between the plates. Note that the angle of deflection is independent of ion mass or charge. Our parameters are l = 12.7mm, d = 6.4mm and V_d = 100V. There is an exit aperture located 63.5mm past the deflection plates which deflected ions cannot pass. In order to send a burst of ions through the exit aperture to the ion detector, the deflection plate voltage is pulsed to zero by the circuit shown in Fig. 2. Typical pulse lengths are 100–300ns, with 7ns rise and fall times. This fast rise time is necessary in order to determine the ion temperature from the analyzer output pulse.

After passing through the exit aperture, the ions travel down a long section of tubing. This serves as the time-of-flight length. In general, the longer the tube, the better the m_i/q_i resolution and the more accurate the ion temperature measurement. In our case the maximum length was set by space limitations to be $L = 1.20$m. This length gives typical TOF's of several microseconds.

At the end of the flight an electron multiplier serves as the ion detector. A Vacumetrics AEM-1000 multiplier is used which has a rise time of 10ns and is small enough to fit inside a standard $1\frac{3}{8}$-inch diameter tube. The multiplier gain is 5×10^5 at 2kV. The electron multiplier supply voltage is the same bias voltage used to accelerate the ions. The advantage of this is that only one high voltage power supply is needed. The disadvantage is that changing the multiplier gain means changing the accelerating voltage for the ions, and thus the TOF and the focusing properties also change. Because large peak currents are drawn from the multiplier (typically 100μA), a 300pF vacuum compatible, glass capacitor is placed across the resistor from the last dynode to ground. The multiplier output is amplified by a PAR 115 wideband preamp with a gain of ten. All signal cables are terminated in 50Ω.

The magnetic field lines from the Constance baseball magnet are parallel to the axis of the TOF analyzer, with a typical field strength of 90G at the entrance. The entire length of the analyzer is magnetically shielded to insure that there are no ion gyroradius effects and to prevent gain loss of

the electron multiplier. Ion gyroradius effects would result in a limit to the perpendicular temperature that an ion could have and still reach the electron multiplier. The magnetic shielding doubles as a high voltage shield since the entire analyzer floats at the bias voltage.

II. Data acquisition and averaging

The TOF analyzer can produce an ion spectrum every 20μsec. Since the usual time scale of interest is several hundred milliseconds, data averaging is performed. Besides the signal-to-noise ratio improvement, data averaging smooths out the statistical fluctuations in particle counts which comes from low ion currents. On Constance, the major source of noise is from soft X-rays. Because the TOF analyzer is a line-of-sight instrument, X-rays can pass through the apertures and strike the electron multiplier. Summing many spectra averages the X-rays out to an offset current. (It is possible, however, to altogether block X-rays from entering the TOF analyzer by taking advantage of the curved magnetic field lines.) A second source of noise is from hot electron endloss. Electrons with kinetic energy greater than about 40keV will enter the analyzer and pass by the deflection plates unaffected, thus contributing to the noise signal.

The primary method of signal averaging is to digitize the electron multiplier output at 100MHz, and then sum the spectra using a hardware signal averager. This setup consists of a Transiac 2001s transient digitizer linked

to a Transiac 4001 signal averaging memory. Spectra can be summed with 8 bits of accuracy at a rate of 1kHz. Thus over a period of one second a signal-to-noise ratio improvement of 32 can be obtained.

A second method of data averaging is with a gated integrator and boxcar averager. The gate of the boxcar is scanned over the ion spectrum in order to perform the data averaging, with a scan lasting from .1–1 second. The signal-to-noise ratio improvement with the boxcar is twelve times less than with the hardware signal averager; this can be improved on somewhat by narrowing the portion of the spectrum being averaged over by the boxcar. The boxcar has an advantage, however, in that the gate can be set to look at one particular ion species. It can then follow the amplitude of that ion species on a very fast (20kHz) time scale.

III. Experimental results

A typical TOF spectrum is shown in Fig. 3 for an argon plasma. This data is the sum of 1000 spectra taken over 1 second. The TOF parameters are $V_p = 115$V and $V_b = 2.50$kV. A deflection plate pulse length of 150ns was used in order to resolve the highest charge states. This amount of time was too short, however, to allow the slowest Ar^+ and Ar^{2+} ions to pass by the deflection plates; thus their heights are too low by 90% and 40% respectfully. Because of fringe electric fields, the minimum required pulse length is actually twice as long as it takes an ion to travel the length of the

deflection plates. The highest charge state of argon extracted was Ar^{11+}. In addition many impurities are evident, the dominant ones being atomic and molecular hydrogen (hydrogen is the normal working gas of Constance). Also seen are nitrogen, oxygen and carbon, along with various molecular combinations. All ion species are peaked on the lowest charge state.

The ion particle current can be found by dividing the electron multiplier output current by the multiplier gain and the electron yield for ion impact (γ). An absolute calibration of γ for various ion species is difficult, mainly because γ is strongly affected by the surface condition of the dynode material.[8,9] Many experiments have shown that γ decreases with ion mass and increases with charge state,[8–10] but the reported amounts vary considerably. Since the relative increase in γ with charge state falls as the ion energy increases, this effect is deemphasized for the TOF analyzer. We calibrated γ by analyzing the height of individual counts from the electron multiplier corresponding to different ion species. We found no correlation between γ and ion mass or charge to within the 20% experimental uncertainty for elements up to argon.

A blowup of the first two argon charge states is shown in Fig. 4 for a deflection plate pulse length of 300ns. This pulse length allows all of the argon ions to pass through the deflection plates. The plasma conditions are the same as for Fig. 3. The exponential rise of the pulses gives an ion end-loss temperature of 33eV for Ar^{+} and 60eV for Ar^{2+}. These temperatures are too high to be accounted for by electron drag alone; it is believed that

the ions are being heated by the strong electron microinstability. These ion temperatures, and in particular the increase in ion temperature with charge state, were independently confirmed from doppler broadening of argon spectral lines. Similar results were obtained in oxygen plasmas. This confirmation is important because large fluctuations in the plasma potential could have distorted the analyzer output pulses, leading to TOF ion temperatures which were too high. The temperature increase with q_i is consistent with mirror confinement models.[11]

Conclusions

A TOF analyzer has successfully been used to measure the extracted charge-state distribution and ion endloss temperature of an ECRH mirror plasma. Because an electron multiplier is used as the ion detector, the main source of error in determining the ion particle currents is in knowing the electron yield for ion impact of the dynode material; however, γ appears to be relatively independent of ion mass or charge for elements up to at least argon. The rise time of the TOF analyzer pulses can be used to find the ion endloss temperature for each ion species. As with all such measurements, care must be taken that a hot ion tail is not mistaken for the temperature of the bulk ions. Large fluctuations in the plasma potential are another possible source of error, but do not appear to be a concern because the TOF temperatures agree with temperatures determined from doppler broadening of visible spectral lines. It should be remembered that the ion temperatures

measured by the TOF analyzer are endloss temperatures, and may not be the same as the confined temperatures.

Acknowledgments

The authors would like to thank Ken Rettman for fabricating many of the parts for the TOF analyzer. This work was performed under D.O.E. contract no. DE-AC02-78ET51013. C. Petty was financially supported by the Magnetic Fusion Energy Technology Fellowship administered by Oak Ridge Associated Universities.

References

[1]R.S. Post, *et. al.*, Plasma Physics and Controlled Nuclear Fusion 1984: Tenth Conference Proceedings, London, 12-19 September 1984 (IAEA, Vienna, 1984), Vol. 2.

[2]D.L. Smatlak, X. Chen, B.G. Lane, S.A. Hokin, R.S. Post, Phys. Rev. Lett. **58**, 1853 (1987).

[3]J. David Pinkston, Martin Rabb, J. Throck Watson and John Allison, Rev. Sci. Instr. **57**, 583 (1986).

[4]D. Rathmann, N. Exeler and B. Willerding, J. Phys. E: Sci. Instrum. **18**, 17 (1985).

[5]J.A. Browder, R.L. Miller, W.A. Thomas and G. Sanzone, Int. J. Mass Spectrosc. & Ion Phys. **37**, 99 (1981).

[6]I.G. Brown, J.E. Galvin, R.A. MacGill and R.T. Wright, Rev. Sci. Instr. **58**, 1589 (1987).

[7]E. Harting and F.H. Read, *Electrostatic Lenses* (Elsevier Scientific Publishing Company, New York, 1976).

[8]S.C. Brown, *Basic Data of Plasma Physics* (M.I.T. Press, Cambridge, 1966).

[9]S. Flügge, *Handbuch der Physik* (Springer, Berlin, 1955).

[10]C.F. Barnett, G.E. Evans and P.M. Stier, Rev. Sci. Instr. **25**, 1112 (1954).

[11]David E. Baldwin, Model for ion confinement in a hot-electron tandem mirror anchor, Lawrence Livermore Lab. Rep. UCID-18802 (1980).

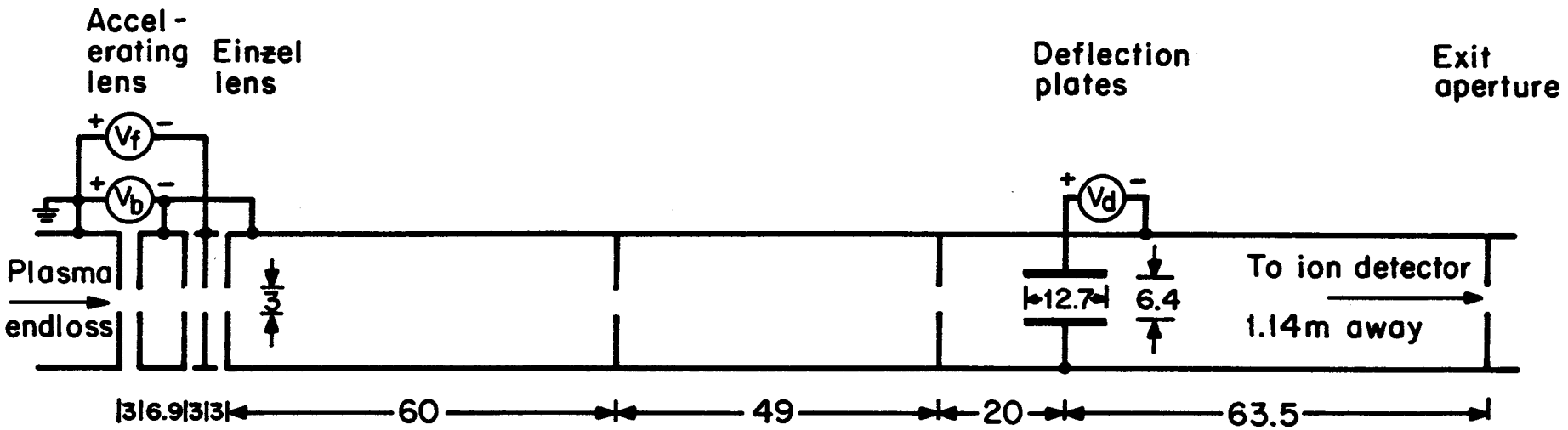

FIG. 1. Diagram of accelerating/focusing lens, collimators and deflection plates. All dimensions are in mm.

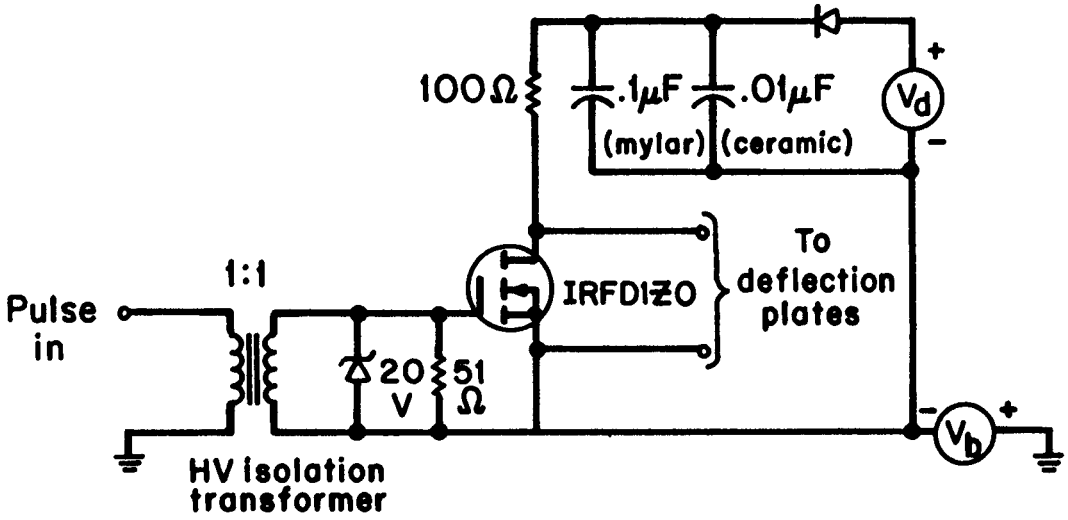

FIG. 2. Fast switching circuit for deflection plates.

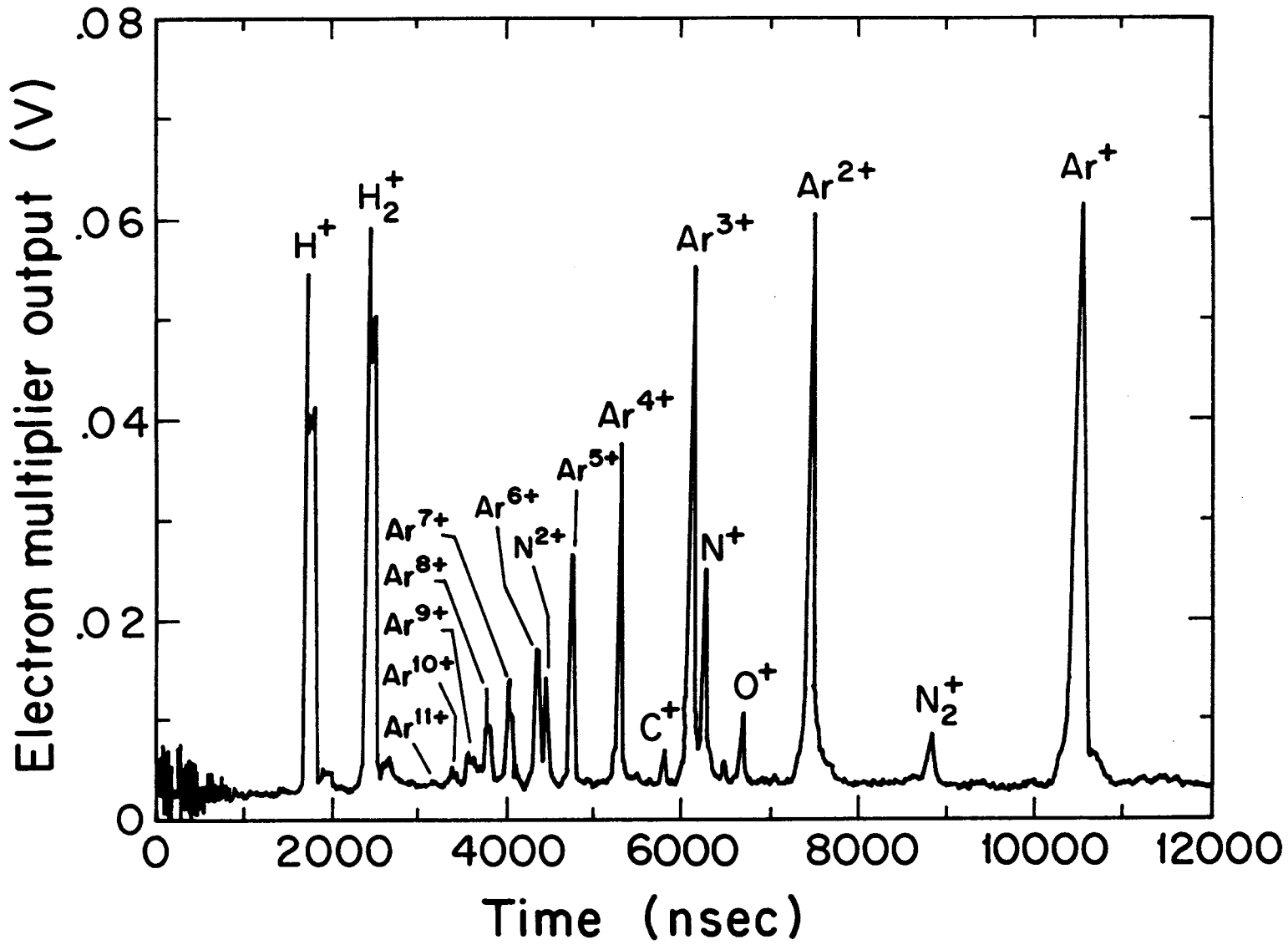

FIG. 3. Time-of-flight spectrum for an argon plasma, the sum of 1000 spectra over 1 second. The secondary peaks following the H^+ and H_2^+ peaks are from fast hydrogen neutrals striking the second dynode of the electron multiplier.

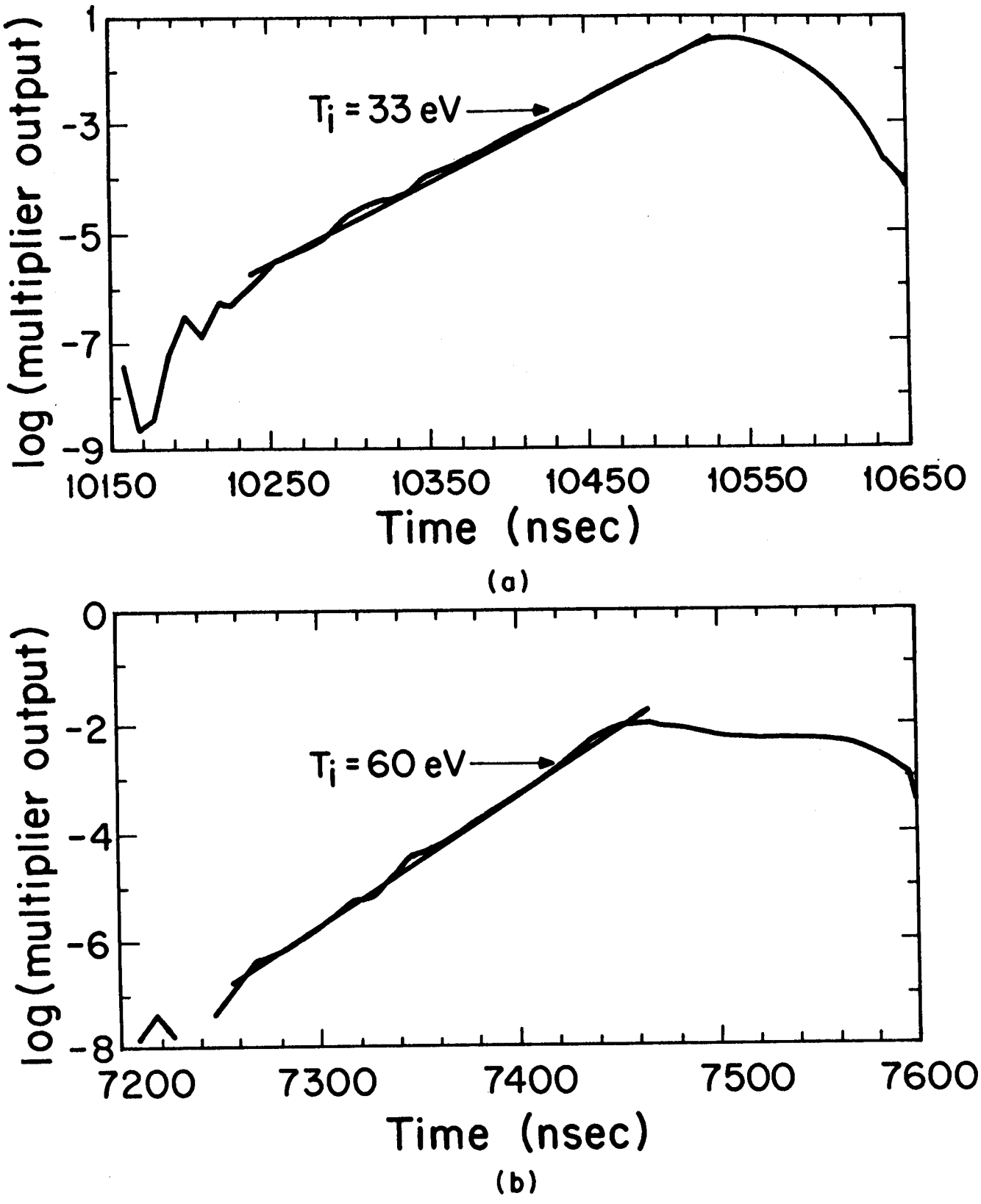

FIG. 4. Logarithmic plot of the electron multiplier output pulse to calculate ion endloss temperatures for a) Ar^{+}, b) Ar^{2+}.