Electron temperature measurements using a 12-channel array probe

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The electron temperature in a pulsed high-$\beta$ ($\beta = 2\pi n k T / B^2 \approx 1$) plasma is studied as a function of time using a miniature array of 12 planar Langmuir probes. Instead of sweeping the bias voltage on the collectors, each is set at a different voltage corresponding to points along the characteristic $I-V$ curve. A fast-analog multiplexer, together with a computerized data-acquisition system, allows determination of $T_e$ to within a few percent accuracy, with a time resolution of 1 $\mu$s. The probe is used to study temperature fluctuations and heat transport in a plasma current sheet.

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INTRODUCTION

Although other methods exist, the most common technique for determining the mean kinetic energy of electrons in low-temperature ($T_e < 200$ eV) plasmas utilizes the so-called Langmuir probe, after the pioneer in experimental plasma physics who first worked out the theory of such a device. The collecting area may be spherical, cylindrical, or planar in shape, each one having its own geometrically determined characteristic curve for gathering electron current as a function of bias voltage. For large negative voltages, only the most energetic electrons can overcome the retarding potential and be collected. As the bias of a plane probe is increased, the collected electron current increases exponentially for a Maxwellian distribution. Saturation occurs at the plasma or space potential $V = V_e$ and for $V < V_e$,

$$I_e = I_{e,\text{sat}} \exp\left[ e(V - V_e)/kT_e \right],$$

where

$$I_{e,\text{sat}} = -\frac{n_e e A (kT_e / 2\pi m_e)^{1/2}}{\sqrt{2}};$$

$A$ being the area of the probe. There is a corresponding term due to the ions; however, with $T_i \ll T_e$ and $M_i > m_e$ the ion current can be neglected in this treatment as it is a small correction for argon

$$[I_{i,\text{sat}} / I_{e,\text{sat}} = (\pi m e / 2M_i)^{1/2} = 0.005] .$$

By plotting the log of the measured current versus probe bias, one can determine the electron temperature from the inverse slope of the straight-line fit. And if the noise level can be minimized to a few percent or less, the average kinetic energy or effective temperature can be determined for any non-Maxwellian, isotropic distribution, or for bi-Maxwellian distributions in a magnetic field $T_i \neq T_e . ^4$

I. PRINCIPLE OF OPERATION OF THE NEW PROBE

One would like an instantaneous snapshot of the kinetic state of the plasma at a given time. The conventional technique is to vary the probe bias and to measure the collected current. This is usually done with a voltage ramp, but due to the finite sweep time, the temporal resolution of $T_e$ is limited. Also, the faster the sweep rate of the electronic circuit the more critical stray reactances in the external measuring circuit become. A more important factor is the response time of the surrounding plasma sheath to the changing probe bias, which is limited by the ion response to varying electric fields.

By using a probe with many individually collecting surfaces, each biased at a different fixed voltage [Fig. 1(a)], an approximation to the true probe characteristic is obtained when monitoring the collected currents for each independent subprobe [Fig. 1(b)]. The effect of lead capacitance is negligible since the large variation in voltage for a single swept probe is replaced by an array of 12 subprobes with constant bias and nearly constant probe currents. Note that this method is different from a recently reported technique where, instead of fixed bias voltages, two fixed values of collector current are selected on the $I-V$ curve and the corresponding voltage difference $\Delta V$ is measured to infer $T_e$, assuming a Maxwellian distribution. That method, however, does not yield information on the plasma density or space potential. The present method, by using many points, yields enough information to reconstruct the entire $I-V$ curve [Fig. 1(c)]. One can even take the second derivative and obtain the velocity distribution function for any isotropic non-Maxwellian distribution. The electron density $n_e$ and space potential $V_e$ can be obtained by sampling a few points in the saturation region. By using two such probes one can perform correlation measurements to study heat flow and temperature fluctuations.

II. CALIBRATION, ACCURACY, AND TIME RESOLUTION

The collectors currently in use are 0.38-mm-diam tantalum wires mounted in ceramic and then faced off and polished to yield an array ($4.5 \times 4.5$ mm$^2$) of 12 nearly identical probe surfaces. The effective collecting areas are measured, after a thorough plasma discharge cleaning, by biasing all 12 collectors at a fixed voltage and recording the ratios of current. Differences in surface area of a few percent from collector to collector are later taken into account when reconstructing the $I-V$ curve.

The probe size has to be compared with the Debye shielding parameter $\lambda_D$, defined as

$$\lambda_D = (kT_e / 4\pi n_e e^2)^{1/2}.$$  

For our plasma the Debye length $\lambda_D = 0.022$ mm for $T_e = 10$ eV, $n_e = 1 \times 10^{12}$ cm$^{-3}$. The collecting area should
have a radius $r \gg \lambda_d$, and the interprobe spacing $\Delta d$ of the array should be even larger so that the probes do not influence each other. We chose $r = 0.19 \text{ mm}$ and $\Delta d = 0.88 \text{ mm}$. The total probe width $\Delta W = 4.5 \text{ mm} \ [\text{Fig. 1(a)}]$. The maximum value of electron current collected will be the saturation current density $J_{\text{sat}} = e n_{\text{th}} \langle v \rangle$ times the probe area, which is approximately 10 mA for the above density and temperature. For this current a 100-$\Omega$ series resistor is used to give $V_{\text{sh}} = 1 \text{ V}$. The capacitance to ground for each channel is typically 50 pF, which gives an upper frequency response $f_{\text{max}}$ of

$$f_{\text{max}} = \left(2\pi RC\right)^{-1} = 32 \text{ MHz}.$$  \hfill (3)

For smaller currents in the high-energy tail of the $I-V$ curve, where $I = 0.1 J_{\text{sat}} = 1 \text{ mA}$, a 500-$\Omega$ shunt is chosen, so that $V_{\text{sh}} = 0.5 \text{ V}$. The larger resistor reduces the RC frequency response to 6 MHz. It should be noted that the ultimate response is limited by the size of the probe itself. If there are density variations across the probe face, an accurate assessment of $T_e$ is not possible. For density perturbations traveling at sound speed $\left[C_s = (kT_e/M_e)^{1/2} = 5 \times 10^5 \text{ cm/s}, T_e = 10 \text{ eV}\right]$, $f_{\text{max}} = C_s/\Delta W = \frac{5 \times 10^5 \text{ cm/s}}{4.5 \text{ mm}} \approx 1 \text{ MHz}$. \hfill (4)

So for the present system, the upper frequency limit is set by plasma effects rather than the electronic circuit.

The time-varying collector currents are measured using 1% resistors (100–500 $\Omega$). A schematic of the probe biasing circuit is shown in Fig. 2. The capacitors are connected to the charging supply until a pretrigger (50 ms before the plasma pulse) activates the relays which allow the capacitors to float for about 100 ms. This ensures that no ac ripple from the charging supply creeps into the amplifier stage during the measurement, which lasts for 50–100 $\mu$s. Each probe is biased at a potential $V_{\text{cap}}$, which is the sum of $V_s$ and the additional $V_{\text{cap}} = n \Delta V \ (n = 1, \ldots, 12)$ which increases as one moves down the resistive tape line. The capacitance is large enough (1200 pF) so that the applied voltage $V_{\text{cap}}$ remains constant.

Fig. 1. (a) Cross section of multichannel probe tip. (b) Block diagram of probe biasing and current measurement circuit. $\Delta V$ is the constant voltage difference between adjacent collectors. $I_{\text{sat}}$ is the electron saturation current collected by the probe when biased at the plasma potential $V_s$. (c) Reconstructed $I-V$ characteristic. Small circles are measured points. Solid curve below $V_s$ is exponential fit.

Fig. 2. Electrical schematic of probe biasing circuit. Variable 1-k$\Omega$ resistor adjusts the magnitude of $\Delta V$. Probe currents are measured using shunt resistors $R_{\text{sh}}$. 

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to within 0.1% while current is being drawn ($I_{sh} = 1 \text{ mA}$). Small high-frequency bypass capacitors are added in parallel to give fast time response. To obtain the true probe bias $V_{p}$, the shunt voltage $V_{sh}$ must be subtracted from the applied bias $V_{cap}$, so that now both the current and probe voltage are functions of time:

$$V_{p,n}(t) = V_{cap,n} - V_{sh,n}(t) = (V_{cap,1} + n\Delta V_{sh}) - I_{sh,n}(t)R_{sh,n},$$

(5)

where $n = 1, 2, ..., 12$. The shunt voltages are amplified and then multiplexed (4:1) into fast (20-MHz, 8-bit accuracy, Le-\text{Croy 2256}) analog-to-digital converters (ADC's). The amplifier stages are calibrated with a known input signal to determine their respective gains. The analog multiplexer utilizes 16 AM1000's which typically switch from one channel to the next within 50–70 ns [Fig. 3(a)]. A multiplexed signal is shown in Fig. 3(b). Three of the levels are shunt voltages and the lowest level is a zero line which is used as a reference to aid in the computer analysis. Using the fastest sampling rate of ADC's, half of the 100-\mu s plasma reconnection experiment can be analyzed. A LSI 11/23 minicomputer is connected with a CSPI arithmetic processor (150 k direct access memory) which can store up to 100 different shots. The data are then analyzed to yield the ensemble average value of $T_{e}(t)$, deviations from an exponential (Maxwellian) distribution, and shot-to-shot rms values $\delta T_{e}(t)$, where

$$\langle T_{e}(t) \rangle = \frac{1}{N} \sum_{i=1}^{N} T_{e,i}(t),$$

(6)

$$\delta T_{e}(t) = \left( \frac{1}{N} \sum_{i=1}^{N} (T_{e,i}(t) - \langle T_{e}(t) \rangle)^2 \right)^{1/2},$$

(7)

**Fig. 4.** Electron temperature $T_{e}$ (top trace) and standard deviation from Maxwellian fit (lower trace) in an argon discharge ($n_e = 1 \times 10^{17} \text{ cm}^{-3}$).

**Fig. 5.** Spatial scan of electron temperature $T_{e}$ vs time during a magnetic reconnection experiment. Distance covered ($\approx 40 \text{ cm}$) roughly coincided with the extent of the current sheet present during the event.
and $N$ is the total number of shots to be averaged over $<N<100>$.

III. APPLICATIONS

After making the initial calibrations, an afterglow plasma was examined to test the probe. The resultant $I$-$V$ curve is Maxwellian to within 2% (Fig. 4). The error is determined by fitting the measured points to a straight line on a semilog plot using the method of least squares. The standard deviation $\sigma$ from the straight line fit is plotted as the lower trace in Fig. 4. One can see the temporal decay of the electron temperature from 5 to 3 eV in several tens of microseconds during the afterglow period. This test also confirmed, as expected, that the probe is insensitive to density variations and plasma potential changes associated with the plasma decay.

The plasma in which we wanted to diagnose temperature fluctuations is used to study magnetic field line reconnection. Figure 5 shows a plot of $<T_e(t)>$ versus radial position and time during the initial phase of the reconnection experiment (20-shot average). The temperature peaks off axis are due to strong Ohmic heating which develops in those regions. These measurements are consistent with earlier single-sided Langmuir probe measurements which had been limited to sampling a single probe sweep of 5-$\mu$s duration over many shots. So, in addition to improving the time resolution, the present technique provides a continuous time dependence of $T_e$ in a single shot.

Using two such probes, one can utilize correlation techniques to study thermal diffusion. Fluctuations in the plasma current density $J_p$ during reconnection lead to fluctuations in the level of Ohmic heating [$\eta J_p^2$] which can be detected as temperature maxima diffusing across the magnetic field away from the heat source (Fig. 6). By biasing a small conducting anode plate above the local plasma potential, these fluctuations can be greatly enhanced and triggered at a specific time during the reconnection event. A simple pulse-height analysis program selectively correlates only shots ($\geq 50\%$) where $\Delta T = T_e(t) - <T_e(t)> > 1$ eV. Figure 7(a) shows normalized correlations of two probe signals versus delay time $\tau$ for different probe tip separations $\Delta x$. From this data a speed of propagation $v_T = 5 \times 10^2$ cm/s is found [Fig. 7(b)]. Using the equations governing heat flow, i.e., $Q_i = n k T_e V_T$ (definition of a heat flux) and

$$Q_i = -K_i \nabla \cdot \mathbf{T}_e$$

we find $K_i = 1.4 \times 10^4$ erg/s cm deg. This value is 15 times the classical cross-field diffusion coefficient based on Coulomb collisions:

$$K_i = \left( \frac{3.2 n k T_e \tau_c}{m_e} \right) \left( 1 + \omega_{ce}^2 \tau_c^2 \right)^{-1}.$$

![Fig. 6. Temporal fluctuations in electron temperature $T_e$ with and without an applied current pulse $I_p \approx 15$ A drawn to a small (6-cm$^2$) anode disk. Probe is located at $\Delta x \approx 3$ cm upstream and $\Delta x \approx 1$ cm from the side of the anode disk.](image)

![Fig. 7. (a) Two-probe correlation product of electron temperature $T_e$ vs delay time $\tau$. Probe 1 is fixed and probe 2 is moved in 1-cm steps along the x axis, $\Delta x =$ probe tip separation. $T_e(T_{with\ pulse} - T_{no\ pulse})$. (b) Phase speed of maximum correlation product from above.](image)
One factor which we think may explain the increase in $K_1$ is the presence of both ion-acoustic and magnetic turbulence in the region of interest. This could contribute to an increase in the effective perpendicular heat conductivity of the electrons.

IV. DISCUSSION

By using a miniature array of collectors, each biased at a different fixed potential corresponding to points on the characteristic $I-V$ curve, time resolved measurements of the local temperature, density, and space potential can be made. The present system described here has an order-of-magnitude improvement in temporal resolution over conventional swept probe techniques. Moreover, using two or more such probes, it is now possible to directly measure time-dependent temperature fluctuations and to study thermal diffusion processes. The effect of the magnetic field is minimal in analyzing the probe traces for probe plane normals parallel to $B$ and with probe dimensions $\Delta x \leq r_L$. Future applications include the addition of a collimating grid to the front of the probe which would increase the angular resolution. This would enable the study of nonisotropic distributions in greater detail.

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