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# ANALYSIS OF TRIPLE LANGMUIR PROBE MEASUREMENTS IN THE NEAR-EXIT REGION OF A GAS-FED PULSED PLASMA THRUSTER

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## Abstract

Triple Langmuir probes were used to measure electron number density, and electron temperature in the near-exit region of a laboratory model gas-fed pulsed plasma thruster. Triple Langmuir probe data was obtained on a plane parallel to the thruster electrodes at radial distances of 3 and 7 cm downstream of the propellant inlet and angular positions of 0, 10, 20, and 30 degrees. The thruster was operated with Xe propellant, 2 J per pulse, and a mass flow rate of 3 mg/s. Analysis shows that average density at the thruster exit plane is in the range of $5\times10^{18}$ to $2.5\times10^{19}$ $m^{-3}$ and temperature is in the range of 0.5 to 4 eV. At a radial distance of 4 cm downstream from the exit, the density is in the range of $2\times10^{18}$ to $1\times10^{19}$ $m^{-3}$ and temperature in the range of 0.2 to 1.4 eV. Temperature averaged over the duration of a pulse is in the range of 0.4 to 1.3 eV and shows angular and radial variation.

## Nomenclature

| | |
|---|---|
| $A$ | probe area |
| APPT | ablative pulsed plasma thruster |
| $d_s$ | sheath thickness |
| GFPPT | gas-fed pulse plasma thruster |
| $I$ | current |
| $\bar{I}$ | sample-average current |
| $J_{eo}$ | random electron thermal current |
| $J_i$ | ion flux at the surface of an electrode |
| $Kn$ | Knudsen number |
| $L$ | probe length |
| $M_i$ | mass of ion i |
| $n$ | number density |
| $\bar{n}_e$ | sample-average electron number density |
| $<\bar{n}_e>$ | time-averaged electron number density |
| $r_p$ | probe radius |
| $s$ | probe spacing |
| $t$ | time |
| $T$ | temperature |
| $\bar{T}_e$ | sample-average electron temperature |
| $<\bar{T}_e>$ | time-averaged electron temperature |
| $V$ | voltage |
| $\bar{V}$ | sample-average voltage |
| $Z$ | ion charge number |
| $\beta$ | parameter characterizing ion current variation with $\chi$ |
| $\lambda_D$ | Debye length |
| $\chi$ | non-dimensional potential of an electrode with respect to plasma potential |
| $\eta$ | non-dimensional $\beta$ |
| $\bar{\sigma}$ | standard deviation |

Subscripts:

| | |
|---|---|
| $d2, d3$ | difference between 1 and 2 or 3 |
| $e$ | electron |
| $f$ | floating |
| $i$ | ion |
| $1, 2, 3$ | electrode 1, 2, 3 |

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## Introduction

The Gas-Fed Pulsed Plasma Thruster (GFPPT) was first introduced in the early 1960's. Development progressed for a short time, but interest waned mainly due to a lack of fast acting gas valves.[1] At that point, interest in the Ablative Pulsed Plasma Thruster (APPT) began to increase, eventually leading to several flight demonstrations.[2] Interest in the APPT decreased however, and the design was all but abandoned. New small satellites and missions requiring precise control and higher $I_{sp}$ than chemical propulsion options resulted in renewed interest in both Ablative and Gas-Fed PPT's.

Science Research Laboratory Inc., NASA, AFOSR, and Princeton University, through development and maturation of recent GFPPT's, has re-initiated the investigation of the GFPPT as a potentially viable thruster. The SRL GFPPT overcomes the limitations of gas valve actuation time through innovative pulsing circuitry allowing the thruster to fire multiple times while the valve is open. This effectively allows the thruster to operate in a burst mode, allowing multiple discharge pulses at rates of several kilohertz while the gas valve is open. Operation at these pulse frequencies yield near 100% mass utilization. Gas leakage through fast acting valves will be overcome through the use of a plenum reservoir. A low-leakage, slow acting valve controls flow from the propellant tank to the plenum while a relatively high-leakage, fast acting valve controls flow to the thruster. This system allows for the plenum to be filled when thrusting but prevents leakage during down time.[3]

As with any onboard propulsion system, the characterization of plume properties of the GFPPT is important in the establishment of this technology. The GFPPT plume is expected to consist of fast propellant ions, neutrals from incomplete ionization, and material from erosion. In addition, as with other electric propulsion thrusters, charge exchange ions and neutrals may be found in the plume. Experimental characterization and modeling of electric thruster plumes provide the means of assessing possible plume-spacecraft interactions.[4-8] Additionally, plume properties and composition are important in improving thruster performance and optimization of design. This paper presents the first measurements of plasma properties in the near-exit region of a modern GFPPT. The experimental setup used in this investigation utilized triple Langmuir probes to measure electron temperature ($T_e$) and density ($n_e$). Measurements were obtained at 3 and 7 cm downstream from the propellant inlet (at the exit plane and 4 cm from the exit plane respectively) for angles up to 30 degrees from the centerline. This paper describes the experimental setup, data reduction, error analysis, and results.

## Experimental Apparatus

### Thruster and Facility

Experiments were conducted in one of the vacuum tank facilities at NASA's Jet Propulsion Laboratory. The tank, with diameter of 2.4 m and length of 5.8 m, was cryogenically pumped down to a pressure of $1.2\times10^{-6}$ torr. The laboratory model GFPPT used in this experiment is shown in Fig. 1. The exit channel consists of two slightly flared plates that form the anode and cathode. The gas inlet is at the base of the channel below the single ignitor. The thruster was operated with Xenon propellant, 2 J per pulse, and a mass flow rate of 3 mg/s. The thruster mount designed for this experiment was capable of being rotated up to 45 degrees off the thruster centerline with the center of rotation located at the base of the thruster channel.[9] Thruster firings consisted of a train of 5 pulses with measurements of the first pulse in each train. Each pulse lasted approximately 3 $\mu s$.

### Diagnostics and Procedures

Diagnostics included symmetric triple Langmuir probes mounted on a linear translation stand. Triple Langmuir probes were selected based on their direct display capability and our previous experience in pulsed plasma thruster plume environments.[6] The theory of operation of symmetric triple probes was introduced by Chen and Sekiguchi[10] and Chen.[11] Tilley et al.[12] implemented an ion current collection model based on Laframboise's data. A symmetric triple probe, similar to the one used in our experiments, consists of three identical probes (or electrodes) placed in the plasma as shown in Fig. 2. One of the probes (probe-2 in Fig. 2) is allowed to float in the plasma and a fixed voltage $V_{d3}$ is applied between the positive and negative probes as indicated in Fig. 2. In this figure, both probes 1 and 3 are biased negative with respect to the floating probe however since probe-1 is less negative, it is designated as the positive probe while probe-3 is designated the negative probe. The resulting voltage difference $V_{d2}(t)$ and collected current $I_3(t)$ are measured and allow the evaluation of $T_e(t)$ and $n_e(t)$ using the following equations.[12]

$$\frac{1}{2}=\frac{1-\frac{1}{2}\left(\left[1-\beta V_{d2}\right]^{0.5}+\left[1+\beta\left(V_{d3}-V_{d2}\right)\right]^{0.5}\right)\exp\left(-\chi_{d2}\right)}{1-\exp\left(-\chi_{d3}\right)} \tag{1}$$

$$n_e=\frac{(2\pi)^{0.5}\frac{I_3}{A}}{e\left(\frac{kT_e}{M_i}\right)^{0.5}\left(\left[B+\left(\chi_{d3}-\chi_{d2}\right)+\chi_f\right]^{\alpha}-\left[B+\chi_f\right]\exp\left(-\left[\chi_{d3}-\chi_{d2}\right]\right)\right)} \tag{2}$$

In our experiment $V_{d3}=12$ V and the current $I_3(t)$ were measured through the shunt with $R_{sh}=48$

Ω. Voltage measurements from probe-1 and probe-2 provided the necessary voltage difference $V_{d2}(t)$. Data collection was initiated with the trigger pulse sent to the thruster capacitor. The probes were made out of tungsten wires with radius $r_p = 0.125\times10^{-3}$ m and length $L = 10^{-2}$ m. Probes were placed within an alumina tubing with an outer diameter of $6.28\times10^{-3}$ m resulting in spacing between the probes of $s \cong 10^{-3}$ m. Alumina was used due to its low sputtering yield, ability to withstand high temperatures and electrical insulating properties.

Implementation of the triple probe in the GFPPT plume requires careful consideration of plasma and probe parameters that enter in the evaluation of $T_e$ and $n_e$. Estimates of all parameters in Table 1 are obtained assuming that the plume is composed of single-ionized $Xe^+$, with $T_e \approx 1-5\,eV$, $T_i = 0.25\,eV$ and $n_e \approx 10^{18}-10^{20}\,m^{-3}$. From Table 1 it is evident that the plasma plume is dense ($r_p > \lambda_D$) and it may be assumed that the probes operate in the collisionless regime ($Kn \geq 1$) with little interference due to sheath interactions ($s >> d_s \geq \lambda_D$). The errors and uncertainty associated with the parameters described in Table 1 as well as other factors are discussed during our error analysis.

**Table 1:** Parameters related to triple probe with $r_p = 0.125\times10^{-3}$ m, $s \cong 10^{-3}$ m operating in a GFPPT plume composed of $Xe^+$ and $T_i = 0.25\,eV$.

| Conditions | $r_p/\lambda_D$ | $s/d_s$ | $Kn_{ii}$ | $Kn_{ei}$ |
|---|---|---|---|---|
| $n_e = 10^{18}\,m^{-3}$, $T_e = 1eV$ | 17.1 | 10.1 | 12.4 | 184.7 |
| $n_e = 10^{18}\,m^{-3}$, $T_e = 5\,eV$ | 7.6 | 8.3 | 12.4 | 3694. |
| $n_e = 10^{20}\,m^{-3}$, $T_e = 1\,eV$ | 170.9 | 57.0 | 0.19 | 2.4 |
| $n_e = 10^{20}\,m^{-3}$, $T_e = 5\,eV$ | 76.4 | 46.7 | 0.19 | 45.7 |

Probe measurements were then taken at 0, 10, 20, and 30 degrees from the centerline on the plane parallel to the electrodes at 3 cm and 7 cm downstream of the propellant inlet as shown in Fig. 3. A complete set of data was obtained, collecting data at each position in Fig. 3 without opening of the tank followed by a repetition of data collection along the centerline to examine differences due to probe contamination. Ten pulses were recorded at each location 3 cm downstream while five pulses were recorded at each location 7 cm downstream of the inlet.

## Data Reduction and Error Analysis

A typical set of voltage $V_{d2}(r,\theta,t)$ and current trace $I_3(r,\theta,t)$ measurements is shown in Fig. 4. Along with signal noise Fig. 4 indicates a large burst of noise before the pulse begins which is believed to be due to the discharge of the GFPPT capacitor or igniter. The voltage and current traces were smoothed using the loess smoothing function to remove noise and results are shown in Fig. 4. Due to measurement of the background and residual plasma, traces did not return to the zero after the pulse. Using the smoothed voltage and current data, $T_e(r,\theta,t)$ and $n_e(r,\theta,t)$ are obtained using the triple probe model equations.[6,12] Residuals occurring due to smoothing of the traces over all averaged pulses are approximately 5 %.

Uncertainty in the measurements of $T_e(r,\theta,t)$ are associated with the modeling of the ion current with the non-dimensional parameter $\eta = \beta(kT_e/e)$.[10-12] Assuming that the uncertainty in $\eta$ is a function of the temperature ratio, $0 \leq T_i/Z_iT_e \leq 1$, the uncertainty for values of $\chi_{d3} = e|V_{d3}|/kT_e \approx$ 5-10 is less than 5 % which increases weakly for higher values of $\chi_{d3}$. In this experiment, $2.6 \leq \chi_{d3} \leq 13.1$ necessitating the use of Chen[11] where uncertainty is calculated as 15% for $0.2 \leq \eta \leq 15$.

Error and uncertainty in the calculated values of $n_e(r,\theta,t)$ using triple probes is approximately 40-60 % for $7 \leq r_p/\lambda_D \leq 100$, $5 \leq \chi_{d3} - \chi_{d2} \leq 12$ and assuming that $0.2 \leq T_i/Z_iT_e \leq 5.0$.[12] In GFPPT's however, the temperature ratio is expected to be below 1, decreasing the uncertainty in the experiment. The Petersen/Talbot curve fit to Laframboise's ion current model used for data analysis is optimal for $5 \leq r_p/\lambda_D \leq 100$ but higher ratios will still provide a very good estimate.[12]

No sheath interactions are expected in our experiment since $s/d_s >> 1$ as shown from Table 1. In cases where $Kn_{ii} \leq 1$ shown in Table 1 there is an increase in ion current of approximately 10-20%.[12] For $Kn_{ei} > 200/(r_p/\lambda_D)$, a condition met throughout the experiment, the effects of electron collisions on the electron current may be ignored.[12] This error may be larger in cases of very dense plasmas and probes not aligned with the flow. The latter issue may not be of concern in our measurements since data were collected very close to the exit of the thruster.

Voltage measurements were made to approximately ± .06 V. A thin-film 1% resistor was used as a shunt to measure the current. Probe cleaning was not performed due to the slow turnaround of the facility and the limited amount of time available. Errors due to probe contamination from electrode deterioration or other sources are illustrated in Fig. 5. Contamination accounts for a deterioration of approximately 25% of the peak flux after 60 pulse trains.

Spatial resolution of the probes is a function of the volume taken up by the exposed cylindrical section of the probe. In addition, probe movement was accomplished using somewhat crude instruments in this experiment leading to a total spatial resolution of approximately ± 1.5 cm.

Therefore, for all measurements in this experiment, the maximum uncertainty in $T_e(r,\theta,t)$ is approximately 15% while the maximum uncertainty in $n_e(r,\theta,t)$ is approximately 60% and is reported on all data plots with a spatial accuracy within ± 1.5 cm. Contamination accounts for an approximate 25% drop in the temperature and number density over 60 pulse trains (300 pulses) and error due to smoothing is approximately 5%.

## Data Analysis and Discussion

Figure 6 shows typical electron density and electron temperature traces obtained for $r = 7$ cm and $\theta = 10$ degrees. These traces show the shot-to-shot variability as well as the unsteady character of the GFPPT plume as it passes by the triple probe. In order to account for this variability average voltage and current traces are obtained as

$$\bar{V}_{d2}(r,\theta,t) = \sum_{i=1,N} V_{d2}^i(r,\theta,t) \Big/ N \quad (3)$$

$$\bar{I}_3(r,\theta,t) = \sum_{i=1,N} I_3^i(r,\theta,t) \Big/ N \quad (4)$$

where $i$ indicates the $i$-th pulse and $N$ is the total number of traces. Average voltage and current traces were then smoothed producing the average smoothing errors given previously as approximately 5 %. The standard deviation of both the average number density and average temperature are shown in Table 2. The triple probe theory was then applied using the sample-averaged $\bar{V}_{d2}(r,\theta,t)$ and $\bar{I}_3(r,\theta,t)$ traces to obtain the average temperature $\bar{T}_e(r,\theta,t)$ and density $\bar{n}_e(r,\theta,t)$ profiles. The results are presented in Fig. 7 and Fig. 8. Figure 7 shows profiles at 3 cm downstream of the propellant inlet of the GFPPT. The maximum $\bar{n}_e$ is 2.25 x10$^{19}$ m$^{-3}$ at the centerline and decreases to 1.40 x10$^{19}$ m$^{-3}$ at $\theta = 30^0$. At $r = 3$ cm maximum $\bar{T}_e$ is 3.75 eV and decreases to 1.75 eV at $\theta = 30^0$. Figure 8 presents the profiles at 7 cm downstream from the propellant inlet of the GFPPT. Maximum $\bar{n}_e$ is 10$^{19}$ m$^{-3}$ at $\theta = 0^0$ and decreases to 7.75 x10$^{18}$ m$^{-3}$ at $\theta = 30^0$. Similarly, maximum $\bar{T}_e$ is 1.43 eV at $\theta = 0^0$ and decreases to 0.9 eV at $\theta = 30^0$. These data exhibit the angular and radial variation of the plume.

**Table 2:** Standard Deviation for $\bar{n}_e$ and $\bar{T}_e$ evaluation

| Position $(r,\theta)$ | $\bar{\sigma}(T_e)$ (%) | $\bar{\sigma}(n_e)$ (%) |
|---|---|---|
| (3, 0)[1] | 62.5 | 90.2 |
| (3, 0)[2] | 53.3 | 52.1 |
| (3,10) | 40.4 | 33.2 |
| (3,20) | 50.2 | 42.8 |
| (3,30) | 33.0 | 27.9 |
| (7, 0) | 55.4 | 48.8 |
| (7,10) | 60.6 | 53.8 |
| (7,20) | 37.7 | 36.8 |
| (7,30) | 38.5 | 39.8 |

The time-averaged electron temperature and density over the pulse duration $P$ for a location $(r,\theta)$ are also obtained

$$\langle T_e \rangle(r,\theta) = \int_0^P \bar{T}_e(r,\theta,t)dt \Big/ P \quad (5)$$

$$\langle n_e \rangle(r,\theta) = \int_0^P \bar{n}_e(r,\theta,t)dt \Big/ P \quad (6)$$

Figure 10 shows the time-average plume properties. The angular variation at $r = 7$ cm is much smaller than at $r = 3$ indicating rapid expansion of the plume. Time-average temperatures are in the range of 0.4-1.4 eV and show considerable radial and angular variation.

## Conclusions

Measurements of the electron temperature and electron number density in the plume of a gas-fed pulsed plasma thruster were taken in a vacuum facility at the NASA Jet Propulsion Laboratory using symmetric triple Langmuir probes. Data was collected at two radial positions, $r = 3$ cm and $r = 7$cm from the propellant inlet, at four different angles, 0, 10, 20, and 30 degrees from the centerline. Error analysis of the triple probes was presented and it was concluded that the maximum error in $T_e$ evaluation is approximately 30% and in $n_e$ approximately 60%.

Analysis shows that average density at the thruster exit plane is in the range of $5x10^{18}$ to $2.5x10^{19}$ $m^{-3}$ and temperature is in the range of 0.5 to 4 eV. At a radial distance of 4 cm downstream from the exit, the density is in the range of $2x10^{18}$ to $1x10^{19}$ $m^{-3}$ and temperatures in the range of 0.2 to 1.4 eV.

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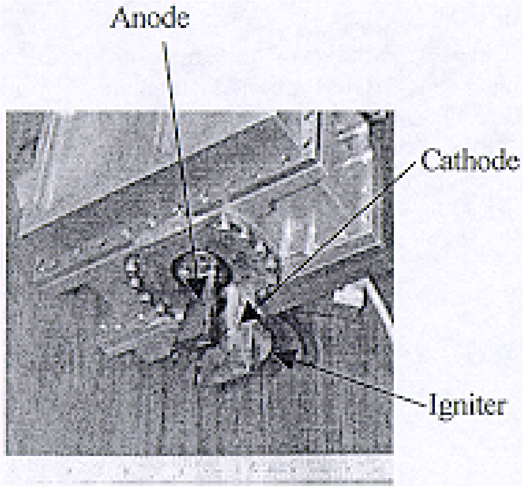


**Figure 1.** The GFPPT thruster used in the experiments. The nozzle is formed by the flared plates. The igniter can be seen attached to bottom plate.

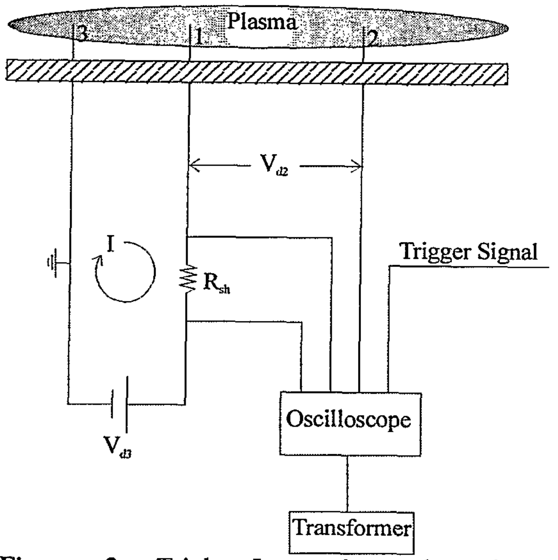


**Figure 2.** Triple Langmuir probe electrical schematic.

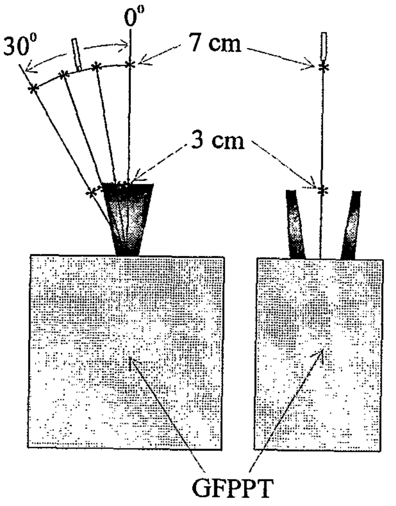


**Figure 3.** Radial and angular measurement locations with respect to the propellant inlet.

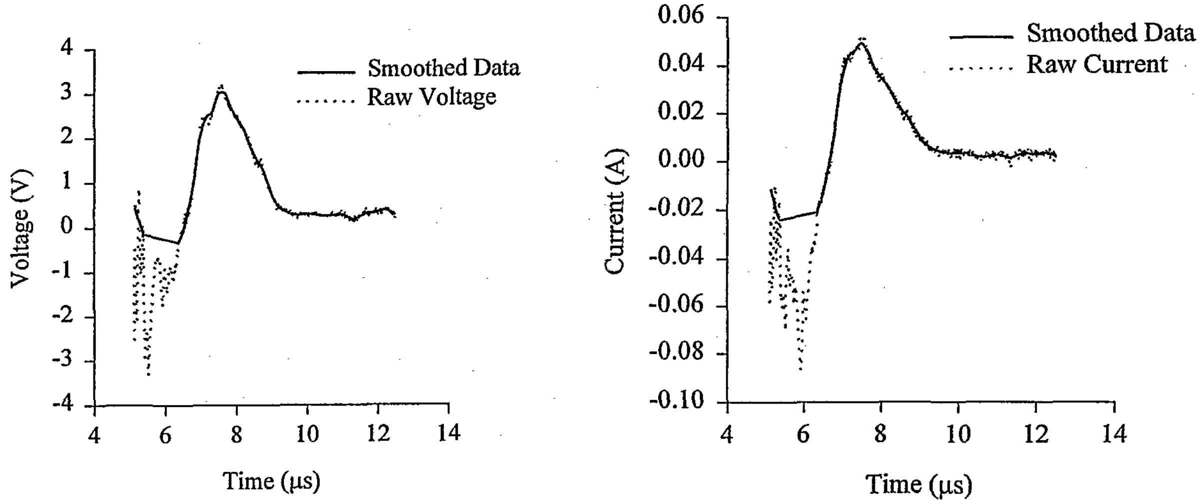


**Figure 4.** Voltage $V(r,\theta,t)$ and current $I(r,\theta,t)$ measured at $r = 3$ cm of a GFPPT. Smoothed traces are shown for comparison.

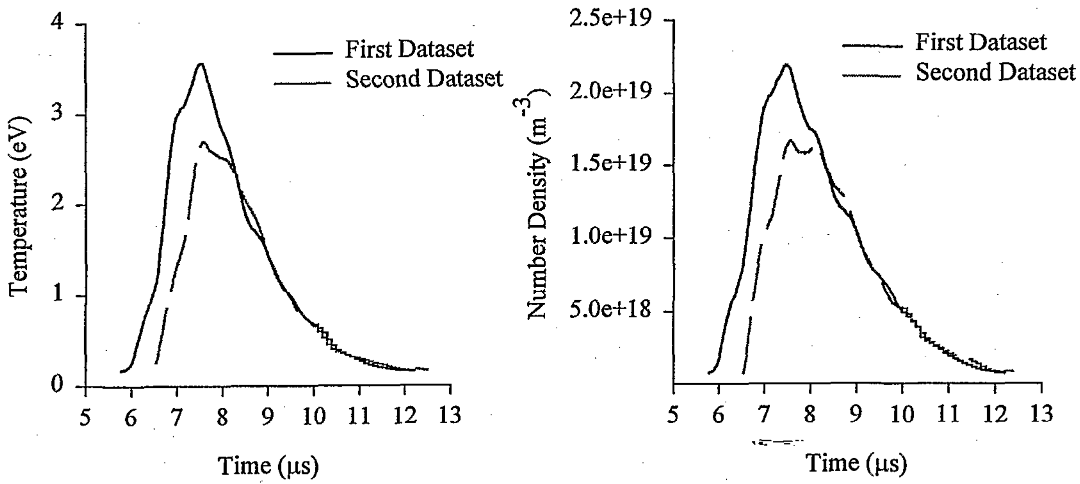


**Figure 5.** Effects of contamination on triple probe measurements after 60 GFPPT pulse-trains.

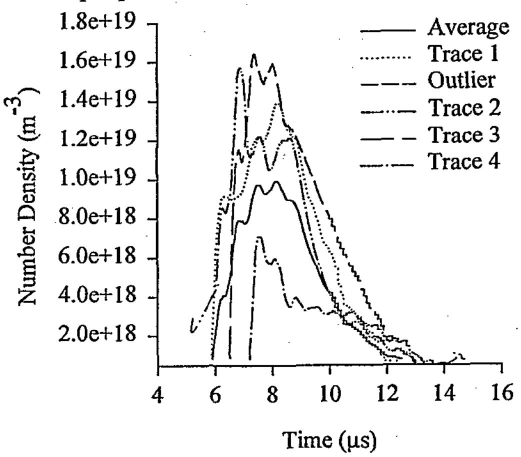


**Figure 6.** Number density traces measured at $r = 7$ cm from the propellant inlet of a GFPPT

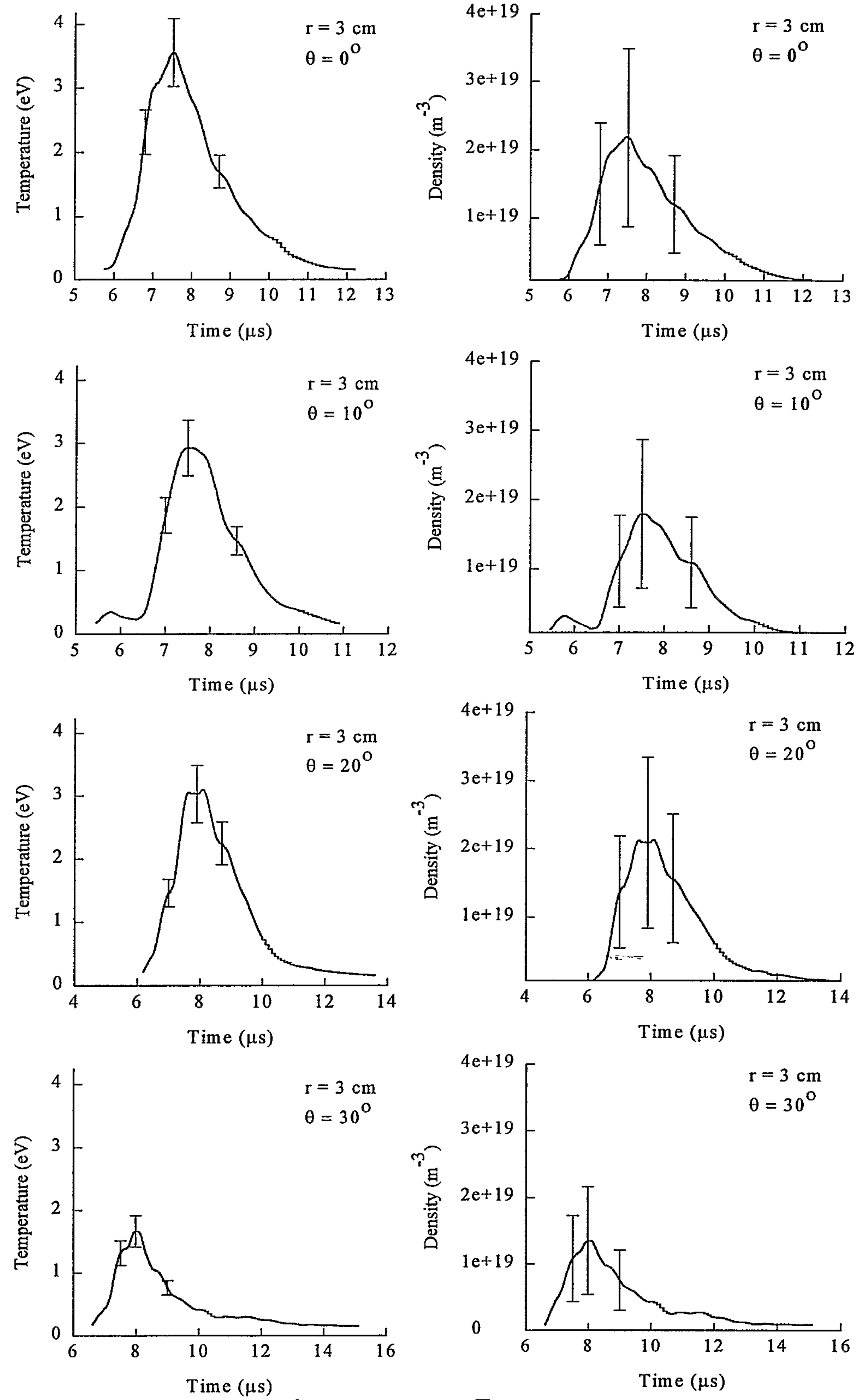


**Figure 7.** Sample-averaged density $\overline{n}_e$ ($m^{-3}$) and temperature $\overline{T}_e$ (eV) at $r = 3$ cm downstream from the propellant inlet of a GFPPT.

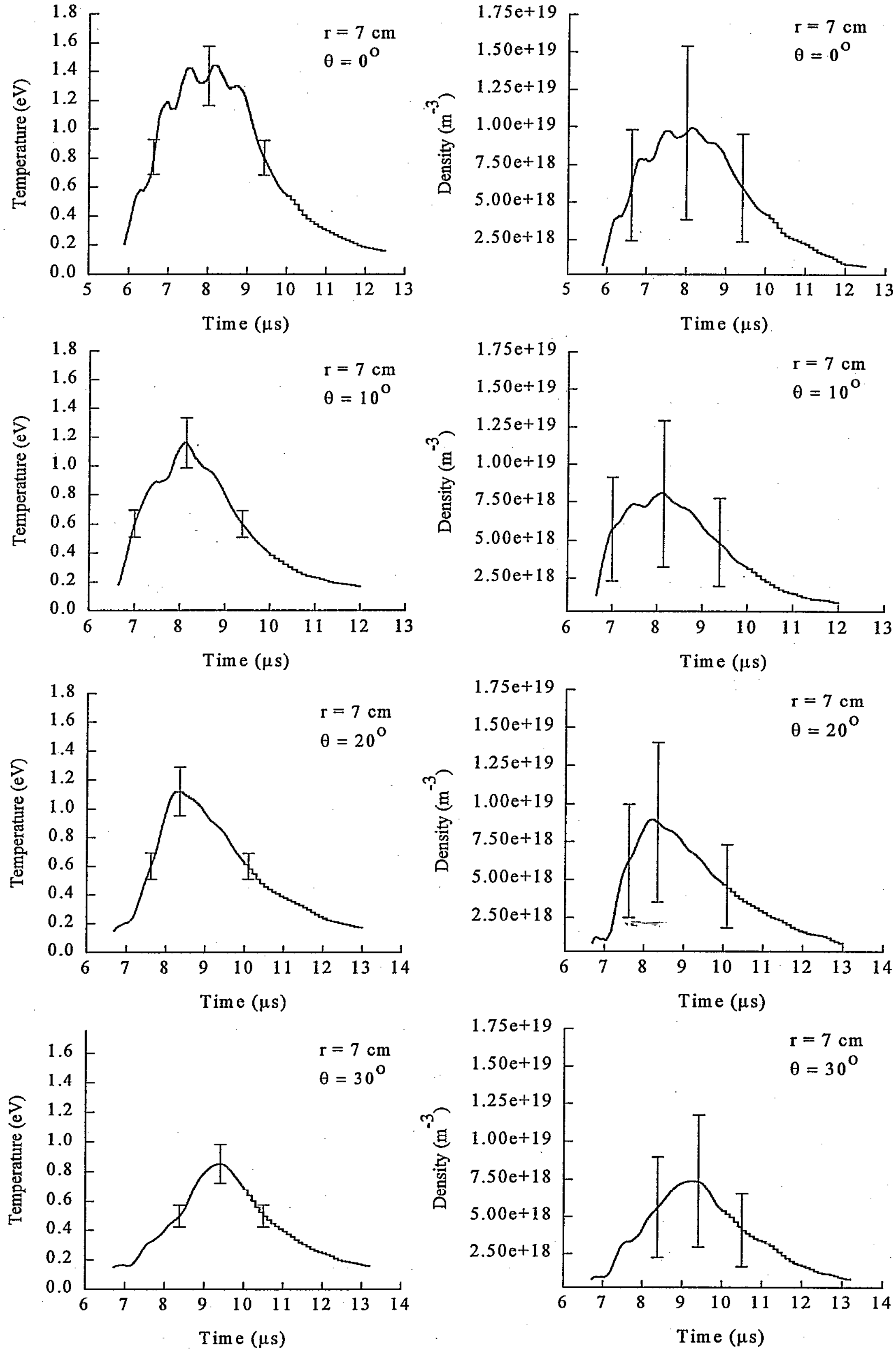


**Figure 8.** Sample-averaged density $\overline{n}_e$ ($m^{-3}$) and temperature $\overline{T}_e$ (eV) at $r = 7$ cm downstream from the propellant inlet of a GFPPT.

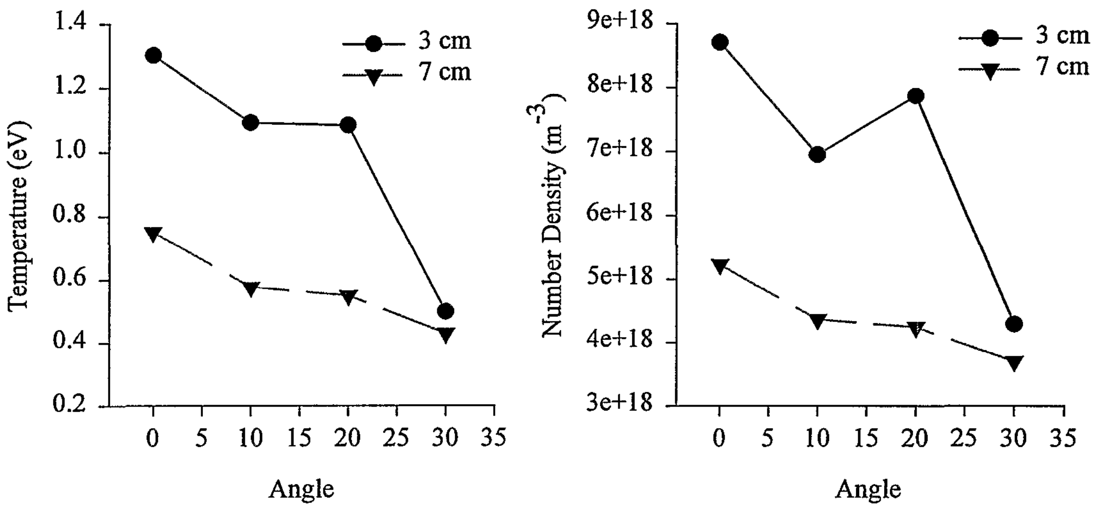


**Figure 9.** Time-averaged temperature $\langle \overline{T}_e \rangle$ and number densities $\langle \overline{n}_e \rangle$ in the near-exit region of a GFPPT