Sweep Langmuir Probe and Triple Probe Diagnostics for Transient Plasma Produced by Hypervelocity Impact

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Abstract Two techniques are applied to diagnose characteristic parameters of plasma created by hypervelocity impact, such as electron temperature and electron density. The first technique is a sweep Langmuir probe (SLP), which is a new apparatus based on a dual channel circuit that can compensate for stray capacitance and obtain a good synchronicity, so that electrostatic turbulence with a good temporal resolution can be acquired. The second technique is a triple Langmuir probe (TLP), which is an electrostatic triple Langmuir probe diagnostic system, in which no voltage and frequency sweep is required. This technique allows to measure electron temperature, electron density as a function of time. Moreover, the triple Langmuir probe diagnostic system allows the direct display of electron temperature and semidirect display of electron density by an appropriate display system, the system permits us to eliminate almost all data processing procedures. SLP and TLP were applied to obtain fluctuations of the characteristic parameters of plasma generated by hypervelocity impact. As an example of their application to time-dependent plasma measurement, the electron temperature and electron density of plasmas were acquired in hypervelocity impact experiments. Characteristic parameters of plasma generated by hypervelocity impact were compared by the two kinds of diagnostic techniques mentioned above.

Keywords: hypervelocity impact, plasma, sweep Langmuir probe (SLP), triple Langmuir probe (TLP), electron temperature, electron density

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1 Introduction

Langmuir probes are the most basic and widely used plasma diagnostics technique [1]. They can provide the measurement of electron temperature, electron density, and plasma potential. In plasma fluctuation or transient plasma studies, however, the traditional I-V curves are not available since the parameters are time-dependent. In that case, a Langmuir probe based on harmonic technique [2] or sweep voltage [3-6] could be developed. The good spatial and temporal resolution with a sweep voltage makes the Langmuir probes feasible to diagnose transient plasmas.

Measurements using Langmuir probe techniques are complicated by the fact that the observed quantities, ion saturation current and floating potential, are a combination of the basic plasma parameters such as electron temperature, electron density, and plasma potential. In particular the conventional current-voltage (I-V) characteristic curve can only provide reliable measurements of the equilibrium temperature but lack detailed temporal behavior.

In order to increase temporal resolution, the technique more commonly used is the triple Langmuir probe. This technique requires a floating double probe biased to collect the ion saturation current and an additional floating single probe, which allows us instantaneous measurements of electron temperature, electron density, and floating potential, as well as their fluctuations [7]. This method eliminates the time consuming data analysis required in curve-fitting current-voltage characteristics to obtain plasma parameters [8]. Another technique uses a sweep double probe technique [9,10], which fits the measured current fluctuations as a function of bias voltage to a double probe model. However, measurements performed with these techniques are complicated by probe shadowing, phase delay, and decorrelation effects [11].

The aim of the work is to compare characteristic parameters of plasma created by hypervelocity impact obtained by using a sweep Langmuir probe and a triple Langmuir probe in similar experimental conditions.

2 Diagnostic systems and theory

2.1 Sweep Langmuir probe diagnostic system

The conventional Langmuir probe method is very famous as a probe to measure plasma with constant den-
sity. But this technique cannot be applied to measure such transient plasma as plasma plume produced by pulsed plasma thruster and plasma generated by hypervelocity impact.\textsuperscript{[7]} In this study, we adopted the SLP diagnostic system to measure transient plasma generated by hypervelocity impact.

Fig. 1 is the SLP diagnostic system chart. A function signal generator provides the sweep voltage for the Langmuir probe. The sampling frequency of the oscilloscope is 500 kHz, and the sampling length is 20 ms; The oscilloscope records sweep voltage (CH1) and voltage (CH2) acting on the probe. When the difference between voltage (CH1) and voltage (CH2) is divided by resistance $R$, we would obtain the current flowing through the probe.

![Diagnostic system chart of the sweep Langmuir probe](image)

Herein, we assume that the plasma is at quasi-stable state in every half period (100 $\mu$s). We can obtain a current-voltage ($I$-$V$) characteristic curve in every period of voltage sweep, and the electron temperature of the plasma is related to ($I$-$V$) characteristic curve. Thus, we can obtain the variation in electron temperature with time by calculating every $I$-$V$ characteristic curve acquired from every half sweep period.

### 2.1.1 Sweep Langmuir probe theory

The measurement is based on the non-linearity of the single Langmuir probe characteristics. The basic Langmuir probe theory is summarized as follows. Biasing the probe with voltage $V_s$ referred to the ground electrode, one can measure the current flowing through the probe to get $I$-$V$ characteristics. The parameters of the local plasma around the probe tip can be estimated by the simplest theory of the Langmuir probe. Assuming the ions of the plasma are single charged particles, the electrons of the plasma obey a Maxwellian velocity distribution, and a stationary equilibrium is maintained between the probe and plasma. The current flowing through the probe can be written as

$$I_p = I_s e^{(V_p - V_s)/kT_e}, \quad \text{for } V_p < V_s,$$

$$I_p = I_e, \quad \text{for } V_p \geq V_s,$$

(1)

where $I_s = -enA\sqrt{\frac{kT_e}{2\pi m_e}}$ is the electron saturation current, $I_i = \frac{1}{2}enA\sqrt{\frac{kT_e}{M}}$ the ion saturation current, $e$ the electron charge, $m_e$ the electron mass, $M$ the ion mass, $n$ the plasma density, $A$ the probe area, $V_p$ the probe potential, $k$ the Boltzmann constant. From Eq.(1), one can get

$$\ln\left(\frac{I_p}{I_e}\right) = \frac{e}{kT_e}(V_p - V)$$

(2)

The electron temperature $T_e$ may be obtained from the slope of $\ln(I_p) \sim V_p$.

### 2.1.2 Voltage sweep technique

Time evolution of plasma parameters is obtained if the voltage sweep is continuously performed at a frequency $f_{\text{sweep}}$ higher than twice the frequency band $f_{\text{fluc}}$ of the fluctuating plasma parameters.

When an alternating current (AC) voltage $V_s = U_0$ is applied to the probe, the probe voltage and current will be changed at the same frequency. The time evolution of plasma parameters may be obtained if the voltage sweep is continuously performed at frequency $f_s$ higher than the changing frequency of the plasma in this case. When a sweep voltage is applied to the probe, if the sweep period is short enough so that the plasma is at quasi-stable state during the sweep period, the plasma parameters are considered to be not varied with time. However, the sweep frequency should be low enough so that a sheath can form around the probe.

For reliable sweep Langmuir probe measurements, the operational frequency of the circuit must satisfy the relations

$$2f_{\text{fluc}} \leq f_{\text{sweep}} \leq \frac{1}{\tau_{\text{sheath}}}.$$  

(3)

Here $\tau_{\text{sheath}}$ is the time which is needed for the probe sheath to form.

### 2.1.3 Sweep Langmuir probe data processing

We know that the frequency of sweep voltage is 5 kHz in the experiment and every sweep period is 200 microseconds. The plasma is considered quasi-stable in every half period and we can acquire an $I_p$ corresponding to $V_p$ characteristic curve. The slope of $\ln(I_p) \sim V_p$ is the reciprocal value of the electron temperature; furthermore, electron density will be obtained. The same method applied in the whole physical process. Finally, we can acquire a series of electron temperatures and electron densities at various instants of the physical process. The following relationship of slope for $\ln(I_p) \sim V_p$ is satisfied

$$\text{slope} = 1/T_{eV},$$

(4)

where $T_{eV}$ is electron temperature, the unit of which is electron-volt (eV).

### 2.2 Triple Langmuir probe diagnostic system

#### 2.2.1 Diagnostic system

In the present study, we adopted a triple Langmuir probe diagnostic system to measure transient plasma...
created by hypervelocity impact. Fig. 2 is a chart of the triple Langmuir probe diagnostic system. A fixed bias voltage \( V_{d3} \) is applied between tip 1 and 3, which is provided by a dry battery group, from which different voltage values can be chosen. The sampling frequency of the oscilloscope is 1 MHz for every channel, and the sampling length is 20 ms. Channel 2 (CH2) of the oscilloscope records floating potential, channel 1 (CH1) of the oscilloscope records potential of probe 1, and channel 3 (CH3) of the oscilloscope records the anode potential of the externally applied voltage source. When the difference between voltage (CH1) and voltage (CH3) is divided by resistance \( R \), we can obtain the current flowing through resistance \( R \) and the current obtained is used for calculation of electron density.

\[ T_e \equiv \frac{V_{d2}}{\ln 2 \times \left\{ 1 + \exp \left[ -0.2567 \left( \frac{V_{d3}}{V_{d2}} \right)^2 \right] \right\}} \times \{ 1 - \exp \left[ 0.9968 \left( 2 - \frac{V_{d3}}{V_{d2}} \right) \right] \}, \]  

where the unit of \( T_e \) is electron-volt eV.

Next, let us consider electron density, using \( T_e \) calculated by the above formula. Electron density \( n_e \) (cm\(^{-3}\)) is obtained by

\[ n_e = \left( M \right)^{1/2} A f_1 \left( V_{d2} \right), \]  

\[ f_1 \left( V_{d2} \right) \equiv 1.05 \times 10^3 \left( T_e \right)^{-1/2} \left( \exp \left( eV_{d2}/kT_e \right) - 1 \right)^{-1}, \]

where \( A \) is the surface area of probes and \( M \) is the atomic weight or molecular weight of the ion. Units of \( n_e \) (cm\(^{-3}\)), \( I \) (\( \mu \)A), \( T_e \) (eV) are used.

3 Example of application of the triple Langmuir probe diagnosis

3.1 Experimental system

3.1.1 Experiment parameters

Material of the projectile is Al2024-T4, which is a solid sphere with a diameter of 6 mm. Material of the target is also Al2024-T4, which is a panel with a thickness of 25 mm. The projectile was loaded by a Two-Stage Light Gas Gun. The experimental parameters are listed in Table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>Shot Impact velocity (km/s)</th>
<th>Incidence angle (°)</th>
<th>Pressure of impact chamber (Torr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.05</td>
<td>45</td>
<td>0.9</td>
</tr>
</tbody>
</table>

3.1.2 Rectangular coordinate system and layouts of the probe

In order to position the probes, we used a Cartesian coordinate system \( (x, y, z) \) with the origin at the point of impact, where \( +z \) means the height (in centimeters) above the target surface, \( +y \) the distance up of the impact point, and \( +z \) the distance away from the projectile line of flight in a right-handed sense. The triple probe with diameter of 0.5 mm and length of 10 mm is placed away from the impact point, and the sweep Langmuir probe with diameter of 0.5 mm and length of 10 mm is also placed away from the impact point. The probe diameter is less than the electron mean path (about 2 mm under present conditions \(^{[13]}\)). Space layouts of the probes are so arranged that the experiment is equipped with two probes symmetrically arranged on both sides of the plane which is perpendicular to the target and trajectory. Table 2 lists the layout and parameters of the probe.

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Table 2. Layout and parameters of the probe

<table>
<thead>
<tr>
<th>Shot No.</th>
<th>Distance between trigger point and impact point (mm)</th>
<th>Probe No. of the probes (mm)</th>
<th>Rectangular coordinates of the probe</th>
<th>A classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>642</td>
<td>1</td>
<td>(−50, 0, 75)</td>
<td>Sweep Langmuir probe</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>(50, 0, 75)</td>
<td>Triple Langmuir probe</td>
</tr>
</tbody>
</table>

3.2 Experimental results and discussion

When the projectile strikes the target at hypervelocity, a strong shock wave is created in the target and projectile. When the shock wave arrives at the rear of the target, tensile stress works and destruction is caused, and the same event occurs in the rear of the projectile. When the target is thick, the tensile stresses are neglected because the shock wave is attenuated more strongly. Therefore, the force that should be considered in the collision for a thick target is only elastic force. The appearances of a target after impact are shown in Fig. 3.

(a) The scars after impact, metal target, (b) The amplified scars after impact, metal target

Fig.3 The appearances of a target after impact

The oscillating voltage waveform applied to sweep Langmuir probe 1 is shown in Fig. 4(a), and the current waveform of sweep Langmuir probe 1 is shown in Fig. 4(b) during shot No. 1, respectively. Fig. 4(c)∼(d) are typical curves of the probe $I_{pr} \sim V_{pr}$ and $\ln(I_{pr}) \sim V_{pr}$ between 180 µs and 298 µs after being triggered, respectively.

(a) Potential on sweep Langmuir probe, (b) Current on sweep Langmuir probe, (c) Typical curve of the probe current-voltage, (d) Typical relationship of the $\ln I_{pr} \sim V_{pr}$

Fig.4 Experimental results of the sweep Langmuir probe
One can know from Fig. 4(c) that electron saturation current could not be acquired in the typical current-voltage curve of the probe. The reason is that carried signals provided by the function signal generator is not enough.

The raw voltage waveforms obtained from tip 2, 1 and 3 of the triple Langmuir probe 2 are shown in Fig. 5(a), (c) and (e), and the smoothed voltage waveforms are shown in Fig. 5(b), (d) and (f) during shot No.1.

The raw and smoothed current waveforms of probe 2 flowing through non-inductive resistor R are shown in Fig. 6(a)−(b) during shot No.1.

The distance between trigger point and impact point of projectile interacting target is 642 mm in the experiment. According to the speed of the projectile, we could know that the projectile impacted the target at the moment about 106 µs after being triggered. One could see from Fig. 4 and Fig. 5 that the signals of probes 1 and 2 were received at a moment about 104±10 µs after being triggered. As the distance from the impact point to probe tips is about 9.0 cm for probes 1 and 2, the velocities of the plasma moving to probe 1 and 2 were almost the same as estimated to be about 2.5±0.375 km/s. The electron temperature can be obtained from Eq. (9), and the electron density can also be acquired from Eq. (10). The electron temperatures and electron densities at the positions of the sweep Langmuir probe 1 and the triple Langmuir probe 2 are shown in Fig. 7 during the whole physical process.


Fig. 5 Experimental results of the triple Langmuir probe
In the experiment, we consider in the present paper only the physical process at the stage from the beginning to 1.0 ms. According to early stage laboratory experiments, the duration of the plasma generated by hypervelocity impact is about 4.0 ms, which means that voltage and current peaks should not exist after 4.0 ms. In fact, this phenomena can be explained that plasma cloud arriving at the impact chamber wall was rebounded and interacted with plasma cloud expansion since in the experiment the impact chamber was not large enough. The interaction among charged particles mentioned above can generate strong shock wave, which make plasma increase. One can also find from Fig. 7(a)∼(b) that electron temperature and electron density at the symmetrical position received from both sides of trajectory had an approximate synchronicity.

The surface areas of both kinds of probes satisfy $A = \pi dh + \pi d^2 / 4$, where $d$ and $h$ are probe diameter and length in the experiment, respectively. The maximum electron temperature value of the triple Langmuir probe was near 1.7 eV during the whole physical process in the experiment, however, average electron temperature value was approximate 0.8 eV. Under the current experimental condition, the average electron density in the experiment was about $1.06 \times 10^{12}$ cm$^{-3}$, which was measured by the triple Langmuir probe. However, the electron temperature and electron density acquired by using the sweep Langmuir probe were lower than the values obtained by using triple Langmuir probe.

The measurement results depend on the experimental conditions. The results are believed to be correct with error less than one order of magnitude. The plasma did produce in the hypervelocity-impact, and the plasma density is not very high. Since the environment in the chamber is very poor, there are some disadvantageous factors which affect the measurement of plasma characteristic parameters. Many tests should be done later to get more information of the impact-generated plasma. Next, we will measure plasma characteristic parameters in the same experimental condition by using other Non-contact-type optics or microwave diagnostic tools.

4 Conclusions

Sweep Langmuir probe (SLP) is based on a dual channel circuit that compensates for stray capacitance, so that we can investigate the electrostatic turbulence with good temporal resolution. The SLP provides reliable measurement of the plasma parameters, as well as their fluctuations. A Langmuir probe with sweep voltage may be used to diagnose the transient plasma such as one generated during hypervelocity impact Al2024-T4 target. The time-dependent current-voltage charac-
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teristic of the probe can be obtained, and the plasma parameters may be deduced accordingly. The SLP diagnostic system proposed appears to be more useful for the diagnosis of rapidly varying time-dependent plasmas, such as the plume diagnostic for hypervelocity impact and the pulsed plasma thruster.

Sometimes the characteristic frequencies of the power spectrum of electron temperature are over 100 kHz. In this situation, sweep Langmuir probe is not yet reliable, because of frequency abasing, thus the triple probe technique becomes the commonly used method to measure the electrostatic fluctuations. The triple probe system does not require any voltage or frequency sweep, so that this not only simplifies the measuring equipment, but also may greatly improve the response time in measurements compared with other probe methods, and the triple Langmuir probe system enables us to display instantaneous values of plasma parameters directly or semi-directly on appropriate display units.

In view of the features mentioned above, the instantaneous direct-display system given in this paper appears to be most useful for the diagnosis of rapidly varying time-dependent plasmas, such as in the cases of geophysical and astrophysical observation by means of vehicles, and in the measurements of transient plasma.

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References


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