Article ID: 1000-5773(2012)03-0325-08

Double-Langmuir Probe Diagnostics of Plasma Produced by Hypervelocity Impact 2024-T4 Aluminum Target*

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Abstract: In some types of plasma, there did not exist an electrode or reference point. The electrode or reference point was needed when applying a bias voltage to a Langmuir probe. To acquire the characteristic parameters of transient plasma generated by hypervelocity impact, diagnostic system was established. The new electrostatic probe diagnostic system utilizing the double-Langmuir probe was given, in which no voltage and frequency sweep was required. This method can measure electron temperature and electron density as a function of time. This new instrument was based on a double-channel circuit, the current and voltage spectra were obtained from the probe synchronously by a digital oscilloscope. The aim of this work was to apply the double-Langmuir probe diagnostic system to time-dependent plasmas generated by 2024-T4 aluminum projectile hypervelocity impact 2024-T4 aluminum target.

Key words: hypervelocity impact; plasma; double-Langmuir probe; electron temperature; electron density

CLC number: O383; O531 **Document code**: A

1 Introduction

In some plasma, there did not exist an electrode or reference point. This reference point was needed when applying a bias voltage to a Langmuir probe. In other situations, the plasma potential may change with time, which will create difficulties in maintaining a constant voltage difference between a probe and the plasma potential. In these situations, single-Langmuir probes were not readily applicable[1-9]. In order to overcome some limitations of the single probe, Sharda, et al.[10] developed a technique which involved the use of two single-Langmuir probes biased with respect to each other and isolated from the ground[11-13]. This allows the probes to electrically float with regard to the plasma, therefore allowing the probes to follow the changes in the plasma potential.

2 Theory

A double-probe consists of two electrodes that are inserted into a plasma. The spacing between the probes must be small enough that the properties of the plasma can be considered to be constant in the interval. In the case of a cylindrical double-probe, the electrodes are nothing more than two exposed lengths of wire. The double-probe has the advantage that the electron current being drawn to either

* **Received date**: 2011-05-05; **Revised date**: 2011-11-14
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probe will never exceed the ion saturation current which typically is much lower than the electron saturation current. Thus, the disturbance of the plasma by the probes is minimized. However, because the electrons will only be the very energetic ones or the high-energy tail of a Maxwellian distribution, the majority of the electrons will not be sampled by this method[14].

In some instances, a potential difference might exist between Tip 1 and Tip 2 without a measured current. This would have the effect of shifting the characteristic to either side of the origin. This could be a symptom of the floating or contact potentials not being equal for the two tips. Alternatively, a strong potential gradient may exist in the immediate vicinity of the probes. The condition that the double-probe is floating relative to the plasma means that no net current is flowing, we can obtain the following

$$I = I_{i2} - I_{e2} = I_{e1} - I_{i1} \tag{1}$$

The electron saturation current density to a tip in the transition region is given by the following equation

$$j_e = \frac{1}{2} n_e \sqrt{\frac{2kT_e}{\pi m_e}} \exp \frac{\varphi}{kT_e} \tag{2}$$

Where j_e is electron saturation current density, n_e is electron density, φ is electron potential which the unit is eV, k is Boltzmann constant, T_e is electron temperature, m_e is electron mass. According to Eq. (2), we can obtain the electron saturation current, which is expressed as follows

$$I_e = A \cdot \frac{1}{2} n_e \sqrt{\frac{2kT_e}{\pi m_e}} \exp \frac{\varphi}{kT_e} = A j_{eo} \exp \frac{\varphi}{kT_e} \tag{3}$$

where $j_{eo} = \frac{1}{2} n_e \sqrt{\frac{2kT_e}{\pi m_e}}$ is the random electron current density, and A is the current collecting area of the probe. The electron saturation current at Tip 1 and Tip 2 is

$$\begin{aligned} I_{e1} &= A_1 j_{eo} \exp \frac{\varphi_{e1}}{kT_e} \\ I_{e2} &= A_2 j_{eo} \exp \frac{\varphi_{e2}}{kT_e} \end{aligned} \tag{4}$$

Where φ_{e1} and φ_{e2} are electron potentials of Tip 1 and Tip 2, respectively.

If we substitute this into Eq. (1) using the relationship $\varphi_b = \varphi_2 - \varphi_1$, after some modification we have the following relationship

$$\frac{I + I_{i1}}{I_{i2} - I} = \frac{A_1}{A_2} \exp \frac{\varphi_b}{kT_e} \tag{5}$$

This is the general formula for the double-probe current as a function of voltage. For a symmetric probe, the areas are equal and the ion saturation current becomes $I_{i1} = I_{i2} = I$. With these simplifications, Eq. (5) will become

$$I = I_i \cdot \frac{\exp \frac{\varphi_b}{kT_e} - 1}{1 + \exp \frac{\varphi_b}{kT_e}} \cdot \frac{\exp\left(-\frac{\varphi_b}{2kT_e}\right)}{\exp\left(-\frac{\varphi_b}{2kT_e}\right)} = I_i \cdot \frac{\exp \frac{\varphi_b}{2kT_e} - \exp\left(-\frac{\varphi_b}{2kT_e}\right)}{\exp \frac{\varphi_b}{2kT_e} + \exp\left(-\frac{\varphi_b}{2kT_e}\right)} \tag{6}$$

Upon further simplification, we obtain the equation of the double-probe characteristic for equal area electrodes as following

$$I = I_i \cdot \tanh\left(\frac{\varphi_b}{2kT_e}\right) \tag{7}$$

The value for the ion saturation current in Eq. (7) can be found from experimental data by extrapolating the flat parts of the I-V curve to the y-axis. Using this value for the ion saturation current, the equation for the double-probe characteristic can be fitted in order to obtain the electron temperature.

Alternatively, another way of determining the electron temperature is through the slope of the *I-V* curve at the origin by using the experimental value of ion saturation current. The slope of the *I-V* curve can be found by taking the derivative of Eq. (10) as following

$$\frac{\mathrm{d}I}{\mathrm{d}\varphi_b}=\frac{I_i e}{2kT_e}\mathrm{sech}^2\left(\frac{\varphi_b}{2kT_e}\right)=\frac{I_i e}{2kT_e}\cdot\frac{4}{\exp\dfrac{\varphi_b}{kT_e}+2+\exp\left(-\dfrac{\varphi_b}{kT_e}\right)} \tag{8}$$

The slope at the origin can be calculated to be

$$\left.\frac{\mathrm{d}I}{\mathrm{d}\varphi_b}\right|_{\varphi_b=0}=\frac{I_i e}{kT_e} \tag{9}$$

From Eq. (9) the value for T_e can easily be found. Once I_i and T_e are known, the electron density n_e can be found easily from this equation, assuming $n_i = n_e$.

$$I_i=\frac{1}{4}Aen_e\overline{C}_i \tag{10}$$

Where $\overline{C}_i=\sqrt{\dfrac{8kT}{\pi m_i}}$ is the mean ion speed. Therefore, a simple rearrangement of Eq. (10) leads to an expression for the electron density

$$n_e=\frac{4I_i}{Ae\sqrt{\dfrac{8kT}{\pi m_i}}} \tag{11}$$

3 Probe Construction and Electronics

Fig. 1 is the double-Langmuir probe diagnostic system chart. Some bias voltage is applied between Tip 1 and Tip 2. We shall make the potential of Tip 2 positive with respect to Tip 1. Since the entire double-probe system is not connected to any other electrodes, the system will electrically float. No net current will be drawn by the two tips therefore both tips will be negative with respect to the plasma.

A cylindrical Langmuir probe is a conducting tip placed into plasma at one end and attached to various electronics at the other. For this experiment, only symmetrical probes were used, in which each of the two tips used have equal exposed length and surface area. The tips of the probe in this experiment were made of copper wire. Alumina tubing was used to hold the wires as shown in Fig. 2. The copper wires were fed through two of the three holes with the third holes left empty. Fig. 2 is the double-Langmuir probe construction.

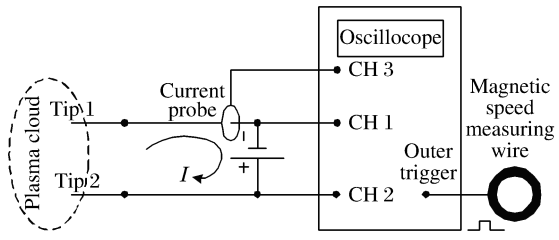


Fig. 1　Chart of double-Langmuir probe diagnostic system

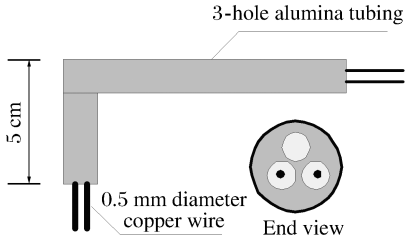


Fig. 2　Double-Langmuir probe construction

In the experimental circuit, SYV50-3 coaxial cables were used to carry the signal from the copper tips to a flange with electrically-isolated Q9 type connectors on it. The double-Langmuir probe conductors were attached to the center conductor of the SYV50-3 coaxial cable. The isolated flange was used so that the outer ground ring on the coaxial cables would be isolated from the impact chamber and could

be grounded.

On the external side of the impact chamber flange, more SYV50-3 coaxial cables were used to connect the probe inputs to the measurement oscilloscope. The bias voltages for the double-probe measurements were supplied by a dry batteries group, which is composed of 1.5 volt type dry battery.

The measurements were recorded on a Tektronix TDS2403 four-channel digital oscilloscope. The oscilloscope had a bandwidth of 500 MHz and a sampling rate of 1 MS/s. The current flowing through each of the tips was measured by using one Tektronix TCP202 Hall effect current probe. The current probe interfaced with the oscilloscope allowing for display of the current waveforms as a function of time on channels three (CH 3) of the oscilloscope.

4 Example of Application for the Double-Langmuir Probe Diagnosis

4.1 Experimental System

Two-stage light gas gun launched a macroscopic projectile of metal sphere. After flying certain distance in target chamber, the metal sphere is separated from the sabot, and then impacts the target. Double-Langmuir probes are located at the downrange positions of backing plate through support setting, which is located far away from the mainstream of ejectors generated by hypervelocity impact. The measured signals in expanding plasma clouds are obtained by double-Langmuir probe and input measuring system which transports voltage signals by coaxial cables. Voltage signals collected by double-Langmuir probe are input to oscilloscopes. Fig. 3 is the schematic of experimental set-up.

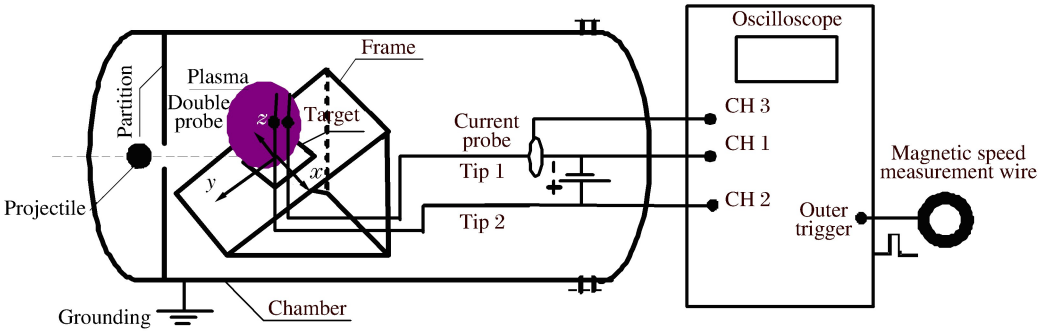


Fig. 3 Schematic of experimental set-up

4.1.1 Experimental Parameters

Material of the projectile is 2024-T4 aluminum, which is a solid sphere with a diameter of 6 mm. Material of the target is also 2024-T4 aluminum, which is a panel with a thickness of 20 mm. In the experiment, the impact velocity of the projectile on target is 6.12 km/s, the incidence angle of the projectile impacting target is 30°, respectively, and the pressure of impact chamber is 78 Pa.

4.1.2 Layout and Parameters of 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 $+z$ measured the height above the target surface, $+y$ the distance uprange of the impact point, and $+x$ the distance away from the projectile line of flight in a right-handed rule.

Probes with diameter of 0.5 mm and length of 5 mm are placed away from the impact point. The probe diameter is less than the electron mean path (about 2 mm under present conditions[7]). The experiment is equipped with two probes arranged on the one side of the trajectory which is perpendicular to the target. The coordinate of the centers of the double-Probe 1 and Probe 2 are (50, 0, 75) and (50, 120, 95), respectively. The unit of coordinate is millimeter.

4.2 Experimental Results and Discussion

When the projectile impacts 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 increased, and the same case occurs in the rear of the projectile. When the target is thick, the tensile stresses are neglected because the shock wave is attenuated stronger. Therefore, the force that should be considered in the collision for a thick target is only elastic force. The appearance of a target after impact is shown in Fig. 4.

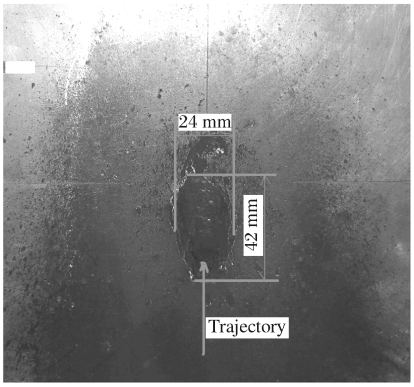
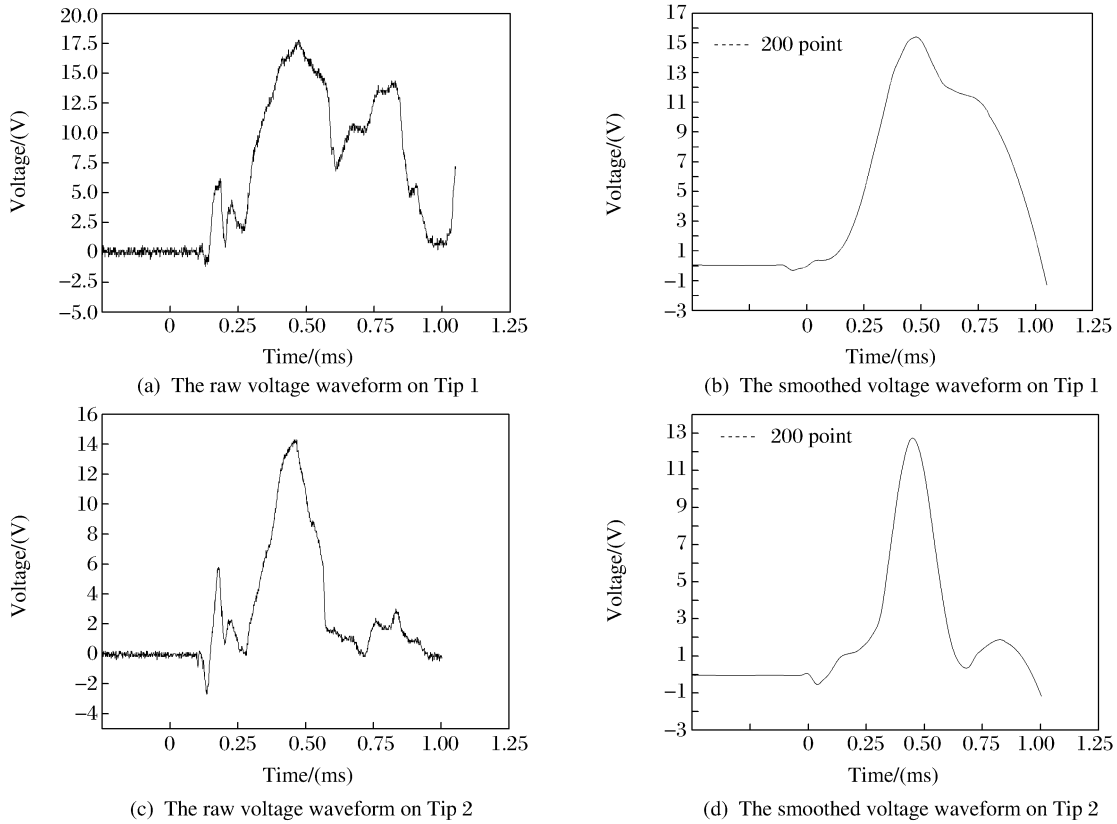


Fig. 4　The appearance of a target after impact

The raw voltage waveforms obtained from Tip 2 and Tip 1 of the double-Langmuir Probe 1 are shown in Fig. 5(a), Fig. 5(c), and the smoothed voltage waveforms obtained from Tip 2 and Tip 1 of the double-Langmuir Probe 1 are shown in Fig. 5(b), Fig. 5(d) during shot No. 1.



(a) The raw voltage waveform on Tip 1　(b) The smoothed voltage waveform on Tip 1

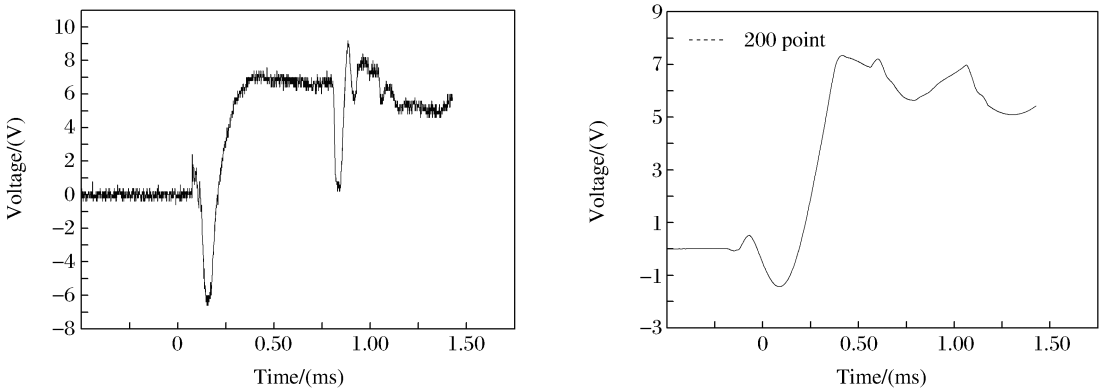
(c) The raw voltage waveform on Tip 2　(d) The smoothed voltage waveform on Tip 2

Fig. 5　Experimental results from Probe 1

The raw and smoothed voltage waveforms obtained from Tip 1 of the double-Langmuir Probe 1 are shown in Fig. 6(a), Fig. 6(b) during shot No. 1.

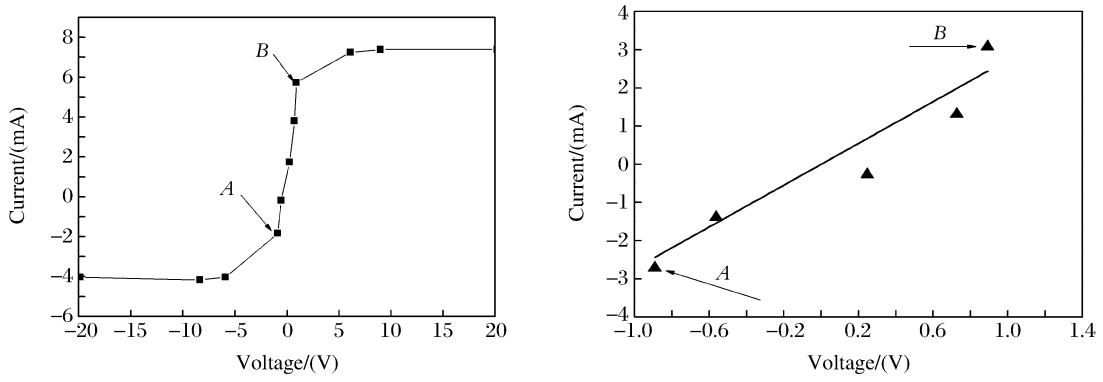
In the experiment, the distance is 640 mm between trigger point and impact point of projectile interacting target. According to the authentic speed of the projectile, we can know that projectile impacted target at the moment about 104 μs after being triggered. One can see from Fig. 4 that the

signals of Probe 1 and Probe 2 were received at a moment about (104±6)μs after being triggered. Since the distance from the impact point to probe tips was about 9.0 cm for the Probe 1, and the distance from the impact point to probe tips was about 16.1 cm for the Probe 2, we can know that the velocity of the electron moving to Probe 1 and Probe 2 were almost as estimated to be about (2.500±0.375)km/s and (2.200±0.375)km/s, respectively.



(a) Raw voltage waveform on Tip 1 (b) Smoothed voltage waveform on Tip 1

Fig. 6 Experimental results from Probe 2



(a) Typical *I-V* curve (b) Linear fit of voltage-current curve between *A* and *B*

Fig. 7 Typical experimental results from the double-Langmuir Probe 1

The value for the ion saturation current in Eq. (10) can be found from experimental data by extrapolating the flat parts of the *I-V* curve to the *y*-axis, which is 2.9 milliampere in Fig. 7. Using this value for the ion saturation current, the equation for the double-probe characteristic can be fitted in order to obtain the electron temperature. Fitting formula of Fig. 6(b) can be obtained by using Origin 8.0 data processing software.

$$I = 2.732\,9V + 0.885\,83 \tag{12}$$

Here, I is current, the unit is mA; V is voltage, the unit is V.

The electron temperature can be obtained from Eq. (9), which is about 1.06 eV, and the electron number density can also be acquired from Eq. (11), which is about 6.3×10^{12} cm^{-3}. Similarly, electron temperature and electron number density of Probe 2 can also be acquired. The characteristic parameters of plasma obtained from the Probe 1 and Probe 2 are listed in Table 1.

Table 1　The characteristic parameters of plasma

Probe No.	Ions current I_i/(mA)	Electron temperature T_e/(eV)	Electron number density n_e/(cm^{-3})
1	2.9	1.06	6.3×10^{12}
2	2.0	0.72	5.8×10^{11}

The measurement results depend on the experimental conditions. The results are believed correct on error of less than one order. 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 disadvantage factors which affected measurement of plasma characteristic parameters. Many experiments should be done later to get more information on the impact-generated plasma. Next, we will measure plasma characteristic parameters in the same experimental condition by using other non-contact-type optic diagnostic tools.

5　Conclusions

The double-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 for measurements compared with other probe methods to the order of one microsecond. Experimental results show that double-Langmuir probe is reliable to diagnose transient plasma created by hypervelocity shocks.

In view of the features mentioned above, the double-Langmuir probe given in this paper appears to be most useful for the diagnosis of rapidly varying time evolution plasmas, such as in the cases of geophysical and astrophysical observation by means of vehicles, and in the other measurements of the transient plasma.

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超高速碰撞 2024-T4 铝靶产生等离子体的朗缪尔双探针诊断

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摘要: 有些等离子体,本身并不存在电极和参考点,而该电极或参考点是提供偏压朗缪尔探针所必需的。为了获得超高速碰撞所产生等离子体的特征参量,建立了一种新的静电探针诊断技术,该技术不需要扫描频率,其探针可用于测量与时间相关的电子温度、电子密度。该诊断系统基于双通道电路,电流和电压谱通过数字示波器同步输出。研究的主要目的是,应用双朗缪尔探针诊断 2024-T4 铝弹丸超高速碰撞 2024-T4 铝靶时产生的瞬态等离子体。

关键词: 超高速碰撞;等离子体;双朗缪尔探针;电子温度;电子密度

中图分类号: O383;O531 **文献标识码**: A