ISSN NO: 9726-001X
Volume 11 Issue 03 2023

JOURNAL OF CURRENT SCIENCE

USING PLASMA MEASUREMENTS TO UNDERSTAND HOW CRATERS DEVELOP ON ALUMINUM FOAM WHEN SUBJECTED TO HIGH-VELOCITY IMPACTS

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Abstract

An unusual crater with a small entrance and a big hollow, like a turnip, is supposedly created when a fast-moving projectile hits aluminium foam. When an impact occurs on a material with a larger porosity, it is thought that the material creates a debris cloud, and the crater is thought to be formed when the cloud is scattered within the target material. Furthermore, evidence of melting has been found, which is thought to be a result of the impact's high temperature. The correlation between the temperature of a plasma created by high-speed collision and the temperature at impact has not been established, although it is theoretically possible. Because the temperature measuring instrument must avoid colliding with the projectile, taking readings at the impact location is a challenging task. Consequently, it is crucial to monitor plasma diffusion and quantify plasma at points other than the impact location. The aforementioned claims are supported by high-speed impact studies detailed in this article, which used a triple probe and a high-speed camera to monitor plasma. Ritsumeikan University's Impact Engineering Laboratory conducted the high-speed impact experiment using a vertical gas pistol. The substance that was intended to be struck had an impact speed of 400 m/s. A minimum exposure period of 1.0 μs and a maximum frame speed of 1.4 Mfps were features of the high-speed camera. The high-speed camera captured the flash at the instant of collision, while the triple probe approach analysed plasma signals.

Key words: High-speed impact, Plasma, Triple probe method, Temperature, Aluminum foam, Crater

1. Introduction

Much space debris exists in orbit around the Earth. The amount of the space debris increases annually with the disposal of space crafts and collision between pieces of space debris (NASA, 2015). The speed of the space debris at a geosynchronous orbit is approximately 3 km/s, and approximately 7-8 km/s at a low Earth orbit distance. The speed with which space debris impacts the Earth is approximately 10 km/s.

Space debris greater than 10 cm across can be observed from the ground, and space crafts are able to avoid collisions with debris of this size. However, space debris under 10 cm across is not able to be observed or avoided. Even these small pieces of space debris colliding with space crafts induce functional loss or destruction because their impact energy is proportional to the square of the debris speed. One example of such a space debris collision occurred to an artificial satellite in 2009 (NASA, 2009). Therefore, countermeasures addressing space debris collisions are an important focus for the future of space development.

In 2009, a high-speed impact experiment was performed on aluminum foam to develop a debris shield that could defend spacecraft against space debris (Ryan et al., 2009). In this experiment, a uniquely shaped crater was formed around the impact point. The crater had a narrow entrance and then a large internal cavity, like a turnip. Figure 1 shows the cross section of such a turnip-shaped crater, where the red line outlines the shape of the crater. Traces of compaction and melting were confirmed on the surface of this crater: the compaction was caused by the spreading of the debris cloud, and the melting was caused by the high-speed impact. However, it is very difficult to measure the temperature at the impact point with standard methods for two main reasons. One reason is that a thermometer placed on the target is instantaneously destroyed upon impact. The other reason is that there was not enough time resolution to measure transient temperatures at the impact point.

Plasma and flash emissions have been confirmed at high-speed impact (Tang et al., 2012, Tandy et al., 2014). It is conceivable that the temperature of a plasma induced by high-speed impact could indicate the temperature at impact, although this relationship has not yet been proven. Measuring plasma at the impact point is difficult because the projectile collide with the measuring device. Therefore, it is necessary to measure plasma at a distance from the impact point and observe the diffusion of the plasma. In this paper, high-speed impact experiments were performed in which the plasma was measured with a triple probe and a high-speed camera, for the purpose of confirming that the plasma temperature could indicate the temperature at impact.

2. Triple probe method

A single probe method was invented by Langmuir and Mott-Smith in 1962, in which a measuring probe was inserted in a plasma to measure the plasma parameters, such as electron temperature, electron density, and floating potential. The technique has been further improved by optimizing the plate and sphere shapes and double probe method using two probes (Amemiya et al., 2005). Plasma induced by high-speed impact is an instantaneous and unstable phenomenon. It is difficult for a single probe method or even a double probe method to measure this phenomenon (Chen, 1964). In this paper, a triple probe method (Chen and Sekiguchi, 1965) was used to measure the electron temperature of plasma induced by high-speed impact. Figure 2 shows the diagnostic device used in the triple probe method, referred to as the triple probe device.

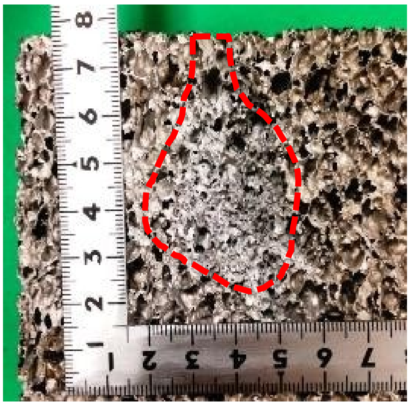

Fig. 1 Turnip-shaped crater.

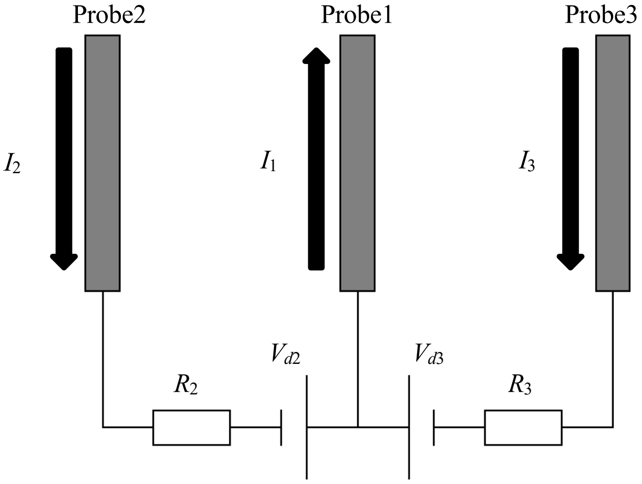

Fig. 2 Triple probe circuit.

The triple probe device consisted of three parallel copper wires, two power sources, and two resistors, as shown in Fig. 2. I_1, I_2, and I_3 represent the current flowing into each probe. V_{d2} and V_{d3} represent the voltages of the power sources. Each current was calculated using Eqs. (1), (2), and (3), respectively, in which S represents the probe surface J_e and J_i represent the electron saturation current and ion current density, respectively, and k and e represent Boltzmann's constant and electric charge, respectively.

$$-I_1 = -SJ_e \exp(-\phi V_1) + SJ_i \tag{1}$$

$$I_2 = -SJ_e \exp(-\phi V_2) + SJ_i \tag{2}$$

$$I_3 = -SJ_e \exp(-\phi V_3) + SJ_i \tag{3}$$

Equation (4) was derived from Eqs. (1), (2), and (3).

$$\frac{I_1 + I_2}{I_1 + I_3} = \frac{1 - \exp(-\phi V_{d2})}{1 - \exp(-\phi V_{d3})} \tag{4}$$

In Eq. (4),

$$\phi = \frac{e}{kT_e} \tag{5}$$

The electron temperature is calculated from Eqs. (4) and (5).

3. Experimental procedure

High-speed impact experiments were performed at Ritsumeikan University's Impact Engineering Laboratory (Shiga, Japan) with a vertical gas gun with a diameter of 15 mm and a length of 2 m; the gas gun is shown in Fig. 3. The maximum projectile speed was approximately 500 m/s (Gardiner et al., 2016).

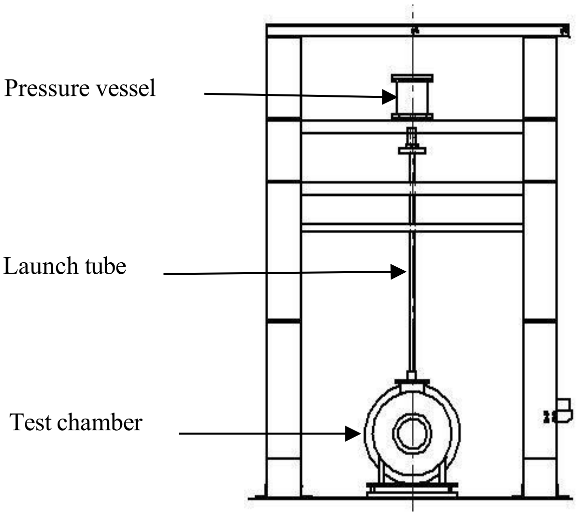

Fig. 3 Vertical gas gun.

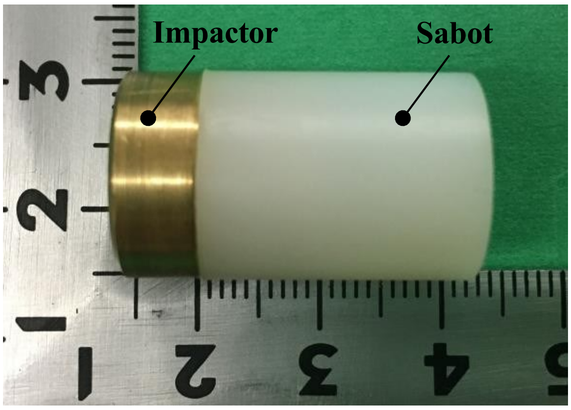

Fig. 4 Projectile.

The projectile consisted of a brass impactor and polyethylene sabot as shown in Fig. 4. The projectile speed was measured using the magnet-coil method. The sabot was equipped with a magnetic coil to measure the projectile speed. A high-speed camera (Phantom v711; Vision Research, Inc.) with a maximum frame rate of 1.4 Mfps and a minimum exposure time of 1 μs was used to photograph the high-speed phenomenon. Figure 5 shows the experimental setup and Table 1 provides specifications of the experimental components.

Two triple probe devices were used to measure plasma parameters as shown in Fig. 6 (one device has been omitted from Fig. 5 because of the larger scale of that figure). In this study, the triple probe device had a diameter (*D* in Fig. 6) of 1 mm and a length (*L* in Fig. 6) of 10 mm. The distance (*d* in Fig. 6) between the wires was 1 mm. The parameters of the triple probe devices are presented in Table 2.

The copper wires were insulated except at the measurement section (refer to dotted line section in Fig. 6). The three wires were fixed by SUS tube. The outputs of V2out and V3out were measured by DL850 ScopeCorder (Yokogawa Meters & Instruments, Corp.), with a sampling rate of 10 MS/s and a vertical resolution of 12 bit. The layout of the triple probe device is illustrated in Fig. 7. The coordinates of the tips of the triple probe devices 1 and 2 were (15, 0, 5) and (-30, 0 10), respectively (the origin was the center of the impact point).

Table 1 Specifications of experimental components.

Projectile	Size [mm]		Mass [g]	Impact speed [m/s]
	Impactor	Sabot		
	ϕ14.8×6	ϕ14.9×20	16	430
Target	Material	Size [mm]		
	A5052	55×65×t20		
High-speed camera	Spatial resolution [pixel]	Exposure time [μs]	Frame rate [fps]	
	112×136	4.6	200,000	

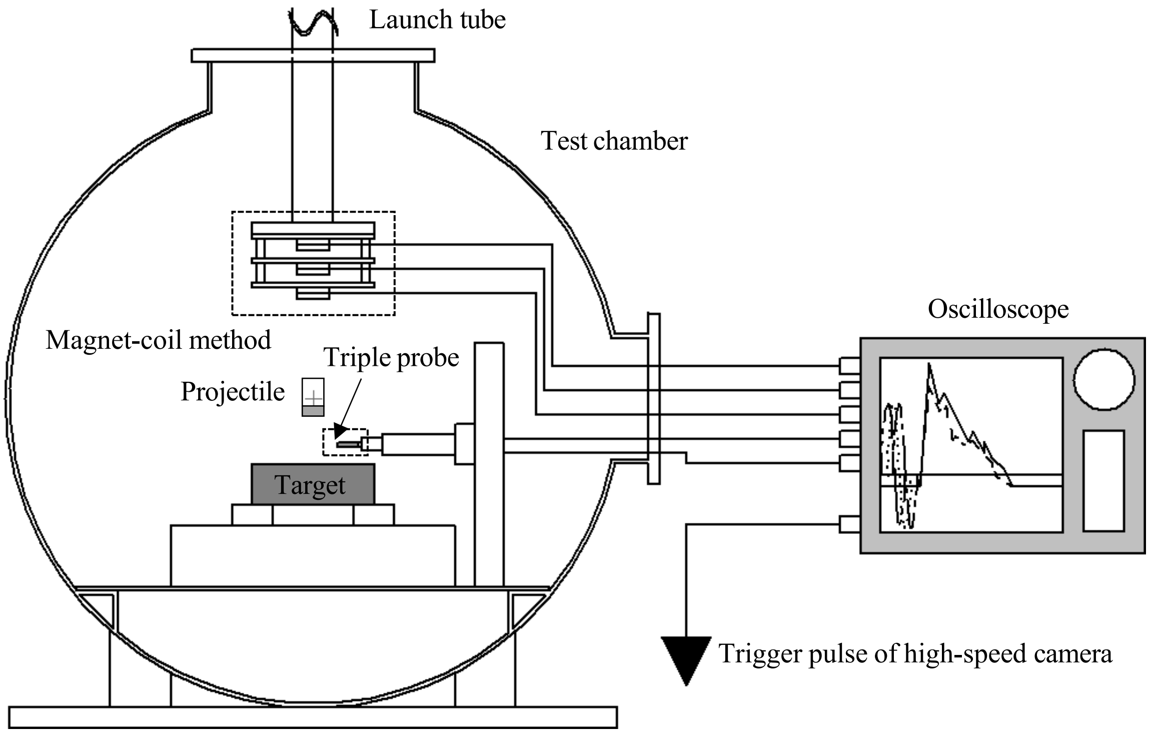

Fig. 5 Experimental setup.

Table 2 Triple probe parameters.

R_2 [Ω]	R_3 [Ω]	V_{d2} [V]	V_{d3} [V]
700	700	3	12

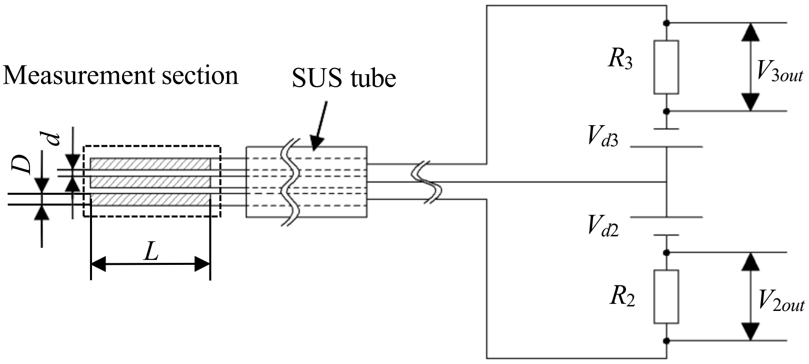

Fig. 6 Schematic of triple probe devices.

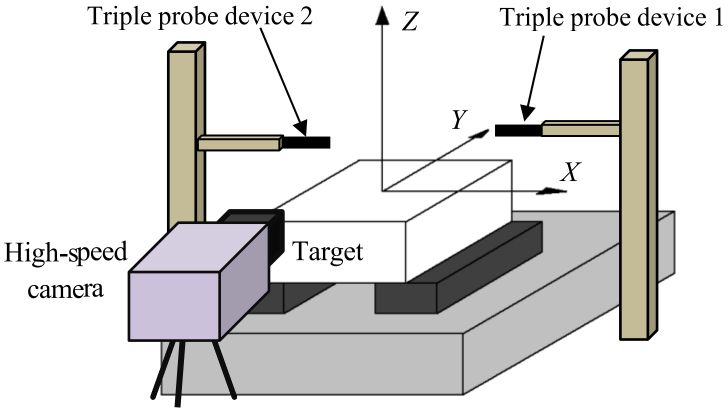

Fig. 7 Coordinate system imposed on the target.

4. Results and discussion

The projectile speed was 432 m/s. Figure 8 shows selected frames from the high-speed camera. The numerals under each image indicate the time elapsed after the impact. An impact flash (dotted line in Fig. 8) was confirmed at the right side of the images for approximately 150 μs. It was estimated that projectile (solid line in Fig. 8) inclined to the left.

The original output signal of triple probe device 1 is shown in Fig. 9. Triple probe device 2 was not able to measure the plasma. The output of V_{2out} almost disappeared after 30 μs, indicating that the plasma had diffused and the helium used to accelerate the projectile reached triple probe device 1 after 30 μs. The plasma signal was measured for approximately 150 μs. Figure 10 shows the magnified waveform from between 5 μs and 10 μs, which indicates that the plasma reached triple probe device 1 at 7.5 μs. After the experiment, the distance from the impact point to the tip of triple probe device 1 was 10.3 mm. The plasma diffusion speed was calculated to be approximately 1.37 km/s. Figure 11 shows the current for each probe. I_2 and I_3 were calculated from V_{2out}/R_2 and V_{3out}/R_3, respectively. I_1 was the sum of I_2 and I_3. Figure 12 shows that the electron temperature was obtained from Eq. (4) and Eq. (5): the maximum electron temperature was found to be 4.92 eV, and the average electron temperature was found to be 3.52 eV.

The duration of the flash observed by the high-speed camera agreed with the time of the output signal from the plasma. Only triple probe device 1 at the side observed the flash emission, as obtained from the plasma signal. These results show that the plasma was included in the flash emission.

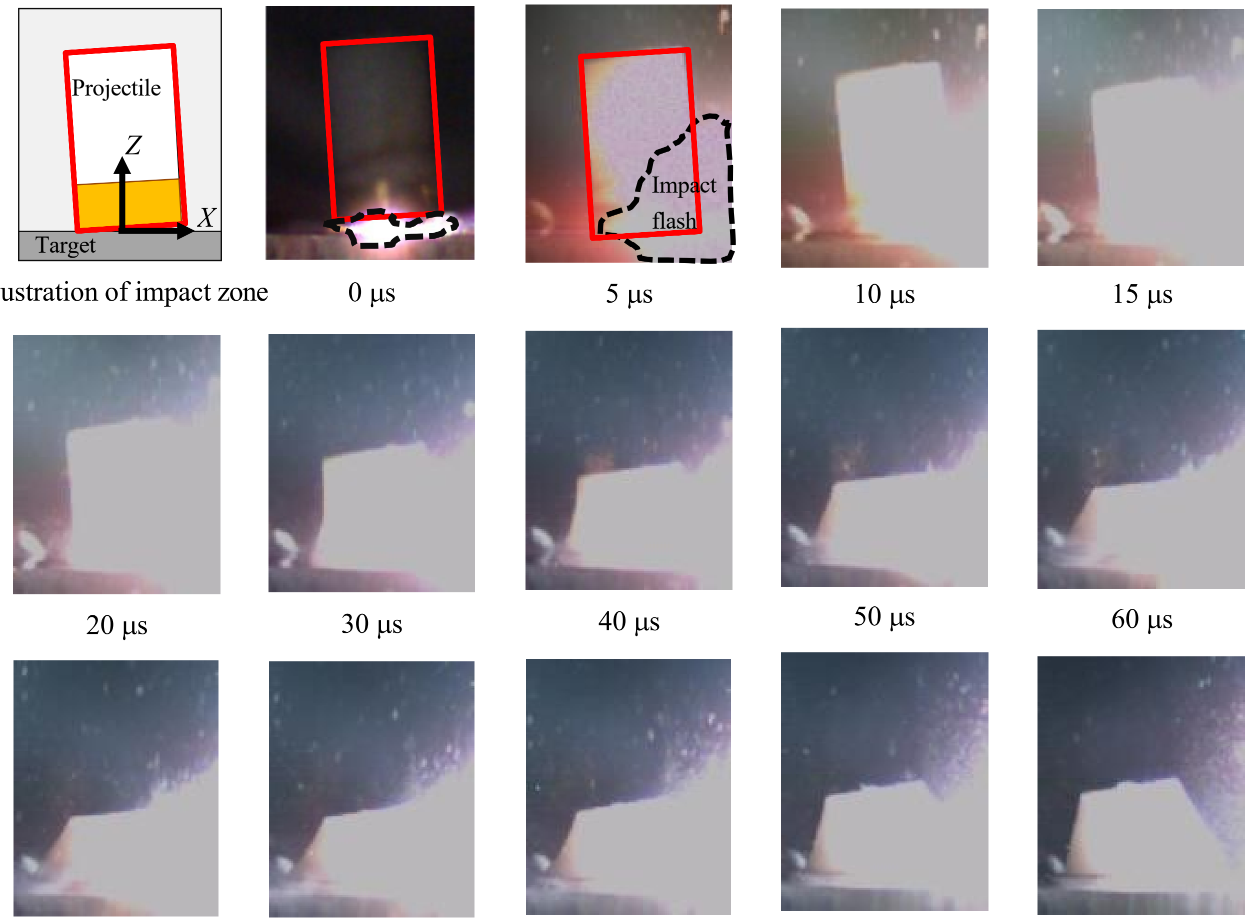

Illustration of impact zone, 0 μs, 5 μs, 10 μs, 15 μs

20 μs, 30 μs, 40 μs, 50 μs, 60 μs

70 μs, 85 μs, 100 μs, 130 μs, 150 μs

Fig. 8 High-speed framing images of impact flash.

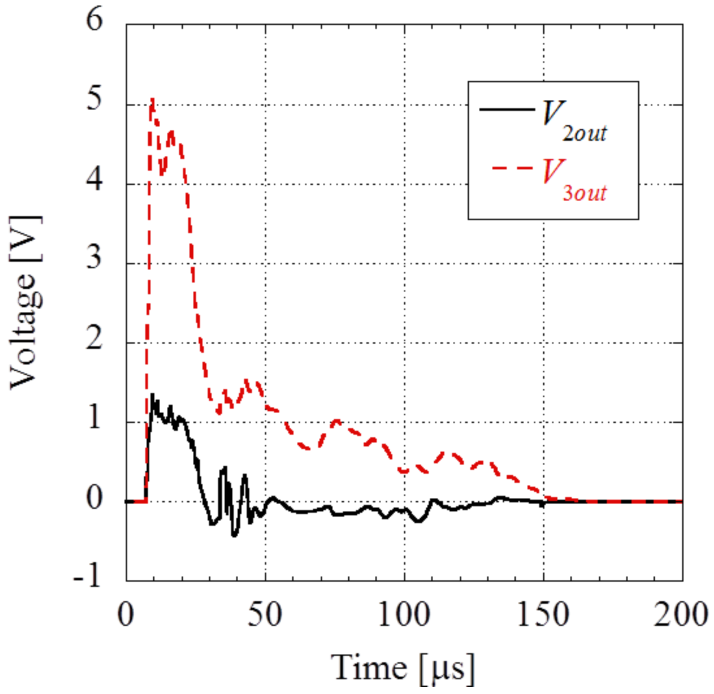

Fig. 9 Output signal of triple probe devices 1.

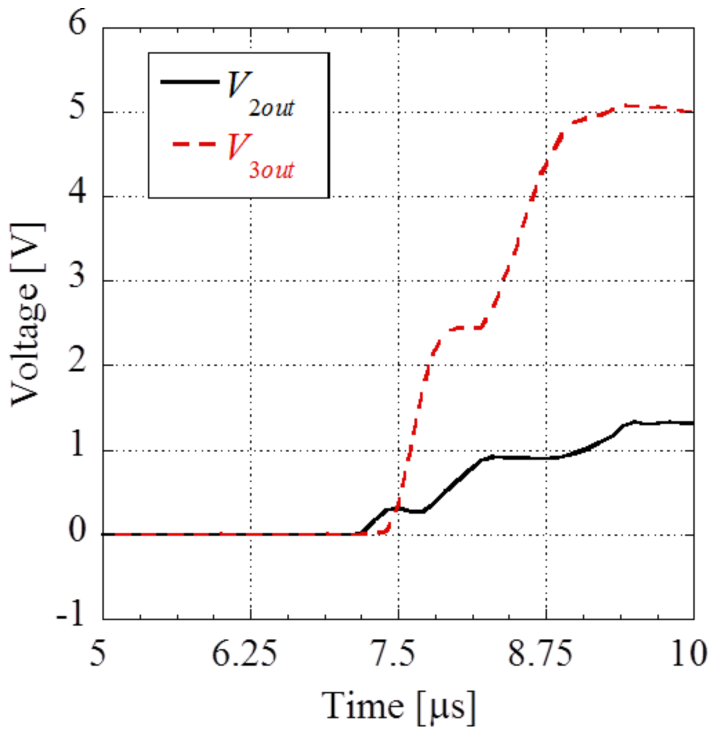

Fig. 10 Magnified waveforms from between 5 μs and 10 μs.

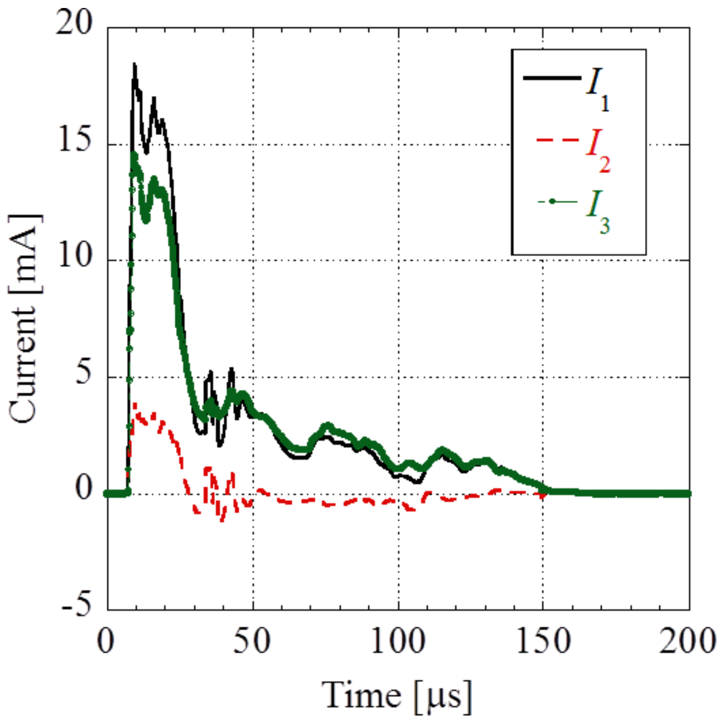

Fig. 11 Each current in triple probe device 1.

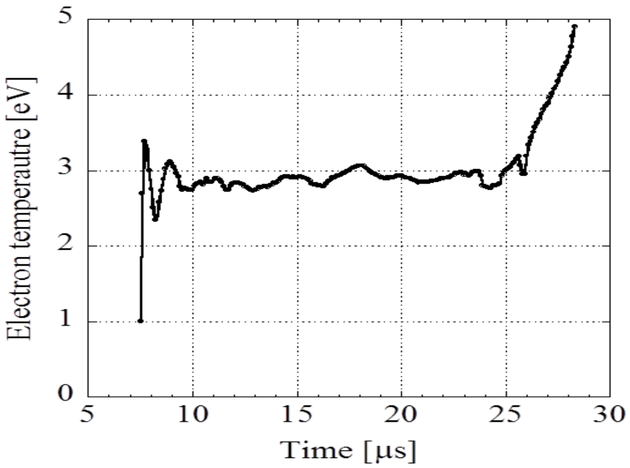

Fig. 12 Electron temperature.

5. Conclusion

Using a high-speed camera and two triple-probe devices, an impact experiment was conducted at high speed. Here is a brief summary of the findings:

(1) At 7.5 microseconds after collision, the plasma was identified by the triple probe instrument. It was estimated that the plasma diffusion speed was about 1.37 km/s. Electron temperatures ranged from an average of 3.52 eV to a high of 4.92 eV.

(2) For around 150 μs, flash emission was verified on the right side of the pictures.

(3) Consistent with the timing of the plasma output signal, the high-speed camera recorded the flash's duration. The flash emission, as determined by the plasma signal, was only picked up by the side triple probe device 1. According to these findings, the plasma was a component of the flash emission.

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