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journal or publication title	Procedia Engineering
volume	103
page range	279-286
year	2015-04-29
URL	http://hdl.handle.net/10228/00007261

doi: info:doi/10.1016/j.proeng.2015.04.048

Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 103 (2015) 279 – 286
Procedia Engineering
www.elsevier.com/locate/procedia

The 13th Hypervelocity Impact Symposium

Development of Micro-Particles Accelerator with Pulse Formation

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Abstract

Space debris is one of major problems for recent space developments. When micro-debris of several hundred in diameter impacts spacecrafts, it may cause mission interruption. To design a safe and reliable space craft, we have to evaluate the risk of micro-debris impact by conducting ground-based hypervelocity impact experiments. To achieve these objectives, this study deals with the development of a plasma gun in which a plasma is created by applying high current and then accelerated by its own diffusion and Lorentz force. We think that it is important for accelerating projectiles to a higher velocity to shorten the current rise time and with a high plasma density. Therefore, to increase the velocity of the projectile, we examined the influence of the rise time and the plasma density. We conducted the experiments by a plasma gun and a WCR (Weak Current Removal) circuit to shorten the rise time and a short plasma gun to obtain a high-density plasma. These experimental results showed that it is necessary for accelerating to increase the maximum electric current, to adjust shooting the plasma to the peak time of the current and to increase the density of plasma.

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Keywords: Space debris, hypervelocity impact, plasma

Nomenclature

D_c	crater depth (cm)
d_p	the projectile diameter (cm)
H	Brinell hardness of the target
ρ_p	projectile density (g/cm^3)
ρ_t	target density (g/cm^3)
c	sound velocity in the target (km/sec)
V_p	projectile velocity (km/sec)
F	force of transmitted to the projectile by the plasma (N)
P	dynamic pressure (Pa)
A	sectional area of the projectile (m^2)
ρ	plasma density (kg/m^3)
V_{plasma}	velocity of the plasma (m/s)
m	mass of the plasma (kg)
Volume of the plasma gun (m^3)	
Sectional area of the plasma gun (m^2)	
L length of the plasma gun (m)	

1. Introduction

Space debris is non-functional manmade objects in outer space, and it is one of the major problems in recent space developments. It orbits at a velocity of 7~8 km/Sec in the low Earth orbit, and a relative impact velocity could be up to 10~

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15 km/Sec. When a spacecraft is impacted by space debris more than 1 cm in diameter, it can cause serious damage to the spacecraft. Several hundred of μm debris also may also cause mission interruption. Figure 1 represents the relationship between impact flux and debris size. The micro-debris impact flux is higher than that of larger size debris. To design safe and reliable spacecraft, it is important to evaluate the risk of debris impact with the space environment models. However, data on micro-debris larger than 200 μm impacts are insufficient to design the spacecraft. We have to collect more impact data by conducting ground-based hypervelocity impact experiments to evaluate the risk of the micro-debris impacts. To achieve these objectives, the authors are developing a high voltage pulse power accelerator for micro particles.

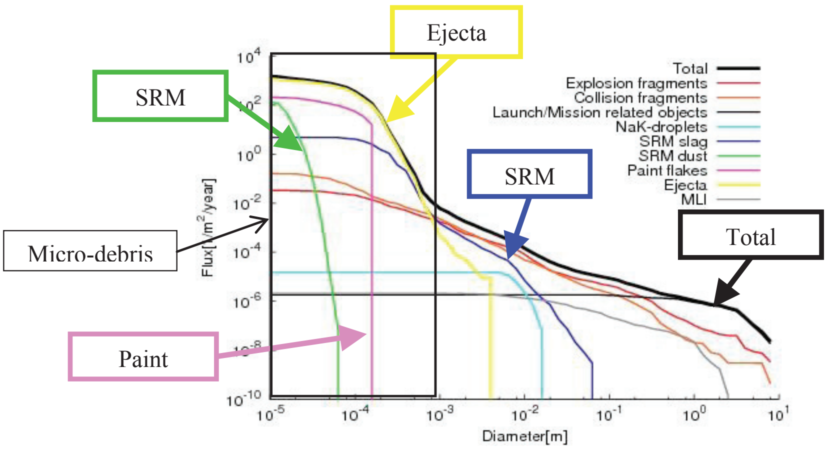


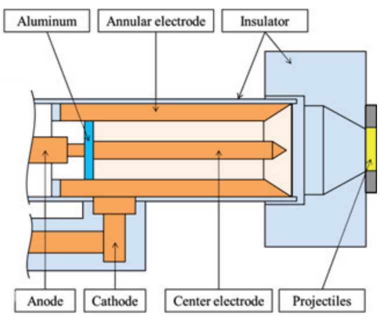
Fig.1. Generation causes of debris calculated by MASTER 2009 (Altitude of 680km) [1]

2. Plasma gun

2.1 Plasma gun

A plasma gun is an electromagnetic accelerator in which plasma is created by applying high current and then accelerated by its own diffusion and Lorentz force. A conventional powder gun has a limited velocity because of the sound velocity of its combustion gas. In contrast, an electromagnetic accelerator like a religion and a plasma gun theoretically has no limit of velocity. At present, two representative plasma guns were developed at the Auburn University and the Technical University Munich. The plasma gun developed at the Auburn University can accelerate projectiles of 50~150 μm in a diameter. In the Technical University Munich, the plasma gun can accelerate projectiles of several decades μm in a diameter, and these guns are used to simulate effects of micrometeorites and micro-debris hypervelocity impact.[2-4] In Kyushu Institute of Technology, to simulate the debris of 200 μm or more in diameter impact, the plasma gun has been researched since 2008.[5]

Figure 2 represents a conceptual configuration of the coaxial plasma gun. It consists of a center electrode and an annular electrode. A center electrode is 300 mm in length and 12 mm in diameter, and an annular electrode is 300 mm in length, 28 mm in internal diameter and 50 mm in external diameter. These electrodes are made of oxygen free copper and covered with insulators.

(a) 

(b) 

Fig.2. (a) Structure of the coaxial plasma gun and (b) the plasma gun overview

Figure 3 represents the acceleration principle of the coaxial plasma gun. An aluminium foil is connected between two electrodes as plasma source. A capacitor bank is discharged through electrodes into the plasma gun. Then the aluminium foil is transformed into plasma by Joule heating, and a magnetic field is generated around the electrodes. Therefore, the plasma is accelerated along the coaxial electrode by Lorentz force and its own diffusion. The center electrode has a conical shape in its extremity. Lorentz force affects toward a center because current flow from an annular electrode to the center electrode, and the plasma is compressed. The compressed plasma pushes and accelerates projectiles installed in the extremity of the gun.

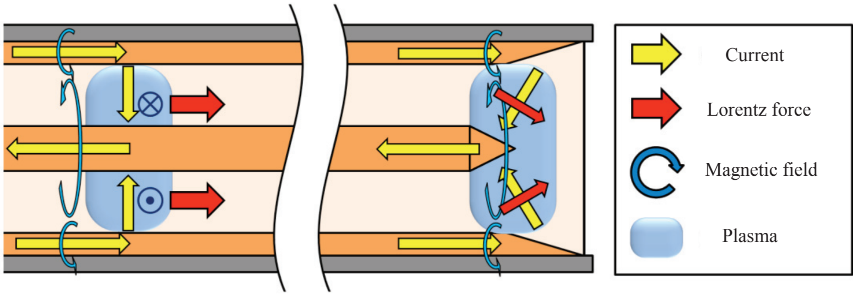


Fig.3. Acceleration principle of the coaxial plasma gun

2.2 Test equipment

Figure 4 represents a schematic overview of the test equipment. The test equipment consists of a capacitor bank, a plasma gun, in a vacuum chamber, a flight tube of 1.12 m in length and a test chamber to install the target. The capacitor bank is connected to the plasma gun by coaxial cables and copper electrodes. To simulate the outer space environment, the air inside the test equipment inside is evacuated by two vacuum pumps.

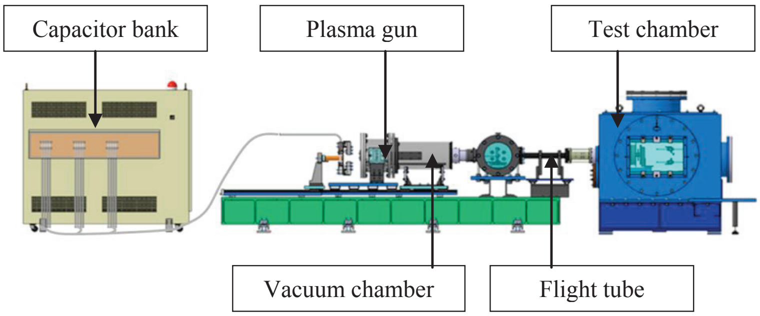


Fig.4. Schematic overview of the test equipment

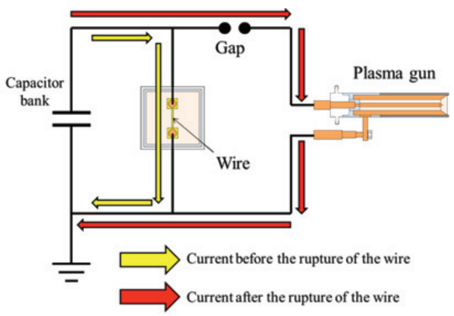
3. Weak current removal (WCR) circuit [6-7]

We use a capacitor bank to supply storing energy to an accelerator. This capacitor bank is connected to the plasma gun by coaxial cables and copper electrodes. Table 1 represents specifications of the capacitor bank. The rise time of the current is about 40 μsec when the plasma gun is used. The plasma was shot before the maximum current flew into the plasma gun because of the long rise time. Therefore, we developed a weak current removal (WCR) circuit to shorten the rise time.

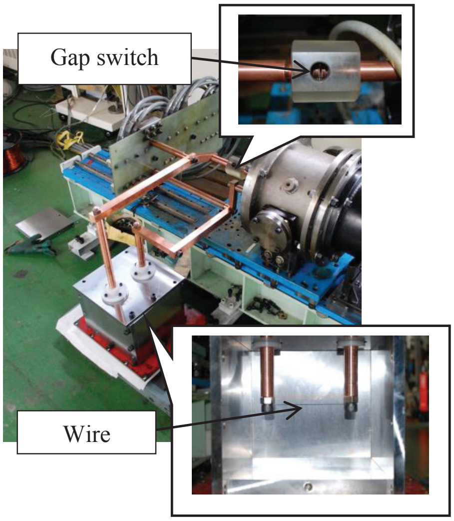
Figure 5 represents the WCR circuit concept. This circuit is composed of a metal wire which is connected to the plasma gun in parallel, and an electrode gap switch. When the electric current begins to flow, it has a small value and flows through the metal wire. In this case, the current does not flow into the plasma gun because of the electrode gap switch. When the current value rises, the metal wire explodes. Then, a spark discharge is generated by the electrode gap switch, and the current flows into the plasma gun. The rise time is shortened by cutting the first weak current and shifting the time, which the current flows through the plasma gun.

Table 1. Specifications of the capacitor bank

Storing energy	100 KJ
Capacitance	750 μF
Maximum charging voltage	16 KV
Maximum discharge current	500 Cu
Inductance	0.487 μH
Rise time	40 μsec



(a)



(b)

Fig.5. (a) WCR circuit image and (b) WCR circuit with a metal wire and a gap switch

4. Plasma density

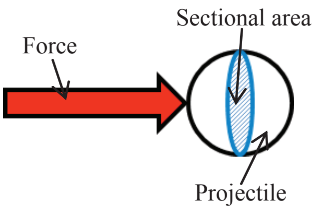
The force transmitted to the projectile by the plasma (figure 6 (a)) is shown by Eq. (2).

$$F = PA = \rho V_{plasma}^2 A/2 \tag{2}$$

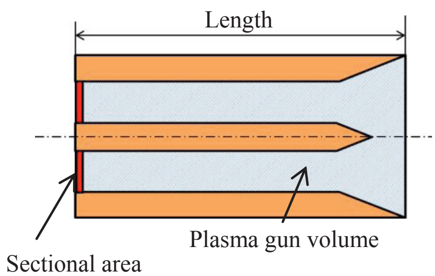
In Eq. (2), the larger force is caused by the high plasma density. The plasma density is shown by Eq. (3).

$$\rho = m/V = m/SL \tag{3}$$

To get a high plasma density, the plasma gun volume (figure 6 (b)) must decrease. Therefore, the length of the plasma gun has to be shortened. We produced the plasma gun with a length of 100 mm, and compared the velocity of the 100 mm plasma gun to that by the 300 mm plasma gun.



(a)



(b)

Fig.6. (a) Image of the force and (b) Image of the plasma gun

4. Experiment

We have conducted an experiment by the coaxial plasma gun and the WCR circuit to examine the influence of the current rise time and plasma density. To examine the influence of the rise time, we compare projectile velocities by the plasma gun only with velocities by the plasma gun and the WCR circuit. We used stainless steel wire of 1.2mm in diameter and two copper wires of 0.9 mm in diameter to change the rise time. To examine the influence of the plasma density, we experimented with two type plasma guns and compared each projectile velocity, and measured plasma mass and calculated the plasma density. The plasma mass has been known by measuring the aluminium foil mass before and after the experiment.

In these experiments, the pressure in the test equipment was less than 50 Pa. The charging voltage of the capacitor bank was 16 KV. 200 µm diameter alumina beads were used as projectiles, and the target was an aluminum alloy (A2024) plate.

The current was measured by Rogowski coil. To measure velocity of a projectile, we measured a crater depth showed figure 7 with the digital microscope and calculated by means of the following Cour-Palais equation [8].

$$D_C = 5.52 \times d_p^{19/18} \times H^{-1/4} \times \left(\rho_p / \rho_t\right)^{1/2} \times \left(V_p / c\right)^{2/3} \tag{1}$$

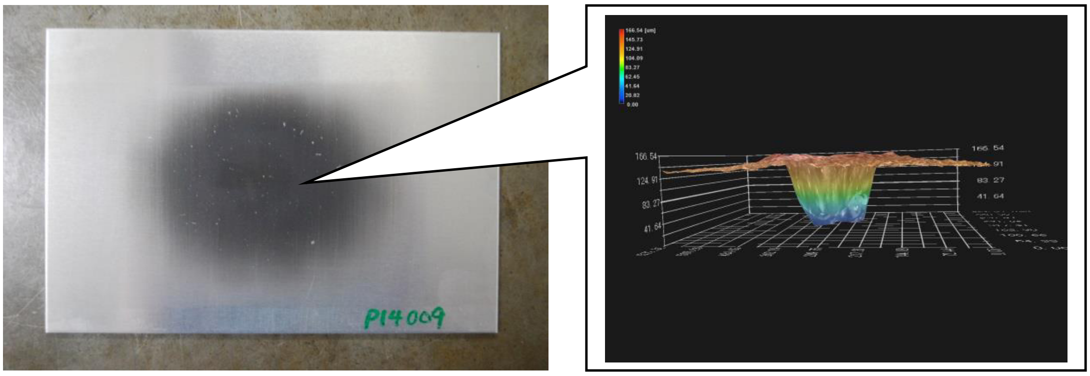


Fig.7. Target and clatter by digital microscope

5. Results

5.1 Results of the WCR circuit

Figure 8 represents the current flowing from the capacitor bank and into the plasma gun and the wire in the WCR circuit. When the electric current begins to flow, it flowed through the wire and did not flow into the plasma gun. In this case, a rise time was about 30 µsec. Figures 9 and 10 represent the current and the velocity with the plasma gun of 300 mm in length, respectively. The rise time was shortened by using the WCR circuit and changing the wire's type and diameter. However, the more the rise time was shortened, the more projectile velocity decreased. This phenomenon was caused by the maximum current decrease. To examine the influence of rise time shorting, we conducted an experiment with the same maximum current. Table 2 represents the result of this test. In this test, when the rise time was shortened, the velocity decreased. Shorting the rise time caused the short acceleration time of the plasma. According to the above results, to obtain a maximum acceleration of the plasma, it is necessary to increase the electric current and to adjust shooting the plasma to the peak time.

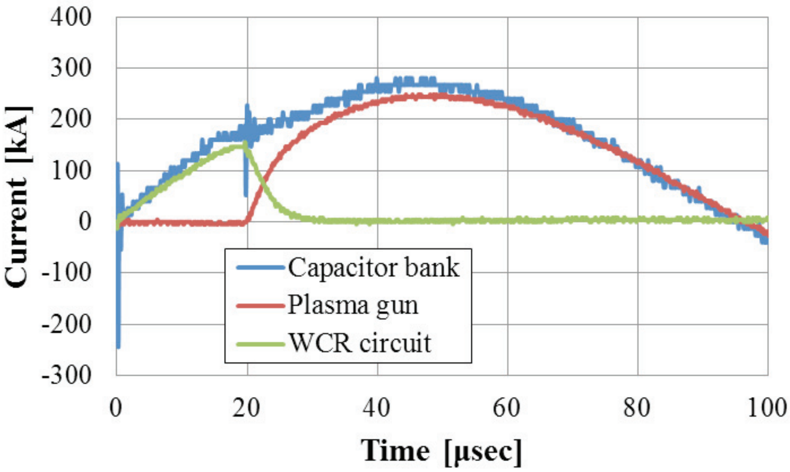


Fig.8. Current wave form

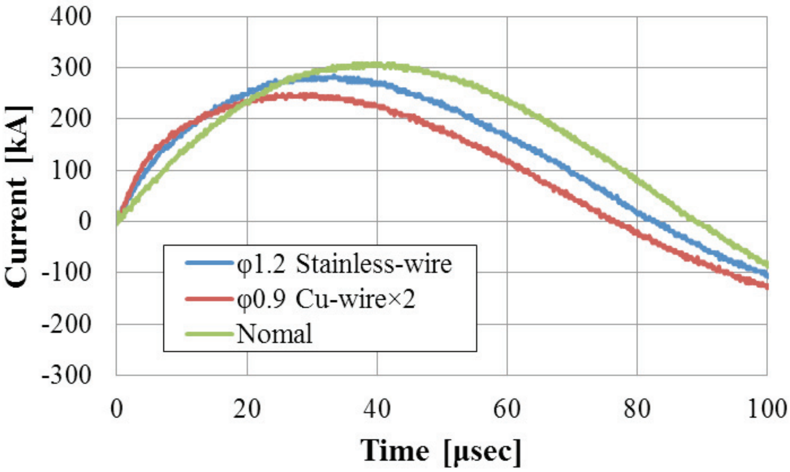


Fig.9. Current vs. Time

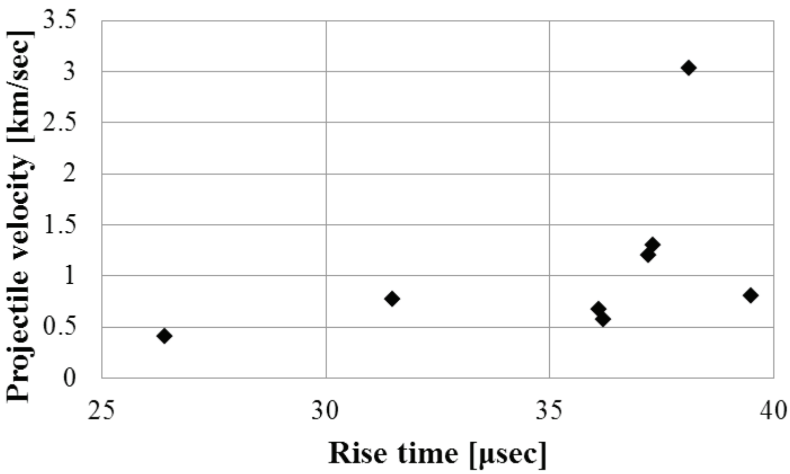


Fig.10. Velocity vs. Rise time with the plasma gun in length of 300 mm

Table 2. Influence of the rise time

Maximum current [kA]	Rise time [μsec]	Velocity [km/sec]
281	38.0	1.7
280	31.5	0.77

5.2 The results of the plasma density

Figure 11 represents the velocity with the plasma gun in length of 100 mm and 300 mm. By taking into consideration the dimension of the gun, the projectile velocity by the 100 mm plasma gun was larger than that of the 300 mm plasma gun. Table 3 shows the average plasma density. The density of the 100 mm plasma gun was higher than that of the 300 mm plasma gun. These results show that the high plasma density is able to increase the velocity of projectiles.

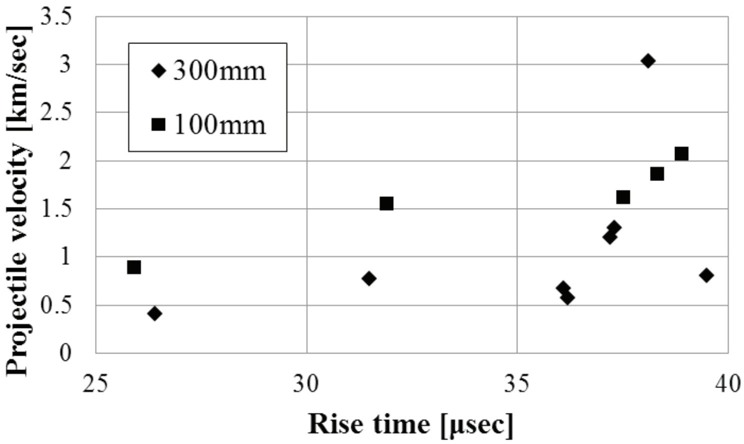


Fig.11. Velocity vs. Rise time with the plasma gun in length of 100 mm and 300 mm

Table 3. Average plasma density

Length of the plasma gun [mm]	Average plasma density [kg/m^3]
300	0.200
100	0.895

6. Conclusion

We developed a WCR circuit to shorten the rise time of the electrical current. The rise time was shortened by using the WCR circuit and changing wire's type and diameter. However, Using the WCR circuit caused the maximum current decrease and the projectile velocity was smaller than that with the plasma gun only.

To examine the influence of the plasma density, we used a plasma gun with length of 300 mm and 100 mm. The velocity by the 100 mm plasma gun was larger than that by the 300 mm plasma gun.

In these experiments, the projectile velocity reached a maximum speed of 3km/sec and an average speed of 2km/sec.

According to above results, to increase the velocity of projectiles, it is necessary to increase the maximum electric current, adjust shooting the plasma to the peak time of the current and increase the density of plasma. We plan to develop the pressure coil to increase the plasma density and the circuit for the pulse compression to increase the maximum current and adjust the current peak time.

Acknowledge

It is noted that the present experiments were done at Laboratory of Spacecraft Environmental Interaction Engineering, Kyushu Institute of Technology.

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