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Small carry-on impactor of Hayabusa2 mission ☆

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ABSTRACT

A Japanese spacecraft, Hayabusa2, the successor of Hayabusa, which came back from the Asteroid Itokawa with sample materials after its 7-year-interplanetary journeys, is a current mission of Japan Aerospace Exploration Agency (JAXA) and scheduled to be launched in 2014. Although its design basically follows Hayabusa, some new components are planned to be equipped in Hayabusa2 mission. A Small Carry-on Impactor (SCI), a small explosive device, is one of the challenges that were not seen with Hayabusa. An important scientific objective of Hayabusa2 is to investigate chemical and physical properties of the internal materials and structures. SCI creates an artificial crater on the surface of the asteroid and the mother spacecraft observes the crater and tries to get sample materials. High kinetic energy is required to creating a meaningful crater. The SCI would become complicated and heavy if the traditional acceleration devices like thrusters and rocket motors are used to hit the asteroid because the acceleration distance is quite large and guidance system is necessary. In order to make the system simpler, a technology of special type of shaped charge is used for the acceleration of the impact head. By using this technology, it becomes possible to accelerate the impact head very quickly and to hit the asteroid without guidance system. However, the impact operation should be complicated because SCI uses powerful explosive and it scatters high speed debris at the detonation. This paper presents the overview of our new small carry-on impact system and the impact operation of Hayabusa2 mission.

1. Introduction

Japanese asteroid explorer Hayabusa launched in 2003 rendezvoused with its target asteroid Itokawa in mid-September, 2005. Hayabusa autonomously performed two touchdowns in November, 2005. It took a lot of pictures and investigated the surface of the asteroid during its stay at Itokawa [1–3]. Although it had many troubles, it came back from Itokawa with sample materials after its 7-year-interplanetary journeys.

Under these situations, the next asteroid exploration project started supposing a launch in 2014 [4]. The spacecraft is called Hayabusa2 and its design basically follows Hayabusa. Hayabusa2 is a similar sample return mission to the Hayabusa however the type of the target asteroid is different from that of Hayabusa. Asteroid Itokawa, explored by Hayabusa is a rock-rich S-type one. Hayabusa2 will go to a C-type asteroid. Both C-type and S-type asteroids consist of rocks, but C-type asteroids are considered to have organic and water materials. Hayabusa2 has two objectives to discover: organic matters and water

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in the solar system and relationship between life and ocean water. C-type asteroids are the most common variety and many of them are in the outer part of the asteroid belt beyond 2.7 AU. An asteroid, called 1999 JU3, is chosen as the target of Hayabusa2 mission because it is considerably easy to reach. It has a similar orbit as that of Itokawa and it is in the orbit that occasionally comes close to the earth orbit.

Hayabusa2 is planned to be equipped with some new components. Small Carry-on Impactor (SCI) is one of the new challenges. The observations by Hayabusa discovered that Itokawa was rubble-pile body with the macro-porosity [5]. No direct observational data as for their internal structures and sub-surface materials were available, however. One of the most important scientific objectives of Hayabusa2 is to investigate chemical and physical properties of the internal materials and structures in order to understand the history of formation of small bodies such as small, un-differentiated asteroids. In order to achieve this objective, the SCI is required to remove the surface regolith and create an artificial crater on the surface of the asteroid.

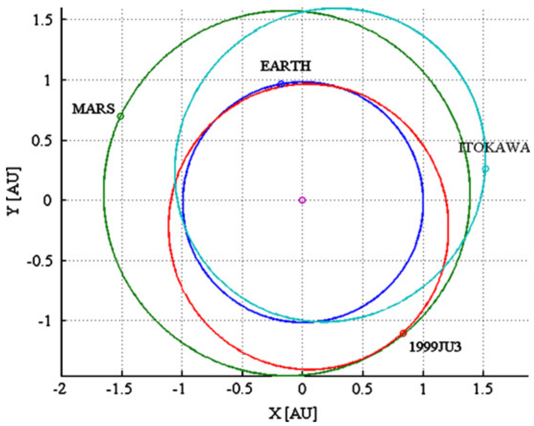

Fig. 1. Orbit of 1999 JU3. It is relatively easy to reach because it comes close to the earth orbit occasionally.

High kinetic energy (i.e. about 2 km/s impact speed and 2 kg impact mass) will be required to make a meaningful crater on the asteroid. But the traditional acceleration devices such as rocket motors and thrusters are difficult to hit the asteroid without a guidance system because the acceleration distance is large. To overcome this difficulty, the powerful explosive is adopted to accelerate the impact head. By this means, the required period for the acceleration becomes shorter than 1 millisecond and it becomes possible to crash into the asteroid. On the other hand, it has one serious problem. The broken pieces of the impact system are scattered when the explosive detonate, and these fragments may damage the spacecraft. Consequently, the spacecraft will move behind the asteroid to get out of the "line of fire".

This paper describes the overview of the small carry-on impactor system and the results of the development tests. And this paper also shows the outline of the impact operation of Hayabusa2 mission.

2. Mission scenario of Hayabusa2

2.1. 1999 JU3

The target body of Hayabusa2 is a small C-type asteroid, 1999 JU3. It is classified as a near earth asteroid (NEA). Its semi major axis is about 1.19 AU and eccentricity is about

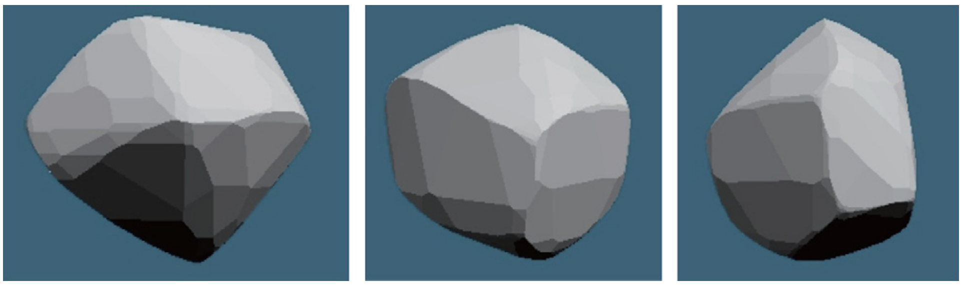

Fig. 2. Expected shape of 1999 JU3. Different from Itokawa, the shape is almost-spherical. Its diameter is expected to be 1 km.

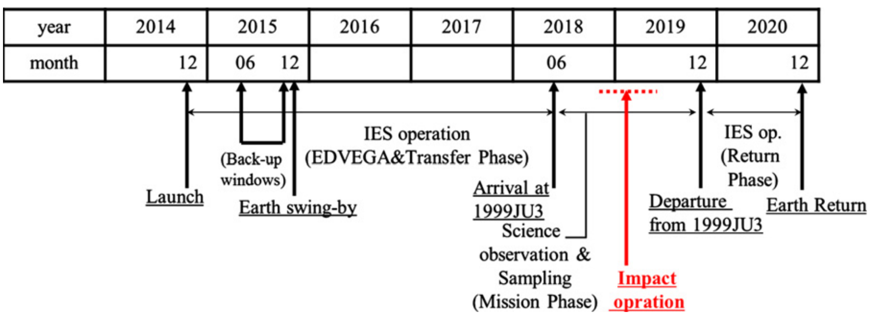

Fig. 3. Mission scenario of Hayabusa2. Hayabusa2 will reach the target in the middle of 2018 and come back to the earth at the end of 2020.

0.19. It is relatively easy to reach because it is in the orbit that occasionally comes close to the earth orbit (Fig. 1). Past observations show that the diameter is approximately 1 km and it looks like a sphere [6,7]. Fig. 2 illustrates the expected shape of 1999 JU3. The rotation period is approximately 7.6 h. The density is expected to be 500–4000 kg/m^2 and the gravity constant is estimated to be 11–92 m^3/s^2.

2.2. Mission scenario

The best timing to launch to 1999 JU3 is 2014 and the backup launch opportunity is June and December, 2015 and Hayabusa2 will reach the target in the middle of 2018 (Fig. 3). Like Hayabusa, Hayabusa2 will use the Electric Delta-V Earth Gravity Assist (EDVEGA) technique and it will use its ion engines to rendezvous the target after Earth swing-by (Fig. 4). After the arrival, Hayabusa2 will stay there about one and half years as the period of mission phase and will depart from the asteroid at the end of 2019. It will come back to the earth at the end of 2020. The operations at the asteroid will be similar to those of the previous Hayabusa, but a new challenge will be added. The impactor will be used to dig the asteroid surface. And the spacecraft will observe the resultant crater by the cameras and it will try to touchdown to collect the fresh material of the asteroid after the impact (Fig. 5).

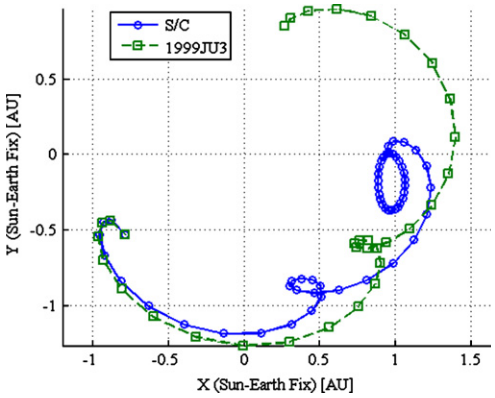

Fig. 4. Transfer trajectory to 1999 JU3. The relative velocity at the arrival is controlled to be zero by the ion engine. It takes two and half years to get to the asteroid.

3. Small carry-on impactor system

3.1. Outline

Among many means to observe the sub-surface materials of asteroid, the simplest way is to drill and mine inner materials from the asteroid. However, the mining under small gravity is very difficult and the long stay on the asteroid's surface is danger because of the high temperature (max. 400 K). Using the blast from explosive is a possible way to blow regolith away, but, the pollution of soil with chemical compounds will become a problem for sampling. After considerable discussion, a high speed carry-on type impactor is adopted to remove the surface regolith and create an artificial crater in the Hayabusa2 mission.

The biggest challenge of this kinetic impact system is how to accelerate the impact head. The NASA's Deep Impact was the direct impact mission from the interplanetary orbit and its impact timing was during the approach to the asteroid. Consequently, there is no need to accelerate the impactor. However, as SCI is a carry-on type impact system and its impact timing is after rendezvous, it should accelerate the impact head by itself. The required velocity is more than 2 km/s. Although traditional acceleration devices like rocket motors can achieve the required speed, the acceleration force is small and it takes long time to achieve the final velocity. Consequently,

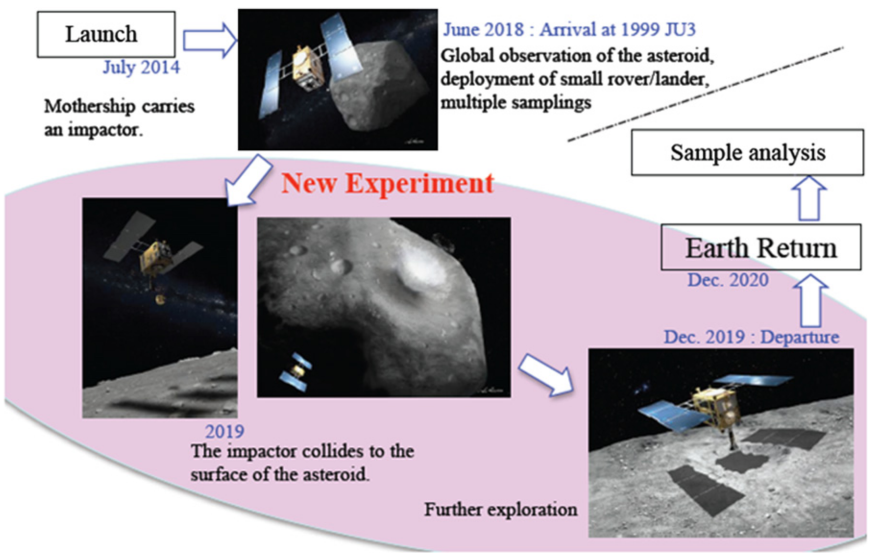

Fig. 5. Mission outline of Hayabusa2. The impact operation will be conducted at later stage of the mission phase.

the acceleration distance will become too large and to hit the asteroid without the guidance and control. Because the assigned weight and size for the impact system is strictly restricted, the system should be small and simple. After reviewing many acceleration methods, the technology of a special type of shaped charge is applied to our impact system. This technology was originally created to penetrate a hard target [9,10]. Powerful explosive is filled in the metal case, and it has a liner in the shape of a shallow dish (Fig. 6). The force of the blast deforms the liner to a bullet shape (i.e. cold forging). The velocity of the formed projectile is about 2000 m/s. Also, the deformation and the acceleration period is less than 1 ms: therefore, the acceleration distance can be small. Additionally, the attitude disturbances during explosion do not affect the flight direction of the projectile due to the short deformation period. Consequently, the impact head flies out in the direction at the moment of ignition.

With this technology, the impact system will become small and simple, and able to crash into the asteroid without guidance and control system. The only thing to do is to separate SCI in the direction to the asteroid. In practice, the spin for the attitude stabilization is given by the separation mechanism. This spin is for the attitude stabilization between separation and ignition not for the stabilization during the explosion.

Our impact system has one obstacle to be solved. Because the explosive is very powerful, the container of the explosive and the other components of SCI will be destroyed and many fragments are to be scattered when the explosive detonate (Fig. 7). As the velocity of the broken pieces is very high like the formed impact head, they may hit the spacecraft and leave a significant damage. To avoid this, the spacecraft must quickly move away from SCI after the separation.

3.2. Configuration

SCI is a spin type small spacecraft mounted onto the bottom panel of the mother spacecraft (Fig. 8). The body shape is cylindrical, consisting the electric part and explosive part (Fig. 9). The explosive unit is conical and it is attached to the bottom of SCI. Because the explosive is very powerful and it has possibility to damage people and other devices, the explosive part can be easily detached for the safety during the pre-flight test phase. The explosive is ignited by the safe and arm device (SAD) which includes a detonator. SAD separates the detonator from the main explosive in a safe status. Arming will be conducted after the separation from the main spacecraft. The length of SCI is about 300 mm, including separation device, and the diameter is about 300 mm. Total weight, except for separation mechanism, is about 15 kg. The sequencer controls the arming and the ignition. The sequence will be installed to SCI from the mother spacecraft through the wired interface

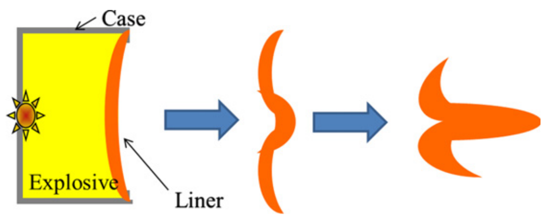

Fig. 6. Special type of shaped charge. The metal liner is deformed and accelerated by explosive blast.

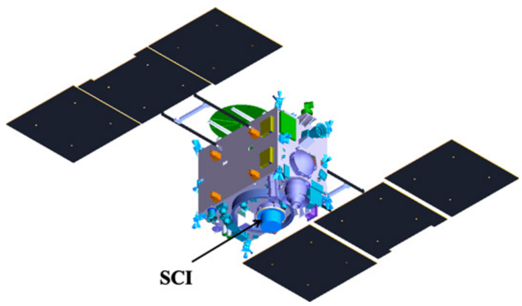

Fig. 8. SCI is mounted onto the bottom panel of the mother spacecraft. In the impact operation, it is separated from the mother spacecraft.

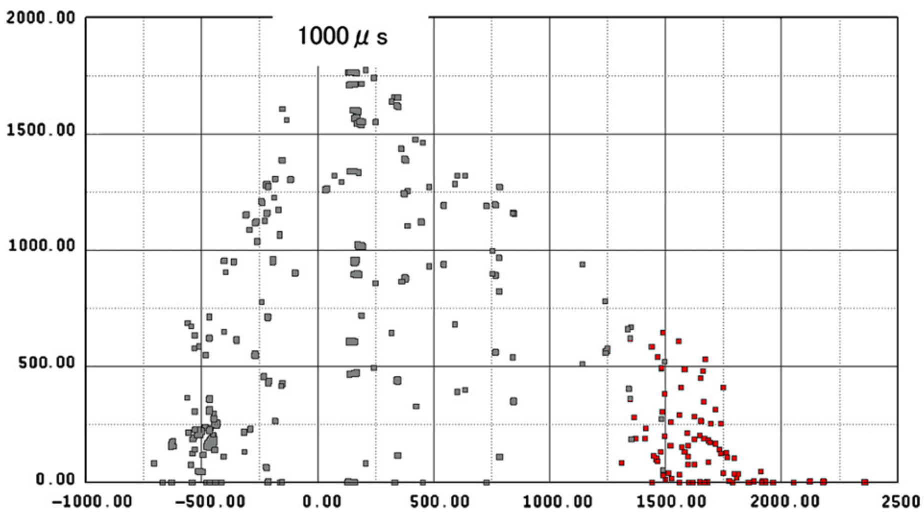

Fig. 7. Broken pieces of the metal case. As the velocity of the pieces is very large, they may damage the mother spacecraft.

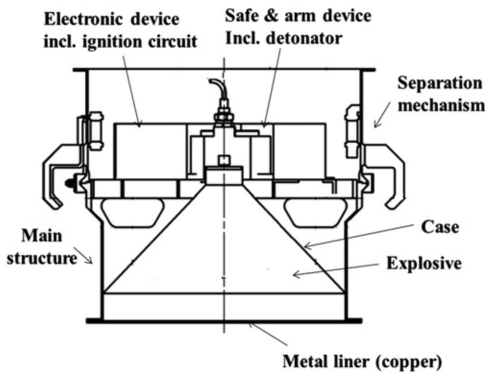

Fig. 9. Configuration of SCI. The shape of the explosive part is circular cone. The explosive part occupies the largest part of SCI.

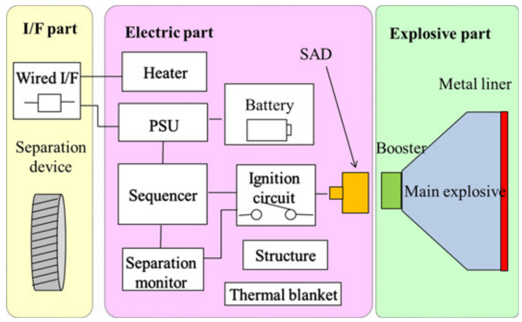

Fig. 10. Block diagram of SCI. Sequencer controls the arming and ignition. The wired interface is cut before the separation.

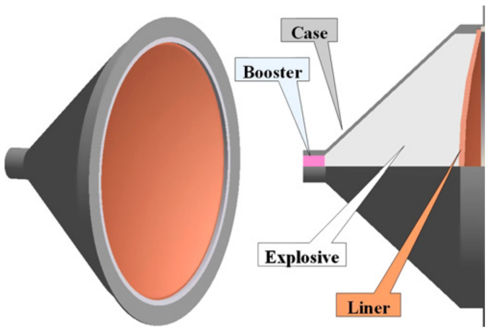

Fig. 11. Shape of explosive part. It has a liner face in the shape of a shallow dish. The weight of the explosive is about 4.5 kg.

before the impact operation. The interface cables will be cut by the wire cutter before the separation. Primary cells are used for the inner power supply. Fig. 10 shows the block diagram of SCI Fig. 11.

3.3. Explosive part

The body of the explosive part is conical shape stuffed with full of explosive (Fig. 11). The liner is made from ductile metal such as tantalum, copper and iron. In the Hayabusa2 mission, the liner is made of pure copper in order to avoid the soil and mineral from contamination because pure copper can be found only in the earth and it can be easily distinguished from the materials of the asteroid. The diameter of the explosive part is less than 300 mm. The total weight of the explosive part is about 9 kg and the explosive weighs about 4.5 kg. The liner in the shape of a shallow dish weighs about 2.5 kg. The shock wave generated by the explosive reaches the center of the liner first. Then the central part of liner is distorted forward and the liner is formed into bullet shape. The final velocity of the projectile is more than 2 km/s, and the weight of the formed projectile is about 2 kg. The shape of the formed bullet can be designed by changing the shape and thickness of the liner and metal case. In Hayabusa2 mission, the shape of the bullet is designed to be a shell-like shape to make the diameter of crater large (Fig. 12). Conversely the crater becomes deeper than shell type when the solid type bullet is used.

As very high energy is required for the acceleration, the powerful explosive, cyclotetramethylene tetranitramine known as HMX has been chosen. HMX is the one of the most powerful explosive and its explosive velocity reaches 9000 m/s [11]. Additionally, it is relatively insensitive. It is very important for the safety. As the pure HMX is in a powder state and difficult to handle, the explosive powder is bound together in a matrix using small quantities of a synthetic polymer. It is known as Polymer-bonded explosive (PBX).

4. Development test of explosive part

4.1. Crater making experiment

In the earliest stages of the development of SCI, the velocity of the impact head and crater making ability of the explosive part were confirmed by the experiment with a very small model (Fig. 13). The diameter of the small model is about 50 mm and the weight of the explosive is about 150 g. The result of the speed measurement indicated that the velocity of the impact head exceeds 2000 m/s and the diameter of the impact head after forming is about 20 mm. General river sand was used as the target for the experiment. The sand lifted into the air after impact (Fig. 14). The diameter of the resultant crater was about 600 mm and the depth was about 110 mm. Although the size and the weight of the projectile was small (20 mm in diameter, 30 g), quite large crater was created in this experiment. By considering the result of this experiment, the result of the past micro-gravity experiments and the result of the crater making simulation, the diameter of the crater in Hayabusa2 mission is expected to be more than 2 m.

4.2. Long distant flight experiment

If the explosive part is designed/ developed improperly, the speed and shape of the bullet becomes irregular and the accuracy of its flight direction becomes worse, and there is a possibility that the bullet goes into pieces. In order to verify the design, production reliability and performance of the explosive part, many flight tests were conducted.

At the beginning, the explosive part was designed with the numerical calculations. Next, the sub-scaled flight tests were conducted to check the validity of the computational

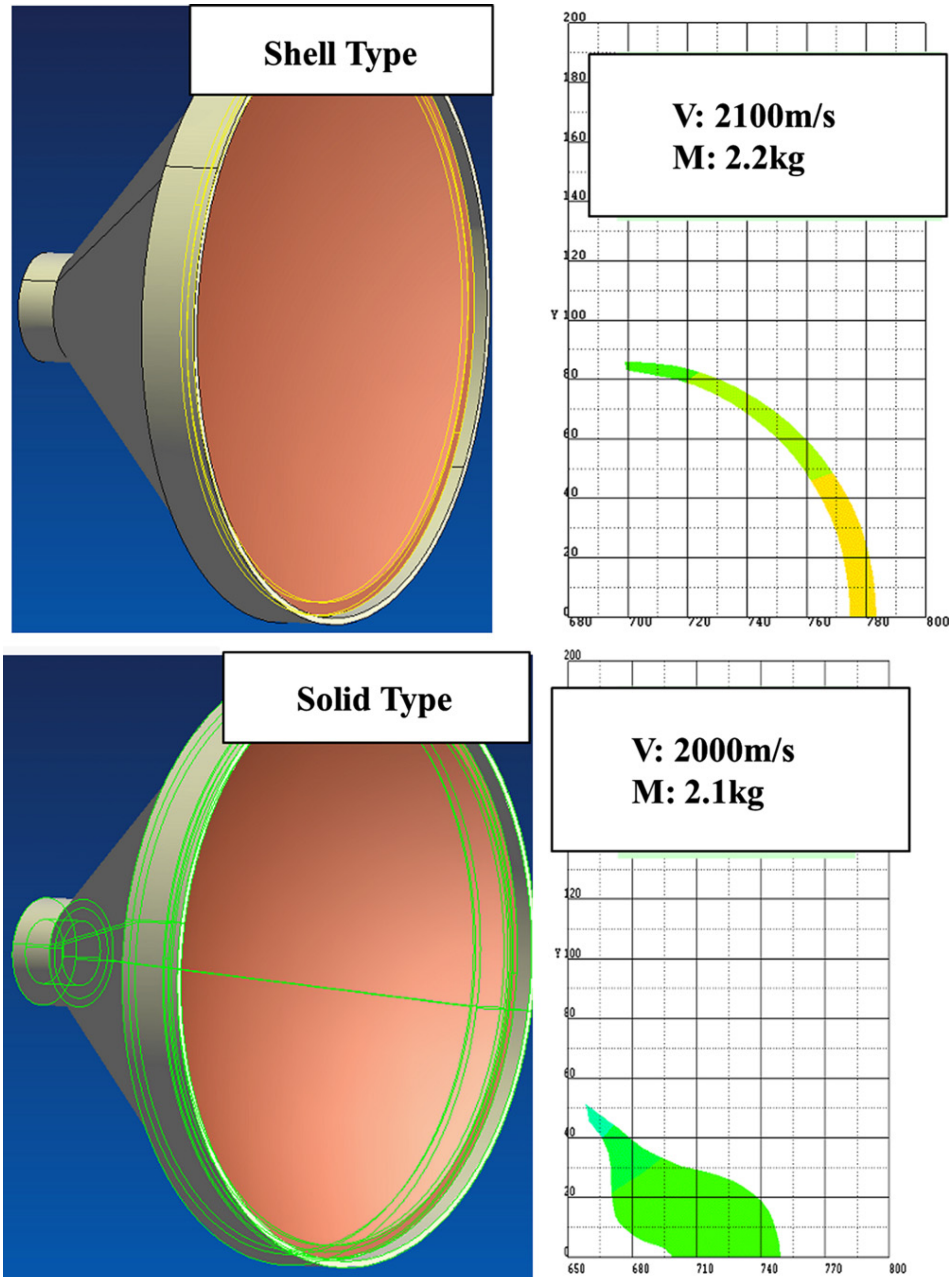

Fig. 12. (Upper) Shell type projectile and (lower) solid type projectile. The shape of the impact head can be designed by changing the shape and thickness of the liner.

design. A sub-scale test is easy to perform because the amount of the explosive of a sub-scale model is much smaller than a full-scale model. Therefore, the repeatability of the bullet formation is confirmed by the sub-scale flight tests. As it is thought that the manufacturing sensitivity of the small scale model is worse than the full scale model, a sub-scale test is a very important step of the development of the explosive part. And then, a long distant flight experiment was conducted to confirm the performance of the explosive part.

The flight distance of the long distant flight test was about 100 m (Fig. 15). The shape and speed of the formed liner were observed by high-speed cameras and chip-boards and a target screen detected the flight direction. Half and full scale models were tested in this experiment. The photographs captured by the high speed camera are shown in Fig. 16. The liner was formed as designed and the velocity of the liner was about 2000 m/s. An error of the flight direction was less than 1°. The results of the long distant flight experiment are summarized in Table 1.

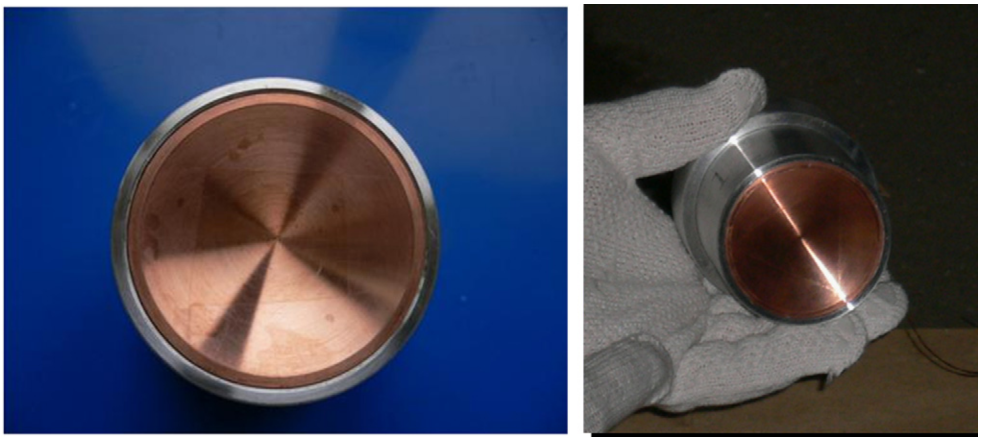

Fig. 13. Small model of the explosive part. Weight of the explosive is about 150 g.

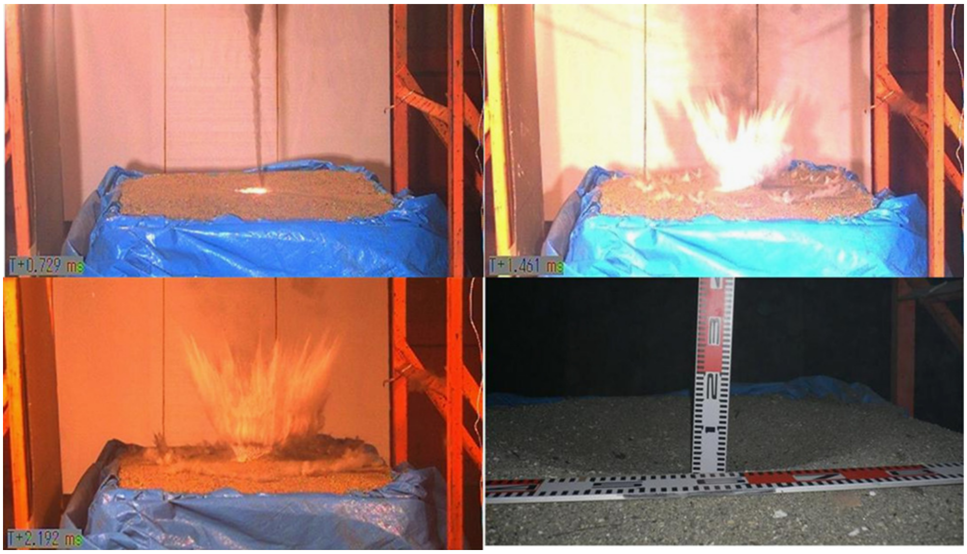

Fig. 14. Results of crater making experiment under 1 G gravity. Diameter of the resulting crater was about 600 mm.

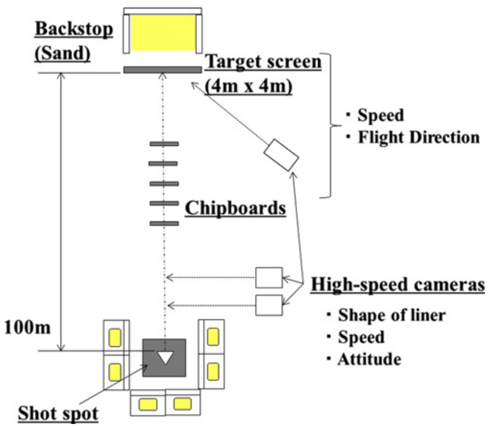

Fig. 15. Configuration of long distant flight experiment. The images of the impact head were captured by the high-speed cameras and the flight accuracy was evaluated by the target screen.

5. Impact operation

5.1. Operation outline

As described, SCI has no attitude and position control functions. Therefore the mother spacecraft should aim the asteroid and separate it at an appropriate position. After the separation, SAD switches from a safe to arm state, and it detonates during a free-fall motion. The timing of the detonation is controlled by the sequencer on SCI. The mother ship should escape from the separation position because debris is scattered when the explosive detonate and eject from the asteroid comes from the impact point. Fig. 17 illustrates the outline of the impact operation. The mother spacecraft starts escape maneuver just after SCI separation and moves behind the asteroid. During the maneuver, the deployable camera (DCAM) is separated from the mother spacecraft and it transmit the impact

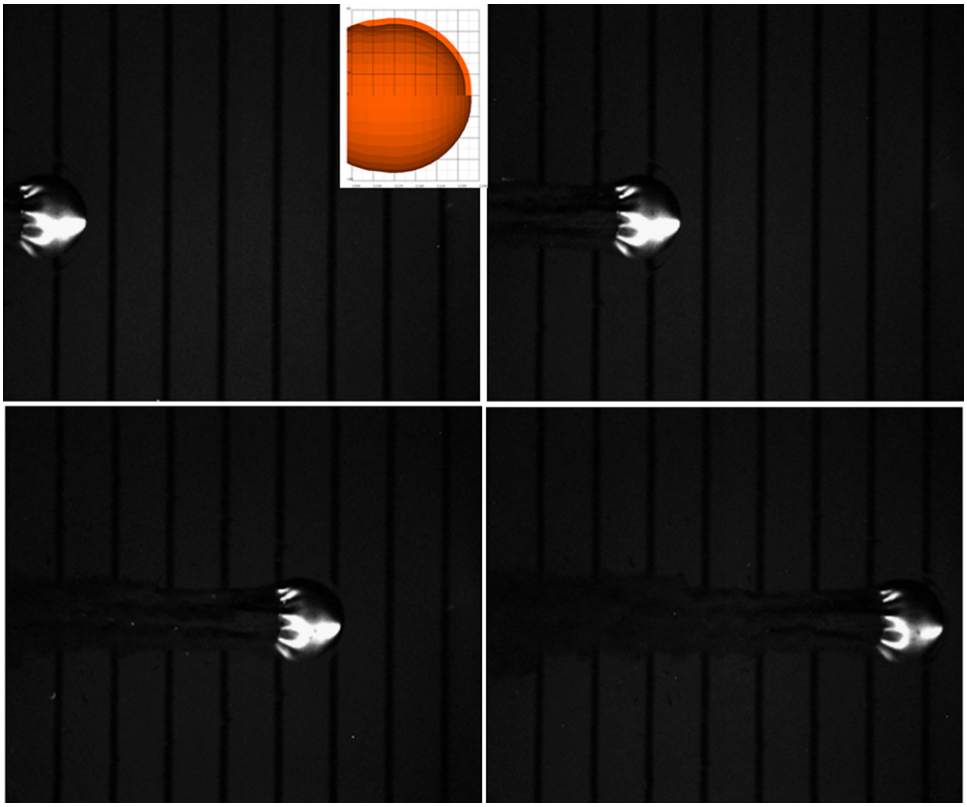

Fig. 16. Shape of the formed impact head. It is almost same as the result of the computational simulation.

Table 1
Summary of long distant flight experiment. The variabilities of the speed and fight direction error are sufficiently small.

No.	Size	Temperature	Velocity of liner (m/s)	Diameter of liner (mm)	Flight direction accuracy (deg.)
1	Half	Normal (21 °C)	2127	57	0.48
2	Half	Hot (50 °C)	2161	68	0.23
3	Half	Hot	2139	72	0.41
4	Half	Hot	2167	65	0.33
5	Half	Cold (0 °C)	2158	66	0.40
6	Half	Cold	2164	65	0.44
7	Half	Cold	2181	68	0.68
8	Full	Normal	2054	131	0.10
9	Full	Normal	2050	126	0.61
10	Full	Normal	2048	127	0.45

image. DCAM was used in a JAXA-made solar sail, IKAROS mission to take pictures of the solar sail [12].

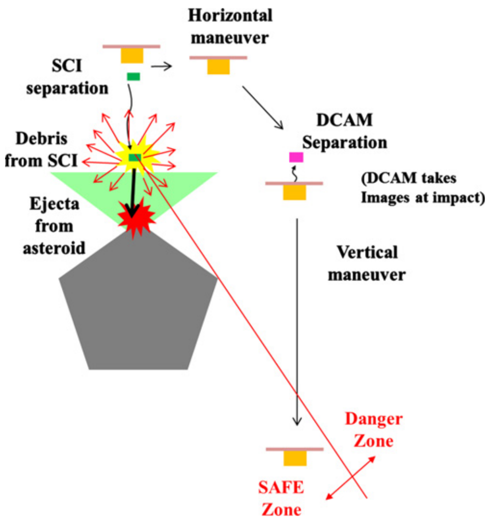

Fig. 17. Outline of the impact operation. Mother spacecraft should escape to avoid the debris and ejecta.

5.2. Time to detonation and impact accuracy

The timing of the detonation is one of the most important parameters of the impact operation. If the time to detonate is short, the required delta-V for the escape maneuver becomes large. On the other hand, if the time to detonate is long, SCI free-falls to reach the asteroid surface. Moreover, the accuracy of impact reduces because the variation in the position of SCI at the detonation becomes large. The expected SCI positions at the detonation calculated in Monte Carlo simulation (Fig. 18). The separation altitude of this simulation is 500 m. The variability of the position spreads with time due to the separation error. SCI reaches the asteroid's surface in many cases after 3600 s from the separation. It is unacceptable for making crater. One way to avoid this is to separate SCI at higher altitude.

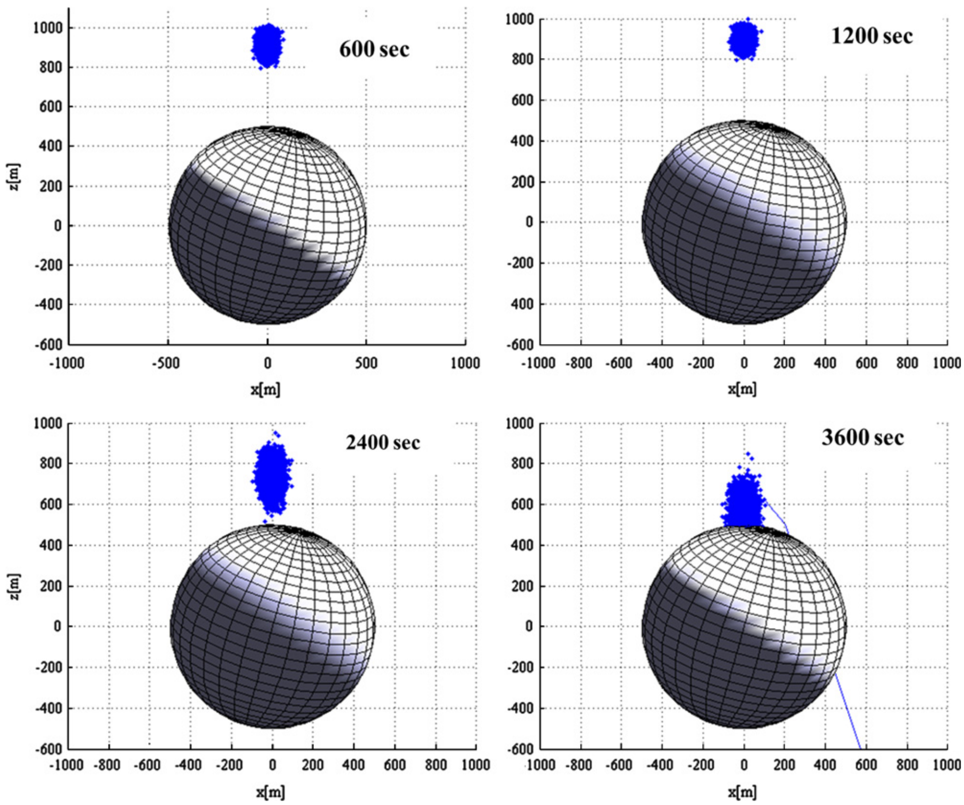

Fig. 18. Variation in SCI position. It spreads with time because it has the velocity error at the separation.

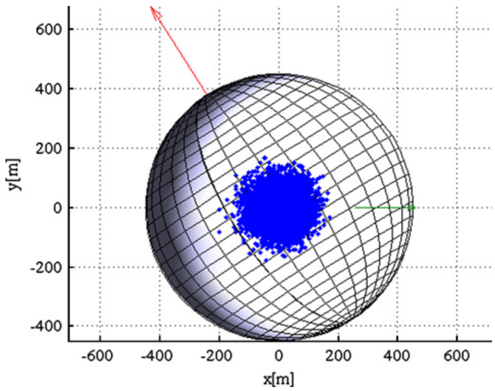

Fig. 19. Result of impact simulation. The error radius is about 200 m. The error of the impact point largely depends on the attitude error of SCI.

But it is not a good solution because the impact accuracy becomes worse. Therefore, we should choose the appropriate timing of detonation. By considering both the impact accuracy and the amount of the delta-V for the escape maneuver, 2400 s of time to detonation is the best timing.

The impact accuracy depends on the accuracy of position and velocity of mother spacecraft at the separation and separation velocity of the separation device. And it also depends on the attitude of SCI. If the tip-off rate is large at separation, the nutation motion of SCI becomes large and the impact accuracy becomes worse. The pointing error should be less than 20°. The separation device of SCI uses a similar technology to that of the Hayabusa's reentry capsule and the velocity error and tip-off rate of the SCI's separation device will be confirmed in separation tests. Fig. 19 shows

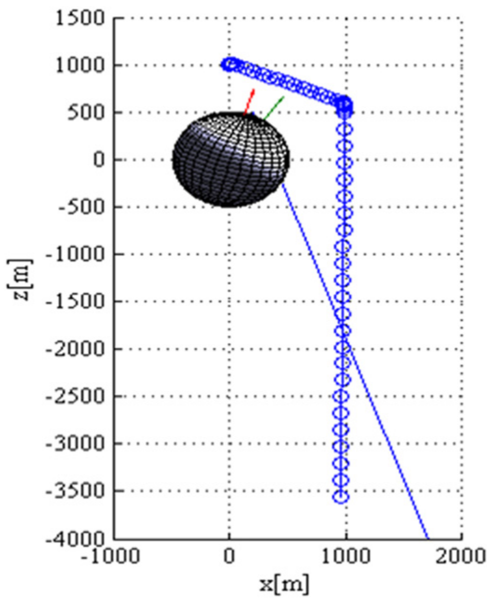

Fig. 20. An example of escape maneuver. Total delta-V is about 10 m/s when the escape period is 40 minutes.

the result of the impact simulation. This result indicates that the error of the impact point is about 200 m in radius.

5.3. Escape maneuver

A key parameter of the escape maneuver trajectory design is the maneuver distance in horizontal direction. If it is small, the delta-V for the escape maneuver can be reduced, but the risk of the collision with 1999 JU3 becomes greater. So, it should be chosen appropriately considering the accuracy of the control force of thrusters. In Hayabusa2 mission, it is expected that the delta-V error is less than 5% by using the accelerometer. Fig. 20 shows an example of escape maneuver. The total delta-V is about 10 m/s. It is quite large but acceptable.

6. Conclusion

One of the most important scientific goals of Hayabusa2 mission is to investigate chemical and physical properties of the internal materials and structures. SCI is an ultra-speed impactor which is required to achieve the assignment to create an artificial crater on the asteroid's surface. But hitting the asteroids by using the traditional acceleration device is considered impracticable. Therefore, a new technology of the special type of shaped charge is applied to our impact system. By using the technique, it becomes possible to crash the impact head into the asteroid even if there is no guidance system. The speed and flight accuracy of the impact head were checked in the long distant flight tests and it was confirmed that the acceleration performance of the new technology satisfied our requirements. On the other hand, the escape maneuver after separation is required for the safety of the mother spacecraft because SCI scatters many fragments when it detonates.

Now we are developing this new impact system supposing a launch in 2014. Because the impact accuracy of SCI depends largely on the performance of the separation device, it will be confirmed in a separation test. And one more long distant flight test will be performed after environmental tests to verify the final performance of the acceleration function.

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