F5

# 九州工業大学での超高速衝突研究の20年の歩み

## 20-Year History of Hypervelocity Impact Researches in Kyushu Institute of Technology

○赤星保浩（九工大）
○Yasuhiro AKAHOSHI(Kyutech)

1997年2月より超高速衝突実験を開始し、来年2月で丸20年経過する。この20年間で、バンパーシールド開発、非球形状飛翔体によるデブリ雲形成、太陽電池パドルの衝突誘起放電、超高速衝突イジェクタ実験の国際標準化（ISO11227の制定）、デブリ回収用銛発射装置の開発などに取り組んできた。本講演ではこれまでの成果を紹介するとともに、今後の研究の方向性について言及する。

I've started hypervelocity impact research at February, 1997. About 20 years have passed since its start. During these period, I and my students have studied on development of bumper shield, formation of debris cloud due to impact of non-spherical projectile, discharge of solar panel due to hypervelocity impact, international standardization of hypervelocity impact test procedure of ejecta tests (ISO112277), development of harpoon system to recovery space debris and so on. In this talk, I would like to introduce the past research results and the future of research direction of space debris.

# 九州工大に設置している軽ガス銃

Small Gun (6/20)
V=2-6km/s

Large Gun (5, 14, 30/60)
V=2-5km/s

# The 7th Space Debris Workshop

## 20-Year History of Hypervelocity Impact Researches in Kyushu Institute of Technology

20th October, 2016

Prof.Dr.Yasuhiro AKAHOSHI
Chairperson of Graduate School of Mechanical Engineering
Division of Space Engineering,
Department of Mechanical Engineering, Faculty of Engineering
Kyushu Institute of Technology





## Acknowledgments

This study has been partially supported by Grant-in-Aid for Scientific Research (A, No.13305065), (B, No.24360351), (C, No.21560819) and Grant-in-Aid for Young Scientists(B, No.18760608). And a part of this study was collaborated with JAXA and IHI.

I would also like to express my gratitude to students and graduated students in Computational Laboratory since 1990. Moreover I would like to appreciate Prof.Takayama (Tohoku Univ.), Prof.Sato (Iwate Medical Univ.), Dr.Yasaka and Prof.Handa (Kyushu Univ.), Dr.Kitazawa (IHI), Prof.Nishida(Nagoya Inst.of Tech.) and others who have supported my researches so far.

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1. Introduction
2. Whipple Bumper
3. Discharge due to Hypervelocity Impact
4. Standardization of Test Procedure (ISO11227)
5. Closure






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Department of Mechanical Engineering, Kyushu Institute of Technology

http://www.kyutech.ac.jp/

The 7th Space Debris WS@JAXA(2016. 10. 18-20)

# 九州工業大学
# 平成30年度改組計画等の概要

（平成28年8月10日）

国立大学法人 九州工業大学

http://www.kyutech.ac.jp/archives/025/201608/kaisoPR160810.pdf

国立大学法人
九州工業大学

# 学科の再編（平成30年度）

| 工学部（旧） |
|---|
| 建設社会工学科 |
| 機械知能工学科 |
| 総合システム工学科 |
| 電気電子工学科 |
| 応用化学科 |
| マテリアル工学科 |

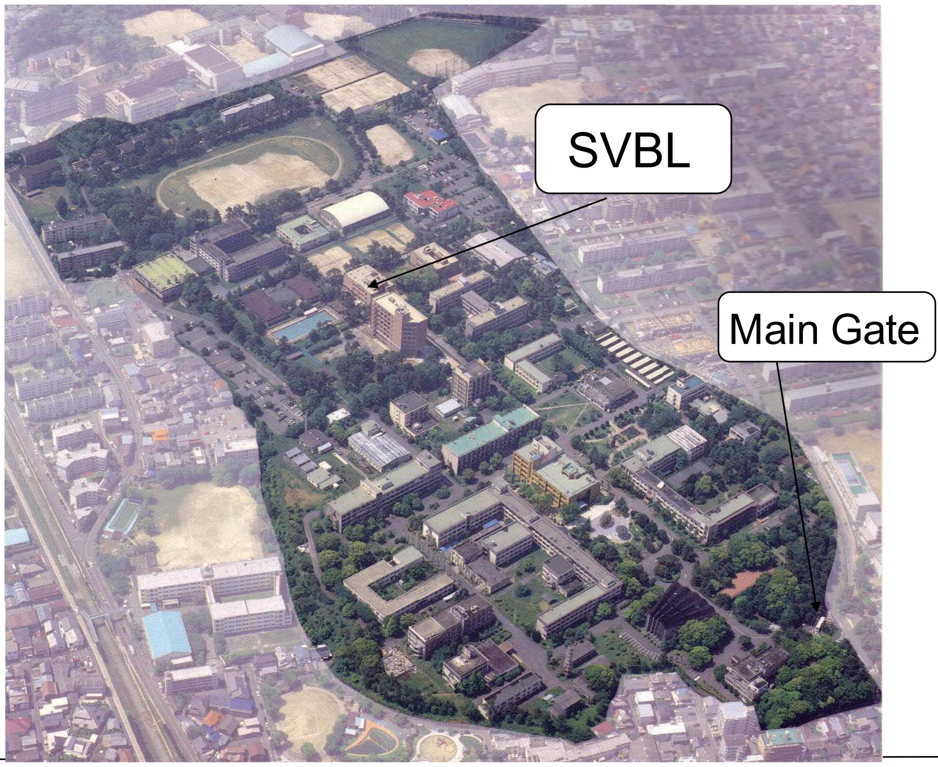
| 工学部（新） | |
|---|---|
| 建設社会工学科 | 建築学コース／国土デザインコース |
| 機械知能工学科 | 機械工学コース／知能制御工学コース |
| 宇宙システム工学科 | 機械宇宙システム工学コース／電気宇宙システム工学コース |
| 電気電子工学科 | 電気エネルギー工学コース／電子システム工学コース |
| 応用化学科 | 応用化学コース |
| マテリアル工学科 | マテリアル工学コース |

A new department of space system engineering will start at April,2018.

本計画は、設置認可申請のための大学による構想であり、変更する場合があります。

http://www.kyutech.ac.jp/archives/025/201608/kaisoPR160810.pdf

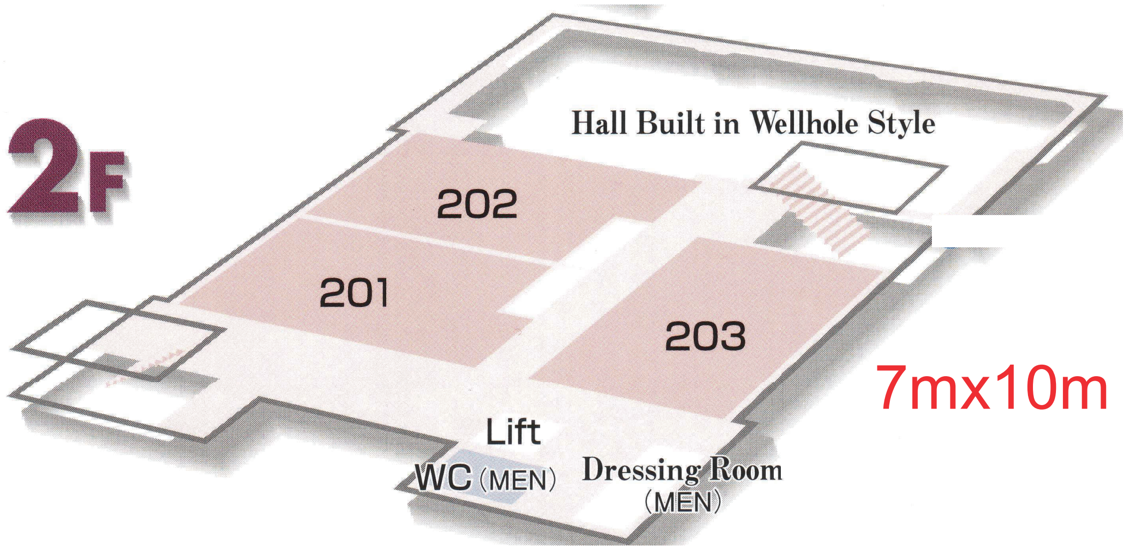




Satellite Venture Business Laboratory
(Funded in FY1995, Constructed in FY1996)

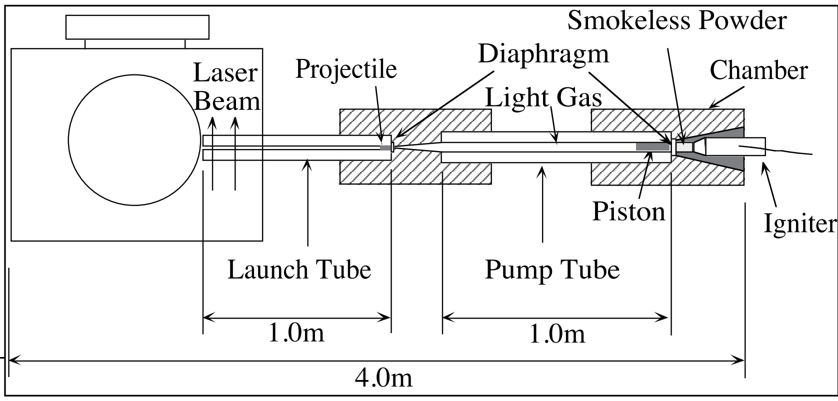







Two-Stage Light Gas Gun was installed at Room 203 on 2nd floor, February 1997, and operated here until March 2003.

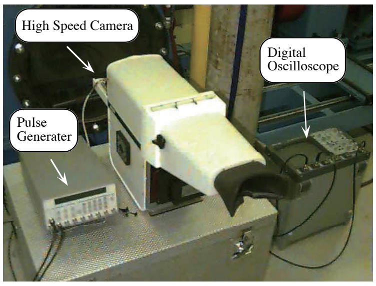
# Two-Stage Light Gas Gun（25mm/5mm） Delivered by J.Osawa Group Co.,Ltd., Manufactured by Sanwagiken



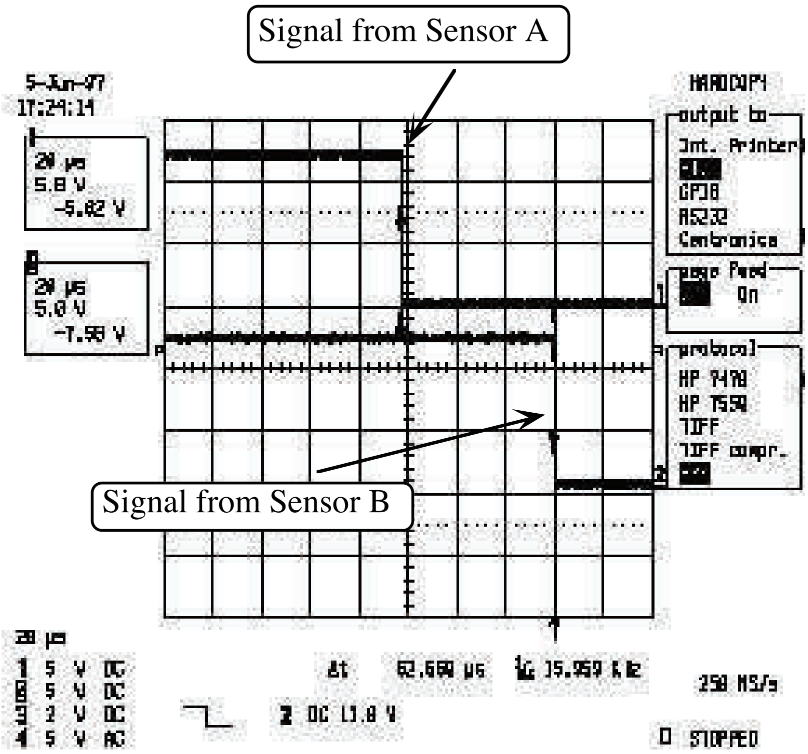


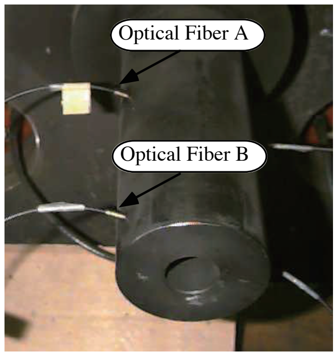


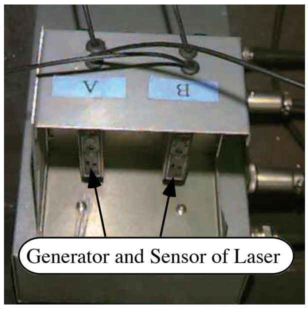

# First Image taken by IMACON792




| | |
|---|---|
| Delay Time for Flash (μsec) | 90 |
| Delay Time for Imacon (μsec) | 110 |
| Framing Rate (frames/sec) | 5 x`$10^5$ |



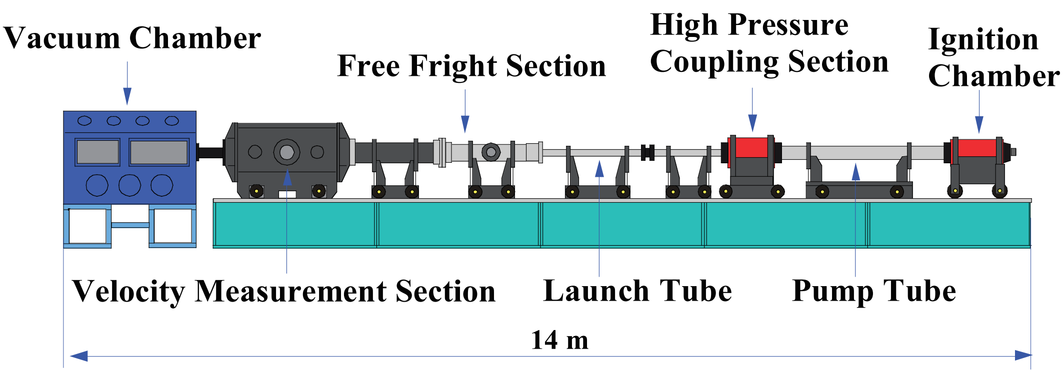

**Velocity : 1.59km/s**





# Large Two-Stage Light Gas Gun

was moved from Tohoku Univ. to Kyutech 2002, and operated at June, 2003.




| Length | Pump Tube | | Launch Tube | |
|---|---|---|---|---|
| | Bore | Length | Bore | Length |
| [m] | [mm] | [m] | [mm] | [m] |
| 14 | 60 | 3.1 | 14 | 2.6 |


Two-stage light gas guns were moved from SVBL to this new impact test facility at March, 2003.

Hypervelocity Impact Test Facility was re-named as Center for Hypervelocity Impact Tests at July, 2011.





# Two-Stage Light Gas Guns at Kyutech

Small Gun (6/20)
V=2-6km/s

Large Gun (5, 14, 30/60)
V=2-5km/s

# Contents







# Whipple Bumper

**Projectile**

diameter: d (cm)

density: $\rho_p$ (g/cc)

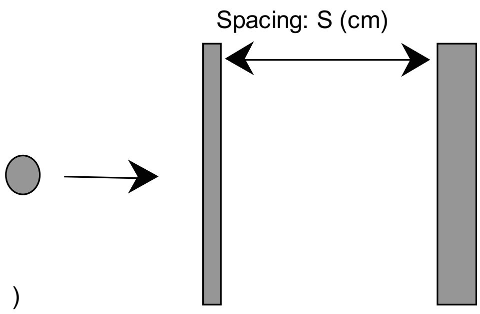
mass: M (g)

velocity: V (km)

angle from normal: $\theta$ ( deg )

norm. vel : $V_n$ (km/s)

$V_n = V \cos \theta$




**Bumper**

Thickness: $t_b$ (cm)

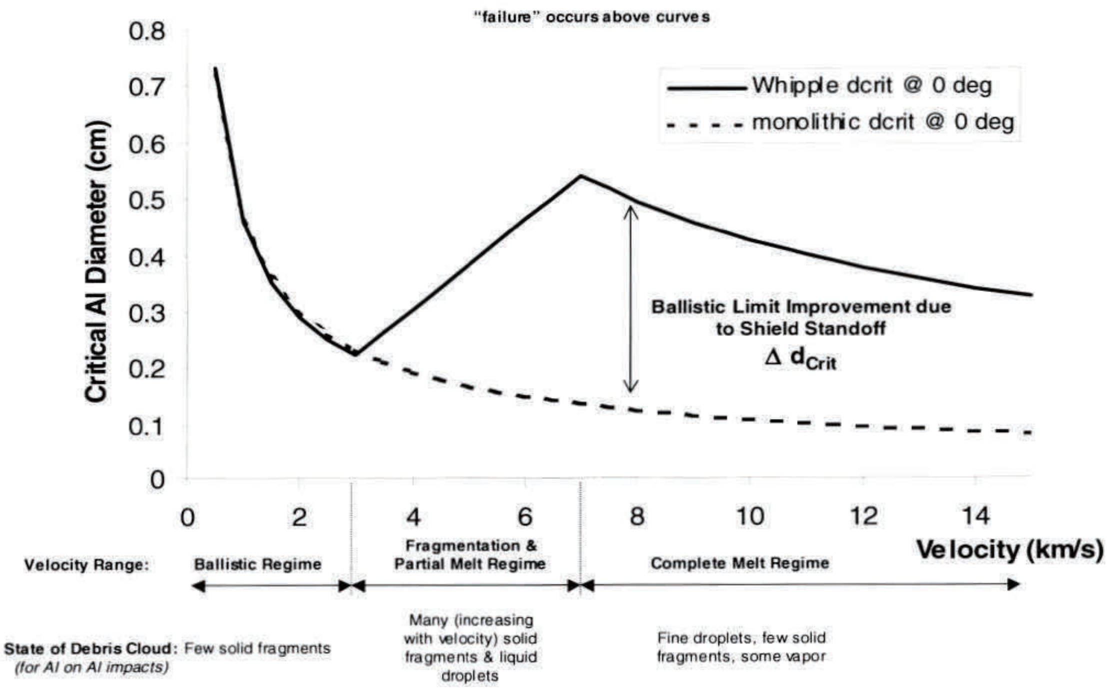
density: $\rho_b$ (g/cc)

**Rear wall**

Thickness: $t_W$ (cm)

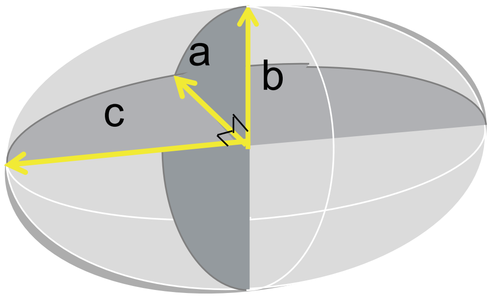
yield strength: $\sigma$ ( ksi )

# Ballistic Limit Curve






# Ellipsoidal Projectiles




a=b

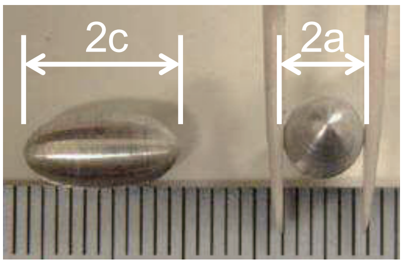
Aspect Ratio : f=c/a

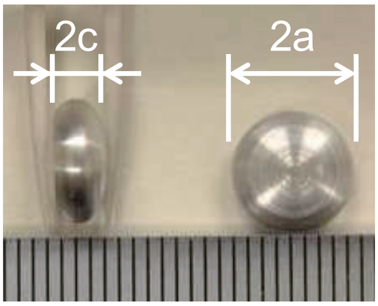




# Ellipsoidal Projectiles

Material: Al2024-T4
Mass: 0.5g




Sphere
f=1.0
a=b=c=7.00mm

Prolate Ellipsoid
f=2.0
a=b=5.56mm
c=11.12mm

Oblate Ellipsoid
f=0.5
a=b=8.84mm
c=4.42mm

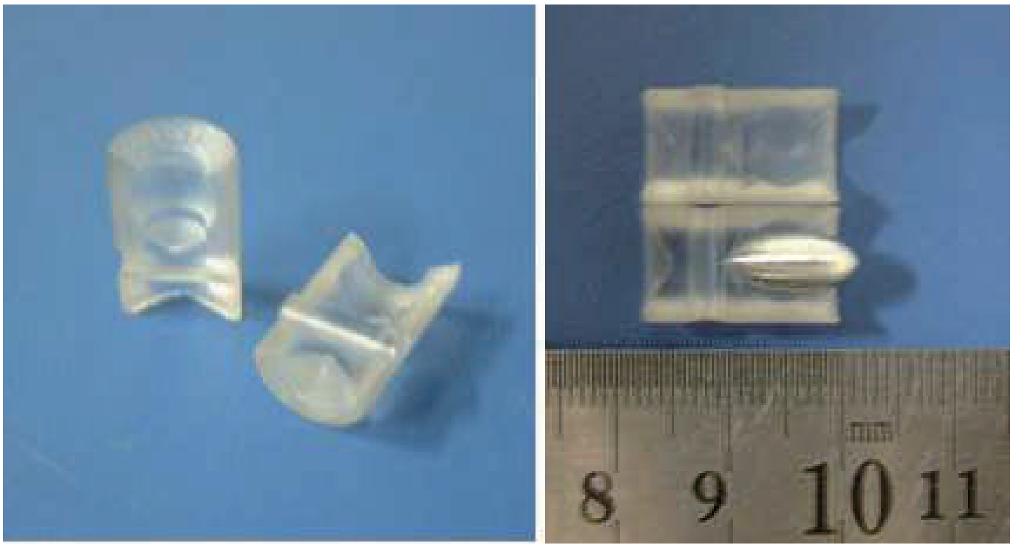



**Fig. Shape of Current Sabot and Ellipsoidal Projectile**
**( a=5.560mm, c=11.778mm)**

Aspect Ratio : 2.12

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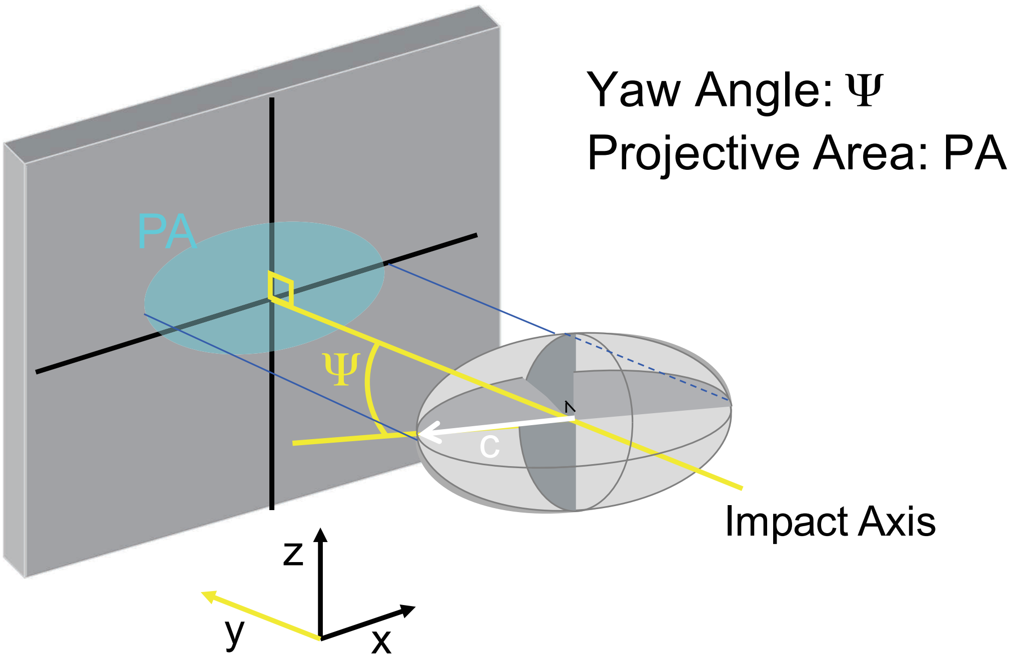
# Ellipsoidal Projectiles



# Experimental Results

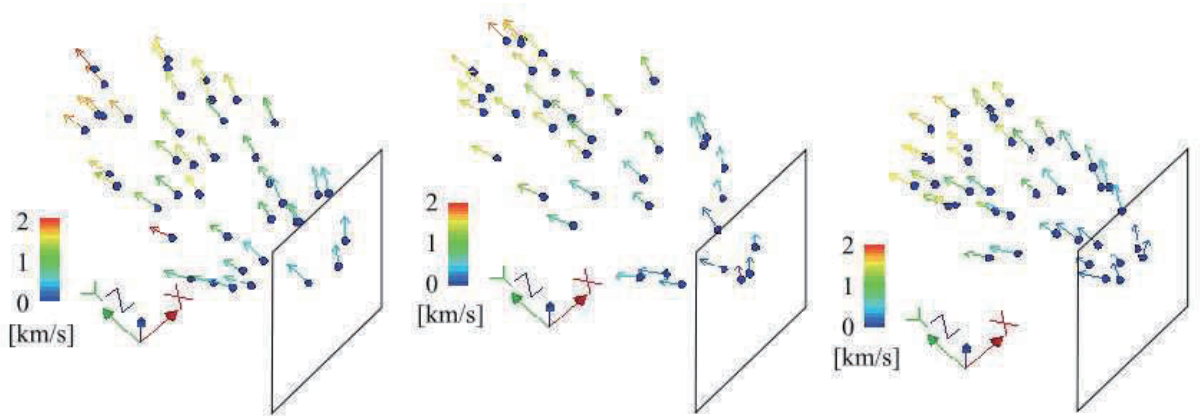
| Experiment No. | | Aspect Ratio: f | Yaw Angle: Ψ[deg] | Projective Area: PA[mm²] | Impact Velocity: $V_p$[km/sec] |
|---|---|---|---|---|---|
| KTS 03 | 237 | 1.0 | - | 154 | 2.16 |
| | 257 | 2.0 | 67.5 | 183 | 2.18 |
| LTS 04 | 094 | | 35.0 | 137 | 2.11 |
| | 096 | | 30.0 | 128 | 2.01 |
| | 097 | 0.5 | 22.5 | 232 | 2.07 |
| | 098 | | 67.5 | 147 | 2.13 |

Target: Al6061-T6 Plate, 2mm in Thickness





# Velocity Distribution

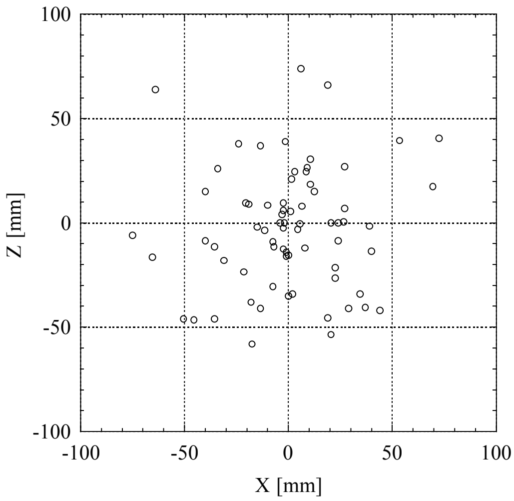



Sphere (PA=154)  f=2.0 (PA=183) ψ=67.5  f=2.0 (PA=128) ψ=30.0

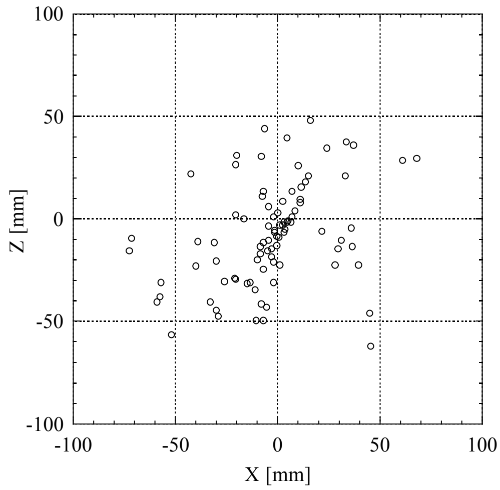
Prof.Sato gave me much information on Flash X-ray photography.

This study was partially supported by JSPS Grants-in-Aid for Scientific Research.

# Distributions of Fragments




Sphere (PA=154)




f=2.0 (PA=183)





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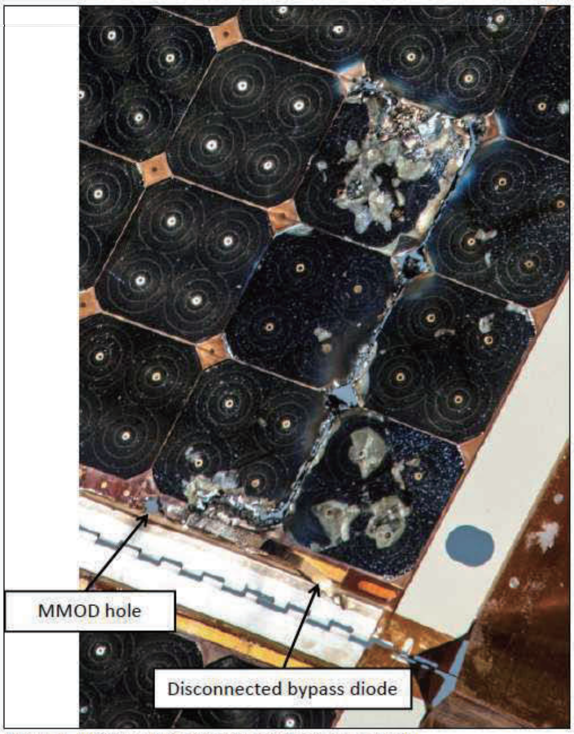

Figure 5. ISS Solar Array 3A damage (front of panel 58).

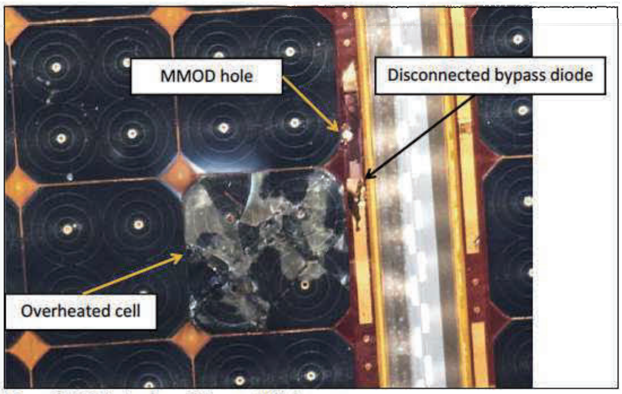

Figure 6. ISS Solar Array 2A, panel 66 damage.

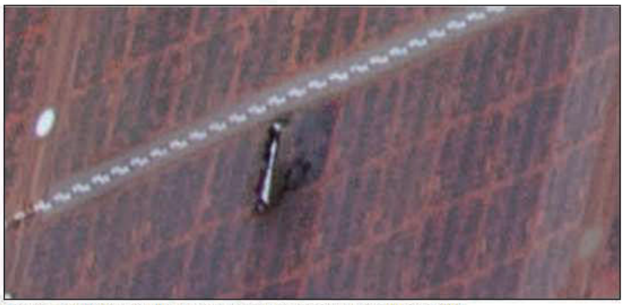
Figure 7. Another burned area in ISS Solar Array 3A (panel 42).

NASA Orbital Quarterly News
Vol.18, Issue4, Oct.2014

Department of

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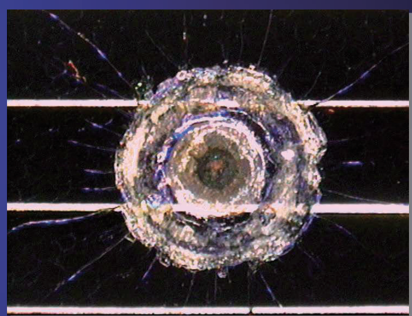
## Debris impact on the solar array

**Debris Impact on the solar array**

**Mechanical damage**

- Surface damage of the cell
- Destruction of the structure


Impact crater on the solar array of EURECA

**Electrical damage**

**Discharge through plasma generated by debris impact**

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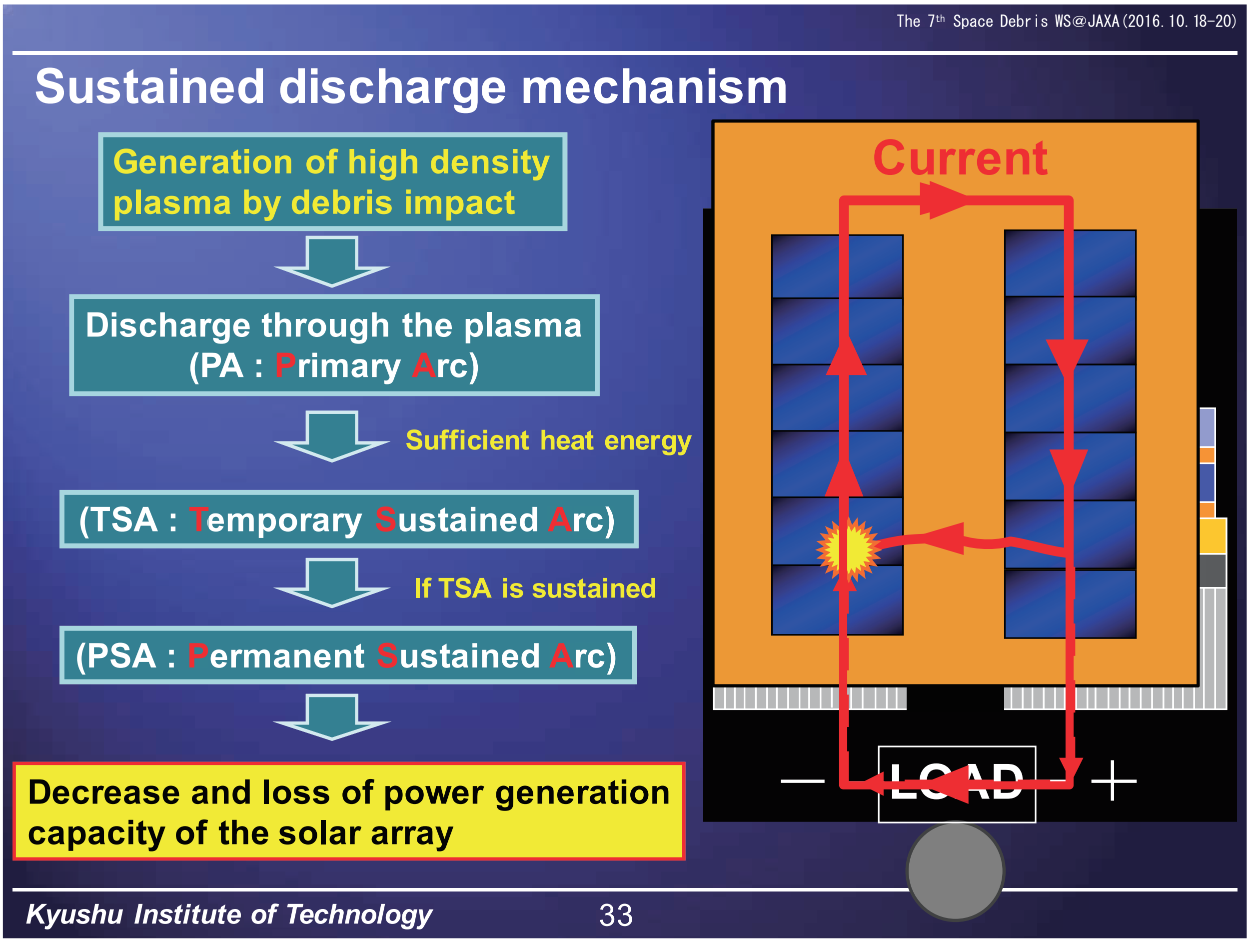


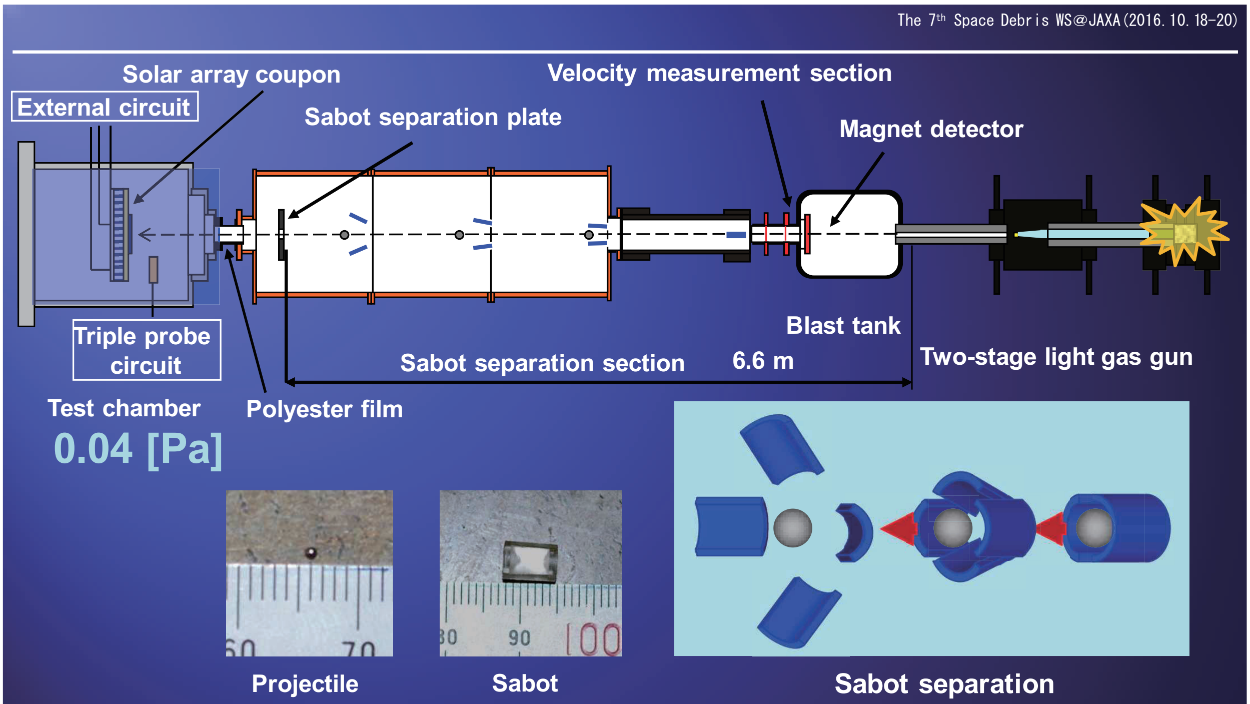


| Material | Shape | Diameter[mm] | Mass[mg] | Velocity[km/s] |
|---|---|---|---|---|
| SUJ-2 | Sphere | 1 | 3.9 | 3.5~4.0 |
| Al2017 | Sphere | 3 | 39 | 2.0~5.0 |

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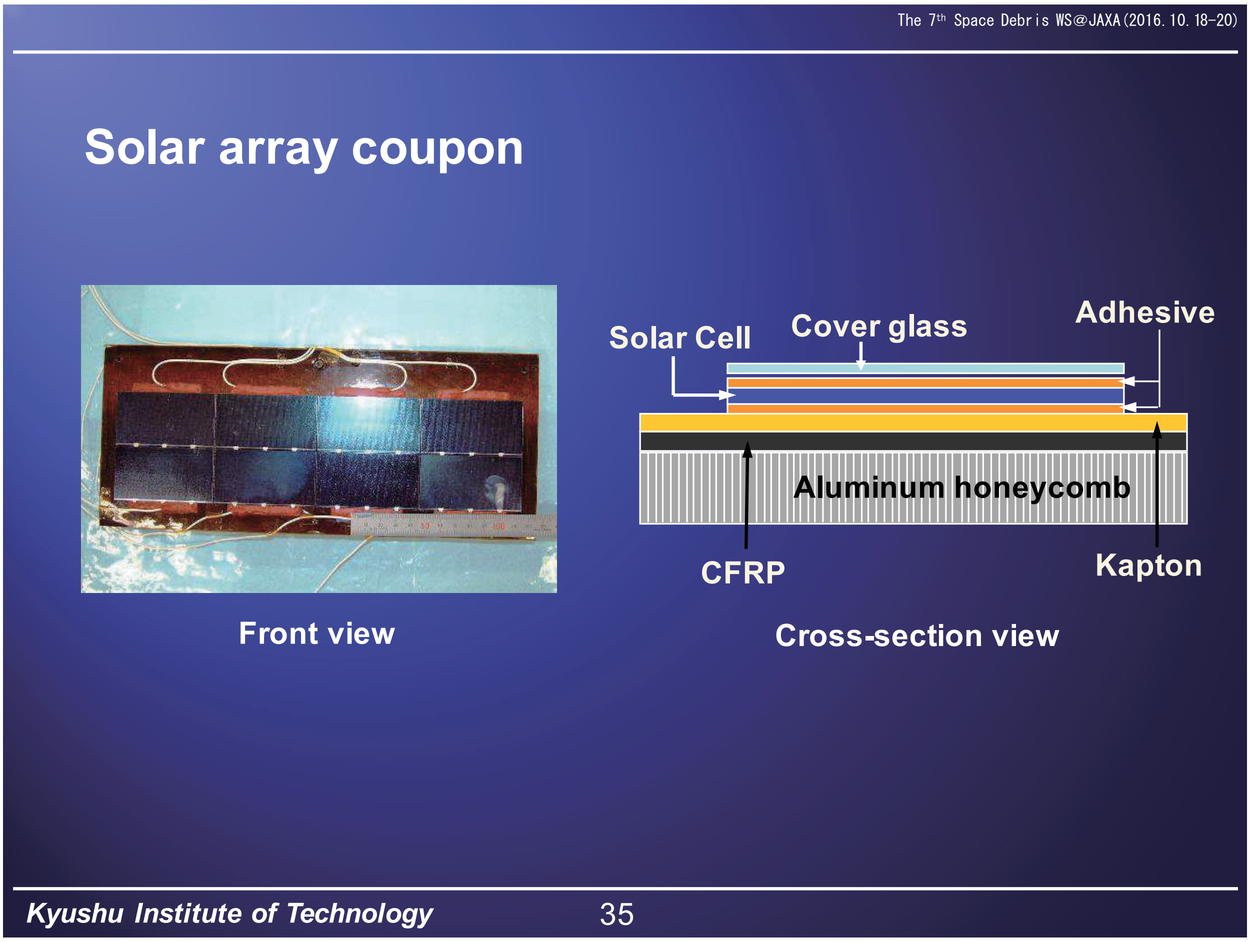
The 7th Space Debris WS@JAXA (2016. 10. 18-20)
Solar array coupon
Solar Cell
Cover glass
Adhesive
Aluminum honeycomb
CFRP
Kapton
Front view
Cross-section view
Kyushu Institute of Technology
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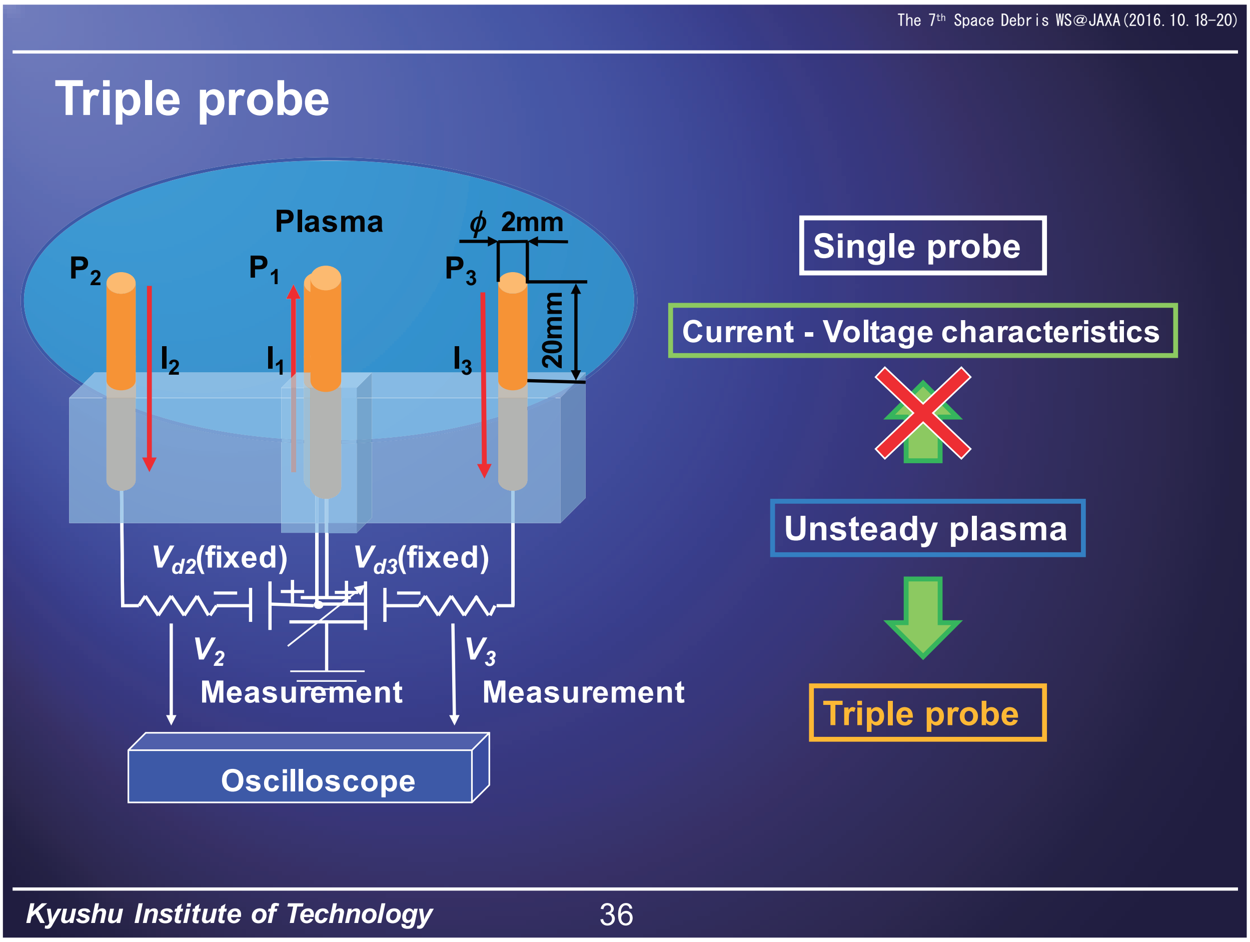
The 7th Space Debris WS@JAXA (2016. 10. 18-20)
Triple probe
Plasma
ϕ 2mm
P2
P1
P3
I2
I1
I3
20mm
Vd2(fixed)
Vd3(fixed)
V2
V3
Measurement
Measurement
Oscilloscope
Single probe
Current - Voltage characteristics
Unsteady plasma
Triple probe
Kyushu Institute of Technology
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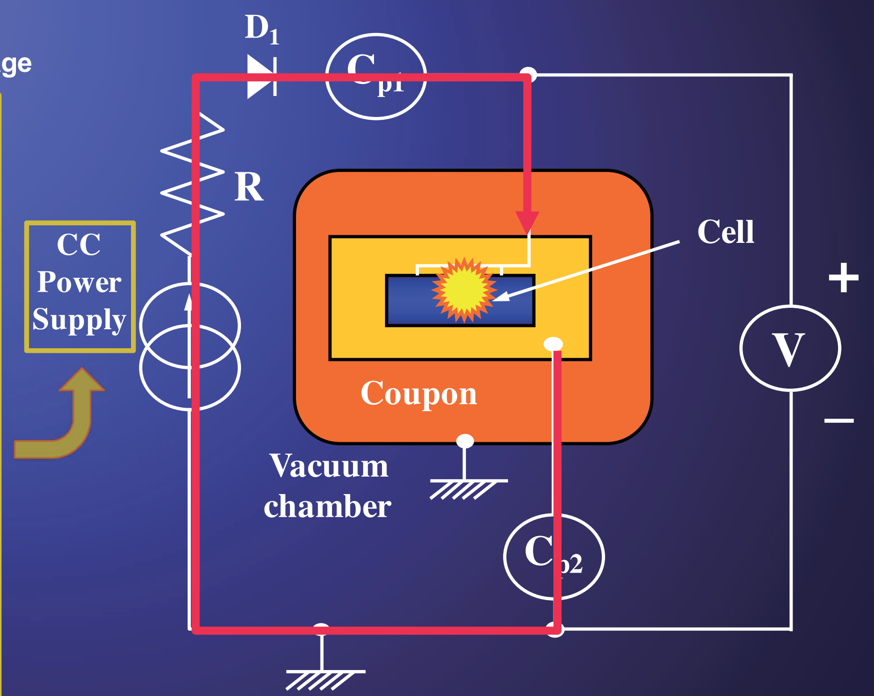
# External circuit

Applied current and voltage

| Voltage [V] | Current [A] |
|---|---|
| 142 | 3.6 |
| | 4.8 |
| 192 | 2.4 |
| | 3.0 |
| | 3.6 |
| | 4.8 |

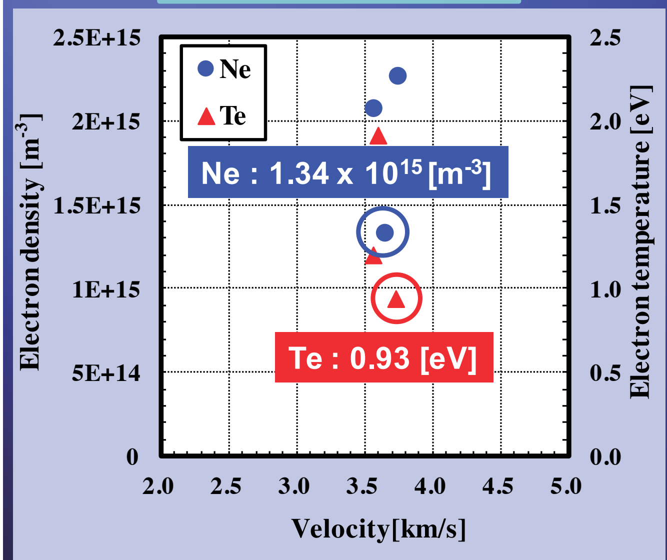







# Measurement results of plasma

Electron temperature : Te
Electron density : Ne




Relation of electron density and electron temperature to impact velocity

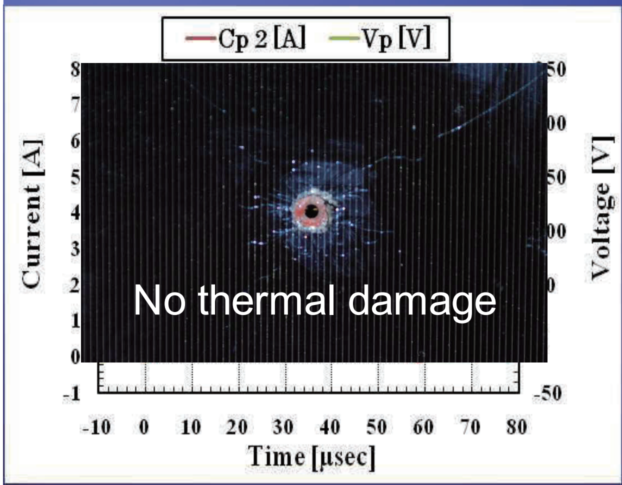
Plasma environment on the Low Earth Orbit

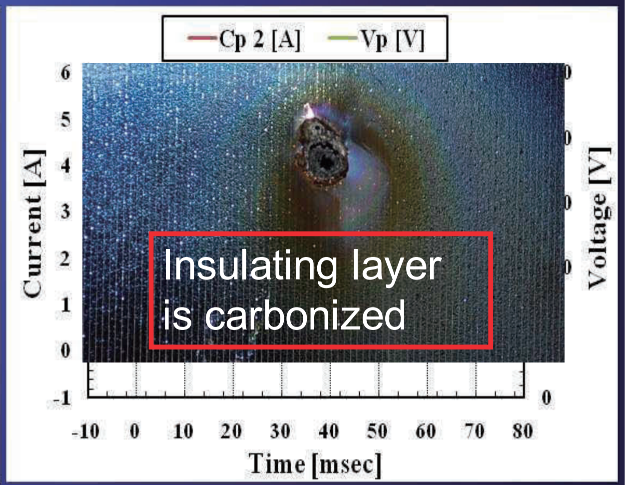
Te : 0.09 [eV]
Ne : 1 x $10^{11}$ [$m^{-3}$]

Measurement results (Minimum value)
Te : 0.93 [eV]
Ne : 1.34 x $10^{15}$ [$m^{-3}$]

High temperature and density plasma are generated

## Results of TSA/PSA generation




Time histories of currents and voltage range after impact

TSA

PSA



The 7th Space Debris WS@JAXA (2016. 10. 18-20)

Research on discharge due to hypervelocity impact was shutdown because of funding problem 2009.

On the other hand, EMI (Ernst Mach Institute) started research on discharge due to hypervelocity impact around 2010.

18-20)

# SUSCEPTIBILITY OF SOLAR ARRAYS TO MICROMETEOROID AND SPACE DEBRIS IMPACT

**Martin Schimmerohn** [(1)], **Martin Rott** [(2)], **Andreas Gerhard** [(3)], **Frank Schäfer** [(1)], **Gianfelice D'Accolti** [(4)]

[(1)] *Fraunhofer EMI, Eckerstr. 4, 79104 Freiburg, Germany, Email: martin.schimmerohn@emi.fraunhofer.de*
[(2)] *Technische Universität München, Boltzmannstr. 15, 85748 Garching, Germany, Email: m.rott@lrt.mw.tum.de*
[(3)] *Airbus D&S GmbH, Robert-Koch-Str. 1, 82024 Taufkirchen, Germany, Email: andreas.gerhard@astrium.eads.net*
[(4)] *ESA/ESTEC, Keplerlaan 1, NL-2200 AG Noordwijk, The Netherlands, Email: gianfelice.daccolti@esa.int*

## ABSTRACT

The susceptibility of solar arrays to micrometeoroid and space debris impact was studied in a comprehensive study to clarify 1) whether, 2) in which manner and 3) under which conditions GEO telecom satellite solar arrays are affected by hypervelocity impact events. Impact induced discharges have been generated in highly instrumented impact experiments using a two-staged light gas guns and a plasma dynamic accelerator. The discharges were found to be temporary and without consequences for the functioning of the power generating network of state-of-the-art solar arrays designs. Permanently sustained destructive discharges have been generated for current-voltage characteristics that are significantly exceeding current ESD safe levels. The highest risk of impact induced failure of GEO solar arrays is posed by micrometeoroids and space debris hitting transfer harness cable bundles on its rear side.

European Space Power Conference, pp. 619-625, 2014

## 6. ACKNOWLEDGEMENT

This work was funded by German taxpayers through the European Space Agency under contract 22462/09/NL/GLC in support of the ARTES 5.1 contribution by the German Space Agency.





# Contents

# 第60回宇宙科学技術連合講演会

## 「2F09　超高速衝突に関する国際規格(ISO11227)の改定検討について」

２０１６年９月７日

九州工業大学
工学研究院　機械知能工学系　宇宙工学部門　教授
赤星　保浩

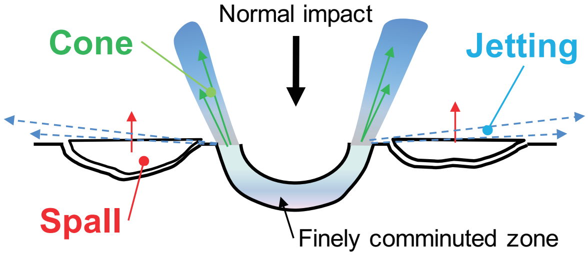




## Background ~ What is Ejecta? ~

The secondary debris generated by the impact of debris to the spacecraft is called **Ejecta**

The ejected mass of brittle material is about 100 times larger than the mass of a projectile




**Process of ejecta**

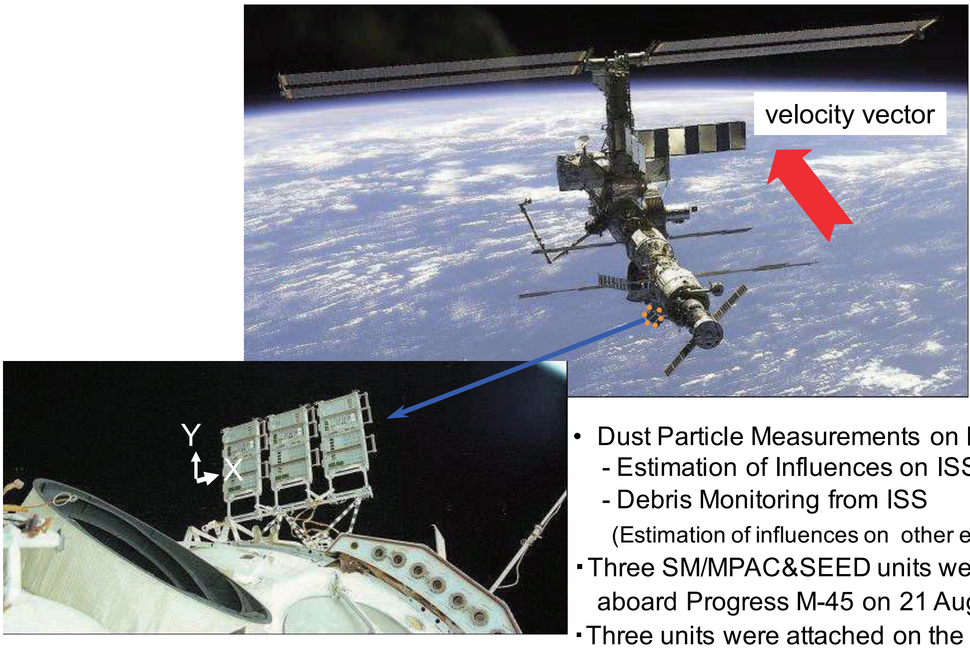
(ref.: Rival M., J.C. Mandeville, "Modelling of ejecta produced upon hypervelocity impacts", Space debris 1 (1999), p.45-57.)

- **Large and low velocity fragments**
- **Emitted by a brittle fracture near free surfaces**
- **60-90% of total ejected mass**

- **Small and high velocity fragments**
- **Generated from projectile and target**

- **Only less than 1% of total ejected mass**

# SM/MPAC&SEED units during exposure



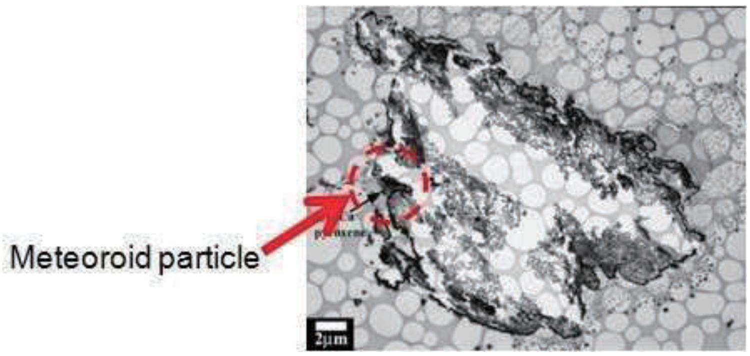

(RAM side view)

- Dust Particle Measurements on ISS
  - Estimation of Influences on ISS surface
  - Debris Monitoring from ISS
  (Estimation of influences on other exposed devices)
- Three SM/MPAC&SEED units were launched aboard Progress M-45 on 21 August 2001.
- Three units were attached on the outside of the Russian Service Module.

Ref:Y.Kitazawa et al, "Current Problems of Meteoroid & Debris Environment Models and Related Studies of JAXA", EGU208.



# Example of Ejecta




TEM picture of captured particle

A meteoroid particle was found in the captured particle at ISS Russian module, which is a paint fragment.

⇩

The captured particle (secondary debris) was ejected from spacecraft surface impacted by the meteoroid.

# Selection of surface coatings and materials for spacecraft to mitigate the generation of small space debris.

Pre NWIP outline for ISO Meeting May 2006

**J.C. Mandeville,** Mandespace
**M. Dinguirard,** Onera, Toulouse

ONERA

Presented at 9th Meeting of Orbital Debris Co-ordination Working Group (ODCWG) at CNES in October 25-27, 2006

The 7th Space Debris WS@JAXA (2016. 10. 18-20)

# Standards Development Process

Proposed by Dr.Mandeville in 2006

Submitted in 2007

Akahoshi joined in 2008

Published at Sept. 15, 2012.

| Stage name | Product name | Acronym |
|---|---|---|
| Preliminary stage | Preliminary work item (project) | PWI |
| Proposal stage | New proposal for a work item | NP |
| Preparatory stage | Working draft(s) | WD |
| Committee stage | Committee draft(s) | CD |
| Enquiry stage | Draft International Standard | DIS |
| Approval stage | Final draft International Standard | FDIS (CDV only in IEC) |
| Publication stage | International Standard | IS |

Work → **Originator**

WG Approval → **Originator and others from the working group**

SC Approval → **Working Group**

WG Approval → **SC14**

SC Approval → **ISO HQ**

ISO HQ Approval → **Member Bodies**

Member Body Approval (2 Months)

INTERNATIONAL STANDARD ISO 11227

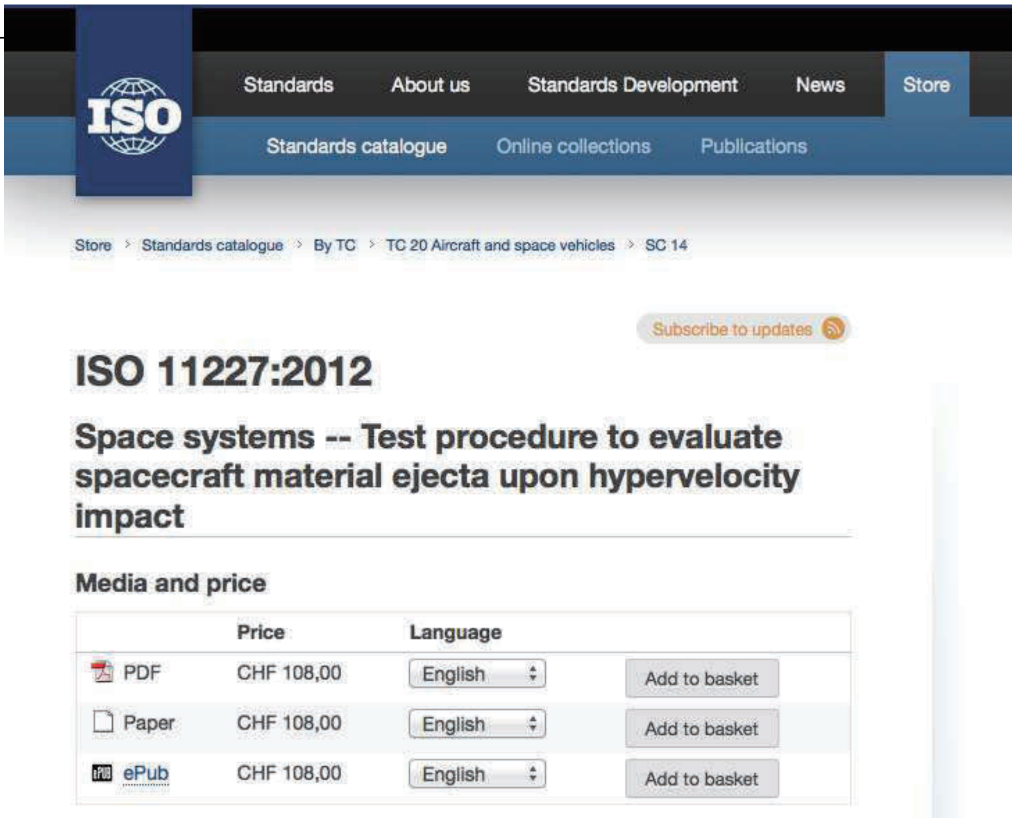
**Published at Sept.15, 2012**

**Space systems — Test procedure to evaluate spacecraft material ejecta upon hypervelocity impact**

This standard is collaboration work with JAXA and IHI, and this activity is partially supported by JSPS Grants-in-Aid for Scientific Research.

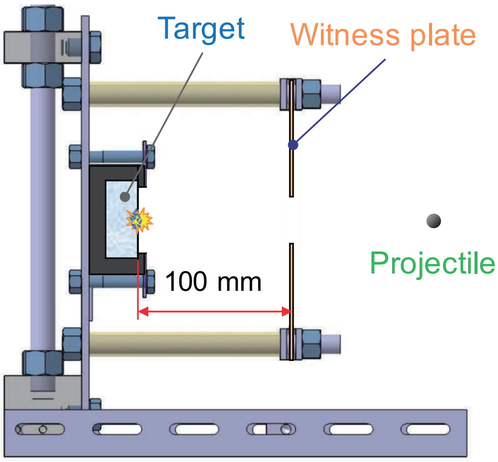







http://www.iso.org/iso/catalogue_detail.htm?csnumber=57535

# Experimental condition




Configuration diagram of target

## Projectile

Material : aluminum (Al1050)
Shape : sphere
Size : diameter of 1mm
Impact velocity: around 5km/sec

## Target

Material : synthetic fused silica
Size : 50 x 50 x 20mm
Supporter : sponge rubber

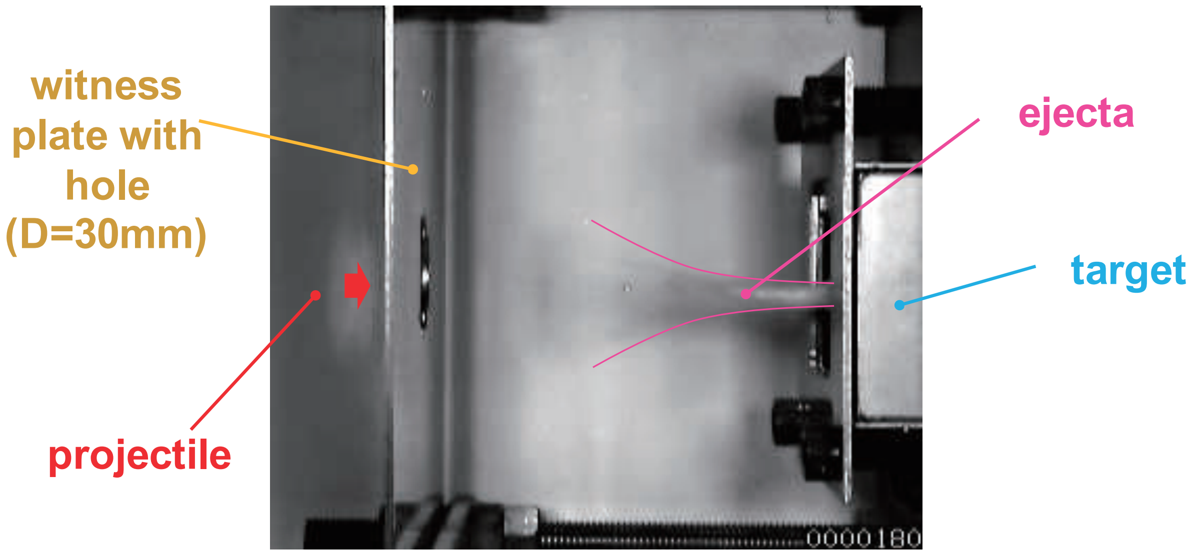
## Witness Plate

Material : Copper (JIS H3100 C1100-1/4H)
Hole diameter : 30 mm at its center
Surface : machined finish

Witness plate is in 100 mm front of target



# Snapshot of high-speed video



# Experimental Results

| Test number | Alloy and temper | Surface treatment | Distance between T and WP [mm] | Impact velocity [km/sec] | Ejecta mass [mg] | Zenith angles of ejection [deg] | Crater diameter [mm] | Spall diameter [mm] | Cone Diameter [mm] |
|---|---|---|---|---|---|---|---|---|---|
| 09-036 | C1100P -1/4H | Buffing | 100 | 4.86 | — | — | 2.60 | 12.83 | - |
| 09-039 | | | | 4.95 | — | 36 | 3.14 | 13.52 | 145 |
| 09-101 | | Chemical polishing | | 4.03 | 88.5 | 33 | 4.16 | 8.33 | 130 |
| 09-102 | | Buffing | 50 | 3.92 | 80.4 | 46 | 3.71 | 9.09 | 105 |
| 09-117 | | | 100 | 3.71 | 70.2 | 35 | 3.69 | 8.52 | 140 |
| 09-119 | C1100P -O | | | 4.14 | 84.9 | 33 | 4.27 | 9.90 | 130 |
| 09-120 | C1100P -1/4H | Nothing | | 4.17 | 83.2 | 36 | 4.47 | 10.93 | 145 |

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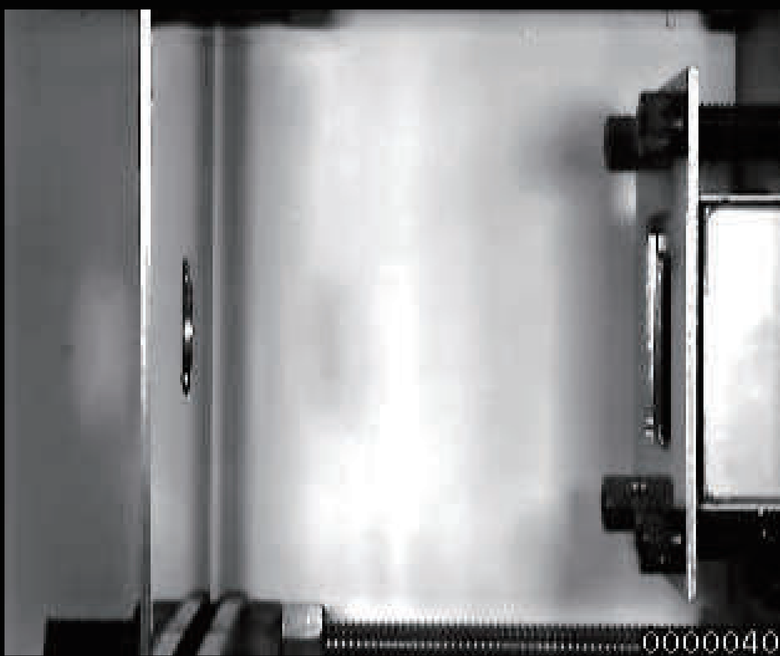
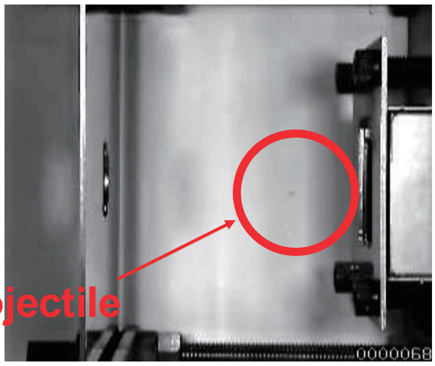
# High-speed Video 09-101

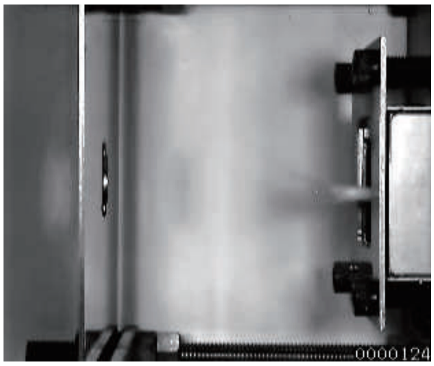




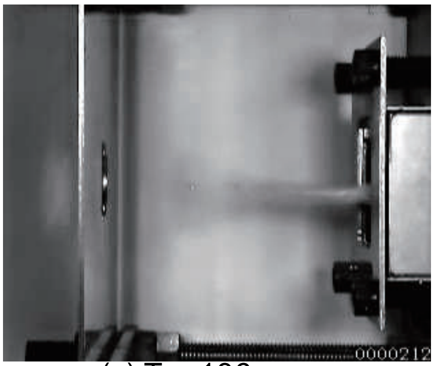

Experimental results Shot No. 09-101
V= 4.03 km/sec, Witness plate – Target: 100 mm
Recoding rate: 250 kfps, Pixels: 312 x 260 pixels




(a) T = - 8usec




(b) T = 48usec




(c) T = 136usec

Spall ejecta will go through the hole of the witness plate.

(d) T = 228usec





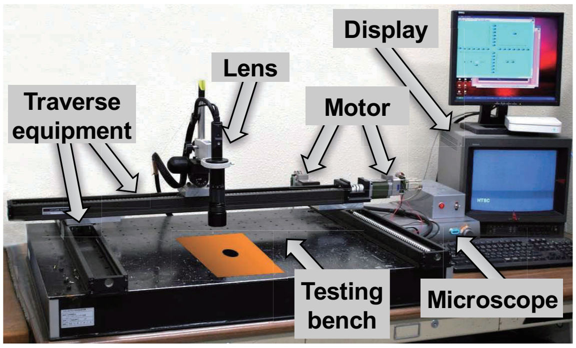
**6.3.2** The fundamental analysis of test results will be documented in a tabular form, as shown in the Table 1:

**Table 1. Fundamental Analysis for Test results**

(xxx: values to be filled in after the tests)

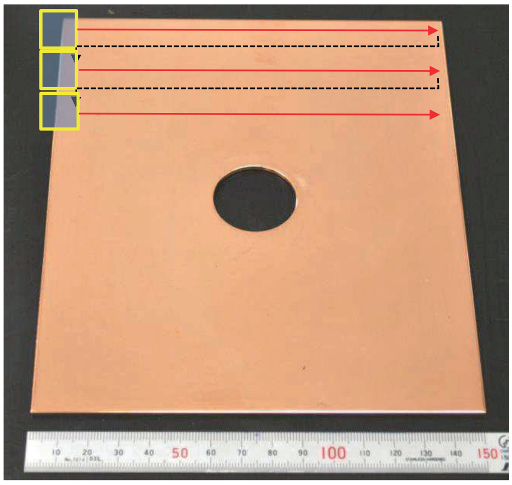
| | | | | | |
|---|---|---|---|---|---|
| **total amount of ejecta (mg) : $M_e$** | xxx | target mass before impact (mg) | xxx | target mass after impact (mg) | xxx |
| **Size distribution of crater diameter, D** | | **0.025 mm to 0.05 mm** | **0.05 to 0.1 mm** | **0.1 to 1 mm** | **>1 mm** |
| **front side** | **number of craters** | **xxx** | **xxx** | **xxx** | **xxx** |
| **rear side** | **number of craters** | **xxx** | **xxx** | **xxx** | **xxx** |
| **projectile** | **mass** xx | | | | |

# Previous Microscope system




Microscope system

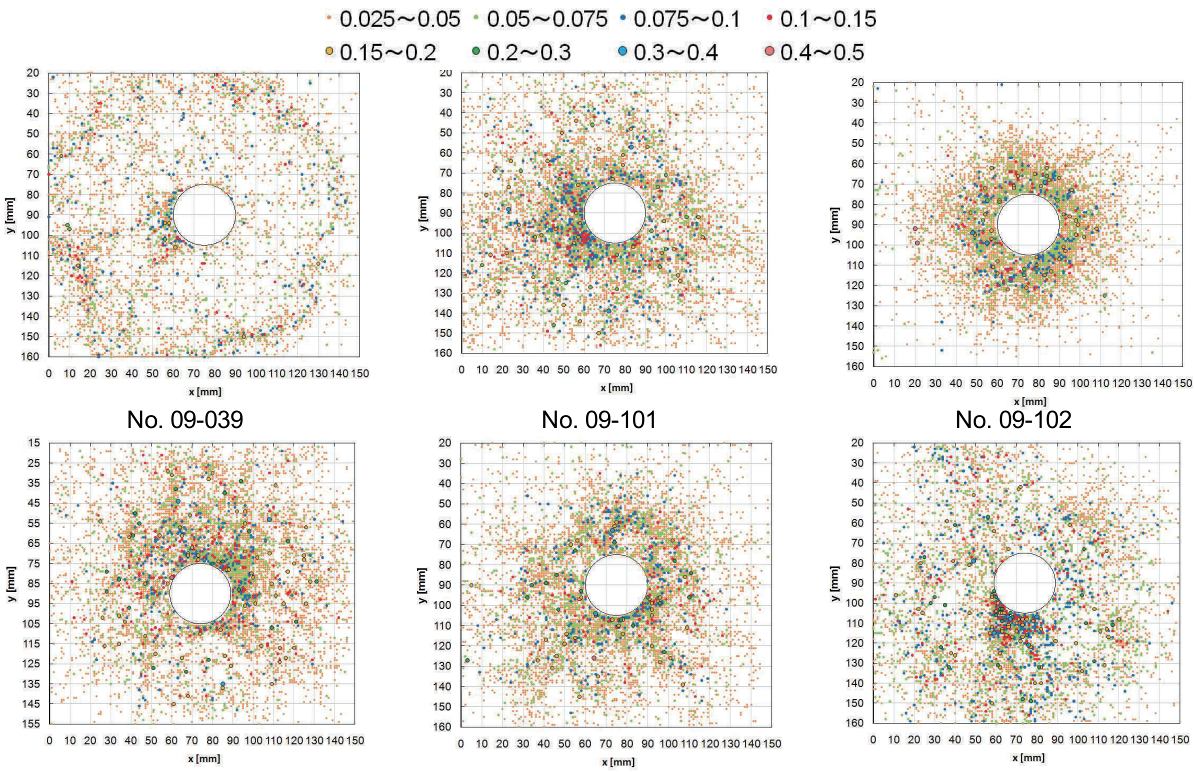
| Magnification | Resolution [pixels] | Size per pixel [um] |
|---|---|---|
| 35 ~ 245 | 640 x 480 | 14 ~ 2 |



Scanning direction

scan feed






No. 09-039 No. 09-101 No. 09-102

No. 09-117 No. 09-119 No. 09-120

### 6.5 Additional tests

In order to investigate the ejecta process in more detail, if the facility is able to perform such tests, it is recommended that the following additional tests be performed:

a) incidence angle varying from 0° to 75°, in 15° steps;

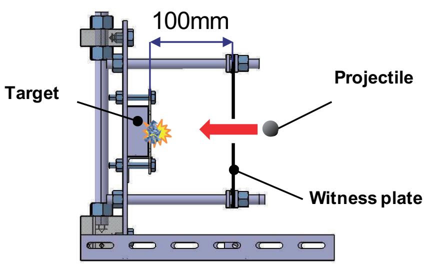
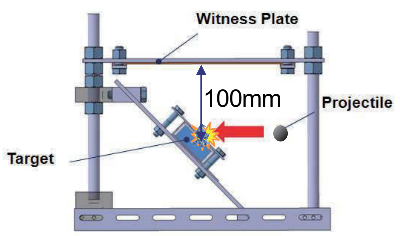
b) velocity varying from 1 km/s to 16 km/s.

In section 6.5 impact angle of 15º, 30º, 45º, 60º and 75º as well as 0º are recommended. However experimental configuration on oblique impact is not specified in ISO11227.





# Experimental Condition

| | Normal Impact | Oblique Impact |
|---|---|---|
| Configuration |   |   |
| Impact angle | 90° | 45° |
| Target | Fused Silica (50 mm× 50 mm×20 mm) | |
| Projectile | Material : Aluminum alloy (A2017)<br>Diameter : 1 mm<br>Mass : 1.6mg<br>Impact velocity : 5 km/sec | |
| Witness plate | Copper (180 mm×150 mm×2 mm), Polished | |
| | Diameter of hole : 30mm | No hole |

# Comparison of Ejecta Mass

| Test No. | Impact angle | Impact velocity [km/sec] | Projectile mass [mg] | Ejecta mass [mg] |
|---|---|---|---|---|
| 11-072 | 90° | 4.87 | 1.7 | 156.6 |
| 11-082 | | 4.99 | 1.7 | 144.5 |
| 12-072 | 45° | 5.01 | 1.5 | 167.7 |
| 12-074 | | 5.09 | 1.5 | 154.4 |

Ejecta mass is almost the same between normal impact and oblique impact (θ=45°).

# Summary of Experimental Results based on Table 1 in ISO11227

| | Test No. \ Size | 0.025 to 0.05 [mm] | 0.05 to 0.1 [mm] | 0.1 to 1 [mm] | > 1 [mm] | Total number |
|---|---|---|---|---|---|---|
| Normal | 11-072 | 3215 | 510 | 58 | 0 | 3783 |
| | 11-082 | 3557 | 578 | 49 | 0 | 4184 |
| Oblique | 12-072 | 33180 | 9594 | 1196 | 0 | 43970 |
| | 12-074 | 33258 | 7611 | 1050 | 0 | 41919 |

**Although ejecta mass is almost the same, the number of craters on WP in case of oblique impact is much larger than that of normal impact.**

## Annex C
(informative)

## Ejecta measurement methods

At least two parameters shall be measured during hypervelocity impact tests in order to characterize the ejecta:

— total mass ejected;

— size distribution of fragments (as an option, the velocity of fragments, in magnitude and in direction).

The choice of method is left to the discretion of the user on the premise that there is no absolute measurement method and that it will depend on the instrumentation available at the facility performing the tests. Some guidelines are given in this annex. More details are available in Reference [6]. Recent experimental set-up and preliminary results are described by K. Sugahara *et al.*[15] and by A. Francesconi *et al.*[20].

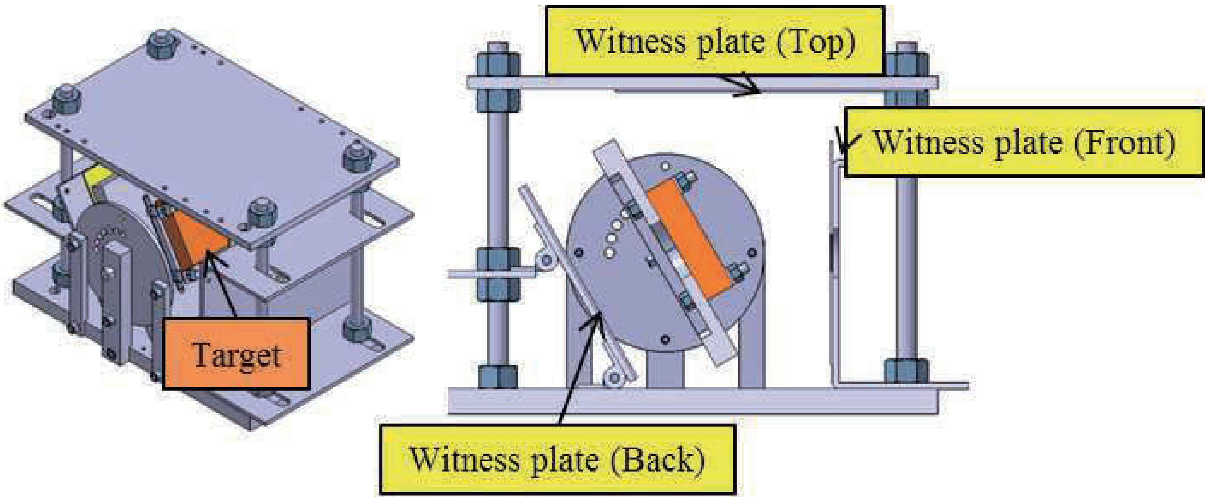
a) The total mass ejected is obtained by measuring the weight of the target before and after the test. It can also be derived from measuring the volume of the impact crater.

b) The size and spatial distribution of the fragments can be obtained with a metal witness plate and adequate conversion equations. A copper plate is preferred (composition different from projectile and target). For a normal impact, it will be located up-range of the target (with a hole in the centre in order to let the projectile go through), at a distance of 50 mm to 100 mm; oblique impacts will require a slightly different set-up (a similar witness plate can also be used behind the target in order to study the down-range ejecta, if perforation occurs). The plate size will typically be 250 mm × 150 mm, with a thickness of 2 mm. The sample holder plate will be a similar aluminium plate, out of which a 60 mm × 60 mm square is cut in the centre in order to study the rear-side ejecta, if any. A possible set-up, such as the one used at the Kyushu Institute of Technology[9] is shown in Figure C.1 and Figure C.2.

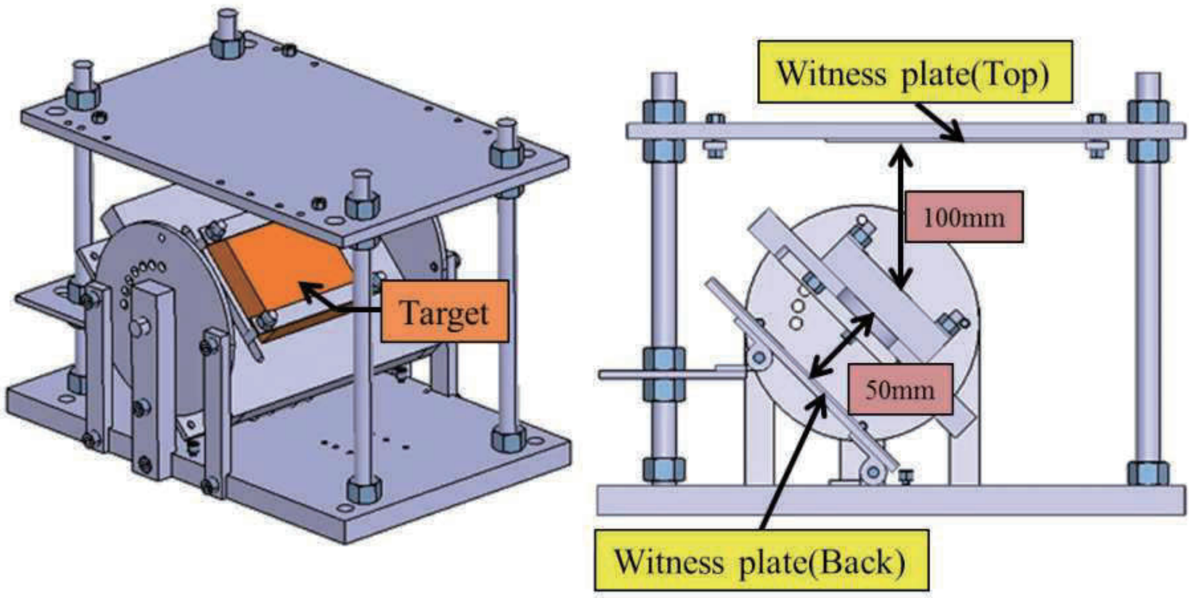
The analysis of impacts on the witness plate will provide data on the geometry of the ejecta cloud. Scanning of the witness plate will be made with a medium-power optical microscope and can benefit from automated pattern recognition techniques. As evidenced by Sugahara[15], it is difficult and time-consuming to identify impact features smaller than 25 μm in diameter.



# Impact Angle : 15º and 30º



# Impact Angle : 45º, 60º and 75º








# Contents

In Kyushu Institute of Technology the following subjects on “Hypervelocity Impact” have been conducted since 1997.

(1) Behavior of Debris Cloud
(2) Discharge due to HVI
(3) Test Procedure (ISO11227)

In addition deflection of asteroid and impact test of fan case of jet engine are under study.





Thank you for your attention.

ご静聴ありがとうございました