九州工業大学における宇宙機帯電放電の研究

九州工業大学　宇宙環境技術ラボラトリー

豊田和弘　趙孟佑

放電事故

1997年 静止軌道衛星Tempo-2

発電電力の15％が低下

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世界中の研究機関が調査を開始

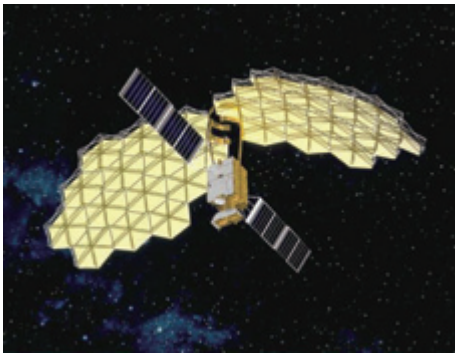
Tempo-2

太陽電池アレイと宇宙プラズマと
の相互作用により放電が発生

持続放電 ⟶ アレイ回路の短絡 ⟶ 電力損失

ETS-VIII

Development of a solar array for ETS-VIII



Engineering Test Satellite VIII (ETS-VIII)
- Launch in 2006
- Geosynchronous Orbit(GEO)
- **110V at 2.64A** electric power generation
- **Silicone** solar cell

Purpose of the ground tests
Determine the design of coupon preventing the sustained arcs

帯電放電試験　2001年~

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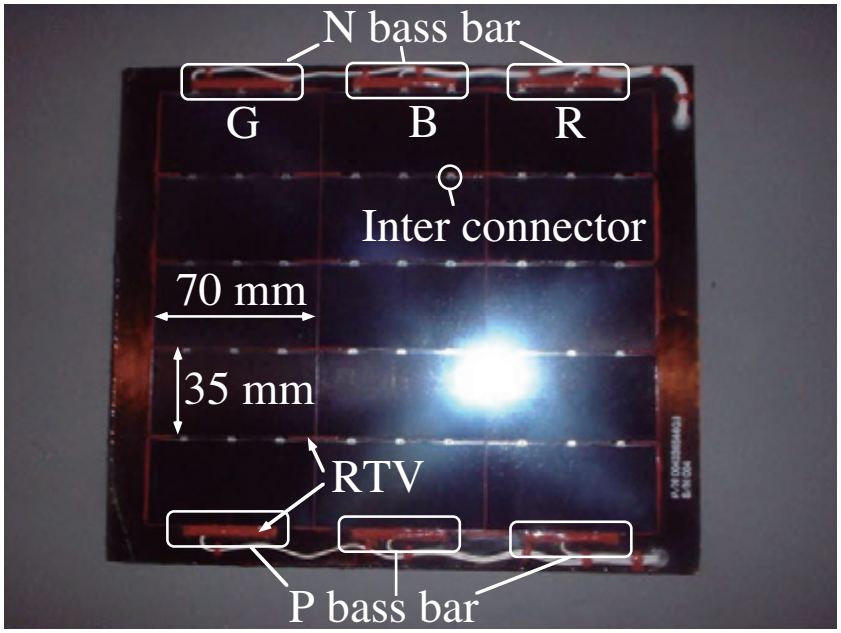
Solar array coupons



We used 3 coupons.

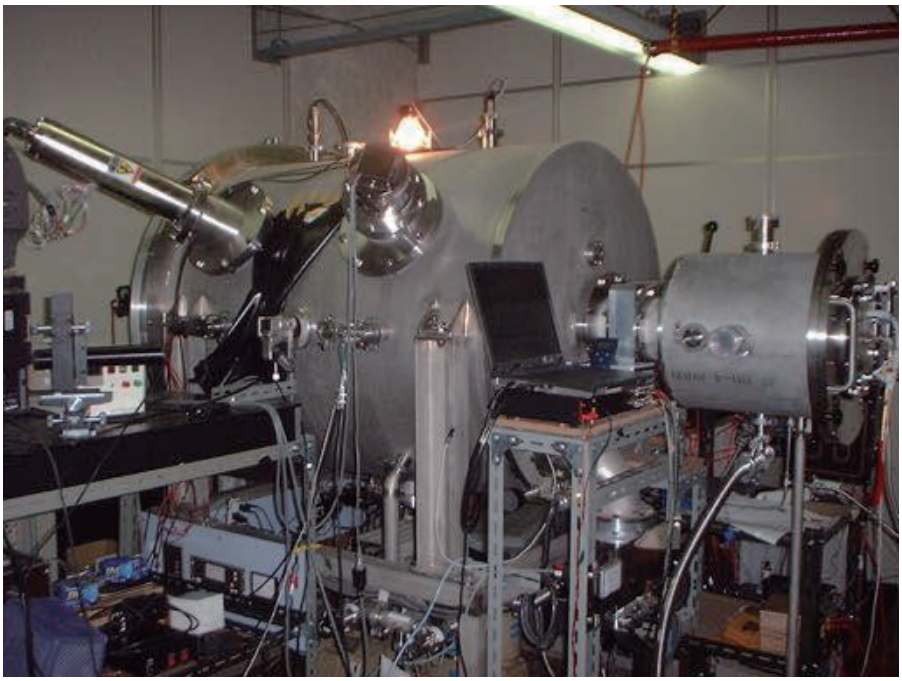
Thick coupon×2 (Case1～3)

Thin coupon×1 (Case4)

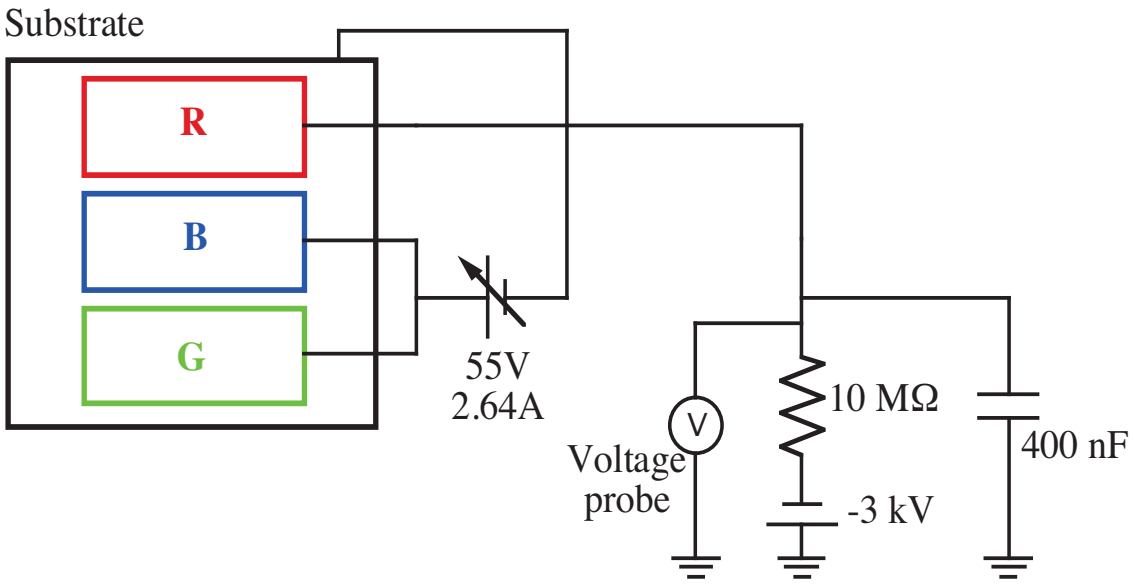
5 ×3 Si cell with IBF

IBF: Integrated Bypass Functi

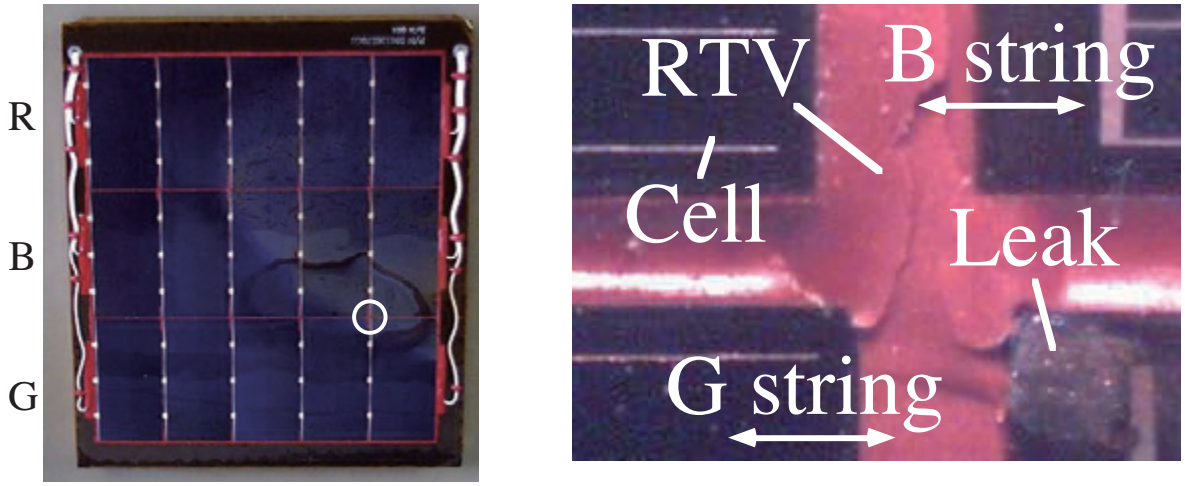
Experimental facility



Experimental circuit



セルの電流リーク箇所



Current leaking point was identified by IR-OBIRCH analysis

IR-OBIRCH (Optical Beam Induced Resistance Change)

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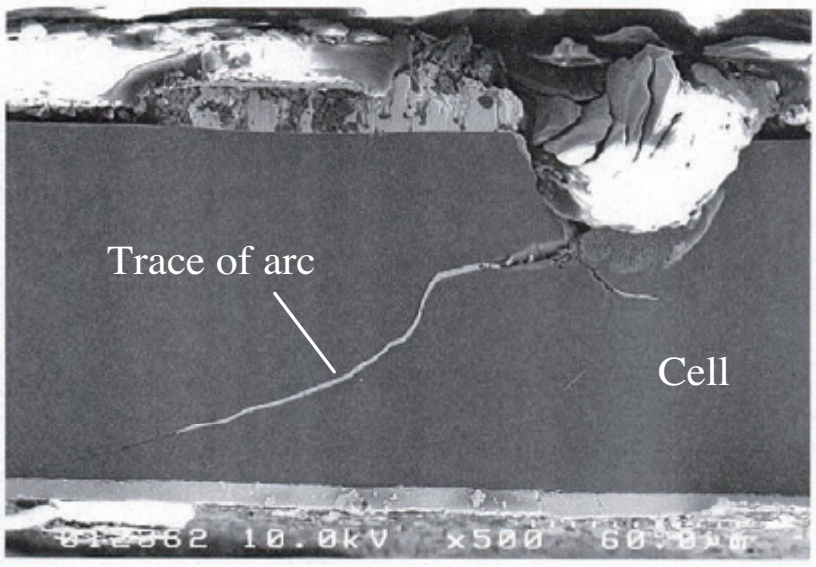
セル断面



Silver was found on the trace of arc by EDX

EDX : Energy Dispersive X-ray Spectroscopy

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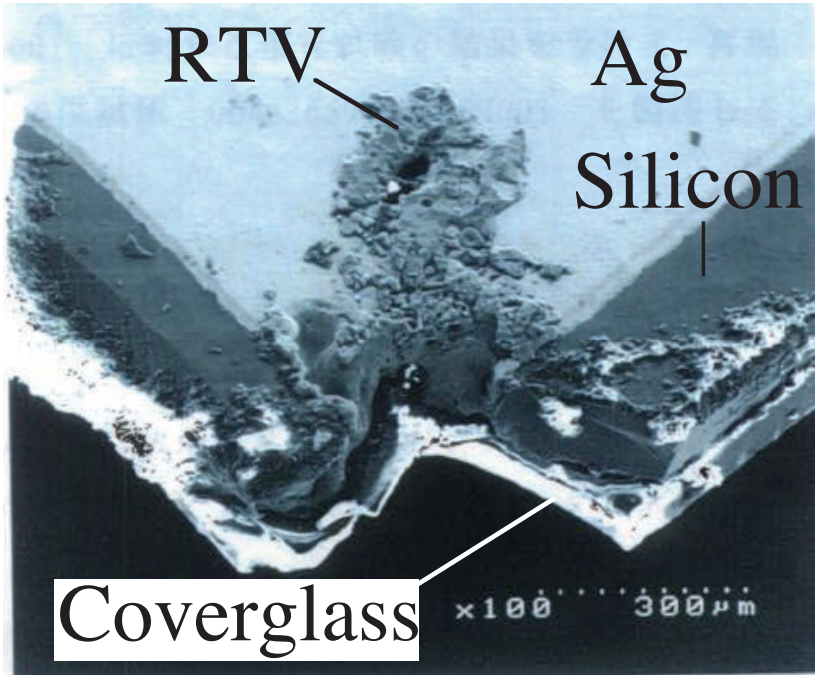
セル裏面



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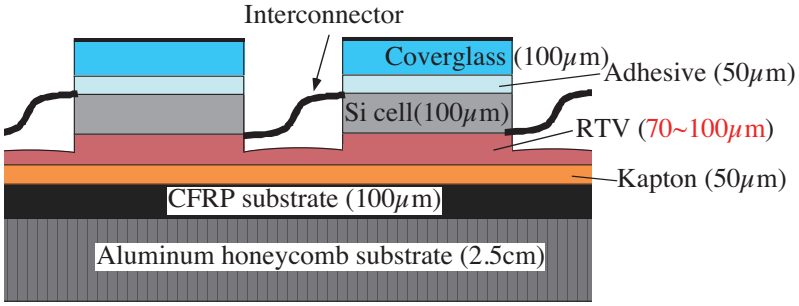
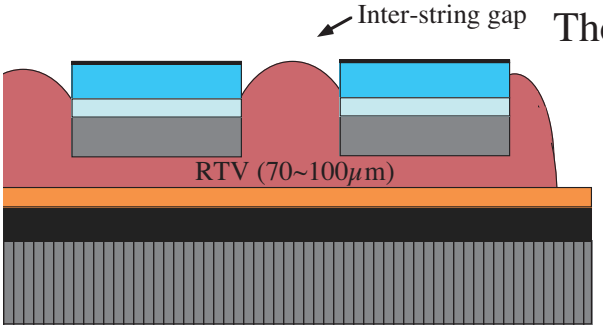
Flight design of coupon for ETS VIII

• No sustained arcs during 30 hours (about 500 arcs)





The amount of RTV should be minimum

To keep insulation between both inter-string gaps and string-substrate

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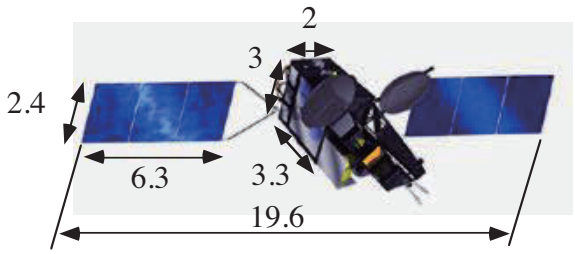
WINDS



Wideband InterNetworking engineering test and Demonstration Satellite (WINDS)

- Launch in 2008
- Geosynchronous Orbit(GEO)
- Electric power generation: 5.2 kW (**50V at 0.6A**)
- **Multi-junction** solar cell

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Test procedure

Measure the threshold of potential difference ΔV_{min} for arcing

Calculate the charge stored in the coverglass

Perform ESD tests using 3 coupons for 20 hours

Calculate the time (t_{IG}) on IG condition over ΔV_{min} and estimate thenumber of arcs

Select one coupon

Perform ESD tests using the selected coupon for the t_{IG} totally

Determine the flight design

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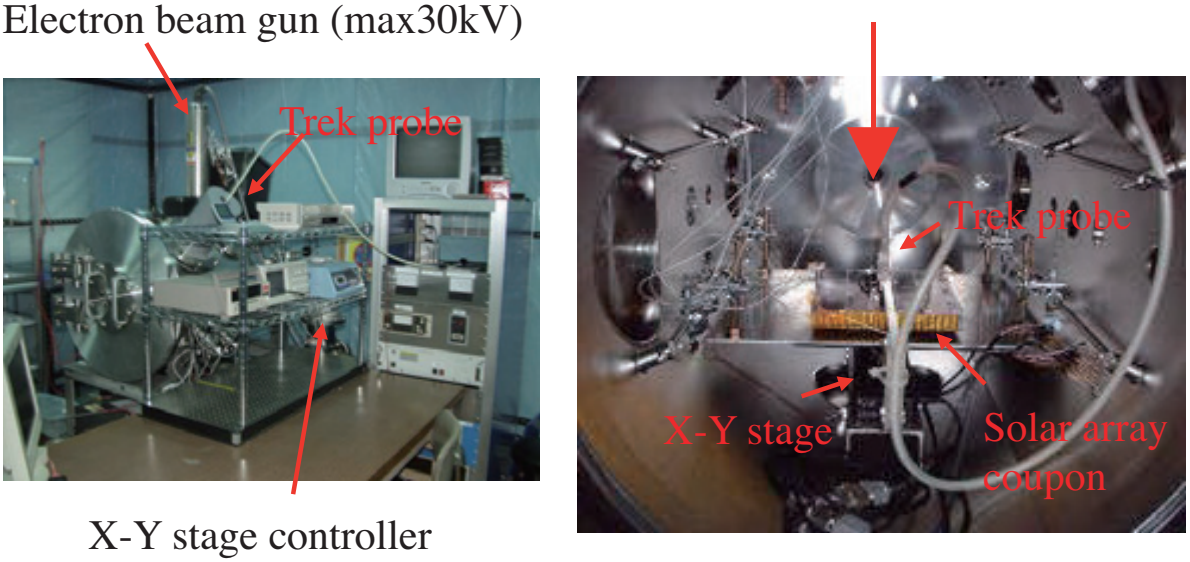
Experimental facility



Vacuum chamber: 0.6m in diameter and 0.9m in length up to $3x10^{-7}$ Torr

Equipment: Electron beam gun, Trek probe, Plasma source, Video analysis system, XY stage, Baking system, UV source

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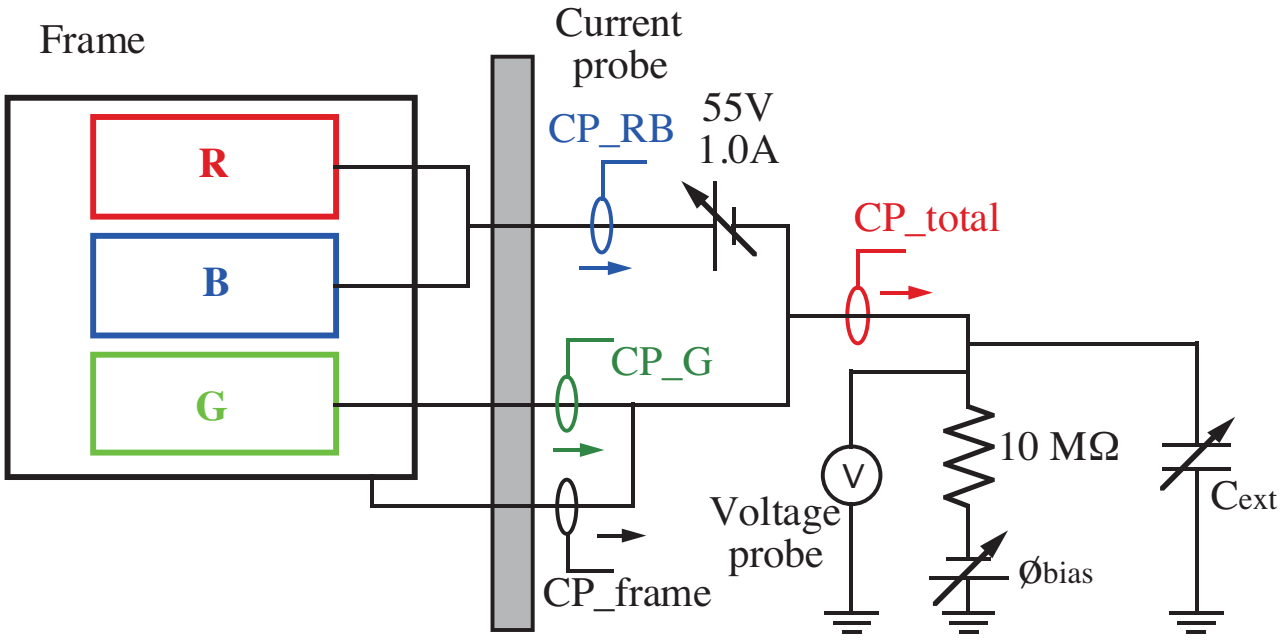
Experimental circuit



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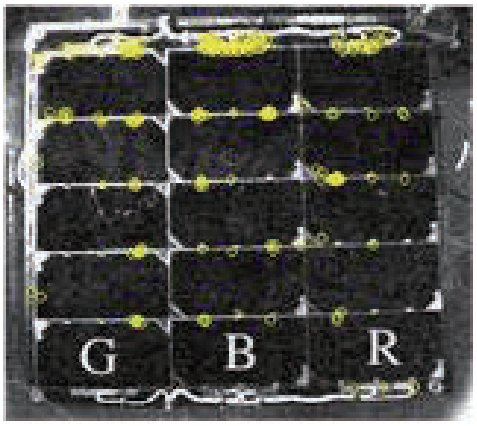
Effect of bus bar coating

Coupon 3



- No sustained arcs
- No difference at arc positions

Select coupon 3 as a flight model

65 hour test
(60 hours from NASCAP calculation)

Case	Position	N_{arc}	I_{ave}, A	I_{std}, A	Q_{ave}, mC	Q_{std}, mC
10	Bus bar	78	122	36	1.23	0.08
10	IC	71	128	34	1.24	0.09
11	Bus bar	43	91	37	0.79	0.05
11	IC	66	88	24	0.75	0.04

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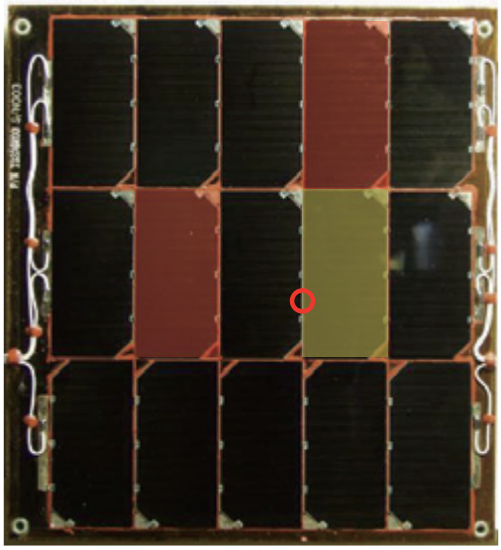
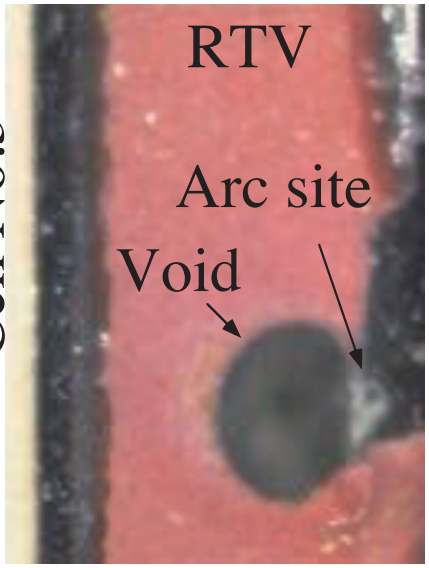
Degraded cells

Coupon 2



IR-OBIRCH method

3 cells were degraded



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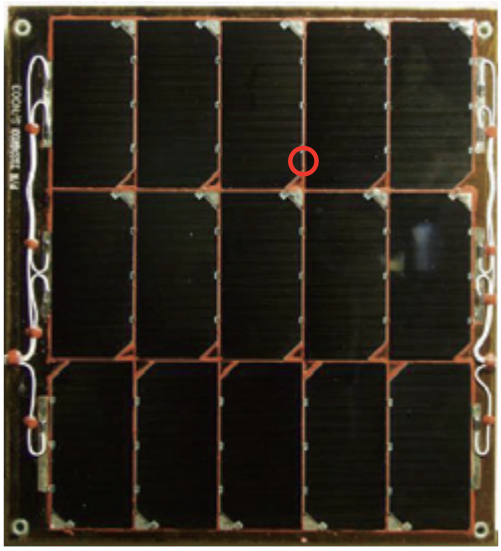
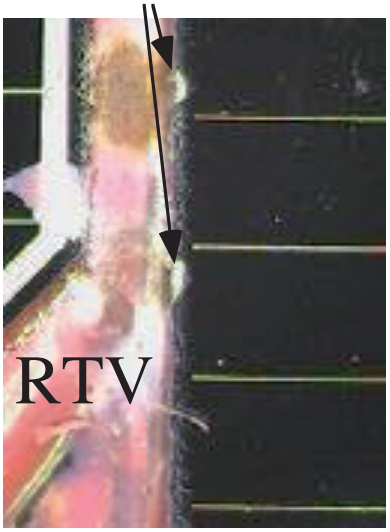
Cell degradation

Coupon 3



Arc site



Cell edge arc can destroy the cell

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Conclusions

- **To suppress the inter-string sustained arc, the gap between strings is grouted with RTV**
- **To suppress the string-substrate sustained arc, the RTV layer between the cells and the Kapton sheet is specified as 100 μm and the RTV layer leaks out at the cell gap in the direction of series connection**
- **There is no coating of bus bar with RTV**
- **To avoid trigger arcs at the cell edges, we give the best effort to fill in the voids of RTV by additional RTV**

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WINDS打ち上げ 2008.2.23

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ADEOS II

- みどり２号
  極軌道衛星

2003年10月25日
発電電力が6kWから1kWに低下

熱制御材の帯電

↓

ケーブルと放電

20

検証試験

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宇宙環境技術研究センター

2004年12月　設立

宇宙環境に耐えるモノ作り技術の開発

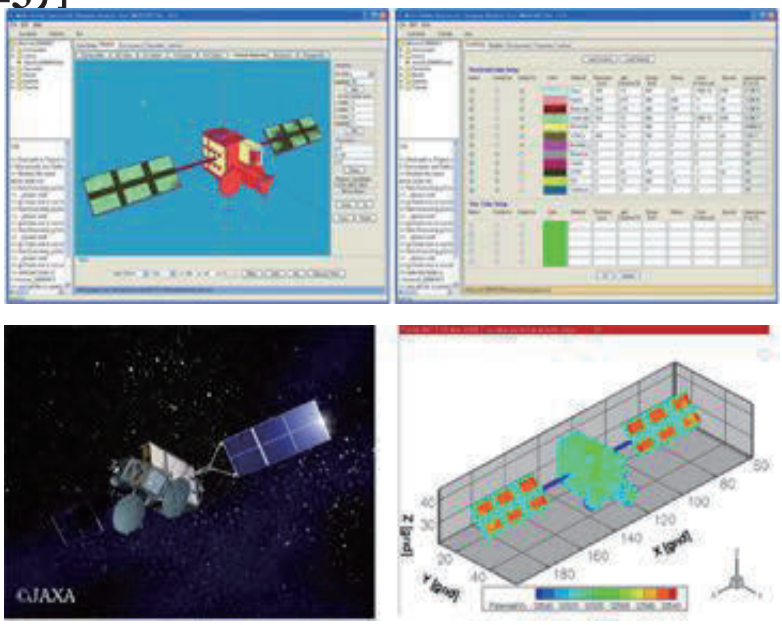
Laboratory of Spacecraft Environmental Interaction Engineering

La SEINE

22

MUSCAT

- Multi-Utility Spacecraft Charging Analysis Tool
- GEO, PEO, LEO
- 2007年3月



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ISO-11221 "Space systems -- Space solar panels -- Spacecraft charging induced electrostatic discharge test methods"

- Measure discharge threshold voltage
- Estimate the number of discharge with charging analysis program
- Calculate external capacitance in test circuit
- Perform ESD test on test coupon with desired number of discharge
- Confirm there is no sustained arc and no degradation of solar cell
- Estimate power degradation due to cell degradation
- Decide design of solar array circuit
- Reflect test result in spacecraft system design

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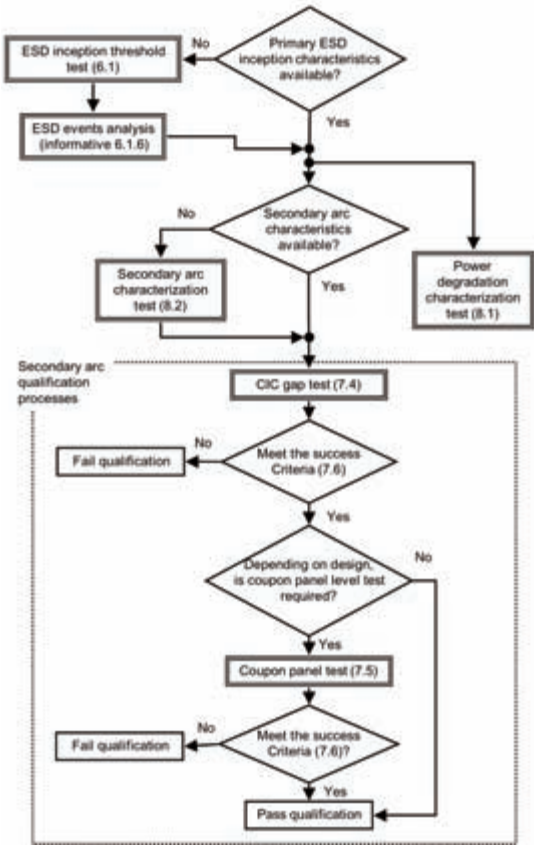

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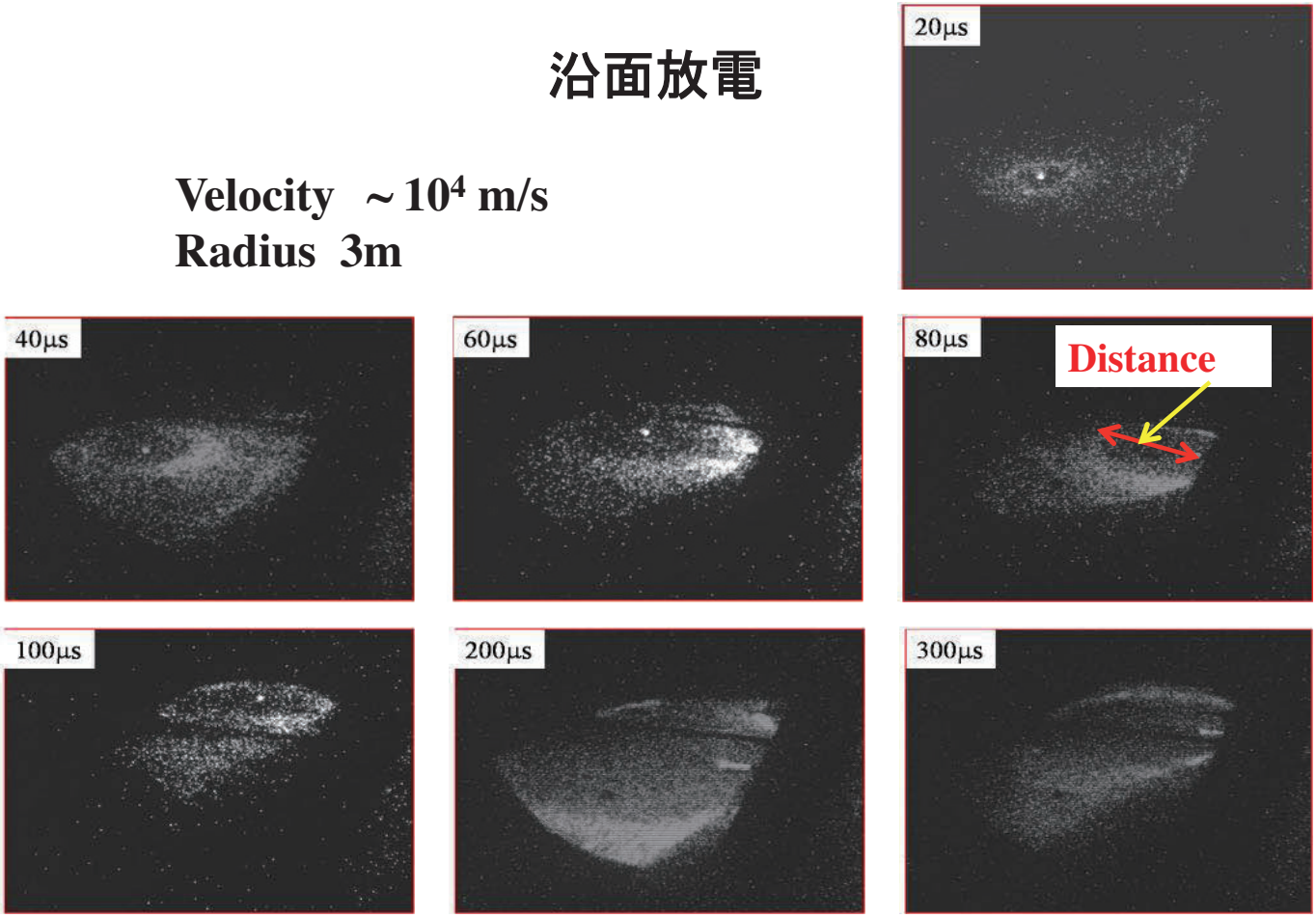
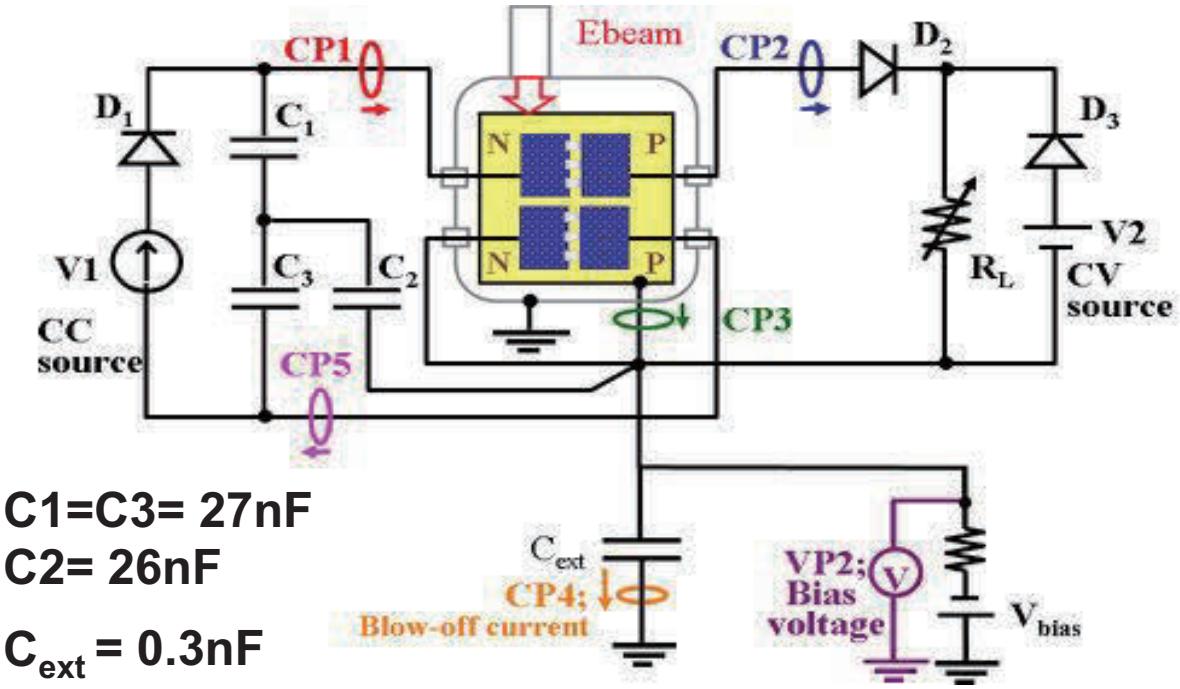
Figure 2: Logic flow of ESD tests

沿面放電

Velocity ～10^4 m/s
Radius 3m



持続放電回路

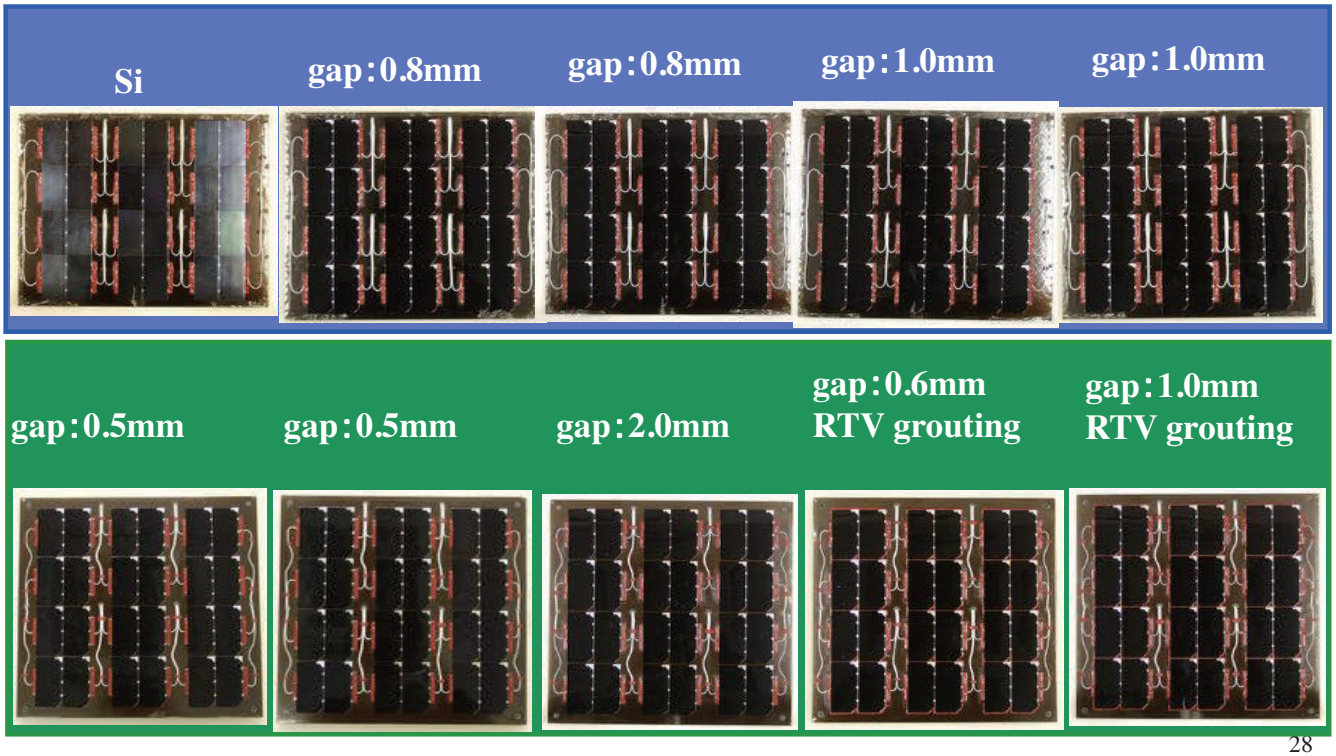


C1=C3= 27nF
C2= 26nF

C_{ext} = 0.3nF

No. 27

帯電・放電設計標準



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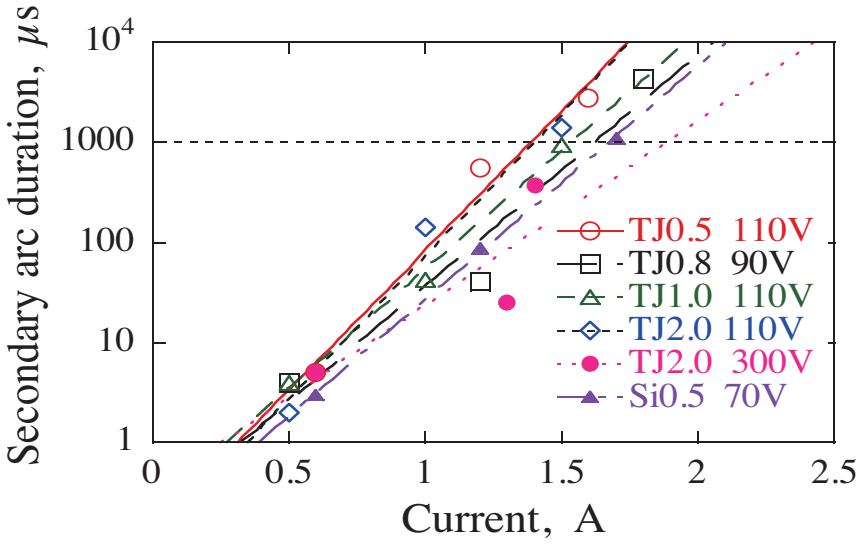
TSA duration



- **TSA duration depends on current value**
- **The duration of 1ms corresponds to PSA threshold**

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TJ 0.5mm

V_{st}, V	I_{st}, A			
	0.5	1.0	1.5	2.0
30	No secondary arc up to 4A			
50	7μs (0.7A)	28μs	4534μs (1.7A)	
70	4μs (0.6A)	250μs (1.2A)	7747μs (1.8A)	
90	54μs (0.5A)	231μs (1.2A)		
110	5μs (0.6A)	552μs (1.2A)	2750μs (1.6A)	

PA **NSA** **TSA** **PSA**

30

TJ 0.8mm

V_{st}, V	I_{st}, A			
	0.5	1.0	1.5	2.0
30	No secondary arc up to 4A			
50		47μs	4086μs (1.7A)	
70	7μs (0.7A)	209μs (1.2A)		
90	4μs	41μs (1.2A)	4384μs (1.8A)	
110	3μs (0.6A)	179μs (1.2A)	7408μs (1.8A)	

PA NSA TSA PSA

31

TJ 1.0mm

V_{st}, V	I_{st}, A			
	0.5	1.0	1.5	2.0
30	No secondary arc up to 4A			
50		12μs	1126μs	4433μs
70	3μs	25μs	1225μs	
90	3μs	7μs (0.9A)	415μs (1.3A)	
110	4μs	42μs	943μs	

PA NSA TSA PSA

32

TJ 2.0mm

V_{st}, V	I_{st}, A			
	0.5	1.0	1.5	2.0
50	No secondary arc up to 4A			
70	7μs			
110	2μs	140μs	1400μs	3900μs
200	3μs (0.7A)	110μs (1.1A)	60μs (1.3A)	
300	5μs (0.6A)	25μs (1.3A)	370μs (1.4A)	

PA NSA TSA PSA

33

Si 0.5mm

V_{st}, V	I_{st}, A			
	0.5	1.0	1.5	2.0
30				
50	PA	PA	PA	PA
70	3μs (0.6A)	88μs (1.2A)	1098μs (1.7A)	
90				
110	4μs (0.6A)	233μs (1.2A)	727μs (1.7A)	

PA NSA TSA PSA

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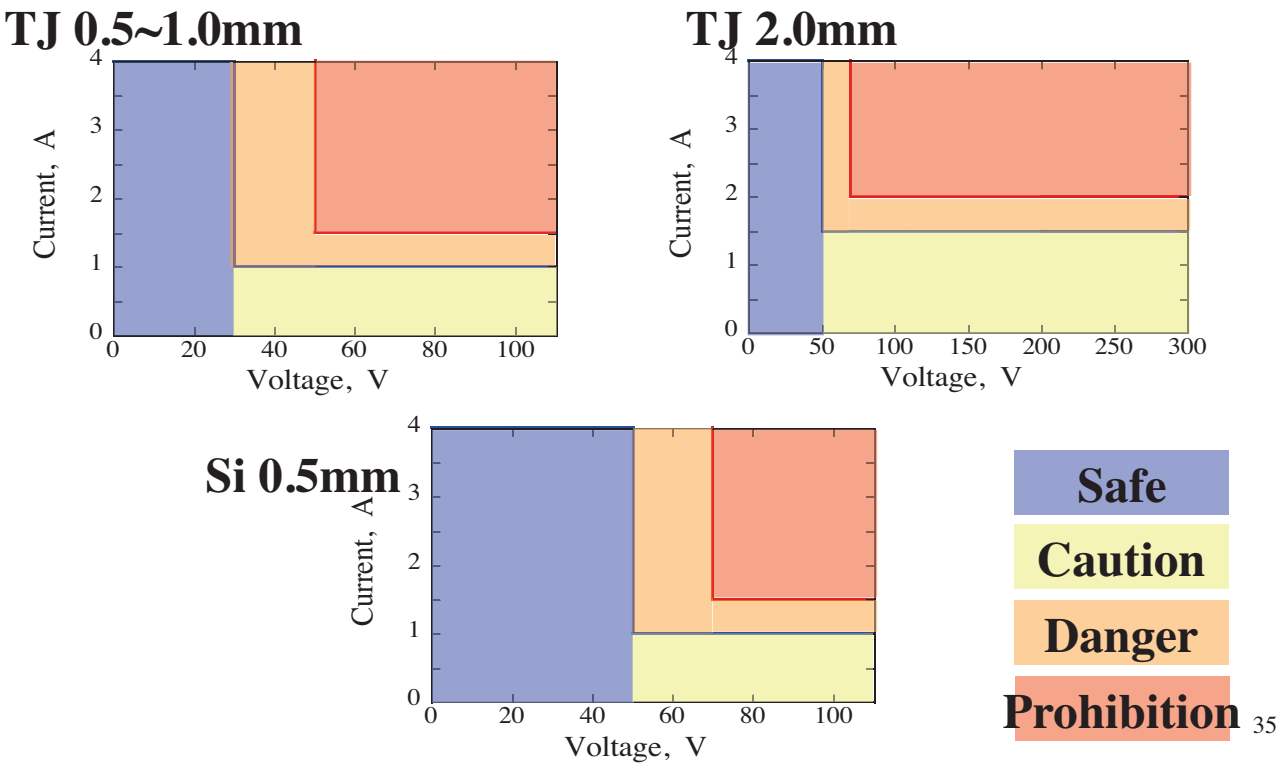
VI map



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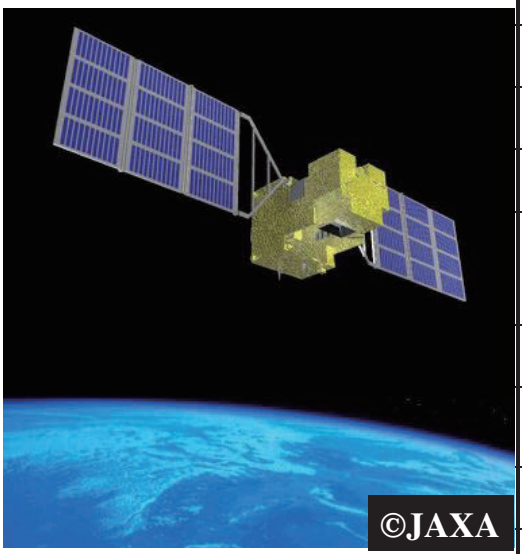
GOSAT



Item	Characteristics
Launch vehicle	H-IIA
Launch	2009.1.23
Launch site	Tanegashima Space Center
Orbit	666km Sun-synchronous inclination angle 98 degree 13:00 local time (3 day cycle)
Weight	1,750kg at launch
Generated electric power	More than 3.77kW (EOL)
Lifetime	5 years
Deployed dimension	3.7m(H) x 13.7m(W) x 2.0m(D)

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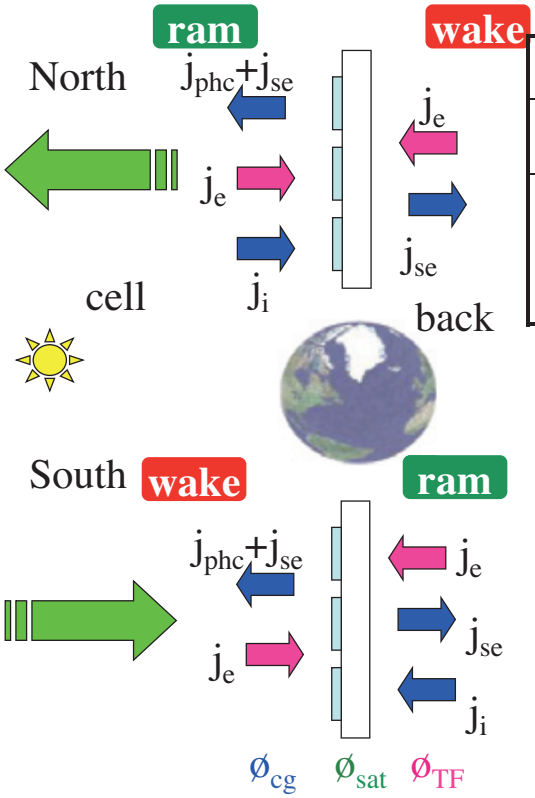
Charging mode



SAP	plasma	ϕ_{sat}	ϕ_{dielec}	Condition
cell	ram	N	0	Plasma IG
back	wake	N	$> \phi_{sat}$	Beam IG
		0 or N	$< \phi_{sat}$	Beam NG

SAP	plasma	ϕ_{sat}	ϕ_{dielec}	Condition
cell	wake	N	$> \phi_{sat}$	Beam IG
		0 or N	$< \phi_{sat}$	Beam NG
back	ram	N	0	Plasma IG

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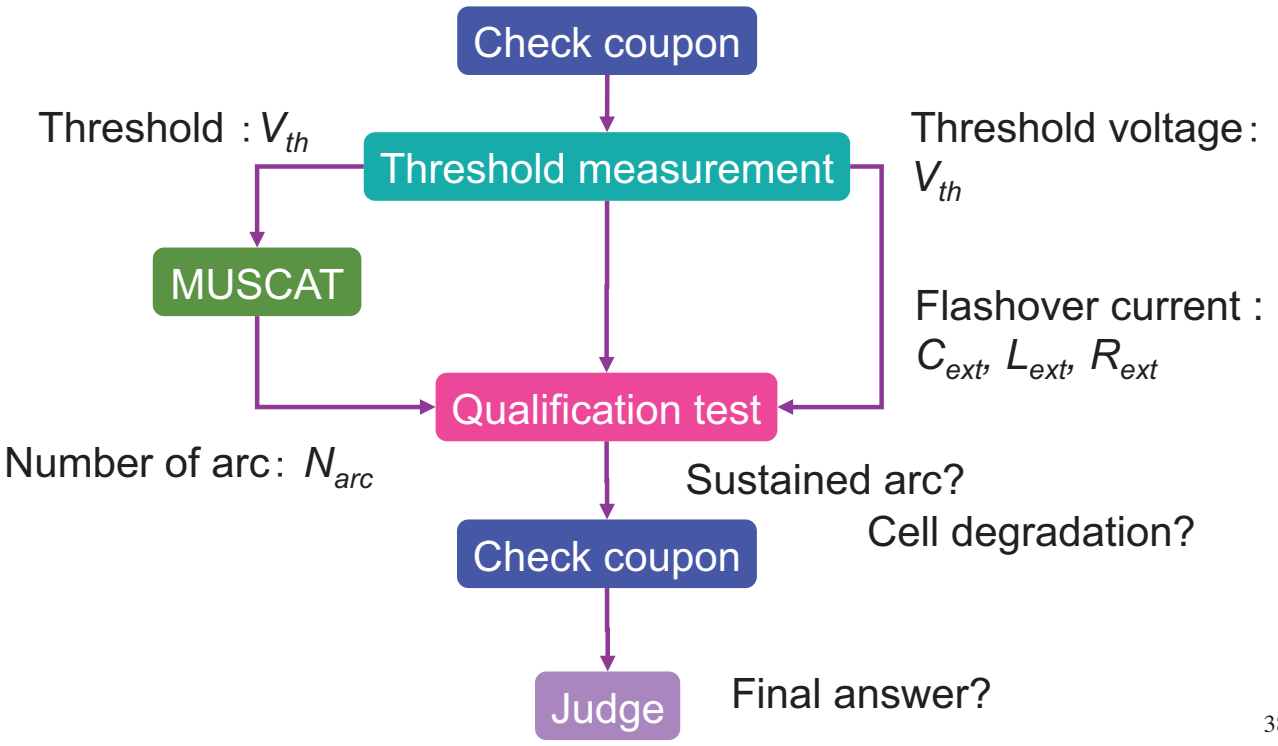
Test procedure



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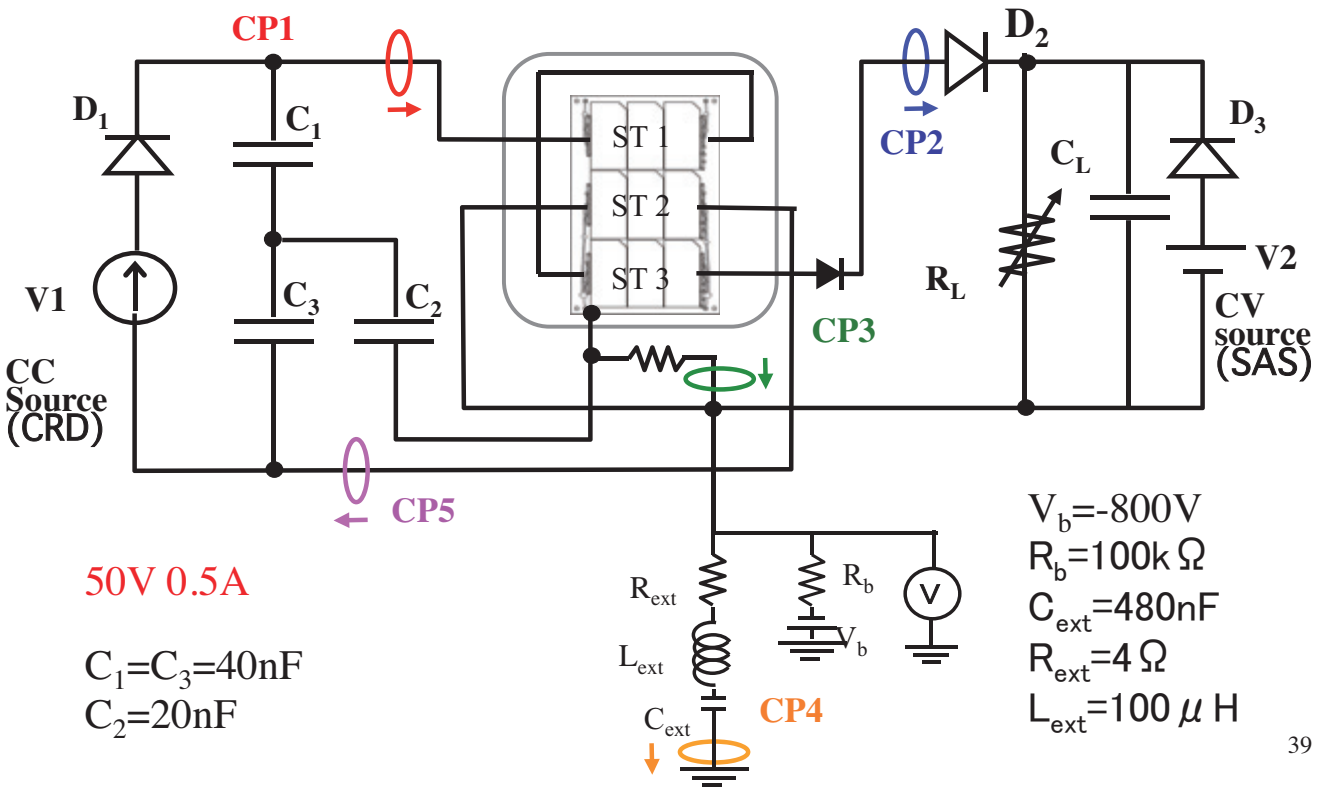
Experimental circuit: plasma IG EOL



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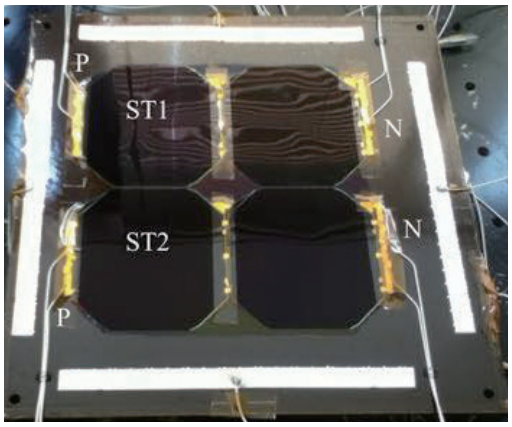
商用衛星

- **Large solar cell**
  - **need ground ESD testing before launch**



- **ISO11221**
  - **Confirm no sustained arc**
  - **Measure cell degradation**

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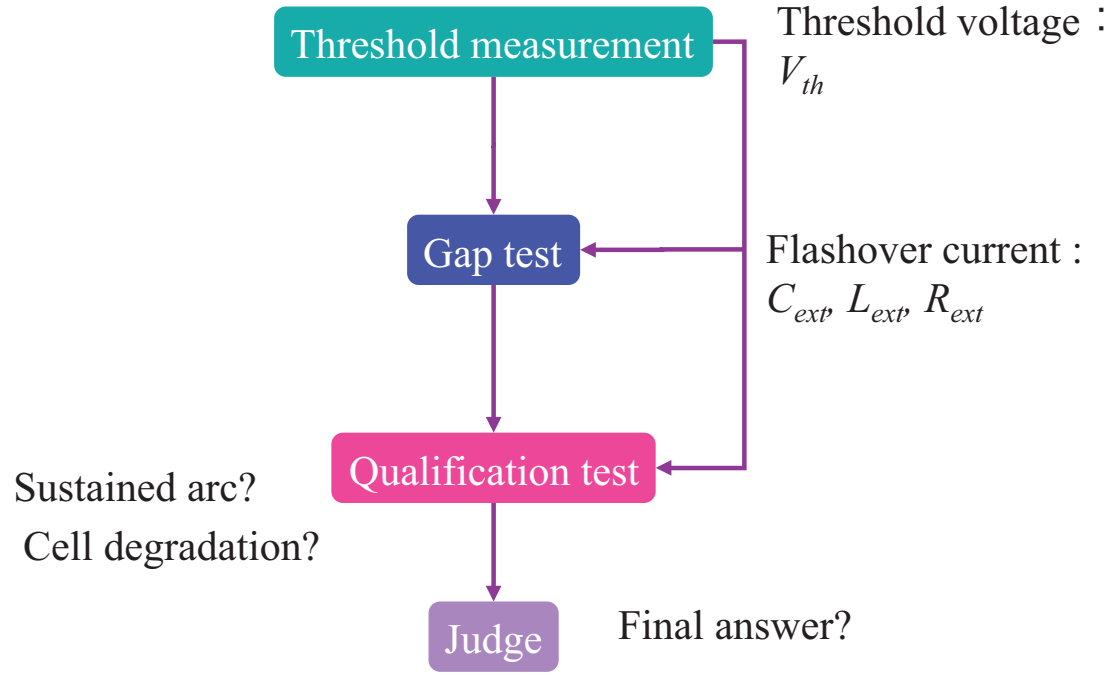
Test procedure

ISO11221



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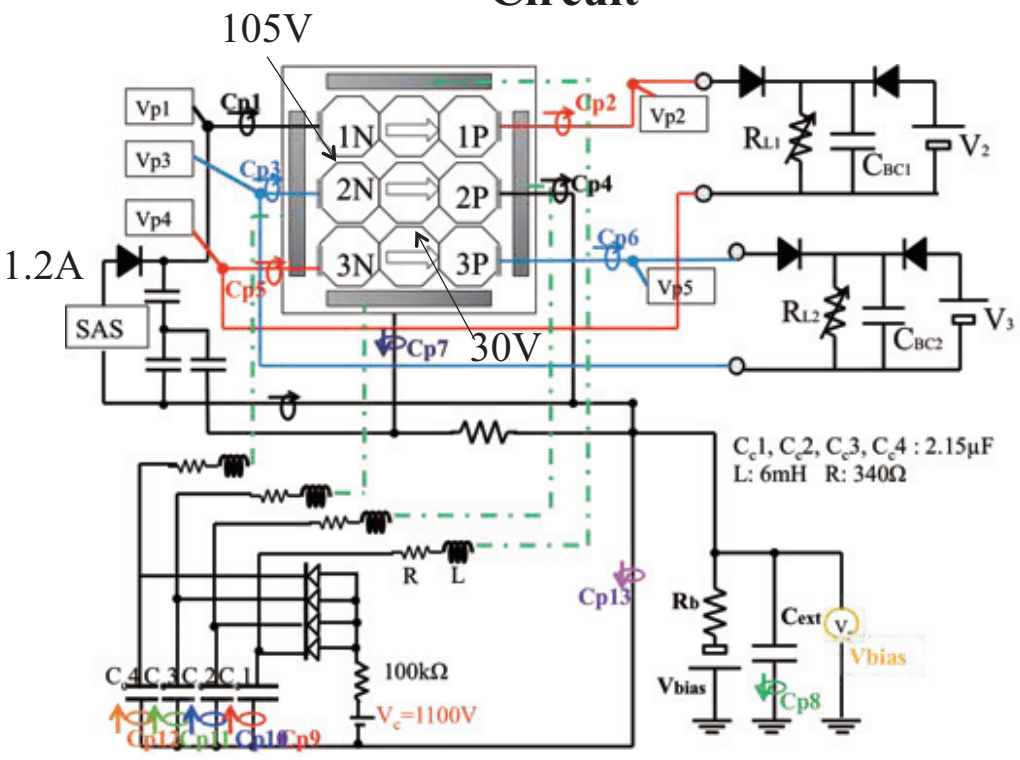
Circuit



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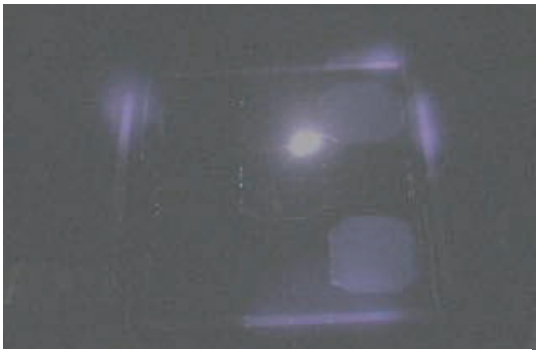
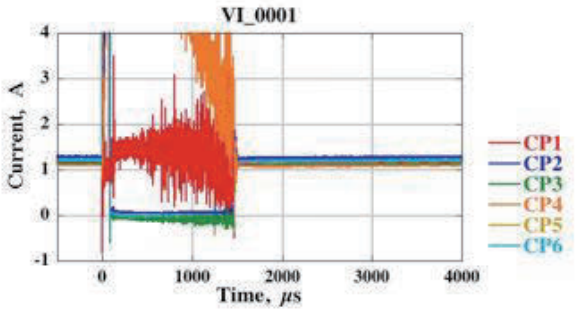
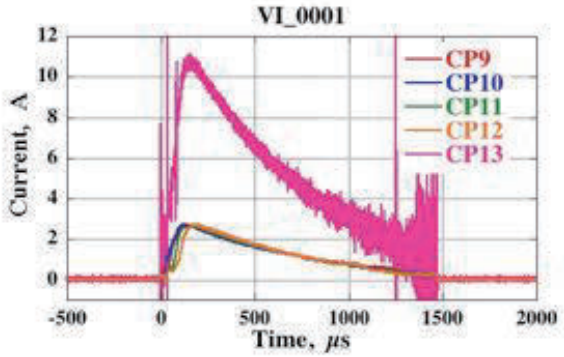
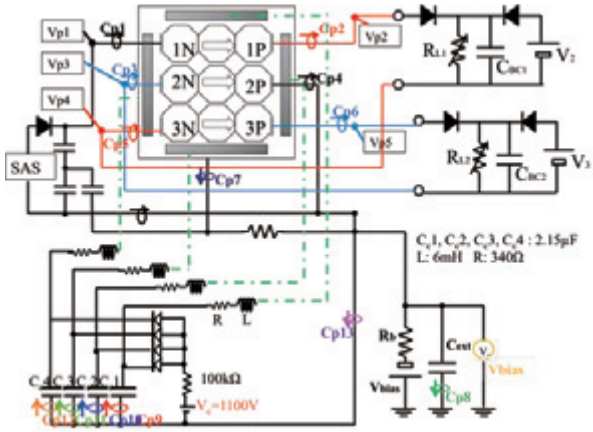
Secondary arc in wide gap









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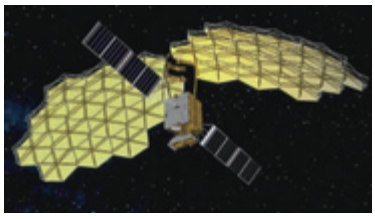
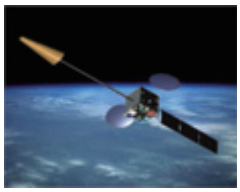
衛星地上帯電放電試験(1999年より)

はやぶさ(2003)

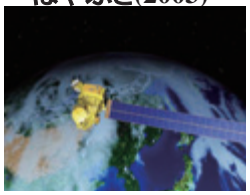


きく8号 (2006)

きずな(2008)



ひまわり7号(2006)

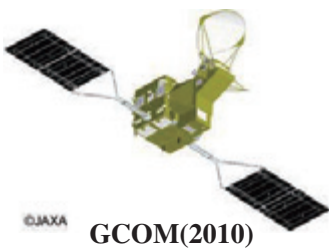


みどり2 (2003)
原因究明作業

だいち(2006)

きらり(2005)

いぶき(2008)



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GCOM(2010)

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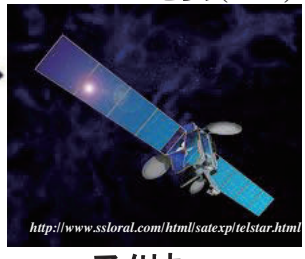
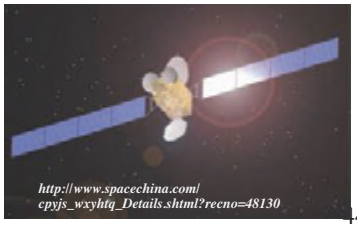
インド



アメリカ



中国

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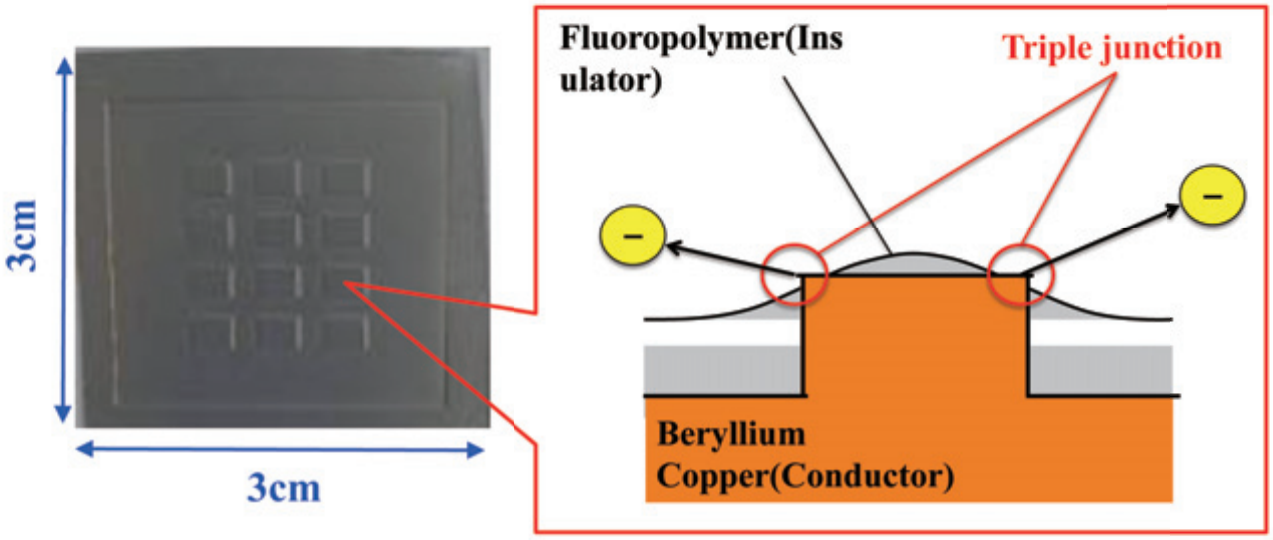
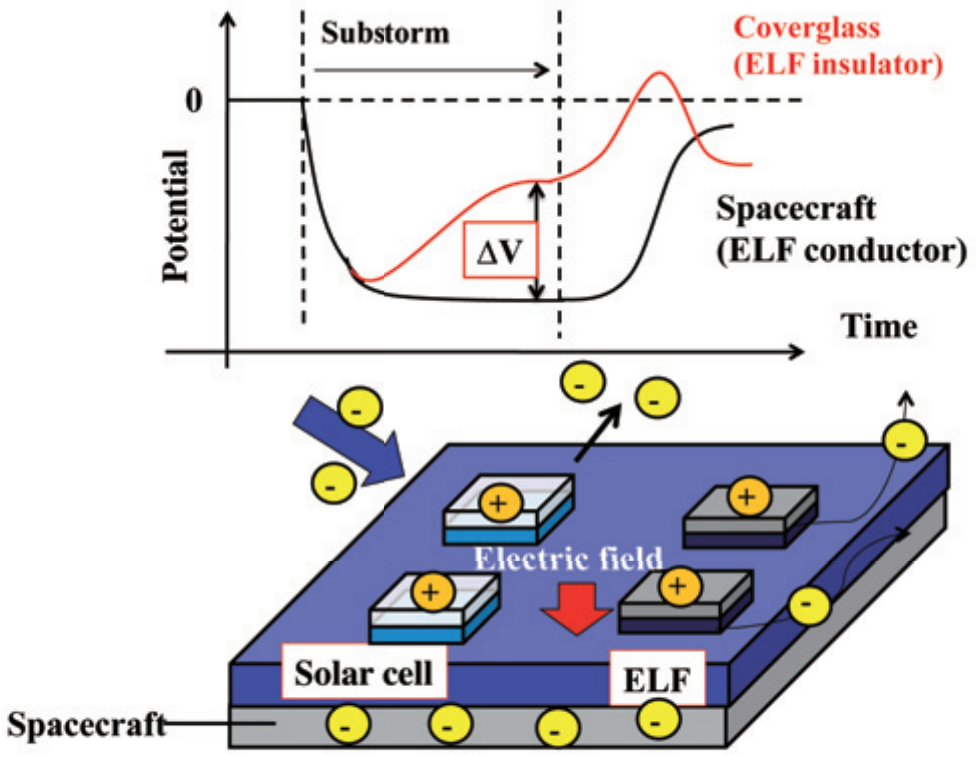
帯電放電抑制

- **ELF: Electron Emitting Film**



45

Charging mitigation principle



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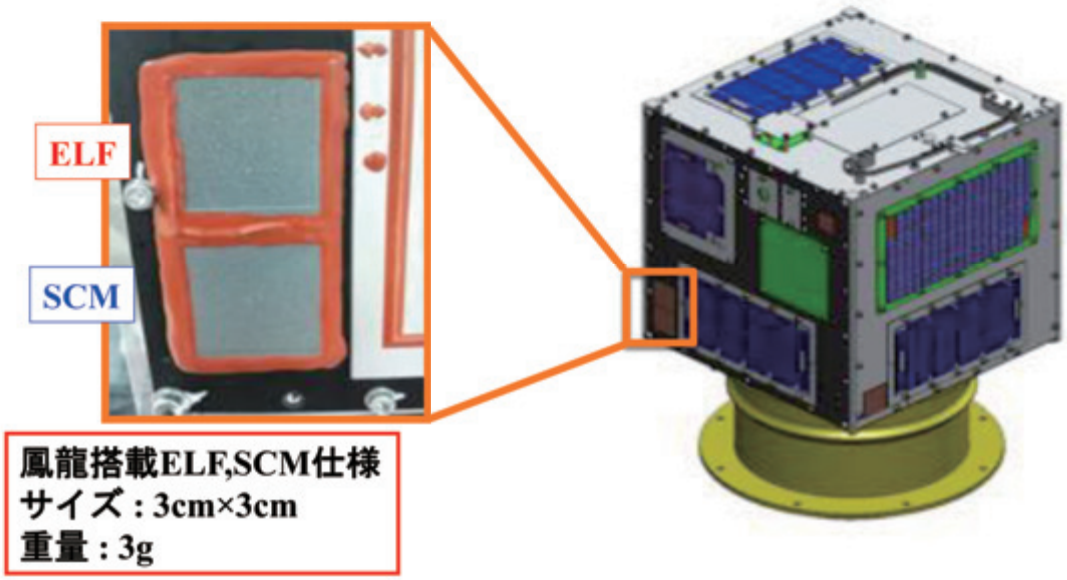
HORYU 2



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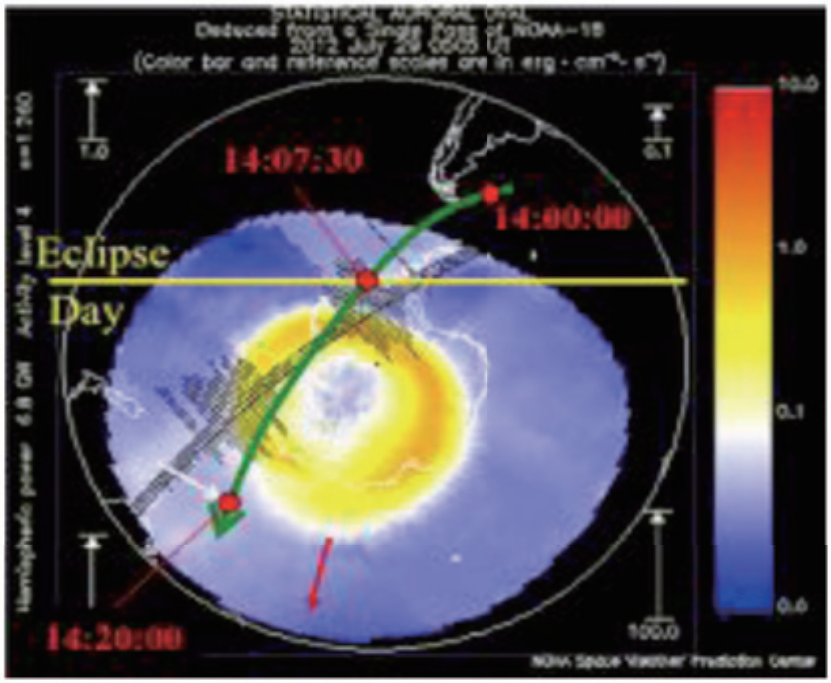
In-orbit demonstration

State of high-energy electron



Aurora strength
Electron energy
Position
orbit
Eclipse/day boundary

action time: 20min
start time14:00:00 JST
end time14:20:00 JST

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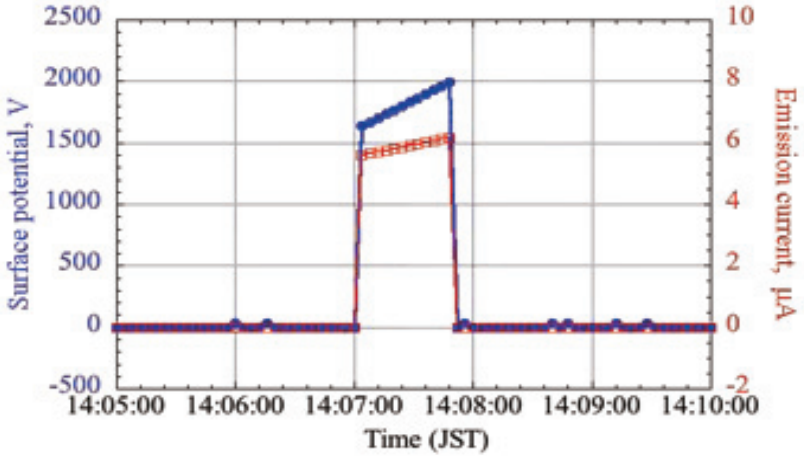
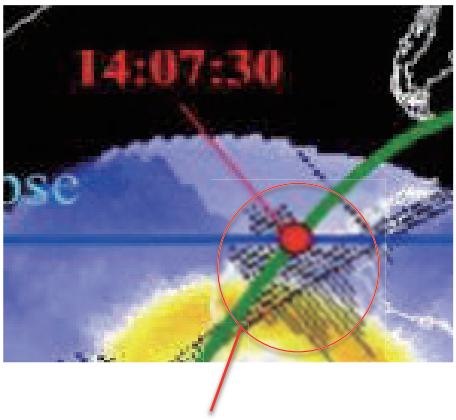
In-orbit demonstration

Test results





Emission of 6μA

Electron energy was very high

ELF operation in orbit was confirmed!

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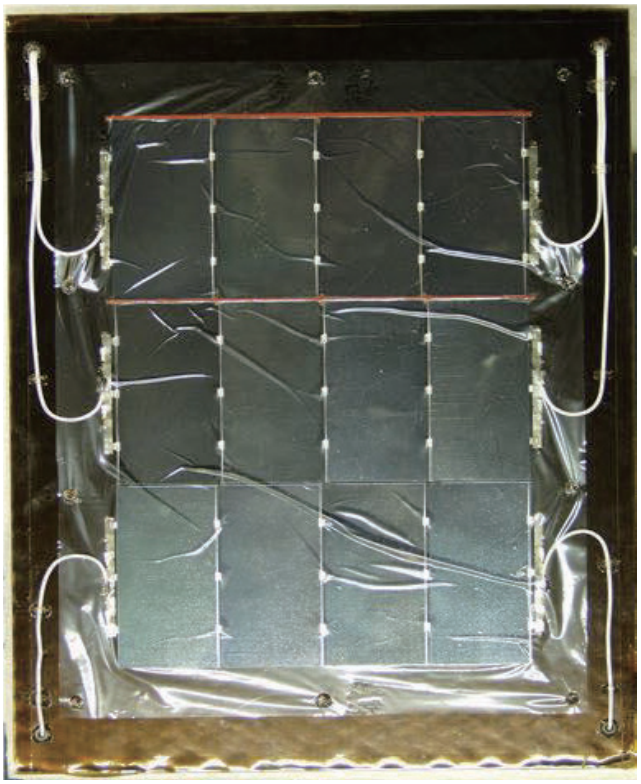
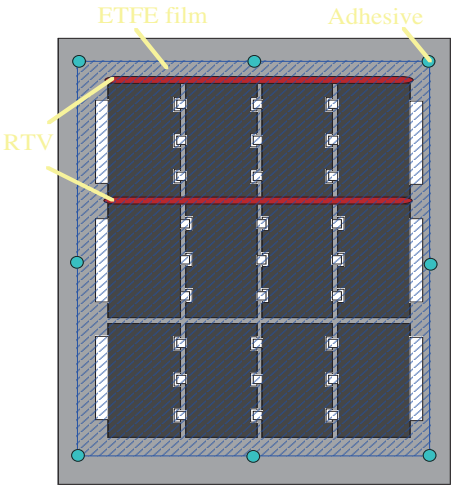
Film coupon

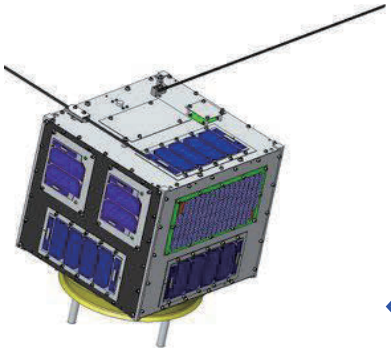




Film thickness: 12.5μm

Overview of HORYU-IIand High Voltage Mission

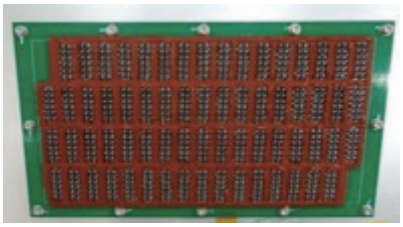
High Voltage Technology Demonstration Satellite ,HORYU-II



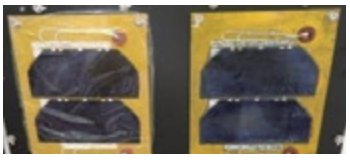
Horyu2
680km Sun-synchronous orbit

Nano-satellites are thus more suitable to higher risk missions

High Risk Mission



Solar arrays for generating high voltage



Solar arrays for mitigating to ESD

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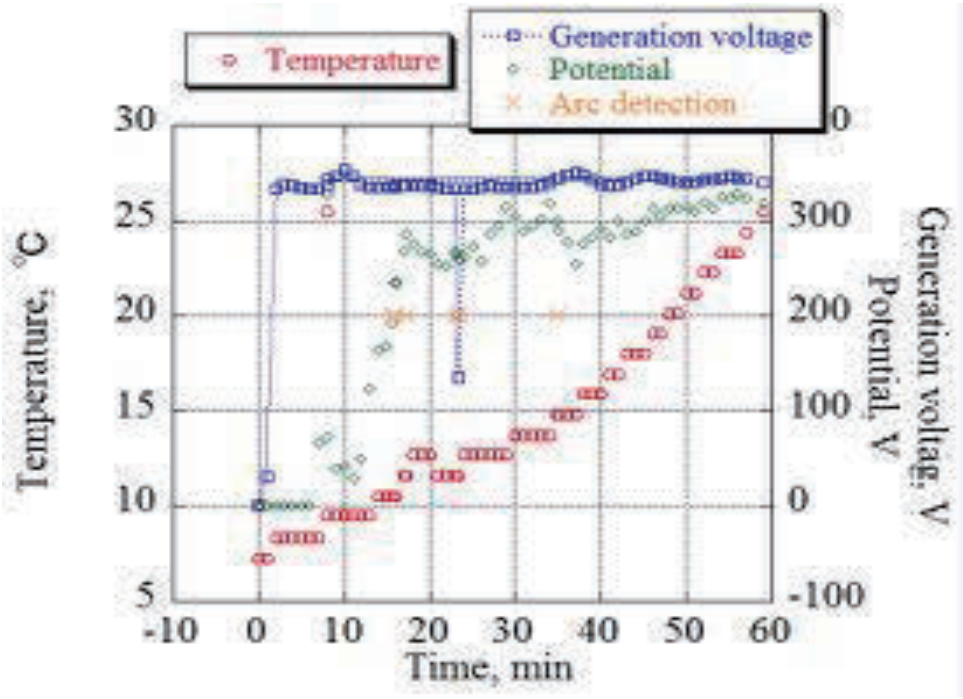
Mode 3: TJ array arcing test mode



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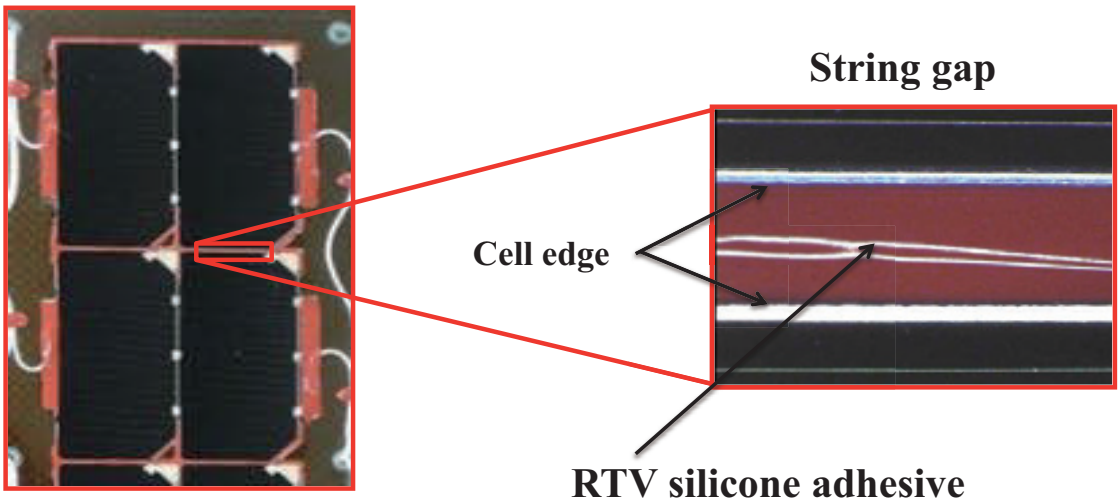
Grouting



Effect of aging on Discharge Tolerance of Grouted Solar Array Panels is unclear

Proton + Electron + Thermal cycling

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Visual examination result

● :Crack

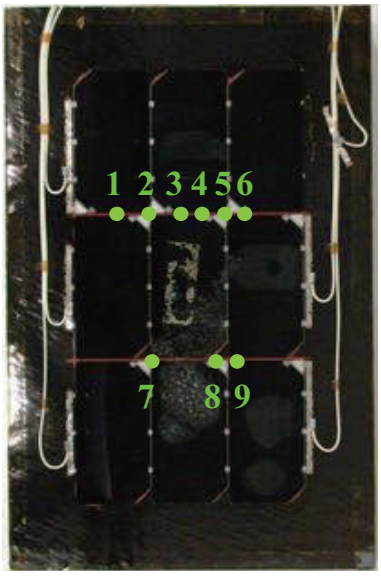
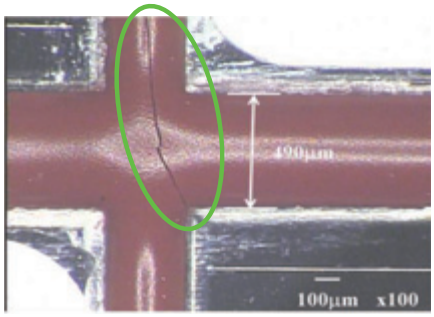
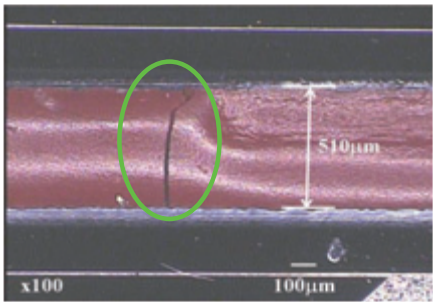


Photo of test coupon after simulated space environment test



Microscope picture of crack 2



Microscope picture of crack 4

Cracks were founded at the 9 points in total.

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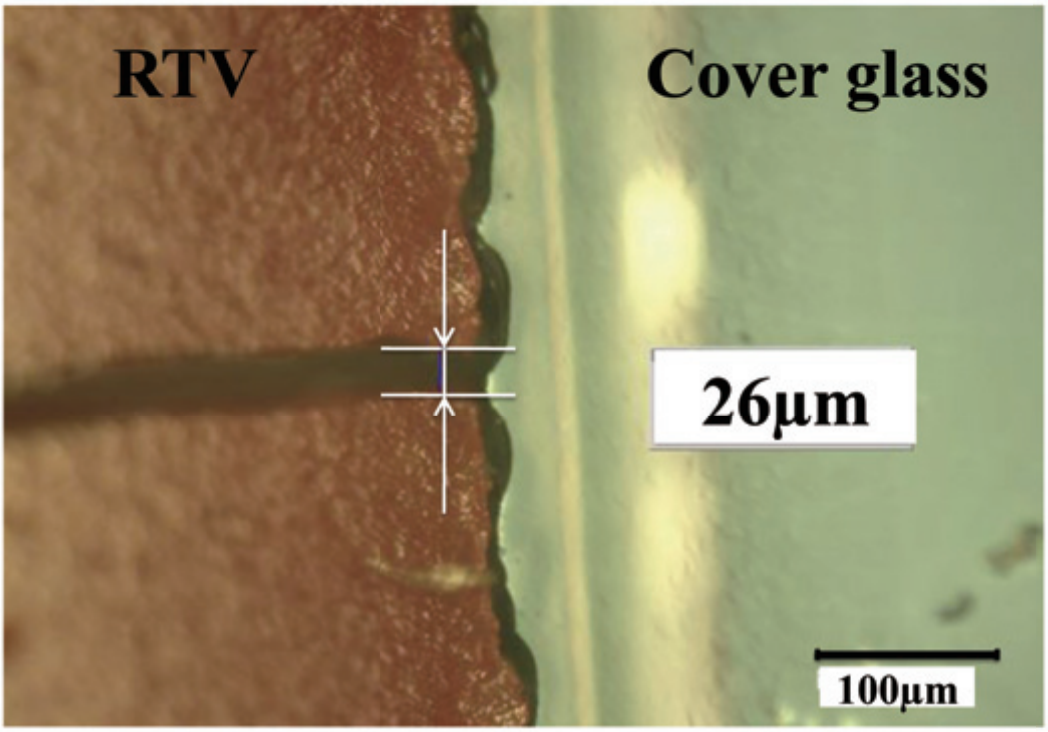
Width of crack



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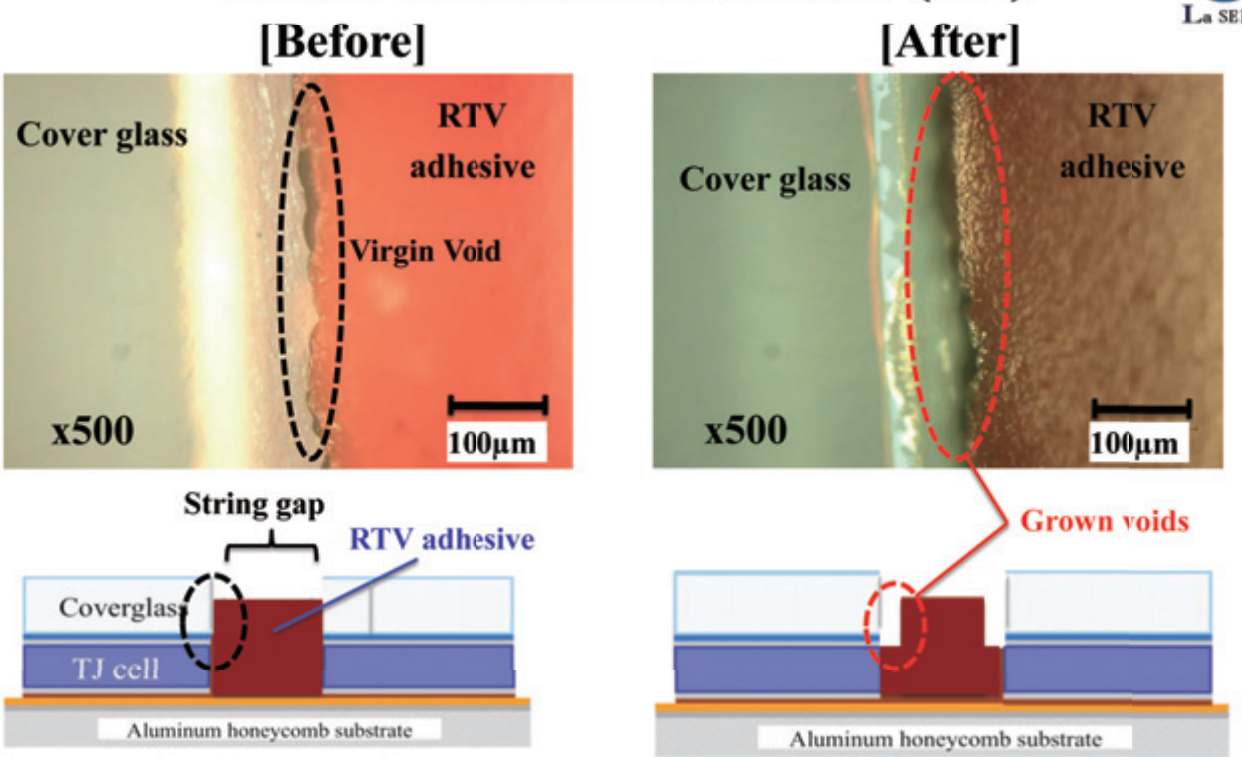
Visual examination result (2/2)



Growth of voids were found
at the interfaces between Cover glass and RTV-adhesive.

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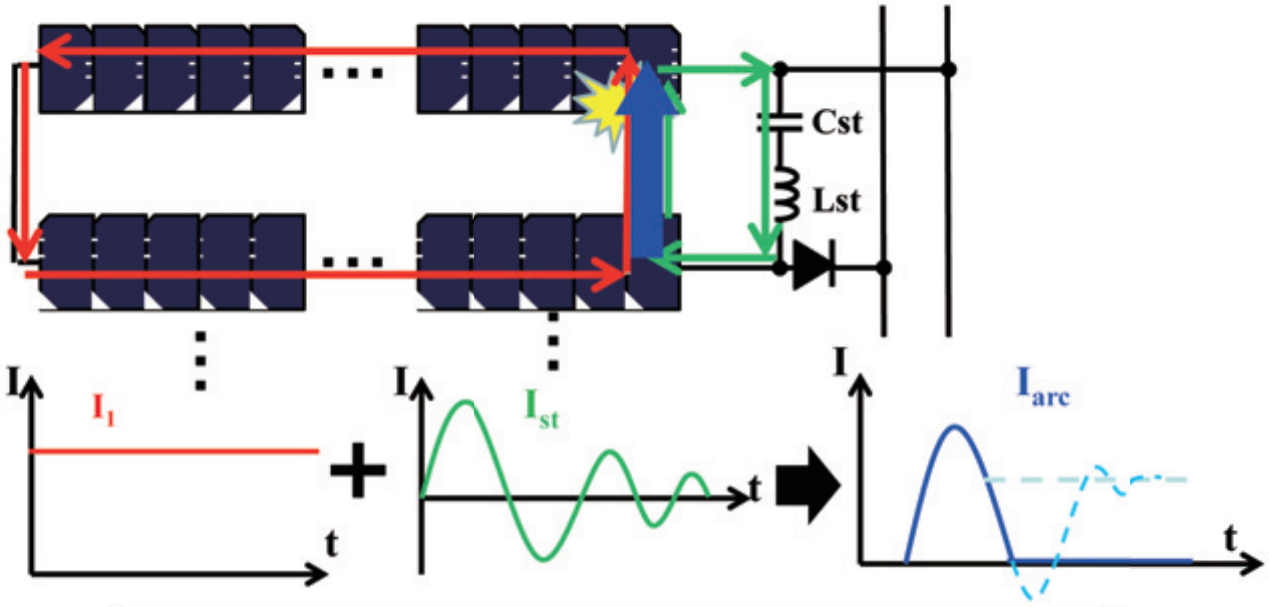
Sustained arc mitigation method



Cut arc current by capacitor and inductor

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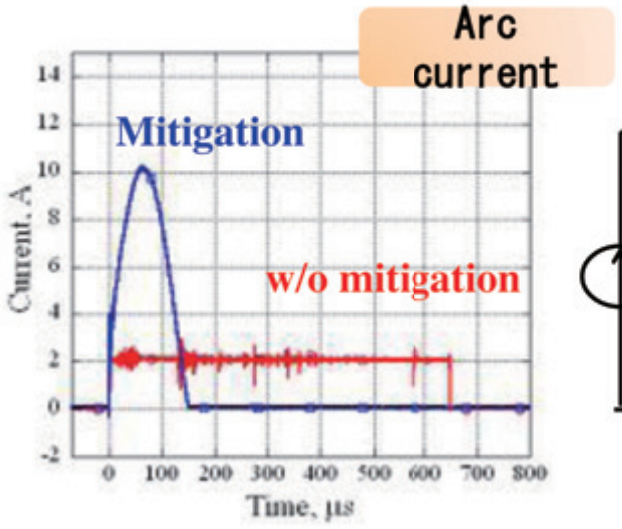
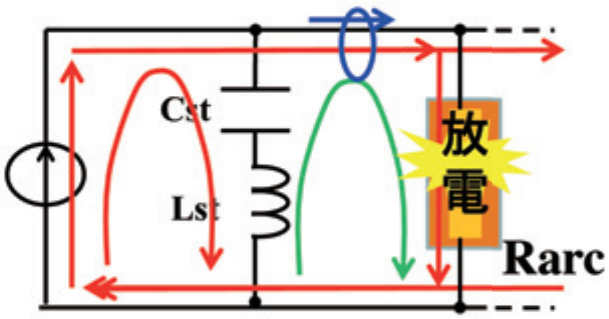
With mitigation method





WD19923 Spacecraft charging potential estimation in the worst case environments

- **Background**
  - **No criteria to estimate worst case of spacecraft charging in each space environment**
  - **Worst charging potential should be tested in ESD ground testing (ISO-11221)**

- **Main purpose**
  - **Provide space plasma environments for worst case differential potential simulation**
  - **Provide how to estimate worst potential difference with simulation code**

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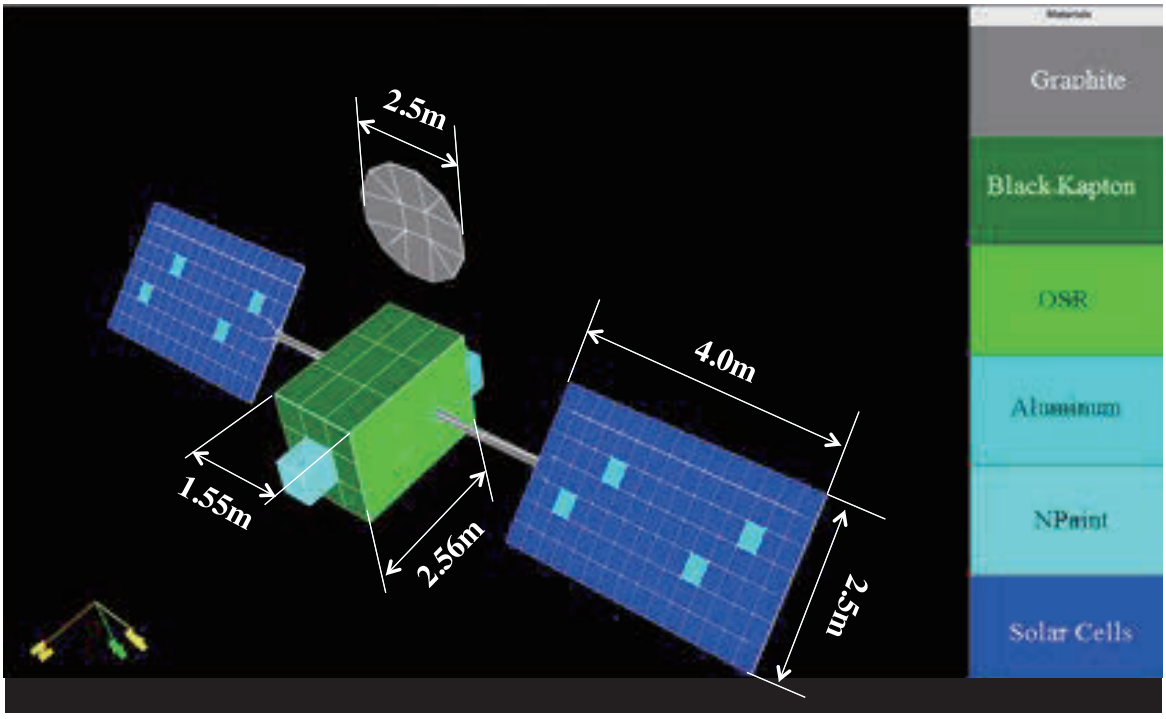
Model: NASCAP-2k



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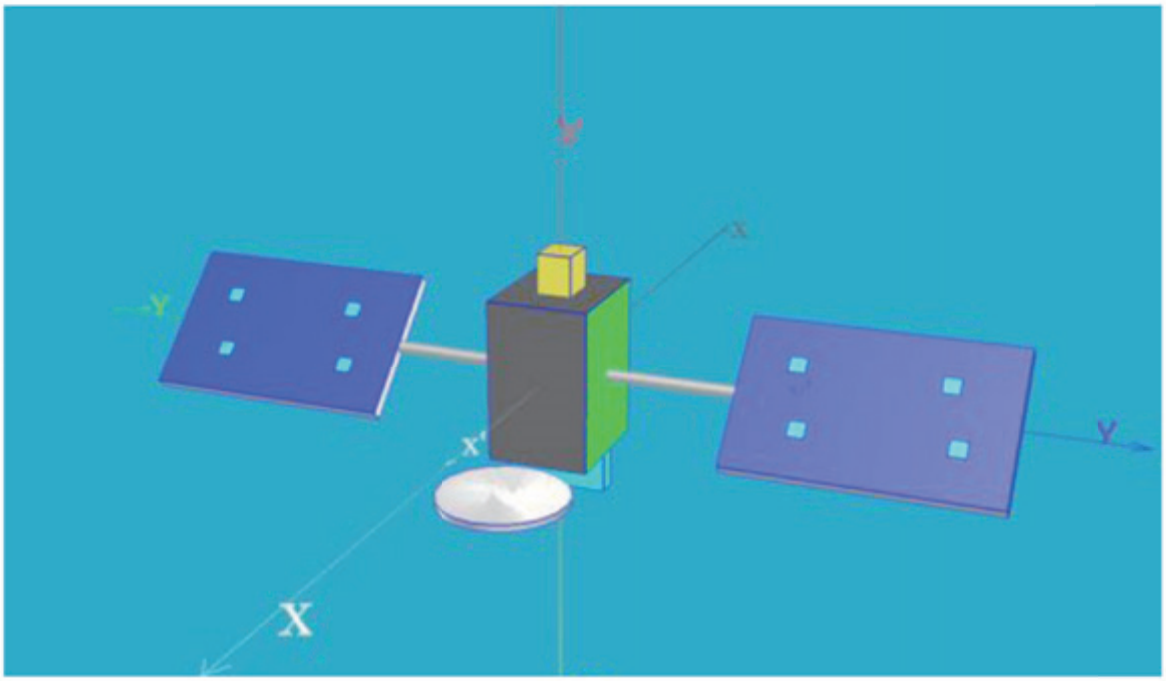
Model: MUSCAT



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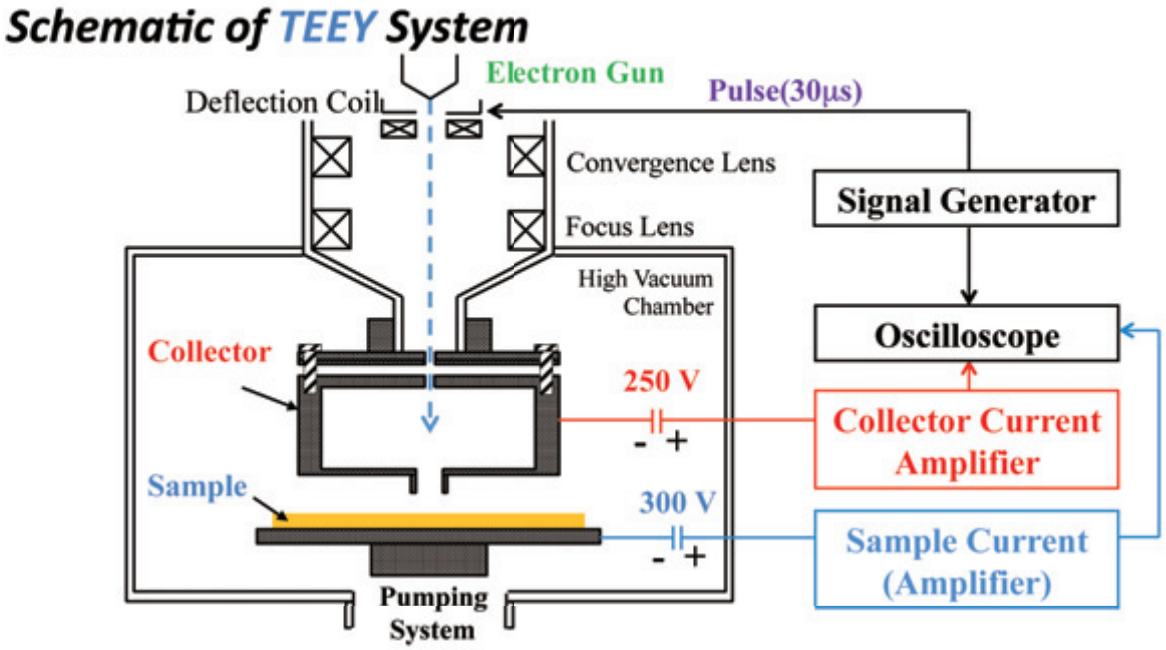
二次電子計測



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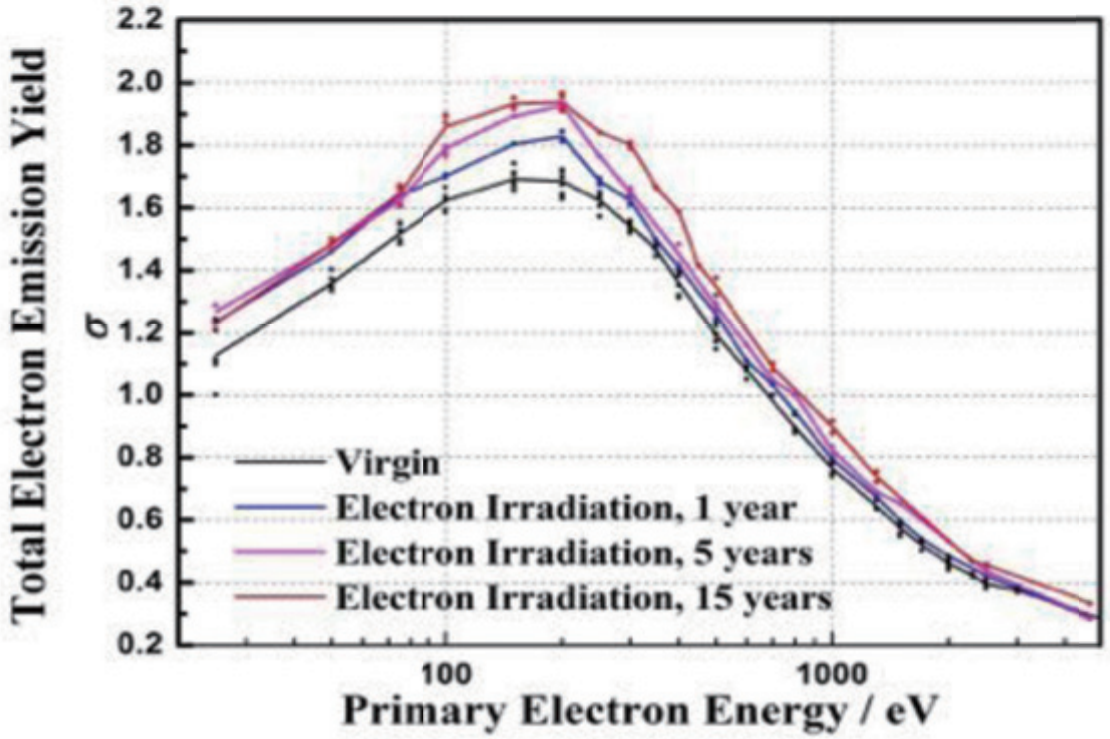
La SEINE

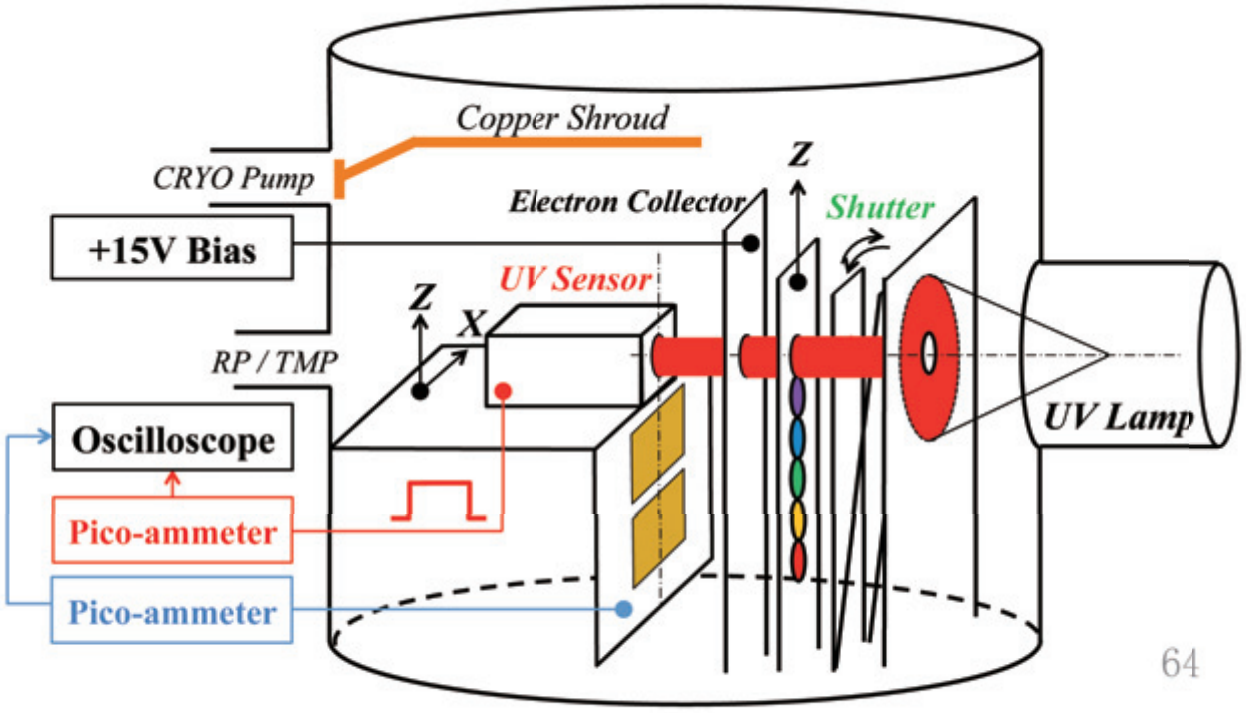
TEEY of Electron Irradiated Polyimide Film



La SEINE

光電子計測

Schematic of PEY System



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Kapton

Factors	TEEY		PEY
	yield	E_{max}	yield
Ultraviolet	↑	—	↑
Atomic Oxygen	↓	↑	↑↓
Electron	↑	—	↓
Proton	—	—	↑

↑ Increase ↓ Decrease — Unchanged

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