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Development of a radiation evaluation method for COTS parts at JAXA -SSD radiation testing method-

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Back Ground

- The Space Parts Technology Roadmap, which sets out JAXA's future development policy for space parts, promotes the use of COTS parts in space.
  - The candidates for COTS parts that are adapted for space are decided based on requests from space manufacturers.

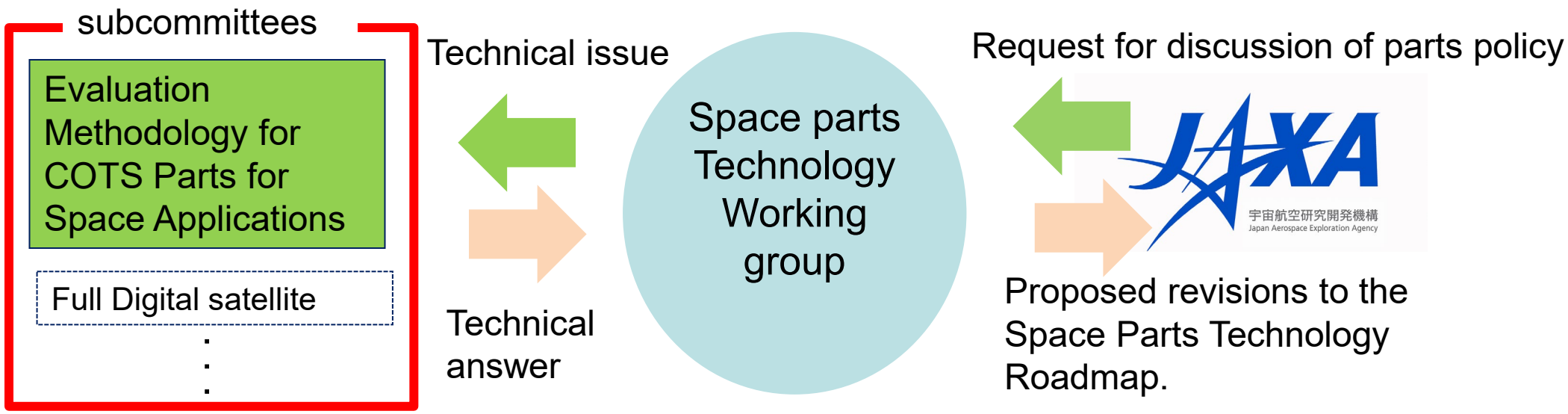


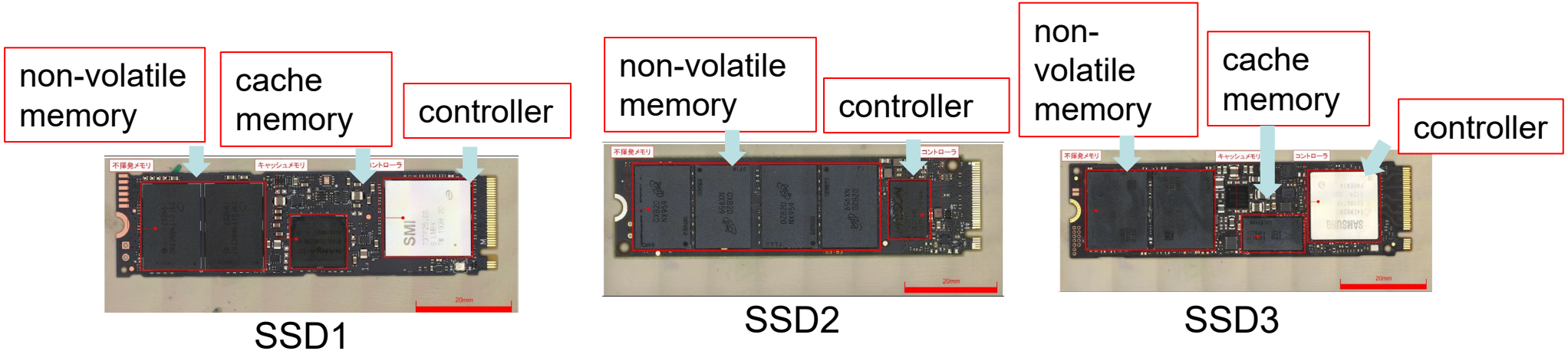
Figure1: Space Parts Technology Roadmap Review System(～FY2023)

Flow of evaluation of methods for adapting COTS parts to space at JAXA

- Procurement of multiple types of COTS parts
  - Investigation and recording of the internal structure of COTS parts
- Implementation of space adaptation tests and evaluation of test results.
- The information obtained through the space adaptation irradiation test would be reflected in JAXA's technical note.
  - Among the space adaptation evaluation tests, the radiation tests require further study of evaluation methods and results.
- The JAXA Handbook of Radiation-Resistant Design (JERG-2-143-HB001) would be updated to reflect the specific radiation testing methods and precautions for test COTS parts.

COTS SSD Test samples

- JAXA procured several types of SSDs(M.2 Type) for test samples. JAXA disassembled and investigated each parts of the SSDs and selected the following three types of SSDs for space adaptation evaluation.
  - Test sample1: SSD1 has a controller, external cache memory and non-volatile memory(type of non-volatile memory cell is 3DTLC NAND)
  - Test sample2: SSD2 has a controller and non-volatile memory(type of non-volatile memory cell is QLC NAND)
  - Test sample3: SSD3 has a controller, external cache memory and non-volatile memory (type of non-volatile memory cell is V-NAND3bit MLC)



COTS SSD Radiation test preparation

- JAXA considered that the biggest issue in using COTS SSDs in space was radiation evaluation. In order to carry out effective radiation resistance evaluations for SSDs, JAXA investigated test cases.

Table1: SSD test case and detectable SEE

SSD test case	Detectable event	Detection methods
SSD(Static) During the irradiation test, the data in the SSD is not read or written.	SEL	Check the current consumption during irradiation. The current consumption value increases intermittently.
	SEU, SEFI, Damage	After the irradiation is complete, or if the irradiation is interrupted, the SSD being tested can be read and written to in order to detect any events.
SSD(Dynamic) **During the irradiation test, data in the SSD is continuously read and written.**	SEU, SEFI	It can be detected by checking the data in the SSD during or after irradiation. If the SSD cannot be accessed during irradiation, it is highly likely that SEFI has occurred.
	Damage	After the irradiation is complete, or if the irradiation is interrupted, the SSD being tested can be read and written to in order to detect any events.

COTS SSD Heavy ion particle radiation test

- JAXA irradiated heavy particle on COTS SSD in Takasaki Ion Accelerators for Advanced Radiation Application(TIARA).
  - Heavy ion irradiation configuration
    - Irradiation source Ar(LET:10～15 MeV/(mg/cm2)) and Kr(LET:38～40 MeV/(mg/cm2))
    - Total fluence over 1×10E+6 p/cm2
    - SSD(static) :Fluence rate ～1×10E+3～4p/cm2/s （The irradiation is stopped several to check the internal data of the SSD.)
    - SSD(dynamic) : Fluence rate ～1×10E+2～3p/cm2/s
    - The irradiation test starts with Ar. Next, the irradiation source is switched to Kr.
  - Plan of Test sequence.
    - In order to evaluate the SEU and SEFI of COTS SSDs, Ar and Kr are used to irradiate SSDs (Dynamic).
    - For the resistance evaluation of SEL in COTS SSDs, Kr irradiation should be performed on the SSD (Static).

Results of Heavy Ion Irradiation on the SSD (Dynamic)

- Ar irradiation test results
  - In the Ar irradiation tests for SSD1, SSD2 and Controller of SSD3, the COTS SSDs stopped operating within Several tens of seconds after irradiation started. The irradiation test was carried out until the SSDs stopped operating normally even after the power was turned back on, but there were no test cases in which the planned fluence amount could be irradiated. ＊
  - SSD3 was destroyed after being irradiated with 1.2×10^5 p/cm2 to cache and non-volatile memory.

- After the Ar irradiation test, the COTS SSD sunder test was determined not to have been destroyed because it was possible to access it normally by sending an initialization command from the COTS SSD test jig.

Results of Heavy Ion Irradiation on the SSD (Dynamic)

- COTS SSD Ar irradiation test results (excerpts)-1
  - The irradiation test was stopped after detecting SEU, at about 1/10 of the planned total fluence.

	Irradiation source	Run No.	Fluence rate [p/cm2/s]	Irradiation time[s]	Total fluence [p/cm2]	Event during irradiation	Post-irradiation work
SSD1 Controller	Ar (LET=15.5 (MeV/mg/cm2))	1	4.5E+2	9	4.0E+3	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		2	5.4E+2	28	2.0E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		3	5.9E+2	77	6.6E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		4	7.1E+2	24	8.3E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		5	7.5E+2	42	1.2E+5	9 sec: 5-bit SEU detection 42 second: SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally

Results of Heavy Ion Irradiation on the SSD (Dynamic)

- COTS SSD Ar irradiation test results (excerpts)-2
  - After the Ar irradiation test finished, the SSD was initialized and it was possible to access the SSD normally.

	Irradiation source	Run No.	Fluence rate [p/cm2/s]	Irradiation time[s]	Total fluence [p/cm2]	Event during irradiation	Post-irradiation work
SSD1 Non-colatile memory	Ar (LET=15.5 (MeV/mg/cm2))	1	8.0E+3	3	2.2E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		2	8.0E+2	0	2.2E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		3	1.2E+2	80	3.2E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		4	1.1E+2	71	4.0E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		5	1.1E+2	51	4.5E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		6	1.2E+2	96	6.7E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering the SSD: SSD inaccessible

Results of Heavy Ion Irradiation on the SSD (Dynamic)

- Kr irradiation test results
  - In the kr irradiation tests for SSD1 , Controller of SDS2 and SDS3, the COTS SSD stopped operating within several of tens seconds after irradiation started. The irradiation test was carried out until the SSD stopped operating normally even after the power was turned back on, but there were no test cases in which the planned fluence amount could be irradiated.
  - The non-volatile memory of SSD2 was destroyed at the ～1 ×10E+4p/cm2 irradiated.
  - The cache memory and non-volatile memory of SSD3 was destroyed at the ～1 ×10E+4p/cm2 irradiated

Results of Heavy Ion Irradiation on the SSD (Dynamic)

- COTS SSD Kr irradiation test results (excerpts)
  - Access to the SSD3 did not recover. Therefore, it was determined that the SSD3 was destroyed.

	Irradiation source	Run No.	Fluence rate [p/cm2/s]	Irradiation time[s]	Total fluence [p/cm2]	Event during irradiation	Post-irradiation work
SDD3 controller	Kr (LET=37 (MeV/mg/cm2))	1	1.3E+2	6	8.0E+3	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		2	1.3E+2	65	9.4E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD inaccessible
SSD3 Non-volatile memory	Kr (LET=37 (MeV/mg/cm2))	1	1.3E+2	42	5.4E+3	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		2	1.3E+2	4	5.9E+3	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD inaccessible

Results of Heavy Ion Irradiation on the SSD (Static)

- Kr irradiation SSD(static)test results
  - SSD1(static) and SSD 2(static) was experiencing SEFI at every checkpoints for the controller, cache memory and flash memory.
  - SSD3(static) was experiencing SEFI at every checkpoints for the cache memory and non-volatile memory. The controller was destroyed at the first checkpoint.
- During the irradiation test, the SSD stopped working, so the test was terminated after about 1/10 of the planned fluence amount had been applied.
- In irradiation tests, no SEL was detected.

Results of Heavy Ion Irradiation on the SSD (Dynamic)

- COTS SSD Kr irradiation test results (excerpts)
  - Access to the SSD3 did not recover. Therefore, it was determined that the SSD3 was destroyed.

	Irradiation source	Run No.	Fluence rate [p/cm2/s]	Irradiation time[s]	Total fluence [p/cm2]	Event during irradiation	Post-irradiation work
SDD3 controller	Kr (LET=37 (MeV/mg/cm2))	1	1.3E+2	6	8.0E+3	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		2	1.3E+2	65	9.4E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD inaccessible
SSD3 Non-volatile memory	Kr (LET=37 (MeV/mg/cm2))	1	1.3E+2	42	5.4E+3	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		2	1.3E+2	4	5.9E+3	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD inaccessible

COTS SSD TID test

- JAXA irradiated gamma ray on COTS SSD in Takasaki Institute for Advanced Quantum Science
  - Irradiation test conditions
    - Gamma ray source is Co60
    - Three specimens were prepared for each of the test specimens SSD1, SSD2, and SSD3.
    - A test system was constructed that could irradiate the nine COTS SSDs prepared at the same time in a single irradiation test.
    - When 100 Gy, 300 Gy, and 1000 Gy are irradiated, the gamma ray irradiation is stopped and the state of the SSD being tested (data reading, writing speed, and power consumption) are checked.
    - After three months have passed since the end of irradiation, the reading and writing speeds and current consumption will be checked again.

COTS SSD TID test results

- The results of the tests confirmed that all SSDs were resistant to doses of 100 Gy or more.
- SSD1 and 2 were destroyed when irradiated to doses of 300 Gy or more but less than 1000 Gy.SSD3 was destroyed when irradiated to doses of 100 Gy or more but less than 300 Gy.

Table2: TID evaluation results for COTS SSDs

Test sample	Measurement results after 100 Gy irradiation	Measurement results after 300 Gy irradiation	Measurement results after 1000Gy irradiation	Measurement after annealing
SSD1	The SSD can be accessed normally.	The SSD can be accessed normally.	The SSD is destroyed Increase in power consumption, decrease in data reading speed, unable to write date.	The same measurement results as 1000 Gy
SSD2	The SSD can be accessed normally.	The SSD can be accessed normally.	The SSD is destroyed Increase in power consumption, decrease in reading speed, unable to write date.	The same measurement results as 1000 Gy
SSD3	The SSD can be accessed normally.	Increase in power consumption, decrease in reading and writing speed.	The SSD3 can not be accessed	The same measurement results as 1000 Gy

Change of irradiation source to COTS SSD

- JAXA conducted SEE and TID evaluations of COTS SSDs with the aim of developing a method for irradiating a large number of SSDs with radiation in a short period of time.
- JAXA was unable to obtain sufficient data for SEE evaluation of COTS SSDs due to the large number of events that occurred.

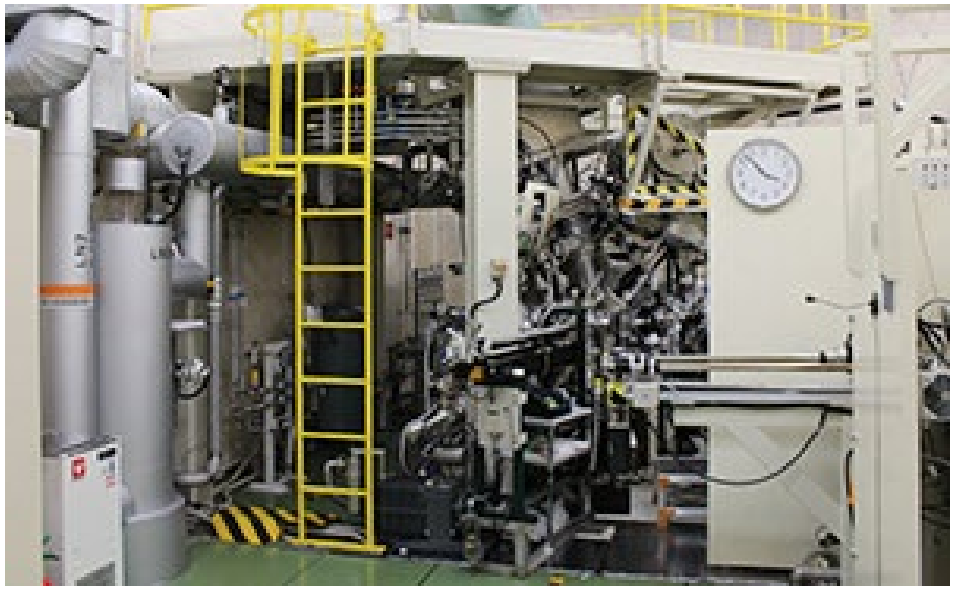


Figure: Electron beam test facility at JAXA

- Therefore, JAXA changed the purpose of the study to conduct detailed radiation tolerance of COTS SSDs.
  - Proton beams were selected for COTS SSD SEE evaluations.
  - Electron beams were selected for COTS SSD TID evaluations.

Preparing for TID resistance evaluation for SSDs

- TID resistance evaluation of SSDs using electron beams.
  - Electron beam irradiation test policy
    - The irradiation dose at which COTS SSD data can no longer be read or written will be accurately measured.
    - The electron beam test was performed on the entire SSD(Dynamic) system for comparison with the Co60 test, after which the controller, volatile memory, and nonvolatile memory were irradiated in that order.
    - The irradiation test is terminated when 1000 Gy or more has been irradiated.If the SSD stops reading or writing data during irradiation, restart the SSD.
    - If data can be read or written, continue the test. If data cannot be read or written, terminate the test.
  - Method for determining the energy of the electron beam used for irradiation
    - The acceleration energy of the electron beam was set at 1.2 MeV.
      - This allows the electron beam to penetrate the IC package and reach the semiconductor part, while the 3 mm thick aluminum plate shields the electron beam from reaching any other part of the target semiconductor.

Electron irradiation Test Results-1

- TID resistance evaluation of SSDs using electron beams.
  - After irradiating the entire SSD with electron beams, we irradiated each element of the SSD with electron beams to obtain radiation tolerance data.

Test sample	Results of electron beam irradiation	Results of gamma ray irradiation
SSD1	SSD was destroyed after 300 -350Gy irradiation.	SSDs were destroyed between 300-1000Gy irradiation
SSD2	The SSD was stopped when irradiated with 260-300 Gy. The SSD stopped when irradiated with 260-300 Gy. The SSD restarted and operated normally, so it was irradiated again.	SSDs were destroyed between 300-1000Gy irradiation
SSD3	SSD operation was destroyed after 110-140 Gy irradiation	SSDs were destroyed between 300-1000Gy irradiation

Electron irradiation Test Results-2

- TID resistance evaluation of SSDs using electron beams.
  - Electron beams were irradiated on each element (controller, cache memory, non-volatile memory) that makes up the SSD.

Test sample	Results of electron beam irradiation
SSD1	The Controller of SSD was operating normally even at 1.3 kGy irradiation. The cache memory and the non-volatile memory could no longer read and write data after 300 Gy irradiation.
SSD2（no external cache memory）	The Controller of SSD could no longer read or write data after 270 Gy irradiation. The non-volatile memory was operating normally even at 1.0 kGy irradiation.
SSD3	The Controller of SSD was operating normally even at 1.3 kGy irradiation. The cache memory could no longer read or write data after 200 Gy irradiation. The non-volatile memory could no longer read or write data after 110-140 Gy irradiation.

Preparation for SEE resistance evaluation for SSD

- JAXA irradiated proton beam(80MeV) on COTS SSD in Research center for accelerator, Tohoku University.
- Proton beams (80 MeV) are used to assess the probability of SEE due to low LET particles.
  - JAXA assess the probability of SEEs at the SSD by irradiating the each element of the SSD with proton irradiation. The total fluence of the proton irradiation was set to be at least 1*10^10p/cm2(≒13Gy). (The aim of this proton irradiation was to assess the effects of recoil atoms.)
    - After the irradiation is complete, check the internal data on the SSD while the power is still on. If the data on the SSD cannot be read or written, first restart the SSD power. If the data cannot be read or written even after restarting, initialize the SSD system to check that it is not faulty.

Proton irradiation test results

- SSD1 and SSD2 stopped working several times during proton irradiation test.
  - No abnormalities occurred in SSD3 when irradiated with proton beams.

Test sample and Status	During proton beam irradiation	SSD operation check after irradiation test
SSD1(Static)	SSD were stopped working when it was irradiated with 5.9E+9p/cm2～ 7.3E+9p/cm2 proton beam to each elements.	It became possible to read and write by restarting the power.
SSD1(Dynamic)	There were cases where the irradiation was carried out as planned and cases where the test stopped halfway through.	There were cases where it worked normally and cases where it worked by initializing.
SSD2(Static)	The irradiation test on the SSD was successfully completed.	There were cases where it worked normally and cases where it worked by restarting.
SSD2(Dynamic)	There were cases where the irradiation was carried out as planned and cases where the test stopped halfway through.	There were cases where it worked normally and cases where it didn't work
SSD3(Static)	The irradiation test on the SSD was successfully completed.	The SSD operated normally.
SSD3(Dynamic)	The irradiation test on the SSD was successfully completed.	The SSD operated normally.

Reflection in the Handbook of Radiation-Resistant Design

- The following was found from the results of the COTS SSD irradiation test.
  - As reported in this presentation, it has been found that there are differences between the events that occur with proton beams and those that occur with heavy particle beams. Therefore, in order to evaluate COTS SSDs, it is necessary to evaluate them with both proton beams and LET heavy particle beams.
- JAXA reflected the results of the irradiation tests on SSDs and the knowledge gained in the technical document. The technical document is added as an applicable document to the chapter on evaluating the space suitability of COTS parts in the JAXA Radiation-Hardened Design Handbook.

Conclusion

- This presentation showed that COTS SSDs are highly sensitive parts to radiation. In order to adopt COTS SSDs on space, the following countermeasures are required.
  - COTS SSDs should be used in subsystems where the risk of losing stored data is acceptable.
  - When using COTS SSDs in satellites, it is necessary to be able to perform initialization processing.
  - Since there is a possibility of data loss in orbit for COTS SSDs, it is necessary to quickly download the data in the COTS SSDs to the ground.

SSD Radiation Test Result(heavy ion beam)-1

- COTS SSD irradiation test results (excerpts)
  - The irradiation test was stopped after detecting SEU, at about 1/10 of the planned total fluence.

	Irradiation source	Run No.	Fluence rate [p/cm2/s]	Irradiation time[s]	Total fluence [p/cm2]	Event during irradiation	Post-irradiation work
SSD1 Controller SSD(Dynamic)	Ar (LET=15.5 (MeV/mg/cm2))	1	4.5E+2	9	4.0E+3	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		2	5.4E+2	28	2.0E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		3	5.9E+2	77	6.6E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		4	7.1E+2	24	8.3E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		5	7.5E+2	42	1.2E+5	9 sec: 5-bit SEU detection 42 second: SSD innaccesible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally

SSD Radiation Test Result(heavy ion beam)-2

- COTS SSD Ar irradiation test results (excerpts)
  - After the irradiation test, the SSD was initialized and it was possible to access the SSD normally.

	Irradiation source	Run No.	Fluence rate [p/cm2/s]	Irradiation time[s]	Total fluence [p/cm2]	Event during irradiation	Post-irradiation work
SSD1 Non-colatile memory SSD(Dynamic)	Ar (LET=15.5 (MeV/mg/cm2))	1	8.0E+3	3	2.2E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		2	8.0E+2	0	2.2E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		3	1.2E+2	80	3.2E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		4	1.1E+2	71	4.0E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		5	1.1E+2	51	4.5E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering The SSD: SSD accessible normally
		6	1.2E+2	96	6.7E+4	SSD inaccessible	Restarting the test equipment: SSD inaccessible Repowering the SSD: SSD inaccessible

SSD Radiation Test Result(electron)

	Test Subject	Electron beam irradiation Test results	SSD operation check after irradiation test
SSD1	whole system	SSD was stopped after 0.3 -0.35kGy irradiation.	The entire SSD is irradiated at once. The variation in dose amount is due to the position of the IC.
	Controller IC	The SSD was operating normally even at 1.3 kGy irradiation, which is set as the test end condition.	After the SSD was exposed to electron beams, it was not possible to read or write data. By restarting the SSD, it was possible to read and write data.
	Cache memory	SSD was stopped after 0.3 kGy irradiation.	After the SSD was exposed to electron beams, it was not possible to read or write data.
	nonvolatile memory	SSD was stopped after 0.3 kGy irradiation.	After the SSD was exposed to electron beams, it was not possible to read or write data.
SSD2	Whole system	SSD was stopped after 0.26 -0.31kGy irradiation.	The entire SSD is irradiated at once. The variation in dose amount is due to the position of the IC.
	Controller IC	SSD was stopped after 0.27kGy irradiation.	After the SSD was exposed to electron beams, it was not possible to read or write data.
	cache memory	N/A	N/A
	nonvolatile memory	SSD operation stopped after 1.0 kGy irradiation	After the irradiation was completed, the SSD was able to read and write data normally.

SSD Radiation Test Result (electron)

	Test Subject	Electron beam irradiation Test results	SSD operation check after irradiation test result
SSD3	Whole SSD	SSD operation stopped after 0.11-0.14 kGy irradiation	The entire SSD is irradiated at once. The variation in dose amount is due to the position of the IC.
	Controller IC	The SSD is operating normally even at 1.3 kGy irradiation, which is set as the test end condition.	After the irradiation was completed, the SSD was able to read and write data normally.
	cache memory	SSD was stopped after 0.20kGy irradiation. (The operation of the SSD stopped temporarily every 20 Gy irradiation.)	After the SSD was exposed to electron beams, it was not possible to read or write data.
	nonvolatile memory	SSD was destroyed after 0.13kGy irradiation.	After the SSD was exposed to electron beams, it was not possible to read or write data.

SSD1 Radiation Test Result(Proton)

Sample name	Test Subject	Proton beam(80MeV) irradiation test results	SSD operation check after irradiation test result
SSD1	Controller IC	SSD(static): SSD was stopped working when it was irradiated with 5.9E+9p/cm2 proton beam.	By restarting the SSD, it became possible to read and write data.
		SSD(Dynamic) 2 irradiation test samples No.1 SSD was stopped working when it was irradiated with 4.3E+9p/cm2 proton beam. No.2 The proton beam irradiation test was completed after irradiating 1.2 × 10E+10p/cm2. (The SSD stopped twice during the irradiation test.)	No.1:It didn't work even after restarting the SSD. It worked after initializing the SSD. No.2: The SSD is operating normally.
	cache memory	SSD(static): 2 irradiation test samples No.1 and No.2: SSD was stopped working when it was irradiated with 6.2E+9p/cm2 proton beam.	NO.1 and No.2:It stopped during the SSD operation check after irradiation. It became possible to read and write by restarting the power.
		SSD(Dynamic) 2 irradiation test samples NO.1 and No.2 The proton beam irradiation test was completed after irradiating 1.2 × 10E+10p/cm2. (Multiple SEUs occurred.)	NO.1 and No.2:It stopped during the SSD operation check after irradiation. It became possible to read and write by restarting the power.
	Non-volatile memory	SSD(static): 1 irradiation test sample SSD was stopped working when it was irradiated with 7.3E+9p/cm2 proton beam.	It stopped during the SSD operation check after irradiation. It became possible to read and write by restarting the power.
		SSD(Dynamic) 1 irradiation test sample The proton beam irradiation test was completed after irradiating 1.2 × 10E+10p/cm2. (The SSD stopped twice during the irradiation test.)	It stopped during the SSD operation check after irradiation. It became possible to read and write by restarting the power.

SSD2 Radiation Test Result (Proton)

Sample name	Test Subject	Proton beam(80MeV) irradiation test results	SSD operation check after irradiation test result
SSD2	Controller IC	SSD(Dynamic): 1 irradiation test sample The proton beam irradiation test was completed after irradiating 1.4 × 10E+9p/cm2. (Due to frequent SSD malfunctions, the irradiation rate was reduced by two digits. As a result, the amount of irradiation at the end of the test was reduced by one digit.)	It stopped during the SSD operation check after irradiation. It became possible to read and write by restarting the power.
		SSD(static) 1 irradiation test sample The proton beam irradiation test was completed after irradiating 1.7 × 10E+9p/cm2.	It stopped during the SSD operation check after irradiation. It became possible to read and write by restarting the power.
	Non-volatile memory	SSD(Dynamic): The four test subjects were irradiated. No.1 and NO.2 The proton beam irradiation test was completed after irradiating 1.1 × 10E+10p/cm2. NO.3 and No.4 SSD was stopped working when it was irradiated with 6.2E+9p/cm2 proton beam.	No.1 and No.2: The SSD are operating normally. No.3 and No.4: The SSD did not work even after rebooting or initialising.
		SSD(static): 2 irradiation sample* (No.1, No.2) The proton beam irradiation test was completed after irradiating 1.1 × 10E+10p/cm2.	No.1 and No.2: The SSD are operating normally.

SSD3 Radiation Test Result (Proton)

sample name	Test Subject	Proton beam(80MeV) irradiation test results	SSD operation check after irradiation test result
SSD3	Controller IC	SSD(Dynamic) 2 irradiation test samples No.1 and No.2 : The proton beam irradiation test was completed after irradiating 1.1×10^10p/cm2.	No.1 and No.2: The SSD are operating normally.
		SSD(Static)1 irradiation test sample The proton beam irradiation test was completed after irradiating 9.4×10E+9p/cm2.	The SSD are operating normally.
	cache memory	SSD(Dynamic) 1 irradiation test sample The proton beam irradiation test was completed after irradiating 1.1×10E+10p/cm2.	The SSD are operating normally.
		SSD(Static)1 irradiation test sample The proton beam irradiation test was completed after irradiating 1.2×10E+9p/cm2.	The SSD are operating normally.
	nonvolatile memory	SSD(Dynamic) 1 irradiation test sample The proton beam irradiation test was completed after irradiating 1.2×10E+10p/cm2.	The SSD are operating normally.
		SSD(Static)1 irradiation test sample The proton beam irradiation test was completed after irradiating 1.1×10E+9p/cm2.	The SSD are operating normally.