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イオンビーム照射を用いる静止軌道デブリの除去

GEO Debris Removal using Ion Beam Irrradiation

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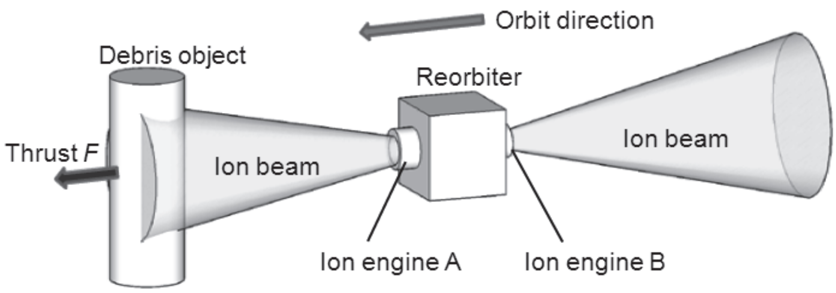
イオンエンジンを利用して静止軌道上の大型デブリを投棄軌道に輸送するデブリ除去方法を提案した。除去機にはイオンエンジンを 2 台搭載し、一方のイオンエンジンから噴射したイオンビームでデブリを照射して推力を与え、その軌道を変更する。他方のイオンエンジンの推力によってデブリとの間隔を一定範囲に保ちつつ、約 300 km 高い投棄軌道まで除去機の高度を上げる。本方式はデブリの把持が不要なため、デブリの詳細形状に依存しないし、回転しているデブリにも適用できる。ミッション検討例では、軌道上初期質量 1.5 ton の除去機を用いて約 170 日で 6 個のデブリが除去できた。本方法に特有な課題であるイオンビームの収束性については、数値計算と基礎実験によって必要な照射効率を達成する目処を得た。ビーム被照射面からのバックスパタリングについては、実験的な評価によって致命的な除去機の汚染問題がないことを確認した。

We proposed a concept for a reorbiter using ion engines to reorbit large GEO debris objects up to a disposal orbit. The reorbiter, equipped with two ion engines, exhausts an ion beam from one of the ion engines to irradiate and thrust a debris object to change its orbit. The other ion engine is operated so that the reorbiter follows the debris object. Their orbits are raised to a disposal orbit approximately 300 km higher. This system can operate without catching debris objects; thus, it can be applied without regard to their detailed shapes or rotations. A typical model mission was studied, and the results showed that six debris objects can be reorbited in about 170 days with a reorbiter of 1.5 ton. The beam convergence and the effects of beam irradiation were recognized as critical issues. Numerical calculations and basic experiments gave a feasibility of the required irradiation efficiency. The back-sputtered materials from the irradiated surfaces were experimentally evaluated, and the results indicated no serious contamination problems on the reorbiter.



イオンビーム照射を用いるデブリ軌道変更の概念
Concept of Space Debris Reorbiting Using Ion Beam Irradiation

January 22, 2013
The 5th Space Debris Workshop

GEO Debris Removal using Ion Beam Irradiation
イオンビーム照射を用いる静止軌道デブリの除去

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Outline

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3. Reorbiter System
4. Example Removal Plans
5. Issues to be Addressed
   - Ion Beam Convergence
   - Effects of Beam Irradiation
   - Non-Cooperative Rendezvous
6. Conclusions

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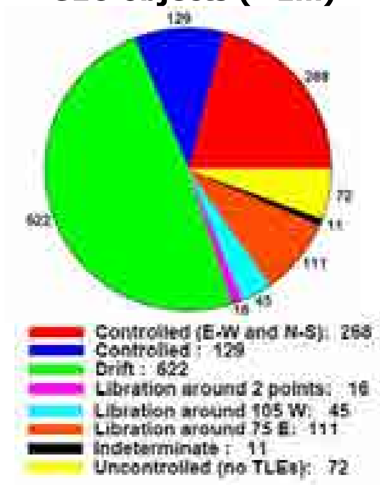
Background

- **Features and Problems in GEO Debris**
  - Debris in GEO will stay there permanently.
  - Not all of GEO satellites have been reorbited after end of mission.
  - Number of debris objects is increasing.
  - Though no collisions have been reported so far, they would bring very serious effects if they occur (no decay by fragmentation).
  - Same librating objects repeatedly approach operational satellites.
  - Development of technologies of space debris removal should be supported (GEO satellite operator)
  - Thus, GEO debris removal will be needed in the near future.

GEO objects (>1m)



Total: 1274
Uncontrolled in total: 877
Status: January 2011
(Reference ESOC)

Object number		
Orbit	> 10 cm	> 1 m
LEO	12,000	1,600
GEO	3,200*	1,000

*Conservative estimate

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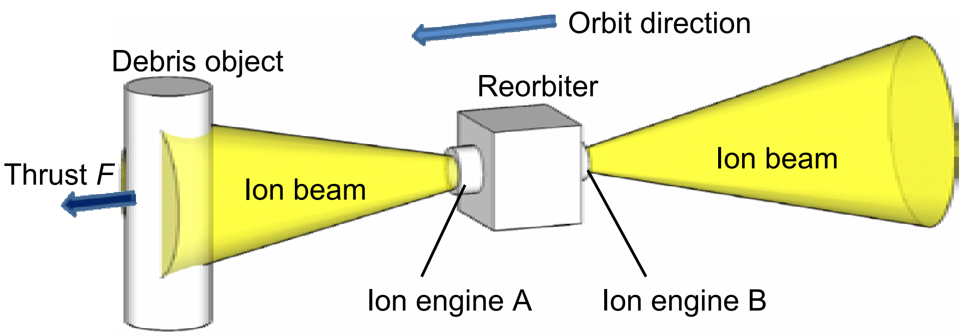
Concept of the Reorbiter (1/2)

- **Operation Procedure**
  1. The reorbiter with two ion engines A and B approaches a debris object.
  2. The ion beam from ion engine A irradiates the debris and gives it a thrust.
  3. This thrust raises the orbit of the debris gradually.
  4. Ion engine B is also operated so that the reorbiter can follow the debris.
  5. The thrusts of the ion engines are adjusted so that the distance between the debris and the reorbiter would be kept with a certain range.
  6. After they reach the disposal orbit about 300-km higher than GEO, the reorbiter returns to GEO to reorbit another debris object.



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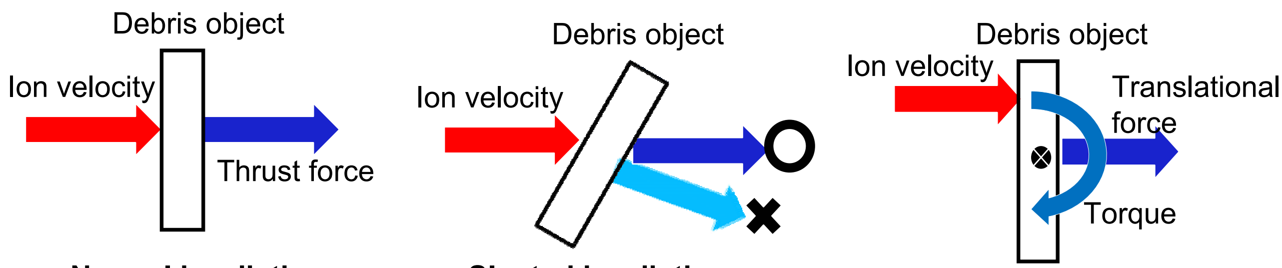
Concept of the Reorbiter (2/2)

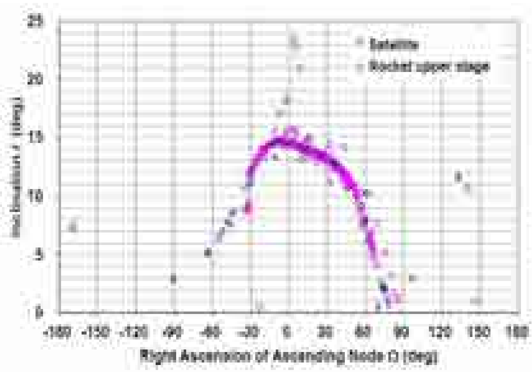
- **Features in comparison with contact ADR**
  - No docking with non-cooperative debris objects
  - No dependence on the details of debris objects
  - No "single-shot" step like harpoon shooting or net casting
- **Features in dynamics**
  - Thrust to a debris object has the same direction as the ion beam, so the thrust direction is independent on its shape and attitude.
    - Collisions of ions to a debris object are almost perfectly inelastic, so momentum of the ions is almost perfectly transferred to the debris object.
    - Irradiation off the center of mass of a debris object causes torque to the debris object, but the translational force is not slanted.



Normal irradiation **Slanted irradiation** **Off-center irradiation**

Reorbiter System (1/4)

- **Sample mission model**
  - Objects in GEO are concentrated near a single curve of RAAN vs. inclination, so efficient reorbit is possible.
  - Six objects with i < 2 deg and Ω < 5 deg.
  - Spin-stabilized satellites and rocket bodies were considered.



Sample Model

Debris object	Mass (kg)	Diameter (m)	i (deg)	Ω (deg)	Apogee above GEO (km)	Perigee above GEO (km)
Satellite#1	125	1.4	13.0	3	0	0
Satellite#2	250	1.6	13.4	2	125	30
Satellite#3	500	2.0	13.7	1	125	-30
Rocket upper stage#1	2000	3.0	14.0	0	125	-125
Rocket upper stage#2	2500	3.7	14.5	-1	30	-250
Rocket upper stage#3	3000	3.7	15.0	-2	-30	-250

Reorbiter System (2/4)

- **Ion Engines**
  - **For Irradiating Debris Objects**
    - Highly converged ion beams are required for efficient irradiation.
    - Then, we can have longer separation to the debris object, safer orbit control and smaller back-sputtering effects, and a smaller system.
  - **For Orbit Control**
    - Conventional ion engines without special requirements.

Ion Engine Requirements

Function	Debris irradiation	Orbit control
Thrust per thruster	20 mN	40 mN(*)
Number	4 + 4 backups	4 + 4 backups
Specific impulse	3000 s	3000 s
Thrust-to-power ratio	25 mN/kW	30 mN/kW
Propellant	Xenon	Xenon
Beam divergence	25% half angle < 3 deg 80% half angle < 6 deg	as is

* Throttled while ascending

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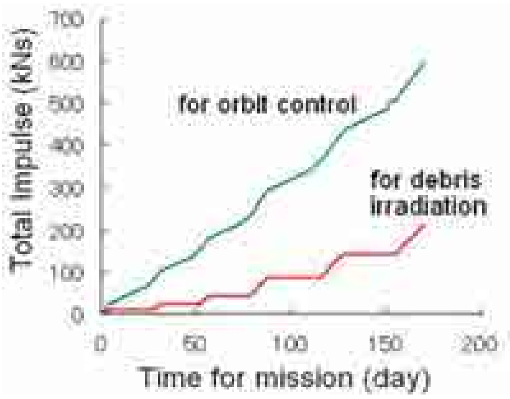
Reorbiter System (3/4)

Total impulse and propellant mass

Total impulse (kNs)	Orbit control	596
	Debris irradiation	212
	In total	808
Xenon mass (kg)	Required	27.5
	Margin (11%)	3.5
	Total	31.0



- **Calculation of ΔV**
  - We assumed the initial reorbiter mass of 1.5 ton and the distance to the debris object of 20 m.
  - Spiral circular orbit transfers, elliptic to circular orbit transfers, and inclination changes are considered.
- **Mission Summary**
  - Six debris objects can be reorbited in 170 days with 31 kg of xenon.
  - For a two-year mission, it would reorbit 24 debris objects.
  - Constraints on the mission period would be propellant mass, ion engine lifetime, and contamination due to back-sputtering.

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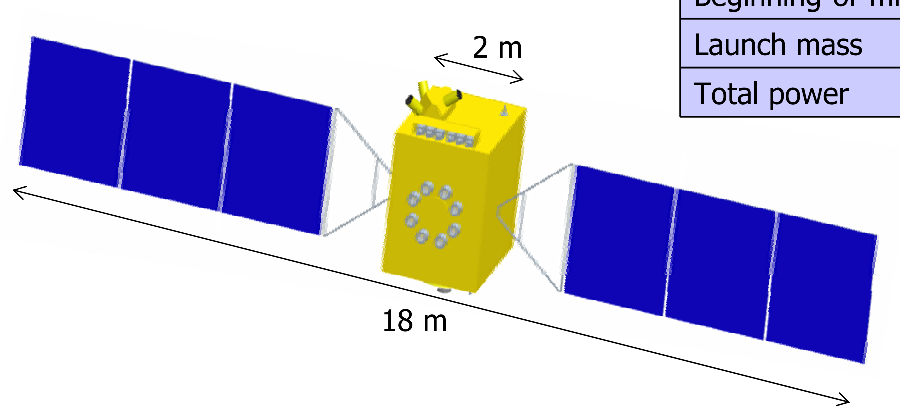
Reorbiter System (4/4)

- **Scale of the Reorbiter System**
  - The scale of the reorbiter was estimated from the specifications of some geostationary satellites with similar power levels.
  - Power consumption of the ion engines is about 5.9 kW.

Mass and Power (Target)	
Dry mass	1240 kg
Propellant (Xenon)	31 kg
Beginning-of-mission mass	1271 kg
Launch mass	2500 kg
Total power	7 kW



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Example Removal Plans (1/4)

- **Candidates for removal**
  - Objects in geopotential wells (librating objects)
  - Objects repeatedly approaching operational satellites
  - Threating objects for GEO satellite operators (forcing frequent collision avoidance maneuvers).
- **Examples**
  - Raduga 1-7 (2004-010A)
  - COSMOS 2379 (2001-037A)
  - Proton-K forth stage Block DM
  - Ekran 4 (1979-087)
- **Additional assumptions for 3-axis satellites**
  - Irradiation only for satellite body
  - 30-m distance apart

Objects in geopotential wells

Characteristic	East well (75 deg)	West well (105 deg)	Trapped in both wells
Payload: Radugas (29), Gorizonts (9), Ekrans (8), etc.	83	39	15
Rocket body: Largely Proton-K forth stages	17	0	3
Debris: 2006 Feng Yun and 1978 Ekran 2	2	0	0
Total	102	39	18
Reference: IAC-11-A6.2.6			

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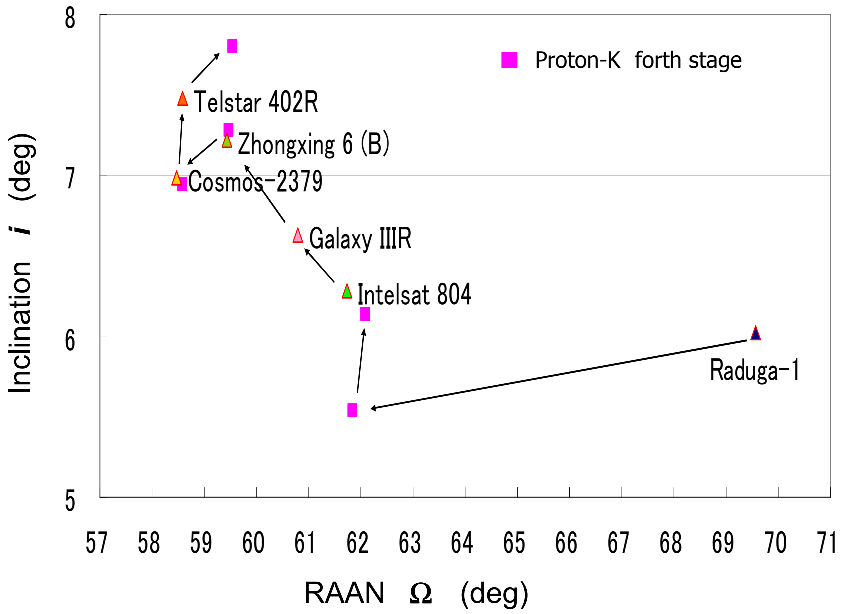
Example Removal Plans (2/4)

- **Removal plan A**
  - Raduga 1 and debris objects around in libration orbit

ID	Name	Class.
04010A	Raduga 1	3AX
03015F	Proton-K forth stage	R/B
05010f	Proton-K forth stage	R/B
97083A	Intelsat 804	R/B
95069A	Galaxy IIIR	3AX
03060D	Proton-K forth stage	R/B
97021A	Zhongxing 6(B)	3AX
01037D	Proton-K forth stage	R/B
01037A	Cosmos-2379	3AX
95049A	Telstar 402R	3AX
01045D	Proton-K forth stage	R/B



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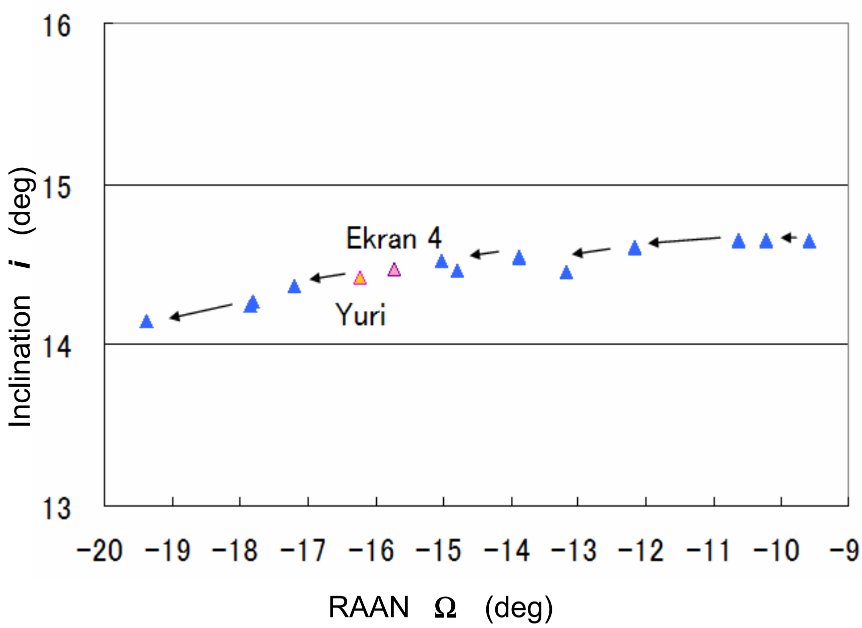
Example Removal Plans (3/4)

- **Removal plan B**
  - Ekran 4 and debris objects around in libration orbit

ID	Name	Class.
81102A	Raduga 10	3AX
81069A	Raduga 9	3AX
81061A	Ekran 7	3AX
80104A	Ekran 6	3AX
80081A	Raduga 7	3AX
79105A	Gorizont 3	3AX
80016A	Raduga 6	3AX
79062A	Gorizont 2	3AX
79087A	Ekran 4	3AX
78039A	Yuri	3AX
79035A	Raduga 5	3AX
79015A	Ekran 3	3AX
77108A	Meteosat 1	SP
78073A	Raduga	3AX



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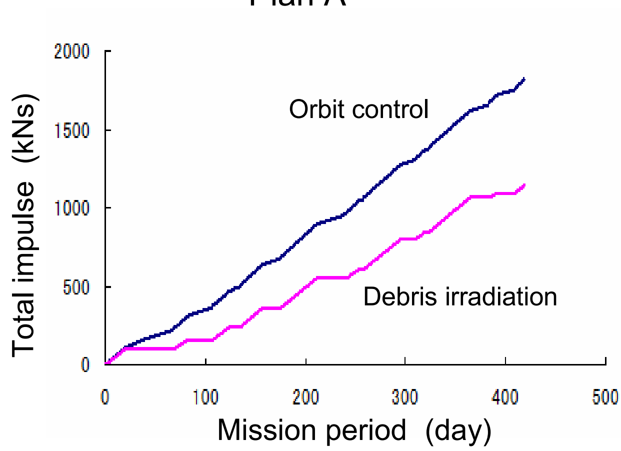
Example Removal Plans (4/4)

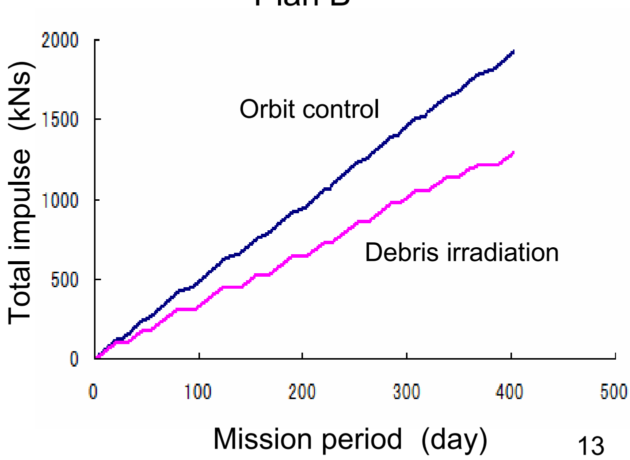
- **Result**
  - This system can conduct GEO debris removal at about 20 tons per year.

Case	# of removed objects	Total removed mass (ton)	Mission period (day)	Required xenon mass (kg)	Removed mass per year (ton/yr)
Plan A (Raduga 1 etc.)	11	26.6	419	101	23.2
Plan B (Ekran 4 etc.)	14	24.5	403	110	22.2

Plan A



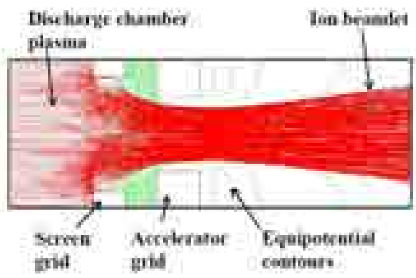
Plan B

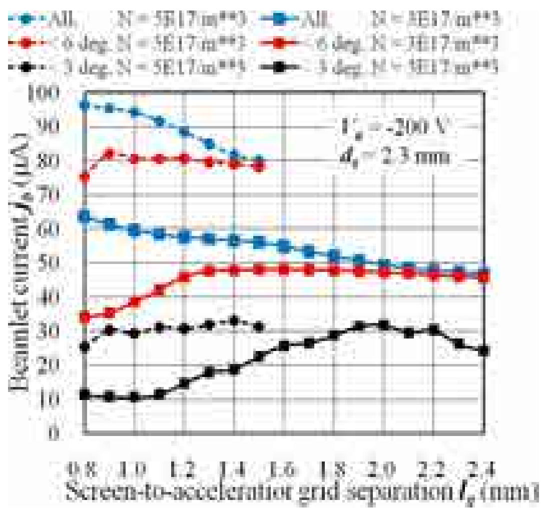


Issues to be Addressed (1/5)

Ion Beam Convergence

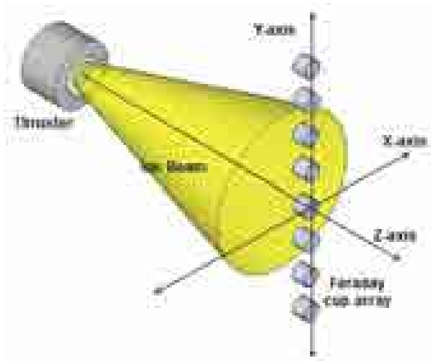
- **Objective**
  - To design ion engine grids for highly converged beam by numerical analysis, and to confirm the convergence capability by experiments.
- **Devices for beam convergence**
  - Reduction of ion density in the discharge chamber would bring smaller repulsive force among ions.
  - Increase in the separation between the two grids would make equi-potential contours flatter.
  - ***These are inconsistent with conventional ion engines.***

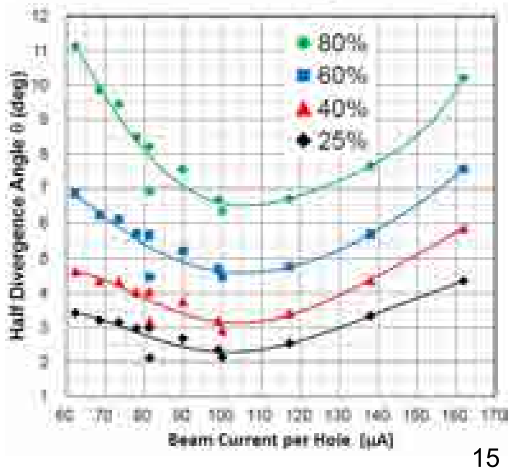




Issues to be Addressed (2/5)
Ion Beam Convergence (cont.)

- **Experiments**
  – A 10-cm thruster with model grids were used.
  – Ion beam was extracted only from the center region of the discharge chamber to achieve uniform beam extraction.
  – 3D beam profiles were measured using a Faraday cup array.
- **Results**
  – 25% divergence angle is smaller than 3 deg for J_b per hole of 80 to 130 μA, and good convergence was confirmed.
  – 80% divergence angle is 6.5 deg at the best case, and a little larger than assumed in the system study.





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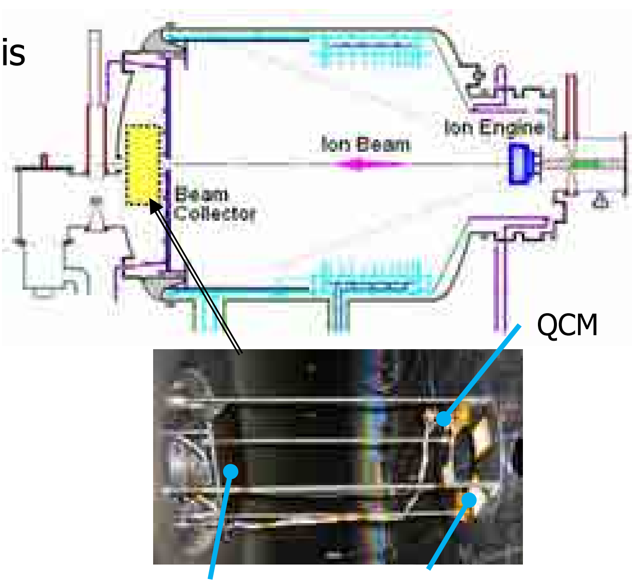
Issues to be Addressed (3/5)
Effects of Ion Beam Irradiation

- **Effects on debris objects and reorbiter**
  – Ion sputtering of debris surfaces is allowable because its effects are not so large to generate new debris.
  – Thermal effects and charging are negligible.
  – Back sputtering to the reorbiter can have contamination effects.
- **Measurements of back sputtering**
  – Sample: glass (solar cell cover) and polyimide (MLI)
  – Radiation surfaces are free of back-sputtering deposition; they usually face north or south.

Contamination measurement



Beam receiver
➢ Polyimide film
or
➢ Cover glass

Contamination receiver
➢ Polyimide film
➢ Cover glass
➢ Al mirror

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Issues to be Addressed (4/5)
Effects of Ion Beam Irradiation (cont.)

- **Thermal properties**
  - Changes are within permissible ranges.
    - Solar absorptivity (α_s) and infrared emissivity (ε) of polyimide increased by the back-sputtering from glass.
    - α_s of glass increased by the back-sputtering from polyimide.

Base material	Back-sputtered material	α_s	ε	Irradiation time*
Polyimide	N/A	0.235	0.506	0
	Polyimide	0.237	0.509	1.9
	Glass	0.252	0.519	1.5
Glass	N/A	0.029	0.737	0
	Polyimide	0.051	0.739	1.9
	Glass	0.030	0.737	1.5

*Equivalent # of reorbited 2-ton debris objects

- **Estimation of solar cell degradation**
  - Transparency decreased by the back-sputtering from polyimide in short-wavelength range.
  - Silicon: 94%, 3-junction: 97%
    - Reorbit of 2-ton 10 debris objects 18 m away and cell facing the sun

Cover glass transparency

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Issues to be Addressed (5/5)
Non-Cooperative Rendezvous

- **General considerations**
  - Research on non-cooperative rendezvous is being conducted for ADR in LEO at JAXA. Its results will be applied to GEO.
  - Easer rendezvous is expected in GEO than in LEO because of weaker gravitation and more stable optical conditions.
  - GPS application in GEO is expected in the future.
- **Study on applicable measurement sensors**
  - **Long distance rendezvous**
    - Debris orbit determination by optical observation from ground
  - **Approach**
    - Capture of debris using long range cameras at 250 km
    - Approach up to 10 km by repeating the relative distance determination using long range and short range cameras
    - Approach up to 100 m and nearer using the cameras and laser sensors
  - **Relative separation maintenance during ion beam irradiation**
    - Navigation using short range cameras and laser sensors

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Conclusions

1. **The proposed reorbiter has numerous advantages over other ADR systems for GEO debris removal.**
2. **This reorbiter can conduct effective GEO debris removal.**
3. **No critical problems are found.**
   - Required beam convergence is attainable.
   - No serious contamination problems are expected.

Issues below have to be addressed in future work.

- Detailed study on non-cooperative rendezvous with low thrusting.
- Operation plans on orbit determination and rendezvous including ground systems
- Evaluation of the beam convergence using real thrusters.
- Detailed study on contamination problems (other surface materials, optical parts, and so on).

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Appendix: Application to LEO Debris

- **Assumptions**
  - Reorbiter mass: 1500 kg
  - Thrust of ion engine for debris irradiation: 80 mN
  - Irradiation efficiency: 25% (Debris irradiating thrust: 20 mN)
  - Debris mass: 2000 kg
- **Results**
  - Long time operation is required for disposal in LEO.
  - Larger electric systems and solar arrays are required in LEO due to shorter sun-lit periods.

Comparison of debria removal time in GEO and LEO

Debris orbit	GEO	800-km alt.	900 km alt.
Disposal orbit	GEO+300 km	630 km alt.*	630 km alt.*
Velocity increment	11 m/s	90 m/s	140 m/s
Time of orbit change	12.6 days	103 days	160 days
No operation during eclipse**	N/A	155 days	241 days

* 25-year orbit life, **1/3 of orbit assumed

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