C3

軌道上実証を目指した導電性テザー技術の研究開発

R&D of Electrodynamic Tether for On-orbit Demonstration

○大川恭志，河本聡美，松本康司，塩見 裕，北村正治（宇宙航空研究開発機構）
○Yasushi Ohkawa, Satomi Kawamoto, Koji Matsumoto, Hiroshi Shiomi, and Shoji Kitamura（JAXA）

低軌道デブリ除去機のデオービット推進系への適用を目指して、JAXA 研究開発本部では導電性テザー（EDT）技術の研究開発を進めている。EDT は、導電性のひも（テザー）に流れる電流と地球磁場との干渉により発生するローレンツ力を推進力として利用する推進系であり、推進剤を必要とせずに大きな速度増分を得ることができる。低コスト・小型・軽量・簡素なシステムの開発が重要となるデブリ除去実現のためには、上記の EDT の特徴は大きな利点となる。本発表では、デブリ除去システム実現に向けた技術実証の1ステップとして検討されている EDT の軌道上技術実証実験に向けた各要素技術の研究開発状況について、その概要を紹介する。

Electrodynamic tether (EDT) technologies have been studied for future active debris removal systems in the Aerospace Research and Development Directorate, JAXA. The EDT is an advanced propulsion system which utilizes the interaction between an electric current through the tether and the geomagnetic field for thrust generation. In order to realize low-cost active debris removal systems, simple and efficient deorbit propulsion is needed, and the EDT is a promising candidate for such a propulsion system because of its propellant-less mechanism and high-efficiency in weight and electrical power. In this presentation, the current research and development status of some key EDT system components are presented.

This document is provided by JAXA.

5th Space Debris Workshop,
Chofu Aerospace Center, JAXA, January 22 & 23, 2013.

R&D of Electrodynamic Tether for On-orbit Demonstration

軌道上実証を目指した導電性テザー技術の研究開発

by
Yasushi Ohkawa, Satomi Kawamoto, Koji Matsumoto,
Hiroshi Shiomi, and Shoji Kitamura
大川恭志、河本聡美、松本康司、塩見裕、北村正治
(Aerospace Research and Development Directorate, JAXA)

1

Outline of Presentation

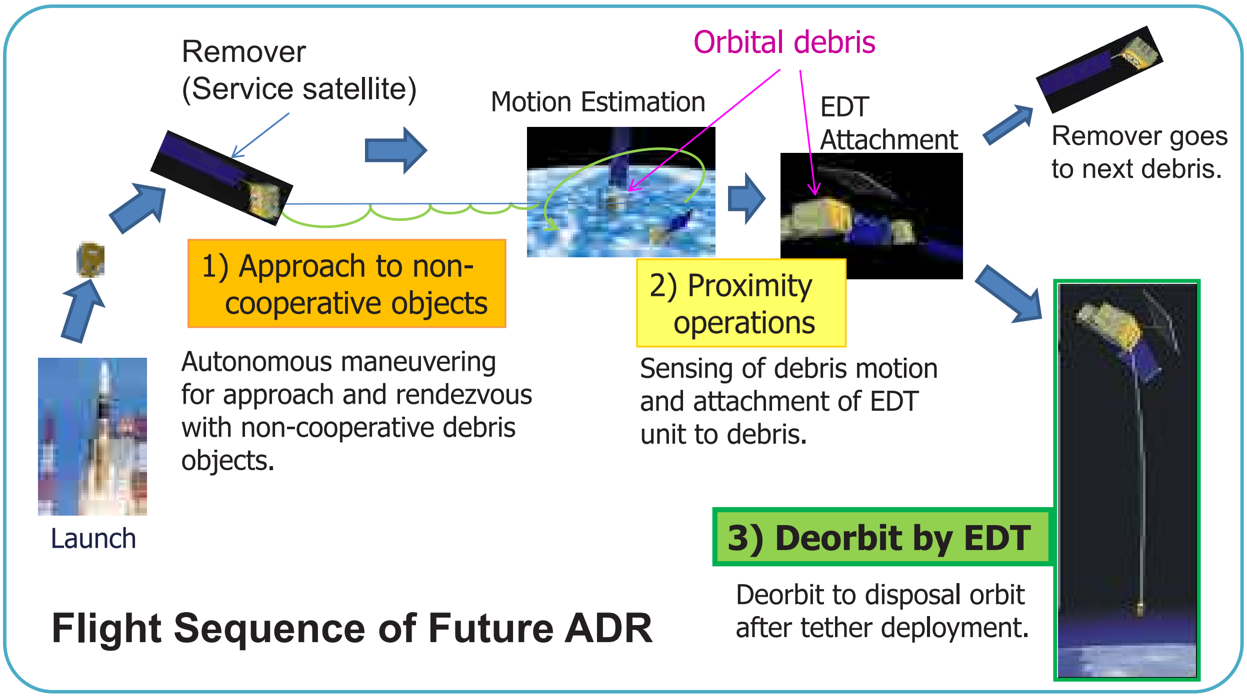
- Concept of Active Debris Removal in LEO
- Electrodynamic Tether (EDT)
  - Fundamentals
  - Advantages and Disadvantages
  - EDT Operation in High Inclination Orbit
- Roadmap to realize ADR equipped with EDT
- Plan for On-Orbit Demonstration of EDT
- Development of Key Components
  - Tether - “Net-type Bare Tether”
  - Electron Emitter - “Field Emission Cathode”
- Conclusion

2

This document is provided by JAXA.

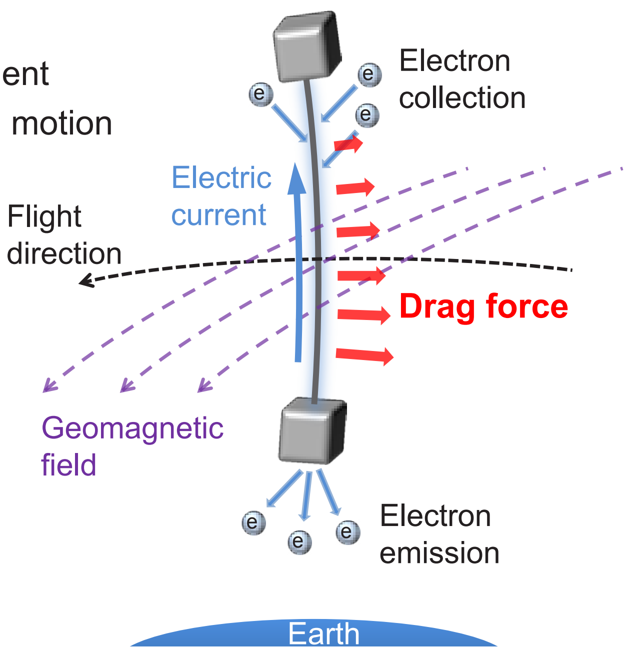
Concept of Active Debris Removal (ADR) in LEO

- Target: Large LEO debris (rocket bodies or defunct satellites)



What is Electrodynamic Tether (EDT)

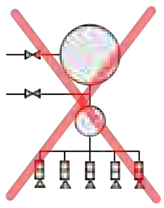
- EDT is “Propellant-free propulsion”
- Fundamentals
  - Attitude stabilization by gravity gradient
  - Electromotive force (EMF) by orbital motion
    - $V_{emf} = (v \times B) L$
  - Electron emission and collection
  - Electric current through tether
  - Lorentz force
    - $F = (J \times B) L$



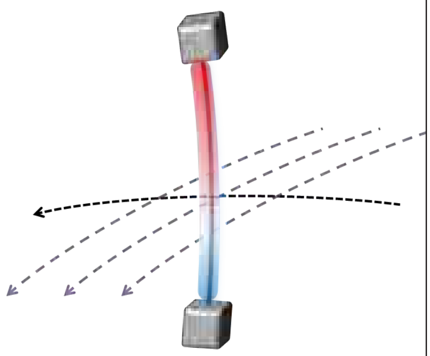
This document is provided by JAXA.

Advantages of EDT for ADR (1)

- Light weight
  - No propellant consumption
  - Large velocity inclement missions do not increase system mass
- Simple system
  - Propellant tanks, valves, and pipes are not required
  - System can be simple and small
- Low electrical power
  - Naturally induced voltage (electromotive force) can be used for thrust generation
  - Electrical power consumption is lower than that for general electric propulsion



No propellant

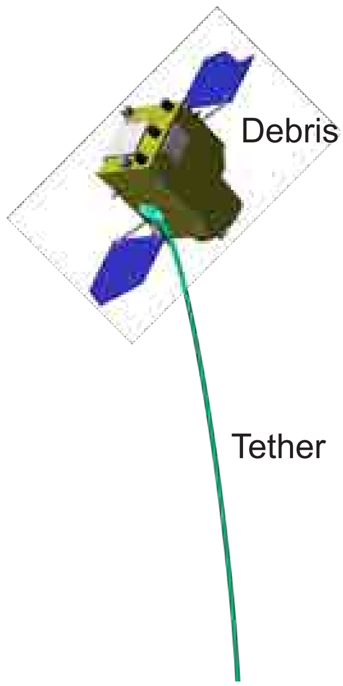


Voltage induction by EMF (Power generation)

5

Advantages of EDT for ADR (2)

- Easy attachment to debris
  - Not requiring strong attachment force because of small thrust of EDT
  - Not requiring alignment between thrust axis and debris' center of mass because small thrust is distributed along tether
  - In general propulsion, thrust axis must be aligned precisely with center of mass of debris to avoid inducing rotation
- No thrust vector control
  - Thrust vector control is not required because EDT thrust is automatically directed towards lowering altitude
  - In general propulsion, thrust direction must be controlled by active attitude control for deorbit



Simple and small system for "Low cost" debris remover.

6

This document is provided by JAXA.

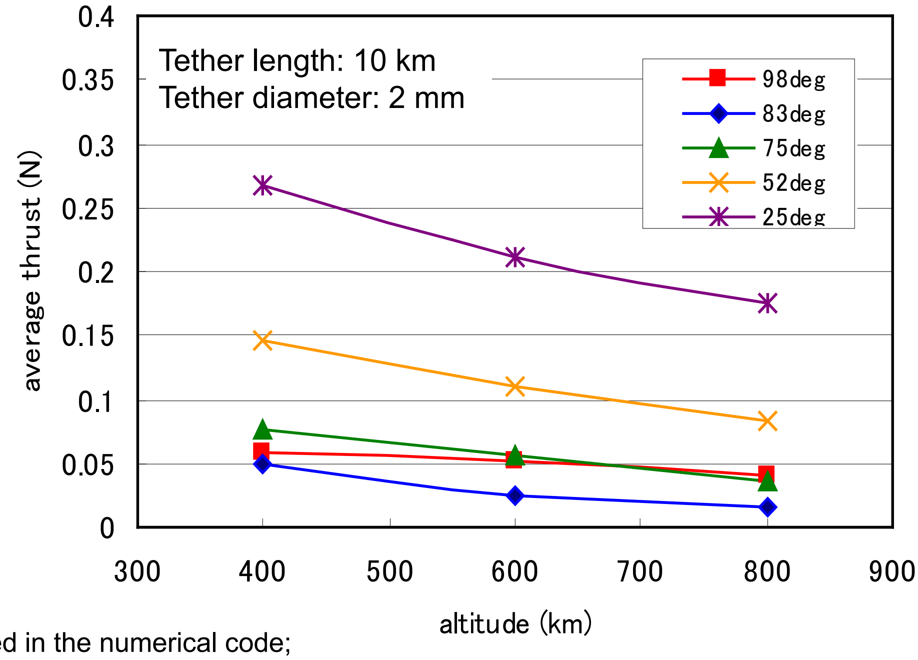
Disadvantages of EDT and Countermeasures

- Long mission duration
  - Deorbit will require several months to a year because of EDT’s low thrust
  - Autonomous operation is needed to reduce operation cost
- Possibility of mission failure due to tether being severed
  - There is a possibility of tether being severed by impacts of small debris objects or micrometeoroids
  - The risk can be reduced by adopting “net-type” tether
- Collision risk with operational satellites
  - There is a collision probability between EDT and operational satellites
  - The risk should be assessed against mission payoff in advance
- Difficulty of controlled re-entry
  - Controlled re-entry is difficult because of EDT’s low thrust
  - Target for removal should be selected considering a hazard to the ground

7

EDT Operation in High Inclination Orbit

- EDT thrust becomes smaller in higher inclination orbits, but is still great enough to transfer debris from SSO



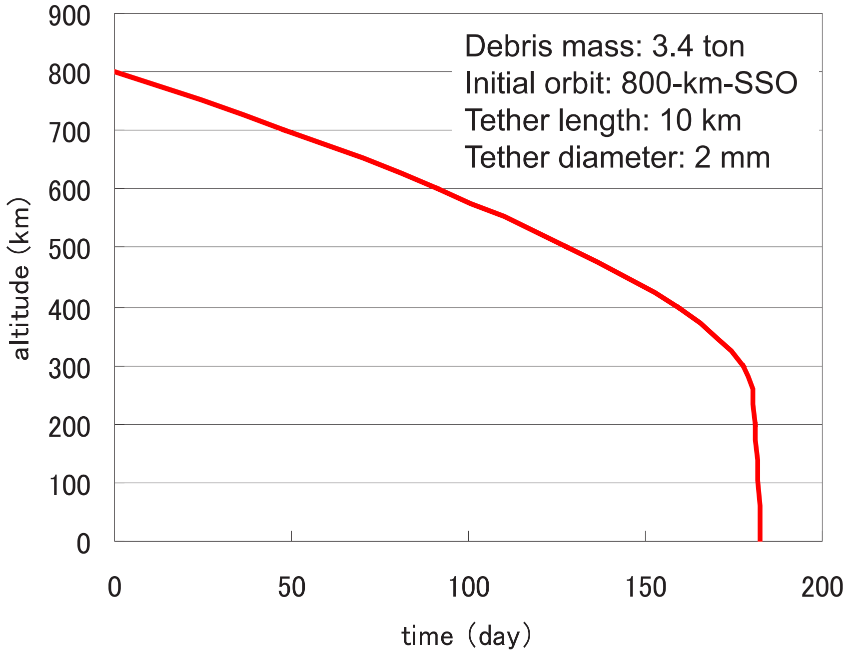
Considered in the numerical code;
Orbital motion, tether flexibility, IGRF magnetic, IRI plasma, and OML electron collection model.

8

This document is provided by JAXA.

EDT Operation in High Inclination Orbit

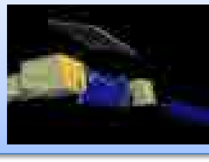
- 10-km-EDT can transfer 3.4-ton SSO debris from 800-km-altitude to atmosphere within a year



9

Roadmap to Realize ADR with EDT

Final Goal :
Continuous active debris removal execution by “**Multi-Debris Removers.**”



System demo of debris removal by “**Single-Debris Remover.**” (Approach, Attachment, and Deorbit)

Flight demo of EDT

R&D on non-cooperative rendezvous, proximity operations, and EDT thrust increase

International discussion on legal and political problems

10

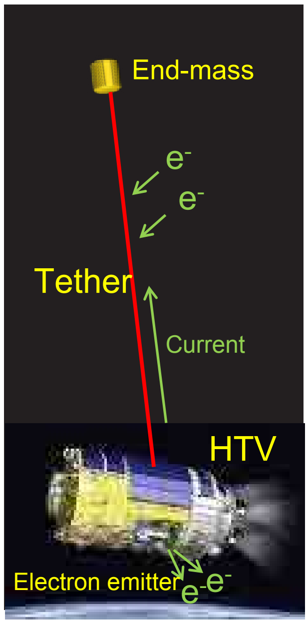
This document is provided by JAXA.

Feasibility Study of EDT Demonstration using HTV

EDT on HTV (H-II Transfer Vehicle)

- Objective
  - Demonstration of EDT key technologies
    - Deployment of bare tether
    - Electron collection by bare tether
    - Electron emission by field emission cathode
    - Current loop formation via plasma
    - Autonomous current control operation

- Flight Sequence
    - HTV leaves ISS and lowers altitude
    - Tether deployment ⎫ 7 days
    - EDT operation ⎭ for EDT mission
    - HTV re-enters atmosphere



Tether length	700 m
Max. tether current	10 mA

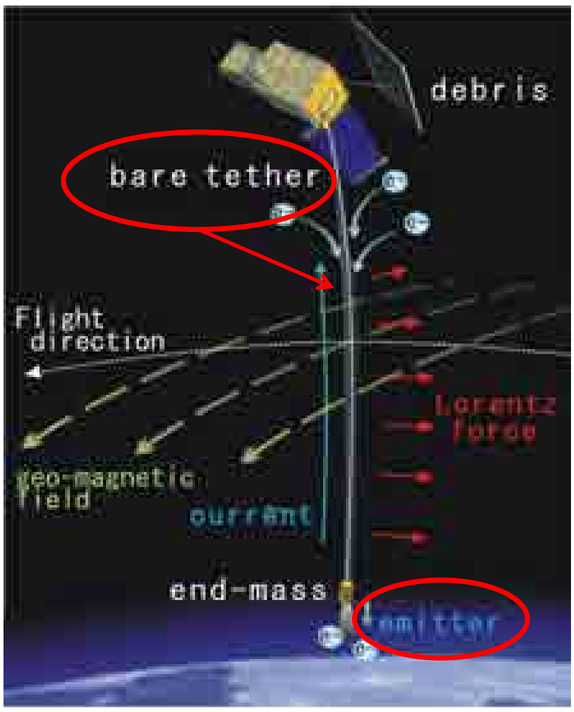
11

Key Components of EDT

Most important components in EDT system are:

- Bare Tether
  - Induces voltage along tether
  - Collects electrons from plasma
  - Generates thrust

- Electron Emitter
  - Emits electrons from tether end
  - Closes electrical current loop via plasma



12

This document is provided by JAXA.

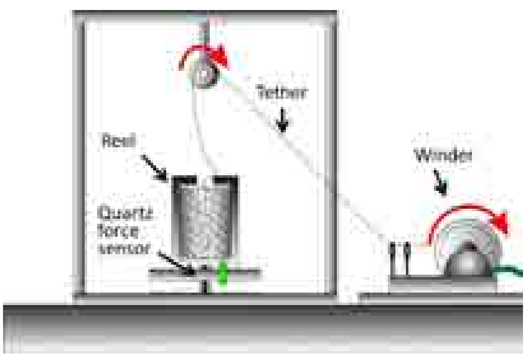
Bare Tether

- Major Requirements for Bare Tether
  - Sufficient strength to withstand tension forces
  - High electrical conductivity to pass electric current and to collect electrons
  - Low surface friction for smooth deployment from reel
  - Tolerance to impacts by small debris to survive in on-orbit environment
- Net-type Bare Tether
  - Fine aluminum wires and stainless steel wires are braided to form a cord
  - Three cords are connected to each other alternately
  - This arrangement creates physical gaps between three cords
    - High resistance to being severed by small debris impacts
    - High efficiency in electron collection from space plasma

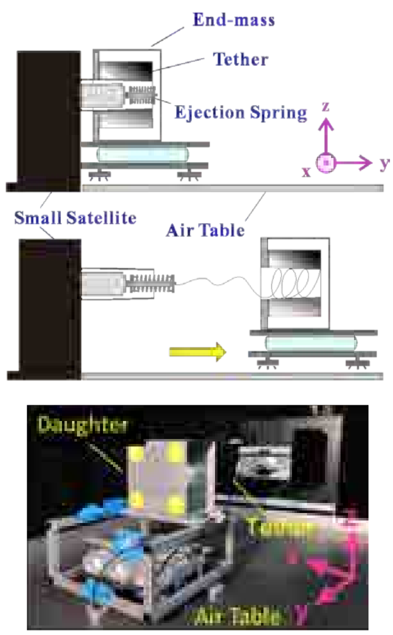
13

Bare Tether

- Various tests have been conducted



Tether deployment friction measurement



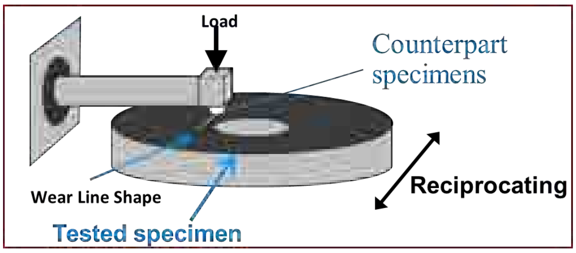
Tether deployment test on air table

14

This document is provided by JAXA.

Bare Tether

- Various tests have been conducted



Reciprocating tribometer

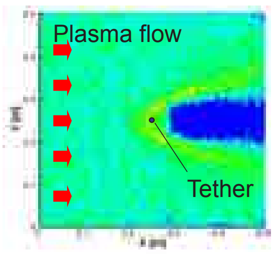
Lubricant for smooth tether deployment

Hyper velocity impact test

15

Bare Tether

- Various tests have been conducted



Electron collection test and analysis

16

This document is provided by JAXA.

Electron Emitter

- Electron Emitter Selection for EDT

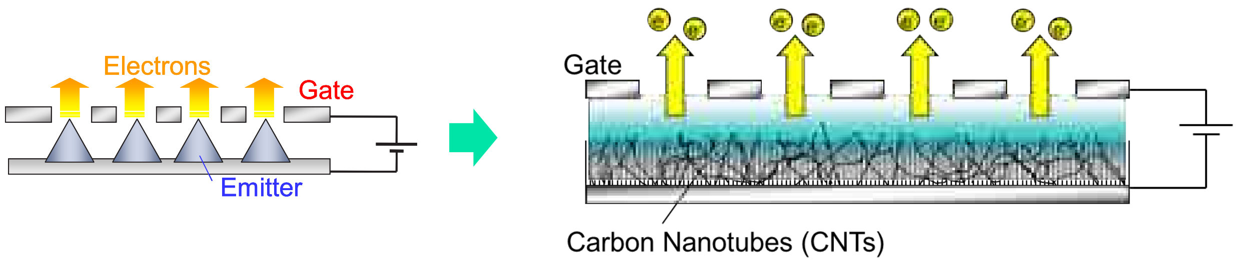
	Advantages	Disadvantages
Field Emission Cathode (FEC)	Small, Simple, Low power	Space charge limit, Not matured
Hollow Cathode	High current density, Matured	Tank and valves, Heat load
RF/ECR Cathode	High current density	Tank and valves, Not matured
Thermionic Cathode	Small, Simple, Matured	Space charge limit, Heat load
Passive Cathode (Photoemission, Ion collection)	Simple, No power	Large area, Low current density

FEC was selected because of its simplicity and potential capabilities.

17

Carbon Nanotube FEC

- There are types of FEC
  - Spindt, Triple junction, Regenerative, Carbon nanotube, etc.
- Features of carbon nanotube (CNT) FEC
  - High field enhancement factor
  - High tolerance to ion impingement and electric breakdown: Operational in low vacuum condition in LEO environment
  - Nanotube structure and chemical stability

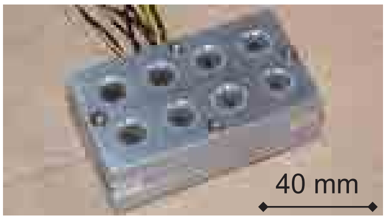


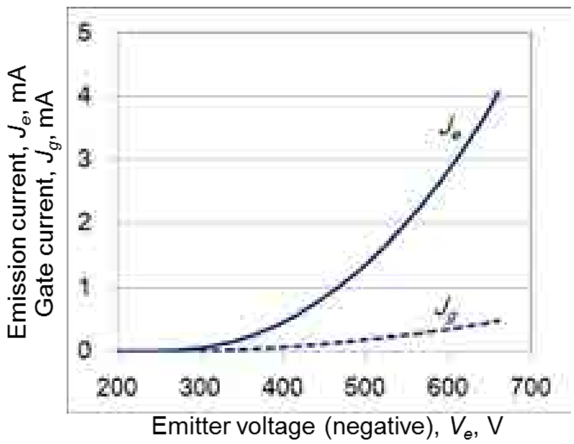
18

This document is provided by JAXA.

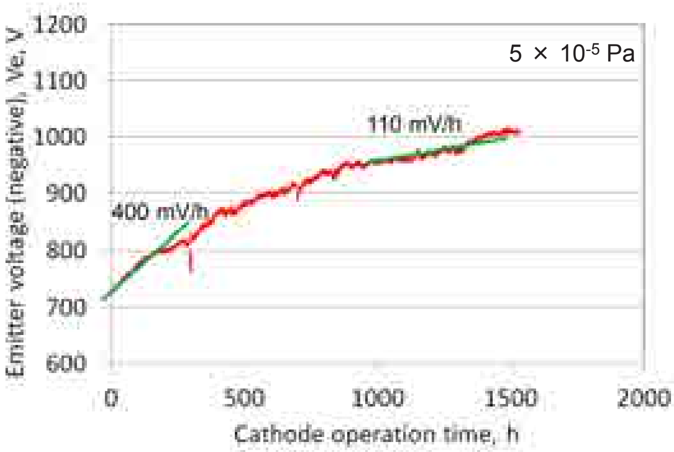
Electron Emitter

- Laboratory Model of FEC
  - Electron emission: 3 mA (nominal)
  - Extraction voltage: 1 kV (EOL)





Typical current-voltage characteristic (BOL)



Extraction voltage required to maintain 3 mA emission during 1,500-hour endurance test

19

Conclusion

- Electrodynamic tether (EDT) is a promising candidate for deorbit propulsion of "active debris remover" because of its:
  - Propellant-less mechanism
  - High-efficiency in weight and electrical power
  - Ease of attachment to debris
  - Ease of operation

→ "Low Cost" Debris Remover

- JAXA has a roadmap to realize "active debris removal" and is proposing a flight demonstration of EDT as the first step.

- Key technologies of EDT including "bare tether" and "field emission cathode" have been studied, so that we can start a project for the demonstration flight.

20

This document is provided by JAXA.