MUSCAT project and its application to plasma plume analysis

Takanobu MURANAKA, Shinji HATTA, Jeongho KIM, Mengu CHO
(LaSEINE, Kyushu Institute of Technology)
Hiroko O. UEDA, Kiyokazu KOGA, Tateo GOKA (JAXA)
E-mail: muranaka@ele.kyutech.ac.jp

Development of MUSCAT (Multi-Utility Spacecraft Charging Analysis Tool) had started in November 2004 as a quantitative spacecraft charging analysis tool in Japan. In the middle of development term, the beta version of MUSCAT has been released on March 2006 as the first version of integrated software. The integrated GUI tool of MUSCAT, called "Vineyard," had been developed, which conducts the MUSCAT simulation on local Windows® PC. Functions of "Vineyard" have parameter input panels including 3D satellite model, data converter from parameters in the GUI format into those in the solver format. As the development of the physical functions, fundamental physical elements such as photoelectron emission, secondary electron emission, auroral electrons had been included. As a result, the solver enables fundamental charging analyses at GEO, LEO and PEO, which makes MUSCAT feasible for multi-utility use. Parallelization and tuning of the code have almost been achieved, and 8CPUs parallel computation can calculate absolute potential of a large-scale satellite model in a half size of maximum computation region of 256x64x128 in two days. Experiments for the code validation were made at LaSEINE in KIT. Spatial distribution of electric potential around the electrode of a Langmuir probe and IV characteristic curve were measured, and we had good agreement in experimental results and the numerical ones. These results show that the physical functions of MUSCAT simulate charging processes quite well.

For a function of plasma plume analysis of the MUSCAT solver, we consider a model of active emission of ions, which employs a fixed analytical beam ion profile and electrons of Boltzmann distribution. Distributions of CEX ions are obtained by PIC method, and electric field is obtained by solving non-linear Poisson equation. Backflow of CEX ions to spacecraft surface would contribute to fluctuations of the surface potential. The modeling and coding of that are now under development. Final version of MUSCAT will be released in March 2007 with this function.

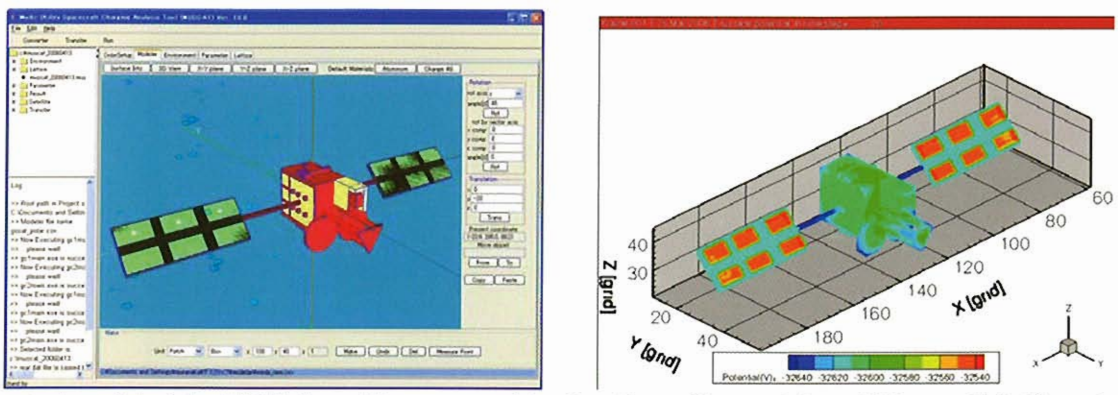

Fig. 1. A model of the WINDS satellite composed by the 3D satellite modeler of "Vineyard" (left), and the numerical result of satellite surface potential of the model (right).

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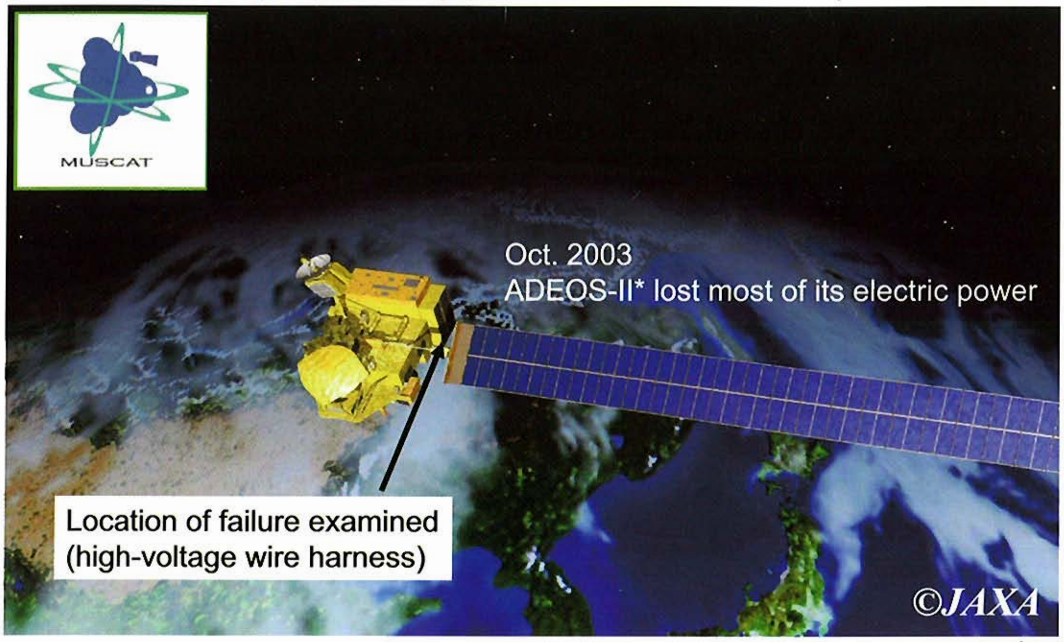
(LaSEINE, Kyushu Institute of Technology)
Hiroko O. Ueda, Kiyokazu Koga, Tateo Goka
(JAXA)

JAXA/JEDI workshop
2-3 October 2006, Tokyo, JAPAN

Quantitative Analysis Tool is Required

Spacecraft Charging-Arcing problem lead to the spacecraft failure



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*ADEOS-II: Polar Orbit Satellite: paddle size 3 x 24 (m) (JAPAN)

MUSCAT: Multi-Utility Spacecraft Charging Analysis Tool

multi-purpose satellite charging analysis tool

- Schedule
  - Nov. 2004 (started)--Mar. 2006 (β ver.) --Mar. 2007 (final ver.)
- Modeling of interaction between spacecraft and space environment
  - Calculation of satellite charging at LEO, GEO, PEO
- High-speed computation
  - Parallelization and tuning of algorithm
  - Calculation completed in half a day with workstation (final)
  - Simple calculation method in the final version (final)
- Graphical User Interface (GUI)
  - 3D satellite modeling with JAVA3D
  - Input of initial parameters (material, environment, numerical)
  - Output of numerical results

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Framework of the development

General overview		JAXA
Code development	Solver Speeding up GUI	KIT
Offering space environmental parameters		JAXA
		NICT
Validation experiment		KIT
		ISAS/JAXA
Validation by large scale calculation		GES(Kyoto Univ., NIPR)

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Functions of the Beta Version

- GUI
  - Integrated GUI tool, "Vineyard"
- Solver
  - Includes fundamental physical element functions at LEO, GEO, and PEO
- Speeding-up
  - Users can perform a large scale computation (full scale:256x128x128)
- Experiment (explain if it has enough time)
  - Fundamental validation of the solver
- Plasma plume analysis (topic of near future work)

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Development of GUI

"Vineyard" conducts computation

"Vinyard"-Integrated GUI Tool

Windows PC

Input parameters

- 3D satellite modeling
- Input parameters of materials etc.

GUI-Solver converter

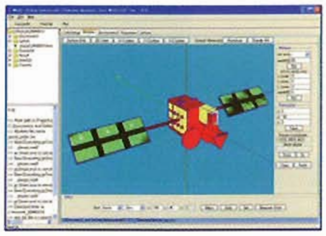
- To converter GUI model to rectangular grid model

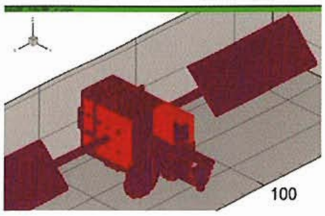
Solver Workstation

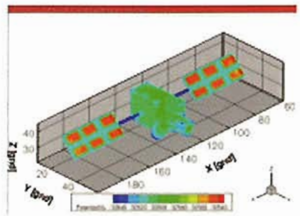
- Speeding up by parallelization

Windows PC

Output of the results







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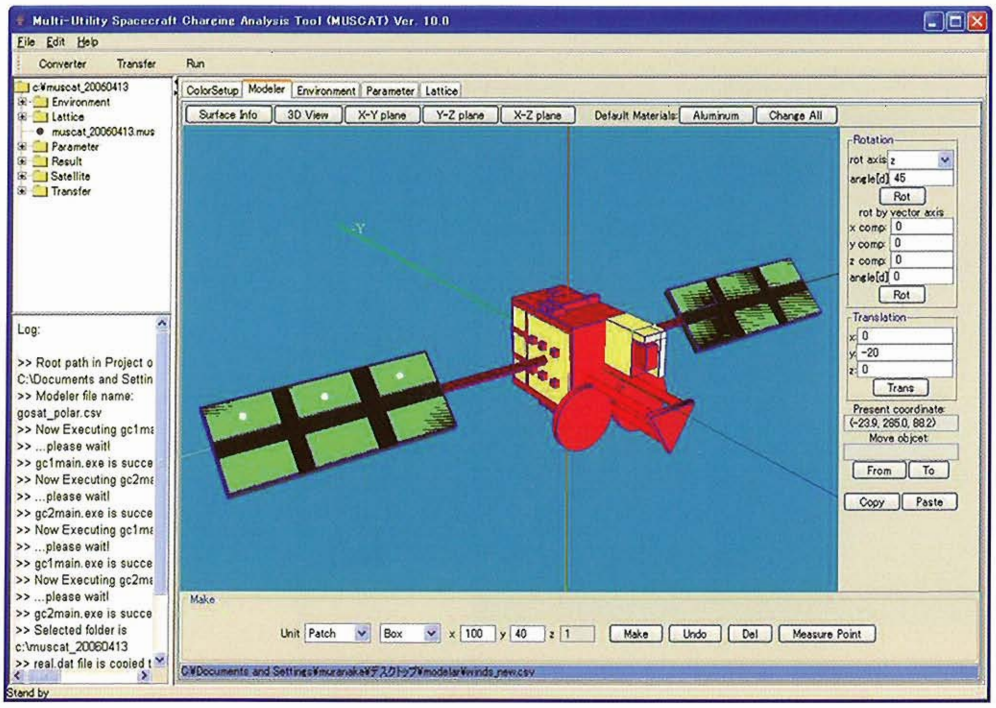
3D Satellite Modeler of "Vineyard"



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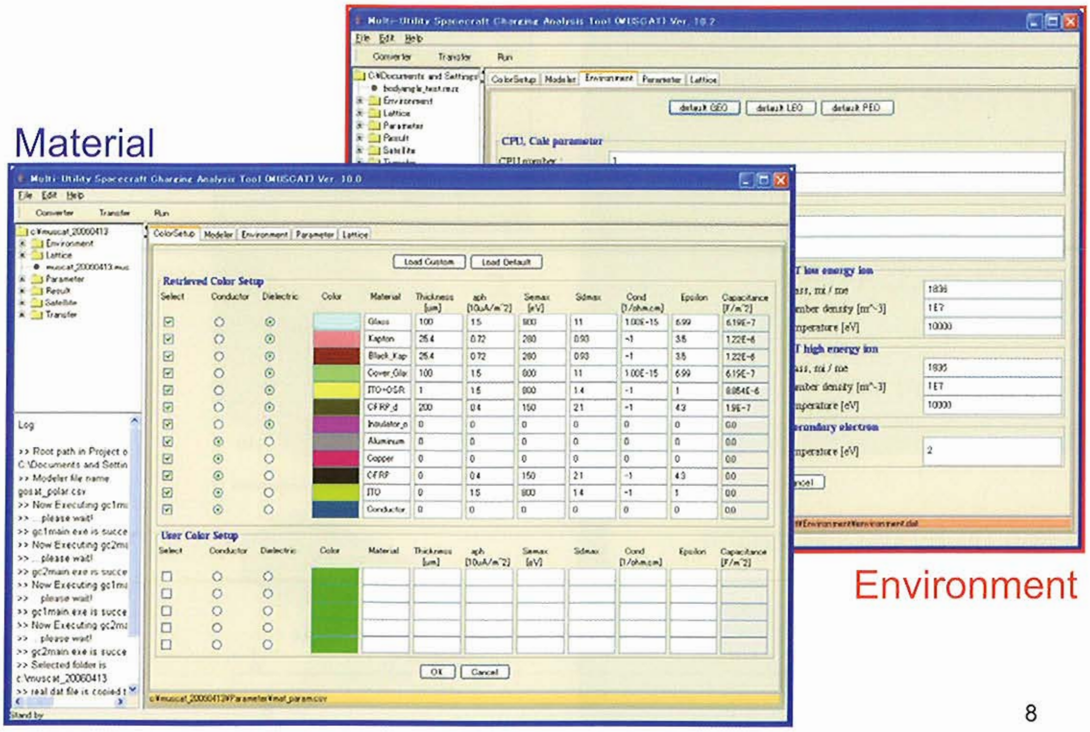
Parameter Setup Panels of "Vineyard"

Material



Environment

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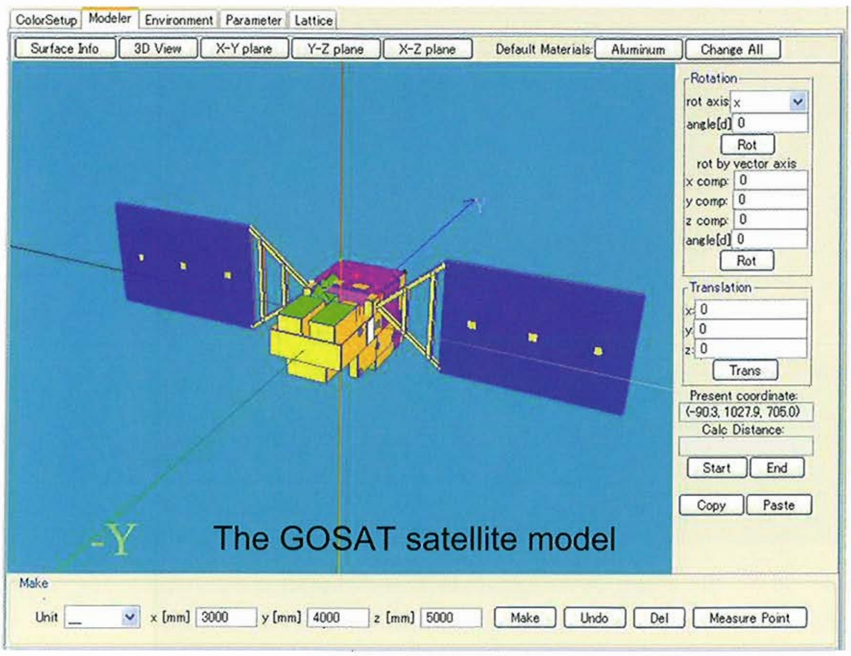
Example of Large Scale Satellite modeling



The GOSAT satellite model

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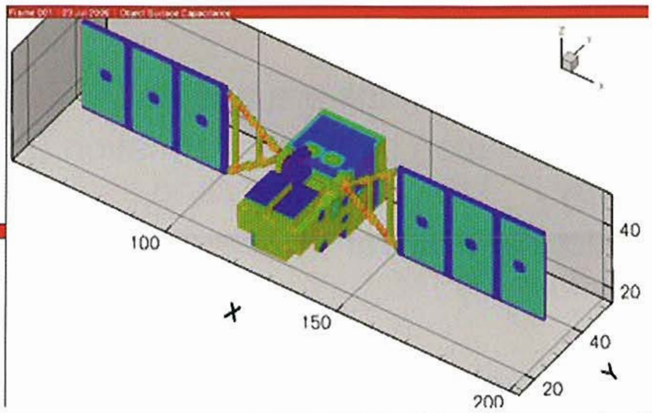
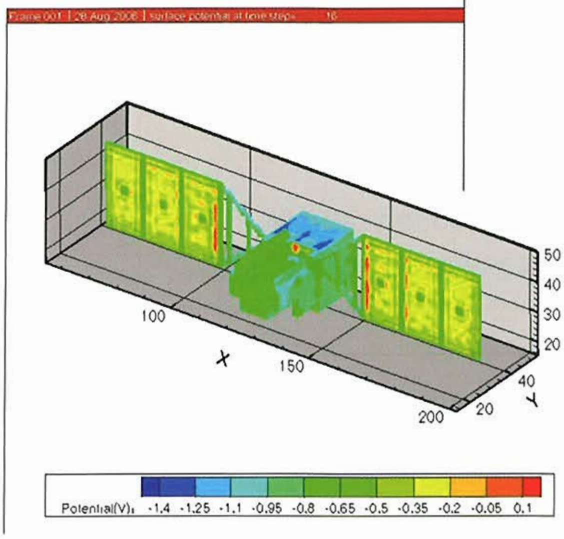
Converter and numerical result

The GOSAT satellite model

Surface Potential
(Numerical Result)





Grid Satellite Object by "Converter"

Scale: 256x64x128
Object element: about 10,000

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Development of Solver

Features of MUSCAT Solver

- Electrostatic(ES) particle code
- Rectangular numerical grids are adopted
- Independent calculation of sheath formation (by PIC) and particle flow (by PT) to reduce iteration time
- Update spacecraft potential by calculating net charge on the spacecraft surface by PT
- Included physical elements in PT part at present
  - Ambient electrons and ions (double Maxwellian distribution option)
  - Photoelectron emission(PEE) & Secondary electron emission(SEE)
  - Bulk conductive current
  - Auroral electrons
- These fundamental physical elements enables users to simulate spacecraft charging at GEO, LEO and PEO

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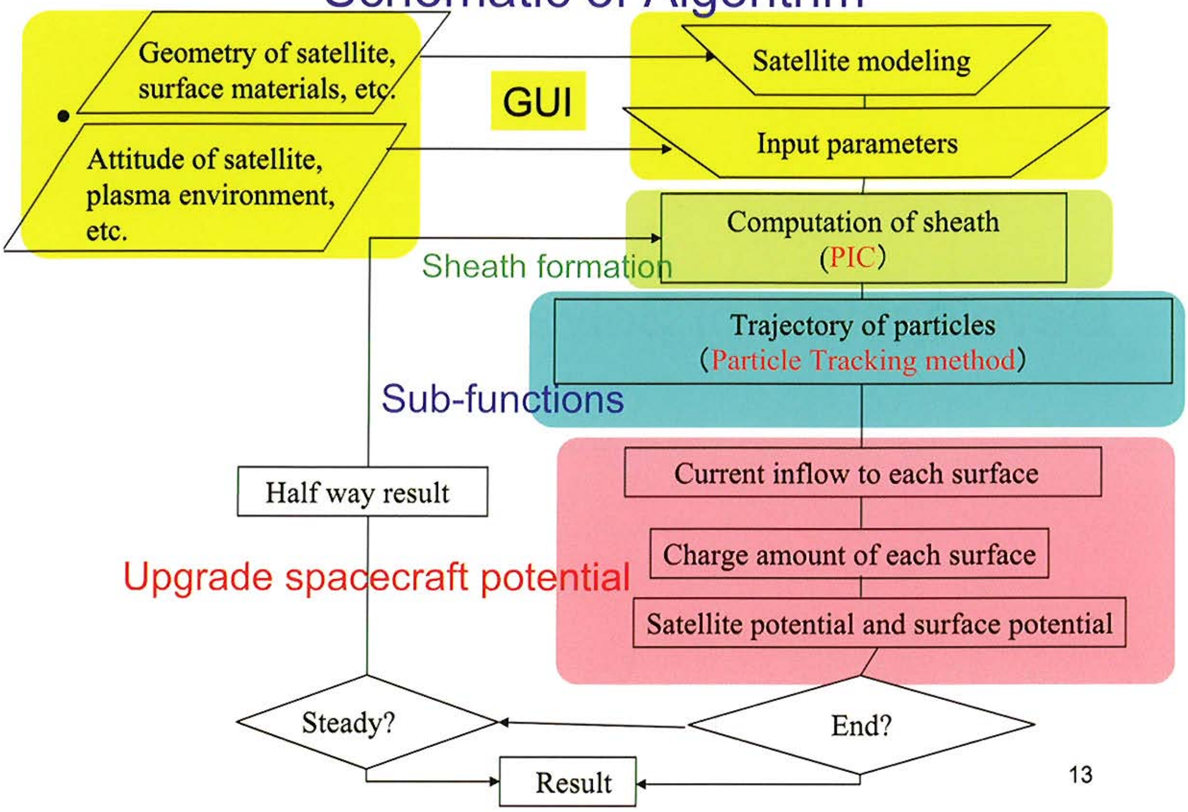
Schematic of Algorithm



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Examples of PEE and SEE Computations

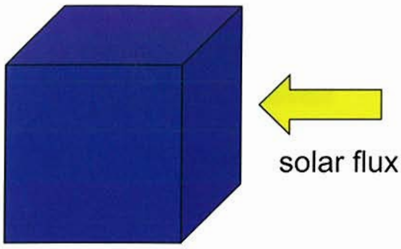
Numerical parameters

Domain (grid)	32x32x32
Object size (grid)	4x4x4
Spatial width (m)	0.2
Temporal width (s)	10^{-5}~10^{-3}

Material parameters

PE current density (A/m^2)	$4.2\text{x}10^{-5}$
PE temperature (eV)	1.5
SE Emax (eV)	300
SE δ_{Emax}	2.0
SE temperature (eV)	2.0

Conductive cube



Floating potential

PE: Photoelectron
SE: Secondary electron

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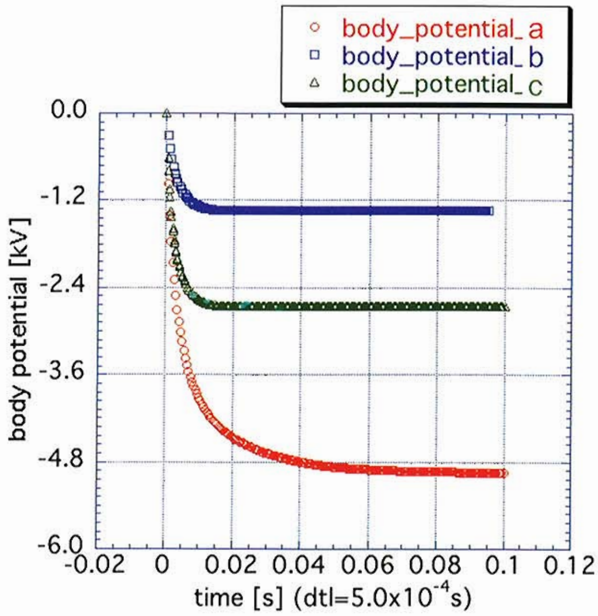
Examples of PEE and SEE Computations



Ambient Ions and Electrons

n=$2\text{x}10^7$ [m^{-3}] , T=1.0 [keV]

$\lambda_D = 52.5$ (m)

	photo	second
a	×	×
b	○	○
c	○	×

Absolute potential

$\phi b > \phi c > \phi a$

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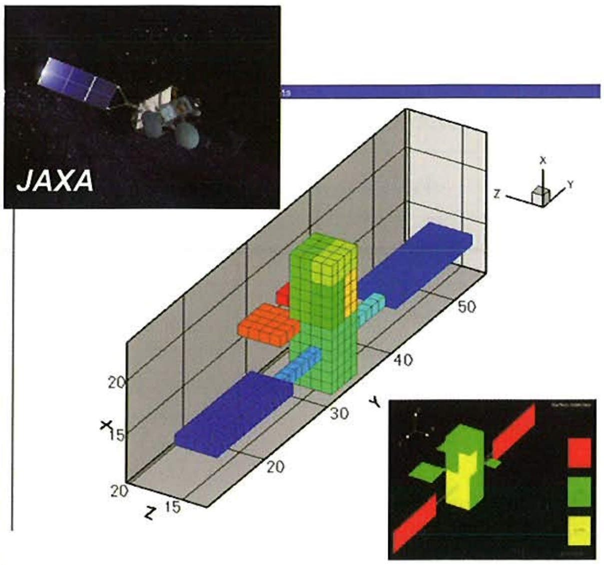
Example of Integrated Solver Test

Numerical parameters

Domain (grids)	32x64x32
Number of grids (object)	610
Spatial width (m)	0.625
Temporal width ($\times 10^{-2}$ s)	1.0-1.7

Environment parameters

Electron density (cm^{-3})	1.25
Electron temperature (keV)	7.5
Ion density (cm^{-3})	0.25
Ion temperature (keV)	10



the WINDS satellite model adopted to MUSCAT calculation

with ambient plasmas, PEE, SEE, conductive current

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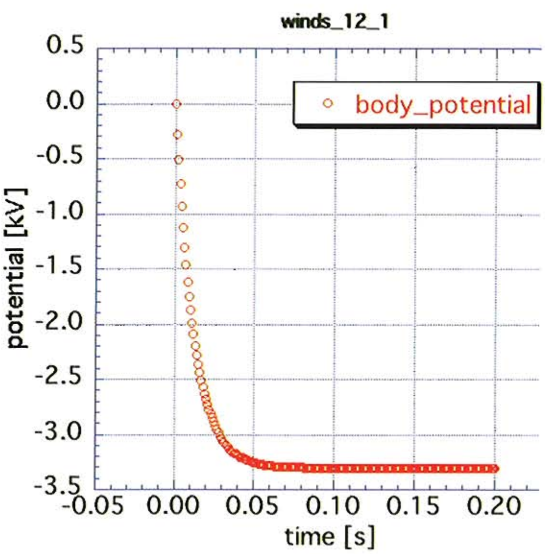
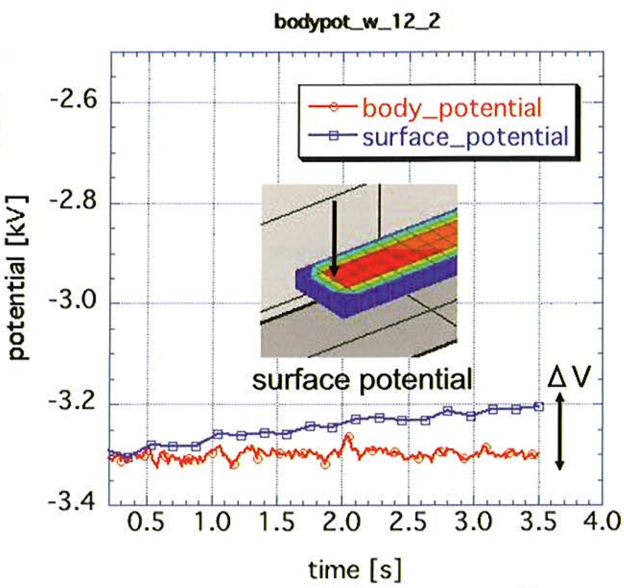
Numerical Result of Absolute Potential

LT=0:00, ΔV=90 (V) @3.5 (s)





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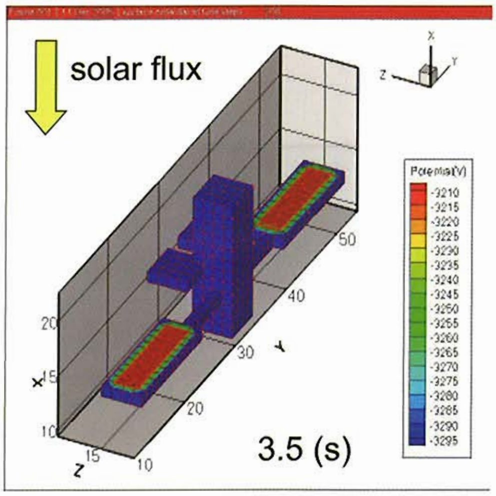
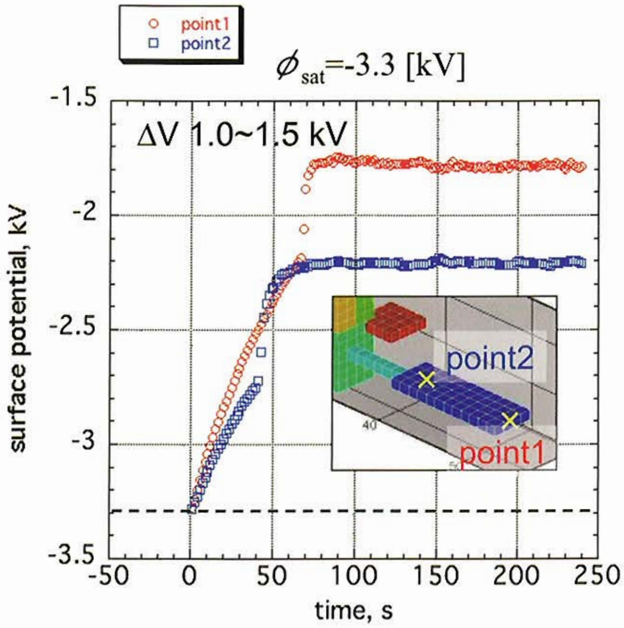
Numerical Results of Differential Voltage

3D-image





ϕ_{CG} >

ϕ_{sat}
for PEE and SEE effects

Absolute potential is fixed at -3.3 kV
to reduce iteration time 18

Speeding up
(Tuning and Parallelization)

Development Platform

- Shared memory parallel (SMP) workstation
  - Server of 2nodes,
  - 4CPUs for each, 8CPUs in total
- CPU Itanium II 1.3GHz
- Memory 16GB
- HD 660GB
- OS
  - SuSE Linux Enterprise Server
- Compiler
  - Intel Fortran for Linux ver.8.1
  - Intel C++ for Linux ver.8.1

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Speeding up of Computation

- Goal of calculation speed (final version)
  - Using workstation on the market,
  - The calculation of PEO satellite is (severe condition to numerical resources),
  - Completed in about half a day
- Status at present
  - Hardware
    - Parallelization with Open-MP to PIC and PT parts
    - Modify particle arrangement to reduce memory access time
  - Algorithm
    - Time step control method (to reduce iteration time)
    - Modification of PT algorithm (to reduce the number of computation for particles)

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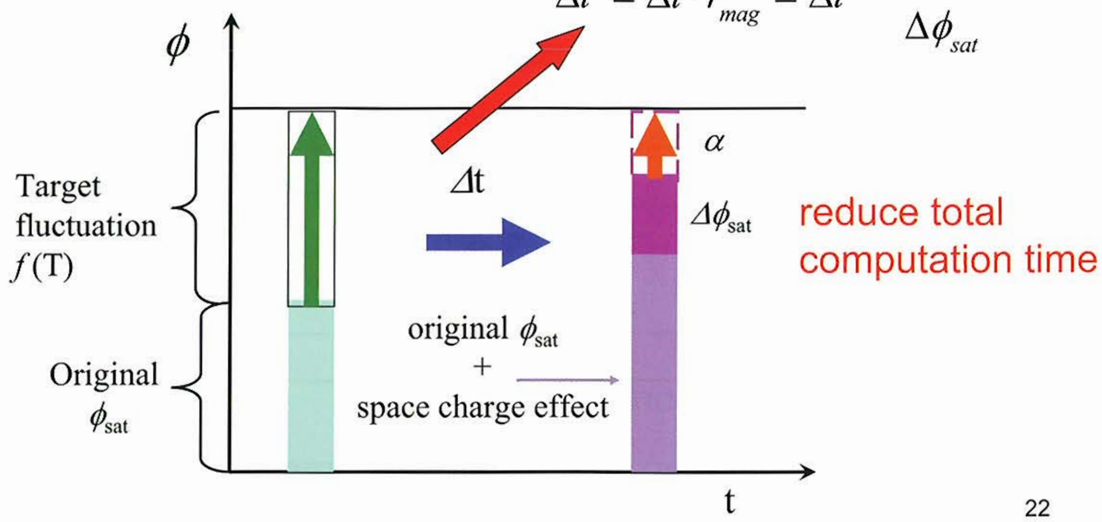
Modification of Time Step Control

Considering the fluctuation of satellite potential

Controlled time step

$$\Delta t' = \Delta t \cdot r_{mag} = \Delta t \cdot \frac{\Delta\phi_{sat} + \alpha}{\Delta\phi_{sat}}$$



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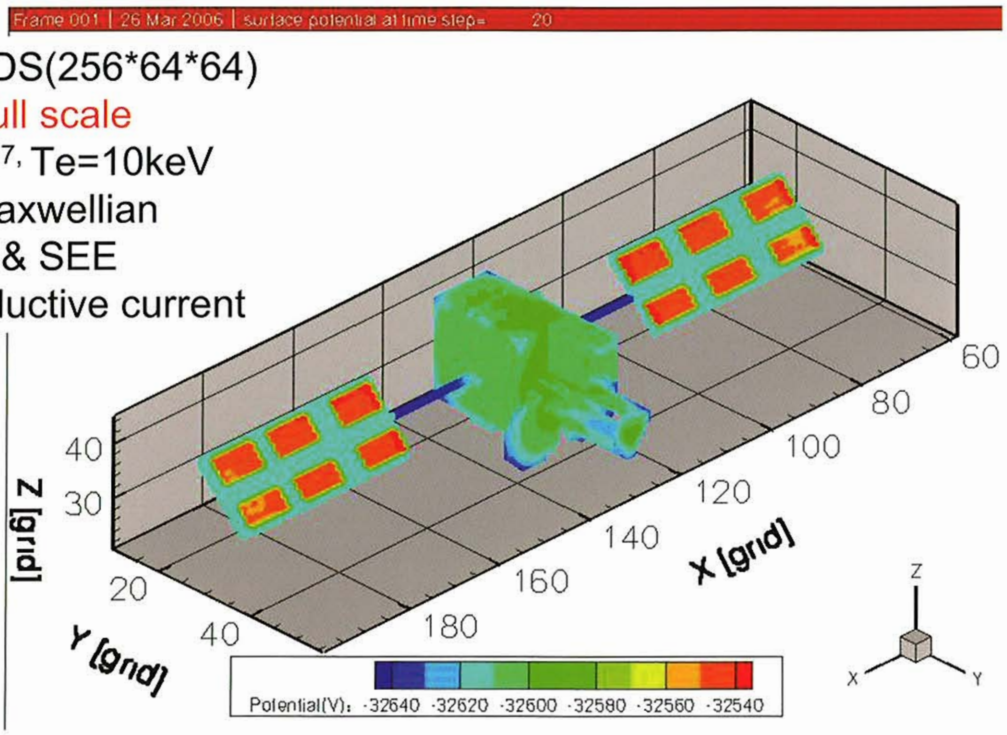
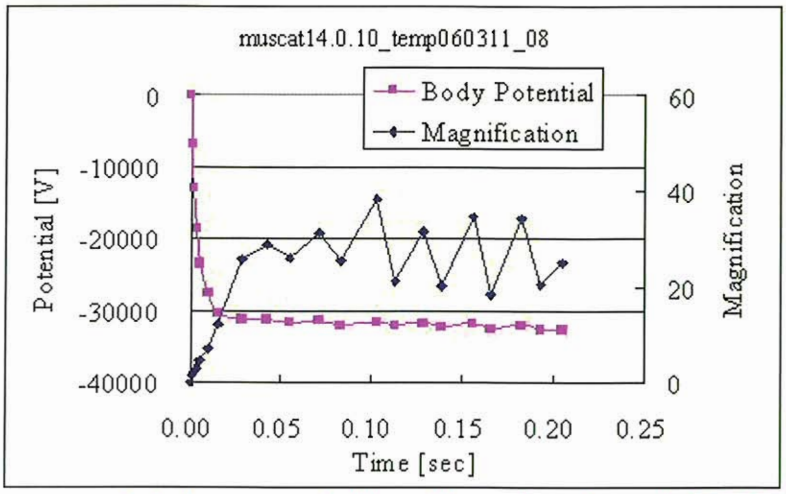
Example of Numerical Result

WINDS(256*64*64)
1/4 full scale
n=10[7], Te=10keV
D. Maxwellian
PEE & SEE
Conductive current



Example of Numerical Result



Total 20step total computation time is almost 1/10 !

(200 steps more w/o time step control)

Computation time: about 2.5h/step with 8 CPUs at present
(almost 2 days in total)

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Application to Plasma Plume Analysis

Application to Plasma Plume Analysis

- Plasma plume analysis for electric propulsion
  1. Contamination of spacecraft by CEX ions
     - Ion flux to spacecraft surface
  2. Power loss due to dense plasmas near solar array paddle
     - Electron density near spacecraft surface
  3. Relaxation of local spacecraft charging
     - Ion flux to the spacecraft surface
  4. Fluctuation of spacecraft potential in the case of neutralization failure
     - Dynamic interaction between neutralizer and plume plasmas
  - For the MUSCAT solver, 1 and 2 are considered

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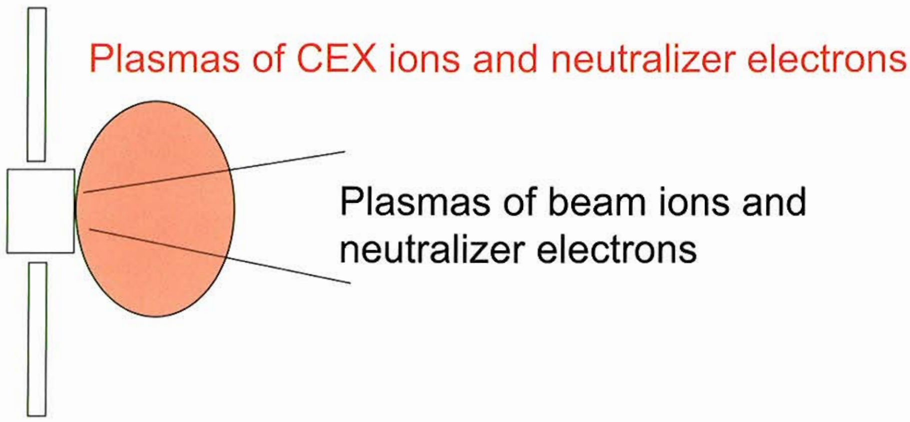
Basic Scheme of Plasma Plume Analysis



- CEX ions generated in beam plasma diffuse from positive electric potential in the beam plasma
- Ambipolar diffusion of CEX ions and neutralizer electrons
- Parameters of n_{bi}, n_e, n_{cex}, Φ, and Te are important

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Basic Scheme of Plasma Plume Analysis

- Plasma plume modeling from 1995

			nbi	ne	ncex	Te	Electric Potential	Maximum Electric Potential in the Beam	Satellite Potential	B.C.
Roy	1996	generic ion thruster	Analytical	Boltzmann	particle	variable	Poisson equation	?	fixed or floating?	Neuman
Oh	1999	SPT100	particle	=nbi+ncex	particle	fixed	$\frac{e\phi}{kT_e}=\ln\left(\frac{n_e}{n_o}\right)$	NA	fixed? array=-92V	NA
Wang	2001	DS1	Analytical	Boltzmann	particle	fixed	Poisson equation	Maximum Φ_p at thruster exhaust	fixed at 0	Neuman
Van Gilder	2000	generic ion thruster	particle	=nbi+ncex	particle	fixed	$\frac{e\phi}{kT_e}=\ln\left(\frac{n_e}{n_o}\right)$	0	fixed	NA
Tajmar	2001	SMART1	particle	=nbi+ncex	particle	fixed	$\frac{e\phi}{kT_e}=\ln\left(\frac{n_e}{n_o}\right)$	Maximum Φ_p at thruster exhaust	fixed at 0	NA
Boyd	2005	SPT100	particle	fluid equation	particle	fluid equation	Poisson equation		dielectric surface	Dirichlet

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Basic Scheme of Plasma Plume Analysis

- Ion beam profile
  - Fixed, obtained analytically [Ref. ex. Roy, 1996]
  - Modeling by "Vineyard" (GUI tool of MUSCAT)

- CEX ions and Electric Potential
  - Obtain time evolution of n_{cex} profile by PIC
  - Solve following non-linear Poisson equation

$$-\varepsilon_o \nabla^2 \phi = e\left(n_{bi}(x) + n_{cex}(x) - n_o \exp\left(\frac{e\phi}{kT_e}\right)\right)$$

n_o: maximum density at plume exhaust point

adopt Newton-Raphson + SOR method

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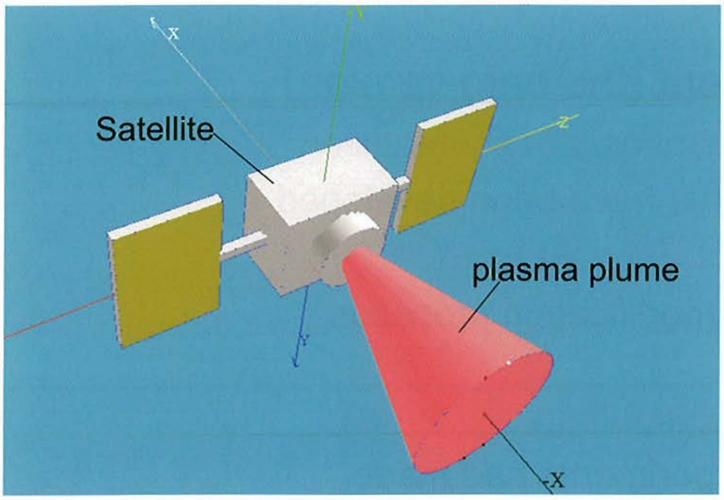
Image of the Plume Modeling by the Final Version of MUSCAT

- Determine Ion engine parameters by GUI



Ion Engine Parameters

- ion(gas) species
- beam ion density
- neutral particle density
- electron temperature
- beam expansion angle

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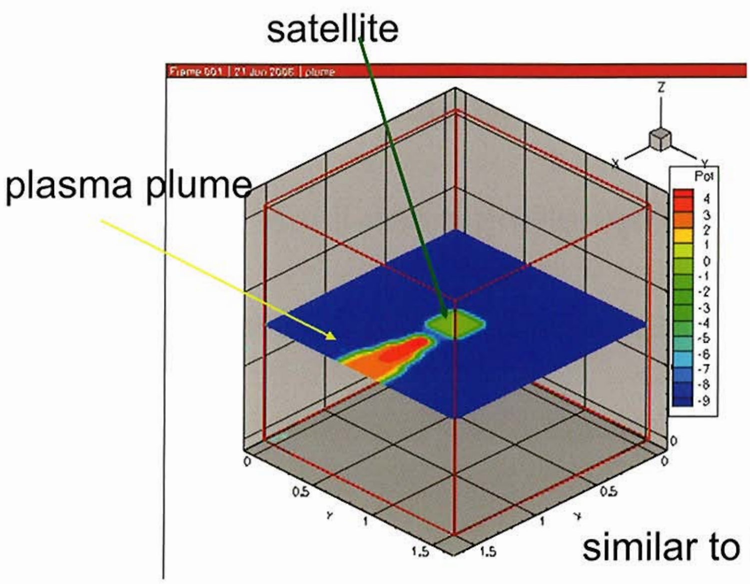
Preliminary numerical result



similar to Dr. Wang's method

- Ion engine parameter: ETS-8

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Summary

- The beta version of MUSCAT had been released
  - The first version of integrated software
- Current status of development (the beta version)
  - Integrated GUI tool “Vineyard” conducts computation
  - Fundamental physical elements have been developed (able to calculate charging at LEO, GEO and PEO)
  - Parallelization and algorithm modification proceeds speeding-up (able to perform large scale computation in 2days)
  - Validation by fundamental experiments had made

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Summary

- Plasma plume analysis
  - Basic scheme of the analysis has been determined
  - Follow CEX ions by PIC
  - Electric potential is obtained by solving a non-linear Poisson equation
  - Initial parameters are installed by MUSCAT modeler

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Future Schedule

- Final version of MUSCAT（April, 2007）
  - Data transfer function by “Vineyard”
  - Tuning and speeding-up (PEO satellite, in half a day)
  - Additional physical elements (internal charging etc.)
  - Further validation by experiments and large scale simulation
  - Feedback from users

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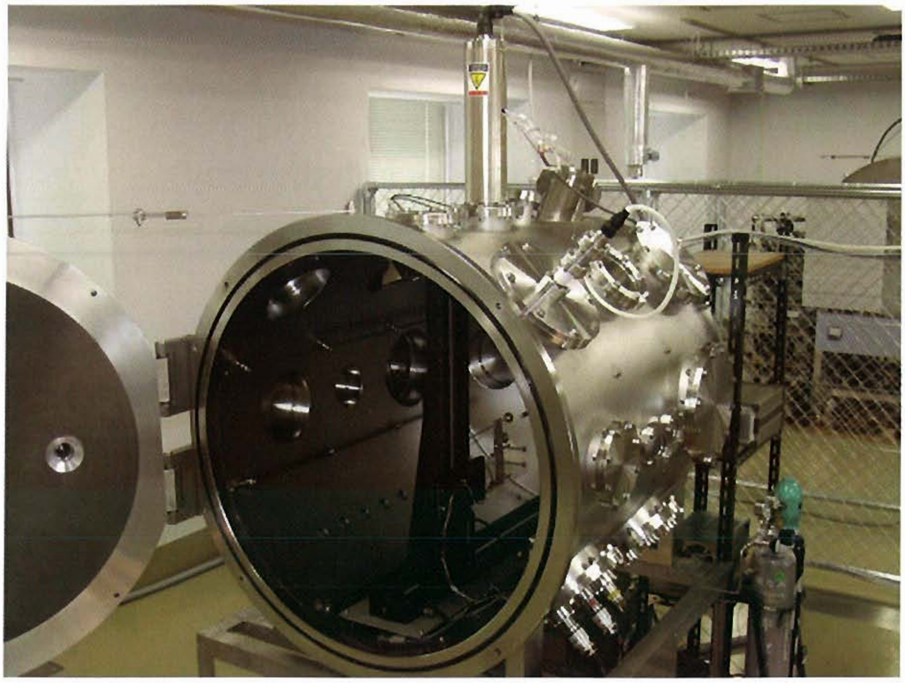
Experiments for Code Validation

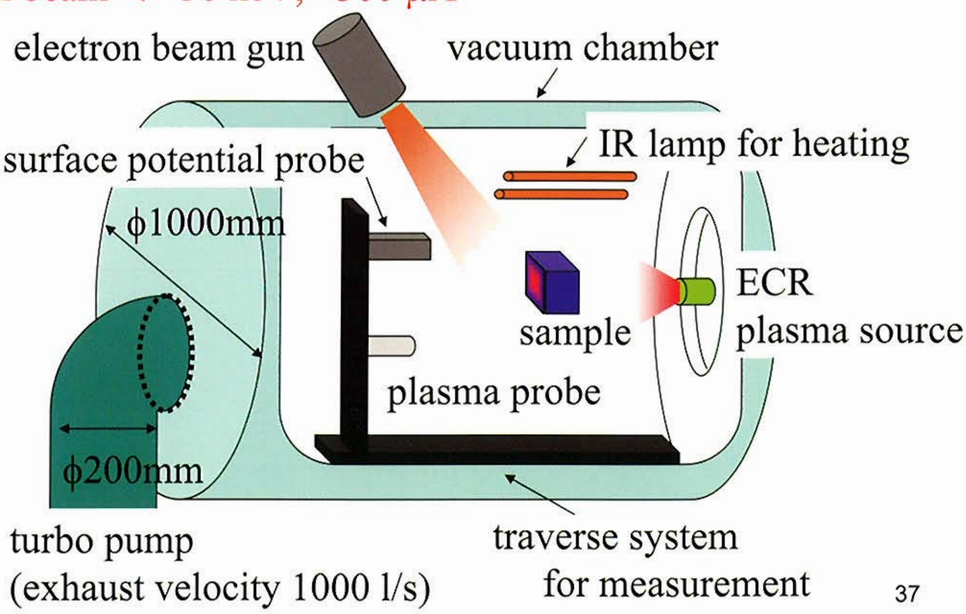
Validation Experiment Facility



Chamber to simulate Polar Earth Orbit Environment 36

Schematic of the Chamber

Simulate LEO, GEO and PEO environment
Ambient plasma: density 10^{11}~10^{12}m^{-3}, temperature 2~3 eV
Electron beam : ~30 keV, ~300 μA



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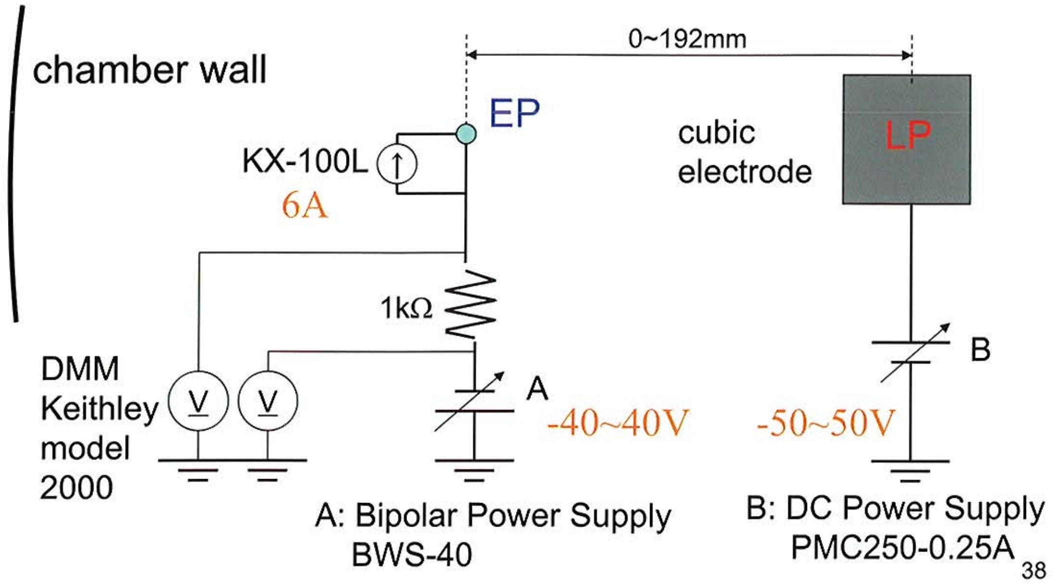
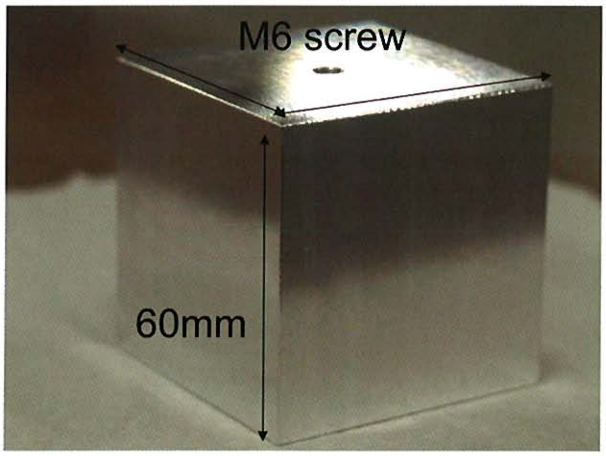
Schematic of Probe Circuit

Emissive probe (EP): for electric potential
Langmuir probe (LP): for IV characteristic curve



Cubic Electrode of Langmuir Probe

Adjust the shape to rectangular grid system of MUSCAT



Aluminum cube
size=$(60\text{mm})^3 \sim (10\lambda_D)^3$
(T=2 eV, n=$3\text{x}10^{12}$ m^{-3})

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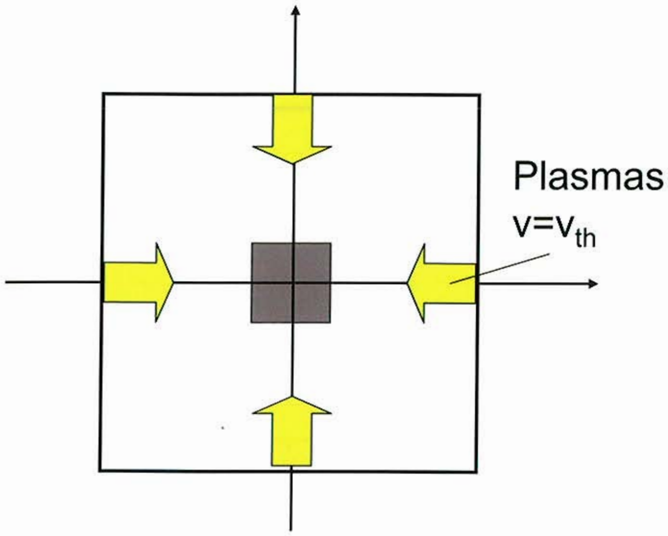
Simulation Geometry

MUSCAT employs Rectangular grid system



size(grids)
domain: 64x64x64
object : 10x10x10

Δx : 6mm(1.0λ_D)

(T=2 eV, n=3x10^{12} m^{-3})

ϕ=0 at the boundary

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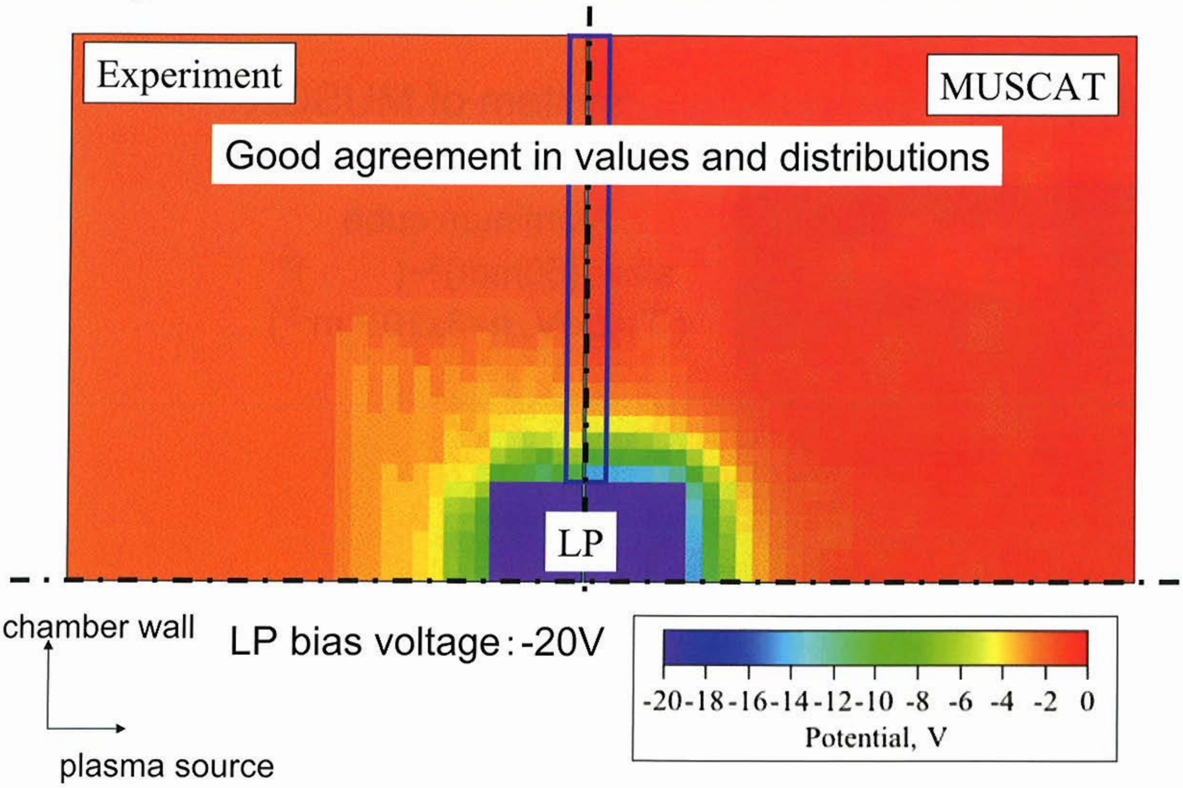
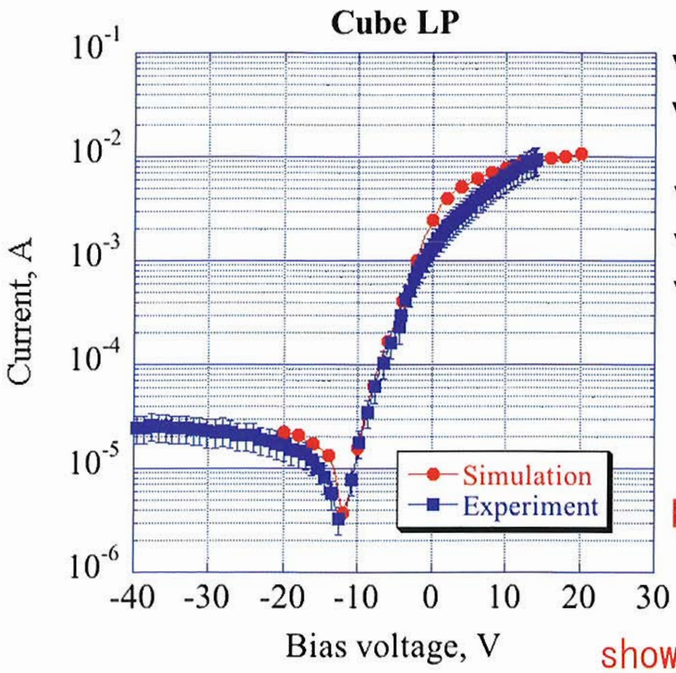
Spatial Distribution of Electric Potential



I-V Characteristic Curves



V is revised by subtracting Vs from Vp

V=Vp-Vs
Vp: probe potential
Vs: space potential(plasma)

Both are in good agreement

shows accuracy of the solver

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