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Space environment (natural and artificial) — Plasma environments for generation of worst case electrical potential differences for spacecraft

Environnement spatial (naturel et artificiel) — Environnements plasmatiques pour la génération de différences de potentiel électrique les plus défavorables pour les véhicules spatiaux

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Foreword

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This document was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

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Space environment (natural and artificial) — Plasma environments for generation of worst case electrical potential differences for spacecraft

1 Scope

This document specifies space plasma environments that lead to the generation of the worst-case surface potential differences for spacecraft. It also specifies how to estimate worst-case potential differences by using the simulation codes provided.

This document includes plasma energy and density in GEO, PEO, and MEO. This document does not include descriptions of plasma energy and density in LEO because large surface charging in LEO is likely to be due to high-voltage power generation by instrumentation of the spacecraft.

This document deals with external surface charging of spacecraft only.

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2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.1
double Maxwellian distribution
electron and proton distribution functions in GEO fitted with two temperatures

Note 1 to entry: Maxwellian distribution is as follows[12]:

$$f(v)=\left(\frac{m}{2\pi}\right)^{3/2}\left[\frac{n_1}{(kT_1)^{3/2}}\exp\left(-\frac{mv^2}{2kT_1}\right)+\frac{n_2}{(kT_2)^{3/2}}\exp\left(-\frac{mv^2}{2kT_2}\right)\right]$$

where

m	is the mass of particle;
k	is the Boltzmann constant 1,380 648 52 × 10^{-23} J/K;
n_1, n_2	are the number density of particle;
T_1, T_2	are the temperature of particle.

3.2
differential voltage
differential potential
potential difference between any two points in spacecraft, especially the insulator surface and the spacecraft body, during differential charging

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3.3
inverted potential gradient
result of differential charging where the insulating surface or dielectric reaches a positive potential with respect to the neighbouring conducting surface or metal: PDNM (positive dielectric negative metal)

3.4
normal potential gradient
result of differential charging where the insulating surface or dielectric reaches a negative potential with respect to the neighbouring conducting surface or metal: NDPM (negative dielectric positive metal)

3.5
surface charging
deposition onto or the removal of electrical charges from external surfaces of the spacecraft

4 Symbols and abbreviated terms

eV electron volt, where 1 eV = 1,602 × 10^{-19} J

GEO geosynchronous orbit

LEO low Earth orbit

MEO medium Earth orbit

PEO polar Earth orbit

Ne electron density

Ni ion density

Te electron temperature

Ti ion temperature

5 Criteria for worst-case environment

The worst-case environment shall be defined as the space environment measured in space that causes the maximum potential difference between the spacecraft electrical grounding body and external non-conductive surfaces or isolated conductive surfaces. Worst-case conditions shall be realistic.

Combinations of densities and temperatures for a valid worst-case condition shall be subject to all of the following:

— reported in the literature or published databases;

— checked to make sure they are based on valid measurements;

— physically realistic (i.e. do not violate energy density or other physical requirements); and

— verified using good spacecraft charging codes (i.e. COULOMB-2, MUSCAT, SPIS, NASCAP-2k).

This document is a part of spacecraft charging design.

6 Procedures for application to spacecraft design

Spacecraft charging simulation should be carried out at an early stage of spacecraft design. Ideally, this should be before selecting the materials for those spacecraft surfaces that will be exposed to the space environment.

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Use worst-case environments mentioned in Clause 7 as input parameters for charging simulations.

Material properties for spacecraft charging can change after exposure to the space environment. If possible, employ simulation tools using material properties after the appropriate space environmental ageing. See Annex C.

Radiation induced conductivity can change the bulk resistivity of materials. If possible, employ simulation tools that use the material properties after exposure and ageing in the appropriate space environment [11].

In the computer simulations, use the appropriate spacecraft geometry, material data, and environmental conditions. Run the simulation from a zero charging initial condition until differential potentials fully develop.

For examples of simulation codes, see Annex A. Note, however, that the list of codes in Annex A is not exclusive.

7 Space environments for worst-case simulations

7.1 GEO worst-case environment

The double Maxwellian distribution contained in Table 1 shall be used for worst-case simulation.

Table 1 — Space environment cases simulated

***Ne*1** m^{-3}	***Te*1** eV	***Ne*2** m^{-3}	***Te*2** eV	***Ni*1** m^{-3}	***Ti*1** eV	***Ni*2** m^{-3}	***Ti*2** eV
2,00E+05	400	2,30E+06	24 800	1,60E+06	300	1,30E+06	28 200

Other worst cases have been proposed. See Annex B for comparisons. m_e and m_i are 9,109 383 56 × 10^{-31} kg and 1,672 621 9 × 10^{-27} kg, respectively.

7.2 PEO and MEO worst-case environments

The worst-case plasma environment in PEO and MEO will be updated as more published measured environments become available. See Reference [3] for one published PEO environment.

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Annex A
(informative)

Spacecraft charging analysis tools

A.1 COULOMB-2

COULOMB-2 code[4] can be applied to modelling of spacecraft charging in PEO and GEO. For building of the spacecraft geometrical models and modelling results visualization, the SALOME platform is used. Plasma currents are computed in terms of Langmuir equations and particle trajectory modelling. Integral equation method is used for electrostatic equation solving. Database of electro-physical properties of typical spacecraft materials is also included in the code. The code is not easily available outside Russia.

A.2 MUSCAT

MUSCAT[5] is a fully 3D particle code that can be applied to spacecraft in LEO, PEO and GEO. Its algorithm is a combination of PIC and particle tracking. A parallel computation technique is used for fast computation. It has a JAVA-3D based graphical user interface for 3D modelling of spacecraft geometry and output visualization. The surface interactions included in the NASCAP series and SPIS are modelled. A material property database is also included. The code is commercially available.

A.3 NASCAP-2k

The most recent NASCAP code (NASCAP-2k) is available, free, to US citizens only. This is a comprehensive code with realistic geometry. It is reported to combine the capabilities of NASCAP-GEO, NASCAP-LEO and POLAR. The code is not easily available outside the US.

A.4 SPIS

SPIS[6] is a fully 3D PIC code that allows the exact computation of the sheath structure and the current collected by spacecraft surfaces for very detailed geometries. Surface interactions including photo-electron emission, back-scattering, secondary-electron emission and conduction are modelled. The source code is freely available from www.spis.org and a mailing list provides a limited amount of support.

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Annex B
(informative)

Round-robin simulation[7]

B.1 Round-robin simulations with NASCAP-2k

In order to estimate the degree of charging on spacecraft in GEO charging environments, a generic spacecraft model was constructed. It is shown in Figure B.1. The back sides of the arrays were covered with graphite. Dimensions of the model are the following.

The body is X: 1,86 m; Y: 1,55 m; Z: 2,56 m. The NPaint box on the top is X: 0,62 m; Y: 0,516 m; Z: 0,62 m. The aluminium box at the bottom is X: 0,30 m; Y: 1,55 m; Z: 0,62 m. The solar arrays have a width of 2,5 m; length: 4,0 m; thickness: 0,10 m; twist: 45 degrees. The solar array booms are 2,0 m long and 0,10 m square in cross-section. The round antenna is 2,5 m in diameter and separated from the body by 0,3 m. Material properties are shown in Table B.1.

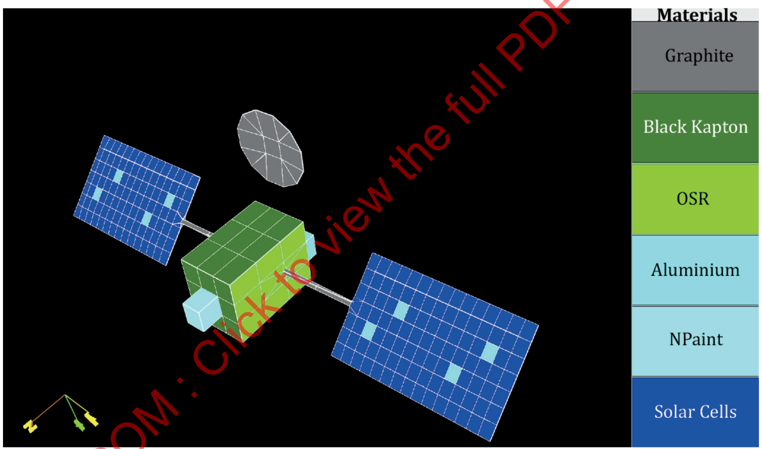

Figure B.1 — Calculation model with NASCAP-2k

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Table B.1 — Material properties

Coverglass material	Dielectric constant	Thickness m	Bulk conductivity $\Omega^{-1}m^{-1}$	Atomic number	δ_{max}	E_{max} keV	Proton yield	Proton max eV	Photoemission A m^{-2}	Surface resistivity Ω/square	Atomic wt amu	Density kg m^{-3}
Graphite	1	1,00E-03	−1	4,5	0,93	0,28	0,455	80	7,20E-06	−1	12,01	2 250
Aluminium	1	1,00E-03	−1	13	0,97	0,3	0,244	230	4,00E-05	−1	26,98	2 699
Black Kapton®[a]	3,5	2,50E-06	−1	5	5,2	0,90	0,455	140	5,00E-06	−1	12,01	1 600
Kapton®[a]	3,5	1,27E-04	1,00E-16	5	2,1	0,15	0,455	140	2,00E-05	1,00E+16	12,01	1 600
Solar cells (MgF2)	3,8	1,25E-04	1,00E-13	10	5,8	1	0,244	230	2,00E-05	1,00E+19	20	2 660
OSR	4,8	1,50E-04	1,00E-16	10	3,3	0,5	0,455	140	2,00E-05	1,00E+19	20	2 660
NPaint	3,5	1,27E-04	1,00E-16	5	2,1	0,15	0,455	140	2,00E-05	1,00E+16	12,01	1 600

[a] Kapton® is the trade name of a product supplied by DuPont. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of the product named. Equivalent products may be used if they can be shown to lead to the same results.

This model was placed in simulated GEO environments in the NASCAP-2k spacecraft charging code and allowed to charge for 2 000 s of time. The environments used were daylight and eclipse in these proposed worst cases.

The electron and ion densities and temperatures for these environments are given in Table B.2.

Table B.2 — Space environment cases simulated

Environment name	*Ne1* m^{-3}	*Te1* eV	*Ne2* m^{-3}	*Te2* eV	*Ni1* m^{-3}	*Ti1* eV	*Ni2* m^{-3}	*Ti2* eV
SCATHA-Mullen1	2,00E+05	400	2,30E+06	24 800	1,60E+06	300	1,30E+06	28 200
SCATHA-Mullen2	9,00E+05	600	1,60E+06	25 600	1,10E+06	400	1,70E+06	24 700
ECSS-E-ST-10–04C (SCATHA 1979)	2,00E+05	400	1,20E+06	27 500	6,00E+05	200	1,30E+06	28 000
NASA Worst Case	1,12E+06	12 000			2,36E+05	29 500		
ATS-6	2,36E+06	29 500			2,36E+05	29 500		
MIL-STD-1809	2,36E+06	3 100	6,25E+05	25 100	6,00E+05	200	1,20E+06	28 000
Galaxy 15	4,58e+04	55 600			1,00E+05	75 000		

After charging for 2 000 s, the computed quantities were tabulated in Table B.3 — minimum potential (Min Chg), maximum potential (Max Chg), frame potential (Frame) — and derived from these were (Max-Min), the largest differential potential, and (Max-Frame), the inverted gradient maximum differential potential.

Table B.3 — Simulation results of NASCAP-2k

	Daylight charging after 2 000 s					Night-time charging after 2 000 s				
	Min Chg	Max Chg	Abs Chg (frame)	Max-Min	Max-Frame	Min Chg	Max Chg	Abs Chg (frame)	Max-Min	Max-Frame
Galaxy15	−802	9,56	2,751	811,56	6,81	−17 820	−17 410	−17 590	410	170
NASA Worst Case	−9 286	−1 518	−2 415	7 768	3 940	−13 230	−5 687	−9 153	7 543	3 466
ATS-6	−13 910	−3 617	−5 779	10 293	2 162	−18 310	−9 733	−13 220	8 577	3 487
SCATHA-Mullen1	−11 870	−5 236	−8 468	6 634	3 232	−11 980	−6 752	−10 950	5 228	4 198

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Table B.3 *(continued)*

	Daylight charging after 2 000 s					Night-time charging after 2 000 s				
	Min Chg	Max Chg	Abs Chg (frame)	Max-Min	Max-Frame	Min Chg	Max Chg	Abs Chg (frame)	Max-Min	Max-Frame
SCATHA-Mullen2	−10 940	−4 077	−6 753	6 863	2 496	−11 160	−6 010	−9 736	5 150	3 726
ECSS-E-ST-10–04C (SCATHA 1979)	−10 870	−3 512	−5 640	7 358	2 128	−11 430	−6 050	−9 521	5 380	3 471
MIL-STD-1809	−5 728	−1 407	−2 267	4 321	860	−6 312	−3 393	−5 509	2 919	2 116

Reference [8] and Reference [9] have established that the best GEO Daytime Charging Index for both absolute and differential charging is the electron flux above about 9 keV. Using this criterion, the proposed worst-case charging environments can be ranked according to their F (E > 9 keV) in Table B.4.

Table B.4 — Environment ranking according to high energy electron flux

Environment	*F* > 9 keV e⁻/cm²s	Rank
SCATHA-Mullen1	5,75E+09	1
SCATHA-Mullen2	4,08E+09	2
ECSS-E-ST-10–04C (SCATHA 1979)	3,19E+09	3
ATS-6	2,26E+09	4
MIL-STD-1809	2,11E+09	5
ATS-6 day 178,1974	2,08E+09	6
ATS-6 day 217,1974	1,98E+09	7
NASA Worst Case	1,70E+09	8
Galaxy15	1,79E+08	9

From these efforts, it can be seen that NASCAP-2k calculations on the generic spacecraft model show that the worst-case single Maxwellian environment for differential charging (day or night) is ATS-6, followed by the NASA Worst Case environment, and at night the worst-case double Maxwellian environment for differential charging in eclipse is SCATHA-Mullen1, whereas in the daytime, the worst-case double Maxwellian for (Max-Frame) is SCATHA-Mullen1, but for (Max-Min) is ECSS-E-ST-10-4C.

B.2 Round-robin simulations with MUSCAT

The calculations were performed with the multi-utility spacecraft charging analysis tool (MUSCAT). Figure B.2 shows the spacecraft model for calculation. The size is the same as for the calculation model of NASCAP-2k. The material properties are also the same as NASCAP-2k, listed in Table B.1. The material of the yellow box is Kapton®[1)] instead of NPaint, but this should not matter since from Table B.1, their properties are identical.

1) Kapton® is the trade name of a product supplied by DuPont. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of the product named. Equivalent products may be used if they can be shown to lead to the same results.

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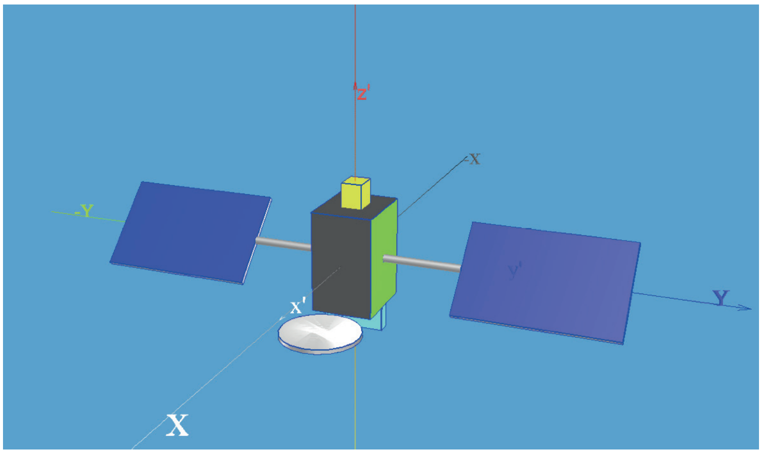

Figure B.2 — Calculation model of MUSCAT

Table B.5 shows the plasma environments used for MUSCAT simulations. The LANL-KIT environment was added to the list. This environment was picked up as worst case from LANL satellite data[7]. The LANL-KIT, ATS-6, and NASA Worst Case environments are simulated as single Maxwellian distributions, and the others are double Maxwellian distributions.

Table B.5 — Plasma environments for MUSCAT

Environment name	*Ne*1 m^{-3}	*Te*1 eV	*Ne*2 m^{-3}	*Te*2 eV	*Ni*1 m^{-3}	*Ti*1 eV	*Ni*2 m^{-3}	*Ti*2 eV
LANL-KIT	5E+06	13 500			2,5E+05	5 000		
ATS-6	1,20E+06	16 000			2,36E+05	29 500		
NASA Worst Case	1,12E+06	12 000			2,36E+05	29 500		
SCATHA-Mullen1	2,00E+05	400	2,30E+06	24 800	1,60E+06	300	1,30E+06	28 200
SCATHA-Mullen2	9,00E+05	600	1,60E+06	25 600	1,10E+06	400	1,70E+06	24 700
ECSS-E-ST-10–04C (SCATHA 1979)	2,00E+05	400	1,20E+06	27 500	6,00E+05	200	1,30E+06	28 000

The calculation dimension is 64 × 256 × 64. The grid size is 0,1 m. The angle of sunlight is perpendicular to the solar array paddle surface.

Table B.6 shows the daylight simulation result of MUSCAT. The simulation results after about 2 000 s were listed — minimum potential (Min Chg), maximum potential (Max Chg), frame potential (Frame) — and derived from these were (Max-Min), the largest differential potential, (Max-Frame), the inverted gradient maximum differential potential, and (Min-Frame), the normal gradient maximum differential potential. The SCATHA-Mullen1 plasma environment showed worst environment for body potential, inverted potential gradient, and normal potential gradient.

Table B.6 — Daylight simulation results of MUSCAT

	Time s	Min Chg	Max Chg	Abs Chg (frame)	Max-Min	Max-Frame	Min-Frame
NASA Worst Case	2 000	−14 600	−40	−1 820	14 600	1 780	−12 800
ATS-6	2 000	−19 400	−70	−3 400	19 300	3 330	−16 000
SCATHA-Mullen1	1 835,5	−41 500	−350	−16 100	41 200	15 700	−25 400
SCATHA-Mullen2	2 038	−34 000	−60	−10 300	33 900	10 300	−23 700
ECSS-E-ST-10–04C (SCATHA 1979)	2 006,6	−28 800	−160	−7 450	28 600	7 290	−21 400
LANL-KIT	2 021,1	−38 800	−290	−15 000	38 500	14 800	−23 700

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Table B.7 shows the night-time simulation results of MUSCAT. The SCATHA-Mullen1 environment showed the maximum inverted gradient potential.

Table B.7 — Night-time simulation results of MUSCAT

	Time s	Min Chg	Max Chg	Abs Chg (frame)	Max-Min	Max-Frame	Min-Frame
NASA Worst Case	2 000	−43 700	−42 900	−43 300	870	402	−468
ATS-6	2 000	−63 800	−63 200	−63 500	600	270	−330
SCATHA-Mullen1	2 000	−107 000	−102 000	−105 000	5 600	3 420	−2 170
SCATHA-Mullen2	2 000	−112 000	−107 000	−110 000	4 890	2 700	−2 190
ECSS-E-ST-10-04C (SCATHA 1979)	2 000	−70 000	−67 100	−68 600	2 870	1 520	−1 350
LANL-KIT	2 000	−72 900	−71 800	−72 300	1 030	468	−566

B.3 Round-robin simulations with SPIS

The calculations were performed with the SPIS 4.0. The spacecraft body shown in Figure B.2 was used for the simulation. The result is shown in Table B.8. The SCATHA-Mullen1 showed the worst case of potential difference (Max-Min) in daytime.

Table B.8 — Simulation results of SPIS after 1 000 s

	Day (sunlight)				Night (eclipse)			
	Chg Time	Max Chg OSR	Min Chg (frame) BK	Max-Min	Chg Time	Max Chg (frame) BK	Min Chg OSR	Max-Min
ATS-6	1 018,231 1	−5 750,13	−6 557,49	807,358 7	1 006,941	−20 401,7	−21 824,5	1 422,831
NASA Worst Case	1 045,626 2	−2 294,53	−2 766	471,463	1 020,852	−14 266,5	−14 670,9	404,392
SCATHA-Mullen1	1 004,722 2	−14 556,7	−17 812,2	3 255,459	1 039,86	−25 935	−26 800,1	865,148
SCATHA-Mullen2	1 016,937 3	−12 057,2	−14 265,7	2 208,484	1 015,197	−24 943	−26 396	1 453,012
ECSS (SCATHA1979)	1 011,441 8	−10 416,5	−11 873,4	1 456,912	1 012,197	−24 581,7	−26 439,4	1 857,685

B.4 Conclusions

Round-robin simulations were performed with the same simulation model and environments between NASCAP-2k, MUSCAT, and SPIS. All simulations showed large amounts of charging in all the proposed worst-case environments. There was a divergence of charging predictions in three tools, with MUSCAT giving uniformly larger values of (Max-Min) in all daylight environments and NASCAP-2k giving larger values of (Max-Min) for most night-time environments. It is unclear why MUSCAT gave much larger values of frame charging in the night-time than were the largest electron temperatures in the environment. However, be that as it may, for all-around frame and differential charging, the SCATHA-Mullen1 double Maxwellian plasma environment showed the largest maximum inverted gradient potentials in both MUSCAT, NASCAP-2k, and SPIS simulations, and can be reliably used as a worst-case environment for spacecraft design and testing.

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Annex C
(normative)

Material properties

C.1 Simulation condition

The calculations were performed with the multi-utility spacecraft charging analysis tool (MUSCAT). Figure C.1 shows the spacecraft model for calculation. The satellite model for simulation was a cube of 3 m. The satellite body is aluminium. The insulator is mounted on +X face and +Y face. The Kapton® and the coverglass CMG100-AR were used as insulators.

The calculation dimension is 32 × 32 × 32. The grid size is 0,5 m. The angle of sunlight is (1, 0, 1).

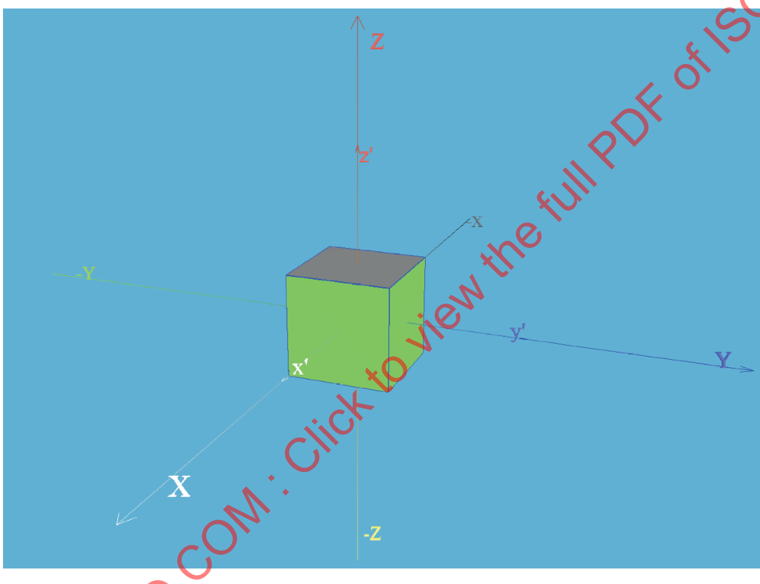

Figure C.1 — Calculation model

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Table C.1 shows the plasma environment for the calculation. These environments were used in the round-robin simulation between MUSCAT and NASCAP-2k. The SCATHA-Mullen1 is the double Maxwellian distribution and was selected as the worst-case environment from the results of the round-robin simulation. m_e and m_i are 9,109 383 56 × 10^{-31} kg and 1,672 621 9 × 10^{-27} kg, respectively.

The material properties for the simulation are listed in Table C.2. Three materials were used in the simulation. The secondary electron yield and photoemission were measured for Kapton® after ageing effect of proton, electron, UV, and AO. The bulk conductivity was also measured after proton and electron irradiation. The bulk conductivity after UV and AO was not measured, so the same value as nominal sample was used for UV and AO.

The secondary electron yield of CMG100-AR was also measured after proton, electron, and UV irradiation. Multi means the irradiation of proton, electron, and UV. The secondary electron yield after multi-irradiation was same as UV irradiation. The typical values were used for the other properties.

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C.2 Results

Table C.3 shows the simulation result with the insulator of Kapton®. The light side means the Kapton® mounted on the surface of +X. The dark side means the Kapton® mounted on the surface of +Y. The frame is the potential of aluminium. The potential of frame was within 3 kV difference from −13 kV to −10,7 kV. On the other hand, the potential difference between Kapton® and frame had a large distribution from −8,9 kV to 0,6 kV for light side, from −17,5 kV to −6,5 kV.

Table C.4 shows the simulation result with the insulator of CMG100-AR. The result also had a large distribution in potential after ageing.

Table C.1 — Plasma environments

Environment name	*Ne*1 m^{-3}	*Te*1 eV	*Ne*2 m^{-3}	*Te*2 eV	*Ni*1 m^{-3}	*Ti*1 eV	*Ni*2 m^{-3}	*Ti*2 eV
SCATHA-Mullen1	2,00E+05	400	2,30E+06	24 800	1,60E+06	300	1,30E+06	28 200

Table C.2 — Material property

Material	Ageing effect	δ_{max}	E_{max} eV	Photoemission µA m^{-2}	Bulk conductivity $\times 10^{-14}\ \Omega^{-1}m^{-1}$	Dielectric constant	Thickness µm
Aluminium	None	0,97	300	40	−1	1	1 000
Kapton®	None	1,69	150	3,2	0,7	3,5	25,4
	Proton	1,66	150	7,9	1,6	3,5	25,4
	Electron	1,97	150	3,3	2,9	3,5	25,4
	UV	2,12	150	8,7	0,7	3,5	25,4
	AO	1,1	700	3,0	0,7	3,5	25,4
CMG100-AR	Nominal	6,76	1 000	20	1,0	3,8	125
	Proton	2	350	20	1,0	3,8	125
	Electron	6	1 000	20	1,0	3,8	125
	UV and multi	1,8	200	20	1,0	3,8	125

Table C.3 — Simulation result of Kapton®

Ageing	Light side	Dark side	Frame	Light-frame	Dark-frame
Nominal	−17 300	−19 900	−13 000	−4 300	−6 900
Proton	−11 900	−23 400	−10 700	−1 100	−12 600
Electron	−20 400	−29 000	−11 500	−8 900	−17 500
UV	−10 300	−18 200	−10 900	600	−7 300
AO	−16 900	−19 500	−13 000	−3 900	−6 500

Table C.4 — Simulation result of CMG100-AR

Ageing	Light side	Dark side	Frame	Light-frame	Dark-frame
Nominal	−1 800	−19 900	−3 000	1 200	−16 900
Proton	−4 000	−29 800	−6 900	2 900	−22 900
Electron	−2 500	−22 800	−4 500	1 900	−18 300
UV	−4 000	−30 200	−6 800	2 800	−23 500

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C.3 Conclusions

The simulations were performed with different material properties by MUSCAT. The calculated potentials had a large distribution after ageing effect.

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