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Simulation of device in low density plasma: From spacecraft to dust particle

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When a device is immersed in plasma, it will be charged by electrons and ions in plasma. The stable charge potential is controlled by the electrons and ions kinetic energy. When the electrons and ions energy distributing function are complex, or when the device is complex in geometry and circuit structure (for example, some charge leak channel exist), the theory calculating of charging potential is difficult and the numerical simulating is needed.

The major difficulties of the simulating contain the follow issues: 1) The charging time is much longer than the characteristic time of ion/electron moving. A typical scene is the spacecraft charging in space plasmas. Here the charging stable time varies between several millisecond to several hours. 2) The geometry and material conductivity are complex, so the Poisson problem need some artificial boundary conditions to consider the charging effect. 3) Besides the absorbing of ion/electrons, the charging mechanisms include the photoemission (PE), secondary electron emission (SEE), charge leak, field emission, and so on. These effect values varied several orders but cannot be neglected both.

We designed a multi timescale framework to solve the all problems.

The fundamental method is Particle-In-Cell (PIC) algorithm. A capacitance Matrix based method is introduced to solve the charging potential by the absorbing charges in the conductors. PE and SEE are considered in the PIC with Monte-Carlo (MC) methods.

An Equation-Free-Multi-Timescale framework is used to solving the slow potential varying. The charge simulating consists of the follow code loop:

(1) Executing some(M) PIC/MC steps to get the plasma relaxation.

(2) Executing N PIC/MC steps to get the charging values ΔC of the device. So the charging current on the device is ΔC/(NΔt).

(3)Modify the simulating date as Q=Q+KΔC, T=T+KNΔt，U=Poisson(Q).

After every loop, compare the charging current in step (2) with the current in the prior loop. If the current values are close, increase the K, else decrease the K.

The charge leak on the Ohm electrical connection is solve between the loop with simple Ohm Laws. However, because the leaking charge can be estimated too large, the leaking values will be limited by some physical considering. PE effects will be limited by similar consideration: Conductor Potential dominated by PE should have a value around 0-5 Volts.

Poisson Solver must be customized to satisfy the upper requirements. We use a Capacitance Matrix method to construct the Poisson Boundary Conditions: introduce the ansatzes $[Q]=[C][U]$, where Q and U are the list of the charges and the voltages on the conductors. The C is Matrix of the conductor capacitance and can be solved by energy or flux calculation. Then the voltage can be gotten with [U]=[D]([Q]-[Q_0]), where [D] can be gotten from [C] and [Q_0] is the conductor charge by zero voltage [1]. The limitation of leak and PE are added to the Poisson solver.

The device geometry is modeled on structure mesh with simple material sets [2]. Where a simple lighting tracing algorithm is used to calculate PE.

Benchmarks of the code are executed in the scene of spacecraft charging in space and dust particle in space plasmas.

References

[1] Plasma Sources Sci. Technol. 33 (2024) 045003

[2] 19th Chin. Plasma sci. Tech. Conf., Dalian, 2019

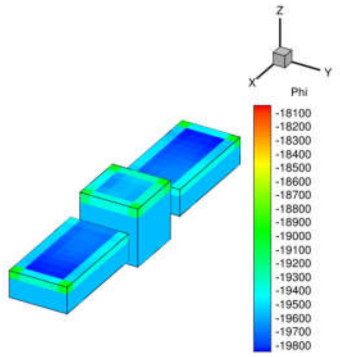

Figure 1: The charging of a satellite in HEO space plasma

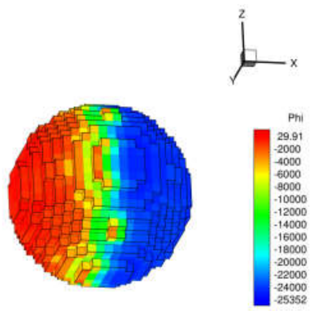

Figure 2: A dielectric sphere charging in HEO plasma with sun light illuminates. On the sun light surface, the potential is fixed to small positive values.