PIC/DSMC Simulation of Vacuum Arc Discharge with Active Anode

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Abstract: PIC-MCC models are presented for vacuum arc discharges. The 1D PIC-MCC model is used to investigate mechanism of plasma formation. The electron avalanche is reached when the neutral density is large enough such that the mean free path of electrons becomes smaller than the distance between two electrodes. The effects of the field emission current and copper evaporation rate on the time-to-breakdown are studied. The time-to-breakdown is smaller in 1D model under the similar boundary conditions compared to 2D.

Keywords: PIC/DSMC Simulation, vacuum arc, anode spot

1. Introduction

Understanding the mechanism of plasma build-up in vacuum arcs is essential in vacuum interrupters and vacuum arc ion sources. The vacuum arc is a metal vapor arc in a vacuum environment. The metallic neutrals are not background gas but from erosion of cathode body by evaporation and/or sputtering. It is known that the vacuum arc is initiated by electron emission from the cathode. It heats the electrode and causes explosive-emission or the evaporation from the cathode surface. The plasma build-up and expansion in vacuum arc was modeled in [1-5] with the help of kinetic PIC-MCC method. Due to high calculation time requirements, the PIC-MCC methods were used for the inter-electrode gap with length not exceeding a few tens of microns. For the plasma expansion in the gap of 1 mm in size, the MHD approach was used [6].

The kinetic approach provides much more detailed information and can operate in the parameter range where MHD is not applicable. In this paper the vacuum arc discharge will be studied using the PIC-MCC method.

2. Method description

The particle modeling is equivalent to solving the Boltzmann equation by assuming that the decoupling of collisionless motion and collision [7]. The particle simulation method has been studied separately by two types of researchers. Plasma physicists, who are interested in the simulation of charged particle, have developed the particle-in-cell (PIC) method or the PIC-MCC method if including the Monte Carlo treatments of collisions. On the other hand, aerodynamicists have developed direct simulation Monte Carlo (DSMC) method of neutral species since the pioneering work of Bird [8]. For vacuum arc, both the neutrals and charged particles are tracked, so the PIC-MCC/DSMC method will be used. The computing sequence for PIC-MCC/DSMC method is shown in Fig. 1.

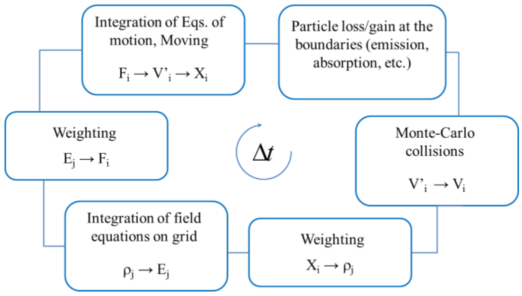

Fig. 1 Computing sequence for PIC-MCC method.

3. Model validation

Our code has a lot of collision modules and surface models for boundary. The collision modules include Coulomb collision, elastic collision, excitation, ionization, charge transfer, and recombination. We use the TA method [9] to deal with Coulomb collisions. The surface models include the electron emission, the neutral evaporation, sputtering and secondary electron emission.

Coulomb collision is tested as follows. The initial velocity distribution is anisotropic Maxwellian with T_z not equal to T_x

$$f(\vec{v}) = \left(\frac{2\pi k}{m_e}\right)^{-3/2} T_x\sqrt{T_z}\exp\left(-\frac{m_e(v_x^2+v_y^2)}{2kT_x}-\frac{m_e v_z^2}{2kT_z}\right), T_x \neq T_z$$

Electron-electron Coulomb collision will lead to an isotropic Maxwellian distribution with T_z equal to T_x as shown in Fig. 2. For the Coulomb collision test we use electron density 10^{10} cm^{-3}, T_z equal to 5 eV, and T_x equal to 4 eV. The coulomb collision module is found to produce results quite well with that from theory.

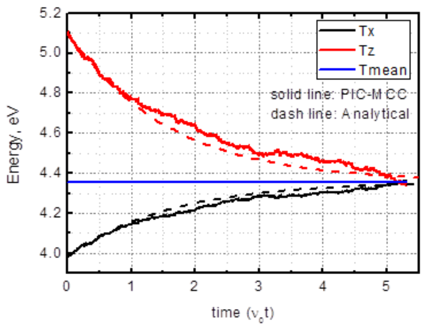

Fig. 2 Coulomb collision test.

The validation of particle move and field solve modules are shown by the space-charge-limited current (SCLC) in a plane diode. In the simulation, the gap distance is set as 0.01 cm while the applied voltage is 10 kV. The simulated SCLC is also in good agreement with Child-Langmuir equation as shown in Fig. 3.

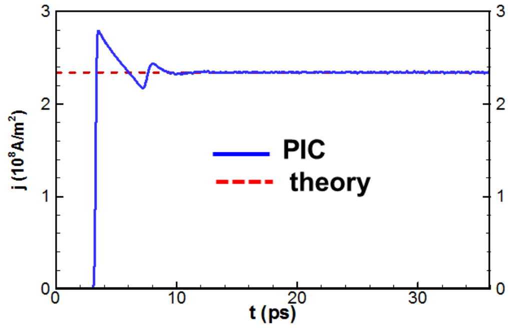

Fig. 3 Current density in a plane diode.

After validating separate push and collision modules as well as field solvers, we would like to compare the results from the whole code with that from Ref. [1]. Time evolution of e−, Cu, and Cu+ average densities are shown in Fig. 4 for vacuum arc discharge with Cu cathode, which is quite close to that from "Aleph" and "ArcPIC".

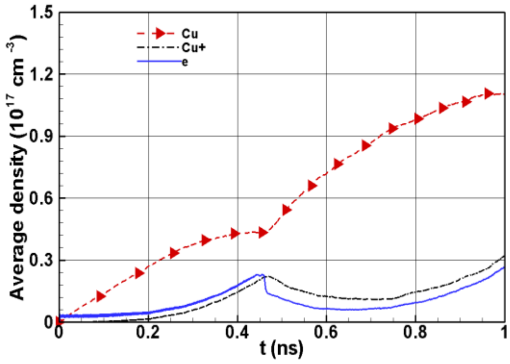

Fig. 4 Time evolution of e−, Cu, and Cu+ average densities for vacuum arc discharge with Cu cathode.

4. Results and discussions

The code is then used to calculate the vacuum arcs with active anode. Fig. 5 shows the schematics for the simulation. The following boundary conditions are assumed on the walls:

a. Dirichlet V =0 and V=25 on cathode surface 1 and 3;
b. Neumann dV/dn =0 on surface 2 and 4;
c. Influx of e on surface 1 and 3 are according to Murphy and Good approximation;
d. Influx of Cu on surface 1 and 3 according to Hertz-Knudsen approximation;
e. Particles that hit surface 1 and 3 disappear;
f. Particles that hit surface 2 or 4 reflect.

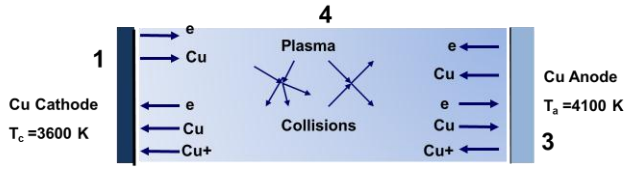

Fig. 5 Schematics for vacuum arc discharge simulation with active anode.

Fig. 6 shows the calculated particle densities, electron temperature and ion temperature respectively. It is found that the maximum Cu density is close to the anode because the anode temperature is larger than the electron temperature. The electron temperature is about several eV, and the minimum Te is located close to the anode due to high collision frequency. The ion temperature T_i increases when ions move from anode to cathode.

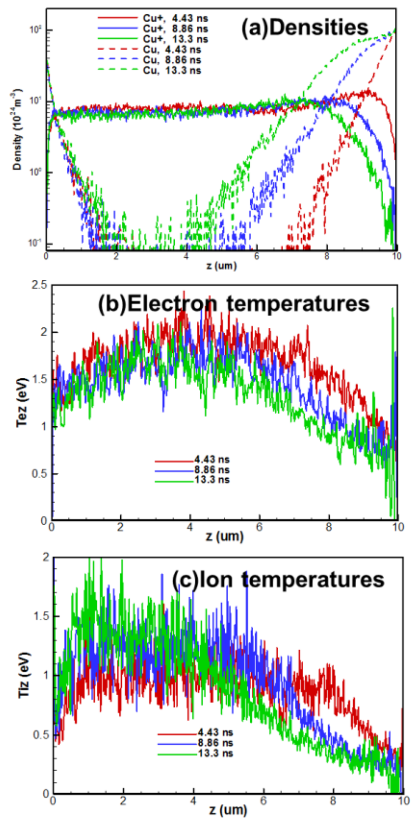

Fig. 6 (a) densities, (b)electron temperature, and (c) ion temperature from 1D simulation of vacuum arc discharge with active anode.

After that, the anode temperature is varied to investigate the mechanism of plasma formation during vacuum arc discharge. It is found that the electron avalanche is reached when the neutral density is large enough such that the mean free path of electrons becomes smaller than the distance between two electrodes. The effects of the field emission current and copper evaporation rate on the time-to-breakdown are studied in detail using 1D PIC model. The time-to-breakdown decreases with the increasing copper evaporation.

2D3V PIC simulation in R-Z coordinate is also performed. The time-to-breakdown is smaller in 1D PIC model under the similar boundary conditions. The reason is that the particles move in one direction in 1D PIC model, which causes the larger particles number density and the ionization rate. Fig. 7 gives an example of ion distribution during the simulation. More results will be reported on the conference site.

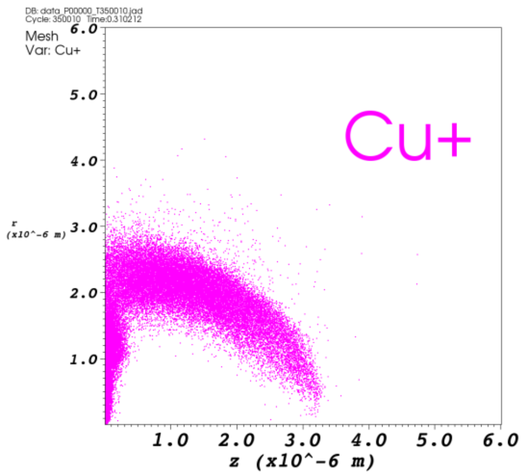

Fig. 7 Cu+ distribution from 2D simulation.

5. Conclusion

The 1D PIC-MCC model is used to investigate mechanism of plasma formation. It is found that the electron avalanche is reached when the neutral density is large enough such that the mean free path of electrons becomes smaller than the distance between two electrodes. The effects of the field emission current and copper evaporation rate on the time-to-breakdown are studied in detail using 1D PIC model. The time-to-breakdown decreases with the increasing copper evaporation. By comparing with 2D PIC simulation result, the particles move in one direction in 1D PIC model, which causes the larger particles number density and the ionization rate. The time-to-breakdown is smaller in 1D PIC model under the similar boundary conditions.

6. References

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