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Three-dimensional hybrid simulation on plasma jet formation in Zirconium-Deuterium multi-component vacuum arc discharge

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Metal vapour vacuum arcs (VAs) are widely used in various fields of industry, such as circuit breakers, ion sources, electrical thrusters, and deposition systems. Although experiment is still the main research tool for VAs, numerical modeling has recently made rapid progress in their study. In recent years, our group has developed particle-in-cell (PIC) method [1-3] as well as fluid method [4-6] to simulate the process of vacuum breakdown, plasma jet formation and ion acceleration etc. In this paper, we report a three-dimensional hybrid simulation on the plasma jet formation in vacuum arc discharge with a Zirconium-Deuterium cathode. The hybrid model aims to take advantage of both fluid simulation with low computation cost and particle simulation with high predictive ability with phase-space information of micro-particles. The quasi-neutrality approximation is used in the hybrid model [7, 8], in which ions or neutrals are treated as super-particles by the PIC method, and electrons are treated as inertia-less fluid. The computational cycle is as follows: the velocity of ions is updated by interpolated electromagnetic field using Boris method, and further altered by electron-ion friction force; the position of ions is updated using its velocity, and boundary condition is checked; the magnetic field B is advanced by Faraday's law; the current density is computed by Ampere's law in which the displacement current is neglected; the electric field is computed by general Ohm's law. To obtain high-order accuracy of field solution, the predictor-corrector method is used with virtual-pushing of particle position. The electron density is directly obtained by quasi-neutrality condition, and electron velocity is calculated by the current density and obtained electron density. Inside the computational cycle, the Coulomb collisions between D-D, Zr-Zr and D-Zr ions are performed using Nanbu's method [9], and Monte Carlo collision can be activated by sampling electron macro-particles from their density, velocity and temperature. Electron temperature is updated by considering energy loss between electron-neutral collisions, as well as heat conduction and diffusion. The constraint on spatial step is determined by the minimum of inertial length and mean free path of ions. The constraint on temporal step is usually determined by the ion collision time, resistive term of magnetic diffusion equation, and the stability criterion for waves in the whistler limit [10]. After carefully choosing the appropriate space and time step, we performed hybrid simulation on the plasma jet formation in millimeter scale in all three dimensions. Both single and multiply cathode spot (CS) plasma jet are studied. The radius of one CS is 50 microns with a nominal current density of $3 * 10^9 A/m^2$. The simulated result showed a different behavior of angular distribution of ions with light and heavy mass, which agrees with previous experiment and other simulations.

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