Introducing Merlino2D, an open-source fluid code for gas discharge simulations

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Introduction

We introduce Merlino2D, an open-source MATLAB code for the simulation of low-temperature gas discharges and plasma-based devices. The code operates on unstructured triangular meshes and enables robust time-dependent simulations in two-dimensional domains using both Cartesian and cylindrical coordinates. It also provides a native interface to the open-source Lisbon KInetics Boltzmann solver (LoKI-B).

Model Description

The code implements a fluid plasma model. For each species s, the continuity equation

$$\frac{\partial n_s}{\partial t} + \nabla \cdot \Gamma_s = \Omega_s \tag{1}$$

is discretized using the finite volume method (FVM). For air discharges, photoionization source terms can also be included according to the model described in [1]. In addition, the contribution of the surface charge density, σ, to the electric field can be taken into account when simulating dielectric barrier discharges. The particle fluxes are evaluated under the drift–diffusion approximation, $\Gamma_s = -D_s \nabla n_s + \mathrm{sign}(q_s)\,\mu_s n_s \mathbf{E}$. Boundary conditions for the continuity equations at electrodes are taken from [2]. Equation (1) is coupled with the Poisson equation,

$$\nabla \cdot (\varepsilon_r \mathbf{E}) = \frac{\rho}{\varepsilon_0}, \tag{2}$$

which is discretized using the finite element method (FEM).

Traditional plasma simulation codes often employ explicit or semi-explicit time integration schemes. These methods are subject to stability constraints, which severely restrict the time-step size. Fully implicit schemes allow for much larger time steps, but their application to plasma simulations is often limited by the high computational cost associated with the resulting nonlinear systems.

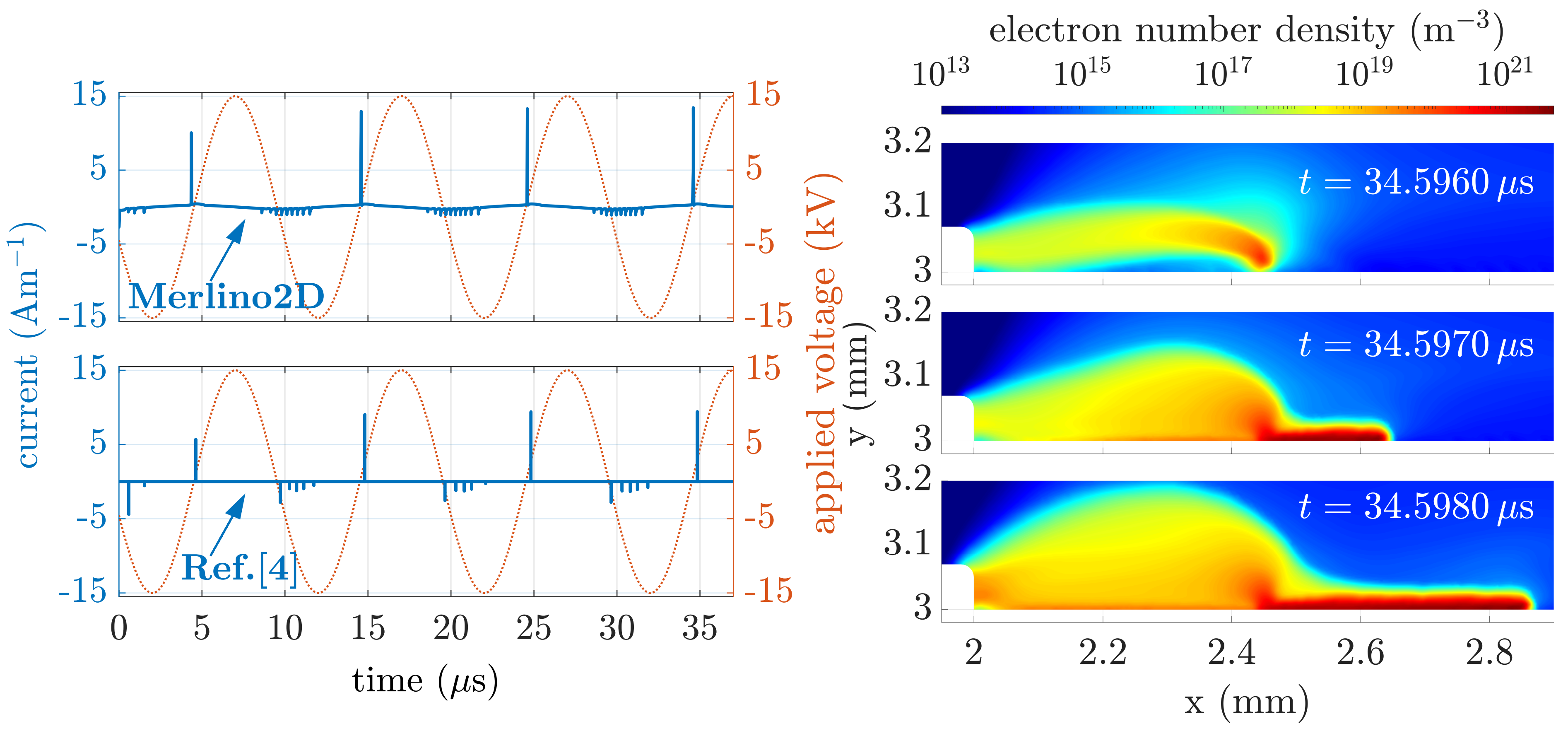
To overcome this limitation, Merlino2D adopts a differential-algebraic equation (DAE) formulation [3],

$$\frac{dn}{dt} = f(t, n, \varphi), \tag{3}$$

$$0 = g(t, n, \varphi), \tag{4}$$

where the Poisson equation is treated as an algebraic constraint and the electric potential is included in the state vector. This approach yields a sparse Jacobian matrix, reducing memory requirements and computational cost. Combined with adaptive time stepping, it provides an efficient framework for simulating the highly stiff behavior characteristic of plasma discharges.

Results



(a) Current and applied voltage (b) Electron density

Figure 1: Surface DBD results corresponding to the benchmark case of [4]. Dielectric layer: 3 mm, $\varepsilon_r = 3.2$. HV electrode: 70 μm x 2 mm. Grounded electrode: 5 mm. $V_{HV} = 15 \times 10^3 \sin(2\pi 10^5 t)$ kV. $\gamma_{see_{HV}} = 5 \times 10^{-2}$, $\gamma_{see_{diel}} = 1 \times 10^{-2}$.

Figure 1a compares the discharge current predicted by Merlino2D with the results reported in [4], showing good qualitative agreement. In both cases, a pronounced positive current peak is observed during the positive voltage half-cycle, whereas the negative half-cycle exhibits a higher pulse frequency accompanied by lower pulse amplitudes. Figure 1b illustrates the electron number density during the inception and subsequent propagation of the positive streamer initiated during the fourth electrical cycle.

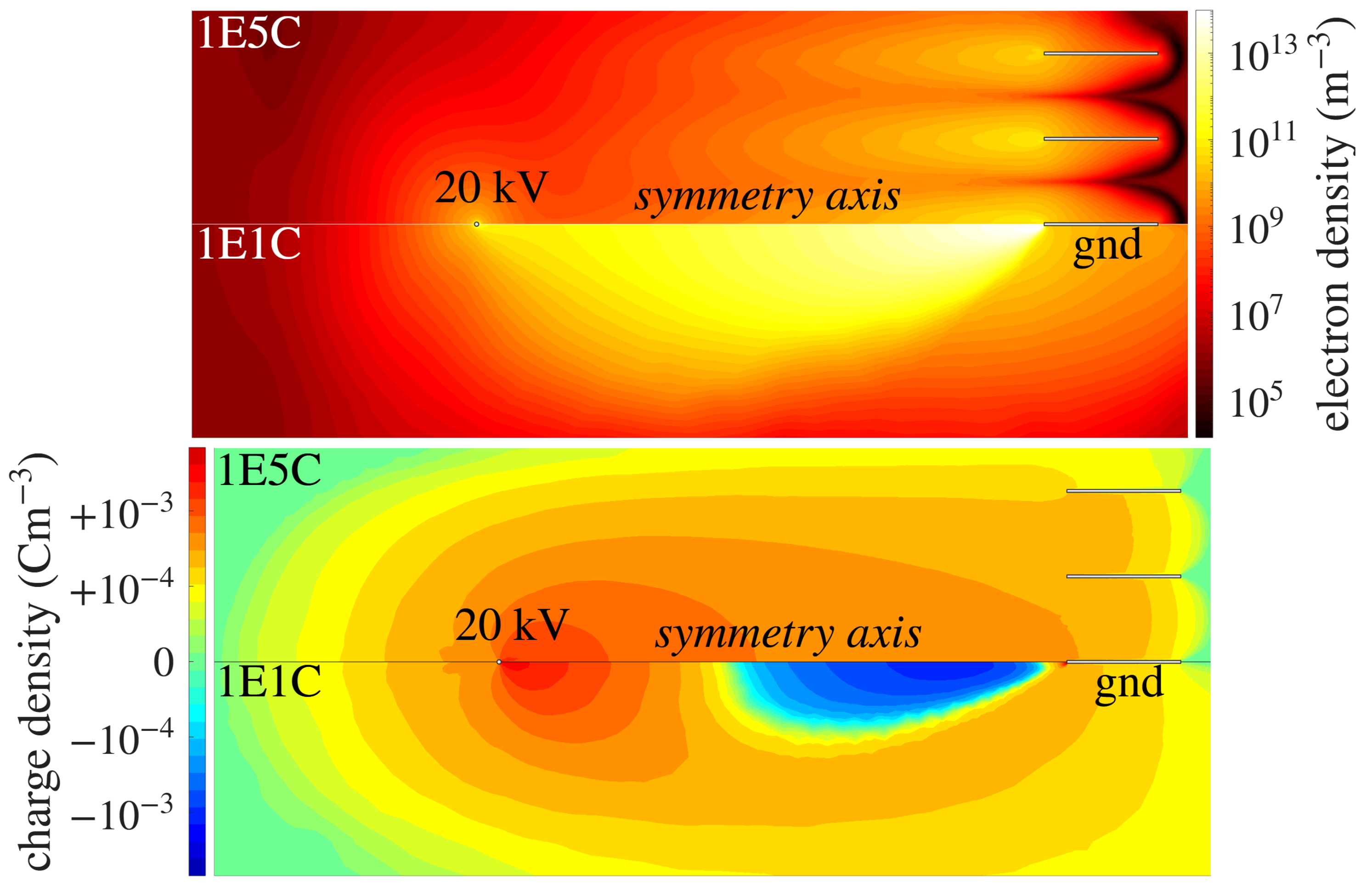


Figure 2: Steady-state electron and space-charge density distributions for a corona discharge in air in a wire–blade geometry. Wire radius: 50 μm, blade electrodes: 4 mm x 100 μm, $\gamma_{see} = 1 \times 10^{-2}$. Top: one wire and five blades. Bottom: one wire and one blade. The simulation employs the 4-species, 13-reaction kinetic model of [5]. Photoionization is modeled according to [1].

Figure 2 shows a simulation of a corona EHD thruster with a gridded collector. The results highlight the critical influence of the number of conductors composing the grid on device performance. Low collector densities lead to high electric fields at the cathode surface, promoting back ionization and the formation of a negative space-charge region. This effect ultimately reduces the effective thrust and degrades the thruster performance.

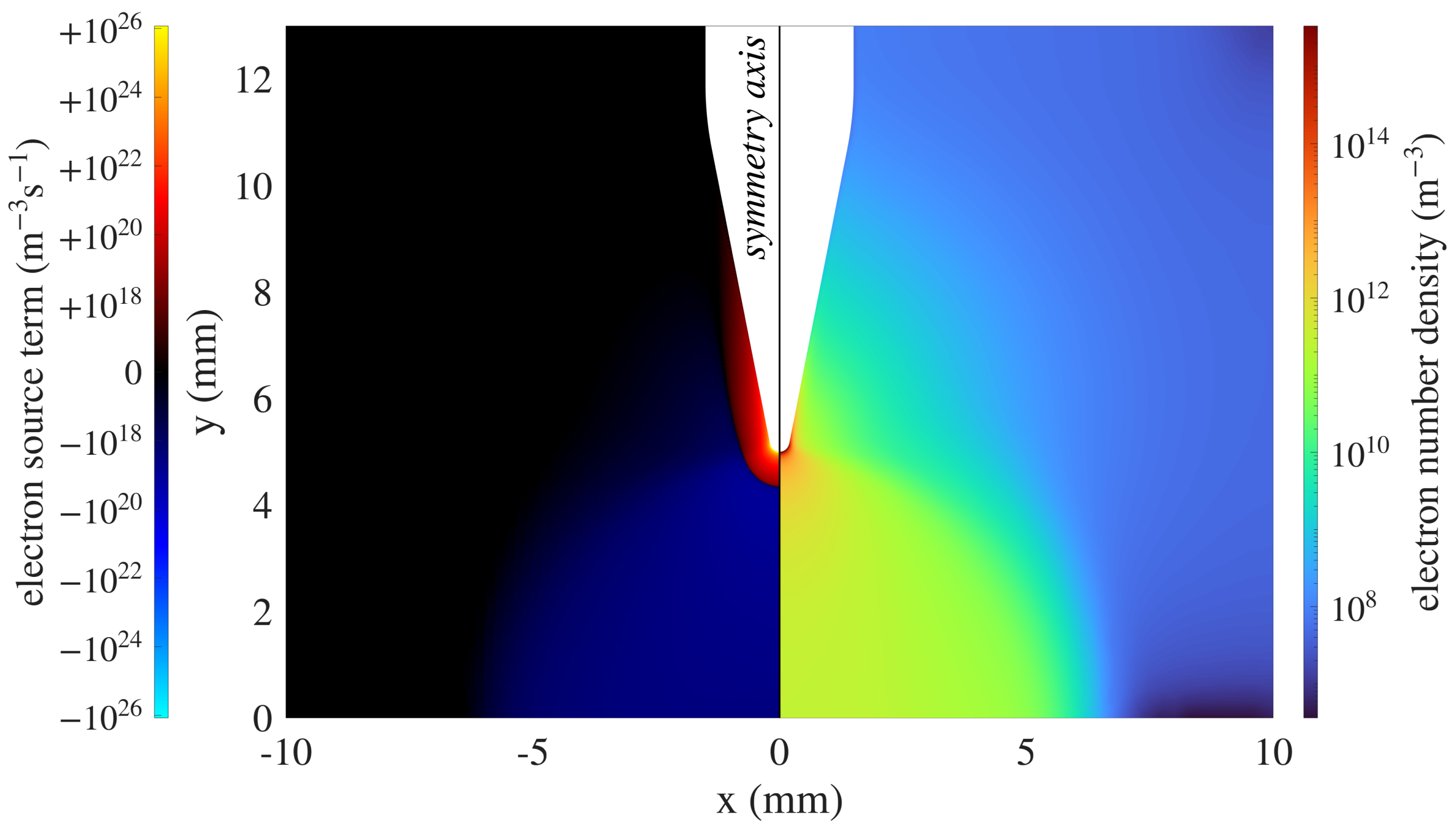


Figure 3: Steady-state electron density and electron source term (Ω) for a corona discharge in air in a point–plane geometry. Curvature radius: 200 μm, $d = 5$ mm, $\gamma_{see} = 1 \times 10^{-2}$. The simulation employs the 4-species, 13-reaction kinetic model of [5]. Photoionization was also considered.

Figure 3 presents the results of a corona discharge simulation in a point–plane geometry. The plane electrode is grounded, while a voltage of 9.4 kV is applied to the needle electrode. The source-term distribution indicates that electrons are primarily generated near the cathode region due to the high electric field, while they are progressively depleted in the bulk through kinetic processes.

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