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A paradigm of kinetic simulation including atomic and relaxation processes: a sudden event in a lightning process

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Abstract. A comprehensive particle based integrated code including atomic and relaxation processes has been developed. By using the code, we have investigated the lightning process of compressed neon gas that in a uniformly applied electric field. After a long time interval, streamers are slowly developed from a tiny ionization spot that is initially set. Then a complicated branching is suddenly and also explosively triggered, leading to fine net-like structures or sprites. Electromagnetic radiations are emitted from the sprite and show a low-power wave number spectrum, suggesting that the sprite exhibits a fractal nature.

1. Introduction

Interaction among various material states and photons and charged particles leads to a complex plasma state, in which multiply charged ions and free electrons, neutral atoms and molecules are mixed with each other. Such a mixed plasma state exhibits a nature as an 'active medium', which is strongly non-equilibrium and non-stationary, and produces remarkable dynamics through nonlinear interactions. Such states can be seen not only in laboratory plasmas, but also in natural plasmas, such as aurora, lightning, Solar flares, inter-stellar medium, accretion disks, etc. Those topics include attractive common physics related to non-local collective phenomena where atomic and relaxation processes play an essential role.

The particle-in-cell (PIC) method that solves the nonlinear wave–particle interaction has been widely used in simulating plasma dynamics. However, most of them made an *a priori* assumption of an ideal plasma as an initial condition. For applications utilizing relatively high-Z gas and/or materials, atomic and relaxation processes play an important role in determining the interaction.

Here, we have developed a three-dimensional extended particle based integrated code, EPIC3D, in which complex atomic and relaxation processes are taken into account [1]. Based on the code, we performed a simulation of the lightning/discharge process of a compressed neon gas and successfully reproduced key physical processes such as streamer formation and sprite events. Lightning and discharges are a well-known event, but the details have not been fully clarified. The understanding of the process is crucially important not only from the academic viewpoint but also for various industrial applications.

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2. Simulation model of EPIC3D

Here we describe EPIC3D, which was originally based on a fully relativistic three-dimensional electromagnetic PIC technique. The photon field is classically treated by the Maxwell equations in terms of electric and magnetic field $(\mathbf{E}, \mathbf{B})$ or its potential form $(\mathbf{A}, \phi)$. The charge density ρ and current density $\mathbf{j}$ are assigned on each spatial grid using the cloud-in-cell (CIC) method. For the $(\mathbf{A}, \phi)$ version, the Poisson equation as well as the continuity equation are imposed, while for the $(\mathbf{E}, \mathbf{B})$ version, a local solver technique is employed [2]. We extended the model by incorperating the ionization and relaxation processes described in the following.

2.1. Collision and relaxation process

We here introduced a *relativistic pairing method* by successive binary collisions of particle pairs, which precisely conserves the momentum and energy before and after the collision event in a relativistic regime. It has been certified in [3] that the method successfully resolves non-local electron heat transport where the temperature scale length becomes comparable to that of the electron mean free path and the assumption of the Fick's law (or diffusion approximation) breaks up.

2.2. Ionization process due to photon field (Optical Field Ionization-process)

We introduced an additional dimension in each atom that represents the internal electronic state of the atom [4]. The ionization rate $W_j^{(k)}(E)$, where the suffix denotes the kth electronic state of jth atom, is calculated from the local electric field E. Here we employed a cycle-averaged tunneling ionization rate of the Ammosov–Debre-Krainov (ADK) formula [5]. Then, the ionization index defined in the range $\{0,1\}$ is obtained as

$$R_j^{(k)}(t) = 1 - \exp\left[-W_j^{(k)}(E)\Delta t\right]. \tag{2.1}$$

When the condition $R_j > R[0,1]$ is satisfied, a free electron with the zero kinetic energy ($E_\mathrm{e} = 0$) *is created* and then the ion charge state is increased by one. Here, $R[0,1]$ represents the random number defined in the range $\{0,1\}$.

2.3. Ionization process due to electron impact

Here we utilize the electron–ion pairs introduced in Sec. 2.1 for the Coulomb collisions inside the computational mesh. After the Coulomb scattering takes place $(\mathbf{p}_\mathrm{e}^{(i)} \rightarrow \mathbf{p}_\mathrm{e}^{(f)})$, the ionization index is obtained from the cross section of electron impact ionization $\sigma_i^{(e)}(E_\mathrm{e})$. Thus, the ionization event is successively determined for every electron–ion pair. In the case where the ionization is switched on, a free electron with $E_\mathrm{e} = 0$ is created from the ion. The ionization energy is subtracted from that of the Coulomb-scattered electron to keep the total momentum and energy conservations.

3. Simulation of lightening process

Recently, lightning phenomena, which are observed in the Earth's atmosphere and also in various industrial devices, have attracted much attention [6]. Here, we performed lightning simulation for compressed neon gas with a density of around $4.6 \times 10^{20}\,\mathrm{cm}^{-3}$ (17 times the ideal gas). A tiny ionization spot with Ne^{+2}

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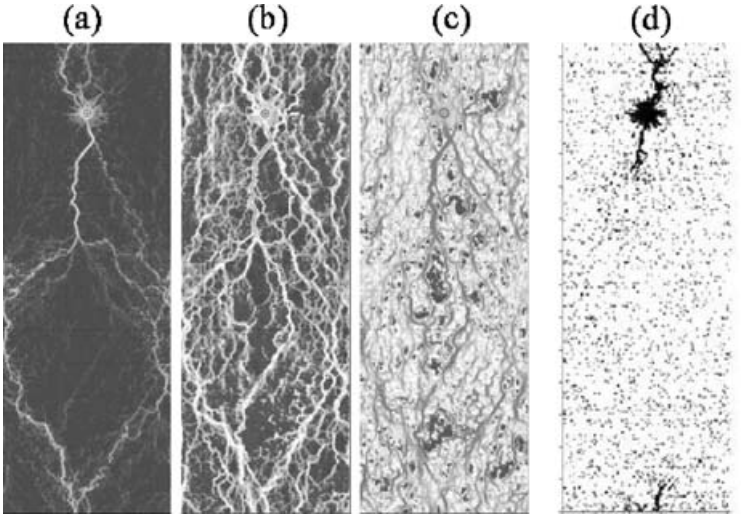


Figure 1. Ion density distribution at three different times, (a) 44.3, (b) 45.3, (c) 45.9 ps, after prominent streamer formation and avalanches takes place. Fig. 1(d) illustrates the ion spot distribution prior to the avalanche.

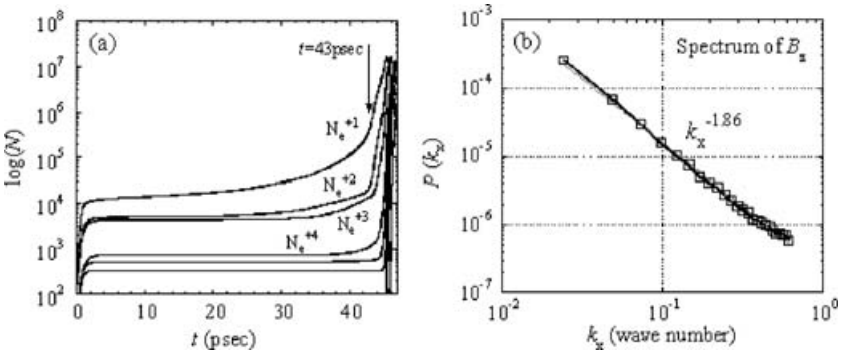


Figure 2. (a) Time history of ion density for different charge states. An avalanche of Ne^{+1} ion is triggered around $t = 43$ ps. (b) Wave number spectrum of self-induced B_z field during the avalanche process at $t = 45.3$ ps. The power law dependence with $k_x^{-1.86}$ is obtained.

is initially set to trigger discharge and a high-voltage electric field, $E = 10^7$ V cm^{-1}, is uniformly applied in the system.

Figure 1(a)–(c) shows the dynamics of ion charge density and Fig. 2(a) shows the time history of the ion density with the charge state q. As seen in Fig. 2(a), the abundance of Ne^{1+} is found to slowly increase for a long time scale, but suddenly exhibits an explosive (exponential) growth at around $t = 43$ ps. Followed by the growth of Ne^{1+} ions, ions with higher charge state ($q \geqslant 2$) also explosively increases with the growth rate larger than that of Ne^{1+}. A macro-scale ionization channel, referred to as a *streamer*, develops from the initial ionization spot (Fig. 1(a)). Then, the neighboring streamers connect with each other (Fig. 1(b)) and evolve to small-scale net-like structures as seen in Fig. 1(c). It is found that enormous branches with different spatial scales are contained.

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We investigated the underlying physical mechanism of the sudden event. Figure 1(d) illustrates the spatial distribution of ion charge state before the explosive event takes place ($t = 42$ ps). It is seen that lots of tiny ionization spots appear in the entire system. When the number of spots (or *packing fraction* of the spots) exceeds a certain value, micro-scale discharges are triggered between neighboring spots. Such local events simultaneously take place over a wide spatial region and cause an avalanche-like propagation. This is considered to be the origin of explosive sprite generation. It is noted that the process is similar to that of forest burning or percolation dynamics.

We also observed electromagnetic emissions from the system. Figure 2(b) illustrates the wave number spectrum of the induced magnetic field at $t = 45.9$ ps. A low-power spectrum is observed, suggesting that the structure shows a fractal nature that has no special scales. It should be noted that a similar spectrum was observed from low-frequency electromagnetic signals during a lightning event in the atmosphere [7].

4. Conclusions

We have successfully performed the simulation of a lightning process using a newly developed code and found prominent ionization dynamics that may be categorized as a 'sudden event'. The dynamics are tightly linked to a complex structure formation such as a streamer and sprite. The observed ionization spots are considered to be an effective initial condition leading to the sudden event. Thus, in contrast to a fully ionized ideal plasma, active plasma accompanied by atomic processes leads to a new type of nonlinear dynamics. From the viewpoint of industrial applications, we may need to suppress such a lightning event.

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