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Modeling of inception and structure formation of discharge based on percolation transition

パーコレーション転移モデルによる放電の突発性、構造形成の解明

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As an application of the concept of the plasma phase transition, we show a simulation based on the percolation model, which reproduces the sudden structure formation of discharge. Taking the dynamics of the ionization, the simulation is also found to reproduce the observed pre-discharge activities and development of the stepped leader.

1. Introduction

Discharge is useful from light sources, environmental technologies such those for disposal of waste gas and water, plasma processing, to nuclear fusion. However, for instance, high pressure discharge occurs suddenly, through a complex path with branching and detouring. Such discharges show highly stochastic behavior, which has not yet been fully understood. We present a simulation analysis of discharge based on the percolation transition [1], which reproduces interesting behaviors of discharge.

2. Percolation model

We perform calculation of the discharge between plane electrodes. In the percolation model, the discharge area is divided into cells using meshes, and each cell is determined to be either insulator or conductor, which corresponds to neutral gas and ionized plasma, respectively. The current and potential are calculated for each mesh point based on the Kirchhoff's current law.

In the original model with random ionization, the threshold concentration of plasma region is determined to be 0.59 in the case of two-dimensional square lattice. When the concentration exceeds this threshold, the discharge occurs immediately through a path sometimes with branching and detouring, which is similar to those experimentally observed [2]. The result suggested that not only the development of tip of streamers but random remote ionization in the medium should be the origin of the sudden structure formation of discharge [3]. On the other hand, branching of growing streamers has been explained on the basis of Laplacian instability [4], and its structure has been reproduced using fractal models [5]. Thus a model, which is applicable to a wide variety of discharge including streamers and leaders, is desired, based on better understating of their underlying physics.

In the present study, the model is extended to include the dynamics of ionization. We calculate the formation and extinction of ionized cell based on a probability, and the spatial distribution of the ionized cells for each time step. We assume that the ionization rate increases as a square of local electric field as E^2, and the extinction rate decreases as the current j as $1/(1+j/j_0)$ beyond a reference value of j_0. Furthermore, the time dependent circuit equation is solved taking geometrical capacitance and inductance into account.

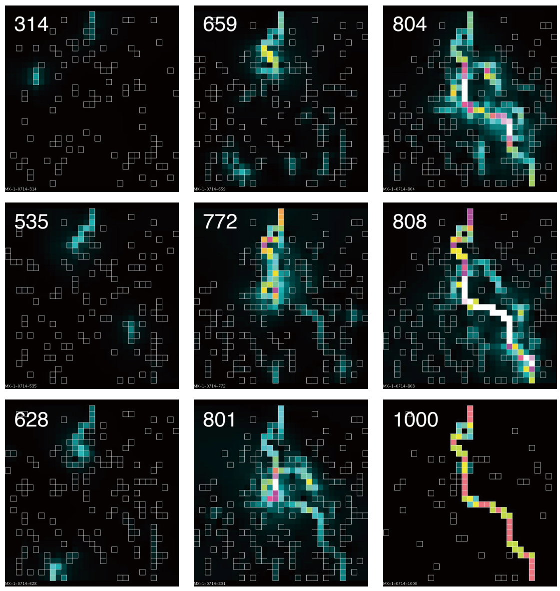

Fig.1. Profiles of current showing the development of a leader. The number in each figure corresponds to 1/100 of calculation steps. Open squares show the ionized cells, and the current is shown by the color.

3. Result

Figure 1 shows an example of the results. The calculation is carried out using 31x31 meshes and assuming the voltage is applied between upper and lower plane electrodes. 5 meshes long tip is placed at the center of the upper electrode.

It is shown that firstly pre-discharge activity with arrested leaders [6] appears from the tip, then a leader starts to grow, and finally breakdown occurs.

Spatial and temporal evolution of the discharge for same run is shown in fig.2. Before the growth of the leader, flashes are seen in the streak image, which can also be identified as the current pulses. This current originates from the formation and extinction of the ionization region, which causes charge and discharge of spatial capacitance.

The growth of the leader is shown to be stepwise, because clusters of the ionized region are produced, and the growth of the leader occurs when the leader and cluster are connected. Furthermore, as the length of the leader increases, the electric field at the tip increases. This leads to increasing probability of ionization and the speed of growth of the leader, along its propagation.

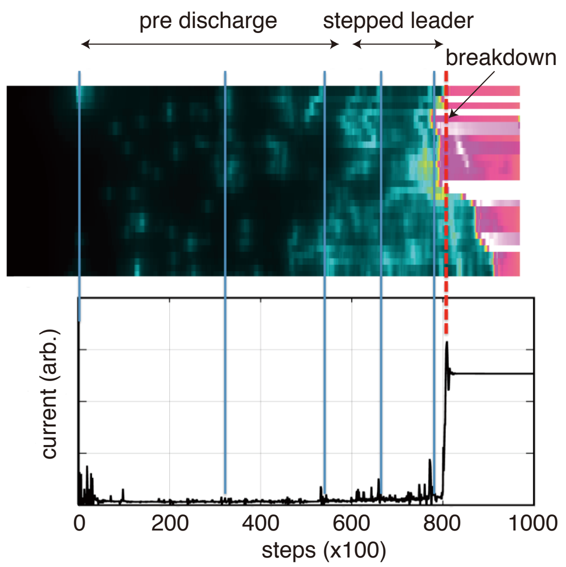

Fig.2. Simulated streak image from temporal and spatial evolution of the discharge and corresponding current at the upper electrode.

As we determine the distribution of ionized region using a probability, each run shows different result, from which statistical behavior of discharge can be investigated as shown in fig.3.

It is shown that the probability of discharge is one at high concentration, which decreases rapidly when the concentration of the ionized region becomes lower than a limiting value. At the same time, the dispersion of the breakdown time increases significantly.

At the high concentration, the leader develops immediately so that breakdown occurs after short time. At the low concentration, only less frequent pre-discharge activities are seen without the growth of the leader.

4. Summary

We use the percolation model to simulate stochastic behavior of discharge, which could not be taken into account in the previous models [7]. Comparisons with experiments are being planned to improve the present model and to determine the rate of formation and extinction of the ionized region from the experimental conditions such as applied electric field and material constants.

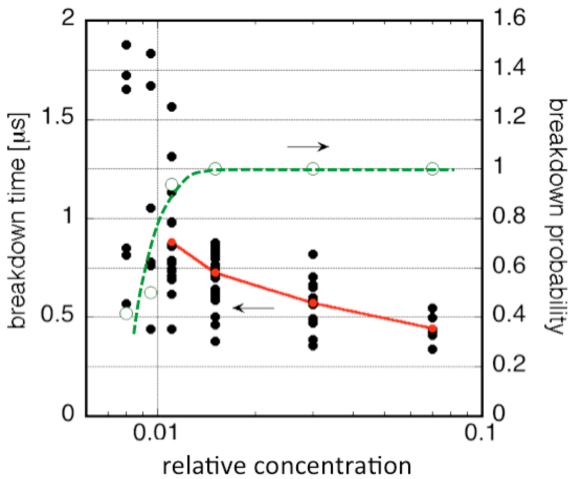

Fig.3. Statistics of the calculated discharge, showing the breakdown probability (open circle and green line), and breakdown time from each run (closed circle) and its averaged value (red line).

Acknowledgments

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