S-R4-1

Underlying physics of plasma production and ionization process

趣旨説明、プラズマ生成・電離過程の奥に潜むもの

Yasuaki Kishimoto
岸本　泰明

Graduate School of Energy Science, Kyoto University, Uji, Kyoto 611-0011, Japan
京都大学大学院エネルギー科学研究科 〒611-0011 京都府宇治市五ヶ庄

All plasmas are produced from neutral medium via complex atomic and molecular processes. During such discharge processes, many types of prominent spatio-temporal dynamics and structures are revealed, e.g. sudden change of the state, avalanche dynamics, fine branched structures, etc., which are seen to be probabilistic and non-diffusive. From advanced simulations and models including atomic processes, and also experimental observations using ultra-fast diagnostic techniques, those processed are found to be understood by the percolation transition and associated critical phenomena. We present simulations/models, and experimental observations and studies the underlying physics processes of discharges.

1. Introduction

Plasma production and ionization processes, where discharges and lightning are typical examples, are complex exhibiting prominent spatio-temporal structures [1]. The sudden trigger of the event followed by the avalanche dynamics and emergence of complex fine branched structures are the universal nature, which remind us that the process is probabilistic so that they are hardly predicted and controlled. The change of the state in neutral medium (solid, liquid, gas) has been successfully described as phase transition under the assumption of the thermodynamics equilibrium. However, no formal theory exists regarding the plasma production as one of the phase transition. This may be partially due to the fact that the ionization process which consists not only of various kinds of particle (atoms and molecules, charged macro- particles, multiple changed ions, electrons etc.), but also of various kinds of electromagnetic fluctuations. Namely, the existing concept is not simply introduced and a new paradigm is necessary.

In order to understand such complex discharged process, we explored theoretical and computational models which include various atomic processes in describing complex non-equilibrium and non-stationary ionization processes [2,3], diagnostic techniques in discharge experiments available for the observations of complex spatio-temporal dynamics and structures. Specifically, from the simulation studies, we have reached an idea that the discharge process exhibits a percolation dynamics where probabilistic process characterized by a critical parameter plays an essential role. We also found that the process can be classified into three fundamental processes with different time and spatial scales as discussed in Sec.2. which leads us a guiding principle in understandings the complex discharge phenomena. We found that the non-local process associated with plasma kinetics such as runaway particles play an important role.

2. Discharge kinetic simulation

In order to elucidate the complex ionization process, we explored an extended particle based integrated simulation code, EPIC3D, which includes various atomic processes and collisional relaxation processes. Using the code, we performed a discharge simulation for a high pressure neon gas with the density of $4.6x10^{20}cm^{-3}$, where the electric field of $E=10^7 V/cm$ is uniformly applied in the system. A tiny ionization spot with Ne^{+2} is set initially to trigger the discharge.

Figures 1 shows the dynamics of ion charge density at 40, 44 and 45psec, respectively. Note that no significant events happen up to 40psec (a), but after a few psec later, i.e. 44psec (b), a streamer like structure is triggered suddenly across the whole system, followed by micro-scale branching leading to a global net-like structure during 1 psec, i.e. 45psec (c). Figure 2(d) illustrates the spatial distribution of the ion charge state at 40psec before the sudden branching takes place, i.e. t=42psec (b). Many tiny ionization spots are found to be emerged in the entire system. When the number of spots (or equivalently “packing fraction” of the spot) exceeds a certain critical value, micro-scale discharges are triggered among neighboring spots. Such many local branching events propagate leading to an explosive dynamics over the wide reagion. Such a process is similar to that of forest burning modeled by the percolation theory, which exhibits the characteristics of critical phenomena.

The generation of many ionization spots which distributes over the system results from runaway electrons with long mean free path due to the applied high voltage. Similar process has been discussed as the origin of lightning. A Monte Carlo simulation of the generation of energetic particles (runaway electrons, positrons, photons etc) and their cascading is shown in Fig.2 [4], leading to similar ionization spots.

3. Classification into three elementary processes

From the evidences discussed in sec.2, we have classified the sudden explosive event into three fundamental physical processes :

① **<u>the formation of initial condition,</u>**
②**<u>the trigger and chain reaction,</u>**
③**<u>subsequent global structure evolution and pattern formation,</u>**

which provide a guiding principle in understanding the complex discharge phenomena. Namely, it can be seen that the global and sudden discharge evens result from the organic connection of these processes. Specifically, the item ①, where non-local dynamics of particles and electromagnetic fluctuations play essential roles, is an important ingredient, which is referred to as *the science of initial state*. The dynamics of Figs 1 (a), (b), (c) correspond to ①,②,③,respectively. Note that these ingredients have a similarity to those of percolation and related critical phenomena.

4. Experiments observation and percolation dynamics and modeling

We have performed various experiments and also explored a theoretical modeling based on the classification in Sec.3 in subsequent discussions.

In **S-R4-2**[5], the branching condition and temporal streamer evolution are investigated using ultra-fast ICCD camera (corresponds to ② and ③). Specifically, the laser induced density and/or field fluctuations are found to be a factor in triggering the streamer initiation (① and ②). In **S-R4-3**, the underwater pulsed discharge experiments are arranged to clarify the trigger mechanism of the streamer and its evolution. The change of the state prior to the initiation of the discharge is observed for the first time (①), which is consider to originate from the change of reflective (dielectric) constant. In **S-R4-4**, high voltage impulse discharges in air initiated by laser are investigated. Runaway electrons, which are considered to play an important role triggering subsequent discharges, are found to be produced and the source is identified (① and ②). In **S-R4-5**, a model based on the percolation theory including ionization and recombination processes is presented. The sudden structure formation is successfully reproduced. The wide class of morphology in experiments is found to be explained by this model suggesting the percolation transition capture essential feature of discharges.

4. Summary

Complex discharge processes were investigated computationally, theoretically and experimentally. The process is found to show a similar nature as the percolation transition which exhibits critical phenomena. The process is classified into three fundamental processes, which leads to a guiding principle in understanding discharges.

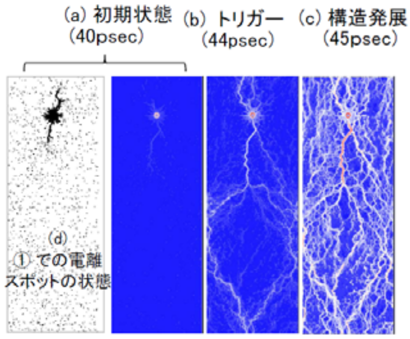

Fig.1 Ion charge density from EPIC3D simulation of discharge of compressed neon gas at three time scales [1,2]

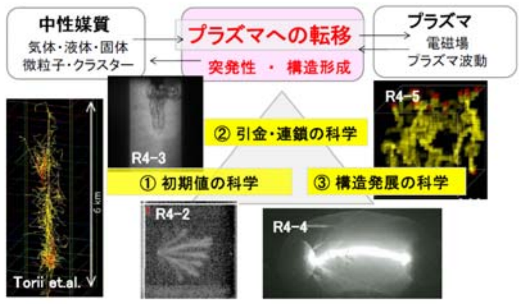

Fig.2 Transition phenomena from neutral fluid to plasmas and classification into three fundamental processes [2-7]

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