Kinetic study on gas discharge plasma generated by focused microwaves

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Gas discharge plasmas generated by μs-pulse focused microwaves are investigated. The model is based on a self-consistent solution to Helmholtz equation for microwave field, particle continuity equations, and the energy balance equations, coupled with plasma kinetics. Two recent experiments were studied: a. sub-Megawatt (MW) X-band 9.4 GHz microwave breakdown in 200 Pa nitrogen; b. MW-class W-band 110 GHz microwave breakdown in 1~100 Torr air. In case a, the tracked density of electronic states $N_2(C^3\Pi_u)$ agreed with the measured intensity from second positive system (SPS) of optical emission spectroscopy (OES). In case b, the simulation results reproduced the dependence of nitrogen vibrational and translational temperature on microwave fields and air pressure measured by OES. The underlying mechanisms for above coincidences were unveiled.

1. Introduction

The microwave gas breakdown has applications in beamed energy propulsion, stand-off detection, and plasma heating in ITER. While the focused microwave beam was usually used in the experiments, the theoretical predictions generally used the model of plane electromagnetic (EM) wave. However, the discharge parameter is sensitive to the spatial field amplitude. The difference between plane EM beam and focused beam used in experiments should be noted, especially in the study of energy deposition into gas breakdown plasma.

We develop a plasma fluid model to study the gas discharge plasma generated by focused microwaves. The model calculates the particle densities, electron temperature, nitrogen vibrational T_v and translational temperature T_g, and is time dependent with microwave transmission and reflection considered in the Helmholtz wave equation. Here we studied two recent experiments: a. sub-MW X-band microwave breakdown in 200 Pa nitrogen [1]; b. MW-class W-band microwave breakdown in 1~100 Torr air [2]. The plasma decay in the afterglow is also investigated. The following just shows some important results, and more will be reported in the conference site.

2. Results and discussions

2.1. X-band microwave breakdown in nitrogen

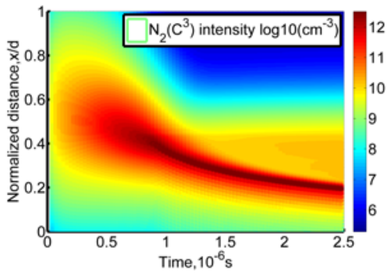

Fig. 1. Spatial and temporal distribution of excited states.

The spatial and temporal behaviour of particle density for excited states $N_2(C^3\Pi_u)$ during pulsed microwave discharge in nitrogen is shown in Fig. 1. The spatial position of density peak moves upstream toward the microwave source (x=0), accompanying the propagation of plasma electrons. The diffusion ionization front of plasma electrons impact neutral gases and generate excited states during its path toward microwave source. The de-excitation processes of quenching higher level excited states and optical transition emission result in generation of lower level excited states. The spatial integral of $N_2(C^3\Pi_u)$ density shows similar trend with the previously measured intensity of SPS [1].

2.2. W-band microwave breakdown in air

The dependences of T_v and T_g on gas pressure are shown in Fig. 2 near the breakdown threshold. The dependence of T_v on gas pressure from 1~100 Torr shows a Paschen-type curve. The vibrational excitation is strongly dependent on electron density, reduced electric field, and the microwave plasma interacting time duration [3]. The T_g shows a monotonic decrease with pressure, and the fast gas heating is attributed mostly to the available thermal energy in quenching of electronic excited states.

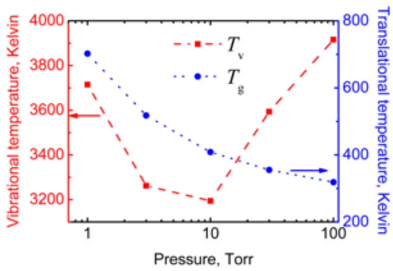

Fig. 2. Vibrational and translational temperature as a function of gas pressure near breakdown threshold.

3. References

[1] M. Mesko, Z. Bonaventura, P. Vasina, *et al.*, Plasma Sources Sci. Technol. **15** (2006) 574.

[2] J. S. Hummelt, M. A. Shapiro, and R. J. Temkin, Phys. Plasmas **19** (2012) 123509.

[3] W. Yang, Q. Zhou, and Z. Dong, Phys. Plasmas **24** (2017) 013111.