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# Period Multiplication in a Continuous Time Series of Radio-Frequency DBDs at Atmospheric Pressure

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**Abstract.** As a spatially extended dissipative system with strong nonlinearity, the radio-frequency (rf) dielectric-barrier discharges (DBDs) at atmospheric pressure possess complex spatiotemporal nonlinear behaviors. In this paper, the time-domain nonlinear behaviors of rf DBD in atmospheric argon are studied numerically by a one-dimensional fluid model. Simulation results show that, under appropriate controlling parameters, the rf DBD can undergo a transition from single-period state to chaos through period doubling bifurcation with increasing discharge time, i.e., the regular periodic oscillation and chaos can coexist in a long time series of the atmospheric-pressure rf DBD. With increasing applied voltage amplitude, the duration of the periodic oscillation reduces gradually and chaotic zone increases, and finally the whole discharge series becomes completely chaotic state. This is different from conventional period doubling route to chaos. Moreover, the spatial characteristics of rf period-doubling discharge and chaos, as well as the parameter range of various discharge behaviors occurring are also investigated in this paper.

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**Key words**: Atmospheric radio-frequency discharge, period-doubling bifurcation, chaos.

## 1 Introduction

Recently, there has been growing concern about radio-frequency atmospheric pressure glow discharges (APGDs) that benefit many industrial fields [1–5] for its removing of vacuum chamber and its capability of offering non-equilibrium plasma. A large number of experimental and numerical works have been carried out to investigate the modes of

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rf APGD and their influence on plasma stability [6–8]. Commonly, in higher discharge current radio-frequency APGDs are unstable and easy to evolve into arc plasma. One of the effective solutions to prevent the glow-to-arc transition is employing dielectrically insulated electrodes to control the unlimited growth of discharge current [8]. This means radio-frequency dielectric barriers discharge (DBD) can provide stable glow plasma at high discharge current and therefore have more extensive application prospects.

As the most familiar route to chaos, period multiplication theory has been applied to various areas like laser system [9], plasma [10–16] and so on. Using iteration method, the equation solution can be in order or out of order corresponding to different coefficients, for example, the famous Logistic map. DBD system is a spatially extended dissipated system with strong nonlinearity. Under appropriate operation conditions, various oscillations and instabilities could occur in this discharge system. Pervious investigations have shown that period multiplication and chaotic phenomena have been observed in atmospheric-pressure DBD operating at kilohertz frequency range [15,16]. These nonlinear behaviors appearing in atmospheric-pressure DBD could change the plasma structure and affect plasma stability. Therefore it is important to study the nonlinear behaviors in radio-frequency DBD, not only to improve plasma stability but also to control rf APGD operation modes in different modes to meet different application requirements.

The aim of the present work is to study numerically the transition from periodic discharge to chaos occurring in a continuous time series of rf DBD in atmospheric argon, as well as their parameter dependence based on a one-dimensional fluid model.

## 2 Model

Present study is based on a one-dimensional, self-consistent fluid model developed for APGD that has been used in previous studies [15–17]. The rf DBD is generated between two dielectrically insulated parallel-plate electrodes connected externally to a sinusoidal voltage. The work gas is pure argon. To focus on temporal nonlinear behaviors of rf DBD, complex chemical processes are ignored and only direct ionization and recombination processes are considered. Since the electrode gap size is much smaller than the width of the electrode, we assume that the atmospheric DBD under study maintains uniform in the direction perpendicular to that of the externally applied voltage. The diffusion-drift approximation is used. Hydrodynamics equations are used to describe the temporal evolvement of rf DBD. The densities of argon ions and electrons are described by continuity equations, which are as follows:

$$\frac{\partial n_e}{\partial t}+\frac{\partial j_e}{\partial x}=S_e, \tag{2.1a}$$

$$\frac{\partial n_p}{\partial t}+\frac{\partial j_p}{\partial x}=S_p, \tag{2.1b}$$

where $t$ and $x$ are the time and interelectrode axial distance, respectively. $n_e$ and $n_p$ represent densities of electron and ion, respectively. $j_e$ and $j_p$ represent flux densities of