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Dynamics of plasma channel in a parallel-plate plasma gun

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ABSTRACT

Lumped parameter models for describing dynamics of the plasma channel in a parallel-plate plasma gun are compared with the experimental results obtained from two plasma guns with different rail geometries. Comparison between the experiments and the numerical calculations reveals that the lumped parameter models can be utilized to describe the dynamic motion of the plasma channel quite well. Parametric study shows that minimizing the line inductance and increasing the charging voltage on a capacitor as well as minimizing the gas injection time for reducing the mass of the plasma channel are the key factors to increase the flow velocity of the plasma jet ejected from the plasma gun.

1. Introduction

Damages of divertor targets by plasma loads during edge localized modes (ELMs) are critical issue in fusion engineering because they reduce the lifetime of the divertor target. In the case of ITER, the plasma load on the divertor target during ELM is up to tens of GW/m^2 and its duration is approximately a few hundred microseconds. In order to study the effect of ELM to plasma facing components of fusion devices and explore the novel method to relieve heat loads on the divertor target, a small-scale ELM simulator using a pulsed plasma gun with parallel-plate configuration was constructed in our laboratory [1]. However, measurements on the plasma properties of a plasma jet ejected from the plasma gun with a quadruple Langmuir probe revealed that the ion flow velocity was too low to simulate ELM-like plasma and it needed to be increased up to several tens of km/s. Also, it has been recognized that the acceleration of a plasma channel before being ejected from the plasma gun plays an important role for increasing the ion flow velocity of the plasma jet.

Prediction of an ion flow velocity at the muzzle of the plasma gun requires understanding of plasma dynamics during the acceleration of a conducting plasma channel in the plasma gun. In addition, the acceleration of the plasma channel is well known to be deeply associated with the discharge current driven by a pulsed power system because the plasma channel is accelerated by electromagnetic Lorentz force. Therefore, dynamics of the plasma channel in the plasma gun can be described appropriately by solving the coupled equation set which combines the circuit equation for the pulsed power system and the equation of motion for the plasma channel.

In this paper, two kinds of lumped parameter models, i.e. a slug model [2] and a snowplow model [3], for describing the dynamics of plasma channel in the plasma gun are utilized to examine the validity of our experimental arrangements and to find the appropriate way to increase the ion flow velocity. Experiments are carried out in two parallel-plate plasma guns with different rail geometries, which are driven by a capacitor discharge. Dynamic motions of the plasma channel along the rail electrodes are recorded by a fast camera to determine the position of the plasma channel with time. Based on the experimental and numerical results, the optimum discharge parameters and rail designs for achieving highest flow velocity at the muzzle of the plasma gun are discussed.

2. Lumped parameter models

A schematic diagram of an equivalent circuit for a plasma gun with parallel-plate rail electrodes and its power supply is depicted in Fig. 1. On the left portion of the figure is the equivalent circuit of a pulsed power system, comprising a capacitor C_0 with an initial charging voltage of V_0, in series with a line resistance R_0 and a line inductance L_0, which are assumed to be constant. A pair of parallel-plate rail electrodes are connected at the right side of the pulsed power system, as shown in Fig. 1. The position of the center of mass

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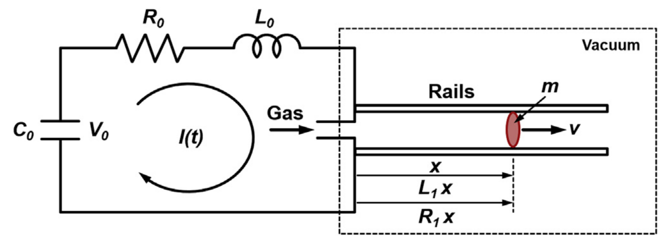

Fig. 1. Schematic diagram of the equivalent circuit for a plasma gun with parallel-plate configuration and its power supply.

of the plasma channel, measured as the distance from the left end of the rail electrodes, is denoted by x. An equivalent circuit for the rail electrodes is expressed as a series connection of a rail resistance R_1x and a rail inductance L_1x, where R_1 and L_1 are the resistive and inductive gradients of the rail electrodes, respectively [2]. Both R_1 and L_1 are assumed be constant. A mass of the plasma channel is denoted by m. The plasma channel completes the circuit between the rail electrodes, and is accelerated along the rail electrodes by Lorentz force exerted by the discharge current $I(t)$.

The lumped parameter models treated here assume that most of the electrical energy going into the plasma channel is transformed into the kinetic energy of it. Also, the resistance and inductance of the plasma channel are assumed to be negligible compared to other circuit parameters. Then, Kirchhoff's law for the equivalent circuit shown in Fig. 1 is written as [2]

$$(L_0+L_1x)\frac{\mathrm{d}I}{\mathrm{d}t}+\left(R_0+R_1x+L_1\frac{\mathrm{d}x}{\mathrm{d}t}\right)I+\frac{1}{C_0}\int_0^t I(\tau)\mathrm{d}\tau = V_0. \quad (1)$$

By differentiating Eq. (1) with respect to the time t, we get the second-order differential equation with respect to the discharge current $I(t)$ as following:

$$(L_0+L_1x)\frac{\mathrm{d}^2I}{\mathrm{d}t^2}+\left(R_0+R_1x+2L_1\frac{\mathrm{d}x}{\mathrm{d}t}\right)\frac{\mathrm{d}I}{\mathrm{d}t}+\left(R_1\frac{\mathrm{d}x}{\mathrm{d}t}+L_1\frac{\mathrm{d}^2x}{\mathrm{d}t^2}+\frac{1}{C_0}\right)I=0. \quad (2)$$

Another relation is obtained by equating impulse to change in momentum [4],

$$\frac{1}{2}L_1\int_0^t I^2(\tau)\mathrm{d}\tau = m\frac{\mathrm{d}x}{\mathrm{d}t}, \quad (3)$$

where the mass of a plasma channel m is assumed to be a constant for a slug model [2], whereas it is assumed to be a linear function of x, i.e. $m_0 + m_1(x - x_0)$ for a snowplow model [4]. Here, m_0 is a constant mass and m_1 is the mass of the plasma channel per unit length along the rail electrodes. By differentiating Eq. (3) with time t, we obtain the equation of motion of the plasma channel for two different models as below:

$$\frac{\mathrm{d}^2x}{\mathrm{d}t^2} = \begin{cases} \dfrac{1}{2m}L_1I^2 & \text{for a slug model,} \\ \dfrac{\frac{1}{2}L_1I^2 - m_1\left(\frac{\mathrm{d}x}{\mathrm{d}t}\right)^2}{m_0+m_1(x-x_0)} & \text{for a snowplow model.} \end{cases} \quad (4)$$

where x_0 is the initial plasma position at $t = 0$.

The coupled nonlinear equation set, Eqs. (2) and (4), can be solved numerically with the initial conditions for the discharge current and the position of the plasma channel given by

$$x(t=0) = x_0, \quad \left.\frac{\mathrm{d}x}{\mathrm{d}t}\right|_{t=0} = 0,$$
$$I(t=0) = 0, \quad \left.\frac{\mathrm{d}I}{\mathrm{d}t}\right|_{t=0} = \frac{V_0}{(L_0+L_1x_0)}. \quad (5)$$

Numerical calculations are carried out with Matlab program language using an embedded 'ode23' solver. It is noted that all lumped parameters given in Eqs. (1)–(5) except for the mass of the plasma channel can be precisely determined from the experiments. Hence, one free parameter m for the slug model or two free parameters m_0 and m_1 for the snowplow model are allowed to be controlled in the simulation.

3. Experimental setup

The schematic diagram of the overall experimental setup used in the present paper is described elsewhere [1]. As described earlier, a pulsed power system based on capacitive discharge is utilized to drive high discharge current to parallel-plate rail electrodes. The electrical energy stored in a high-voltage capacitor of 60 μF capacity is rapidly discharged to the parallel-plate rail electrodes by self-breakdown during the fast injection of gas between the electrodes for 'Type I' plasma gun or by external triggering with a semiconductor switch (ABB, 5STF16F1413 thyristor assembly) for 'Type II' plasma gun (see Table 1). The gas is injected by a piezoelectric valve (Key High Vacuum Products, PEV-1) which is able to adjust the amount of gas by the amplitude and duration of a preset voltage. Argon and hydrogen are used as working gas and the base pressure is maintained below 1×10^{-5} Torr.

Two parallel-plate plasma guns with different rail geometries and operating schemes are used in the experiments. Detailed rail geometries and electrical parameters for two different plasma guns are listed in Table 1. All electrical parameters are determined through the short-circuit test. The rail electrodes are designed to be supported by transparent acrylic plates to prevent mechanical deformation by electromagnetic force and to allow it to take pictures using a fast camera. The cross-sectional view of 'Type II' plasma gun and the typical picture of plasma jet ejected from the plasma gun are shown in Fig. 2. A cylindrical drift tube made of quartz is attached at the end of the plasma gun to prevent the plasma jet from diffusing out in radial direction. The discharge current is measured with a commercial Rogowski coil (PEM, CWT 1500R) and temporal motion of the plasma channel along the rail electrodes is traced by a fast camera (NAC, GX-8). The frame-rate and exposure time of the fast camera are fixed at 250,000 frames per second and 0.7 μs, respectively. In addition, properties of the plasma jet ejected from the 'Type II' plasma gun is diagnosed with a quadruple Langmuir probe [1], as depicted in Fig. 2.

Table 1
Specifications of two types of plasma gun.

Parameters	Type I	Type II
Rail length, mm	200	300
Rail width, mm	25	10
Rail spacing, mm	15	10
Rail inductance gradient L_1, μH/m	0.69	0.46
Rail resistance gradient R_1, mΩ/m	5	17
Capacitance C_0, μF	60	60
Line inductance L_0, μH	4.2	2.53
Line resistance R_0, mΩ	25	34
Triggering	Self	External
Puffing gas	Ar	H_2