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Study on the peak current of power supply during a Hall thruster start-up

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ABSTRACT

It is known that the peak current in start-up process would affect the operation of the power supply system in Hall thrusters. Experimental testing shows that the peak current on the power supply side is elusive with different operating conditions. This causes the setting of over-current value of power supply into dilemma. The formation mechanism of the peak current on the power supply side is discussed and the theoretical boundary is deduced through the measurement of pressures in discharge channel, a given ionization rate and parameters of a Hall thruster. Results show that the analysis and predictions are in reasonable agreement with experimental results.

1. Introduction

Electric propulsion is an energy conversion device, whose electric power converses into kinetic power of propellant. A typical Hall thruster is designed as a symmetric cylindrical structure whose plasma discharge is established through an externally applied crossed electricmagnetic field. The magnetic field is strong enough to lock the electrons in an azimuthal drift within the chamber, it is not strong enough to affect the trajectory of the ions which are essentially accelerated by the axial electric field [1]. The application of Hall thrusters in spacecraft propulsion system for orbit correction, station keeping and orientation puts forward high request to characteristics of thrusters [2,3]. An important characteristic is the start-up of Hall thrusters. The start-up process related to the reliability of whole electric propulsion systems. Though it is intermittent, the surge current would damage insulation of Hall thrusters, or even cause the permanent damage to the power supply unit.

The start-up of Hall thrusters or devices with E plus B configuration has captured much attentions [4–8], especially, the peak current takes place at the start-up moment. For example, Arkhipov et al. commented that the peak current during a Hall thruster start-up is several dozen times as large as a nominal discharge current. Then, he carried out studies at various parameters and concluded that power supply circuit parameters define the time history of the start-up transient9. Liu et al. improved the Taccogna's model by considering the near field plume, and the simulating results have been verified by experiments [10,11]. Fisch et al. contributed the time-resolved images of a thruster start-up with a fast camera, revealing an intensive peak lasting for an ionization-relevant timescale. Results indicated that the modeling of the cathode and azimuthal asymmetry is necessary to understand the start-up process [12]. Experimental study and numerical simulation provided adequate evidences that the peak current at ignition transient is inevitable. The start-up current of Hall thrusters lasts about tens of microseconds and the peak value is hundreds of Amperes [10]. Large impulse currents are a source of electromagnetic interference, which would affect the operation of power supply seriously [8]. However, the present studies are still focus on the peak current on the thruster side. The peak current on the power supply side is not pouring any attentions. The peak current on the power supply side would affect not only the reliability and lifetime of power supply unit, but also the ignition reliability of a Hall thruster. Because the power supply unit must pre-set an over-current value for its safety, the output voltage would be dropped rapidly or even shutdown if the peak current exceeded this setting. Clearly, an infinitely large setting of over-current value is impossible and unscientific. Therefore, the formation mechanism of the peak current on the power supply side is discussed and the theoretical boundary is deduced through the measurement of pressures in discharge

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channel, a given ionization rate and parameters of a Hall thrusters.

The general organization of this paper is as follows: the experimental set-up is given in Sec.2. Section.3 give the experimental results, Section 4 addresses the theoretical analysis through the relationship of internal discharge characteristics of Hall thrusters and electric circuit parameters. The theoretical boundary of the power supply peak current is deduced. The conclusions of this work are drawn in Section 5.

2. Experimental set-up

Our experiments are carried out in Harbin institute of Technology plasma propulsion laboratory. The most relevant features of experimental set-up are highlight as follows: the vacuum facility consists of a 1.5 m diameter and 4 m long vacuum tank of stainless steel with two diffusion pumps, one rotary pump, and three mechanical booster pumps. The experimental thruster is an ATON-type Hall thruster with the outer diameter of 100 mm, inner diameter of 70 mm, and channel length of 50 mm [13]. The propellant is xenon. A hollow cathode is used as electron-source and cathode-neutralizer.

The measuring diagram of start-up is shown in Fig. 1. A filter is placed between the discharge power supply and the thruster, which is a component applied to reduce the discharge current low frequency oscillations in the range of 10–100 kHz. In our experiments, the filter consists of an inductor ($L = 0.1$ mH) and a resistor ($R = 120\ \Omega$) connected in parallel and a capacitor ($C = 10\ \mu$F) connected between the anode and cathode. The current of the power supply (I_p), the discharge current and voltage of the Hall thruster (I_d and U_d), and the current across the capacitor (I_C) in the start-up process is recorded with a Yokogawa DL850 recorded wave analyzer.

3. Experimental results

Referring to the existing research, the characteristics of ignition current are related to the discharge voltage and the anode flow [9–11]. Therefore, the experiments were firstly carried out on different discharge voltage and anode flow. The currents and voltages measured through changing discharge voltage or anode flow are shown in Fig. 2. It can be seen that the peak current of power supply lags behind the discharge current. The values of I_p differ greatly under different discharge parameters. For example, it shown in Fig. 2(a) that the peak value of I_p is smaller than that of discharge current, however, in Fig. 2(b) it is much larger than the peak value of discharge current. This confusing phenomenon causes the setting of over-current value of power supply into dilemma. Though the current surge capability of a laboratory power supply can reach 100–200 A with a big output capacitor, the output voltages will drop-off for dozens of volts at the moment of ignitions. The output capacitor in a flight-type power supply unit will be very small, unusually in the range of 10–50 μF depending on the power rating of power supply. The current surge capability of a flight-type power supply is limited. Therefore, the upper limit value of the peak current on the power supply side is a very important key parameter for a flight-type Hall thruster system design.

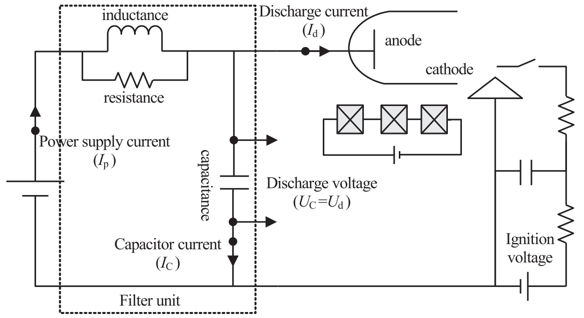

Fig. 1. Schematic diagram of experimental set-up.

4. Theoretical analysis and boundary prediction

4.1. Theoretical analysis on the peak current of power supply

It is known that the peak of discharge current is resulted from the avalanche ionization of atoms at the start-up transient. On closer examination, it can be found that the high transient discharge current peak cause the voltage drop of capacitor in the filter. Then the power supply charges the capacitor through the branch formed by the inductor and resistor, which triggers the peak current of power supply. According to Kirchhoff's current law, the power supply current (i_p) in start-up process can be expressed as:

$$i_p = i_d + C\frac{du_C}{dt} \tag{1}$$

where C is the capacitance of the capacitor. u_C is the capacitor voltage. The start-up process sustains in the order of dozens microsecond, therefore $\frac{du_C}{dt}$ can be replaced by $\frac{\varDelta u_C}{\varDelta t}$. The peak value of power supply current can be approximate expressed as:

$$I_p \approx I_d + C\frac{\Delta U_C}{\Delta t} \tag{2}$$

where $\varDelta U_C$ is the drop voltage of the capacitor in start-up process, $\varDelta t$ is the recovery time of $\varDelta U_C$.

Experimental results show that the discharge current has been steady when the power supply current reaches its peak value. This is also seen in Fig. 2a and b. The investigation of this phenomenon has overstepped the discussions of this paper, but we can therefore conclude that the peak value of power supply is mainly settled by capacitor drop voltage and recovery time. The recovery time, $\varDelta t$, is the time about charge of the capacitor, which can be estimated from the frequency characteristic of the filter circuit. It is known that a RLC network has its own natural frequency. Thus, we can get the period of the capacitor charging and discharging, which is $T = 2\pi LC$. The power supply current is resulted in the voltage drop of the capacitor recovering to its normal value, then $\varDelta t$ is equal to a quarter of the capacitor charging and discharging period. The equation [2] can be rewritten as follows:

$$I_p \approx I_{d0} + C\frac{\Delta U_C}{\frac{\pi}{2}\sqrt{LC}} \tag{3}$$

where I_{d0} is the stable discharge current of the Hall thruster. In our experiments, I_{d0} is around 4 A. L is the inductance of the inductor in the filter.

As we know, the capacitance of the capacitor is almost constant, but the inductance of the inductor is sensitive to the across current due to the magnetic saturation. If we suppose N is the turns of an inductor, l is the length of magnetic path, I is the current pass through the inductor, S is the cross-section of magnetic path, μ_r is the relative permeability, μ_0 is vacuum permeability, $\varPhi$ is the magnetic flux, and H is the magnetic field strength. Then, the inductance of an inductor can be expressed as,

$$L = \frac{\mu_r \mu_0 \cdot N^2 \cdot S}{l}. \tag{4}$$