Novel approach for assessing the electron transport properties in plasma thrusters

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Hall effect plasma thrusters, created on the basis of a magnetized plasma source, are nowadays utilized in space propulsion, and in parallel new thrusters are under development. A great part of the associated scientific research efforts is focused on the correct description of the electron current through the magnetic field in these thrusters, which is a crucial problem for development of fully predictive numerical simulation tools. A novel technique of characterization of electron current by detection of non-stationary magnetic field is proposed. The diagnostic tools are small inductive coils installed around the accelerating channel. A model of localized electron currents, coherent with the measurements, is proposed. From measured the non-stationary magnetic field absolute magnitudes the effective electron collision frequency can be estimated. Its value is sufficient to explain the electron transport.

1. Introduction

A Hall effect thruster (HET) is an advanced propulsion device in which the thrust is created via acceleration of an ion flow by induced electric field. Ions are produced in a low-pressure gas discharge, ignited in an annular channel, in the presence of radial magnetic field (Fig. 1); its strength is chosen in such a way that the electron Larmor radius is much smaller than the channel dimensions, whereas the ion Larmor radius is much larger and thus the magnetic field does not affect ion motion. The reduction of longitudinal mobility of electrons across the radial magnetic field leads to a localized axial voltage drop of the order of the anode-cathode discharge voltage. In such an "E cross B" configuration, electrons drift in the azimuthal direction with an average azimuthal velocity E_z/B_r. Typical values of E_z (10^4 V/m) and B_r (20 mT) lead to average electron energies higher than 10 eV and this magnetically confined electron cloud is very efficient for ionizing the propellant gas. The characteristic plasma density under the condition of quasi-neutrality is ~10^{17}-10^{18} m^{-3}. The ions of Xe, which is the most frequently used in HETs, are typically accelerated to 18 km/s under 300 V of discharge voltage. The charge of ion plume is compensated by electrons emitted by the external cathode. A detailed description of HET can be found in refs. [1-4].

First practical utilization of HETs dates back to 1972 in the frame of Soviet space program [1-3]. Nowadays, HETs are successfully operated on board geostationary communication satellites for the purpose of station keeping [5]. Recently, the successful SMART-1 Moon mission of the European Space Agency, equipped with the Snecma's PPS®1350-G Hall thruster, has demonstrated the possibility to use a HET as the primary propulsion system [6]. New HET models are currently under development to satisfy the requirements of future missions [4].

In spite of many years of research and development there are still open issues in understanding of some basic physical phenomena in HET. This lack of knowledge considerably slows down the new developments and increases their costs. One of such issues is a correct description of electron current through the magnetic field to the anode. In fact, classical diffusion approach (transport by collisions with other particles) fails to give a satisfactory agreement with the experiment – the predicted electron current is at least one order of magnitude lower than the measured one. By this reason, the existing numerical simulation tools are not fully predictive [7,8]. The problematic of HET development and associated basic phenomenon research is discussed in more details in [4]. The problem of particle transport is common for magnetized plasmas. The general approach to treat this problem is to introduce "anomalous" transport, and two hypotheses are proposed to explain it. The "near-wall" conductivity, where the electron collisions with walls increase the effective collision frequency, and an oscillation-assisted (or turbulent) electron transport [1,2,4,9]. The latter is often modeled by the Bohm mobility coefficient $\mu_t = k/(16B)$, where B is magnetic field and k is a tunable numerical factor, in contrast to the classical diffusion coefficient $\mu_c \propto 1/B^2$. By now, neither of theories can confidently predict electron current, and experimental and theoretical investigations are actually focused on both mechanisms [1]. In the present paper, the turbulent "anomalous" electron transport will solely be considered.

The essential way to access the turbulent anomalous transport is to study plasma instabilities in HETs. The HET gas-discharge generates a number of plasma instabilities whose intensities strongly depend on the thruster operating parameters, notably the discharge voltage and the magnetic field [1,2,4,9]. In what is related to the electron transport properties, the high-frequency (HF) azimuthal instability in 5-10 MHz range attracts much attention [10-13] because it can generate so-called quasi-electrostatic waves in low-hybrid frequency range. These waves are known to play an important role in particle transport and acceleration [14].

In this contribution, we present the implementation of new method of assessing the "anomalous" electron transport properties in HETs by way of studying plasma instabilities in a 5 kW class thruster. This work is a logical continuation of the study described in [15] and performed on the lower power (1.5 kW) HET. Hereafter, we describe briefly the principles of the diagnostics, its implementation on the high-power HET and the main results.

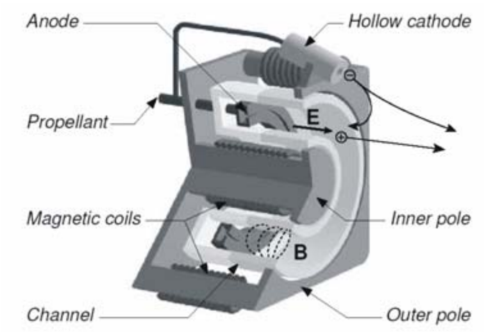

Fig. 1: Drawing of a Hall effect thruster.

2. Experimental Setup

The experiments reported here were performed on the HET PPS®X000ML, a laboratory model of the Snecma's high-power (5 kW) PPS®5000. This thruster is under development for high-power space telecom platforms [16]. The whole campaign was carried out at PIVOINE facility [17] with the following main characteristics: vacuum chamber diameter is 2.2 m, length is 4 m, residual pressure under 20 mg/s mass-flow rate of Xe is 3×10^{-5} mbarr.

The principle of the utilized diagnostics is based on the detection of non-stationary magnetic field by inductive coils according to the Faraday's law:

$$\varepsilon = -d\Phi/dt\,,\ \Phi = NSB \quad (1)$$

where ε is the electromotive force, Φ is the magnetic flux, N is the number of turns, S is the coil surface, B is the magnetic induction. With a properly oriented coil axis it is possible to detect selectively the variations of any component of a non-stationary magnetic field. Coils were fabricated from ordinary 0.8 mm emailed transformer wire. Each coil has 20 loops of ~7 mm in diameter with overall longitudinal dimension of 8 mm. The coil signals are amplified before being transmitted through 50 Ω lines to an oscilloscope. The system "coils + amplifier" was calibrated by observing an output voltage as a response to the magnetic field generated by variable-frequency current in a long conductor placed near the coil (see [15]). Thus, a transfer function was obtained which permits to deduce magnetic field:

$$B(\omega) = U_{acq} f_{tr}(\omega)\,, \quad (2)$$

where $f_{tr}(\omega)$ is transfer function, U_{acq} is amplifier output voltage. Such coils are routinely used for investigating ionospheric plasmas [18]. Magnetic probes are also widely used in different laboratory plasma devices. The basis idea for interpretation of such measurements is generation of non-stationary magnetic fields by charged particles motions.

Four coils were installed around the accelerating channel, at its cut-off plane and outside of the ionic plume. The coils were placed on the same radius at ~20 mm from the channel (Fig. 2); three of them (B2, B3, B4) were oriented in radial, azimuthal and axial directions, the fourth (B1) was in azimuthal direction and shifted relatively the B3 by an azimuthal angle $\Delta\varphi$. Additional probe diagnostics was also installed, as seen in Fig. 2 (in the right-down part).

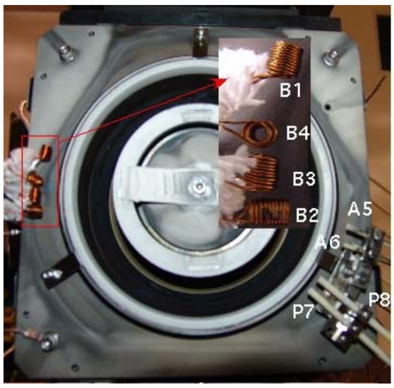

Fig. 2. Picture of the PPS®-X000ML HET equipped with the coils and probes.

3. Results and discussion

The spectrum of typical coil signal (Fig. 3) ranges from tens of kHz to tens of MHz, thus containing most of HET's characteristic frequencies reported elsewhere [1,2,4,9]. A comparison of B3 and B1 signals (oriented in the same direction coils, see Fig. 2) shows that their forms are not very different, and one can distinguish their temporal shift (dephasing) Δt. These direct observations are confirmed by calculating their cross-correlation function (Fig. 5). Red zones in Fig. 5 correspond to the maximum of this function; the horizontal axis is recording time, the vertical axis is signal temporal shift Δt (dephasing).

For the coils B1 and B3 only the azimuthal coordinate varies, and it can be concluded that they detect a rotating in azimuth perturbation (clockwise according to Fig. 2) which generates a non-stationary magnetic field. With $\Delta t = 0.1$ μs (see Fig. 5) the azimuthal propagation velocity is ~ 2.8×10^5 m/s. The same velocity can be obtained from the correlation functions of Langmuir probes. This velocity is close to the electron drift velocity (~10^6 m/s) in the crossed electric and magnetic fields. These observations are in agreement with the earlier studies by antennas and electrostatic probes which reported detection of azimuthal waves [9-11]. In the present studies the HF spectrum (>1 MHz) does not have distinct lines as in [9,11], indicating a more turbulent character of the HF instability.

A parametric study of the non-stationary magnetic field was performed as a function of mass flow rate varied between 6 and 20 mg/s. Discharge voltage and magnetic field were kept constant (U_d=300 V, I_b=20 A). The inferred azimuthal velocity is constant in this range of thruster operation parameters (Fig. 6) and stays ~2.8 10^5 m/s.

Magnetic field has amplitude of ~10^{-5}…10^{-6} T (Fig. 7) being significantly smaller than the stationary magnetic field of 20×10^{-3} T. The HF component of magnetic field (Fig. 7 b-c) was extracted by applying of digital filter. All three components of the non-stationary magnetic field have close magnitude.

The source of such non-stationary magnetic field can be modeled by a system of localized electron currents in the plasma volume, whose absolute value is close to the supposed electron current through the magnetic field. This system rotates in azimuthal direction with a velocity close to the drift velocity in the crossed electric and magnetic fields [15]. These currents can have different orientations and, as was shown in [15], the whole system can represent a spiral-like electron current starting from the cathode and flowing into the channel across the magnetic field.

According to this model the non-stationary magnetic field in the plasma volume (2-4 cm from coils' positions to the center in Fig. 2) is at most one order of magnitude lower the stationary one, thus affecting only a little the electron motion. But the turbulent azimuthal electric field, related to this HF rotating instability, can reach maximum values of 100 V/cm comparable to the axial accelerating electric field. Therefore, the underling mechanism of electron transport across the stationary magnetic field is a drift in crossed fields: a turbulent azimuthal electric field (due to the instability) and the mentioned stationary radial magnetic field (from the thruster magnetization coils, see Fig.1). This mechanism can be found in different magnetized plasmas and in the configuration similar to HET was described in [19]. The present measurements and modeling suggest that electron current through the magnetic field is localized rather than uniformly distributed in the plasma volume. Introducing the friction force between the instability and the electrons, as shown in [15], the electron effective collision frequency can be estimated as <10^6 s^{-1} in the core plasma, being higher than the "classical" collision frequency ~10^5 s^{-1}.

The above estimations of effective electron collision frequency were done combining the measurements outside the core plasma and the model. This frequency can be in principle estimated through the direct intrusive measurements of the HF instability magnitude, but these measurements would disturb the gas-discharge. The proposed model of localized currents intends to describe the physical source of the instability and can permit to reconstruct the anomalous electron current in HET. The future work will be therefore focused on a careful mapping of the non-stationary magnetic field in HETs and on the model validation efforts.

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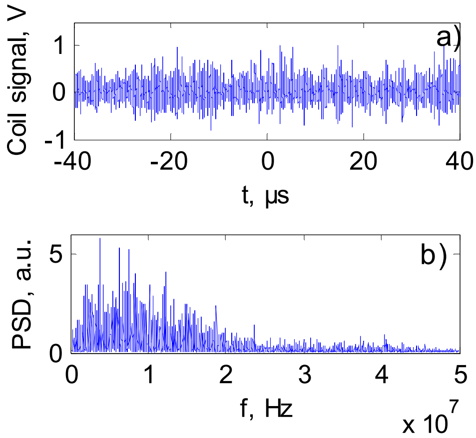

Fig. 3. Typical B3 signal (a) and its spectrum (b).

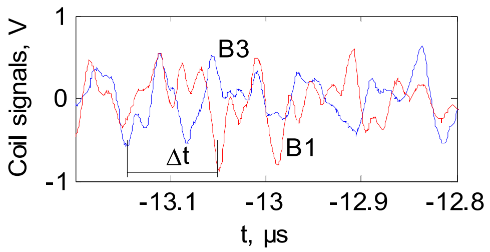

Fig. 4. Zoom of the B1 and B3 signals.

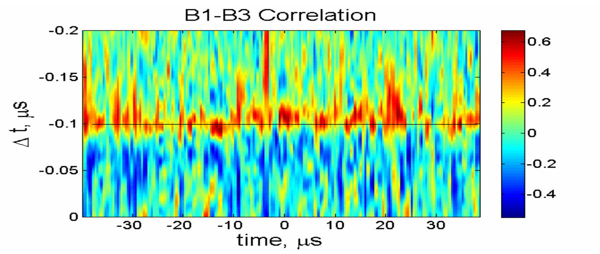

Fig. 5. B1 and B3 cross-correlation function

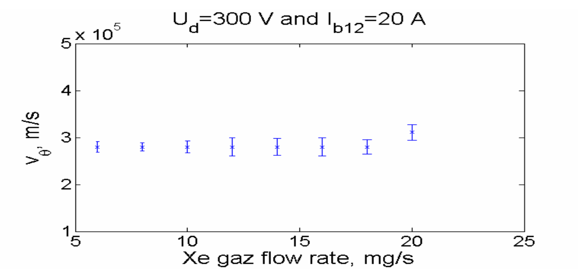

Fig. 6. Azimuthal velocity of the instability as a function of Xe gas mass flow rate

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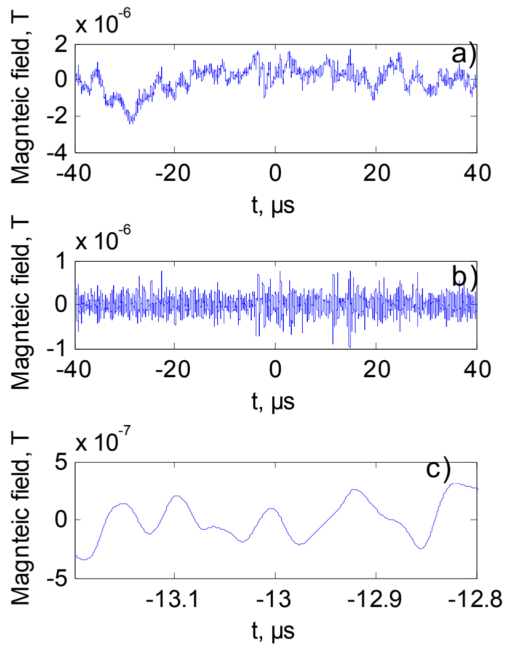

Fig. 7. Magnetic field detected by coil B3; a) total field, b) HF field >1MHz, c) zoom on HF field

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