# CCD Images of Hall Effect Thruster Plume Dynamics After Ultrafast Current Ignition

V. Vial, S. Mazouffre, M. Prioul, D. Pagnon, and A. Bouchoule

***Abstract*—The dynamic behavior of the Hall effect thruster plasma plume is investigated after ultrafast current ignition driven by a metal–oxide–semiconductor field-effect tranistor MOSFET power switch. Time-resolved optical measurements performed with a gated intensified charged coupled device (CCD) camera allow to reconstruct the plume temporal features. Images of the ion beam reveal oscillations in plasma light intensity linked to "breathing" instabilities. The observed periodic variations of the beam divergence originate from the displacement of the ionization layer within the thruster magnetic barrier.**

***Index Terms*—Breathing modes, hall thruster, optical emission, plasma instabilities.**

HALL EFFECT THRUSTERS (HET), also called stationary plasma thrusters or closed electron drift thrusters, are advanced propulsion devices that uses an electric discharge to ionize and accelerate a propellant gas [1]. At present, they are employed for missions like satellite orbit correction and station keeping. The additional utilization of high-power Hall thrusters for orbit topping or raising would also offer significant benefits in terms of launch mass, payload mass and operational life. Moreover, Hall thrusters appear as good candidates to be used as the primary propulsion engine for space probes during interplanetary journey, as confirmed by the successful SMART-1 mission from ESA.

The basic physics of a HET implies a magnetic barrier in a low-pressure direct current (dc) discharge generated between an external hollow cathode and an anode that also acts as gas distributor [1]. The anode is located at the rear of a hollow annular ceramic channel that confines the discharge. A set of solenoids provides a radially directed magnetic field of which the strength is highest near the channel exhaust. The magnetic field is chosen weak enough not to disturb the ion motion, but strong enough to slow down the electron's axial motion. The discharge voltage drop is mostly concentrated in the near-exit section of the channel due to the low electron conductivity in this restricted area. The locally induced axial electric field has two main effects. First, it drives a high electron azimuthal current that is responsible for the efficient ionization of the supplied gas (usually xenon). Second, it accelerates the created ions that form the thruster plasma plume. When operating near 1.3 kW, a ejects ions at 20 km/s, and generates 90 mN of thrust with an efficiency in excess of 50%.

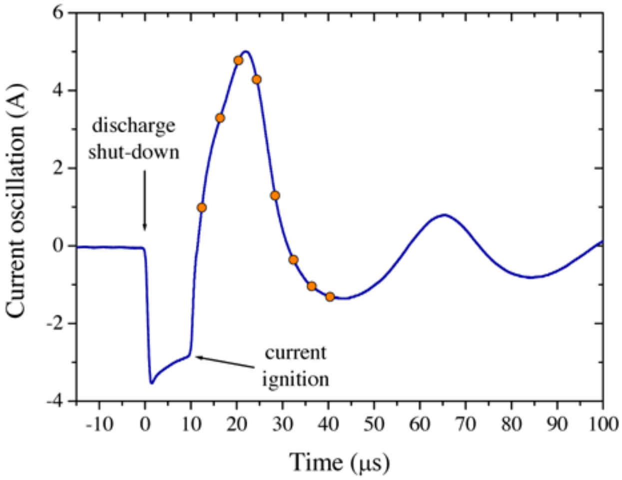

Fig. 1. Anode discharge current oscillations (ac mode) as a function of time after ultrafast externally driven current ignition. Curve originates from the average over 256 waveforms. Mean frequency oscillation is 24.5 kHz. Full circles indicate times at which thruster plume CCD images are taken (see Fig. 2).

Examination of a Hall thruster response to ultrafast current interruptions driven by an optically controlled metal–oxide–semiconductor field-effect transistor (MOSFET) power switch has proven to be a powerful way to untangle part of the complexity of such a magnetized plasma medium [2]. The switch allows fast cancellation and generation of ion and electron currents, as well as electric field on a time scale (around 100 ns) shorter than any characteristic time scale for non turbulent transport phenomena. Among others, this approach based on a pulse perturbation has recently permitted [2]:

1) to determine the electron drift current,
2) to better understand transient ionization phenomena occurring inside the thruster channel,
3) to analyze the ion beam composition and angular energy distribution.

In this paper, high-speed two-dimensional (2-D) mapping of thruster plasma light is employed to reconstruct both ion beam density and plume divergence temporal fluctuations after a fast current ignition that follows a discharge shut down phase.

A laboratory model SPT-100 HET is operated at 300-V applied voltage and 5.42-mg/s xenon flow rate. As shown in Fig. 1, the current ignition follows a 10-$\mu$s power-off time period during which the plasma fully vanishes [2]. A gated

Manuscript received July 1, 2004; revised October 11, 2004. This work was supported by the research group CNRS/CNES/SNECMA/Universities 2759 "Propulsion Spatiale à Plasma."

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Digital Object Identifier 10.1109/TPS.2005.845363

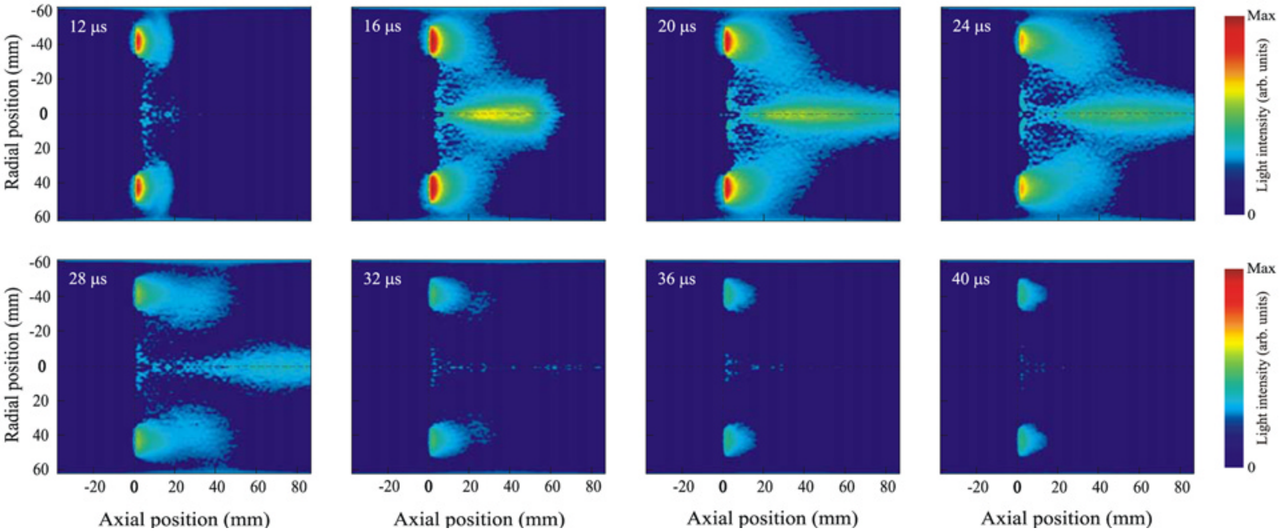

Fig. 2. Series of images of the plasma plume of a SPT-100 Hall effect thruster after ultrafast current ignition. Pictures are obtained by applying Abel transform to photographs taken with a gated ICDD camera under a 90° angle. Both the channel exit plane location $(y = 0)$ and the thruster axis $(x = 0)$ are indicated. Thruster body is located on the left $(x < 0)$. Two bright zones located on both side of the symmetry axis correspond to the annular channel exhaust. Region of relatively high intensity located on-axis corresponds to the region where a part of the ion beam is focused due to an electrostatic lens effect. Note that the light intensity images the $Xe^+$ ion density.

intensified CCD camera, which is triggered on the ultrafast switch signal, captures plume pictures under a 90° viewing angle at various moments after ignition of the plasma [3]. In order to obtain a good time resolution, the gate width is set to 0.1 $\mu$s. To avoid a long exposure time, no optical filter is used in front of the camera, however, the emitted light mostly originates in $Xe^+$ emission lines [3]. A raw CCD image corresponds to the build-up over 10 000 on–off cycles, the frame rate being 10 kHz. Raw images cannot be directly employed to investigate the plume temporal behavior, but real plume features are revealed by performing an Abel transform [3].

The resulting images reveal low frequency light intensity oscillations; i.e., plasma density oscillations, perfectly in phase with the discharge current (see Fig. 2). Such light oscillations are directly connected with the so-called "breathing" mode [4]. This peculiar low frequency instability finds its origin in the ionization and subsequent acceleration of ions created within the channel. The ionization process temporally depletes the neutral density, therefore the ion current decreases until the ionization region is filled again with slow moving atoms. During a discharge-off period, atoms are not consumed and they fill the entire channel. Hence, a large ion bunch is formed at plasma ignition that explains the current burst in Fig. 1.

The ion beam divergence is also affected by current oscillations. The bright zone located on the thruster axis corresponds to the crossing of elementary beams generated at two opposite sides of the discharge channel inner section. It is then a region of high plasma density, in which the light production originates mainly in electron impact excitation processes [3]. The position of this zone delivers information about the beam divergence. As can be seen in Fig. 2, at $t = 12$ $\mu$s, i.e., 2 $\mu$s after current ignition, the central zone is not yet formed, meaning that ions did not yet reach the centerline. The zone appears around $t = 14$ $\mu$s about 20 mm ahead of the thruster exit plane. As can clearly be seen in Fig. 2, the zone is moving downstream in time, which indicates that the ion beam divergence diminishes. The forward displacement of the central bright zone reveals that the flow of ions passing by the chamber inner wall becomes more parallel to the thruster axis. The motion of the "outer" plasma boundary is affected in the same way (see Fig. 2). After 32 $\mu$s, the beam is almost not divergent anymore since the zone almost vanishes. The observed modification of the plume divergence with time is a direct consequence of the displacement of the ionization layer, the region through which ions are produced, within the magnetic barrier. Due to an electrostatic lens effect, resulting from the magnetic field topology, the direction of an ion velocity vector depends strongly upon the exact location the ion is created, the probability the ion experiences a collision being very low. The focusing (or defocusing) effect is naturally more pronounced for ions flowing in the vicinity of the channel walls. As soon as the current decreases, the ionization front moves toward the anode and the electrostatic lens effect is likely to produce a collimated beam of ions, which explains the trend observed in Fig. 2. Note that the mean speed for displacement of the central bright zone increases in time from 2 km/s at $t = 18$ $\mu$s to 4.5 km/s at $t = 26$ $\mu$s, this speed being of course correlated with the ionization front speed.

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