Time-Dependent Ion Velocity Distribution: A novel Heterodyne Laser-Induced Fluorescence with Coupled Wave Excitation

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We propose a laser induced fluorescence heterodyne approach to resolve the time-dependent ion velocity distribution (IVDF) in a Hall thruster. This approach is motivated by studies of low frequency modes of oscillations in Hall thruster, including azimuthal or so-called spoke and axial or so-called breathing oscillations. In this paper, we present the first successful application of this method to an axial mode, by driving coherent breathing oscillations.

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I. Introduction

Plasma oscillations in Hall thrusters have been the dominant source of electron anomalous transport ultimately leading to inefficiencies in the power consumption of commercial spacecrafts. The physics governing these oscillations which in turn lead to anomalous heat and particle transport is not well understood. It is therefore imperative to understand the origins of these oscillations in order to develop control approaches for further improving Hall thruster operations. More specifically, we address the long standing rotating spoke instability(see Ref[2] and reference therein). These oscillations are ubiquitous in Hall thrusters and have been proposed, in addition to Bohm diffusion[1] and near wall conductivity, as a mechanism for cross-field electron transport.

The spoke is known to coherently propagate in azimuthal direction (m=1) in the E x B direction and is observed in the few kilohertz range (see Ref.[3,4] for details description in a cylindrical Hall thruster). To study the spoke instabilities, we propose to first couple to them segmented anodes (see Ref.[6] for details of the approach), and second investigate the perturbation of the velocity distribution measured using the laser induced fluorescence (LIF) diagnostic. Since the spoke's density and its electric field are thought to be in phase, which yield a net electron transport, the goal of this study is to characterize the ion distribution both in presence of intrinsic and driven spoke to determine the electric field. In addition, the collective effect induced by the rotating spoke will provide the means to characterize the dispersion relation of the spoke.

In this work, we discuss the approach necessary to simultaneously measure the total ion distribution and the coherent ion response to the induced perturbation (details of which will be described in Ref.[6]). This approach constitutes the first step in resolving in time the ion velocity distribution function (IVDF). Note that two research groups (see ref[8] and ref[9]) have resolved the time-dependent-IVDF using different techniques that rely on photon counting for each velocity classes.

II. Experimental setup

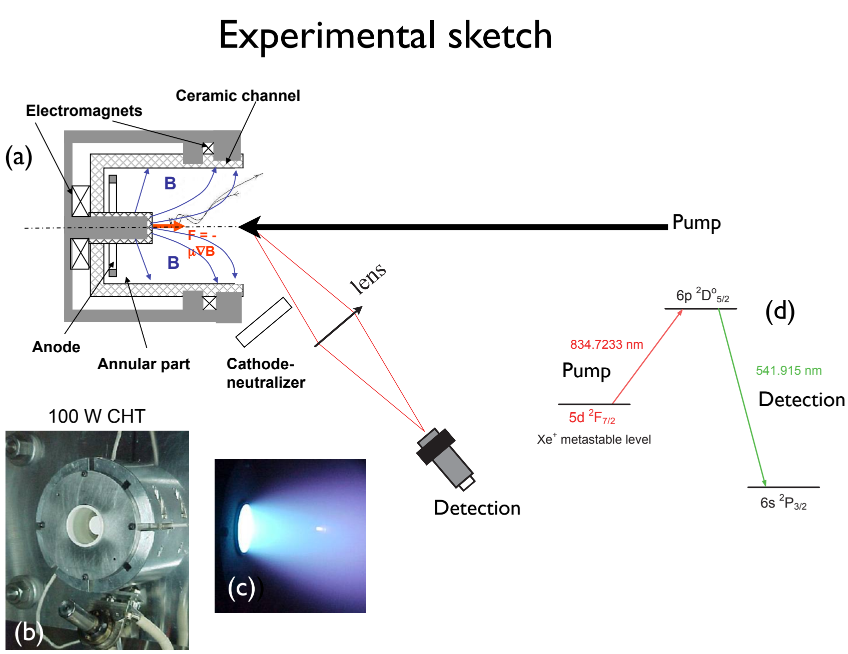

Figure 1. (a) Schematics of the cross-section of the cylindrical Hall thruster (CHT) and LIF diagnostic. (b) Photograph of the CHT. (c) Photograph of plasma ejection from the CHT. (d) Three level LIF scheme used in this paper.

The experiments are performed in a 2.6 cm cylindrical hall thruster (CHT) (see figure 1 (a) - (c)). The design and detailed description can be found in Ref.[5,7] The thruster was operated using xenon propellant with anode flow rate 2.5 sccm and cathode flow rate 1.5 sccm. The background pressure during thruster operation was about 5.1×10^{-5} Torr. The back magnetic coil current was 0.6 A and the front magnetic coil current was 1.27 A in "Direct" configuration. A 0.25 A keeper current was run between cathode emitter and keeper, together with a 12A heating current to stabilize the hollow cathode performance. When the discharge voltage was set to be 225 V, the thruster exhibits strong breathing oscillation at about 11.5 kHz. To couple with this natural oscillation, a 11.5 kHz square wave voltage between 210 V and 240 V was applied on thruster anode. The driven breathing mode was large and periodic as seen by the fast camera.

We measure the ion velocity distribution function (IVDF) using LIF. A tunable diode laser is used to pump the $5d^2F_{7/2}$ Xe^+ metastable level to $6p^2D^0_{5/2}$ as shown in figure 1(d). The laser beam was aligned perpendicular to the thruster exit plan and was injected into the thruster channel at about 1 cm from the thruster axis. The collection of LIF photons is performed $\sim 70°$ degrees with respect to the laser beam. The collected signal was detected using a photo-multiplier with an interference filter centered at 541 nm. In the remainder of this paper, we discuss a novel approach for determining the time-dependent ion distribution based on an heterodyne technique.

III. Development of an heterodyne LIF detection system

Motivated by the need to determine the effects of the spoke on the ion distribution function to potentially unfold the electric field associated with the spoke instabilities, we investigate new heterodyne approach to determine the time-dependent ion velocity distribution as follows:

$$f(t, \mathbf{x}, \mathbf{v}) = f^0(\mathbf{x}, \mathbf{v}) + \mathcal{R}e\left[\sum_{n>0} f^n(\mathbf{x}, \mathbf{v}) \exp\left(-in\omega_D t + i\theta_n(\mathbf{x}, \mathbf{v})\right)\right].$$

Here, ω_D indicates the modulation imposed in the plasma. Note that this could be generalized to include intrinsic modulations of the plasma (e.g., rotating spoke, breathing mode). From the above formulation, two regimes can be studies: one where $f_{pert} = \sum_{n>0} f^n(\mathbf{x}, \mathbf{v}) \exp\left(-in\omega_D t + \theta_n(\mathbf{x}, \mathbf{v})\right)$ is of the same order as $f^0(\mathbf{x}, \mathbf{v})$ and the other where $f_{pert} \ll f^0(\mathbf{x}, \mathbf{v})$. Here, we report on the latter condition to establish a proof-of-principle of this heterodyne approach.

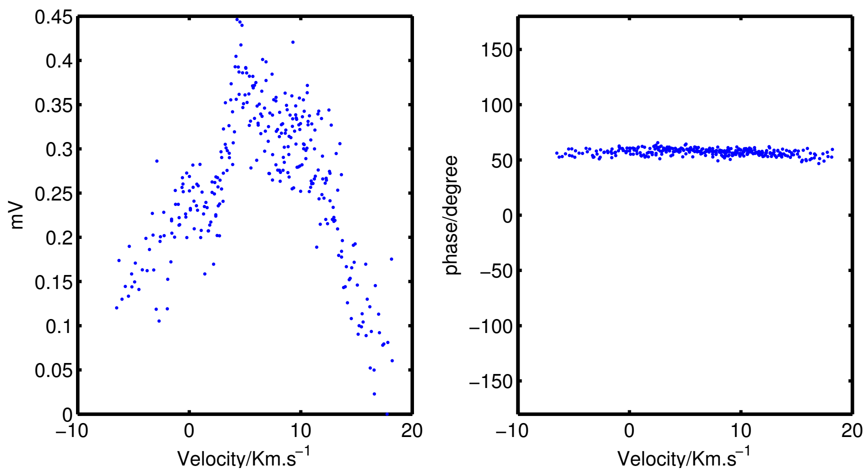

Figure 2. (a) Time-averaged distribution as measured by the lockin (b) Associated phase.

More specifically, the plasma is modulated axially at the breathing mode frequency that is $\omega_D = 11.5$ kHz. In order to decouple the LIF signal from large background oscillations encoded in the broadband light emission, we choose to detect the LIF signal at the $\omega_D \pm \omega_L$, where ω_L is the laser modulation. This approach yields the time-averaged ion distribution function given by $f^0(\mathbf{x}, \mathbf{v})$ as shown in figure 2. The left panel of this figure displays the magnitude of the time-averaged LIF signal corresponding to $f^0(\mathbf{x}, \mathbf{v})$. The right panel shows its associated phase relative to a reference signal that is the modulation frequency (ω_L) of the laser beam. Note that this time averaged distribution function is effectively the equilibrium distribution for the special case $f_{pert} \ll f^0(\mathbf{x}, \mathbf{v})$.

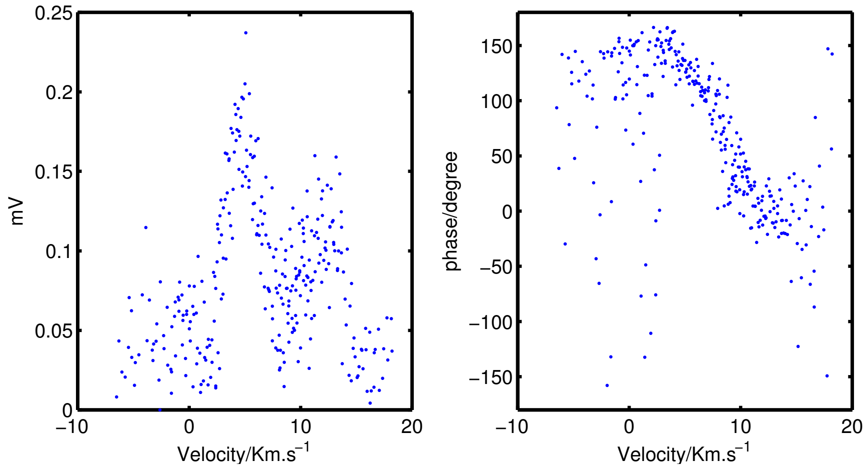

Figure 3. (a) First-order perturbed distribution function. (b) Velocity dependent phase shift $\theta(v)$.

The first order perturbed IVDF(measured at $\omega_D \pm \omega_L$) is shown in figure 3, where the left panel represents the magnitude $-f^1(\mathbf{x}, \mathbf{v})-$ and the right shows its associated phase. This approach is trivial to generalize in order to determine all the perturbed function components ($n > 1$), from which the time-dependent ion distribution can be reconstructed. Using up to the n=1 component, we reconstruct the time evolution of the *truncated* IVDF as displayed in figure 4(a). Figure 4(b) displays few time slices with the time-averaged distributions. Note that accuracy of the reconstructed distribution depends on the order of truncation especially when the applied oscillation is large. Future work will focus on applying this technique to the spoke instabilities and details of this technique will be reported in future publications.

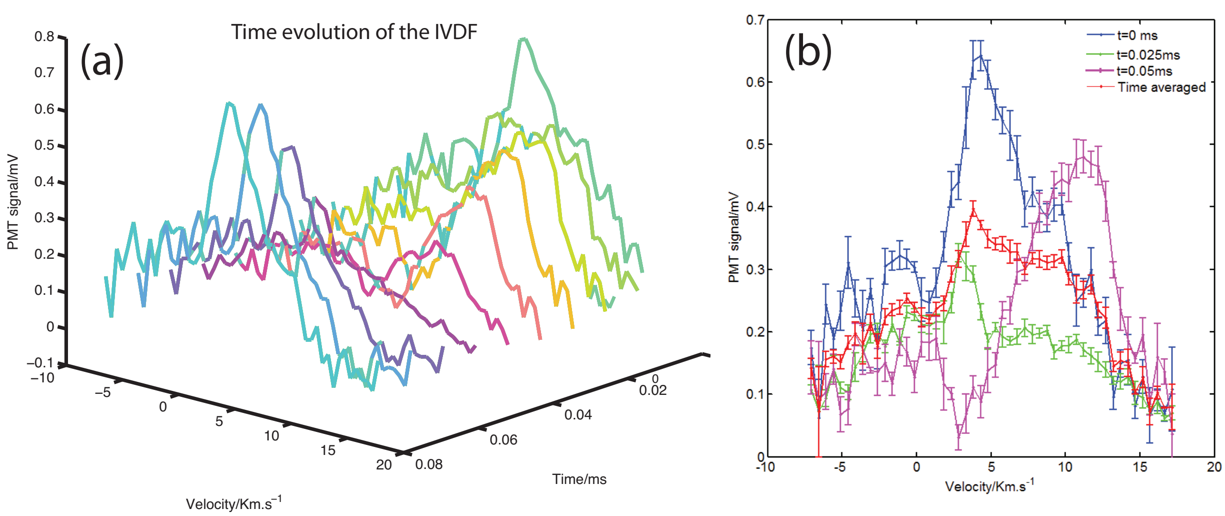

Figure 4. (a) Reconstructed time evolution of the distribution function (up to n=1). (b) Times slices of the reconstructed distribution and comparison with the time-averaged distribution.

IV. summary

This paper described a novel approach for determining the full ion distribution. Based on an heterodyne technique, one can selectively determine each harmonics of the full distribution function and, depending on the level of fluctuations, a time-dependent IVDF can be reconstructed. A proof-of-principle was described in this paper and a detailed description of the application and method will be presented in future publications.

Acknowledgments

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