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Measurement of ion acceleration in the magnetic nozzle of an ECR plasma thruster

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Abstract

The Electron Cyclotron Resonance (ECR) plasma thruster operated with xenon is experimentally studied using laser-induced fluorescence (LIF) spectroscopy. The ion velocity distributions determined from Doppler shift show the axial acceleration of singly charged xenon ions in the magnetic nozzle over several centimeters. LIF results are compared to electrostatic probes measurements.

I. Introduction

Electric propulsion is a growing market for satellites and space probes. Plasma thrusters have a very high specific impulse that enables to significantly reduce the weight of propellant gas and then to increase the payload. Furthermore, it is admitted that future deep space exploration vehicles will rely on plasma thrusters.

In the past few years, interest has increased for quasi-neutral electrodeless plasma thrusters, which do not need an external cathode neutralizer. Unlike Hall Effect Thruster and Ion Grid Engines that use an electric field to accelerate ions, electrodeless thrusters are based on the magnetic nozzle principle: a magnetic field is used to radially confine the plasma in the source and to accelerate simultaneously electrons and ions in the plume.

Among these propulsion systems, Helicon Double Layer Thrusters (HDLT) [1] and other RF based plasma sources [2,3] have received an increasing attention for their ability to produce ions with a kinetic energy higher than 100 eV. Several models have been proposed to explain the acceleration of ions: a sudden drop of potential (double layer) is produced during plasma expansion in HDLT [4], and electron thermal energy is converted into ion kinetic energy in divergent magnetic field [5].

Recently, another type of quasi-neutral plasma thruster has been developed at ONERA, namely the electron cyclotron resonance (ECR) plasma thruster. The principle is based on electron heating - and efficient ionization of the propellant gas - by ECR effects, and ion acceleration under the effect of the ambipolar electric field in the magnetic nozzle. Previous studies have shown that mass utilization efficiency up to 45% and ion energy higher than 300 eV can be achieved in xenon depending on the microwave power and the propellant flow rate [6,7].

In this paper, we present experimental measurements of the acceleration of ions in the magnetic nozzle of our coaxial ECR plasma thruster operated with xenon. The aim is to determine the ion velocity distribution function at different positions and the longitudinal profile of the acceleration process by means of laser-induced fluorescence (LIF) spectroscopy of Xe^+.

II. Experimental

A. Laser Induced Fluorescence setup

Laser Induced Fluorescence spectroscopy is a powerful tool for the characterization of plasma thrusters: it is spatially resolved, non-perturbative, and selective to species. In this study, the Doppler shift of LIF is used to determine the velocity distribution of singly ionized xenon. The $5d[4]_{7/2}$-$6p[3]_{5/2}$ transition of Xe^+ at 834.7 nm is excited by a diode laser and the radiative de-excitation of ions at 541.9 nm is used for the detection of the fluorescence.

A schematic diagram of the laser setup is shown in Figure 1. The laser source is an external cavity tunable diode laser (TDL) centered at 834.7 nm (SDL TC-10). Fine tuning of the laser wavelength is obtained by adjusting the voltage applied to the piezoelectric actuator of the grating (Littrow configuration). This laser has a linewidth of 200 kHz and a mode hop free tuning range up to 60 GHz.

The laser wavelength is monitored using a Fizeau interferometer wave-meter (LM-007) with a 10 MHz resolution. In the meantime, a small fraction of the laser is sent to a Fabry-Perot interferometer with a free spectral range of 640 MHz. The frequency tuning velocity of the TDL (in MHz/s) is determined from the fringes of the interference figure measured with a photodiode. The relative Doppler shift value can then be determined with a good accuracy on the LIF spectra.

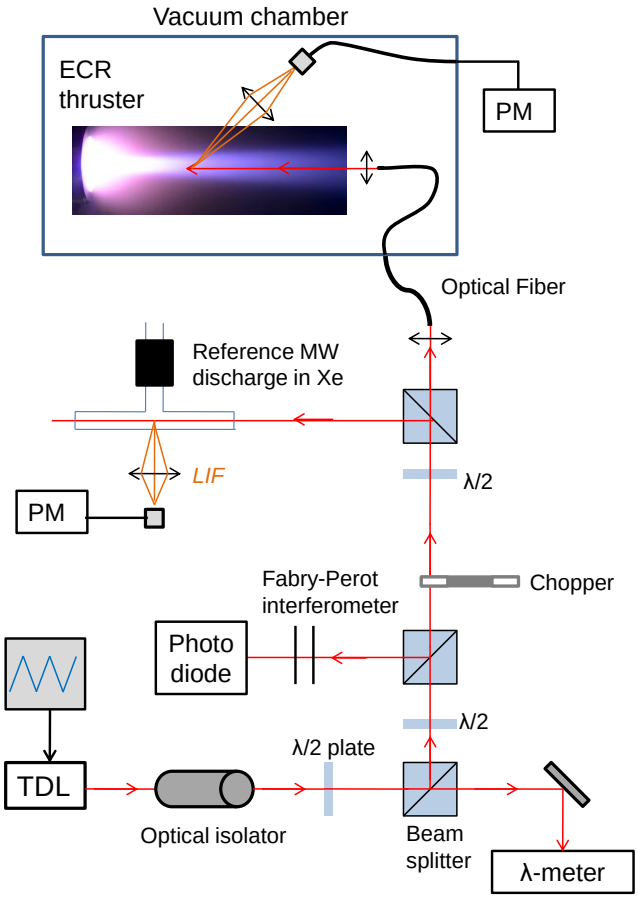


Figure 1. Schematic of the laser setup.

The laser beam passes through an optical chopper in order to perform phase-lock amplification of the fluorescence signals.

The zero velocity reference for xenon ions is given by LIF spectroscopy of a surface wave discharge in pure xenon at low pressure (10 mTorr). The discharge is driven by a magnetron with a power of 50 W. A polarizing beam splitter sends about 1 mW of the laser power to the reference discharge.

The remaining part of the laser beam (about 5 mW) is coupled to a 50 µm optical fiber and sent to the vacuum chamber. The laser is collimated with a diameter of 1 mm using a lens at the output of the fiber. The beam is directed in the axis of the thruster, so only the axial component of ion velocity is measured. The fluorescence radiation of xenon ions is collected at 45° from laser axis by a 25 mm diameter lens coupled to a 400 µm optical fiber.

The two fluorescence detection systems (ECR thruster and reference discharge) use photomultipliers tubes (PMT) for radiation measurement. Interference filters at 541.9 nm (with a FWHM of 10 nm) enable to partly reject parasitic light from the plasma. The PMT signals are amplified using lock-in amplifiers (Stanford Research System SR830 and EG&G 5210) locked at the frequency of the optical chopper. The time constant of lock-in amplifiers and the frequency tuning velocity of the TDL are adjusted as to maintain the profile of the Xe^+ line. An example of LIF signal recorded with the reference discharge is illustrated in Figure 2, with the interference figure of the Fabry-Perot.

The acquisition of photodiode signals and PMT signals, and the control of the TDL tuning voltage are performed with a National Instruments DAQ board.

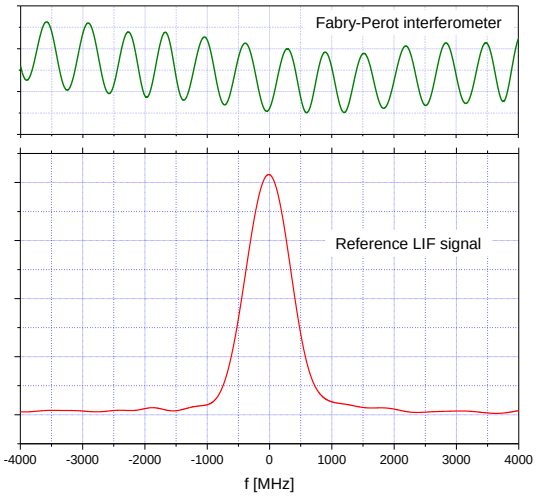


Figure 2. Example of a LIF signal of the reference discharge and Fabry-Perot interference figure.

B. ECR source

The ECR thruster under development at ONERA is designed in a coaxial geometry (see Figure 3). The coaxial line is connected to an antenna 1.5 mm in diameter and to a cylinder 13 mm in diameter. The length of the ECR source is 15 mm. A DC block is inserted in the coaxial line to allow for floating potentials of the coaxial structure.

The ECR source is powered by a standard magnetron generator at 2.45 GHz with an adjustable output power. The power injected into the ECR source is measured with a bidirectional coupler equipped with diodes.

The resonant magnetic field is provided by an assembly of Neodymium permanent magnets placed upstream the ECR source. The magnetic field was chosen to ensure a purely diverging magnetic field in the ECR source and the magnetic nozzle. Measurements of the axial magnetic field performed with a Gauss-meter at different positions along the longitudinal axis of the thruster are shown in Figure 4. The resonant magnetic field at 2.45 GHz (indicated by the red line) is in the middle of the ECR source.

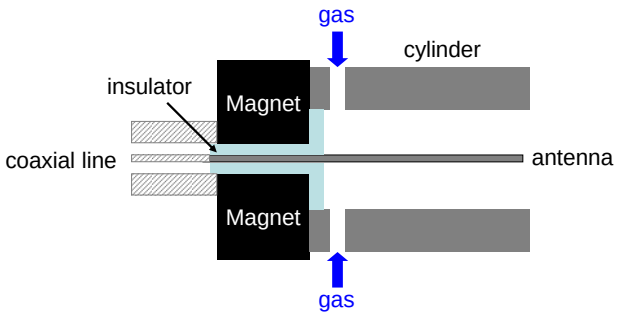


Figure 3. Schematic of the ECR plasma thruster.

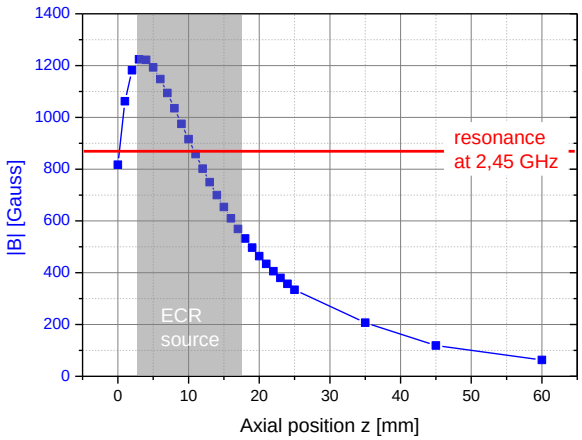


Figure 4. Axial magnetic field amplitude in the ECR source and in the magnetic nozzle

C. Facility

All experiments are carried out in B09 facility at ONERA Palaiseau center. B09 is a cylindrical vacuum chamber 2 m long and 0.8 m in diameter equipped with three Pfeiffer Hipace 2300

turbomolecular pumps (total pumping speed: 2500L/s in xenon) that ensures a base pressure below 10^{-7} mbar, and a background pressure of $7x10^{-6}$ mbar at an operating flowrate of 0.1 mg/s.

The ECR thruster is mounted on a three axis translation stage system that enables to perform longitudinal scans of the ion velocity and to change the diagnostic: LIF spectroscopy, ion energy analysis, .or plasma potential measurement.

The ion energy distribution function (IEDF) in the far field region is measured with a PSM mass/energy ion analyzer (Hiden Analytical) that uses an electrostatic filter and a quadrupole mass spectrometer. It is fixed on a flange about 1.5 m away from the thruster.

The plasma potential is measured with an emissive probe, using the floating point method. The probe consists of a 0.1 mm diameter tungsten wire inserted at the end of a two channels alumina tube. The filament is heated by a current to allow thermionic emission of electrons. The potential of the probe increases with the emission of electrons and then saturates as the plasma potential value is reached.

III. Results and discussion

A. Measurement of xenon ion velocity distribution function (IVDF)

LIF measurements have been performed at different axial positions along the thruster axis. Figure 5 shows the evolution of the IVDF in the plume from 5 mm to 55 mm (distance to the end of the antenna) for a mass flow rate of 0.1 mg/s and a microwave power of 20 W. The spectrum of the surface wave discharge (zero-velocity reference) is given for comparison purposes (blue curve). The amplitude of the Doppler shift clearly increases with the distance to thruster, which shows that Xe^+ is accelerated over the whole range of axial positions.

The profile of ion velocity distribution also varies with the axial position: the IVDF tends to be narrower as the ions are accelerated in the magnetic nozzle. The full width at half maximum is around 2700 m/s at 5 mm and 1400 m/s at 55 mm. This is still wider than the IVDF of the reference discharge (about 700 m/s).

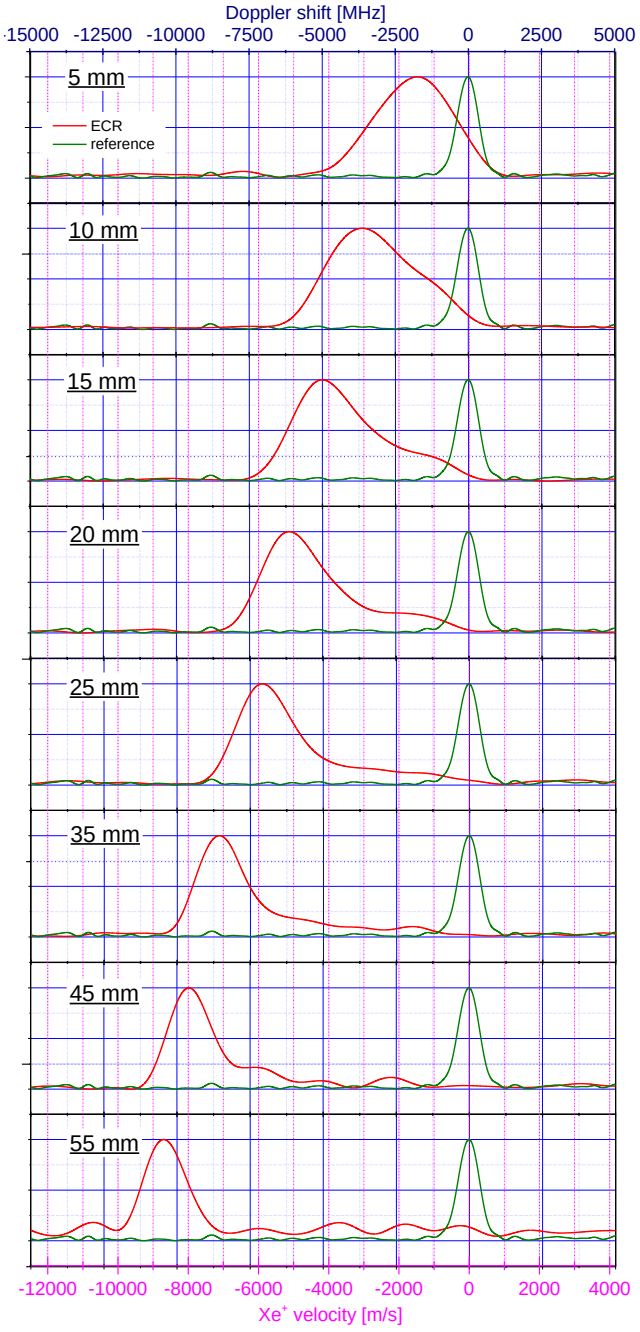


Figure 5. Evolution of Xe^+ axial velocity distribution as a function of axial position. Mass flow rate= 0.1 mg/s, MW power = 20 W.

There are two possible explanations for this phenomenon. The first one is the kinematic compression: the ions are cooled during their acceleration, which modifies their IVDF. The second explanation is the Zeeman splitting: the amplitude of the magnetic field decreases as the ions travel in the magnetic nozzle, so that the Zeeman effect is reduced. The verification of both explanations by spectrum simulation would require

an accurate knowledge of the hyperfine isotopic and nuclear-spin structure of Xe II $5d[4]_{7/2}$-$6p[3]_{5/2}$ transition.

B. Ion acceleration in the magnetic nozzle

The mean ion velocity can be deduced from IVDF obtained in LIF measurements. Figure 6 shows the longitudinal evolution of Xe^+ axial velocity along the magnetic nozzle axis for two mass flow rates (0.06 and 0.1 mg/s). Higher velocities are obtained at 0.06 mg/s, as expected from previous measurements [6]. The acceleration occurs over the whole range of axial positions for both flow rates, and the mean axial ion velocity reaches 13 km/s at 0.06 mg/s and 9 km/s at 0.1 mg/s. These values are still below the final ion velocity deduced from IEDF obtained with the ion energy analyzer at 1.5 m: 19 km/s (230 eV) and 13 km/s (120 eV), respectively. The longitudinal profile clearly shows that the ions are still accelerated by at the furthest axial position of LIF measurements. However, the density of Xe^+ decreases away from the thruster because of ion acceleration and plume divergence, and the signal-to-noise ratio of LIF becomes too low for a proper calculation of velocity.

The longitudinal profile of plasma potential φ in the magnetic nozzle can be determined from the evolution of Xe^+ axial velocity:

$$\varphi = \frac{1}{q}\left(E_i - \frac{1}{2}m_i(v_i)^2\right)$$

where E_i is the total ion energy, m_i the ion mass, v_i the ion velocity, and q the ion charge.

The total ion energy is measured with the ion analyzer in the far field region, and the axial kinetic energy can be deduced from LIF measurements. Figure 7 shows a comparison between the plasma potential deduced from axial velocity and the plasma potential measured with the emissive. The positive error bars of the emissive probe data stand for the underestimation of plasma potential on the order of $1.5T_e/e$ with the floating point method [8] (and assuming T_e is about 10 eV). A good agreement is found between the two methods in the range of axial positions 25-70 mm. The gradient of potential tends to decrease, which explains the long acceleration region of xenon ions in the magnetic nozzle.

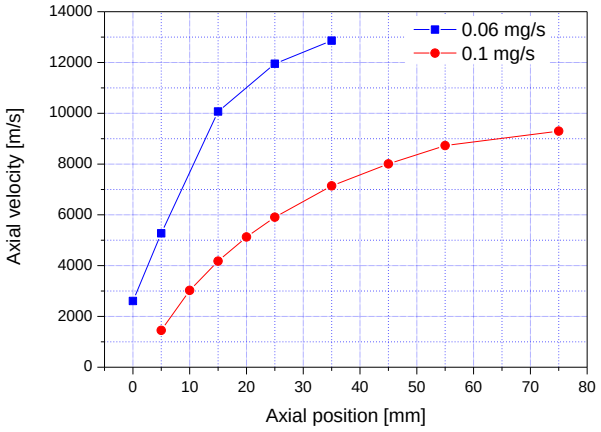


Figure 6. Evolution of Xe^+ axial velocity with distance to thruster.

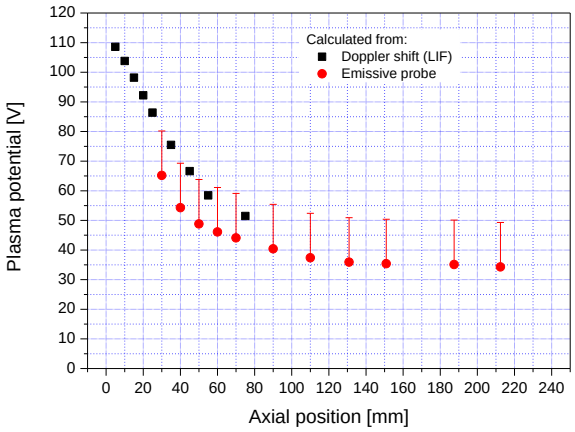


Figure 7. Longitudinal profile of plasma potential measured with the emissive probe and deduced from axial velocity profile. Mass flowrate=0.1 mg/s; MW power=20 W.

IV. Conclusion

Laser-induced fluorescence spectroscopy measurements have shown that the acceleration of singly charged xenon occurs over a long distance in the magnetic nozzle of an ECR plasma thruster. The ion velocity reaches more than 50% of its final value after 5 cm, but the weak variation of the plasma potential in the far field region extends the acceleration zone to several tens of centimeters.

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