Number Density and Velocity Measurement in the Plume of a Micronewton Cold Gas Thruster by Electron Beam Fluorescence and Laser Induced Fluorescence

IEPC-2009-184

Presented at the 31st International Electric Propulsion Conference,
University of Michigan • Ann Arbor, Michigan • USA
September 20 – 24, 2009

D. Packan[1] , J. Bonnet[2] and S. Rocca.[3]
ONERA, Palaiseau, 91120, France

Abstract: New diagnostics techniques have been developed for the characterization of the plume of a cold gas thruster and are demonstrated. The methods are optical and non-intrusive. Electron Beam Fluorescence (EBF) is used to measure absolute number density, and Electron Beam excited Laser Induced fluorescence (EBLIF) is used to measure the velocity. The measurements are made point by point, and can be used to map de field of density and velocity vector in the plume, thus giving access to the total flowrate, thrust vector, and divergence.

I. Introduction

The positioning of satellites requires higher and higher precision as new space missions are developed. Precision is needed both in attitude control, for target pointing, and in position control, for absolute positioning in drag-free experiments, or for relative positioning in formation flying. Because of the higher accuracy and resolution needed, and the lower mass of some scientific satellites, thrusters with performances on the order of 1 µN or less are currently needed.

Micronewton thrusters are being developed and qualified to address these requirements. There are mostly three types of thrusters: plasma thrusters (e.g. FEEP thruster), cold gas thrusters and colloid thrusters. The numerical modeling of these thrusters is challenging because of the complex physics involved, thus ground characterization is essential. Electric probes can be used to measure the flow rates and energy in the plume of electric thrusters (plasma and colloid) but no easy mean is available for cold gas thrusters.

In this paper we demonstrate two non-intrusive diagnostics methods for complete characterization of the plume of a cold gas thruster. With the first diagnostics, the number density in the plume of a cold gas thruster is measured point by point by using Electron Beam Fluorescence (EBF). The principle of EBF is to send energetic electrons (~10 keV) through a gas. The electrons excite the gas, which fluoresces. If the pressure is below typically 1 mbar, the intensity of the fluorescence is just proportional to the number density of species. The signal can be calibrated by sending the electron beam in a gas at a known pressure. This method has been used in the past at Onera for probing shock waves in supersonic wind tunnels.

With the second diagnostics the velocity is measured by coupling Laser Induced Fluorescence (LIF) with EBF. The LIF technique, implemented with a tunable diode, allows to measure the distribution of velocity along the laser axis by measuring the Doppler shift of the fluorescence. But the gases used in cold gas thrusters (nitrogen, argon and Xenon for example) cannot be optically accessed from their ground state because the energy of the first excited state is quite large, and direct excitation would require a deep UV tunable laser which does not exist at this time. Thus excitation from the ground state is performed by an electron beam. Then the laser is applied to one of the excited

---

[1] Reasearch scientist, Physics and Sensing Department, denis.packan@onera.fr.
[2] Reasearch scientist, Physics and Sensing Department, jean.bonnet@onera.fr.
[3] Post-doctoral student, Physics and Sensing Department, simone.rocca@onera.fr.

state created, and pumps it to a higher excited state, where fluorescence is observed. Thus in EBLIF (Electron Beam excited Laser Induced Fluorescence) we have a double excitation of the species, first with the electron beam, second with the laser.

The methods are demonstrated for an argon plume, and with one laser beam. With three laser beams the local velocity vector could be determined from the measure of its projections on the three laser axes.

In both diagnostics (EBF and EBLIF) an electron beam has to be created in a vacuum tank where a thruster is firing. In order to create an electron beam in a low pressure gas, it was preferred to avoid filament electron gun due to their sensitivity to the background pressure (which can rise up to 10^{-3} mbar in the vacuum tank during firing). Instead a secondary-emission electron gun, developed at Onera, has been used. For EBF, in order to probe the plume more quickly the electron beam has been swept with electromagnets, in order to form the equivalent of an electron sheet. This electron sheet can be oriented longitudinally or transversally with respect to the thruster (Figure 1). The gas that emits light forms a section of the plume, which can then be observed with a CCD camera. The spatial resolution is the thickness of the electron beam/sheet, which is typically 1 mm.

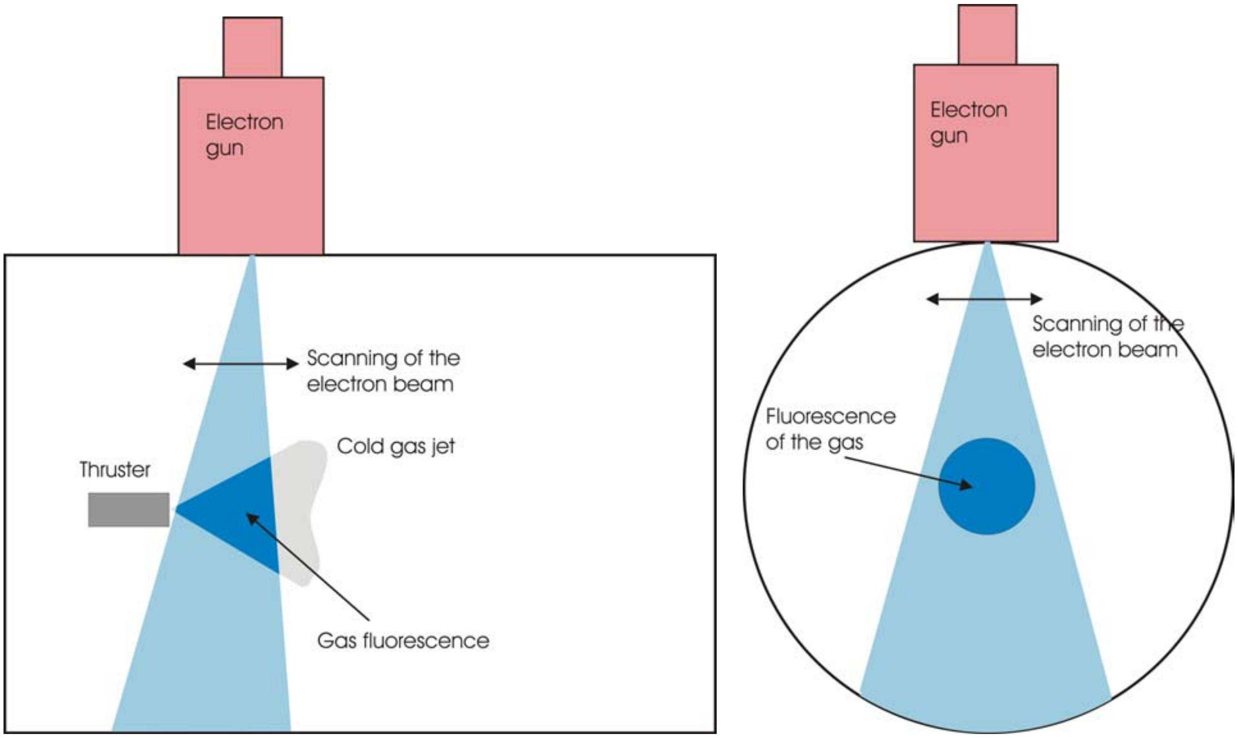

Figure 1. The longitudinal (left) and transverse (right) configurations used to probe the plume.

II. Experimental Set-up

A nitrogen source, composed of nitrogen feed line and a 200 µm pinhole, creates a plume representative of that of a cold gas thruster. It is placed in a vacuum tank 70 cm long and 50 cm in diameter, with 1000 l/s pumping speed. It is fitted with a secondary emission electron gun designed and built at Onera (Figure 2). An electron beam of current typically 1mA and 10 keV is created, and is passed through a slit 1mm wide in order to achieve 1 mm spatial resolution (Figure 3). Two electromagnets sweep the beam parallel to the slit, which creates a sheet 1 mm in thickness. The beam/sheet current is about 100 µA after passing through the slit. The thrust corresponding to the plume flowrate is estimated using previous experiments with a cold gas thruster. The fluorescence is observed with a Pixis CCD camera from Roper Scientific (backthinned, 1340x400 pixels) and a 60 mm f/2.8 lens. Calibration of the signal is obtained when feeding gas in the tank while the thruster is shut off and measuring the pressure inside the tank while recording the intensity of the fluorescence.

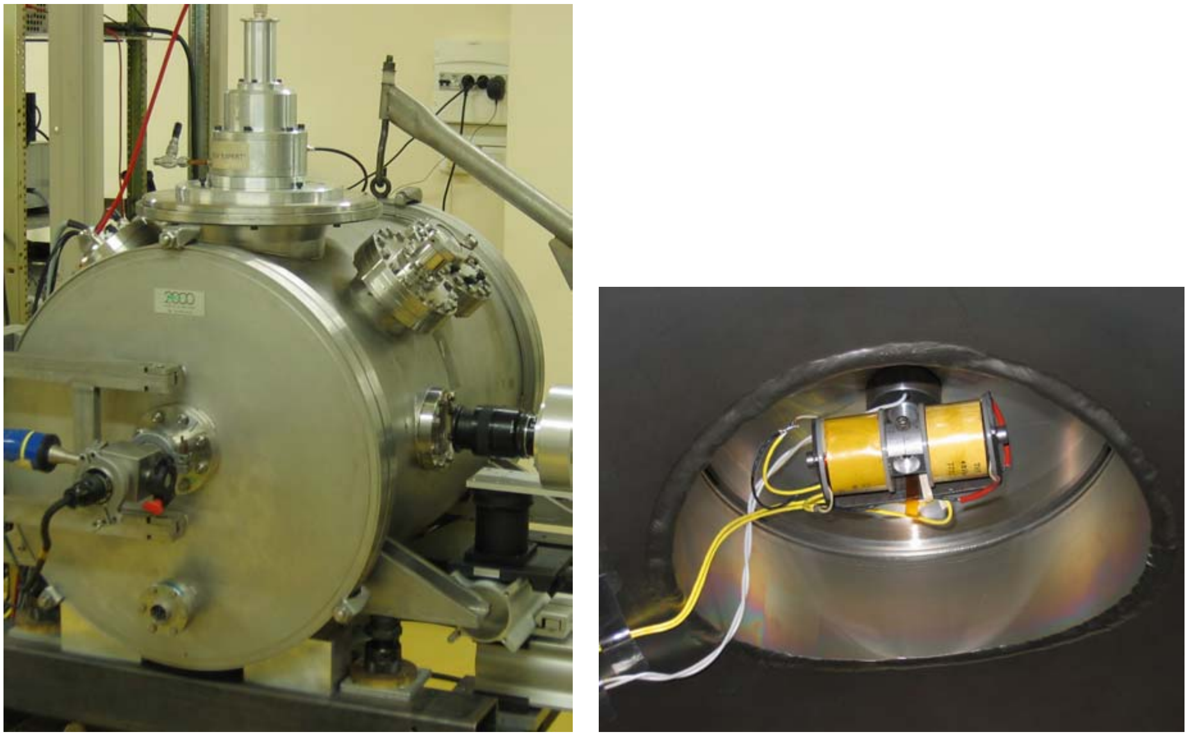

Figure 2. Vacuum tank with electron gun mounted at the top (left) and electromagnets inside the tank used to can the beam (right).

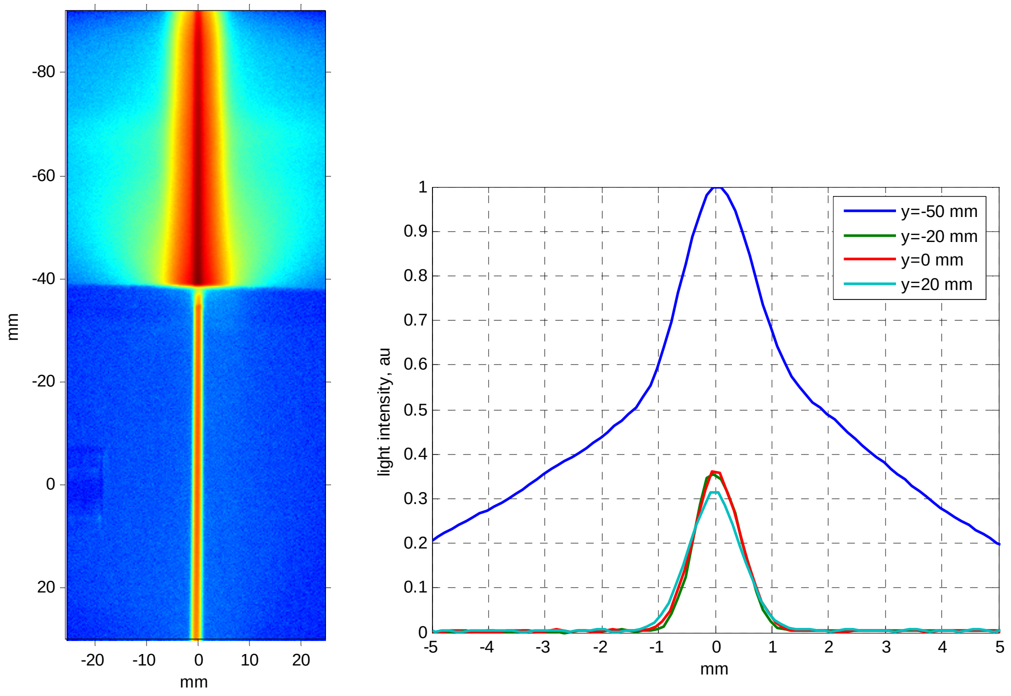

Figure 3. Electron beam passing through the 1 mm slit (left) and resulting intenisty profiles of the beam before and after the slit (right).

For EBLIF, one of the challenges is to make coincident the electron beam, the laser beam and the collection beam (Figure 4). This is achieved with placing actuated mounts in vacuum. The measured volume at the intersection of the three beams is about 1 mm in size.

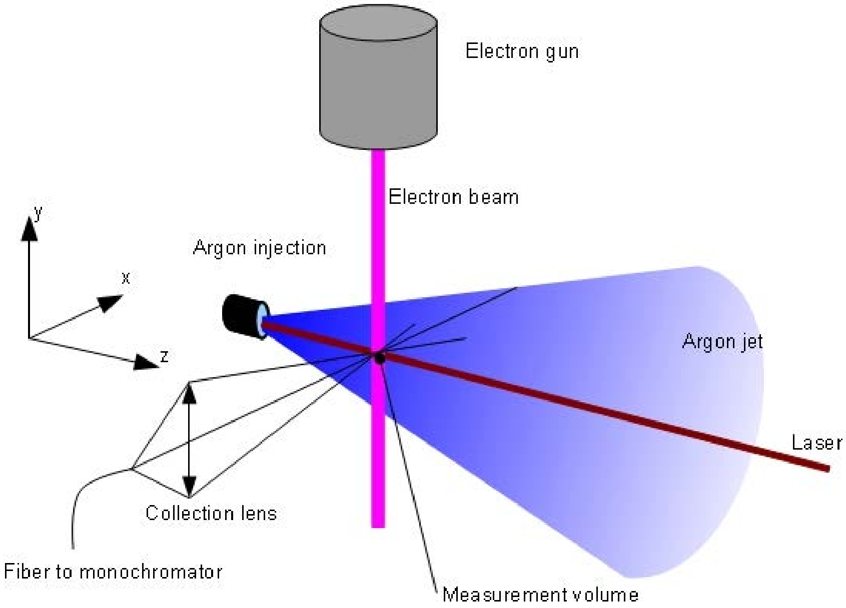

Figure 4. Principle of the EBLIF diagnostics.

For calibration , a 0.2 mbar argon discharge (300 V, 15 mA) is used in order to get a reference LIF signal at zero average velocity (Figure 5). The discharge here is used in place of the electron beam in the vacuum tank in order to create excited states of argon. The laser source is a tunable diode system TOPTICA DL100. The modhop-free tuneable range is about 771.5 nm to 773.2 nm. The argon transition probe is the 4p-4s at 772,3761 nm.
A Jobin-Yvon H 20 monochromator is used for spectral filtering, and the detector is a HAMAMATSU R928 PMT. The wavelength is measured with High-Finesse WS-U lambdameter with a resolution of 5 MHz and absolute precision of 30 MHz.

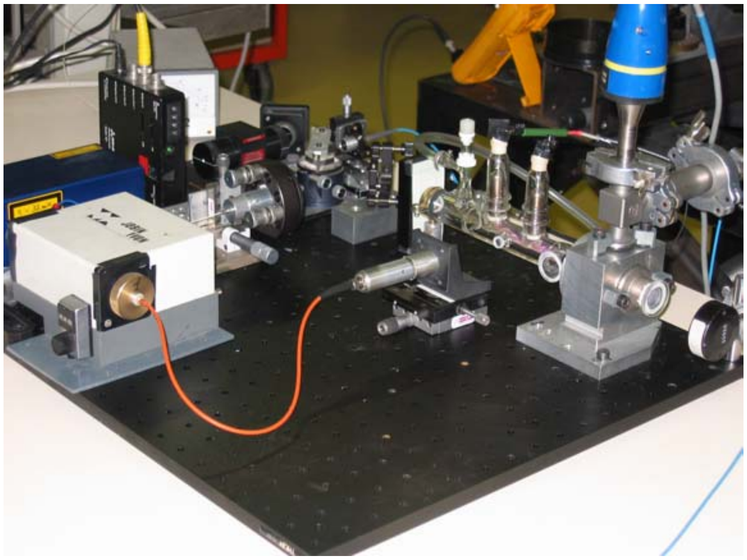

Figure 5. Optical calibration setup of EBLIF.

III. Results for number density measurement

Longitudinal scans

A typical image is presented in Figure 6 and extracted data in Figure 7. The absolute nitrogen number densities are obtained with a depth resolution of about 1 mm. Due to the narrowing of the plume section near nozzle exit, it is estimated that the data is meaningful outward from 2mm downstream of nozzle exit. This method can be applied in any gas. Note that the electron “sheet” was off the centerline of the plume, thus the number density goes down to zero on the left (Figure 7).

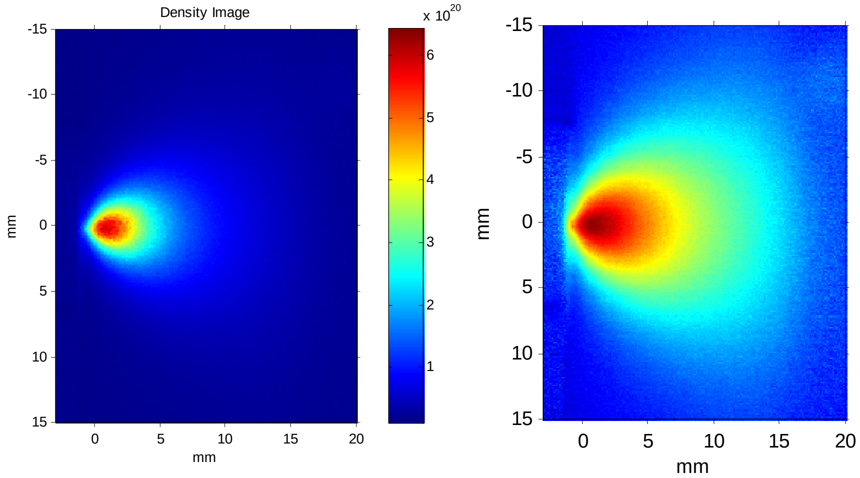

Figure 6. Typical number density maps obtained by EBF after calibration, in linear scale (left) and log scale (right). The unit is m^{-3} and the thrust is about 300 µN.

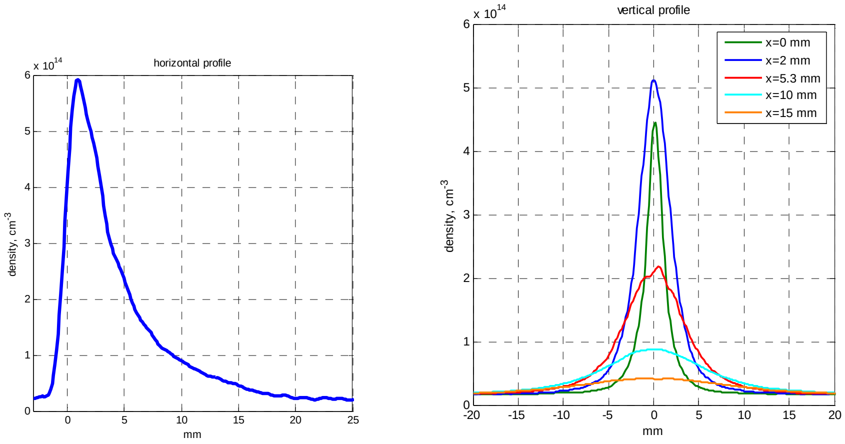

Figure 7. Information that can be extracted from the longitudinal scans : longitudinal density profile at centreline (left) and vertical density profile at several locations (right).

Number density maps have been obtained at several thrust levels. They are shown at the same color scale on Figure 8. The detectivity, depending on the integration time, is a few micronewton.

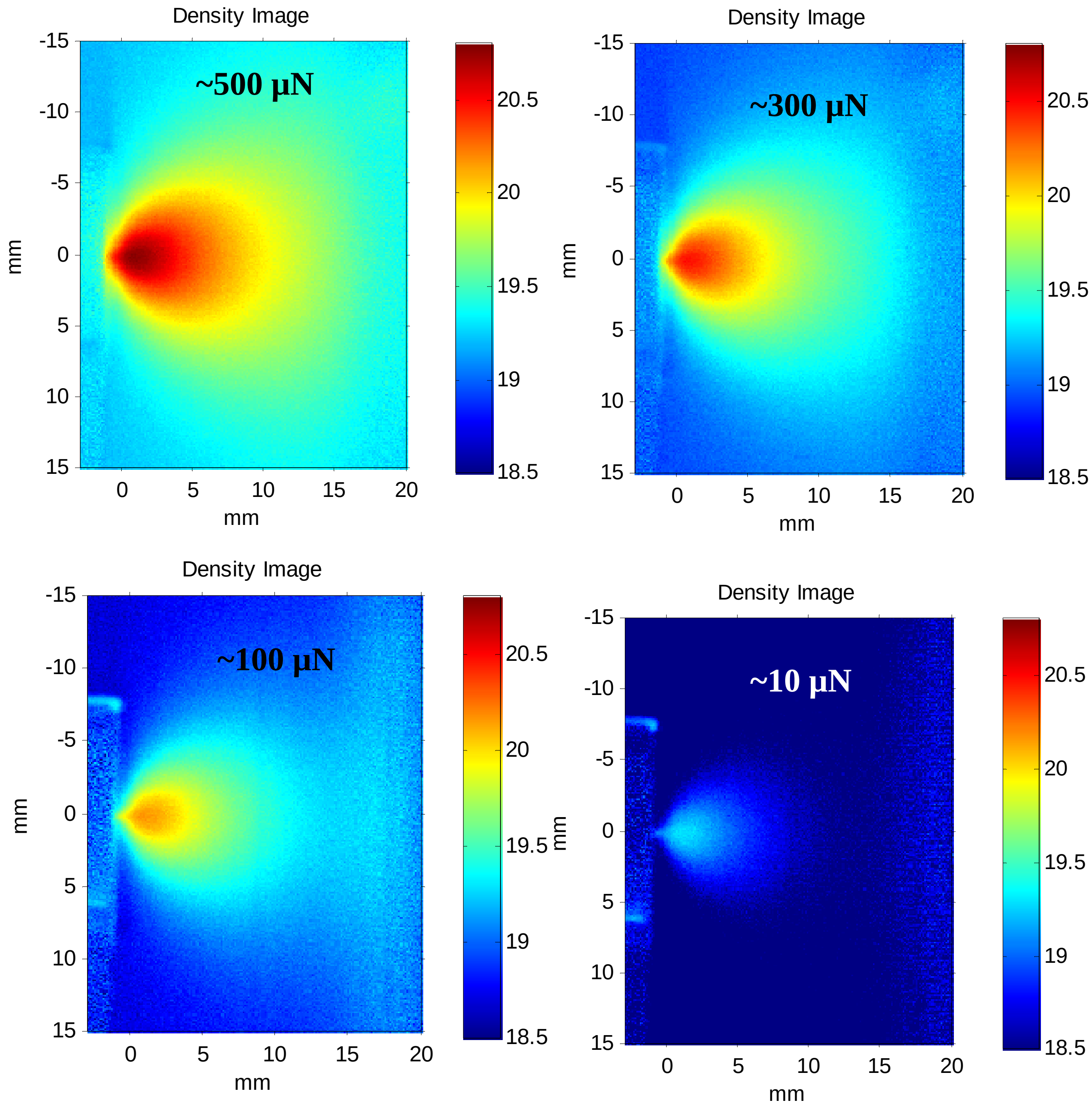

Figure 8. Density maps, at the same scale, for different thrust levels.

Transverse scans
The calibration procedure is illustrated in Figure 9, and the resulting data is shown in Figure 10.

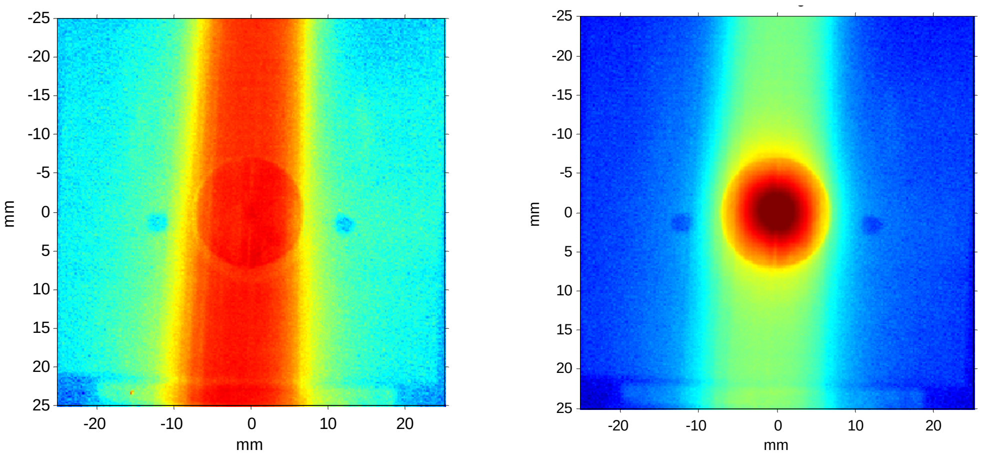

Figure 9. Calibration image in a tank filled with gas (left) and image with the thruster firing (right).

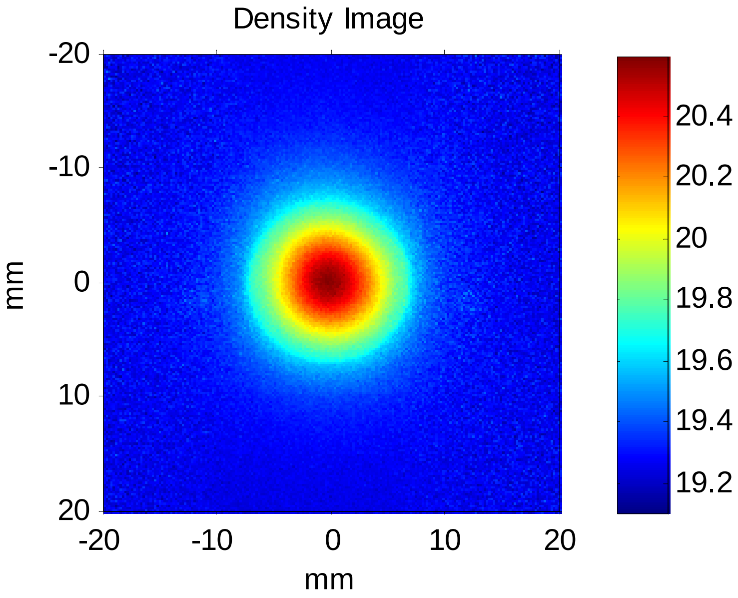

Figure 10. Absolute number density of molecular nitrogen measured by EBF in the plume using a transverse electron sheet orientation. The equivalent thrust is 500 µN. The position of the transverse sheet is 5mm from nozzle exit.

IV. Results for velocity measurements

The results are presented in Figure 11. The Doppler shift of the signal in the plume is clearly visible, and the smaller width (350 MHz instead of 820 MHz) shows that the gas in the plume is cold due to the rapid expansion. Converting the frequencies into velocities, the measured averaged velocity along the laser axis (coincident with the plume axis) is about 550 m/s and the gas temperature is about 70 K.

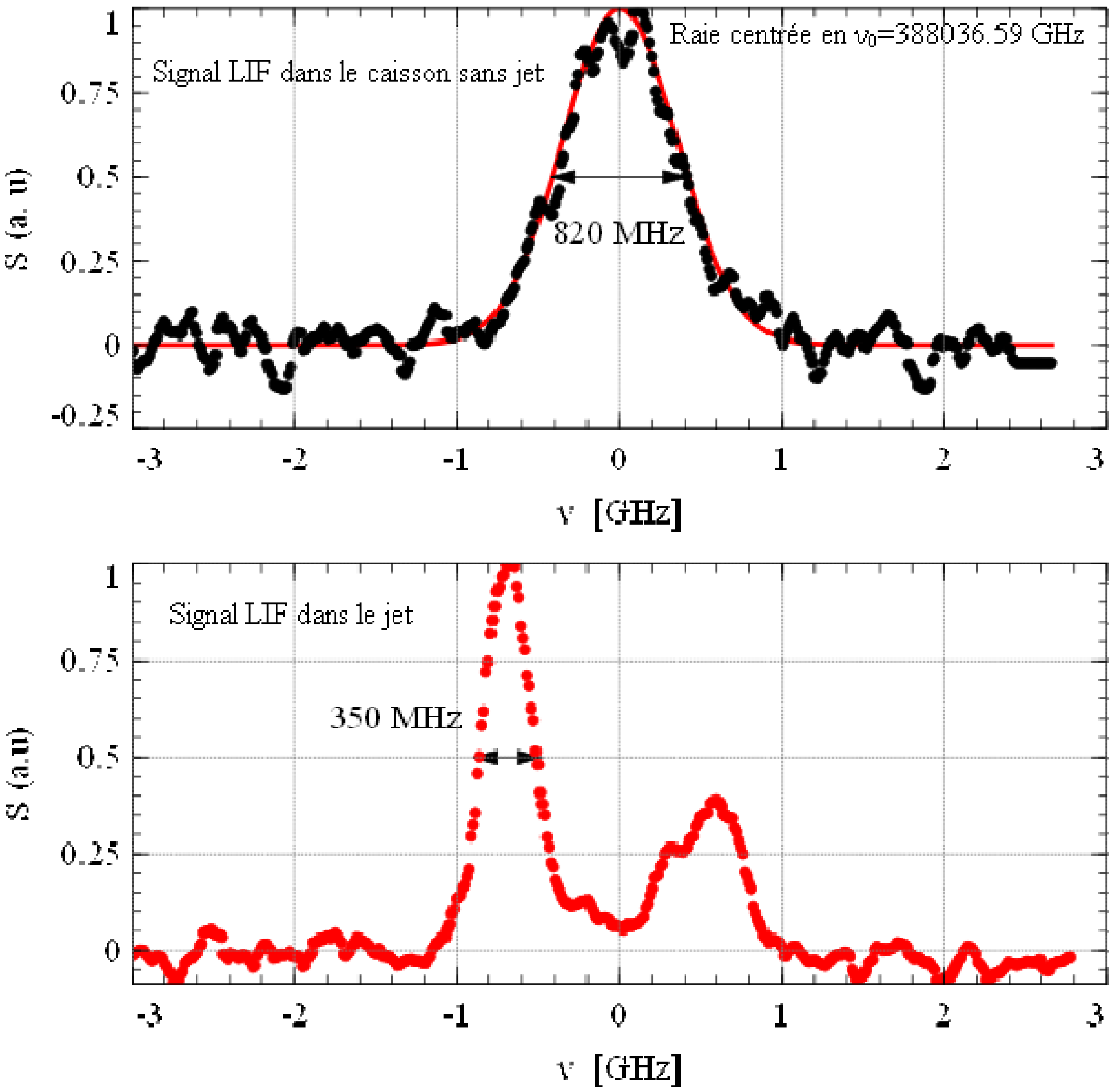

Figure 11. Reference LIF signal obtained in the discharge at zero average velocity (top) and LIF signal obtaine din the lectron beam in the plume (bottom). The peak on the right is an artefact due to laser reflection.

V. Conclusion

We have successfully demonstrated the use of the EBF and EBLIF optical non-intrusive techniques for the measurement of number density and velocity in the cold argon plume of a micronewton thruster. A velocity of 550 m/s and a temperature of 70 K have been obtained at the measurement point. These measurements could be extended to a complete plume scan, and with three laser axes the complete velocity vector field could be obtained, as was done on a cesium FEEP thruster [1]. This data can be used to validate simulation codes. The data could also yield the flowrate and the thrust vector, which is extremely difficult to measure by other means. Better spatial resolution could be obtained by using a higher current electron gun. If a video camera is used, the density images could be used to detect density fluctuations, and thus thrust fluctuations, at a higher bandwidth than can be achieved by a thrust balance. In order to correlate EBF and EBLIF measurements to the actual thrust, these measurements can be done simultaneously with thrust measurement on the Onera micronewton balance [2].

The use of nitrogen is also widespread in cold gas thrusters, and the EBF method applies as well and has been successfully tested. The EBLIF method has been tested on the second positive system of nitrogen, but the signal was too small in the current configuration. Further tests for EBLIF in nitrogen will be done with an optimized optical setup and a higher current electron gun in the future.

VI. Acknowledgments

This study was done in the frame of CNES contract n° 4500026643. The authors acknowledge the support of E. Chesta and D. Arrat from CNES.

VII. References

[1] "Three-component LIF Doppler Velocimetry to measure the neutral cesium flow rate from a cesium-fed FEEP thruster", IEPC-2009-173, P.Q. Elias, D. Packan, J. Bonnet, *31st International Electric Propulsion Conference,* University of Michigan, Ann Arbor, Michigan, USA, September 20 – 24, 2009

[2] "Thrust Measurement with the Onera Micronewton Balance", IEPC-2009-185, D. Packan, J. Bonnet, S. Rocca, *31st International Electric Propulsion Conference,* University of Michigan, Ann Arbor, Michigan, USA, September 20 – 24, 2009