Three-component LIF Doppler Velocimetry to measure the neutral cesium flow rate from a cesium-fed FEEP thruster

IEPC-2009-173

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

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Field Emission Electric Propulsion thruster using liquid cesium is currently actively developed by Alta SpA under ESA funding. For thruster–spacecraft interaction studies and design purpose, it is important to measure the mass flow rate of neutral cesium emitted by the thruster. This measurement requires the characterization of the neutral cesium plume. In this work, this characterization is achieved with a specially developed set-up using LIF velocimetry to probe the three components of the neutral cesium velocity and to measure the absolute number density from a FEEP thruster representative of a flight model. Our results give mappings of the plume velocity and number density along two planes intercepting the neutral plume, for four different thruster operating conditions. Mass flow rate are obtained by integration of the local flow rates within a 5 % uncertainty. The neutral cesium mass flow rate is in the mg/h range; it increases with thrust and with emitter temperature. Mean neutral velocity can be as high as 800 to 1000 m.s⁻¹. Our results show that the neutral mass flow rate is of the same order of magnitude as the ion mass flow rate computed from the thruster current. This work provides the first direct measurement of neutral cesium mass flow rate, thruster efficiency and more generally, the first mapping of the neutral plume from this FEEP thruster. The technique used could be extended to probe dimeric cesium in the plume, or other thrusters with other gases.

Nomenclature

FEEP = Field Emission Electric Propulsion
LIF = Laser Induced Fluorescence

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Isp = Specific impulse
A = Integral of the relative density profile [a.u]
A_{21} = Einstein coefficient for spontaneous emission [s^{-1}]
B_{21} = Einstein coefficient for stimulated absorption [s^{-1}]
c = Speed of light [m.s^{-1}]
C_1 = Calibration coefficient for the first moment I^1 [m^3.s^{-2}]
C_2 = Calibration coefficient for the second moment I^2 [a.u]
dS = Elementary surface element [m^2]
f = Normalized projected velocity distribution function [m^1.s]
F = Normalized velocity distribution function [m^3.s^3]
I = Laser intensity [W.m^{-2}]
I_{Sat} = Saturation intensity [W.m^{-2}]
I^1 = First moment of the fluorescence signal [s^{-2}]
I^2 = Second moment of the fluorescence signal [s^{-3}]
J = First moment of the transmission [s^{-1}]
L_{Ref} = Length of the reference cell [m]
m_{Cs} = Cesium atom mass [kg]
n_{Cs} = Cesium number density [m^{-3}]
n_{Ref} = Cesium number density in the reference cell
q = Cesium mass flow rate [mg.h^{-1}]
Q = Quenching rate [s^{-1}]
_{Ref} = (Subscript) reference quantity
S = Fluorescence signal detected [count.s^{-1}]
T = Transmission coefficient [1]
 u = Microscpic velocity [m.s^{-1}]
U = Averaged velocity along a laser axis [m.s^{-1}]
V = Probed volume [m^3]
 V = Averaged velocity vector [m.s^{-1}]
V_Z = Averaged velocity along the Z axis [m.s^{-1}]
Y = Normalized lineshape function [s]
Z = Cesium number density integrated along the absorption line of sight [m^{-2}]
η = De-excitation rate [s^{-1}]
λ_0 = Transition wavelength [m]
ν = Frequency [MHz]
ν_L = Laser frequency [MHz]
Ω = Solid angle [st]

I. Introduction

SA and Alta are currently developing an electric thruster using the concept of Field Emission Electric Propulsion (FEEP), with liquid cesium as a propellant. Field Emission Electric Propulsion (FEEP) is very appealing for several reasons. First, FEEP thrusters can cover a wide range of thrust, from sub-µN to mN. Second, they have a very good thrust resolution and near instantaneous response capability. Third, they have a high specific impulse (Isp), and thus require small amount of propellant. These features make FEEP thruster very attractive for space mission where fine attitude control and drag compensation are required. This thruster is currently baseline for several missions: Microscope from CNES, LISA Pathfinder from ESA.

The use of such thruster on spacecrafts requires a precise characterization of the thruster-spacecraft interaction; in particular one should consider the effect of the neutral cesium emitted by the thruster. This neutral cesium emission has several detrimental effects. First, neutral cesium emission decreases the thruster Isp, and can affect the mass consumption of the thruster. Second, the neutral cesium can contaminate the surface of the spacecraft. Third, via charge exchange collision, it can lead to the production of slow ions which contribute to both thruster and spacecraft contamination and charging. For all these reasons, it is important to characterize this emission of neutral cesium. For this characterization, the neutral mass flow rate is the macroscopic parameter of primary interest; beyond the determination of this crucial macroscopic parameter, the idea is also to gain a more accurate picture of the physics in the neutral plume emitted by the thruster.
In the 1980s there were several efforts to measure the neutral mass flow rate on early versions of high current cesium FEEP thrusters using a mass spectrometer [5] or direct measurements using a balance [1]. In the latter case, the measurement gives the mass of propellant used per unit time. Subtracting to this value the charged specie mass flow estimated from the emitted current, one obtains a figure for the total neutral cesium mass flow rate which encompasses single atoms as well as dimers or heavier clusters. For a 10 mA current and 1.1µm slit, the flow rate of neutral cesium (with no distinction between atomic cesium and clusters) represented about 30% of the total flow rate. Such measurement could not be successfully done with the current version of the FEEP thruster due to its much lower total flowrate (current < 1 mA).

The particles flux measurements with a mass spectrometer done by Mitterauer [5] on an early FEEP thruster version could yield an estimate of the neutral cesium mass flow rate, with strong hypotheses though. In fact, mass spectrometer measurements are point measurements; thus assumptions have to be made to obtain a mass flow rate from the measurement of the flux collected by the spectrometer at one location. In this case, it was found that the neutral mass flow rate of neutral Cs was in the µg/h range, no larger than 1% of the ion mass flow rate.

These early measurements, while giving interesting orders of magnitude, cannot conclude unambiguously on the contribution of neutral cesium atom. Besides they could not be reproduced on the current version of the thruster. They also support the idea that a full mapping of the neutral cesium plume is desirable to measure accurately the mass flow rate.

In this study, our goal is to obtain this mapping. For this purpose, we use a non-intrusive diagnostic technique tool to measure the absolute number density and velocity vectors of the neutral cesium plume exiting the thruster, along control surfaces intercepting the plume. This technique is the Laser Induced Fluorescence Doppler Velocimetry; it has been previously developed and used at Onera [2] to probe the axial velocity of xenon ions and neutrals from a SPT50 Hall-effect thrusters. In a recent paper, Hargus and Charles [3] have also used this technique to measure two components of the velocity vector along a line on the exit plane of a Hall thruster. In the present work, the technique is extended to three axes (3D-LIF) for the velocity vector, and measures also the absolute neutral atomic cesium number density.

Laser Induced Fluorescence (LIF) involves the pumping of the excited states of a gas sample, using a tunable probing laser, and the subsequent observation of the fluorescence signal coming from the excited particles. In this work, the fluorescence signal comes from the de-excitation of the excited state of cesium, pumped directly from the ground state by a laser at 852 nm. Excitation originating from the ground state is an interesting feature because it allows a direct calibration of the LIF by means of calibration cells with cesium at known pressure. Once calibrated, the integral of the fluorescence signal is proportional to the neutral cesium number density. The frequency shift of the signal can be related, via the Doppler relation, to the velocity of the neutrals.

At present time, the 3D-LIF diagnostic devised in this study is not intended to perform time-resolved measurements. Measurements will be done on a thruster operating at steady state. Unexpected transients due to thruster sparking or emission site disturbances, both in the millisecond range, are smoothed out using acquisition time long enough (a few seconds). Besides, we will not seek to retrieve the projected velocity distribution from the LIF, since, for mass flow rate measurements, averaged velocities only are required. We will focus on the mapping of the neutral cesium number density and 3D velocity vector on two planes located close to the exit plane of the thruster. The goal is to deduce from these mappings the neutral mass flow rate from the thruster. To our knowledge, this is the first time such a complete characterization is sought.

II. Background

A. Cesium-fed FEEP thruster

Field Emission Electric Propulsion (FEEP) generates thrust by ionization of liquid metals and acceleration of the cesium ions by a strong electric field. Ionization occurs at the tip of the emitter electrode, which is wetted by the liquid cesium. An accelerator plate is placed in front of the emitter electrode, as shown in Fig. 1. When a high voltage difference is applied between the emitter and the accelerator, the free surface of the liquid cesium is distorted, and above a certain threshold voltage, forms small cusps at the tip of which the electric field is considerably enhanced. When the electric field reaches a value about $10^9$ V.m$^{-1}$, atoms at the tip of the cusps are spontaneously ionized and an ion beam is extracted. This ion beam is then accelerated at kinetic energies around a 10 keV by the accelerator plate, which generates the thrust.

In this study, an engineering model of a cesium-fed FEEP thruster is used. The thruster is representative of a flight model, in terms of thrust and thermal performances. It has been modified to accommodate two view-ports on its side; this gives an optical access just in front of the accelerator plate. Fig. 1 presents a view of the thruster.
The thrust is controlled by the emitter current and the emitter voltage. Both are computer-controlled using regulated power supplies for the emitter and the accelerator plate. When the thruster fires up, bright spots appear along the emitter tip. The higher the thrust, the more spots there are, as shown in Fig. 2.

Fig. 2 View of the thruster emitter slit at 40 and 100 µN. At 40 µN, few emissive spots can be seen. At higher thrust (100 µN), the slit is almost continuously lighted by the emissive spots.

B. Cesium spectroscopic properties
The transition that is of interest for us in neutral cesium is the so-called “D2” transition at about 852 nm[6]. Historically, people have noticed its two key advantages: it is very intense and it starts from the ground state. The intensity ensures that excitation does not require prohibitively-powerful light sources. And starting from the ground state ensures that the total population of atoms is probed. If one takes a transition starting from an excited state instead, only the small fraction of population in that excited state is probed. This would yield a low intensity of emission and absorption that would not be easily related to the actual number of atoms.

One other property is that the D2 transition is “isolated”: the upper state is radiatively linked only to the ground state. The energy levels and hyperfine splitting of the transition are shown in Fig. 3. Thus it can be considered as close to an ideal two-state system. This and other properties made cesium used in atomic clock, which resulted in numerous studies of the D2 transition and its characteristics are now very well known. It also resulted in the availability of off-the-shelf lasers at its wavelength (about 852 nm). For all these reasons, the D2 transition is ideal to make quantitative measurements on cesium atoms.
Fig. 3  Allowed transitions of the D2 line of neutral cesium

In our study, we focus on the 3 transitions bound to the F=4 hyperfine level of the ground state. Their frequencies are given in table 1.

Table 1  Frequencies from the F=4 ground state

<table>
<thead>
<tr>
<th>Frequency [MHz]</th>
<th>ν₄₃</th>
<th>ν₄₅</th>
<th>ν₄₃ - ν₃₄</th>
<th>ν₅₄ - ν₃₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>F=3</td>
<td>ν₃₄ = 351 721 508.284</td>
<td>ν₄₅</td>
<td>201.42</td>
<td>452.24</td>
</tr>
<tr>
<td>F=4</td>
<td>ν₄₃</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F=5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C. LIF theory

In a neutral cesium vapor, LIF is a diagnostic technique suitable for determining ground state number density. LIF diagnostic involves (a) the pumping of the neutral cesium initially in its ground state E₁ toward and excited state E₂, and (b) the collection of the fluorescence signal resulting from the spontaneous decay of the atom in its excited state toward the ground state.

![Energy diagram of a two-state system](image)

Fig. 4  Energy diagram of a two-state system. The pumping laser beam, when tuned, excites the atoms on E₂ at a rate W. The excited atoms then relax in their ground state E₁ or in another state, with rates A₂₁ and Q, respectively.

Solving the LIF problem, i.e relating the fluorescence signal to the ground state number density, implies rate equations, and thus a time-dependent problem. However, if the time of residence of the sampled population in the probing laser beam is greater than the pumping and fluorescence time, the steady state solution can be considered.
This is the case in our application, because the characteristic pumping time and fluorescence time are of a few tens of nanoseconds, whereas the residence time is in the microsecond range. Thus, the fluorescence signal detected is proportional to the deexcitation rate from the excited state at steady state.

Let us derive the expression for the detected signal. Let $V$ be the volume defined by the crossing of the pumping laser beam and of the detection optic beam, and $\Omega$ the solid angle of the detection optic as seen from $V$. First let us consider a gas of cesium at rest, the fluorescence signal detected, in count per second, is:

$$ S(v) = n_{Cs} V \frac{\Omega}{4\pi} \frac{I/ I_{s\text{at}}(v)}{\eta} $$

(1)

Where $\eta = A_1 + Q$ is the de-excitation rate, $I_{s\text{at}} = \frac{A_1 + Q}{B_1 Y(v)}$ is the saturation intensity of the transition in which $Y$ is the normalized line shape of the transition, centered at $\nu_0 = c/\lambda_0$.

Second, in the case of a gas with a velocity distribution $F(u,v,w)$, because of the Doppler effect, the relative velocity of the gas with respect to the pumping laser changes the transition frequency. Suppose that the laser beam is parallel to the x axis; then the normalized distribution of velocities parallel to the x axis, as seen from a pumping laser is:

$$ f(u) = \int \int F(u,v,w) dv dw $$

(2)

Thus, the fluorescence signal from the fraction of the gas with relative velocity $u$ is:

$$ S_u(v) = n_{Cs} f(u) V \frac{\Omega}{4\pi} \frac{I/ I_{s\text{at}}^u(v)}{\eta} $$

(3)

With $I_{s\text{at}}^u = (A_1 + Q_u)/\left( B_1 Y\left( \nu - \frac{u}{\nu_0} \right) \right)$ is the shifted normalized line shape of the transition, centered at $\nu_u = \nu_0 + u/\lambda_0$. The total signal detected is the sum of contributions of the gas atoms in all velocity classes:

$$ \Sigma(v) = \int S_u(v) du = n_{Cs} \int f_u(v_0 - v) \left[ V \frac{\Omega}{4\pi} \eta \frac{I/ I_{s\text{at}}^u(v)}{1+2} \right] du $$

(4)

By taking the moments of the LIF signal, one gets:

$$ I^1 = \int \Sigma(v) dv = n_{Cs} C_1 $$

(5)

$$ I^2 = \int \Sigma(v)v dv = I^1 \frac{U}{\lambda_0} + I^1 C_2 $$

(6)

Where $U = \int f(u) du$ is the mean gas velocity along the probing laser beam axis, and $C_1$ and $C_2$ are constants to be determined by an appropriate calibration. In our case, the problem is slightly more complex because there are three...
different transitions which add their contribution to the total signal. The generalization is straightforward and will not be detailed here.

III. Principle of the mass flow rate measurement

To measure the neutral cesium mass flow rate \( q \), it is necessary to integrate the mass flux \( m_{Cs} n_{Cs} V \) around a control surface enclosing the thruster:

\[
q = m_{Cs} \int n_{Cs} V n dS
\]

The choice of the control surface is dictated by two criteria. First, to have an accurate measurement of the neutral mass flow rate, the control surface must intercept most of the neutral plume from the thruster. Second, flow measurements across two different surfaces allow cross-checking and thus increase the confidence in the results. For these reasons, two different control surfaces have been defined in the thruster system of coordinates; in Fig. 5 a cross section of the thruster emitter shows coordinate system arrangement. The origin is at the center of the emitter slit.

![Fig. 5 cross section of the thruster emitter, figuring the lateral window dimensions and the approximate Z positions of planes B and C](image)

The two different control surfaces probed intercept the whole plume. They are shown in Fig. 6. The surfaces chosen are, in the thruster coordinates:
- the (X,Y) plane at Z=3 mm (middle of the lateral viewports), named Plane B, just downstream of the accelerator plate;
- the (X,Y) plane at Z=9 mm (thruster exit plane), named Plane C, on the thruster exit plane.

Each of these two planes intercepts virtually all what exits the emitter slit. Thus they will each measure the outflow of neutral cesium, and their measurement should be the same.
Since the three-component LIF Doppler technique used here can only perform point measurements, the integral in (7) is discretized by using a mesh of the control surface. As shown in Fig. 7, the control surface is a plane parallel to the XY plane. Thus the mass flow rate across the control surface is approximated by measuring the number density $n_{C_i}$ and the Z-component of the velocity $V_z$ at the nodes on a mesh of the control surface, and then by using the approximate expression for (7):

$$q = m_{C_i} \sum_{i=1}^{NX} \sum_{j=1}^{NY} n_{C_i} V_z dS_{ij}$$

(8)

Fig. 7 View of the discretized control surface. LIF measurements give cesium number density and Z-velocity at discrete location marked by i,j indexes.

On a given control surface, the velocity vectors at the nodes of the mesh are determined using LIF Doppler velocimetry; the number densities number are measured using LIF calibrated with absorption measurements.

A. Three component velocimetry using LIF-Doppler

A cloud of neutral cesium atoms moving at a speed $u$ along the probing laser beam axis will have its fluorescence peak shifted by $\Delta \nu$ due to the Doppler effect:

$$\Delta \nu = \frac{u}{\lambda_0}$$

(9)
From this equation, we can see that the velocity measurement resolution is directly dependent on the frequency shift measurement resolution. For example, if one wishes a velocity resolution of 10 m.s\(^{-1}\), necessary to resolve the thermal plume, a frequency resolution of 10 MHz at least is required. To achieve this resolution, we calibrate the frequency of the tuned laser using saturated absorption in a reference cesium cell. The peaks in the absorption signal correspond to the transitions frequencies of atoms at zero velocity. An example of this saturated absorption signal is given in Fig. 8. While the laser diode scans the frequency axis, this saturated absorption signal can be used to calibrate accurately the frequency; the resolution is close to the natural linewidth, and is below 10 MHz.

![Saturated absorption signal](image)

**Fig. 8** Saturated absorption signal; the reference of the frequency axis is \(\nu_{34}\), as given in Table 1.

Intermediate peaks frequencies are also precisely known and are also used to calibrate the frequency.

Once the frequency is calibrated, we can compute the second moment of the LIF signal, as given in Eq. (6), where the mean velocity \(U\) along the laser axis appears. Suppose now that we also measured the LIF signal \(S_{R}\) from a reference cell containing neutral cesium at rest.

\[
I_{\text{Ref}}^2 = \int S_{\text{Ref}}(\nu) \nu d\nu = I_{\text{Ref}}^1 C_2
\]  

(10)

From this reference measurement we can compute the calibration coefficient \(C_2\) and then obtain the mean velocity along the axis:

\[
U = \lambda_0 \left( \frac{I^2}{I^1} \right) \left( \frac{I_{\text{Ref}}^2}{I_{\text{Ref}}^1} \right)
\]  

(11)

Repeating LIF measurement in the same volume along three laser axes that form a trihedra yields three projection of the mean velocity. The three components of the velocity vector in the thruster system of coordinate are then recovered at the cost of a simple change of coordinates. Note that to compute the mass flow rate, determining the mean velocity is sufficient; while computing \(I^2\) to get \(U\), any information on the velocity distribution is lost. In our case this is unimportant, as we focus solely on a macroscopic quantity.

**B. Absolute Number density measurement using LIF and Absorption**

Calibrating the measurement to yield the absolute number density is equivalent to determining the proportionality factor \(C_1\) in Eq. (5). There are two possibilities to obtain this factor:

- Use a reference measurement, at a known number density. This is doable using a calibration cell with a known cesium vapor pressure.
- Use another absolute measurement and calibrate the LIF signal against this measurement. This is doable using an absorption measurement.
The option 1, while being more straightforward and flexible by allowing a point calibration (whereas option 2 needs a whole line measurement to perform the calibration), has a big drawback. To calibrate accurately the LIF signal, we have to be sure that the laser intensity in the calibration cell is equal to the laser intensity during the measurement, as $C$ depends on the laser intensity. This is very difficult to obtain, first because calibration cannot be performed at the same time as the measurement; indeed the thruster needs to be off to use the calibration cell. The laser intensity being sensitive to the room temperature, it is difficult to guarantee a repeatable intensity level. Second and more importantly, the calibration cell acts on the laser beam as an optical system that modifies the focalization of the laser beam. Thus, the laser intensity, as seen from the collection optic line of sight, is changed. And indeed, calibration discrepancies have been observed with option 1 during tests.

For these reasons, the option 2 has been chosen. The principle of this measurement is the following:

LIF signals are collected at discrete points along a line parallel to the X axis of the thruster, to get the relative density profile. Along this same line, an absorption measurement is performed. Let $T(\nu)$ be the transmission measured as a function of frequency. It can be shown [4] that:

$$\tilde{J} \ln \left( T(\nu_L) \right) d\nu_L = cst \int n_c dx$$  \hspace{1cm} (12)$$

The proportionality coefficient “cst” is independent of the laser intensity; it can be accurately measured using a reference absorption measurement $T_{\text{Ref}}$ with the calibration cell of known number density $n_{\text{Ref}}$ and length $L_{\text{Ref}}$. Thus, we have

$$\int n_c dx = n_{\text{Ref}} L_{\text{Ref}} \frac{\tilde{J} \ln \left( T(\nu_L) \right) d\nu_L}{\int \ln \left( T_{\text{Ref}}(\nu_L) \right) d\nu_L}$$  \hspace{1cm} (13)$$

Let us define $J$ as $J = \tilde{J} \ln \left( T(\nu_L) \right) d\nu_L$. Eq. (13) can be rewritten as:

$$Z = \int n_c dx = n_{\text{Ref}} L_{\text{Ref}} \frac{J}{J_{\text{Ref}}}$$  \hspace{1cm} (14)$$

Here, the spatial integration is performed between the emission and the collection optics of the absorption system.

The LIF measurement along the X line yields NX discrete measurements $I^i$ at positions $x_i$, $i=1..NX$, as shown in Fig. 7. Measurement $I^i(x_i)$ is at position $x_i$, as shown in Fig. 9. Hence, we can write an estimate of the hatched area. This gives:

$$A = \sum_{i=1}^{NX} \alpha_i I^i(x_i)$$  \hspace{1cm} (15)$$

Where the $\alpha_i$ are coefficients depending on the $x_i$, as given by the trapeze method. Combining Eq. (15) with Eq. (14) and (5), we obtain the following formula to calibrate the LIF signals:

$$C_i = \frac{A}{Z}$$  \hspace{1cm} (16)$$
IV. Experiment Details

In the previous section we have laid down all the conceptual elements required to compute the mass flow rate. To succeed in measuring the mass flow rate, we need to design a set-up that has the following features:

- Accommodation of a thruster firing a 10 keV ions, in good vacuum conditions
- Probing at discrete points on the whole control surfaces
- Calibration of the frequency using a saturated absorption cell
- Calibration in vacuo using a reference cell
- Laser Probing along 3 axes

A. Vacuum tank facility

We have used Onera B61 vacuum tank facility, which was designed to accommodate electric thruster. It is composed of 2 chambers. The test chamber, where the thruster is mounted, is 600 mm in diameter and 1 meter in length. It can be isolated from the main chamber, which is 1 meter in diameter for 4 meters in length. The thruster is oriented to fire straight in the main chamber. The length of the main vessel reduces the problems due to sputtering by the ion beam. The vacuum tank is fitted with a turbomolecular pump and a cryo-pump, whose pumping speed for Cesium are 1000 l/s and 7000 l/s, respectively. However adsorption of cesium on the tank walls probably led to a much higher effective pumping rate for cesium.

During these measurements, the background pressure in the vacuum tank is on the order of $10^{-7}$ mbar.

B. Experimental Set-up

The setup is made of two sections: the first section generates and analyzes the laser beams. The second section is composed by the optics and actuators in vacuum. One of the challenges of the experiment is that once the thruster is started, the vacuum cannot be broken because it would lead to slit oxidation and end-of-life for the thruster. Thus we had to make provision for alignment and calibration in vacuum (accounting for sputtering on the optics), and most of the optics are mounted on vacuum-rated actuated mounts. The experimental set-up is sketched in Fig. 10; in itself it is composed of three parts. The first part is the laser optical train, the second it the test bench in the vacuum tank, and the third part is the detection stage.

The laser used is a TEC-500 tunable laser Diode from Sacher Lasertechnik. Its modehop-free tuning range is typically $\pm 20$ GHz, centered at around 852 nm. The 10 mW beam goes through a Faraday isolator. A first beam pickoff is used for the saturated absorption; a second beam pickoff is used to monitor the beam power. A third pickoff is used to obtain a reference LIF signal in a gas cell containing pure cesium; a temperature probe located at the surface of the cell is used to compute the vapor pressure in the cell. Then the beam is split in four beams. These beams are directed to the test bench in the vacuum tank, through 50-µm IR-grade optic fibers. Three of these beams
are used for probing the plume along three axes. The fourth beam is used for the absorption measurement across the plume. The laser frequency is driven by sawtooth-shaped sweep signal. The frequency range is swept up and down at 6 Hz.

The test bench located in the vacuum tank is shown in Fig. 12, with the thruster mounted on it. It is composed of three injection IR-grade optics, oriented such as to focus the three laser beams at the same spot. The three focusing beams from these optics, termed L1, L2 and L3, form a trihedra. The size of the focal point is crucial for the spatial resolution; the smaller the better. This is the reason for the choice of 50-μm optic fiber to direct the laser beams, which once focused gives focal points of less than 1 mm in diameter. The crossing of the three focal points, which gives the actual probed volume, is checked using a CCD chip mounted directly on the calibration arm. This crossing can also be checked by direct visualization of the fluorescing laser beams in the cesium plume, as shown in Fig. 11 (the three laser beam are not lit at the same time during measurements). Two detection optics are used for redundancy and to avoid blind spots. Their alignment with the probed volume is checked with the CCD cell by back-tracking a laser beam. Overall, the probed volume, which is the crossing of the laser beams and the detection optic solid angle, is about 1 cubic millimeter. These detection optics are mounted on vacuum-rated motorized mounts; thus they can be aligned while in vacuum. The fluorescence light collect is focused on 600 μm optic fibers, background light is filtered out using a bandpass filter centered at 850 nm. The fluorescence signal is the directed towards a Hamamatsu R636-10 photomultiplier sensitive in the red part of the spectrum.

Fig. 10  Diagram of the experimental set-up for 3-components LIF measurements

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Fig. 11 View of the three laser beams in front of the emitter slit. For this picture, all laser beams are activated at the same time to check their crossing. The beams are visible because they fluoresce in the neutral cesium plume emitted by the thruster operating at full thrust (~ 100 µN).

The test bench is also equipped with lateral optics for lateral absorption measurements along the X axis in the thruster system of coordinate. While the thruster is off, the absorption signal can be calibrated (i.e we measure the $T_{\text{Ref}}$ in Eq. (13) using a reference cell, similar to the ones used in the optical train, mounted on the calibration arm.

Finally, the thruster is mounted on a three axis orthogonal translation system. The reference of the coordinate system is taken when the probed volume, defined by the crossing of the three probing lasers, touches the center of the emitter slit. When the thruster is switched off and pushed back, the calibration arm can be extended to check the laser beams and detection crossing, and to calibrate the absorption.

In the detection stage, all signals are acquired on a National Instrument card at 20 kHz. Prior to sampling, they go through 10-kHz anti-aliasing filters. These signals are:

- the output of the photomultiplier tube collecting the fluorescence from the vacuum chamber;
- the of the photomultiplier tube used for the reference LIF in the cesium cell;
- the laser beam power;
- the saturated absorption signal.
C. Measurement procedure

The measurements are taken for four different operating conditions of the thruster. These conditions are given in the test matrix shown in Table 2.

<table>
<thead>
<tr>
<th>Thrust</th>
<th>Emitter temperature: 35°C</th>
<th>Emitter temperature: 90°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 µN</td>
<td>Case 1</td>
<td>Case 3</td>
</tr>
<tr>
<td>100 µN</td>
<td>Case 2</td>
<td>Case 4</td>
</tr>
</tbody>
</table>

When the emitter temperature reaches steady state, we start the measurement. First, the plane B is probed, then the plane C. Each plane is processed line by line; a line is parallel to the X axis. On each line, several point measurement are taken. The number of points and lines, and dimensions of the planes are given in Table 3.

For each measurement point, 30 to 50 frequency sweeps are recorded, for each laser. Each frequency sweep is calibrated using the corresponding saturated absorption signal. Then the resulting LIF signals are averaged to increase the signal to noise ratio.

For each test case, the calibration of the LIF signal necessary to have the $C_1$ constant is done once using the center line on plane C. The constant $C_1$ is then used to obtain quantitative measurement on both planes. The reason for this choice is that the relative number density profile, sketched in Fig. 9 cannot be fully resolved on plane B, because there are blind spots inside the thruster. Thus, the tails of the profile are unknown and a calibration with a partial relative profile and the absorption signal along this line would be highly inaccurate. On the contrary, on plane C, the relative profile goes to zero at the edges of the measurement plane. Thus we are confident that there no cesium outside of the plane. Examples of relative profiles on both planes are shown below in Fig. 14 and Fig. 15.

The drawback of using $C_1$ obtained from the plane C for the measurement on plane B is that it induces a systematic error. This systematic error is due to absorption of the probing laser beam between plane C and plane B.
### Table 3: Characteristics of the planes

<table>
<thead>
<tr>
<th></th>
<th>Plane B</th>
<th>Plane C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position on Z axis</td>
<td>3 mm</td>
<td>9 mm</td>
</tr>
<tr>
<td>width</td>
<td>30 mm</td>
<td>37 mm</td>
</tr>
<tr>
<td>height</td>
<td>12 mm</td>
<td>35 mm</td>
</tr>
<tr>
<td>spacing between lines: ΔY</td>
<td>2 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td>Increment between points: ΔX</td>
<td>2-4 mm</td>
<td>3-5 mm</td>
</tr>
<tr>
<td>NY (number of lines)</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>NX (number of points per line)</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>Number of points</td>
<td>63</td>
<td>88</td>
</tr>
<tr>
<td>Number of LIF signal required</td>
<td>189</td>
<td>264</td>
</tr>
<tr>
<td>Number of Absorption signal required</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>

### D. Measurement performance

The typical uncertainties of the different measured quantities are summarized in the table 4 below. Due to self-absorption, the mass flow rate computed from plane B measurements can be underestimated by up to 30%. This uncertainty is treated as a random error in the following.

#### Table 4: Uncertainties of the different quantities

<table>
<thead>
<tr>
<th>Measured quantity</th>
<th>Plane B</th>
<th>Plane C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number density n Cs</td>
<td>10% + self-absorption underestimate= &lt;30%</td>
<td>6%</td>
</tr>
<tr>
<td>Velocity</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Flow rate</td>
<td>&lt; 5 % + self-absorption underestimate= &lt;20-30%</td>
<td>&lt; 5%</td>
</tr>
</tbody>
</table>

The sensitivities S(X) in our current conditions are given in Table 5. These numbers correspond to the acquisition time (or rather, number of averaged samples) used in our data acquisition. If more frequency sweeps are taken, the sensitivity can be decreased (i.e. get better) as the square root of the number of sweeps.

#### Table 5: Sensitivity in the conditions of the experiment

<table>
<thead>
<tr>
<th>Measured quantity X</th>
<th>S(X)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point Number density measurement from LIF</td>
<td>$10^{10}$ mbar = 2.4x10^6 cm⁻³</td>
</tr>
<tr>
<td>Velocity measurement</td>
<td>2 m.s⁻¹</td>
</tr>
</tbody>
</table>

Note the absorption is less sensitive than the LIF measurement. This is because the absorption measurement noise is largely due to the laser diode intensity fluctuations, which are below 1%. These fluctuations have a lesser impact on the LIF measurement because the fluorescence signal is not linearly dependant of the intensity.

### V. Results

#### A. Point and Line Signals

Fig. 13 shows the three LIF signals from the three probing laser L1 to L3; the LIF signal from the reference cell is also given. The Fluorescence signals of L1 and L2 are shifted toward the red part of the spectrum, which means that the neutral cesium is flowing toward the laser optics, or, in other word, the neutral cesium flows out of the thruster.
In Fig. 14 (plane B), the three relative density profiles along a line are given. The discrepancies between the curves are due to self-absorption in the high density plume at this location. This is supported by the plot in Fig. 15 (plane C) where the self absorption is much less intense, and where the curves are in very good agreement. Both curves in Fig. 14 and Fig. 15 show that the plume is fairly symmetrical.

Fig. 14  Cesium number density profile along a line, Thrust 30 µN, Emitter Temperature 35°C, plane B
B. Mappings for Case 1

In Fig. 16, Fig. 17, Fig. 18 and Fig. 19, the mappings obtained on plane B and C for the test case 1 (see table 2) are shown. In Fig. 16, the number density mappings on both planes are shown. To be compliant with vacuum science usage, number densities are given in mbar, assuming a constant temperature of 300 K.

The number density mappings in Fig. 16 show that the number density is the largest at the center of the emitter slit. The evolution between plane B and C shows the broadening of the neutral cesium plume. Similarly, the velocity vector fields in Fig. 17 show that the velocity reaches its maximum at the center. The Z velocity mappings shown in Fig. 18 indicate that the maximum axial velocity can be as high as 800 m.s$^{-1}$ and 600 m.s$^{-1}$, on plane B and C, respectively. At higher thrust, the maximum axial velocity can exceed 1000 m.s$^{-1}$ on plane B, at the center of the emitter (X=0). Combining the number density mapping and the Z velocity mapping gives the neutral mass flux mapping, shown in Fig. 19. The mapping on plane B show that the region of maximum flux has a large aspect ratio, which recalls the large aspect ratio of the emitter slit. Since plane B is just 3 mm downstream of the emitter, this shows that the neutral cesium comes from the emitter.
Fig. 16 Neutral cesium number density, along plane B (top) and C (bottom). Thrust 30 µN, Emitter Temperature 35°C. Measurement points are the nodes of the black mesh, which is spline-interpolated for visualization purpose. Along plane B the number density has an elongated peak, corresponding to the active region of the emitter. The number density does not go to zero at the edge of the measurement plane. Along plane C the plume has a broader shape because of the plume expansion.
Fig. 17 Velocity vector orientation, along plane B (top) and C (bottom). Thrust 30 µN, Emitter Temperature 35°C. The size of the vector is proportional to the magnitude of the velocity. The divergence of the beam can be seen from the divergence of the 3D velocity vectors.
Fig. 18  Z Velocity mapping along planes B (top) and C (bottom), for Thrust 30 µN, Emitter Temperature 35°C. Along plane B, the maximum velocity reach 800 m.s⁻¹; the maximum velocity region follows roughly the active region of the emitter
Fig. 19  Particle flux isovalues along planes B (top) and C (bottom), Thrust 30 µN, Emitter Temperature 35°C, given in part.m².s⁻¹. The area enclosed by the black line account for 80% of the total flux.
C. Measured mass flow rates

Results similar to those presented above are obtained for the three other cases; from these data the mass flow rate are computed using Eq. (8). In table 6 below, we summarize the mass flow rates measured for the four test cases recalled in table 2. For comparison, the mass flow rate resulting from the ion current is indicated.

Table 6 Neutral Cesium flow rate for the different thruster conditions. The ion mass flow rate is computed from the current, supposing singly charge ions. The ratio of neutral cesium or ionized cesium to the total mass flow rate is given in each case

<table>
<thead>
<tr>
<th>Case</th>
<th>Thrust (µN)</th>
<th>Temitter (°C)</th>
<th>Plane B (mg/h)</th>
<th>Plane C (mg/h)</th>
<th>Ion (mg/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>100</td>
<td>30</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>35</td>
<td>90</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.25±0.42</td>
<td>3.33±1.11</td>
<td>2.36±0.80</td>
<td>4.78±1.60</td>
<td></td>
</tr>
<tr>
<td>(fraction of total mass flow rate)</td>
<td>53%</td>
<td>49%</td>
<td>65%</td>
<td>58%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.18±0.02</td>
<td>3.41±0.04</td>
<td>3.33±0.05</td>
<td>6.05±0.05</td>
<td></td>
</tr>
<tr>
<td>(fraction of total mass flow rate)</td>
<td>51%</td>
<td>50%</td>
<td>72%</td>
<td>63%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.13</td>
<td>3.46</td>
<td>1.28</td>
<td>3.52</td>
<td></td>
</tr>
<tr>
<td>(fraction of total mass flow rate, neutral mass flow of plane C)</td>
<td>49%</td>
<td>50%</td>
<td>28%</td>
<td>37%</td>
<td></td>
</tr>
</tbody>
</table>

VI. Discussion

A. Neutral mass flow rate measurements

The flow rate measurements summarized in Table 6 calls for a few comments. First, neutral mass flow rate is as high or even higher than the ion mass flow rate. This observation differs markedly from the early results of Mitterauer [5], but is of the same order of magnitude as the results of [1] which take into account the total mass flow rate due to neutrals including droplets. The order of magnitude of our measurements has been checked using absorption measurement, which can be easily calibrated. Besides, we have also checked that the high number density is not due to a background cesium accumulation. Spot checks outside of the plume, while the thruster is firing, have shown that the cesium number density is below the detection limit of our setup. Our data show unambiguously that the neutral mass flow rate is not negligible and should be taken into account while dimensioning the propellant mass.

Second, the profile of mass flux plotted for each plane show that most of the neutral cesium flow through the central part of the measurement planes. This is illustrated for example in Fig. 19, where black curves outline the area accounting for 80% of the total measured flow rate. The presence of this central peak indicates that even though the measurement plane does not cover completely the thruster exit plane (see for example Fig. 6), the flow rate obtained should be within 5% of the total mass flow rate.

Third, there is a clear correlation between the emitter temperature and the neutrals flow rate. At a given thrust, the higher the emitter temperature is, the larger the mass flow rate. Similarly, at a given emitter temperature, the higher the thrust is, the larger the neutral cesium atom mass flow rate. As a first approximation, we could decouple the effect of thrust and emitter temperature, and suppose that the total neutral mass flow rate is the added contribution of a thermal plume resulting of cesium evaporation and a thrust-dependant plume. Thus one could write

\[ q = q_{\text{thermal}} + q_T \]  

Supposing that the mass flow rate \( q_T \) depends linearly of the thrust, we find that \( q_{\text{thermal}} = 0.2 \text{mg/h}, q_T = 0.033T \text{[µN]mg/h} \) and \( q_{\text{thermal}} = 2.2 \text{mg/h}, q_T = 0.039T \text{[µN]mg/h} \), for emitter temperature of 35°C and 100°C, respectively. The mass flow rate \( q_{\text{thermal}} \) due to the thermal plume increases with emitter temperature, which is expected since the vapor pressure of cesium is a steep function of the temperature [6]. Interestingly, the values of \( q_T \) are quite close for both temperatures, which suggest that the thermal plume and the thrust dependant plume are not closely coupled. Because in our experiment a minimum thrust is needed to operate the thruster, a full mapping of the plume with zero thrust has not been done. Instead of full mapping, spot checks at the center of the plume are done, at zero thrust but with constant emitter temperature. These checks show that the cesium number density does not go to zero while the averaged velocity falls in the 100-200 m.s\(^{-1}\) range.
The underlying physical mechanisms of this thrust dependant plume can be further discussed by considering the maximum averaged velocities measured. At the center of the plume, the cesium velocity magnitude is about 500-1000 m.s\(^{-1}\). At this point, we recall that this is an averaged velocity, i.e., the results of the added contribution of each velocity classes. For comparison, the averaged thermal velocity of a cesium vapor at 35°C would be about 220 m.s\(^{-1}\), and the maximum averaged velocity resulting from an isentropic expansion would be about 310 m.s\(^{-1}\). Thus, there is clearly an effect on the neutral cesium plume that increases its velocity. We can think of three possible causes:

- Acceleration of the neutral vapor by elastic collisions with the fast ions;
- Recombination or charge exchange of cesium ions into fast neutrals in the high number density plasma at the tip of the emitter slit;
- Evaporation of the cesium vapor from fast charged clusters.

If the idea of a neutral cesium plume being composed of a thermal plume and a thrust-dependant plume holds, we would then expect a velocity distribution function of the neutral cesium composed of a shifted Gaussian at thermal speed, and a high velocity component responsible for the high averaged velocity. This would have to be checked in future experiments.

**B. Neutral thrust**

It is interesting to remark that the emission of cesium atoms results in an additional thrust. In fact, we can compute this additional force with:

\[
T_{\text{Neutral}} = -\int [p + m_c n_c \mathbf{V} \cdot (\mathbf{V} \cdot \mathbf{n})] dS
\]  

(18)

In Eq. (18) we can verify that the contribution of the cesium pressure \(p\) is negligible. If we perform this integration on the probed surfaces (planes B and C), we can compute this additional force in the thruster system of coordinates. The results are given in table 7 below. In all cases, the thrust caused by the exhaust of the neutral gas is below 1 \(\mu\)N. Fig. 20 shows the thrust vector computed from plane B for the 4 test cases. The tilt angle of the neutral thrust vector is below 8°.

<table>
<thead>
<tr>
<th>Case</th>
<th>Conditions</th>
<th>Plane</th>
<th>(T_x) ((\mu)N)</th>
<th>(T_y) ((\mu)N)</th>
<th>(T_z) ((\mu)N)</th>
<th>(T) ((\mu)N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(T=30 \mu)N</td>
<td>B</td>
<td>0.014</td>
<td>-0.024</td>
<td>-0.160</td>
<td>0.163</td>
</tr>
<tr>
<td></td>
<td>(T_e=35 ^\circ)C</td>
<td>C</td>
<td>0.020</td>
<td>-0.019</td>
<td>-0.128</td>
<td>0.129</td>
</tr>
<tr>
<td>2</td>
<td>(T=100 \mu)N</td>
<td>B</td>
<td>0.029</td>
<td>-0.062</td>
<td>-0.616</td>
<td>0.620</td>
</tr>
<tr>
<td></td>
<td>(T_e=35 ^\circ)C</td>
<td>C</td>
<td>0.022</td>
<td>-0.066</td>
<td>-0.644</td>
<td>0.469</td>
</tr>
<tr>
<td>3</td>
<td>(T=30 \mu)N</td>
<td>B</td>
<td>0.011</td>
<td>-0.022</td>
<td>-0.156</td>
<td>0.159</td>
</tr>
<tr>
<td></td>
<td>(T_e=90 ^\circ)C</td>
<td>C</td>
<td>0.002</td>
<td>-0.018</td>
<td>-0.192</td>
<td>0.193</td>
</tr>
<tr>
<td>4</td>
<td>(T=100 \mu)N</td>
<td>B</td>
<td>0.040</td>
<td>-0.092</td>
<td>-0.655</td>
<td>0.662</td>
</tr>
<tr>
<td></td>
<td>(T_e=90 ^\circ)C</td>
<td>C</td>
<td>0.021</td>
<td>-0.059</td>
<td>-0.551</td>
<td>0.555</td>
</tr>
</tbody>
</table>
Neutral thrust vectors in the YZ plane for the four cases. Y axis not at scale. Thrust values are negative because of the orientation of the thruster system of coordinates. Neutral thrust is mainly axial; the thrust vector is tilted of at most 8° with respect to the main thrust axis (Z axis).

VII. Conclusion

In this study, for the first time, we have successfully measured the mass flow rate of neutral cesium atoms emitted by a cesium FEEP thruster. To achieve this, we have developed a non intrusive optical diagnostic technique based on the Laser induced fluorescence. We have devised an experimental set-up that allow to measure the three components of neutral cesium velocity, as well as its absolute number density, using absorption spectroscopy as a calibration tool. Using our setup, we have mapped the neutral number density and the 3-component velocities of neutral cesium expelled by an engineering model of a FEEP thruster, for four different operating conditions. From these data, we have obtained the mass flow rate across two control surfaces. The uncertainty of these measurements is between about 5%.

Our results show that the neutral cesium mass flow rate is approximately equal to the charged particle mass flow rate. The measured mass flow rates indicate that the plume is composed of a thermal plume, resulting from cesium vaporization, and a thrust-dependant plume. Indeed, axial velocities are in the 600-1000 m.s\(^{-1}\) range. Even an isentropic expansion cannot account for this magnitude. We think there could be three mechanisms responsible for this high neutral velocity: elastic collisions with ions, inelastic collisions (recombination) or charge exchange collision, and vaporization from charged cluster.

This study brings forward several exciting questions that in our view should be investigated. First, what is the mechanism responsible for the fast neutral velocity? A first step to answer this question would be to deconvolve the LIF signal to find the neutral velocity distribution function. Such a procedure would require considering closely the relative strength of the cesium transitions, as well as the self-absorption effects. A second step would be to obtain not only the projected velocity distributions, but the full velocity vector distribution function (i.e. in phase space), from which the plume structure could be accurately investigated. For this purpose, probing along 3 axes is insufficient. A more complex technique is required.

Second, can this technique be extended to probe other species in the plume, or other type of thruster? As a first step, we could propose to investigate the cesium dimers in the plume. Another step would be to extend our technique to other thrusters, such as Hall effect thrusters, Helicon thrusters or HEMP thrusters. The keypoint here would be to devise the proper set of transitions that would allow a direct calibration. If such transitions could not be found, one could also imagine to extend the technique to two-photon laser induced fluorescence to probe atoms or ions from their ground state.
Acknowledgments

This work was performed under ESTEC 19718/06/NL/HB contract. The authors acknowledge B. Attal-Tretout, N. Dorval, T. Schmid and A. Bresson from Onera for their support during this study, and A. Broc and S. Rocca for their assistance during the experiments.

References