Assessment of the Azimuthal Homogeneity of the Neutral Gas in a Hall Effect Thruster using Electron Beam Fluorescence

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Abstract: A diagnostic of Electron Beam Fluorescence (EBF) has been developed to assess the homogeneity of propellant gas injection through the anode of Snecma PPS®5000 Hall Effect Thruster. EBF technique allows measuring the absolute density of gas at the outlet of the discharge channel. The radial profiles of intensity measured at several angular positions after post-processing of the fluorescence images are used to rebuild the map of absolute density. Azimuthal variations of 5% have been measured on a development anode, with incertitude of 2%.

I. Introduction

One of the main causes of lifetime limitations in Hall Effect Thrusters is the erosion of ceramic walls of the discharge channel due to ion impingement. Azimuthal inhomogeneity of the plasma density in the discharge channel would result in non-axisymmetrical plume which could potentially decrease thruster performance and generate a dissymmetry of the erosion process.

Therefore it is important to assess the azimuthal distribution of neutral gas in the discharge channel. However very few –if any- non-intrusive techniques are capable of measuring accurately the gas density at such low pressure (typically: 10^{-3} mbar) with a good spatial resolution.

In this paper, we present a diagnostic based on electron beam fluorescence for the characterization of the distribution of propellant gas into the discharge channel through the anode, and its demonstration on the anode of a Snecma PPS®5000 Thruster. The thruster is operated is cold gas mode (without discharge) for the measurements of the gas density.

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II. Apparatus and methods

A. Principle of electron beam fluorescence

Electron beam fluorescence (EBF) is a technique for measuring the absolute density of atomic or molecular gas. The principle is based on the injection of high energy electrons in a gas: some particles are excited by direct electron impact (*pumping*) and emit light by radiative de-excitation (*fluorescence*). In appropriate conditions, the intensity of the fluorescence signal is proportional to the density of gas. The energy scheme, shown in Figure 1, is similar to laser-induced fluorescence (LIF).

One of the advantages of EBF is its ability to analyze all types of gases: all atoms and molecules can indeed be excited effectively by inelastic collisions with electrons. Unlike LIF technique, there is no selectivity to species or to energy levels. Moreover, it is possible to analyze all types of atoms or molecules in the ground-state energy level, whereas optical pumping from ground state is not accessible for all species with a laser. For example, the excitation of xenon atom from ground-state with a single photon is not possible with currently available lasers, and two-photon absorption LIF should be used. This last technique is much more complex, lacks sensitivity and requires expensive equipment.

An EBF diagnostic has already been used at ONERA for the characterization of a cold gas thruster[1]. The absolute density number of argon has been measured in the plume and an electron beam excited laser induced fluorescence (EBLIF) technique has also been developed to measure the velocity of atoms.

The energy of electrons in the beam is typically 10 keV with our electron gun. Since the energy required for excitation or ionization of an atom is in the order of magnitude of 10 eV, every single electron can undergo about 1000 inelastic collisions that will lead to excitation or ionization of the gas. The multiple collisions result in deflection of electrons and generation of secondary electrons that can increase the beam divergence and create a halo of light around the beam. In this work, the density of gas was low enough to avoid any significant diffusion of the beam. An example of electron beam fluorescence with a uniform density of gas is shown in Figure 2.

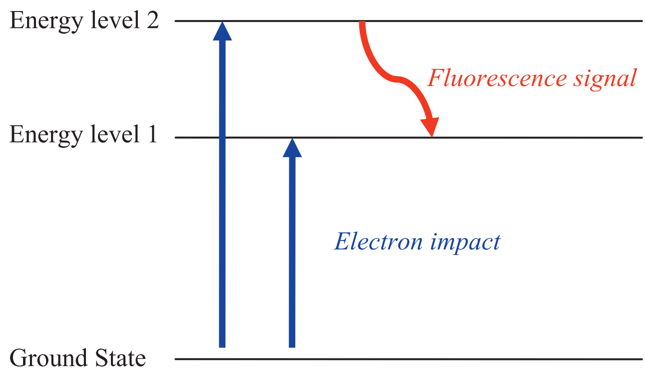

Figure 1. Energy scheme of electron beam fluorescence.

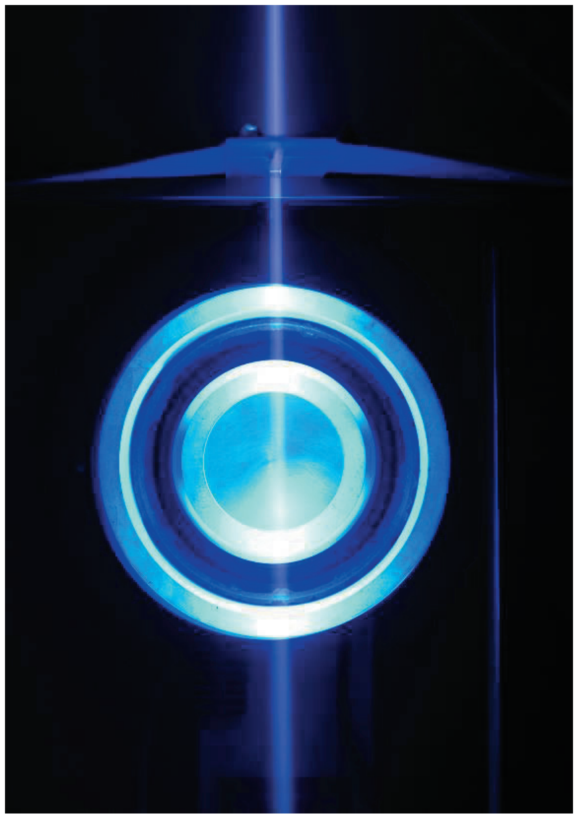

Figure 2. Imaging of the electron beam with a uniform density of xenon in the vacuum chamber in front of a PPS®5000 anode.

B. Electron beam generation

The electron beam is generated by a secondary emission electron gun developed at ONERA, that does not use a filament. The system uses a plasma generated at low pressure (10^{-4} to10^{-2} mbar) in a DC wire discharge that can be operated with any type of gas. Ions are extracted through a diaphragm and accelerated towards an auxiliary cathode biased at -10 kV. Secondary electrons that are emitted by ion impact on the metallic surface are than accelerated backwards and form the high energy electron beam that is injected in the vacuum chamber. The beam current is typically a few hundreds microamperes.

The beam then passes through an axial coil for collimation and through a slit 2 mm or 5 mm wide to improve the spatial resolution of the diagnostic. Two transverse electromagnets driven by a sine-wave generator sweep the beam parallel to the slit, which creates a sheet of electron 2 mm (or 5 mm) in thickness.

The main advantages of secondary-emission electron gun over conventional thermo-ionic electron gun with filament are:

- its robustness (no hot filament that need to be replaced);
- its ability to be operated in a wide range of pressure (up to 10^{-2} mbar) without need of an differential pumping system.

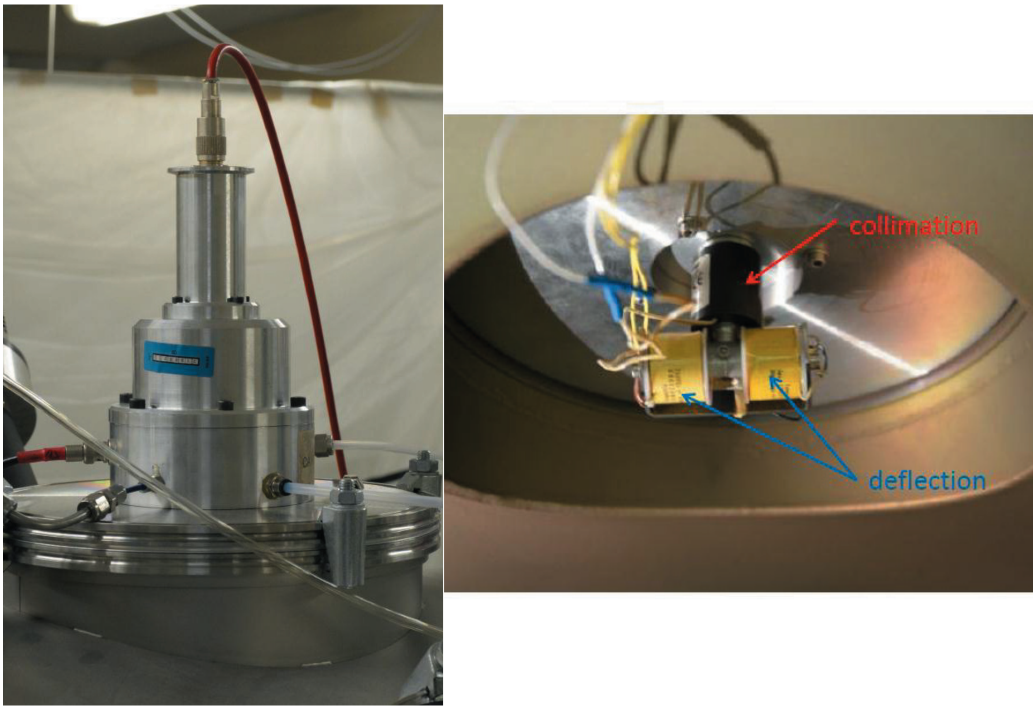

Figure 3. Secondary emission electron gun mounted on the vacuum chamber and electromagnets used for collimation and deflection of the beam.

C. Experimental setup

All tests are performed in B09 vacuum chamber at Onera center of Palaiseau. The vacuum chamber is 0.8 m in diameter and 2 m long (see Figure 4). It is equipped with three turbomolecular pumps that allow a total pumping speed of 2000 L/s for xenon, 2900 L/s for argon, and 3700 L/s for N_2. The ambient pressure is measured with a MKS Baratron gauge (full scale: 0.1 mar) and with a MKS Quattro multi-sensor vacuum transducer. The gas is injected through the anode using a Bronkhorst El-Flow mass flow regulator.

A simple method to obtain the map of density is to sweep the electron beam perpendicular to the channel axis at the outlet of the channel and to acquire an image in front of the thruster. It is then possible to detect azimuthal non-homogeneities. However the multiple reflections of fluorescence light on the walls of the annular channel make the absolute calibration very difficult.

In this work, the electron beam can is swept parallel to the axis of the discharge channel, while fluorescence images are acquired through a window on the side of the vacuum chamber (see Figure 5). The main advantage of this method is the possibility to reduce the intensity level of parasitic light with screens.

The anode is fixed at the bottom of the annular discharge channel (made of ceramics), and the anode-channel assembly is mounted on a system composed of a rotation stage and a translation stage, as shown in Figure 6. The rotation stage is used to change the angular position of the anode with respect to the beam axis, and the translation stage is used to adjust the distance between the assembly and the electron beam. Fluorescence images are acquired using a Pixis CCD camera from Roper Scientific (back-illuminated, 1340 x 400 pixels) and a 50 mm f/1.4 lens.

An example of a raw fluorescence image obtained with the beam swept parallel to the channel axis is given in Figure 7. The radial profile of intensity can then be determined at various distances from the channel exit. The measurement is repeated at different angular position of the anode-channel assembly to rebuild the density map.

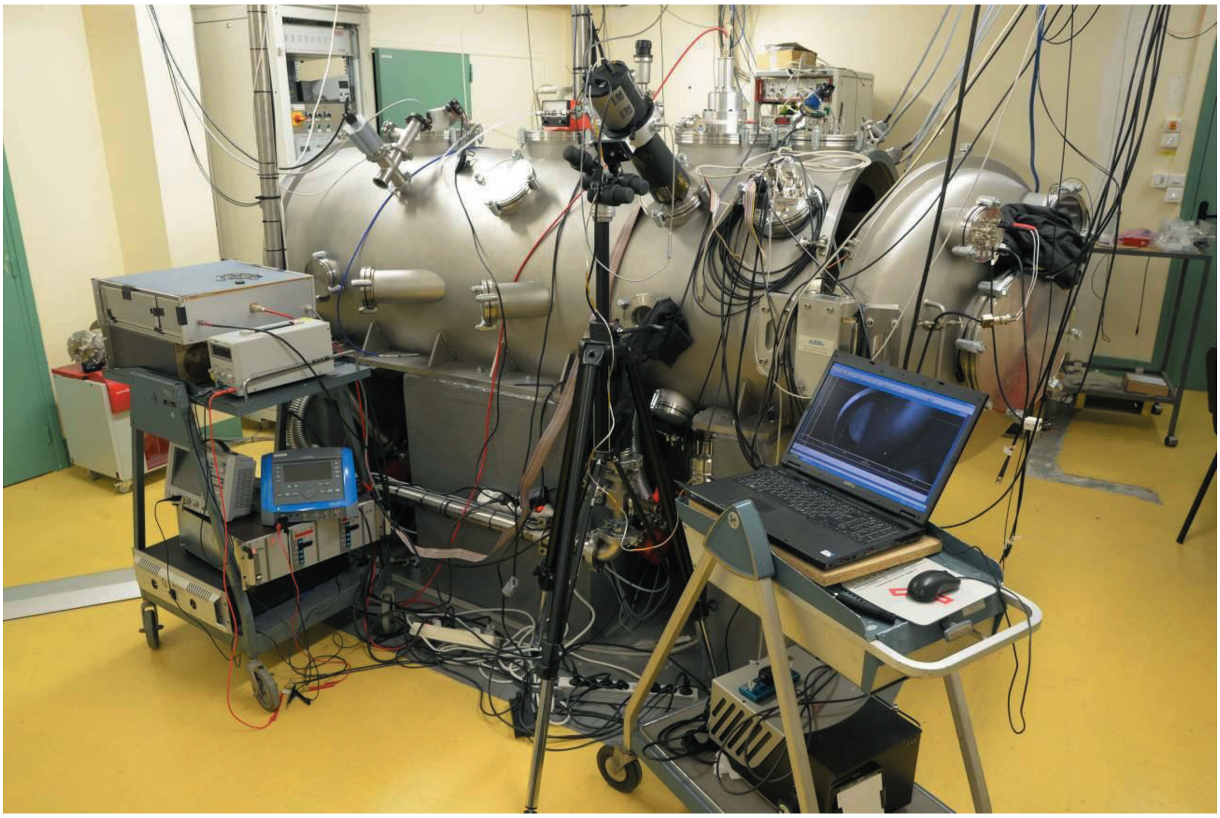

Figure 4. B09 vacuum chamber.

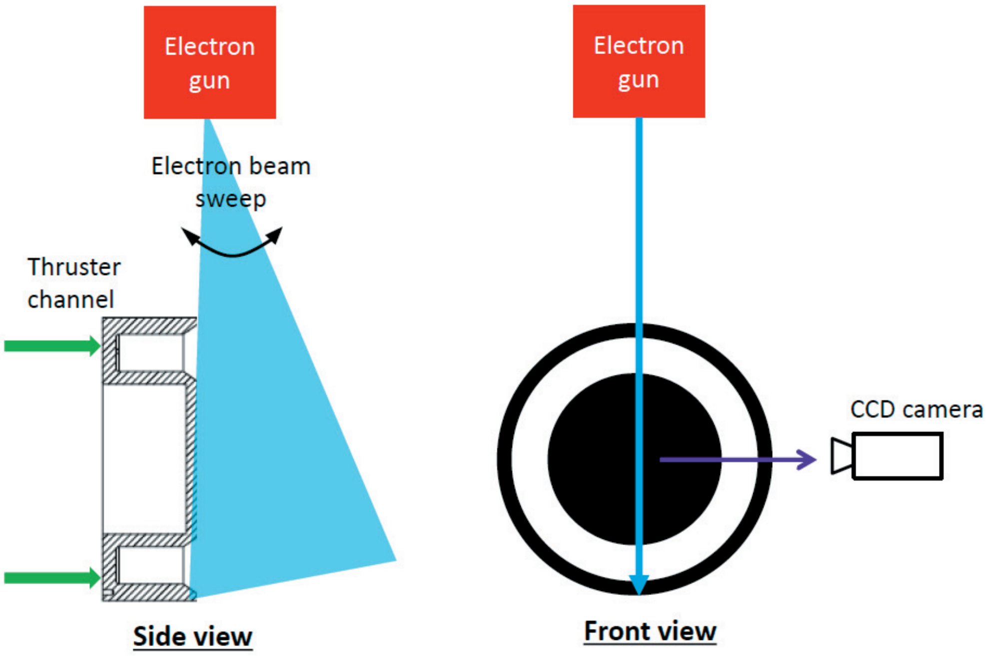

Figure 5. Schematic of the diagnostic with the electron beam swept parallel to the axis of the discharge channel.

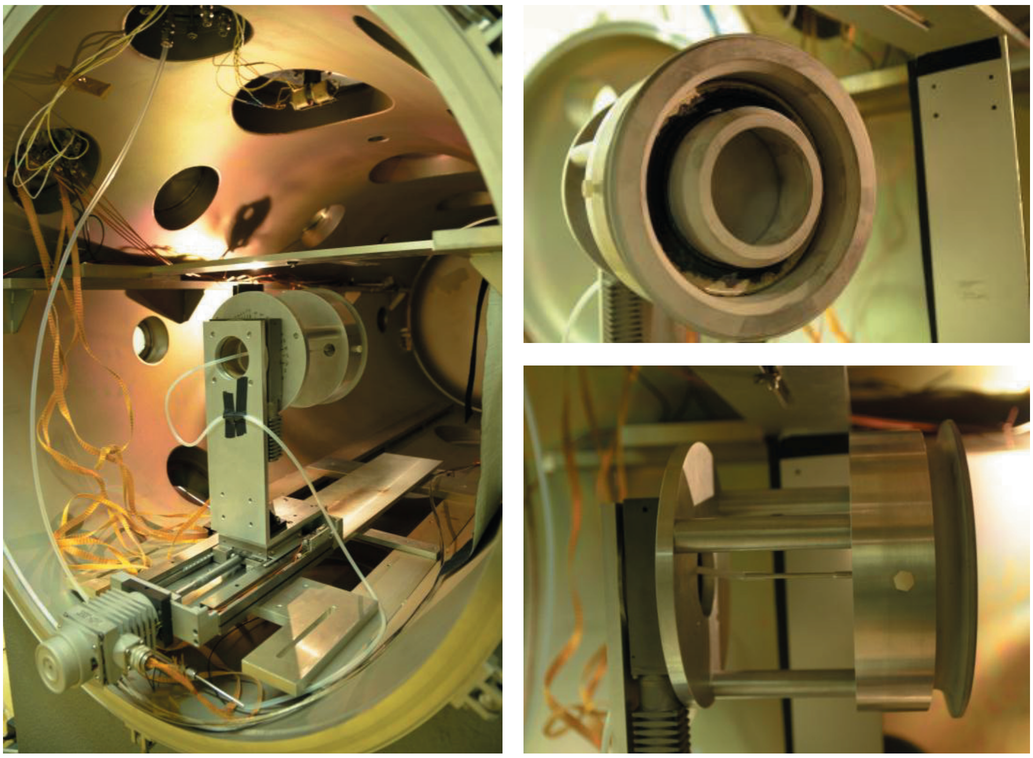

Figure 6. View of a PPS®5000 anode mounted in the EBF system in B09 vacuum chamber.

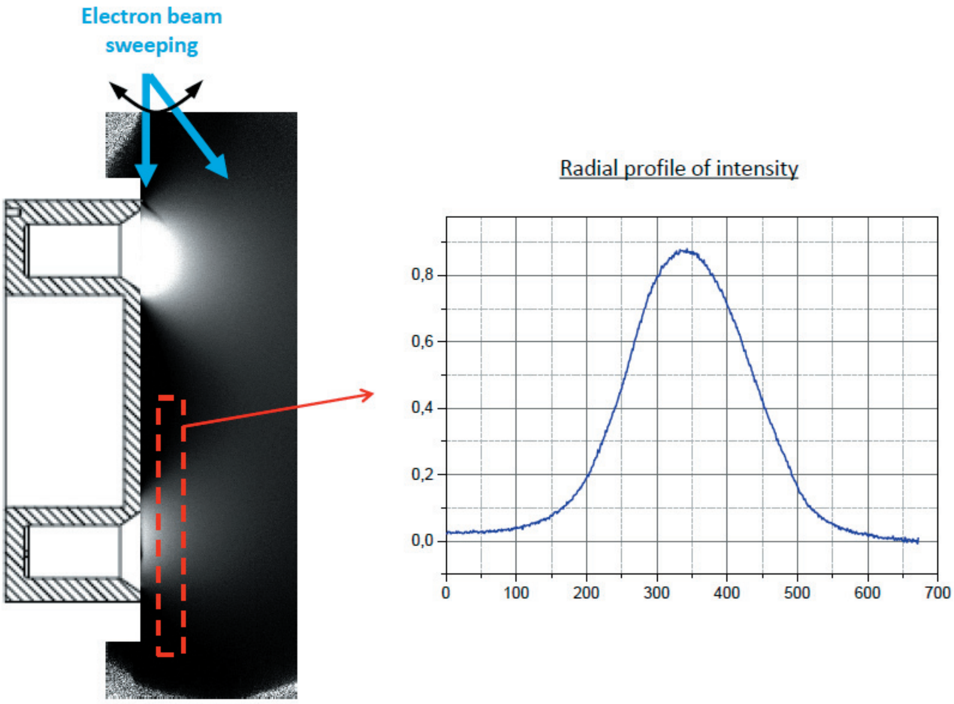

Figure 7. Example of raw EBF image and extracted radial profile (after post-processing) with gas injected through the anode.

D. Post-processing

The analysis of fluorescence images requires post-processing in order to remove all sources of light that may disturb the measurement:

- EBF from the background gas: with B09 pumping capability, about 50% of the fluorescence light is due to ambient gas ;
- Ion beam fluorescence (IBF): an ion beam with energy of 200-300 eV (~ voltage of the wire DC discharge) is generated simultaneously with the electron beam; these ions, which are not deflected by the electromagnets, also produce some fluorescence light that is superimposed to the EBF signal.
- Other parasitic sources of light: the ambient gas that is out of the field of vision of the camera also emit fluorescence light that is partly reflected by the walls of the chamber, and the materials that are bombarded by electrons or exposed to soft X-rays may also emit fluorescence light, as can be seen in Figure 2.

The diagnostic consists in 4 steps.

1. Acquisition of the EBF image with the gas injected through the anode.
2. Acquisition of the EBF background image: the gas injected from a remote location in the chamber, so that the fluorescence signal is only due to ambient gas.
3. Subtraction of background image: it enables to remove the EBF signal due to ambient gas, and a part of the parasitic light.
4. Correction for the spatial response of the diagnostic: the response of the system is not uniform due to the inhomogeneity of the beam sheet and the transmission of lenses.

Typical fluorescence images and radial profiles obtained during the post-processing are shown in Figure 8 and Figure 9.

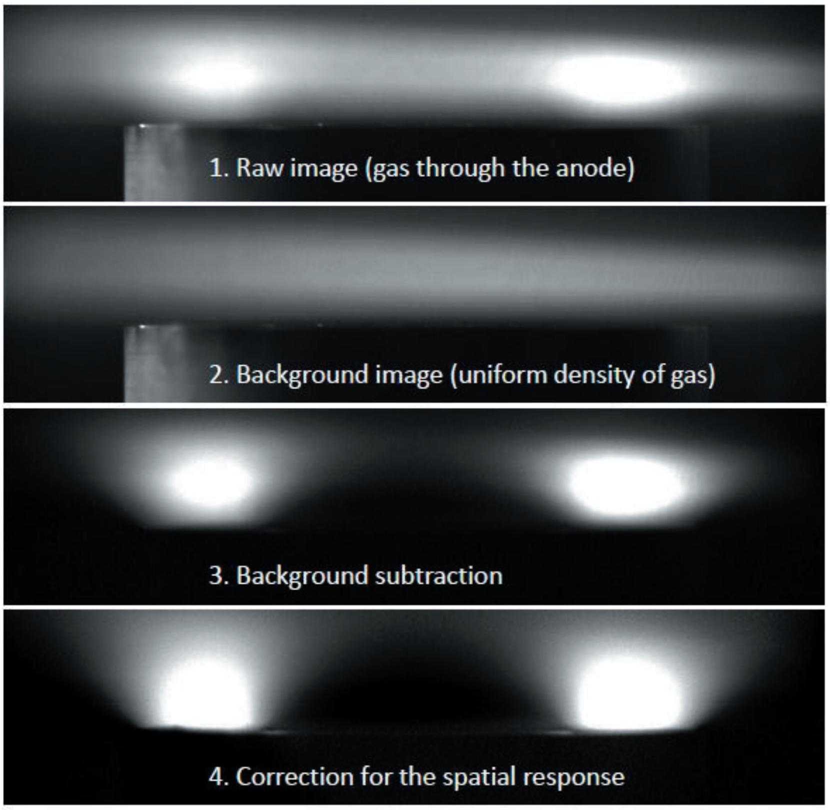

Figure 8. Post-treatment of the fluorescence images.

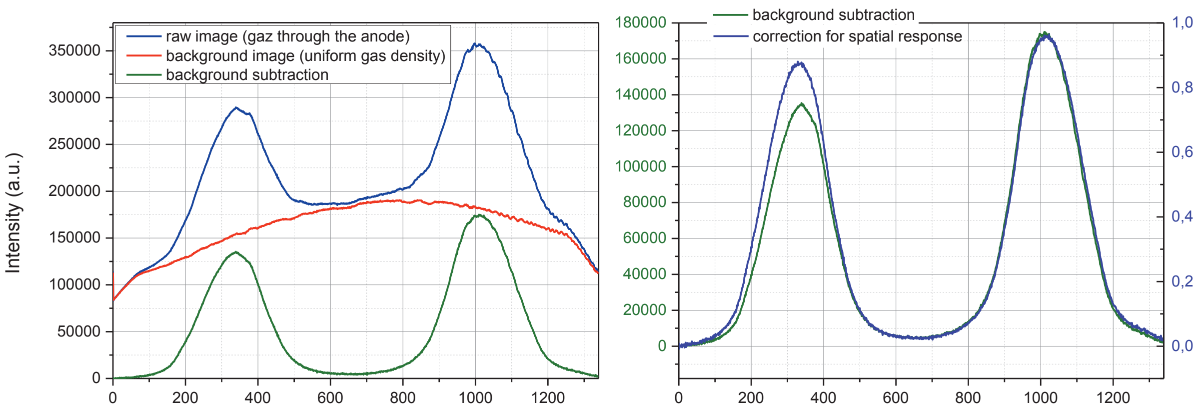

Figure 9. Example of radial profile of intensity during the post-processing steps.

III. Results

A. Characterization of PPS®5000 anodes

The EBF diagnostic, with the post-processing described above, has been used to characterize two anodes of a PPS®5000 Thruster: a development anode, and an anode to which a default has been added. The mass flow rate of xenon is 5 mg/s, and the measurements are performed every 10 degrees. The maps of absolute density are presented in Figure 10.

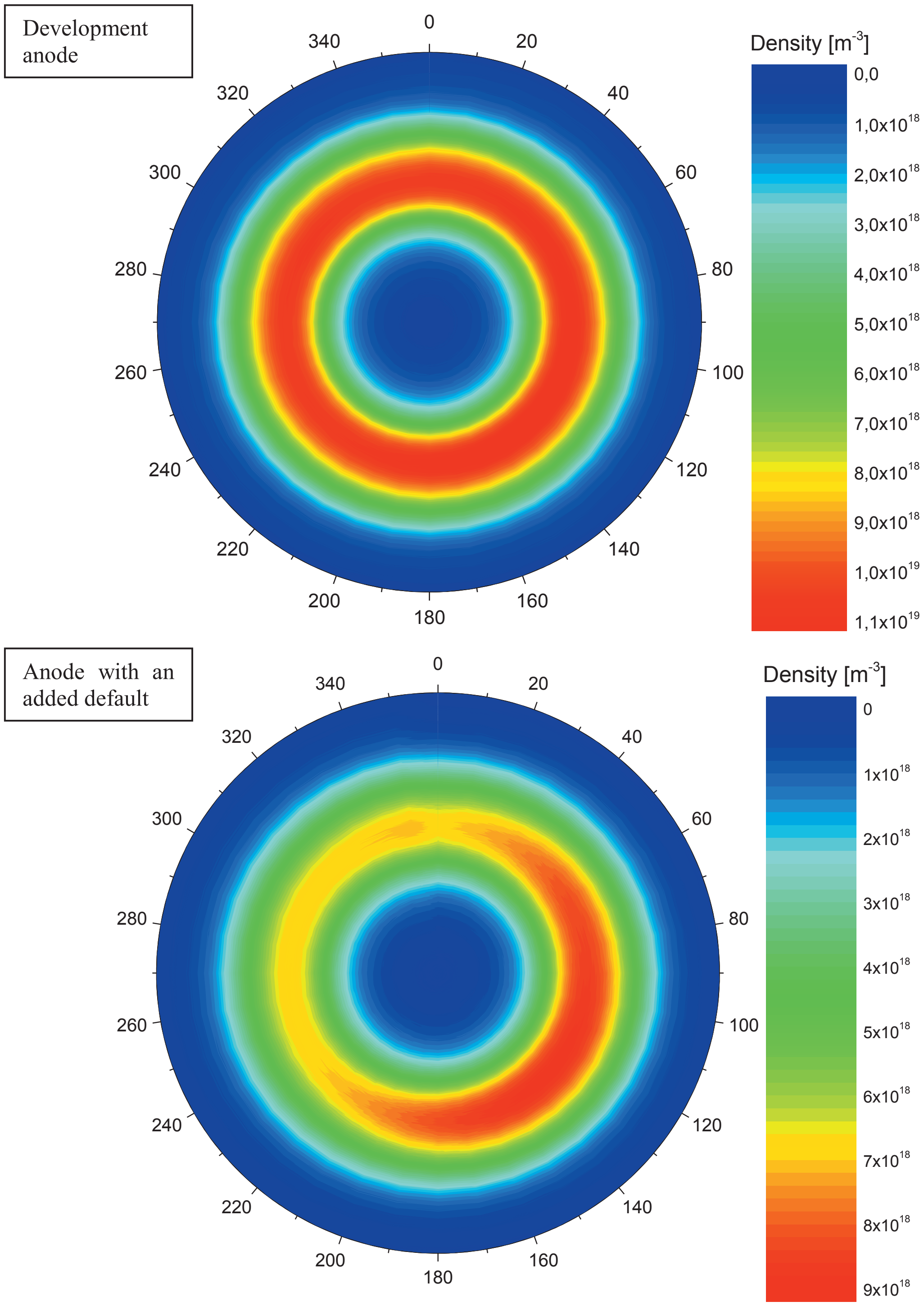

Figure 10. Map of absolute density of xenon for the development anode and when adding a default. Flowrate: 5 mg/s.

The azimuthal distribution of propellant gas can then be determined by taking the fluorescence intensity at the maximum of the radial profile at each angle (see Figure 11). The variations are less than 5% for a development anode, and the results indicate variations higher than 20% when adding a default to the anode. Note that the repeatability of the diagnostic has been verified ; the incertitude on the relative azimuthal profile is about 2%.

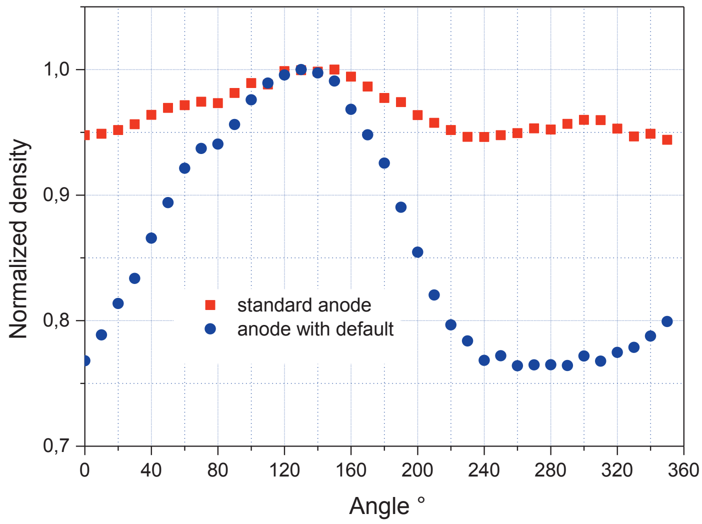

Figure 11. Azimuthal (relative) profile of xenon density for a development anode and when adding a default.

B. Spectral filtering

A promising evolution for this diagnostic is the spectral filtering of the fluorescence signal in order to remove efficiently the parasitic light, and to detect only the fluorescence of the gas. A good application of this is the removal of the intense fluorescence light of the ceramic channel due to soft X-rays (see Figure 2), which saturates the CCD and can cause blooming. In the experiments presented above, the light emitted by ceramic was blocked with a screen. However, screening is not always possible.

The fluorescence spectra of the gas and of the ceramics are measured with an Acton Insight 400 spectrometer (2.8 aperture ratio, gratings at 300 grooves/mm) and the same CCD camera. The measurements are corrected by the spectral response of the optical setup, which is determined using a calibrated deuterium and halogen/tungsten lamp. The fluorescence spectrum of the ceramics (not shown here) is a continuum whose intensity is very low above 650 nm. Figure 12 show the spectra of three different gases: xenon, argon and air. The electron beam energy is 10 keV for all gases. Air spectrum is dominated by first negative system of N_2^+ with the main peak around 391 nm (0-0 transition). An efficient filtering can be obtained with an optical interference filter around this wavelength. Argon spectrum is composed of numerous transitions of neutral Ar and Ar^+. The most intense lines are in the range 750-850 nm. On the other hand the xenon emission is spread across a wide spectral range (many small lines are present, even in the UV), so spectral filtering does significantly reduce the intensity.

We tested spectral filtering with argon using a high-pass filter with a cutoff wavelength at 715 nm. An example of EBF image is presented in Figure 13 (with no screen to mask the ceramics). The azimuthal profile indicates a very good agreement between xenon measurements (without filtering) and argon measurements (with spectral filtering).

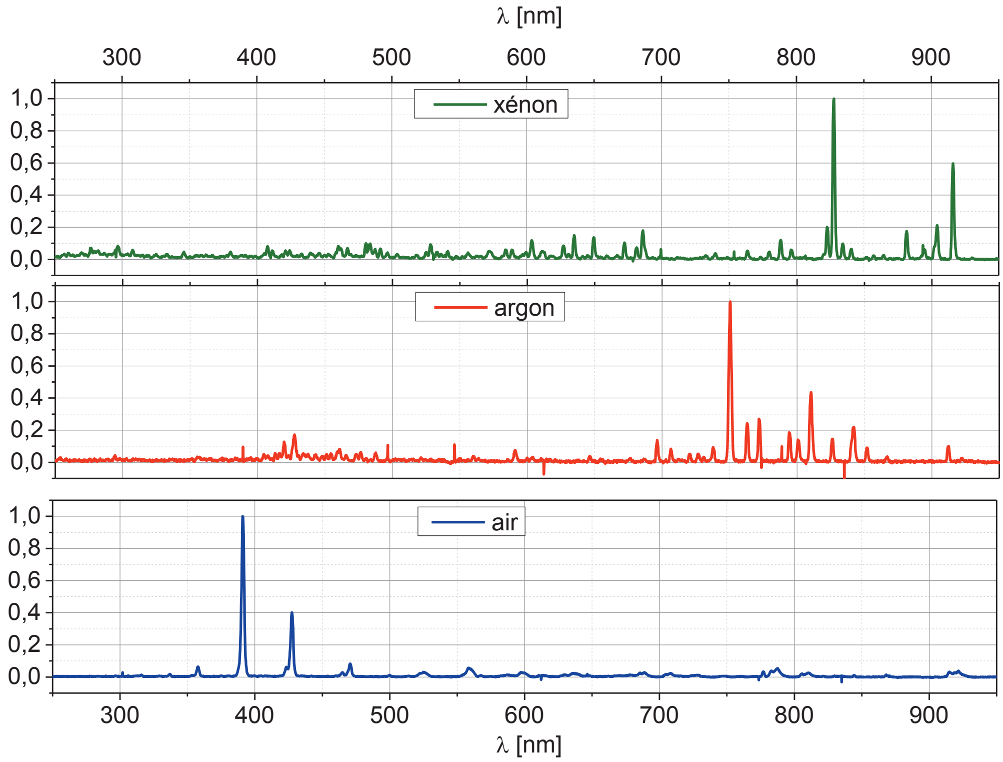

Figure 12. EBF spectra of xenon, argon, and air.

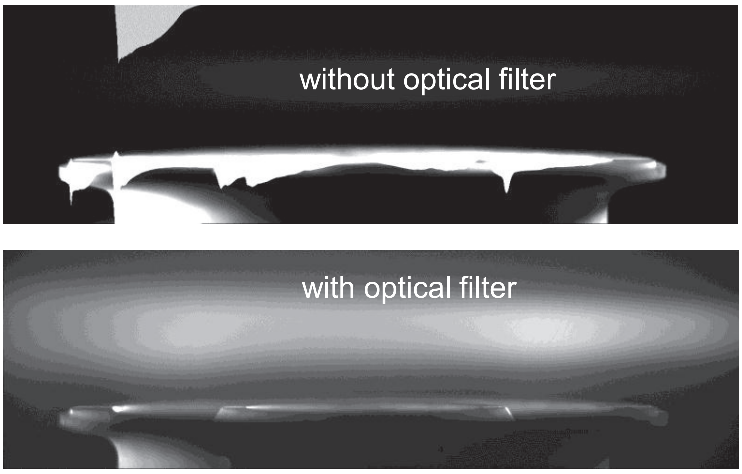

Figure 13. Effect of the optical filter on the fluorescence image with argon. Low pass filter, cutoff at 715 nm.

IV. Conclusion

Electron beam fluorescence has been used successfully to assess the homogeneity of propellant gas injection in the discharge channel of a PPS®5000 Hall Effect Thruster. Azimuthal variations of 5% have been measured on a development anode, with measurement incertitude of less than 2%. Spectral filtering has been evaluated and has enabled to apply the technique even in presence of an intense source of parasitic light. Another improvement could be obtained with pulsing the electron beam on a short duration with a high beam current, which would enable to reduce the acquisition time of the CCD camera, and hence the parasitic light level. Finally, it is worth mentioning that the diagnostic could be automated to be implemented on a production line of anodes.

References

[1] Packan D., Bonnet J., and Rocca S., "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, *31st International Electric Propulsion Conference*, Ann Arbor, USA, 2009.