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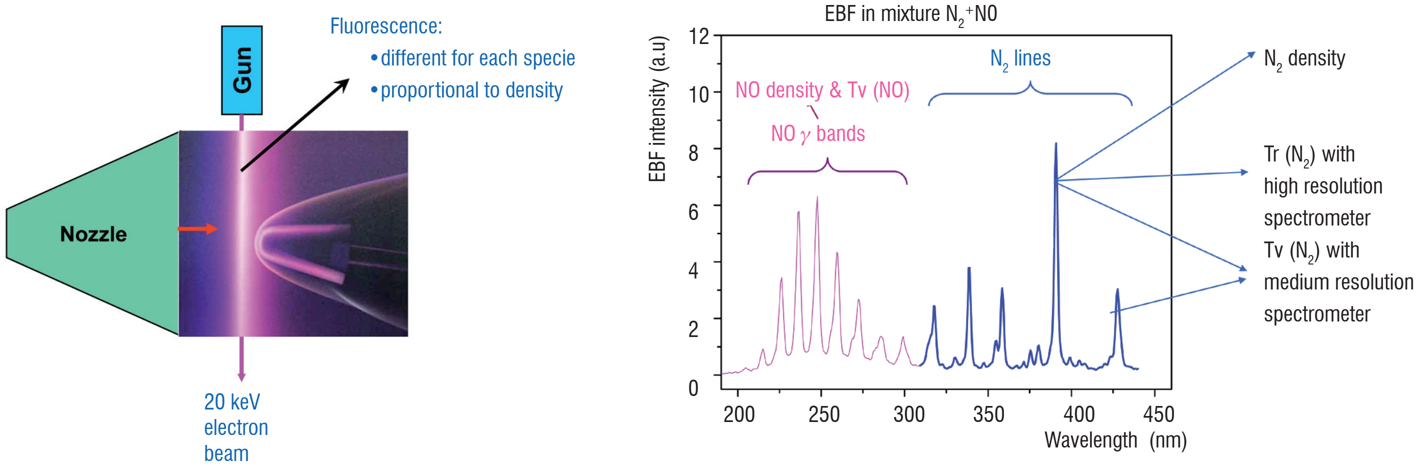
Electron Beam Fluorescence in Hypersonic Facilities

The Electron Beam Fluorescence (EBF) technique is well-suited to providing local measurements in low-density high-speed flows for atmospheric reentry studies. High fluorescence yields are obtained from the excitation of the molecules or atoms of a gas flow with high energy electrons, which makes this technique advantageous for studying very low density gases. The most common measurement is flow field visualization with a sweeping electron beam (or sheet of electrons) from which shock structures of the flow can be observed and in certain cases a density map of the flow field can be obtained. Spectroscopic analysis of fluorescence leads to species detection as well as rotational or vibrational temperature measurements. This is particularly useful for characterizing the shock layer chemistry at non–equilibrium which usually occurs with high speed flows or in studying boundary gas-surface interactions. Velocity measurements are also possible using the Doppler shift principle or with a time of flight method with a pulsed electron beam.

Introduction

Characterization of high enthalpy flows is of paramount importance for improving our understanding of the various tests and experiments carried out in supersonic facilities to simulate the dynamics and the energy exchanges which take place during the re-entry of vehicles through the upper atmosphere. In addition to classical probes, new approaches based on electron beam fluorescence, X-ray scattering and laser diagnostics have been developed to improve our knowledge of hypersonic flows. These new techniques are attractive because they allow for non-intrusive measurement of density, velocity, and translational and vibrational temperatures within the flow field.

The Electron beam fluorescence (EBF) technique is particularly well-suited to low density hypersonic flows (< 10^{16} molecules/cm^3) because high fluorescence yields are obtained from excitation of the molecules or atoms of gas flows with high energy electrons, making this technique advantageous for studying very low density gases. Since its first application in 1953, it has been used in numerous facilities to perform local and non-intrusive measurements of density, vibrational and rotational temperatures Tv, Tr and velocity on different species such as N_2, NO, CO, CO_2 and He (References [1] to [15]). The technique has also been applied on several occasions for in-flight measurements on rockets to probe the shock layer or the upper atmosphere ([12] to [16]).



a) Typical EBF setup in a wind tunnel - Visualization of the electron beam and use of its afterglow to visualize a Mach 10 flow around the ESA EXPERT atmospheric re-entry vehicle

b) EBF spectra of N_2 and NO

Figure 1 - Typical features of the EBF technique

The EBF technique is based on the excitation (and related broadband fluorescence) induced by an electron beam on gas atoms and molecules along the electron beam's path. Figure 1a presents a typical EBF setup in a wind tunnel application. In a low-density gas flow, the use of an energetic electron beam (typically 25 keV) induces a complicated set of excitations in the gas all along the beam. These excitations produce broadband fluorescence ranging from X-rays to infrared. Each molecular or atomic species has its characteristic EBF signature in the form of characteristic vibrational bands or rotational emission lines from which measurements specific to that species can be performed.
For molecular Nitrogen, the main emissions in the UV and visible spectrum (Figure 1b) are mainly the first negative system $N_2^+(1N)$ and the second positive system $N_2(2P)$ from which most of the measurements are made. For NO, the most prominent bands are the gamma bands in the UV between 200 and 300 nm.

For a given species, the spectral analysis of its fluorescence provides the vibrational temperature and even the rotational temperature if high spectral resolution is possible for that species. The density of that species in the flow can be measured from the intensity of one or several of its fluorescence lines. Velocity measurements can also be made by Doppler shift of the radiative emission or with the time of flight method [2][3].
These measurements can be useful in the following applications:

- Validation of aerodynamic simulation codes from wind tunnels or in-flight testing
- Gas-surface accommodation
- Atmospheres of other planets

Parameters	Range
Flow Density	10^{13} -10^{16} molecules/cm^3
Flow visualization	10^{13} -10^{17} molecules/cm^3
Temperatures - of rotation Tr - of vibration Tv	from a few Kelvins to more than 1000 K
Velocity by Doppler shift Velocity by Time of flight	1000 m/s (for density range 10^{18} – 10^{13} molecules/cm^3

Table 1 presents the various parameters which can be measured on nitrogen based flows.

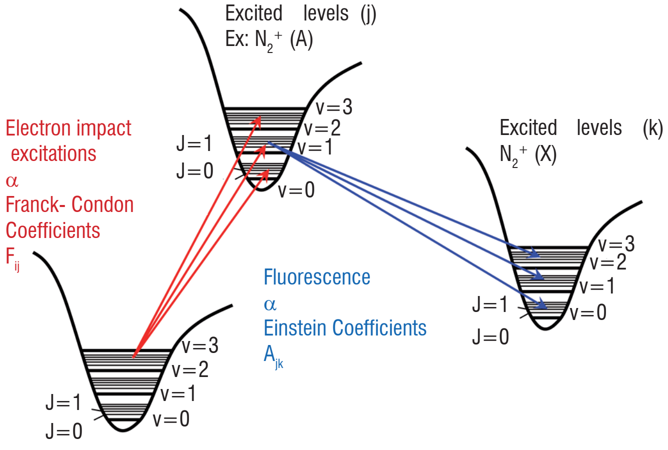
The measurements are:

- non-intrusive
- local (spatial resolution depends mainly on the optical imaging of the fluorescence from the beam which usually has a diameter of 1 mm: we can easily have a resolution of 1 mm^3).

This technique has also been used on other species such as NO, O_2, O and N, mainly to study gas discharges and in Helium flows for high Mach number studies. There is also a renewal of interest in extending the technique to higher densities and to studying CO/CO_2 flows (Mars atmosphere studies) [17].

Measurement principle

Electron impacts on atoms or molecules induce transitions among the energy levels of the atoms or molecules as depicted in Figure 2. The interactions follow dipolar rules for electrons of energy higher than 800 V. For lower energies, quadrupolar excitations are substantial and provide higher fluorescence rates, but these are difficult to use because of the excessive non-linearity between the fluorescence intensity and the electron beam intensity or gas number density. For this reason, and also for sufficient propagation of the beam in a low density gas, the technique is usually applied with electron energies of a few keV. It is then comparable to laser-induced fluorescence (LIF): from knowledge of the radiative emission and excitation coefficients, one traces the intensity of a fluorescence line to the population number density of a fundamental energy level. In fact, in EBF there is broadband excitation of many fundamental levels due to the high energy of the electrons, thereby allowing for measurement of population distributions on many fundamental levels simultaneously.



Intensity of a fluorescence line:

$$I_{jk} = n_j A_{jk} h\nu_{jk} = h\nu_{jk} \frac{\sum_i n_p v_p \sigma_{ij}(E_p) n_i}{\sum_s A_{js} / A_{jk}} \propto n_0$$

n_i, n_j : populations on levels i,j; both are proportional to the total density n_0 of the gas
n_p : density of primary electrons,
ν_p : velocity of primary electrons
E_p : energy of primary electrons, $E_p = \frac{1}{2} m_e \nu_p^2$, m_e being the electron mass
$\sigma ij(E_p)$: cross section of the excitation by electron impact, where A_{jk} is the probability of radiative transition in s^{-1}, h is the Planck constant, ν_{jk} the frequency of the transition j-k

Figure 2 - Electron Beam excitation-fluorescence principle.

The intensity of a fluorescence line is therefore proportional to the total density of the gas n_0 as n_i is proportional to n_0. This linear dependence is valid up to density levels of 10^{16} cm^{-3}. Above that value there are two phenomena which cause deviations from linearity:

- Fluorescence quenching (collisional non-radiative deexcitation)
- Supplementary excitations by secondary electrons (created through ionization from the electrons of the beam, and which have sufficient energy to cause excitation (mainly quadrupolar).

Beam dispersion also becomes important for electron density in excess of 10^{16} cm^{-3}.

Secondary effects	Criteria	Upper density limit n_g in molecules.cm^{-3}
Beam dispersion	Beam propagation length for at least 100 mm	$\leq 10^{16}$
Quenching	Linear relation between intensity of fluorescence and gas density: $I = \alpha n_g$	$\leq 3.\ 10^{16}$
Secondary electrons	Excitations by e_s are less than excitations by e_p	$\leq 10^{16}$

Table 2 – Main causes for EBF limitation to high densities

Measurements examples

Figure 3 recalls the typical setup in a wind tunnel as well as the potential measurements of the EBF technique matched against the appropriate optical detectors.

Density and flow visualization

Density measurements are quite straightforward in a low-density gas (up to 10^{15} molecules/cm^3) where the intensity of fluorescence is directly proportional to the density as shown, see § Measurement principle, page 2. As mentioned above, for higher densities, collisional non radiative deexcitation (quenching) established a non-linear relationship between fluorescence intensity and density when other parameters such as temperature are involved. Nevertheless, qualitative density variation can still be extracted from visible fluorescence for better understanding of flow structure, highlighting shock waves for example. This is usually done by sweeping the beam to illuminate a sheet of the flow, which provides spectacular images of visualization. Figure 4a shows an example of interaction of shock waves between two models placed in a Mach 10 flow (Onera R5 wind tunnel). Figure 4b shows a visualization of the flow structure around a 25/65 sharp double cone obtained by post luminescence from a fixed electron beam. The densities are too high here (> 10^{16} molecules/cm^3) to allow for accurate density measurements with visible fluorescence, but this kind of visualization can help in configuring the models and choosing the right type of interaction for more accurate measurements by other techniques (CARS for instance).

Ways to overcome quenching and other non-linear effects at high densities include accurate modeling of these effects or measurements using X-ray radiation which are not subject to quenching and to spectral broadening. An example of a density profile with the latter method is presented in Figure 5.

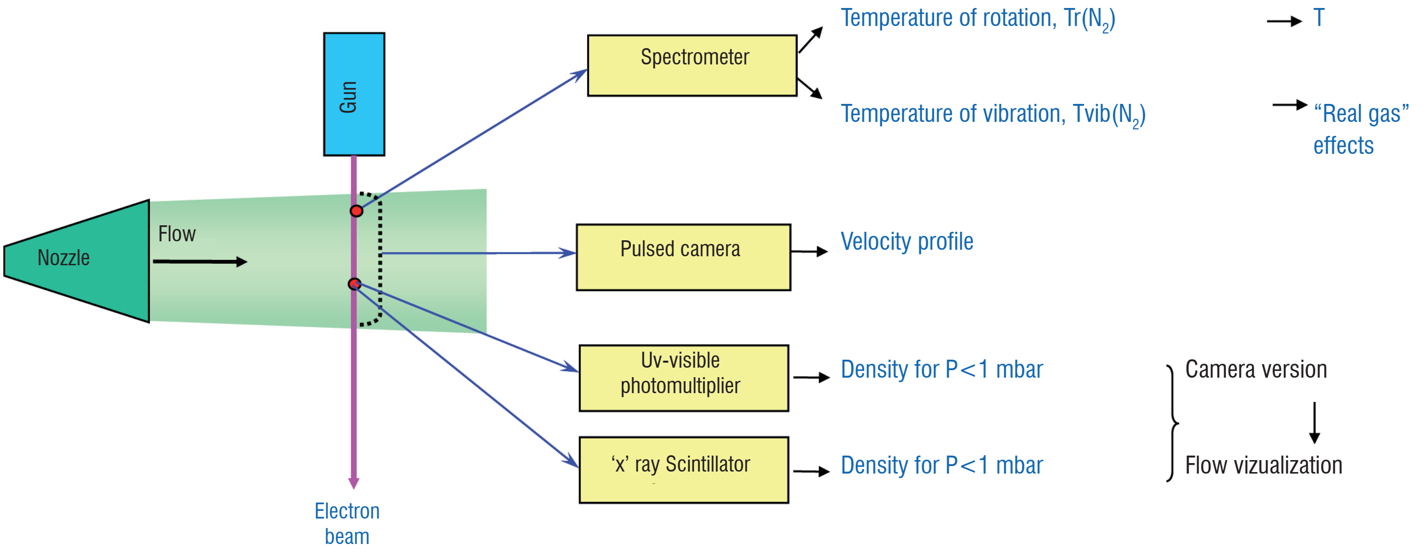
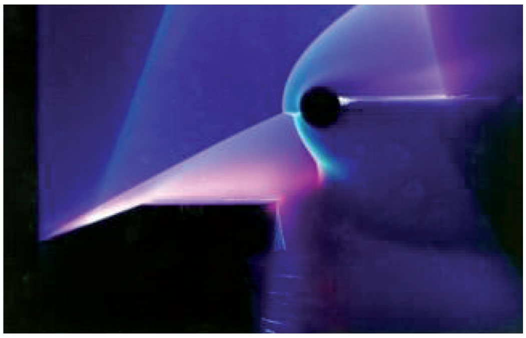
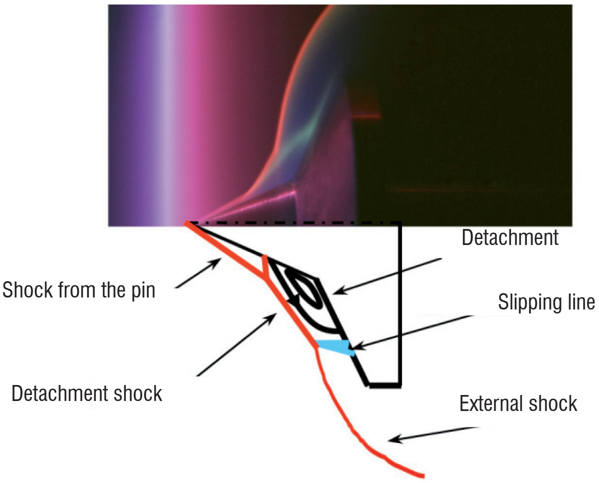


Figure 3 - EBF potential measurements and setups in wind tunnels.



a) Visualization by a sweeping electron beam to study the interaction of shock waves.



b) Visualization by post-luminescence to study flow structure around a 25/65 sharp double cone.

Figure 4 – EBF visualization in a Mach 10 flow.

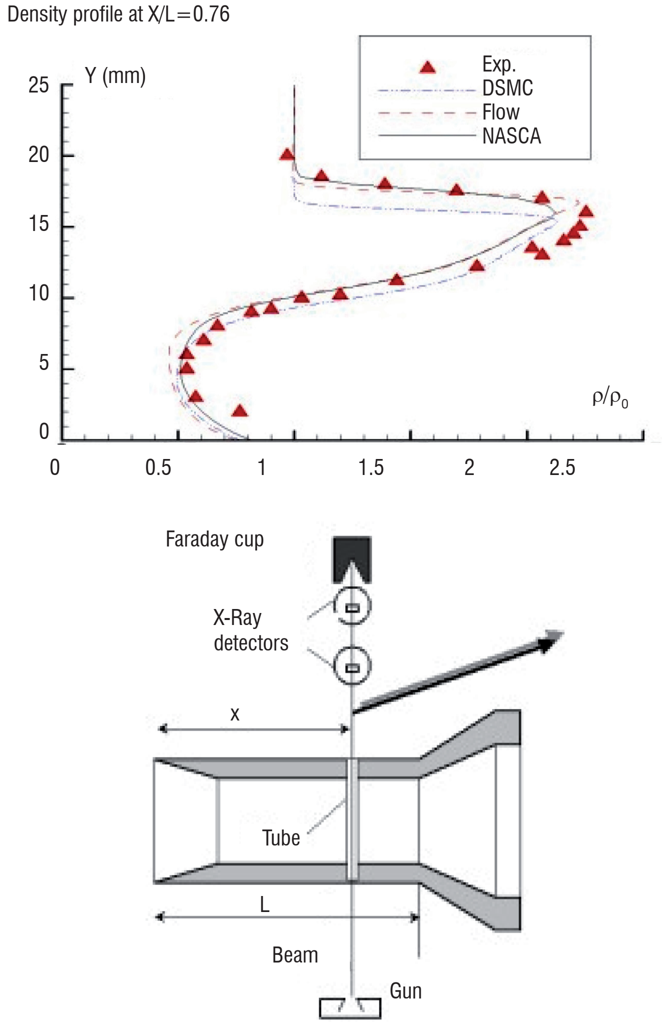


Figure 5 - Flow density profile measurements using electron beam-induced X-ray radiation and comparison to CFD.

Vibrational and rotational temperatures

Measurement of the intensities of the rotational or vibrational lines and the use of the expression in Figure 2 allow for determination of the corresponding temperatures of a molecular species in the gas being studied.

To illustrate rotational temperature measurement capabilities at low and high temperatures, we present here an application which allowed for the characterization of a gas containing two groups of molecules, each one having a different rotational temperature (transient phase). The objective was to measure the rotational temperature of nitrogen molecules reflected from a 5 mm-diameter disc placed in a hypersonic flow.

The experiments were carried out in cooperation with the DLR at the V2G wind tunnel in Göttingen [10] [11]. The Knudsen number (λ/L where λ is the mean free path and L is a representative physical length scale) is set very high by using a low-density flow and a small surface in order to prevent a shock wave being formed in front of the surface: the molecules are just reflected from the surface. Measuring the rotational temperature of these reflected molecules allows us to study how these molecules accommodate to the surface temperature, which can be varied from room temperature up to 1200 K. The effect of the velocity of the incoming molecules has also been studied through variation of the stagnation temperature of the flow from 300 K to 1200 K.

The beam is set to cross the flow vertically at a distance of 1 mm from the disc surface. A simple lens conjugates about 1 mm of the beam on the entrance slit of a high resolution spectrometer. Figure 6a shows the rotational spectrum of only the free flow when the model is away. The rotational temperature in this case is 32 K for stagnation conditions of 1020 K and 5 bar. In front of the disc surface, the rotational structure of the fluorescence (Figure 6.b and c) is more complex as it is a superposition of fluorescence from two groups of molecules: the free flow molecules and those reflected from the surface (here found to be at 1000 K). The density of the reflected molecules can also be deduced from spectrum inversion: it is here seen to be about three times higher than the free flow in the probe volume. The data interpretation is given in reference [11].

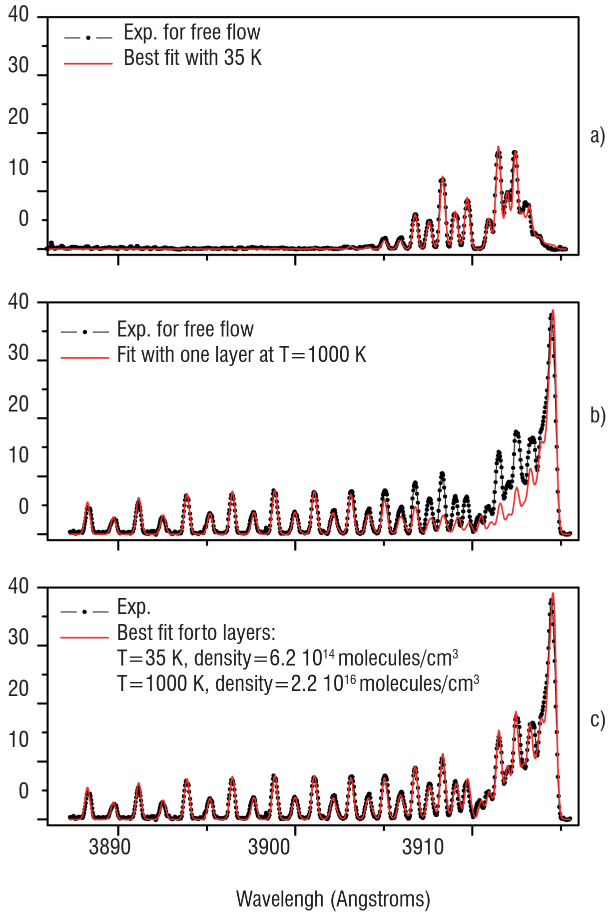


Figure 6 - EBF rotational spectra of reflected molecules by a disc placed in an N2 hypersonic flow { a) spectrum in the free stream at 35 K; b) and c) present the same spectra in the flow at 1 mm in front of the disc but with different simulated spectra to show that there are two groups of molecules: incoming flow at 35K and reflected molecules at 1000K }.

Velocity

Velocity measurements by EBF can be performed using the following methods:

- Doppler shift technique
- Time of flight technique
    - Electrical detection with Langmuir probes
    - Optical detection of afterglow

The Doppler shift technique is quite straightforward and involves simply analyzing the Doppler shift induced in the fluorescence lines observed by a high resolution spectrometer at an angle which is the smallest possible with respect to the flow axis [2]. We will describe more thoroughly here the time of flight method and particularly when it involves optical detection of afterglow.

Velocity Measurements using a classical pulsed electron beam

Gas ionization is an important process among excitations due to electron beams. This phenomenon can be used with a pulsing electron beam to induce columns of plasma which are convected by the flow. The plasma columns contain mainly N_2^+ ions and low energy secondary electrons es produced during the ionization process.

After tagging the flow with these columns of plasma, local velocity measurements can be done by measuring the time of flight of the plasma columns between two chosen points through electrical detection of the N_2^+ ions (or the secondary electrons) with Langmuir probes [3].

The movement of the plasma columns can also be traced by the radiative emissions (afterglow) produced from secondary electron excitations in the columns. Some of the secondary electrons have sufficient energy to excite molecules of the gas producing fluorescence (N_2^+1N and $N_2$2P emissions) similar to the ones due to the excitations by the primary electrons of the beam. These secondary excitations can occur over a relatively long distance downstream from the electron beam depending of the flow velocity and the relaxation time of the secondary electrons. The radiative lifetime τ of the excited molecules is very short ($\tau \sim 60$ ns), which means that the fluorescence can be considered to be emitted at the point of excitation in the columns for flow velocity V less than 10000 m/s.

Velocity measurements can be made here by measuring the distance of flight of the luminous plasma columns during a known time interval. For a single column, a streak and/or intensified camera for example can be used to take snapshot pictures at different known times to follow the column displacement. The opening time must be very short (a few hundreds of nanoseconds for velocities less than 10000 m/s) to freeze the movement of the column at each opening. Usually, the light collected is quite low and image accumulation must be used to enhance detection, but this is possible only if the flow velocity is constant. A further improvement is to use a train of columns induced at regular intervals of time by a pulsed electron beam and perform stroboscopic detection by a camera whose openings are pulsed at the same frequency of the electron gun. Chemiluminescent reactions of N_2(A) metastables (created by the electron beam) with species like NO or OH can also be used to enhance optical detection of the plasma columns [6].

Figure 7 presents an image of acceptable contrast for measuring the free stream velocity in a Mach 10 flow using a frequency of 100 kHz for both the electron gun (see box 1) and the camera pulses. Application inside a shock layer is more difficult as we must first know the local direction of the velocity or the stream line structure.

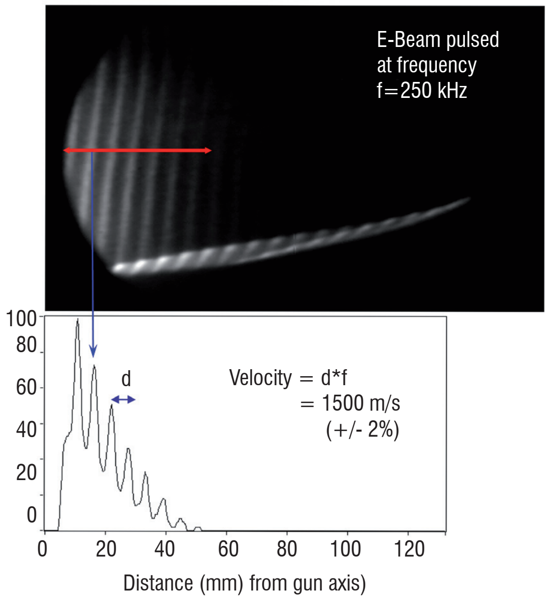


Figure 7 - Velocity measurements using pulsed afterglow. An electron beam pulsed at frequency f (pulse duration of a few hundred ns) induces a train of luminous plasma columns convected by the flow. Flow velocity is proportional to the distance between two successive columns.

Box 1 - Electron guns

The electron gun is a key element in the EBF technique, which requires a thin monoenergetic electron beam of a diameter around 1 mm (for adequate spatial resolution), energy of about 20 keV (for propagation length of a few hundred mm in a gas at pressures of 100 Pa) and current of about 1 mA (for a sufficient fluorescence signal).
At Onera we have developed three types of guns:

- hot filament [1] [2] [3],
- secondary emission (beam or sheet emission) [4],
- pseudo spark [8] [18] [19],

Their main characteristics are presented in Figure B1- 01 and Table B1 - T1.

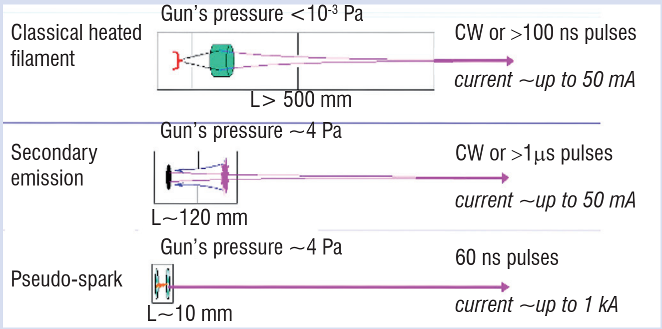
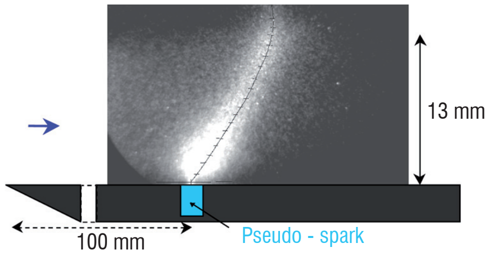


Figure B1 - 01 - The three main types of electron guns

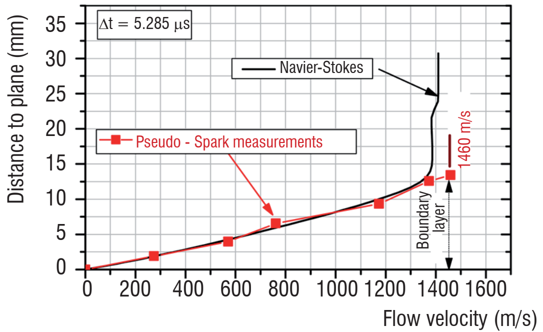
Gun	Measurement duration	Repepition rate	Measurements
Classical gun (Hot filament) (beam 30 kV, 1 m A, diam 1, 0.1 mm)	100 ns to CW	CW or pulsed up to 10 MHz	All EBF measurements in low enthalpy conditons (Hi/RTa <10)
Pseudo-spark (beam 60 kV, 100 A,diam 1 mm)	30 ns to 5 µs	Pulsed up to 1 kHz	Velocity in all conditions; sufficiently miniature to be placed inside a body in the flow
Secondary emission (25kV, 10 mA, diam 1 mm)	1 µs to CW	CW or pulsed up to few kHz	All EBF measurements

Table B1 - T1 Main properties and performances of different types of electron gun

Usually heated filament electron guns (and pseudo-spark in a few experiments) are used to generate the electron beam in wind tunnels. But these devices are quite difficult to use in flight experiments because of their relatively large weight and energy consumption as well as secondary vacuum requirements for their operation.



Snapshot showing the convected plasma column



Results of velocity profile

Figure 8 - Velocity profile measured by a pseudo spark electron from within a flat plate model in the Onera R5 Mach 10 wind tunnel.

Velocity measurements across the boundary layer in hypersonic flows using a pseudo spark electron-beam-assisted glow discharge

Instead of image accumulation, one can try to increase the afterglow by using a more intense electron beam or some technique to increase the number of excitations in the plasma column. One such method is to use a so-called "pseudo spark" type electron gun which by principle of operation delivers a pulsed beam of some tens of nanoseconds (see box 1). However, the high current intensity (a few amps) remains insufficient for single-shot detection with an intensified CCD. One way to further increase the afterglow is to create and maintain a glow discharge in the plasma column created by the pseudo spark beam through proper electrical ground connections [8].
This pseudo spark technique offers the further advantage of being quite small in dimensions so that it can be placed inside a model to measure the velocity profile in a shock layer of simple geometry. We present in Figure 8 an example of a velocity profile across a boundary layer obtained with an electron gun inside a model in the Mach 10 low-density hypersonic R5 wind tunnel at Onera. In these experiments, an intense pulsed electron beam is emitted by a very small

Box 2 - EBF for in - flight measurements

Based on the advent of a new compact electron gun designed from the secondary emission principle, Onera is studying a laboratory prototype to demonstrate the feasibility of obtaining a compact EBF instrument for in-flight measurements onboard an atmospheric re-entry vehicle as shown in Figure B2 - 01.

The perimeter of development for the in-flight EBF system will have at least the following measurement objectives:

- Species density:ρ/ρ_∞ profile across a shock layer. The species is N_2 and possibly NO in the event of atmospheric re-entry or CO and CO_2 in the case of a Martian re-entry.
- Temperature of vibration T_{vib} and/or temperature of rotation $T_{rotation}$ of one of the above mentioned species;

The measurements are to be made with a spatial resolution on the order of a few mm^3 along a line perpendicular to the wall of the vehicle. The segment of the line to be measured is of a minimum length of 100 mm with the center at about 300 mm from wall of a vehicle. The measurements are to be provided at a minimum repetition rate of 10 Hz in the altitude range of 50 km to 70 km.

Measurements at higher altitudes are possible with this technique but at the expense of a lower signal to noise ratio which can partly be compensated for by a longer integration time ($\sim$1 s) and lower repetition rate ($\sim$1 Hz). Measurements are less likely below 50 km due to non-linearity in the fluorescence signal as well as high beam dispersion and attenuation.

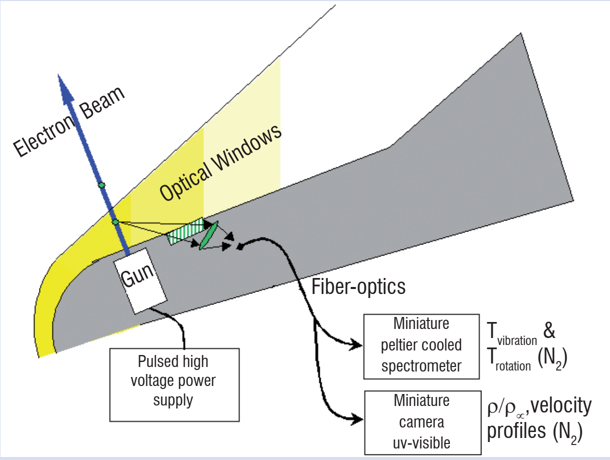


Figure B2 - 01 - Electron beam fluorescence measurements on board a re-entry demonstrator

The EBF prototype will use an electron gun to produce a pulsed (around 10 Hz) electron beam of about 20 keV energy, about 1 mA intensity and 2 mm diameter which will be emitted through a small diameter (few mm) opening on the vehicle wall. A turbo-molecular pump and high-voltage power converters operating from 24 V are needed for the beam emission. Two optical detectors (one camera and one spectrometer) will be used to observe, through specific optical windows on the vehicle wall, the fluorescence induced by the electron beam. The data collected will be transmitted to the vehicle controller for recording and/or tele-transmission. The processing of the data will be done during the post-flight analysis.

The design studies leading to the final configuration presented in figure B2 - 02 used many off-the-shelf components selected for their potential to be easily upgraded for space applications. The obtained prototype is quite compact, occupying a volume of 370 x 300 x 250 with few interfaces for data communications and a low-voltage power supply. The mass of the instrument is around 11 kg but there are still ways to reduce the mass through further optimization of the design.

One of the validation tests of the final laboratory prototype was done in a small transparent vacuum chamber. This chamber is a cylinder of 300 mm diameter and of 400 mm length with the cylindrical part made of 8 mm thick glass. There are metallic plates on the top and bottom of this cylinder. The EBF assembly base plate has been adapted to the top plate where appropriate holes have been drilled for the prism windows and the electron beam exit. The bottom plate is equipped with the necessary feed-throughs for pumping and pressure monitoring. Figure B2 - 03 shows the setup disposed on an office table. Alongside the cylinder there is an electronic box which was specially manufactured to manually control the operation of the EBF assembly. This electronic box also includes a converter to provide 24 V power to the EBF prototype from a standard 220 V power supply.

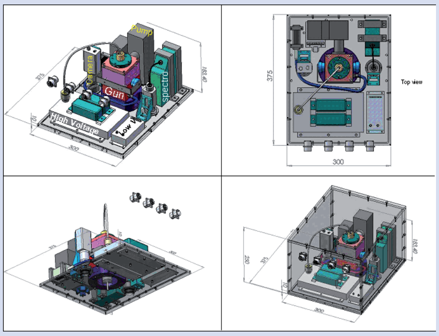


Figure B2- 02 - EBF final assembly design for the laboratory prototype

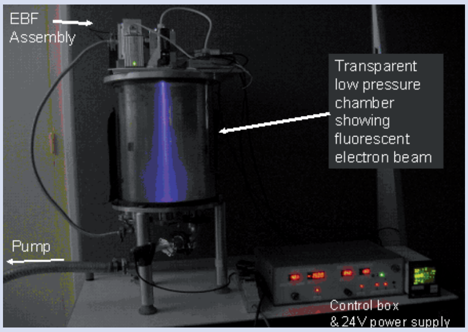


Figure B2- 03 - Tests of the laboratory prototype for an inflight EBF instrument

(2cm x 3 cm) pseudo-spark [18] [19] electron gun located inside the model (2D grounded metallic plate).

It penetrates the flow from a 0.3 mm hole across the surface, and traces the path of a high-voltage glow discharge in some ten nanoseconds. The filamentary discharge is instantaneously connected to a high voltage capacitor via a thin, high-voltage metallic rod placed parallel to the flow axis and 100 mm away from the gun exit. This maintains the gaseous filament very bright for a few microseconds. The initial linear pattern of the discharge then closely follows the streamlines which are known in this case. It is verified that no distortion occurs when the discharge is triggered within the same gas at static pressure.

At a precise time delay (5 μs) after the electron gun actuation, a CCD camera is opened briefly (250 ns) to image the position of the luminous column convected by the flow (Figure 8). The local velocity of the stream versus the distance above the plane is simply deduced from the horizontal displacement of a given point during the selected delay time.

The observation field extends 20 mm above the model. As a calibrated grid is used to determine the magnification of the optics, the global accuracy of this method can be estimated to 50-100 m/s. For identical aerodynamic conditions, the measured velocity profile compares correctly to the results of a numerical Navier-Stokes calculation.

Conclusion

Onera has further developed the EBF technique through new methods and electron guns and extended the application to high enthalpy flows together while rendering it less complex for routine use in wind tunnels. The challenge now is to use this technique for in-flight measurements in the flow around a reentry vehicle for Earth reentry studies or probing of the atmospheres of other planets, and Onera has already taken steps in this direction through the development of a prototype described in box 2 ■

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