Development of a compact Electron Beam Fluorescence (EBF) instrument for high enthalpy flow characterization

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ABSTRACT

A prototype based on the Electron Beam Fluorescence Technique (EBF) is being developed for in-flight measurements in the shock layer of a re-entry demonstrator. The measurement objectives are rotational and vibrational temperatures of N_2 as well as the densities of N_2 and NO at different positions in and outside a shock layer. There is also renewal of interest in extending the technique to higher densities and to probe CO/CO_2 flows (Mars atmosphere studies).
The present paper gives a brief description of the status of the instrument with details on the optimization work performed to miniaturize the electron gun and the study of induced fluorescence of some gases and mixtures in laboratory vacuum chamber.

1. INTRODUCTION

The characterization of high enthalpy flows is of paramount importance for an improved understanding of various tests and experiments which are conducted in supersonic facilities to simulate the dynamic and the energy exchanges which take place during the re-entry of vehicles through the upper atmosphere. The Electron Beam Fluorescence (EBF) has been identified as a good candidate among non intrusive techniques for in-flight data collection of shock layer chemistry. It can provide direct measurements of flow physical properties to be used at a later stage for validation of aerothermodynamics design tools.
The objectives of this measurement technique in re-entry applications is to measure vibrational and rotational temperatures of N_2 and partial densities of N_2 and NO in at least two selected locations within the flow-field surrounding a re-entry vehicle, for example one point in the shock layer and one point in the free stream. In this way the EBF serves also as an air data system as it provides a direct measurement of the free stream density, the knowledge of which is necessary for post flight analysis.
The EBF density, vibrational and rotational temperatures and velocity in low density hypersonic flows (< 10^{16} molecules/cm^3) on different species are been investigated by many researchers: N_2, and Huber and Miescher for NO, CO and CO^+ by Krupenie [8], Nicholls and Herzberg [9] [11], CO_2 by Cattolica's team [10].
The technique has also been used on several occasions for in-flight measurements on board rockets to probe the shock layer or the upper atmosphere [4] to [5].). Reference [6] is an excellent long review of the technique is based on the excitation and related fluorescence induced by an electron beam on the gas atoms and molecules along the electron beam path. Figure 1 presents a typical setup of EBF in a wind tunnel application. In a low density gas flow, the use of an energetic electron beam (typically 25 keV) induces excitations in the gas all along the beam. These excitations produce fluorescence emitted at positions where collisions occur between electrons (at relativistic velocities) and molecules Thus EBF spectra usually range from X ray to the infrared. Each molecular or atomic species has its characteristic EBF spectral signature in the form of characteristic vibrational bands or rotational emission lines from which measurements specific to that specie can be performed.

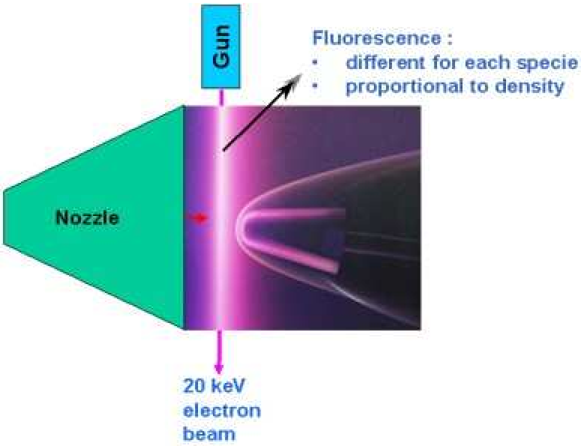


Figure 1 - Typical setup of EBF in a windtunnel - Visualisation of the electron beam and exploitation of its afterglow to visualise a Mach 10 flow around the ESA EXPERT atmospheric re-entry vehicle

For molecular Nitrogen, the main emissions in the UV and visible spectrum (Figure 2) are mainly the first negative system N_2^+ (1N) and the second positive system N_2 (2P) from which most of the measurements are performed. For NO, the most prominent bands are the gamma bands in the UV between 200 and 300 nm.

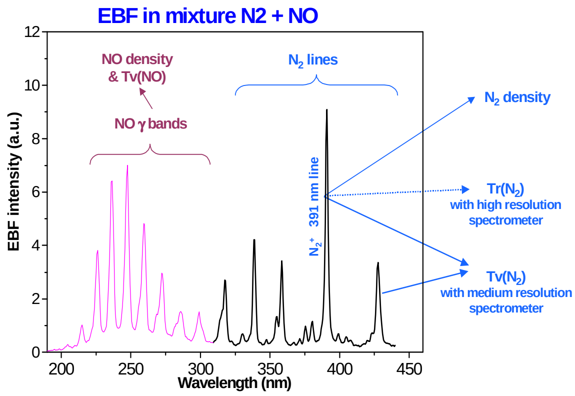


Figure 2: EBF spectrum of N2 and NO

Moreover, the use of mono-energetic electrons allows one, from knowledge of the radiative emission and excitation coefficients (Figure 3), to trace the intensity of a fluorescence line to the population number density of a fundamental energy level.

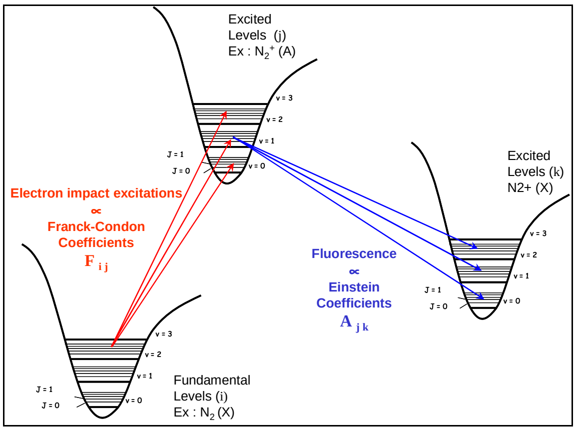


Figure 3- Electron Beam excitation-fluorescence principle

The intensity of a line is proportional to the total density of the probed specie. 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 de-excitation)
- Supplementary excitations by secondary electrons (created through ionization from the electrons of the beam and which have sufficient energy to bring excitations (mainly quadrupolar).

Beam dispersion becomes important also as from 10^{16} cm^{-3} which is therefore upper density limit for the EBF technique.

The EBF measurements can be useful in the following applications:

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

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

Parameter	**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	as from a few Kelvins to more than 1000 K

Table 1- Parameters which can be measured by EBF on nitrogen based flows

2. PROTOTYPE FOR IN-FLIGHT MEASUREMENTS

The EBF technique is well known in ground facilities but has been seldom used for in flight experiments due to its complexity and dimensions particularly for the electron gun.

ONERA has developed in the frame of one of its internal project on hypersonic, a new concept of gun that associates small size, low power consumption and that does not require secondary vacuum to operate. These features are expected to greatly ease the in-flight application of EBF. The prototype of such a gun is illustrated in Figure 4. Ions produced through an electrical discharge between the anode (wire) and the walls are accelerated towards the cathode maintained at a high voltage (- 25 keV). Their impacts against the cathode extract electrons which are accelerated counter-wise and are collimated into a thin beam by the geometry of the system and provide a few mA of beam current. Operation with internal pressure up to 5 Pa of air has been demonstrated.

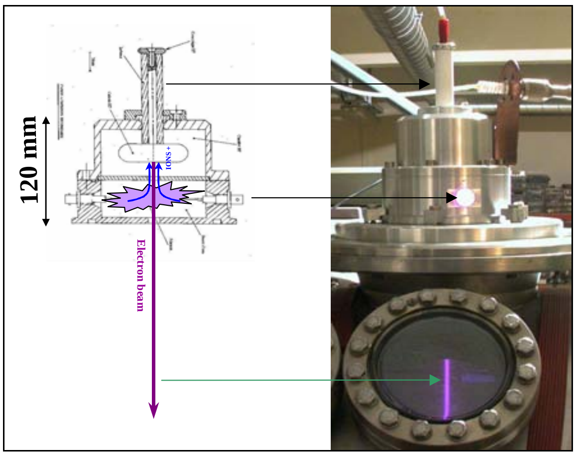


Figure 4 - Miniature electron gun prototype

A single stage differential pumping with a small turbo pump (10 l/s) and a 3 mm conductance is able to maintain less than 3 Pa in the gun with more than 100 Pa outside.

Based on the advent of this new electron gun, ONERA recently carried a study aimed at designing, building and validating a laboratory prototype to demonstrate the feasibility of obtaining a more compact EBF instrument capable of all the envisioned in-flight measurements [2],[3]. The principle of the targeted prototype is shown in Figure 5.

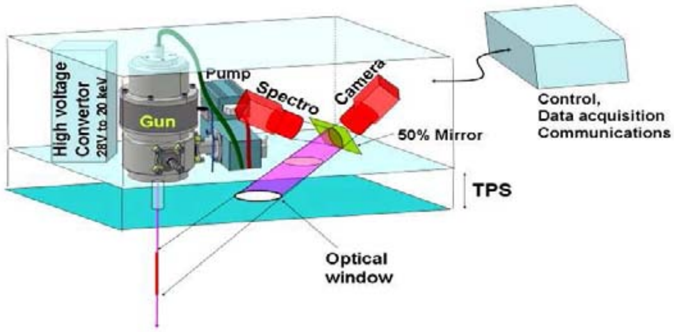


Figure 5- Target EBF assembly

The EBF prototype will use an electron gun to produce a pulsed (around 10 Hz) electron beam of about 25keV energy, about 1 mA intensity and 2 mm diameter which will be emitted through a small diameter (few mm) exit on the vehicle wall. A turbo molecular pump and high voltage power converters operating from 24 V are needed for the beam emission. At least two optical detectors (one CCD camera and one spectrometer) will be used to observe, through one or two optical windows on the vehicle wall, the fluorescence induced by the electron beam. The data collected will be transmitted to the vehicle controller for saving and/or tele-transmission. Processing of the data will be done during the post flight analysis.
The perimeter of development for the in-flight EBF system has been set to have at least the following measurement objectives:

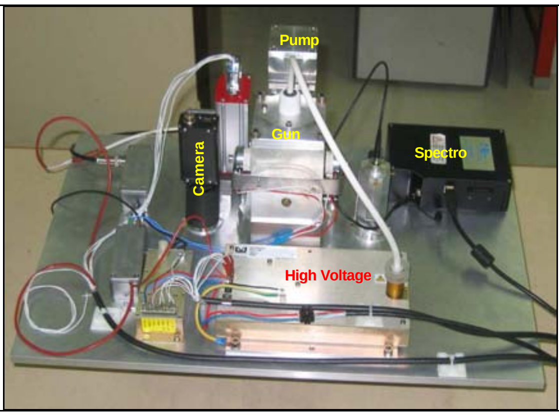
Specie density: ρ/ρ_∞ profile across a shock layer. The specie is N_2 and eventually NO in case of an atmospheric re-entry or CO and CO_2 in case of a Martian re-entry.

Temperature of vibration T_{vib} and/or temperature of rotation $T_{rotation}$ of one of the above mentioned species;

The measurements are to be performed along a line perpendicular to the wall of the vehicle. The segment of the line to be measured is of minimum length of 100 mm with the centre 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 70 km to 50 km. Measurements at higher altitudes are possible with this technique but at the expense of lower signal to noise ratio which can partly be compensated by a longer integration time (~1 s) and lower repetition rate (~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

3. LABORATORY PROTOTYPE

These tests were carried in a vacuum chamber (cylinder 3.6m long and of diameter 0.4m) with nearly all the key components of the EBF assembly positioned on a metallic plate of larger dimensions than a flight dedicated plate (Figure 6a). Such a large plate is required for the coupling (to avoid vacuum leaks when coupling) to the vacuum chamber. Moreover, the vacuum chamber is not large enough to allow complete immersion of the EBF assembly which could therefore not be tested to operate as a whole instrument in vacuum conditions.



a) Assembling of the intermediary EBF setup

b) Operation of the setup showing a fluorescent electron beam

Figure 6- Tests of the intermediary EBF setup in a vacuum chamber

Figure 6b shows the coupling of this intermediary setup to the vacuum chamber and the fluorescence trace of the electron beam during its operation.

The last validation tests of the final laboratory prototype are performed in a small transparent vacuum chamber. This chamber is a cylinder of diameter 300 mm and of length 400 mm with the cylindrical part made of glass of 8 mm thick. There are metallic plates at 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 electron beam exit. The bottom plate is equipped with necessary feed-troughs for pumping and pressure monitoring. **Erreur ! Source du renvoi introuvable.** shows the setup disposed on an office table. Aside the cylinder is placed an electronic box which has been specially manufactured to control manually the operation of the EBF assembly. This electronic box also encompass a converter to provide 24 V power supply to the EBF prototype from standard 220 V power supply.
At first step, the high voltage is limited to 15keV to avoid X-ray emission crossing the glass wall of the cylinder. This result validates the correct operation of the EBF laboratory prototype.

The main objectives of the present study were to demonstrate the feasibility of manufacturing a compact EBF assembly. The next steps now are to adapt this assembly to comply with the harsh environmental requirements for a space flight. The laboratory prototype successfully validated as described above has been manufactured with many off-the-shelf components.

4. EXPERIMENTAL DETAILS AND RESULTS

A spectral analysis of different gases and their mixtures were performed in a vacuum chamber. The data from this spectral analysis will be used for post-experiment data reduction.
In the present experiments a beam of 14 keV induces fluorescence intensity as it propagates through the gas. The vacuum chamber which was maintained at gas pressure between 10^{-3} and 1 mbar at a temperature of 300 K (static mode). A turbo-molecular pump allows making differential pumping between the ion source and the rest of the vacuum chamber.
The fluorescent emission resulting from electron impact and ionization of the gas molecules could be observed through a UV-quartz window.
A Faraday cup mounted to the vacuum chamber was used to collect the electrons after they passed through the chamber, and the current of the beam was thus recorded for each image or spectra collected.

4.1 Imaging fluorescence

A CCD camera system of 1340X400 pixel array was used to make a plane image of the electron beam. This camera allowed the beam dispersion study which consisted of direct measurement of the FWHM of the beam compared to the axial distance.
A filter centered at 391.4 nm with a FWHM bandwidth of 10 nm was used to observe the most prominent transition of N_2, $B^2\sum^+_u$ -> $X^2\Pi_g$. Images of the electron beam fluorescence were recorded at various pressures (0.1 to 1 mbar) and various beam voltages (15 to 27 kV). Each images was corrected from the background and the signal normalized by the beam current.
Figure 7 shows the beam dispersion after 30 cm of propagation. The axis originates at 30 corresponding to the output of the beam through the 1mm diameter.

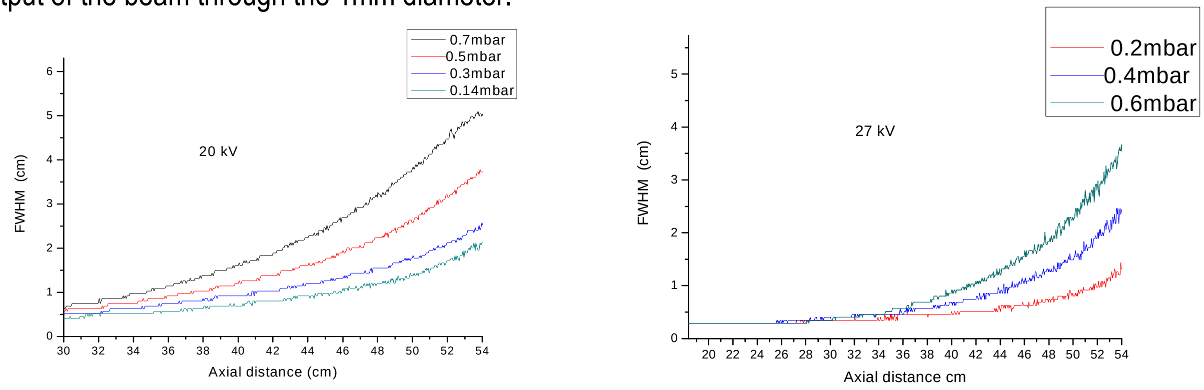


Figure 7: Electron beam dispersion

a) Dispersion a different pressures for 20 keV electron beam energy and b) dispersion at different pressures for 27 keV electron beam energy

4.2 Spectroscopy

A study of electronic spectra of some molecular gases was performed. This study enables to understand the chemical and physical processes that take place in studied atmospheres.
Depending of the interested region we use various spectrometers and various gratings.
- Ocean Optics HR4000 (200 nm to 1100 nm) and 0.2 nm resolution)

- BWTEC spectrometer from 200 to 600 nm

- Princeton's ACTON Instruments spectrometer with 300 grooves/mm grating (1nm resolution) et 2400

grooves/mm grating (0.125nm resolution) covering 175 to 1300 nm.

Spectroscopic investigations are followed by post-data reduction.
Each spectrum was corrected by spectral radiance of the Deuterium lamp as a function of wavelength, (Figure 8 shows the response of the ACTON spectrometer used for data correction and wavelength calibration by using a deuterium lamp and background subtracted from collected spectrum.

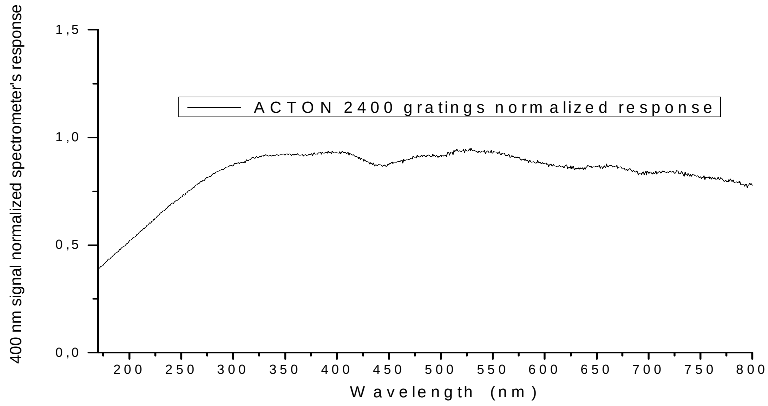


Figure 8: ACTON Princeton 2400 grooves/mm grating normalized response in the region of 170-800nm.Wavelength correction by calibration with a Deuterium lamp.

Following figures show some of spectra for these gas and their mixtures:
Figure 9 shows spectra of N_2/NO mixture gas at a pressure of 0.4 mbar. Vibrational bands between 300 and 450 nm corresponding to nitrogen bands (N_2 1N and N_2 2P) and gamma bands of NO between 200 and 300 bm. Using 2400 grooves/mm grating we can resolve the rotational structure. Figure 10 shows, rotational structure of the first negative system of N_2 ($B^2\Sigma^+_u$ -> $X^2\Pi_g$).
In Figure 11, transition between 190 and 300 nm corresponds to B-X (first negative system) bands of CO+ and comet-tail system of CO+ between 300 and 500 nm.
Figure 12 shows both CO_2^+, $B^2\Sigma^+_u$ -> $X^2\Pi_g$ doublet at 289 nm and the CO_2^+,$A^2\Pi_u$ -> $X^2\Pi_g$ between 337 and 450 nm.
First attempt to identify some systems in a N_2/CO/CO_2 mixture gas is shown in Figure 13

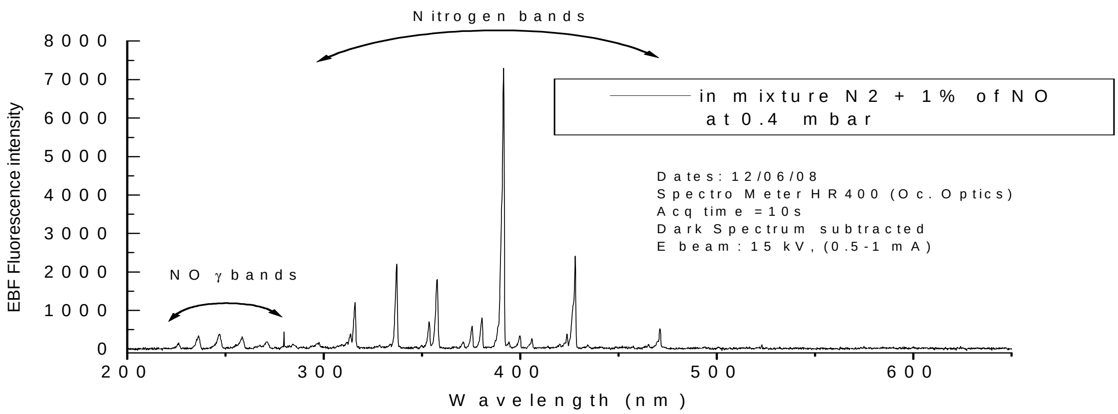


Figure 9: Spectrum of a N_2/NO (99%/1%) mixture gas

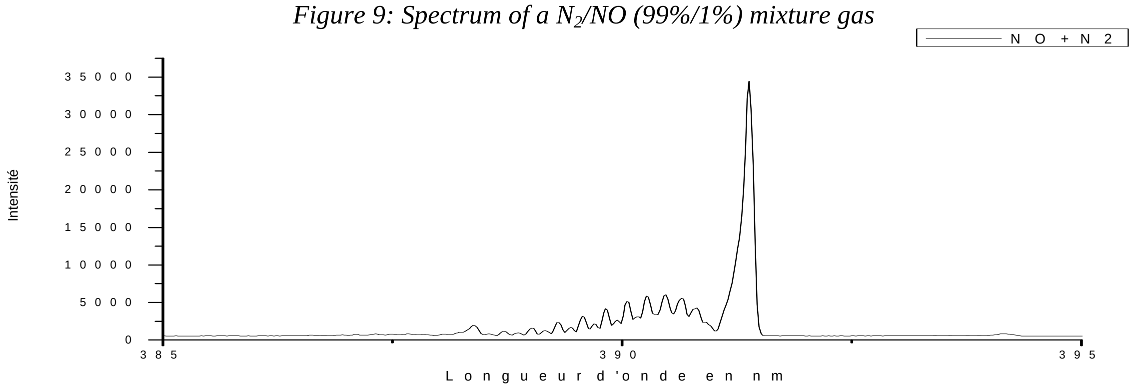


Figure 10: Rotational structure of first negative system of N_2 corresponding to vibrational transition N_2, $B^2\sum+_u$ ->$X^2\Pi g$ (N_2 1N (0, 0)

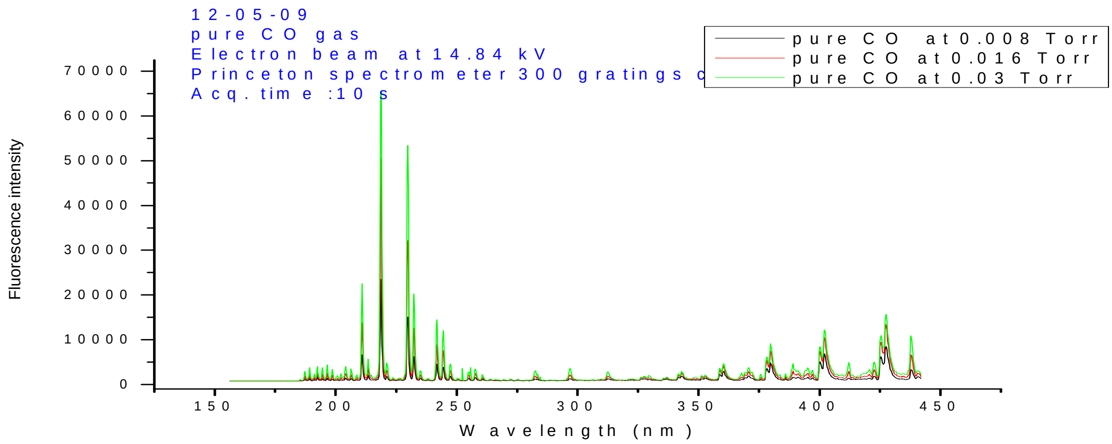


Figure 11: Spectrum of CO pure gas at 14.84 kV and different gas pressures

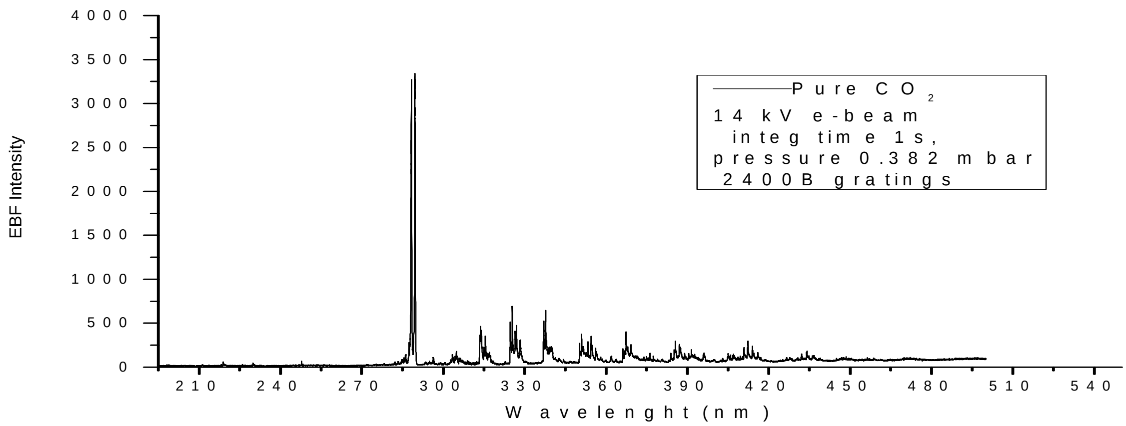


Figure 12: Spectrum of CO_2 pure gas at 0.382 mbar.

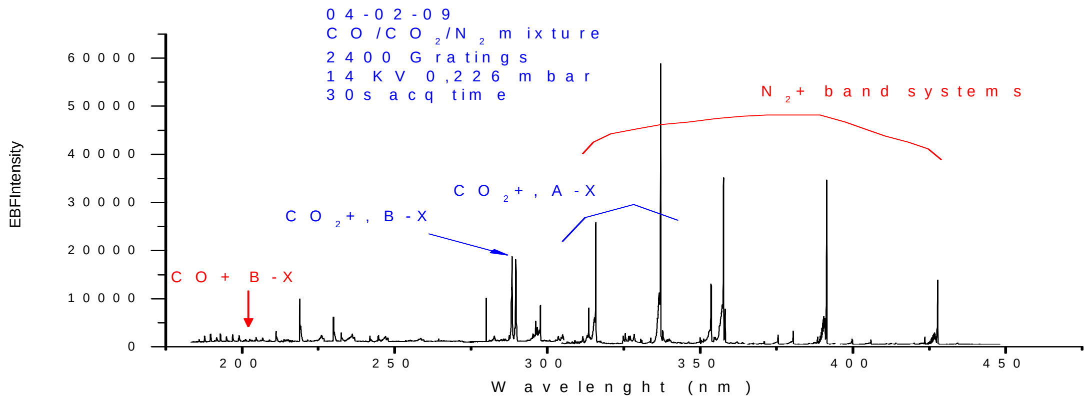


Figure 13: Spectrum of a mixture of N_2/CO/CO_2 (85%/10.5%/4.5%)

5. CONCLUSION

A compact EBF laboratory prototype has been developed in view of in-flight measurements aboard a reentry demonstrator. The in-flight objectives are the same as for ground facilities: simultaneous and multipoint measurements of density, rotational and vibrational temperatures of N_2 as well as density of NO. Other species like CO, CO_2, He and Ar are also possible with this technique provided that the observations are performed at wavelengths corresponding to these species.
The compact assembly encompasses all the main key components of the EBF technique (electron gun, turbo pump, high voltage converters, camera and spectrometer) in a box of 375 mm x 300 mm x 250 mm and weighting about 11 kg with only few electrical interfaces. Most of the components have also a potential to sustain mechanical vibration and shock up to 20g but here further qualification in a specialised facility is needed.
The laboratory prototype has been validated to emit a well collimated electron beam over a distance of at least 300 mm in a vacuum chamber at pressures up to 100 Pa and provided reference images and spectral acquisitions for density profile and Tv temperature measurements.
Spectra of in-flight interesting gases N_2, NO, CO, CO_2 have been recorded and data post-reduction codes are available. A simulation-inversion program is being developed. This program will enable to measure by inversion temperatures and density parameters.

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