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Abstract

The Fulcher band emission spectrum is used to determine rotational temperatures in the FOMSCE plasma setup. The measured temperatures are found to vary from 500 to 700 K, whereas usually in this kind of plasmas they are very close to room temperature. In this paper the interpretation of the spectra will be discussed. The influence of some plasma settings on the measured temperature will be presented.

Introduction

The FOM Surface Conversion Experiment (FOMSCE) is aimed to investigate the potential of surface negative ion production for neutral beam injection. It has been demonstrated that high H^-/D^- current densities can be produced on a negatively biased barium converter surface. In order to obtain a high negative ion yield, the converter must face a plasma with a substantial ion density. On the other hand, the neutral particle density must be kept as low as possible in order to avoid stipping of the negative ions in collisions with neutral particles. The efficiency of this proces is therefore strongly coupled to the plasma characteristics. Molecular emission spectroscopy is one of the available methods to acquire information on the plasma. Here we present first results on measured rotational spectra.

The rotational spectrum of hydrogen

The intensity of a spectral line in emission is given by

$$I^{n'v'J'}_{n''v''J''} = N_{n'v'J'} hc\nu A^{n'v'J'}_{n''v''J''} \quad (1)$$

where n', v' and J' are the electronic, vibrational and rotational quantum numbers of the upper state, n", v" and J" of the lower state and $A^{n'v'J'}_{n''v''J''}$ is the Einstein transition probability. $N_{n'v'J'}$ is the number of molecules in the initial state. If the rotational population of the initial electronic and vibrational state follows a Bolzmann distribution, the intensity distribution within the rotational band is described by

$$I^{n'v'J'}_{n''v''J''} = N_{n'v'J'} C^{n'v'}_{n''v''} \nu^4 S^{J'}_{J''} e^{-(F_{v'}(J'))hc/kT_{rot}} \quad (2)$$

$C^{n'v'}_{n''v''}$ is a constant within a fixed electronic and vibrational state. $F_{v'}(J')$ is the rotational energy of state n'. $S^{J'}_{J''}$ is the line strength. It is a product of the Hund factor and the Hönl-London factor. The Hund factor accounts for the degeneracy that depends on the magnitude of the nuclear spin and the symmetry of the initial and final states of the transition. In the case of hydrogen it is 1 for even, and 3 for odd values of J. The Hönl-London factor depends on the coupling of the rotational motion of the nuclei and that of the electrons. In the case of the studied Fulcher band transitions this coupling is described by the so-called *Hund's case b* [1]. Furthermore, the triplet splitting is negligible. For the Q-branches (no change of rotational quantum number in the transition) the Hönl-London factor is then equal to $\frac{1}{4}(2J'+1)$ [2].

The lines are identified from the calculated wavelengths corresponding to each transition. The total energy T_{tot} of a state (n, v, J) is a sum of electronic, vibrational and rotational energy:

$$T = T_e + G(v) + F_v(J) \quad (3)$$

The rotational and vibrational energy of the H_2 molecule is given in very good approximation by

$$\begin{aligned} G(v) &= \omega_e(v+\tfrac{1}{2}) - \omega_e x_e (v+\tfrac{1}{2})^2 + \ldots \\ F_v(J) &= B_v J(J+1) - D_v J^2 (J+1)^2 + \ldots \end{aligned}$$

With these equations and the molecular constants from table 1 the wavelengths are calculated from the energy difference between the upper and lower states of the studied transitions. The calculated spectrum is accurate

	State	T_e	ω_e	$\omega_e x_e$	B_e	α_e
H_2	$d\,^3\Pi_u$	112702	2371.58	66.27	30.364	1.545
	$a\,^3\Sigma_u^+$	107777	2664.83	71.65	34.261	1.671
	$X\,^1\Sigma_g^+$	0	4395.2	117.99	60.809	2.993
D_2	$d\,^3\Pi_u$	112707	1678.22	32.94	15.2000	0.5520
	$a\,^3\Sigma_u^+$	95938	1885.84	35.96	17.109	0.606
	$X\,^1\Sigma_g^+$	0	3118.4	64.09	30.429	1.0492

Table 1: *Molecular constants of hydrogen and deuterium in the $d\,^3\Pi_u$, the $a\,^3\Sigma_u^+$ and the $X\,^1\Sigma_g^+$ state in cm^{-1}*

enough for the identification of the studied bands. The deviations from the wavelength tables of Dieke [3] are smaller than the experimental uncertanty.

From equation 2 one obtains for a rotational band:

$$ln\,\frac{I_{J"}^{J'}}{\nu^4\,S_{J"}^{J'}} = -\frac{hc}{kT_{rot}}F_v(J) + const \tag{4}$$

This equation states, that from the slope of a logarithmic plot of the normalized intensities versus the rotational energy, a Boltzmann plot, a rotational temperature can be determined. Furthermore, it offers an experimental test for the assumed Boltzmann distribution of the rotational population: deviations from the straight line are deviations from Boltzmann.

The experiment

The FOMSCE surface conversion experiment is described in detail in other papers [4]. Here the main characteristics will be given. The apparatus consists of two chambers connected through a diafragm of 25 mm diameter. In the upper chamber a plasma is produced in a hollow cathode. A magnetic coil around the hollow cathode, up to the diaphragm, confines the plasma. After the diafragm the plasma expands into the lower chamber, where the barium converter and the anode are placed. Futher confinement is achieved with a permanent magnet ring just below the diafragm and another magnetic coil around the anode. The magnetic field and thus the confinement is at minimum at the height of the converter. Only the lower chamber is pumped. This results in a pressure drop over the diafragm; in the upper chamber the pressure is typically 10^{-2} mbar, in the lower or conversion chamber $2{\cdot}10^{-4}$

mbar. In this way a plasma with a high ionization degree is created in the lower chamber. In the center of the plasma column facing the converter an ion density up to 10^{13} cm^{-3} can be reached.

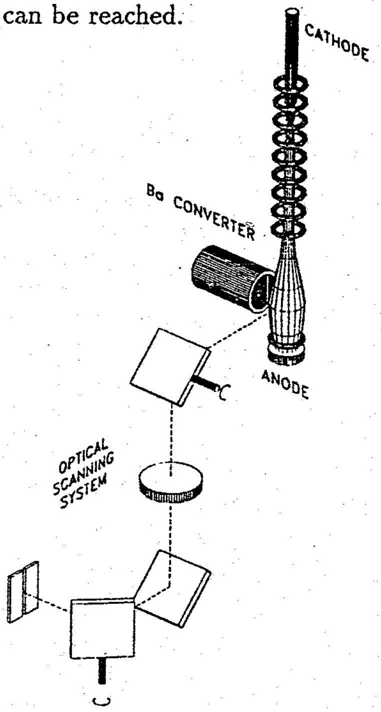

Figure 1: The optical scanning system

The optical scanning system is depicted in figure 1. A 1:1 image of the plasma is made on the entrance slit of the monochromator by a system consisting of a lense and three mirrors. Rotation of the mirrors enables a deplacement of the detection volume in horizontal and vertical direction. The plasma light is analyzed by a 1meter McPherson visible light monochromator and an EG&G model 1422 diode array detector. This system enables simultaneous measurement of a wavelength interval of 120 Åwith a resolution of approximately 50 pm.

Results

The line intensities of the first five lines of the Q (0-0) branch are measured spatially resolved. The measurements are line integrated over the optical path. Plasma settings are p=$2{\cdot}10^{-4}$ mbar, I_{arc} = 20 A and the magnetic

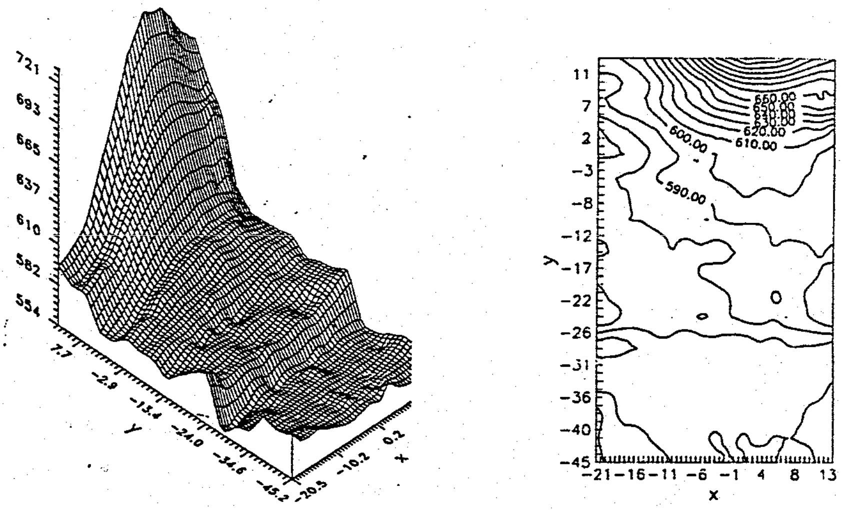

Figure 2: Spatially resolved rotational temperatures. The plasma axis is parallel to the x-axis at the left side of the graph. The converter is approximately at the position x=0, y=-50 mm.

field coil current 250 A. The scanned area is from the plasma center to the converter in horizontal direction and two centimeter above and below the converter center in vertical direction. These were approximately the geometrical limitations from the optical scanning system. The temperatures determined from the measured spectra are depicted in figure 2. The highest rotational temperatures are found close to the plasma center. Apparently the converter has a cooling influence on the plasma.

Discussion

In the low pressure type plasma as generated in the FOMSCE experiment the determination of the thus found temperature is not straightforward. The $d^3\Pi_u$ state of H_2 is assumed only to be excited by direct electron impact on the $X\,^1\Sigma_g^+$ (ground) state, whereas depopulation is fully radiative. This is equivalent to supposing the mean free path is so large that within the life time of excited states ($\sim 10^{-8}$ sec) there will be no(de-)excitations by electron collisions. In other words, ladder excitation is excluded. Another consequence of this direct excitation dominated situation concerns the relation between the measured rotational temperature and the gas temperature. Consider first the (electronic) ground state molecules. They have a thermal distribution over the different rotational states according to the gas temperature. If an electron impact excitation to an excited state takes place, due to it's small mass the electron will not be able to change the angular momentum of the molecule. As a consequence, the distribution of the molecules over the different rotational levels in the upper state will be practically the same as in the ground state. The measured relative densities of the rotational states of the upper level $d\,^3\Pi_u$ reflect the population of the ground state $X\,^1\Sigma_g^+$ and must therefore be associated with the ground state rotational temperature, which is usually equal to the gas temperature. If the calculation from equation 2 and 3 is done with the ground state rotational constants (table 1), the groundstate T_{rot} is obtained.

The interpretation of the rotational spectra of the Fulcher band system needs to be done with great care. We have measured rotational spectra for 5 diagonal bands (0-0),..(5-5) and for a wide range of plasma parameters. Only a minor part of the wealth information enclosed in these measured spectra has been revealed up to now. The determined rotational temperatures do show systematic differences over the diagonal bands. This phenomenon has been observed before and can be attributed to a violation of the assumption that no rotational transitions take place under electron-impact excitation [5]. The influence of this effect on the temperature determined from the Boltzmann plot is temperature dependent. Based on results from others [5], [6] we estimate that the actual temperatures may be 25% lower. However, this matter will be studied in more detail. Therefore we choose to call the here presented results as preliminary. Having said this, some conclusions concerning the plasma determination may be made. The highest temperatures are found close to the plasma axis, at positive y-values. At the position of the converter, x=0, y=-50 mm the temperature is lower but still substantially above room temperature. The coupling between electron and gas temperature is apparently not negligible, as values of typical 600 K are found. The influence of pressure, current and magnetic field will be discussed in a forthcoming paper.

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