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Measurements of plasma edge electron temperature and density using visible spectroscopy in NOVA-UNICAMP tokamak

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Abstract. The electron temperature ($T_e$) and density ($n_e$) at the edge of NOVA-UNICAMP tokamak plasma were determined along the discharge using the concept of particle confinement time ($\tau_P$) uniqueness and spectroscopic measurements of hydrogen Balmer series emissions. We have used three absolutely intensity calibrated spectrometers with photomultipliers for simultaneous measurements of hydrogen alpha, beta and gamma emissions throughout the discharges. With the use of data from Johnson and Hinnov’s table, we have performed an interactive method to find electron temperatures and densities that satisfy the $\tau_P$ uniqueness to obtain the temporal evolution of $T_e$ and $n_e$ parameters. The results achieved are in agreement with the expected values for these parameters at the edge of the NOVA-UNICAMP tokamak plasma.

1. Introduction
In plasma physics the development of diagnostic tools and methods to obtain plasma parameters, like temperatures, densities and confinement times, is an important matter. In this work we present a diagnostic method used to determine the local electron temperature ($T_e$) and density ($n_e$) in the NOVA-UNICAMP tokamak (NUt) plasma using visible spectroscopy, which has the advantage to be a passive method. The NOVA-UNICAMP [1] is a small iron core tokamak with major radius $R = 0.30$ m, plasma radius $a = 0.06$ m, toroidal field $B_T = 0.8$ T and characteristic plasma current of $I_p = 10$ kA.

The use of hydrogen spectral emissions for estimation of particle confinement times ($\tau_P$) in tokamaks is a well known technique. The $\tau_P$ calculation depends on $T_e$ and $n_e$ values and it is our starting point to make the reverse path, that is, the use of $\tau_P$ values to determine electron densities and temperatures.

Each tokamak has a characteristic value for the particle confinement time in a given place of the plasma and its value should be independent of the spectral emission observed. It means that the $\tau_P$ value must be unique in a certain plasma position.

Combining the absolute brightness measurements of the hydrogen alpha, beta and gamma emissions and data from Johnson and Hinnov's tables [2] we have developed an interactive method to find $T_e$ and $n_e$ values that satisfy the $\tau_P$ uniqueness. Using this method it was possible to determine electron densities and temperatures for various time instants along the tokamak discharges.

The main concepts of this diagnostic were developed firstly by Daltriini [3], where the measurements of hydrogen emissions were taken in different tokamak discharges, whereas, in this work the hydrogen emissions, $H_\alpha$, $H_\beta$ and $H_\gamma$, were measured simultaneously using three absolutely
intensity calibrated spectrometers equipped with photomultipliers, avoiding therefore the problem of discharge reproducibility. Furthermore, the light emitted by the plasma was collected using three optical fibers, instead of the lens collection system used before, and a collimation system was adopted to have some degree of spatial definition on measurements.

2. Theoretical model

In pure hydrogen plasma and in the equilibrium condition \(dN_e/dt = 0\) we can use the particle confinement time theory \([2,4,5]\) and combine it with the hydrogen spectral emissions to find the following expression for \(\tau_P\) (considering only the Balmer series):

\[
\tau_P[H_{j2}] = \frac{N_e}{4\pi^2 r_0 R[H_{j2}] B_{j2}}
\]

where \(N_e\) is the total number of electrons in the plasma, \(l\) is the toroidal length, \(r_0\) the peak position of hydrogen emissions \((r_0 \approx 0.8a\) in NUt) and \(B_{j2}\) is the brightness of the \(H_{j2}\) emission \((j > 2)\). The \(R[H_{j2}]\) factor is the average ionization rate per \(H_{j2}\) photon emission rate (for instance, \(H_{32}\), \(H_{42}\) and \(H_{52}\) stands for \(H_\alpha\), \(H_\beta\) and \(H_\gamma\) emissions respectively). The \(R[H_{j2}]\) factor can be written as \([2,3,4]\):

\[
R[H_{j2}] = \frac{l}{j^2} \frac{n_e S}{A_{j2} r_1(j)} \exp[(I_i - I_j)/T_e]
\]

where \(I_j\) is the ionization potential for the \(j\) level, \(A_{j2}\) is the transition probability from level \(j\) to level 2 and \(T_e\) is in eV. The \(S\) and \(r_1(j)\) coefficients, that depends on electron temperature and density, are given in the work of Johnson and Hinnov \([2]\).

In practice, the calculation of \(\tau_P\) values itself are not necessary, being sufficient to calculate the ratio between confinement times for different hydrogen emissions, and to find electron temperatures and densities values that satisfy the relationship:

\[
\frac{\tau_P[H_{a}]}{\tau_P[H_{\beta}]} = \frac{\tau_P[H_{\beta}]}{\tau_P[H_{\gamma}]} = 1
\]

This reduces to calculate only:

\[
\frac{\tau_P[H_{a}]}{\tau_P[H_{\beta}]} = \frac{R[H_{\beta}] B[H_{\beta}]}{R[H_{a}] B[H_{a}]}
\]

and

\[
\frac{\tau_P[H_{\beta}]}{\tau_P[H_{\gamma}]} = \frac{R[H_{\gamma}] B[H_{\gamma}]}{R[H_{\beta}] B[H_{\beta}]}
\]

Now we have two independent equations which allow us to find the \(T_e\) and \(n_e\) parameters.

The equations (4) and (5) show that the ratios between particle confinement times depends only on the measured brightness and its respective \(R\) factors, avoiding difficulties inherent to the determination of \(N_e\), \(l\) and \(r_0\) parameters of equation (1).

3. Analysis method

After calculate the \(R\) coefficients, we made a fine interpolation of this values in function of \(T_e\) and \(n_e\) in order to improve the precision of our measurements.

With the brightness of \(H_a\), \(H_{\beta}\) and \(H_{\gamma}\) emissions and the \(R\) coefficients, we choose, firstly, an electron temperature to start the interactions and then we make calculations of \(\tau_P\) ratios (using equations 4 and 5) for a wide range of electron densities, changing it numerically and trying to find \(n_e\).
values that satisfy the \( \tau_P \) uniqueness. Sample curves of this procedure are shown in figure 1. As we can see in this figure, we have two different values, \( n_e' \approx 8.0 \times 10^{12} \text{cm}^{-3} \) and \( n_e'' \approx 6.5 \times 10^{12} \text{cm}^{-3} \), one for each ratio curve, of electron density satisfying particle confinement time ratios equals to one. The meaning of this fact is that we have used an incorrect value of electron temperature and another attempt with a different value of \( T_e \) is required in order to satisfy the equation (3).

Figure 1. Curves of ratios between particle confinement times in function of \( n_e \), for an electron temperature of 5.52 eV. The \( n_e' \) value satisfy the condition \( \tau_P[H_\alpha]/\tau_P[H_\beta]=1 \) while \( n_e'' \) satisfy \( \tau_P[H_\beta]/\tau_P[H_\alpha]=1 \).

Repeating this procedure for various temperature values, we can observe the behavior of \( n_e' \) and \( n_e'' \) in function of \( T_e \). Figure 2 shows these two curves.

The cross point between the two curves above determines the local \( T_e \) and \( n_e \) values in the plasma that satisfy the \( \tau_P \) uniqueness for a given time instant. The values of \( T_e \) and \( n_e \) in figure 2 are 6.32 eV and \( 8.0 \times 10^{12} \text{cm}^{-3} \), respectively.

This procedure must be repeated for other time instants of the discharge in order to obtain the temporal evolution of \( T_e \) and \( n_e \).

Figure 2. Curves of densities values that satisfy the \( \tau_P \) uniqueness for each \( T_e \) value.

4. Results and conclusions
Using the method previously described, we have determined the temporal evolution of the electron temperature and density at the edge of NOVA-UNICAMP tokamak plasma. The \( T_e \) and \( n_e \) results, shown in figure 3, were obtained in a 7.4 ms tokamak discharge plateau with 12 kA plasma current.
Figure 3. Time evolution of electron density (left) and temperature (right) for a tokamak shot with a work pressure of approximately 1.08×10⁻⁴ Torr.

The average electron temperature obtained in this discharge was 6.9 ± 0.8 eV while the average electron density was (6.7 ± 0.5)×10¹² cm⁻³. The results of $T_e$ and $n_e$ temporal evolution are in agreement with the expected values for these parameters at the edge of the NOVA-UNICAMP tokamak plasma [6]. This indicates that the proposed diagnostic method can be used to monitor the electron densities and temperatures at the edge of tokamak plasmas.

The next step is to apply this technique, using simultaneous measurements of hydrogen emissions, in tokamaks larger than the NOVA-UNICAMP and to compare the results with other diagnostic tools like Langmuir probes and microwave interferometer in the same discharge and radial position.

Acknowledgments
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References