Vacuum Ultraviolet and Visible Spectroscopy Diagnostics on the NOVA-UNICAMP Tokamak

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Three visible and one VUV spectrometers covering four toroidal positions have been set to study He and H plasma created by NOVA-UNICAMP tokamak. Ion temperatures have been measured at the beginning of the tokamak discharge by Doppler broadening of C, O and He lines. The time evolution of carbon line emissions, with different degrees of ionization, showed to have opposite behavior between high and low plasma ionization condition. The high density operation and 2 kHz oscillation present throughout discharge, caused by periodical touching of the plasma with NOVA-UNICAMP tokamak limiter, restrained the increase of ion temperature.

I Introduction

Light emission from the hydrogen and helium plasmas, as well as impurity emissions, have been studied in the visible and vacuum ultraviolet (VUV) spectra, by a set of four spectrometers installed around toroidal equatorial plane of NOVA-UNICAMP tokamak. The use of VUV spectroscopy to study tokamak confined plasmas for the first time in domestic level also is pointed out.

The spectroscopy is a powerful diagnostic tool to study magnetically confined plasma, providing important parameters as ion temperature and density, Z_{eff}, and particle confinement time. The VUV spectroscopy becomes very important at high temperatures, since the emissions of the mostly ionized species is concentrated in VUV and X-ray spectra.

Doppler broadening of line spectra using the well-known formula [1,2] determines the ion temperature

$$T = 1.69 \times 10^8 M \left(\frac{\Delta\lambda_D}{\lambda_0}\right)^2 \qquad (1)$$

where, the ion temperature T is in eV, $\Delta\lambda_D$ (full width at half height) centered at the wavelength of the observed spectra λ_0, and M is the ion mass in atomic units.

Actual value of instrumental broadening effect is taken into account by the formula [1,3]

$$(\Delta\lambda_{\text{meas}})^2 = (\Delta\lambda_D)^2 + (\Delta\lambda_{\text{ins}})^2 \qquad (2)$$

where instrumental broadening ($\Delta\lambda_{\text{ins}}$) is assumed to have a gaussian shape, fact verified by measurements, and Stark or Zeeman [3,4] effects are considered to be negligible [1,2].

Therefore the measurement of a spectral line broadening and the utilization of formulas (1) and (2), allow us to obtain the ion temperature T using CIII and OII emissions in the visible region and CIV in the VUV region.

The four spectrometers, see Fig. 1, set around equatorial plane of tokamak are: a 82-415 Jarrel-Ash Spectrometer with 25 cm focal distance, 590 g/mm and 66 Å/mm dispersion is set at the limiter position (0^0), a 2051 McPherson Spectrometer with 100 cm focal distance, 1200 g/mm and 8,3 Å/mm dispersion is set at 90^0 cw from the limiter position, a SPEX Spectrometer with 75 cm focal distance, 1200 g/mm and 11 Å/mm dispersion is set at 180^0, and a 225 McPherson Spectrometer with 100 cm focal distance, 600 g/mm and 16,6 Å/mm dispersion is set at 225^0. The last measures radiation in VUV and visible up to 6000 Å and has a differential pumping, with a turbomolecular pump, in the pipeline which connect spectrometer to the tokamak.

Formerly, in measurements using hydrogen gas lamp, the VUV spectrometer measured radiation down to 500 Å [5]. However, measuring radiation emitted by our tokamak plasma, the lowest wavelength detectable was 900 Å, probably because of weak line signals in the tokamak plasma and grating deterioration.

For the visible spectrometers, $\Delta\lambda_{\text{ins}}$ have been determined using a He-Ne laser. However, since the VUV spectrometer can not measure the He-Ne laser wavelength, we use for this propose a carbon line emission in the VUV region (1548 Å) using discharges with very low values of ohmic heating and magnetic fields. In this case, by the formula (1), the Doppler broadening is very small, and total width measured can be considered as the instrumental broadening [1].

Finally, we also present the time behavior of carbon lines with different degrees of ionization, using discharges with low ohmic heating and magnetic fields. Although, in this mode, we can not measure $\Delta\lambda_D$, the intensity measurements allow us to drive some conclusions.

The line intensity of a given ionized specie is proportional to its density, and is given by:

$$\frac{dN_j}{dt} = -n_e I_j N_j - n_e \alpha_j N_j + n_e I_{j-1} N_{j-1} + n_e \alpha_{j+1} N_{j+1} + \phi_j \quad (3)$$

where N_j is the density of the ion (j represents the ionization level), n_e is the electron density, I_j is the ionization rate coefficient, α_j is the recombination rate coefficient and ϕ_j is the source term.

A expression for the I_j coefficients is present by Kunze [6]:

$$I_j \cong 7.5 \times 10^{-8} \frac{\eta_j}{E_j} \left[\left(\ln \frac{40T_e}{E_j} \right)^3 + 40 \right] \times \frac{T_e^{1/2}}{E_j + 3T_e} e^{-E_j/T_e} \ \ \mathrm{cm}^3/\mathrm{s} \quad (4)$$

where η_j is the number of electrons in the jth shell, E_j is the ionization energy and T_e is the electron temperature (both E_j and T_e are in eV).

Equations (3) and (4) and line intensity measurements are used to study the fast heating and posterior cooling of the plasma related to the ionization levels of carbon lines.

II Experimental Setup

The NOVA-UNICAMP tokamak, former NOVA II tokamak [7] from Kyoto University-Japan, is a small machine operating at our Laboratory since 1996. Its main characteristics are: major radius of 30 cm, minor radius of 6 cm, plasma current of 10 kA, plasma discharge time of 15 ms, and toroidal magnetic field of 1 T.

A schematic view of the NOVA-UNICAMP tokamak and main diagnostics installed, microwave interferometer, ruby laser Thomson scattering, hard x-ray detector, partial pressure gauge and the spectrometers, can be seen in Fig.1. In Fig. 2 is shown a typical plasma current and loop voltage signals.

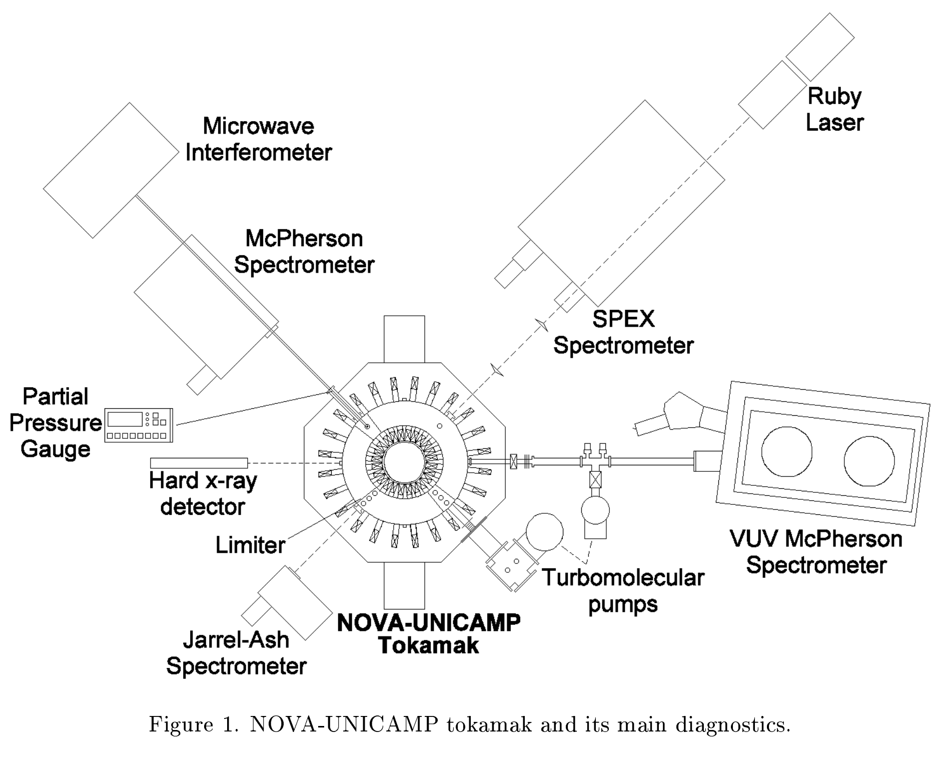

Figure 1. NOVA-UNICAMP tokamak and its main diagnostics.

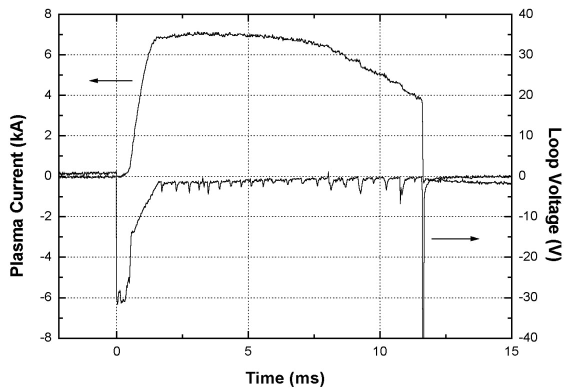

Figure 2. Typical plasma current and loop voltage signals in H gas discharges.

III Experimental Results

The ion temperature has been determined by Doppler broadening line measurements. Using simultaneously four spectrometers we could cover the VUV and visible regions and therefore measuring the most convenient spectral lines for each ion.

The spectral lines used for ion temperature calculations were: HeI 6678Å in helium plasma, OII 4649 Å, CIII 4647 Å and CIV 1548 Å for hydrogen plasma. The temperatures were calculated nearly up to the middle of each discharge. After this point, because of unknown noise effects in the signals, the temperature evolution was not determined.

Usually for ion temperature determination, one should choose well isolated spectra line. In Fig. 3 (top) is shown CIII and OII lines in visible region, where, due to overlapping effect, temperature determinations are jeopardized. Different Doppler broadening and temperatures, 35 ± 14 eV and 23.9 ± 5.2 eV, are obtained for each peak.

At same figure (bottom), where CIV line in VUV region is taken, the spectra is much well defined. The temperature 63.2 ± 9.4 eV is basically the same for two peaks, as should be. The higher temperature is indication that the CIV emission comes from hotter plasma region.

Other CIV emissions in visible region also have been investigated, presenting very weak signals however, and showing again the importance of the VUV spectroscopy.

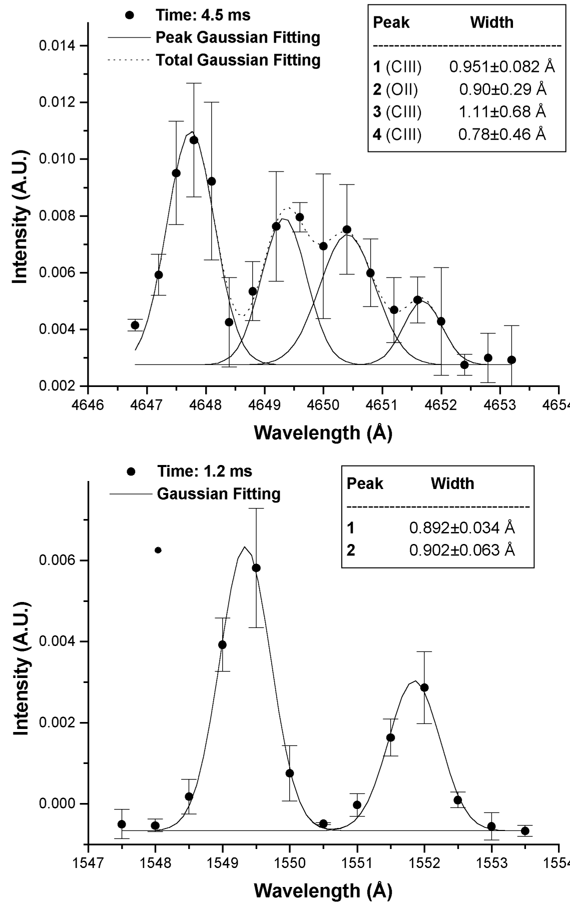

Figure 3. Top: Overlapping of CIII and OII four emission spectra in visible region; notice Doppler broadening deviation for each spectra giving different temperatures for same species. Bottom: VUV spectra of CIV emission; notice very well defined Doppler broadening for both emissions.

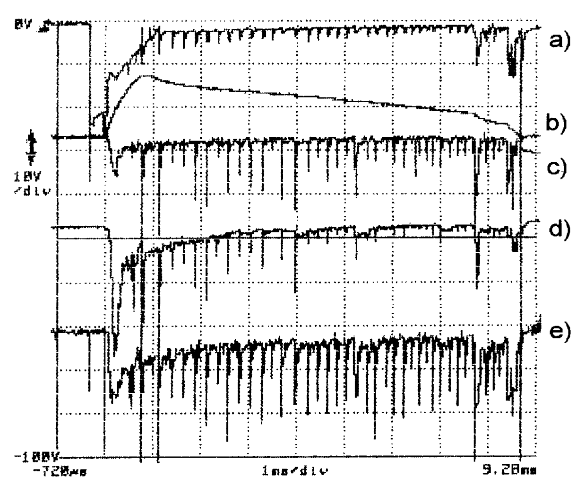

Figure 4. Oscillations of 2 kHz peaks, in loop voltage and spectral line signals at three toroidal positions: a) Loop Voltage; b) Plasma Current; c) H_α-0^0; d) H_α-90^0; e) H_α-180^0.

However, temperature values are lower than that we expected for this machine [7]. Probably, this fact is related with the oscillations observed in loop voltage and spectral line signals. In Fig. 4, the simultaneous measurements of the loop voltage, plasma current, and H_α emissions in three different toroidal positions are shown. We observed that oscillations of about 2 kHz occur at the same time in all toroidal positions during the discharge, but they do not have the same intensity variations. The VUV spectrometer at 225^0, measuring H_β emission, also presented similar results.

These oscillations is seen to be caused by periodical touching of the plasma with limiter, creating high density, $\sim 3 \times 10^{13}$ cm^{-3}, operation of the NOVA-UNICAMP tokamak.

The gas recycling from wall is very common problem in small machines like our tokamak. Fast neutrals produced by charge exchange leave the confinement, reaching the wall, and are trapped, originating the quick decay of plasma density. This will cause sliding away of plasma and touching the limiter, increasing the density again.

In the case of helium operation, as can be seen at Fig. 5, the periodical touching of plasma with the limiter is avoided. This is because the gas recycling is done properly, since the helium neutrals are not stick to the wall as hydrogen, producing therefore more constant plasma density and stable confinement.

The comparison between helium and hydrogen plasma discharges show that the He plasma reaches stable condition faster than the H plasma. As can be seen from Fig. 6, He temperature reach the mean value just a few moments, 0.5 ms, after the beginning of the discharge. However, it does not happen with hydrogen plasma, showing higher temperature only after 4 ms.

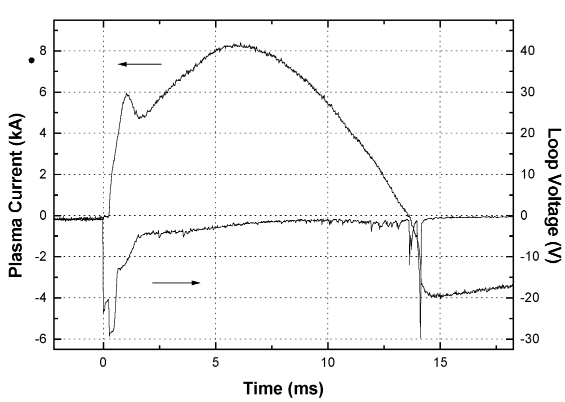

Figure 5. Plasma current and loop voltage signals in helium discharge. Observe the absence of oscillations.

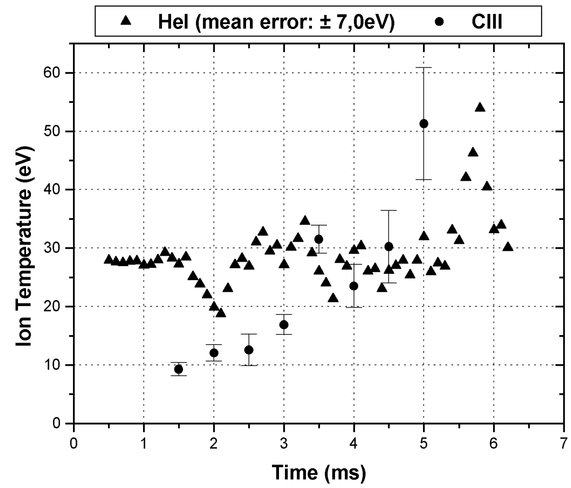

Figure 6. HeI (helium plasma) and CIII (hydrogen plasma) ion temperature.

Using the VUV McPherson spectrometer, the time behavior of carbon lines with different ionization degrees have been studied. We have used discharges with low ohmic heating and magnetic field (toroidal magnetic field = 0,3-0,4 T). In this mode we obtain discharges with high degree of reproducibility, in order to provide more accurate comparisons.

The carbon lines CI 2967 Å, CII 4267 Å, CIII 2297 Å and CIV 1548 Å, together with the typical hydrogen plasma current and loop voltage signals, are shown in Fig. 7. The spectral line signals are taken in different, but similar discharges at the same toroidal position.

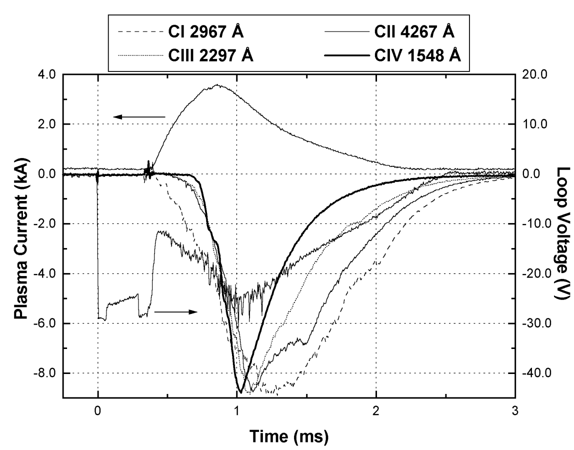

Figure 7. Different ionized carbon emissions.

In Fig. 8, a zoom of the carbon line signals are presented, and where we can observe that the appearance of CI line starts earlier and lasts for longer time, whereas the rise and fall time of the highly ionized CIV line is much faster, reaching the peak value first.

The line start delay is explained by the fact that the plasma takes a certain time to heat and then, to produce more ionized ions. In this way, as the plasma current is established, we observe first CI emission. After, the temperature starts to increase and we see the beginning of the CII emission, followed by the CIII and CIV (more hot plasma) emissions.

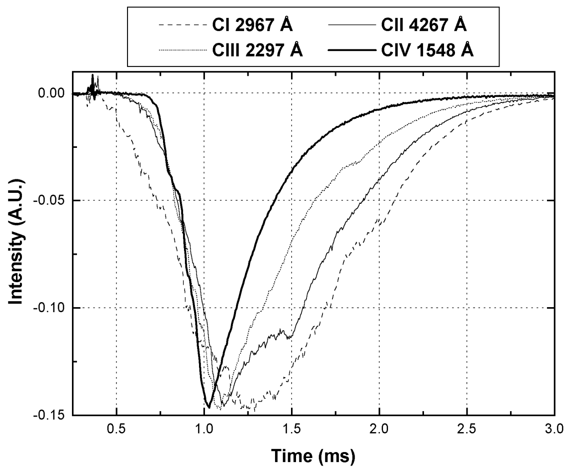

Figure 8. Different ionized carbon emissions (zoom).

The order of appearance of line peaks as observed in the Fig. 8 is opposed to what is usually observed in tokamaks [8] and other fusion machines [9]. The difference here is that the plasma is not totally ionized.

Even in bigger tokamaks, the electron temperature is not so high in the first moments of the discharge [8]. For example, for 3 eV electrons, eq. (4) gives $I_0 \approx 3 \times 10^{-9}$ cm^3/s and $I_2 \approx 5 \times 10^{-16}$ cm^3/s. Once in our machine the density of this mode is approximately 10^{12} cm^{-3}, we have $n_e I_0 \approx 3$/ms and $n_e I_2 \approx 5 \times 10^{-7}$/ms.

Since the time between the plasma current beginning and the CIV peak is less than 1 ms, we confirm, observing these values and the eq. (3) that the plasma is not totally ionized.

The low plasma duration is caused by low magnetic mode discharge, so that the plasma is not well confined. As the plasma column is formed, it expands and touches the limiter (maximum plasma current). After that, the plasma becomes cooler, and the most ionized ions, which are present in low quantities, have populations (and emissions) reduced very fast.

In the case of a long duration discharge with a plasma totally ionized, the particles are heat progressively, so that the number of low ionized species will be reduced with time, leading to opposed results that observed here.

A similar effect of temperature decrease soon after the plasma current peak, can also be seen in the measurements of the HeI temperature in low field discharges. Due to very low ion temperature operation, we have used HeI line instead of impurity lines, as carbon, once Doppler broadening is very hard to be separated from the instrumental broadening. In the Fig. 9, we can see that the ion temperature is increasing approximately up to the plasma current peak (time zero) and then decreases until reach values undetectable by our measurements.

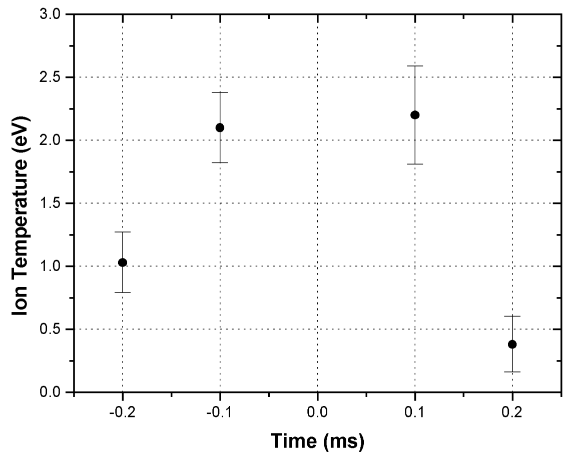

Figure 9. HeI temperature in low energy discharge.

IV Conclusions

The VUV spectroscopy showed to be a powerful diagnostic combined with visible spectroscopy. Simultaneous spectral measurements at the four tokamak toroidal positions showed that the 2 kHz oscillations are global effect having different intensities. For the low density and weak magnetic field discharges, where full ionization is not reached during the short lived plasma, the appearance order of the CI, CII, CIII and CIV lines are opposite to the usual tokamak or theta-pinch discharges with fully ionized plasma. The ion temperature measurements in tokamak condition showed that helium plasma reaches constant temperature much faster than looking at CIII impurity line in the hydrogen discharge.

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