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The Cu spectra as a tool for late plasma focus diagnostics

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Abstract. The visible spectra of Cu I and Cu II species of the late ($t > 1\mu s$ after the pinch) plasma focus have been used to determine the electron temperature and density of the decaying plasma. The intensity ratio of Cu I 4530A and Cu I 4539A lines was used for the determination of the electron temperature. The preliminary results showed a decrease of this parameter from T_e=1.9 eV, as was estimated near the maximum pinch, to T_e=1.3 eV after about 50 μs. A modified Saha equation, using the ion-to-atom (Cu I 5105A and Cu II 4953A) line intensity ratio was applied to determine the electron density. The method gave a decrease of this parameter from 10^{19} cm^{-3} to 10^{17} cm^{-3}.

1. Introduction

The properties in the boundary around the decaying plasma of the late plasma focus are expected to play a significant role for the technological usage of the device. The emission spectra of these plasma regions may be used successfully as a diagnostic tool – i. qualitatively – its consistence of different ions stages, the kind of impurities and ii. quantitatively – for determination of the temperature, electron densities and so on.

Along with the Balmer lines, the discrete lines of some impurities at different stages of ionization dominate the spectra of the latest phases of the discharge of PF-1000 facility [1]. Among them numerous spectral lines of CuI and CuII were observed, due to the incoming of metal vaporized impurities into the plasma at the anode vicinity. The Stark broadening of some of these CuII lines was used to determine the electron density during and after the duration of the pinch, which led to the conclusion that the electron densities measured by the CuII lines exceeded by an order of magnitude those obtained by the Inglis-Teller formula [2]. Therefore further investigations on the Cu spectra were performed, and line intensity ratio and modified Saha equation techniques were implemented for a determination of some late pinch plasma properties.

2. Diagnostics methods

The spectroscopic equipment of the experimental PF-1000 setup, already described in a previous paper [1], consists of an imaging spectrometer (MECHELLE900-type) coupled to an intensified CCD readout (Figure 1). The spectrometer integrates emission lines coming from the bulk of the plasma in which deuterium species exist, and the anode regions, where the metallic impurities are expected. Therefore the observed spectrum is rather complicated.

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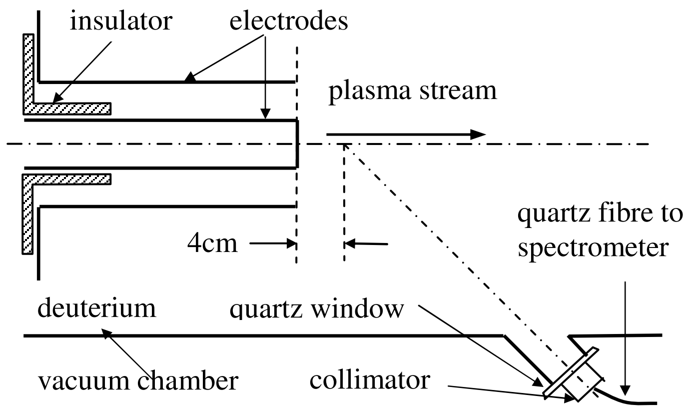
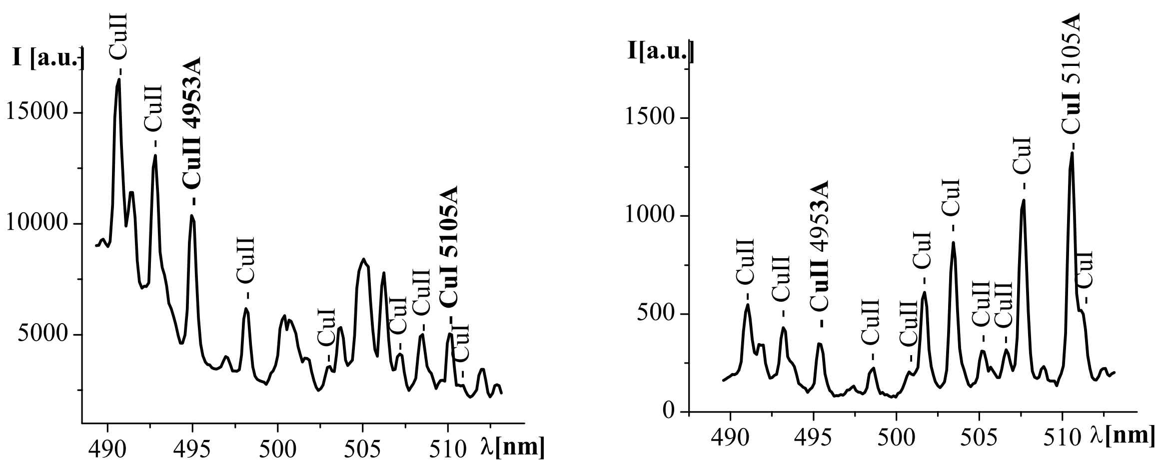


Figure 1. Scheme of optical aliment for time-resolved spectroscopic measurements within PF-1000 facility.

Numerous spectral lines were carefully analyzed and measured, which spectral positions were corrected from an accidental displacement. The feature of the spectra clearly demonstrated that the intensities of CuII lines decreased with time at the expense of the neutral CuI spectral lines (Figure 2). This behavior indicated the fall of the electron temperature during the afterglow, which appeared suitable for the diagnostics of the plasma.



a shot 4048
p = 5 Torr deuterium; t_{exp}= 200 μs; $t_{to\ dip}$= 0μs

b shot 4100
p = 5 Torr deuterium; t_{exp}= 5 μs; $t_{to\ dip}$ = 50μs

Figure 2. Part of optical spectra, showing temporal changes in the intensities of copper spectral lines observed at the maximum pinch (**a**) and about 50 μs after it (**b**). The two spectra demonstrate how, with the growth of time, the falling electron temperature and density lead toward considerable changes in the relative intensities of CuI and CuII lines - decrease (30x) in the intensities of CuII lines, while the decrease in intensities of CuI was weaker (about 3x).

In the decaying plasma of the pinch column (8μs<t<100μs) the stage of ionization is still high enough as evidenced by the presence of an ion spectrum. With electron density above 10^{17} cm^{-3} the radiation losses of the upper copper levels are negligible and a local thermal-equilibrium should hold for these spaces in the emitting plasma. Therefore the intensity ratio of two CuI lines, written in the usual way [3], is:

$$\frac{I_1}{I_2}=\frac{A_1 g_1 \nu_1}{A_2 g_2 \nu_2}\exp(-\frac{E_1-E_2}{T_e})\,. \tag{1}$$

In our case, the indexes 1 and 2 apply for the CuI 4539A and CuI 4530A lines respectively. From this equation the electron temperature T_e can be estimated.

In the case of local thermal-equilibrium, the Saha equation for a given species of the discharge, namely cuprum is: [3]

$$\frac{n_i n_e}{n_a}=2(\frac{mkT}{2\pi h^2})^{3/2}\frac{Z_i(T_e)}{Z_a(T_e)}\exp(-\frac{E^{ion}-\Delta E}{T_e})\,, \tag{2}$$

where $Z_a(T)$ and $Z_i(T)$ are the statistical sums of CuI and CuII respectively, ΔE is the lowering of ionization energy (in this case $\Delta E \approx 0.1$eV), and $E^{ion} = 7.7$eV. It follows, that for the electron density this equation can be rewritten as

$$n_e=6.6\times 10^{21}\frac{n_a Z_i}{n_i Z_a}\exp(-\frac{E^{ion}}{T_e})\,. \tag{3}$$

The lack of data for the neutral copper density and the uncertainties connected with the determination of the statistical sums can be avoided by the use of intensities of CuI and CuII lines. Taking into consideration that in a local thermal-equilibrium the expression for the line intensity of an atom or an ion is in the form:

$$I_{a(i)}=n_{a(i)}\frac{A_{a(i)} g_{a(i)}}{Z_{a(i)}}\exp(-\frac{E_{a(i)}}{T_e})h\nu_{a(i)}\,, \tag{4}$$

we suggest instead of the ratio of atom / ion densities and the statistical sums, the ratio of two CuI and CuII line intensities to be substitute in equation (3). This leads from the relation:

$$\frac{I_a}{I_i}=\frac{n_a}{n_i}\frac{Z_i}{Z_a}\frac{A_a g_a}{A_i g_i}\exp(-\frac{E_a-E_i}{T_e}) \tag{5}$$

to the following from of modified Saha equation:

$$n_e=6.6\times 10^{21}\frac{I_a}{I_i}\frac{A_i g_i}{A_a g_a}\exp(-\frac{E^{ion}+E_i-E_a}{T_e})\,. \tag{6}$$

In the case the index *a* applies for CuI 5105A and *i* for CuII 4953A lines.

3. Results and discussion

Our assumption, in which only close couples of well-isolated lines may be used for measurements by the relative intensity method, sharply reduced the number of useable lines. The need of reliable data for the transition probabilities and the large energy spacing of some transitions narrowed the choice even more. So, finally the couple of Cu I 4530A and Cu I 4539A lines was selected for the determination of the electron temperature and the couple of Cu I 5105A and Cu II 4953A for the electron density respectively (Figure 2).

The spectral data for these lines are as follows:

CuI4539A	4p' $^4F_{5/2}$ - 5s' $^4D_{3/2}$	$E_1 = 7.88$eV	$A_1 = 2.55\times10^7$ s^{-1}
CuI4530A	4s^2 $^2D_{5/2}$ – 4p $^2P_{3/2}$	$E_2 = 6.55$eV	$A_2 = 9.13\times10^6$ s^{-1}
CuI 5105A	4s^2 $^2D_{5/2}$ – 4p $^2P_{3/2}$	$E_a = 3.82$eV	$A_a = 1.95\times10^6$ s^{-1}
CuII 4953A	4d $^1G_4$ – 4f $^1H_5$	$E_i = 17.12$eV	$A_i = 2.04\times10^8$ s^{-1}.

The transition probabilities were taken from Kurucz Atomic Line Database (Harvard-Smithsonian Center for Astrophysics). The data concerning the transition probability of CuII 4953A line correlate with the results of [4].

The results showed a decrease in the electron temperature from T_e=1.9 eV, as was estimated near the maximum pinch, to T_e=1.3 eV after about 50 μs. The values for the electron densities, as obtained by this method near the maximum pinch, amounted to n_e ~10^{19} cm^{-3} and they coincided with the previous estimation [2]. In the late phase (about 50 μs after) the electron density decreased to n_e ~ 10^{17} cm^{-3}.

4. Conclusions

The carefully resolved copper spectrum can be successfully applied for the determination of both the electron temperature via the ratio of Cu I 4539 and Cu I 4530 lines and the electron density through the ratio of Cu I 5105 and Cu II 4953 lines.

Acknowledgments

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