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Optical emission spectroscopy of plasma streams in PF-1000 experiments

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Abstract. The optical spectroscopy in the visible range was used to determine properties of the dense magnetized plasma generated in the PF-1000, a 1 MJ plasma focus device operating in the Institute of Plasma Physics and Laser Microfusion (IPPLM) in Warsaw, Poland. The experiments were performed in a vacuum chamber pumped out to the basic pressure of 2×10^{-5} hPa. The initial pressure of the pure deuterium filling was 2.9 hPa, while that of the deuterium-argon mixture was 1.07 hPa of D_2 and 0.13 hPa of Ar. The deuterium-plasma emission contained the Balmer series (D_α, D_β and D_γ) and a few distinct copper (Cu I) lines originating from the inner electrode material. The emission of the deuterium-argon plasma was rich in Ar II lines. The electron density (n_e), averaged over line of sight, of order of 10^{16} cm^{-3} was calculated on the basis of the D_β and D_γ emission only, because the D_α line was strongly self-absorbed. A group of the Ar II spectral lines was used to estimate the excitation temperature (T_{exc} = 3 eV) by means of a Boltzmann plot. Additionally, the temporal evolution of the electron density was determined on basis of the Stark broadening of the D_β and D_γ lines.

Key words: dense plasma-focus (DPF) • optical emission spectroscopy • deuterium Balmer series • Ar II lines • electron density • Boltzmann plot

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Introduction

Dense and energetic plasma streams generated in plasma-focus (PF) devices are interesting from the point of view of various scientific and technological applications, e.g. development of new plasma technologies for materials engineering [8], solving some nuclear fusion problems by running experiments on plasma-surface interactions under conditions simulating transient events in a future fusion reactor ITER [3, 7] and the fundamental studies of the plasma pinch dynamics. In order to evaluate the performance of a PF facility and to control discharge characteristics it is important to know various plasma parameters. The main ones are the electron density n_e and the temperature T. One of the most precise and most widely used methods to determine the electron density is the visible optical spectroscopy, and in particular analysis of the Stark broadening of the deuterium Balmer lines [5, 6, 9].

It is a well-known fact that a small dose of any inert gas can strongly change plasma parameters and increase the emission of radiation by orders of magnitude. Therefore, studies of an influence of a deuterium-argon mixture on the plasma emission spectra and comparisons of such spectra with the spectrum obtained for pure deuterium plasma spectrum are relevant for the optimization of performance of the PF-device. Operation of the PF with the deuterium-argon mixture might be also interesting from the point of view of studies of the impurity dynamics.

The main aim of this paper is to report detailed spectroscopic studies of plasma streams generated using the PF-1000 facility [4], including a high temporal resolution analysis of the deuterium and argon spectral lines.

Experimental setup

The measurements reported below were performed using the PF-1000 plasma focus device being operated at the Institute of Plasma Physics and Laser Microfusion in Warsaw, Poland [7]. It is a Mather-type facility equipped with coaxial electrodes 460 mm long. The inner electrode, made of copper, has a diameter of 230 mm, while the outer electrode has a diameter of 400 mm and consists of 12 stainless steel tubes, each with a diameter of 80 mm. The inner electrode basis is embraced by a cylindrical ceramic insulator of 152 cm long, which was recently upgraded. The electrodes are located in a vacuum chamber pumped out to the basic pressure of 2×10^{-5} hPa. The initial pressure for the pure deuterium filling was 2.9 hPa, while for the deuterium-argon mixture it amounted to 1.07 hPa for D_2 and 0.13 hPa for Ar. The capacitor bank was charged to 22 kV for shots with the pure deuterium and 24 kV for those with deuterium-argon mixture.

The spectroscopic measurements were taken along the axis perpendicular to the electrode *z*-axis, at a distance of 30 cm from the end of the inner electrode, as shown in Fig. 1.

The visible radiation was collected from a spot with a diameter of 10 mm, corresponding to an open angle of 3.6 degees, and averaged over the line of sight. Since the plasma streams had evidently some density and temperature gradients along the line of sight, all estimates of the electron density and the temperature obtained in this way must be treated as "averaged" or "effective" ones.

The optical signals measured from the plasma were sent via a 10-m-long optical fiber cable (made of MgF_2) to a Mechelle®900 spectrometer equipped with a PCO SensiCam camera. The spectra were recorded in the wavelength interval from 350 nm to 1000 nm. The acquisition time for the spectra was set to 0.1 μs.

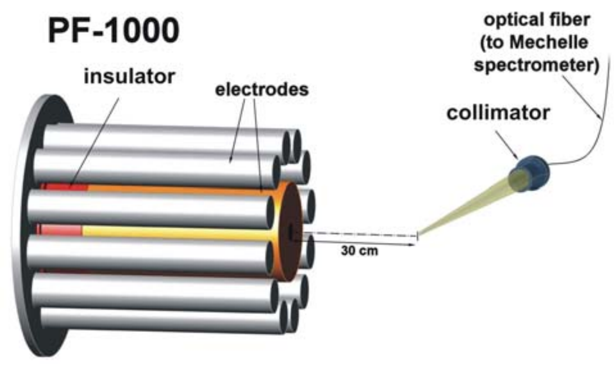

Fig. 1. Geometry of the experimental setup at the PF-1000 facility.

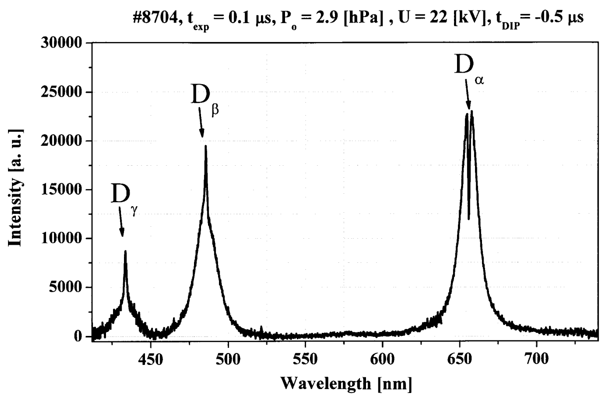

Fig. 2. Spectral lines of the Balmer series recorded from the plasma generated in the PF-1000 device.

Experimental results

Preliminary results obtained from PF-1000 discharges performed with the pure deuterium filling showed that the visible radiation emission consisted mainly of the Balmer series (D_α, D_β and D_γ) from the working gas and a few copper lines (Cu I 406.26 nm, Cu I 465.11 nm, Cu I 510.55 nm, Cu I 515.32 nm, and Cu I 521.82 nm) originating from the inner electrode material. An example of the recorded Balmer series is shown in Fig. 2.

Several series of spectroscopic measurements were performed with the exposure time $t_{exp} = 0.1$ μs and delay times relative to the time of the maximum plasma compression (so-called a DIP) ranging from –2 μs to 7 μs. An example of the observed temporal changes of the D_β and D_γ lines is presented in Fig. 3.

The recorded spectra were wavelength-calibrated using an ArHg lamp and intensity-calibrated using a DW lamp.

It was found that in most of the measurements the emission corresponding to the D_α line ($n' = 3 \rightarrow n = 2$, $D_\alpha = 656.10$ nm) was strongly self-absorbed (as shown in Fig. 2), so the electron density was evaluated on the basis of the D_β ($n' = 4 \rightarrow n = 2$, $D_\beta = 486.03$ nm) and D_γ ($n' = 5 \rightarrow n = 2$, $D_\gamma = 433.30$ nm) lines of the deuterium plasma emission (shown in Fig. 3). Distinct temporal changes in the shape of the D_β line are shown in Fig. 4.

A broadening of the measured transition lines might be caused by a variety of mechanisms, such as

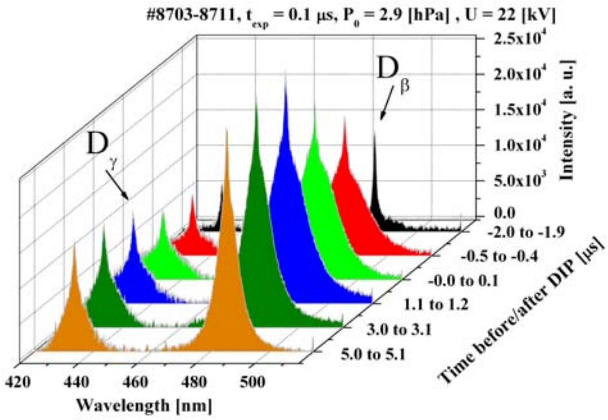

Fig. 3. Dynamics of the D_β and D_γ emission recorded for the PF-1000 discharges.

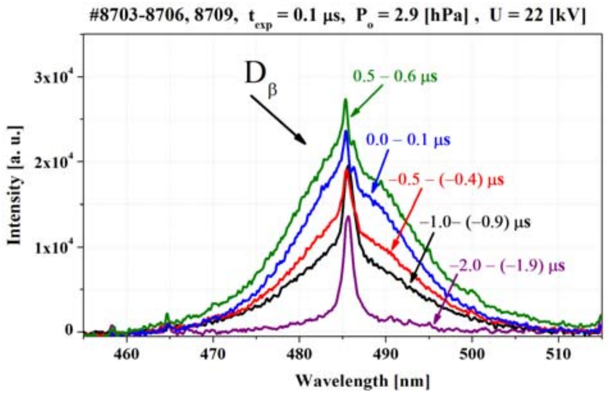

Fig. 4. Dependence of the shape of the D_β line on a time delay in relation to the discharge current peculiarity (DIP).

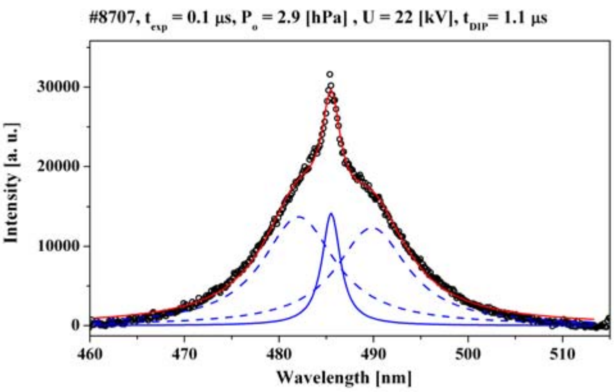

Fig. 5. Broadened profile of the D_β emission in pulsed PF-1000 discharge (open circles – experimental points; blue and red lines – fitted curves).

the Stark, Doppler broadening, and an instrumental broadening.

For the 374.4 nm line the instrumental broadening $\Delta\lambda_{instr}$ was around 0.3 nm, while for the 736.9 nm line it was around 0.56 nm. The instrumental width of the lines was determined on basis of the full width at the half maximum (FWHM) of the Ar and Hg lines in the emission from a low-pressure ArHg calibration lamp.

The Doppler broadening, originating from the velocity distribution of the emitting ions, was calculated from the equation:

$$\Delta\lambda_D = 7.16 \times 10^{-7} \lambda_0 (T / M)^{0.5}$$

where the wavelength λ is expressed in angstroms, the temperature T in kelvins, and the mass of the atom M in the atomic mass units.

The Doppler broadening estimated on the basis of this formula is two orders of magnitude smaller than the measured width of the spectral lines. The gaussian component in the Voight fitting also is negligibly small, so the Stark broadening appears to be the dominant broadening mechanism. The measurement was performed along an axis perpendicular to the z-axis of the plasma focus and the Doppler shift was not observed.

The FWHM value for hydrogen and hydrogen-like lines is related to the electron density n_e by the formula [8]:

$$\Delta\lambda_S = 2.5 \times 10^{-9} \alpha_{1/2} n_e^{2/3}$$

where $\Delta\lambda_S$ is the Stark width in angstroms, $\alpha_{1/2}$ is a fractional semi-half-width parameter, and n_e is the electron density expressed in cm^{-3}. Using this formula the electron density was calculated on the basis of data for the D_β and D_γ lines. The $\alpha_{1/2}$ value was taken from the literature [1].

The observed shapes of the investigated lines (shown in Figs. 3 and 4) suggest that the observation line crossed areas of different plasma densities.

OriginPro 7.5 was used for the analysis of the data. None of the parameters were fixed during the fitting. The example of the fitted D_β emission is presented in Fig. 5. The D_β and D_γ emission was fitted by three Lorentz shape peaks. Taking into account the width of the central peak of the D_β and D_γ lines, a dependence of the electron density (n_e) on a time delay before and after the DIP was determined, as shown in Fig. 6. It was found that the n_e values calculated from the Stark broadening are in a relatively good agreement with the values obtained from the data on the D_β and D_γ lines for instants before and more than 2 μs after the DIP. The increase in the plasma density, as observed at a distance of 30 cm from the outlet of the electrodes, corresponded to the maximum plasma compression and the appearance of fast ion streams emitted from the pinch column. Some discrepancy between the numbers obtained from the D_β and D_γ lines registered close to the DIP might possibly be explained by the Doppler broadening, since one cannot exclude in principle that some deuterons have considerable radial velocities. Unfortunately, it would be very difficult to perform a quantitative treatment of a mixture of the Stark and Doppler effects on the basis of the experimental data available so far.

The electron density was also estimated taking into account the broad Lorentz components (dashed lines in Fig. 5) of the D_β and D_γ lines. The obtained values were two orders of magnitude larger (10^{18} cm^{-3}) then the electron density calculated from the central peak. That suggest different mechanism of the broadening. One of the most probable is the Doppler broadening caused by the interaction of energetic ions with neutral deuterium atoms [2]. One cannot exclude also other mechanisms of the excitation and line broadening, but there is no good theoretical model of a temporal evolution of fast plasma-ion streams emitted from the PF-type discharges.

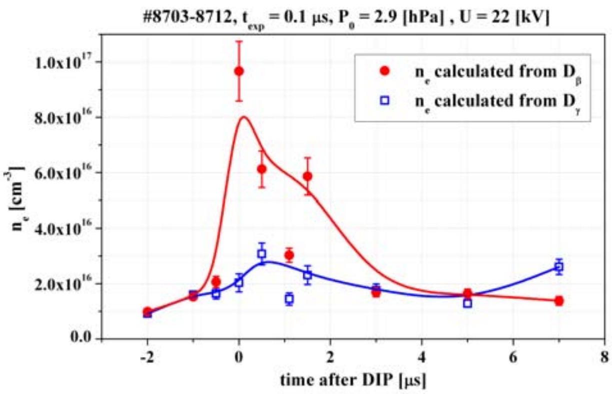

Fig. 6. Electron density values in the PF-1000 experiment, as calculated from the central peak of the D_β and D_γ lines recorded for different instants before and after the DIP.

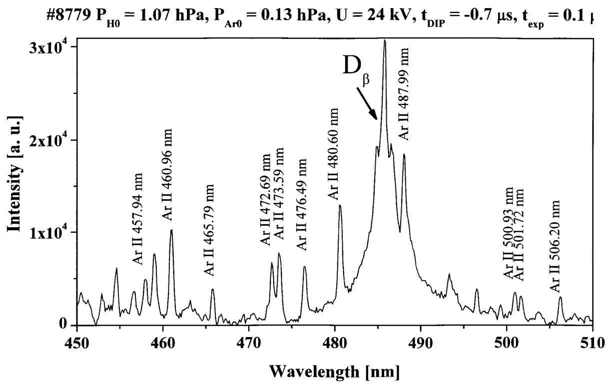

Fig. 7. The optical spectrum recorded for the PF-1000 discharge performed with the argon-deuterium mixture. Most of the assigned lines were analyzed in order to draw the Boltzmann plot.

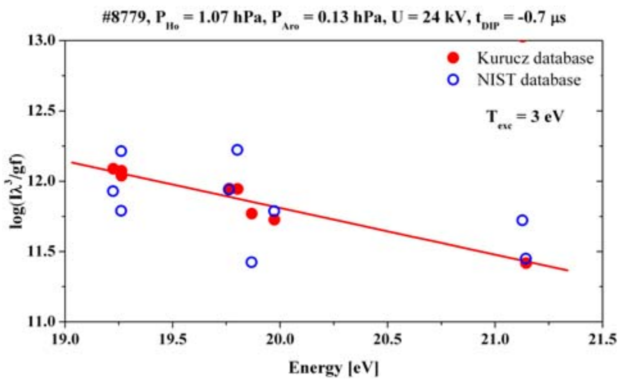

Fig. 8. The Boltzmann plot, drawn on the basis of the recorded Ar II emission. The indicated data points (filled and open circles) represent results of computations performed with the use of different databases.

Unfortunately, the laser-interferometric measurements were performed only in the vicinity of the electrode outlets (at a distance of 0–10 cm from the end of the inner electrode). Therefore, it was impossible to compare the electron density values obtained from the interferometric measurements with the estimates obtained from the spectroscopy.

The intensities of the copper emission lines (see Fig. 2) were too small to be a useful independent source of information on the electron density.

An example of the optical spectrum recorded for a discharge performed with the deuterium-argon filling is presented in Fig. 7. Assuming the presence of LTE, the excitation temperature T_{exc} was estimated on the basis of a Boltzmann plot, as shown in Fig. 8.

The following Ar II lines were used in the Boltzmann plot: 457.94, 460.96, 465.79, 476.49, 472.69, 473.59, 500.93, 501.72 and 506.20 nm. It should be noted that the experimental points on the Boltzmann plot which were calculated on the basis of the Kurucz database (filled circles) were less scattered than those determined on the basis of the NIST database (open circles). The excitation temperature was estimated to be about 3 eV. That was not a high value, but it is reasonable one for the conditions of the experiment.

Summary and conclusions

The most important results may be summarized as follows:

1. The results of the recent spectroscopic measurements, as obtained from PF-1000 discharges performed with a new ceramic insulator, a relatively good agreement was found between the values of the electron density n_e calculated from the Stark broadening of the D_β and D_γ lines, for discharge instants before and more than 2 µs after the current peculiarity (DIP).
2. The observed increase in the plasma density after the DIP (at a large distance of 30 cm from the electrodes ends) corresponded to the phase of the maximum plasma compression of the PF pinch column, accompanied by the emission of fast ions.
3. The excitation temperature, as estimated on the basis of the Boltzmann plot, was equal to about 3 eV. This value seems reasonable for the considered experimental conditions, but must be regarded as a rough approximation only.
4. The shape of the Balmer emission lines could be explained by two different mechanisms. Most probably the central peak is broadened due to the pure Stark broadening, while the broadening of the wings is caused by the interaction of the fast ion beams with deuterium atoms.

Our conclusion is that more detailed spectroscopic measurements for the plasma generated in the PF-1000 device are needed in order to determine plasma characteristics under various experimental conditions and at different distances from the electrode outlets. Particular attention should be paid to strong self-absorption effects. One should also perform additional measurements of the optical emission from the outer layers of the plasma-ion stream in order to determine their influence on the investigated spectrum.

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