PRELIMINARY TEMPORAL CHARACTERISTICS OF SPECTRAL LINES EMISSION FROM PF-1000 DISCHARGES BY MEANS OF MECHELLE®900 SPECTROMETER

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The paper presents results of time-resolved spectroscopic measurements of pulsed plasma streams generated in PF-1000 facility. The use was made of a MECHELLE-900 optical spectrometer, which made possible measurements within the wavelength range from 200 nm to 1100 nm, with exposition times ranging from 100 ns up to 50 ms. Particular attention was paid to investigation of the spectral lines of the Balmer series from the working gas ions (i.e. D_α, D_β, D_γ) and some impurity lines. It is importance not only for estimates of plasma parameters, but also for application-oriented studies.

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1. INTRODUCTION

PF-type discharges have been investigated for many years [1-2]. Fusion produced neutrons, hard and soft X-rays, as well as VR pulses, were studied [2-4]. Dynamics of a current sheath layer during the radial collapse and the pinch phase was analyzed. Studies of PF discharges by means optical spectroscopy were rather scarce and they concerned mostly time-integrated measurements. The main aim of this study, undertaken in a frame of the scientific cooperation of IPJ, Poland, and IPP KIPT, Ukraine, was to perform spectroscopic measurements with a high temporal resolution. Such measurements of deuterium- and impurity-lines could deliver information about temporal changes in plasma density and temperature, as well as about its velocity and power flux.

2. EXPERIMENTAL SET-UP

The reported studies were carried out within the PF-1000 facility equipped with Mather-type electrodes made of thick-wall copper tubes, as described in previous papers [3-4]. The device was operated with the pure deuterium filling under the initial pressure changed from 3 to 8 hPa, and discharges were powered from a condenser bank (1.32-mF) charged up from 24 to 28 kV. To perform time-resolved spectroscopic observations of plasma streams, the use was made of a MECHELLE®900-spectrometer with an intensified CCD readout, which made possible measurements within the wavelength range from 200 nm to 1100 nm, at exposition times from 100 ns to 50 ms [5]. Those measurements were performed side-on, at a distance 4 cm from the electrode ends.

3. EXPERIMENTAL RESULTS

During the optical studies particular attention was paid to studies of the Balmer series of spectral lines from the working gas, i.e., D_α 656.10 nm, D_β 486.029 nm and D_γ 433.298 nm [5]. Also investigated were the spectral lines emitted from Cu-ions, which originated from the electrode rods. The optical system consisted of a collimator and a quartz cable coupled to the MECHELLE ®900-spectrometer. The system had the spatial resolution of about 10 mm. To study temporal changes in the emission of the investigated spectral lines, the spectrometer was synchronized with plasma discharges, and beginning of the exposition was varied. Typical oscilloscope traces are presented in Fig.1.

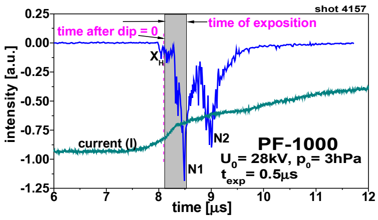

Fig.1.Time-correlation: the discharge current (I), hard X-ray- and neutron-induced signals (N1, N2)

Optical spectra obtained with a long and short exposition are shown in Fig. 2.

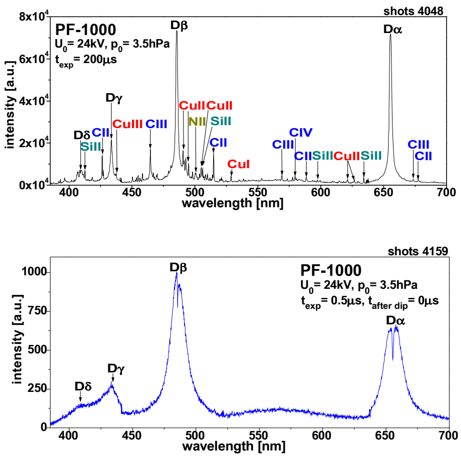

Fig.2. Comparison of the optical spectra, as recorded at a long (200 µs) and short (0.5 µs) exposition for two shots performed at identical experimental conditions

These spectra show that the width of the Balmer lines changes during the PF discharge, and estimates based on the time-integrated data (obtained with long expositions) cannot give information about the real plasma parameters. On the other hand, the Balmer lines recorded with an exposition short enough (in comparison with the

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discharge lifetime), and with different time delays in the relation to the discharge start give valuable information about temporal changes of plasma parameters.

It should be noted that impurity lines, which are visible in the time-integrated (long exposition) spectrum, do not necessarily appear in the flash (short-exposition) spectra. One should also note that the Balmer-line peaks show some reabsorption effects and the estimates should be based rather on their width. A dependence of the Balmer-lines on experimental conditions was determined for different voltages and initial pressures, as shown in Fig. 3.

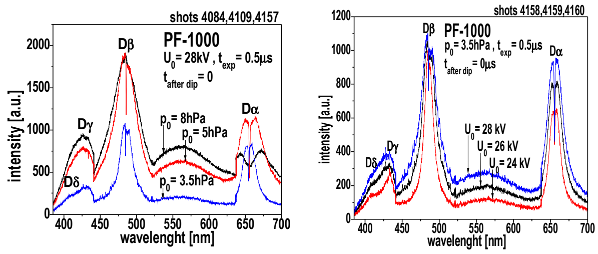
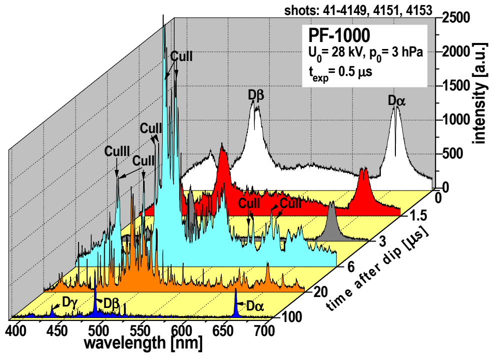


Fig.3. Dependence of the VR spectra on the initial gas conditions (left) and different charging voltages (right)

An analysis of the D_γ, D_β and D_α was based on the best fit of their wings. A dependence of FWHM values for the chosen Balmer-lines (proportional to the electron concentration) on the initial charging voltage was investigated. Optical spectra were also recorded at different delay times of the exposition (t_{delay}), but with the identical exposition (t_{exp}) equal to 0.5 µs. The whole VR spectrum, which was obtained from discharges performed at the same initial gas condition (3 hPa), but with different time delays (time after dip), are shown in Fig. 4.

Fig.4. Temporal changes in the emission of the deuterium



Balmer lines and impurity lines from plasma produced within the PF-1000 facility

An analysis of the recorded spectra showed that all deuterium lines of the Balmer series demonstrated strong broadening and re-absorption effects. Abrupt jumps in the recorded radiation intensity, as observed at some wavelengths, were an artificial effect of the detection system applied. It should be noted that after the current dip (when the fast radial collapse of the current sheath starts), there appears the emission of intense Balmer lines of the working gas (deuterium), characterized by large FWHM values and distinct reabsorption effects. One can also observe a relatively intense continuum without noticeable impurity peaks. The intensity of the Balmer lines drops considerably in about 1 µs, and the highest intensity of the impurity lines is observed about 6 µs after the current dip. During the next 10-15 µs one can observe a decrease in the optical emission of the Balmer and impurity lines. An interesting feature of the PF-1000 experiment is that after about 100 µs one can still observe some Balmer lines.

4. ELECTRON DENSITY MEASUREMENTS

The electron density was estimated by means of three different techniques: the linear Stark broadening of the Balmer series, the quadratic Stark broadening of copper and carbon spectral lines (including the lines of multi-charged ions), and the use of the Inglis-Teller correlation for a shift of the boundary serial. At all the stages of data processing there was applied the GRAMS-32 software.

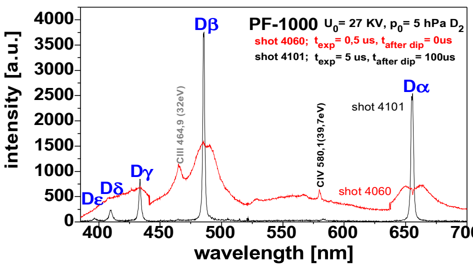
To determine the electron density we used the linear Stark effect for the Balmer series of working gas (H, D) lines and the quadratic Stark effect for impurity ion lines (copper, carbon). It should be noted that theoretical evaluations for high densities $N \gg 10^{17}$ cm^{-3} are not completely reliable for H_β, but they can be treated as the first-order approximation. For H_α this method could not be applied, due to a significant re-absorption. As regards H_γ and H_δ - their contours were merged. Considering accuracy of the N_e determination (from the H_β line shape), the reabsorption induces some increase in estimates of N_e values. On the other hand, these values correspond to a cold pinch periphery, and lower density values may occur in this focus region. The quadratic Stark-effect broadening for copper- or carbon-ion spectral lines is more adequate, taking account the fact that this radiation corresponds to the focus center [6].

Corresponding data on the Stark widths are available for CII lines in [7], for CuII in [8], and for CIII-IV spectral lines in [9]. It is necessary to note that at so-large densities the quadratic Stark effect may be transformed into the linear one. As a result, the estimated N_e values will be lower than the true ones. It is also necessary to mark some distinct features of the reported studies, concerning larger values of the electron density and the observation of the Inglis-Teller effect. This permits us to estimate also the minimum values of N_e, using the corresponding Inglis-Teller formula [10] for a shift of the boundary serial: $\lg N = 23.26 - 7.5 \lg n_{max}$, where n_{max} is the general quantum number for the last Balmer line that was observed as an isolated one (for D_β it was n = 4 and $N_e > 5.5 \times 10^{18}$ cm^{-3}; for D_α it was n = 3 and $N_e > 4.8 \times 10^{19}$ cm^{-3}, correspondingly). It should be noted that such an effect was observed earlier in astrophysics for small N-values (high values of the general quantum number). It seems that so exclusive situation can be met in the plasma-focus or Z-pinch experiments only. That observation was possible due to the high temporal resolution and sensitivity of the recording system. The experimental evidence is shown in Fig.5.

The main results of the electron density measurements within PF-1000 experiment, as performed by means of two methods, are presented in Fig. 6.

Considerable discrepancies between the D_β and CuII data can be explained by non-homogeneity along the observation axes, since the CuII data corresponded to a relatively hot part of the compression zone. The observed strong self-absorption of D_α is an additional proof of this fact. As regards the N_e peak values, there were observed some "good" shots, when the D_β line was merged (the Inglis-Teller effect described above) and we obtained $N_e \sim 4.8 \times 10^{19}$ cm^{-3}. Such spectra were observed, when the beginning of the exposition coincided with the focus formation, and the time exposition was short enough ($\leq$ 500 ns). The high-density phase of the focus (~ 4-5 µs) exceeded considerably the generation time of X-rays, neutrons and other high-energy radiations (~100 ns). That constituted a proof of non-equilibrium and unsteady-state mechanisms. The diffusion of copper ions (from the central electrode to the focus region) promotes the disintegration of the plasma focus column.

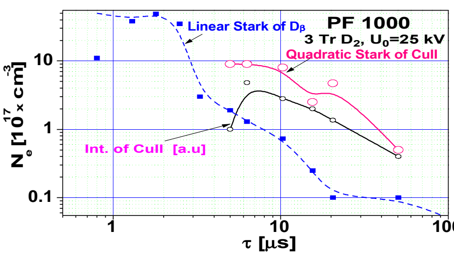
Fig.5. Example of optical spectra of the pulsed plasma



streams emitted from the PF-1000 facility. The detection conditions were for shot 4060; $t_{after\ dip}$= 0 µs, t_{exp}= 0,5µs, and for shot 4101: $t_{after\ dip}$= 100 µs, t_{exp}= 5µs

Fig.6. Electron density and concentration of copper ions in the focus of PF-1000 discharge as a function of time

As regards materials from the outer electrode, spectral lines (of Fe-, Ti-, and Ni-ions) have not been identified in



the recorded spectra.

5. SUMMARY AND CONCLUSIONS

The most important results of the studies described in this paper can be summarized as follows:

- Time-resolved spectroscopic measurements, performed for the first time in the PF-1000 facility, have shown that the VR spectra change considerably during the discharge.
- After the current dip the emitted optical spectrum contains mainly very wide Balmer lines of the working gas, e.g. deuterium, and a relatively intense continuum. The intensity and width of the Balmer lines decreases step by step, and numerous impurity lines appear about 1 µs after the discharge current peculiarity (dip).
- The highest intensity of impurity spectral lines is achieved about 6 µs after the current dip, but the lines become very narrow. The impurity emission decreases slowly, and it becomes negligible after 100 µs, but intense narrow Balmer lines can still be detected.
- A high electron density (about 10^{19} cm^{-3}) within the focus region was observed for a relatively long period (2-4 µs) after the current dip.

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ПРЕДВАРИТЕЛЬНЫЕ ВРЕМЕННЫЕ ХАРАКТЕРИСТИКИ ЭМИССИОННЫХ СПЕКТРАЛЬНЫХ ЛИНИЙ РАЗРЯДОВ НА PF-100, ПОЛУЧЕННЫХ С ПОМОЩЬЮ СПЕКТРОМЕТРА MECHELLE®900

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В работе представлены результаты спектроскопических измерений с разрешением по времени импульсных плазменных потоков, генерируемых на установке PF-100. Предпочтение было отдано оптическому спектрометру MECHELLE-900, который позволяет проводить измерения в пределах длин волн от 200 nm до 1100 nm с экспозицией времени в интервале от 100 ns до 50 ns. Особое внимание было уделено исследованию спектральных линий Бальмеровской серии для ионов рабочих газов (т.е. D_α, D_β, D_γ) и некоторых примесных линий. Это важно не только для оценки параметров плазмы, но и для прикладных исследований.

ПОПЕРЕДНІ ТИМЧАСОВІ ХАРАКТЕРИСТИКИ ЕМІСІЙНИХ СПЕКТРАЛЬНИХ ЛІНІЙ РОЗРЯДІВ НА PF-100, ОТРИМАНИХ ЗА ДОПОМОГОЮ СПЕКТРОМЕТРА MECHELLE®900

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У роботі представлені результати спектроскопічних вимірів з дозволом за часом імпульсних плазмових потоків, генерируємих на установці PF-100. Перевага була віддана оптичному спектрометрові MECHELLE-900, що дозволяє проводити виміри в межах довжин хвиль від 200 nm до 1100 nm з експозицією часу в інтервалі від 100 ns до 50 ns. Особлива увага була приділена дослідженню спектральних ліній Бальмеровської серії для іонів робочих газів (тобто D_α, D_β, D_γ) і деяких ліній домішок. Це важливо не тільки для оцінки параметрів плазми, але і для прикладних досліджень.