# SPECTROSCOPIC STUDIES OF PLASMA STREAMS GENERATED IN A 1-MJ PLASMA-FOCUS FACILITY WITH AND WITHOUT GAS-PUFFING


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The main aim of the reported experimental session was to study operational characteristics of a modified PF-1000U facility during a free propagation of a plasma-stream and its interactions with a carbon-fiber composite (CFC) target. The facility was equipped with an axial fast-acting valve for additional gas puffing into a region close to the electrodes outlets. Experiments were carried out with and without the gas puffing in chosen instants before the application of high voltage pulse. The operational regimes of the facility were established by changing these parameters and the initial charging voltage. To record optical spectra of the plasma radiation the use was made of a Mechelle®900 spectrometer coupled with a CCD-camera sensitive in a wavelength range of 300...1100 nm. During all reported experiments the exposition time was equal to 100 ns, but a time delay was changed to obtain data for different discharge phases. The performed spectral measurements enabled to study plasma dynamics, to identify plasma impurities, and to estimate electron densities and temperatures. The electron density in a free-propagating plasma stream was calculated from a linear Stark-effect observed for the $D_\alpha$ spectral line.



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## INTRODUCTION

Investigation of optical spectra emitted from plasma streams is of primary importance for the determination of a composition and dynamics of such objects. Optical emission spectroscopy has already been used for the investigation of intense pulsed plasma-ion streams generated within the 1-MJ plasma focus facility at the IPPLM [1-3], but the PF-1000 facility recently has been modernized. The aim was to increase discharge currents and neutron yields, and to produce plasma-ion streams of higher concentration and energy. The applied modifications, and particularly the application of an additional gas puffing have made it necessary to perform new detailed spectroscopic measurements for determination of the best operating regimes. Such regimes were identified when the plasma parameters reached the highest values and the small number of impurity spectral lines was observed.

The main aim of the reported study was to perform detailed spectroscopic measurements in the modified PF-1000U facility and to determine the optimal regimes for further investigations of plasma-target interactions.

Since a carbon fibre composite (CFC) is one of the most interesting materials for fusion technology, e.g. as a constructional material to be used in plasma facing components of fusion facilities, it was of interest to investigate its behaviour during interaction intense plasma streams from the PF-1000U facility. In particular, the aim of the detailed spectroscopic measurements was to investigate spectral lines of various carbon species produced by plasma interactions, dynamics of the emission of such impurities, which form the transient plasma layer in front of the surface [4, 5], as well as the instants when such carbon lines appear in the plasma.

## 1. EXPERIMENTAL SET-UP

The main modification of a Mather-type PF-1000 facility was the installation of an axial fast-acting valve for an additional gas-puffing into a region close to the electrodes outlets, as shown in Fig. 1.

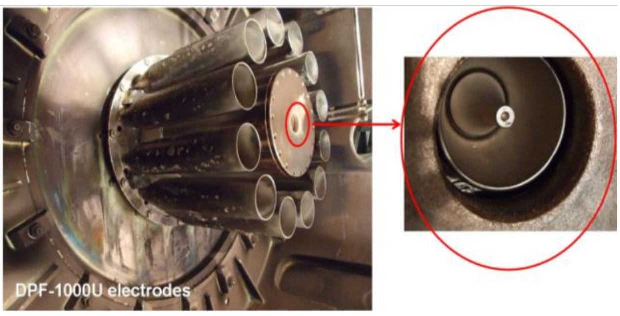


*Fig. 1. Electrodes of the modified PF-1000U facility and the outlet nozzle of the fast-acting gas-valve*

The working gas was pure deuterium under the chosen initial pressure $p_0$. Operational regimes of the PF-1000U facility were chosen by changing the initial filling pressure in a vacuum chamber, and using the puffing of about 1 $cm^3$ deuterium under the pressure of 2 atmospheres, at different instants, i.e. 1.5 or 2 ms before the application of a high voltage pulse.

In order to record optical spectra of the plasma radiation the use was made of a Mechelle®900 spectrometer coupled with a CCD-camera operating in a wavelength range of 300...1100 nm. During all reported experiments the exposition time was equal to 0.1 μs, but a time delay was changed to collect data for different discharge phases. The performed spectral measurements were used to investigate plasma dynamics, to identify plasma impurities, and to estimate the main plasma parameters, i.e., an electron density and temperature.

The electron density in a free-propagating plasma stream was calculated on the basis of a linear Stark-effect observed for the $D_\alpha$ spectral line.

To study interactions of such plasma streams with the CFC target, it was placed at the *z*-axis of the PF-1000U facility, at a distance of 9 cm from the electrodes ends, i.e., in the plasma-focus zone. During interactions of plasma streams with such a target the spectral lines of different carbon species were studied.

In the described experiments with CFC-targets the electron temperature was estimated from the ratio of different spectral lines of the chosen carbon species.

## 2. EXPERIMENTAL RESULTS

### 2.1. STUDIES OF FREE-PROPAGATING PLASMA STREAM

Some examples of the optical spectra, which were recorded in different instants of PF-1000U discharges, are presented in Fig. 2.

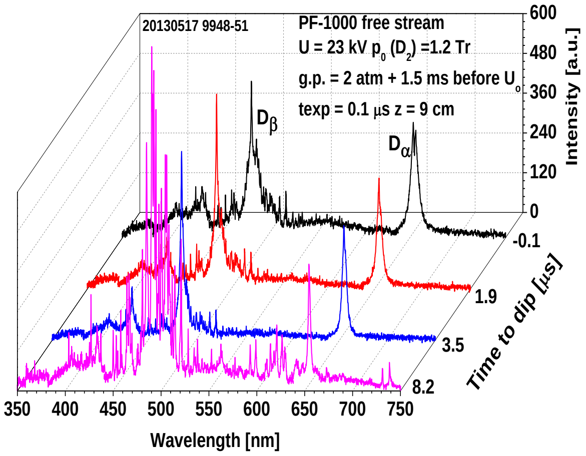


*Fig. 2. Temporal changes of the optical spectra recorded for PF-1000U shots with the gas puffing*

Those measurements made it possible to investigate dynamics of the emission of spectral lines of the working-gas and impurities. It was observed that the intense spectral lines of impurities appear in about 8 μs after the current peculiarity (so-called dip). For discharges performed without any gas puffing, the spectral lines of contaminations were more intense and observed almost during the whole discharge.

A comparison of the experiments results, which were obtained with and without the additional gas puffing, has shown that when the gas-puffing was applied the plasma electron density during the first phase of the PF-1000U discharge was considerably higher. In contrary, during the later phases of discharges with and without the gas-puffing the electron densities were very similar, as shown in Fig. 3.

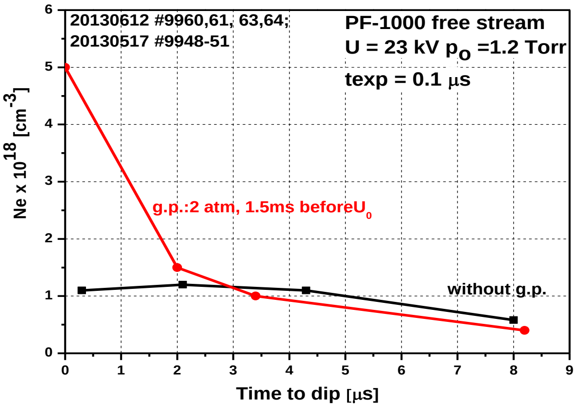


*Fig. 3. Temporal behavior of plasma electron density without gas puffing (black line) and with gas puffing application (red line)*

The reported experiments were carried out at two different initial pressures of deuterium in the vacuum chamber. The main studies were performed at $p_0$ equal to 1.2 and 1.8 Torr, respectively. The spectroscopic measurements were carried out without and with the gas puffing, as described above.

The obtained results showed that at the initial deuterium pressure $p_0 = 1.8$ Torr, and with the additional deuterium puffing, the electron density in the free-propagating plasma stream reached the highest values. During the first microsecond of the discharge it amounted to $\boldsymbol{N_e} = (6...7)\cdot 10^{18}$ cm$^{-3}$, as shown in Fig. 4.

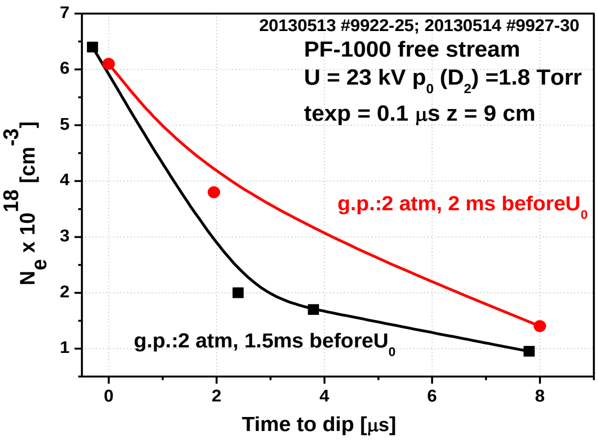


*Fig. 4. Electron density of a free plasma stream as a function of time, at $p_o$ = 1.8 Torr ($D_2$) and different instants of the gas puffing (1.5 and 2 ms before the discharge initiation)*

It should here be noted that at the lower initial pressure $p_0$ = 1.2 Torr the electron densities were also slightly lower, as shown in Fig. 5.

Nevertheless, during later phases of the PF-1000U discharges, i.e. 4...8 μs after the current dip, the electron density $\boldsymbol{N_e}$ decayed considerably (to values < $10^{18}$ cm$^{-3}$). In all investigated cases differences in behaviour of the electron density were not very large (see Figs. 4, 5).

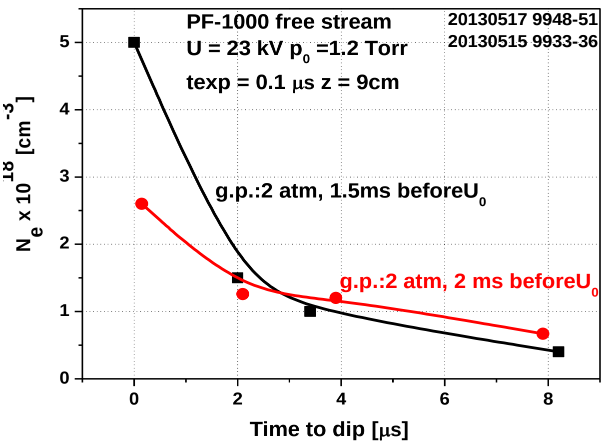


*Fig. 5. Electron density of a free plasma stream as a function of time, at $p_o$ = 1.2 Torr ($D_2$) and different instants of the gas puffing (1.5 and 2 ms before the discharge initiation)*

## 2.2. INTERACTIONS OF PLASMA STREAM WITH A CFC TARGET

During the PF-1000U experiments carried out with a CFC target placed in front of the electrodes outlets, as described above, the recorded optical spectra revealed not only deuterium Balmer-lines, but also numerous spectral lines corresponding to different ionization stages of carbon.

In particular, there were identified intense C II spectral lines (the strongest at 426.7 nm) and some spectral lines from higher ionization stages, i.e. C III lines (the most intense at 464.7 and 465.0 nm) and C IV lines (e.g. at 581.19 nm), as presented in Fig. 6.

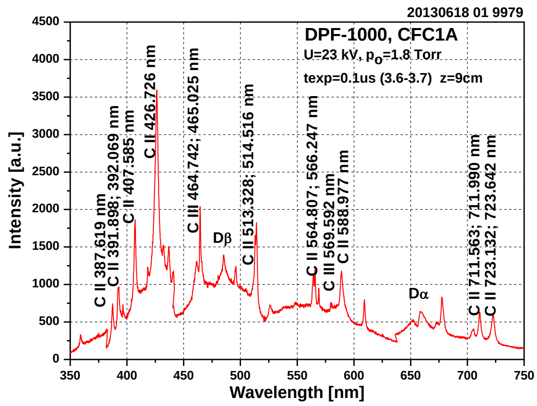


*Fig. 6. Optical spectrum of deuterium plasma during plasma-surface interaction with CFC material*

Particular attention was paid to a comparison of the behaviour of carbon species during discharges performed without and with the additional gas (deuterium) puffing. The results obtained from those experiments are presented in Figs. 7, 8.

It can easily be noticed that the carbon lines emission from the PF-1000U discharges without gas puffing appeared earlier and was slightly higher, but this fact has not influenced on plasma parameters considerably.

One can suspect that less intensive spectral lines of carbon species, as observed for discharges with the gas puffing, resulted from the injection of an additional amount of the working gas, which could carry away portion of carbon ions produced from the CFC-target placed near the electrode ends.

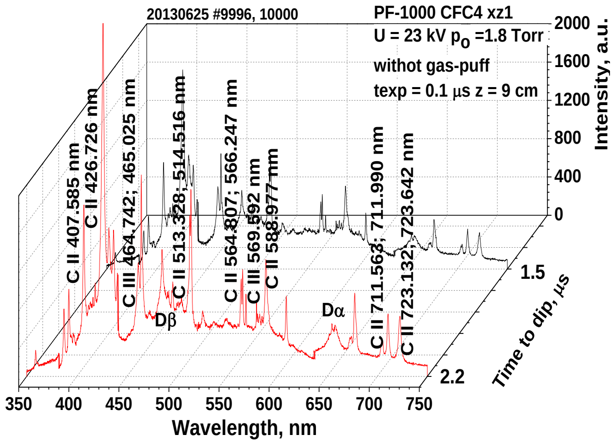


*Fig. 7. Temporal behaviour of optical spectra measured near the CFC-target surface for PF-1000U discharges without any gas puffing*

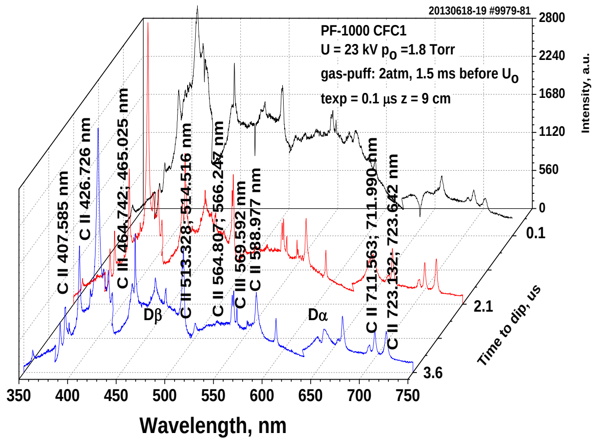


*Fig. 8. Temporal behaviour of optical spectra measured near the CFC-target surface for PF-1000U discharges with the gas puffing*

For the described target experiments the electron temperature was estimated from the ratio of the C IV – 580.1 nm and C III – 569.6 nm spectral lines. Its maximum value amounted to $T_e$ = 3.3...3.5 eV. Low values of temperature could be explained by averaging along observation angle and along the chord during recording of optical spectra. The behaviour of a plasma electron temperature showed its small dependence on time and operating conditions.

## CONCLUSIONS

The most important results of the reported study can be summarized as follows:

1. The investigation of important operational features of the modified PF-1000U facility was performed during the free propagation of a plasma stream, and during interactions of intense plasma streams with CFC-targets.

2. Spectroscopic measurements of the optical emission were performed within the PF-1000U facility at different experimental conditions and various operational regimes.

3. The maximum plasma electron density, as estimated from the spectroscopic measurements, amounted to $N_e = (6...7)\cdot 10^{18}$ cm$^{-3}$ during the first phase of the discharge, and it showed a low dependence on the initial conditions. In the later phases, i.e. after 4…8 µs, this density decreased considerably (to values $< 10^{18}$ cm$^{-3}$).

4. In experiments with the CFC targets there were recorded spectral lines of carbon in different ionization stages (the highest was C IV).

5. The intensity of the carbon radiation during discharges without any additional deuterium puffing was higher than that with the puffing,

6. The plasma electron temperature, as calculated from the ratio of intensities of the chosen spectral lines (C III and C IV), amounted to $T_e$ = 3.3...3.5 eV, only.

In conclusions it might be stated that optical emission spectroscopy should be applied simultaneously with other diagnostic techniques, e.g. laser interferometry, in order to verify quantitative data about electron densities.


## ACKNOWLEDGEMENTS

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## СПЕКТРАЛЬНЫЕ ИССЛЕДОВАНИЯ ПЛАЗМЕННЫХ ПОТОКОВ, ГЕНЕРИРУЕМЫХ 1-МДж ПЛАЗМЕННЫМ ФОКУСОМ С НАПУСКОМ ГАЗА И БЕЗ НЕГО


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Главной целью докладываемой экспериментальной сессии было изучение рабочих характеристик модифицированной установки PF-1000U во время свободного распространения плазменного потока и его взаимодействия с углеродной мишенью CFC. Установка была переоснащена специальным быстро действующим клапаном для дополнительного напуска газа в зону фокуса (область, близкую к концам электродов). Эксперименты проводились с импульсным напуском и без напуска газа в выбранные моменты времени до применения импульса высокого напряжения. Рабочие режимы установки PF-1000U определялись изменениями этих параметров и начального зарядного напряжения. Чтобы зарегистрировать оптические спектры плазменного излучения использовался спектрометр Mechelle®900 с подсоединенной к нему CCD-камерой, чувствительной в диапазоне 300…1100 нм. Во время всей серии экспериментов время экспозиции было равно 100 нс, но время задержки спектрометра изменялось для получения данных в различные фазы разряда. Выполненные спектральные измерения касались динамики плазмы, идентификации примесей в плазме, так же как и оценок электронной плотности и температуры. Электронная плотность в свободном плазменном потоке рассчитывалась из линейного штарк-эффекта, наблюдаемого для спектральной линии $D_\alpha$.


## СПЕКТРАЛЬНІ ДОСЛІДЖЕННЯ ПЛАЗМОВИХ ПОТОКІВ, ЩО ГЕНЕРУЮТЬСЯ 1-МДж ПЛАЗМОВИМ ФОКУСОМ З НАПУСКОМ ГАЗУ ТА БЕЗ НЬОГО


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Основною метою в експериментальній сесії, що доповідається, було вивчення робочих характеристик модифікованого пристрою PF-1000U під час вільного розповсюдження плазмового потоку та взаємодії з вуглецевою мішенню CFC. Установка була обладнана спеціальним швидким клапаном для додаткового напуску газу в зону фокусу (область, близька до кінців електродів). Експерименти проводились без напуску та з напуском газу до подачі високої напруги. Робочі режими визначались змінами цих параметрів та початкової зарядної напруги. Для того, щоб зареєструвати оптичні спектри випромінювання плазми використовувався спектрометр Mechelle®900 із CCD-камерою, чутливою в діапазоні довжин хвиль 300…1100 нм. Під час всієї серії експериментів час експозиції був 100 нс, але час затримки спектрометра змінювався, щоб отримати дані в різні фази розряду. Проведені спектральні вимірювання стосувались динаміки плазми, ідентифікації домішок у плазмі, так як і оцінок плазмової густини та температури. Електронна густина у вільному плазмовому потоці розраховувалась з лінійного штарк-ефекту, що спостерігався для спектральної лінії $D_\alpha$.