Influence of gas conditions on electron temperature inside a pinch column of plasma-focus discharge

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Abstract. The paper reports on soft x-ray emission from high-current discharges in PF-1000U facility operated at 170 kJ. The discharges at static conditions were performed with pure deuterium (D₂) and a mixture of D₂ and neon (Ne). In shots with the gas-puffing 1 cm³ of D₂ or a (D₂+Ne) mixture was injected 2 ms before the discharge initiation. Time-integrated x-ray images from a Be-filtered pinhole camera showed that the pinch microstructure depends strongly on gas conditions. In shots with the D₂-, (D₂+Ne)- or He-puffing distinct “filaments” and “hot-spots” were observed. Time-resolved x-ray pulses were recorded with 4 filtered PIN-diodes which recorded signals from 2 regions of 3 cm in diameter (at z = 3 cm and 6 cm from the anode). From a ratio of x-ray pulses, measured behind different filters, it was estimated that at the static D₂-filling electron temperatures (Tₑ) were from 90 eV to 200 eV. At the D₂-filling and -puffing additional x-ray spikes were emitted from “hot-spots” with Tₑ twice higher. In shots at the (D₂+10%Ne)-filling Tₑ was 4 keV. In shots with the (D₂+Ne)-mixture puffing intense “hot-spots” were formed, and Tₑ reached 2.2-7.5 keV. At the same conditions “filaments” were reproducible macroscopically, but “hot-spots” were irreproducible.

1. Introduction

Studies of x-rays emitted from high-temperature plasma provide valuable information about its structure, composition and temperature [1-2]. Such studies were performed during many experiments with a modernized PF-1000U facility, but they concerned mainly time-integrated x-ray pinhole images recorded at different gas conditions [3]. More extensive studies of x-rays from PF-1000U experiments, which were carried out with two pinhole cameras, were reported in an earlier paper [4]. In those studies there were also performed time-resolved measurements with filtered PIN diodes, which observed different regions of the pinch column, but the analysis of x-ray peaks concerned only their correlations with current filaments and hot-spots visible in time-integrated x-ray images. Detailed time-integrated x-ray measurements were performed later and attention was focused on various microstructures (current filaments and hot-spots), but the time-resolved x-ray signals were correlated with the observed current filaments only [5]. More accurate x-ray measurements in the PF-1000U facility and estimates of the electron temperature were performed recently, but analysis of time-integrated pictures was not very detailed [6-7]. Therefore, the main aim of this paper was to report on new detailed x-ray measurements carried out by means of a filtered pinhole camera and four PIN diodes,
which were located behind pinholes with different filters. The first aim was to compare new time-integrated x-ray images which might supply information about differences in the pinch internal structure. The second aim was to analyze time-resolved x-ray signals (recorded behind different filters) and to estimate plasma electron temperatures.

2. Experimental setup
The described experiments were performed in a modernized PF-1000U facility which was equipped with two coaxial electrodes of 46 cm in length, oriented horizontally [8-9]. The outer electrode was composed of 12 stainless-steel tubes (each of 8 cm in diameter), distributed symmetrically upon a cylindrical surface of 40 cm in diameter. The inner electrode was made of a thick-wall copper tube of 23 cm in diameter, surrounded at the base by a ceramic insulator of 8.5 cm in length. The outlet of that electrode was closed by a thick copper plate with a central 4.5-cm-diam. hole, where was placed a nozzle of a fast gas-valve. That valve could be triggered (from an additional condenser bank) 1.5-2.0 ms before the application of a high-voltage pulse, which initiated the main PF-1000U discharge. During that initiation the inner electrode (at high potential) played a role of the anode, and the outer one was the grounded cathode. The discharges were supplied from a large condenser bank 1.33 mF, which was charged to the voltage of \(U_0 = 16\) kV and stored 170-kJ energy.

Plasma discharges were investigated with x-ray framing cameras and x-ray pinhole cameras recording time-integrated x-ray images. For time-resolved studies of x-rays the use was made of PIN-type semiconductor detectors, which were placed behind filtered pinholes [10]. There was also used a four-frame camera with a microchannel plate (MCP) which recorded UHV and XUV images. An arrangement of the applied diagnostic equipment is shown in figure 1a.

![Diagram](image)

**Fig. 1.** (a) Cross-section of the PF-1000U chamber, which shows positions of the diagnostic equipment, (b) observation fields (each for two PIN diodes) for time-resolved x-ray measurements.

During all investigated discharges the total fusion-neutrons yield \(Y_n\) was measured by means of several silver-activation counters located around the PF-1000U chamber, and time-resolved measurements of hard x-rays and fusion-neutrons were performed with several scintillation probes placed at different distances from the electrodes outlets.

In the reported study time-integrated x-ray images of plasma were recorded with x-ray films placed inside a pinhole camera, which was oriented at 75° to the \(z\)-axis and looked at the inner electrode outlet and pinch column of about 10 cm in length. It was equipped with an input 500-\(\mu\)m diaphragm covered by a 10-\(\mu\)m Be-filter, which enabled to record x-rays of energy > 1 keV.

To record time-resolved x-ray signals from a pinch column, the use was made of four PIN-diodes of the Hamamatsu-S9055 type, which were placed behind a diaphragm with four 100-\(\mu\)m pinholes covered by different absorption filters. The whole set of the PIN diodes, produced by the ACS Ltd, Poland, was situated in a small vacuum chamber pumped out by a turbo-molecular pump [10]. The diodes windows were removed to detect photons < 1 keV. These PIN-diodes were shielded by 7-\(\mu\)m or 10-\(\mu\)m Be-filters. Each pair of the diodes observed another 30-mm-diam. region of the pinch column, as shown in figure 1b.
To estimate the plasma electron temperature \( (T_e) \) it was taken into account that recording the x-ray emission at a wavelength \( \lambda \) (and energy \( E = \hbar c/\lambda \)) behind a filter \( (j) \) the total intensity of the x-radiation depends on \( T_e \) and is given by the known formula [11]

\[
I_2 \propto \lambda^{-2} \left( \frac{k}{T_e} \right)^{-1} \exp \left[ -\frac{E}{kT_e} - \sum \mu_j(E) \times d_j \right]
\]

where the subscript \( j \) describes a specific material, \( \mu_j(E) \) is the absorption coefficient of the filter material, and \( d_j \) is its thickness. Since the used absorption filters were made of the same material (Be) the summation was not needed. High-temperature plasma without considerable impurities was considered, and under assumption that \( T_e \) are high enough (to neglect recombination and linear x-ray emission) the Bremsstrahlung emission (characterized by the Maxwellian distribution) was taken into account only. Those assumptions were consistent with results of the OES measurements [12], which showed a small amount of impurities lines during the maximum compression \( (t = 0) \). They agreed also with results of computations of a short thermalization time for a dense plasma column. Hence, using two identical detectors (PIN-diodes denoted by 1 and 2) which observed the same plasma region, but were shielded by Be-filters of a different thickness \( (d_1 \) and \( d_2) \), it was possible to estimate \( T_e \) from the ratio of x-ray emission intensities \( (I_1/I_2) \) measured behind these filters [11].

Since the reported measurements were performed with the PIN-diodes, which were located behind the identical pinholes covered by the 7-μm and 10-μm Be-filters, it was possible to estimate \( T_e \) values from a diagram showing a dependence of the \( I_1/I_2 \) ratio on a \( T_e \) value, as presented in figure 2.

![Filter Be 1.3 & 1.85 mg/cm²](image)

**Fig. 2.** Ratio of the x-ray intensities recorded behind 7-μm and 10-μm Be-filters, as a function of \( T_e \).

### 3. Experimental results

The reported studies of soft x-rays in PF-1000U facility consisted of an analysis of time-integrated images from the Be-filtered pinhole camera, and time-resolved signals from the filtered PIN diodes. The preliminary analysis was started by conversion of raw x-ray pinhole pictures into colour-enhanced equidensity-contour images by means of an OriginLab program. Taking into account the experiment configuration the magnification coefficient was determined, and the gray-scale was converted into 17 colour-levels, as presented in figure 3.

![Colour-enhanced equidensity images](image)

**Fig. 3.** Colour-enhanced equidensity images of the X-rays emission from discharges: \#11523 \( (p_0 = 1.2 \text{ hPa } D_2, U_0 = 16 \text{ kV, } Y_e = 1.1 \times 10^{10}) \), and \#11542 \( (p_0 = 1.2 \text{ hPa } D_2 + D_2\text{-puffing, } Y_e = 9.6 \times 10^{10}) \).
From the images presented above one could easily deduce that the use of the additional D₂-puffing induced a considerable increase in the soft x-rays emission. The length of the plasma jet was about 10 cm, but there were observed some microstructures, which probably corresponded to hot-spots.

For the discharges imaged in figure 3 there were also recorded time-resolved signals from the PIN diodes described in Section 2. On the basis of those signals and the diagram presented in figure 2 it was possible to estimate values of the local electron temperature \(T_e\), as shown in figure 4.

![PIN diodes signals](image1.png)

**Fig. 4.** Soft x-ray signals from two observation regions, as recorded for discharge #11523 (performed at \(p_0 = 1.2\) hPa D₂ and \(U_0 = 16\) kV) and for discharge #11542 (performed with the additional D₂-puffing), and values of the local \(T_e\).

The results presented above showed that in the discharge #11523 the local \(T_e\) values in the 1\(^{\text{st}}\) observation region (with the centre at \(z = 3\) cm) changed from 140 eV to 200 eV, while those in the 2\(^{\text{nd}}\) region (with the centre at \(z = 6\) cm) decreased from 100 eV to 90 eV. In the discharge #11542 the local \(T_e\) values were higher, in the 1\(^{\text{st}}\) region they changed from 210 eV 375 eV, and in 2\(^{\text{nd}}\) region they rose from 100 eV to 220 eV. The narrow spikes observed during the second x-ray pulse, particularly for shot #11542, might be explained as signals from hot-spots with noticeable higher \(T_e\). All the \(T_e\) values (estimated with an experimental error of \(\pm 30\%\)) seemed to be reasonable, taking into account the results of earlier studies of PF-type discharges [6].

Analogous measurements of the soft x-ray emission were also carried out for discharges performed with a (D₂+Ne)-filling, as shown in figure 5.

![Colour-enhanced equidensity images](image2.png)

**Fig. 5.** Colour-enhanced equidensity images of X-rays emission from two discharges at the initial filling: \(p_0 = 1.2\) hPa (90\%D₂ + 10\%Ne) and \(U_0 = 16\) kV: #11576 (with no additional gas-puffing, \(Y_n = 3.9 \times 10^{10}\)), and #11588 (with additional puffing of a (75\%D₂ + 25\%Ne) mixture, \(Y_n = 3.1 \times 10^{11}\)).

The use of the (90\%D₂ + 10\%Ne) mixture caused also an evident increase in the soft x-ray emission. The application of the additional puffing of the (75\%D₂ + 25\%Ne) mixture did not induced any considerable change of the plasma column length, but it caused a decrease in the pinch diameter, and the formation of more distinct hot-spots. It should be noted that such effects were also observed for other discharges performed under the similar gas-conditions, but the image of shot #11588 presented the pinch column of the smallest diameter.
For the discharges imaged in figure 5 time-resolved x-ray signals from the PIN diodes were also recorded. On the basis of those signals and the diagram shown in figure 2 it was possible to estimate values of the local $T_e$, as shown in figure 6.

![Fig. 6. Soft x-ray signals from two observation regions.](image)

The results presented above showed that for discharges with the (90%$D_2 + 10%Ne$) filling the structure of the recorded x-ray signals was more complicated, i.e., the number of the observed spikes was increased, and the estimated $T_e$ values were considerably higher. In the discharge #11576 the local $T_e$ values in the 1st observation region decreased from 4.15 keV to 2.2 keV, while those in the 2nd region changed from 580 eV to 730 eV. In the discharge #11588 (with the additional gas-puffing) $T_e$ values in the 1st observation region changed from 0.5 keV even to 7.5 keV, while those in the 2nd region changed from 175 eV to 275 eV. It should, however, be noted that for discharges with the use of a Ne-admixture the $T_e$ estimation errors were much larger (reaching even ±80%) because of two reasons. The first was the fact that the thickness of two filters was too small to estimate $T_e$ in the optimal range on the curve presented in figure 2. The second was the appearance of a very intense Ne-line (of energy equal to about 1 keV) which induced a strong increase in the soft x-ray emission, and larger inaccuracy of $T_e$ estimations.

During the recent experimental session there were also performed discharges with the pure $D_2$-filling and the additional He-puffing [13]. For the discharge #11830 the use was made of the XUV camera, which recorded frame-pictures, each with the exposition time equal to about 2 ns. The conversion of those white-black pictures into colour-enhanced images (as it was done earlier for the x-ray pinhole pictures) made it possible to observe a very complicated filamentary structure and numerous hot-spots, as shown in figure 7.

![Fig. 7. Analysis of three XUV frame-pictures.](image)
The results obtained for shot #11830 showed that for discharges with the pure D2-filling and He-puffing there were also observed some spikes which corresponded to hot-spots visible in the XUV pictures. The estimated $T_e$ values were lower than those for discharges with the D2-puffing (figure 4). The $T_e$ values in the 1st observation region changed from 115 eV to 160 eV, but there was also a spike characterized by 260 eV. The $T_e$ values in the 2nd region were equal to 100-125 eV only.

4. Summary and conclusions
The most important results of the reported studies can be summarised as follows: Plasmas generated in the PF-1000U facility were studied under different gas conditions. Time-integrated x-ray pinhole pictures, time-resolved x-ray signals from PIN diodes, and XUV images showed that the pure D2-discharges (with and without any gas puffing), as well as those performed with the (D2 + Ne) filling and (D2 + He)-puffing, produced dense plasma emitting intense x-rays. The recorded time-resolved x-ray signals made it possible to determine a ratio of x-rays intensities ($I_1/I_2$) for two observed plasma regions. From that ratio it was estimated that: For the pure D2-shots the $T_e$ values were 140-200 eV in the 1st region and about 100 eV in the 2nd region, and for the D2+He shots the $T_e$ values amounted to 210-375 eV and 100-220 eV, respectively. For the D2+He shots the $T_e$ values were lower and reached 115-160 eV and 100-125 eV only. When the (90%D2 + 10%Ne)-puffing was applied, the $T_e$ values in the considered regions amounted to 4.15-2.2 keV and 580-730 eV, respectively, and when the (75%D2 + 25%Ne)-puffing was added those values reached even 7.5 keV. Estimation errors for lower $T_e$ values were about ±30%, but those for higher $T_e$ might amount even ±80%. The reasons of this difference were too small thicknesses of the Be-filters and inaccuracies in the determination of x-ray peaks profiles. To determine $I_1/I_2$ values the x-ray signals should be integrated, but for narrow x-ray pulses one might use their amplitudes ratio.

In conclusions – it should be noted that: 1. The estimated high $T_e$ values (observed particularly for discharges with the additional gas-puffing) corresponded evidently to filaments and hot-spots which could be quasi-stable for a relatively long period, as was shown in earlier PF studies [14-15]; 2. At the pure D2-filling the use of the He-puffing did not rise $T_e$ because the x-ray emission intensity depended not only on amount of electrons (linked to Z value), but also on the plasma compression and density, which determined the electrons deceleration and the Bremsstrahlung emission; 3. The application of a heavier admixture (e.g. Ne) in the filling and puffing induce evidently the formation of more plasma microstructures; 4. The obtained high $T_e$ values (up to 7.5 keV) are consistent with those observed in other PF experiments, where $T_e$ ranging to 5-10 keV were found [6, 16].

References
[1] Plasma Diagnostic Techniques, Edit. R.H. Huddleston, S.L. Leonard (Academic Press, 1965).
[2] M. J. Sadowski, and M. Scholz, Plasma Sources Sci. Technol. 17 (2008) 024001.
[3] P. Kubes, M. Paduch, et al., Phys. Plasmas. 21 (2014) 082706.
[4] W. Surala, M. J. Sadowski, et al., Nukleonika 60 (2015) 303-308.
[5] M. J. Sadowski, M. Paduch, et al., Plasma Sources Sci. Technol. 24 (2015) 055003.
[6] E. Składnik-Sadowska, D. Zaloga, et al., Plasma Phys. Control. Fusion 58 (2016) 095003.
[7] E. Składnik-Sadowska, M. J. Sadowski, et al., PAST Ser. Plasma Phys. No 6 (2016) 112-116.
[8] M. Scholz, L. Karpinski, et al., Nukleonika 57 (2012) 183-188.
[9] D. Zaloga, E. Składnik-Sadowska, et al., Nukleonika 60 (2015) 309-314.
[10] SXRDs Soft X-ray Detection Set; Abridged Description (ACS Ltd. Warsaw, 2015).
[11] R. C. Elton, NRL Report 6738 (NRL, Washington, DC, USA, 1969).
[12] E. Składnik-Sadowska, R. Kwiatkowski, et al., PAST Ser. Plasma Phys. No 1 (2013) 279-283.
[13] D. R. Zaloga, Research on emission of visible and X-ray radiation, and estimations of electron temperature in discharges of plasma-focus type, PhD Thesis (NCBJ, Swierk 2017) – in Polish.
[14] M. Sadowski, H. Herold, et al., Phys. Letters 105A (1984) 117-123.
[15] P. Silva, and M. Favre, J. Phys. D: Appl. Phys. 35 (2002) 2543.
[16] W. L. Harries, Final Technical Report NASA-CR-1132500 (Old Dominiun Univ., Norfolk 1974).