

INVESTIGATION OF X-RAY EMISSION FROM HIGH-CURRENT DISCHARGES OF THE PF TYPE

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The invited paper reports on measurements of soft x-rays emitted from hot plasmas produced in a modernised PF-1000U facility. The discharges were performed at the D₂-filling with or without a Ne-admixture, under the initial pressure of 0.9 or 1.5 Torr and at the initial charging voltage equal to 16 or 18 kV. Time-integrated x-ray images were recorded with a pinhole camera situated side-on, at an angle of 75° to the z-axis. Differences in the pinch column structure were observed. Time-resolved measurements were performed with four PIN diodes located behind filtered pinholes. Two couples of PIN diodes (with Be-filters of 7 and 10 μm in thickness) observed 30 mm-diam. regions which had centres at a distance of 30 and 60 mm from the electrode outlets. From the recorded time-resolved x-ray signals the electron temperatures (T_e) were calculated. For the pure D₂-discharges the estimated T_e values ranged from 75 to 250 eV depending on the discharge conditions. For discharges with a Ne-admixture T_e values were higher and reached about 800 eV.

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INTRODUCTION

Measurements of x-rays emitted from high-temperature plasma supply valuable information about its structure, composition and temperature [1-2]. Such measurements were performed during extensive studies of high-current pulse discharges within a modernised PF-1000U facility, but they concerned mainly a comparison of time-integrated x-ray pinhole images recorded at different initial gas conditions [3]. More detailed measurements of x-rays from discharges in PF-1000U experiments, which were carried out with two pinhole cameras, have been reported in another paper [4]. In that study there were also performed preliminary 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-posts recorded on time-integrated x-ray images. Detailed time-integrated x-ray measurements were performed later and attention was focused on the observed microstructures (i.e., current filaments and hot-spots), but the time-resolved x-ray signals were correlated with the observed current filaments only [5]. Some time-integrated x-ray measurements and analyses of fast electron beams were carried out in another experiment, but it was performed in a smaller PF-360U device [6]. More accurate x-ray measurements in the PF-1000U facility and some estimates of the electron temperature have been performed recently, but the use was made of two PIN diodes only [7].

The main aim of this paper was to present results of new detailed x-ray measurements carried out by means of a filtered pinhole camera and four PIN diodes, which were located behind pinhole collimators with different filters. The first aim was to compare the time-integrated x-ray images which could supply information about differences in the internal structure of the pinch column. The second aim was to analyse time-resolved x-ray

signals recorded behind different filters, and to estimate values of the plasma electron temperature.

1. EXPERIMENTAL SET-UP

The reported experiments were carried out within the modernised PF-1000U facility which was equipped with 460 mm long coaxial electrodes. The outer electrode was composed of 12 stain-less steel tubes (each of 80 mm in diameter) which were distributed symmetrically upon the 400 mm diam. cylindrical surface. The inner electrode (anode) was a 230 mm diam. copper tube of closed by a copper plate with a 50 mm diam. central hole. That hole contained a fast-acting gas valve oriented along the z-axis.

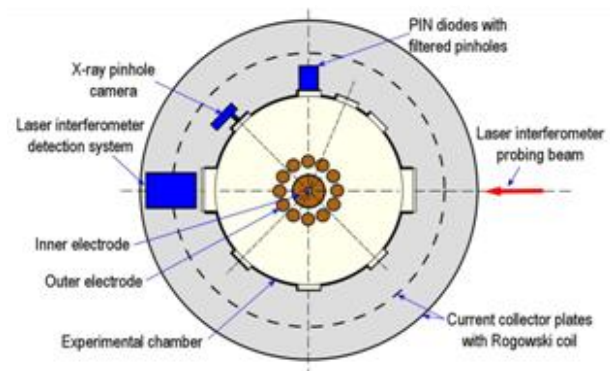


Fig. 1. Cross-section of the PF-1000U chamber, which shows positions of the diagnostic equipment

During the investigated discharges in the PF-1000U device there were recorded voltage and current-waveforms, as well as laser-interferometer images (with a spatial resolution of 500 μm) which were obtained from a multi-frame Mach-Zehnder system equipped with a Nd:YLF laser (generating 1-ns pulses, at λ = 527 nm). Also recorded were hard x-ray and neutron-signals from scintillation probes, as well as neutron yields from silver-activation counters [8-10].

Other diagnostic tools were placed around the PF-1000U chamber, as shown in Fig. 1.

In order to record time-integrated x-ray images the use was made of two pinhole cameras equipped with sensitive x-ray films. The first camera had a 1000 μm diaphragm and a 500 μm thick Al-filter, while the second camera had a 200 μm diaphragm and a 10 μm thick Be-filter. They were oriented at different azimuthal angles, but the both cameras looked the PF pinch column.

In order to obtain time-resolved x-ray signals from the investigated PF-1000U discharges the use was made of four PIN diodes of the Hamamatsu S9055 type, which had active areas of 0.2 mm in diameter and could record photons < 1 keV. They were located behind four separate 100 μm diam. pinholes which were shielded by different absorption filters. These PIN diodes, were placed inside a small vacuum chamber pumped out by a turbo-molecular pump [11]. A general view of a fragment of the PF-1000U chamber with the installed x-ray pinhole camera and the whole set of the PIN-diodes is shown in Fig. 2.

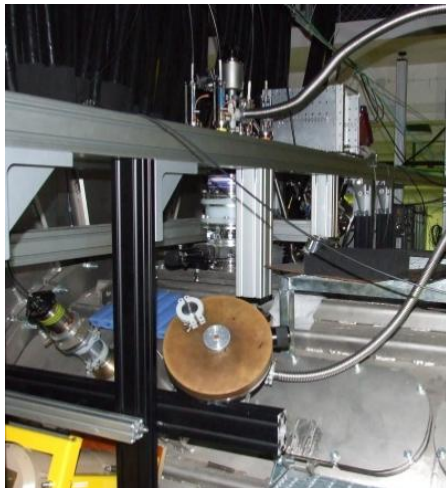


Fig. 2. X-ray pinhole camera with a rotated film and the PIN diodes system installed at the PF-1000U chamber

Due to the use of the separate collimators the PIN diodes could detect x-rays from chosen parts of the plasma pinch column. During the reported experiments a 30 mm diam. viewing field of two PIN diodes, equipped with different absorption beryllium (Be) filters (of 7 and 10 μm in thickness), was chosen on the z-axis, with its centre at a distance of 30 mm from the electrode ends. The second identical couple of the PIN diodes observed another 30 mm diam. field, with the centre at a distance of 60 mm from the electrodes, as shown in Fig. 3.

According to tests of the applied Hamamatsu S9055 diodes, which were performed in the ACS Ltd. Laboratory, the rise time of these detectors was about 100 ps, the fall time amounted to 220 ns, and the FWHM was equal to about 300 ps [11]. Their temporal responses did not depend considerably on the used electronic cables.

It should be mentioned that the applied Be-filters of different thickness were chosen in order to make it possible to estimate electron temperature (T_e) values of

plasma column emitting the observed x-radiation. For this purpose the use was made of a dependence of the x-ray intensity on the wavelength (λ) and energy ($E = hc/\lambda$) of the radiation, the T_e value of the emitting medium, and the absorption of the applied filters. (characterised by their absorption coefficients $\mu_j(E)$ and thicknesses d_j). This dependence is described by the known formula

$$I_\lambda \propto \lambda^{-2} (kT_e)^{-1/2} \exp\left(-E/kT_e - \sum \mu_j(E) \cdot d_j\right),$$

where the subscript j describes different filter materials characterised by their absorption coefficients $\mu_j(E)$ and thicknesses d_j [12].

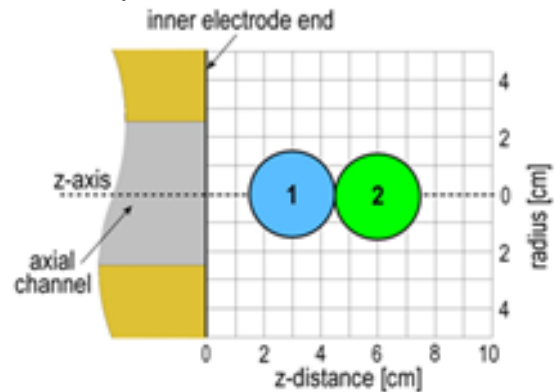


Fig. 3. Viewing fields of the PIN diodes during the x-ray measurements in the PF-1000U experiment

On the basis of the formula given above it was possible to compute the ratio of the x-ray intensities measured behind the chosen Be filters versus the electron plasma temperature, as shown in Fig. 4.

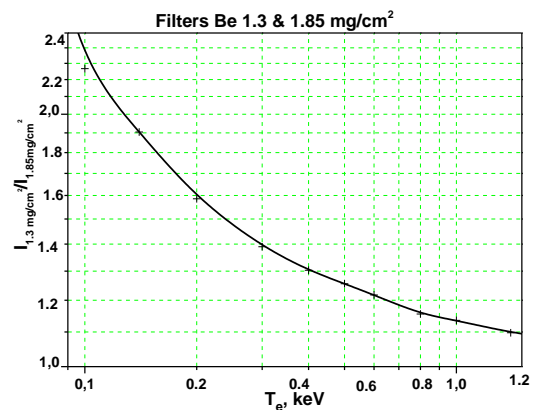


Fig. 4. Ratio of the x-ray intensities recorded behind Be-filters of 7 μm (1.3 mg/cm^2) and 10 μm (1.85 mg/cm^2) in thickness, as a function of the electron temperature

It should, however, be noted that the described measuring technique might be applied under specified conditions only: 1. The absorption filters are made of the same material (in this case Be); 2. The observed plasma discharges do not contain many impurities; 3. The Bremsstrahlung emission from plasma is characterized by the Maxwellian distribution; 4. The measured T_e values are high enough to neglect an influence of the recombination effects.

2. EXPERIMENTAL RESULTS AND DISCUSSION

The reported recent series of experiments in the PF-1000U facility was started by performing routine diagnostic measurements. The preliminary discharges were carried out at the pure D_2 -filling at the initial static pressure of 0.9 or 1.5 Torr, and the initial charging voltage of the condenser bank equal to 16 or 18 kV. The discharge current waveforms and the current-derivative (dI/dt) traces, as obtained from the Rogowski coil, were correlated with signals from the scintillation probe (recording hard x-ray and neutron pulses) as well as with the time resolved signals from the PIN diodes described above. An example of typical waveforms and temporal correlations is presented in Fig. 5.

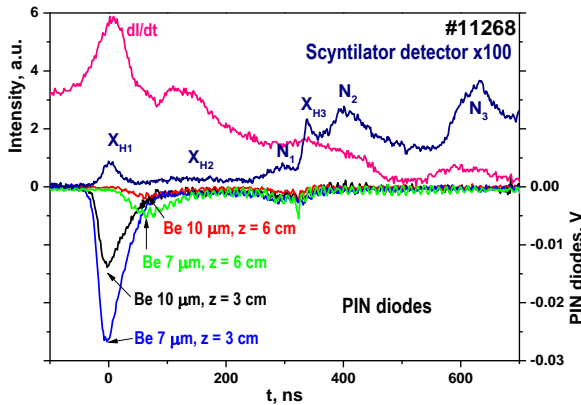


Fig. 5. Signals obtained from the PF-1000U discharge #11268. Current derivative waveform (dI/dt) is correlated with hard x-ray (X_H) and neutron pulses (N), as well as with soft x-ray signals from two pairs of the PIN diodes

From the presented example one can easily see that the investigated discharge produced three hard x-ray peaks and three distinct neutron pulses, which were shifted in relation to the hard x-ray peaks by a time-of-flight of neutrons to the scintillation detector (equal to about 280 ns). The distinct soft x-ray signals were emitted during the first hard x-ray emission only, and a time shift between signals from the first pair of the PIN diodes and those from the second pair of the detectors was evidently caused by some delay of the emission of that from the first one.

An interferometric image and a time-integrated x-ray pinhole image, which were obtained for a typical for PF-1000U discharge under static gas conditions, are shown in Fig. 6.

In order to estimate the average electron temperature (T_e) values in the observed regions of the plasma column, a more detailed analysis of the x-ray signals from two pairs of the PIN diodes was performed. An example of such an analysis is presented in Fig. 7.

From a comparison of the signals intensities in the diagram shown in Fig. 4 it was estimated that in the considered discharge the T_e values in the first region and the second one were equal to 180 and 100 eV, respectively.

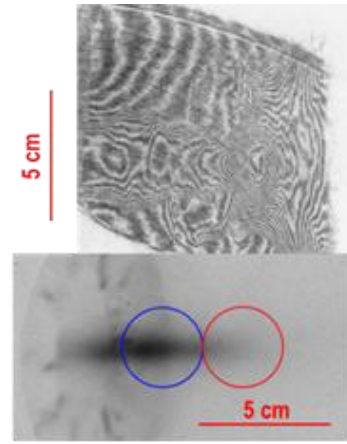


Fig. 6. Comparison of the image obtained with a laser interferometer with that recorded with an x-ray pinhole camera from a PF-1000U discharge # 11269. Two circles show the observation fields of the PIN diodes

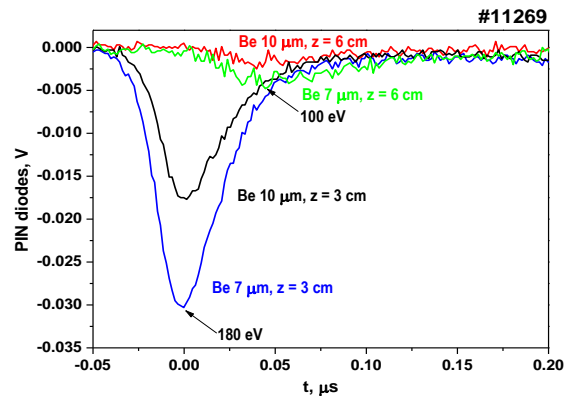


Fig. 7. Time-resolved x-ray signals from two pairs of the filtered PIN diodes, as recorded for the PF-1000U discharge #11269 which was performed under the static gas conditions, at $p_0 = 2.0$ hPa D_2 and $U_0 = 18$ kV

In subsequent experiments the discharges in the PF-1000U facility were carried out at the dynamic gas conditions, i.e., with the additional gas puffing of 1 cm^3 of pure deuterium, under the pressure of 0.1 MPa, at the instant of about 2 ms before the main discharge initiation. An example of the soft x-ray signals, which were recorded at such conditions, is presented in Fig. 8.

From the signals presented in Fig. 8 one can easily see that (in contrary to discharges at the static gas conditions) the application of the additional gas puffing caused a more complex structure of the x-ray emitting regions. In addition to the first x-ray signals there were emitted other short pulses (spikes). From a comparison of the signals intensities from Fig. 8 and the diagram shown in Fig. 4 it was estimated that in the considered discharge the T_e values in the first region (placed closer to the electrode ends) were 210, 265 and 550 eV, respectively. In the second (more distant) region the T_e values were evidently lower and they amounted to 115 and 110 eV only.

The observed x-ray spikes and a rise in T_e value, as observed with a time shift of 160...180 ns, might be explained as a result of the formation of tiny plasma-filaments and hot-spots, which can be characterized by higher plasma densities and temperatures [2, 13-15].

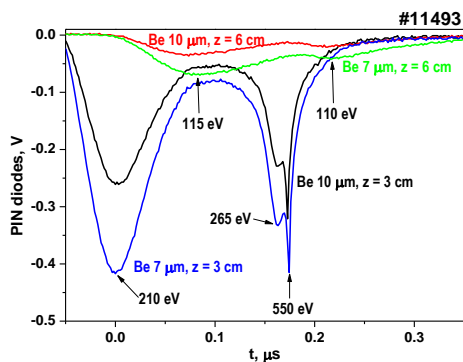


Fig. 8. Time-resolved x-ray signals from two pairs of the filtered PIN diodes, as recorded for the PF-1000U discharge #11493 which was performed at $p_0 = 1.2$ hPa D_2 and $U_0 = 16$ kV, but with the use of the additional D_2 -puffing (about 2 ms before the main discharge)

The next series of discharges within the PF-1000U facility was performed with the addition of a small neon (Ne) admixture. From earlier studies [16-19] it was known that at the application of a heavier gas there appear distinct hot-spots. Such effects have also been observed during the discharges investigated in the described PF-1000U experiments, as shown in Fig. 9.

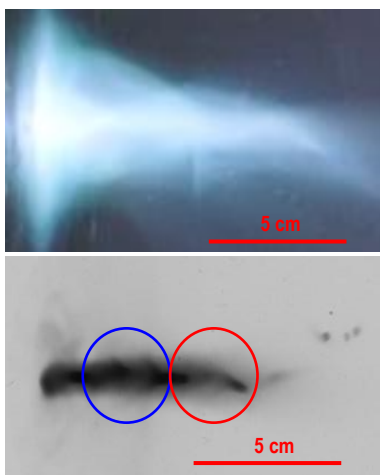


Fig. 9. Comparison of the time-integrated picture of the visible radiation with that taken with an x-ray pinhole camera for a PF-1000U discharge # 11501, which was performed under the static filling at $p_0 = 1.2$ hPa $D_2 + 1\%$ Ne_2 , GPD_2 and $U_0 = 16$ kV

The x-ray pinhole image presented in Fig. 9 has proved that during the investigated PF-1000U discharge in the viewing fields of the PIN diodes there were formed several distinct hot-spots. These tiny plasma regions could have a considerably higher density and temperature, what might induce the emission of intense x-ray spikes. In order to estimate the T_e values for the considered discharge a detailed analysis of the soft x-ray signals from the PIN diodes was performed, as shown in Fig. 10. On the basis of the x-ray signals presented in Fig. 10 and the diagram shown in Fig. 4 it was estimated that in the considered discharge the T_e values in the first observation region were equal to 315, 470, 830 and 740 eV, respectively. In the second observation region, similarly to the discharges without any admixture, the T_e values were lower and they amounted to 86, 135 and 105 eV only.

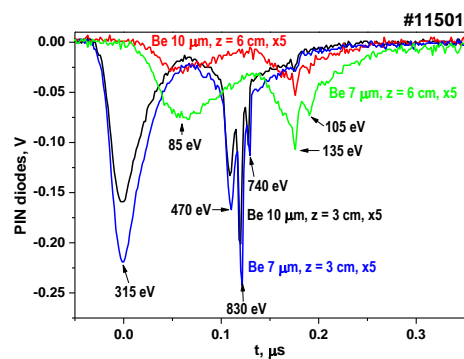


Fig. 10. Time-resolved x-ray signals from two pairs of the filtered PIN diodes, as recorded for the PF-1000U discharge #11501 performed with a small Ne admixture

It should here be noted that the highest values of T_e were obtained on the basis of distinct x-ray spikes, which were probably emitted from the observed hot-spots. This hypothesis has been confirmed by the fact that the number of the recorded spikes corresponded to the number of the distinct hot-spots. In fact, in the x-ray pinhole image shown in Fig. 9 there were visible 3 distinct hot-spots in the first observation field, and 2 hot-spots in the second field. The corresponding numbers of x-ray spikes were recorded upon the time-resolved signals shown in Fig. 10.

From an analysis of the x-ray signals presented in Fig. 10 it might also be deduced that the considered hot-spots (and the corresponding x-ray spikes) appeared with some delays in relation to the main x-ray pulse, which was well correlated with the dI/dt peak (see above). From the waveforms presented in Fig. 10 it was estimated that these delays ranged from about 100 ns to about 130 ns in the first region, and from about 130 ns to about 150 ns in the second region.

From the analysis of the considered x-ray spikes it might also be deduced that the living time of the individual hot-spots was of the order of the width of the recorded x-ray spikes, i.e., it ranged from several ns to about 10 ns.

SUMMARY AND CONCLUSIONS

The most important results of the studies described above can be summarised as follows: 1. High-current pulse discharges in the PF-1000U facility were carried out under static initial gas conditions in pure deuterium, at the dynamic conditions realised by the additional puffing of deuterium, and at the application of a small admixture of a Ne-gas; 2. The routine diagnostics confirmed the results of the earlier experiments performed in this facility, but particular attention paid to time-resolved measurements of soft x-rays emitted from two chosen regions of the plasma pinch column; 3. In the discharges carried out at the static gas filling the x-ray pulses were well correlated with the dI/dt peak, and it was estimated that T_e values in the 1st and the 2nd region were about 180 and 100 eV, respectively; 4. In the discharges performed with the additional deuterium puffing some plasma micro-regions of an increased x-ray emission were observed near the electrode ends, and the T_e values were estimated to range from 210 to 550 eV in the 1st pinch region, and to about 110 eV in the 2nd region; 5. During the PF-1000U discharges

carried out with a small admixture of a Ne-gas, in the pinch column there were observed distinct plasma-filaments and hot-spots, those emitted intense x-ray spikes, and the estimated T_e values in the hot-spots formed near the electrode end ranged from about 300 eV to above 800 eV; 6. It was deduced that the distinct hot-spots were formed with a delay of 100...150 ns in relation to the first main x-ray pulse (corresponding to the pinch compression) and they could exist from several to about 10 ns.

It might be concluded that the time-integrated and time-resolved x-ray measurements supply valuable information about the emission characteristics and changes of the T_e values in the observed pinch regions. In order to collect more data such measurements should be continued under different gas conditions. Particular attention should be focused on studies of hot-spots, because they are local sources of intense x-ray spikes (induced probably by some higher-energy electron beams), but they are possibly connected also with sources of fast ion beams which play important role in nuclear fusion reactions.

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ИССЛЕДОВАНИЕ РЕНТГЕНОВСКОГО ИЗЛУЧЕНИЯ СИЛЬНОТОЧНЫХ РАЗРЯДОВ В УСТАНОВКАХ ТИПА ПФ

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Описаны измерения мягкого рентгеновского излучения горячей плазмы, генерируемой в модернизированной установке ПФ-1000U. Разряд происходит в вакуумной камере при напуске дейтерия D2 с добавкой Ne и без, начальное давление составляло 0,9 и 1,5 Торр, а рабочее напряжение – 16...18 кВ. С помощью камеры обскура, расположенной под углом 75° относительно оси z, зарегистрированы рентгеновские снимки с временным разрешением. Наблюдается разница в структуре пинча. Измерения с временным разрешением проводились с помощью четырёх диодов, расположенных за отверстием с фильтром. Две пары диодов (с бериллиевым фильтром толщиной 7 и 10 мкм) передавали изображение из зон радиусом 30 мм, центры которых находятся на расстоянии 30 и 60 мм от среза электродов. Анализ сигналов рентгеновского излучения с временным разрешением позволил оценить электронную температуру (T_e). Для разрядов с чистым дейтерием величина электронной температуры варьируется от 75 до 250 эВ в зависимости от условий разряда. Для разрядов с добавкой неона температура была выше и достигала 800 эВ.

ДОСЛІДЖЕННЯ РЕНТГЕНІВСЬКОГО ВИПРОМІНЮВАННЯ СИЛЬНОСТРУМОВИХ РОЗРЯДІВ У ПРИСТРОЯХ ТИПУ ПФ

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Описані вимірювання м'якого рентгенівського випромінювання гарячої плазми, що генерується в модернізованому пристрої ПФ-1000U. Розряд відбувається у вакуумній камері при напуску дейтерію D₂ з домішкою Ne та без нього, початковий тиск складав 0,9 та 1,5 Торр, а робоча напруга – 16...18 кВ. Рентгенівські знімки з часовим розділенням зареєстровані за допомогою камери обскура, яка знаходилась під кутом 75° відносно осі z. Спостерігається різниця в структурі пінча. Вимірювання з часовим розділенням проводились за допомогою чотирьох діодів, що розташовані за отвором із фільтром. Дві пари діодів (з берилієвим фільтром 7 та 10 мкм) передавали зображення із зон радіусом 30 мм в плазмі, центри діодів розташовано на відстані 30 та 60 мм від электродів. Аналіз сигналів рентгенівського випромінювання з часовим розділенням дозволив оцінити електронну температуру (T_e). Для розрядів з чистим дейтерієм величина електронної температури змінюється від 75 до 250 еВ в залежності від умов розряду. Для розрядів з домішкою неону температура сягає 800 еВ.