STUDIES OF X-RAY RADIATION ON THE PLASMA FOCUS FACILITY PF-3

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The investigation of the spectral and amplitude characteristics of the X-ray radiation of the plasma focus facility PF-3 (W_{max}= 2.8 MJ) has been done. A diagnostics set for X-ray measurements is described. The total energy radiated from the pinch in the spectral range 0.4 ÷ 1.5 keV at the stored energy up to 1 MJ is ~ 10 kJ. Registration of the X-ray radiation spectral structure in the Ne-discharge within the long wavelength spectrum part (~ 100 ÷ 300 eV) have been first done at PF-3-facility. Conclusion about necessity to take into account this spectral range in the total balance of radiation energy has been done.

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1. INTRODUCTION

As known, the facility of a "Plasma Focus"-type (PF) is a source of various radiation: neutron one, fluxes of accelerated particles, electrons as well as ions, microwave radiation, X-ray radiation in a wide range of wavelengths.

The experiments on the study of the X-ray radiation driven by the PF-3-facility are represented in a given paper.

The PF-3-facility is a PF-one with the so-called "flat" geometry of the electrodes (Filippov-type). The facility parameters are:

- capacity of the capacitor bank – 9.2 mF;
- maximal charging voltage – 25 kV;
- maximal stored energy – 2.8 MJ;
- minimal external inductance – 15 nH;
- diameter of the chamber – 2.5 m;
- diameter of the anode – 0.9 m;
- height of the insulator – 0.25 m.

The experiments were done at the storage energy up to 1 MJ and at the discharge current amplitude up to 3 MA.

2. TASK STATEMENT

The production and the study of high power pulses of X-ray radiation (XRR) under operation with heavy strongly-radiating gases (Ne, Ar) is traditionally one of the main directions of the studies at PF-3-facility. A specific feature of the radiation generation from a dense hot Ne-pinch ($n \geq 10^{19}$ cm^3; $T \leq 1$ keV) is that a great part of the radiated energy occurs in the K-shell lines of Ne. The quanta energy in this case is ~ 1 keV [1]. At using the PF as a driver for compressing various types of the liners [2] the plasma temperature essentially drops, being equal ~ 50 ÷ 100 eV. The necessity in measuring XRR in the range from 100 eV emerges. The problem is complicated by a radiation flux weakening in a working gas (1 ÷ 5 Torr Ne). Moreover, PF is the source of a harder radiation emerging under interaction of a plasma current sheath (PCS) and of electron beams with the anode surface. The quanta energy of such a radiation can be located in the range 5 ÷ 100 keV.

The goal of a given study is the investigation of the spectral and amplitude characteristics of the soft X-ray radiation from the pinch (100 eV ÷ 1.5 keV), as well as the hard X-ray radiation from the anode surface. A diagnostics set, allowing one to solve the mentioned task, is described.

3. DIAGNOSTICS TECHNIQUES

3. 1.PIN-HOLE CAMERAS

Pin-hole cameras are used for obtaining two-dimensional images of the radiation zone, integral in time. The usage of the filters of various materials, differently thick, allows one to produce the pinch images in various spectral ranges. Be, 5 ÷ 50 μm thick, and Al, 1.5 ÷ 10 μm thick, are usually used as filters. The pin-hole diameter is varied from 10 μm to 200 μm, dependent on the radiation intensity and on the disposition of the pin-hole camera. Using the pin-hole, 10 ÷ 30 μm, and a film, low sensitive to a visible light, one can avoid the usage of a filter. The usage of multi-hole cameras allows one to produce the pinch images in various spectral ranges on one frame.

3. 2.SEMICONDUCTOR DETECTORS

Two types of semiconductor detectors are used for obtaining the radiation characteristics in time:

- detectors with the Al-layer sprayed upon a sensitive element – SPPD-11 – for the measurements in the range 0.4 ÷ 100 keV;
- open detectors – RPPD-11 – allowing one to register the radiation with the quanta energy from 10 eV.

The semiconductor detectors are sometimes used for the X-rays yield measurements in the integral mode.

3. 3.X-RAY SPECTROGRAPH

Spectral structure of the Ne-radiation study in the range 10 ÷ 100 Å was performed with a grazing-incidence spectrograph, having a concave diffraction – golden covered – lattice replica (R = 1 m, 1200 lines per millimetre). A distance from the input slit to the lattice centre is 70 mm, angle of incidence is 4°, inlet beam aperture is ~ 1°. The radiation was registered with the photofilm located perpendicular to the Rowland circle, at the different distances from the lattice centre. Such a disposition provided the least defocusing for the only chosen wave-length, λ_{foc}. However, the input beam aperture restriction to 1° has allowed us to produce the spectra with the acceptable line defocusing in a rather wide wavelength range, $\Delta\lambda \sim 0.5\ \lambda_0$. In a given study we have used two distances, 104.5 mm and 143 mm, with the maximal focusing at the wavelength of 25 Å and 66 Å respectively, that has provided the permissible defocusing in the whole range of interest for us (10 ÷ 100 Å).

A diagram of the X-ray diagnostics equipment location is shown in Fig. 1. When the diagnostics element is placed at the angle 90° to the facility axis, the soft X-ray radiation from the pinch only is registered. In this case, the distance to the pinch is ~ 1.5 m. When the diagnostics element is installed at the chamber axis, both the soft and the hard radiation spectrum components are registered. The distance to the pinch can be varied from 0.3 m to 3 m. When the diagnostics element is installed at the angle 60° to the facility axis, a soft X-ray radiation from the pinch and a relatively-soft component of the hard radiation, emerging under interaction of the current plasma sheath with the anode surface, are registered. In this case, the distance to the pinch is ~ 0.5 m.

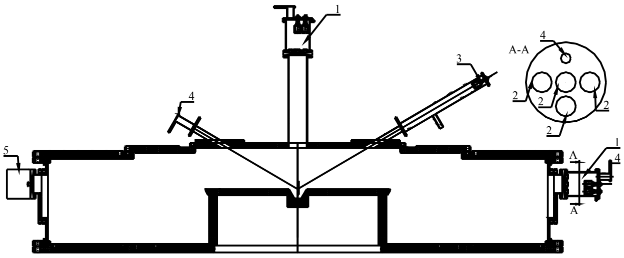


Fig. 1. Diagram of X-ray measurements. (1 – detector head; 2 – pin-diodes; 3 – hard X-ray pin-hole; 4 – pin-hole cameras; 5 – X-ray spectrograph)

A detector head including the pin-hole camera and four SPPD-type detectors, has been developed and used. The design provides the installation of replaceable filters and of neutral attenuators. The detector head is supplied by an autonomous evacuation set. The detector head can be installed at the facility axis, as well as at the lateral chamber wall.

The X-ray spectrograph can be installed at the angle of 90° to axis, as well as at the branch pipe, 60° to axis. The necessity in the spectrograph installation at the angle of 60° (at the more close distance to the pinch) is caused by the significant absorption of a soft radiation (100 ÷ 300 eV) in a working gas.

All the diagnostics branch pipes are supplied with vacuum locks. The central part of the anode is changeable. An insertion with a conical deepening, 100 mm in diameter and 80 mm deep is usually used. An insertion with diagnostical orifices can be used, when necessary.

EXPERIMENTAL RESULTS

The typical pinch images produced with the pin-hole cameras are given in Fig. 2. Fig. 2 (a) was obtained in 30 sequential shots and illustrates a very good (~ 1 mm) pinch reproducibility in a space (at the geometrical anode centre) from shot to shot that is of importance under operation with the liner loadings. Fig. 2 (b,c) represents the pinch images produced by the one pulse with the pin-hole cameras located at the angles of 60° and 90° to the facility axis. The hot zone dimensions (quanta energy > 0.6 keV) are ~ 5 mm in diameter and ~ 5 cm in high.

An analysis of pin-hole images shows that ~3/5 of the pinch length are located over the anode plane and 2/5 of it are located in the conical deepening in the central anode part.

The usage of semiconductor detectors, SPPD-11 and RPPD-11-types, allows one to perform the X-ray radiation measurements in the range 100 eV ÷ 100 keV. An absolute spectral sensitivity of the detector is given in the passport data. Sensitivities of the filter-detector systems in the whole energy range were calculated for each filter-detector combination, taking into account spectral absorption characteristics of a given filter.

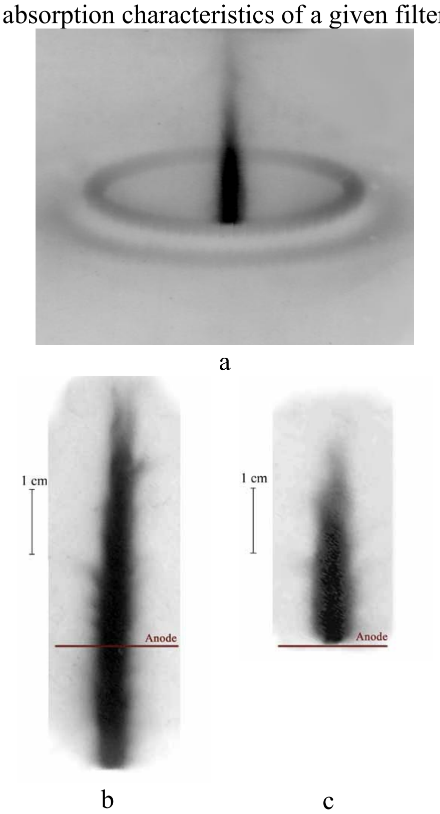
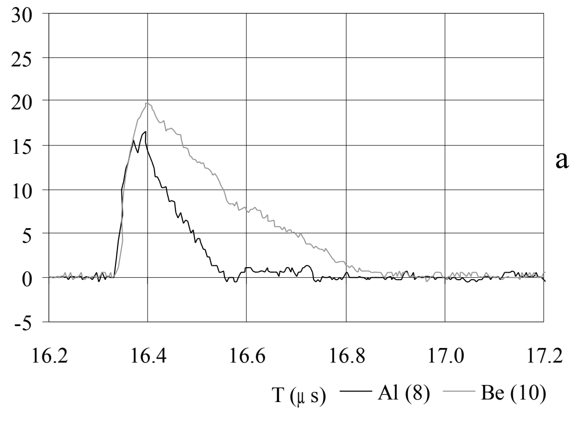


Fig. 2. Pin-hole camera images

One pair of filters (Be 24 μm and Al 8 μm) was selected by their thickness in such a way that their sensitivities coincide at the quanta energies < 1.5 keV (due to Al K-jump).



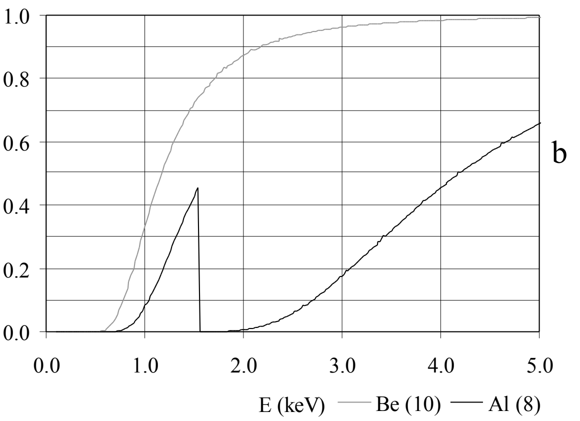


Fig. 3. Soft X-ray measurement

A difference in the indications of these two channels corresponds to the radiation with the energy > 1.5 keV. The measurements done at the angle 90° to system axis showed that – within the measurement error (a few percents) – the signals of two detectors coincide that speaks about the absence of a noticeable amount of radiation from the pinch with the quanta energy > 1.5 keV.

The signal behavior in time beyond the filters, Be 10 μ m and Al 8 μm, is shown in Fig. 3a. One can judge about a mean-effecting quanta energy (assuming a radiation mono-energy) by the ratio of the signal areas. Obtained ratio $S_{Be}/S_{Al} = 2.4$ corresponds to the energy of 1.2 keV (Fig.3b).

The oscillograms of hard X-ray radiation (Al-filter, 0.6 mm thick + Cu-filter, 150 μm thick, 60° to the axis) and those of soft X-ray radiation (Al-filter, 8 μm thick, 90 ° to the axis) are shown in Fig. 4. Some advancing of the hard X-ray pulse is stipulated by interaction of a current shell with the anode surface on the early stages of the compression (before dense pinch formation)

For estimating the radiation hardness, the ratio of the signals with the filters 0.6 mm Al and 0.6 mm Al + 0.15 mm Cu has been measured. This ration turns out to be equal ~ 3. An average-effective energy of ~ 30 keV corresponds to such a ratio.

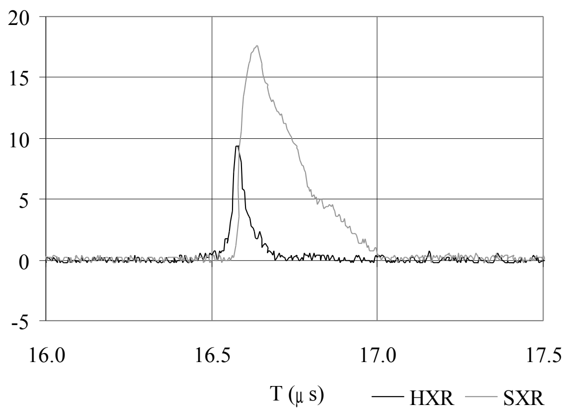
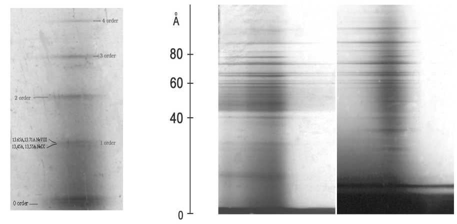


Fig. 4. Oscillograms of hard X-ray and soft X-ray pulses

The results of measuring the spectral distribution of the soft X-ray radiation in the range 100 eV ÷ 1.5 keV, obtained with the above-described X-ray spectrograph is given in Fig. 5. Each spectrogram was obtained for 5 discharges.



Be (10 μm) C (0.08 μm) Without filter

Fig. 5. X-ray spectra in discharges with pure Ne

Using carbonic filters, one can distinctly see the K-jump of carbon (43.8 Å) that serves as an initial benchmark in the procedure of decoding the spectra. The spectrograph slit diaphragming in the longitudinal direction – it makes the spectrograph similar to the pin-hole camera – has allowed one to judge on the transversal pinch dimensions by the characteristic film fogging. The densitogram study allows one to identify the series of Li-like lines of Ne. However, a part of them can be the lines of He-like NeIX. An insufficient spectral resolution of the instrument, ~ 1 Å, does not allow one to make a more definite conclusion. A jump in the carbon absorption hides a short wavelength part (λ < 43.8 Å) of the lines of this series.

The usage of Be 10 μm as a filter in a number of experiments has allowed one to observe the short wavelength (~ 10 Å) Ne-ion lines in higher orders. In this case, the long wavelength lines are too weak and not seen.

The main result of this study is in that the registration of the spectral X-ray radiation structure in the Ne-discharge within the long wavelength spectrum part (~ 100 ÷ 300 eV) have been first done at PF-3-facility. The spectral resolution of the instrument didn't allow us to realize an unambiguous identification of all the lines in the mentioned range. However, the presence of rather intense lines allows one to make the conclusion about the necessity of taking account of this range in the total energy balance of radiation.

CONCLUSION

A set of diagnostics for X-ray measurements on the PF-3 facility has been developed.

The X-ray radiation from PF has been studied in three spectral ranges:

- Soft X-ray radiation of Ne-pinch in the range 0.4 ÷ 1.5 keV. Pinch size is ~ 5 mm in diameter, ~ 5 cm high. The radiation duration is a few hundreds nanoseconds. The total energy radiated from the pinch in this spectral range is ~ 10 kJ.
- Hard X-ray radiation provided by an interaction of the PCS and electron beams driven in the pinch with the anode surface. An average energy of this radiation is ~ 30 keV.

The presence of rather intense Ne-ion lines in the range 100-300 eV makes necessary to take into account of this range in the total radiation energy balance.

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ДОСЛІДЖЕННЯ РЕНТГЕНІВСЬКОГО ВИПРОМІНЮВАННЯ УСТАНОВКИ ПЛАЗМОВИЙ ФОКУС ПФ-3

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Проведено дослідження спектральних і амплітудних характеристик рентгенівського випромінювання плазмовофокусної установки ПФ-3 ($W_{макс}$= 2.8 МДж) у трьох спектральних діапазонах. Описано діагностичний комплекс для вимірювання рентгенівського випромінювання. Повна енергія, що випромінюється пінчем у спектральному діапазоні 0.4 – 1.5 кеВ при енергії накопичувача до 1 МДж, складає ~ 10 кДж. Вперше на установці ПФ-3 проведено спектральні вимірювання випромінювання у довгохвильовій частині спектру 100-300 еВ при розрядах у неоні. Зроблено висновок про необхідність врахування цього діапазону у загальному енергетичному балансі випромінювання.

ИССЛЕДОВАНИЕ РЕНТГЕНОВСКОГО ИЗЛУЧЕНИЯ УСТАНОВКИ ПЛАЗМЕННЫЙ ФОКУС ПФ-3

В.И. Крауз, В.В .Мялтон, В.П. Виноградов

Проведены исследования спектральных и амплитудных характеристик рентгеновского излучения плазмофокусной установки ПФ-3 ($W_{макс}$= 2.8 МДж) в трех спектральных диапазонах. Описан диагностический комплекс для измерения рентгеновского излучения. Полная энергия, излучаемая пинчом в спектральном диапазоне 0.4 – 1.5 кэВ при энергии накопителя до 1 МДж, составляет ~ 10 кДж. Впервые на установке ПФ-3 проведены спектральные измерения излучения в длинноволновой части спектра 100-300 эВ при разрядах в неоне. Сделан вывод о необходимости учета этого диапазона в общем энергетическом балансе излучения.