

Research on Correlation of X-Ray Pulses with Electron-, Ion- and Neutron-Emission from High-Current PF-Discharges

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Abstract – The paper describes the emission characteristics of high-current discharges studied in MAJA-PF and PF-360 devices, operated at IPJ, and PF-1000 facility operated at IPPLM. Particular attention was paid to studies of the detailed sequence of emission phenomena within individual discharges. Measurements performed within MAJA-PF determined the temporal correlation of X-rays, neutrons, electron-beams (in different directions) and high-energy ion-beams (mainly along the z-axis). It was found that the two-pulse neutron-emission dominates at all the investigated conditions within PF-360. Using the time-of-flight (TOF) technique, it was estimated that energy of fusion-neutrons in the first peak, measured at $\theta = 10^\circ$ and 77° , was (2.65 ± 0.13) MeV and (2.47 ± 0.15) MeV, respectively. That anisotropy confirmed the dominance of the beam-target mechanism. The two-pulse neutron emission was compared with the visible-radiation and X-ray pictures, which were taken with micro-channel plates within the mega-joule PF-1000 facility. Effects of the shortening of a pinch plasma column and the formation of dense spherical structures were observed.

1. Introduction

Plasma-Focus (PF) devices, i.e. the non-cylindrical high-density Z-pinch facilities, which can generate dense magnetized plasma of fusion parameters, have been investigated in various laboratories for many years. Such plasmas, produced within the pinch regions located at the discharge symmetry-axis, are efficient sources of the intense electromagnetic (EM) radiation and corpuscular emission. The EM radiation is usually emitted in a wide energy range, from the infrared- and visible-radiation to UV, X- and γ -rays. Relativistic electron beams (REB), fast beams of accelerated ions originating from the working gas, admixtures and impurities, as well as fusion reaction products (fast protons and neutrons from D-D reactions) are also observed [1]. Measurements of the neutron emission characteristics deliver information about behavior of deuterons in plasma, their heating

and accelerating processes, and they are usually carried out in medium- and large-size PF facilities.

Studies of PF-type discharges have also some application aspects. There are some possibilities to use such devices, especially for the soft X-ray lithography, electron-beam lithography, medical microscopy, positron emission tomography (PET), production of very small devices (MEMS), and X-ray or neutron flaw-detection.

The investigation of the corpuscular and electromagnetic radiation, as carried out in many laboratories all over the world, have also been performed within two medium-size facilities MAJA-PF [2, 3] and PF-360 [4, 5], operated in Swierk, Poland (since the middle of the 80s), as well as within the large-size PF-1000 (since the end of 90s) [6, 7]. The main aim of this paper is to summarize the recent studies on the correlation of the corpuscular and X-ray emissions with other phenomena, which have been performed within these three facilities.

2. Experimental set-ups and diagnostics

The described investigations have been performed within the MAJA-PF, PF-360 and PF-1000 facilities, all equipped with Mather-type coaxial electrodes. The first machines could deliver peak currents of 500 kA and 1.8 MA, respectively, while PF-1000 could deliver 2-2.3 MA. The MAJA-PF device has a tubular 72-mm-diameter inner electrode, and a 124-mm-diameter outer one, which consists of 16 copper rods of 298 mm in length. That device was operated at 37-44 kJ, with the initial charging voltage up to 32-35 kV and the initial filling pressure equal to 1.0-2.5 hPa of D_2 or D_2+Ar mixture. The PF-360 facility has been equipped with a 120-mm-diameter inner electrode and a 170-mm-diameter outer one, both made of copper tubes of 300 mm in length. The facility was operated at 99-121 kJ, with the initial charging voltage up to 28-32 kV and the initial filling pressure varied from 2.6 to 10 hPa of D_2 . The PF-1000 was operated at energy of 600-740 kJ and charging voltage of 30-33 kV. That facility has been equipped with the copper inner electrode of 230-mm in diameter and 600-mm in length and a squirrel cage type outer electrode, which

consists of 12 stainless steel 40-mm diameter rods distributed around a 400-mm-dia. cylinder. In PF-1000 experiments the initial deuterium filling pressure was about 5.3 hPa.

To perform time-resolved measurements within both devices at IPJ-Swierk the use was made of the routine electrical-diagnostic equipment: Rogowski coils – for measurements of the total discharge current, and high-voltage dividers – for recording inter-electrode voltages. In order to carry out time-resolved measurements of neutron pulses, there were applied scintillation-pmt probes located inside paraffin shields and collimators, which were placed at different angles to the z-axis, at chosen distances from the PF pinch region. To investigate temporal characteristics of the electron emission the use was made of Cherenkov-type detectors equipped with the rutile (in MAJA-PF) and diamond (in PF-360) radiators. In order to record soft and hard X-ray pulses the use was made of miniature scintillation detectors covered with different Al-foil filters. Time-resolved measurements of ion-beams were performed by means of ion magnetic analyzers (in PF-360), and scintillation detectors with appropriate Al-filters (in MAJA-PF).

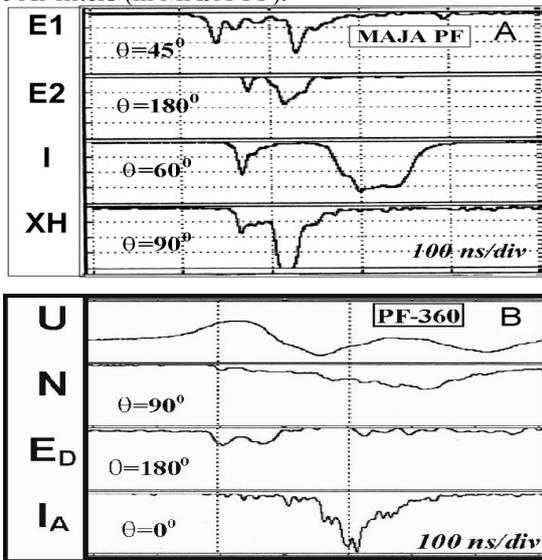


Fig. 1. Time-resolved signals, as recorded: (A) - for a MAJA-PF discharge at $U_0 = 32$ kV, $E_0 = 37$ kJ, $p_0 = (1.7$ hPa $D_2 + 5\%$ Ar) and $Y_n = 2.2 \times 10^9$, (B) - for a PF-360 discharge at $U_0 = 28$ kV, $E_0 = 113$ kJ $p_0 = 4.7$ hPa D_2 , and $Y_n = 5.9 \times 10^9$. Notations: U – voltage; E1 and E2 – e-beam signals from the Cherenkov detector with the rutile radiators; E_D - e-beams signal from a diamond radiator; N – neutrons and hard X-ray signal; I – ion signal, I_A - signal of 600-keV deuterons from a magnetic analyzer; XH - hard X-rays

The PF-1000 was equipped with the routine diagnostic tools and with a set of neutron, X-ray and electron time-resolved measuring-system, but we was mainly interested in measurements of dynamics of a current sheath (CS) observed in the soft X-ray and visible

radiation. The use was made of a soft X-ray micro-channel-plate (MCP) detector (consisting of 4 quadrants with 2-ns gating time), shielded with a polyester, which transmitted the radiation in a window of 200-300 eV and above 600 eV. Four optical frame-cameras with a gating time of 1 ns, and the inter-frame separation of 10 - 20 ns, recorded the emitting plasma in the 10 nm visible spectral window near 589 nm.

3. Experimental results

Measurements of the time-resolved signals, which were performed for different corpuscular and X-ray emissions simultaneously, enable a temporal sequence of phenomena during the pinch phase of the investigated PF discharges to be determined. Two sets of time-resolved signals, as recorded within MAJA-PF and PF-360 facilities, are shown in Fig.1.

During experiments within the MAJA-PF device, there were performed time-resolved studies of the correlation of pulsed electron-beams (measured in different directions) with hard X-ray pulses, ion beams (mainly in the axial direction), and fusion-neutron pulses. The distinct ion peaks and the emission of high-energy e-beams at angles of 45° to the z-axis (as shown in Fig.1A) and of 90° , have been observed within MAJA-PF experiments. The amplitudes of the time-resolved electron signals have been relatively low, and the mechanism of the e-beam generation has been unclear, but it might be connected with Rayleigh-Taylor instabilities, which appear often upon the current sheath surface.

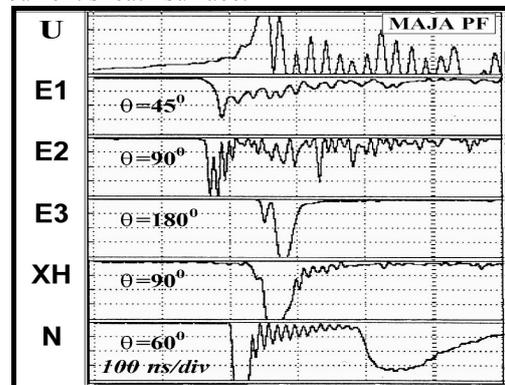


Fig. 2. Time-resolved signals recorded for the MAJA-PF discharge at $U_0 = 32$ kV, $E_0 = 37$ kJ, and $p_0 = (1.7$ hPa $D_2 + 5\%$ Ar) and $Y_n = 2.5 \times 10^9$. Notations: U – inter-electrode voltage; E1, E2, and E3 – e-beam signals from the Cherenkov detector with rutile radiators registered for different directions (E3 registered by means of 50-keV of electron magnetic spectrometer channel radiator); XH - hard X-ray signal; N – neutrons with hard X-ray signal

The emission of the main electron beams along the main z-axis in the up-stream direction together with ions (recorded by means of the magnetic analyzer), neutrons, and X-ray signals, has been observed in the

mentioned above case and also within PF-360 discharge, as shown in Fig.1B.

The case of a relatively intense emission of electron beams at 45° and 90° to the z-axis, together with electron beams emitted along the main z-axis (and registered by means of 50-keV channel of the electron magnetic-spectrometer), as well as with significant neutron- and hard X-ray-signals, is shown in Fig.2.

During the recent experiments within the PF-360 facility the investigation of time-resolved neutron signals has been performed with the use of scintillation neutron-probes. The set of four channel time-resolved fast neutron signals for PF-360 is presented in Fig.3. It was observed that a time delay between X_n and N_n (for $n = 1, 2$) was about 360 ns for NP1 and NP4 probes (located at a distance of 860 cm from the electrodes outlet) or about 130 ns for NP2 and NP3 probes (located at a distance of 290 cm).

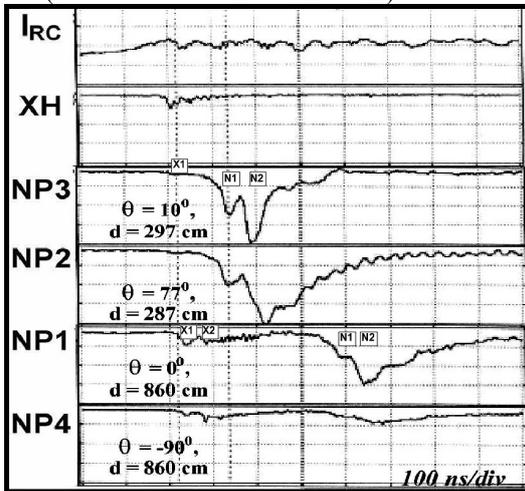


Fig. 3. Time-resolved neutron signals from NP3, NP2 probes (located at the distances of 297 cm and 287 cm from the inner electrode outlet) and NP1, NP4 probes (located at the distances of 860 cm), as recorded within the PF-360 facility at the operational conditions: $U_o = 30$ kV, $E_o = 113$ kJ, $p_o = 8.0$ hPa D_2 , and $Y_n = 1.22 \times 10^{10}$. Additional signal: I_{RC} – the total discharge current from Rogowski coil, XH - hard X-ray signal. Successive neutron and hard X-ray pulses are denoted as N1, N2, and X1, X2

Analyzing many sets of the time-resolved signals from the two neutron probes NP3 and NP2, energy of neutrons emitted in the first neutron peak could be estimated by the TOF method. The NP3 probe was positioned almost end-on (at the angle $\theta = 10^\circ$ to the z-axis, and at a distance $d = 297$ cm), while the NP2 was placed side-on (at the angle $\theta = 77^\circ$ to the z-axis, and at a distance $d = 287$ cm). The appearance of two-neutron peaks (with a relatively small first peak) upon the time-resolved neutron signals was observed in about 75% recorded traces.

For this analysis the traces with distinct X1 peaks

were taken into consideration only. A time shift (Δt) was measured between the maximum of the X1 peak and the beginning of the wide neutron peak. The analysis, as performed for PF-360 at the deuterium pressure p_o varied from 6.0 to 8.0 hPa, gave the maximum neutron energy in the first peak: $E_n = (2.47 \pm 0.15)$ MeV at $\theta = 77^\circ$ and $E_n = (2.65 \pm 0.13)$ MeV at $\theta = 10^\circ$. Two exemplary sets of the neutron signals, as obtained from PF-360 discharges, are shown in Fig.4.

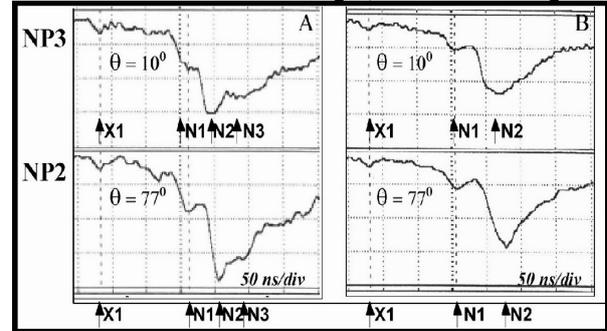


Fig. 4. Time-resolved neutron signals from NP3 and NP2 probes (located at the distances of 297 cm and 287 cm from the inner electrode outlet), as recorded within the PF-360 facility at the operational conditions: (A) - $U_o = 29$ kV, $E_o = 106$ kJ, $p_o = 6.25$ hPa D_2 , and $Y_n = 2.16 \times 10^{10}$; (B) - $U_o = 30$ kV, $E_o = 113$ kJ, $p_o = 7.95$ hPa D_2 , $Y_n = 1.41 \times 10^{10}$. Successive neutron pulses are denoted as N1, N2, and N3

One can easily identify three neutron peaks in the first case (A) and two neutron peaks in the second cases (B). The maximum neutron energy within the first peak (N1) for the two presented cases were: 2.74 MeV and 2.76 MeV, as determined at the angle of 10° , and 2.39 MeV and 2.62 MeV, as determined at the angle of 77° . It demonstrates an evident anisotropy in the investigated first peak fusion-neutron emission, which confirms the role of non-thermal neutron production mechanisms.

The evolution in time of the neutron pulses and other corpuscular and X-ray radiation phenomena should be correlated with the visible and soft X-ray frames, as one can observe within PF-1000 facility discharges (see Fig.5 and Fig.6). At the beginning an intensively radiating region of the pinch, located of about 2 cm in front of the anode top, was observed (Fig.5A). At this time one can observe the start of the downstream collapse-effect in the dense plasma region up to the distance of 6 cm from the anode front. This movement is finished at $t = 0$. At this instant the minimum diameter of the narrow radiating pinch column was about 0.5 cm, and its length was about 5 cm. A dense spherical structure of about 1 cm in diameter (and a life-time of about 30-50 ns) was formed at the end of presented sequence (Fig.5C-D).

A sequence of the soft X-ray MCP frames, as recorded within PF-1000 facility, is shown in Fig.6.

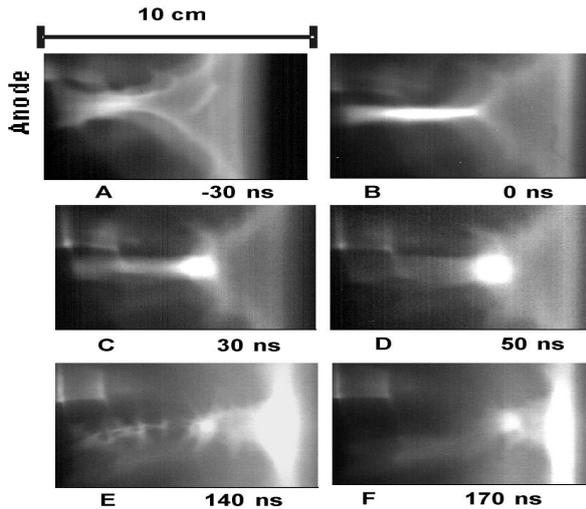


Fig. 5. Typical sequence of MCP frames recording VR, as obtained within PF-1000 experiment

The first pinch (Figs.6A–B) was 4-8 cm in length and 1-2 cm in diameter. This diameter was relative stable and considerably larger than that recorded in the VR frames. Within the period $t = 50-100$ ns (Fig.6C) intensity of the radiation decreased and we recorded only a contour showing some $m = 0$ instabilities.

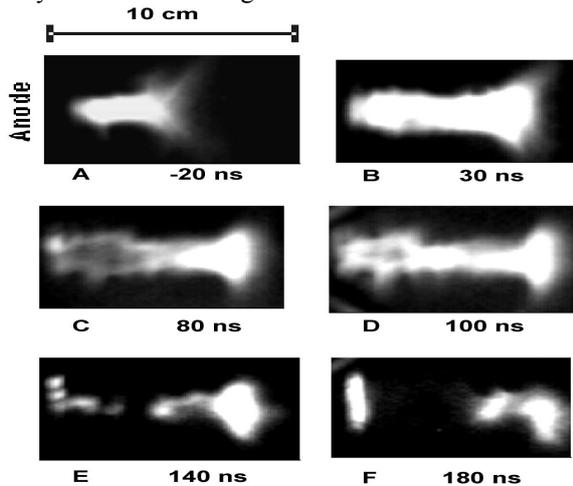


Fig. 6. Typical sequence of MCP frames recording soft X-rays, as obtained within PF-1000 experiment

4. Discussion of results and conclusions

The example of time-resolved measurements of the corpuscular emission and X-rays radiation within MAJA-PF facility, shown in Fig.1A and Fig.3, proved that the electron emission can be observed at different angles ($\theta = 45^\circ$ and 90°). The ion signals suggested that high-energy ion beams ($E_{\text{deut}} > 220$ keV) do not appear before the $t = 0$ instant, but they are emitted several ns later. The ion emission within PF-360 seems to be not-reproducible in time. The 600-keV deuterons (shown in Fig.1B) could be emitted 40 ns

after the $t = 0$ instant, while deuterons (recorded with a pinhole camera) could appear at the earliest 10 ns before that instant. It says about a stochastic character of the appearance of sources of the fast ion emission.

The set of the time-resolved signals, as recorded in MAJA-PF experiments and shown in Fig.2, suggests that the sequence of the emission phenomena is as follows: 1 – the emission of electron beams at $\theta = 90^\circ$, 2 – the emission of e-beams at $\theta = 45^\circ$ (both probably connected with the Rayleigh-Taylor instabilities), 3 – the maximum compression ($t = 0$ instant) and the emission of X-rays correlated with the main e-beams, which are recorded in the up-stream direction.

A small neutron peak (N1), which is often observed within PF-360 discharges is correlated with the X1 pulse and it starts at the instant of the maximum compression. Measurements of energy of neutrons in the first pulse (N1), as performed at $\theta = 10^\circ$, gave the value $E_n = (2.65 \pm 0.13)$ MeV, which is lower than that reported for a small-size (about 3 kJ) PF facilities. It should be noted that an analysis of the neutron energy spectrum could be performed more precisely at higher Y_n and longer measuring bases.

Similar studies of the correlation were performed also by a PF-1000 team (at IPPLM, Warsaw). The two-pulse neutron emission, as observed within PF-1000 device, was compared with MCP frames recording VR and X-rays. The effects of shortening of pinch plasma column and creation of dense spherical structure were observed.

The most important results of recent studies can be summarized as follows:

- A detailed sequence of the emission phenomena has been studied and determined for single discharges carried out within PF-type facilities in IPJ-Swierk.
- Using diagnostic techniques applicable for studies of dynamics of the current sheath (VR and soft X-ray MCP detectors) all the correlation phenomena could be analyzed much deeper and more precisely.

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