NUKLEONIKA 2016;61(2):161–167
doi: 10.1515/nuka-2016-0028

ORIGINAL PAPER

DE GRUYTER
OPEN

Measurements of fast electron beams and soft X-ray emission from plasma-focus experiments

Władysław Surała,
Marek J. Sadowski,
Roch Kwiatkowski,
Lech Jakubowski,
Jarosław Żebrowski

Abstract. The paper reports results of the recent experimental studies of pulsed electron beams and soft X-rays in plasma-focus (PF) experiments carried out within a modified PF-360U facility at the NCBJ, Poland. Particular attention was focused on time-resolved measurements of the fast electron beams by means of two different magnetic analyzers, which could record electrons of energy ranging from about 41 keV to about 715 keV in several (6 or 8) measuring channels. For discharges performed with the pure deuterium filling, many strong electron signals were recorded in all the measuring channels. Those signals were well correlated with the first hard X-ray pulse detected by an external scintillation neutron-counter. In some of the analyzer channels, electron spikes (lasting about dozens of nanoseconds) and appearing in different instants after the current peculiarity (so-called current dip) were also recorded. For several discharges, fast ion beams, which were emitted along the *z*-axis and recorded with nuclear track detectors, were also investigated. Those measurements confirmed a multibeam character of the ion emission. The time-integrated soft X-ray images, which were taken side-on by means of a pinhole camera and sensitive X-ray films, showed the appearance of some filamentary structures and so-called hot spots. The application of small amounts of admixtures of different heavy noble gases, i.e. of argon (4.8% volumetric), krypton (1.6% volumetric), or xenon (0.8% volumetric), decreased intensity of the recorded electron beams, but increased intensity of the soft X-ray emission and showed more distinct and numerous hot spots. The recorded electron spikes have been explained as signals produced by quasi-mono-energetic micro-beams emitted from tiny sources (probably plasma diodes), which can be formed near the observed hot spots.

Key words: electron beams • X-ray emission • plasma focus • hot spots

W. Surała[✉], R. Kwiatkowski, L, Jakubowski,
J. Żebrowski
National Centre for Nuclear Research (NCBJ),
7 Andrzeja Soltana Str., 05-400 Otwock/Swierk, Poland,
Tel.: +48 22 273 1417, Fax: +48 22 779 3481,
E-mail: wladyslaw.surala@ncbj.gov.pl

M. J. Sadowski
National Centre for Nuclear Research (NCBJ),
7 Andrzeja Soltana Str., 05-400 Otwock/Swierk, Poland
and Institute of Plasma Physics and Laser Microfusion
(IPPLM),
23 Hery Str., 01-497 Warsaw, Poland

Received: 10 September 2015
Accepted: 11 December 2015

Introduction

Experimental research on X-rays and electron beams, as well as ion beams and fusion products that are emitted from PF-type discharges has been carried out with different PF facilities in various laboratories for many years [1–8], but there are still some unsolved questions concerning mechanisms and characteristics of these electromagnetic and corpuscular emissions.

In general, it is well known that soft X-ray (SXR) pulses are generated by electrons stopping (Bremsstrahlung) inside plasma, and hard X-ray (HXR) pulses are produced mainly by fast electron beams interacting with metal electrodes, but it is not known where and when such electron beams are generated and accelerated. One of possible explanations is a hypothesis that some electrons are accelerated inside miniature plasma diodes, which can be formed due to magnetohydrodynamic (MHD) instabilities of current filaments observed in PF discharges, and particularly inside pinch columns [1, 4]. This hypothesis has been partially confirmed by experimental observations of current filaments and so-called hot spots (i.e., microregions of an increased X-ray emission) observed on soft X-ray pinhole images, but there is no theoretical model that might be used to compute dimensions and characteristics of such filaments and hot spots [9, 10]. Therefore, it is necessary to investigate each new PF facility experimentally.

Since an old PF-360 machine [7] operated at NCBJ in Swierk, Poland, has been modernized, it has been decided to perform new measurements of the X-ray and electron emission from the present PF-360U facility. The studies of soft X-ray pulses and fast electron beams emitted from high-current pulsed discharges of the PF-type are of importance not only for the determination of emission characteristics of the given experimental facility, but also for investigation of plasma dynamics and particle acceleration processes.

Experimental setup

The modified PF-360U facility is equipped with Mather-type coaxial electrodes made of thick-wall copper tubes, which at their bases are separated by an insulator and connected with a current collector fixed at one end of a large (about 60 cm in diameter and 100 cm in length) vacuum chamber. The outer electrode of 170 mm in diameter and the inner electrode of 120 mm in diameter are 300 mm in length. The inner electrode base is embraced by a cylindrical ceramic-insulator of 70 mm in length. The inner electrode outlet is closed by a copper plate with a central 40-mm-diameter hole, which can be used for axial measurements of electron beams emitted in the upstream direction. A general view of the PF-360U experimental chamber is presented in Fig. 1.

The PF-360 chamber is usually filled up with pure deuterium at the initial pressure ranging from 4 to 7 hPa, but some experiments are also performed at filling containing admixtures of other gases. Plasma discharges within the PF-360U facility are usually supplied from a condenser bank, which can be charged up to 30 kV, 126 kJ. Under such conditions, the maximum discharge-current intensity reaches about 1.5 MA in about 5 μs after the discharge initiation.

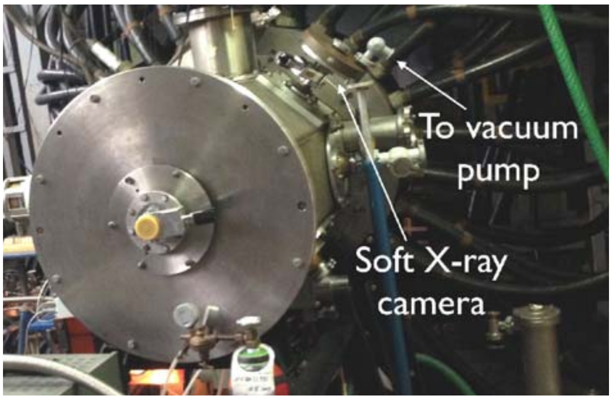


Fig. 1. General view of the PF-360U experimental chamber with a soft X-ray camera mounted on the left wall of the chamber.

In the PF-360U facility, similar to other PF devices, during the final compression of a current sheath after the main current peculiarity (a so-called current dip), a dense plasma pinch column (plasma-focus) is formed at the z-axis, near the electrode outlets. This dense and high-temperature plasma emits intense X-rays, energetic electron beams (mostly in the upstream direction), and fast ion beams (mainly along the z-axis). It also emits products of the D-D fusion reactions, i.e. fast neutrons and protons emitted in all directions.

In the reported experimental studies, the discharge current waveforms were recorded by means of a standard Rogowski coil and a fast digital oscilloscope. To record time-resolved hard X-ray signals and fusion-produced neutrons, the use was made of a shielded measuring head (equipped with a scintillation detector of the NE-102a type and XP2020 Hamamatsu® photomultiplier), which was placed at a distance of 5 m from the electrode ends. The total neutron yield was measured by means of two or three silver activation counters situated around the main experimental chamber.

To record time-integrated soft X-rays images of plasma discharges, the use was made of a pinhole camera placed in a diagnostic port side-on the experimental chamber and oriented at an angle of 75° to the z-axis. The location of the X-ray pinhole camera and an electron analyzer is presented in Fig. 2.

To perform measurements of fast electron beams emitted through the axial channel in the inner electrode, the use was made of two different magnetic analyzers, each of which could be connected with a vacuum tube fixed behind the main current collector. A reason for the use of two different analyzers was to perform a comparison of two detection methods (i.e. Cherenkov-type detectors and organic scintillators), as well as the cross-checking of recorded electron-beam signals and widening of a measurement range, due to individual analyzer characteristics.

The first magnetic analyzer was equipped with an inlet diaphragm and two strong and relatively

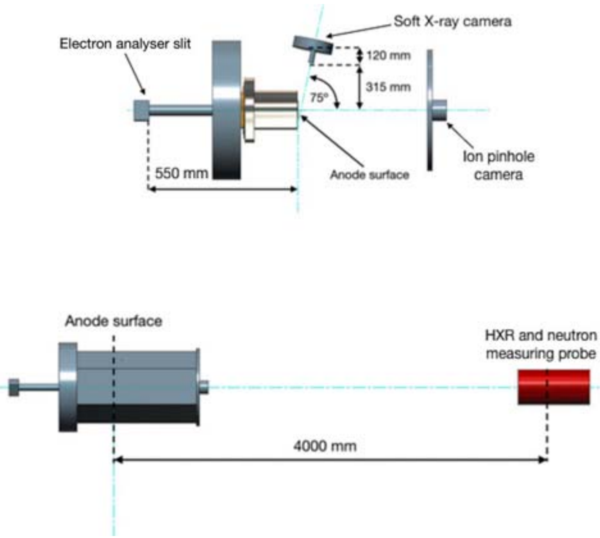


Fig. 2. Location of diagnostic tools used for measurements of soft X-rays and fast electron beams within the PF-360 experimental chamber.

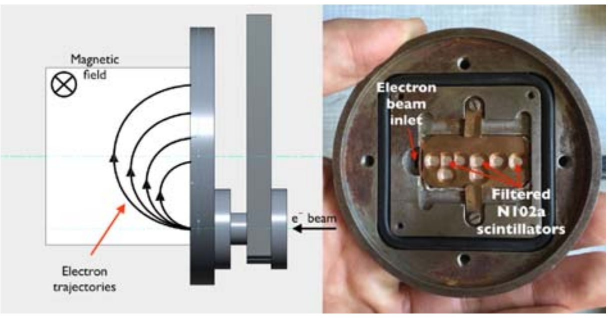


Fig. 3. Side-on view of the small magnetic analyzer with a 180° deflection of the analyzed electrons (top) and a view of the plate with several miniature scintillation detectors (bottom).

large permanent magnets, placed on the both sides of an incoming electron beam. They deflected the analyzed electrons by 180° and separated them according to their energies. These electrons could be recorded by means of a shielded X-ray film or a set of miniature scintillation detectors, which were connected through separate optical fiber cables with fast photomultipliers located inside a Faraday cage. The energy range of this analyzer was 41–715 keV. A scheme of the analyzer described above is shown in Fig. 3.

The second electron spectrometer (of a cylindrical shape) was equipped with an inlet diaphragm and two strong miniature permanent magnets, which were fixed just behind this diaphragm. The deflected electrons could be recorded by a strip of an X-ray film shielded by an aluminum foil, or by several small Cherenkov-type detectors located at different angles to the z-axis. Those detectors were made of miniature aluminum-nitride (AlN) crystals and coupled through separate optical cables with fast photomultipliers placed in the Faraday cage mentioned above. A low-energy threshold of the AlN detectors was equal to about 66 keV, but they were shielded by light-tight 10-μm-thick Al filters, eliminating all electrons of energy <32 keV. Hence, the energy range of the described spectrometer was from 76 to about 300 keV (determined by the analyzing magnetic field and angular positions of the detectors). A view of this spectrometer is presented in Fig. 4.

The X-ray pinhole camera was equipped with an inlet 500-μm-diameter diaphragm covered by a 10-μm- or 25-μm-thick beryllium absorption filter which eliminated X-rays of energy <1 keV or <1.2 keV, respectively. Time-integrated X-ray images were recorded on a sensitive X-ray film fixed upon a rotated support, which enabled to make pictures of about 12 discharges.

An additional diagnostic tool was a small ion pinhole camera equipped with exchangeable solid-state nuclear track detectors (NTD) of the PM-355 type shielded by a 2-μm-thick Al-foil that eliminated deuterons of energy <220 keV. This camera was usually situated at the z-axis, at a distance of about 1 m from the electrode ends, and it enabled time-integrated measurements of the accelerated primary ions (mostly deuterons) as well as studies of their spatial distributions to be performed.

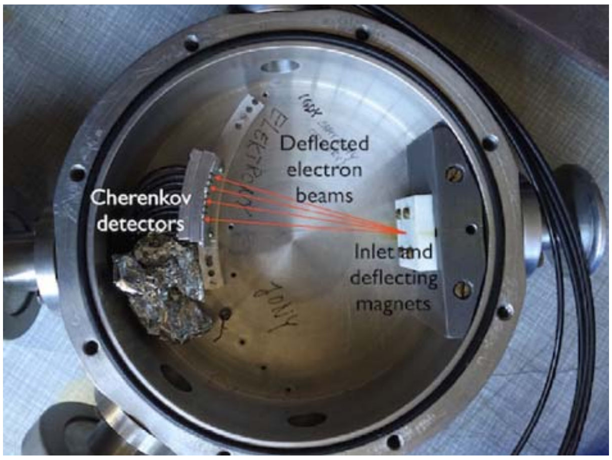


Fig. 4. View of a cylindrical magnetic spectrometer (without a cover plate) and trajectories of deflected electrons of energy in a range from about 50 keV to about 290 keV, which could be recorded by miniature Cherenkov-type detectors.

Experimental results and discussion

During the described experimental campaign with the PF-360U facility, about 100 discharges have been performed at the charging voltage U_0 = 29–30 kV and at different initial gas conditions, i.e. at a pure deuterium filling and at the deuterium filling with a small volumetric admixture of argon (4.8%), krypton (1.6%), or xenon (0.8%). The main aim of the application of these heavier noble gases was to investigate their influence on the soft X-ray emission and characteristics of the emitted electron beams.

Particular attention was focused on time-resolved measurements of electrons in different energy channels of a miniature magnetic spectrometer. A comparison of the electron-induced signals and those corresponding to hard X-rays and neutrons, as measured for a PF-360U shot #44, is presented in Fig. 5.

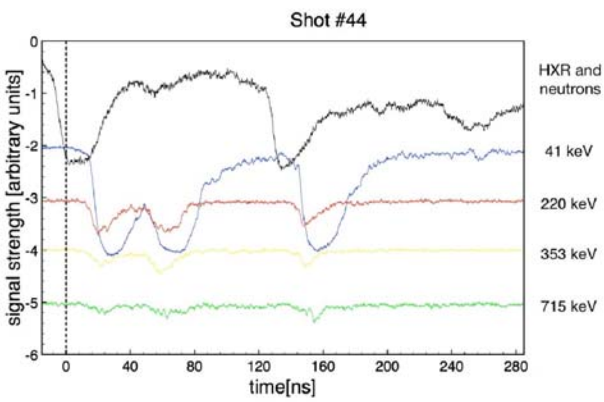


Fig. 5. Signals of hard X-rays and neutrons (from in a scintillation detector) in a comparison of those induced by fast electrons in different energy channels of a miniature magnetic spectrometer, as measured for shot #44 performed at the pure deuterium filling p_0 = 6.5 hPa, U_0 = 30 kV, I_{max} = 1.3 MA, Y_n = 1.01 × 10^{10}. The instant t = 0 corresponded to the current dip.

From the presented waveforms, one can see that in a case when one or two hard X-ray peaks were generated the first signals in all the measuring channel appeared almost simultaneously (with a delay <20 ns), while the next electron signals were observed up to 1 μs later. Amplitudes of the signals in the lowest energy channel were the highest ones, and since a N102a scintillator response (i.e., light output) is monotonically increasing with an electron energy value [11] in the considered spectral range, one can deduce that the population of electrons of energy equal to about 1 keV was the largest. Populations of electrons of higher energies (equal to 220, 353, and 715 keV) were evidently smaller. For 29 deuterium discharges (shots), time shift between initial hard X-ray pulse peak and electron beam signal peaks for all energy channels was calculated. The obtained results revealed that a hard X-ray pulse preceded electron beam signal with an average time of 17 ± 2 ns. A hardware latency (i.e., time of flight to the detectors, transit time in PMTs, signal cables, optic fibers, as well as detectors response time, etc.) differences for the HXR and electron signals did not exceed 6 ns and for most electron energies were below 3 ns, hence one can deduce that the initial electron and X-ray pulses originated at different instants. Time of flight (TOF) of electrons from the anode surface to the analyzer differed by 3 ns for the electrons of the lowest and highest recorded energy, and remains in a good agreement with the experimental data (the initial electron beam pulse was usually recorded almost simultaneously in all channels). It should also be noted that in different measuring channels, there were also recorded some narrow spikes corresponding to mono-energetic electron microbeams. The appearance of such microbeams could be explained by the acceleration of some electrons within tiny plasma diodes (formed probably near hot-spots), as described in our earlier papers [12, 13] and in the introduction.

Time-resolved measurements of the fast electrons were carried out for many PF-360U discharges performed with the pure deuterium filling, but in some cases, the appearance of mono-energetic electron microbeams has not been observed, as shown in Fig. 6.

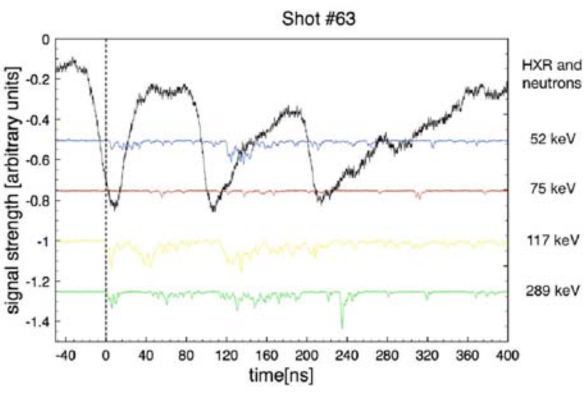


Fig. 6. Electron signals from different energy channels of the magnetic spectrometer and hard X-rays and neutrons signals measured for a shot #46 performed at the pure deuterium filling p_0 = 6.5 hPa, U_0 = 30 kV, I_{max} = 1.33 MA, Y_n = 1.58 × 10^9. The instant t = 0 corresponded to the current dip.

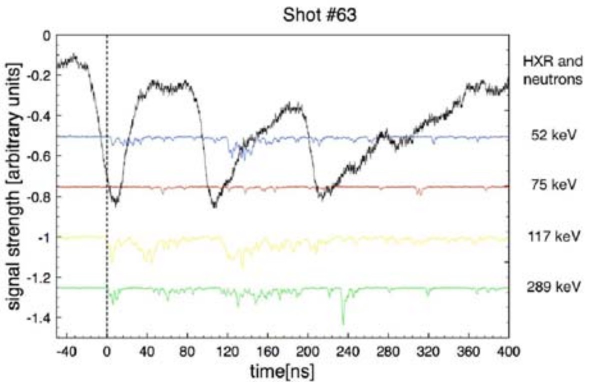
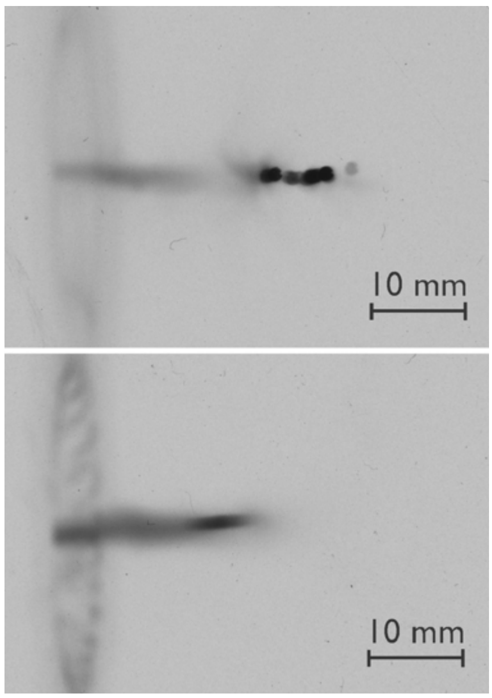


Fig. 7. Electron signals from different energy channels of the magnetic spectrometer and hard X-rays and neutrons signals measured for a shot #63 performed at the pure deuterium filling p_0 = 6.5 hPa, U_0 = 30 kV, I_{max} = 1.4 MA, Y_n = 1.15 × 10^{10}. The instant t = 0 corresponded to the current dip.

In other energy channels of the magnetic spectrometer, e.g., 52, 75, 117, and 289 keV, the main electron peaks and narrow spikes were also observed, as shown in Fig. 7.

In order to investigate the spatial structure of plasma discharges, simultaneously with electron measurements, time-integrated pinhole images of the soft X-ray emission were recorded, as presented in Fig. 8.

One can easily see that the pinch column shows some filamentary structures, e.g., the recorded X-ray pinhole images present regions of an increased X-ray



a

b

Fig. 8. X-ray pinhole images of two different PF-360U discharges performed with a pure deuterium filling: (a) shot #66, (b) shot #78. Without any gas admixture, the pinch structure was more uniform and reproducible during different discharges. Experimental conditions were: p_0 = 6.5 hPa, U_0 = 30 kV, I_{max} = 1.4 MA, Y_n = 9.76 × 10^8 (for shot #66), and p_0 = 6.5 hPa, U_0 = 30 kV, I_{max} = 1.42 MA, Y_n = 9.84 × 10^9 (for shot #78). The instant t = 0 corresponded to the current dip.

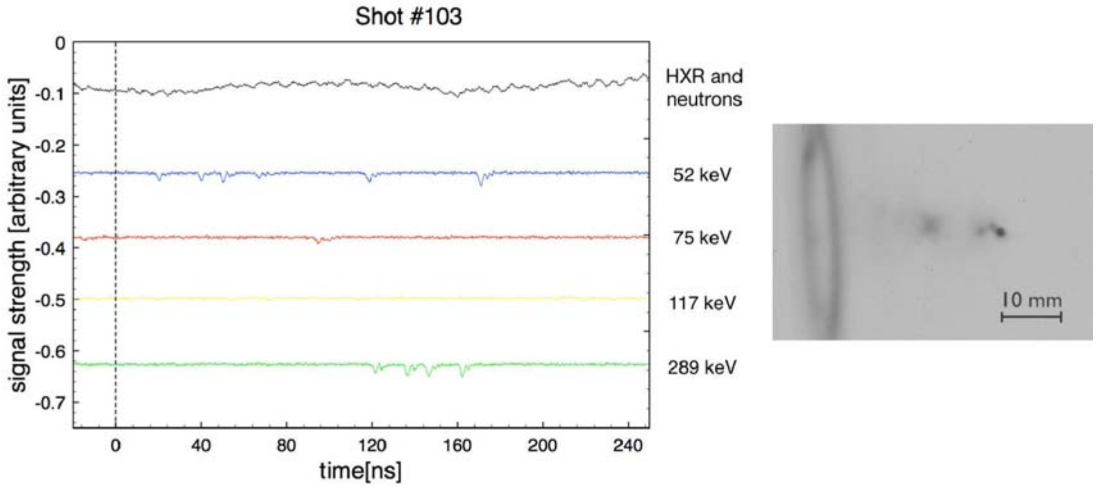


Fig. 9. Time-resolved electron signals from spectrometer no. 2 (left) and X-ray pinhole image (right) for shot #103 performed with an argon (4.8% volumetric) admixture. Experimental conditions were: p_0 = 6.5 hPa, U_0 = 30 kV, I_{max} = 1.46 MA, Y_n = 3.86 × 10^8. The instant t = 0 corresponded to the current dip.

emission not only inside the pinch, but also upon the inner electrode edge, which might be explained as places of current filament attachments. These effects are more visible in the X-ray pinhole image of a shot #78.

To study the influence of a heavy gas admixture, another series of electron and X-ray measurements was performed for PF-360U discharges carried out using a small argon (4.8%) admixture.

It can be seen that in these cases, the electron--induced signals were weaker, but they demonstrated similar features, and X-ray pinhole images showed the appearance of distinct hot spots. It can be explained by a stronger stopping of electrons in a heavier gas and an increase in the Bremsstrahlung emission (proportional to Z^2, the square of the target atomic number).

An example of the time-resolved electron signals and X-ray pinhole image from a PF-360U discharge performed with the argon (4.8%) admixture is presented in Fig. 9.

In this case, the influence of the argon admixture was stronger and more electron spikes and more distinct hot spots could be observed.

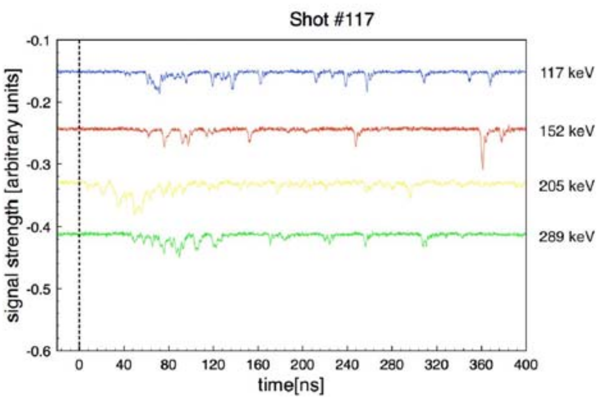


Fig. 10. Time-resolved electron signals recorded with a cylindrical analyzer and Cherenkov detectors for shot #117 performed with a krypton (1.6% volumetric) admixture. Experimental conditions were: p_0 = 6.5 hPa, U_0 = 30 kV, I_{max} = 1.44 MA, Y_n = 3.79 × 10^9, 30 kV. The instant t = 0 corresponded to the current dip.

The next series of PF-360U discharges was performed using the deuterium filling with a small (1.6%) krypton admixture. The time-resolved electron signals from spectrometer no. 2 for a shot #117 are presented in Fig. 10, and corresponding time-integrated images of the soft X-rays (recorded side-on) and fast ions (recorded end-on) are shown in Fig. 11.

It should be noted that other energy channels were observed because the use was made of the second magnetic analyzer with the Cherenkov-type detectors, as described above. It can, however, be seen that for discharges with the krypton admixture more electron spikes were recorded and more distinct hot spots were observed. The number of the fast ion microbeams (recorded end-on by means of the ion pinhole camera) did not correspond exactly to the number of the visible hot spots, but not all plasma microdiodes might produce corresponding hot spots [13].

Other examples of the results obtained from PF-360U discharges performed with the krypton admixture are presented in Fig. 12.

In those cases, the observations from the previous krypton experiments have been confirmed, and more distinct hot spots were recorded in the

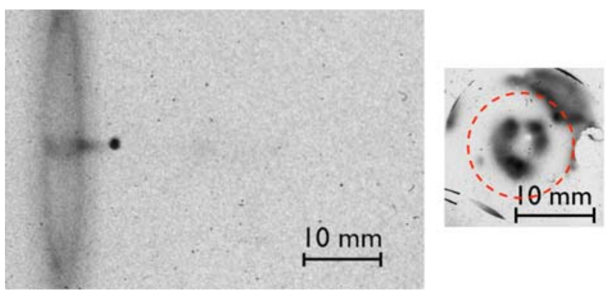


Fig. 11. Time-integrated X-ray pinhole image recorded side-on (left) and ion pinhole image recorded end-on at a distance 30 cm with the magnification factor 1:6 (right, magnified area marked with dashed line) for a shot #117 performed with a krypton (1.6% volumetric) admixture. Experimental conditions were: p_0 = 6.5 hPa, U_0 = 30 kV, I_{max} = 1.44 MA, Y_n = 3.79 × 10^9. The instant t = 0 corresponded to the current dip.

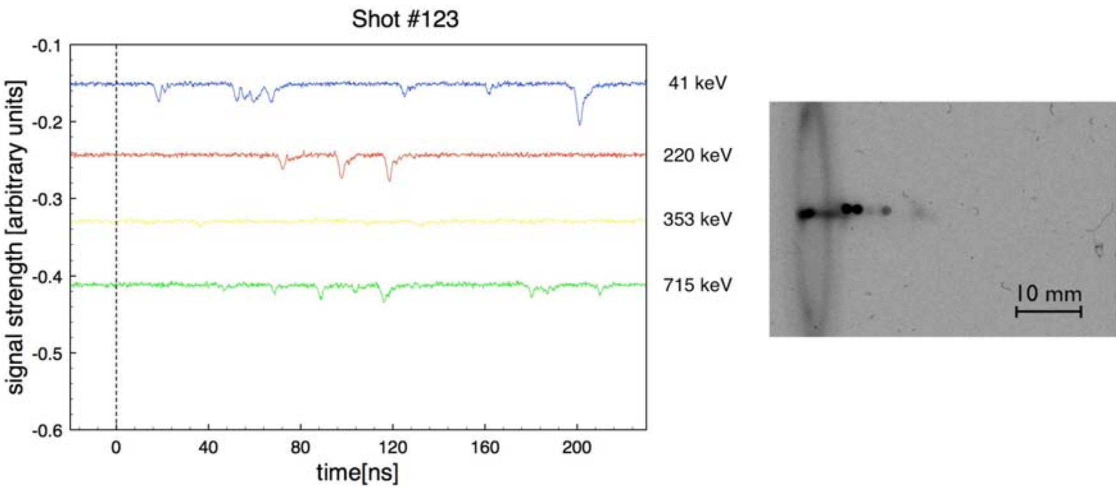


Fig. 12. Time-resolved electron signals from miniature spectrometer and time-integrated X-ray pinhole image of shot #123 performed with a krypton (1.6% volumetric) admixture. Experimental conditions were: p_0 = 6.5 hPa, U_0 = 30 kV, I_{max} = 1.4 MA, Y_n = 1.01 × 10^9. The instant t = 0 corresponded to the current dip.

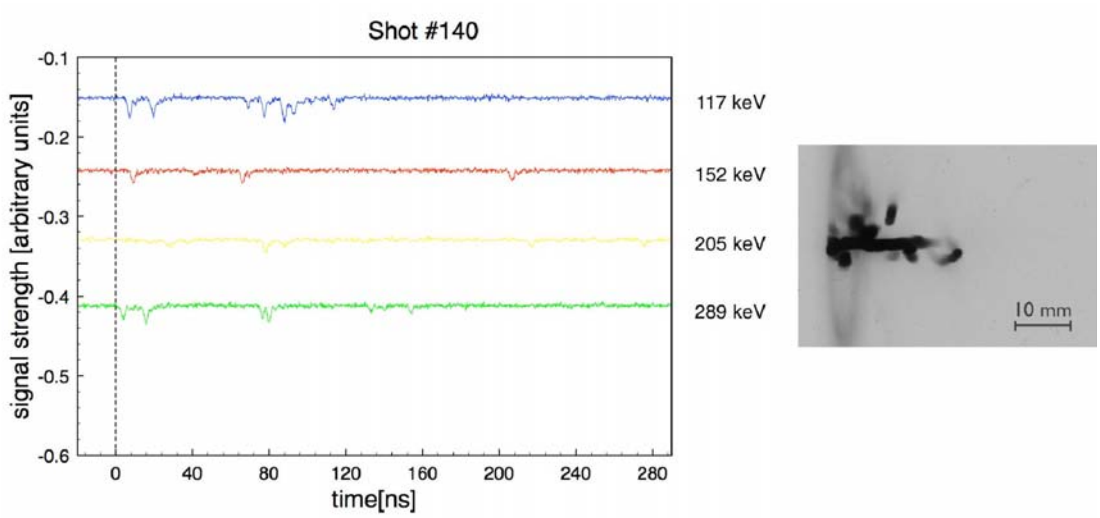


Fig. 13. Time-resolved electron signals (from spectrometer no. 2) and time-integrated X-ray pinhole image recorded for a shot #140 performed with a xenon (0.8% volumetric) admixture. A heavier admixture results in intensified X-ray emission from the discharge. Experimental conditions were: p_0 = 6.5 hPa, U_0 = 30 kV, I_{max} = 1.45 MA, Y_n = 1.36 × 10^9. The instant t = 0 corresponded to the current dip.

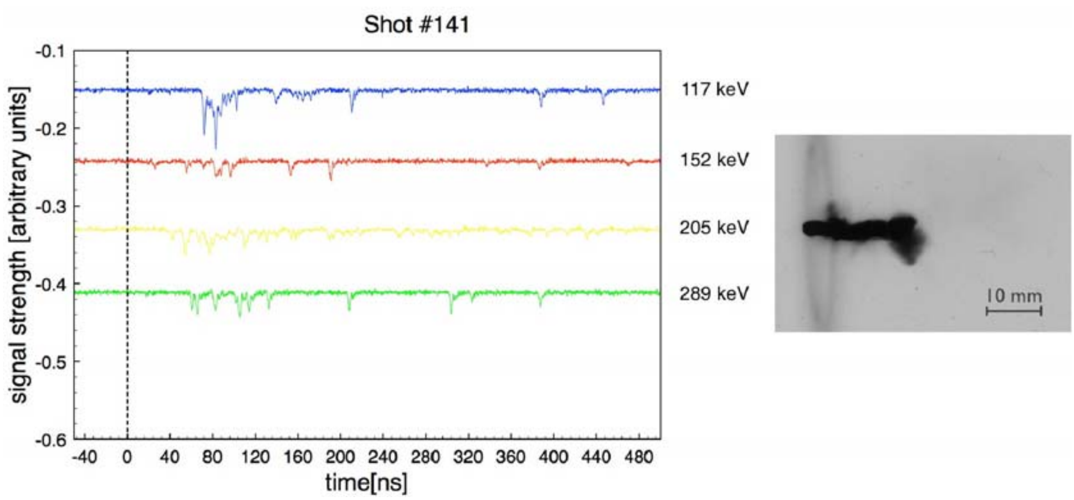


Fig. 14. Time-resolved electron signals (from spectrometer no. 2) and time-integrated X-ray pinhole image recorded for a shot #141 performed with a xenon (0.8% volumetric) admixture. It should be noted that the intensified X-ray emission corresponds to more numerous electron beams appearance. Experimental conditions were: p_0 = 6.5 hPa, U_0 = 30 kV, I_{max} = 1.45 MA, Y_n = 2.77 × 10^9. The instant t = 0 corresponded to the current dip.

analyzed discharges. It was observed that shots with heavy noble gas admixtures differed from those performed with the pure deuterium filling (as in Fig. 8) in a number of the recorded beams, their energy, and fine structure of the discharge. In general, images obtained with pure deuterium were more homogenous, with smaller number of filaments and hot spots. It did not mean a lack of those microstructures inside the PF discharge, but their visibility might be mitigated by less intense X-ray emission.

To study the influence of heavier admixtures in more details, the last series of PF-360U discharges was carried out with the use of a still heavier noble gas, i.e., the deuterium filling with a small admixture (0.8%) of xenon was applied. The time-resolved electron signals (recorded with a cylindrical spectrometer) and corresponding time-integrated X-ray images from two successive shots are presented in Figs. 13 and 14.

In comparison with shots performed with noble gas admixtures (like in Fig. 12), a xenon admixture resulted in more intense X-ray emission. In particular, some correlation between the intense X-ray emission and more numerous electron spikes was found. Moreover, the recorded electron spikes were shifted toward the higher energy end of the spectrum when the gas admixture was heavier. The number of intense hot spots was also larger.

Summary and conclusions

The most important results of the described experiments can be summarized as follows:

1. The time-resolved measurements of fast electrons emitted through the axial channel in the PF-360U inner electrode, which were performed by means of magnetic analyzers, showed relatively strong electron pulses in all measuring channels (from 41 to 715 keV).
2. In some measuring (energy) channels, electron spikes appearing with a different time delay, which might be explained as mono-energetic electron microbeams from different microsources (probably plasma diodes), were also recorded.
3. The time-integrated soft X-ray images of the investigated PF-360U discharges showed the appearance of some filamentary structures and hot spots, which could be formed near plasma microdiodes accelerating some electrons to high energies (recorded as electron beam pulses up to 1 μs after the current peculiarity with energies up to 715 keV).
4. The application of a heavy noble-gas admixture, e.g., of argon, krypton, and xenon, reduced intensity of the measured electron beams, but it increased the emission of soft X-rays and enabled some more intense and numerous fine structures (hot spots) to be observed.

It can be concluded that some characteristics of the fast electron beams and soft X-rays emitted from discharges within the PF-360U facility have been determined, but correlations of such e-beams with fine structures in the plasma pinch column should be investigated in more detail.

This work was performed at the NCBJ in Otwock-Świerk, Poland.

References

1. Sadowski, M., Herold, H., Schmidt, H., & Shakhatre, M. (1984). Filamentary structure of a pinch column in plasma focus discharges. *Phys. Lett. A*, *105*, 117–123.
2. Bernard, A., Bruzzone, H., Choi, P., Chuaqui, H., Gribkov, V., Herrera, J., Hirano, K., Krejci, A., Lee, S., Luo, C., Mezzetti, F., Sadowski, M., Schmidt, H., Ware, K., Wong, C. S., & Zoita, V. (1998). Scientific status of plasma focus research. *J. Moscow Phys. Soc.*, *8*, 93–170.
3. Scholz, M., Sadowski, M., & Szydlowski, A. (1999). Studies of the x-ray emission from high-current discharges performed in PF-1000 facility at different operational conditions. *J. Tech. Phys.*, *40*(Suppl. 1), 113–116.
4. Jakubowski, L., & Sadowski, M. J. (2002). Hot-spots in plasma-focus discharges as intense sources of different radiation pulses. *Brazil. J. Phys.*, *32*, 187–192.
5. Skladnik-Sadowska, E., Baranowski, J., Sadowski, M., & Zebrowski, J. (2002). X-ray and corpuscular emission from different plasma discharges of axial symmetry. *J. High Temp. Mat. Proc.*, *6*, 23–34.
6. Zebrowski, J., Sadowski, M. J., & Jakubowski, L. (2004). Studies of electron beams and x-rays within different plasma-focus devices. *Czech. J. Phys.*, *54*(Suppl. C), C256–C263.
7. Zebrowski, J., Sadowski, M. J., Czaus, K., Paduch, M., & Tomaszewski, K. (2004). Peculiar features of plasma-focus discharges within PF-360 facility. *Czech. J. Phys.*, *54*, 643–659.
8. Scholz, M., Paduch, M., Tomaszewski, K., Stepniewski, W., Bienkowska, B., Ivanova-Stanik, I., Karpinski, L., Miklaszewski, R., Sadowski, M. J., Jakubowski, L., Skladnik-Sadowska, E., Szydlowski, A., Malinowska, A., Kubes, P., Kravarik, J., Barvir, P., Klir, D., Tsarenko, A., & Schmidt, H. (2006). Recent results of MJ plasma-focus experiment. *AIP Conf. Proc.*, *808*, 207–210. http://dx.doi.org/10.1063/1.2159354.
9. Sadowski, M. J., & Scholz, M. (2008). The main issues of research on dense magnetized plasmas in PF discharges. *Plasma Sources Sci. Technol.*, *17*, 024001.
10. Kubes, P., Klir, D., Kravarik, J., Rezac, K., Paduch, M., Pisarczyk, T., Scholz, M., Chodukowski, T., Bienkowska, B., Ivanova-Stanik, I., Karpinski, L., Sadowski, M. J., Tomaszewski, K., & Zielinska, E. (2012). Energy transformation in column of plasma-focus discharges with MA currents. *IEEE Trans. Plasma Sci.*, *40*(2), 481–486.
11. Nuclear Enterprises. (1980). *Scintillation materials*. Sighthill, Edinburgh, Scotland. Retrieved from http://www.hpicorg.com/downloads/Nuclear%20Enterprises%20Scintillation%20Materials%20-%201980.pdf.
12. Surala, W., Sadowski, M. J., Paduch, M., Zielinska, E., & Tomaszewski, K. (2015). Recent measurements of soft X-ray emission from the DPF-1000U facility. *Nukleonika*, *60*(2), 303–308.
13. Sadowski, M. J., Paduch, M., Skladnik-Sadowska, E., Surala, W., Zaloga, D., Miklaszewski, R., Zielinska, E., & Tomaszewski, K. (2015). Soft x-ray studies of plasma-focus pinch structures in PF-1000U experiments. *Plasma Sources Sci. Technol.*, *24*, 055003.