Demonstration of X-Ray Emission From an Ultraminiature Pinch Plasma Focus Discharge Operating at 0.1 J Nanofocus

Cristian Pavez and Leopoldo Soto

***Abstract*—Recently, it has been demonstrated that it is possible to produce a pinch focus discharge with a device operating at only 0.1 J, i.e., nanofocus (NF). Evidence of pinch has been obtained from electrical signals and from images in the visible region of the plasma dynamics registered with a single-frame image-converter camera with few nanoseconds of exposure time. Here, the evidence of X-ray emission from the NF device is presented (NF: 5 nF, 5–10 kV, 5–10 kA, 60–250 mJ, and 16-ns time to peak current). The experiments were performed using submillimetric anode radii. Evidence of X-ray emission from this ultraminiature pinch plasma focus device that operates at only 0.1 J/shot is shown for discharges in H_2, Ar, and Ne.**

***Index Terms*—Miniature plasma focus (PF), miniature Z-pinch, nanofocus (NF), X-ray nanoflash.**

I. Introduction

IN THE LAST years, the experimental studies in plasma focus (PF) apparatii at the Chilean Nuclear Energy Commission (CCHEN) have been extended to devices operating under 1 kJ of stored energy, i.e., in the range of hundreds and tens of joules [2]–[8]. Moreover, a device that operates with only 100 mJ has been recently designed and constructed, i.e., nanofocus (NF) [1]. Pinch evidence from electrical signals and from visible plasma images with temporal resolution was obtained in the NF operating at 0.1 J. In those experiments, the plasma dynamics was studied using a visible ICCD camera gated at 4-ns exposure time [1]. Discharges in hydrogen at 1–20 mbar, with an initial charge of 6.5 kV (i.e., 0.1 J), were performed using a Cu anode radius of $a = 0.8$ mm partially covered by an insulator. Pinch evidence in the current-derivative signals was observed in the discharges at 3 mbar in H_2. A clear evidence that a radial compression (pinch) actually occurred was the dip observed in the current derivative, concurring with a drop in the electrical current and a small peak in the voltage signal. A current peak of 4.5 kA was obtained. The dynamics observed from the photographs was consistent with the following: 1) The plasma is initiated over the insulator; 2) the plasma covers the anode; 3) there is a radial compression of the plasma over the anode; and 4) finally, the plasma is separated from the anode in the axial direction. The time from stages 1) to 4) is about 40 ns [1].

Small pinch devices are not only interesting for pure plasma research. They could also be particularly suitable for field applications [6]. More remarkable is that they constitute a safe radiation on–off source. On the one hand, the PF is particularly suited for pulsed neutron applications with a reduced danger of contamination compared to conventional isotopic radioactive sources. A passive radioactive source of neutrons with similar energy ($\sim$2.5 MeV, for instance, ^{252}Cf or Am/Be) emits continuously, thus carrying inconveniences in handling and storing. In turn, PF sources would not have such activation problems. On the other hand, the intense X-ray pulses produced by bremsstrahlung radiation from localized electron beams and from hot spots are excellent candidates for radiography of moving objects [13] and for microelectronic lithography [14], [15].

The pulsed radiation (neutrons and X-rays) from plasma foci has a duration of a few nanoseconds. In particular, X-rays have a wavelength of nanometers or less, so it is reasonable to call them "nanoflashes."

PF devices are being studied in some laboratories for applications in microlithography by using devices working in thousands and hundreds of joules. One of the present challenges for microlithography is to increase the spatial resolution. Two features determine the spatial resolution: the radiation wavelength λ and the source size. One or both should be decreased in order to increase the spatial resolution. The wavelength depends mainly on the gases used in the discharge (soft X-rays from inside the plasma column by thermal bremsstrahlung and line radiation, $\lambda \sim 10-1$ nm) and on the anode material (hard X-ray from beam–target bremsstrahlung, electron beams colliding with the anode, $\lambda \sim 1-0.01$ nm). As far as it is known, PF devices operating at low energy, with an energy density in the plasma of the same order than larger devices, practically produce radiation with the same wavelengths than bigger devices [6]. In this point, smaller devices do not appear

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to be advantageous. However, regarding the source size, smaller devices have better performance. In fact, on the one hand, the soft X-ray sources are inside of the plasma pinch column and correspond to hot or bright spots living short times (nanoseconds or less). It has been shown that the size of the plasma pinch column scales linearly with the anode radius a. The pinch radius is $\sim 0.12a$, and the pinch length is $\sim 0.8a$ [6], [9]. According to the observations in devices of kilojoules to megajoules, the bright spots have typical dimensions lower than 0.1 times the pinch diameter, i.e., less than $\sim 0.024a$. On the other hand, hard X-rays are produced from electron beams colliding with the anode. The electrons are extracted from the plasma column; thus, it is reasonable to consider that the electron beam diameter is on the order of the pinch diameter, i.e., $0.24a$; thus, the effective size of the target is of the same order. In summary, the source size of soft X-rays is on the order of $\sim 0.024a$ or less, and for the hard X-rays, it is on the order of $\sim 0.24a$.

According to our studies, the anode radius a scales with the stored energy of the device E as $a^3 \alpha E$ [5], [6]; thus, devices working with less energy produce X-ray sources of smaller sizes. Therefore, to increase the spatial resolution of radiographs and for lithography applications, the development of miniaturized PF devices with submillimetric (or less) anodes is relevant. Encouraged by the aforementioned discussion, the characterization of the emitted X-rays and size source in the ultraminiaturized pinch focus discharge (NF: 0.1 J/shot) is being carried out at CCHEN, and the evidence of X-ray emission from the NF is presented here.

II. Experimental Setup

A. NF

Using the experimental fact that the plasma energy density parameter and the drive parameter are practically constant in all of PF devices that operate in the range from 50 J to 1 MJ [5], [6], [9], [10], an ultraminiature device, "NF" (4.9 nF, 4.8 nH, ~5–10 kV, ~5–10 kA, 60–250 mJ, and 16-ns time to peak current), was constructed. The design and electrical characterization of the device have been described in [10]. The anode material used was copper, and the anode diameter was 0.8 mm. The total dimensions of the device are 20 cm × 20 cm × 5 cm. The sketch of the apparatus is shown in Fig. 1.

B. Diagnostics

The diagnostics for the experiments reported here include electrical signal and X-ray detection.

The current temporal derivative was measured using a Rogowski coil; the charging voltage was controlled using a resistive divider.

Radiographs of an array of aluminum filters of 30-, 45-, and 60-μm thickness on a photosensible film were performed. The correlation of the X-ray emission with the discharge was obtained using a BPX 65 diode without mica and covered with 10 μm of aluminum. Experiments have been performed in hydrogen, argon, and neon.

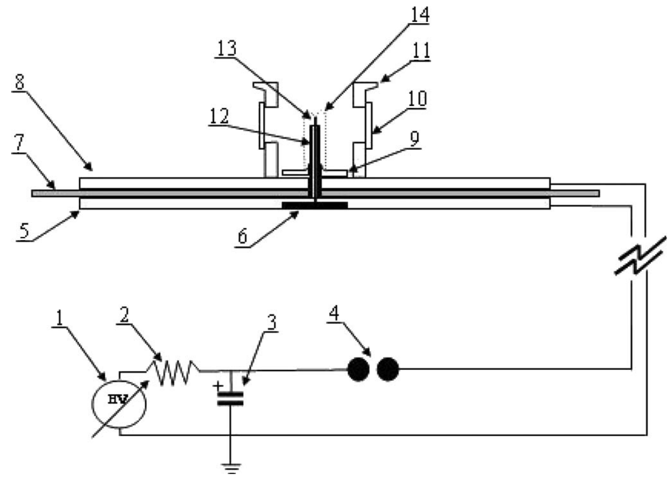

Fig. 1. Sketch of the NF discharge device. (1) Power supply. (2) Charging resistance (100 MΩ). (3) Capacitor (28 nF). (4) Spark gap. (5) Anode. (5 and 8) Pair of 200-mm-diameter brass electrodes forming the capacitor to drive the discharge (~5 nF). (6) Anode. (7) Dielectric, four PVDF films of 80-μm thickness. (8) Cathode. (9) Cathode. (10) Optical windows. (11) Discharge chamber. (12) Alumina tube. (13) Anode. (14) Plasma sheath between the anode and the cathode. A (3) primary capacitor of 28 nF charges, by means of a pulse, the driven capacitor (~5 nF) formed by the (5 and 8) parallel plates [1].

III. Results

The NF was operated in hydrogen, argon, and neon at 6.5-kV charging voltage (0.1 J). A current peak on the order of 4.5–6 kA was obtained close to 16 ns after the initiation of the main discharge.

For discharges in H_2, a BPX 65 diode without mica and covered with 10 μm of aluminum was implemented and placed at 27 mm radially from the anode axis. No signals in the BPX diode were observed, probably due to the low intensity of the radiation. Then, a diagnostic, including the integration of several discharges, was performed. Radiographs of an array of aluminum filters of 30-, 45-, and 60-μm thickness on an HP5 Ilford film were obtained operating the discharge at 0.4 Hz. The intensity of the X-rays was not enough to produce radiographs in a single shot, and over 1000 shots were necessary to integrate in one film. Fig. 2 shows the radiographs after 1200 shots; different levels of gray are clearly observed, demonstrating that the NF produces X-rays.

In order to estimate an effective mean energy of the X-ray emitted by this ultraminiature pinch focus discharge, a monoenergetic radiation was assumed. When a monoenergetic radiation interacts with an element, the classical exponential radiation decay relation through the matter is $I(x)/I_0 = \exp(-K \cdot x)$, where $I(x)/I_0$ is the normalized radiation intensity after traveling a distance x inside the material characterized by a linear attenuation coefficient K. From this relation, it is possible to obtain an effective linear attenuation coefficient k when different gray shades of the digitalized images are linked to the $I(x)/I_0$ ratio. This method [11] allows obtaining a correlation between K and the X-ray energy [12]. Thus, analyzing the radiographs in Fig. 2, a linear attenuation coefficient $K = 751 \pm 49$ cm^{-1} and an effective mean energy of 4.3 ± 0.3 keV were obtained.

Fig. 3 shows the spot on the anode of the NF device after some thousand discharges. The spot is probably due to the

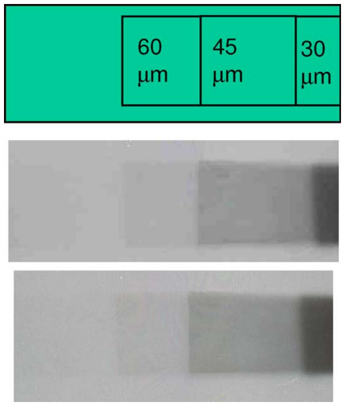

Fig. 2. Radiographs of an array of aluminum filters of 30-, 45-, and 60-μm thickness on an HP5 Ilford film obtained after 1200 integrated shots of the NF operating at 0.4 Hz. Assuming a monoenergetic X-ray emission, an effective mean energy of 4.3 ± 0.3 keV is estimated from the radiographs.

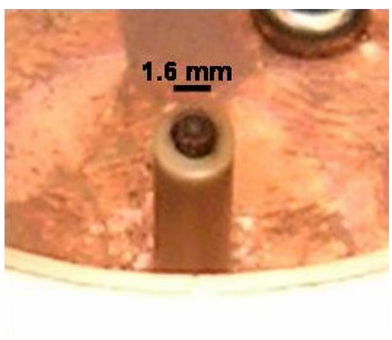

Fig. 3. Spot on the anode of the NF device after about thousand discharges. A spot is observed on the anode. The diameter of the anode is 1.6 mm, and the size of the spot is on the order of 200 μm. The spot is probably due to the erosion produced by the electron beams impinging on the anode and by the interactions of the plasma pinch.

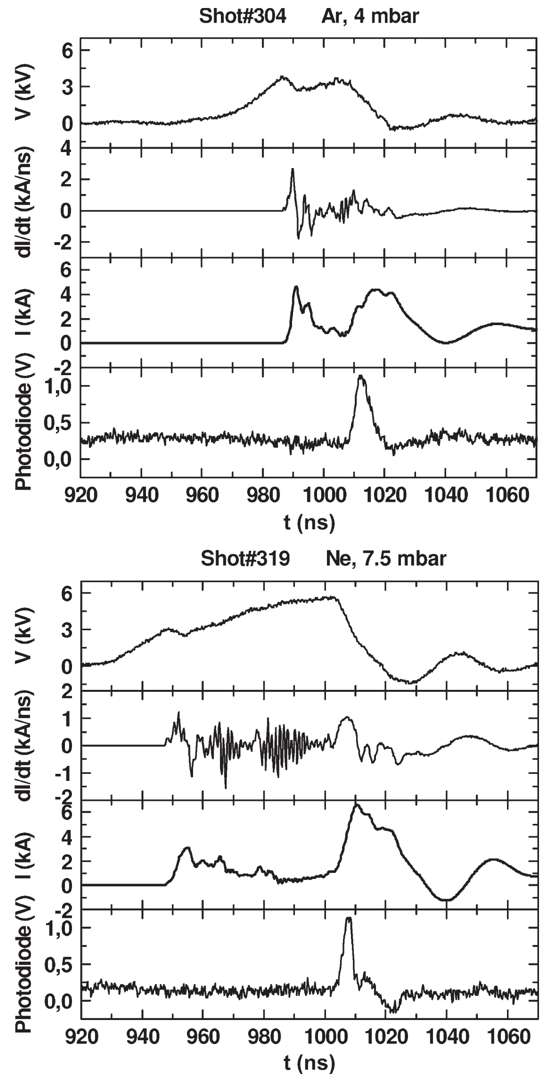

Fig. 4. Signals in an X-ray photodiode in correlation with the discharge for Ar and Ne.

erosion produced by the electron beams impinging on the anode and by the interactions of the plasma pinch. The diameter of the anode is 1.6 mm, and the size of the spot is on the order of 200 μm, i.e., $\sim 0.25a$. Note that this is on the same order of the expected size of the plasma column. Thus, it is reasonable to consider that the spatial jitter of the plasma column and the electron beams is low in comparison with the plasma pinch diameter. It is also reasonable to consider that the effective size of the X-ray source working in repetitive mode and integrating more than 1000 shots is on the order of $0.25a$, i.e., 200 μm.

Additionally, discharges in argon and neon were performed for pressures in the range 2–20 mbar (Fig. 4). Signals in the BPX 65 p-i-n (without mica and covered with a 10-μm filter of Al) were obtained in the range 4–13 mbar for argon and in the range 5–15 mbar for neon. Fig. 3 shows the signal in the p-i-n BPX 65 in correlation with the discharge. From the signals, an X-ray pulse is observed starting with the main discharge with a maximum that is close to the peak current. The pulse duration (FWMH) is on the order of 5 ns or less.

IV. Discussions and Summary

Evidence of X-ray emission from this ultraminiature pinch focus discharge operating at 0.1 J, i.e., NF, has been obtained. Assuming a monoenergetic X-ray emission, an effective mean energy of 4.3 ± 0.3 keV is estimated from the radiographs obtained operating the NF in H_2. In the PF discharges in hydrogen, the main source of X-ray radiation is the interaction of the electron beam from the focus region with the anode. When electron beams are directed onto the anode with energy greater than the K-shell energy, the dominant line radiations are K_α and K_β. In the case of these lines, the energy is between 8 and 9 keV approximately. This value is greater than the results obtained in our experiments. Then, we could conclude that the energy of the electron beams is less than the K-shell energy. Regarding the rough method used and the assumption of a monoenergetic emission in the data analysis, it is possible to consider that the ultraminiature pinch focus discharge (NF) operating only at 0.1 J/shot emits X-rays of some kiloelectronvolts of energy probably from the bremsstrahlung radiation of electrons impinging on the anode. The effective size of the X-ray source from the NF working in repetitive mode (0.4 Hz and integrating more than 1000 shots) is on the order of ~ 200 μm.

In addition, in discharges in Ar and in Ne, short pulses of X-rays have been detected with a p-i-n diode. The emission occurs close to the peak current, and the pulse duration (FWMH) is on the order of 5 ns or less. This radiation is probably due to bremsstrahlung from the thermal electrons in the plasma.

Future works are required in order to obtain a better characterization of the X-ray emission. In particular, the size source for single-shot discharges and for integrated shots of the discharge operating in the repetitive regime, like a quasi-continuum source, will be studied using a pinhole camera. In the case of a single shot, a multichannel plate combined with a pinhole camera will be used. In addition, anodes with smaller radii will be tested.

In summary, evidence of X-ray emission from an ultraminiature pinch focus discharge operating in H_2, Ar, and Ne at only 0.1 J/shot has been shown. This is the smallest pinch PF device in the world in which X-rays have been detected.

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