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Hard X-ray dose intensity and spatial distribution in a plasma focus device using thermoluminescence dosimeters

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Abstract. In the present study, X-ray emission dose characteristics from a small Mather-type PF device in various pressures of argon as the operating gas were studied. The PF device was powered by a 12 μF capacitor at 25 kV charging voltage. Time-integrated hard X-ray (HXR) emission was investigated using thermoluminescence dosimeters (TLDs). These detectors were calibrated with ^{60}Co and ^{131}Cs sources. Twenty-four dosimeters were placed at four different radial distances from the axis of the electrodes at the top of the anode to measure the dose spatial distribution at the top of the anode for different pressures (0.5–1.3 mbar). At each radius, six dosimeters were placed circularly with equal angular intervals on the inner surface of the device chamber. It was found that the optimum pressure for the highest yield of X-ray is 0.9 mbar. The maximum measured dose was 17 mGy per shot at the top of the anode and about 0.5 mGy per shot at 90° with respect to the anode axis. Furthermore, these results showed that the dose at each radius is symmetrical at 360° around the top of the anode, but X-ray distribution follows an anisotropical behaviour. A fast plastic scintillator was also used for time-resolved HXR detection, and a linear relation was observed between the amplitude of the scintillator-PMT signals and TLD responses.

Keywords. Hard X-rays; plasma focus; thermoluminescence dosimeter; argon gas; scintillator detector.

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1. Introduction

Plasma focus (PF) devices are coaxial guns consisting of two cylindrical electrodes placed in a chamber filled with a few mbar of gas. These devices have been built with capacitor bank energies ranging from a few joules to megajoule with subsequent variation in the physical size of the device. The principle of a dense PF device operation lies on the conversion of energy stored electrically in a capacitor bank into electromagnetic acceleration and forming a plasma layer, called the plasma sheath. The Lorentz force pushes the sheath towards the end of the electrodes. Finally, the sheath arrives at the anode end, compresses it to hot and dense focussed plasma (DPF) [1]. In order to achieve the best efficiency for the maximum pinch compression, this should coincide with the first peak of the discharge current.

PF devices are known as efficient pulsed radiation sources of hard and soft X-rays, charged particles and fast neutrons from D–D reactions (when operated in deuterium) [2]. PF device is particularly attractive for X-ray generation because of its operational simplicity, compact size, portability and cost-effectiveness. Due to these advantages, PF device is used in many interesting applications including X-ray and electron-beam lithography [3,4], radiography [5], generation of soft X-ray (SXR) spectral lines of highly charged heavy-metal ions [6], and material research [7].

In particular, the radiation spectrum of the X-rays from DPF is mainly emitted by two different mechanisms. Soft X-rays (<5 keV) are generated by thermal bremsstrahlung emission in the hot plasma column. On the other hand, hard X-rays (>5 keV) are produced by bremsstrahlung of impacting electron beams on the anode [8]. X-rays from the PF device depend upon many factors such as the applied voltage, operating pressure, gas composition, electrode parameters, insulator, material and length of the anode.

In the past few years, many efforts have been done to study the effects of different experimental parameters such as applied voltage, operating pressure, and design parameters of the electrodes (shape, material, and length of the anode) on X-ray yield of the PF device [9–13]. In recent years, a few research studies have been performed on the yield of X-rays of the PF device in different situations which would have been useful for investigating the possibility of using PF device as an alternative to radioisotope sources in special applications such as radiography from biological specimens [14] and small non-biological samples [15]. Moreover, radiography with this device remains a charming issue in experimental studies. Roomi and Habibi [16] supported the claim that the operating pressure is an effective parameter on the yield of SXR and HXR emitted from a 4 kJ plasma focus. They found that at higher operating pressures (4 torr) of nitrogen gas, the yield of SXR photons increases over 20–30% in comparison with the yield at lower pressures. Roomi *et al* [17] studied the effect of applied voltage and nitrogen gas pressure on X-rays emitted from Amirkabir Plasma Focus (APF) Facility [16]. They found that by increasing voltage, the intensity of X-ray emission increases. Vahedi *et al* [18] investigated the temporal behaviour of the emitted X-rays from a 90 kJ PF device and found optimum conditions for X-ray production; their results showed that at each discharge voltage, there is an optimum pressure in which the pinch current as well as the HXR and SXR yields are maximum [17]. Their results also revealed that the optimum pressure increases linearly with the operation voltage. Castillo-Mejia *et al* [19] showed that the radiation intensity from a 2 kJ PF device in a single shot is high enough to obtain fine-resolution radiographs in very short exposures (about 10 ns). Furthermore, they found a linear relation between responses of TLDs and a scintillator signal. Raspa *et al* [5] reported that the HXR dose emission from a small PF (4.7 kJ) was 53 ± 3 μGy per shot on the axis at 53 cm from the top of the anode, and they also observed uniformity of dose within a half-aperture angle of 6°. Farnikova *et al* [20] and Castillo *et al* [21] reported the utilization of TLDs as X-ray detectors for plasma diagnostics; for instance; Aragi *et al* [22] investigated the radiation emission intensity from a low-energy PF device using TLDs. Then, they discussed the regime of optimum operation pressures in which dose intensity was the highest for several gases.

Nowadays, radioisotopic sources are being used in nuclear-agriculture centres. Stimulation of plants and animals requires small doses and causes non-inheritable alterations. Irradiations with doses from 0.01 to 10 Gy (10–1000 rad) may have a stimulating effect; for example, they may result in a richer harvest. This technique is promising especially in the case of small-seeded plants (such as tobacco, grass, clover, cotton, tomato, and paprika), because the volume of the seed necessary for large cultivated areas is relatively small. The costs of irradiation are, as a rule, directly proportional to the volume of the substance to be irradiated [23].

In order to take a general view on the X-ray dose emission in a PF device, a list of experiments carried out by other researchers as well as experimental details is summarized in table 1. In this table, for instance, the X-ray dose in one shot of a plasma focus in a 37 kJ PF device was reported to be about 12.09 mGy by Tafreshi and Saeedzadeh [24]. Considerable differences in experimental conditions prevent us from having a proper comparison of these results. Nevertheless, after correction of dose values on the basis of source-to-dosimeter distance, a general law can be concluded: the more energy a device produces, the more X-ray dose we have.

By comparing the values in table 1, it can be said that fortunately, radiation intensity in a single shot from any PF device (even PF devices with energy of the order of 0.1 kJ) is high enough to be used in radiography applications. The minimum X-ray dose for having a good picture at 1 m distance from the X-ray source is about 0.001 mGy [19]. Of course, this value depends on the type of X-ray film, the distance from the X-ray source, and the type of the material.

In the present study, the intensity of X-ray dose produced by a small PF device was investigated. Furthermore, the effects of operating pressure on the characteristics of the HXR emission were studied. TLD and fast scintillator-PMT detector were used as detection instruments. This investigation is intended to be a confirmation of the anisotropical behaviour of the X-ray emission which is due to the electron acceleration in the PF devices that was observed by other researchers [26] and to present the results of the symmetrical

Table 1. X-ray dose from PF devices.

Authors	Energy of the device (kJ)	Gas	Pressure (mbar)	Source-to-dosimeter distance (cm)	Maximum dose per shot (mGy)
Mejia *et al* [19]	2	Deuterium	1.5	100	0.001
Tafreshi and Saeedzadeh [24]	37	Argon	–	Outside the chamber on the window	12.09
Aragi *et al* [22]	0.1	Argon	0.133	10	0.0035
	0.1	Nitrogen	0.133	10	0.003
	0.1	Helium	1.066	10	0.01
	0.1	Hydrogen	0.133	10	0.002
Raspa *et al* [5]	4.7	2.5% Argon + 97.5% Deuterium	3.5	53	0.053
Pavez *et al* [25]	0.4	Hydrogen	10.5	23	0.017

behaviour of X-ray dose emission from the PF devices. All these results will help theoretical physicists to introduce a comprehensive model of plasma physics that involves main mechanisms of the X-ray emission.

2. Procedure and experimental set-up

This investigation was carried out in UIPF1, which is a Mather-type PF device. This device was powered by a single coaxial capacitor of 12 μF capacitance and 30 kV maximum potential. Charging of this capacitor at 25 kV with 3.75 kJ stored energy gives about 191 kA peak discharge current. The measured total external inductance of the device is 169 nH. A simple trigatron spark gap was used as a switch to transfer the stored energy from the capacitor bank to the electrodes of the system. The central electrode (anode) is made of copper, with 139 mm length and 26 mm diameter. The coaxial cathodes are formed by six copper rods, each of 10 mm diameter and 149 mm length, arranged in a squirrel cage configuration around a circle of 80 mm diameter. The insulator is a ring-shaped Pyrex tube of 60 mm length located at the base of the anode to separate the anode and the cathode. The plasma focus electrodes were enclosed in a stainless steel chamber of 320 mm height and 280 mm diameter. The arrangement of electrodes and insulator are shown in figure 1. To prevent vapour from affecting the impurities collected in the working gas during the experiments, the chamber was evacuated to 10^{-3} mbar by a rotary pump before each measurement. After evacuation, the chamber was filled with fresh argon (Ar) gas to a particular pressure (0.5–1.3 mbar). The time derivative of the current ($\mathrm{d}I/\mathrm{d}t$) was measured using a Rogowski coil. A four-channel, 200 MHz oscilloscope was employed to record the signals from the diagnostics. The time-resolved and the time-integrated HXR emissions were detected simultaneously using a fast plastic scintillator-PMT detector and thermoluminescence dosimeters (TLDs), respectively. The fast plastic scintillator-PMT detector (BC-400, a cylinder with length and diameter of 5 cm) was located horizontally at 100 cm away from the anode top (pinch area). In addition, the TLDs (GR-200A, a circular chip with 4.5 mm diameter and 0.8 mm thickness) were replaced inside the chamber.

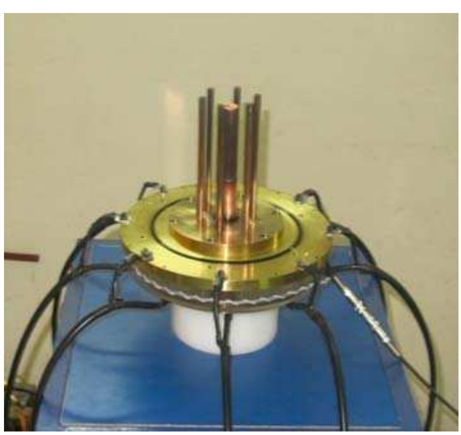

Figure 1. Structural details of plasma focus electrodes of UIPF1.

This type of TLD has many advantages, such as high sensitivity (65 times higher than that of TLD-100), low detection limit (less than about 1 μGy), 'insensitivity' to scattered sunlight and minimum fading ($<5\%/\text{yr}$). These dosimeters are sensitive to the extensive ranges of X-ray energy; from a few keV to 3 MeV. For this reason, the energy, response and dose calibrations were adjusted by using ^{60}Co and ^{137}Cs standard sources. All TLDs were annealed at 240°C for 10 min before each radiation. After 24 h of irradiation, the glow curves were measured using a TLD reader, and with a heating rate of 6°C/s from 135°C to 240°C. In order to measure HXR intensity, all TLDs were covered with a 100 μm aluminum shield to stop soft X-rays (with energy less than 5 keV).

Spatial distribution of X-rays in each DPF shot was investigated at 15 cm from the top of the anode (X-ray source). For this purpose, a set of 24 TLD chips were placed inside the chamber around four circles having 2.5, 4, 5.5, 7 cm radii. In each circle, six dosimeters were placed in equal angular intervals. Experimental set-up of the TLDs in this experiment is shown in figure 2. Also, in order to determine HXR dose at different positions, three TLDs were placed horizontally at 22 cm outside the chamber in front of the plexiglass window.

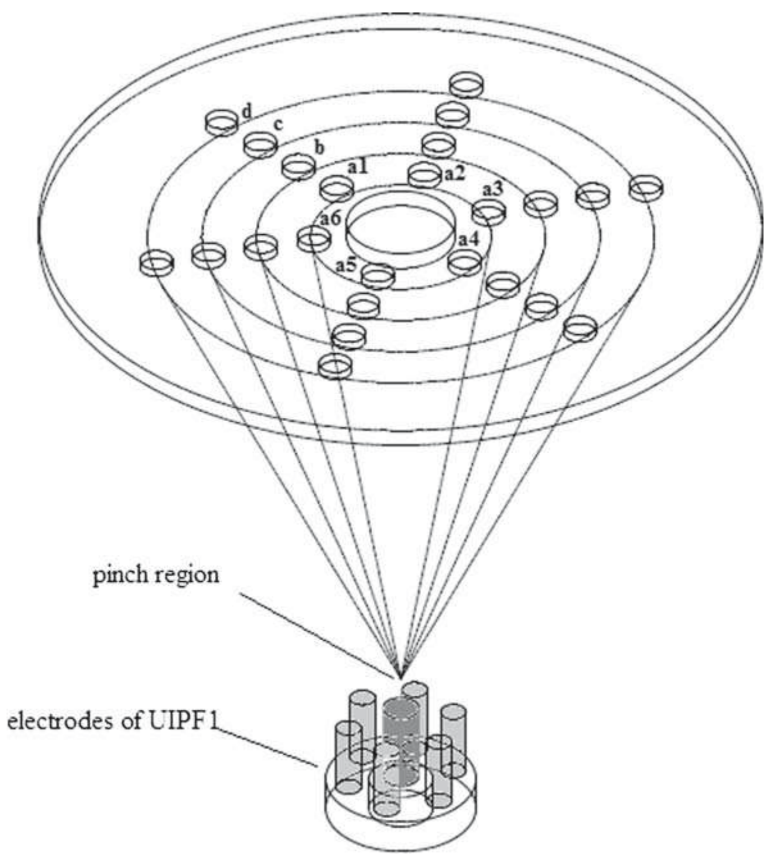

Figure 2. Experimental set-up of the TLDs inside the PF chamber: radii of rings a, b, c and d are 2.5, 4, 5.5 and 7 cm, respectively.

3. Results and discussion

All the experiments were performed at an applied voltage of 25 kV and pressures of 0.5, 0.6, 0.8, 0.9, 1.1 and 1.3 mbar of argon gas. The experimental data obtained by the detectors were averaged over seven shots to reduce statistical errors. Figure 3 shows a typical current derivative signal, HXR signal and glow curve of the TLD that were

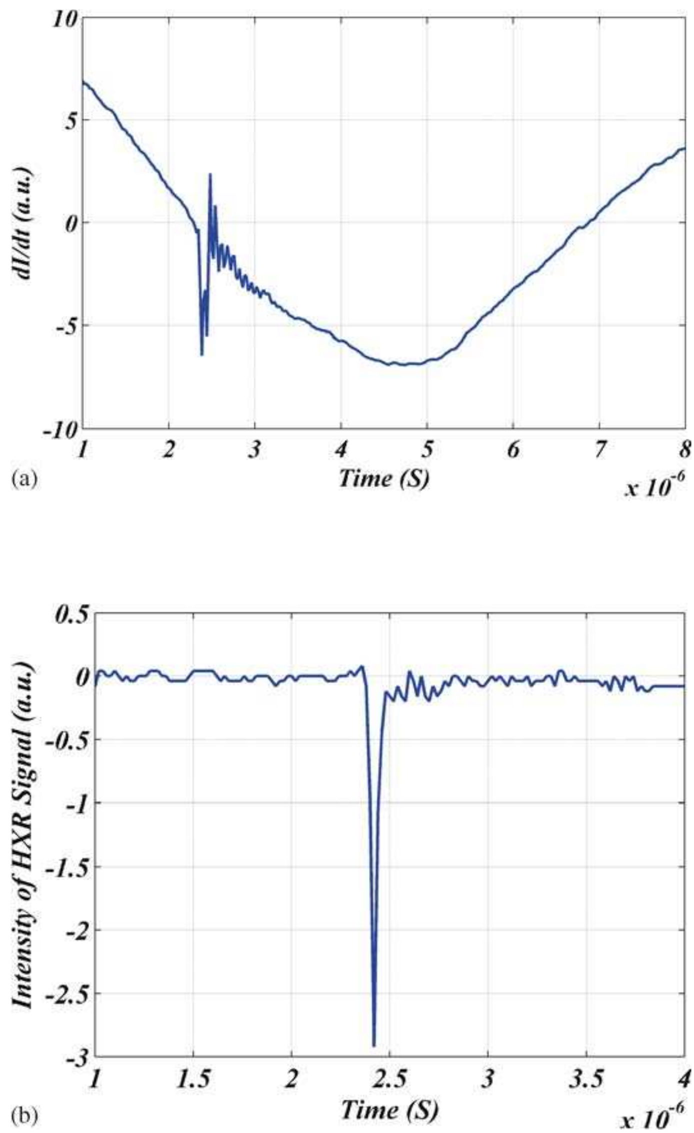

Figure 3. (**a**) Typical current derivative, (**b**) HXR signals obtained by scintillator detector glow curve of a TLD at a gas pressure of 0.8 mbar and an applied voltage of 25 kV of UIPF1 PF device.

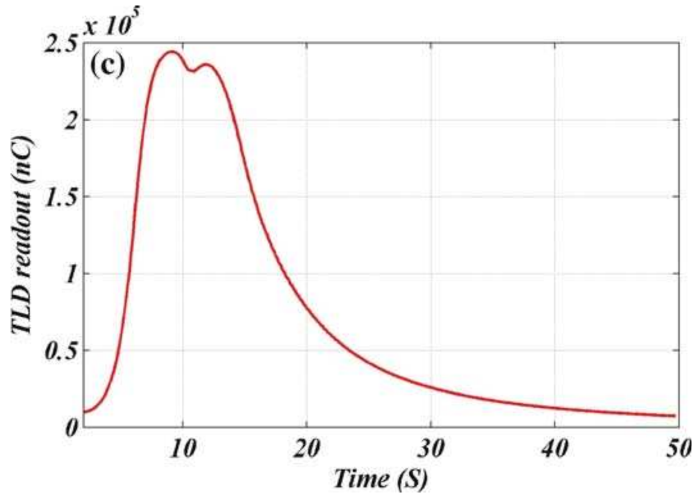

Figure 4. The glow curve of a TLD at a gas pressure of 0.8 mbar and an applied voltage of 25 kV of UIPF1 PF device.

obtained by Rogowski coil and scintillator-PMT detector, respectively at 25 kV voltage and 0.8 mbar pressure. Figure 4 shows the glow curve of the TLD obtained by the TLD reader under the same condition. The dip on the current derivative signal is related to the production of the hot and dense plasma column, and confirms the plasma focussing occurrence in the UIPF1 device. The width of HXR pulse in all shots was about 100 ns (see figure 3).

In order to study the effect of gas pressure on the intensity of X-ray emission, the average radiation dose inside the plasma focus chamber from all the TLDs as a function of gas pressure in the range of 0.5–1.3 mbar was measured and the results are shown in figure 5. The results showed that the maximum and minimum dose values were about 17 and 6 mGy at 0.9 (optimum pressure for HXR) and 1.3 mbar of argon gas pressure, respectively. It can be seen that the dose value increases with the filling pressure in the range of 0.5–0.9 mbar and follows a decreasing trend at higher pressures. Figure 6 shows HXR intensity (the area under the curve of the HXR peak) registered by scintillation

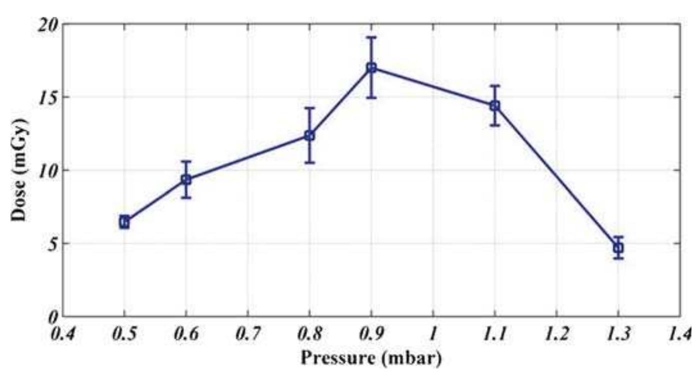

Figure 5. Average X-ray dose inside the PF chamber vs. pressure of the argon gas.

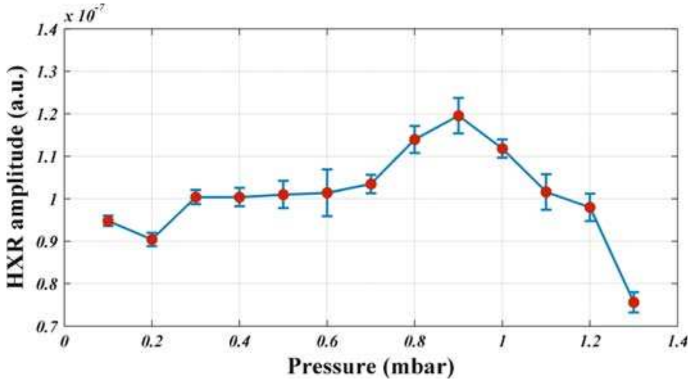

Figure 6. Variation of the HXR intensity vs. gas pressure.

detector vs. gas pressure. Figures 4 and 5 show that the gas pressure has a significant effect on the HXR emission, and that there is a good agreement between the responses of the two applied detectors.

In order to study the angular distribution of X-ray dose, dose values at four radii (from 2.5 to 7 cm with 1.5 cm intervals) were measured. Figure 7 shows the intensity of radiation dose inside the chamber as a function of radial distances from the axis of the electrodes at the top of the anode for different gas pressures. In low gas operating pressures (e.g. 0.5 and 0.6 mbar), the highest intensity of radiation dose was measured at a distance of 5.5 cm from the anode face along the anode axis. In medium and high gas operating pressures such as 0.8, 0.9 and 1.1 mbar, the maximum dose achieved was at 7 cm. Furthermore, the results show that the spatial anisotropy of X-ray emission varies under different pressures; this special behaviour has been reported previously in the case of neutron emission from PF [27]. Hard X-ray yield depends on gas pressure because of the differences in electron acceleration and other mechanisms of emissions, which are not fully understood yet. Observation of the maximum amount of dose value at a radial distance of 7 cm from

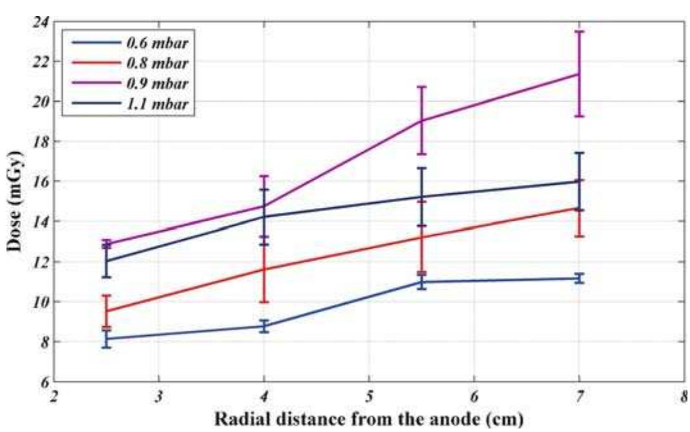

Figure 7. X-ray dose vs. radial distances from the axis at the top of the anode in different argon gas filling pressures from UIPF1.

Table 2. Dose values in mGy at 15 cm from the top of the anode and radial distance of 2.5 cm from the axis of the electrodes.

Pressure (mbar)	TLD 'a1'	TLD 'a2'	TLD 'a3'	TLD 'a4'	TLD 'a5'	TLD 'a6'
0.6	8.094 ± 0.546	7.981 ± 0.764	8.228 ± 0.128	7.688 ± 0.498	8.918 ± 0.684	7.909 ± 0.742
0.8	10.623 ± 0.969	9.631 ± 0.476	8.844 ± 0.548	8.425 ± 0.347	9.95 ± 0.416	9.637 ± 0.539
0.9	13.184 ± 0.931	12.863 ± 0.312	12.996 ± 0.248	12.868 ± 0.679	12.821 ± 0.691	12.593 ± 0.512
1.1	12.145 ± 0.141	12.042 ± 0.246	12.076 ± 0.117	11.946 ± 0.721	12.176 ± 0.194	12.201 ± 0.432

the centre is probably due to the bimodal (anisotropic) distribution of X-ray source. A similar anisotropy in X-ray emission was reported by Etaati *et al* [26].

According to some studies on the ion acceleration from the PF devices, it could be observed that ions are produced in non-axial directions [28]. On the other hand, Roshan *et al* [29] mentioned that the same mechanism governs ion and electron acceleration in the PF devices [30]. Therefore, it can be concluded that electrons are accelerated in non-axial directions too. Hence, X-ray emission in the PF device, which is due to the bombardment of the anode by high-energy electrons, will have an anisotropic behaviour. The same behaviour of X-ray emission from the PF devices were observed by other researchers [26,31]. The anisotropic behaviour of X-ray emission from the PF device is a complicated phenomenon which is not fully understood yet; so for the future, it is required that theoretical physicists develop a physical model for pinch phase of plasma focus in which X-rays can be produced in different directions.

Results of dose measurement on the ring with a radius of 2.5 cm on the TLD holder (figure 2) for three gas pressures are given in table 2. The dose values of the six TLDs in each ring showed that the spatial distribution of X-ray emission is symmetrical.

X-ray dose was also measured behind the plexiglass window of the device chamber and the results are shown in table 3. It can be seen that the highest amount of dose is about 0.43 mGy at 0.9 mbar of argon. It should be mentioned that this amount is sufficient for typical screen-film radiography (0.001 mGy) [19]. In addition, the results showed that a small PF device can produce HXR dose in the order of a few 0.1 mGy in one shot outside the chamber. HXR dose can be increased from 0.01 to 1 Gy (sufficient dose for stimulating plants and animals) [23] in a rep rate working mode with $f = 10$ Hz when the operating time is in the range of 60 to 600 s. Therefore, for the stimulation of plants and animals, the small PF device is not affordable. Nonetheless, high-energy plasma focus should be used for special applications such as production of short-lived radioisotopes (SLRs) [32]. Our results are comparable with that reported by Raspa *et al* [5]. In accordance with table 1,

Table 3. X-ray doses behind the plexiglass window, outside the PF chamber at different gas pressures.

Gas pressure (mbar)	0.5	0.6	0.8	0.9	1.1	1.3
Dose value (mGy)	0.198 ± 0.008	0.215 ± 0.013	0.227 ± 0.018	0.438 ± 0.017	0.397 ± 0.024	0.245 ± 0.031

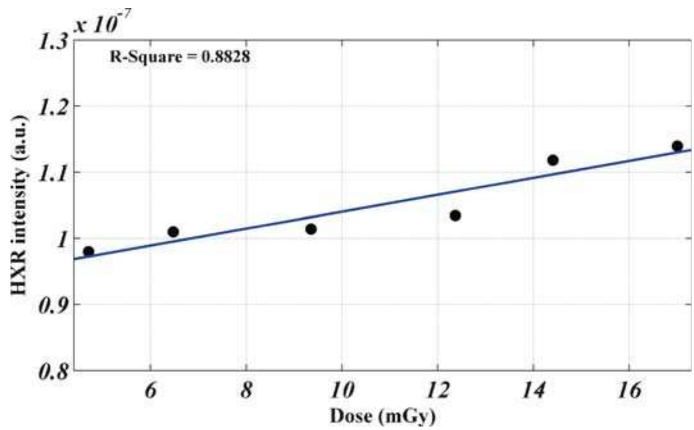

Figure 8. Scintillation detector signal vs. TLD response for X-rays from a UIPF1 (detectors placed outside the chamber).

Raspa *et al* [5] reported that HXR dose emission per shot from the 4.7 kJ PF device was about 53 μGy on the axis 53 cm away from the source. Considering the inverse square law, this dose value would be about 0.307 mGy at 22 cm from the pinch region which is very close to the results listed in table 3. Moreover, personal monitoring was carried out by placing the five TLD at 4 m from the source (user location). The results show that dose value is about background level at this position. This dose level is so low that no additional shielding was required for X-ray emission from UIPF1 PF device during the experiments.

To investigate the correlation between the TLD response and the scintillation detector signal, both detectors were placed outside the discharge chamber in front of a 5 mm thick plexiglass window 100 cm away from the anode. Figure 8 shows the correlation between responses of the TLDs and scintillator-PMT detector signal. It can be seen that there is a roughly linear relation between the two detectors. The linear behaviour offers a special advantage: it is possible to know (immediately after viewing the scintillator-PMT signal) if the dose was enough to capture a sharp picture without testing earlier.

4. Conclusion

In this study, radiation dose values in the UIPF1 PF device with argon as a filling gas were estimated. The results showed that the optimum gas pressure for HXR production was 0.9 mbar at 25 kV applied voltage. Radiation dose of this optimum condition was found to be about 17 mGy. At this pressure, dose measurements using TLDs in different radial distances from the axis of the electrodes at the top of the anode inside the chamber showed that the maximum dose was obtained in 7 cm radius. Moreover, the results showed that the gas pressure affected the X-ray distribution. Therefore, the operating pressure had a significant role in the X-ray distribution from the PF device. Furthermore, the dose measurement showed that the spatial distribution of X-ray emission was anisotropic. The linear relation between the amplitude of the scintillator-PMT signal and the absorbed dose was also confirmed in these measurements.

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