Journal of Fusion Energy, Vol. 21, Nos. 3/4, December 2002 (© 2003)

Study of X-ray Emission from a Compact Diode Operated by a High-Inductance Capacitor Discharge

M. Z. Khan,[1,4] S. Ahmad, M. Zakaullah,[1] A. Waheed,[2] R. Ahmad, and G. Murtaza[3]

A compact diode comprising a flat plate anode and a sharp-edged cathode (a piece of razor blade) energized by 0.5 μF capacitor charged to 30 kV is investigated for optimization of X-rays emission vis-à-vis separation between electrodes and width of the cathode, which is responsible for electron emission by impact of electric field. It is a high-inductance system, the parasitic inductance is found to be 353 $\pm$ 5 nH, and the recorded peak discharge current is just 35 $\pm$ 02 kA. The maximum X-ray emission is observed for a 2-mm-wide cathode with an interelectrode separation of 3 mm. The X-ray yield in 4π-geometry is found to be 34 $\pm$ 3 mJ with a wall-plug efficiency of 0.015 $\pm$ 0.001%. The X-ray emission occurs about 200 ns after the application of high voltage, synchronized with the dip in current wave form. The low efficiency of the system for X-ray generation is attributed to high parasitic inductance.

KEY WORDS: X-ray generation; compact diode; field emission.

I. INTRODUCTION

A significant progress has been realized in the development of flash X-ray sources capable of emitting high average power, because of the large number of potential applications. These X-ray sources are very useful in the investigation of high-speed phenomena [1], biomedical radiography [2], preionization of high-pressure gas discharge laser [3], and, more recently, in the photoexcitation of molecular [4] and atomic systems for fluorescence studies [5] and time-resolved X-ray diffraction studies [6]. Currently the available systems are based upon one of three methodologies: synchrotrons [7], laser plasmas [8], and electron-beam target interactions [9]. These systems are often large, complex, and expensive. So, the challenge is the development of small systems capable of operating at high repetition rates and emitting a high-dose per shot of X-rays with energy ranging from a few keV to a few hundred keV while minimizing cost and maintenance.

The conventional X-ray diode operates in vacuum with closely spaced electrodes that are powered with a high-voltage pulse discharge. Various kinds of X-ray generators have been developed using different pulse-forming networks with storage energies ranging between several hundreds of millijoules to several hundreds of joules [10,11].

Pouvesle *et al.* [12] developed a flash X-ray machine based on Blumlein configuration close to the one designed by the Dallas group [13], but with a big improvement in the ratio of X-ray output to the size and weight of the source less than 0.15 m^3 and 80 kg, respectively. With dose rates exceeding 1.4 kRmin^{-1} at the output window with photon energies up to 50 keV, from the pulses of tens of nanoseconds duration, this device is easily transportable, while operating voltages were lowered to 20–30 kV. This device can be included in various types of industrial systems or laboratory experiments. A big improvement of the system that allows a longer lifetime with the stability of the dose per shot realized at repetition rates

[1] Department of Physics, Quaid-i-Azam University, 45320 Islamabad, Pakistan.
[2] PINSTECH, P.O. Box 2151, 44000 Islamabad, Pakistan.
[3] Government College University, Lahore, Pakistan.
[4] To whom all correspondence should be addressed. E-mail: mzk_qau@yahoo.com

0164-0313/02/1200–0211/0

to 50 Hz was readily obtained with the use of a sliding-rotating anode [14].

Zakaullah and Worley [15] studied an X-ray emitting diode of impedance 2.3 Ω with a knife-edge cathode energized by a 90-kV, 30-J, solid dielectric Blumlein driver of 10-ns pulse length. X-ray emissions from titanium, copper, molybdenum, tin, tantalum, and lead anodes were analyzed. It was concluded that it may be used as characteristics or continuum radiation source of choice, and may find applications in various disciplines such radiography, crystallography, X-ray contact microscopy, and X-ray backlighting.

Zakaullah *et al.* [16] operated a low-energy (2.3 kJ) plasma focus in an enhanced Cu K_α line emission mode. In the side-on direction, 0.4 J/sr line radiation is recorded. In 4π-geometry, 40 J of energy is found to be emitted as X-rays, out of which 8 J is in the form of Cu K_α. The radiation yield represents a system efficiency of 1.7% for overall X-ray emission and 0.35% for the Cu K_α line. The plasma focus may find application as a radiation source in X-ray diffraction experiments.

Shafiq *et al.* [17] investigated K-series line radiation emission of Mo and Cu from a low-energy Mather-type plasma focus. The maximum Mo and Cu K-series line emission of about 0.05 J/sr and 0.17 J/sr is observed at hydrogen filling pressure of 2.0 mbar. Total X-ray emission and efficiency in 4π-geometry are also obtained with values 4.12 J and 0.18% at 2.0 mbar.

Shafiq *et al.* [18] investigated the X-ray emission from a low-energy (2.3 kJ) plasma focus operated with hydrogen as the filling gas. Different high-Z metallic discs are inserted at the anode tip. Shafiq *et al.* [18] studied the X-ray emission in the 5.0–9.0 keV and 13.0–25.0 keV energy range. The maximum value of the total X-ray emission in 4π-geometry is found to be 29.4 ± 0.2 J, 3.43 ± 0.05 J, and 4.00 ± 0.02 J with Pb, W, and Mo inserted anodes, respectively, and corresponding wall plug efficiencies for X-ray generation were found to be 1.28%, 0.15%, and 0.20%.

In this paper, X-ray emission from a compact diode energized by a high-inductance capacitor discharge is reported. Specifically, attention is paid to optimize the diode parameters for enhanced X-ray emission. Section II presents experimental arrangement and diagnostics. Results and discussion are presented in Section III and conclusions are given in Section IV.

II. EXPERIMENTAL ARRANGEMENT

The electrode system of compact diode consists of an anode, which is a flat plate of brass with the thickness of 10 mm and diameter of 30 mm. At its surface, different metal targets may be mounted. The cathode is knife edged and is a replaceable piece of commercial razor blade. It is suspended in the chamber with a specially designed holder. The cathode holder is a brass plate of 30 mm diameter and 20 mm thickness, which is attached, with an outer brass plate of 257 mm diameter and 10 mm thickness. This outer plate is connected to the ground plate of the capacitor through six hexagonal brass rods used to reduce the inductance of the system. The anode header is connected to the high-voltage terminal of the capacitor through a sparkgap (used as a switch). A schematic diagram of the compact diode system is shown in Fig. 1. The electrodes are enclosed in a cylindrical vacuum chamber made of an approximately 57-mm-thick wall of ertlon with four openings/ports. One port is used to fit the capsule type (Edwards CG3) gauge to measure the vacuum in the chamber, and a rotary van pump is connected to the second port to obtain a vacuum upto 10^{-2} mbar, which is adequate in this experiment. The compact diode system is energized by a single 0.5 μF, 30 kV (225 J) capacitor, with a discharge current of about 35 ± 2 kA.

To analyze the X-rays, two Quantrad PIN diodes that have a 100-mm^2 effective area, with 125-μm-thick active layer masked with Ni (17.5 μm) and Co (20 μm) filters are used. The transmission characteristic of the filters set (17.5 μm Ni, 20 μm Co) along with response of the PIN diode is given in Fig. 2. These curves are obtained by using the data given in the *Handbook of Spectroscopy* [19]. The Co filter has the absorption edge at 7.709 keV and allows transmission of X-rays in the 4–7.709 keV windows. The absorption edge of Ni lies at 8.333 keV and allows transmission of the Cu–K_α line of 8.047 keV. Thus the difference of transmission in the Ni and Co filters may be considered corresponding to the Cu–K_α line radiation. Further, a photomultiplier tube XP2020 coupled with 50-mm × 50-mm cylindrical plastic scintillator NE102A with 3-mm-thick aluminum light shield is positioned at 13 ± 0.5 cm from the point where the X-rays are emitted. A four-channel 200-MHz GOULD 4074A oscilloscope and a computer are used to record electrical signals.

III. RESULTS AND DISCUSSION

Discharge in the compact diode is studied under a vacuum of 10^{-2} mbar at different interelectrode spacing and width of the razor, with a total discharge energy of 225 J at a fixed charging voltage of 30 kV.

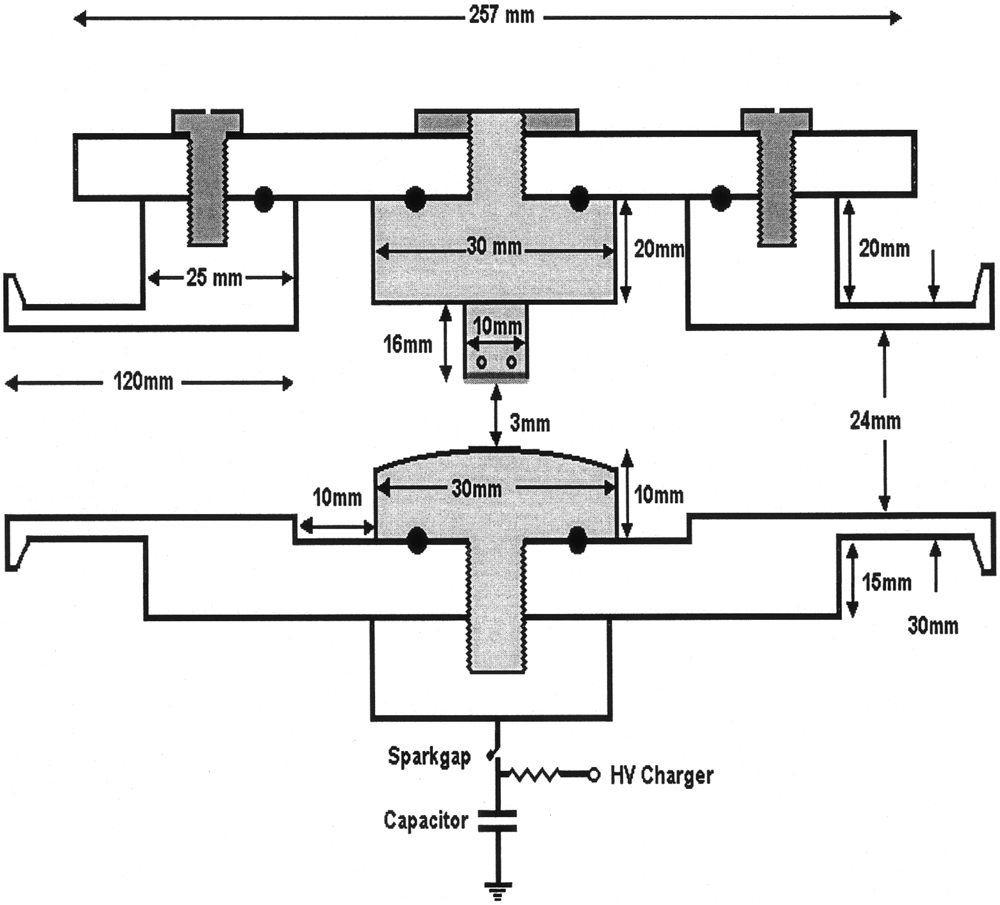

Fig. 1. The schematic of compact diode electrode system.

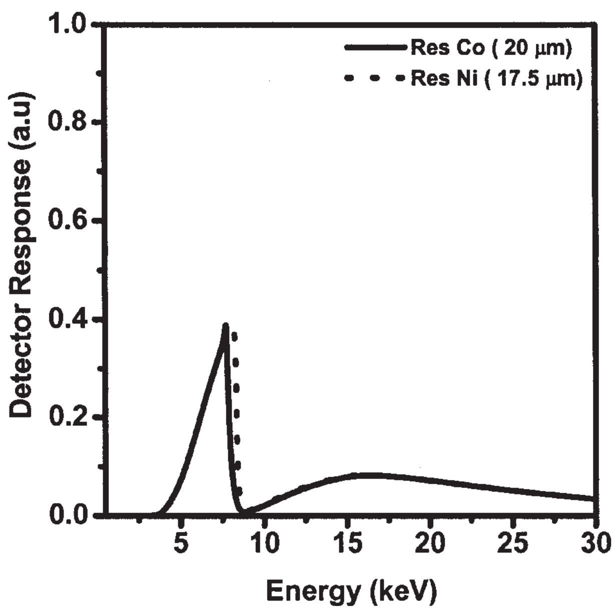

Fig. 2. Response curves of PIN diode detectors masked with Ni (17.5 μm) and Co (20 μm) filters.

The sharp-edged razor blade is replaced, and the surface of the anode is cleaned every five shots. The peak discharge current (35 $\pm$ 2 kA) is recorded using the signal from the Rogowski coil. The total parasitic inductance of the system (including capacitor, spark-gap, the compact diode, and the return current path) is found to be around 353 $\pm$ 5 nH.

The PIN diodes are used to detect the X-rays for Cu–K_α with a Ross filter pair of 17.5 μm Ni and 20 μm Co. The X-ray emission is also detected using a photomultiplier tube (PMT) and plastic scintillator (NE102A) combination for every shot. A typical PMT signal is shown in Fig. 3, which shows that the X-ray pulse width (FWHM) is 35 $\pm$ 2 ns. The pulse is recorded 200 $\pm$ 10 ns after the application of high voltage. The internal transit time of the PMT is 28 ns. Therefore one concludes that the X-ray emission is about 170 ns after the application of high voltage. There is a small dip in the current waveform of the Rogowski coil, which synchronizes with the PMT signal. This observation

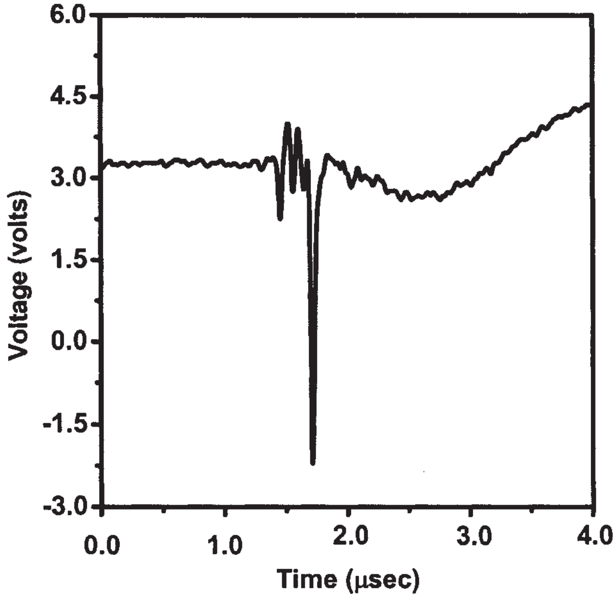

Fig. 3. X-ray emission waveform recorded by a photomultiplier tube coupled with plastic scintillator NE102A.

reveals that the discharge in the compact diode undergoes Z-pinch type compression.

The X-ray emission and the wall plug efficiency in 4π geometry is estimated using the relation [20,21]

$$Y = \frac{Q_{exp}(4\pi)}{d\Omega S(E)T(E)}$$

where $Q_{exp} = \int \frac{Vdt}{R}$ (Coulombs), $\int Vdt$ is the difference in the area under the waveforms with two respective filters, $S(E)$ is the average sensitivity of the detector (taken form the Quantrad brochure), $T(E)$ is the average transmission of the filter, $R = 50\ \Omega$, in the recent experiment, $d\Omega = da/r_o^2$ (sr.) is the solid angle subtended by the detector at the center of the anode,

where $da = \pi r^2$;
$r = 0.4$ cm is the radius of the exposed area of each detector
$r_o = 26 \pm 1.0$ cm is the distance from the detector to the center of the anode.

The variation of Cu–K_α emission as a function of separation of the electrodes is described in Fig. 4. The highest Cu–K_α yield in 4π-geometry, which is recorded at a separation of 3 mm, is 8 mJ, and the corresponding efficiency is 0.003%. Figure 5 shows the variation of total X-ray emission and efficiency against the separation of electrodes. Maximum X-ray emission and wall plug efficiency in 4π geometry for interelectrode separation of 3 mm and for 2-mm-wide

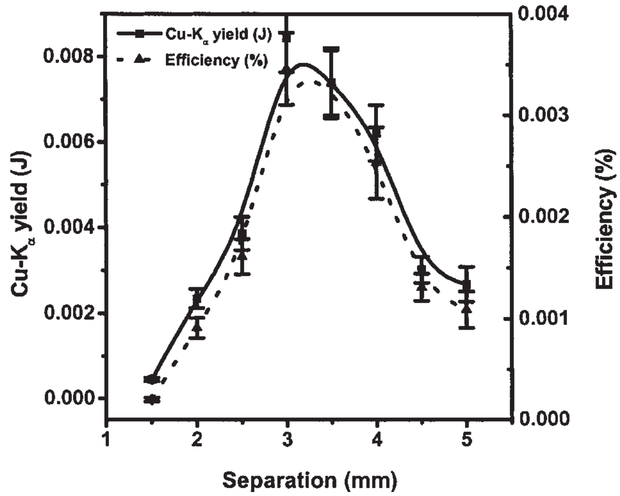

Fig. 4. Variation of Cu–K_α yield in 4π-geometry and system efficiency vs separation of electrodes having a constant width of razor blade (2 mm).

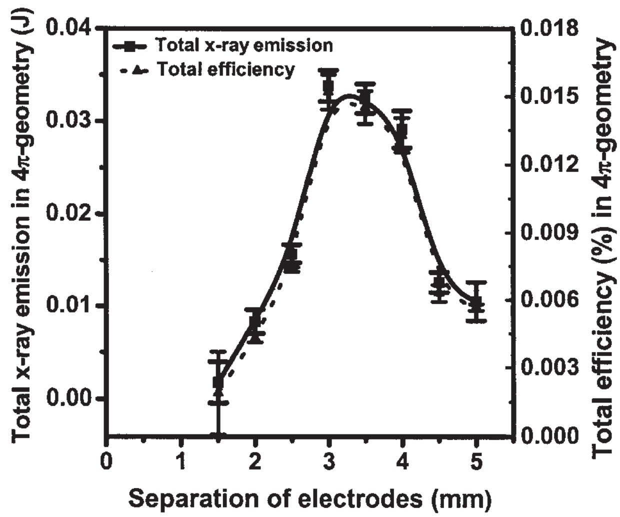

Fig. 5. Variation of total X-ray emission in 4π-geometry and system efficiency vs separation of electrodes having a constant width of razor blade (2 mm).

razor blade (cathode) is 34 ± 3 mJ and $0.015 \pm 0.001\%$. When the separation of electrode is reduced from the optimum value, the electrons may penetrate deeper into the target, which may cause enhanced self-absorption of X-rays, causing reduction in emission. When the interelectrode spacing is increased beyond the optimum value, the electric field intensity is reduced, which decreases the field emission, causing reduction in emission. Similarly, the variation in the width of the razor blade gives rise to a variation in current density. The data reveals that the width of 2 mm corresponds to the current density, which is most favorable for X-ray emission in the present system.

IV. CONCLUSIONS

A capacitor bank of discharge energy 225 J energizes a compact diode comprising a flat-plate anode and a sharp-edged cathode. The compact diode system is investigated for optimization of X-ray emission by changing the interelectrode spacing and width of the cathode, which is observed for a 2-mm-wide cathode and for 3-mm interelectrode spacing. The maximum efficiency of the compact diode for total X-ray emission is found to be 0.015%. The efficiency of the system is expected to be increased further by lowering the parasitic inductance of the system and increasing the charging voltage.

ACKNOWLEDGMENT

This work was partially supported by Higher Education Commission and Pakistan Science Foundation Project No. PSF/R&D/C-QU/Phys (199).

REFERENCES

1. E. Sato, H. Isobe, and F. Hoahino, *Rev. Sci. Instrum.* **57**, 1399 (1986).
2. E. Sato, *et al., Rev. Sci. Instrum.* **61**, 2343 (1990).
3. E. Sato, *et al., Rev. Sci. Instrum.* **62**, 2115 (1991).
4. J. I. Levatter and Z. Li, *Rev. Sci. Instrum.* **52**, 1651 (1981).
5. C. Cachoncinlle, *et al., J. Phys. D.* **23**, 984 (1990).
6. I. V. Tomov, P. Chen, and P. M. Rentzepis, *Rev. Sci. Instrum.* **66**, 5214 (1995).
7. I. L. Spain and D. R. Black, *Rev. Sci. Instrum.* **56**, 1461 (1985).
8. H. Milchberg, R. R. Freeman, and S. C. Davey, *Advances in Laser Science II* (M. Lapp, W. C. Stwalley, and G. A. Kenny-Wallace eds.), *AIP Conf. Proc.* **160**, 179 (1987).
9. J. D. Ivers and J. A. Nation, *Rev. Sci. Instrum.* **54**, 1509 (1983).
10. A. Ikhlef and M. Showronek, *IEEE Trans. Plasma Sci.* **54**, 669 (1993).
11. A. Shikoda, *et al., Rev. Sci. Instrum.* **65**, 850 (1994).
12. J. M. Pouvesle, *et al., Rev. Sci. Instrum.* **64**, 2320 (1993).
13. C. B. Collins, F. Davanloo, and T. S. Bowen, *Rev. Sci. Instrum.* **57**, 863 (1986).
14. E. Robert, *et al., Ann. Phys. (Paris)* **19**, 167 (1994).
15. M. Zakaullah and J. Worley, *J. App. Phys.* **88**, 1251 (2000).
16. M. Zakaullah, *et al., Appl. Phys. Lett.* **78**, 877 (2001).
17. M. Shafiq, *et al., Phys. Lett. A*, **302**, 23 (2002).
18. M. Shafiq, *et al., Plasma Source Sci. Technol.* **12**, 199 (2003).
19. J. W. Robison, *Handbook of Spectroscopy* (Cleveland, OH, CRC 1974).
20. M. Zakaullah, *et al., Plasma Source Sci. Technol.* **9**, 592 (2000).
21. M. Zakaullah, *J. Fusion Energy* **19**, 143 (2000).