

## A Flash X-Ray System Based on Flat Pulse Marx Generator and an industrial pinch diode for Radiographic applications

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### Abstract

A compact flash X-Ray generation system using Folded Pulse Forming Line type Marx generator rated for 225kV, 5kA, 100ns; in conjunction with an industrial pinch diode has been developed at APPD, BARC. The pinch diode with pencil shaped tungsten anode placed at the centre of the circular SS cathode; is used to produce flash X-rays by Bremsstrahlung process with the frequency in the region of hard X-rays. The flash X-rays produced are characterized using a FUJIFILM phosphor imaging plate BAS SR2025. The source size is determined using pinholes of size 50, 100 and 250 $\mu$ m. The flash X-ray radiographs of various technological important objects were taken to see the performance of FXR system. To assess spatial resolution of the system a radiograph of an IC- processor chip is recorded to see the internal microstructure. The details of design, beam characterization and applications of the flash X-ray radiography system are presented in this paper.

Key words: Marx generator, Pinch diode, Flash X-rays, Imaging plate, Pinhole, X-ray radiography

### Introduction

Flash X-rays radiation sources have wide range of applications for the investigation of high speed phenomena like explosion and impact processes, transient radiation effects on electronics and biological systems, non destructive testing of materials under short term extreme conditions of stress and temperature by employing radiography technique etc [1-3]. Most radiographic studies require small X-ray source size for better resolution and for radiation effect studies radiation dose is of importance. The flash X-ray sources have advantage to conventional X-ray tubes in term of their very high dose rates and very short duration pulse, therefore, can be used in the radiography of dynamic processes, which gives blurred images when radiographed via a conventional X-ray source. The short duration pulse gives freedom to freeze the motion of moving object. Flash X-ray sources are also utilized for radiography of radioactive samples, it can discriminate the radiation coming from radioactive sample in this time domain. Flash X-rays have greater penetrating power; they are used in non destructive testing of high density materials for finding structural flaws if any in the bulk of thick samples. The flash X-rays are produced by impact of high energy electrons on a target as in conventional X-ray tubes. In conventional X-ray tubes, anode currents of few milliamperes are used, whereas the flash X-ray tubes requires anode currents in kA range to emit flash of X-rays during a very short time. These large currents cannot be obtained by normal heated cathodes; therefore cold cathodes are used in flash X-ray generation. The flash X-ray generator consists of mainly the X-ray tube often called a diode and a pulsed high voltage source. When instantaneous high voltage pulse is applied between the cold cathode and the anode, high electric field gets created and electrons are emitted from the surface of the cathode by explosive field emission process. This process occurs only during the very short period of a pulse when vacuum discharge takes place. The electrons accelerated by the field between the electrodes impinge on the anode i.e. target producing X-rays by

Bremstrahlung process. A variety of techniques are used to generate high voltage pulses like Marx generator, spiral generator, pulse transformer and pulse forming line [3-6]. A compact flash X-Ray generation system is developed at APPD, BARC using Folded Pulse Forming Line (FPFL) type Marx generator rated for 225kV, 6kA, FWHM 100ns in conjunction with an industrial pinch diode. This Marx generator has the advantages of higher peak power rating, compactness, low cost and reliability and can deliver about 3 times more current than a conventional system made of discrete components. The description of flash X-ray system, the beam characterization, X-ray spot size determination and spatial resolution of flash X-ray system and our initial applications of FXR for NDT of some technologically important material components is described in this paper.

### Flash X-ray System

Flash X-Ray (FXR) generation has been carried out using Folded Pulse Forming Line (FPFL) type Marx generator (225kV, 6kA, 100ns) and FXR tube. The basic principle of Marx is to charge a number of capacitors in parallel and discharges them in series by a set of switches, thereby boosting the voltage. The maximum output voltage of Marx under the actual operating conditions depends on the load impedance, the voltage drops across the switches and internal impedance of the Marx generator. Fig.1 shows the schematic diagram of X-ray tube. Cold cathode, two-electrode vacuum tubes are used to generate short and intense bursts of hard X-rays.

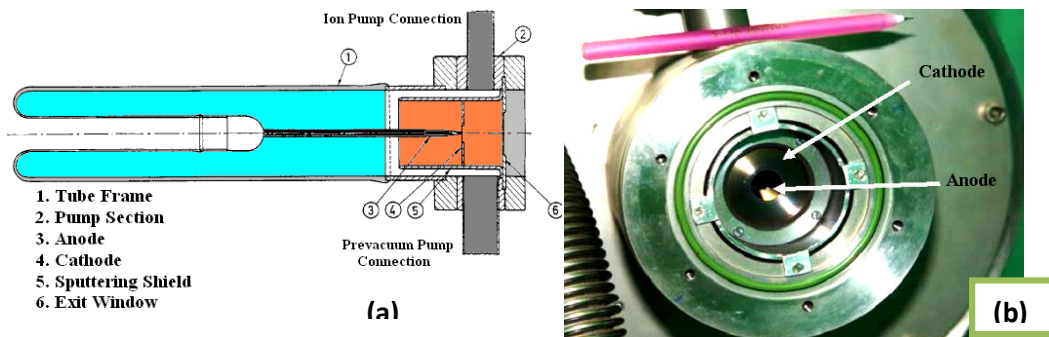


Fig.1. (a) Schematic diagram of FXR tube (b) Anode cathode configuration in FXR tube

An industrial pinch diode is used to generate electron beams from S.S cathode and high Z-anode to convert these electrons to Flash X-rays by Bremstrahlung process. The electrodes are replaceable and tube life is almost unlimited. The anode is a tungsten rod of 6 mm  $\phi$  with 33 mm length of which 12 mm length is tapered at one end to a tip of 1 mm  $\phi$ . The cathode is an annular ring made of 1mm thick stainless steel with a central hole of 10 mm and 36mm outer  $\phi$ . Anode is placed right at the middle of the circular annulus of the cathode (fig.1b). A 2mm thick, 40 mm  $\phi$  aluminium window placed 38mm away from the anode tip provides outlet for the X-rays emitted. The tube is demountable, continuously pumped in the pressure



Fig.2. The complete FXR system connected to complete FXR system is shown in fig.2. When high pulsed output voltage applied to the anode and cathode is kept at ground potential, due to field emissions, electrons are ejected from the surface of the cathode and get accelerated and gain

very high kinetic energy. When these electrons collide with the anode, they decelerate under the high electric field of the high Z tungsten nucleus resulting in emission of bremsstrahlung radiations, with frequency in the region of hard X-rays. The output of an X-ray tube is given by the equation,  $\frac{dD}{dt} = KIV^n$  where  $\frac{dD}{dt}$  is radiation intensity (dose rate), I = tube current, V = anode-cathode voltage, and K is the function of anode material. The radiation intensity varies as  $V^{2.5}$  over a wide voltage range. The voltage on the tube is given by  $V = \frac{Z_L}{Z_L + Z_0} V_0$ , where,  $V_0$  = total charging voltage,  $Z_L$  = tube impedance,  $Z_0$  = pulsar impedance.

### Characterization of flash X-rays

The flash X-ray beam emerging out from the exit window of the system is characterized using the imaging plate (IP) and to record X-ray beam spot size and radiographs of the object. IP made of BaFBr: Eu<sup>2+</sup>, a storage phosphor is a two-dimensional radiation detector. It is widely used for medical and industrial radiography, autoradiography, X-ray diffraction experiments, and transmission electron microscopy [7-8]. The advantages of IP include high spatial resolution, high sensitivity and a linear response to radiation dose over five orders of magnitude. The latent image formed by incident radiation is stored as F<sup>+</sup> centers and Eu<sup>3+</sup> ions in the phosphor. The latent image can be read out by irradiating the IP with He-Ne laser ( $\lambda=633$  nm). The laser excites trapped electrons to recombine with Eu<sup>3+</sup>. The decay of Eu<sup>3+</sup> to Eu<sup>2+</sup> causes the emission of photons ( $\lambda=400$  nm). The process is called photostimulated luminescence (PSL). A photomultiplier tube collects the PSL intensities. The resulting signal is converted and stored as a digital image and displayed on a monitor. After reading, the IP is exposed to strong visible light to erase the residual image and it can be reused. In our experiments Fujifilm IP BAS-SR2025 is used and read on FUJIFILM BAS-5000 scanner with 50 $\mu$ m resolution and 4000 sensitivity and data is stored in 8 bits gradation. Image is corrected for the background noise. The PSL intensities of selected area of the radiograph are obtained and analyzed using the software provided with the scanner. Fig.3 shows the schematic experimental arrangement for recording the image of direct beam using IP. The direct beam from the FXR source is recorded with IP at a distance of 80 mm from the Al window.

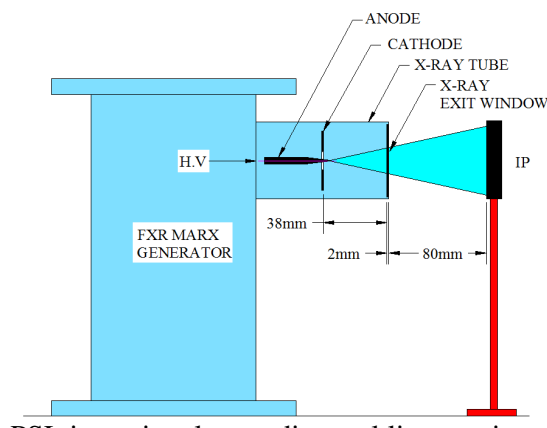


Fig.3. Experimental arrangement for recording the image of direct beam

The X-ray image obtained is shown in fig.4. The image covers the whole area of the IP i.e. 200 x 250 mm<sup>2</sup>. The beam shows isotropic intensity distribution with maximum X-ray Intensity at the centre. The central spot has diameter of ~ 40 mm and covers an area with a uniform intensity of ~2.85x10<sup>4</sup> PSL/mm<sup>2</sup>. This spot may correspond to the X-rays originating from and around the anode tip and received with some divergence on the IP kept at a distance ~ 120 mm from the anode tip. Intensity profile of the image as a plot of

central spot, a region of constant intensity is also evident at the peak of the intensity profile. The intensity from the centre of the image to the edges looks to be not smoothly decreasing but changing in steps. This is also evident from the IP image pattern which is made of concentric rings of decreasing intensity separated by a gap of less intensity. A surface profile of x-ray beam registered on IP is shown in fig.6. One

may visualize the X-ray intensities radiated from different portions of the tapered anode portion; maximum from the tip of anode.

The radiation dose received on the IP is calculated from PSL/mm<sup>2</sup> values of 27 positions along the diagonal of the beam passing through the centre. The PSL/mm<sup>2</sup> values were first converted to fluence photons/cm<sup>2</sup> by taking sensitivity of IP as 1.24x10<sup>-4</sup> (sensitivity = PSL/cm<sup>2</sup> ÷ Photons/cm<sup>2</sup>) at average photon energy of bremsstrahlung radiation as 100keV [9-10]. The radiation dose was calculated using the relation Dose = (μ<sub>en</sub>/ρ)(N)(E) where μ<sub>en</sub>/ρ is mass energy absorption coefficient of air in cm<sup>2</sup>/g = 2.672x10<sup>-2</sup>; N the photons/cm<sup>2</sup> and E energy per photon in MeV. The plot of PSL/mm<sup>2</sup> and Dose in mR with various positions on the IP is shown in fig.5. The dose is maximum ~ 1R at the centre corresponding to PSL/mm<sup>2</sup> value of 2.85x10<sup>4</sup> and minimum of ~30mR at the edges of the IP (PSL/mm<sup>2</sup> = 784).

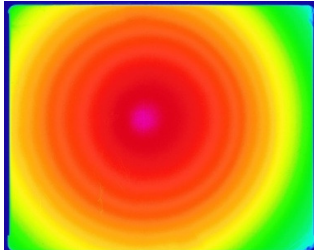


Fig.4. Direct beam as received on IP kept at 80 mm from X-ray exit window

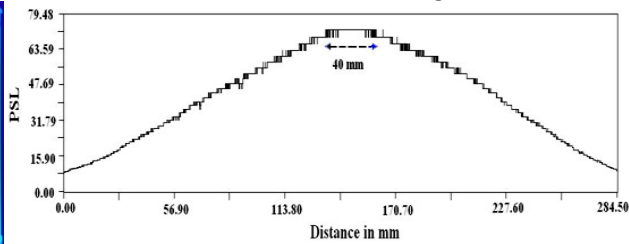


Fig.5. Intensity line profile of the direct beam along diagonal (left bottom to right top)

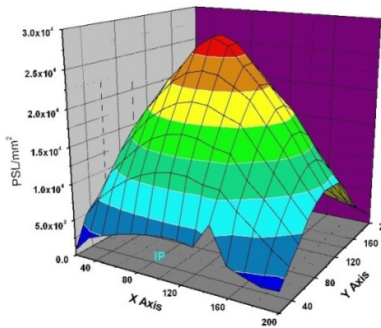


Fig.6 surface profile of x-ray beam

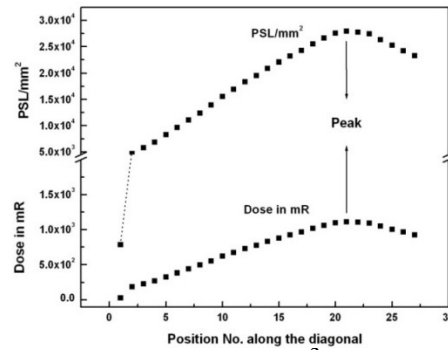


Fig.6. PSL/mm<sup>2</sup> and Dose received on IP

### Flash X-ray source size

The source size is determined using pinholes of size 50, 100 and 250μm kept in between the imaging plate and X-ray exit window of the system. The pinhole was mounted on the X-ray exit window at a distance of 40mm and IP was kept at a distance of 5mm from the pinhole. The resulting images are shown in figs 7(a-c) respectively. The line intensity profiles of the spots in vertical and horizontal section the spot centre were measured and fitted to Gaussian distribution as shown in figs. 7(a,b,c). The FWHM of the peaks were used to calculate the

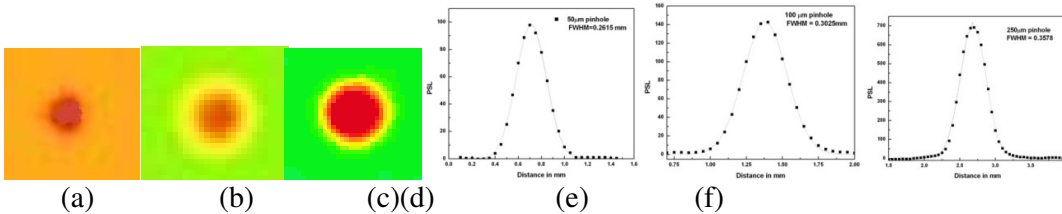
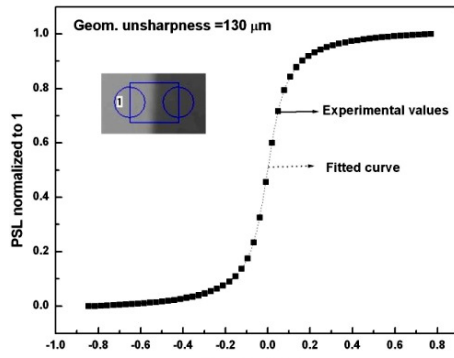


Fig.7. The x-ray images of (a) 50 μm (b) 100μm and (c) 250μm pinholes and corresponding Gaussian profiles (d-f) respectively

object size i.e. the source size using pinhole equation. The calculated sizes were 2.08, 2.42 and 2.86 mm respectively. Taking in to consideration the peak broadening and scattering effects, the smallest value of 2.08mm obtained from the 50µm pinhole was considered as the source size..

### Spatial Resolution of FXR radiography setup

In radiography spatial resolution is defined as the ability of an imaging system to display two adjacent structures as being separate and sharply and clearly defined. The resolution depends



on the thickness of the sample, sample to detector distance, the track size and the range of X-rays in the image plate. It is expressed in terms of total unsharpness,  $U_t$  and evaluated by obtaining "edge-spread" function, ESF. The image plate is partially covered with a 50µm Pb foil and is exposed to flash X-rays. The IP is then read with 50µm scanning pitch. The profile is shown in fig.8. The profile is fitted to a function of type  $ESF = P1 + P2 \cdot \arctan(P3(x - P4))$ , where P1, P2, P3, and P4 are fit parameters [11]. The total unsharpness is given by  $U_t = 2/P3$ . A value of  $U_t = 130 \pm 10 \mu m$  is obtained.

Fig.8. Pb edge spread data (discrete points) fitted to ESF (dotted line). The radiograph is shown in the inset

### Applications

Radiography with flash X-rays is very valuable in practice to investigate nuclear implosion, high speed processes and for nondestructive testing of materials. As high energy and intense source, flash X-rays can be used for radiography of thicker objects and selectively see the parts with high and low absorption coefficients with good contrast in much less time compared to normal X-ray radiography. Therefore, it may be useful in nuclear, aerospace, ordnance industries. With this aim radiographs of various objects which are normally subjected to neutron radiography are recorded. Fig. 9(a) shows flash X-ray radiograph of an aero engine turbine blade casted in Titanium alloy with internal air circulation channels. It gives a good insight of internal structure of the blade and is comparable to that obtained with neutrons [11]. In view of non availability of neutron sources flash X-ray radiography should serve the purpose of NDT. Fig. 9(b) shows radiograph of an IC- processor chip. It shows the

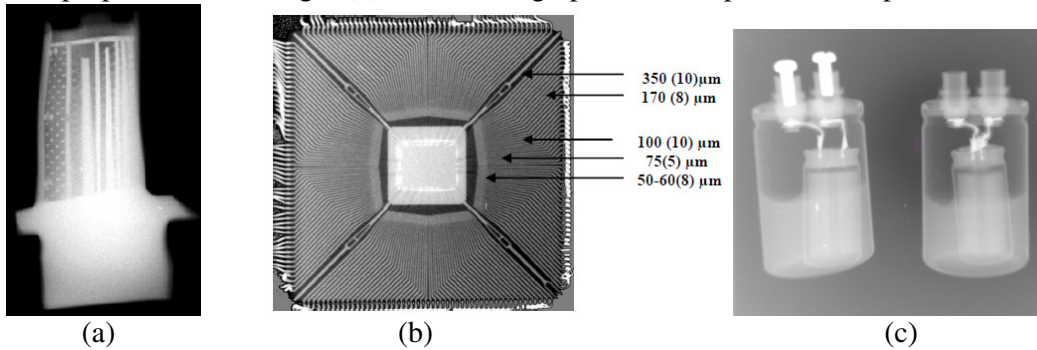


Fig.9. Radiographs of (a) aeroengine turbine blade (b) IC processor chip (c) large size condensor

internal structure with highly resolved tracks in the periphery of the core. The interconnection tracks of the size up to 50 to 75 µm are clearly seen in this radiograph. Fig.9(c) shows radiograph of two large size (~50mm dia) condensers used in reactor control electronics; the one to the right is intact and that to the left is in failed during the operation with fused



electrodes inside the pot. The differential absorption of X-rays due to empty portion and electrolyte filled portion is also clearly seen.

### Conclusions

A compact flash X-Ray generation system using Folded Pulse Forming Line type Marx generator rated for 225kV, 6kA, 100ns; and an industrial pinch diode has been developed. The X-ray beam was characterized using the phosphor imaging plate. The dose is maximum  $\sim 1\text{R}$  at the centre corresponding to  $\text{PSL}/\text{mm}^2$  value of  $2.85 \times 10^4$  and minimum of  $\sim 30\text{mR}$  at the edges of the IP ( $\text{PSL}/\text{mm}^2 = 784$ ). Spatial resolution of the FXR imaging system using ESF is calculated as  $130 \pm 10 \mu\text{m}$ . As high energy and intense source there is possibility of using flash X-rays for radiography of thicker objects and selectively see the parts with high and low absorption coefficients with good contrast in much less time compared to normal X-ray radiography.

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### References

- [1] C. Ekdahl, Modern electron accelerators for radiography, IEEE Trans. Plasma Sci. 30, 254, 2002.
- [2]. R. Germer, X-ray flash techniques, J. Phys. E Sci. Instrum. **12** 336.1979
- [3] J.M. Pouvesle, et al Compact flash X-ray sources and their applications, Nucl. Instrum. Meth. B **113** 134.1996
- [4] F. Davanloo et al , Flash X-ray sources powered by Blumlein pulse generators, Nucl. Instrum. Meth. **56** (1991) 1068.
- [5] F. Davanloo, C.B. Collins and F.J. Agee, Ultra-fast flash X-ray pulses produced by Blumlein devices, Nucl. Instrum. Meth. B **241** (2005) 276.
- [6] A. Sharma, et al "First results of KALI-30 GW with 1 MV flash X-rays generation and characterization by Imaging plate" J. INST, **9**, P 07011, 2014.
- [7] A.M. Shaikh et al Flash X-ray Radiography, with Phosphor Imaging Plate - The e-J NDT, **20**(6) 2015, ISSN 1435-4934 www.ndt.net and references there in.
- [8] M. Sonada et al, Computed radiography utilizing scanning laser stimulated luminescence, Radiology, **148**, 833, 1983.
- [9] N. Izumi et al, X-ray and neutron sensitivity of imaging plates LLNL-CONF-643255, SPIE, 2013
- [10] A.M. Shaikh, Determination of Sensitivity and saturation limit of phosphor imaging plates for photon energies up to 1.25MeV, paper to be presented in NDE2015, India
- [11] Akhtar M. Shaikh, Applications of various imaging techniques in neutron radiography at BARC, Trombay, 18th WCNDT, www.ndt.net /article/ wcndt 2012 papers/646\_wcndtfinal.00647.pdf.