Indigenous Pulsed X-ray and Neutron Sources for Non-destructive Material Characterization

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INTRODUCTION

Pinch plasma devices such as plasma focus [1-2], x-pinches and Z-pinches [3] are based on plasma generated and driven byhigh currentdischarges in gas or thin metallic wire/ foils. The plasma is made to implode into a line or a point and can yield a burst of intense and powerful radiations including energetic electrons/ ions, X-rays and also neutronswhen used with deuterium with or without tritium. The advantage of such sources over conventional ones such as X-ray or neutron tubes and isotope based systems is that they can be indigenously prepared in compact versions which are portable, cost effective and safe (due to short duration of emissions) and may be used for applications like X-ray lithography in microelectronics, X-ray back lighter for dynamics of moving objects and radiography of biological samples or non-destructive material interrogation if used with neutrons. These sources can be highly intense with short pulse width and also emit wide energy range of X-ray energies from soft to extremely hard.
Plasma focus device produces radiation by magnetic compression of hot dense column of plasma formed at the end of coaxial electrodes. By using suitable gas such as deuterium, nitrogen and argon, radiation of several types and different yields can be produced. The X-rays produced in the process are of tens of ns width and range up to hundreds of keV. When used as a fusion neutron source, it can be used to activate and characterize materials especially fissiles. The latter process has been utilized by us to assay fissile material like U-235 through delayed neutron and gamma emissions [4-5].
Using Fujifilm X-ray image plates as detectors for X-ray imaging, due to its sensitivity over wide range of energies up to hundreds of keV, a 12.5kJ (MEPF-12) plasma focus device has also been used for radiography of objects with varying thicknesses. We have characterized the radiographic system in terms of important imaging parameters related to contrast, resolution and X-ray energy. The imaging parameters estimated are X-ray emission profile, spatial resolution of detection system and energy range by step wedge method and spot size using pinhole camera. The spatial resolution of the radiographic system has been estimated by analyzing the line and edge spread function of a thin (25 µm thick) lead strip and resolution strip. The spatial resolution is found to be 147±10µm.
The energy information of the source could be helpful for choosing the windows and filters to get better contrasts for samples of variable thickness. Energy profile of X-rays has been estimated by filter transmission method. Aluminum and copper step wedges with step size of 2 mm and 170 µmrespectively and total thickness varying from 2mm-14 mm for Al and 170um-1.2mm for Cupasted on image plate have been used for energy dispersed X-ray profile estimated from 8 keV to 34 keV and 8 keV to 50 keV. The lower limit of 8 keV arises from 5 mm Perspex window used in the set up.
The X-ray spot size of plasma focus device has been measured by pin-hole camera of magnification ~1. The pinhole image of the source shows that a bright spot is formed at the centre, which could be the pinch region. Different samples of varying thickness such as BNC

connectors, computer RAMs, and copper studs have been radiographed as also some samples placed inside metallic boxes.Under properly chosen diagnostics these devices can be used for radiography of fast moving objects.
Recently, other plasma pinch sources such as X-Pinch have gained significant attention as a source for radiography of low density plasma and thin biological samples because of its small source size (~µm), short pulse width (ns) [6]. Source size can besufficiently small underproperly chosen conditions so that it can be usedfor point-projectionradiography. A feasibility study has been carried out with the copper wire X-pinch along with image plates. Radiographs have been generated using different thin foils of variable thicknesses to study the X-ray transmission.
All above works with their prospective application are discussed in the following.

EXPERIMENTAL

(a) Pinch Devices

In our laboratory we have developed a number of systems based on mainly plasma focus with some recent activity on Z-pinch or X-pinch plasmas. Various plasma focus systems are summarized in Table-1 below.

Table-1: Features of Various Plasma Focus Based Devices at APD, BARC.

Sr. No.	PF Device	Overall Dimensions	Energy	D-D N-yield/ Pulse	D-T yield/ Pulse width (Expected)	Major Applications
1.	Palmtop, Sealed, Portable (PTPF-P1)	4 cm D x 8 cm L	100 J (5 kV) Battery based	$10^4 – 10^5$/ 15 - 20 ns	$10^6 – 10^7$/ 15 – 20 ns	Detector test
2.	Compact, Sealed, Portable (SPF-P2)	3.4 cm D x 8 cm L	200 J (10 kV) Battery based	$10^5 – 10^6$/ 25 – 30 ns	$10^7 – 10^8$/ 25 – 30 ns	Detector test
3.	Compact, Sealed, Portable (SPF-P2_1)	2.9 cm D x 5.8 cm L	200 J (10 kV) Battery based	$10^5 – 10^6$/ 25 – 30 ns	$10^7 – 10^8$/ 25 – 30 ns	Detector test
4.	Compact (MPF-1)	5 cm D X 12 cm L	1.2 kJ (25 kV)	$10^3 – 10^7$/ 25 – 30 ns	$10^5 – 10^9$/ 25 – 30 ns	Detector test
5.	Compact (MPF-3)	5 cm D X 18 cm L	3.3 kJ (25 kV)	$2x10^8$/ 35 – 40 ns	$2x10^{10}$/ 35 – 40 ns	Radiography Activation
6.	Medium Size, (MEPF-12)	30 cm D X 30 cm L	12.5 kJ (25 kV)	$1.2x10^9$/ 46 ns	$3x10^{10}$/ 30-40 ns	Radiography Activation
7.	Cable Based Medium Energy (MEPF-17)	80 cm D x 60 cm L	17 kJ (24 kV)	1.3 $X10^9$/60 ns	1.3 $X10^{11}$/ 60 ns Fig. 1.	Radiography Activation
8.	Large size (HEPF-55)	80 cm D x 60 cm L	55 kJ (18 kV)	10^9/100 ns	10^{11}/100 ns	Radiography Activation

9.	Large Size-Under Progress (HEPF-272)	80 cm D x 110 cm L	272 kJ (40kV)	10^{11}	--	Radiography Activation

Recently experiments have been initiated on development and characterization of Z-pinch (X-pinch) based configurations to have a well defined point source for application in material investigations.An schematic of such devices is shown in Fig.1.

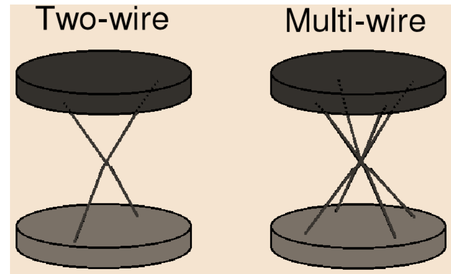

Fig.1.Schematic of X-Pinch

X-pinch system was mounted on a11μF capacitor typically charged to 20 KV with 233 μm diameter x 20 mm long copper wires being used for pinch. The thin foils to be radiographed were kept at the image plate placed 25 cm from the centre. After irradiation the image plates were read on FUJIFILM BAS-5000 scanner with 50μm resolution, and 4000 sensitivity.

(b) Applications to Non-destructive Evaluation of Materials

(i) Assay of Fissile Materials using Neutrons: In one of significant utilization of plasma focus based device as a pulsed neutron source, it has been employed for active interrogation of fissile materials. To overcome saturation of neutron detectors by the source neutrons, we have utilized signatures of delayed neutrons and delayed gammas emitted from ^{235}U containing samples irradiated by thermalized neutrons from the source. The samples were placed in a polypropylene cavity for moderation of source neutrons. The delayed neutrons resulting from the induced fission in samples have been monitored using a bank of long He-3 detectors consisting of six 1 meter long tubes and coupled to a pulse processing and counting system of 16K input size MCS/MCA. Counting has been carried out with 2048 input size with 50 ms dwell time in MCS mode. Delayed gammas from the induced fission in ^{235}U have been monitored by a large area (4”x2”) NaI(Tl) detector placed just above the samples.To avoid the source and prompt neutrons/gammas a delay of 50 ms has been given to the counting system.

(ii) **Radiography with X-rays:** The Mather type plasma focus device operated at 11.5 kJ energy has been used for radiography. Its top flange is made of 6 mm SS and get better contrast for thin metallic samples, a 5 mm thick Perspex window has been used, which can transmit more than 8 keVX-rays with 5% transmission.To get better field of view the image plates were kept at 40 cm from the surface of window, which is almost 50 cm from the X-ray source.

The time resolved X-ray measurements have been carried out with NE102 scintillation detector coupled with photo multiplier tube. Fuji films make X-ray image plates have been used for radiography of objects. For pinhole imaging in axial direction the image plate was kept inside the mounting assembly having 100μm pinhole and 5 μm aluminum filter.

The materials to be radiographed were pasted at the image plate cassette. The image plates were read on the GE make typhoon Trio scanning system with 50μm resolution and best sensitivity.

For energy measurement step wedge of aluminum and copper has been used of step size

2mm and 0.17mm. The intensity through the step wedge is given by

$$I = I_0 e^{-\mu(E)x}$$

The thickness vs energy has calculated for 5% intensity transmission. The transmitted X-rays through the image plate for the thickness have been plotted with the 5% intensity transmission value of energy.

A resolution strip and lead foil of 25µm thickness has been radiographed for spatial resolution of the system. Spatial resolution of the system has been measured by the edge spread function at different edges of the foil. A line spread function along the line in the resolution has been estimated for the resolution.

(iii) Radiography using Neutrons: The plasma focus has also been utilized as neutron source for radiography and characterized using neutron and X-ray imaging plates. It was seen [7] that the intensity of thermal neutrons obtained by moderating 2.45 MeV neutrons from this 11.5KJ plasma focus device is sufficient to radiograph an object of 10 mm thickness.

RESULTS AND DISCUSSIONS ON RECENT EXPERIMTNTS

The time resolved X-rays has been monitored by scintillation detector coupled to photo multiplier tube. The oscilloscope records of the dI/dt and scintillators output are shown in the Fig2. The pulse width of the X-ray is found out to be 50 ns, which makes the device suitable for radiography of transient events in the dynamic systems.

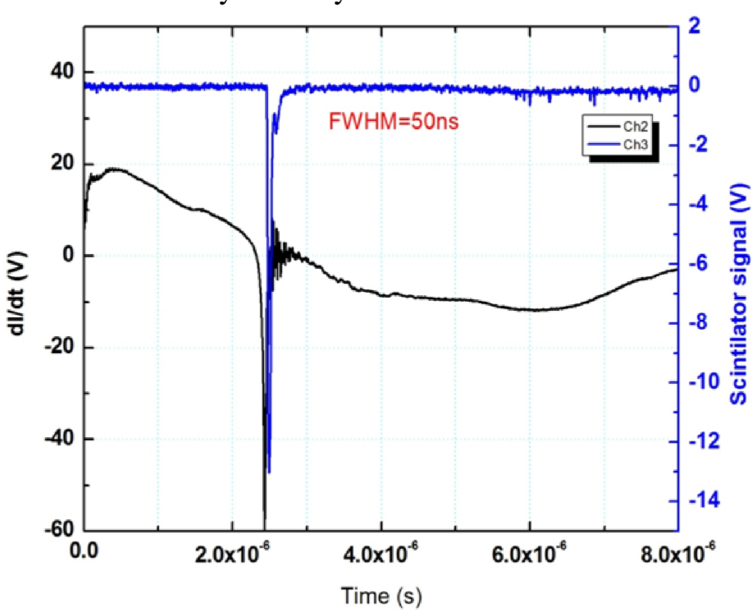

Fig. 2 The oscilloscope record of the dI/dt and scintillators output

The spot-size in the axial direction is determined by the pinhole camera with a 100µm pinhole and 5 µm thick aluminum foil. The pinhole image of the plasma focus device is shown in Fig 3. Central dense spot has a size ~1 mm which could be the dense pinch region of the plasma.

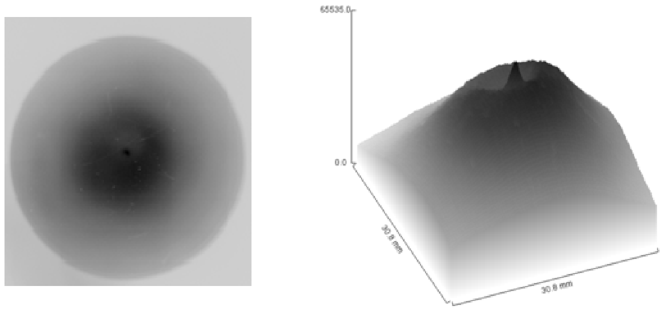

Fig 3X-ray pinhole image in the axial direction

The resolution depends on the thickness of the sample, sample to detector distance, range of X-rays in the detector material and in-homogeneities in X-ray beam as well as theimage plate type. The spatial resolution (quoted in terms of the parameter “total unsharpness, U_T”) is experimentally measured by scanning the grey level intensity of radiograph of a sharp edge object. In present work a 25 µm lead foil was used as sharp edge object.The gray valuesalong a line at the edge of the Pb foil is measured and the plot of gray values with the distance is fitted with the edge spread function [8]as displayed in Fig. 4.

$$ESF = P_1 + P_2 Tan^{-1}(P_3(x - P_4))$$

where x is the position coordinate and P1, P2, P3 and P4 are curve fitting parameters. The spatial resolution (U_T) of the image determined by the above equation is $U_T = 2/P3$ corresponding to a value of 147±10 µm for various interface regions in the image.

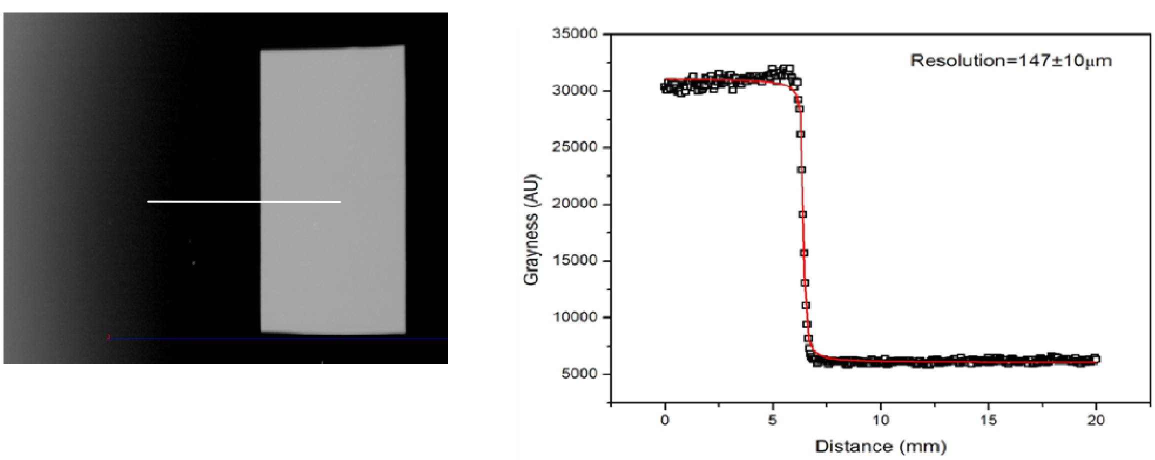

Fig 4 Spatial resolution by edge spread function (a) the radiograph of 25 µm lead strip (b) intensity profile along the line A

The energy profile of the source estimated with the step wedges of aluminum and copper is shown in the Fig 5 and 6. The count values along the steps shows that the maximum X-ray

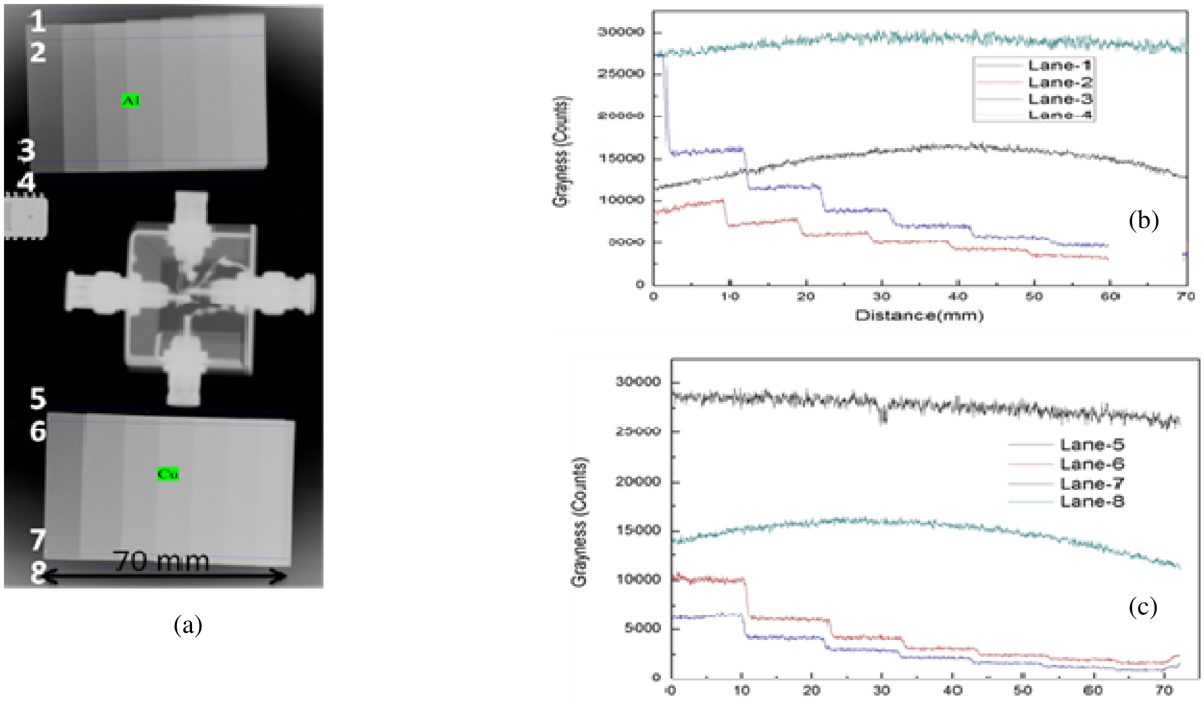

Fig. 5 The X-ray energy profile estimation (a) the transmitted greyness through the aluminium and copper step wedge. (b) The line profile in the aluminium along lane 1, 2, 3 and 4. (c) line profile in copper along the lanes 5,6,7 and 8.

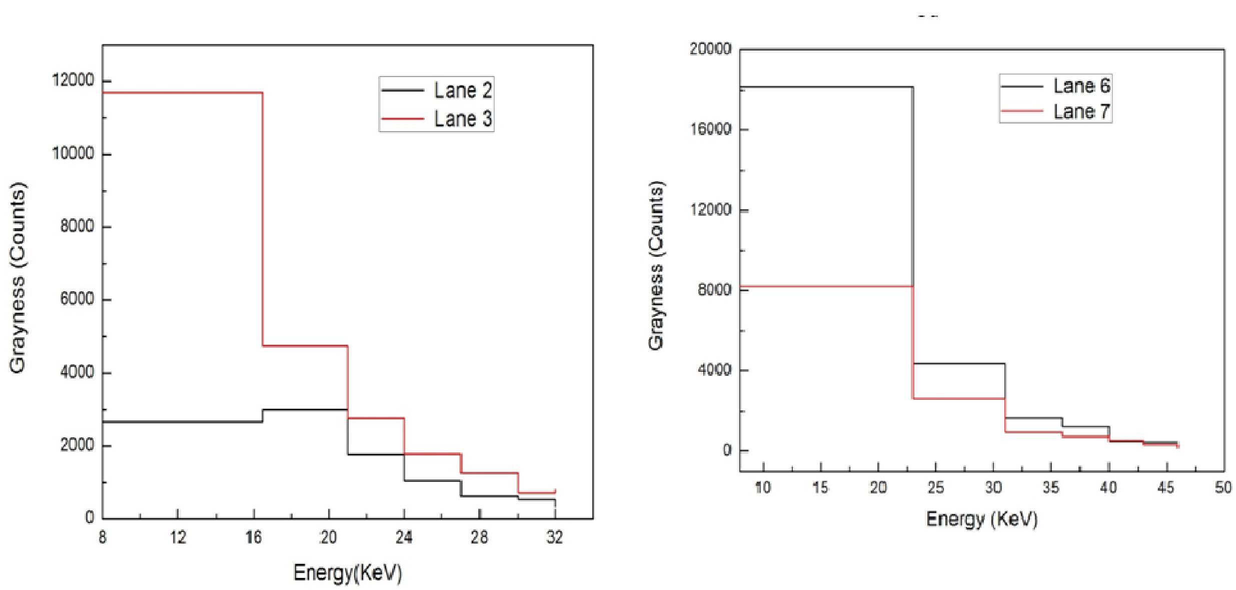

Fig. 6 Energy profile of X-rays recorded at the image plate placed at 50 cm from the centre of source (40 cm from the surface) (a) X-ray profile along the lane 2 and lane 3 in Aluminium (b) the X-ray profile along the lane 6 and 7 in cu.

emission is in the lower energy region (0-8KeV), but there is a significant contribution of X-rays in the higher energy region also. The energy information of the source could be helpful for

choosing the windows and filters to get better contrasts for samples of variable thickness.
The effect of appropriate window selection can be understoodin Fig 7, where we have placed the samples inside 2 mm aluminum box. The images of different BNC's are quite clear. The reason could be the less contributing lower energy X-rays are attenuated by the front Al plate, the higher energy X-rays are the only contributing to the image.

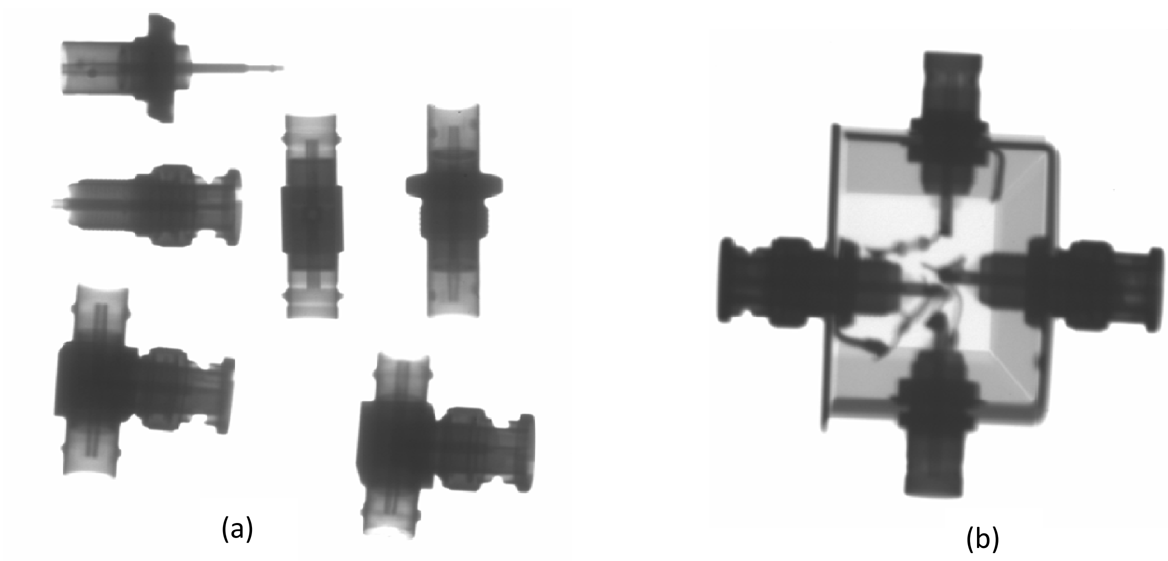

Fig. 7. (a) X-ray radiograph of BNC connectors kept inside the 2 mm thick metallic Al box (b) X-ray radiograph of BNC connectors in the distribution box

X-Pinch: the X-rayradiographs using x-pinch source are shown in Fig 8. The X-raytransmission

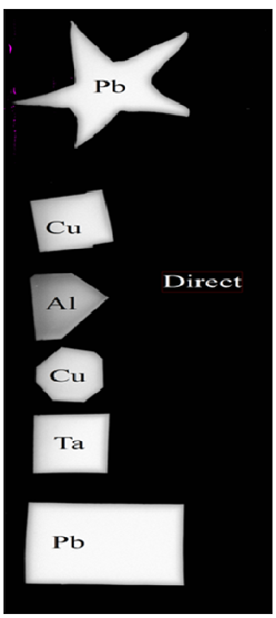

Fig 8 the X-ray radiograph of thin foils with x-pinch system.

Table-2. Transmission Values through Various Filters.

Material	Thickness µm	X-ray transmission (Gray scale)
Pb	*1mm	--
Cu	50µm	18.90
Al	25µm	295.81
Cu	25µm	41.06
Ta	25µm	4.84
Pb	25µm	1.36
Direct		19681.00

through different filters is listed in the Table 2. The profile of X-ray emission is not uniform along the length where the filters are placed, therefore the counts obtained through different filters have been normalized with the nearby X-ray intensity of direct exposure. It is seen from the table that the major part of X-rays are attenuated by the aluminum 25 μm foil. This suggests that the major intensity of X-rays is in soft X-rayenergy region.

SUMMARY AND CONCLUSIONS

We have developed and employed various pinch plasma based in-house developed devices for non-destructive characterization of materials. Their typical characteristics have been listed along with source characterization and application as a pulse X-ray and neutron source. The imaging parameters of radiographic assembly with 11.5KJ plasma focus device have been investigated extensively. Spatial resolution could be improved by use of image plate having higher resolution.X-ray energy profile could be utilized for selecting the window material as well as size and the type of objects to be radiographed. From the radiographs and the energy profile it can be inferred that these devices are suitable for assaying fissile materials as also for radiography of various objects especially biological samples due to their low energy requirements. In the context of make in India program, these devicesare cost effective and versatile in nature.

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