Generation and dose distribution measurement of flash x-ray in KALI-5000 system

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Flash x-ray generation studies have been carried out in KALI-5000 Pulse power system. The intense relativistic electron beam has been bombarded on a tantalum target at anode to produce flash x-ray via bremsstrahlung conversion. The typical electron beam parameter was 360 kV, 18 kA, and 100 ns, with a few hundreds of A/cm^2 current density. The x-ray dose has been measured with calcium sulfate:dysposium ($CaSO_4$:Dy) thermoluminescent dosimeter and the axial dose distribution has been characterized. It has been observed that the on axis dose falls of with distance $\sim 1/x^n$, where n varies from 1.8 to 1.85. A maximum on axis dose of 46 mrad has been measured at 1 m distance from the source. A plastic scintillator with optical fiber coupled to a photomultiplier tube has been developed to measure the x-ray pulse width. The typical x-ray pulse width varied from 50 to 80 ns. © *2008 American Institute of Physics.* [DOI: 10.1063/1.3005485]

I. INTRODUCTION

High power pulsed intense relativistic electron beams (IREB) have been employed for flash x-ray generation via bremsstrahlung conversion in the anode. Flash x-ray sources have higher radiation power than continuously emitting conventional x-ray tubes which makes them useful for the investigation of nontransparent high speed transient phenomena. Different types of flash x-ray sources used in the radiography have been reported previously.[1,2] The radiation intensity at a distance of 1 m or more can vary from 1 to 1000 R depending on the specific application. The on axis dose rate for x-ray beams at 1 m distance has been reported proportional to V^{β} where V is the electron beam voltage.[3] For a wide range of anode-converter materials, $\beta \sim 2.8$ gives a good dose estimate.[1,3] The pulse width of the x rays can be determined using Si *p-i-n* diodes or scintillator crystals coupled by fiber optics to streak cameras or photodiodes or photomultiplier tubes (PMTs).[4–6] Effective radiography requires a smaller source size and higher dose rate. Photoconducting detector arrays, transmission grating spectrometers, time-resolved x-ray pinhole cameras, x-ray crystal spectrometers, silicon photodiodes, etc., can be used for source profile characterization.[7]

The high intensity pulsed electron beam of KALI-5000 (Kiloampere linear injector: maximum output voltage 1 MV, output impedance 18 Ω, and pulse duration 100 ns) system is used to develop a flash x-ray source. KALI-5000 consists of a 1.5 MV, 25 kJ Marx generator, 1 MV, 5 kJ Blumlein-type transmission line, and 60 kA electron beam diode with voltage and current diagnostics.[8] It has been demonstrated that KALI-5000 system is capable of generating IREB in the presence of significant prepulse voltage.[9,10] This system has been operated with and without the presence of a prepulse voltage, to produce the bremsstrahlung flash x-ray on a tantalum target in a planar diode configuration. The axial and the radial dose distribution are characterized using $CaSO_4$:Dy thermoluminescent dosimeters (TLDs) as well as using the optical densitometer to measure the dose distribution of exposed x-ray films. The pulse width measurement of the x ray has been done using a plastic scintillator +optical fiber+PMT assembly.

This article reports the details of experimental results on the generation and dose distribution measurements of flash x-ray in KALI-5000. In Sec. II, the experimental setup and diagnostics have been discussed. Section III presents the experimental results followed by the conclusions in Sec. IV.

II. EXPERIMENTAL SETUP AND DIAGNOSTICS

A. X-ray diode

The schematic of the experimental setup is shown in Fig. 1. A graphite cathode with an outer diameter of 70 mm and a 40° taper is used to generate intense relativistic electron beams. The anode consists of 90 mm diameter, 1 mm thick

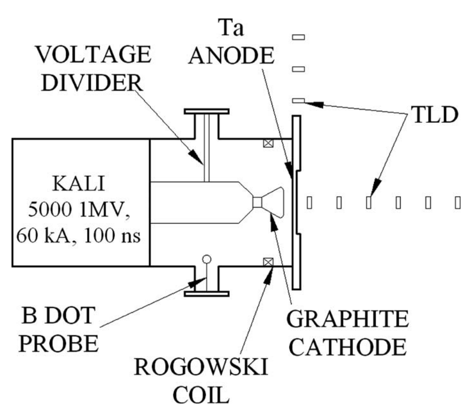

FIG. 1. Schematic of the experimental setup.

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TABLE I. Diode operating parameters for the dose measurement in KALI-5000 using TLD.

Diode voltage (kV)	Diode current (kA)	Anode-cathode gap (mm)
300	18	29
320	20	29
300	18	29
364	18	24
346	18	24
247	34	18

tantalum disk. The diode chamber is maintained at a vacuum level of 2×10^{-5} mbar with the help of a diffusion pump backed by a rotary pump. Beam diagnostics employed are aqueous copper sulfate resistive divider for beam voltage and Rogowski coil and a B-Dot probe for beam current measurement.

B. Dose measurements

The x-ray dose was measured with TLDs for three different anode-cathode (A-K) gaps: 18, 24, and 29 mm. For 29 mm A-K gap, the system was operated in the presence of significant prepulse voltage coming before the main voltage pulse.[9,10] In this case, the TLDs were placed along the axial direction at distances of 0.5, 10, 30, 70, and 100 cm from the anode window and at 15, 30, and 40 cm in the radial direction. Three consecutive shots were taken in this setup.

For 24 and 18 mm A-K gaps, the prepulse voltage was reduced significantly by incorporating an additional inductance in the MARX charging side. For 24 mm A-K gap, the TLDs were placed along the axial direction at distances of 0.5, 10, 25, 50, 75, and 100 cm from the anode window. For 18 mm A-K gap, the TLDs were exposed to one single shot of x rays. The operating parameters for all the three configurations are shown in Table I

C. Dose distribution from x-ray films

For 29 mm A-K gap, x-ray films (sensitivity equivalent to D4 Kodak x-ray film) were also exposed under similar operating conditions. The films were placed at distances of 20, 25, 30, 40, and 50 cm in the axial direction. Since the dose falls off as we go away from the source, the films placed nearer to the source will receive a higher dose compared to the films placed farther and correspondingly there will be variation in the optical density with distance of these exposed films. The dose corresponding to different optical densities are obtained from an optical density versus dose calibration curve.

For obtaining the optical density—dose calibration curve, x-ray films (D4) were exposed to an x-ray source of voltage 280 kV and a few milliampere current. Each film has been exposed for different time intervals. The optical density of these films were found and then plotted with the dose to obtain the curve, which is a linear fit as shown in Fig. 2. The x-ray dose variation with respect to distance for a diode voltage of 300 kV and A-K gap separation of 29 mm is thus plotted using the optical density-dose calibration curve and is shown in Fig. 3.

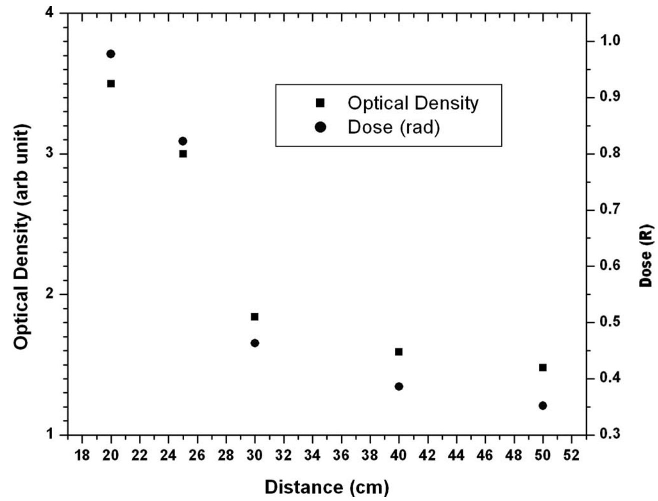

FIG. 3. X-ray dose distribution with distance.

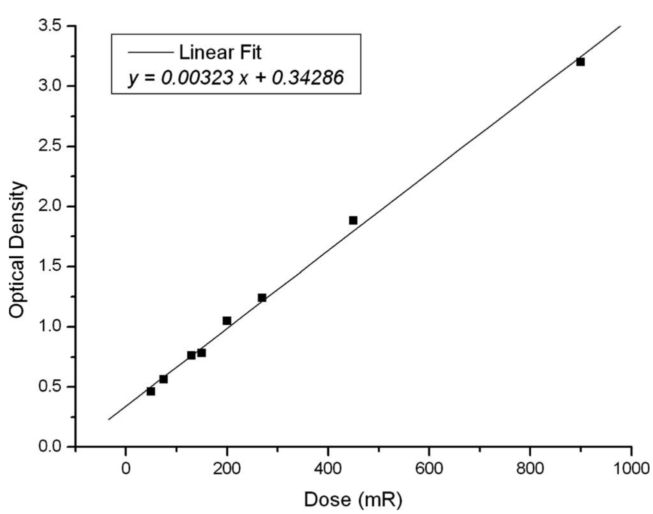

FIG. 2. Optical density-dose calibration curve.

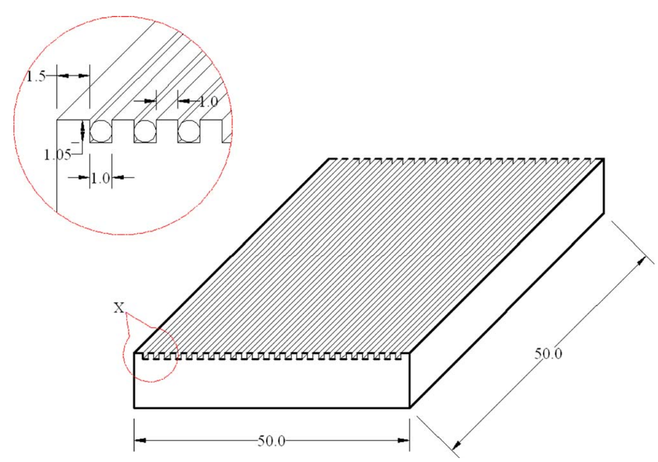

FIG. 4. (Color online) The sketch diagram of a typical middle layer scintillator piece showing the grooves and fiber alignment details. There are 16 grooves on one face of this rectangular bar with one fiber placed inside each groove.

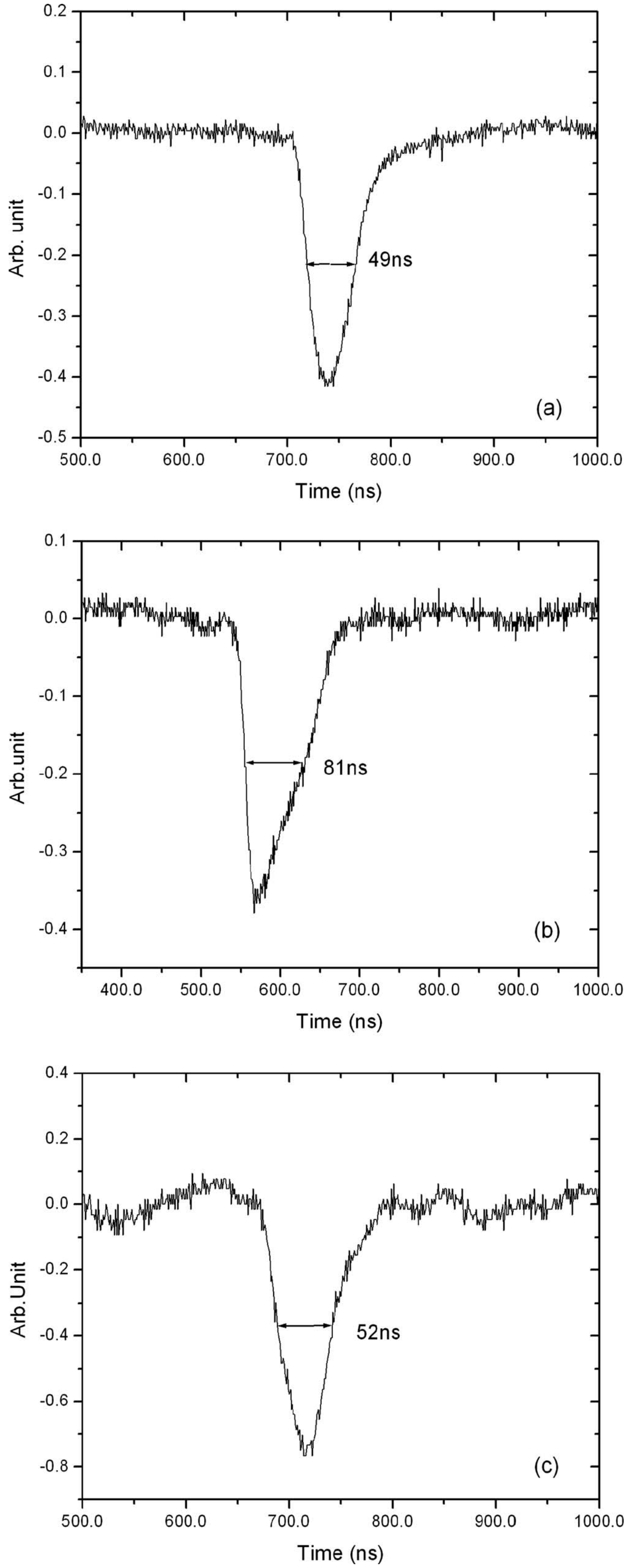

FIG. 5. Flash x-ray pulses. (a) x-ray pulse for shot No. 1 of Table III. (b) and (c) are for shot Nos. 2 and 6 of Table II, respectively.

D. Pulse width measurement with plastic (scintillator +optical fiber+PMT) setup

For temporal characterization of flash x rays, a scintillator+optical fiber+PMT system has been developed.

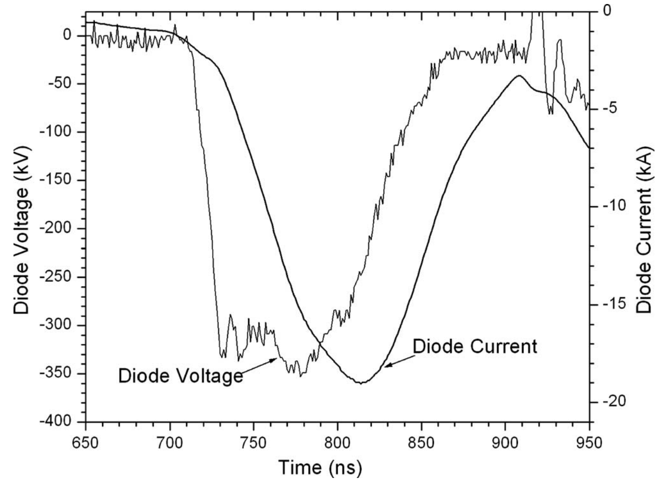

FIG. 6. The diode voltage and diode current waveforms for 24 mm A-K gap.

Pulse widths were measured with the scintillator kept along the axial direction and also at an angle of 65° from the axis. Experiments were conducted for two A-K gaps: 24 and 18 mm.

Plastic scintillators having properties equivalent to BC-408 were used. Wavelength shifting optical fibers of 1 mm diameter were used for light transport. A number of grooves for fixing the fibers to the scintillators were made on the surface of the scintillators. Five $5\times5\times1$ cm^3 blocks of scintillator were machined for 16 grooves, each groove having 1 mm width and 1.1 mm depth. Each fiber is 3 m in length and a total of 80 fibers have been used. The length of the fiber is not very long in order to minimize attenuation losses but not too short in order to meet the minimum bending radius criterion. The conventional minimum bending radius of these fibers is ten times the fiber diameter. A good surface finish and polished ends are essential to prevent light losses at the read out interface as well as the scintillator-fiber interface. The polished fibers were fixed in the scintillator grooves with Bicron 600 optical cement. Bicorn cement has the same refractive index as that of the scintillator and its light transmission above 400 nm wavelength is more than 98%. The scheme of scintillator coupling is illustrated in Fig. 4 for a typical layer scintillator piece.

After fixing the fibers in to the scintillators, the five scintillator blocks were glued together using optical glue to form a $5\times5\times5$ cm^3 cuboids. The x-ray receiving end of the scintillator along with the fibers was then polished. The other open ends of the fibers were bundled together. Sixteen fibers each were bundled to a polyvinyl chloride tube and five such tubes are bundled and glued to the inside of a 51 mm diameter Perspex tube known as "cookie." The diameter of the cookie matches that of the PMT end window. This end of the fibers along with the cookie was polished. In order to reduce the light losses from the scintillator, it was wrapped with Tyvek-a paper white reflecting foil made of polyethylene. The scintillator and fiber assembly were finally covered by black Tedler foil for light tightness.

TABLE II. X-ray FWHM with diode voltage and current for 24 mm A-K gap.

Shot No.	Diode voltage (kV)	Diode current (kA)	X-ray FWHM (ns)
1	361	15	125
2	369	19	81
3	397	21	71
4	359	17	63
5	385	18	47
6	395	20	52
7	397	21	50
8	373	16	40
9	346	18	42

III. EXPERIMENTAL RESULTS

The flash x-ray waveforms are shown in Fig. 5. Figure 6 displays the diode voltage and diode current waveforms. The pulse width obtained [full width at half maximum (FWHM)] has been tabulated with the operating parameters in Tables II and III. The first three data are for measurements done with the scintillator kept along the x-ray source axis and the last six are those in which the scintillator was kept at an angle of 65° from the source axis. It was observed that the pulse width is around 70–80 ns except for one value which is 125 ns. Using the same diagnostics larger duration (up to 300 ns) x-ray pulse can also be measured.[5] There is not much variation in the pulse height obtained.

The x-ray FWHM measured at 65° from the source axis is close to 50 ns except for shot No. 4 where it is 63 ns. For shot Nos. 8 and 9, the scintillator was kept behind concrete blocks (thickness ~3 in.) and the pulse width obtained is around 40 ns. The pulse height also reduced for these two shots.

With 18 mm A-K gap, the measurements were done with the scintillator kept at 65° angle. The maximum pulse width obtained varies from 49 to 65 ns. Shots were also taken with the scintillator being blocked by concrete bricks, but no output pulse was obtained.

The x-ray dose obtained from the TLDs shows a maximum of 46.1 mrad at a distance of 1 m from the source. This was obtained with a 24 mm A-K gap and a diode peak voltage of 364 kV. The dose versus distance graph is plotted in Fig. 7.

The dose relation[1] is approximately given by

$$\frac{\text{rad at } 1-m}{\text{Coulomb}} = 1290 \times V^{2.8} \exp\left[-\frac{(V+0.5)\beta}{0.67\pi}\right], \qquad (1)$$

where V is the applied voltage in megavolts and β is the electron beam relativistic velocity. The calculated dose using

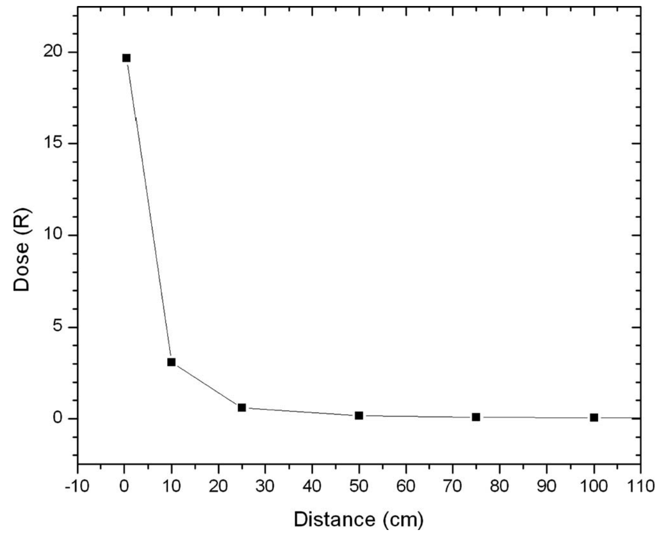

FIG. 7. The x-ray dose variation with respect to distance along the source axis as measured with TLDs for 24 mm A-K gap.

this equation corresponds to 45 mrad which matches closely with the experimental value.

For 29 mm A-K gap, the axial as well as radial dose distribution is given in Fig. 8. At 1 m from the axis, a dose of 40 mrad was obtained. The calculated dose using Eq. (1) in this case is 34 mrad. With 18 mm A-K gap, the dose obtained at 1 m was considerably less compared to the other two operating conditions.

To find how the dose falls off with distance, let us assume $d\alpha(1/x^n)$, where d is the on axis dose, x is the axial distance from the source and n is a real number. So, $d=(k/x^n)$, where k is the proportionality constant.

$$\log(d) = \log(k) - n \log(x). \qquad (2)$$

From the experimentally obtained dose for 24 and 29 mm A-K gaps, $\log(d)$ versus $\log(x)$ graph was plotted. The value of n has been obtained as 1.85 and 1.8, respectively, for the two A-K gaps using linear curve fitting as shown in Fig. 9. It was found that this dependence is obeyed for dose values at

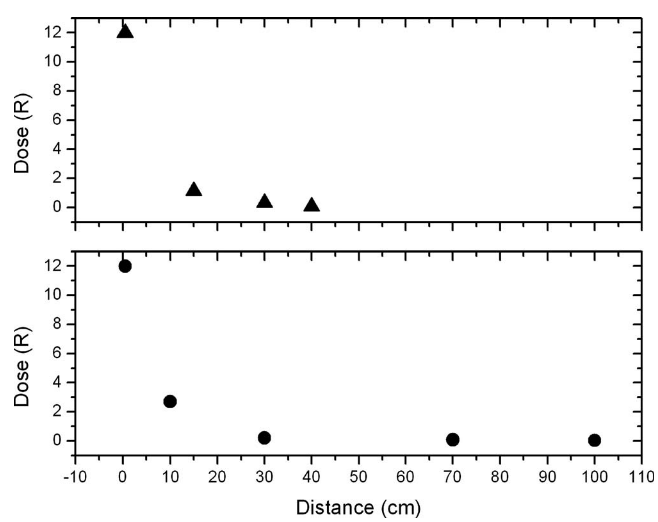

FIG. 8. The x-ray dose variation with respect to distance axial as well as radial, measured using TLDs for 29 mm A-K gap.

TABLE III. X-ray FWHM with diode voltage and current for 18 mm A-K gap.

Shot No.	Diode voltage (kV)	Diode current (kA)	X-ray FWHM (ns)
1	265	33	49
2	257	32	63

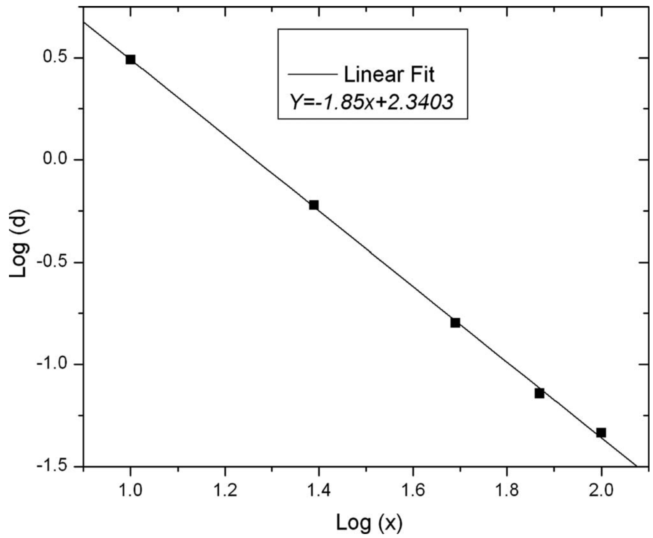

FIG. 9. Log-log plot of x-ray dose with respect to axial distance for 24 mm A-K gap. x is the axial distance from the source in cm and d is the dose in rad.

a distance of 10 cm from the source and beyond.

Stainless steel samples of various thicknesses were kept with D4 x-ray film at a distance of 10 cm and exposed to x-ray with a peak diode voltage 310 kV and current 18 kA at 29 mm A-K gap. Figure 10 shows x-ray film image. The center dark region shows a dose of 1R which has been obtained from the optical density-dose calibration curve.

IV. CONCLUSION

IREB from KALI-5000 pulse power system has been used to generate flash x rays. A plastic scintillator +optical fiber coupled to a photomultiplier tube has been developed to measure the nanosecond x-ray pulse width. It was observed that the x-ray pulse width varies from 50 to 80 ns for different shots. The x-ray dose distribution measurements have been carried out for 18, 24, and 29 A-K gaps and a maximum on axis doses of 46 and 40 mrad has been obtained at 1 m distance for 24 and 29 mm A-K gaps, respectively. The theoretically calculated dose from voltage-current waveform for 24 mm A-K gap corresponds to 45 mrad which matches closely with the experimental value. The axial dose distribution has been characterized by optical density versus dose calibration of x-ray films and also using TLDs. It has been observed that the on axis dose falls of with distance $\sim 1/x^n$, where n varies from 1.8 to 1.85.

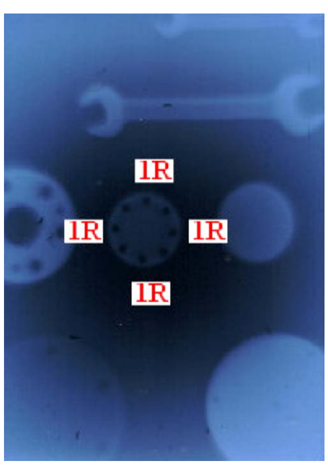

FIG. 10. (Color online) X-ray film image of SS samples of various thicknesses.

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