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Conical Pinched Electron Beam Diode for an Intense Pulsed X-ray Source

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Synopsis

A conical pinched electron beam diode operated by Marx generator reliably produced an intense pulsed X-rays up to 60mR/shot at 25cm. The diode consisted from a cylindrical cathode, an anode of a conical shaped plastic with a central metal pin. A triple junction around the edge of the central pin allowed to make a large gap distance(25∼30mm, for about 100kV), compared with the gap distance(3.5mm) of an ordinary vacuum spark diode made of all metal electrodes and consequently stable X-ray emission from the diode. An intense pulsed X-ray in a single shot increased sharply; $V^4c \sim V^5c$ as the voltage increase of the capacitor of the Marx generator. The diode was operated by two Marx generator with different stored energy(10 kJ and 0.1kJ). The X-ray emitting efficiency was higher for the diode operated by the smaller Marx generator. The spectrum of X-ray was studied by the absorption method.

Keywords; electron beam diode, Marx generator, pulsed X-ray source, X-ray spectrum, triple junction

1.Introduction

Recently, it has been shown that pulsed power systems have great capabilities for industrial manufacturing and other field.[1] These including materials research by electron and ion beams, flue gas cleanup, medical product sterilization, biomedical processing and so on. Production of a pulsed intense pulse X-ray is one of the important field of the pulse power application.

Application fields of X-ray have made new progress due to recent development of high intensity X-ray sources such as the synchrotron and high-brightness plasma X-ray source and developments in the super precision mechanical technology which have made possible to prepare new types of X-ray optical elements. These application includes the X-ray optical devices such as the X-ray micrograph, X-ray microprobe and X-ray lithography.[2-5]

Among the plasma X-ray source, the gas puff z-pinch[6], the plasma focus[7,8] and laser plasma X-ray source[9] have produced the intense pulsed X-ray strong enough for these purpose. On the other hand, the vacuum spark(flash) X-ray source still have an importance due to its high radiation power, simple structure and low cost of the apparatus.[10-13]

Here we presented a conical pinched electron beam diode as a point source of an intense pulsed X-ray, which emitted X-ray in stable manner. Main difference compared with the ordinary flash X-ray source was that the anode was made of a conical shaped plastic with a central metal pin. This type of diode was previously investigated by myself as an intense focused ion beam source.[14] A triple junction[15], where metal-insulator-vacuum comes to one point, formed at the edge of a center metal pin, allowed to make a large gap distance(25∼30mm, for about 100kV) and consequently the intense pulsed X-ray was emitted in a stable manner. The diode was operated by a low impedance Marx generator(200kVmax., stored energy; 10 kJ) and a compact Marx generator(120kVmax., stored energy; 0.1kJ). The X-ray intensity increased very much sensitive to the applied voltage to the diode.

2.Experimental apparatus

The geometrical dimensions of a conical pinched electron beam diode(CPED) and an ordinary vacuum spark X-ray diode(OVD) used in this experiment were shown in Fig1(a) and Fig.1(b), respectively. The CPED consists of an anode made of a conical shaped plastic insulator(70mm in outer diameter) with a Mo

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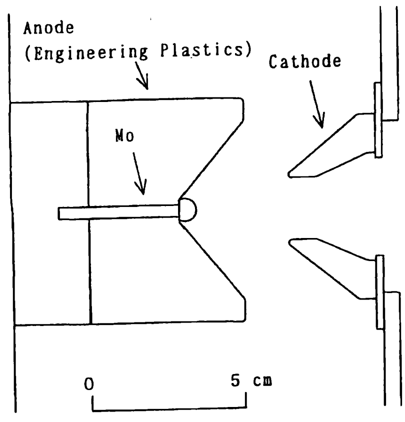

Fig.1.(a) A conical pinched electron beam diode(CPED) for intense X-ray source.

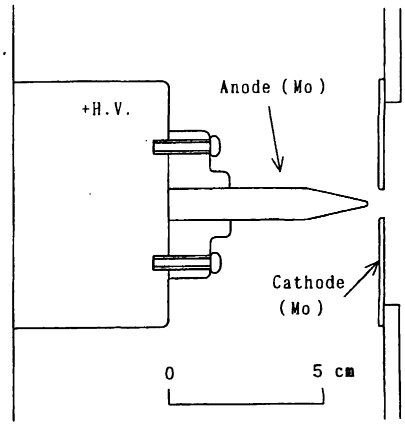

Fig.1(b) Ordinary vacuum spark X-ray diode(OVD).

central pin and a metal(stainless steel) cathode with a hole 20mm diameter. The anode was in a conical shape expecting a sharp concentration of the electron beam to the central pin. This diode was similar to the diode investigated by one of ourselves as an intense pulsed ion source [14]. The distance from the top of central pin to the cathode edge was 25～30 mm, which is over 7 times larger than the gap distance for the OVD for the same operation voltage. The diode was driven by a low impedance Marx generator [16] consisting of four 2 μF, 50 kV capacitors with carefully designed low inductance circuits. Usually it was operated at peak voltage of 100～140kV(stored energy;2.5kJ～4.9kJ). The voltage supplied to the anode through 1 Ω resistor. The diode current, voltage were measured by a Rogowskii coil and a low inductance voltage divider installed at the interface flange.

The OVD made of all metal(Mo) electrode(Fig.1(b)) was operated by the same Marx generator for comparison. The vacuum discharge was only accomplished in this experiment by the gap distance shorter than 3.5mm. The vacuum chamber was evacuated to the pressure lower than 6×10^{-3} Pa by an oil diffusion pump.

In an another case, the conical pinched electron beam diode(CPED) was operated by a compact Marx generator(120kVmax., stored energy;104.4J). In Fig.2, the electric circuits and the CPED are schematically shown. One capacitor stack was 58 nF, 30kV and 4 stacks were connected in series by two triggered spark gap switches. The CPED was composed from the anode of conical shaped plastic of 52mm outer diameter with brass central pin and the aluminum cathode with a hole of 10 mm diameter. The gap distance from anode to the top of the central pin was about 20mm.

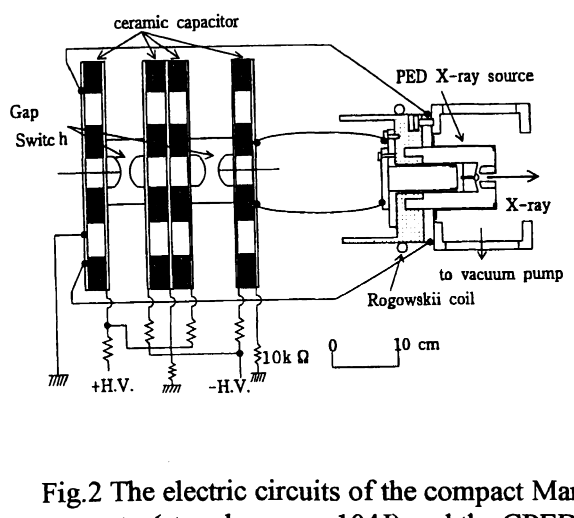

Fig.2 The electric circuits of the compact Marx generator(stored energy; 104J) and the CPED.

The intensity of hard X-ray was measured by a plastic scintillator of 26mm in diameter and 38mm in length and a photo multiplier. For the measurement of soft X-ray, the pin-photo-diode was used in order to detect the soft components of the spectra. The beryllium plate in 25 μm thickness was used to cut the visible light and UV. To eliminate the saturation of signal and the absorption of the soft X-ray in the air, the vacuum chamber extended about 200 cm from the cathode and the detectors were installed behind the Mylar window of 100 μm thick at 249.5 cm from the anode pin. The hard X-ray was measured at 480 cm from the diode.

The X-ray dose in one discharge shot was measured by the dosimeter placed at 25 cm from the diode. The sensitivity of this detector was in the range of $h\nu$ =20 keV to 100 keV.

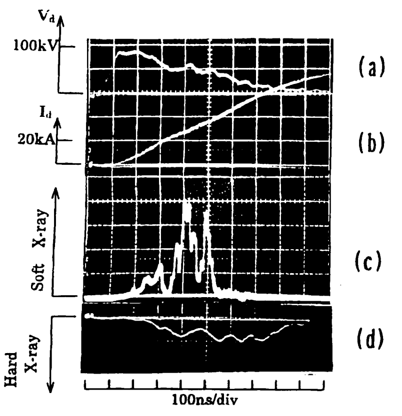

Fig.3. 3(a); the typical diode voltage, 3(b); diode current, 3(C); soft X-ray signal, 3(d); hard X-ray signal for the CPED.

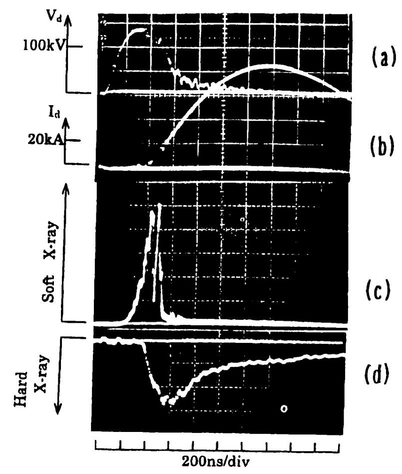

Fig.4. 4(a);the typical diode voltage, 4(b);diode current, soft X-ray signal, 4(c);hard X-ray signal for the OVD.

3.Experimental results and discussion

3.1 Characteristics of the discharge and X-ray emission from the CPED and the OVDThe diode voltage, diode current, soft X-ray signal and hard X-ray signal are shown in Fig.3(a)-3(d) for the CPED. The X-ray intensity of both energy range increased at about 200ns after the start of voltage rise on the anode. The intense X-rays were emitted from the CPED during when the diode voltage was about 50kV and the current was 20 to 40kA. At the X-ray emission phase, the diode voltage have a little hump and the current a little dip compared with the sine curve. This indicated increase of the diode impedance due to the pinch of the electron current channel. Many peaks in the X-ray signal indicates multiple pinch of the electron beams during the anode potential kept high(~several hundreds ns). The input power to the diode reached to 2GW at the peak.

X-ray pinhole photograph of the diode was taken by an instant film camera installed behind the Pb plate with 1mm hole. The X-ray photograph shows the X-ray is emitted from the central Mo pin(6.7mm dia.). It can be expected that instantaneous origin of X-ray is smaller than the area of head of Mo pin.

In Fig.4(a)~(d), typical wave forms of the signals for the OVD were shown. The peak intensity of X-rays was almost the same as that from the CPED. When the peak out put voltage from the Marx generator was 120 kV, the discharge was accomplished at the gap distance shorter than 3.5mm. The X-ray emission was sensitive to small change, as small as 0.3mm, of the gap distance. Because of the electrode erosion, the start of the discharge became to be delayed from the high voltage supply to the diode and finally to be failed after several discharge shots.

The optimum A-K gap distance for the CPED was 7.4 times longer than that for the OVD for the same voltage. Change of the gap distance of the CPED in a few mm made only a small effect on the diode behavior and X-ray output. Usually the triple junction at which metal electrode, insulator and vacuum comes together in one point, made strong electric field around it resulting easy vacuum breakdown.[15] In the CPED type diode, the triple junction was at the outer edge of the central Mo pin. The triple junction could not be formed when the outer edge of Mo pin was not contact firmly to the plastic anode surface. For the stable discharge, we must be sure to make the triple junction. After many discharge shots(about 50 shots), the anode plastic around the edge of Mo pin was eroded and the discharge became to be unstable.

It can be expected that a conical shaped ceramic insulator instead of the plastic makes longer life time of the triple junction and the CPED.

3.2 Characteristics of the CPED X-ray source

The dose of hard X-ray in one discharge shot measured by the X-ray dose meter at 25 cm from the CPED depending on the peak out put voltage from the Marx generator; V_M was shown in Fig.5. This indicated that the dose of hard X-ray increased as $V_M^{5.4}$, which was very steep function of the peak voltage. The maximum X-ray dose of 60 mR at the peak voltage of 140 kV(stored energy; 4.9 kJ) was obtained.

The dependence of the peak intensity of soft X-ray in the signal measured by the pin-photo-diode on the

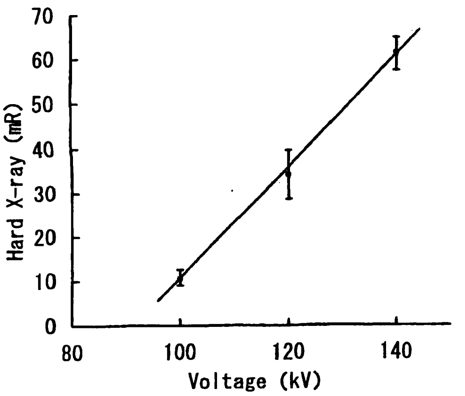

Fig.5. The dose of hard X-ray in one shot from the CPED measured by the dose meter at 25cm depending on the peak out put voltage from the 10kJ Marx generator.

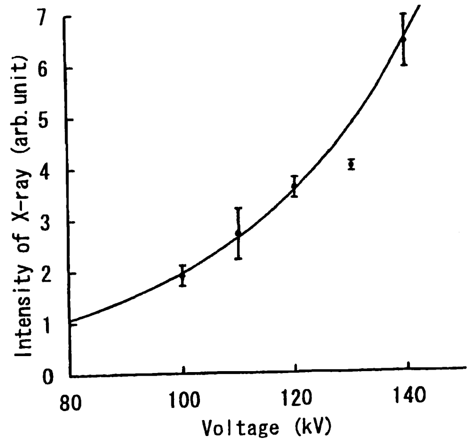

Fig.6. The dependence of the intensity of soft X-ray from the CPED on the peak out put voltage from 10kJ Marx generator.

peak out put voltage from the Marx generator; V_M was shown in Fig.6. The intensity increased as $V_M^{3.6}$.

The time derivative of the X-ray dose D(t) is shown as[10,17)]

$$D(t)=K_cI(t)V^2(t)+K_LI(t)[V(t)-V_K]^{1.7}$$

where I(t) and V(t) denote the instantaneous values of current and voltage at the X-ray emission phase, respectively. V_K is the minimum excitation voltage of the K series of the anode material and 17.4kV for molybdenum. The constants K_C and K_L are coefficients for the Bremsstrahlung and the line radiation, respectively. The validity of this equation is accepted for the X-ray emission of the energy range below 100keV.

The stored energy of the Marx generator($1/2CV^2_M$) increases in proportional to V^2_M. The maximum current ;I(t) is in proportional to V_M and voltage ;V(t) is also in proportional to V_M. These leads to $D(t)\sim K_cI(t)V^2(t) \propto K_cV^3_M$. The peak intensity of hard and soft X-ray increases much higher dependence on the V_M. We cannot explain the dependence, however, one of the possible explanation for this dependence is an electron pinch by the self field and the electrode plasma effect.

The spectrum of X-ray was studied by the absorption method. Fig.7(a) shows the measured X-ray intensity depending on the thickness of the aluminum absorber in front of the hard X-ray detector. As this curve

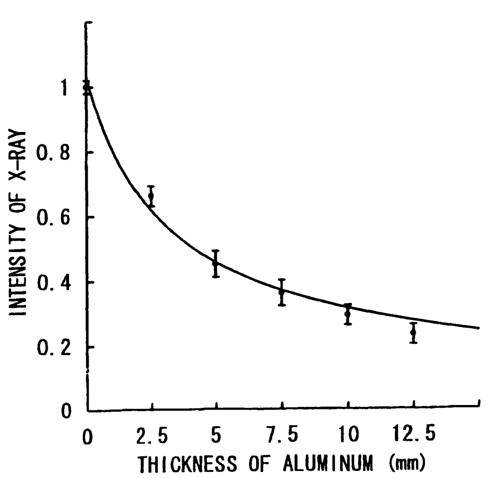

Fig.7(a). The X-ray intensity of hard X-ray component depending on the thickness of the aluminum absorber in front of the scintillator.

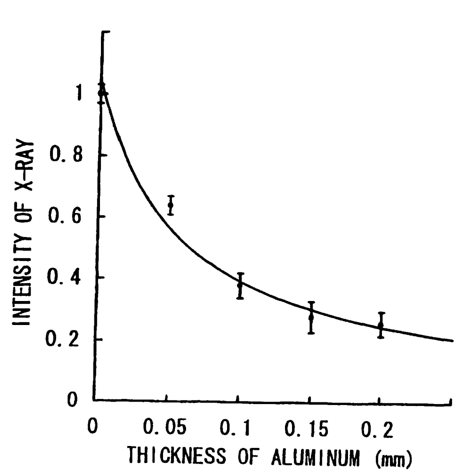

Fig7(b). The X-ray intensity of soft X-ray component depending on the thickness of the aluminum absorber in front of the pin photo-diode.

closely fitted, in 0~7.5mm aluminum thickness, to the calculated absorption curve of X-ray having the energy of h ν =45 keV, the X-ray spectral range can be roughly estimated to about 45 keV. The curve at 7.5-12.5mm which did not be fitted, indicated the emission more higher energy X-ray component.
Fig.7(b) shows the measured X-ray intensity depending on the thickness of the aluminum absorber in front of the soft X-ray detector. This curve closely fitted, in 0~0.1mm of aluminum thickness, to the calculated absorption curve of X-ray having the energy of h ν =9keV. At the thickness of the filter thicker than 0.1mm, higher energy component of X-ray was observed.

3.3 Operation of the CPED by a compact Marx generator

A similar CPED described in the previous section was operated by a compact Marx generator(120kVmax., stored energy; 104.4J). Fig.8(a)~(c) show typical wave forms of the diode voltage, the diode current and the soft X-ray measured by the pin-photo-diode. The maximum diode voltage and current were about 80kV and 3.5kA, respectively. The X-ray pulse was appeared during high voltage on the anode and a few hundreds A of

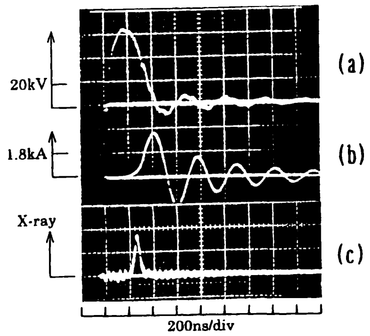

Fig.8. 8(a); typical wave forms of the diode voltage, 8(b); the diode current and 8(c); the soft X-ray signal operated by the compact Marx generator.

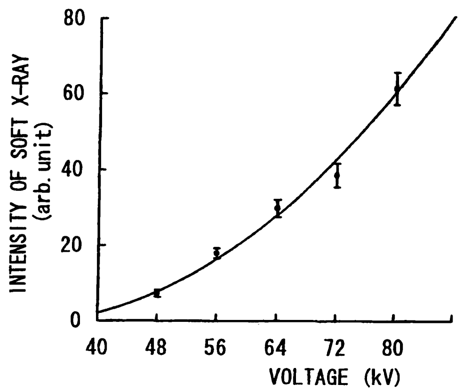

Fig.9. The dependence of the peak intensity of soft X-ray from the CPED on the peak out put voltage; V_M , operated by the compact Marx generator.

the diode current. The dose of hard X-ray in one shot was measured at 11 cm of the CPED by the X-ray dose meter. The dose increased as increased the peak voltage(V_M=56 kV to 80 kV) of the Marx generator as $V_M^{4.8}$. The X-ray dose was 5.5mR measured at 11cm from the diode and at the peak voltage from the compact Marx generator; 80 kV, stored energy;46.4 J. The X-ray emission efficiency from the CPED operated by the compact Marx generator was 23mR/kJ after correction of the measured distance from the diode. The X-ray dose 35mR measured at 25 cm from the CPED operated by the 10kJ Marx generator at the peak out put voltage of 120kV; (stored energy; 3.6kJ) gives the efficiency of 9.7mR/kJ. Intensity of Bremsstrahlung X-ray from electron beam bombarded metal is proportional to the atomic number of the anode material. Because the atomic number of the brass(alloy composed from Cu and Zn) is smaller than that of Mo, we could not attribute this difference to the change of material of central pin. The X-ray emission efficiency for the compact Marx generator is 2.4 times larger than the efficiency for the large Marx generator. High efficiency X-ray emission was obtained by the compact Marx generator under conditions relatively high diode voltage and smaller diode current.

Fig.9 shows the dependence of the peak intensity of soft X-ray on the peak voltage; V_M. The peak intensity increased as $V^{4.9}{}_M$. This is steeper dependence on the V_M compared that from the CPED operated by the 10kJ Marx generator.

X-ray spectrum was also measured by the aluminum absorption method. The hard X-ray component measured by the scintillator photo multiplier detector system was fitted to the absorption curve at h ν =55 keV in the range 0~12.5mm thickness of aluminum as shown in Fig.10(a). The absorption curve shown in Fig.10(b) for the soft X-ray component measured by the pin-photo-diode was fitted to the calculated curve of h ν =17.5 keV. Relatively higher X-ray energy compared with the previous experiment is due to the

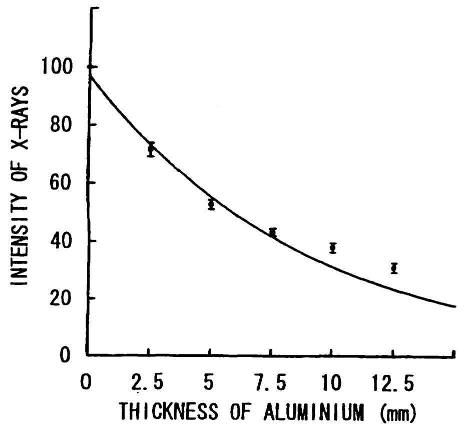

Fig.10(a) The absorption curve of the hard X-ray component measured by the scintillator photomultiplier detector.
V_M=80 kV.

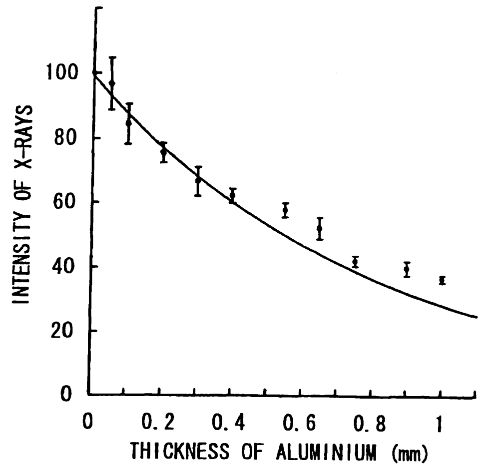

Fig.10(b) The absorption curve of the soft X-ray component measured by the pin-photo- diode.
V_M=80 kV.

absorption of soft component of X-ray by the air between the CPED and the detector placed at 41 cm from the CPED.

Relatively high voltage used in this experiment improved the reproducibility of X-ray intensity and relatively low current reduced the damage on the electrode.

4.Conclusion

The conical pinched electron beam diodes, which had a special anode consisted from a conical shaped insulator and a central metal pin, were operated by two Marx generators of stored energy of the 10kJ and 0.1kJ. Compared with the ordinary vacuum spark diode made of all metal, the CPED X-ray source has the advantages of the large A-K gap distance and the stable X-ray emission.

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