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SAND-74-5262
Conf-740809--7

NANOSECOND TIME RESOLVED X-RAY DIAGNOSTICS OF RELATIVISTIC ELECTRON BEAM INITIATED EVENTS*

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ABSTRACT

The dynamic behavior of a test sample during and shortly after it has been irradiated by an intense relativistic electron beam (REB) is of great interest to the study of beam energy deposition. Since the sample densities are far beyond the cutoff in the optical region, flash x-radiography techniques have been developed to diagnose the evolution of the samples. The conventional approach of analyzing the dynamic behavior of solid densities utilizes one or more short x-ray bursts to record images on photographic emulsion. This technique is not useful in the presence of the intense x-rays from the REB interacting with the sample. We report two techniques for isolating the film package from the REB x-ray pulse.

One arrangement employs a microchannel plate electron multiplier array (CEMA) to convert the incident x-ray image to an amplified electron "image." This image is proximity focused onto an aluminized plastic scintillator held at 5-10 kV relative to the CEMA output face. A streak camera shielded from the x-rays is used to record the time varying image on the 2 ns persistence scintillator. The resolution limitation is primarily that of the image converter, i.e., 5 ns and 5 line pairs/mm.

To achieve higher sensitivity and resolution, an arrangement employing two microchannel plates has been developed. In this device, two channel plates are immersed in a long uniform solenoidal

*This work was supported by the U. S. Atomic Energy Commission.

magnetic field; the electrons generated by the first plate are guided by the magnetic field lines to the second plate which increases the system gain by $> 10^3$. Placed a few mm behind the second plate is a phosphor screen which in turn is directly connected to film via a fiber optic face plate. In this way, isolation of the x-ray burst from the long persistence phosphor and film is achieved by using a long solenoid. The temporal resolution (approximately 3 ns) can be gained by the appropriate gating of the channeltron plates and/or grids. The spatial resolution is governed by the channel plate "pores" size, by electron orbit characteristics in the solenoidal magnetic field, and by the effective x-ray source geometry.

By using these two methods, nanosecond time resolved x-ray pinhole photographs and flash x-ray radiograph of REB initiated events have been achieved.

INTRODUCTION

The present experiments are directed at examining the focusing of $\sim$ 1 MeV, 500 kA, 60 ns duration electron beams onto samples and measuring the resulting dynamic response.

The radiographic diagnosis of targets driven by intense electron beams presents some unusual problems. The intense x-radiation produced by interaction of the electron beam with the target can itself be used to estimate the driving beam deposition uniformity, but precludes the use of an independent flash radiography source for diagnosis of samples during the beam pulse. After the driving beam ends, flash radiographic methods must rely on a recording system which can be rendered sensitive only during the diagnostic x-ray burst. Since the physical arrangement demands that the diagnostic flash x-ray source and the recording device be placed some distance from the target ($\simeq$ 45 cm in the work reported here), the x-ray source size must be small and intense, and the detector must be sensitive to enable observation of detail. We describe the development and testing of prototype x-ray cameras employing microchannelplates to convert the x-ray image to electrons and amplify the electron image to a level at which a photographic emulsion coupled to a phosphor screen can be exposed.

IMAGE FORMATION

Channel electron multiplier arrays (CEMA) consist of 1-2 mm thick plates made from a honeycomb of 14-50 micron diameter tubes (See references (1) and (2)). The channels are coated with a resistive secondary emissive substance electrically connected at each end with a conductive metallic coating which is evaporated onto each face of the plate. The electric field which results when ~ 1 kV is placed between the plate faces causes each channel to act as an electron multiplier with gain of several thousand. Incident flux, such as photons with energy sufficient to create photoelectrons, charged particles or fast neutrals can be detected. Since the CEMA channels are small, magnetic fields up to 400 gauss can be applied without diminishing the gain; indeed some gain increase results from magnetic fields parallel to the channel axes. The output CEMA face is customarily placed a few mm from a metallically overcoated phosphor screen which is held ~ 5 kV positive with respect to the CEMA. This technique, known as proximity focusing is described by Owen (3).

GATING OF IMAGE

Two methods for gating image signals from channelplates are available. The CEMA may be used steady-state and the electron image can be gated by using a grid. However, the CEMA has a broad range of output electron energies from 0 to several hundred electron volts, with more than 90% of the current < 30 eV. A fairly large grid voltage would be required to keep the high energy electrons from producing fog on the image.

A more convenient gating method is to switch the CEMA itself. Since the CEMA gain varies exponentially with the voltage, the effective risetime of a gating pulse is faster than its actual risetime. In addition, the magnetically focused device mentioned in the next section requires the imaging electrons to be as monoenergetic as possible. The CEMA output face is maintained at a fixed negative bias potential relative to a nearby grid, and a gating voltage is applied to the CEMA input face. Gain switches from 0 to several thousand in a nanosecond are possible.

A low impedance pulse source is necessary to drive the 100 pf of residual capacitance present across a 75 mm dia CEMA. The metallic coatings may have to be made thicker on some CEMA plates to minimize resistive drops during pulsing; production plates produced by Galileo (4) were used for the work reported here.

To test the ability of CEMA's as gating elements for fast x-ray events, the following apparatus was employed. A CEMA proximity focused onto a phosphor screen was placed in a vacuum chamber. A pinhole was arranged to image the target of a Febetron 705 electron accelerator (5) onto the CEMA. (The 705 is a 2 MeV, 5 K amp, 70 ns accelerator.) The gating pulse was generated by electronically discharging a 100 pf capacitor into a 50 Ω cable. A D.C. bias voltage of 0-300 volts in series with the 600 V pulse was used to vary the gain of the CEMA. A series of pictures was produced showing the distribution of the Febetron beam on its target at various times during the pulse (see Fig. 1).

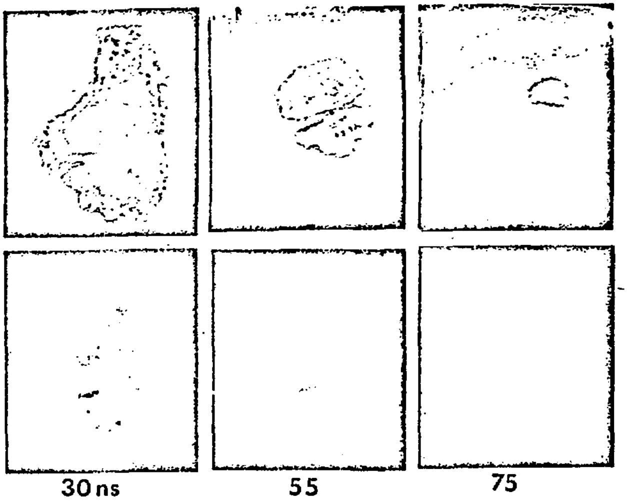

FIGURE 1

The time resolved pinhole pictures of x-rays produced by a Febetron electron beam interacting with a carbon plate with a lead strip opposite the beam side were made at the times indicated after beam triggering. The top row of isodensity contours demonstrates that a useful contrast range can be obtained with CEMA plates. The exposure times were < 5 ns. The diameter of the x-ray source at 30 ns was ~ 1.5 cm, and the sharpness of the image was limited by the 3 mm dia pinhole used to obtain a 1:1 image on the CEMA.

An arrangement using a CEMA with a sheet of aluminized NE 102 scintillator plastic (persistence < 3 ns) replacing the relatively slow P-11 phosphor screen has been reported by Bettinali, Pecorella, and Roger (6). This apparatus with the CEMA run with constant potentials can be used as an intensity booster and x-ray to light converter in conjunction with a standard TRW Model 1D streak or framing camera. The success of using CEMA's directly in the gated mode and the usefulness of a series of pictures obtained in rapid sequence prompted us to design a multiple frame system with five pin holes which "focus" an object onto five small independently gated CEMAS. This option will be available for use with the sensitive magnetically focused x-ray camera described in the next section.

MAGNETICALLY FOCUSED DUAL CEMA X-RAY CAMERA

As mentioned in the introduction, one of our requirements is a high resolution x-ray camera which will not pre-expose film when gated off during a massive x-ray burst, but will have sufficient gain to record pictures of samples flashed with x-rays from relatively modest sources. (We used a Febetron Model 730, which is a 300 keV, 5 K amp, 30 nsec pulser, and apertured its 5 mm dia source size to 1-2 mm dia.) The arrangement is shown in Fig. 2.

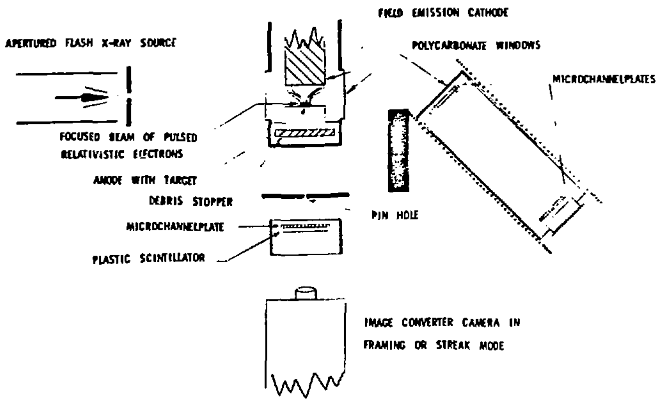

FIGURE 2

Experimental arrangement for producing time resolved flash x-ray pictures and examining electron beam behavior. To produce time resolved still pictures such as those in Fig. 1, the plastic scintillator may be replaced by a slower, more efficient phosphor screen coupled by fiber optics to photographic emulsion; the CEMA is pulsed on to control the exposure in this mode.

A gated CEMA is used to convert the x-ray image into an electron image which is accelerated to ~ 1 kV by a fine grid a few mm from the CEMA face. This electron image is magnetically focused by a uniform solenoidal field onto a second CEMA 40 cm away, which is proximity focused to a P11 phosphor screen on a fiber optic face-plate. A Polaroid 4 x 5 film holder with all ferromagnetic parts removed (to avoid magnetic field distortion) allows direct coupling of the image from the fiber optics to the film. This device is shown in Fig. 3. In operation, the input end of the camera is placed as close as possible to the object under examination, with the camera angled to allow shielding of the P-11 phosphor and film from the x-ray burst. The 730 Febetron is pulsed typically at times from 0.1 to 1 microsecond after the end of the target pulse, and both CEMA's are gated on with a pulse ~ 100 ns long to reduce timing problems associated with jitter.

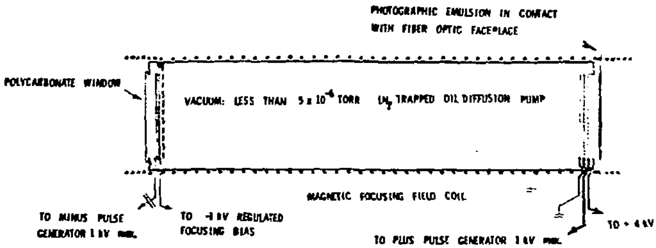

FIGURE 3

Schematic showing the bias arrangement for gated operation of the dual channeltron x-ray camera.

An example of a sample in the form of a sphere mounted to the anode of the Hydra electron beam accelerator (see Martin[7]) is shown in Fig. 4 before and after irradiation.

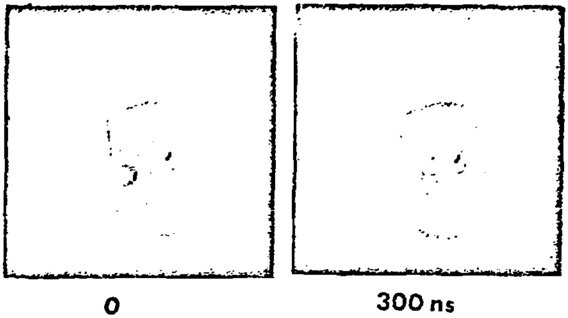

FIGURE 4

Flash x-ray shadowgraph of a spherical sample before and 300 nanoseconds after a 50 ns long interaction with a ~ 300 kiloampere, 650 kilovolt electron beam.

RESOLUTION LIMITS IMPOSED BY GEOMETRY AND ELECTRON OPTICS

Geometry

Approximate relations governing shadow imaging determined by geometric factors are easily derived. We assume the pinhole which apertures the source is a transparent hole in an opaque medium. (As one decreases the hole size in an actual medium, the angular field of view decreases and the ratio of x-ray leakage through the material relative to flux through the hole increases, resulting in an effectively broad source of hard x-rays.) In practice, we desire as small an effective source P of x-rays as possible.

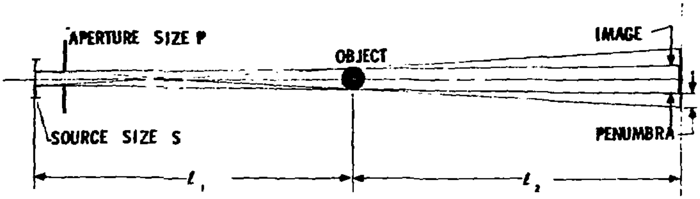

FIGURE 5
Geometry for x-ray imaging.

Referring to Fig. 5, we see that the magnification is given by

$$M = 1 + \ell_2/\ell_1 \quad , \tag{1}$$

and the penumbra size is given by

$$\delta = P(M-1) = P\ell_2/\ell_1 \quad . \tag{2}$$

For the sharpest image, the source size should be as small as possible or placed at a large distance, and the detector should be placed as close to the sample as possible. However, limits are imposed by problems associated with detector quantum efficiency. The number of photons reaching the camera per unit area in the uniformly illuminated region is given by

$$\phi = \frac{N_o\ P^2}{S^2}\ \frac{1}{(\ell_1+\ell_2)^2} \quad , \tag{3}$$

where N_o is the primary flux per sterradian.

The number of photoelectrons created per imaging element is then

$$N_e \doteq \frac{\pi N_o\ P^2}{4\ S^2}\ \frac{d^2\ Q}{(\ell_1+\ell_2)^2} \quad , \tag{4}$$

where Q is the quantum efficiency and d is channel diameter. If we neglect saturation effects i.e., assume that each photon which results in a photoelectron in a channel contributes linearly to the film density, we wish to have ~ ten or more photoelectrons to use the full range of film density. (The gain attainable with two CEMA plates is sufficient to record one photoelectron.) If the quantum efficiency is 10%, one then requires ~ 100 primary x-ray photons fall on each channel to obtain a useful contrast range. If the gain is so high that one photoelectron saturates the photographic image, the statistical limitation becomes more severe. With ten photons arriving at a channel, there is (for 10% quantum efficiency) only a 50% chance of recording a signal. One would want on the average at least 3 photoelectrons per channel to keep the counting statistics acceptable. One can recognize that using a CEMA with small channel sizes will improve image quality only if the photon intensity or quantum efficiency are increased to keep N_e statistically meaningful.

The x-ray source we employed for the results shown here with the dual channeltron camera yielded ~ 10^{11} photons/Sr taking into account a normalization factor for absorption in windows; its 5 mm source diameters were apertured to P = 1.5 mm. The distance $\ell_1+\ell_2$ was 1 m. The channelplate employed had channel center-to-center distance d = 53μ, and its quantum efficiency was assumed ~ 10%. Using these parameters, Eq. (4) gives N_e = 2.5 photoelectrons per channel. One thus expects the picture quality to be impaired by photon noise.

Electron Optics

Electrons entering a magnetic field B with some perpendicular velocity component $v_\perp$ gyrate about the magnetic field lines with a frequency $\omega = \frac{eB}{m}$ dependent only upon the magnitude of B, and a gyoradius given by

$$r = \frac{mv_\perp}{eB} \quad , \qquad (5)$$

where m and e the electron mass and charge. If B is arranged parallel to a stream of electrons leaving a planar surface (i.e., the accelerating grid) with velocity $v_{||}$, focusing will occur at intervals along the field lines wherever integral numbers of gyroperiods are completed. The relation

$$B = \frac{10.6\sqrt{V}}{L} \quad , \qquad (6)$$

where B is in gauss, V in volts, and L in cm gives the focusing condition. When there is dispersion in $V_{||}$, focusing will be degraded if $V_\perp$ is non zero because particles will complete gyro-orbits at different positions along the axis. One can readily show that for a point electron emitter with parallel electron energy spread

$\Delta E_{||}$ and perpendicular energy $E_{\perp}$, the circle of confusion f at a focusing plane defined by Eq. (6) is

$$f = L \sqrt{E_{\perp}} \ \Delta E_{||} / E_{||}^{3/2} \quad . \qquad (7)$$

For the parameters used in the prototype model, L = 40 cm, $E_{||}$ = 1 keV, $\Delta E_{||}$ was ~ 30 eV, and $E_{\perp}$ is assumed to be 30 eV. The electron optics limited resolution is thus ~ 0.2 mm. By examining the image of the grid wires visible on the output, we have shown the prototype instrument capable of resolving 5-10 line pairs per millimeter. The electron optical limit on resolution can be easily improved (by increasing $E_{||}$) to exceed any practical limitations imposed by source size (see Eq. (2)) or by channel size.

We note that if extremely short exposure times or gating times are used on the input CEMA, the effective $\Delta E_{||}$ may be made smaller by gating the output stage on for a short interval exactly after the transit time determined by L and $E_{||}$. In any case, it is essential that the gain maximum of the output CEMA fall one transit time later than the maximum signal from the input CEMA. If this condition is violated the "tail" of the electron distribution from the input CEMA may be responsible for most of the image on the output; $\Delta E_{||}$ is large for this tail and the focusing will be greatly impaired.

CONCLUSIONS

We have demonstrated that channelplates can be used as fast gated hard x-ray detectors. The prototype x-ray camera demonstrates the utility of CEMA's in magnetically focused image systems. The inherent spatial resolution is limited only by channel size and x-ray scattering in the input stage. Several problems should further be examined to extend understanding of the device. Current saturation effects due to space charge build-up and channel resistance at high dose rates should be explored, as well as possible broadening of $E_{||}$ under these conditions. The quantum efficiency of CEMA;s for energetic x-rays can be improved according to Tosswill (8), and prototype commercial devices have been examined by Timothy (9). If the new CEMA's are operated at low gain so they do not saturate at the high dose rates required for short exposure times, their use should improve the picture quality for photon noise limited applications.

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