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High speed (≤ 250 ps) high gain X-ray shutter camera

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Abstract

A high speed X-ray shutter tube has been developed for laser induced plasma imaging. The limiting exposure time is in the 250 ps range and 5 images can be recorded on the same laser shot, in order to provide a 5 spectral channel analysis of the plasma. A high light gain is obtained from a microchannel plate inserted in the 50 Ω transmission line, which provide the adapted structure to reach such a time exposure. We present the main performances of this camera.

Introduction

The laser-matter interaction program undertaken at Limeil requires the investigation of the X-ray emissions from the induced plama in the 1 to 10 keV range. For two dimension imaging we have developed an X-ray shutter tube with a 250 ps exposure time.

A standard biplanar shutter tube may have exposure time limited in the nanosecond range by the rise-time that can be expected from the R.C. time constant resulting from the proximity between the photocathode and screen. For the X-ray spectral range, the screen can also be excited by the incident X-ray photons which are transmitted through the photocathode. An adapted structure has been designed to avoid these parasitic effects.

Image converter tube's design

The shutter tube has been designed and built by L.E.P.* [1]. In the visible spectral range HR 4225 shutter tube has reach exposure times as short as 250 ps by integrating both photocathode and screen in a 50 Ω transmission line[2].

Basically, the same structure has been used in the X-ray range but a microchannel plate (M.C.P.) has been integrated in order to simultaneously enhance both light gain and cut-off ratio ; this structure is shown in figure 1 :

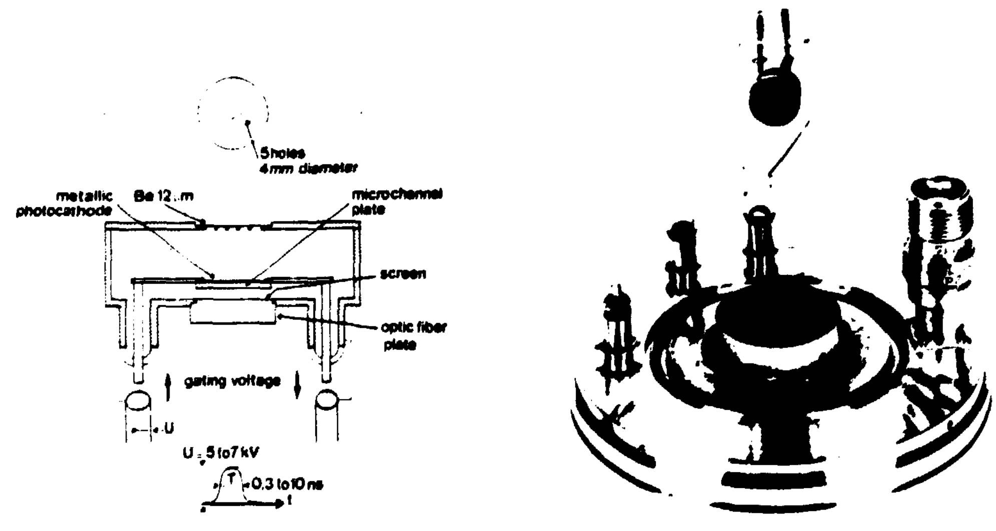

Figure 1. High speed X-ray shutter tube

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- The 12 μm beryllium window transmitting 70 % to 100 % of the 1 to 10 keV incident X rays is supported by a mechanical holder. This holder has 5 holes of 4 mm diameter aligned along the tube's diameter. The beryllium window isolates the inside of the tube from the atmospheric pressure.

- The X-ray converter is constituted by 0.35 μm gold layer deposited on a second beryllium foil (10 μm thick) which is directly in contact with the M.C.P.

- The M.C.P. intensifies the electron image converted in the gold photocathode when the electrical potential is applied ; when the voltage is not applied the M.C.P. acts as a thick glass absorber for the incident X-ray and prevents from the formation of a parasitic image on the screen.

- A P 11 screen, deposited on a fiber optic plate is covered with a thin Aluminum layer.

- Two coaxial connectors allow the electrical pulse to be transmitted from the generator, through the tube, to the adapted 50 Ω terminal load.

Let us now explain more precisely the tube's behaviour. When the high electrical voltage U is applied through the connector to the gap between converter and screen, since the M.C.P.'s output is not metallized, U is capacitively divided into:

· U_{MCP} which appears between M.C.P.'s input and output,

· U_{VAC} which appears between M.C.P.'s output and screen,

with $U = U_{MCP} + U_{VAC}$ (1)

The thickness and dielectric constant of the two gaps are chosen to respectively obtain $U_{MCP} = 1000$ V and $U_{VAC} = 5500$ V if $U = 6500$ V, giving an electron gain in the 10^3 range for the microchannel plate. The electrons leaving the M.C.P.'s output are then accelerated onto the screen by the output field and the 5 images appear on the fiber optic plate.

The tube has been designed to operate with electrical gating pulses in the 1 to 10 ns range. The maximum voltage U_{max} is 7 keV.

The recording film is directly coupled to the output fiber optical plate to allow the maximum light transmission.

Expected performances

X-ray photon gain : G

If G_{PC} , G_{MCP} , G_{SC} are the gain of the Be-gold converter, microchannel plate, and screen, we have

$$G = G_{PC} \cdot G_{MCP} \cdot G_{SC} \quad (2)$$

. For $G_{SC} \approx 20$ ph/e (experimentally determined from measurement made on proximity focused output stage with integrated (M.C.P.), and for $G_{MCP} \approx 10^3$ e/e and $G_{PC} = 0.08$ e/ph (mean experimental value from 2 to 6 keV) :

G = 1600 photons/photon

So, in the 1.5 to 10 keV the photon gain of the image converter tube will roughly remain in excess of 1000.

Spatial resolution

The main limitations are in the output stage and M.C.P. since the photoelectrons emitted by the converter are collimated in each individual channel which is 12 μm in diameter. The output stage, roughly similar to XX 1370 S20 streak tube will limit the resolution in the 12 to 13 $\ell p.mm^{-1}$; but an additional noise, coming from the M.C.P. and function of the electron gain can also reduce the image quality.

In the shutter mode, an additional loss may be expected, essentially for the shortest subnanosecond time exposures if the electrical gating pulse is not perfectly shaped since in that case the focus is optimum only when the voltage is maximum.

Exposure time : τ

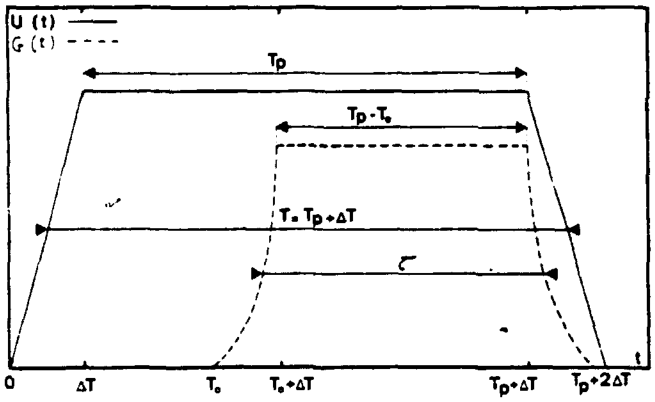

Figure 2. Voltage and gain variation versus time (theoretical example)

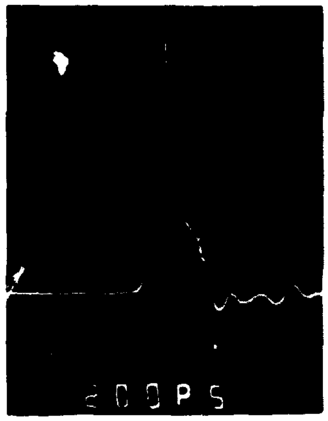

Figure 3. X-ray pulse

It can be defined as the F.W.H.M. of the photon gain G(t). But in fact, if we suppose that the electrical pulse U(t) is shaped as shown in figure 2, the photon gain G(t) is plotted on the other curve since :

- during 0 and T_O = 800 ps, which corresponds to the transit time of photoelectrons through the M.C.P. and to the screen, no image can be built and G = 0
- the rise and fall time are modified in two different ways : the fluctuations of transit time in the M.C.P. broaden G(t) but, on the contrary, the exponential variation of the gain G = f(U) steepens G(t). So :
  - for long electrical gating pulses T_p, the exposure time is roughly $\tau = T_p - T_O$
  - for short electrical pulses ($T_p \approx T_O$) we have to experimentally determine the exact exposure time.

Another feature can be deduced form the tube's design : since the gating voltage is propagating through the 50 Ω line at a speed $v = 2.10^8$ m.s^{-1}, two successive images are activated at times roughly separated by 200 ps ; so that, if a short X-ray pulse illuminates the 5 holes at the same time (figure 3) when the rising front of U(t) propagates along the transmission line (z-axis), the lumination of each image is representative of the photon gain obtained locally ; in that way, we have a spatial representation of the risetime of G(t) since z = vt.

Experimental results

X-ray camera

An X-ray imaging camera including an X-ray optics made of 5 pinholes has been designed to operate the shutter tube. The 5 images are recorded in 5 different spectral channels and allow a better understanding of the plasma emissions.

The voltage pulse generator is a laser-triggered spark-gap associated with a pulse shaping line. It may deliver pulses up to 7 kV with 0.15 ns rise and fall times and 0.3 to 10 ns duration according to the length of the shaping line. With a short duration laser pulse we may expect a maximum of 300 ps triggering jitter.

Experimental set-up

The shutter tube has been mounted on an X-ray pulse generator operating with a laser beam focused on a plane metallic target. The laser pulse duration is 60 ps F.W.H.M. and may have an energy up to 5 J. The X-ray pulse shape measured with an XVHR06 photodiode coupled to a TSN 660 oscilloscope (total rise time = 90 ps) is shown on figure 3.

As the X-ray optics was not used, the 5 circular zones of the photocathode were illuminated with the same X-ray exposure. The window was protected by an additional 50 μm beryllium foil so the energy of the X-ray photons impinging on the photocathode was higher than 1 keV.

In order to easily operate the camera we first used the 10 ns high-voltage pulse generator and the output images were recorded on 3000 ASA Polaroïd film through a lens open at 1/1.4 with a magnification of 1. Only two photographs were taken with HP4 negative film (400 ASA) to measure the spatial resolution. With a 1.2 ns electrical generator we also obtained the same density level under the same operating conditions ; furthermore it was possible to record the falling front of the light gain as previously mentionned (see "exposure time").

As we were interested in seeing how this tube worked with short electrical pulses we operated it with the 300 ps generator and HP4 film. But we had many difficulties to synchronize the X-ray pulse and the electrical pulse because of the jitter of the latter one.

Nevertheless we can derive some qualitative results.

Spatial resolution

Test patterns made of metallic bars regularly spaced were put in front of the five holes. Figure 4 shows three examples of records taken in different conditions.

	Electrical pulse Duration	voltage	Test pattern periodicity (ℓp/mm) 4 5 6 10 12	Laser energy on target	Max density over fog
	T	U		Ei	D
a	10 ns	5,2 kV (G = 560)		22 mJ	1,31
b	300 ps	3,2 kV (G = 16)		280 mJ	0,28
c	300 ps	3,2 kV (G = 16)		2,2 J	0,86

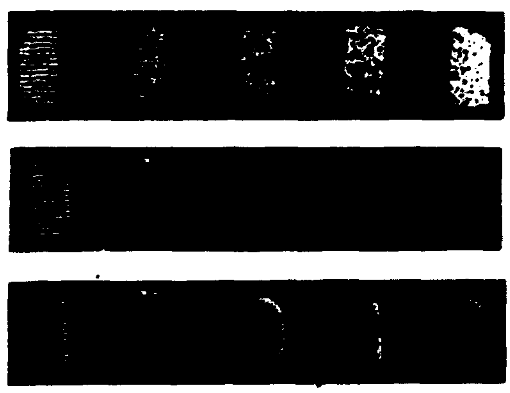

Figure 4. Spatial resolution tests

It can be seen that the limiting spatial resolution is a function of both light gain and exposure time ; it varies between 6 and 10 $\ell p.mm^{-1}$.

Cut-off ratio (C.O.R.) and sensitivity S

Cut-off ratio. It is the ratio of screen brightness in the cut-off mode to screen brightness in the focus mode with the cathode illuminated with a constant illumination level in both modes of operation.

We have experimentally determined, for the maximum X-ray flux corresponding to the full 5 J laser energy, the following results :

- a fully saturated image on the film, when the voltage is maximum on the tube,

- no signal at all when no voltage is applied.

This is a satisfactory behaviour since it demonstrates that no direct X-ray degrades the actual image.

As we could not attenuate the incident X-ray flux without changing its spectral distribution, the experimental determination of the cut-off ration has not been carried out. It is theoretically expected to be in the 10^5 range.

Sensitivity. This sensitivity depends on both the M.C.P.'s gain and the film. For HP4 film, a density of 0.3 over fog density (which is generally 0.3) needs 5.10^9 photons/cm^2. So, for the maximum gain the corresponding value of 3.10^6 X-ray photons/cm^2 incident on the photocathode gives an idea of the tube's sensitivity. On figure 4, we have written down experimental values of pulse voltage (and rough value of gain), laser energy on target and maximum film density over fog.

Operation with a 300 ps generator

Since the electrical pulse width is shorter than the electron transit time in the M.C.P., the shutter tube should remain shut. Nevertheless we obtained good images shown in figure 4b, 4c and figure 5. We observed the same phenomena on Polaroïd film with the 1200 ps generator and our timing measures showed that the images of figure 5 were the representation of the flat part (a) and falling front (b) of the light gain ; but we never obtained a representation of the rising front.

a b

Figure 5. Images given by the tube when operated by a 300 ps generator (the curve under the images is the densitometry of those images along the dotted line ; the electrical pulse propagates from left to right).

Conclusion

The experiments carried out with this high speed X-ray shutter camera have demonstrated that the 6 to 10 ℓp.mm^{-1} has been achieved with exposure time in the subnanosecond range (≈ 300 - 400 ps). Transients in the sub 100 ps range are observed for light gain so that we are confident in the performances of this device which can be used as a multichannel spectral imaging system for laser induced plasmas.

Acknowledgments

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