The impact of high-voltage pulse technology on high-speed photography

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ABSTRACT

A main contributory factor towards the ability to achieve high time resolution with various imaging devices has been the development of fast high voltage pulse generators. These generators are used for remote ramp generators in streak cameras, for driving blanking circuitry and for gating image tubes. Pulse generators based mainly upon avalanche technology and are now capable of sub 100ps rise times to voltages greater than 10kV. Repetition rates are now sufficiently high that significant signal averaging can be performed in suitable applications.

1. INTRODUCTION

To obtain highly time resolved images it is necessary to use image convertor cameras in which the photoelectrons are manipulated by electromagnetic fields. Whilst streak cameras have been able to use relatively slow electronics to achieve very high time resolution, imaging cameras have generally needed fast gating electronics.

Many schemes exist for gating images, but until the advent of the fast avalanche pulse generators, it was necessary to use photoconductive switches to generate the gating pulses. Whilst these switches are very simple, and can be reliable, they invariably require access to a short pulse laser that is well synchronized to the event under investigation. In addition the repetition rate is set by the laser system and so is usually low. This prevents the use of relatively cheap sampling oscilloscopes for the setting up of the camera. Such a factors have limited the usefulness of these cameras.

Work on avalanche pulse generators has resulted in pulsers being available that can generate several kV into 50Ω rising in less than 100ps. These pulse generators can be made extremely reliable with lifetimes exceeding 10^{10} shots, and may have jitter with respect to a low level trigger signal of ~10ps. In addition they can have repetition rates up to several kHz. Even at a few hundred Hz they can be used with sampling equipment.

Avalanche pulse generators certainly do not produce waveforms as clean as do photoconductive switches. However, the gating of a photoelectron current is extremely non-linear. This means that the fidelity of the electrical gate pulse does not have to be very high.

These pulse generators have also affected streak camera development. Whilst various avalanche circuits have been used routinely in streak cameras for many years, it has recently become practical to develop simpler streak tubes with a quite low deflection sensitivity and yet still achieve high streak rates.

2. PULSE GENERATOR DEVELOPMENT

In the early eighties pulse generators were developed that used strings of avalanche transistors to produce pulses of about 1.5kV into 50Ω with rise times of 500ps. In addition, following work in the Soviet Union, pulsers based upon avalanche diodes were developed. The diodes need pulse charging and can generate pulses in the 1 to 2 kV range. Pulse lengths are limited but rise times are extremely fast (~70ps). The diodes used are not very reliable and have to be individually characterized. The diodes exhibit a long delay (several ns) between the application of voltage and breakdown. This delay precludes stacking them to increase the output per assembly. To achieve higher output powers it is possible to select matched devices and parallel them up. This is a relatively long process. In contrast, the avalanche transistor pulsers can be made with little or no selection and strings of devices can easily be made into high voltage units. Developments in devices have improved the rise time of these pulse generators so that sub 100ps rise times are readily available. The power handling of these devices has also increased greatly and generators of many kV can be assembled. Indeed, the performance quoted for the latest generators is limited by the test gear.

Recent pulse generators can produce 1MW per module and one can expect to see further improvements soon. The avalanche transistor based pulse generators can also be made with adjustable pulse lengths and voltage. It should be possible to make pulse generators that produce continuously variable pulse lengths from 100ps to 6ns in producing in excess of 3kV into 50Ω. Work on arbitrary waveform generators and high fidelity pulse shaping is also in progress.

Many gated cameras require drive pulses at impedances significantly lower than 50Ω. Photoconductive switches can be made at almost any reasonable impedance, however, for avalanche pulsers impedance matching transformers based upon cables or striplines are able to provide impedances down to about 1Ω. Pulses are fairly easy to modify. Pulse inverting, shaping or slowing of edges is all fairly easy allowing various configurations for driving all types of load. The generators are electrically robust, the outputs may be fired into each other, shorted or run into open circuits.

The performance of currently available pulse generators is indicated with an example shown in figure 1. These waveforms were obtained from compact bench top units. The measuring equipment comprised Barth© attenuators and Tektronix sampling equipment.

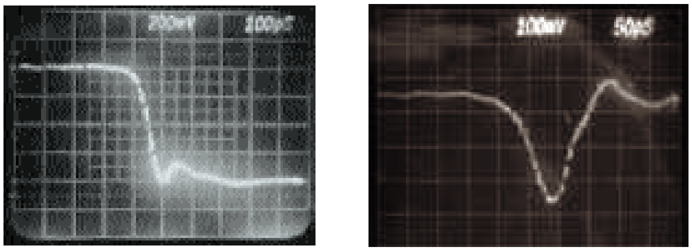

Figure 1. Formed and unformed pulses. On the left a pulse at 2kV and 100ps per div. On the right a formed pulse at 1kV and 50ps per div.

3. THE GATED OPTICAL INTENSIFIER

Modern wafer intensifiers can easily be gated to achieve high time resolution. Gating is achieved by switching the voltage between the photocathode and the input side of the microchannel plate (MCP). The voltage requirement for generation 2 (e.g. S20 cathodes) type tubes is low. Several tens of volts can produce a change of gain in excess of 10^6. However, as the gate duration is reduced to below about 1ns on an 18mm tube (at longer pulse lengths on larger tubes) aperturing effects begin to occur. The observed effect is that different parts of the cathode gate at different times. This is due to the charge having to diffuse into the central region of the cathode. The diffusion rate is set by the resistivity of the cathode and the cathode to MCP capacitance. Attempts have been made to reduce the effective cathode resistivity. However, by using capacitive coupling to the cathode and a fast high voltage pulse generator connected to a mesh attached to the outside of the wafer tube, it is possible to gate a standard tube very quickly, (~100ps). At these fast gate times the tube has to be well turned on to avoid transit time spreading between the cathode and the MCP.

The intensifier gating configuration is shown in figure 2. Note that because the voltage is capacitively coupled no current has to flow in the photocathode. Consequently its resistivity is no longer important. The high cathode to MCP capacitance results in only a small fraction of the applied voltage being coupled to the cathode. However, the use of a high voltage pulse can couple sufficient voltage to achieve a very high extinction ratio. The electronics may drive the gating mesh at several points so that the turn on time can be limited by the velocity of the electric wave in the glass and by the electron dynamics.

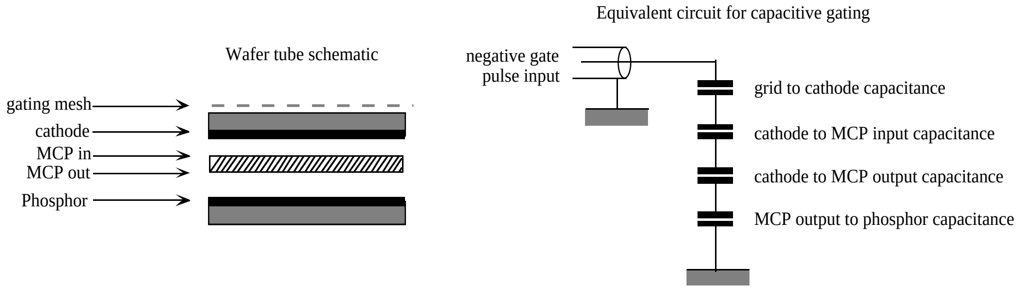

Figure 2. Capacitive coupling to the cathode removes the necessity for gating currents to flow in the cathode.

As the pulse generators can operate at high repetition rates (several kHz) it is easy to use sampling techniques. In order to characterize the gating of the tube one may use a fast laser diode and probe the gating both in space and time. The high repetition rate may also be used to average many images and improve the signal to noise ratio. In a ranging device this could be linked to scanning of the temporal window to produce images which reject scattered light and maintain a long depth of view or select light from a specific distance.

The gated detectors have been used for several applications. For example in an experiment at Rutherford Appleton Laboratory, it was shown that induced spatial incoherence (ISI) failed to prevent filamentation of a laser beam in a plasma, see figure 3.

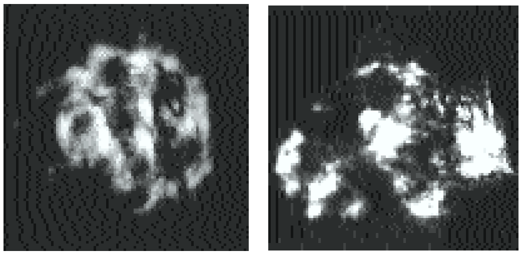

Figure 3. Filamentation of a laser beam with ISI in a plasma. On the left the beam with no plasma and on the right with plasma.

Recently there has been interest at imaging through soft live tissue for the detection of tumors. Using a combination of a fast laser pulse and turning off a gated optical intensifier as soon as the direct line of sight laser light reaches the intensifier, it may be possible to reject most of the scattered light paths, see figures 4 and 5. Although at present it is possible to gate the intensifiers down to only about 100ps, the turning off is thought to be much faster, probably faster than 10ps. Simple computer modelling of the response of the intensifier to the gate signal confirm this belief. It is hoped to make test measurements using a 5ps laser diode pulse generator which will soon be available.

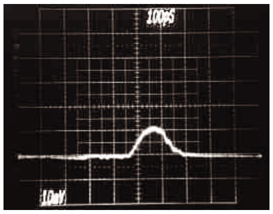

Figure 4. The response of the gated intensifier when capacitively gated with a 120ps pulse. Time into the gate pulse goes from right to left. Note the fast turn off compared to the slower turn on.

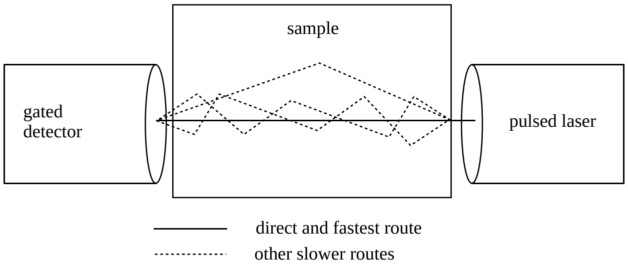

Figure 5. By turning off a gated detector as soon as the direct line of sight light has arrived one can reject the various scattered paths. Application could include looking through live tissue to detect small changes in transmission. Such changes could be dye induced to enhance contrast.

4. GATED X-RAY IMAGERS

Several research groups in various countries now routinely use gated MCPs to produce X-ray images. The MCP often acts as the primary detector, the intensifier and the gating structure in these devices. Gating well below 100ps has been available for some time. Early work again required the use of photoconductive switches to drive the necessary large gate currents for these devices. However, avalanche pulse generators have largely replaced them.

Photoelectrons are produced by incident x-rays near the entrance of a microchannel hole. They are accelerated into the plate by the gate voltage. The gate signal must appear across the MCP and consequently the high dielectric constant of the MCP material requires that low impedance drives and large currents are used. The current required is proportional to the width of the gated image. In more recent devices thinner MCPs are used to reduce the gate duration. This again increases the current necessary. At present available pulse generators are capable of about 1MW per module, this is reduced by pulse forming to about 300kW. Such a module would drive a microstrip on a 250μm thick MCP of about 3Ω, equivalent to an image 11mm wide.

The MCP is coated to place a gating structure on the input surface. As the surface resistivity of the MCP is high, several gated areas may be established on one plate. Each area may have its own bias and gate supply. This permits several frames to be taken for one unit.

The wave speed through the MCP is slow (due to the large dielectric constant). Consequently different areas of the MCP in the direction of propagation of the pulse are gated at different times. This can cause temporal smearing similar to that experienced with focal plane shutters in conventional cameras. Alternatively it can be used to provide several sequential images of an event by using a suitable arrangement of imaging devices, e.g. a pinhole array.

In order to improve the temporal resolution further it is possible to use the nonlinear nature of the MCP (i.e. gain versus voltage). The MCP can be reverse biased so that only part of the applied gate waveform forward biases the MCP. This part of the gate pulse could have a fraction of the width of the whole pulse. Gate pulses of >3kV into 50Ω and 75ps f.h.w.m. are readily available, see figure 1. As only about 1.5kV is necessary to gate the MCP the effective gate width can be reduced significantly by reverse biasing the MCP to half of the gate pulse.

5. X-RAY STREAK CAMERAS

X-ray streak cameras are now in common usage at many laboratories around the world. They are used in experiments investigating the radiation from sources ranging from laser produced plasmas, through z-pinches, to synchrotron radiation. Cameras have become simple to use, rugged and reliable. High voltage pulse technology permits the ramp circuit to be remote from the streak tube. This makes the tube assembly far more compact than earlier designs.

Recent developments have enabled several workers to push the time resolution to below 3ps. In order to achieve this high time resolution it is necessary both to reduce the transit time spread of photo-electrons as they traverse the tube and also to reduce the contribution from the static image width of the cathode.

The transit time spread comes from three parts of the camera, the cathode itself which produces photo-electrons with a spread in energy, the initial acceleration region (between the cathode and mesh) and the main lens. Several workers have either removed the lens entirely or switched to a lower dispersive magnetic lens. We have kept the electrostatically focussed lens, but increased the extraction field, mainly by reducing the cathode to mesh spacing and by improving the vacuum to provide a higher breakdown voltage. In order to reduce the initial spread of electron energies the cathode material is changed to either potassium iodide or potassium bromide. Whilst the iodide is preferred from an energy spread view, it has been found hard to vacuum deposit. Many cathode substrates are destroyed by the coating process which puts lots of holes in the them. A few turn out to be fine. Obviously more investigation is required here.

The contribution from the static image of the slit can be reduced in two ways. Firstly, the slit may be narrowed and the tube resolution improved. Secondly, the sweep speed can be increased. The advantage of this latter approach is to allow more light to enter the camera and consequently maintain the sensitivity (subject to the space charge not being a problem). The price one pays for this approach is firstly a greatly reduced temporal window and secondly, that the slit image curvature becomes a significant part of the temporal window, see figure 6. Experiments are planned to try to reduce this effect which is due to the transit time of electrons from the cathode edge being longer than from the center.

Using high voltage avalanche pulsers it has been possible to achieve sweep speeds of 0.8ps mm^{-1}. Even higher speeds are possible now but the slit image curvature needs to be removed to make these high speeds useful. In order to achieve very high sweep speeds two things are necessary. Firstly the transit time of the electrons past the deflection structure must be reduced and secondly the ramp voltage must be increased significantly. The former requires even more of the latter. The voltage achieved currently is 8kV on each sweep plate, i.e. 16kV across the plates. With this arrangement there is no evidence of dynamic defocussing. This is an effect whereby the focal plane of the image moves as a result of the sweeping. It is thought that the small deflection structure reduces this effect.

Using cameras with these modifications, research workers have achieved 3ps time resolution using gold cathodes. This represents the anticipated ultimate temporal response of a gold cathode in this camera. Figures 6 and 7 show pictures obtained of X-ray sources produced by a laser produced plasma. A group at the Max Planck Institut have operated at up to 0.8ps mm^{-1} and shown that time resolution is limited by the gold cathode. A research group at Imperial College have operated at 3.3ps mm^{-1} with potassium bromide cathodes to achieve high time resolution of X-ray spectra. As yet no definitive measurement of the temporal resolution of the camera has been made.

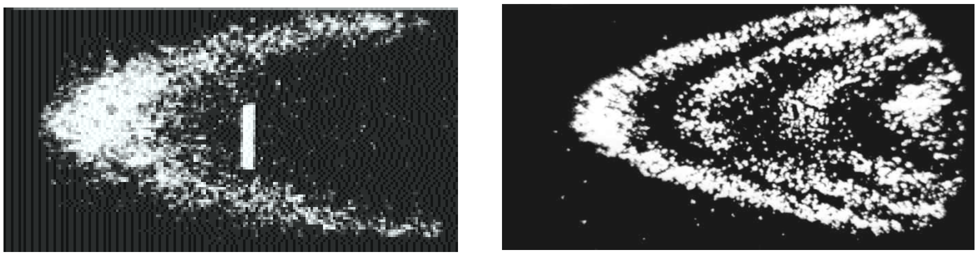

Figure 6. On the left a streak X-ray emission from a laser produced aluminium plasma, the laser was a 500fs 10^{17}Wcm^{-2} KrF. The cathode material was gold on 1000Å formvar. The severe slit image curvature is obvious. The streaks on the right are the raw KrF pulses via an etalon to measure the sweep speed. The 500fs pulses are separated by 14.14ps, giving a sweep speed of about 0.8ps mm^{-1} at the camera output.

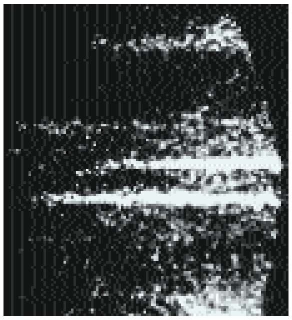

Figure 7. Sweeps of x-ray spectral lines Al Heγ (6.31Å) and Si Lyman α(6.17Å) from a layered target. The sweep calibration gives 3.3ps mm^{-1} at the camera output and a 7ps delay in the onset of Si emission.

6. CONCLUSION

The availability of high voltage fast pulse generators has dramatically effected the design of several cameras used for high speed photography. In particular it has eliminated the need for access to a laser system to achieve highly time resolved images in both x-ray and visible imaging. With more recent pulse generator designs it is possible to drive arrays of highly synchronized cameras or to gate large areas of MCPs.

Exciting new areas of development are appearing by combining the fast gated imagers with fast laser pulses for ranging and stray light rejection. The high repetition rate available may enable ranging systems to work with laser diodes to provide compact systems for imaging in visually poor environments.

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