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Nanosecond Frame Cameras

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Abstract

The advent of CCD cameras and computerized data recording has spurred the development of several new cameras and techniques for recording nanosecond images. We have made a side by side comparison of three nanosecond frame cameras, examining them for both performance and operational characteristics. The cameras include; Micro-Channel Plate / CCD, Image Diode / CCD and Image Diode / Film; combinations of gating / data recording. The advantages and disadvantages of each device will be discussed.

Key Words: high speed photography; nanosecond framing; transient imaging.

Introduction

A fast framing camera is the combination of a fast shutter or gate with an image recording device. Most cameras generally use two separate devices to provide these functions. Mechanical shutters and rotating mirrors are too slow for nanosecond image gating. Electronically gated intensifier tubes have been developed for nanosecond shuttering. The traditional combination of a gated image intensifier tube with film has been the mainstay of nanosecond imaging for a generation[ii]. Several commercial cameras have come to the market combining a gating tube with an electronic imager but none yet has demonstrated the performance of film cameras. The rapid improvement of electronic image detectors (CCD's & etc.) along with the aging of long used systems precipitated this review.

Two gating devices were considered in this study, the proximity focused image diode and the micro channel plate. The image diode simply uses a high voltage to accelerate electrons across a narrow gap between a photo-cathode and a phosphor. The diode is shuttered, by gating the high voltage (up to 15kV). A thin aluminum film over the phosphor blocks light but requires a higher voltage for the electrons to penetrate into the fluor. The diode has only limited gain (<100) but its advantages include high dynamic range with a linear gray scale and high resolution.

The micro channel plate (MCP) intensifier adds a plate of semiconducting microscopic tubes between the photocathode and fluor. An accelerating voltage across the plate creates a shower of 10^3-10^6 electrons for each photoelectron. This electron gain is extremely useful in low light conditions but comes at the cost of resolution, dynamic range and available diameter. The MCP is easier to shutter than the diode, in that only the cathode-channel plate gap bias (200-300V), instead of the full acceleration voltage, need be gated.

Film has been the primary recording medium for nanosecond imaging applications. It is generally used in direct contact (butt coupled) with the output face of the shuttering tube. The resolution of modern films significantly exceeds the limits imposed by the shuttering tubes. The logarithmic response of film is well matched to the large dynamic range of many targets. With proper development a dynamic range $>10^6$ is commonly achieved with black & white films. Electronic image recorders, e.g. CCD's & etc, although not equal to the best films, have improved to the point where they are a good match to the gating tubes. The convenience of instant readout is making the electronic camera quite desirable.

The basis of this comparison is the camera developed by Larry Shaw, which for the last twenty or so years, has been the mainstay of nanosecond framing at several Lawrence Livermore Laboratory facilities. The camera uses a 75mm diode shutter and film for recording. The camera high voltage is Krytron switched. The minimum gating time of 15-20ns, is limited by the electronic properties of the tube. Sheet film (4"X 5") is pressed directly against the back face of the camera. Films used with the camera are generally Kodak T-Max 400 or P-3200, with the equivalently rated Polaroid films used for setup[iii]. The maximum resolution, (12lp/mm) is limited by the tube. There is also some degradation of resolution (to 8-10lp/mm) if the rise and fall times of the gating voltage are a significant portion of the exposure. The resolution degradation can be mitigated, by using an illumination source that is pulsed shorter than the tube gate. The dynamic range of the camera appears to be limited only by the film and the damage threshold of the photocathode. These cameras are generally grouped in pairs viewing a beam splitter to provide two frames through the same lens (figure 1).

Figure 1. A single frame 75mm Diode camera module. The output face of the diode is the disk at the center. The Graflock back holds a standard 4x5" film holder. A cam over spring back presses the film against the tube and a vacuum in a groove around the tube insures intimate contact with the film.

The number of resolvable elements realized across the recorded image is a primary merit factor for a camera. This is the product of the resolution and field of view. Eliminating lensing from the equation, this can be best described as the convolution of the resolutions of both the shutter and recording medium, times the characteristic dimension of the detector. This is not a trivial exercise especially with digital cameras in that two different criteria are used to define resolution. The resolution of shutter tubes and film are described as resolvable sinusoidal line pairs per millimeter at a contrast of 5%. Digital camera resolution is generally defined by the pixel size. In the Nyquist limit it requires a minimum of 2.3 pixels to resolve a line pair. When two resolution degrading elements are used in series the combined limit is one over the square root of the sum of the squares of the individual components. In the case of the Shaw camera the 75mm tube with 12lp/mm resolution provides 900 resolvable line pairs across its diameter. The film with a resolution 50-100 lp/mm does not significantly degrade the resolution. A digital detector would require a minimum of 2070 pixels across the tube diameter to have the same resolution as the tube. However, as a tube and detector are coupled in series at least twice the pixel count, or >4000 pixels, would be necessary to prevent a significant degradation of the resolution of the tube. This, of course, assumes that the coupling of the two devices is accomplished in a loss less fashion.

The other significant criterion for a camera is the dynamic range and the ability to discern small light level variations at all levels of illumination. The logarithmic response of film is ideal for this purpose. The electronic cameras have a linear response and loose small variation sensitivity at low illumination levels. Film at normal development has an exposure or light level range of 10^3-10^4 over which a 5% contrast variation is resolvable. A linear digital system requires 15 bits above noise to provide the same result. The tube dynamic range may also be a limiting factor. The diodes are linear over many orders of magnitude of illumination, limited only by damage to the photocathode for short gates. The MCPs loose dynamic range at shorter gating times because of current limits in the plate. This is the primary reason for the LLNL preference for diodes.

Tube development has resulted in claims of increased resolution to 30lp/mm. This comes from improvements in the phosphor layer. However, although 75 mm are available on special order, their quality has declined due to poor quality fiber output face plates. With the higher resolution the commercially available 40mm tubes should provide the same number of resolvable elements as the older 75mm tubes. The limiting gating times of the 40mm proximity focused diodes should decrease to 5-10ns. Smaller diodes and MCPs of 18 and 25 mm diameters, are also available, which allow shorter gating times but yield fewer resolvable elements.

The number of resolvable elements across tubes of various diameters was estimated from the manufacturers claimed resolutions. The resolution in line pairs per millimeter, multiplied by the diameter of the active area gives the field of view in line pairs. Assuming a square CCD is inscribed within the diameter of the tube then the side of the CCD is $2^{-1/2}$ times the diameter. The Nyquist limit requires 2.3 pixels per line pair and the resolution loss mating the tube to the CCD requires an additional factor of two. Table 1 summarizes these calculations for the standard tube sizes. These resolution numbers and pixel calculations apply to both MCP and proximity diodes. Additionally the minimum gating times for the diodes have been estimated based on the electrical properties of the tubes and are, consistent with the performance of the 75mm tubes.

Tube Dia.	Resolution lp/mm	Field of View lp/dia	Pixels*	Min Diode Gate ns
75mm	12	900	2957	15
40mm	30	1200	3942	5
25mm	30	750	2464	2
18mm	30	540	1774	0.5

Table 1.

***Number of pixels on inscribed square to realize tube resolution.**
(fov X 3{Nyquist} X 2 {coupling loss} / 1.4 {inscribed square})

Nanosecond times are too short for mechanical image deflection or electronic frame readout, precluding the multiframe techniques used at lower speeds. Two approaches commonly used for multiframing are electronic image deflection and aperture sharing of multiple single frame cameras. In both cases there is a severe penalty for the multiple frames. Deflectable intensifier tubes divide the number of resolvable elements of the tube by the number of images. Aperture sharing divides the available light by the number of images. With the increased use of pulsed laser illumination aperture sharing has become the preferred technique. The 75mm cameras are usually aperture shared in pairs, with a beam splitter and distortion corrector (figure 2). Groupings of up to four pairs are commonly used in the field (Figure 3).

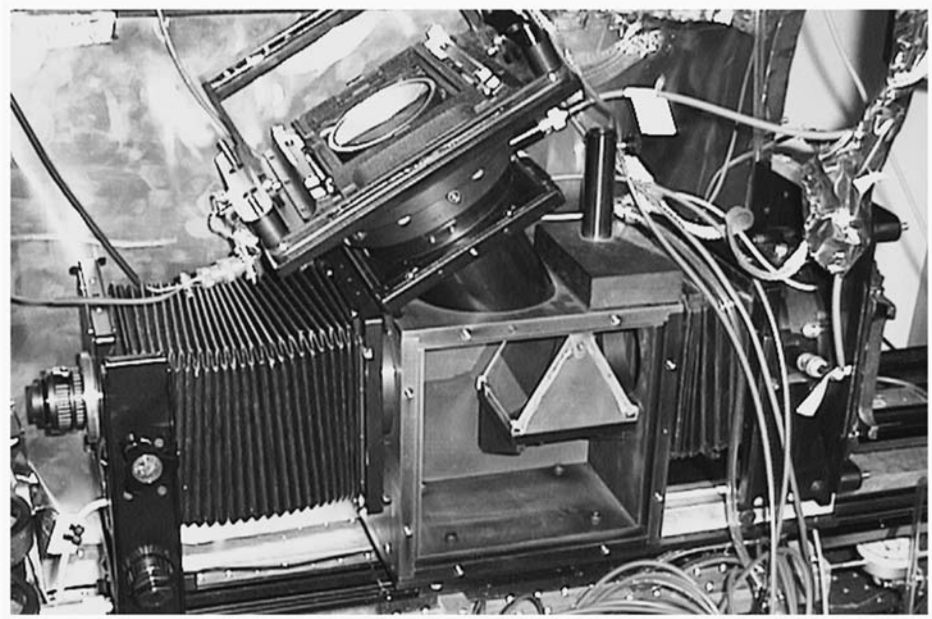

Figure 2. Two frame assembly with side cover removed to show beam splitter & compensator. For the camera comparison experiments the camera module on the right was replaced with the test camera.

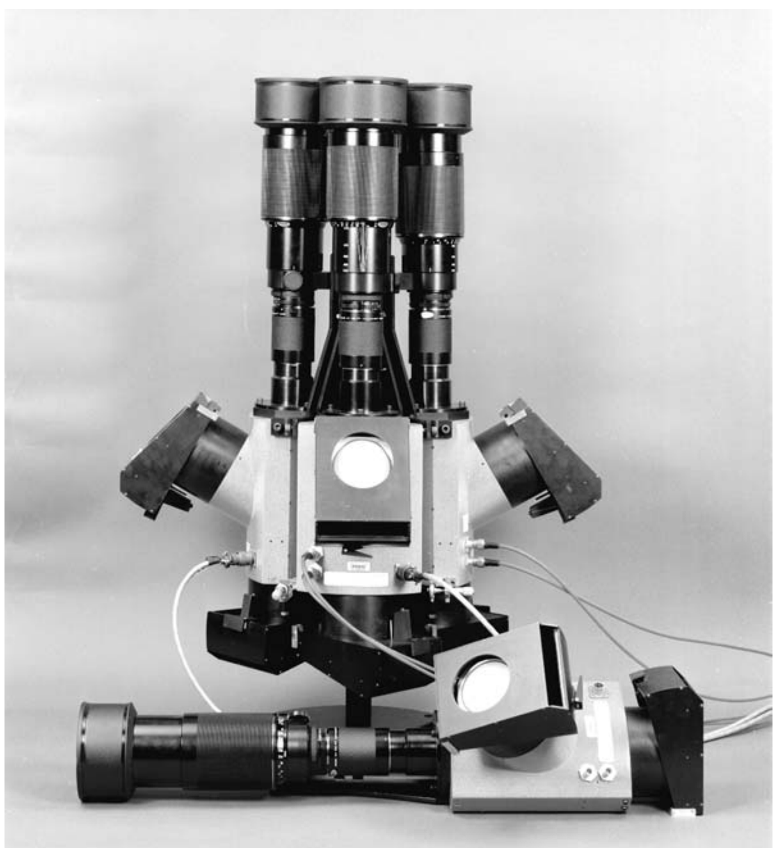

Figure 3. The ‘8 Frame Camera’ an assembly of four, two frame modules, equipped with long lenses for field use.

Test Description

Several commercial cameras in various states of development were demonstrated in the LLNL Micro Detonics Facility[iv]. Only two cameras, both from the same manufacturer, were able to obtain useful data on real shots. One was an eight frame aperture shared camera using 18mm MCPs coupled to 576x385x8bit CCDs. The other camera was a single frame 25mm proximity focused diode coupled to a 1280x1024x12bit CCD. Both cameras were set up to replace one frame of a 75mm two frame film camera. They shared common lensing and magnification. The 1ns illumination pulse was used as the timing reference and all cameras were triggered with the laser pulse in the middle of the frame. Each camera was used at its limiting gate, 5ns for the MCP, 200ns for the 25mm diode and 20ns for the 75mm diode. The cameras viewed a 1mm long exploding bridge wire, emersed in water, at a magnification of about 12X. The illumination laser was fired, and camera frame center was 100ns after the burst of the wire. The laser back illuminated the experiment in Schlieren mode to view the shock waves in the water. The expanding vapor cloud from the wire is also self luminous providing a good test of dynamic range.

Cameras from three other vendors were brought to the facility for demonstration but all failed to record images. This was due to software inadequacies or limited understanding of the camera operation by the demonstrator. In two cases the demonstration cameras were not a complete or functional system or product.

Test Results

The results of these tests clearly demonstrated the differences of the three cameras. The film used for the 75mm diode was T-Max 400, developed normally in T-Max-RS developer. Films were digitized using a 12 bit Polaroid 45I scanner and all images were analyzed using both Photoshop 5. and IP Lab Spectrum 3.52. The comparison of the MCP camera with the 75mm is shown in figure 4. The electronically recorded images are shown full frame but the film records are cropped, eliminating the unused portion of the tube. Normally a higher magnification would be used with the 75mm camera to take advantage of the larger area. All are shown at the same magnification. The MCP does not have either the number of resolvable elements or the dynamic range of the film camera. The limited dynamic range of the MCP is particularly evident in the line scans through the same locations of the two images (figure 5). At minimum gate, 5ns, the MCP delivered less than 32 gray levels, 5 bits, even though displayed as an 8 bit image. The signal also saturated in the brightest portion of the image.

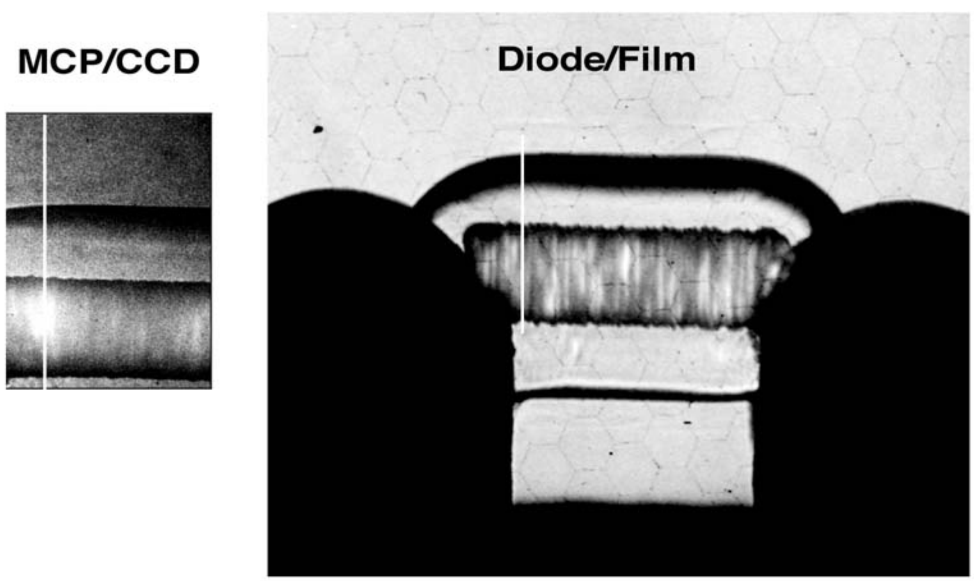

Figure 4. Exploding wire images recorded simultaneously with the MCP / CCD & Diode / Film cameras. The white lines indicate the locations of the scans shown in figure 5.

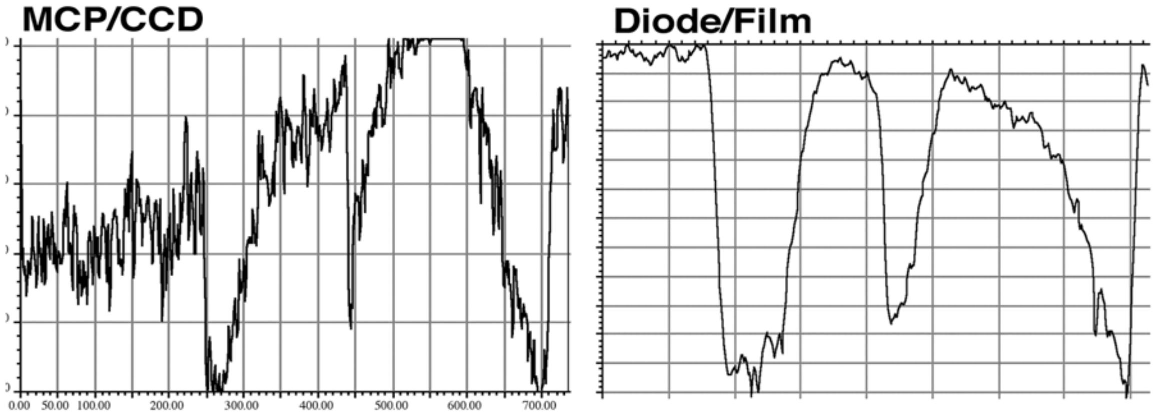

Figure 5. Image brightness vs. position scans from the above images.

Images made with the 25mm Proximity focused diode / 1280x1024x12bit CCD camera were much closer to the 75mm camera in quality (figure 6). Resolution is virtually the same albeit over a smaller area. Differences in the rendering of the two images are due to polarization effects on the beamsplitter and the significantly different gate times of the two tubes. Unfortunately the CCD image was recorded at a low light level so that the full dynamic range of the camera was not exercised. The banding across the CCD image is due either to a fixed pattern noise in the CCD or ghosting (charge leakage) from the brighter portions of the image. Although limited in image size, the performance of this camera begins to demonstrate the technology that could eventually replace the old system.

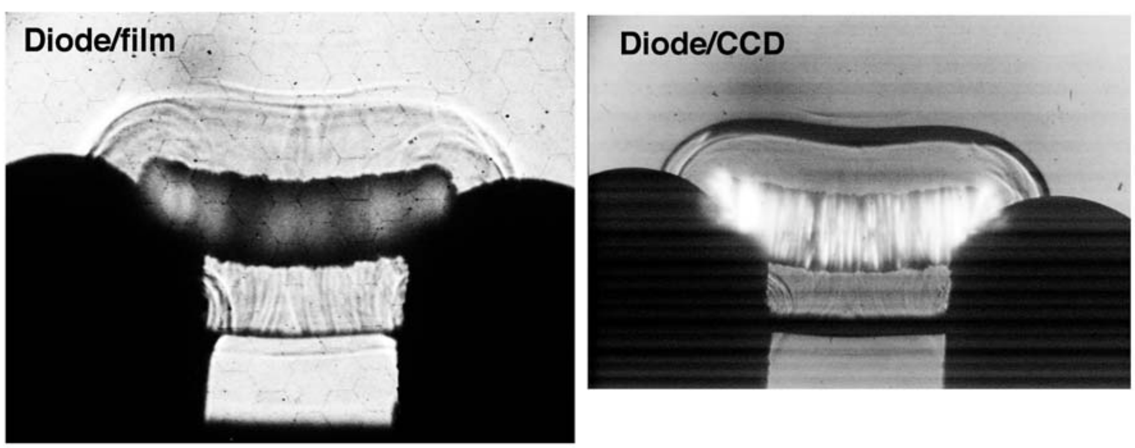

Figure 6. Simultaneous images taken with the Diode / Film and Diode / CCD cameras.

Future Considerations

Large mega-pixel CCD image chips with 16-bit dynamic range are now becoming available. Their pixel count, size & shape are fairly well matched to a 40mm tube with 30 lp/mm resolution. A concern about close coupling proximity focused diode with a CCD, is the noise spike from the diode and its potential to disrupt the function of the CCD. Short pulse (~5ns) high voltage gating circuitry, for the diodes, would pose a developmental challenge to most camera manufacturers. Twelve bit software has become quite common but the limited availability of 16 bit camera & image analysis software is a concern. (Note; Photoshop 5. and IP Lab Spectrum 3.52 currently support 16 bit analysis)

The cameras at LLNL are used for non-repeatable single shot field applications, often in hostile environments. This places certain additional requirements on the functional design of a camera. The delay between a trigger signal and the camera turn on must be short and the shot to shot variation, jitter, less than the minimum gate. The camera operating system must be absolutely reliable and self tending. The system must be immune from electrical noise with either a high voltage (>20v) or fiber optic trigger and a multiple trigger lock out. Data must be automatically archived to nonvolatile memory without operator intervention and have sufficient power reserve to preserve the data with a post event power loss. A set up mode must be provided for to allow alignment & focus of the camera. Camera setup parameters must also be nonvolatile with the previous setup available at power up. Other than power the camera should only require an arm and fire signals from the operating system with no automated internal time limits.

Conclusions

Several vendors have or claim to have nanosecond frame cameras. Most are based on 18-25mm MCPs coupled to ~1k X 1k arrays with a maximum of 12 bit electronics. Several of the cameras are grouped in multiframe arrays. Only one vendor demonstrated a camera with an operating system suitable for field applications. None of the available units has either the number of resolvable elements or dynamic range of the 75mm proximity focused diode / film 'Shaw' camera. A camera using 40mm proximity focused diode with 30 lp/mm resolution coupled with a chip of 4k X 4k X 16 bits, may have the potential of matching the performance of the 20 year old design.

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[i] This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

[ii] L. L. Shaw, et al., 16th Intern. Cong. On High Speed Photography, 1984

[iii] Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

[iv] A. M. Frank, 18th Intern. Cong. On High Speed Photography, 1988