Novel Electronic Readout Systems For Photon Counting Imagers

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ABSTRACT

Previously we have described several types of charge division electronic image readouts for microchannel plate based imaging detectors developed at MSSL, primarily for space astronomy applications. These have included the wedge and strip anode[1] (WSA), the Vernier anode[2] - a high-resolution readout, capable of exploiting the limiting spatial resolution offered by the microchannel plate, and FIRE[3] - a imaging device operating at event rates in excess of 10 MHz.

MSSL and Photek have now joined in a collaboration to develop an intensifier based imaging system designed to employ this range of readout systems for general laboratory use. The image intensifier uses the image charge technique[4,5] whereby the event charge is used to induce electrical signals on the capacitively coupled readout pattern, obviating the requirement for the readout to be inside the vacuum enclosure. The image readout is manufactured as a separate component, and can be interchanged to suit the specific application requirements. The intensifier tube design can be generic enabling it to be used with a variety of image readouts designs.

We describe the image intensifier and electronic design, including the common charge amplifier, event timing and computer interface. We discuss the anticipated performance of the various readout systems - Wedge and Strip, Vernier and FIRE in terms of spatial resolution, maximum count rate, and timing resolution.

Keywords: photon counting, electronic imaging, sealed intensifier, induced charge, image readout,

1. INTRODUCTION

The traditional Gen II intensifier tube, used in large numbers for military night vision, was designed to fulfil the requirement for a relatively simple, rugged and compact device to augment human vision. In the current scientific marketplace, the demands of quantitative image measurement have led to various adaptations to the Gen II design in order that image data can be quantified and collected for analysis. These modifications invariably include some form of electronic imaging component. Since the unmodified intensifier produces a light output, an obvious candidate for the electronic detection element is a CCD. Such intensified CCD hybrid devices are commercially available[6] and perform successfully for a variety of applications.

However intensified CCDs are not necessarily the best choice where high time and position resolution, coupled with mechanical simplicity, are required. Direct electronic imaging, whereby the position coordinate of the MCP output charge is directly determined, is a well-known alternative having an immediately obvious elegance of simplicity. This method uses an anode comprising a pattern of electrodes to collect the MCP charge. The anode has a one to one geometric correspondence with the detector input and the image format is highly flexible. The charge signal is directly detected by electronic means and no intermediate stages involving additional high voltage, phosphors, fibre-optics and optical coupling are required. The design of the electrode structure defines the method by which the charge centroid coordinate is determined and wide variety of designs have been developed, offering performances optimised over a wide envelope of image resolution, timing resolution, and count rate parameter space. The potential benefits of direct electronic image readout of microchannel plate detectors, be it using charge division, delay line, coincidence schemes etc, have been well documented[7]. However the inclusion of such devices within an intensifier tube has always in the past, presented difficulties.

Mounting an internal readout anode inside an intensifier tube body requires that it is UHV compatible and capable of surviving a high temperature bake-out. This can pose problems where thin film techniques are used due to material diffusion and surface chemistry effects altering its electrical properties. Electronic readouts require a minimum of there electrical feedthroughs. These cannot be made as an integral part of the intensifier body, as for the microchannel plate contacts, and the inclusion of extra feedthroughs poses its own design problems plus the added possibility of leaks. Many of these devices require an extended charge footprint, which is normally achieved by allowing charge cloud expansion to occur in an extended drift region. This often necessitates and enlarged intensifier body at the back end presenting further mechanical difficulties. The extra tube components increase the chance of a processing stage or component failure, resulting in the loss of the tube.

A technique known as image charge[4,5] has been previously described which overcomes virtually all of the problems associated with incorporating electronic readouts into intensifier tubes. It also provides significant benefits in terms of manufacture, device performance, and operational flexibility. An image intensifier built using the image charge technique is as simple to construct as one using a phosphor output and contains no extra components. A resistive layer, commonly made of Germanium, replaces the phosphor and localizes the signal charge whilst it is measured using the charge induced on a remote readout. Only one electrical contact is required within the intensifier, and this is provided by an integral component of the intensifier body in the normal method. The enlarged charge footprint commonly required for electronic readouts is accomplished by the geometric spread of the induced charge through the substrate and can be tuned by changing the geometry. The intensifier does not accommodate the readout and thus does not suffer from difficulties encountered with collected charge readouts as described previously. A generic intensifier design can be manufactured which is suitable for use with a variety of readouts such as discrete pixel anodes, wedge and strip anode, Vernier anode, FIRE etc. The readout substrate can be physically separated from the intensifier body. This in-built flexibility allows a single intensifier tube to be used with different readouts optimized for different applications. Since the charge can be proximity focused on to the resistive layer, the event charge can be proximity focused on to the resistive layer, improving high resolution performance by eliminating magnification of MCP charge centroid errors which limit ultimate resolution.

2. IMAGE CHARGE

Use of the Image Charge technique allows an intensifier to be designed utilizing an anode external to the tube structure, i.e. outside of the vacuum chamber. This brings several construction advantages, such as the ability to change the anode design to suite the experimental requirements without breaking the vacuum seal and also the reduced need for electrical contacts to the vacuum chamber. Figure 1 shows a proposed design of an intensifier incorporating the image charge technique in a sealed vacuum detector.

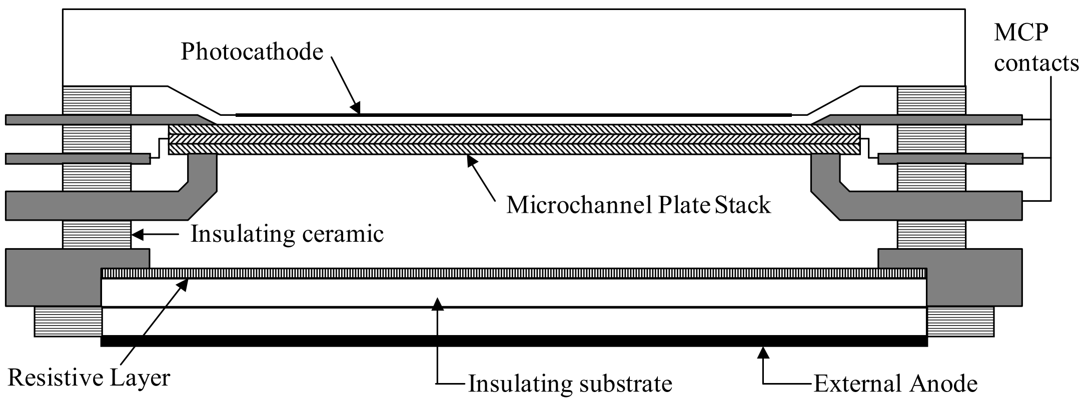

Figure 1. Basic design of a sealed-tube image charge detector.

Instead of being directly collected by a readout pattern, the electrons ejected from the microchannel plate are incident on a resistive layer which has a suitably high surface resistance to locate the charge long enough for the external electronics to determine the its centroid position. Initial experiments have used germanium layered on an insulating glass substrate with resistances of about 1GΩ/square. The presence of the insulating glass layer means that the resistive layer and the external anode form a capacitor which allows the charge pulse to be induced on to the readout pattern. The relative signal levels on the pattern electrodes reflect the same ratios which would occur if the pattern was used to directly collect charge. The signals are then fed to the amplifying electronics and the charge levels measured. The image charge technique effectively decouples the readout pattern from the high voltages inside the tube.

The Germanium layer resistance is chosen so that the time constant for event charge dissipation is significantly longer than the time constant of the charge measurement electronics. The charge begins to spread as soon as it arrives on the Germanium, and we have measured the increase in size of the charge footprint as a function of time by varying the electronic shaping time constants. In practice, the detector geometry is arranged so that the footprint of the collected charge is small, i.e. the anode is proximity focused, and the Germanium time constant is significantly longer than the electronic shaping time constants. Thus the major factor determining induced charge footprint size is the thickness of the substrate between the Germanium anode and the position readout. The charge leakage from the Germanium to ground effectively resembles a slow baseline shift, which is filtered out by the faster measurement electronics.

Image charge removes the need for electrical contacts through the vacuum chamber to the anode, and the resistive layer only needs a single contact. This contact does not carry the signal and therefore does not need the normal precautions for high frequency charge pulses. Another advantage is that the anode can be made larger than the image area so that distortion effects at the edge of the anode are minimized, without impacting on the tube design.

Since the charge is spatially localized by the resistive sheet during the time it is measured, and the footprint results from the geometry of the coupling dielectric, a charge division anode detects the true capacitance ratio as determined by the electrode geometry. This is how the charge division technique is meant to work. Many of the effects degrading the performance of charge division readouts are absent with image charge.

1. The electrode ratio distortions caused when secondary electrons are produced during charge collection[8], and giving rise to image instability and nonlinearity, are not present.
2. The charge division readout is not degraded by partition noise caused by the random distribution of the collected charge cloud.
3. The magnification of the charge centroid error (resulting from an inhomogeneous charge distribution), which occurs when a charge cloud is allowed to expand to suit a charge division anode used in collection mode, is not present.

An anode design like the Wedge and Strip requires a minimum size of charge footprint to overcome modulation effects[9]. This is achieved by allowing the charge cloud to spread after exiting the microchannel plate. For a given MCP configuration there is a minimum distance between MCP and anode required to allow the electron cloud to expand to the required size, placing restrictions on the mechanical design of the detector. However in the case of the image charge technique, the charge cloud does not need to expand in the gap between MCP and anode, since an enlarged charge footprint is naturally produced by the geometry of the dielectric coupling substrate. Hence the tube design can be more compact. Figure 2 shows a simplified diagram of the process and the advantage of the image charge technique.

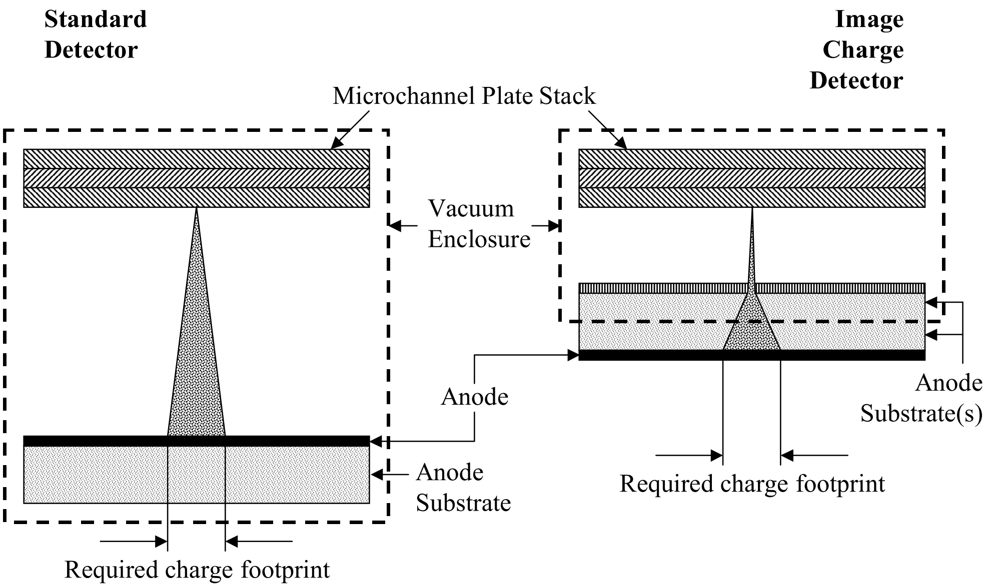

Figure 2. Electron spreading in a standard detector and an image charge detector.

The image charge technique does have features, which restrict its operation. A small fraction of the collected charge is induced on to electrodes in the detector i.e. the MCP output contact, etc. This leads to a small decrease in the readout charge, which is typically 76% of the collected charge, resulting in a small degradation of the signal to noise ratio. The resistance of the Germanium must be sufficiently high to localize the charge during measurement, but not allow charge up at high count rates. Readouts designed for high rate applications will require a lower Germanium resistance than those using longer shaping times. However, these limitations are insignificant compared with the advantages offered.

3. IMAGING TECHNOLOGY OPTIONS

We have demonstrated the operation of the image charge technique with several types of charge division devices. In all cases performance is equal or better than that achieved using direct electron collection. The manufacture and operation of our first image charge WSA has proven to be reasonably straightforward. We obtained the data shown in figure 3 using an existing WSA pattern, manufactured with our laser machining process, and consisting of copper conductors on a 2 mm thick fused silica substrate. The WSA pattern had a pitch of 980 μm and active area of 40 mm diameter. The resistive layer was manufactured by sputter coating with germanium. A position resolution of 27 μm FWHM without pinhole image deconvolution represents better than 1000×1000 pixel format, an excellent result for a WSA even at the relatively low gain of 10^7 electrons. Even more pleasing was the obvious improvement in linearity, despite non-optimized resistance and substrate geometry causing an oversized charge footprint and edge distortions. Analysis of the data showed the position shift with count rate to be ± 5μm up to 4×10^4 cts^{-1}, insignificant with respect to the position resolution, and likely to be a result of electronic effects which can be overcome.

Vernier anode has been shown to be capable of exceeding the resolution provided by the microchannel plates themselves, with 10 μm FWHM resolution. We have recently confirmed that this level of resolution is also available using image charge mode. Figure 4 shows an image of a focused spot of UV illumination projected on to an open faced microchannel plate detector using a Vernier position readout, as yet unoptimized to suit the image charge geometry. The detector uses a chevron pair of Photonis microchannel plates with 12.5 μm diameter pores. The UV spot diameter is ~0.5 mm, and within this area, the pore structure of the front MCP is clearly visible. Thus the Vernier anode provides microchannel plate limited imaging resolution in both collect charge and image charge modes.

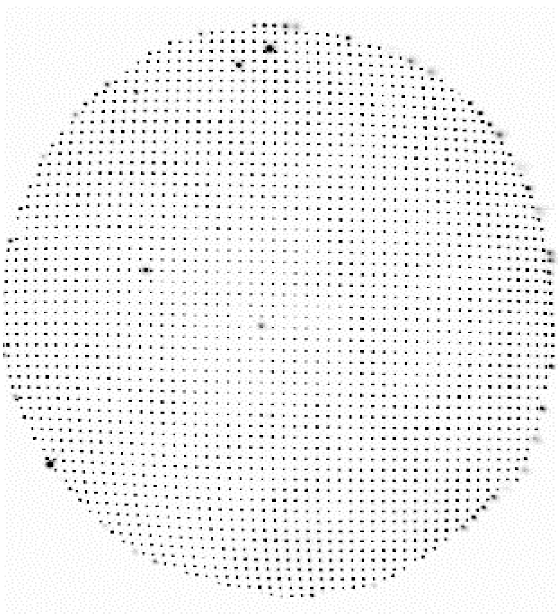

Figure 3 shows an image from the first induced charge WSA. The pinhole mask image demonstrates a resolution of 27 µm FWHM before deconvolution.

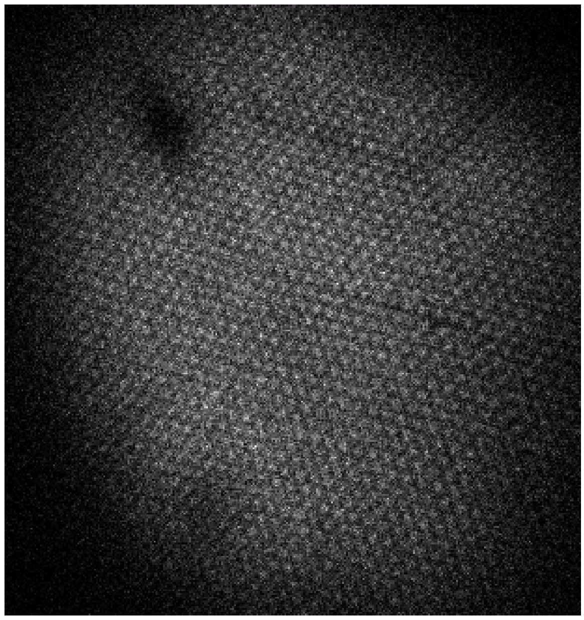

Figure 4. A Vernier anode image, using image charge, of a 1 mm diameter illuminated area. The Vernier readout easily resolves the pores in the top MCP.

So far we have demonstrated the performance of the readout devices previously mentioned in the image charge mode. In the future we intend to investigate the operation of both the high speed FIRE readout, and discrete pixel devices, and demonstrate the application of all devices to a generic design of intensifier using image charge coupling.

4. ELECTRONIC DESIGN

1. Charge Measurement Electronic Design

The electronics of the system are separated into four distinct sections as shown in figure 5.

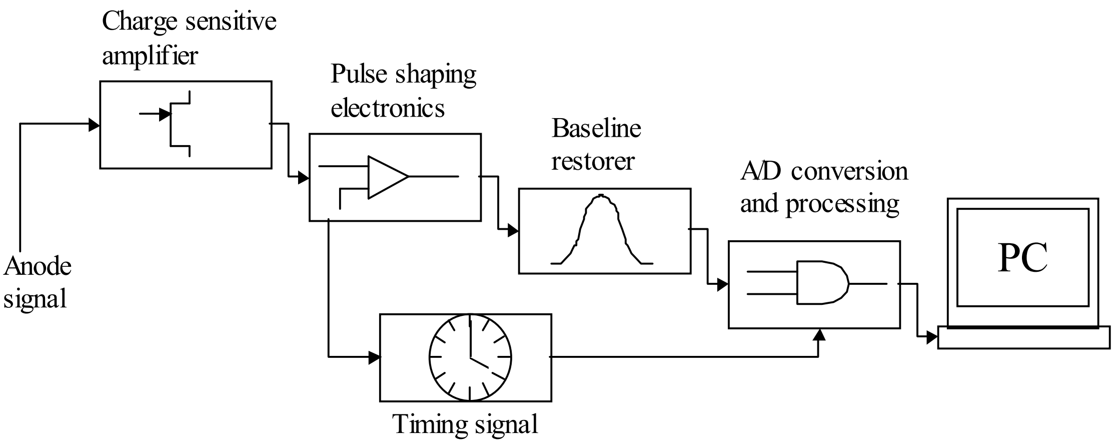

Figure 5. A functional diagram of the electronics system for wedge and strip type readouts

The electronics have been designed with the core performance aims of the system in mind; resolution, count rate, response time and dynamic capacitance. Detailed analysis reveals that an overall compromise has to be reached, because if a factor is improved it is to the detriment of one or more of the others.

The resolution of the image depends in part on the precision with which it is possible to measure the magnitude of the charge pulses generated at the anode. In terms of the electronics, the main contributing factors are the electronic noise and the linearity of the response with increasing pulse height. Noise in electronic circuits can become extremely complex, but we have attempted to identify the main sources of noise in the circuit and their magnitude. An important factor to consider is at the end of the analogue electronics where digital conversion takes place. For example, if a 14bit converter is used, 1 bit represents about 0.003% of the mean signal. Therefore any attempt to reduce the noise to a value below this level would serve no purpose and could reduce other performance parameters, e.g. the ability the handle voltage building up at the input at a high count rate. With this in mind, the noise generated (particularly in the charge sensitive amplifier) from each component was balanced with the other performance targets of the circuit.

The count rate depends on the total pulse width and more specifically, (depending on the accuracy requirements) the time taken for the pulse tail to return to the baseline. We have chosen a unipolar pseudo-Gaussian pulse shaping circuit as described by Mosher[10] to minimize the dead time of the pulse, which requires the additional circuit of the active baseline restorer. Initial experiments have confirmed that any non-linearity caused by this circuit is within acceptable limits. The problem of stray capacitance cannot be ignored, however, and for this reason the design has also considered the physical dimensions of the electronics and only surface mount components have been used. We have also designed for the electronics to be as close to the anode as possible.

The response time of the circuit is determined by the rise time of the front-end of the amplifying electronics where a double-FET system is being used to improve the response. The dynamic capacitance is generated by a feedback loop in the amplifying circuit and is required to dominate the capture of the anode charge pulse over stray capacitance that may exist around the anode, in the connecting cables, etc.

The digital processing scheme is summarized in figure 6. The amplified pulse is converted in a 14bit analogue to digital converter (A/D) and then passed into the multiplexer. A timing signal is taken from further upstream in the pulse shaping electronics and is latched in the timing counter. All the information is then passed to the controlling logic where parallel/serial conversion takes place and it is sent through a 300Mbit/s fibre optic link to a card in the PC.

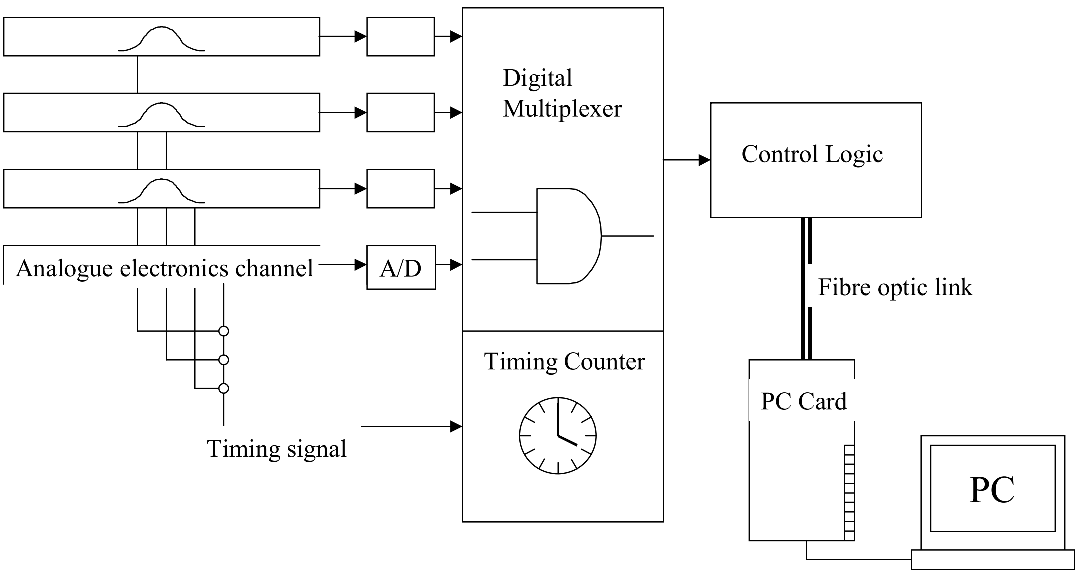

Figure 6. A schematic showing the functional layout of the digital processing electronics

The current design is for four input channels to allow for resistive anode or Wedge & Strip designs, but it can be easily adapted up to nine channels to enable working with anode designs such as the Vernier.

2. High Speed Charge Comparison Electronics

The bandwidth of charge division readout anodes used with MCPs is usually limited by the speed of the acquisition electronics. We are designing a novel charge division anode that does not require analogue to digital conversion. The Fast Imaging Readout and Electronics (FIRE), a new concept in high speed imaging. The system comprises a microchannel plate intensifier coupled to a charge division image readout using high speed, multichannel electronics. It has a projected spatial resolution of up to 128 x 128 pixels, though the image format is inherently flexible, and the potential for rates up to 100 million events per second with nanosecond timing resolution.

The readout pattern has a planar electrode structure and collected charge from each event is shared amongst all electrodes, grouped in pairs. The unique design of the readout obviates the need for charge measurement, usually the dominant process determining the event processing deadtime. Instead, high speed signal comparators are used to define a binary code from which the position co-ordinate is directly mapped.

The signals from the anode are not high enough to drive comparators directly and, in consequence, an amplifier is required for each electrode. This equates to a pair of amplifiers per bit of resolution, i.e. 22 amplifiers are required for a 128 x 16 pixel readout. Amongst the solutions being investigated for high speed amplification are silicon MMIC amplifiers (Monolithic Microwave Integrated Circuit), which have the necessary wide bandwidth, low noise and high gain.

The signals from the amplifiers can be as short as 1ns. If the comparators sample the incoming pulses directly, propagation delay skew of as little as 100ps between the signals could give an erroneous position. Thus peak and hold circuits are required. The ECL logic gate output circuit was investigated as a novel solution to this problem.. The gates used in this circuit are operating in their linear region, a mode in which they are not characterized. The peak and hold is reset by a high speed transistor once the data from the comparators have been latched. The signals from the peak and hold circuits are sampled by latching comparators, type Motorola 10E1652, which have ECL logic level outputs, a propagation delay of <1ns and programmable hysteresis.

The acquisition controller latches the comparators' states, stores the result in a register, clears the peak and hold circuits and then writes the registers' output to a bank of FIFOs. The data from the FIFOs is histogrammed to build up an image. The controller interleaves occasional reads from the histogram RAM and sends data to the host computer which uses a lookup table to give real X,Y coordinates.

A prototype anode with a 32x32 pattern has been manufactured on a fused silica substrate and mounted within a microchannel plate detector using direct charge collection mode. Tests using charge sensitive amplifiers have indicated that the pattern is operating as expected. However experiments using 20 channels of the high speed MMIC amplifier design have indicated that crosstalk between electrodes is limiting the signal dynamic range, and a redesign of the front end amplifiers is being investigated. However, we are confident that we will only marginally sacrifice our speed specification by this redesign.

We have demonstrated the feasibility of a very high performance anode pattern, which obtains its speed advantage by avoiding an analogue to digital conversion stage. Prototype very high speed support electronics have been designed and novel use of RF and ECL circuits have been demonstrated. The electronics require no changes to allow different pattern shapes and resolutions. The electronics can be optimized in a power consumption/speed/cost trade off, making it suitable for ground use at high speed and for space flight in a slower, lower power form.

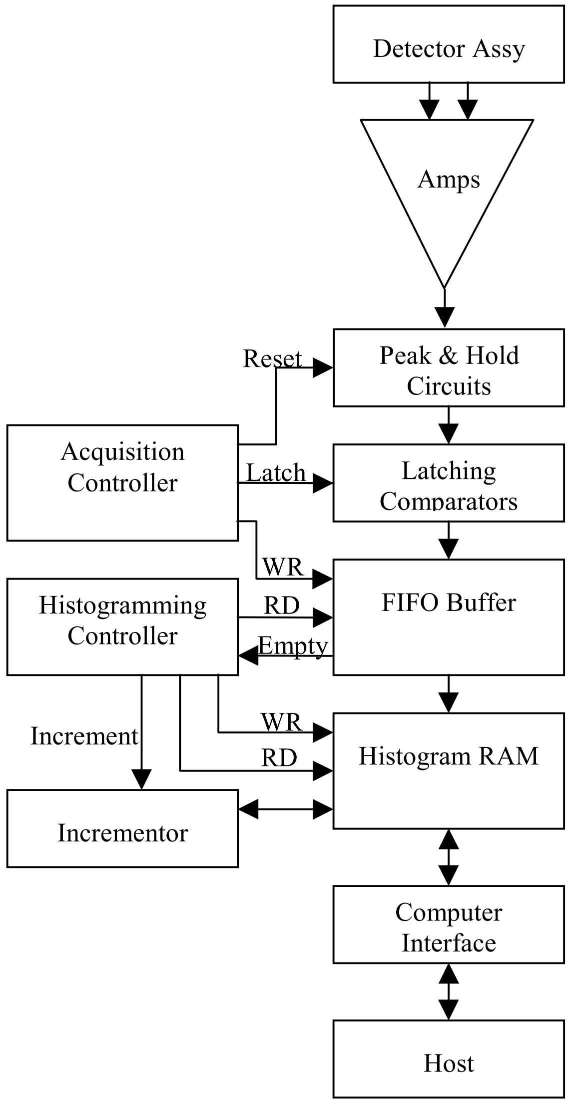

Figure 7. A block diagram of FIRE electronics design.

5. ANTICIPATED PERFORMANCE

The imaging performance demonstrated in this paper, was obtained using an open-faced microchannel plate detector having gain, configuration and geometry similar to sealed tube intensifiers. We anticipate that readout performance will not be comprised in sealed tube devices, apart from possible wavelength dependent degradation as a result of photocathode proximity focusing. Table 1 shows the anticipated performance of sealed intensifiers under development for the different readout types available.

	Count rate	*Spatial resolution*
Wedge and strip anode	200 kHz	Up to 1000×1000
Vernier anode	100-200 kHz	4000×4000
FIRE	10 MHz	128×128

Table 1. The anticipated performance specifications of intensifiers under development.

6. CONCLUSIONS

A strong synergy exists between the ongoing position readout developments at MSSL, as typified by the Vernier anode and FIRE, and the image charge technique. The former provide the potential for very high resolution and linearity or high count rate, their performance only being constrained by the detector processes, particularly anode secondary electron production. The image charge technique allows the full potential of these and other charge division anodes to be realized. The application of both high technology readouts, the image charge technique, and the development of a new charge measurement system, to an intensifier design from Photek, offers exciting potential for new detector systems. In addition, the manufacture of a generic intensifier capable of operating with a variety of image readouts offers a new level of flexibility for these devices.

7. ACKNOWLEDGEMENTS

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