AN IMAGE INTENSIFICATION SYSTEM FOR ULTRA-VIOLET LIGHT

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ABSTRACT

An Image Intensification System sensitive to ultra-violet (UV) light is described. It is a multistage system, composed of an UV objective, two Image Intensifiers (II), a Fiber Optics Taper (FOT) and a Charge Coupled Device (CCD) array. This system is applied to the readout of a Parallel Plate Proportional Imaging Chamber (PPPIC). The system's performance is analyzed and future developments are discussed. Some preliminary results are presented.

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1. **INTRODUCTION**

Successful combinations of a gaseous avalanche chamber with an optical readout system have been reported as a new type of tracking detector characterized by its high capability of pattern recognition [1-6]. The principle of operation is to recognize ionization tracks produced by high energy particles through the observation of the light emitted from electron avalanches, generated from the tracks, with the help of an Image Intensifier System. The opto-electronic readout allows the use of only a small number of analog readout channels, in contrast with the usual non-multiplexed electronic readout.

In addition, Charpak et al. [6], have proven that the detector can be operated in proportional mode, where not only collected charges but also light intensity are proportional to the energy deposited into the detector. This gives a new possibility to measure particle energy by detecting the light intensity together with particle trajectories.

It is essential for the detector to have a high quality optical readout system optimized to extract effectively the full information delivered by the imaging detector.

The aim of our development is the readout of one of these Imaging Chambers [5] via a low-light level UV imaging system. The main problem in this imaging chamber is that only a minute amount of UV light is emitted [7]. Because the whole system's pattern recognition should not be limited by the readout system's performance, but only by the physical processes within the chamber, the opto-electronic camera has to be very sensitive and with a good resolution.

The requirements of such an application lead us to use a UV transparent objective followed by a multistage Image Intensification System attached to a Charge Coupled Device (CCD) array. In this work we describe succinctly the chamber and in more detail the opto-electronic chain. Some preliminary results are also presented.

2. **THE DETECTOR**

2.1 **The chamber**

The prototype detector is composed of a drift space and an amplification structure. The drift space has a drift distance of 5 cm in which an electric field of 200 V/cm is applied. The amplification structure consists of two meshes, distant by
9 mm, where an electric field of 8600 V/cm is applied. This is followed by a window made of Aclar, which is transparent to UV light above 250 nm. The detector has an active area of 15 cm × 15 cm. It works with a gas mixture of argon (90%) + methane (8%) + triethylamine (TEA) (2%).

2.2 Light generation

The electrons produced by an incident high energy particle in the drift space will drift under the influence of the applied electric field and enter the amplification structure, where the electric field is strong enough to initiate electron avalanches.

During avalanche formation, triethylamine molecules are excited and emit light peaked at 280 nm and with a quantum yield near unity [7,8].

2.3 Developments

The most straightforward future development will aim to observe ββ-decay in xenon. One could imagine a larger detector filled with a Xe + TEA gas mixture in which the trajectories of the two electrons resulting from the ββ-decay of $^{136}$Xe could be visualized together with the energy released, providing much better event selection capability than the current detectors.

There might be a possibility to apply the detector to the detection of showers for proton decay, by coupling the detector to a high-density converter.

Another potential use of the detector is the observation of highly complex Ring Imaging Cherenkov (RICH) radiation in the relativistic heavy ion experiments.

3. THE OPTO-ELECTRONICS CHAIN

3.1 The objective

In order to project the image from the Chamber's anode of 15 cm × 15 cm onto the photocathode of the first II, having a diameter of 25 mm, we need a tenfold demagnification of the image. For this purpose we used an objective made of quartz lenses. This choice was motivated by the wavelength range of the light to be imaged, 240–320 nm, for which the usual optical glass does not show good transmission properties.
In order to collect as much light as possible the objective must have a small F/#. Furthermore, it must be well aberration corrected to obtain enough spatial resolution.

The lack of components for UV imaging in the market lead us to use an UV objective with a F/# of only 4.5. The light collection efficiency of this objective is twenty times smaller than that which would be obtained with an objective having an F/# of 1. Nevertheless, the gain of the whole system is sufficient to obtain highly contrasted pictures.

3.2 The image intensifiers

The active section of our system is composed of two IIIs. The first one, receiving the UV light from the chamber through the objective, is essentially a wavelength converter with a poor gain. The second, receiving visible light from the first, is a standard high-gain MicroChannel-Plate (MPC)-II. Both IIIs have a diameter of 25 mm.

The first II is a proximity focused single stage diode, with a diameter of 25 mm. In this kind of II the photocathode and the phosphor are placed a few millimetres apart and a HV of \( \sim 15 \) kV is applied between them. The gain is achieved by electron acceleration. Defocalization of the image is avoided by placing the photocathode and the anode very close together.

The II used has a bialkali photocathode deposited over a quartz window. This combination makes it sensitive to the UV light, with a relative sensitivity of \( \sim 90\% \) in the spectral area of interest. The quantum efficiency is \( \sim 8\% \). On the output window, an X3 phosphor is deposited on a Fiber Optics (FO) faceplate, allowing a very efficient collection of phosphor's light and also a efficient coupling to the next stage. The relatively small photonic gain of this stage, \( \sim 20 \) photon/photon, makes it a wavelength converter from UV to visible light, allowing the use of a standard II in the next stage.

The second stage, is a 25 mm MCP-II. In this kind of II a high gain is achieved by an electron multiplication process in the MCP. The electrons emitted by the photocathode are electrostatically focused on the MCP, multiplied there and then proximity focused on the output phosphor. This structure allows a gain of \( \sim 30\,000 \) photon/photon making it the main amplifier of the chain.
Both the input and output windows are made of FO faceplates, allowing the image to be transmitted from the previous and to the next elements simply by placing them in contact. The photocathode is S20, and the phosphor is P20.

3.3 The fiber optics taper

Since the CCD we use has a smaller diagonal (7 mm) than the 25 mm diameter output face of the IIs, we need a demagnifying element.

For this purpose we used a FOT. The taper is an image guide, the image being transmitted undistorted from one side to the other, but its size being reduced (or increased). Essentially, it is a coherent FO bundle with one side larger than the other. This is made by reducing the diameter of each individual fiber in the bundle by the desired ratio.

This solution is much better than the use of a lens because it is free of aberration and defocusing, it is more compact (30 mm long) than what can be achieved with an objective, allowing for a mechanically more simple, stable and compact chain. On top of that it has an energy transmission efficiency better than any lens and it is cheaper than an objective and its mechanical mounting.

Together, the objective and the taper, provide a geometrical demagnification of 35, from the 15 cm x 15 cm of the chamber to the 4.320 mm x 5.824 mm of the CCD.

3.4 The charge coupled device

It is the use of a CCD to collect the light from the chamber that constitutes the big advantage of this system with respect to those that read the chamber information by sampling the charge deposited at a wire matrix. In fact, the last solution supposes the simultaneous reading of all the wires; for this an immense amount of electronics is needed.

On the contrary, the CCD has a built-in multiplexing feature, thus having only one output. The images can also be viewed directly on a TV monitor or digitized for further processing. Another advantage of CCD's is their large dynamic range, ~ 2000.
We used a CCD matrix of 144 x 208 pixels, with a pixel size of 30 μm x 28 μm. The projected pixel size on the chamber's anode is 1.1 mm x 1 mm, which gives the limit of the spatial resolution of the system.

The coupling of the CCD to the taper is made through a FO window that is glued over the chip at manufacture. This is absolutely needed if we want to bring the image onto the CCD via a FOT instead of a lens. The FO window gluing has to be done carefully because the light source's image (at the end of the fibers in this case) must be very near the silicon's surface, otherwise the image will appear defocused.

The CCD we used has an anti-blooming feature that can be used to fast-clear it. The blooming effect appears when an overexposed pixel leaks electrons to the adjacent pixels, blurring the image. To avoid this, the manufacturers added to each pixel a kind of diode, kept at a constant voltage, that becomes conductive if the number of electrons in that pixel becomes too large. The applied voltage determines the maximum number of electrons in each pixel.

If, in an exposed CCD, we put these diodes at a convenient potential, the electrons in each pixel will leak to ground, thereby clearing the image. This can be done as fast as 1 μs, in contrast with the several milliseconds needed to read (and clear) the CCD. The practical importance of this feature is that in particle physics experiments there are usually a large fraction of background events that we do not want to read out. They can be discarded by fast-clearing the CCD, making the system ready for the next event in a time far shorter than the one needed to clear the CCD by reading it.

4. **PERFORMANCES OF THE OPTO-ELECTRONICS CHAIN**

4.1 **Gain**

The combined optical gain of the complete set-up is 360, this being the ratio of taper output image brightness to the screen image brightness. The gain – in units (w/cm²)/(w/cm²) – is distributed among the several stages as follows (Appendix):

- lens 0.0041,
- first II 15,
- second II 16000,
- taper 0.37.
This optical gain combined with the CCD's sensitivity of 1.4 \text{ V/\mu J/cm}^2 leads to an electro-optical gain of 2.8 \times 10^{-8} \text{ V/(photon/mm}^2). This means that the output voltage of a pixel that images an area of the chamber's anode, where one photon per square millimetre is emitted during the integration time of the CCD, will be 2.8 \times 10^{-8} \text{ V.}

From the values above we can see that the lens is by far the worst element of the chain and, as said before, the first II has a small gain, its primary function being wavelength conversion.

The photon density on the track left by a Minimum Ionizing Particle (MIP) is 8.6 \times 10^5 \text{ photon/mm}^2, corresponding to an output of 24 \text{ mV} in the pixels imaging that track. This voltage is in the linear region of the CCD, between the noise and saturation levels, and is proportional to the particle's energy loss dE/dx.

4.2 The resolution

The limiting spatial resolution of the chain is imposed by the CCD because of the sharp cut at the Nyquist frequency. Since the pixel dimensions are 30 \text{ \mu m} \times 28 \text{ \mu m}, the vertical and horizontal resolutions turn out to be respectively 16 \text{ lp/mm} and 18 \text{ lp/mm} over the CCD. At the Nyquist frequency, just before the sharp cut, the CCD has a contrast of 50%.

Over the chamber's anode we have a limiting resolution of respectively 0.46 \text{ lp/mm} and 0.51 \text{ lp/mm} at 30\% contrast, considering the image degradation from the other elements in the chain. Above these spatial frequencies we cross the Nyquist frequency and no object can be identified.

5. RESULTS

The following images (figs 1-2) have been photographed from a video display connected to the CCD camera.

In fig. 1 we can see two pions passing through the chamber, one of them producing several $\delta$-electrons. One of those electrons, by chance, goes through a circular path that ends near the track of the pion.
In fig. 2 several pions cross the chamber from left to right. One of them interacts just before entering the chamber, producing three particles that can be detected by their non-parallel tracks, converging to a common vertex.

Fig. 1

Fig. 2

6. IMAGE PROCESSING

To use the full information contained in the CCD images, we used an IBM PC AT equipped with image processing hardware from Data Translation. This hardware consisted of a DT2851 Frame Grabber, capable of digitising TV pictures with a resolution of 512 * 512 * 8 bit pixels and a DT285B Auxiliary Frame Processor. The frame grabber can display images in R-G-B false colour, allowing us to show different ionization intensities as different colours. This greatly enhances the information
content of the images compared to black and white pictures. In addition, the DT2851 can process images in real time, e.g. by subtracting pedestals to reduce noise. For higher level image processing, like N x M convolutions, the DT2851 frame grabber interfaces to the DT2858 Auxiliary Frame Processor.

We have written software which allows to do the following:

(a) Digitize images.
(b) Enhance image contrast and display false colour images.
(c) Write digitized images to disk in a compressed format.
(d) Print false colour images on an IBM Colour Ink Jet Printer.
(e) Histogram grey levels for the full image.
(f) Do simple track fitting.
(g) Histogram grey levels along selected tracks.

As an example, we show in fig. 3(a) an image from alpha particle tracks with in fig. 3(b) the histogram of grey levels along the indicated track. This histogram closely resembles the Bragg curve for the ionization along an alpha particle track, which gives us confidence in the linearity of the system and in our ability to do ionization measurements. Although these first results are very encouraging, further study is necessary to calibrate and fully understand the system.
7. **FUTURE DEVELOPMENTS**

7.1 **The objective**

The light gathering power of a lens goes like the inverse square of the $F/#$. Some tradeoff exists between $F/#$ and field depth, but in this application we have almost no field depth requirements because the image over the chamber's anode is less than 1 mm thick.

Therefore, it is desirable to have an objective with the smallest possible $F/#$, the practical limit being about or less than 1. This could represent a gain increase by a factor of 20.

The main problem in this area is that there are practically no UV objectives available off-the-shelf in the industry, calling for a customized design. This rises the prototype cost to a high level, making any improvement rather expensive.

7.2 **The image intensifiers**

The actual system has several drawbacks at the level of the IIIs. We are using a two-stage system, each one having a different role:

(a) The first II is a wavelength converter and has a low gain.
(b) The second II is responsible for system's gain, but insensitive to UV light.

This solution is neither efficient nor economical. Also there are some light losses in the coupling between stages. This suggests the use of a single high-gain II sensitive to UV light to replace the two element chain. This single II must have some special characteristics as stated below.

In particle physics experiments event rates are often very high. For instance, in the SPS proton-antiproton there is an event every 4 μs. Since the time between successive events is much smaller than the time needed to read out the CCD, one has to stop light from reaching the CCD during this readout period. In a MCP-II this is usually possible by dropping the voltage between the photocathode and the entry of the MCP. In this case electrons from the photocathode cannot reach the MCP and the image is therefore not transmitted.

In the present system the first II is not gateable at all and the second, being of a type suitable to be gated, has a built-in power supply that we cannot switch fast
enough. So the future II should be of a type suitable for fast gating in order to produce single event images of the Imaging Chamber.

Another constraint in a particle physics application is that usually only a small fraction of the events are interesting and have to be recorded. Therefore, if an event is rejected, we want to be able to clear the detector as fast as possible, to be ready for the next event. In our case this is possible by using the fast clear feature of the CCD, on the condition that the image on the phosphor of the II has disappeared. In other words, the persistence of the phosphor must be shorter than the time between events.

The P20 phosphor of the MCP II in the present set-up has a persistence on the order of 10 ms, making it unsuitable for any application that requires some speed. Therefore, the next system must have a fast phosphor, P46 or other, that suits it to fast data erasing. Since this II is supposed to be coupled to a CCD, it is desirable to have its phosphor emitting at a wavelength matching as much as possible the spectral peak sensitivity of the CCD: A "red" phosphor.

Resuming, the good II for Imaging Chamber readout should have the following characteristics:
- UV sensitive,
- gateable,
- high-gain,
- fast "red" phosphor and
- cheap.

It is impossible to reach all these characteristics in a realistic II, but industry supplies IIs having characteristics close to these. Their IIs are UV sensitive, gateable, have high gain, a fast green phosphor and are reasonably expensive.

7.3 The taper

Active II tapers that reduce the image's size while enhancing its contrast by a factor of ~ 10 are available in the industry. This would substitute with advantage the actual passive FOT which has insertion and transmission losses by a factor of ~ 2.

7.4 The charge coupled device

The main improvements to be done at the CCD level concern the upgrading of present features and not the inclusion of something new. In fact, we are using a
somewhat special CCD. The inclusion of a FO window and the need of an anti-
blooming fast enough for our purposes reduces considerably the possible choices of
this device from the range offered by the industry.

The CCD we use has a very modest number of pixels (144 x 208) compared with
the usual number of pixels of the industrial CCDs (~ 300 x 350) or the state-
of-the-art CCDs reaching to the Megapixel. This makes the CCD the worst element
of the chain in terms of detail resolution and it would be convenient to use a bigger
CCD.

Also it would be convenient to reduce the readout and fast-clear times in order
to get higher data acquisition rates.

Of course these improvements depend on the potential of the industry to manu-
facture such devices at a reasonable price. Recently, some II-CCD assemblies with
FOT coupling have become available as standard products which extend the number
of pixels to 288 x 550 with fast-clear and 384 x 576 without fast-clear.

8. CONCLUSION

We have been able to successfully develop an UV Image Intensification System,
with enough performance to achieve good results in the optical readout of Parallel
Plate Proportional Imaging Chamber (PPPIC). It is already foreseen to use the sys-
tem in several branches of Particle Physics. Some performance enhancements are
possible using actual state-of-the-art opto-electronic components, allowing this
image amplifier to be used in even more demanding applications.
A1. THE GAIN OF IMAGE INTENSIFIER CHAINS

The important gain parameter of an II chain is the power per unit area gain, or the ratio of light’s power density at the output by the power density at the input. That is because the output of most imaging light detectors, eye included, is proportional to brightness (light concentration) and not to the total energy flowing out of a surface. We define an amplification stage to be everything which lies between successive output planes of IIs. The total system’s gain is then

\[ G_{te} = \pi \sum_{i=1}^{N} C(i-1, i) \cdot \alpha(K(i), P(i-1)) \cdot Gw^o(i) / M(i), \]

where,

- \( N \) is the number of IIs;
- \( C(i-1, i) \) is the coupling loss factor introduced by the coupling elements of the ith stage; it depends on i-1 because it is influenced by the angular and spectral distribution of the light coming from the previous II;
- \( \alpha(K(i), P(i-1)) \) is the spectral matching factor between the phosphor \( P \) of the i-1 II to the photocathode \( K \) responsivity of the ith II;
- \( Gw^o(i) \) is the intrinsic gain of the ith II;
- \( M(i) \) is the geometrical magnification of the ith stage. That is the ratio of output to input linear image dimensions;
- \( G_{te} \) is the total radiant emittance gain of the system.

Since IIs are not equally sensitive over the whole spectrum, their gain depends on the spectral distribution of the light coming from the preceding stage. This dependence is summarized in the source-detector spectral matching factor \([9]\) defined as

\[ \alpha(det, source) = \int_0^{\infty} \sigma(det) \cdot w(source) \, dl / \int_0^{\infty} w(source) \, dl, \]
where $\sigma$ is the relative spectral sensitivity of the detector and $w$ is the relative spectral distribution of the source's light. By relative is meant that the peak relative spectral distribution/sensitivity is one. Both are dependent on the wavelength $\lambda$.

To characterize the gain of an II independently of the incoming light, we define his intrinsic gain as being the gain of the II when illuminated by a monochromatic light source at the wavelength of maximum sensitivity. If the gain is measured in radiometric units, watt from now on, this coincides with the maximum gain of the II, $G_w^0$. The power gain of an II imaging some light source is then

$$G_w = \alpha(\text{photocathode, source}) \cdot G_w^0.$$  

The coupling elements are usually lenses or FO light guides. The light gathering efficiencies of these elements is proportional to the square of their numerical apertures.

For a lens (or objective) the coupling loss factor is

$$C(\text{lens}) = m^2 \cdot \frac{T}{(4 \cdot F^2 \cdot (m + 1)^2)},$$

where $m$ is the linear geometrical magnification between image and object, $F$ is the lens $F/\#$ and $T$ is the lens transmissivity.

For a FOT the coupling loss factor is

$$C(\text{taper}) = (D_n/D_w)^2 \cdot (A_n/A)^2,$$

where $D_n$ and $D_w$ are respectively the diameters of the narrow and wide sides of the taper and $A_n$ the taper's narrow side numerical aperture. $A$ is the numerical aperture of the FO window from which the taper is supposed to receive the light. The light is supposed to flow from the wide to the narrow side of the taper.

The above two formulas apply to Lambertian light sources or, what is the same, to phosphor screens.

A2. **THE CAMERA**

In the following images (figs 4–8), we can see some aspects of the total assembly as well as some individual parts.
In fig. 4 we can see the exterior aspect of the assembly, composed by the UV objective and the body, containing the II's, the taper and the CCD. The pins of it are accessible in the rear where some of the CCD's drive electronics are directly plugged. The cable connects to the rest of the electronics. The assembly is 40 cm long, with a diameter of 10 cm and weights 1.5 kg.

The individual parts of the chain are displayed in fig. 5, showing (dismounted) the first II (wavelength converter), the second II (the black cylinder) and the FOT (the white cylinder between the two metallic flanges). The CCD is mounted in the second metallic flange.
A closer look at the assembly (fig. 6), showing the CCD drive electronics.

The two next images (figs 7 and 8) show us the FOT and the imaging properties of it; in this case, when viewed from the wide side. Usually it is used in the opposite direction, as a demagnifier.
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Fig. 8
REFERENCES


