CERN–PPE/94–212
19 December 1994
CERN–LAA/SF/94-34
7 December 1994

# POSITION SENSITIVE PHOTONCOUNTING WITH AN ISPA-TUBE

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## Abstract

The newly developed Imaging Silicon Pixel Array (ISPA)-tube consists of a photocathode viewed at 30 mm distance by a silicon chip, which contains 1024 pixels with 75 µm x 500 µm edges. With this tube we imaged, as an example of a weak light source, β-tracks ($^{90}$Sr) traversing a fused square bundle (2.5 mm edges), which contains 1600 individual scintillating fibres of 60 µm transverse dimension. Simultaneously we counted the number of photoelectrons/mm (hit density) at different source positions along the 2 m fibre bundle, with potential differences varying from 10 kV to 26 kV between photocathode and pixel anode of the ISPA-tube, and at different threshold settings of the pixel chip. The obtained hit densities are compared with those measured with a Hybrid Photomultiplier Tube (HPMT), which contains a silicon pin diode as anode instead of a pixel chip.

## INTRODUCTION

In two recent papers [1, 2], we reported on the first successful applications of an Imaging Silicon Pixel Array (ISPA)-tube[#1]. Fig. 1 shows a photograph (a) and the layout (b) of a magnetic focussed ISPA-prototype[#2]. It represents a vacuum sealed cylinder of 40 mm length and 35 mm diameter, which encloses a 18 mm diameter photocathode evaporated onto an optical fibre window for collimated light passage. This photocathode is at 30 mm distance viewed by a 8 mm × 4.8 mm area silicon chip[#3] , containing 1024 pixels of 75 μm × 500 μm size[#4]. Each pixel is bump-bonded to its individual front-end electronics, composed of preamplifier, comparator, delay line, coincidence logic and memory element, providing a binary response to the photoelectrons [3, 4][#5]. The pixels are readout in a parallel line mode[#6]. The delay-lines permits triggering and the strobed output allows for gating the ISPA-tube. A potential difference accelerates the photoelectrons from the photocathode towards the anode chip.

As an example for a weak light source, we used photons from scintillating plastic fibres of 60 μm transverse dimension arranged in a coherently fused bundle[#7] of square cross-sections with 2.5 mm edges [5 ] and 2 m length. This bundle was closely attached to the fibre optic window of the ISPA-tube. It contains 1600 fibres separated from each other by a fluorinated polymethacrylate cladding [6 ].

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[#1] Assembled and manufactured by BV Delft Electronische Producten (DEP), NL-9300 AB Roden, The Netherlands. The chip was wire bonded at U.C.I. Microélectronique, F-91946 Les Ulis, France.

[#2] ISPA-tube prototypes with electrostatic or proximity focussing are also envisaged, depending on the applications considered.

[#3] In front of the chip a diaphragm limits the active chip surface to 7 mm x 4 mm.

[#4] These are the pixel dimensions presently available. In future, they could be adapted to the needs of the experimental applications.

[#5] We are indebted to E. H. M. Heijne, who kindly provided us with the silicon chip. The CERN-ECP Microelectronics group designed it and supervised its manufacturing at different places: Canberra Semiconductor NV, B-2430 Olen, Belgium (silicon pixel array); GEC-Marconi Materials Technology Ltd, Caswell Towchester NN 128 EQ, United Kingdom (bump bonding); Smart Silicon System SA, CH-1012 Lausanne, Switzerland (electronics).

[#6] The 64 columns of 16 pixels can be readout at a frequency of 5 to 10 MHz, resulting in readout times of 6 to 12 μs.

[#7] Produced by Kuraray Co. Ltd, Tokyo, Japan.

## EXPERIMENTAL ARRANGEMENT

The experimental arrangement was very similar to that of photoelectron counting with an HPMT [7] and is displayed in fig. 2a . It is based on $\beta^-$- particles emitted from a 37 MBq $^{90}$Sr source located in Plexiglas (fig. 2b) to avoid noticeable Bremsstrahlung contribution. The electrons were collimated through a 8 mm long and 0.6 mm wide slit (figs 2b, 3 and 4) before they traversed the fibre bundle stretched along the groove in an aluminium bench above the source. Minimum ionizing betas were selected by two photomultipliers viewing in coincidence a common piece of plastic scintillator arranged above the fibre bundle. The coincidence counters had threshold settings to accept only photoelectrons arising from minimum ionizing betas with kinetic energies between 0.8 MeV and 2.8 MeV (endpoint energy of the $^{90}$Y-spectrum). The photons reaching one end of the fibre bundle were detected with the ISPA tube gated by the coincidence signals of the two photomultipliers H1 and H2.

An important feature of the electronic chip is its adjustable threshold setting, common to all pixels of the chip. It cuts all signals lower than the wanted threshold energy $E_{thr}$. The whole pixel array shows a threshold distribution with, in our case, a measured standard deviation ($\sigma_{thr}$) of about 3.4 keV (equivalent to 940 electron-hole pairs). This requires a careful threshold setting for the chip, which must take into account this distribution. Too low a setting will cause several pixels to fire because of electronic noise. Too high a setting will prevent many pixels to fire with the wanted photoelectron signals.

The number of photoelectrons k generated at the photocathode per track follows a Poisson distribution with average <k> (see rel. 3 in ref.[7]). This is related to the measured average number of pixels firing per track <p> via the relation :

$$<k> = -N \ \ln\left(1 - \frac{<p>}{N}\right) \qquad (1)$$

where N is the number of pixels within one pixel column (33 in our case) facing a track through the fibre bundle. Both numbers <k> and <p> depend on the source distance from the photocathode. The ratio <k>/<p> indicates finally, how many photoelectrons hit in average one firing pixel. This gives us the correction factor to be applied on the measured hit density, which varies between approximately 1.12 (at 0.2 m source distance) and 1.02 (at 2 m source distance).

## MEASUREMENTS AND RESULTS

Fig. 3 shows a sample of electron tracks through the fibre bundle. The ISPA-tube was not operated in a magnetic field and its silicon chip was oriented in such a way, that the electron beam direction was along the 75 μm pixel widths i.e. normal to the 500 μm pixel lengths. This resulted in better granularity for hit-counting and reduced as much as possible multiple hits within a pixel. Fig. 4 displays the result of integrating $10^4$ tracks on one picture. It can be seen that most of them go through the two central pixel rows viewed by the collimating slit. Average multiple scattering angles for three track positions are also indicated and show that the pixel hits outside the two central rows are due to multiple scattering of betas during their passage through the fibre bundle. The few hits outside the indicated fibre bundle cross-section are due to the absence of magnetic focussing.

Fig. 5 shows the relation between the counted photoelectrons per mm (hit densities) and the applied acceleration potential between photocathode and silicon chip anode. The source was positioned at 0.2 m fibre distance from the photocathode. The parameters in fig. 5 are the threshold potential settings for the silicon chip. Since the creation of one electron-hole pair requires on average 3.6 eV energy deposition in silicon, the acceleration potentials can be calibrated in numbers of created electron-hole pairs. In our case, we must deduce the energy lost in an insensitive silicon layer of 0.5 μm, which ranges between 2.7 and 1.0 keV energy loss, depending on the photoelectron energy.

The hit densities for different pixel thresholds are plotted versus the source position (distance from the light detecting ISPA-photocathode) in fig. 6 for 25 kV potential difference. They were evaluated by summing up all pixel hits of $10^4$ tracks at each indicated source position, correcting them for multiple hits per pixel (ratio <k>/<p>), and dividing them by the thickness (2.5 mm) of the fibre bundle. The full lines are from light attenuation measurements with the same fibre bundle (this measuring procedure is explained in refs [6, 7] ). The measured ISPA-points fit to the normalized attenuation curves.

## DISCUSSION

The indicated measuring points fit to the drawn curves in fig. 5, which represent the relation between the average number of firing pixels per track <p> and the average number <k> of photoelectrons hitting the pixels per track :

$$\langle p \rangle = \langle k \rangle \; F\,(E_0, E_{thr}, \alpha) \qquad (2)$$

The function F represents the convolution of all charges released in the individual pixels from photoelectrons of energy $E_0$ [keV] and the distribution of pixel thresholds $E_{thr}$ [keV] (number of electron-hole pairs × 3.6 eV):

$$F\left(E_0\ ,\ E_{thr},\ \alpha\right) = (1-\alpha)\int_0^{E_0} G(E)\ dE + \alpha\int_0^{E_0} D(E)\ G(E)\ dE \qquad (3)$$

$$G(E) = \sqrt{2\pi}\ \sigma_{thr}\ e^{-\left(E-E_{thr}\right)^2/2\sigma_{thr}^2} \qquad (4)$$

where $\sigma_{thr}$ (3.4 keV=940 electron-hole pairs) is the standard deviation of the threshold distribution for all pixels of the silicon chip, D(E) represents the distribution of energies deposited in the pixels by the backscattered photoelectrons and $\alpha \approx 0.2$ is the electron backscattering coefficient for silicon (see refs [7, 8]).

The first integral in relation (3) represents the contribution of non-backscattered photoelectrons ($1-\alpha \approx 0.8$), and the second one that of backscattered photoelectrons, which deposit energies exceeding the threshold energies of the pixels in question (relation (4)). From fig. 5 we learn, that due to the threshold distribution of the pixels ($\sigma_{thr}$ = 3.4 keV), there exists no well defined threshold energy (step function) for the whole pixel array. Single pixels feature however sharper thresholds, but centered at different potentials as shown in fig. 7. Therefore, the hit densities (fig. 5) approach a plateau in an asymptotic way only, which finally indicates the hit density of an ISPA-tube not limited by a maximum potential difference (25 kV). The asymtotic value for 2.6 V threshold setting is ≈ 3.6 photoelectrons per mm.

The hit densities in fig. 6 must be compared to the average value obtained with HPMT-measurements (5.75 $\mathrm{mm}^{-1}$ at 0.20 m, table 2 in ref. [9]). The difference is partly due to photoelectron backscattering, where only the small deposition $E>E_{thr}$ (relation (4)) contributes to the hit density, and partly from reduced light transmission through the fibre optic window of the ISPA tube as compared to the clear glass-window of the HPMT.

## CONCLUSIONS

To conclude, we have counted single photoelectrons in a position sensitive way with an ISPA-tube. This is in particular relevant, if structures of weak light sources are to be resolved, e.g. in astronomy, biology, medicine. As a first step into this last application, we are going to test the spatial resolution achievable with $\gamma$–rays, detected by appropriate inorganic crystal configurations and the ISPA-tube.

The characteristics of the ISPA-tube are mainly dictated by its anode chip. The ISPA-tube spatial resolution depends on the pixel size, and its electronic background on the uniformity of the individual pixel responses. Future improvements of this uniformity will allow ISPA-tube operations at considerably lower potential differences (10 kV ÷ 15 kV) with an efficiency equal to the reported one.

## ACKNOWLEDGEMENTS

We are indebted to Prof. A. Zichichi for his continuous interest and generous support of our work. We thank E. Heijne and M. Campbell for their advices. We also thank F. Cindolo for his help in software and hardware, and A. Menchikov for re-designing part of the data acquisition electronics.

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## FIGURE CAPTIONS

Fig. 1 a) Photograph and b) schematic diagramme of the ISPA-tube.

Fig. 2 a) Schematic experimental arrangement with block diagramme of the electronic components.

b) Source and its containment together with the coincidence counters H1 and H2: (1) $^{90}$Sr source; (2) collimators (two slits of 1 mm and 0.6 mm width and 2.5 mm and 8 mm length, resp.); (3) common support structure for source and coincidence units ; (4) bench, housing the fibre bundle (5) in its groove; (6) light guides from scintillator piece (7) (with (8) inactive β-filter of 1 mm thickness) leading to the two PM R 1635 (9).

Fig. 3 β-tracks traversing the fibre bundle imaged with the ISPA-tube which faces the bundle (dashed squares), and the collimator slits of the $^{90}$Sr-source.

Fig. 4 Integration of $10^4$ β-tracks. Most tracks are imaged with the two central pixel rows, corresponding to the collimator-slit of the $^{90}$Sr-source. Three multiple scattering angles at 0.5 mm, 1 mm, and 1.5 mm track length, show roughly possible track deviations caused by this effect. The halo around the bundle cross-section is in addition due to the missing magnetic focussing of the ISPA-tube, which causes deviations for a few photoelectrons from their correct paths. The extreme grey levels differ by roughly a factor of ten.

Fig. 5 Hit densities measured (points) with different threshold settings of the chip array at 0.2 m $^{90}$Sr-source distance from the ISPA-photocathode. The drawn curves, calculated from eqs. 3 and 4, allow an extrapolation to potential differences exceeding the limit of 25 kV imposed by the manufacturer[#1]. The zero shift for the number of created electron-hole pairs takes the silicon dead layer (0.5 μm) into account.

Fig. 6 Hit densities of the fibre bundle for different threshold settings of the chip array versus the $^{90}$Sr-source distance from the ISPA-photocathode. The measuring points follow the normalized attenuation curves measured for the same bunlde with the anode current of a photomultiplier according to the procedure described in ref. [6].

Fig. 7 Dependence of two individual pixel-counts from the potential difference between photocathode and chip anode. The convolution of all pixel responses of the chip array finally results in the hit density curves of fig. 5. The counts below the threshold setting are partly due to the integrated Gaussian distribution of single hits and partly due to signals from double hits within the same pixel (which provide almost twice the charge and therefore overcome the threshold setting). The standard deviation ($\sigma = 1.3$ keV) for each pixel differs considerably from the convoluted $\sigma_{thr} = 3.4$ keVfor the whole pixel array.