

# First test measurements of a 64k pixel readout chip working in single photon counting mode

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## Abstract

The Medipix2 chip is a pixel detector readout chip consisting of 256 x 256 identical elements, each working in single photon counting mode for positive or negative input charge signals. The chip is designed and manufactured in a 6-metal 0.25  $\mu\text{m}$  CMOS technology. This paper describes several electrical measurements which have been carried out on the chip prior to detector bump bonding using a dedicated readout system. Threshold linearity and variation has been measured for both electron and hole collection. The noise is  $\sim 100 e^-$  rms and the threshold can be adjusted to  $\sim 120 e^-$  rms for both polarities. The minimum operating threshold is  $\sim 1000 e^-$ .

**Keywords:** photon counting, pixel, CMOS, X-rays, Medipix.

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## 1 Introduction

There is growing interest in the application of pixel detector technology to fields outside of elementary particle physics. In response to this interest a number of developments are taking place which are well summarized in [1]. One of the most ambitious of these developments is the Medipix2 chip [2] which has been supported by a large multi-national collaboration [3]. In this paper we report on first detailed measurements of the electrical behaviour of the chip. In particular, measurements of the noise, threshold variation and minimum threshold are presented.

## 2 Brief review of the chip architecture

The Medipix2 chip is composed mainly of an *active area* of 256 x 256 pixels. Each pixel measures 55 x 55  $\mu\text{m}^2$  resulting in a total sensitive detection area of 1.98  $\text{cm}^2$  representing 87 % of the entire chip area. The *periphery* includes the IO control logic, 13 8-bit DACs and 127 IO wire-bonding pads. The *periphery* is placed at one side of the chip allowing for three-side buttability. Most of the wire bonding pads are arranged in a single row but there are also 5 lateral IO wire-bonding pads which can be used to make a daisy chain between neighbouring chips. In a multi-chip configuration, an example of which is shown in Figure 1, there would be no dead area between neighbouring chips but there is a slight loss in spatial resolution as two 165  $\mu\text{m}$  wide pixel rows and columns are used to cover the unavoidable gaps between the chips.

Both the analog and digital circuits have been designed to operate with independent 2.2 V power supplies with a total analog power consumption of  $\sim 500$  mW. The digital power consumption varies as a function of the readout frequency and peaks during the readout phase. Using an 80MHz clock the peak digital consumption is  $\sim 100$  mW. The chip contains around 33 million transistors.

## 2.1 Pixel Cell

The pixel cell works in photon counting mode. When a charged particle interacts in the detector material it deposits a charge which drifts towards the collection electrode. This charge is then amplified and compared with two different thresholds that form an energy window. If the detected charge falls inside this energy window a 13-bit digital counter is incremented. If the high threshold is set below the level of the low threshold all hits above the low threshold are counted. Figure 2 shows the schematic of the Medipix2 pixel cell.

The Pixel has two working modes depending on the CMOS input *Shutter* state. When the *Shutter* signal is low the pixel is in acquisition mode. In this case, the output of the double discrimination logic is used as the clock of the counter as described above. When the *Shutter* is high an external clock is used to shift the data from pixel to pixel.

Each pixel has eight independent configuration bits. Six of them are used for the fine threshold adjustment (three bits for each discriminator), one for pixel masking, and one to enable the input charge test through the 8 fF on-pixel capacitance. Each pixel has 504 transistors and a static power consumption of  $\sim 8 \mu\text{W}$ . Particular care has been taken in the design in order to minimize any systematic deviations in the behaviour of the cells as a consequence of effects such as top-down power supply voltage drops.

## 2.2 The Periphery

When the matrix is accessed to perform any IO operation the data is organized in 256 columns of 256 x 13 bits. Therefore each chip has 851968 bits to be read or written for any matrix IO operation. The *Medipix2* uses a high-speed *LVDS* (*Low Voltage Differential Signaling* [4]) logic for configuration and serial readout. Readout may also be carried out using a parallel 32-bit single-ended CMOS bus for applications requiring even higher frame rates. The setting of the configuration register in the matrix and of the

13 8-bit DACs is always done serially through the LVDS receivers. Using a clock of 100 MHz the matrix is readout in less than 9 ms through the serial port, while using the parallel option the readout is done in 266  $\mu$ s.

### **3 Electrical measurements on the matrix**

In order to characterize the electrical behaviour of the chip prior to detector bump bonding precise and complete measurements for both electron and hole collection have been carried out.

To perform these different measurements a dedicated readout system was used. The readout chain consists in a PC/PCI standard acquisition card sitting in a PC connected through a 68-pin cable to an interface card called Muros2 [5]. This card generates the various digital signals and analog voltages needed to operate the chip and acts as an interface between the chip and the PC. The Medipix2 chip is glued to a custom-designed chipboard and is in turn connected through a 64-pin VHDCI<sup>1</sup> cable to the Muros2 card. The full readout chain is controlled with specially designed software running under LabWindows [6] called Medisoft4 [7, 8].

An Agilent 81110A GPIB<sup>2</sup> controlled pulser generator was used to provide the precise electrical input pulse necessary to measure the performance of the pixels.

In order to estimate the injected charge in each pixel two parameters have been extracted from simulations. Firstly, the injection capacitance could not be calibrated, but only estimated from the data on layer-to-layer capacitance provided by the chip manufacturer. And secondly, the analog buffers used to transmit the external test pulse to each column have a certain attenuation that could not be measured but only estimated

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<sup>1</sup> VHDCI stands for Very High Digital Cable Interconnect

<sup>2</sup> GPIB stands for General Purpose Interface Bus. This bus is also known as IEEE-488.

from HSPICE simulations. All numbers given in electrons ( $e^-$ ) are based on these both estimates.

To extract the effective low and high thresholds as well as the electronic noise from each pixel the *hat-curve* method was used. Setting the low and high thresholds to a fixed value (usually through two internal 8-bit DACs) 1000 pulses were applied to each pixel and the counter value read out. The test input charge is gradually increased from no counter counts (under threshold) to 100% hits (inside energy window) and, for bigger input charges, to no counter counts (over threshold), see Figure 3. The effective low threshold is at 50% of the rising edge of this *hat-curve* while the effective high threshold is at 50% of the falling edge. The charge difference between 97.7% and the 2.3% in both slopes is four times the rms noise of the front-end seen for each discrimination branch assuming gaussian distributed noise. The electronic noise found for both thresholds and collection modes is  $\sim 100 e^-$  rms at the default preamplifier current. Tuning this current the electronic noise can be lowered to  $\sim 90 e^-$  rms.

It is possible to tune the threshold using the 3-bits available for each threshold in each pixel. However, since there are 65536 pixels in the matrix two assumptions have been made to speed up the threshold adjustment calculation procedure. Firstly, having one analog buffer to restore the calibration pulse for each column allows us to pulse all the columns and several rows at once. It has been found experimentally that pulsing 16 or less rows simultaneously the calculated threshold was unchanged. And secondly, as the average DNL<sup>3</sup> is less than 2% for all the 3-bit threshold adjustment current DACs present in the chip a linear interpolation between the code 0h (*LowCode*) and the code 7h (*HighCode*) has been made to calculate the intermediate adjustment distributions.

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<sup>3</sup> Differential non Linearity

In Figure 4 two plots are shown. The top plot shows the threshold adjustment distributions for negative charge collection; while the bottom one shows the same for positive charge collection. In each plot there are 2 histograms corresponding to the *LowCode* and the *HighCode* for the low unadjusted threshold and 2 histograms corresponding to the *LowCode* and the *HighCode* for the high unadjusted threshold. The mid point between the *LowCode* and *HighCode* distributions is the centre of the new adjusted distribution for each threshold. All the histograms are successfully fitted with a gaussian distribution. From each fit the threshold mean and sigma can be extracted. The sigma of the unadjusted threshold dispersion is around 450 e<sup>-</sup> rms for negative charges whilst for positive charge collection it is around 250 e<sup>-</sup> rms. Some systematic behaviour has been detected for electron collection. This is thought to be due to an unforeseen sensitivity of the discriminator to top-down power supply voltage drops for this polarity only. Nevertheless by tuning each pixel threshold with the 3-bit adjustment the systematic and random mismatches are corrected achieving a sigma around 120 e<sup>-</sup> rms for both thresholds and for each collection mode.

The threshold linearity is shown in Figure 5. Although the threshold setting should be linear up to 80 Ke<sup>-</sup> the threshold linearity scan was limited to injected charges up to 12 Ke<sup>-</sup> in order to work in the linear range of the external pulser. Each data point of the plot in Figure 5 shows the mean threshold and  $\pm 1\sigma$  of the threshold variation for different global low thresholds from 0 to 12 Ke<sup>-</sup> set using the internal THL 8-bit DAC. Note that the threshold variations indicated on this curve are subsequent to threshold tuning. For these measurements the chip was working in single discrimination mode. The measured non-linearity is less than 3% over the studied range.

An important measurement for applications that need to detect low energy particles is the effective minimum threshold. Applying the calculated equalization map the global

threshold can be lowered to a mean minimum of  $\sim 1000 e^-$  with a sigma of  $\sim 180 e^-$  rms for both collection modes. It may be possible to further reduce this variation with a more sophisticated threshold tuning procedure. Figure 6 shows the threshold distribution for electrons which has been tuned at around  $4000 e^-$  and then reduced to  $1100 e^-$ . Figure 7 shows an image taken with the Medisoft4.0 [7, 8] with the previous settings and injecting 1000 pulses of  $2 Ke^-$  simultaneously to the pixels selected by the Medipix2 and CERN logos while keeping all the rest of the pixels in the matrix unmasked. Some missing columns and one defective column are evident but the unpulsed pixels are otherwise quiet.

#### **4 Conclusions and future work**

The Medipix2 has been successfully measured and calibrated prior to bump bonding. The measurements done in the chip are in almost perfect agreement with simulations. The chip has a threshold variation of  $\sim 450 e^-$  rms for electron collection and  $\sim 250 e^-$  rms for hole collection before adjustment. After tuning the threshold variation is  $\sim 120 e^-$  rms for both collection polarities. The electronic noise is  $\sim 100 e^-$  rms depending on the amplifier biasing. The minimum threshold is  $\sim 1000 e^-$  for both polarities. The differential non-linearity of the threshold is less than 3% over  $12 Ke^-$ .

The first Medipix2 chips bump-bonded to Silicon detectors will be available shortly. It will then be possible to explore the potential of the chip for different applications. Moreover the new assemblies will permit a precise calibration of the values described in this paper. Looking ahead, 4-chip detectors (*Quads*) have been fabricated and are ready to be assembled to readout chips resulting in a total sensitive area of greater than  $8 cm^2$  with more than 256k active pixels.

In future larger areas should be covered. Using present day interconnect techniques one edge of the chip is always reserved for IO. It is becoming increasingly popular in the

microelectronics industry to drill holes through the readout chip to bring in power supplies and other signals anywhere across the chip surface. Such techniques may be applied in future pixel readout chip designs to obtain the desired 4-sided buttability.

## 5 Acknowledgments

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## Figures

Figure 1: Lateral and top view of a 4 chip structure. Between chips there will be special pixels 3 times longer than normal.

Figure 2: Schematic of the Medipix2 pixel cell.

Figure 3: *Hat-curve* for electron and hole collection. From the rising and falling edge of each curve and electronic noise of  $\sim 100 e^-$  rms can be extracted for both thresholds.

Figure 4: Electron collection (Top): 1.a: Adjusted low threshold, 1.b: Adjusted high threshold; 1.c: Unadjusted low threshold *LowCode*; 1.d: Unadjusted low threshold *HighCode*; 1.e: Unadjusted high threshold *HighCode*; 1.f: Unadjusted high threshold *LowCode*. Hole collection (Bottom): 2.a: Adjusted low threshold, 2.b: Adjusted high threshold; 2.c: Unadjusted low threshold *LowCode*; 2.d: Unadjusted low threshold *HighCode*; 2.e: Unadjusted high threshold *LowCode*; 2.f: Unadjusted high threshold *HighCode*.

Figure 5: Threshold linearity in electrons collection mode up to  $12 Ke^-$ .

Figure 6: Example of minimum threshold distribution in electron collection mode.

Figure 7: Image taken using the calculated threshold adjustment map and applying the logo mask to the Testbit. The rest of the matrix is unmasked, the equivalent low threshold is set at  $1.1 \text{ Ke}^-$  and 1000 pulses of  $2 \text{ Ke}^-$  were injected to each pixel simultaneously.

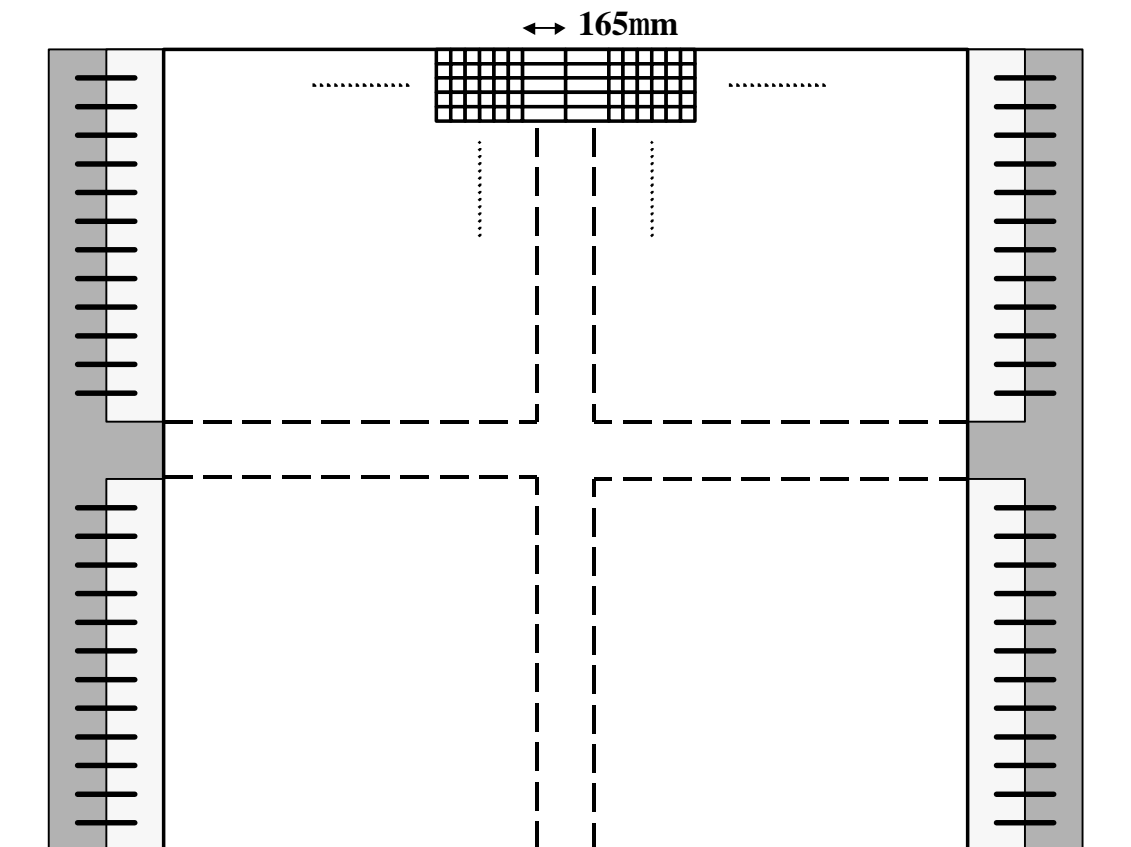
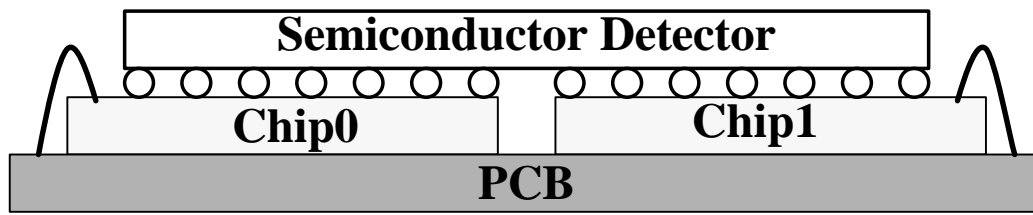


Figure 1

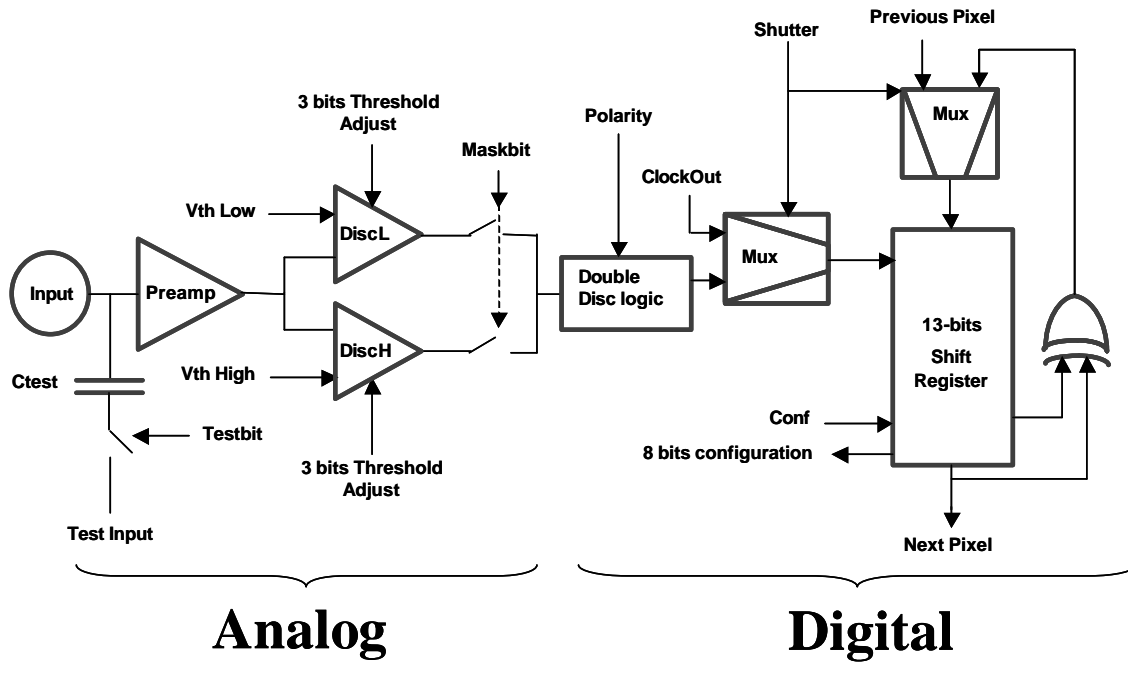


Figure 2

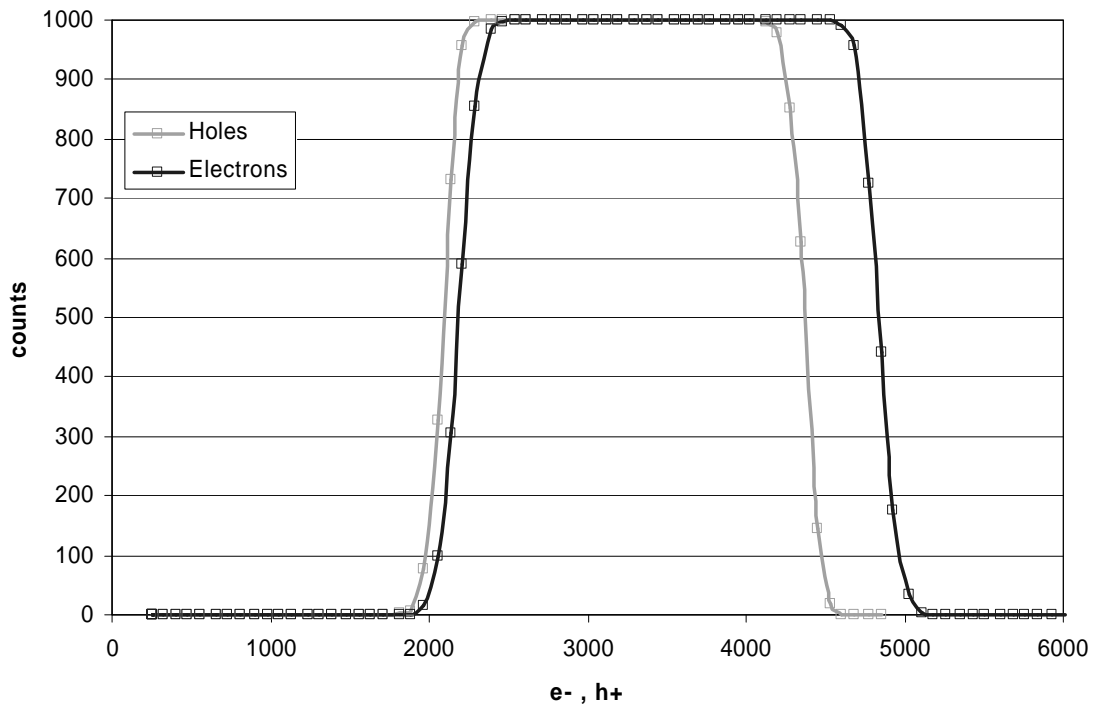


Figure 3

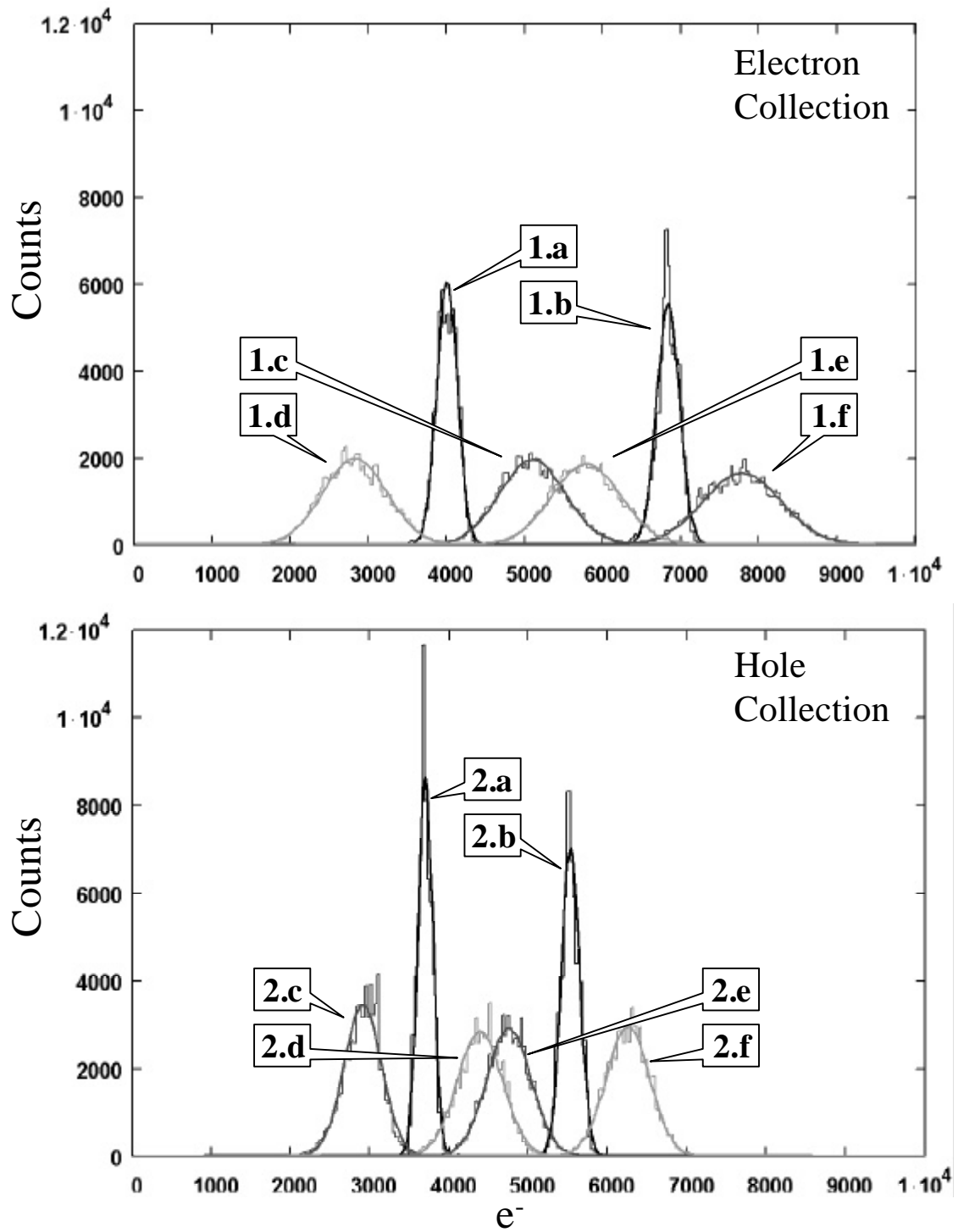


Figure 4

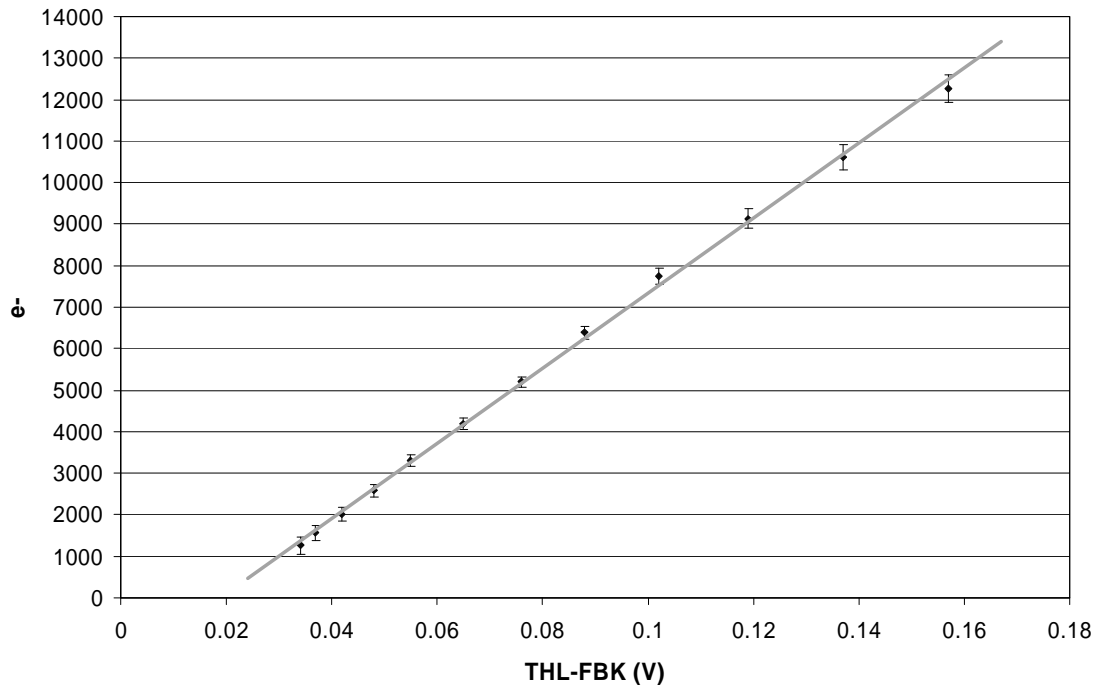


Figure 5

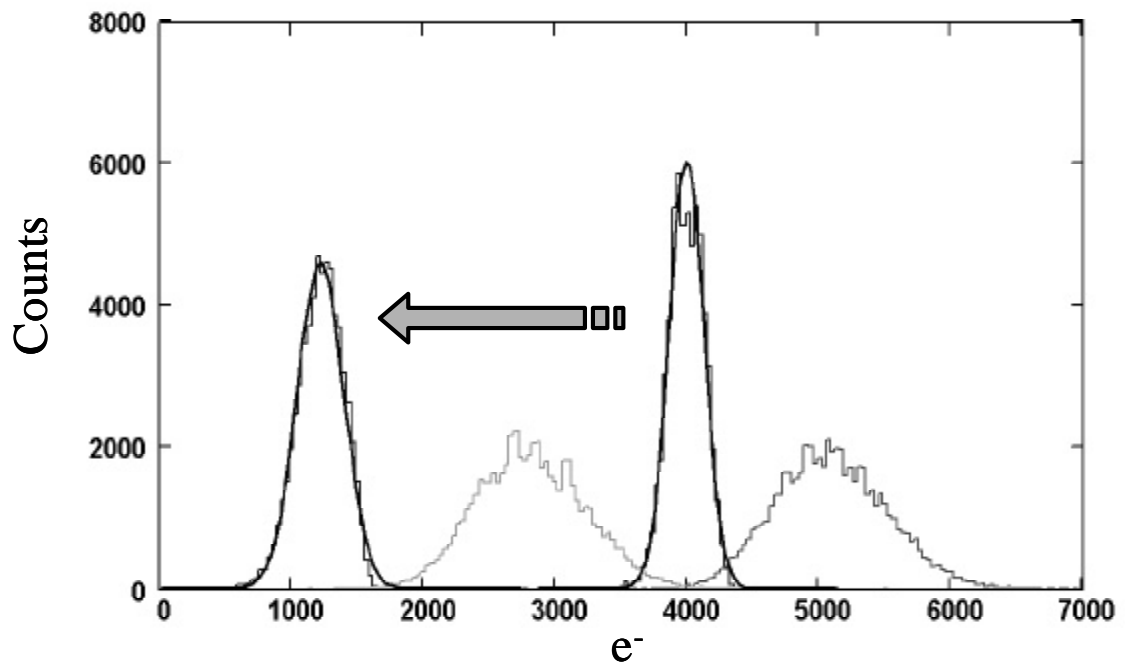


Figure 6

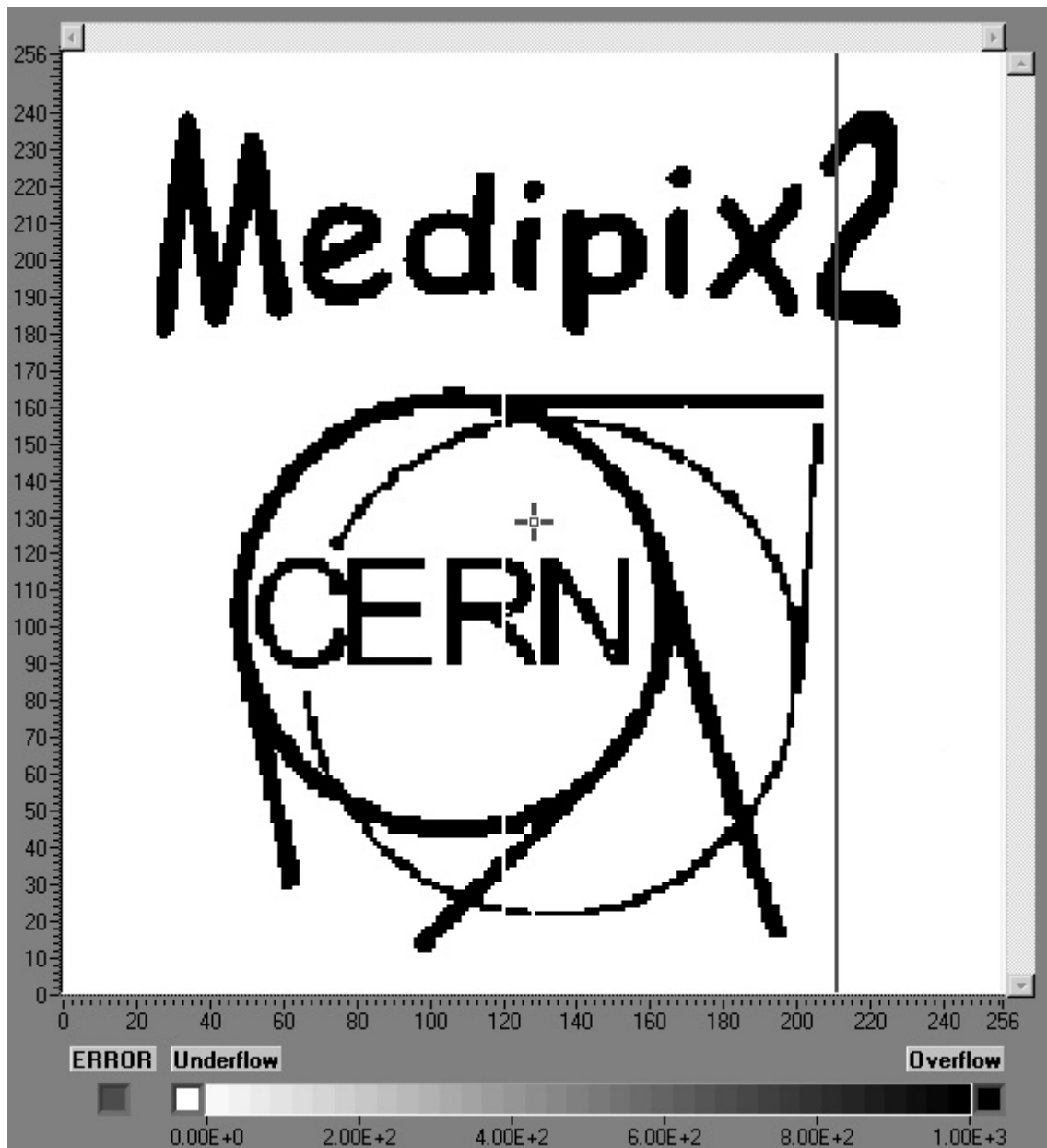


Figure 7