Beam tests of a CCD tracker for vertex detector application

T. Tsukamoto [a,⋆], T. Kuniya [a], H. Watanabe [a], A. Miyamoto [b], Y. Sugimoto [b], T. Ookawa [c], S. Takahashi [c], N. Tamura [c], N. Togashi [c], K. Abe [d], T. Nagamine [d], H. Sumiya [d]

[a] *Department of Physics, Saga University, Saga 840, Japan*

[b] *KEK, High Energy Accelerator Research Organization, Ibaraki 305, Japan*

[c] *Department of Physics, Niigata University, Niigata 950-21, Japan*

[d] *Department of Physics, Tohoku University, Sendai 980-77, Japan*

Abstract

We have studied the performance of a CCD tracker using minimum ionizing particles (MIP's) from KEK PS beam line. The detector consists of three layers of CCD sensors manufactured by Hamamatsu Photonics, which suppress the dark current at surface by one order of magnitude compared with that of the conventional ones. We have observed MIP's can be detected with sufficient signal to noise ratio even up to +5°C. The position resolution as well as the detection efficiency of this detector are also given.

1 Introduction

Vertex detectors will play a crucial role to investigate TeV physics at future linear colliders [1]. CCD (Charge Coupled Device) is one of the best candidates for this application because of its unambiguous reconstruction capability (2 dimensional pixels), less occupancy (large granularity) and less multiple scattering (thin detector)) [2].

For future linear collider application, we have been studying properties of CCD at room temperature in order to achieve a compact cooling system [3]. In addition to the reduction of the material for the cooling system, smaller difference of temperature between construction phase and operation enables one to keep the detector mechanically stable.

At room temperature, however, there has been difficulties to use CCD sensors as a tracker because of the increase of dark current. A novel method called as Multi Pinned Phase (MPP) operation is proposed to suppress the dark current [4]. We adopt a system manufactured by Hamamatsu Photonics which achieves MPP operation and succeeds in suppression of the thermal excitation of electrons at surface by factor 20 compared with normal non-inverted operation mode.

⋆ Corresponding author.
Tel: +81 952 28 8536; Fax: +81 952 28 8547;
E-mail: ttoshio@cc.saga-u.ac.jp

	CCD1	CCD2	CCD3
CCD active layer	S5466 10μm	S5466† 50μm	S5466 10μm
driver	C5934-1010	C5934-0909‡	C5934-1010

Table 1. Detector setup (†special made, ‡low gain).

2 Experiments

A CCD tracker is exposed to 1.6GeV pions extracted from 12GeV proton synchrotron (PS) at KEK. The detector consists of three layers of CCD chips (Hamamatsu S5466). Each chip has 512×512 pixels and the pixel size is 24μm×24μm. Two types of sensors which have different epitaxial layers; 10μm and 50μm, are used in the experiment (Table 1). CCD's are driven at a rate of 250kHz/pixel by the circuits C5934(Hamamatsu). It takes 1.3sec to read one frame including dummy pixels. Readout cycle of 4sec is also tried in order to synchronize with the PS cycle.

The detector is kept in a constant temperature box together with driving circuits. The data are taken at different temperatures, −15°C, −5°C, +5°C, +15°C and +25°C, with and without beam exposure. At each temperature, three impinging angles of the beam, 0°, 45° and 60° are chosen with respect to the direction perpendicular to the surface of the CCD detectors

3 Properties of the dark current

3.1 Temperature dependence

Thermal excitation of electrons in the bulk of silicon gives rise to the dark current and its temperature dependence is proportional to

$$T^2 \times exp\,(-\varepsilon_g/2k_BT)$$

where T is temperature in Kelvin, k_B is Boltzmann constant and ε_g is the energy gap of silicon which is given by $1.16-(7.02\times 10^{-4}T^{3/2})/(T+1108)$ eV [5].

We have performed 2 parameter fit by varying a normalization and allowing an offset of the temperature: $T \rightarrow T+\delta T$. As is shown in the Figure 1, the results fits very well to the formula. A slight difference from the measured temperature is seen, which indicates an offset of T is $+2.8\pm0.7K$.

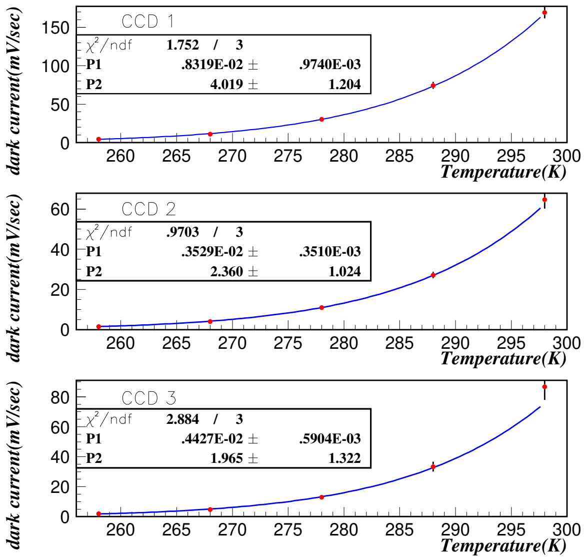

Fig. 1. Temperature dependence of the dark current.

3.2 Gain and readout noise

Data without beam exposure is used to define a "dark frame" which is the average of pedestals pixel by pixel. Due to the non-uniformity of the dark current among pixels, it is necessary to subtract this "dark frame" from data event by event bases. After the correction, we get Gaussian-shaped distributions of the dark current (Figure 2).

The width of this distribution (σ_{noise}) increases as temperature T gets higher, where the dominant source of noise is the fluctuation of the dark current. Together with the dark current itself ($Dark$), one can evaluate

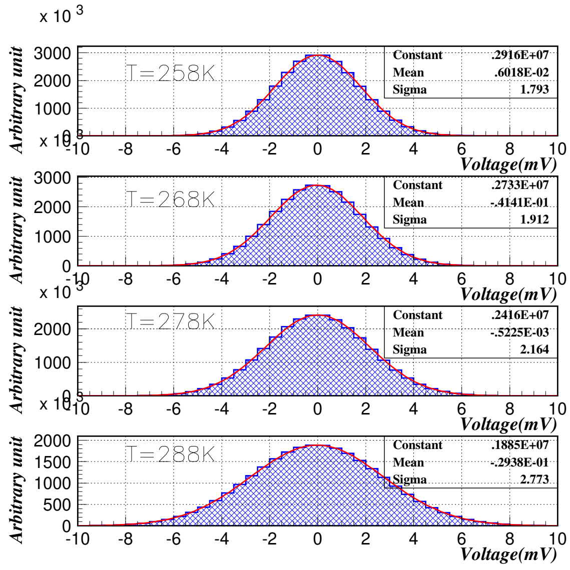

Fig. 2. Fluctuation of the dark frame at each temperature.

the gain ($Gain$) and the noise ($\sigma_{readout}$) of the system. Assuming Poisson fluctuation for the number of electrons excited thermally, one gets

$$\sigma^2_{noise}(T) = Gain \cdot Dark(T) + \sigma^2_{readout}$$

As is seen in Figure 3, measured points fit well to the formula.

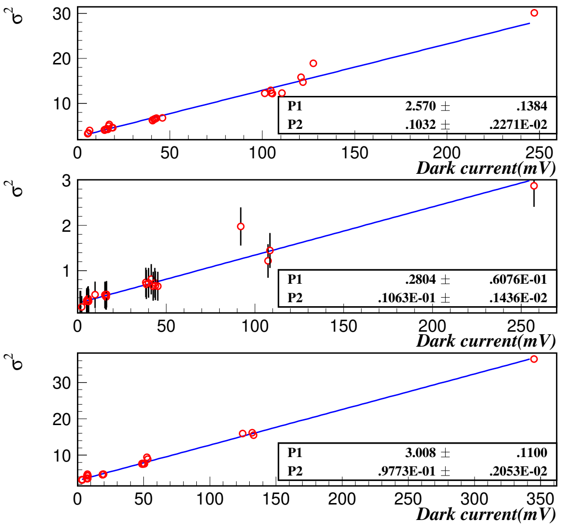

Fig. 3. Analysis of σ_{noise} versus dark current.

We obtain readout noise in mV to be 1.6±0.4, 0.5±0.3 and 1.7±0.3, for CCD1, CCD2 and CCD3, respectively. Gains in $\mu V/e^-$ are also estimated to be 103.2±2.3, 10.6±1.4 and 99.7±2.1, which are comparable with the direct calibration using $^{109}C_d$ (X-rays: 22keV, 26keV) 100.2±0.1, 9.6±0.1 and 112.6±0.1, for CCD1, CCD2 and CCD3, respectively.

4 Signal to noise ratio

Response to charged particles is examined by finding clusters in the CCD's. Clustering size is tried from 2×2 to 5×5 where the 2×2 is found to be sufficient for normal incident particles. Figure 4 shows the signal to noise ratio (S/N) measured at −15°C.

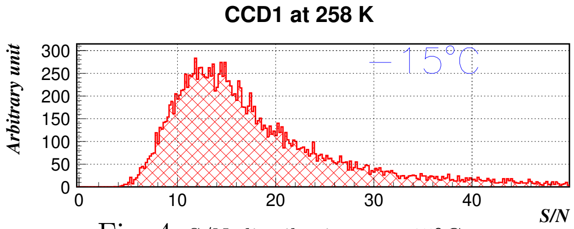

Fig. 4. S/N distribution at −15°C.

As the temperature increases, the S/N is affected by the increase of the dark current, which can be seen in the Figure 5. A sufficient performance with S/N more than 10, however, is obtained even up to +5°C.

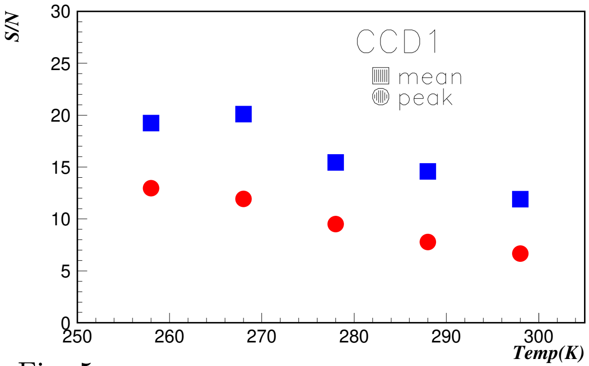

Fig. 5. S/N as a function of temperature with 1.3sec readout cycle.

Number of electrons generated is proportional to the path length of the charged particle in CCD's. Figure 6 demonstrates its dependence, where one can see the active layer of CCD2 is 5 times larger than that of CCD1 and CCD3. The number of electrons generated per μm in CCD's is estimated to be 60.8±6.2 at the peak of Landau distribution and 108.3±2.6 in mean value.

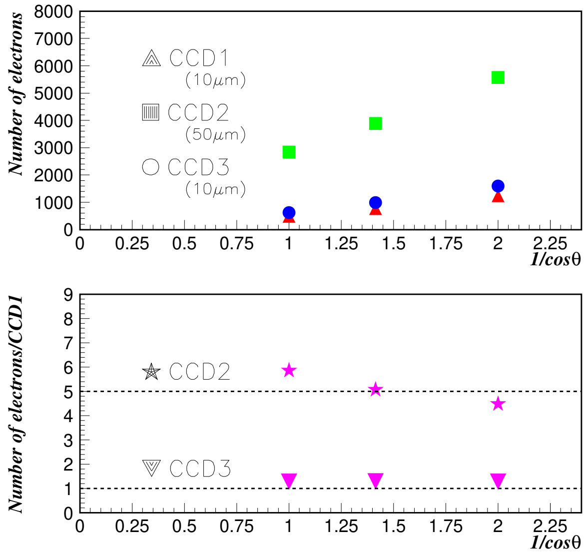

Fig. 6. Number of generated electrons versus path length.

5 Tracking efficiency and position resolution

After the alignment, detection efficiency is measured by looking for associated clusters in CCD2 expected from CCD1 and CCD3. Signal of less than 20% of the peak position at +5°C is taken as inefficiency, where this threshold corresponds to about $2\sigma_{noise}$ at +5°C. The inefficiency is found to be less than 1% up to +5°C.

Extrapolated points from CCD1 and CCD3 to CCD2 is used to evaluate the position resolution. Figure 7 shows projected distribution of position resolution. As is summarized in Table 2, we get constant resolutions over the temperature. By combining all, the resolution is found to be 13.0±0.2μm.

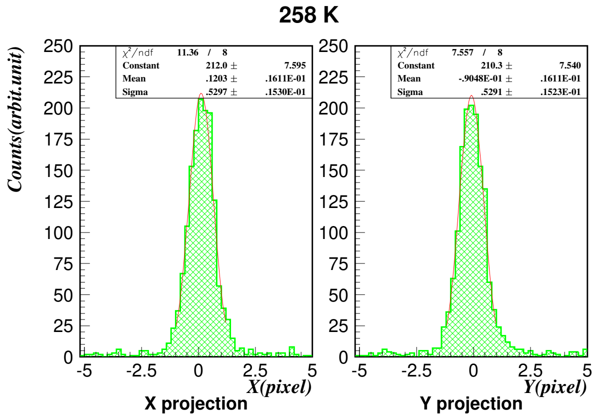

Fig. 7. Position resolution at −15°C.

Temp.	−15°C	−5°C	+5°C	+15°C
ΔX (μm)	12.7 ± 0.4	13.1 ± 0.4	12.6 ± 0.6	13.6 ± 0.6
ΔY (μm)	12.7 ± 0.4	13.3 ± 0.4	12.7 ± 0.8	14.0 ± 0.7

Table 2. Position resolution at each temperature

We have used the standard packages from Hamamatsu for this experiment which have 1.2mm $A\ell_2O_3$ behind the chips. Due to this material, the measured resolution is deteriorated by multiple scattering. Material effect is studied by GEANT full simulation, which is found to be 10.3±0.2μm. By subtracting it, the intrinsic resolution is estimated to be 7.9±0.4μm.

6 Conclusion

We have studied the performance of a CCD tracker using 1.6GeV pions extracted from 12GeV proton synchrotron at KEK. Behavior of the dark current versus temperature is carefully analyzed. The width measurement of the dark current distribution is found to be useful to obtain the gain of the system as well as its intrinsic noise.

Thanks to the MPP operation, we have found MIP's can be detected with sufficient S/N (∼10) even up to +5°. Intrinsic resolution of

$7.9 \pm 0.4\mu$m is obtained for $24\mu\mathrm{m} \times 24\mu$m pixels with the detection efficiency of 100% within 1% error.

Acknowledgements

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