Radiation tolerance of FPCCD vertex detector for the ILC

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Outline

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- CTI measurement
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  - Fat-zero charge injection
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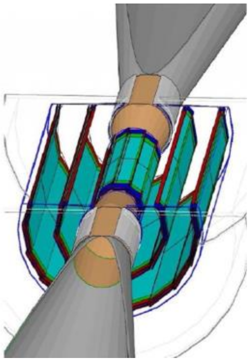
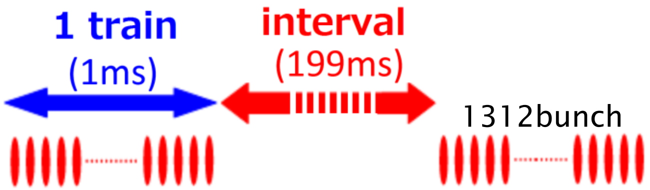
Introduction

Vertex detector for ILC



- Less than a few % pixel occupancy for precise tracking
  - When 25μm×25μm pixel detector accumulates signal in 1 train, pixel occupancy is more than 10%.

- Two solutions of pixel occupancy
  ① Many readout in a train
  ② Small pixel size



Beam structure of ILC

② → **Fine Pixel CCD =FPCCD**

Pixel size $(5\mu m)^2$ achieves a few % pixel occupancy!

Radiation damage

- Main radiation for VTX detector in ILC
  $(1312\text{bunch},\ 0.5 \times 10^{7}\text{sec},\ \mathrm{E_{CM}} = 500\text{GeV})$
  - Electrons and positrons from pair background
    - 2.07×10^{11} e / cm^2 /year → 1.29×10^{10} 1MeVn_{eq} / cm^2 / year
  - Neutrons from beam dump
    - 9.25×10^{8} 1MeVn_{eq} / cm^2 / year

- Influence on CCD caused by the radiation
  - Increase of dark current
  - Increase of hot pixels
  - Degradation of CTI ←todays topic
  - Flat band voltage shift
  - Spurious charge

→We performed neutron irradiation test for prototype FPCCD.

Charge Transfer Inefficiency

CCD transfers signal charge from pixel to pixel to be read out in the end. Ideally charge is transferred completely. But by lattice defect from radiation damage etc., charge is lost and charge transfer efficiency get worse.

- Charge Transfer Inefficiency
  - CTI is defined as inefficiency of one transfer pixel to pixel.
  - Signal charge is Q_0 and it will become Q_n after n times transfers.

$$Q_n = Q_0(1 - CTI)^n$$

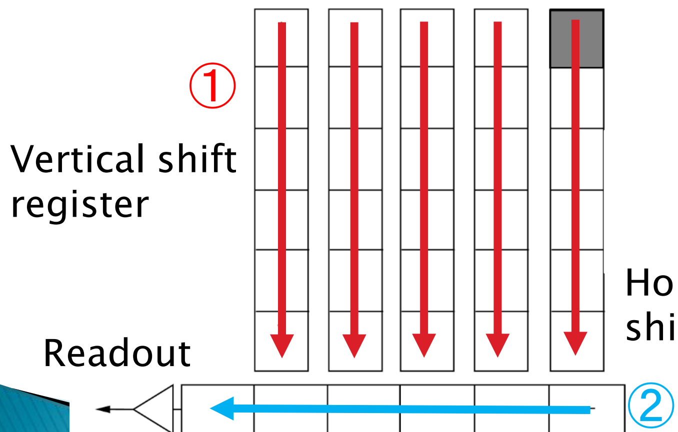
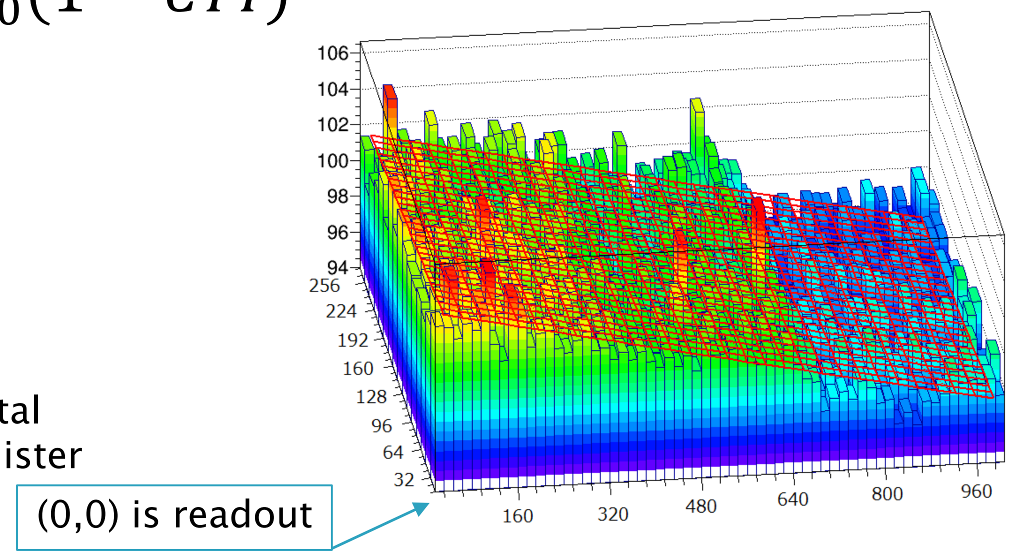


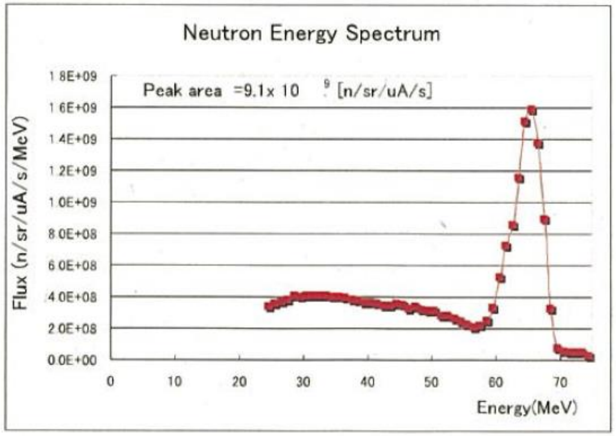
Image of CCD



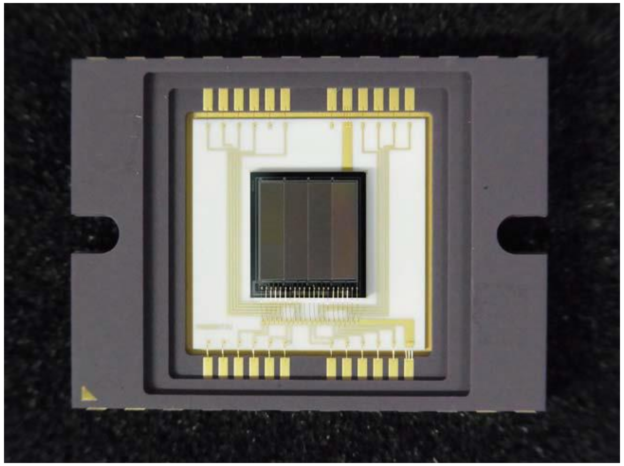
Signal distribution of irradiated CCD

CTI measurement

Neutron beam test



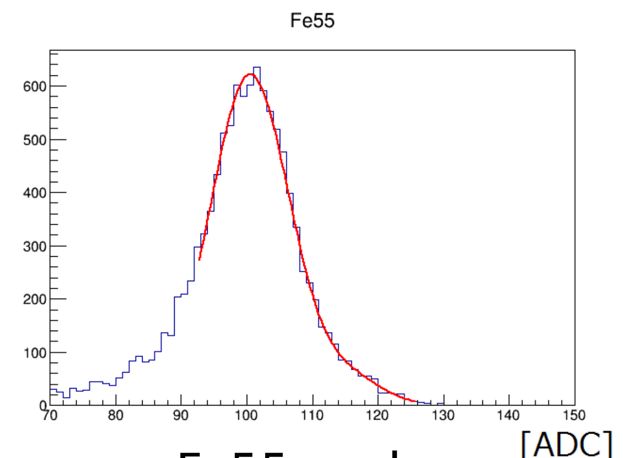
- Date：2014/10/15-17
- Place：CYRIC@Tohoku University
- Neutron beam produced from 70MeV proton beam
  - Li + p → Be + n
- Fluence: 1.78×10^{10} 1MeVn_{eq}/cm^2 (1.5h)
- Prototype of CCD
  - Pixel size：$(6\mu m)^2$
  - Horizontal register size:
    - $\boldsymbol{6\mu m \times 12\mu m}, 6\mu m \times 18\mu m, 6\mu m \times 24\mu m$
  - Number of pixels：1024x255
  - Made by HPK
  - Model number：CPK1-14-CP502-07



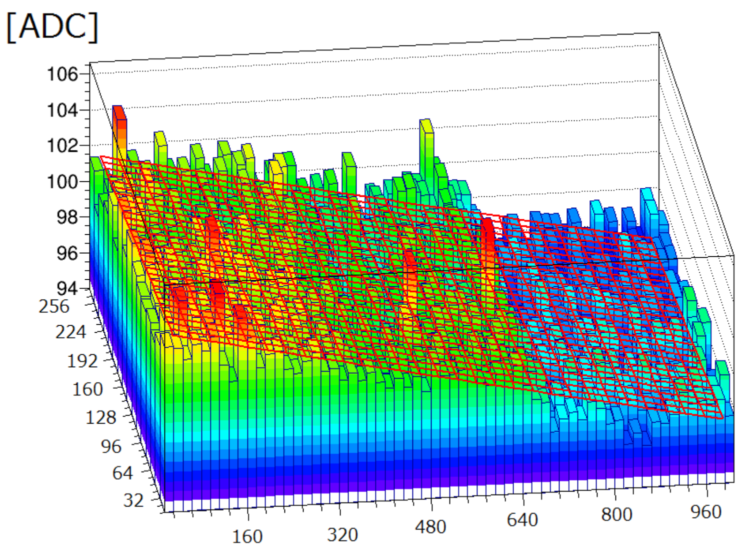
CTI measurement

- Condition
  - Temperature: −40℃
  - Frequency: 6MHz
  - Fe55 X-ray
    - Peak position of 5.9keV peak in each pixel
    - Signal height distribution in CCD
- Fitting
  - $Q(x,y) = Q_0(1 - CTI_h)^x(1 - CTI_v)^y$
- Result

$$\begin{cases} CTI_h = (5.93 \pm 0.05) \times 10^{-5} \\ CTI_v = (7.32 \pm 0.22) \times 10^{-5} \end{cases}$$



Fe55 peak



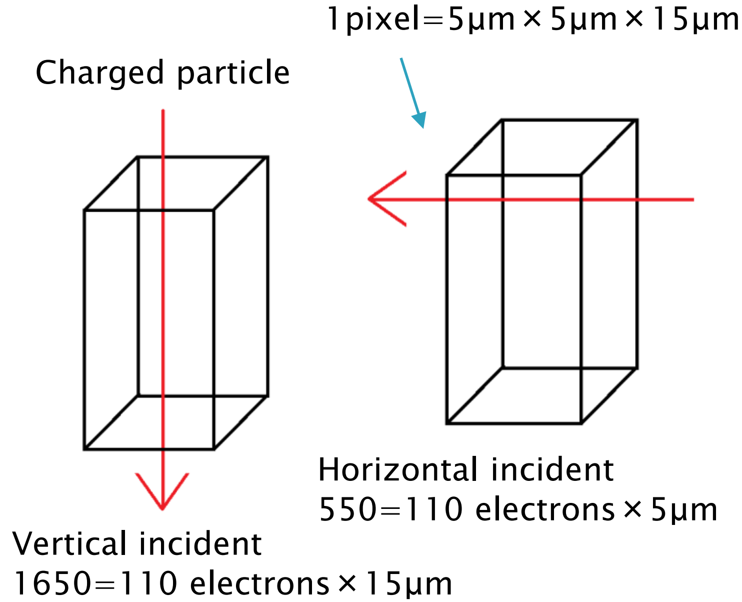
Signal distribution of irradiated CCD

Requirement for CTI

- Requirement for S/N ratio: 10
- Noise: 42 electrons
- Smallest signal: 550 electrons
  - MIP generates 110 electrons/μm in silicon.
  - When MIP enters to a pixel horizontally, it passes through 5μm silicon.

$$42 \times 10 < (1 - CTI)^{11000} \times 550$$
$$\therefore CTI < 2.45 \times 10^{-5}$$

  - Number of pixel: 11000



Radiation tolerance

- Radiation $(1312\text{bunch},\ 0.5 \times 10^7 \text{sec}, \mathrm{E_{CM}} = 500\text{GeV})$
  - Pair backgrounds: 1.29×10^{10} 1MeVn_{eq} / cm^2 / year
  - Neutron: 9.25×10^{8} 1MeVn_{eq} / cm^2 / year
- Target tolerance
  - 3 years operation and safety factor of 3
  - → 1.24×10^{11} 1MeVn_{eq} / cm^2 with $CTI < 2.45 \times 10^{-5}$
- 1MeV equivalent neutron fluence at CYRIC
  - 1.78×10^{10} 1MeVn_{eq} / cm^2
  - $CTI = 5.93 \times 10^{-5}$
- Factor 17 improvement is required
  - $\frac{1.24\times10^{11}\ 1\text{MeVn}_{eq}/\text{cm}^2}{1.78\times10^{10}\ 1\text{MeVn}_{eq}/\text{cm}^2} \times \frac{5.93\times10^{-5}}{2.45\times10^{-5}} = 17$

CTI improvement

Fat-zero charge injection

- Improvement of CTI
  - The cause of degradation of CTI is lattice defect

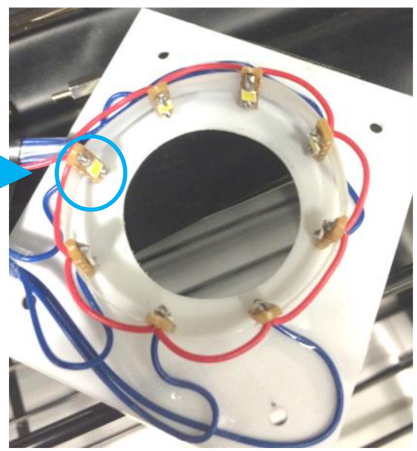
  ⇒ Additional charge are injected to fill up the lattice defects before the signal charge is transferred.

- Fat-zero charge injection
  - Fill lattice defect by background current
  - CCD is irradiated by light from LED and produced charge is treated as fat-zero charge.

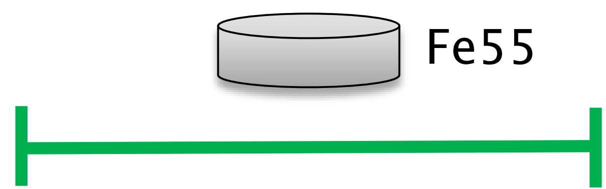
Setup

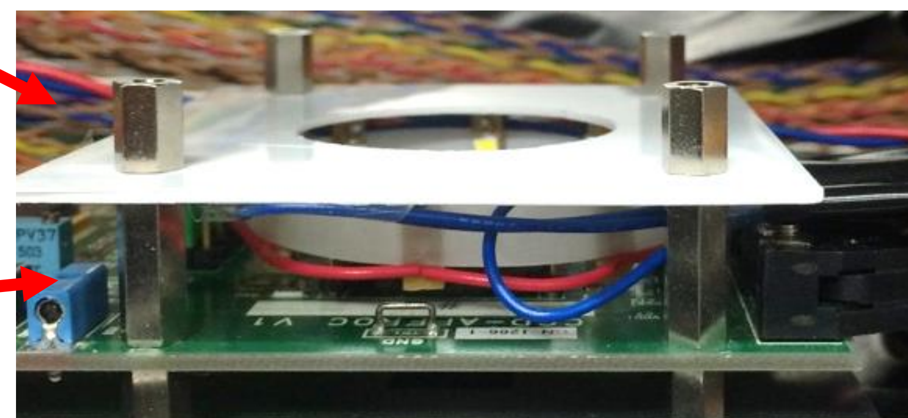
- 8 LED were put around the CCD in the equal space.
- LEDs are connected in parallel and same voltages are applied.
- Fe55 source is located over the center hall.

LED



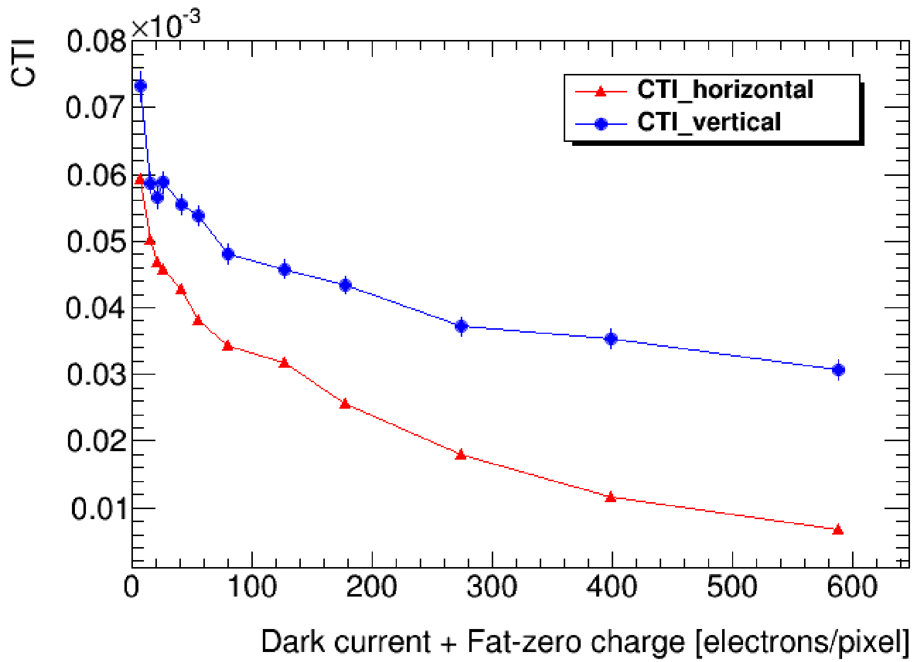
CCD





Result

- No fat zero charge
  - $CTI_h = (5.93 \pm 0.05) \times 10^{-5}$
  - $CTI_v = (7.32 \pm 0.22) \times 10^{-5}$
- 600 electrons injected
  - $CTI_h = (6.75 \pm 0.04) \times 10^{-6}$
  - $CTI_v = (3.07 \pm 0.15) \times 10^{-5}$
- Factor 9 improvement for CTI_h and factor 2 improvement for CTI_v are achieved.
  - Number of horizontal transfer is much larger than number of vertical transfer. Improvement of CTI_h is dominant for charge loss.



Requirement for CTI with Fat zero charge

- Shot noise of Fat-zero charge
  - →Requirement for CTI gets strict
- Correction

$$\sqrt{42^2 + N_{Fatzero}} \times 10 < (1 - CTI)^{11000} \times 550$$

$$\therefore CTI < 1.24 \times 10^{-5}, \text{ when } N_{Fatzero} = 600$$

$$(CTI < 2.45 \times 10^{-5}, \text{ when } N_{Fatzero} = 0)$$

- Required improvement
  - Factor 34 improvement has to be achieved with fat-zero charge 600
  - Fat-zero charge injection has achieved factor 9 improvement
  - → Another factor 4 improvement is necessary

Possible improvement

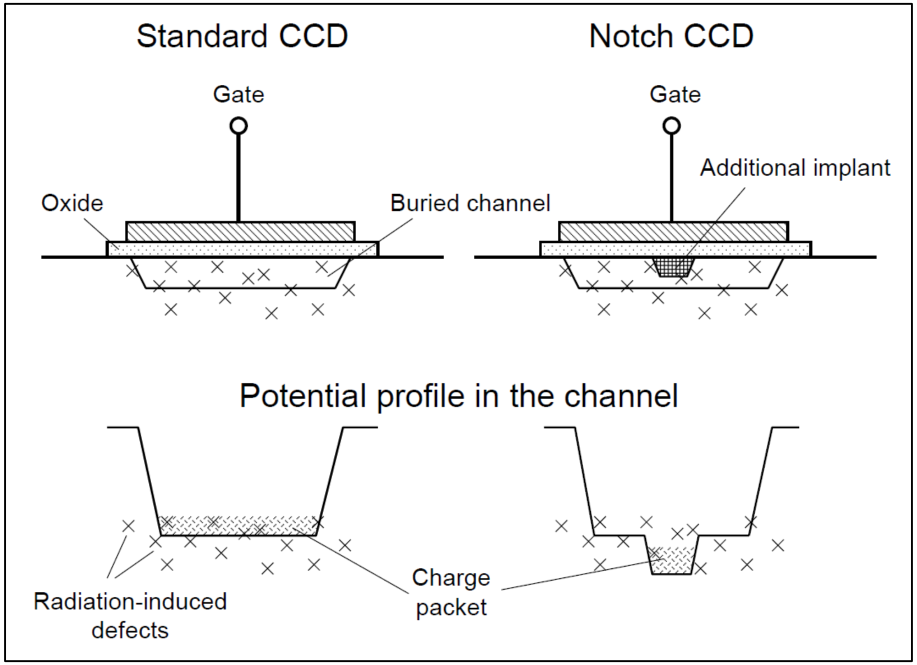
- Fat-zero charge effect depends on horizontal register size

Register size	No Fat zero charge	600 electrons	Improvement
$6\mu m \times 12\mu m$	$CTI_h = 5.93 \times 10^{-5}$	$CTI_h = 0.68 \times 10^{-5}$	Factor 9
$6\mu m \times 18\mu m$	$CTI_h = 5.45 \times 10^{-5}$	$CTI_h = 1.05 \times 10^{-5}$	Factor 5
$6\mu m \times 24\mu m$	$CTI_h = 4.85 \times 10^{-5}$	$CTI_h = 1.89 \times 10^{-5}$	Factor 3

- Fat-zero charge improvement can be more effective by small horizontal register ($6\mu m \times 6\mu m$)

Possible improvement

- Notch channel
  - Signal charge encounters less traps if it is transferred through narrower channel
  - Narrower channel than pixel (shift register) width is called “notch channel”
  - Fat-zero charge injection is more effective
- Annealing
  - Annealing at ~100 deg is reported
  - CTI improvement by x2~3 after 168h 100℃ annealing
- Noise reduction
  - Requirement for CTI gets lax



Summary

- CTI degradation was observed in neutron irradiated FPCCD prototype.
- Fat-zero charge injection was performed to recover the performance
  - Factor 9 improvement for CTI_h and factor 2 improvement for CTI_v were achieved.
- There are much damage by pair backgrounds
  - For electron tolerance, factor 4 improvement is required.
  - Possible improvement
    - Small horizontal register
    - Notch channel
    - Annealing
    - Noise reduction

Electron Tolerance

- Pair backgrounds
  - 6.32/hits/cm^2/BX at E_{CM}=500GeV
- Expected hits/year assuming 0.5x10^7 sec operation
  - 6.32 x 1312 (BX/train) x 5 (train/sec) x 0.5 x 10^7 (sec) = 2.07 x 10^{11} e / cm^2/year