Radiation tolerance of the FPCCD

31th March 2017, Annual ILC detector meeting

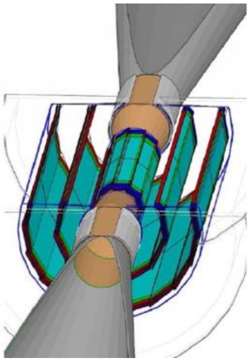
Tohoku University
Shunsuke Murai on behalf of FPCCD group

Outline

- Introduction
  - Vertex detector FPCCD
  - Radiation damage
- Neutron irradiation test
  - Measurement of performance for prototype FPCCD
  - Improvement of CTI
- Summary

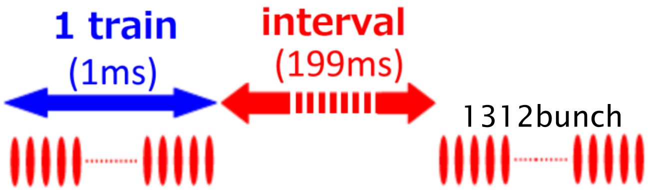
Introduction

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

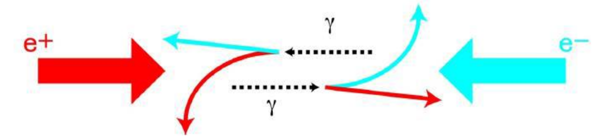


Beam structure of ILC

② → **Fine Pixel CCD =FPCCD**

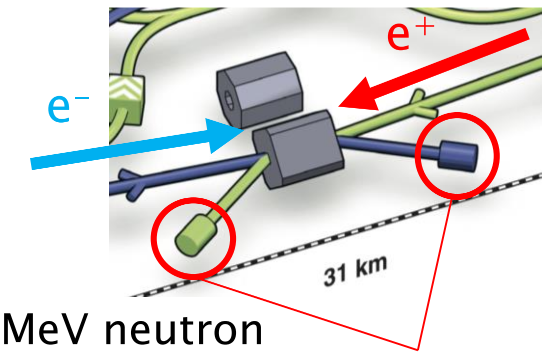
Pixel size $(5\mu m)^2$ achieves a few % pixel occupancy!

Radiation damage

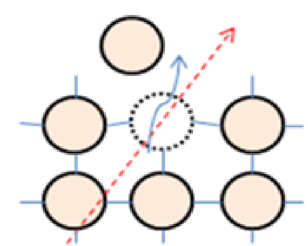


Pair background

- Radiation in the ILC $(1312\mathrm{bunch},\ 0.5 \times 10^{7}\mathrm{sec}, \mathrm{E_{CM}} = 500\mathrm{GeV})$
  - Pair background: 2.07×10^{11} e / cm^2 /year
  - Neutrons from beam dump: 9.25×10^{8} $1\mathrm{MeVn_{eq}}$ / cm^2 / year
- Influence on CCD caused by the radiation
  - Bulk damage – lattice defects: displacement of silicon atoms
    - Non-ionizing energy loss(NIEL): energy which used to bulk damage in energy loss of radiation
  - Surface damage – ionization in the silicon dioxide
- NIEL hypothesis
  - Assumption that bulk damage is proportional to NIEL
  - Damage of 30MeV electrons is 16 times smaller than 1MeV neutron
    - 2.07×10^{11} e / cm^2 /year → 1.29×10^{10} $1\mathrm{MeVn_{eq}}$ / cm^2 / year
- Requirement for radiation tolerance
  - 3 years operation and safety factor 3
  - →1.24×10^{11} $1\mathrm{MeVn_{eq}}$ / cm^2



Beam dump

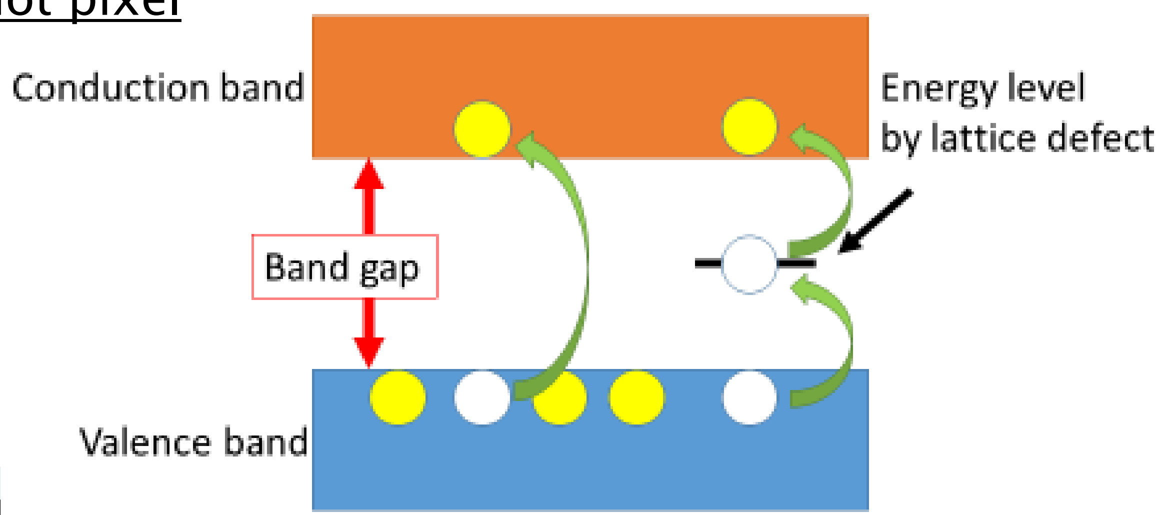

Lattice defects image

Dark current and hot pixel

Dark current: thermal excited electrons which is readout as signal

Hot pixel: pixel whose dark current is larger than normal pixel

- Influence from radiation
  - Increase of lattice defects
    - Energy level is generated by lattice defect in band gap and probability of thermal excited to conduction band is increased.
    - →Increase of <u>dark current</u>
  - Generation of defect cluster
    - Collision of heavy particles like neutron or proton causes multiple collision and defect cluster which is displacement of multiple atoms. So that dark current is increased ununiformity.
    - →generation of <u>hot pixel</u>



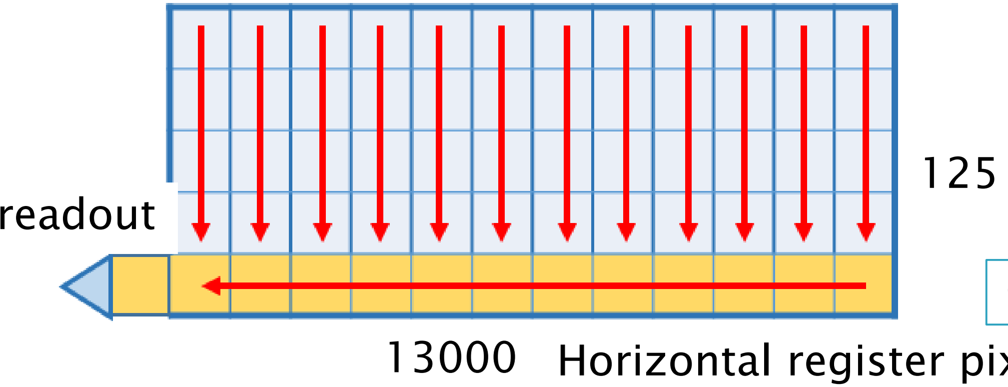
Degradation of charge transfer inefficiency

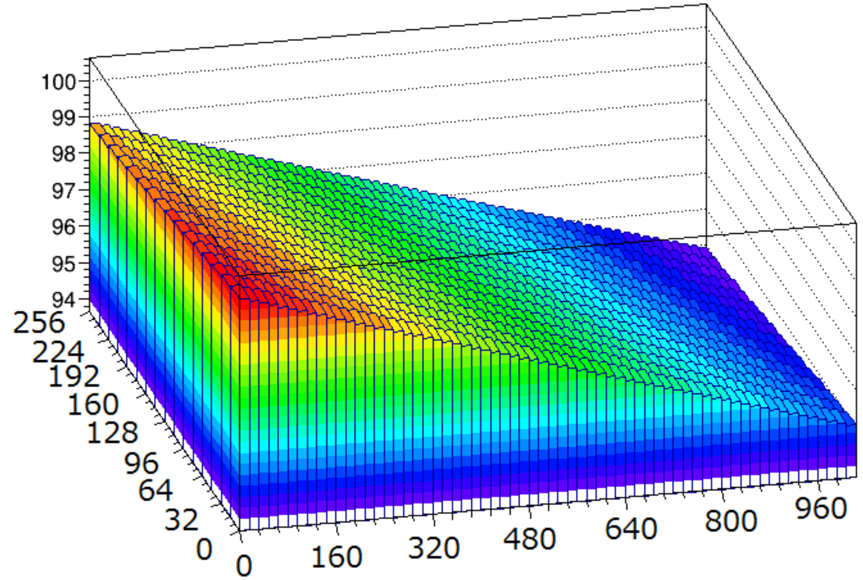
- Charge Transfer Inefficiency (CTI)
  - Charge loss is caused by trap in lattice defects.
  - It is defined as inefficiency of one transfer from pixel to pixel.
  - Signal charge is Q_0 and it will become Q_n after n times transfers.

$$Q(x,y) = Q_0(1 - CTI_h)^x(1 - CTI_v)^y$$

In ILC experiment, number of horizontal transfer is 13000 and that of vertical transfer is 125. Horizontal transfer is dominant in charge loss.

Vertical transfer pixels





(0,0) is readout

Plot of the expression
x, y axis is place of pixel
Z axis is signal hight

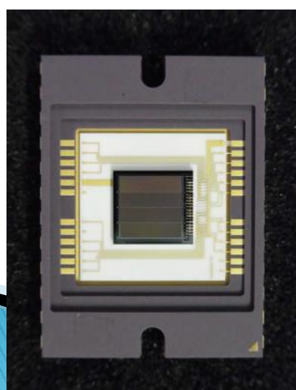
Neutron irradiation test

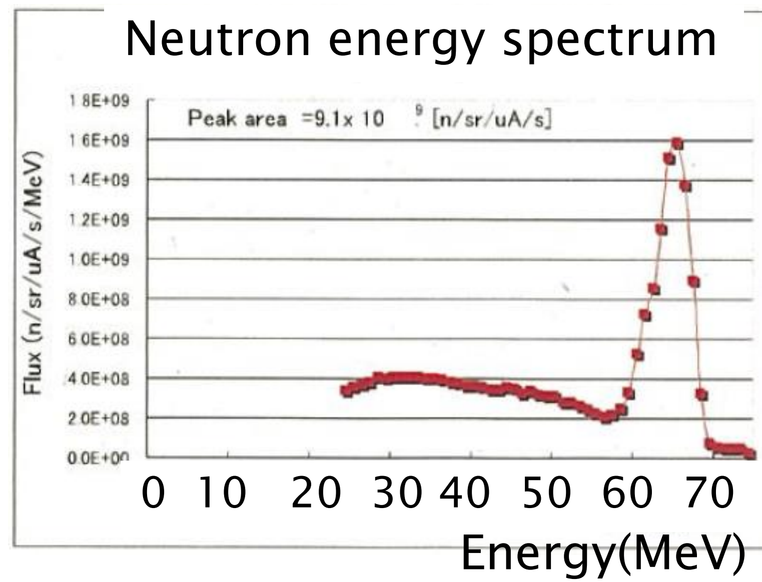
Neutron irradiation test

- Date：2014/10/15-17
- Place：CYRIC@Tohoku University
- 65MeV Neutron beam
  - It is produced from 70MeV proton beam
  - Li + p → Be + n

CYRIC Annual Report 2010-2011

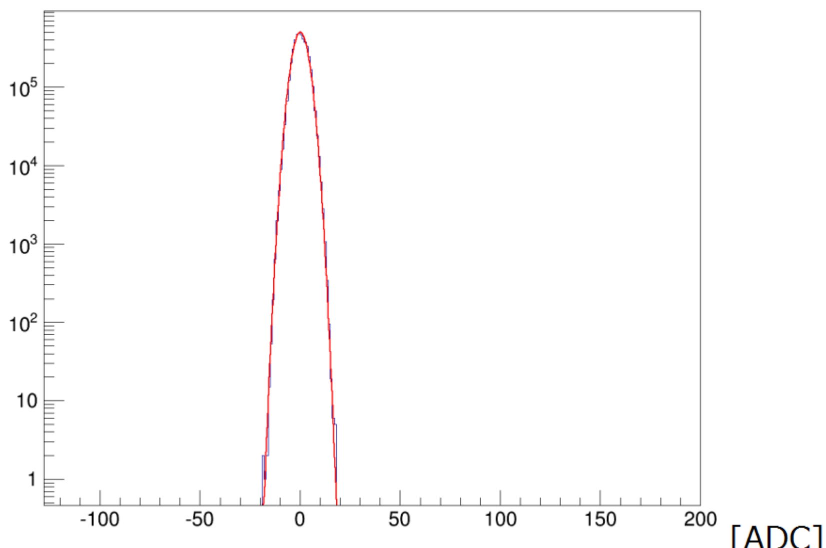
- Fluence: $1.78 \times 10^{10}\ 1\mathrm{MeV} n_{eq}/cm^2$ (1.5h)
  - 1/7 of required NIEL damage
- Prototype FPCCD is used
  - Pixel size: $(6\mu m)^2$



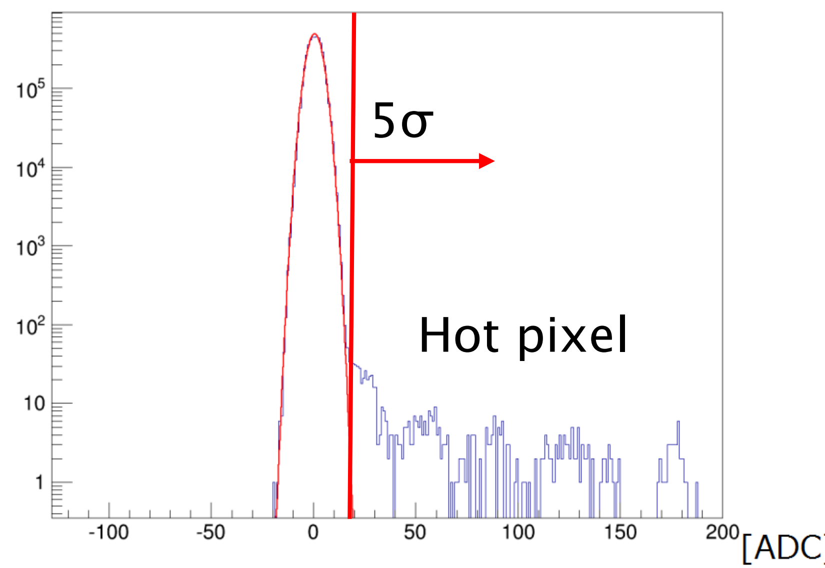


Dark charge and hot pixel

- Dark charge(200msec)
  - Before irradiation: −0.0006 electrons@−40℃
  - After irradiation: 0.76 electrons@−40℃
- Hot pixel fraction
  - Before irradiation: $(7.49 \pm 1.91) \times 10^{-7}$@−40℃
  - After irradiation: $(1.03 \pm 0.19) \times 10^{-6}$@−40℃



Before irradiation
exposure time 5sec@−40℃

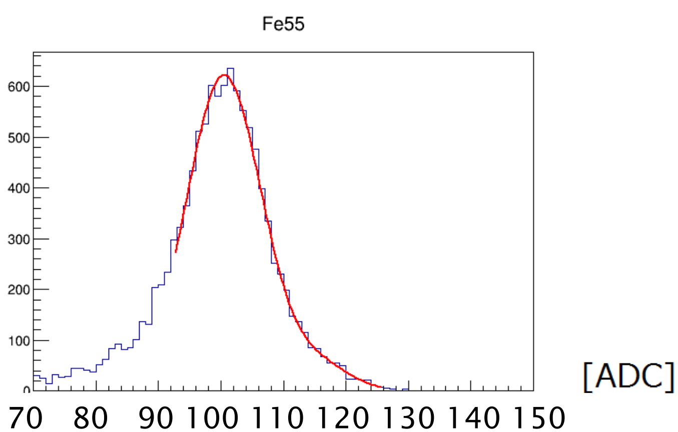


After irradiation
exposure time 5sec@−40℃

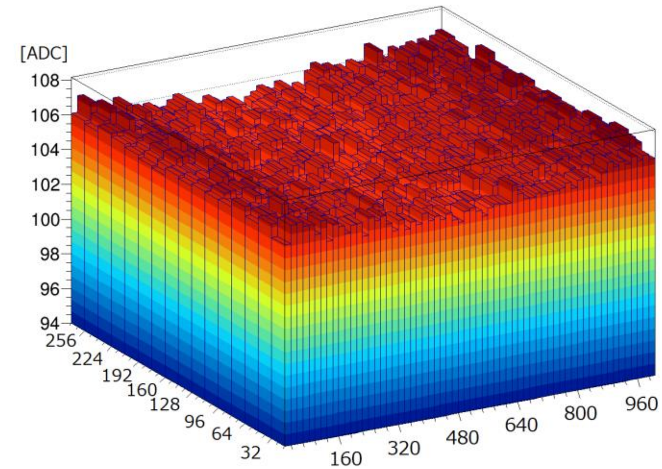
CTI measurement

- Condition
  - Temperature: -40℃
  - Clock frequency: 6MHz
  - Source : Fe55
    - 5.9keV X-ray is used for signal
- Fit function
  - $Q(x,y) = Q_0(1 - CTI_h)^x(1 - CTI_v)^y$
- result

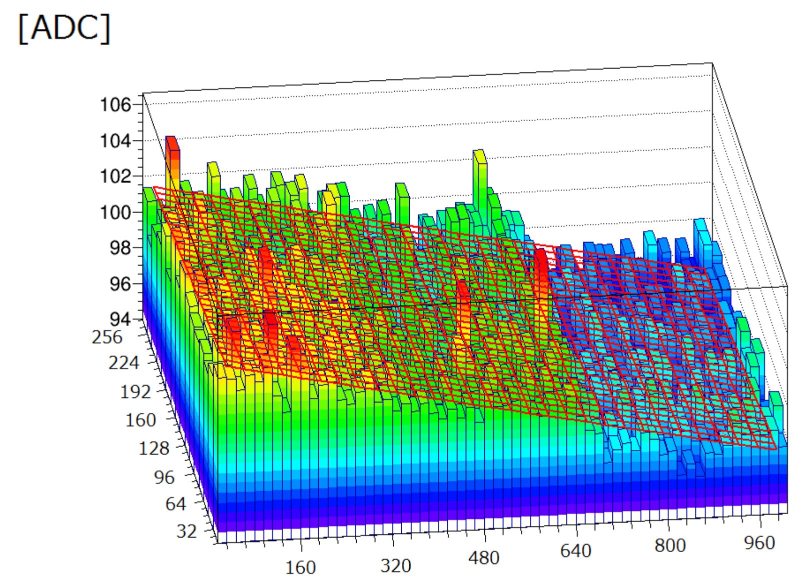
$$\begin{cases} CTI_h = (5.93 \pm 0.05) \times 10^{-5} \\ CTI_v = (7.32 \pm 0.22) \times 10^{-5} \end{cases}$$



Fe55 peak



X-ray Signal distribution before irradiation



X-ray Signal distribution after irradiation

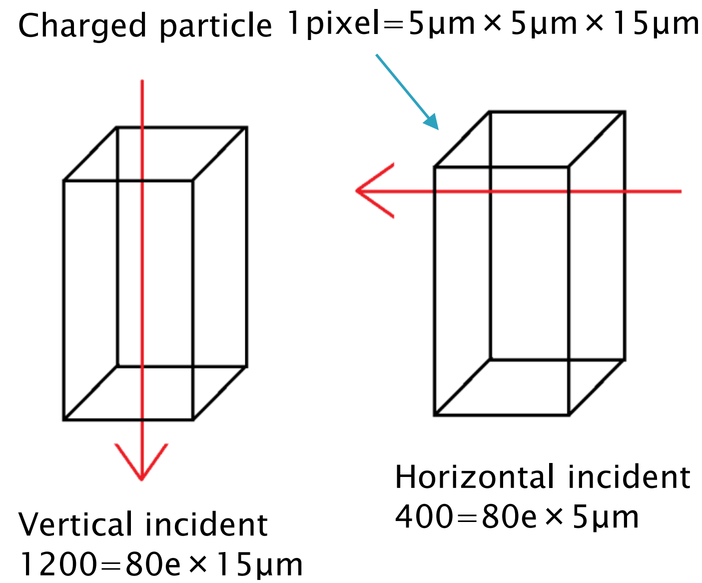
Evaluation of performance

- Neutron fluence in CYRIC: 1.78×10^{10} $1MeVn_{eq}$ / cm^2
- Required radiation tolerance: 1.24×10^{11} $1MeVn_{eq}$ / cm^2
  - It is 7 times lager than fluence in CYRIC
  - 3 years operation $(1.5 \times 10^{7}\mathrm{sec})$ and safety factor 3
- Evaluation of performance
  - Each result was worsen 7 times to compare with requirement.
  - Dark charge (200msec)
    - 0.76 electrons x 7 = 5.32 electrons
    - It is enough small comparing with noise 42 electrons
  - Hot pixel fraction
    - $(1.03 \times 10^{-6}) \times 7 = 7.21 \times 10^{-6}$
    - It is enough small comparing with requirement for pixel occupancy

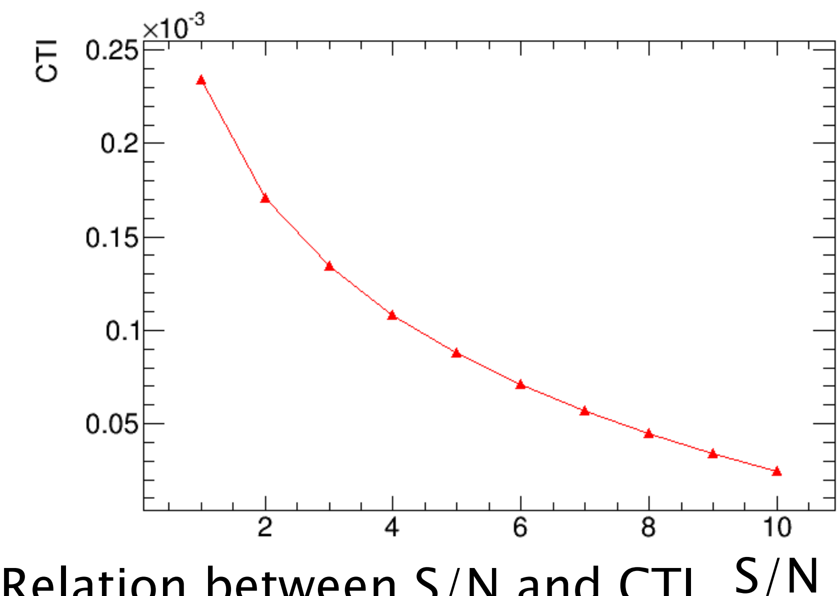
Dark charge and hot pixel are not problem in ILC

Requirement for CTI

- Large CTI means small signal charge
  →S/N gets worse
- Noise: 42 electrons
  - Width of dark charge(200msec)
- Minimum signal: 400 electrons
  - MIP generates 80e/μm in silicon
  - MIP pass 5μm when it enter horizontally



- $S/N = \frac{(1-CTI)^{11000} \times 400}{42}$
  - Number of transfer: 11000
- Evaluation of performance
  - $(5.93 \times 10^{-5}) \times 7 = 41.5 \times 10^{-5}$
  - S/N=0.1
  - →CTI should be improved
    - Goal of S/N=10
    - $CTI < 2.45 \times 10^{-5}$



Relation between S/N and CTI

CTI improvement

Fat-zero charge injection

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

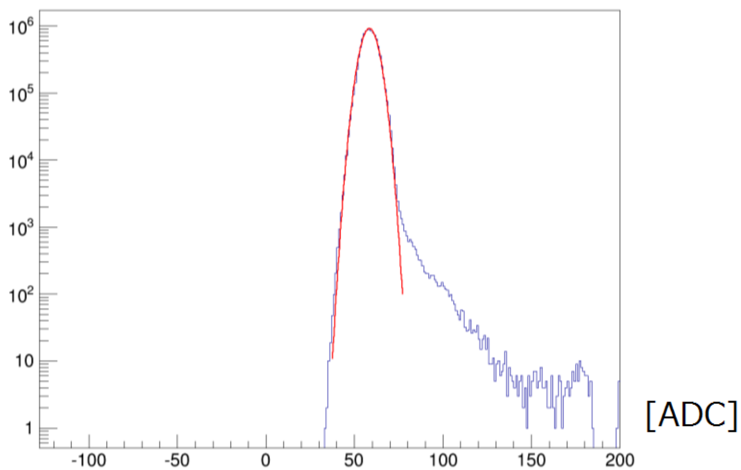
  ⇒ Additional charge are injected to fill up the lattice defects before the signal charge is transferred.

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

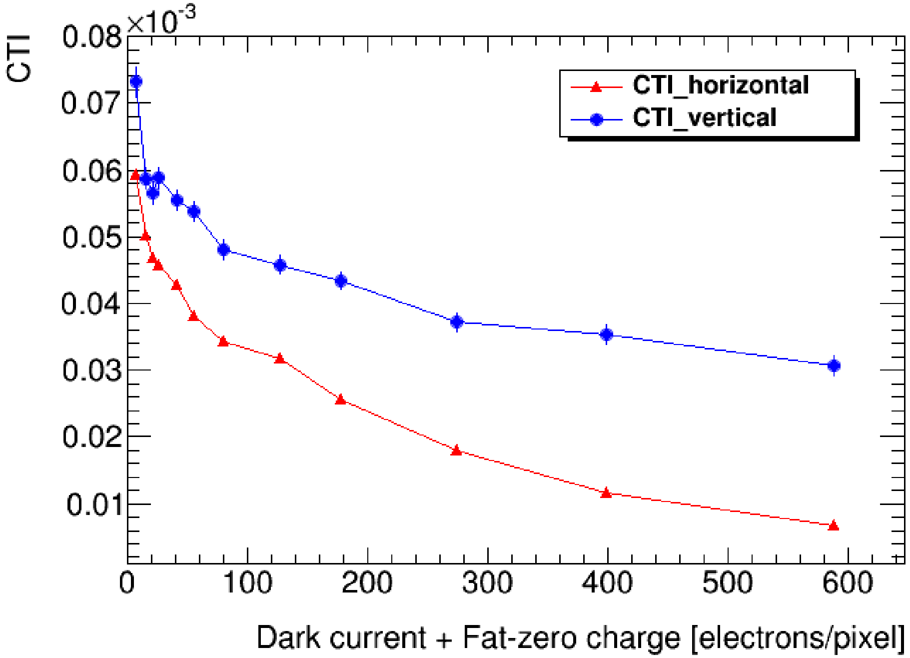
Result

	No fat-zero charge	600e/pixel injected
CTI_h	$(5.93 \pm 0.05) \times 10^{-5}$	$(0.68 \pm 0.04) \times 10^{-5}$
CTI_v	$(7.32 \pm 0.22) \times 10^{-5}$	$(3.07 \pm 0.15) \times 10^{-5}$

- 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.



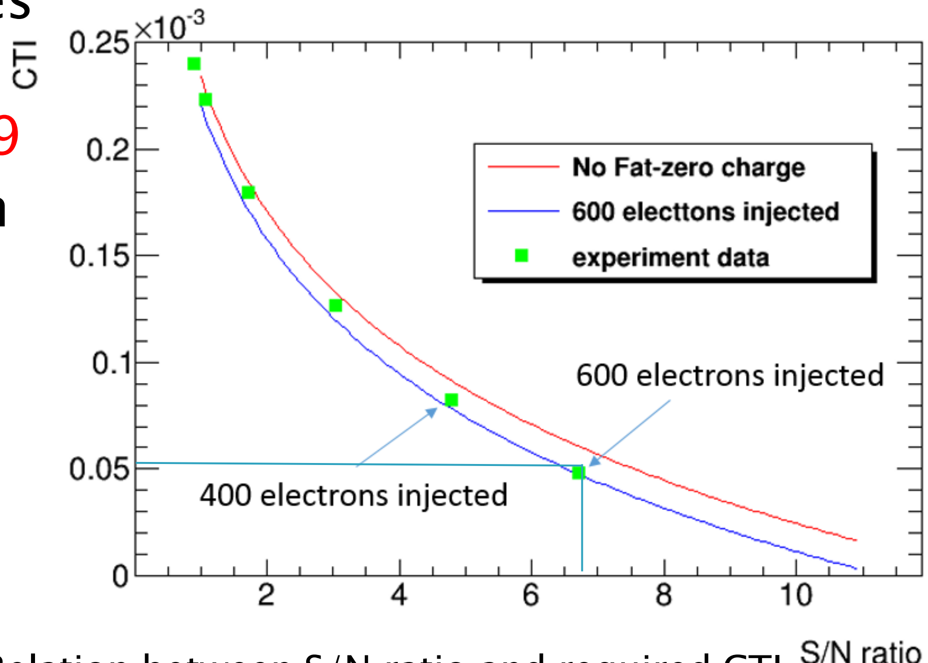
Dark charge with 600 e injected
Pedestal is shifted by fat-zero charge



Requirement for CTI with fat-zero charge

- Shot noise by fat-zero charge
  - Shot noise makes strict
- Evaluation of performance
  - Measured CTI is multiplied 7 times to compare with requirement
  - S/N ratio with 600e injected is 4.9
  - →It is smaller than the goal which is S/N=10
  - CTI should be more improved

$$S/N = \frac{(1 - CTI)^{11000} \times 400}{\sqrt{42^2 + N_{Fatzero}}}$$



Relation between S/N ratio and required CTI
Plots are the measured CTI multiplied by factor 7

Possible improvement

- Fat-zero charge effect depends on horizontal register size
- Notch channel
- Annealing
- Noise reduction

Summary

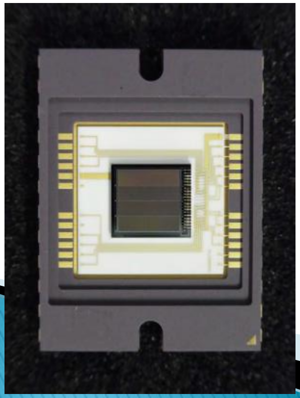
- Degradation of performances is observed in neutron irradiated FPCCD prototype.
  - Dark charge：increase to 0.76e which is enough small against noise
  - Hot pixel fraction: increase to $(1.03 \pm 0.19) \times 10^{-6}$ which is enough small against pixel occupancy
  - CTI: S/N = 0.14
- CTI improvement by fat-zero charge injection
  - Factor 9 improvement for CTI_h and factor 2 improvement for CTI_v are achieved.
- Dark charge and hot pixel is OK for ILC operation however CTI should be more improved.

Estimation of pair background

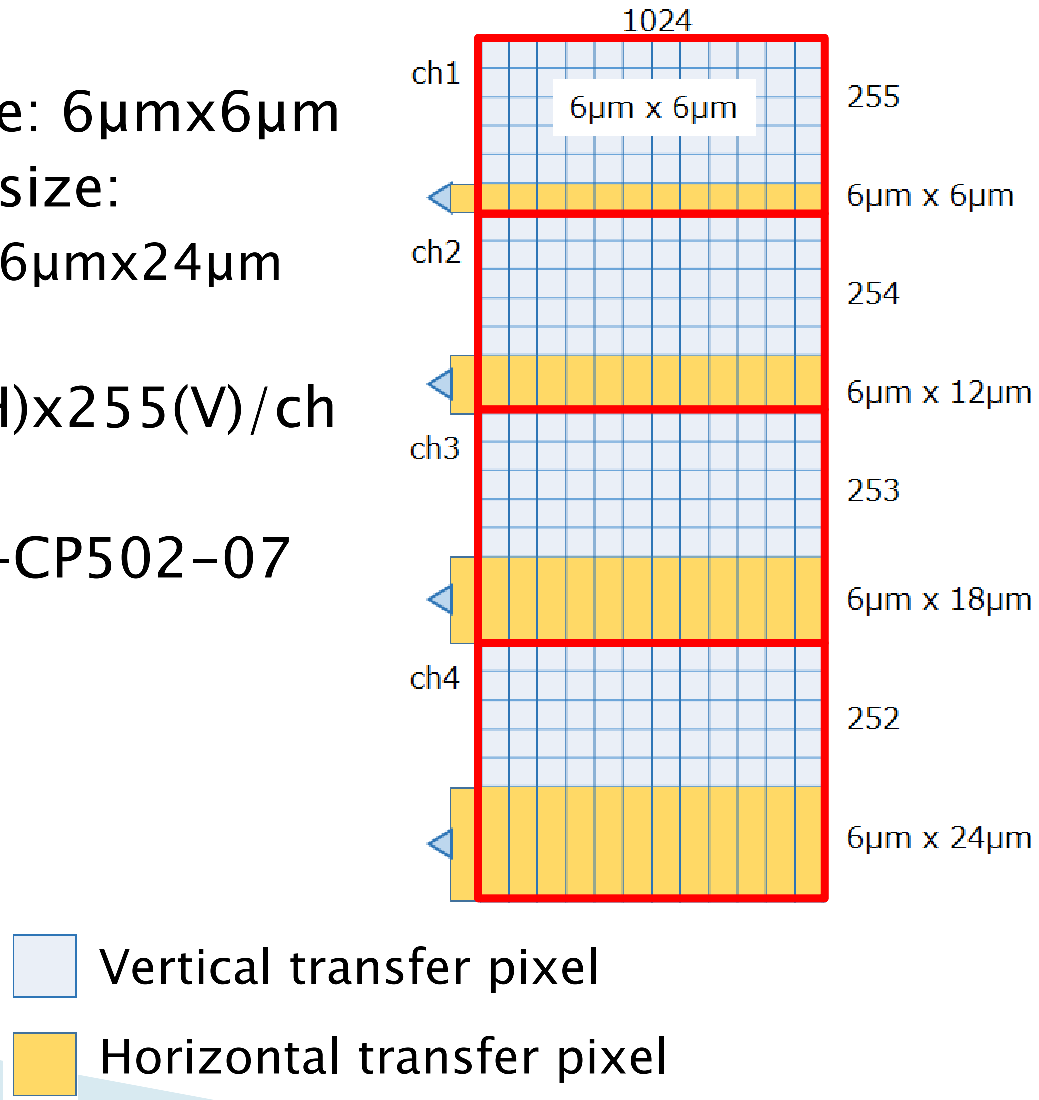
- Pair backgrounds
  - 6.32/hits/cm^2/BX at E_{CM}=500GeV
- Expected hits/year assuming $0.5x10^7$ sec operation
  - 6.32 x 1312 (BX/train) x 5 (train/sec) x 0.5 x 10^7 (sec) = 2.07 x 10^{11} e / cm^2/year

Prototype FPCCD

- Prototype FPCCD
  - Vertical transfer pixel size: 6μmx6μm
  - Horizontal transfer pixel size:
    - 6μmx12μm, 6μmx18μm, 6μmx24μm
    - Ch1 cannot work
  - Number of pixels：1024(H)x255(V)/ch
  - Made in HPK
  - Model number：CPK1-14-CP502-07

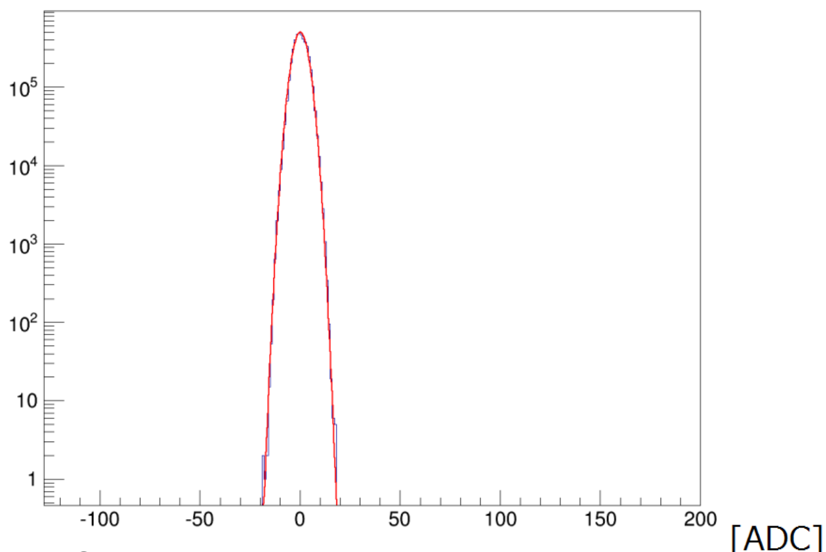


Prototype FPCCD image

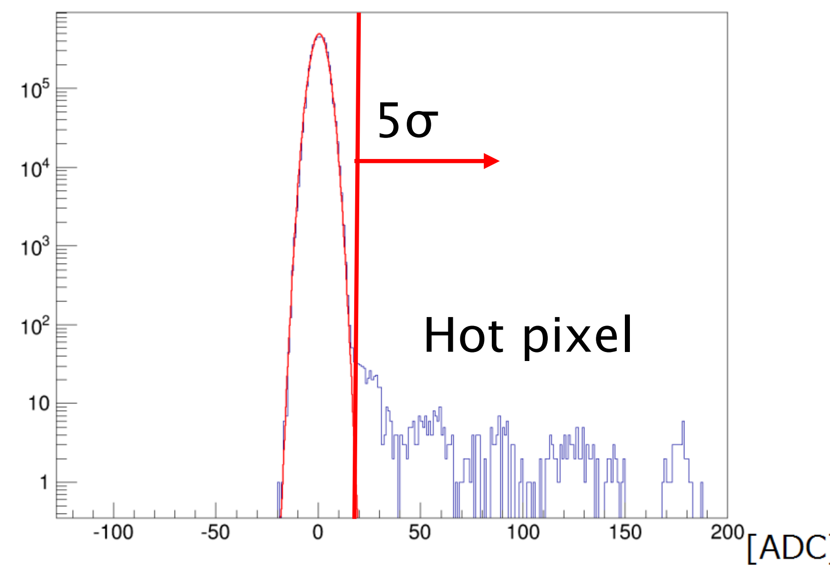


Measurement of dark current and hot pixel

- Dark current
  - Dark charge is measured as a function of exposure time →The slope is dark current
- Hot pixel fraction
  - Fraction $= N_{hot} / N_{all}$
  - Measured as a function of temperature



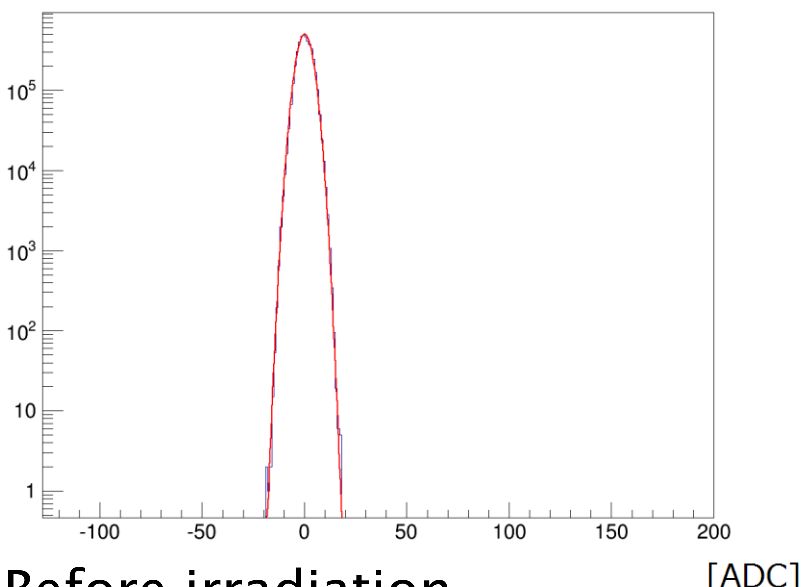
Before irradiation
exposure time 5sec@−40℃



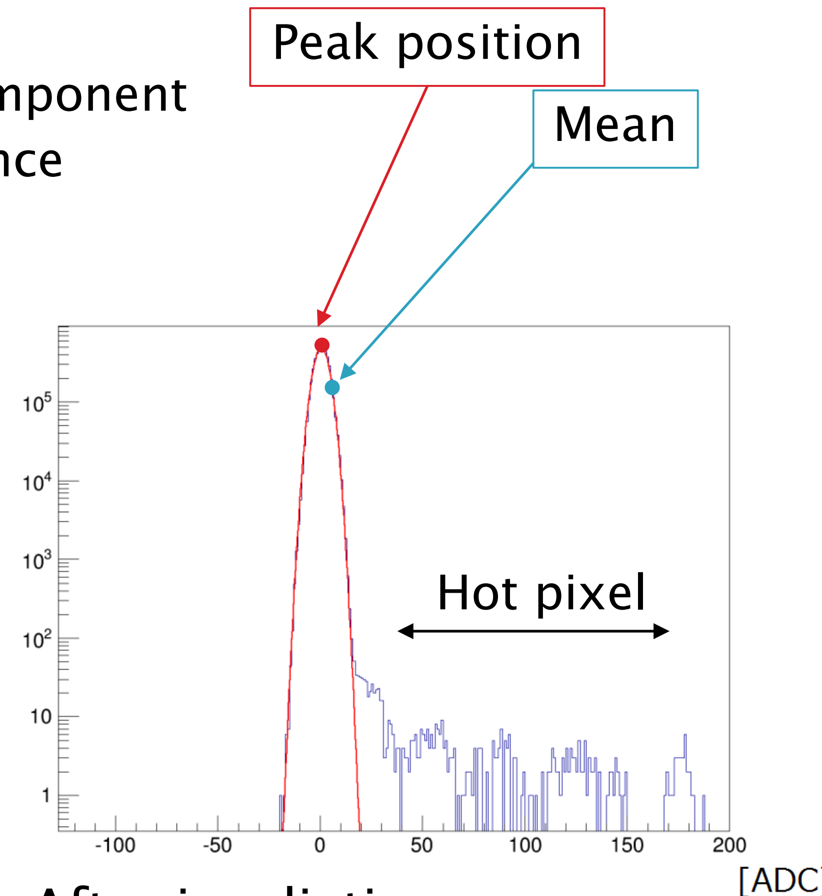
After irradiation
exposure time 5sec@−40℃

Dark current measurement

- Exposure time：5, 10, 30, 60sec
- Temperature：−30℃, −40℃
- Influence of Hot pixel
  - Peak position： only Gaussian component
  - Mean： Including hot pixel influence



Before irradiation
exposure time 5sec@−40℃



After irradiation
Exposure time 5sec@−40℃

Dark charge (200msec)

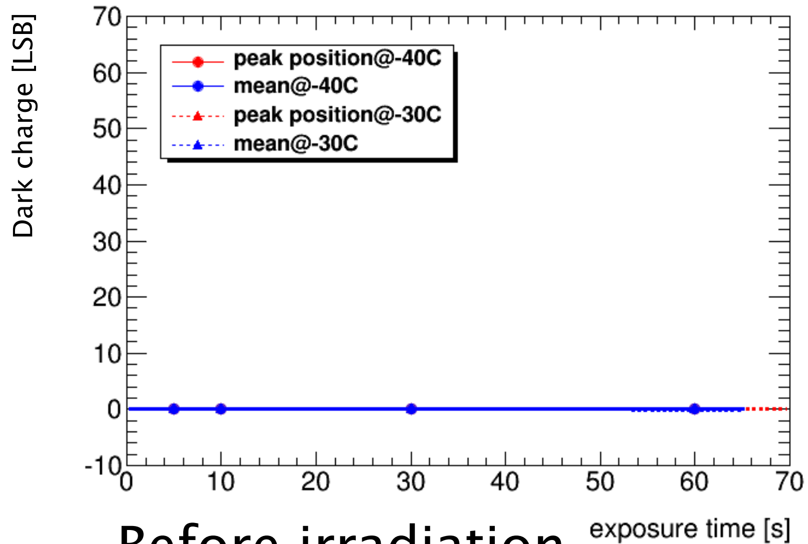
- Dark charge(200msec)
  - Dark current(slope) is scaled
  - 200msec is train gap
- Noise
  - It corresponds to width of dark charge in 200msec→42electrons

dark charge after irradiation (200msec)

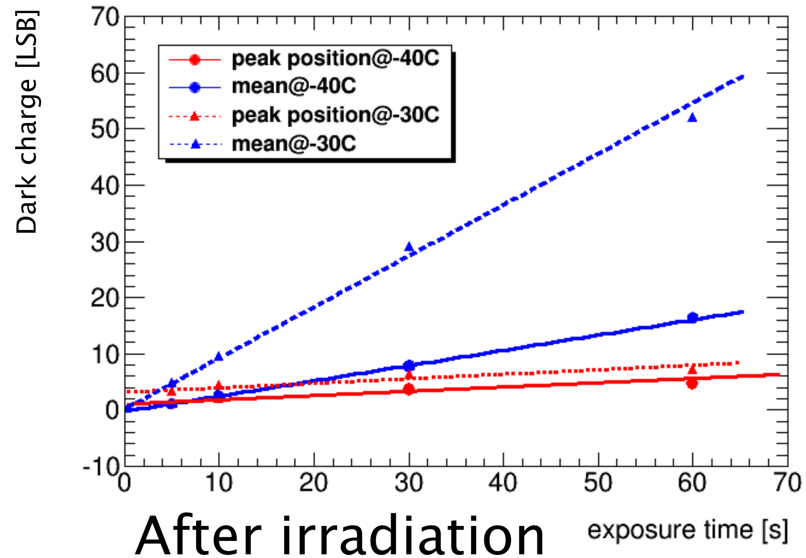
	−30℃	−40℃
Mean	2.5e	0.76e
peak	0.23e	0.22e

(1LSB=14e)

→dark charge in 200msec is enough smaller than noise

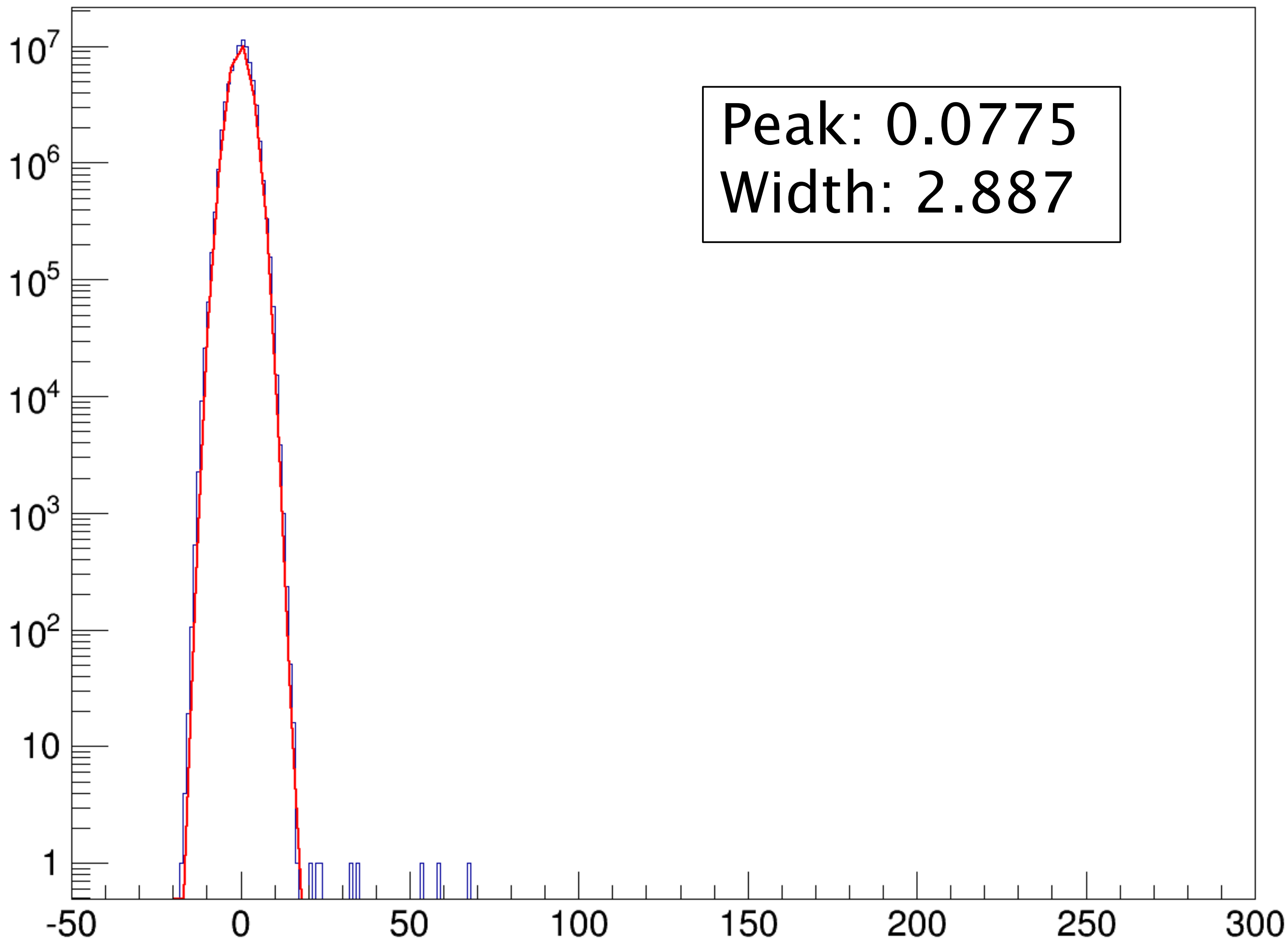


Before irradiation



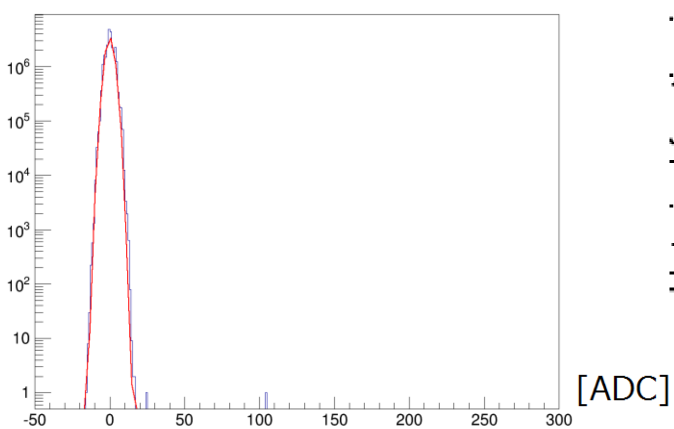
After irradiation

Dark charge 200msec

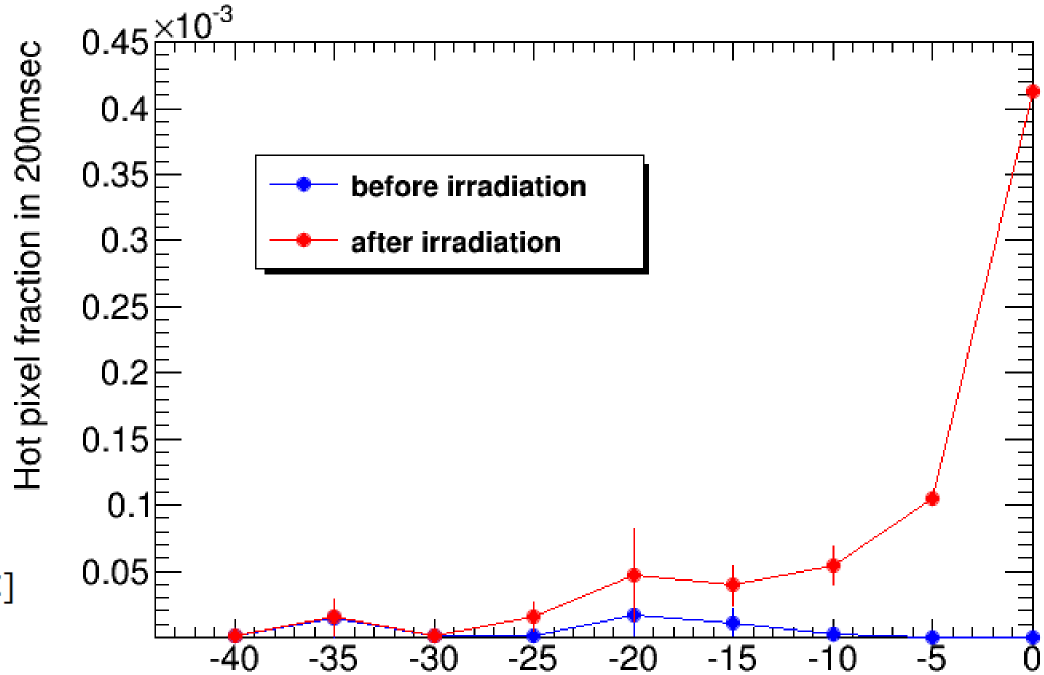


Hot pixel fraction

- Hot pixel fraction is decreasing along temperature decreasing
- It can be enough small against pixel occupancy by low temperature −40℃
  - Before irradiation: $(7.49 \pm 1.91) \times 10^{-7}$@−40℃
  - After irradiation: $(1.03 \pm 0.19) \times 10^{-6}$@−40℃



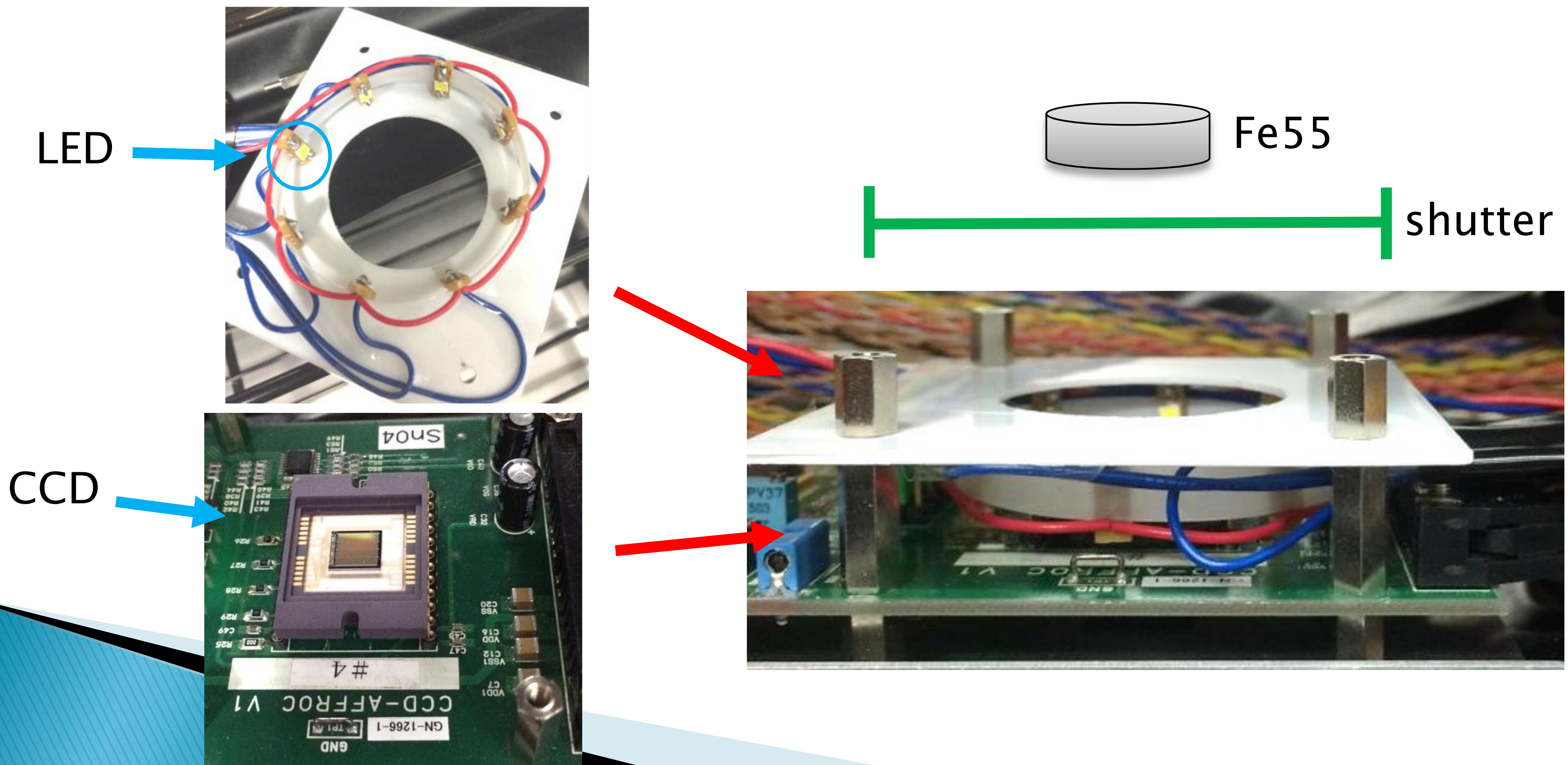
After irradiation
exposure time 200sec@−40℃



Relation between hot pixel and temperature

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.



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

E. Martin, et al. IEEE Trans, Nucl. Sci. vol. 58, No.3, 2011

- Noise reduction
  - Requirement for CTI gets lax