R&D status of Neutron tolerance

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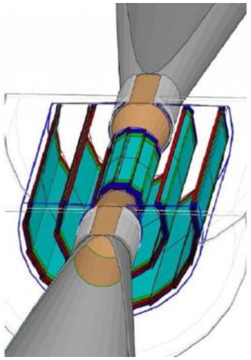
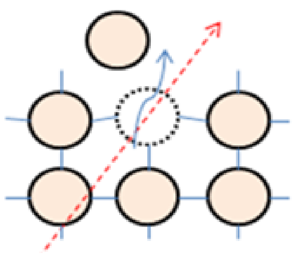
FPCCD Vertex Detector



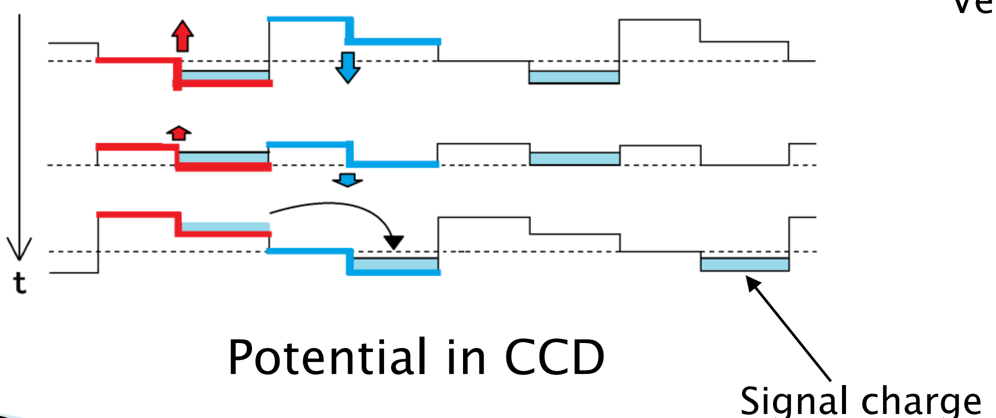
- Fine-Pixel CCD (FPCCD) feature

Minimum pixel size		$(5\mu m)^2$	high impact parameter resolution
Number of pixels		$\sim 4 \times 10^9$	Low pixel occupancy ~1%
Thickness	Si	$50\mu m$	Low multiple coulomb scattering and low pixel occupancy
	Epitaxial layer	$15\mu m$	
Read out		In the train gap ~200msec	No ElectroMagnetic Interference
Temperature		−40℃	Suppression of CTI and dark current

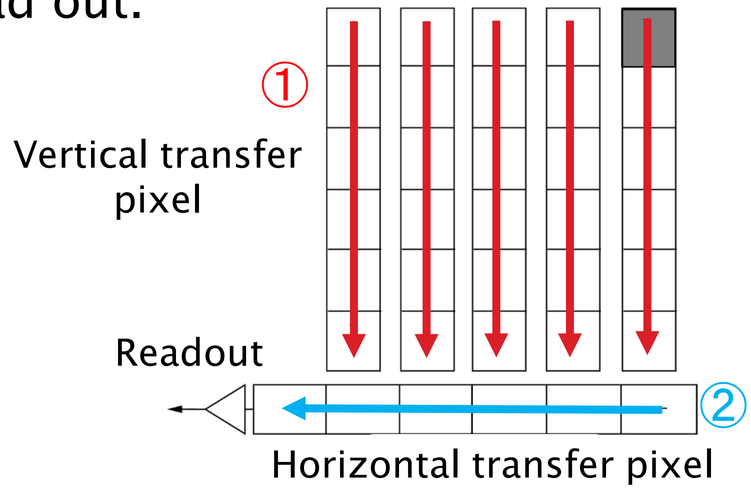
Radiation damage



- Lattice defect in semiconductor (Si)
  - It is caused by heavy particles like neutron and high energy electrons.
  - It occurs charge loss in signal transfer.
- Signal transfer in CCD
  - Signal charge is transferred to be read out.
  - It is trapped by lattice defect.



Potential in CCD

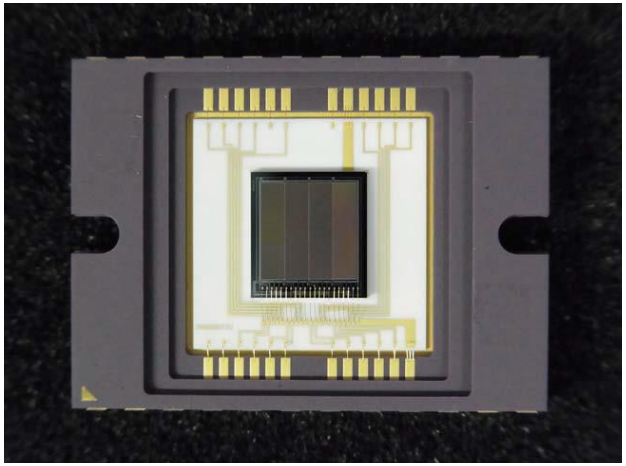


CCD mechanism

FPCCD prototype

- 2 types of small prototype
  - They have 4 channels.
  - Ch1 is dead in both prototypes.

1. Mix CCD
   - Pixel size: $(6\mu m)^2$, $(8\mu m)^2$, $(9.6\mu m)^2$ and $(12\mu m)^2$
2. $6\mu m$ CCD
   - Pixel size: $(6\mu m)^2$
   - Horizontal register size: $6\mu m \times 6\mu m$, $6\mu m \times 12\mu m$, $6\mu m \times 18\mu m$, $6\mu m \times 24\mu m$



Neutron Irradiation Test

- Date: 15-17th Oct. 2014
- Place: CYRIC in Tohoku Univ.
- Fluence: $1.78 \times 10^{10} n_{eq}/cm^2$ for 6um CCD (1.5h)
  $2.38 \times 10^{10} n_{eq}/cm^2$ for mix CCD (2h)
  - They correspond to 19 and 26 years, respectively, at ILC beam time shared by ILD/SiD.

- Result of mix CCD was presented by Ito-san last year.
- Today I will focus on 6um CCD.

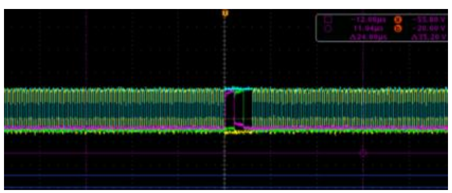
Improvement of charge transfer

- After irradiation bad transfer was occurred in ch2 and ch3.
- By changing vertical CLK pulse width $8\mu s$ to $255\mu s$, it is improved.

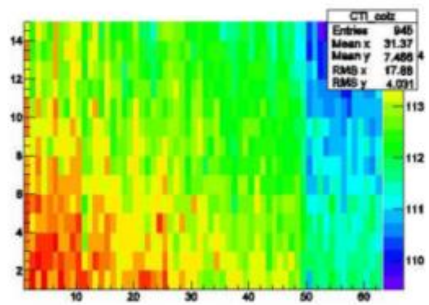
2D plot of Fe55 peak

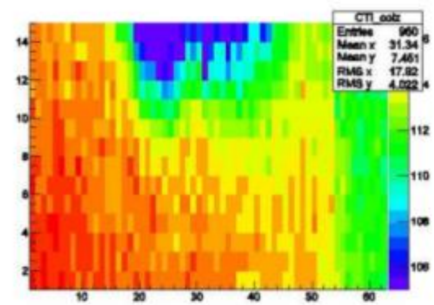
CLK pulse

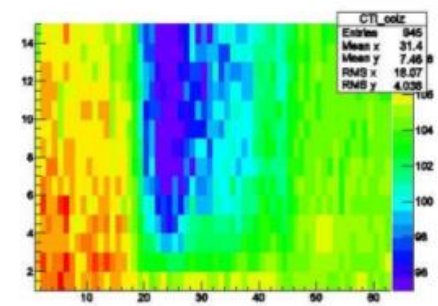
ch4 ch3 ch2

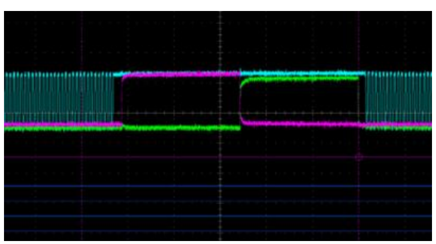


$8\mu s$

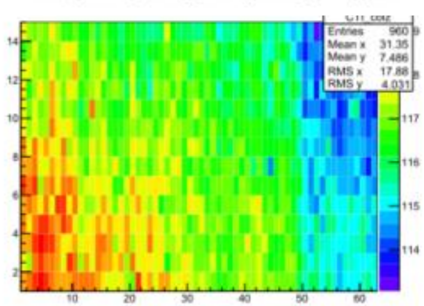


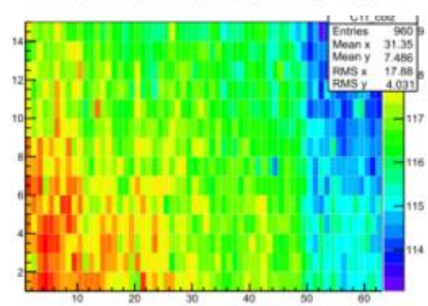


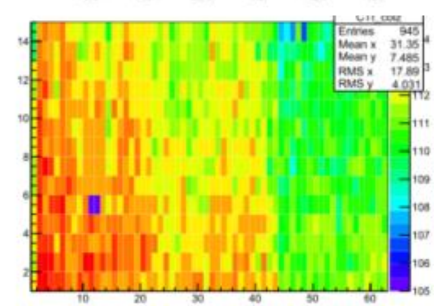




$255\mu s$







CCD was measured by this CLK pulse width

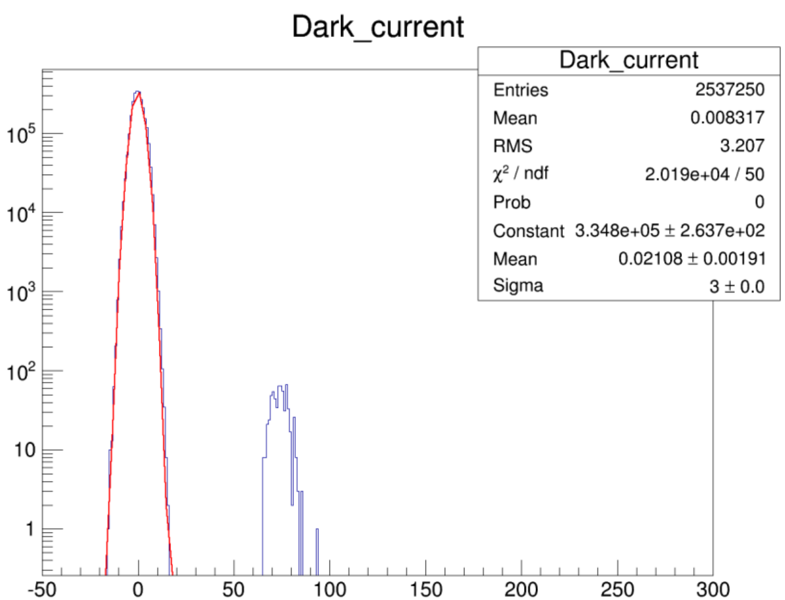
Performance of FPCCD

- 3 Parameters to measure radiation tolerance
  - Average dark current of all pixels
  - Hot pixel fraction
  - Charge transfer inefficiency

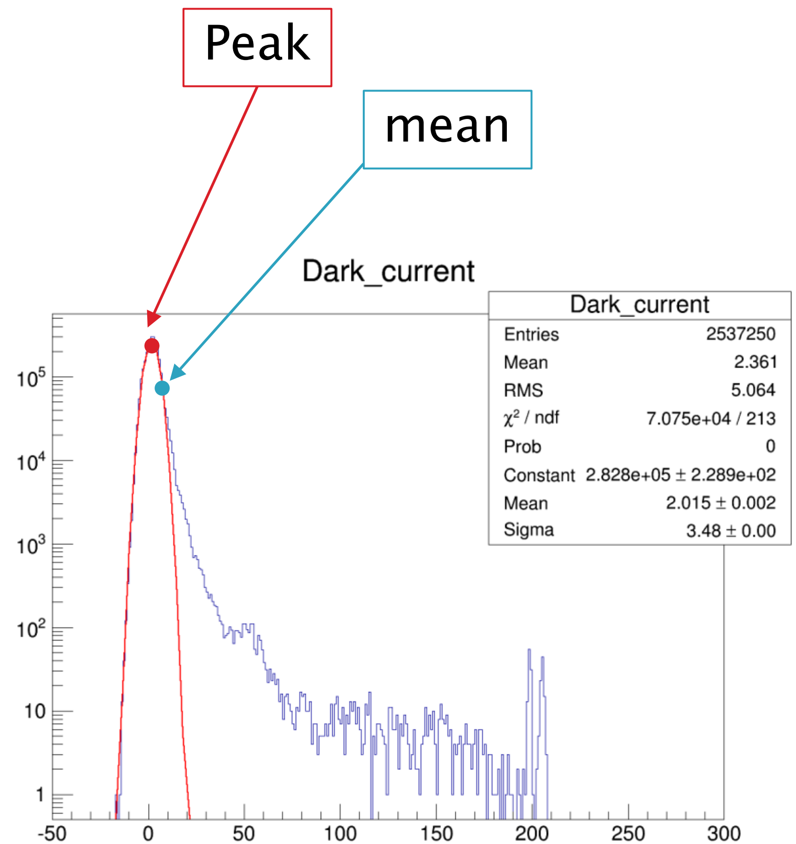
- We measured 3 parameters above 3, 9, 23 and 199days after irradiation to see the annealing effect.
  - FPCCD chip is kept at room temperature (~23℃).

Average dark current of all pixels

- Exposure time: 5, 10, 30, 60sec
  - Charge from dark current is accumulated proportional to exposure time.
- Temperature: −30, −40℃
- Measured with two method
  - Peak position: Gaussian component
  - Mean: tail effect is included



Before irradiation 10sec@−40℃

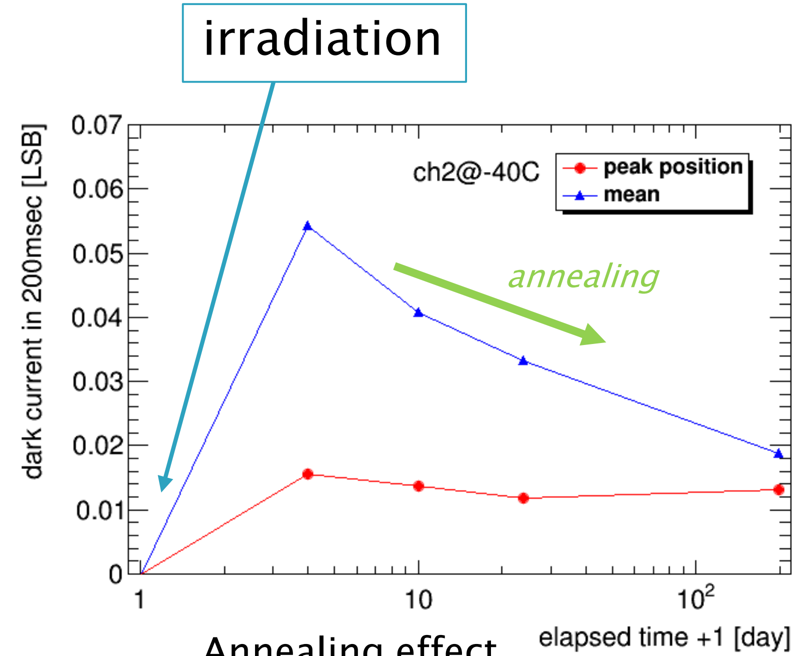


After irradiation 10sec@−40℃

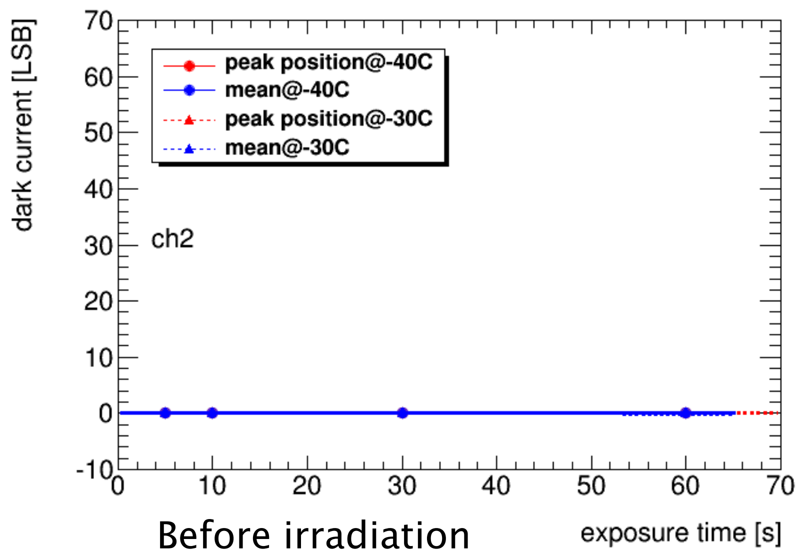
Average dark current

- Before irradiation: almost 0 in −30℃ or less.
- After irradiation: much smaller than dark current width. (sigma=3.42[LSB])
- Dark current is no problem.
- Annealing effect@room temp.: little

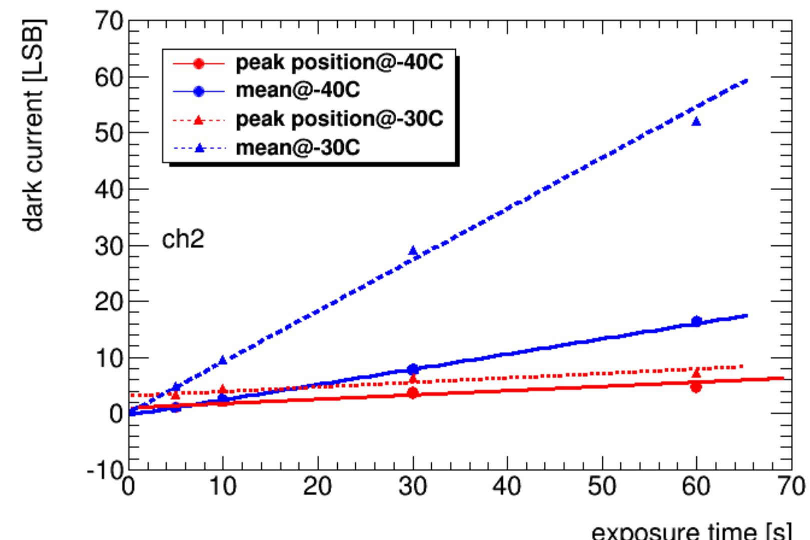
Dark current in 200msec	−30℃ [LSB (= 14e)]	−40℃ [LSB (= 14e)]
Mean	$(1.8 \pm 0.001) \times 10^{-1}$	$(5.4 \pm 0.005) \times 10^{-2}$
Mode	$(1.6 \pm 0.003) \times 10^{-2}$	$(1.5 \pm 0.002) \times 10^{-2}$



Annealing effect



Before irradiation

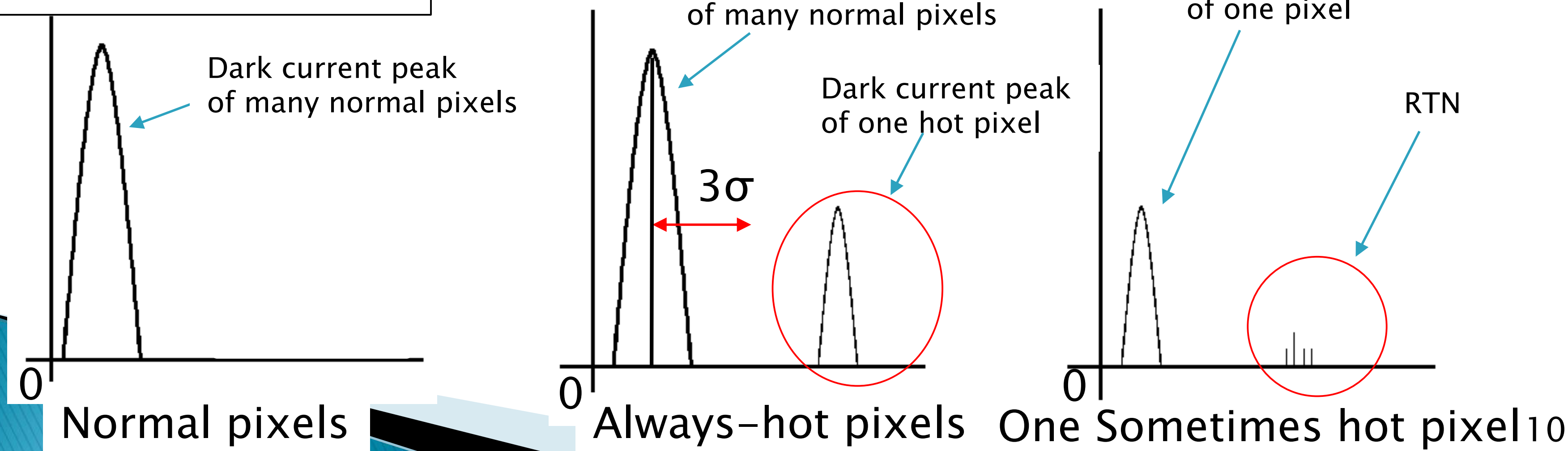


3days After irradiation

Hot pixel

- 2 kinds of hot pixel
  - Always-hot pixel
    - Dark current is always large.
  - Sometimes-hot pixel
    - Dark current is usually small but sometimes large because of random telegraph noise(RTN).
- Definition of hot events
  - When signal charge is larger than 3 sigma of dominant dark current peak, we call it hot event.

Illustrations of ADC distribution



2 definition of hot pixel fraction

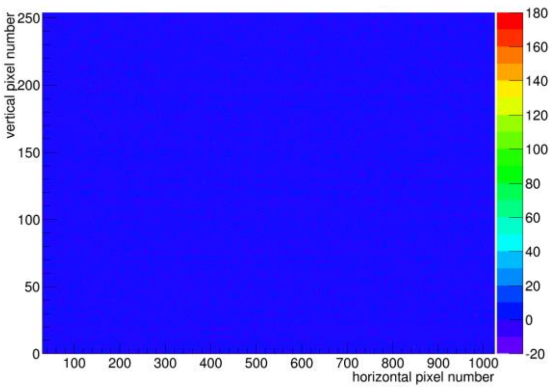
- Fraction of always-hot pixels (without RTN)
  - Hot event probability of one pixel is more than 80%, it is defined as always-hot pixel.
  - $Fraction = \frac{N_{always}}{N_{total}}$
  - This fraction indicates fraction of dead pixels.
- Fraction of all hot events (with RTN)
  - $Fraction = \frac{\sum N_{event,i}}{N_{total} \times N_{measure}}$
  - This fraction is effective for occupancy in the real experiment.

Hot pixel fraction

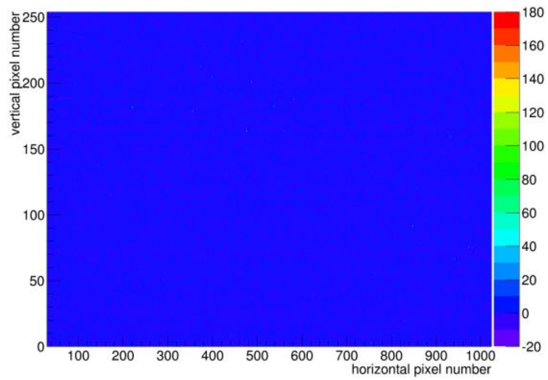
- These are dark current maps in 5sec exposed. At −40℃, number of hot pixels is almost same before and after irradiation.
- In these figures, red point are hot pixel in 200msec exposed.

Before irradiation

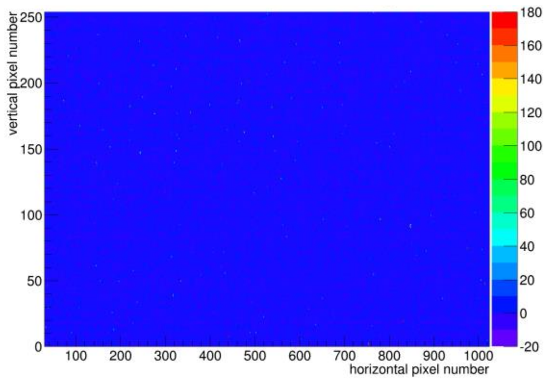
−40℃



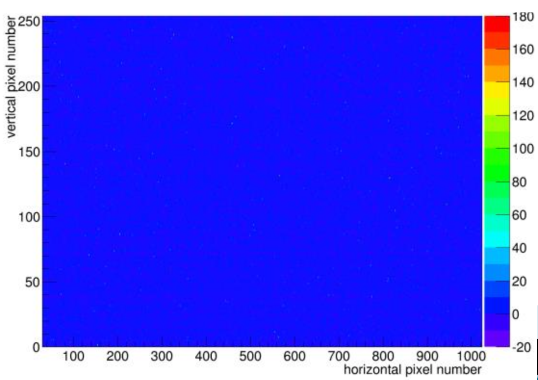
0℃

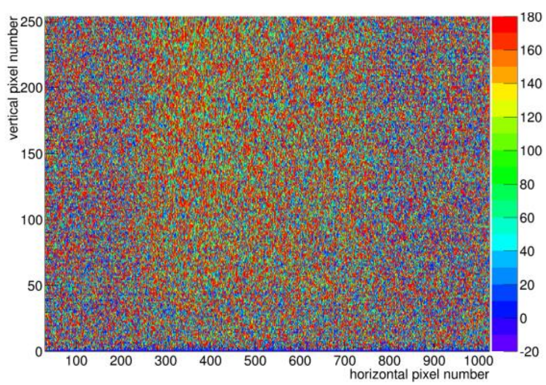


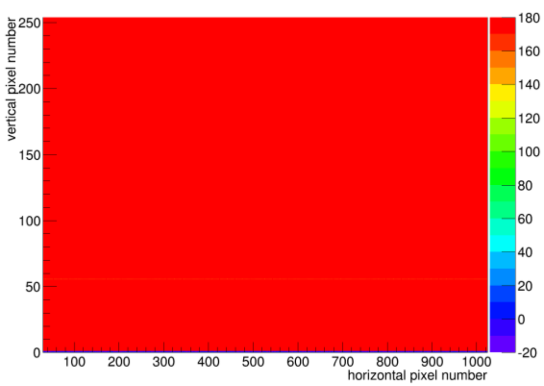
20℃



3days After irradiation

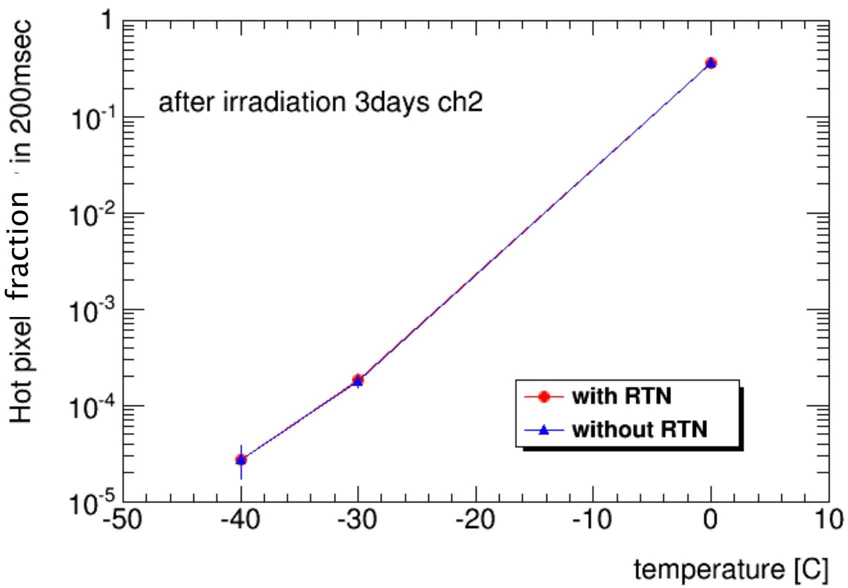


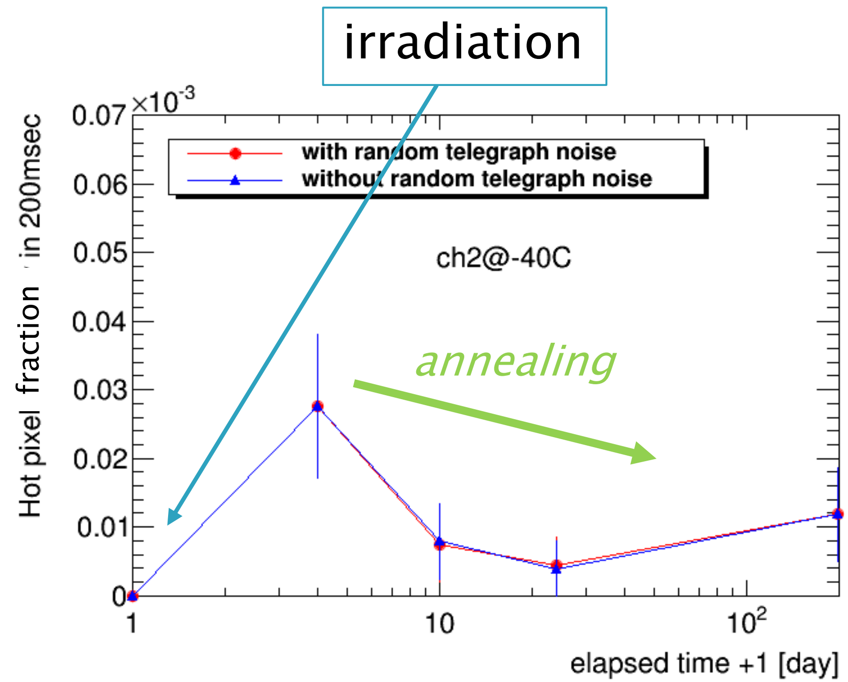




Hot pixel fraction

- To count hot pixels in 200msec, signal charge in 5sec exposed was translated to signal charge in 200msec exposed.
- 2 kind of fractions is almost same.->RTN is a few.
- Hot pixels are suppressed enough at -40℃.
  - Before irradiation: Fraction is 0.
  - 3 days after irradiation: Fraction is 2.76×10^{-5} at -40℃.
- Little annealing effect is seen.





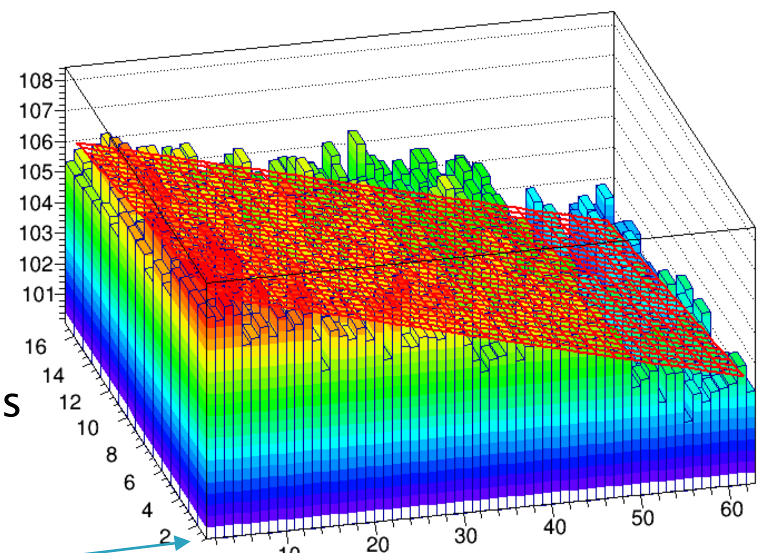
CTI (Charge Transfer Inefficiency)

- CCDs transfer 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., charges are lost.
- CTI
  - Signal charges defined as S become f(x,y) after transfer x times horizontally and y times vertically.

$$f(x,y) = S(1 - CTI_h)^x (1 - CTI_v)^y$$

$$\begin{cases} CTI_h : \text{ horizontal direction} \\ CTI_v : \text{ vertical direction} \end{cases}$$

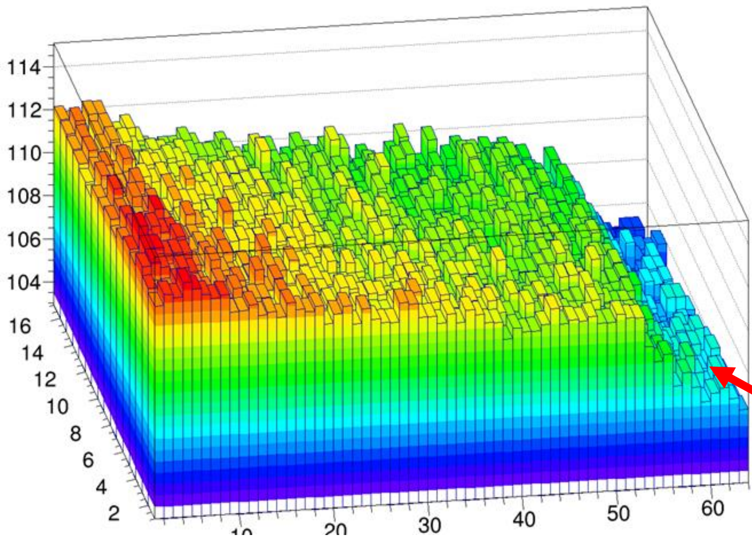
Signal height of Fe55 X-ray
in each super pixel=16x16pixels
After irradiation



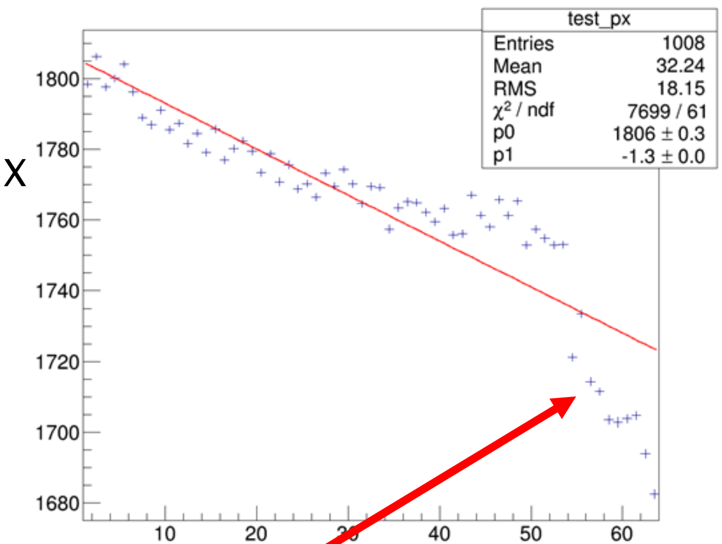
(0,0) is readout

CTI (Charge Transfer Inefficiency)

2D plot of Fe55 peak after irradiation



Projection to X



Unknown source of charge loss

Under investigation

CTI

Channel	Horizontal register size	Horizontal CTI (CTI_x)	Vertical CTI (CTI_y)
Ch2	$6\mu m \times 12\mu m$	$(3.49 \pm 0.03) \times 10^{-5}$	$(6.34 \pm 0.10) \times 10^{-5}$
Ch3	$6\mu m \times 18\mu m$	$(4.59 \pm 0.03) \times 10^{-5}$	$(6.15 \pm 0.10) \times 10^{-5}$
Ch4	$6\mu m \times 24\mu m$	$(3.92 \pm 0.03) \times 10^{-5}$	$(6.24 \pm 0.11) \times 10^{-5}$

- In real experiment, one read out has 13000x128 pixels.
- Signal of the farthest pixel from read out is transferred 13000 times horizontally and 128 times vertically.

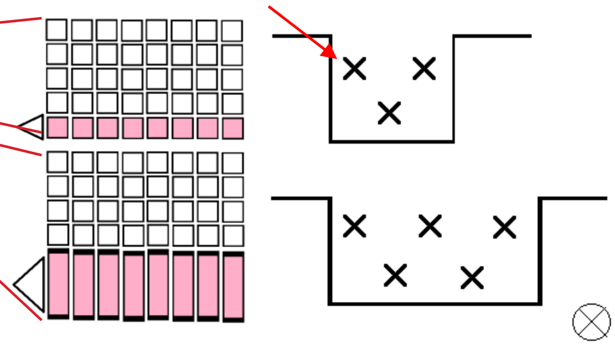
$$(1 - 3.49 \times 10^{-5})^{13000} \times (1 - 6.34 \times 10^{-5})^{128} = 0.63$$

- Even the farthest pixel, signal remains 63%.

Horizontal register pixel size

- Different horizontal register size
  - 4type: $6\mu m \times 6\mu m$, $6\mu m \times 12\mu m$, $6\mu m \times 18\mu m$, $6\mu m \times 24\mu m$
- Charge loss in transfer
  - It is caused by Si lattice defects.

Prototype FPCCD



Small horizontal pixel
→ Number of traps is small.

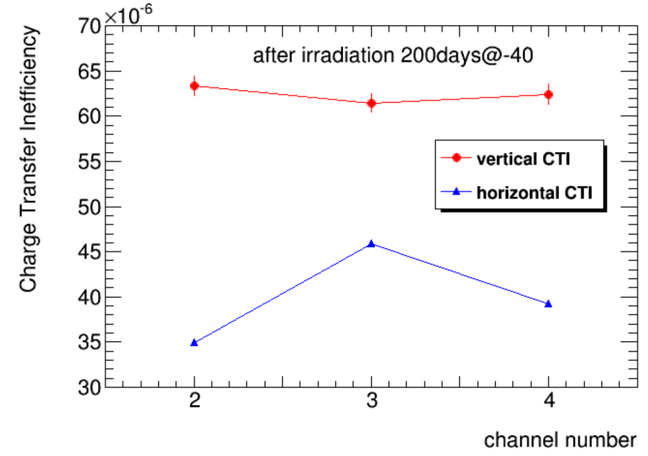
Large horizontal pixel
→ Numbers of traps is large.

CTI may decrease as horizontal register size gets smaller.

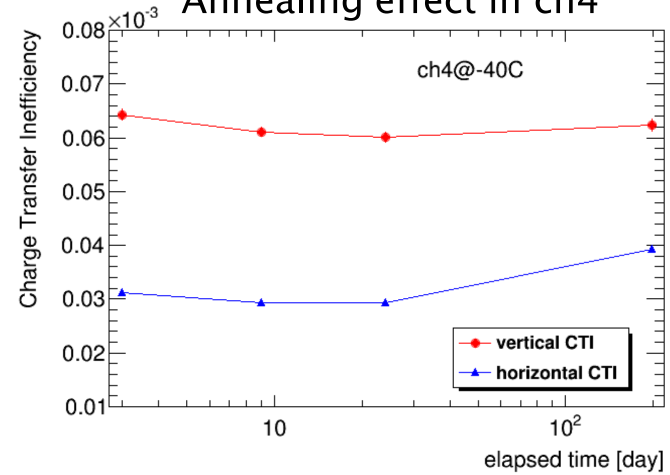
CTI

- CTI should decrease as horizontal register size gets smaller. But CTI in ch3 is largest.
- Vertical CTI is same in each channel, which is consistent since vertical transfer pixel size is same in each channel.
- Annealing effect is not seen.

Relation of CTI and channel



Annealing effect in ch4



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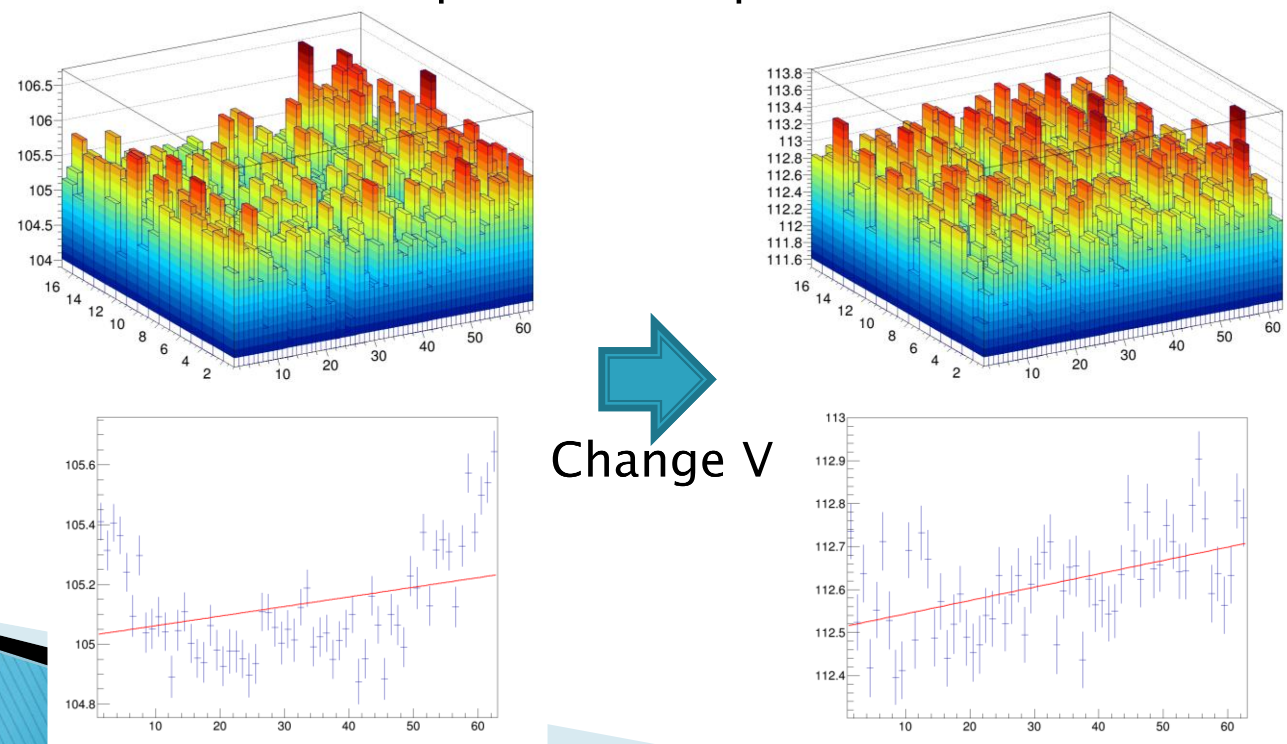
Work in progress

- Before irradiation there is a dent in Fe55 distribution.
  - Disappearance of a dent in ch4 was observed by changing CLK pulse voltage.
  - I am searching the dependence of CLK pulse voltage and finding proper voltage

2D plot of Fe55 peak@ch4



Summary and Plan

- Neutron tolerance is still studied.
  - Dark current: very small
  - Hot pixel fraction: very small
  - CTI: maximum charge loss is 37% (63% remained)

- Plan
  - Dependence of CLK pulse voltage
  - Dependence of CLK pulse frequency
  - Dependence of temperature
  - Measure with 200msec integration time

Back up

Vertical CLK pulse width

- Signal charge is read out in the train gap ~200ms
- 13000x128pixel data is read out with 10Mpixel/s
- Time of horizontal transfer is following
  - $\frac{13000 \times 128 pixel}{10 Mpixel/s} = 166 msec$
- One vertical transfer can use following time
  - (200-166)ms/128=266usec