# Radiation Hardness of a P-Channel Notch CCD Developed for the X-ray CCD Camera onboard the XRISM Satellite

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Hiroshi Tsunemi (Osaka University), and the XRISM Xtend team

# Contents

# X-ray CCD for astronomical use

## history of standard focal-plane detectors in Japan

**new satellite**

| | ASCA (1993-2001) 417kg | SUZAKU (2005-2015) 1700kg | HITOMI (2016) 2700kg | **XRISM (2021-)** |
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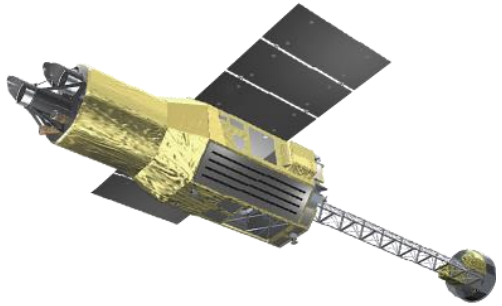
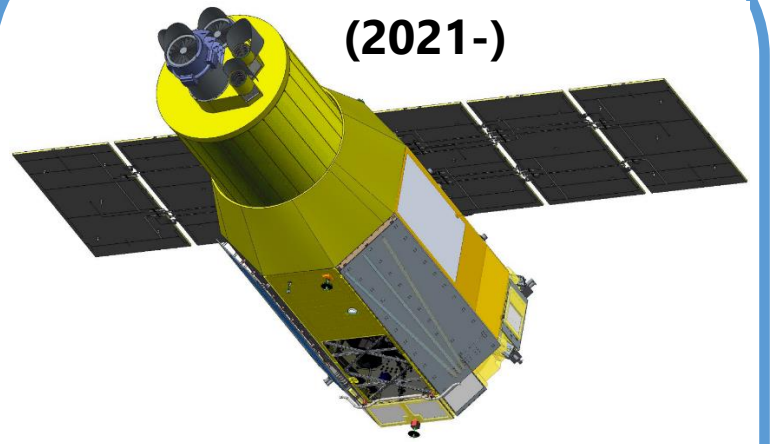
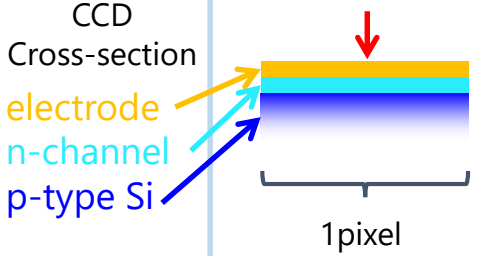
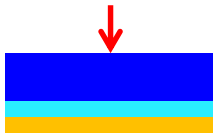
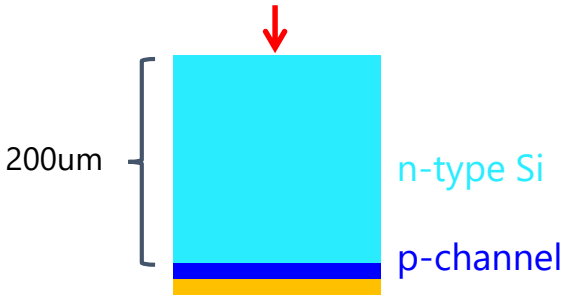
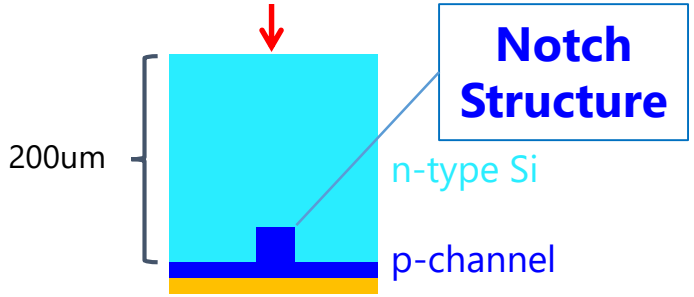
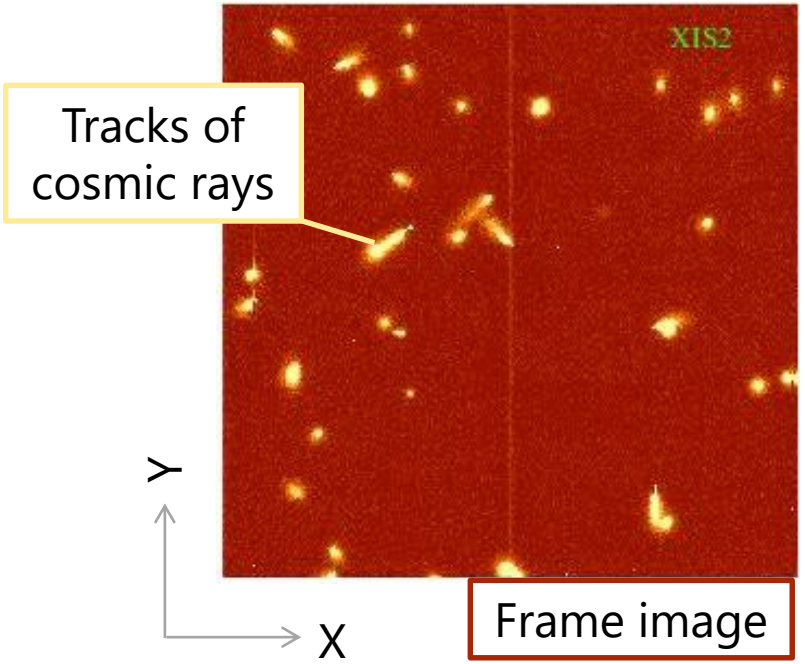
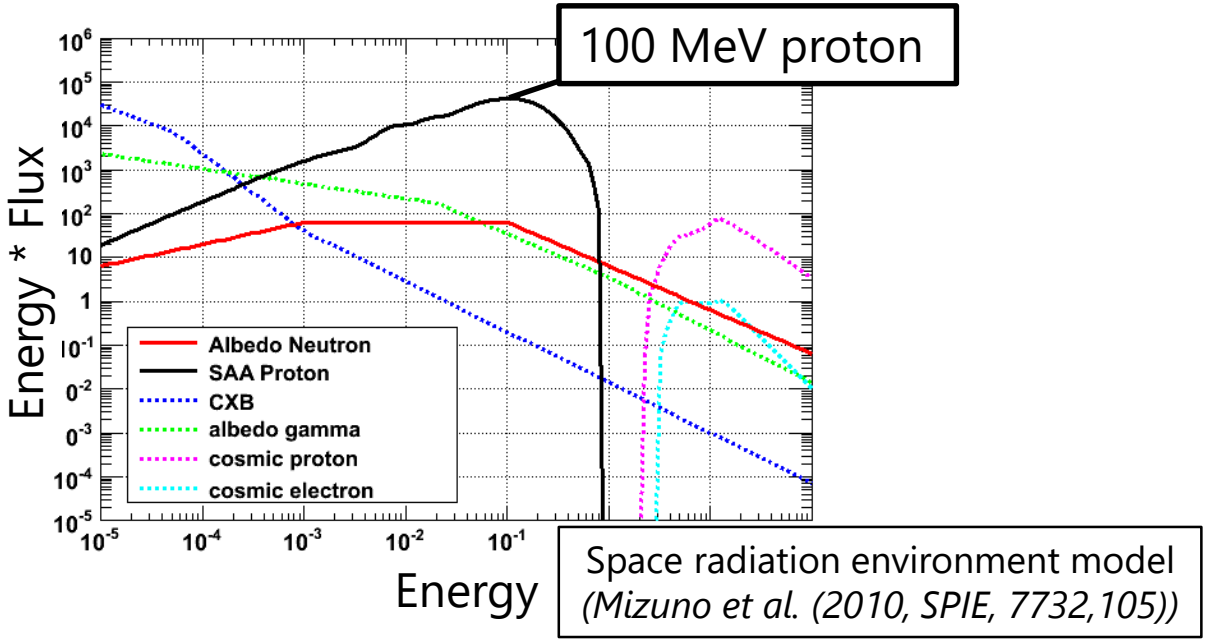
| |  |  |  |  |
| CCD Cross-section |   |  |   |   |
| type | N-ch FI CCD | N-ch BI CCD | P-ch BI CCD | P-ch BI CCD (**w/ notch**) |

# Radiation damage in space

**For space application, radiation hardness is one of the most important properties.**

- A CCD in space is severely exposed to cosmic rays.
  - These particles produce lattice defects -> worsen the efficiency of charge transfer.



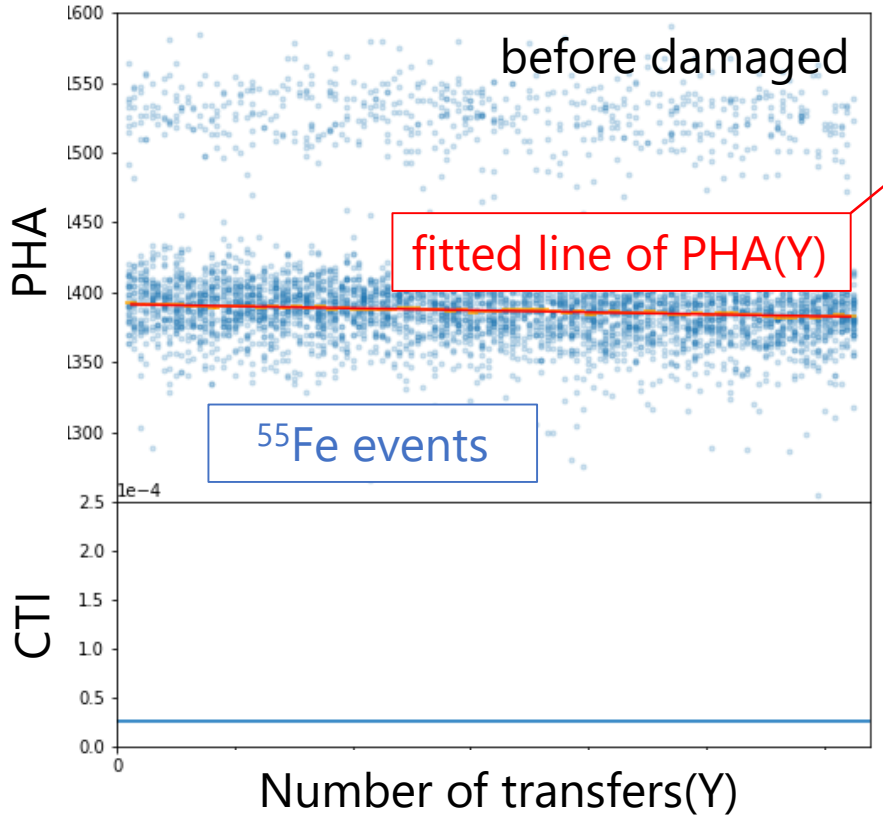




- In the case of XRISM, ~100 MeV protons in SAA are the major source of irradiation damage.
- If the camera body is simplified into 20mm thick Al, The dose rate of the CCD is **260 rad/year.**

# CTI degradation

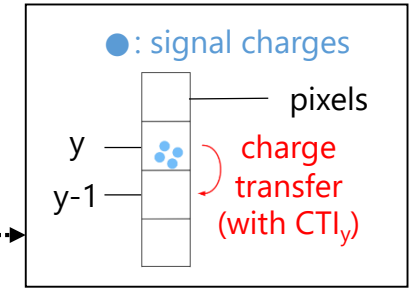
An indicator of the radiation damage is **Charge Transfer Inefficiency (CTI)**.

- CTI is defined as the fraction of charge loss in a single pixel transfer, and which is **measured by fitting pulse height (PHA) as a function of the number of transfers(Y)**.




$$\mathrm{PHA}(Y) = \mathrm{PHA}_0 \times (1-\mathrm{CTI}_1) \times (1-\mathrm{CTI}_2) \times \cdots \times (1-\mathrm{CTI}_Y)$$
$$= \mathrm{PHA}_0 \times \prod_{y=1}^{Y} (1-\mathrm{CTI}_y)$$

- $Y$: the number of transfers
- $\mathrm{PHA}_0$ : pulse height w/o charge-transfer loss
- $\mathrm{CTI}_y$ : CTI in a transfer from $y$ to $y-1$




If CTI is independent of Y, the function is simplified into:

$$\mathrm{PHA}(Y) = \mathrm{PHA}_0 \times (1-\mathrm{CTI})^Y \ (\mathrm{CTI}_y = const. =: \mathrm{CTI})$$

If an imaging area damaged uniformly, CTI remains constant.
**If damaged non-uniformly, CTI changes as Y increases.**

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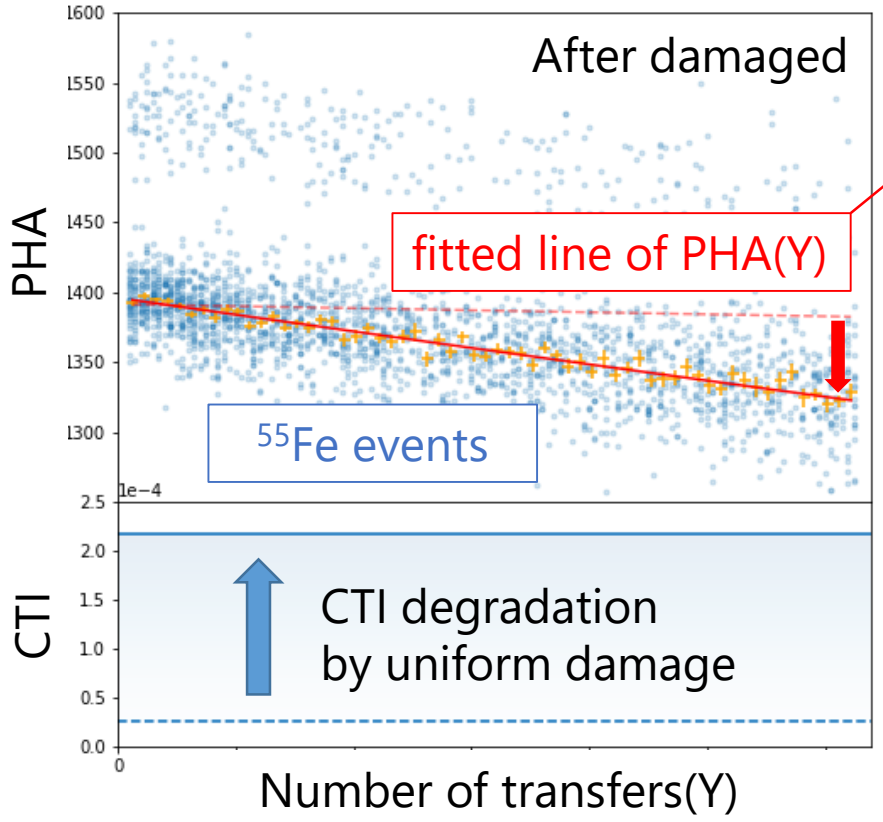


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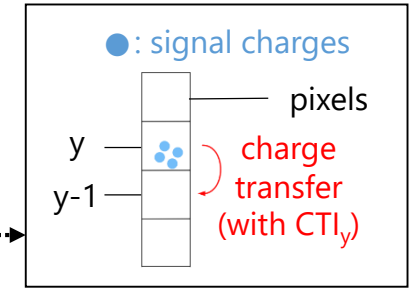


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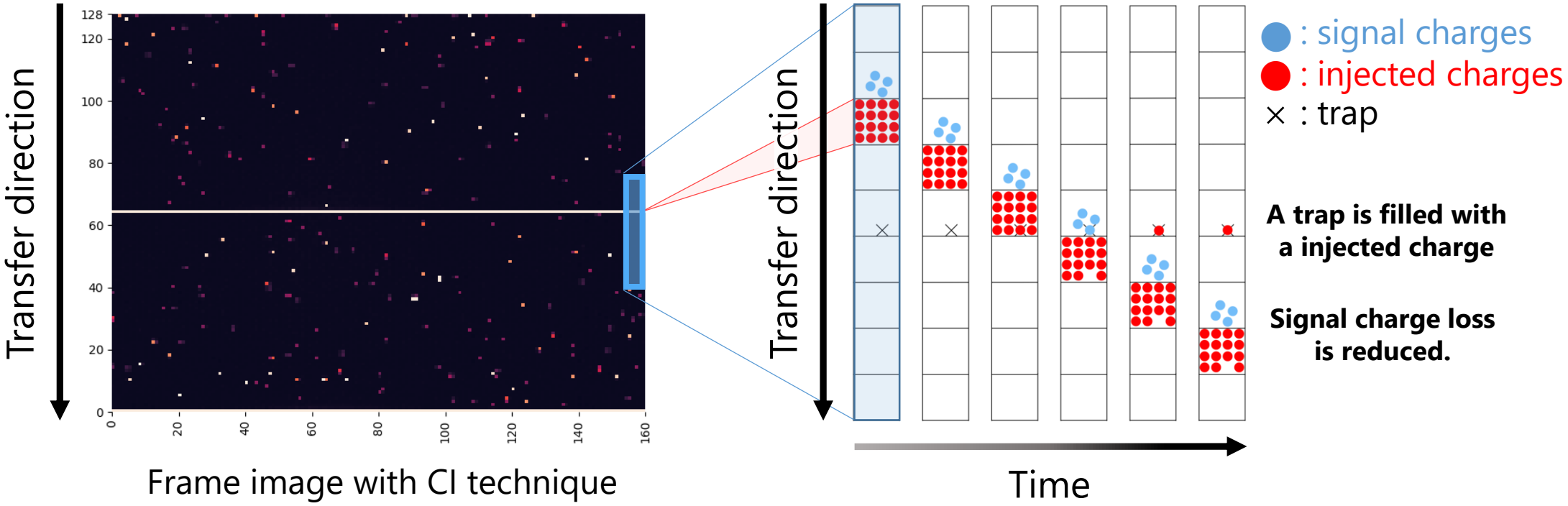
# Mitigation of radiation damage effects

In order to reduce radiation damage effects, we applied some methods to our device.

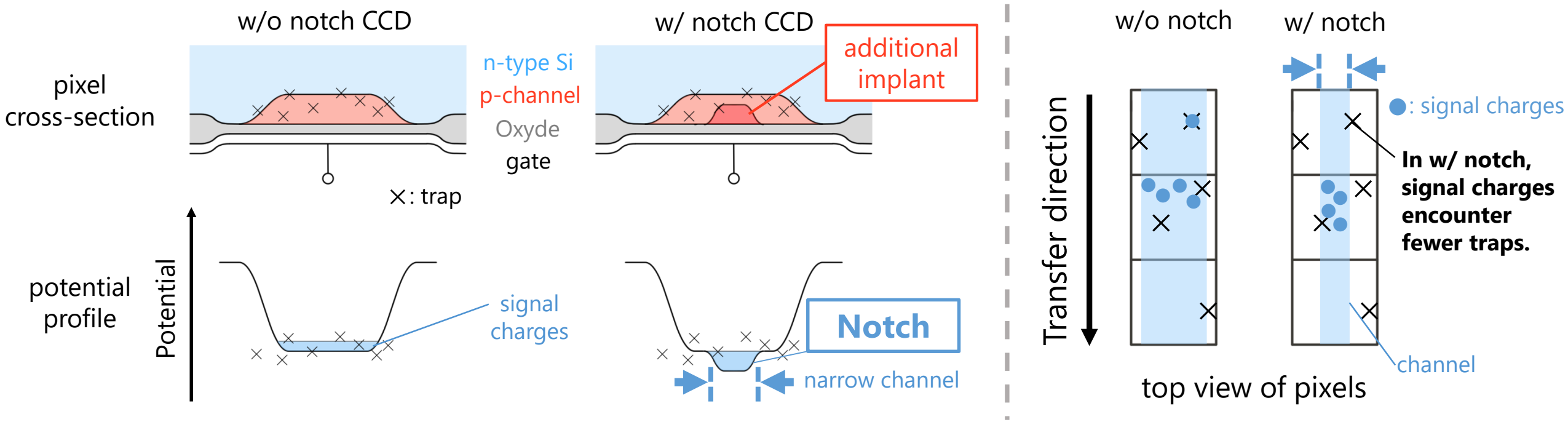
- One of them is a Charge Injection (CI) technique.




- This technique was adopted for the Hitomi CCD, and is also used to the XRISM CCD.

# Notch channel technology

## The notch structure is newly employed to improve radiation tolerance.




- By increasing the implant concentration in the narrow region of the buried-channel, a notch is formed at the bottom of the channel potential. -> reduce the probability of charge interaction with traps
- **For space application, we need to know the radiation hardness of new device and whether the notch structure works as expected.**

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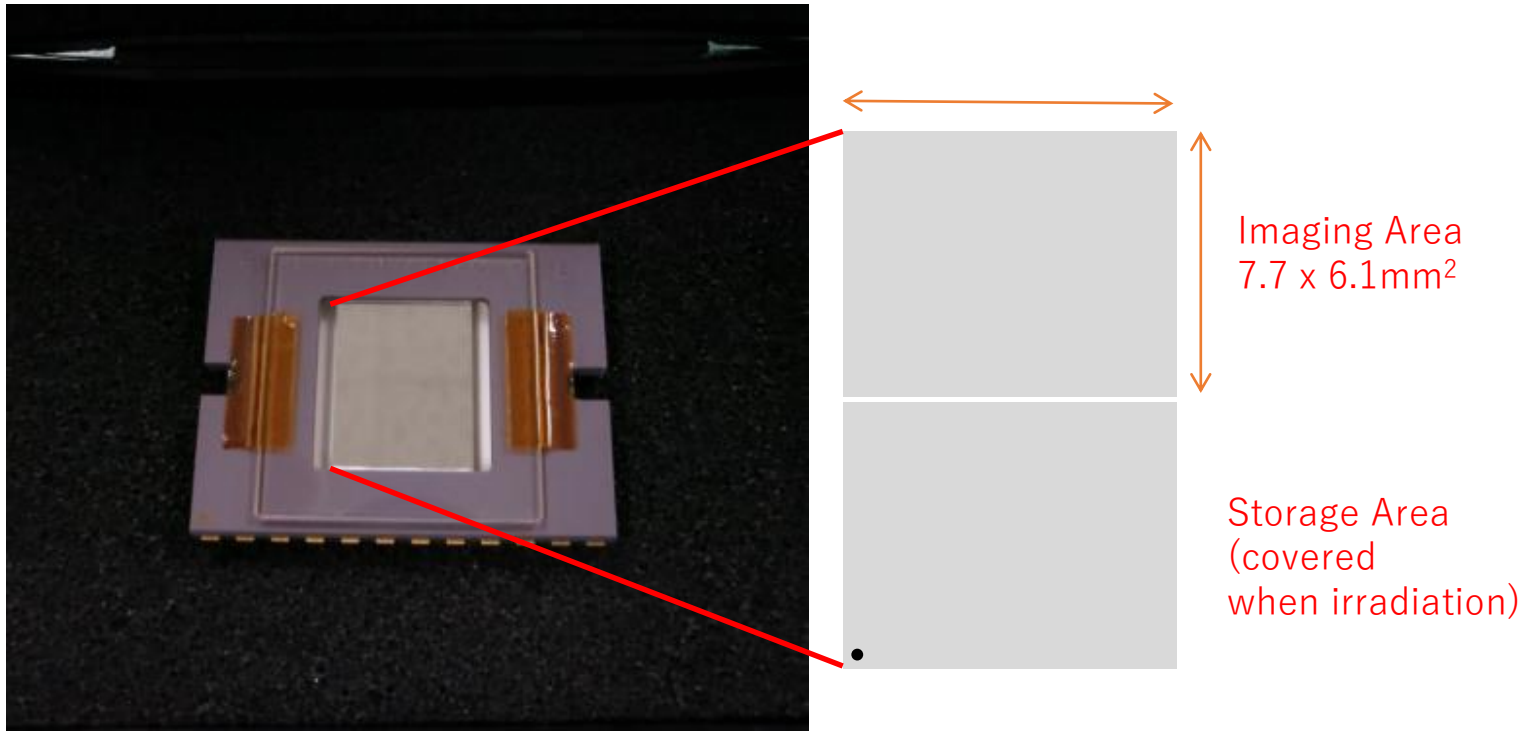
# CCDs used in the experiment




Specifications of the mini-CCD

| | | |
|---|---|---|
| type | | frame-transfer |
| pixel size | | $24 \times 24\ \mu m^2$ |
| binning | | $2 \times 2$ |
| clocking | | 2 phase(H & V) |
| exposure cycle | | 4 sec/frame |
| operating temperature | | $-110\ ^\circ C$ |
| imaging area size | | $7.7 \times 6.1\ mm^2$ |
| format | w/o binning | $320(H) \times 256(V)$ |
| | w/ binning | $160(H) \times 128(V)$ |

**We fabricated two mini-CCDs (<u>w/ notch</u> and <u>w/o notch</u>) for the experiment**

- The storage area was covered when irradiation
- These devices differ from the flight model in terms of imaging area size & format

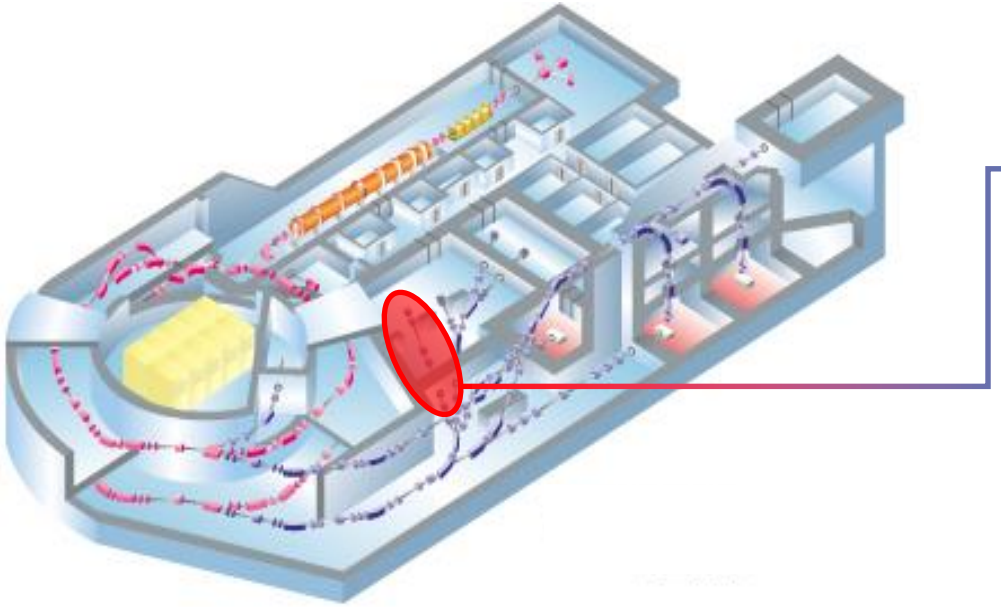
# Proton irradiation in HIMAC

## The experiment was performed in HIMAC

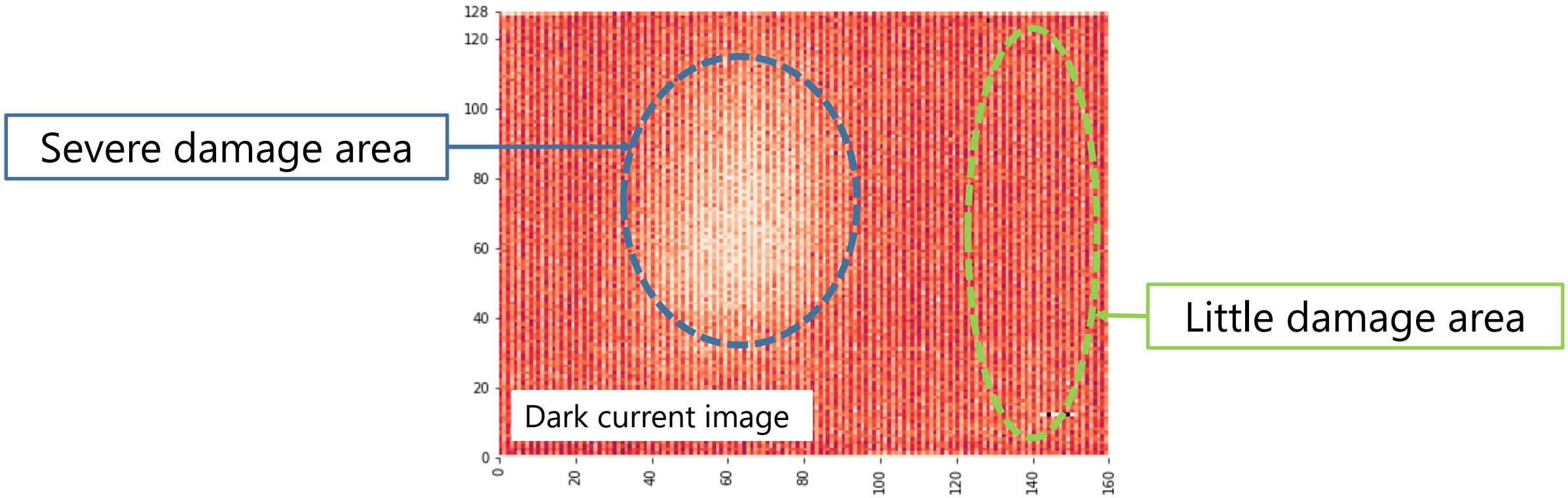
- HIMAC is a synchrotron facility for heavy ion therapy.
- The beam directly entered imaging area of unpowered CCD under atmospheric pressure at room temperature.
- After irradiation, the devices were delivered to a lab and exposed X-rays with $^{55}$Fe for CTI measurement.

Summary of the experiment

| | | |
|---|---|---|
| date | 2018/4/24-29 | |
| beam line | HIMAC PH1 | |
| nuclide | p | |
| energy | 100 MeV | |
| radiation dose | 1,118 rad | (w/ notch) |
| | 676 rad | (w/o notch) |



# Proton irradiation in HIMAC




**Since the beam width is smaller than imaging area, <u>the damage is not uniform</u>**

- The irradiation was concentrated around the center of the imaging area
- We had to consider the non-uniform radiation damage. -> **CTI becomes a function of Y row**

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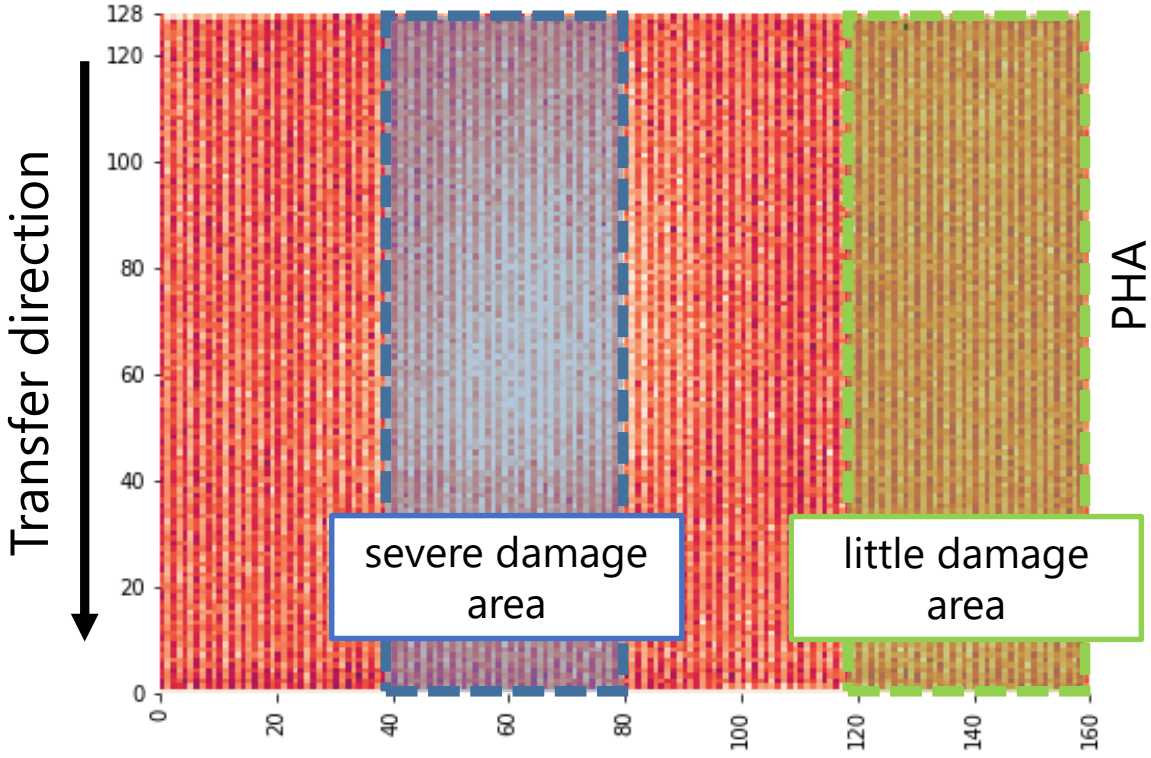
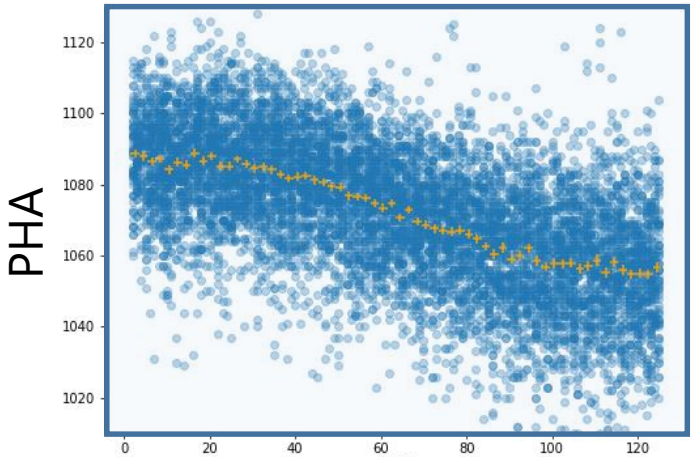
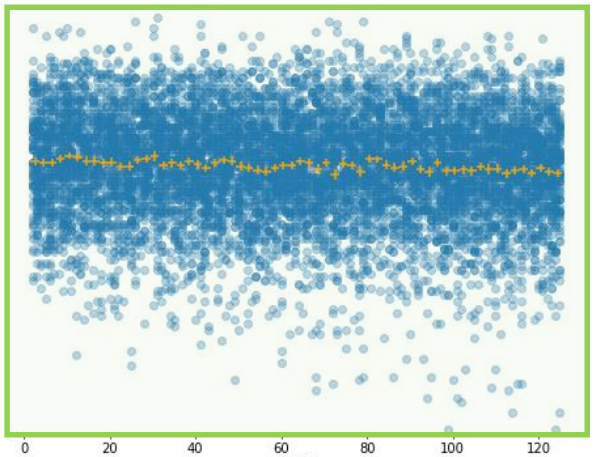
- Introduction
- Proton irradiation experiment
- **Analysis**
- Summary

# PHA as a function of the number of transfers

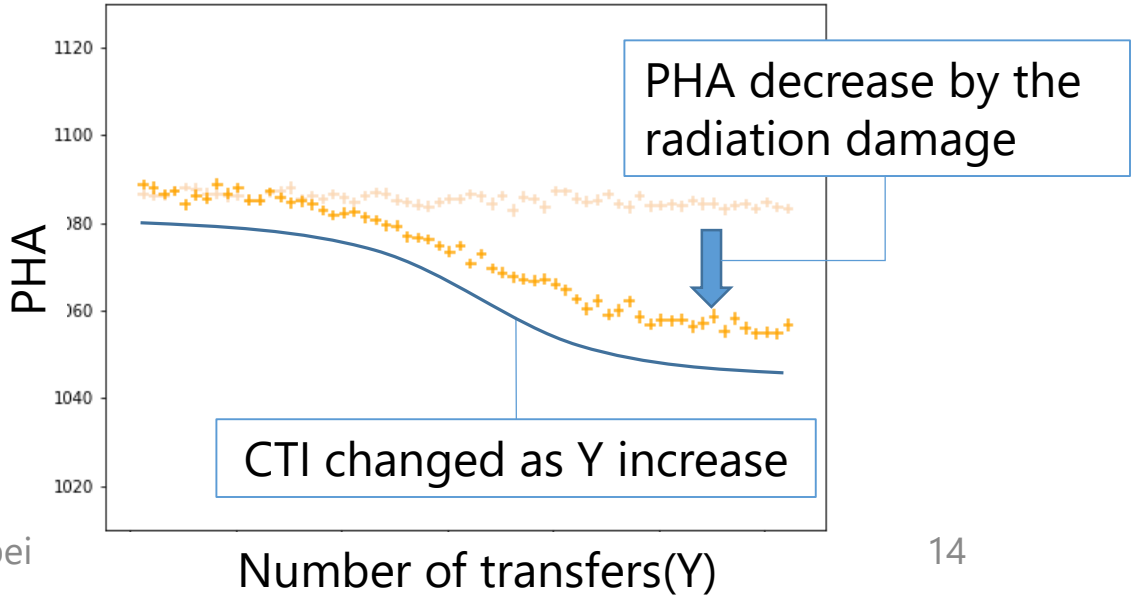



**We defined two damage area.**

- The Severe damage area is defined: 40 < X < 80
- the events in the severe damage area apparently & non-linearly lost charges as Y increases.
  - **This means CTI is a function of Y row.**



# CTI as a function of the number of transfers

**We measured non-uniform CTI as below.**

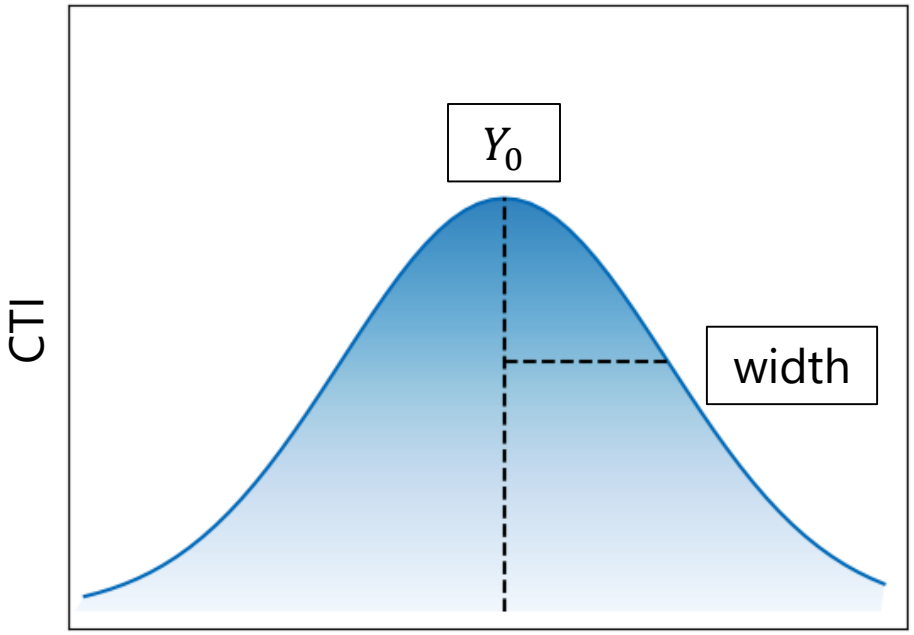
- Pulse height(*PHA)* is a function of Y (with considering the binning):

$$\mathrm{PHA}(Y) = \mathrm{PHA}_0 \times (1-\mathrm{CTI}_1)^2 \times (1-\mathrm{CTI}_2)^2 \times \cdots \times (1-\mathrm{CTI}_Y)^2$$
$$= \mathrm{PHA}_0 \times \prod_{y=1}^{Y} (1-\mathrm{CTI}_y)^2$$

- **We assumed that $\mathrm{CTI}_y$ is a <u>Gaussian function</u>** because the beam distribution can be approximated as 2D Gaussian function.

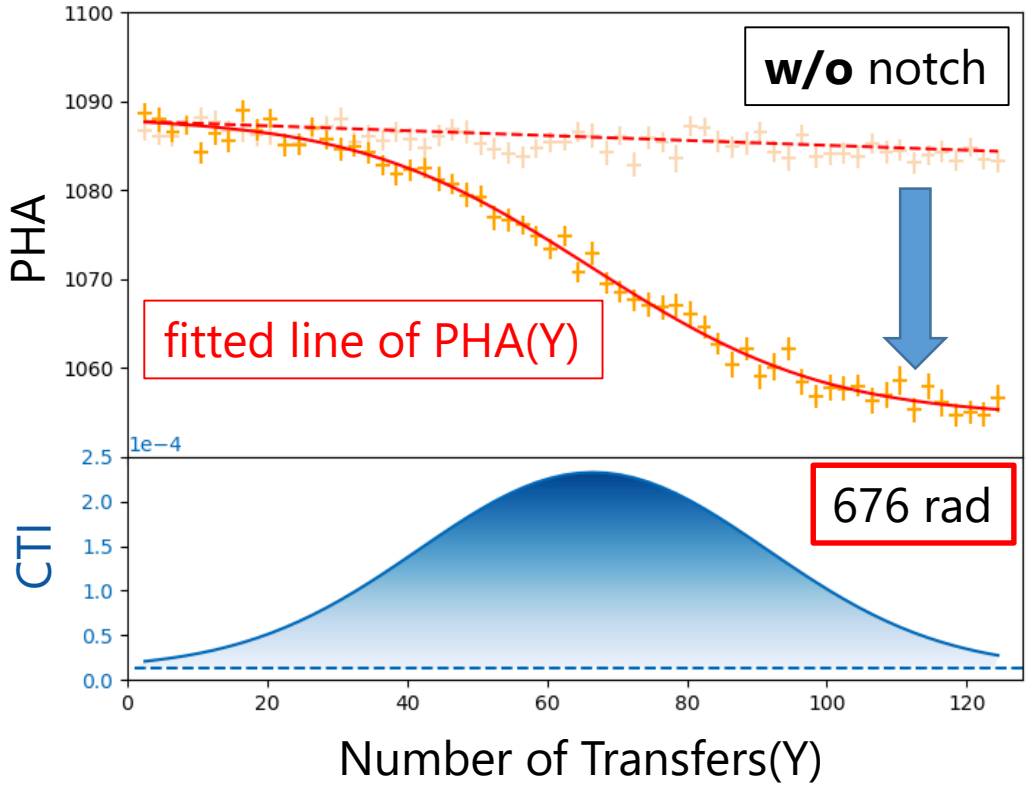
$$\mathrm{CTI}_y = c \exp\left\{-\frac{(y-Y_0)^2}{2\sigma^2}\right\} + cti_{const}$$

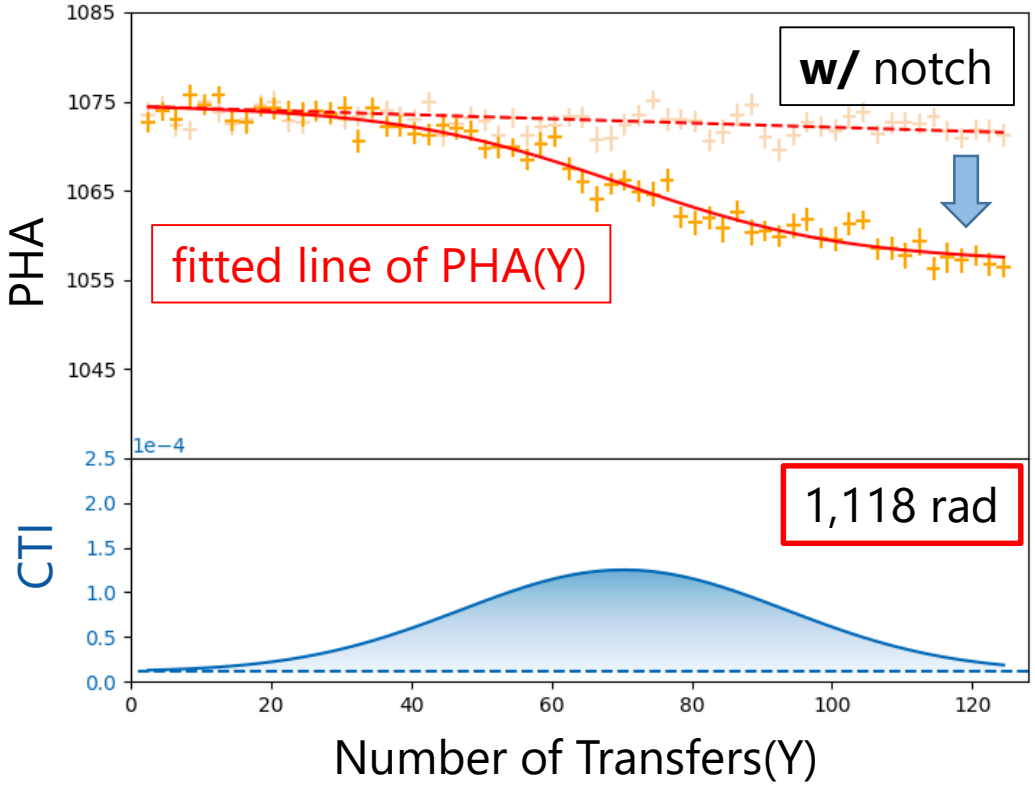
  - $Y_0$ : Y coordinate of the center of the beam
  - $\sigma$ : beam width



# Measurement of CTI

**The fit results are below:**




- **All of the data are <u>well described by the CTI model</u>.**
- **The CTI degradation of w/ notch CCD is smaller than that of w/o notch CCD.**

# Estimation of radiation dose at Y row

**In order to know the relation of CTI and radiation dose, we need to estimate the dose amount of each Y row pixels.**

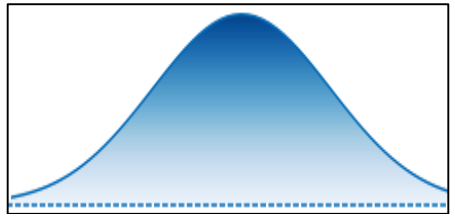
The radiation dose of Y row pixels:

$$\mathrm{dose}(y) = c \int_{Y=y}^{Y=y+1} \int_{X=40}^{X=80} f(X,Y)\,dX\,dY$$

- $\mathrm{dose}(y)$: the radiation dose of $y$ row pixels
- c: the total radiation dose
- f: beam distribution function

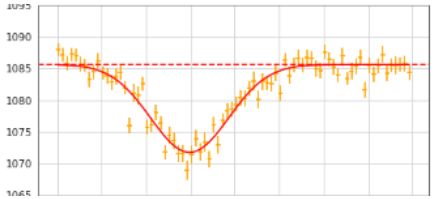
- Since the total radiation dose was measured, we were able to estimate the radiation dose by integration of the beam distribution over each Y row pixels.

CTI

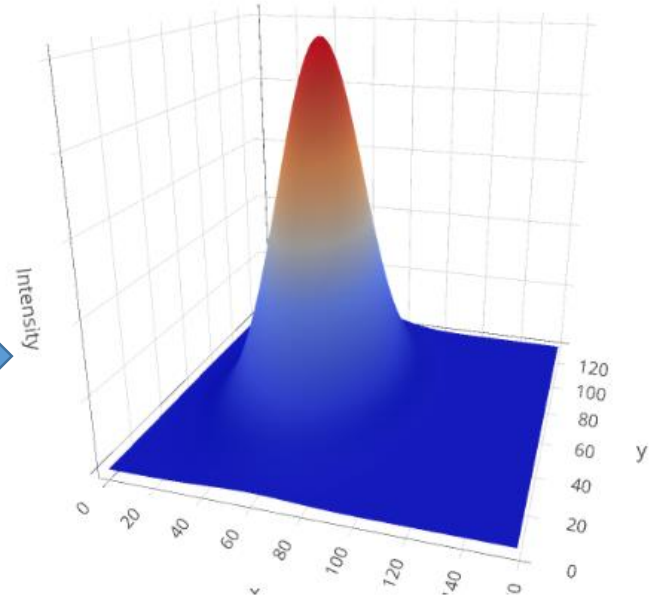


CTI profile (vertical)

PHA




PHA profile (horizontal)

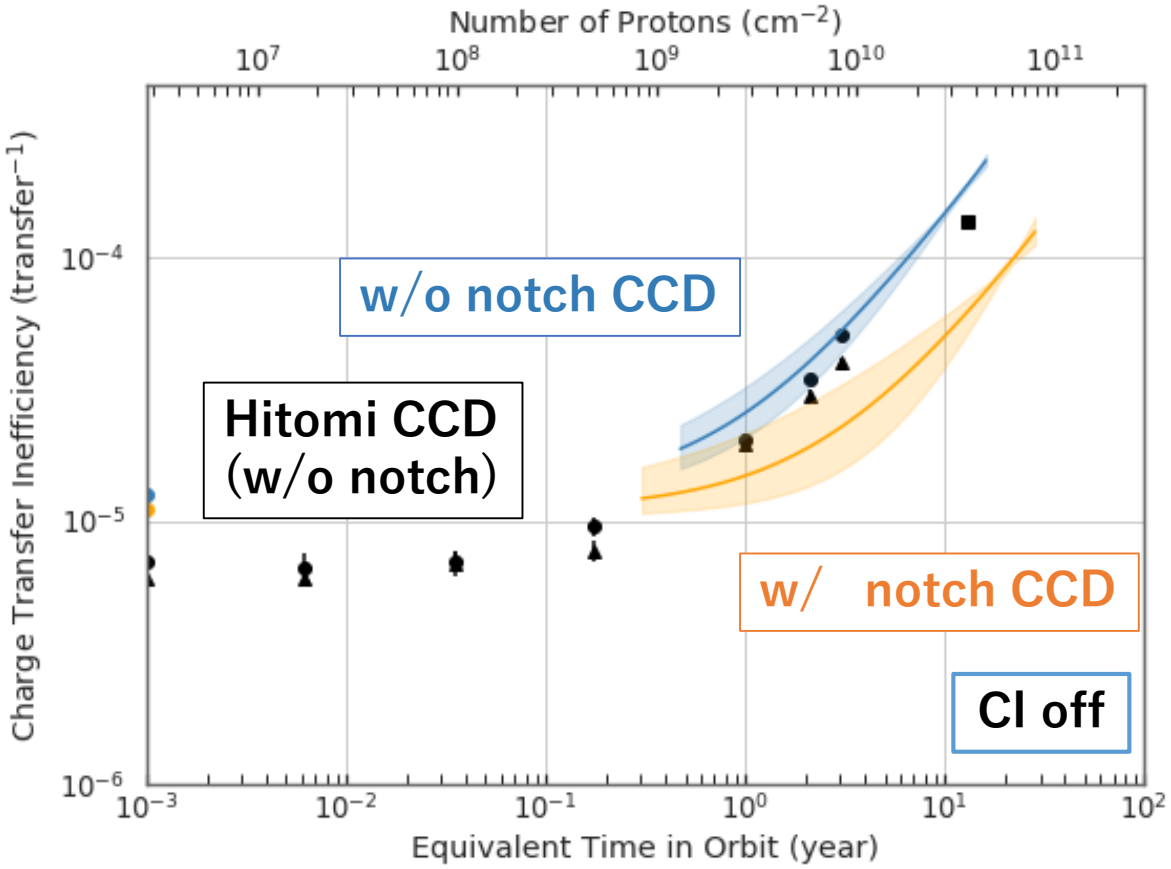


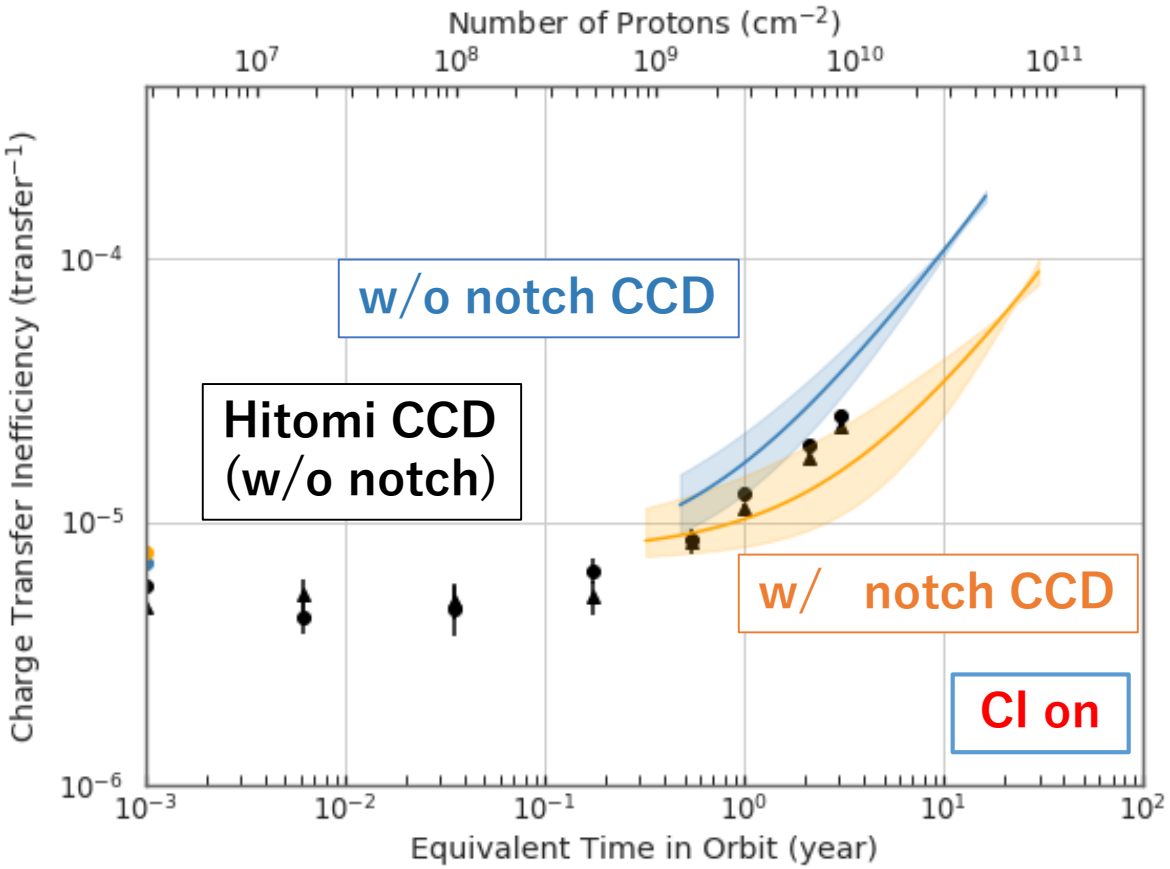

estimated beam distribution

In the beam distribution, we assumed that:

1. the distribution is approximated as a 2D Gaussian function.
2. The vertical and horizontal widths are estimated from CTI and horizontal profile of PHA, respectively.

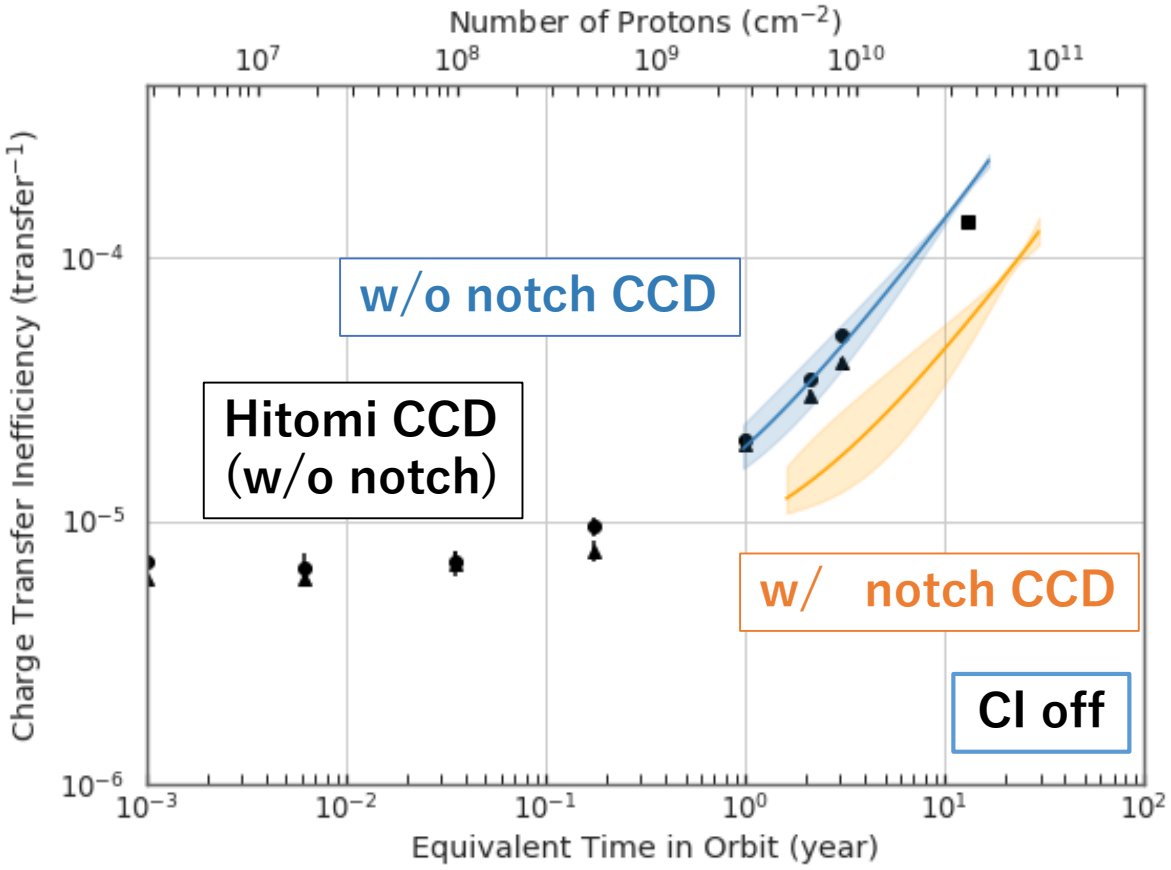
# CTI as a function of radiation dose

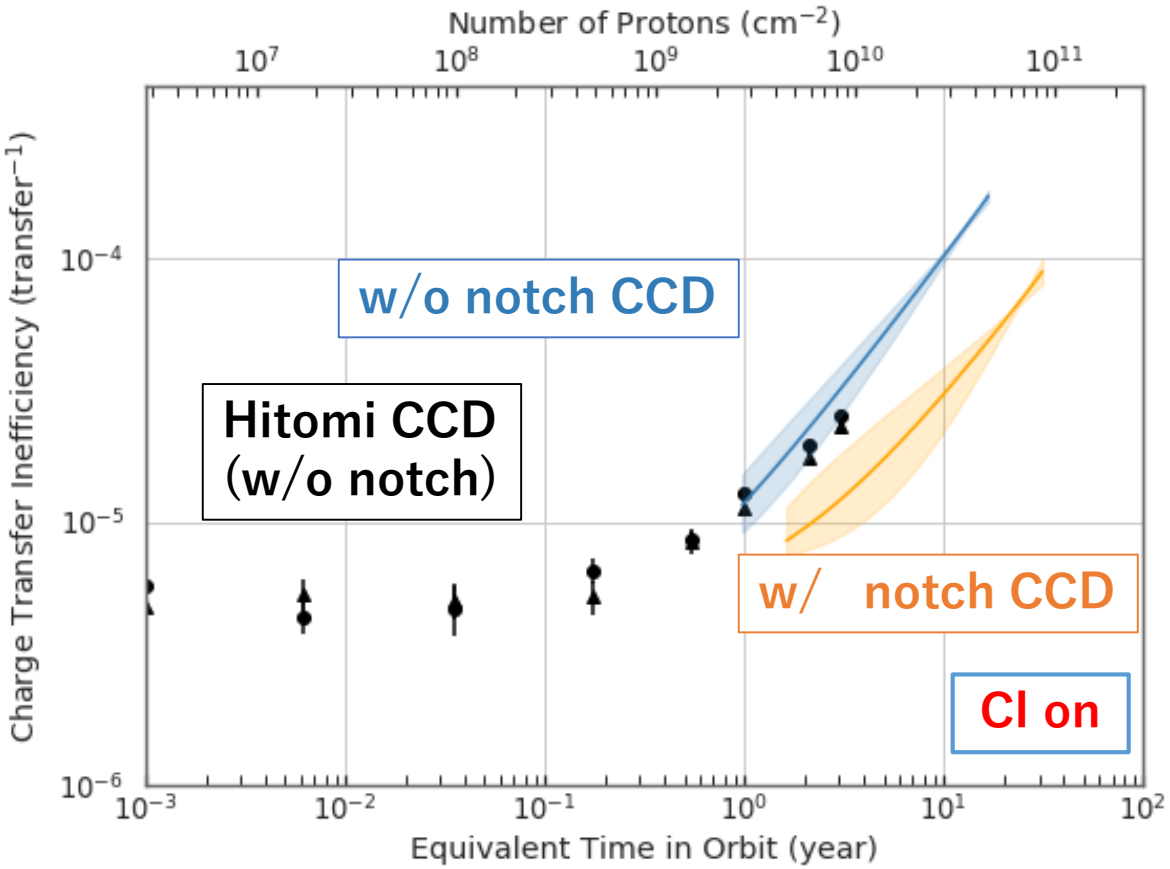



1. **CTI of w/ notch CCD is significantly reduced in comparison with those of conventional CCDs.**
   **-> the new notch CCD is radiation tolerant for the space application with a sufficient margin.**
2. **It is confirmed that the CI technique is effective for both types of CCDs.**
3. **Although w/o notch CCD is the same as the Hitomi CCD, the black dots are located between two lines.**

# Considering the difference of initial CTI




Since initial CTI is dependent on lot number, we considered the difference of initial CTIs between this result and the past one for comparison.

- Assuming the same initial CTIs between the new CCDs and the Hitomi CCD, the above results are obtained.
  -> **The initial CTIs seem a factor of the apparent difference of these results**.

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# Summary

- We performed a proton irradiation experiment on a new type of p-channel notch CCD for the XRISM satellite.
- The radiation doses of the w/ notch device and w/o notch device are 1,118 rad and 676 rad, respectively.
- The result shows that w/ notch CCD has the significantly higher radiation hardness than w/o notch CCDs including the one adopted for Hitomi.
- This proves that the new CCD is radiation tolerant for the space application with a sufficient margin.