The CIGS semiconductor detector for particle physics

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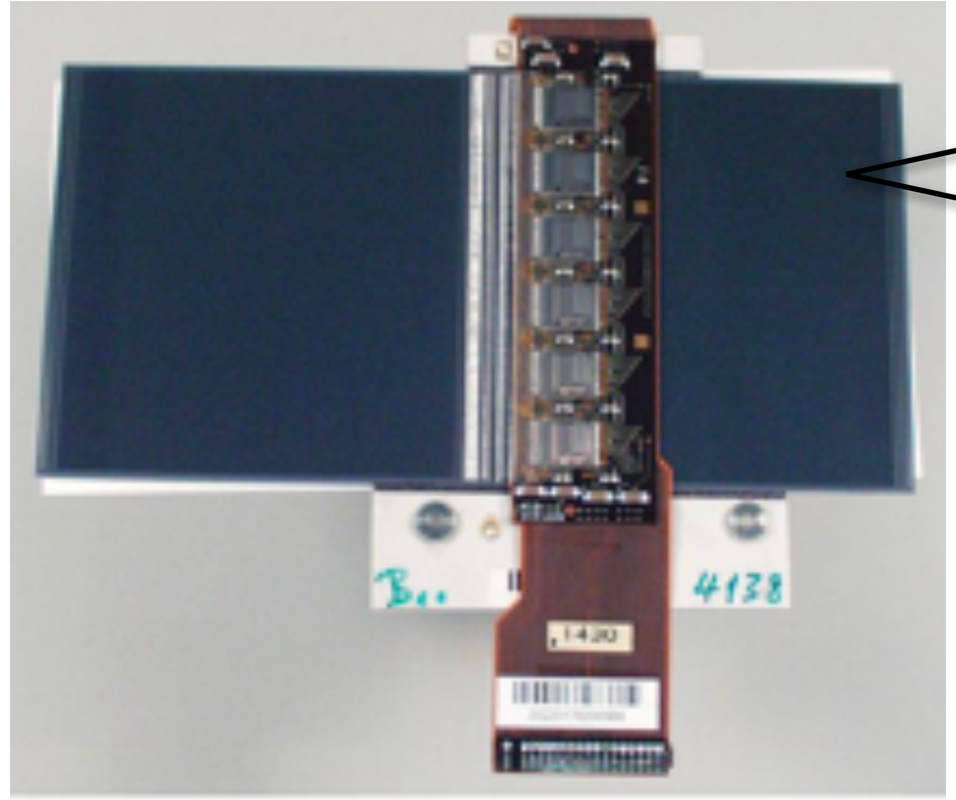
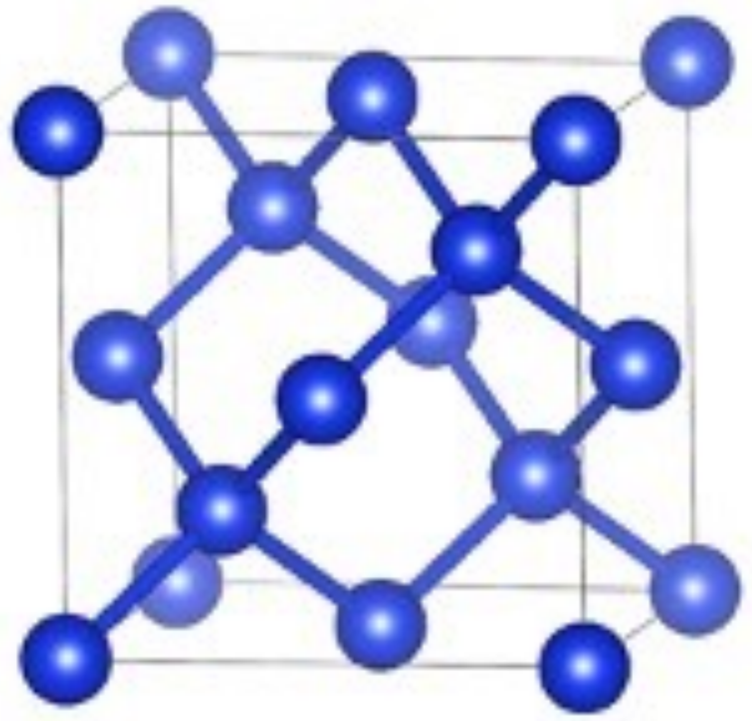
iWoRiD2023 2023/6/27

Semiconductor detector

Silicon semiconductor detector (ATLAS SCT)

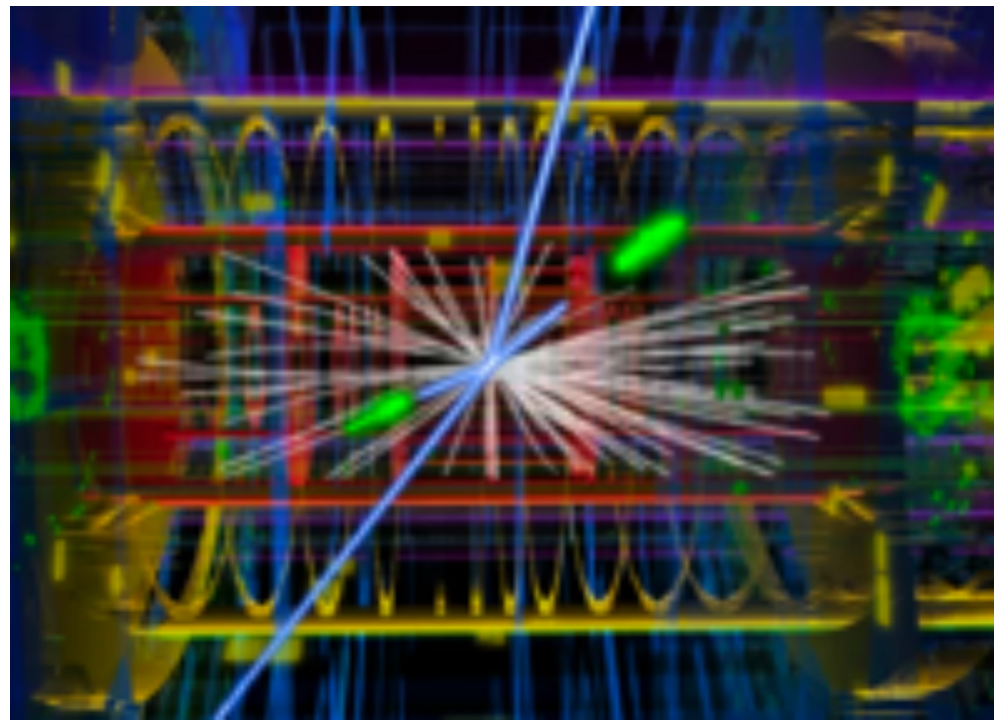


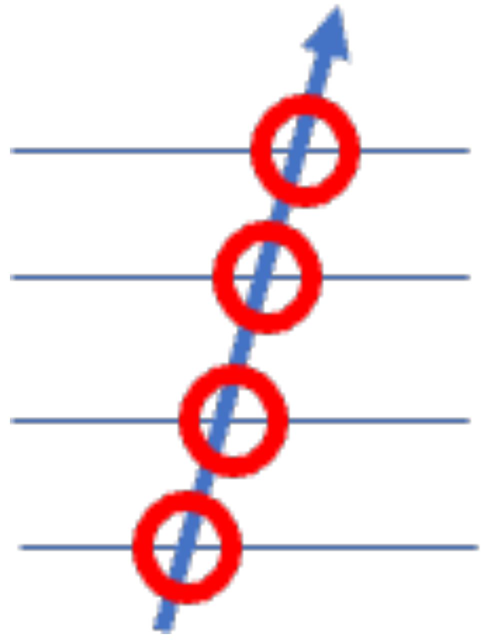
Silicon crystal



- Silicon crystal is the mainstream
  - Crystal is high quality

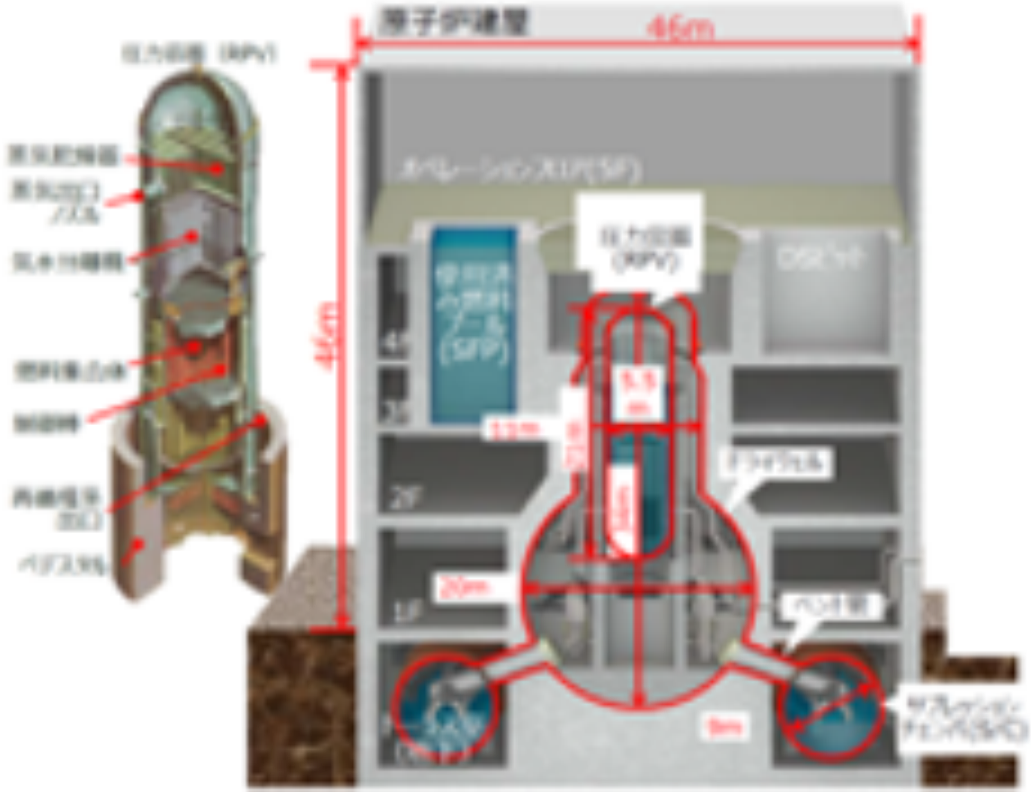
Particle physics

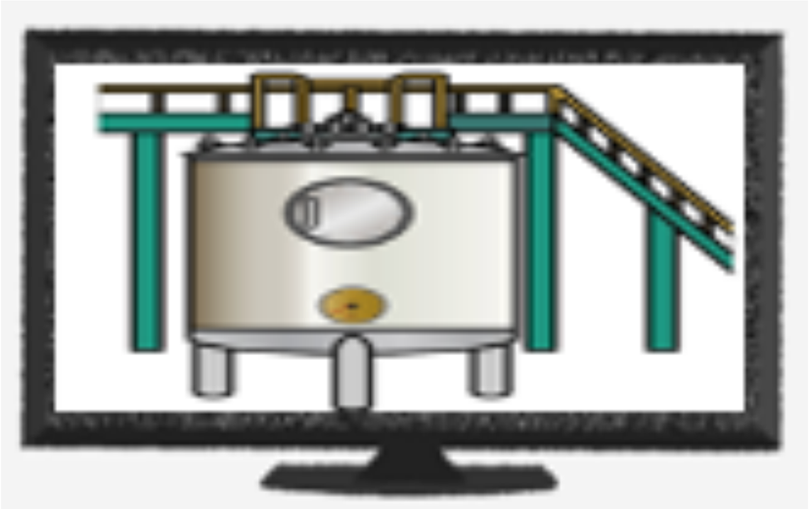




Particle tracking

Camera in nuclear plant

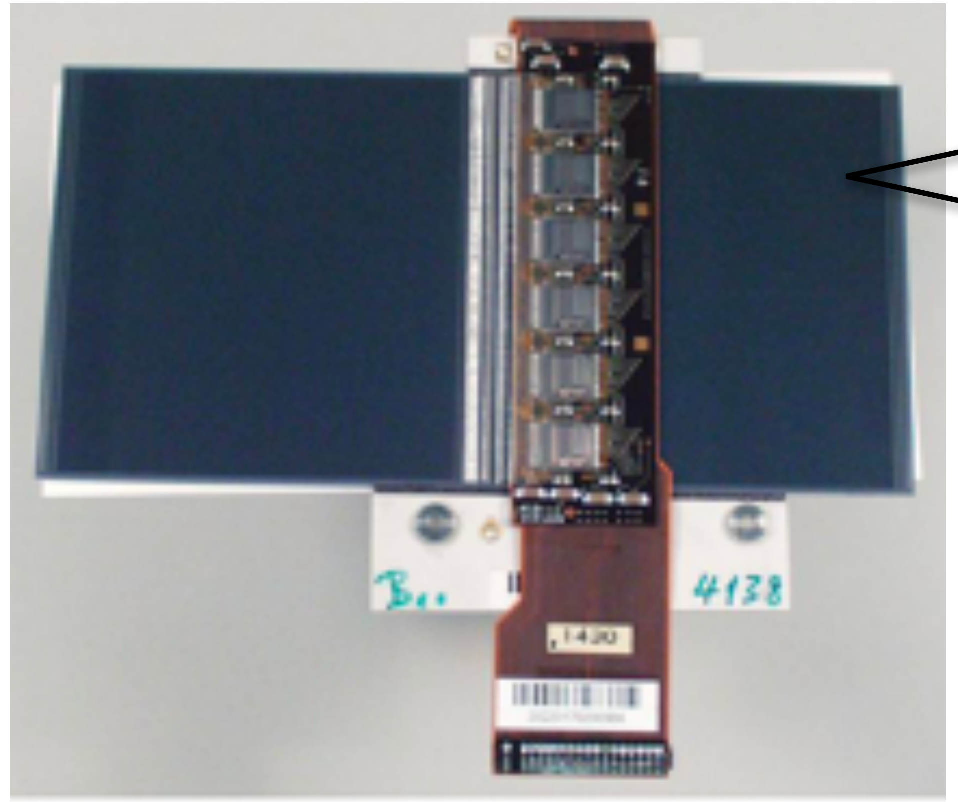


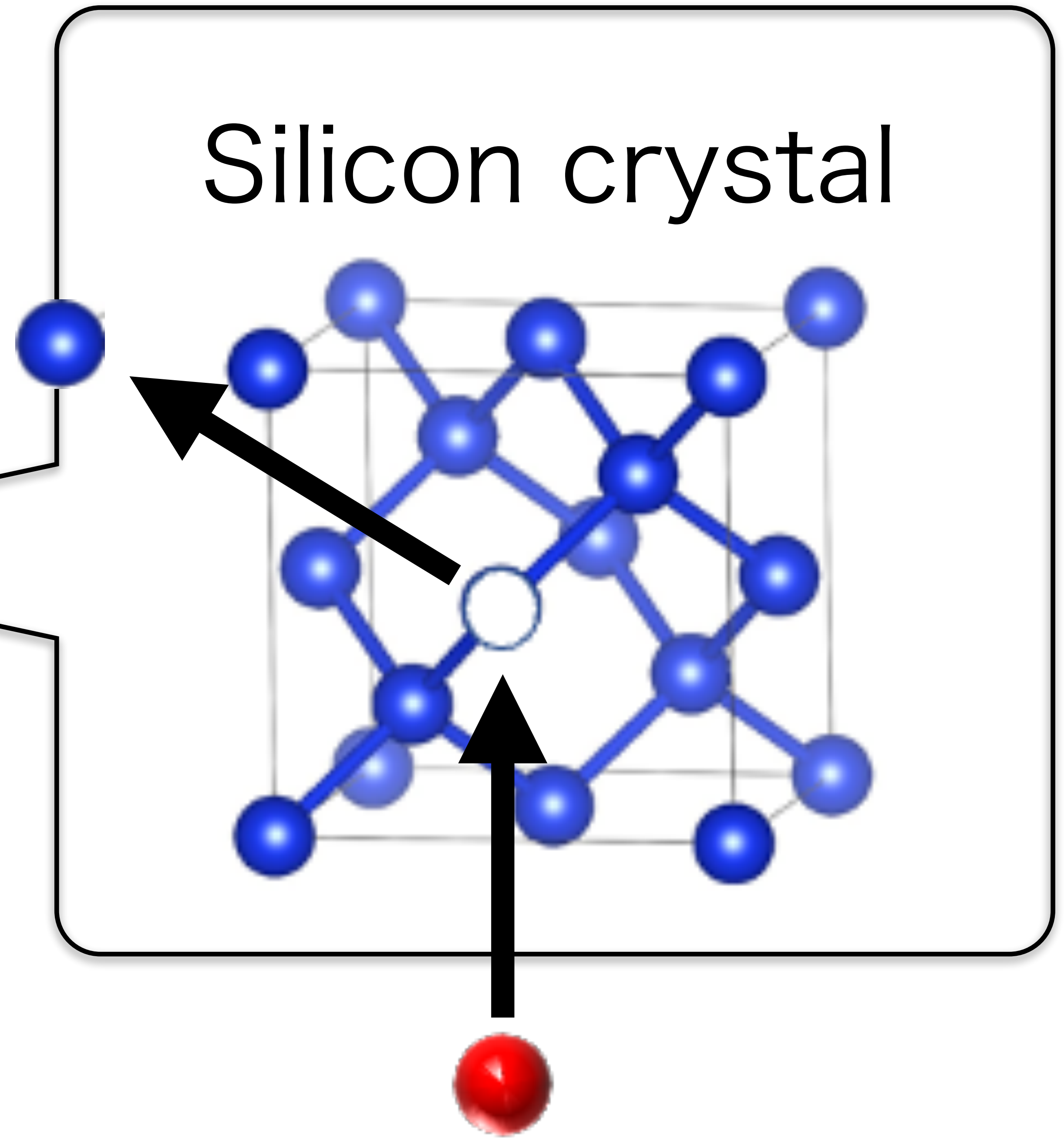


Monitor

Malfunction in the high radiation environment

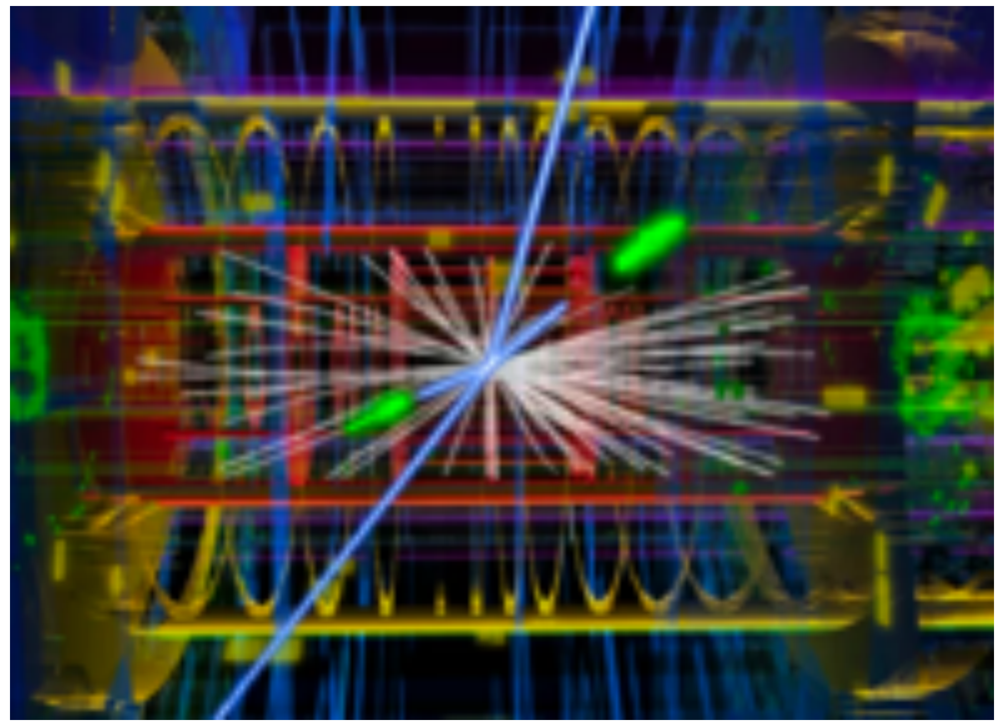
Silicon semiconductor detector (ATLAS SCT)

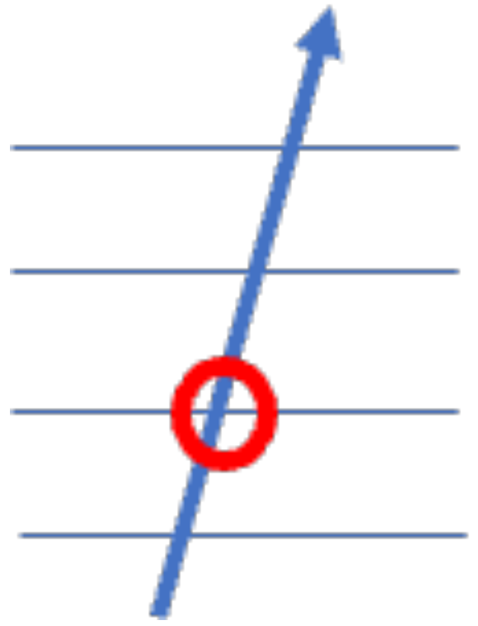




Radiation (proton, neutron..)

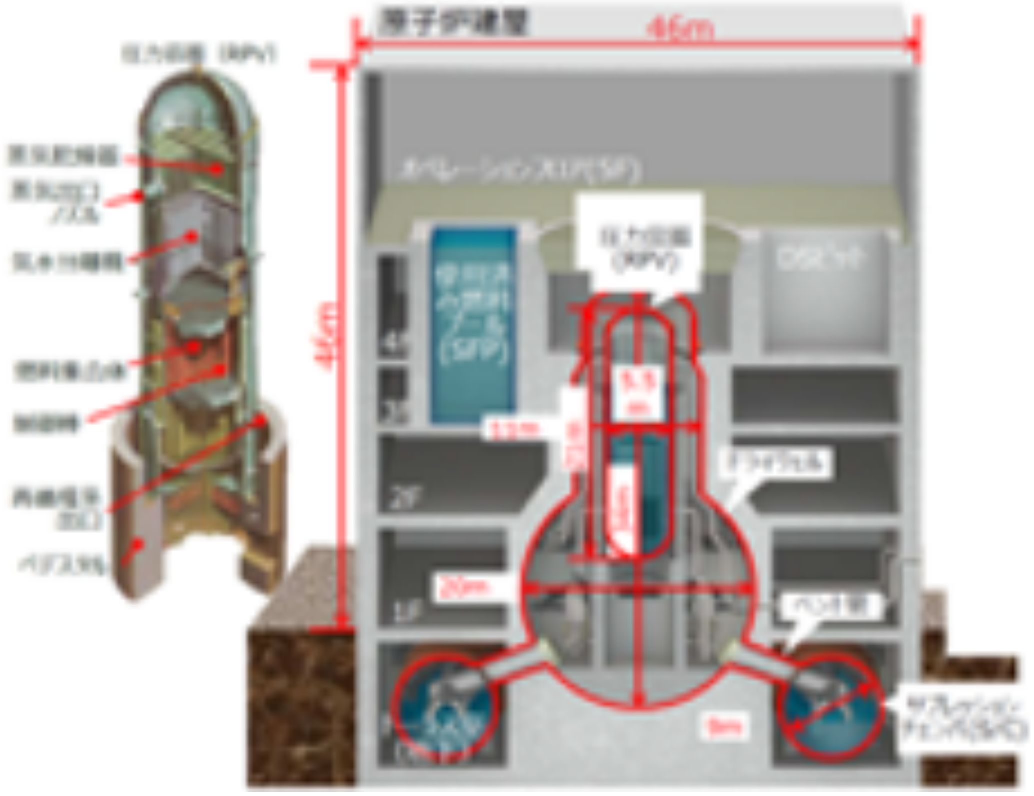
Particle physics





Degrading tracking performance

Camera in nuclear plant

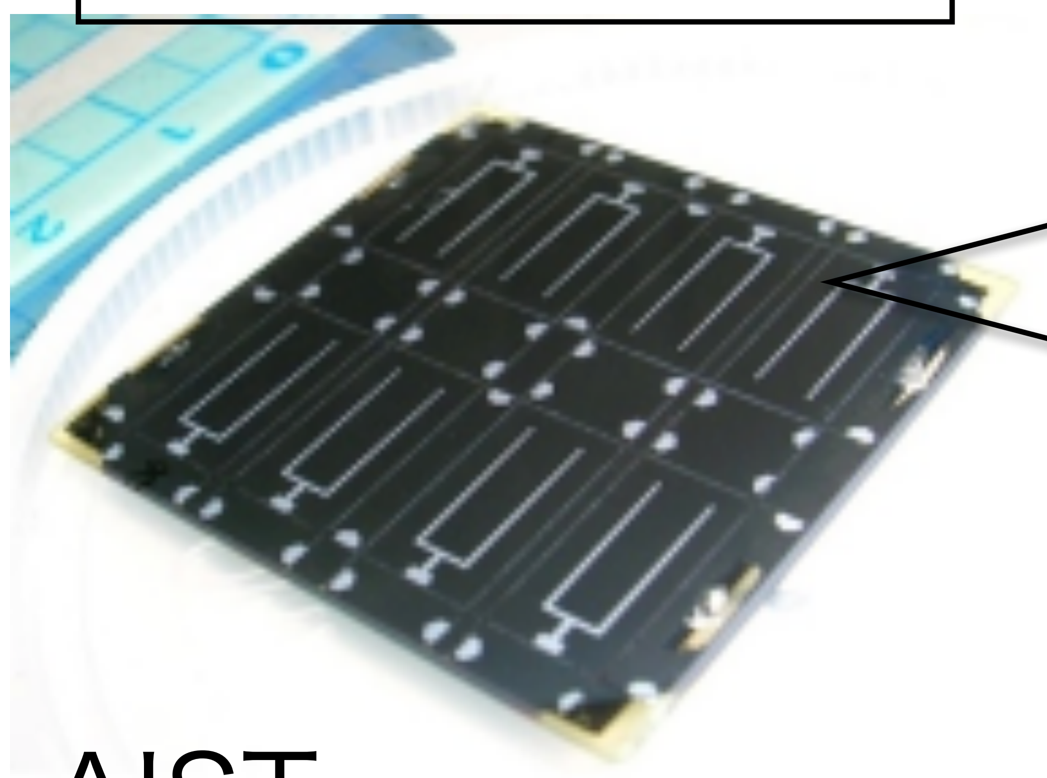


Broken

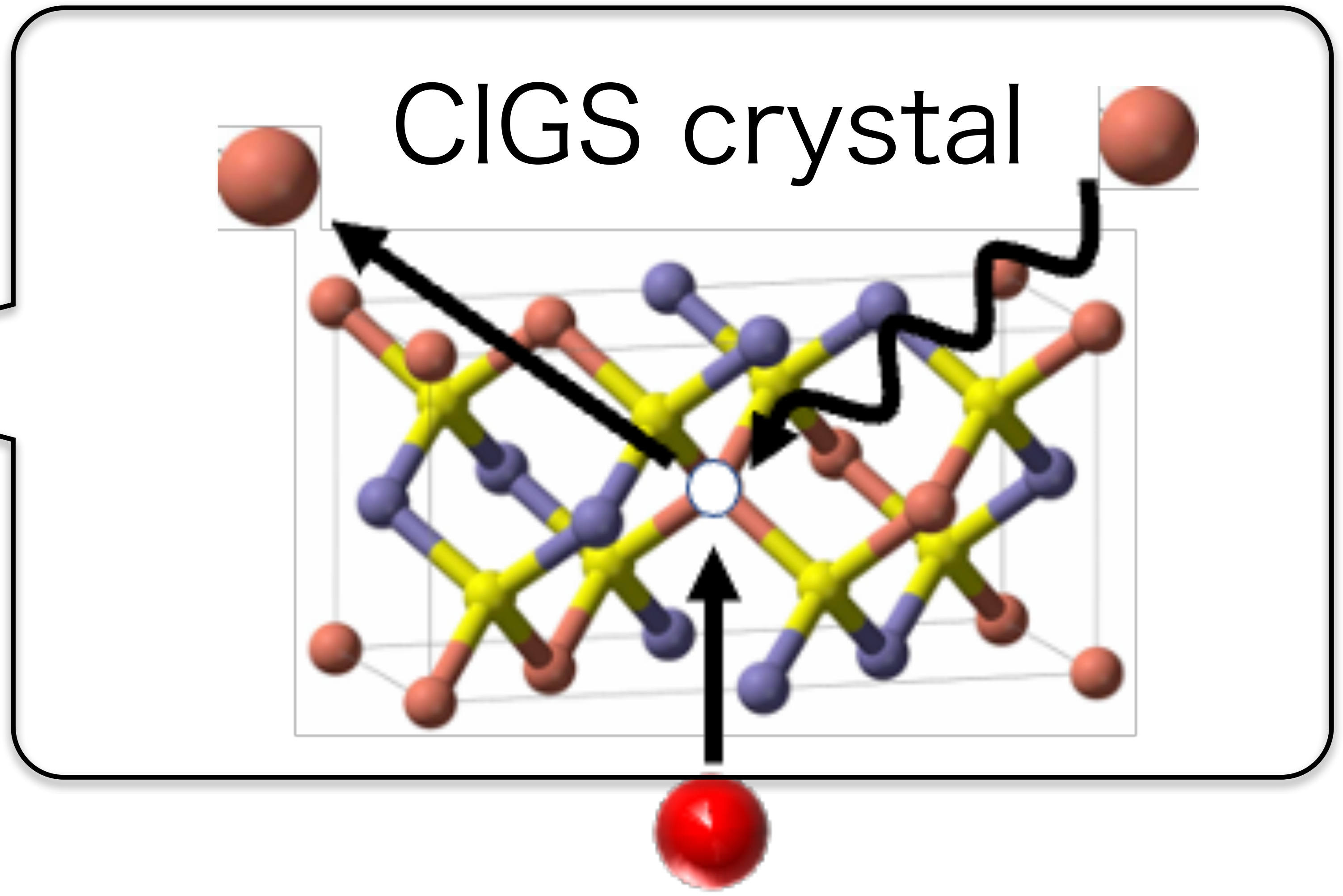
- Radiation causes the lattice defect by nucleus scattering
  - Degrading semiconductor properties
  - Increasing leakage current

Recovery type semiconductor : CIGS : Cu(In, Ga)Se_2

CIGS solar cell

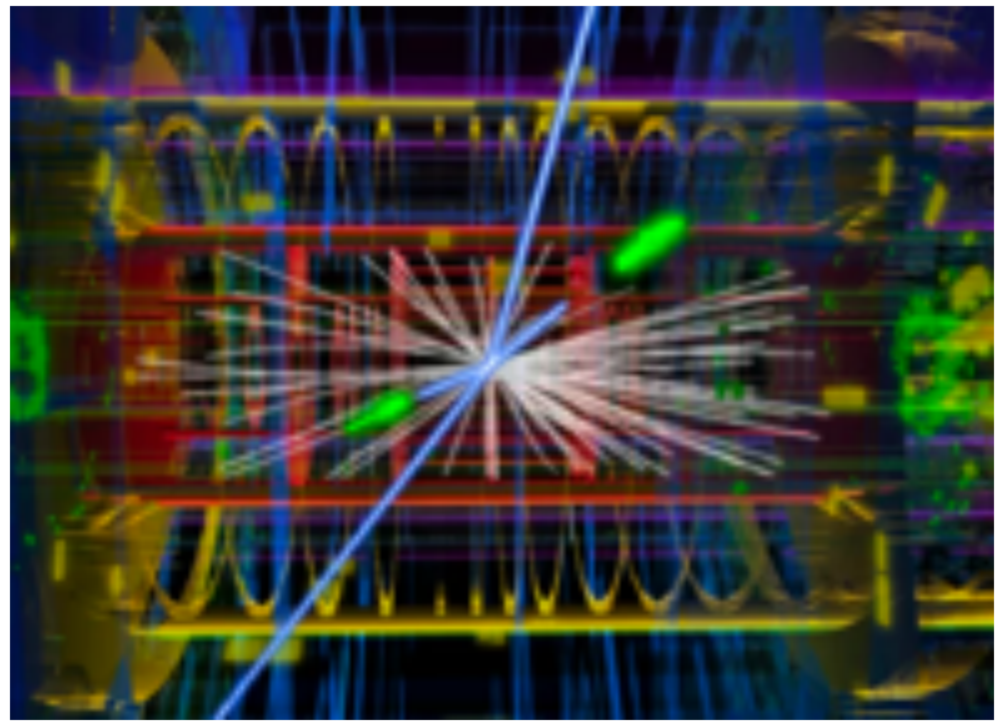


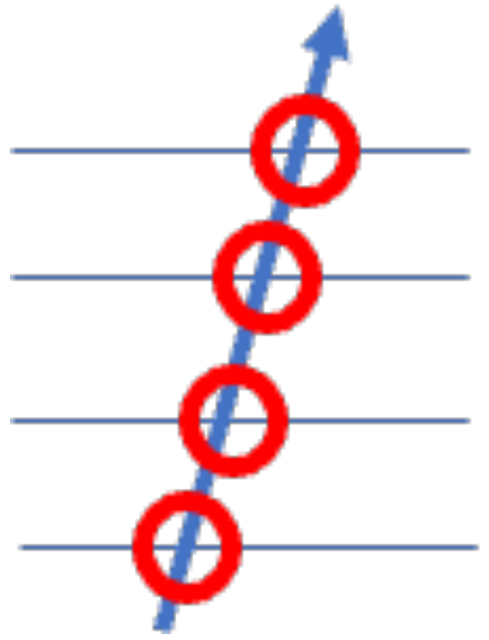
AIST



Radiation (proton, neutron..)

Particle physics

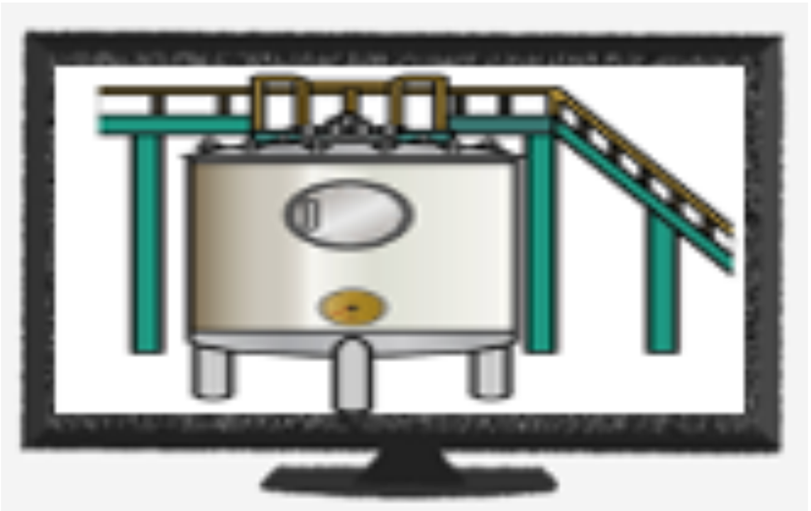




Particle tracking

- Recovery by the compensation of defects by heat annealing.
  - Cu-ion and/or Alkali-ions (mixed at production) may fill in defects.
  - High radiation tolerant solar cell has been investigated by JAXA.

Camera in nuclear plant

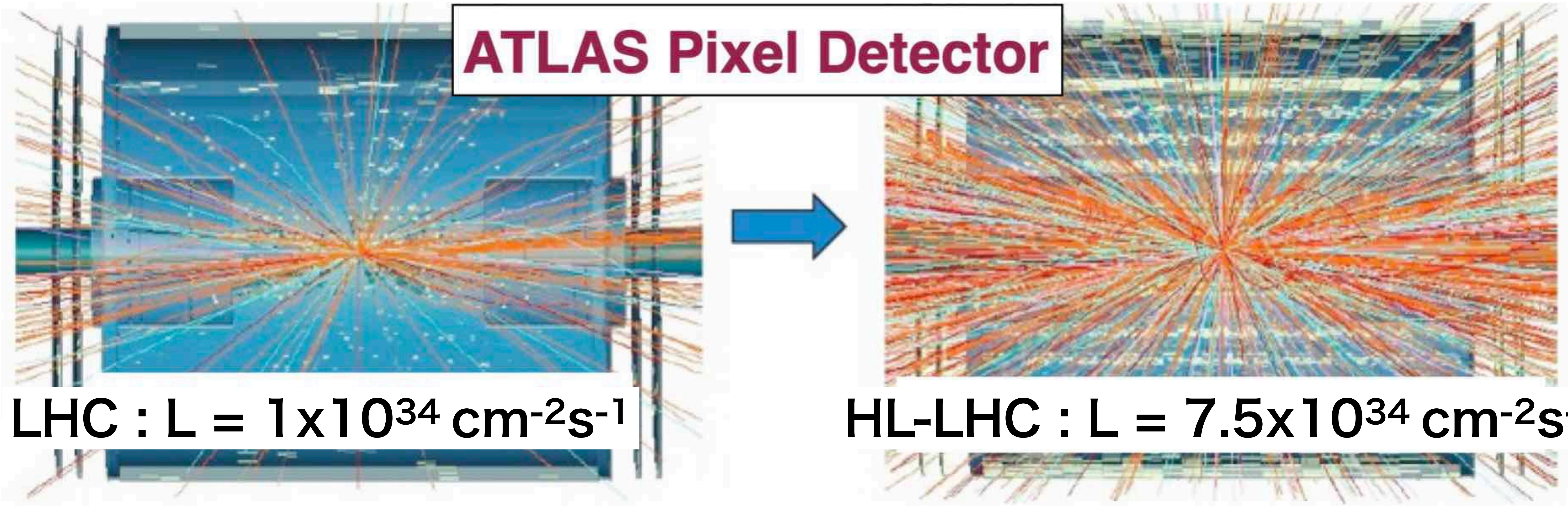


Monitor

Solar cell >> High radiation tolerant particle detector !

Radiation level example : LHC-ATLAS experiment

- New particle search (heavier) -> high energy and/or high luminosity



~20 pp collision / bunch crossing ~200 pp collision / bunch crossing

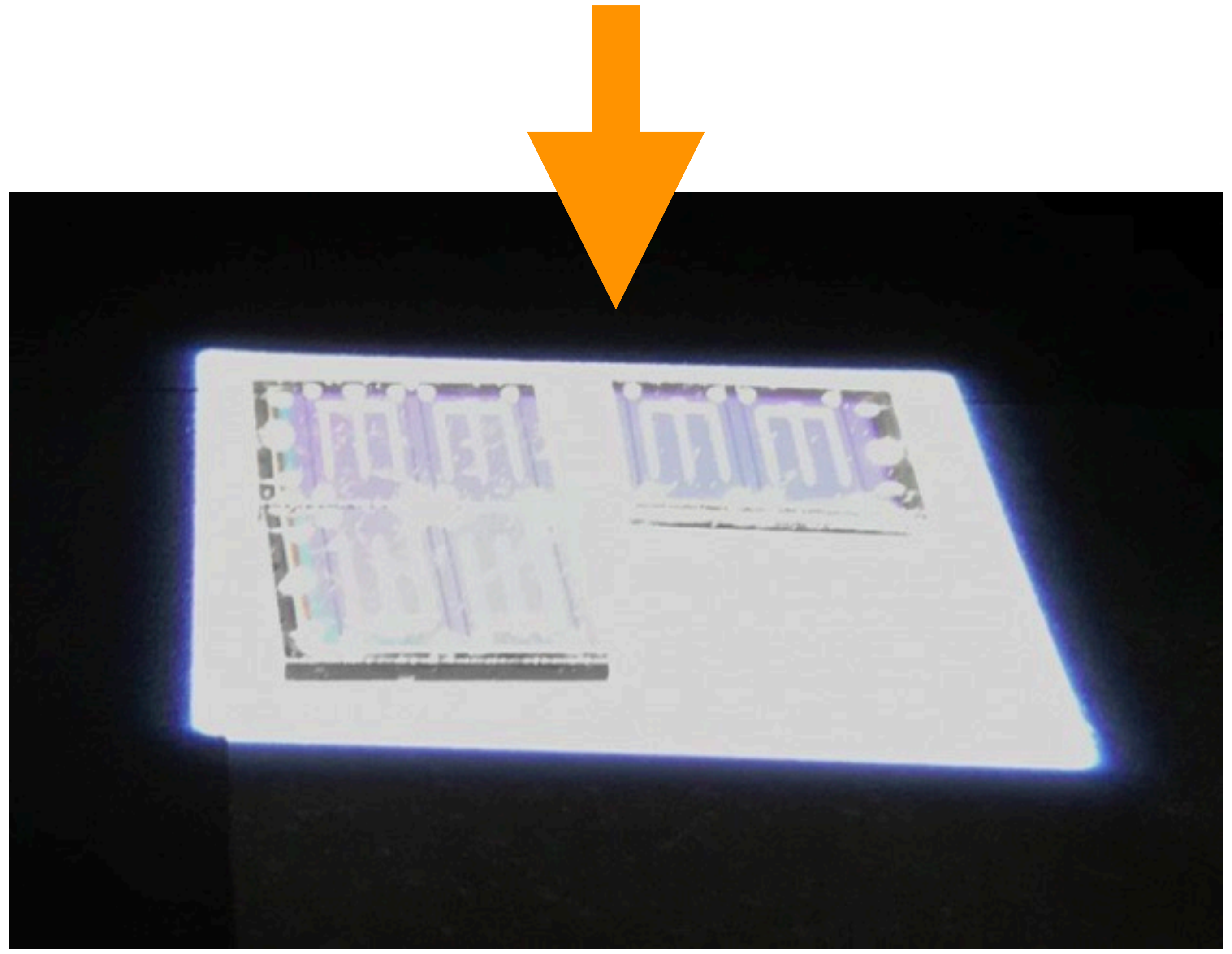
	LHC		HL-LHC		FCC/HE-LHC
NIEL (1 MeV $n_{eq.}/cm^2$)	10^{15}	—x10→	10^{16}	—x10→	10^{17}
TID (MGy)	0.7		7		70

Inner most layer will be replaced at half of experimental period

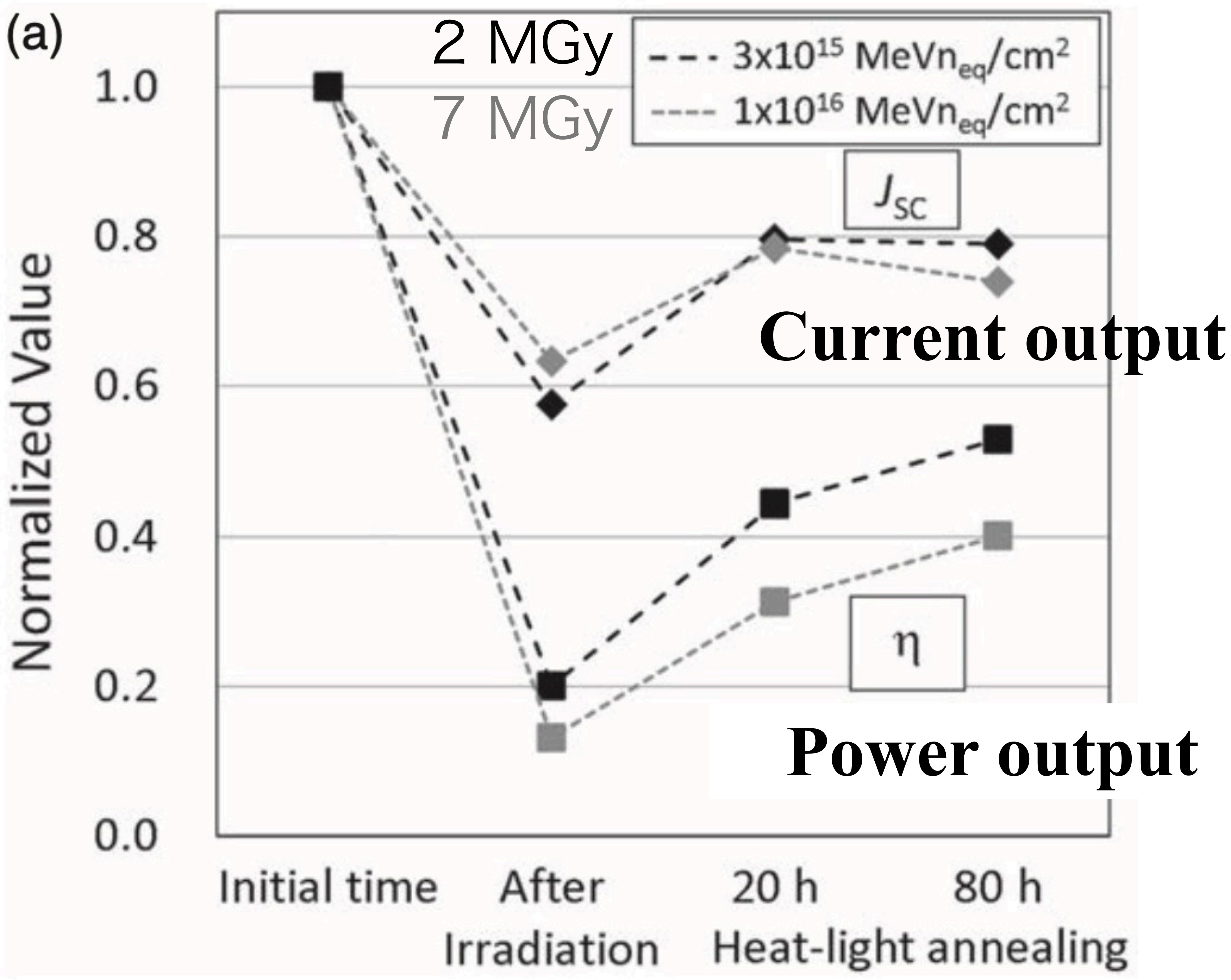
Radiation tolerance for the CIGS solar cell

- 70 MeV proton irradiation at CYRIC, Tohoku University.
  - $3x10^{15}$ and 10^{16} (1 MeV $n_{eq.}/cm^2$)
  - 2 and 7 MGy

Annealing by sun light equivalent (1 Sun, 95°C)

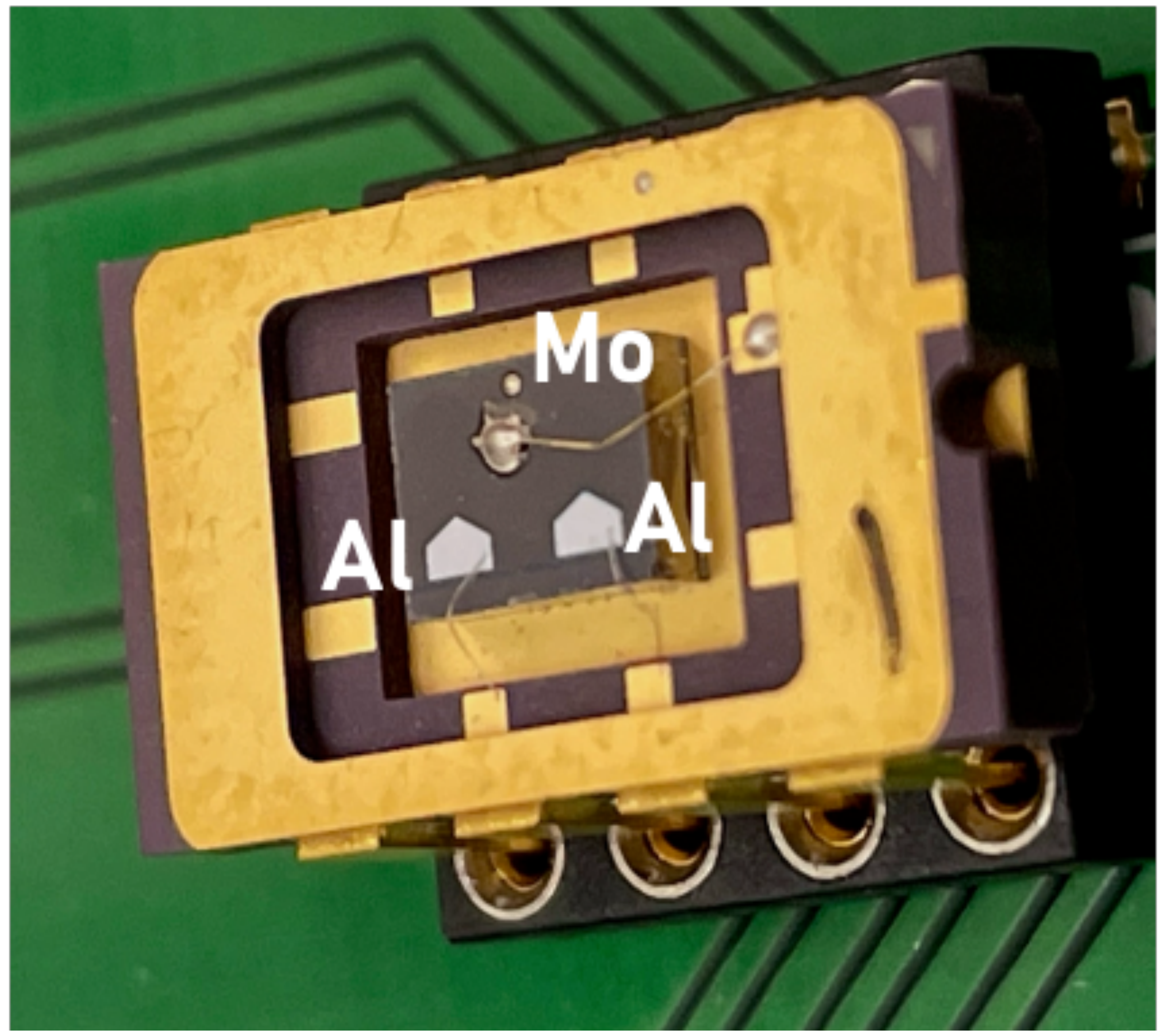


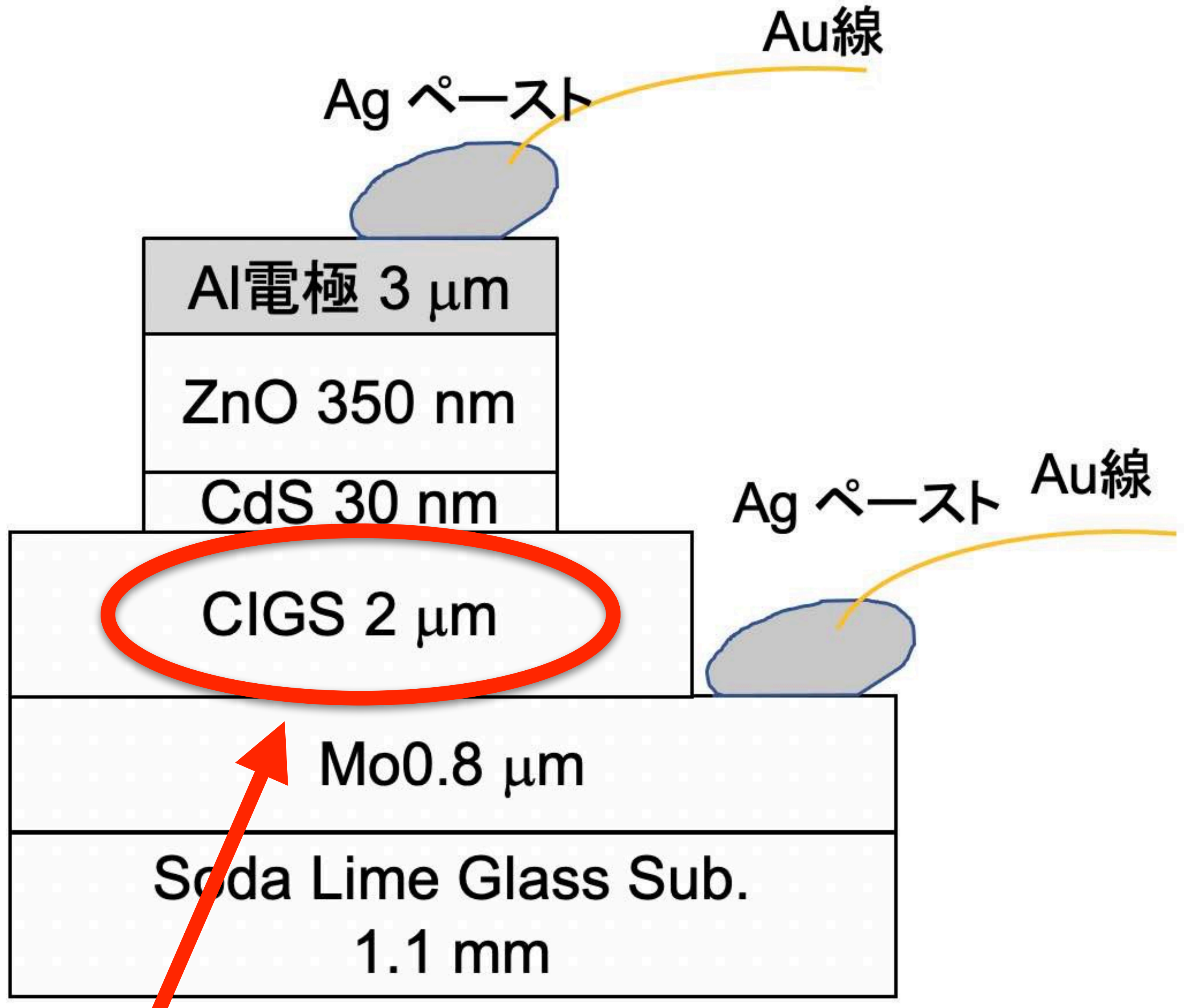
Jiro Nishinaga *et al* 2023 *Jpn. J. Appl. Phys.* **62** SK1014



Recovery is confirmed.

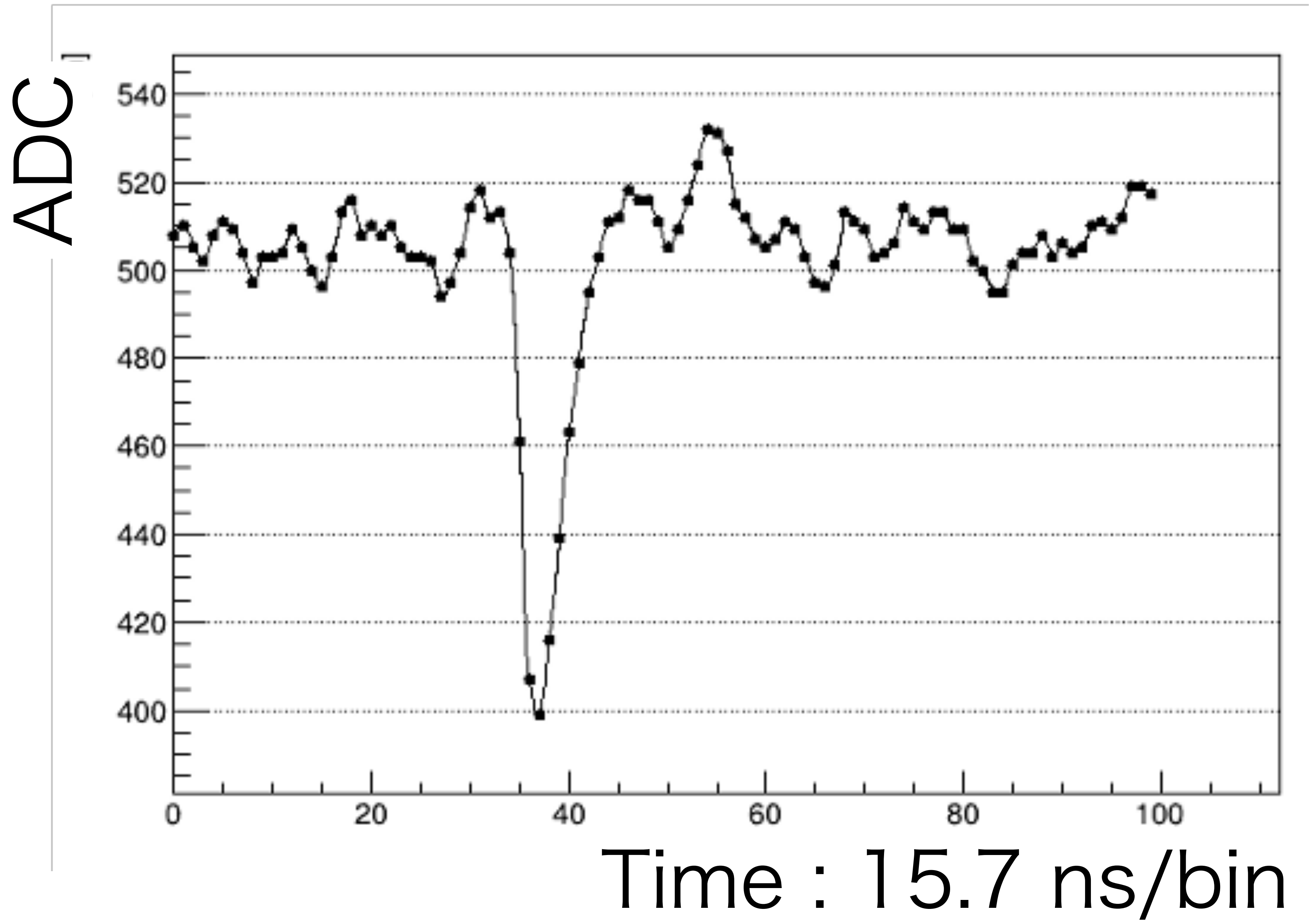
Detecting alpha-particle by the p-n structure CIGS.





Normally, CIGS is p-type

Thickness : ~2 um



Output is expected as GEANT4 estimation

Band Gap

CIS : 1.0 eV, CGS : 1.7 eV

Si : 1.1 eV

Density

CIGS : 5.7 g/cm^3

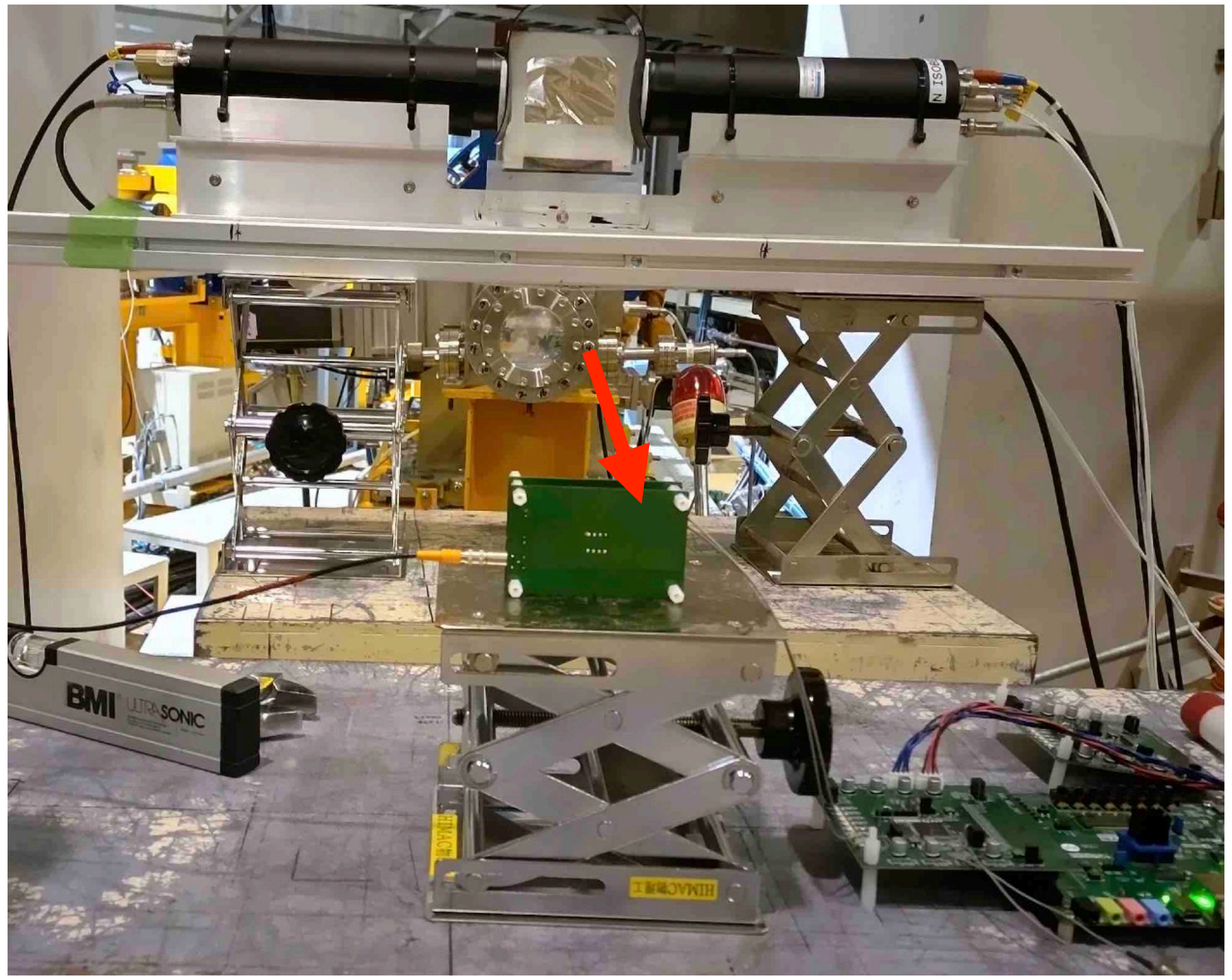
Si : 2.33 g/cm^3

- Alpha 5.3 MeV, 2 um CIGS
  - 0.45 MeV -> (120 k e/h pairs) -> 19.2 fC

Beam test @ HIMAC
(Heavy Ion Medical Accelerator in Chiba)

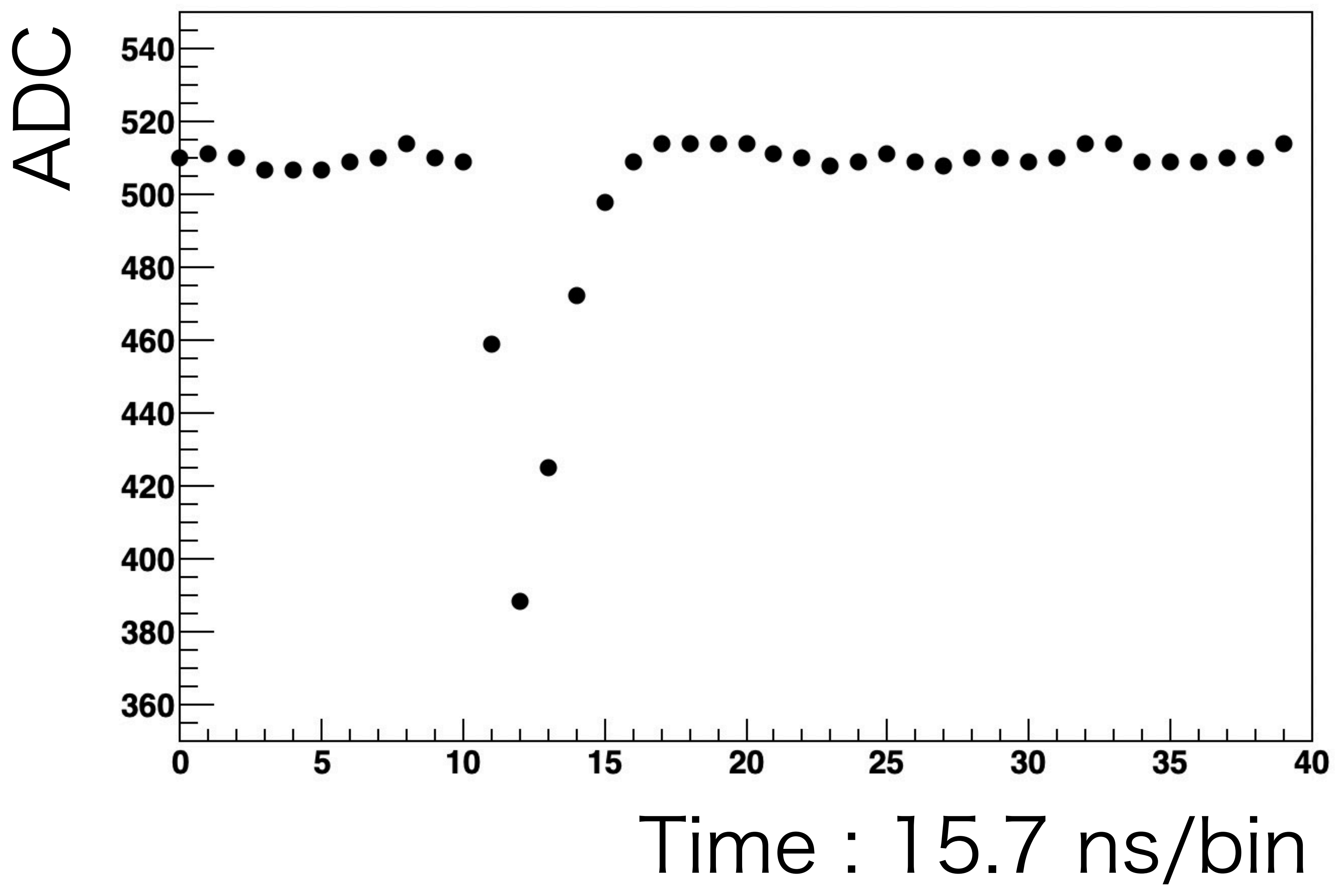
- 2022 1/9 - 1/10, 2022 11/24-11/25
- Heavy ions deposits large energy in the detector -> Detectable with thin layer.
  - $^{132}Xe^{54+}$ 400 MeV/n @ 2 um-thick CIGS : 6.5 MeV -> 277.3 fC
  - MIP@300 um-thick silicon : 0.11 MeV (22k e/h pairs) -> 3.6 fC

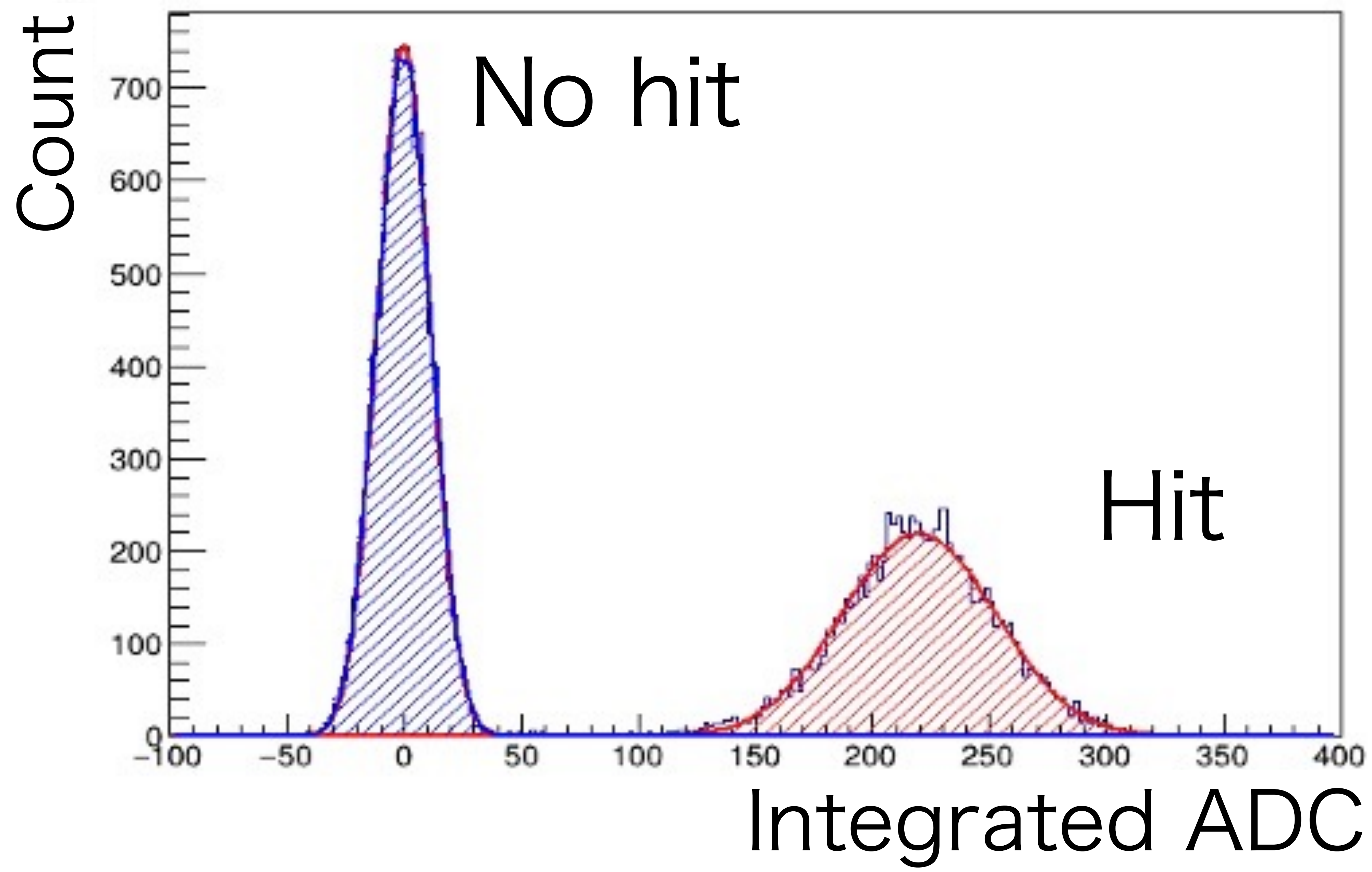
x100!



- Beam condition
  - 400 MeV/n Xe-132 beam
  - φ ~ 4 mm (measured by fluorescent plate)
  - 10^4 - 10^7 ppp in 3.3 s cycles.

CIGS output by Xe ion

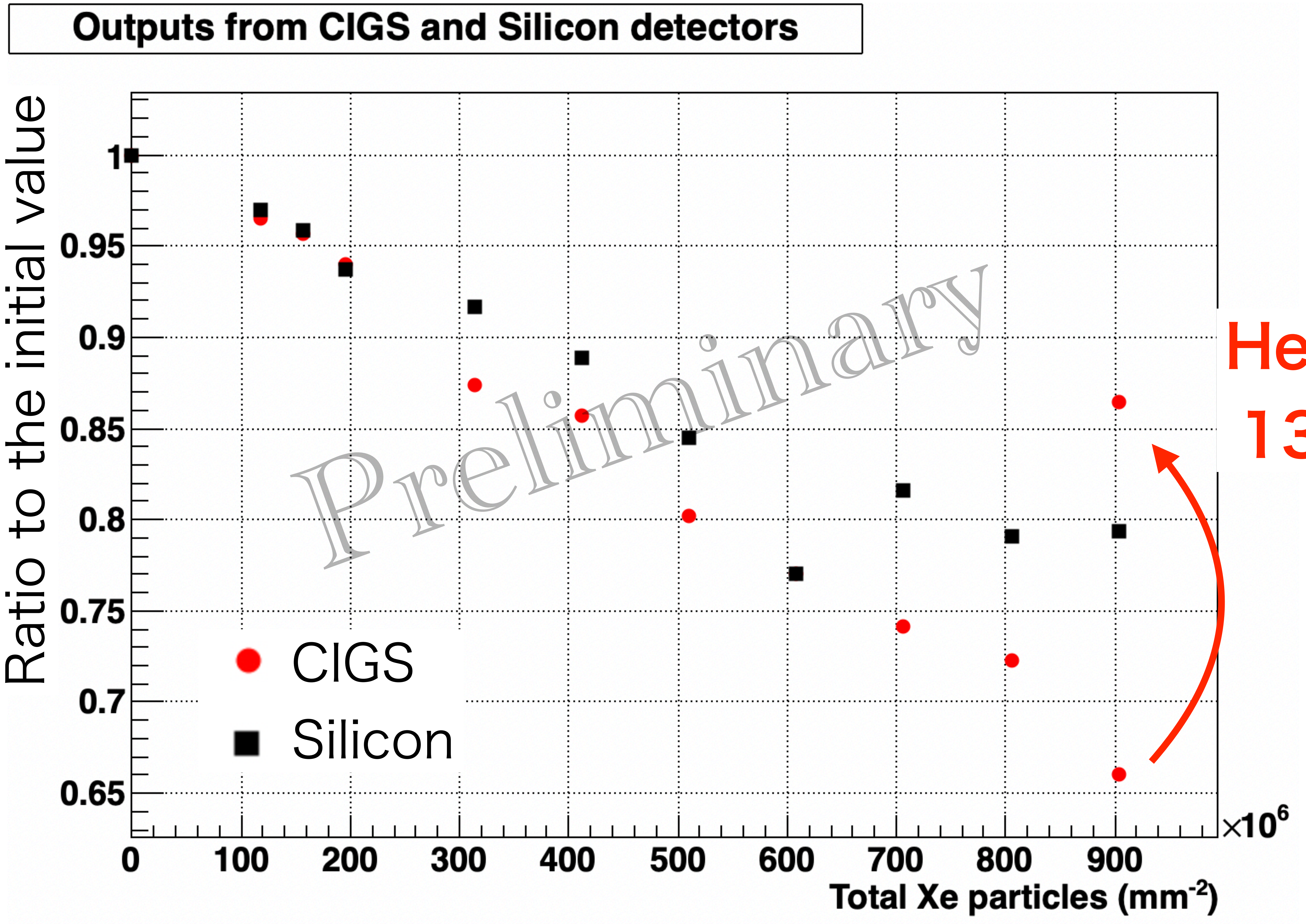




The CIGS detector successfully detects single particle !

FIrst irradiation at 2022 Jan.

Radiation damage and recovery for the 2 µm thick CIGS 1



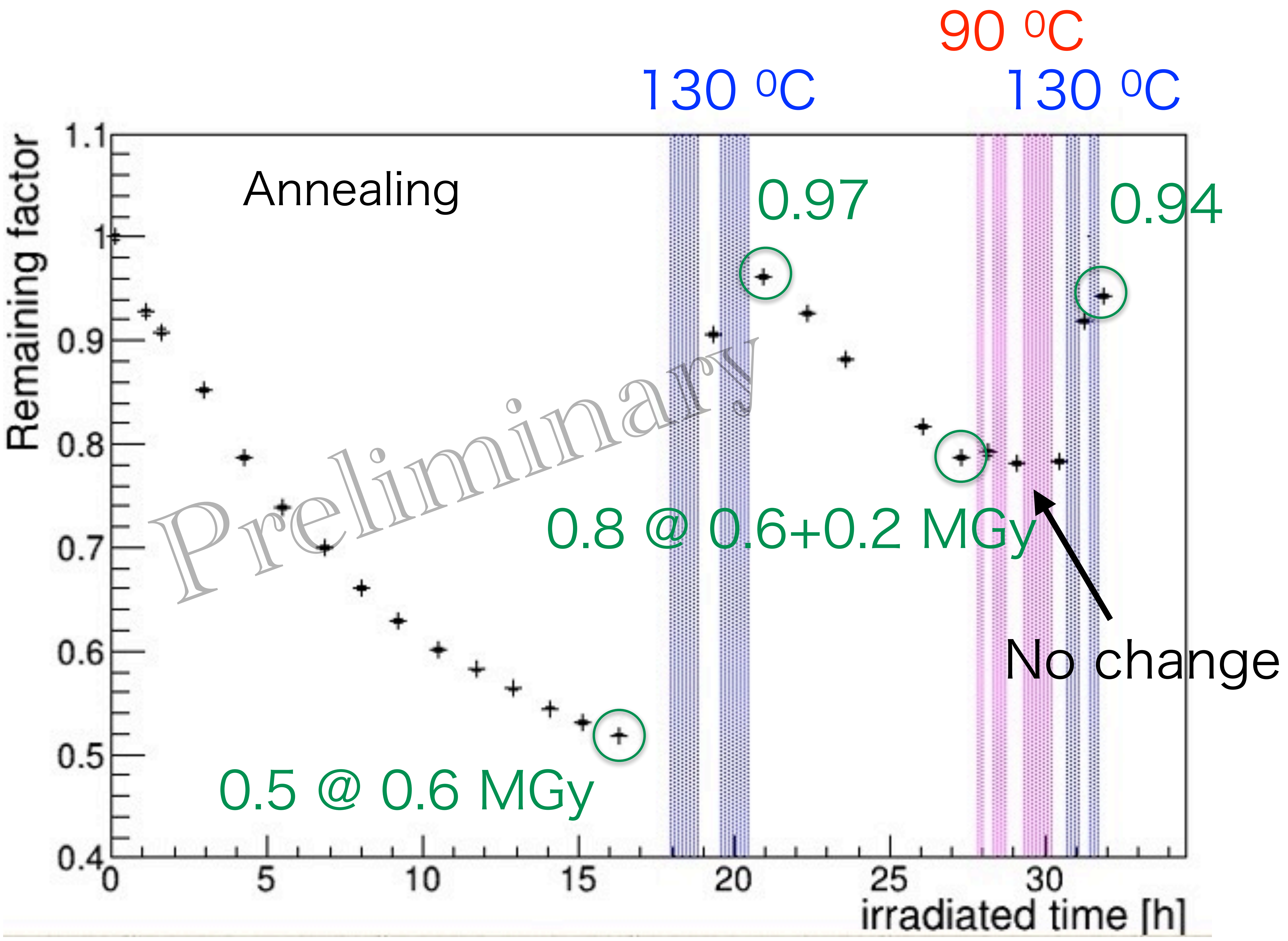
Heat annealing 130℃, 5 hours

TID ~ 80 kGy

- Recovery is confirmed. We can develop as a particle detector with a recovery feature !

Irradiation at 2022 Nov.

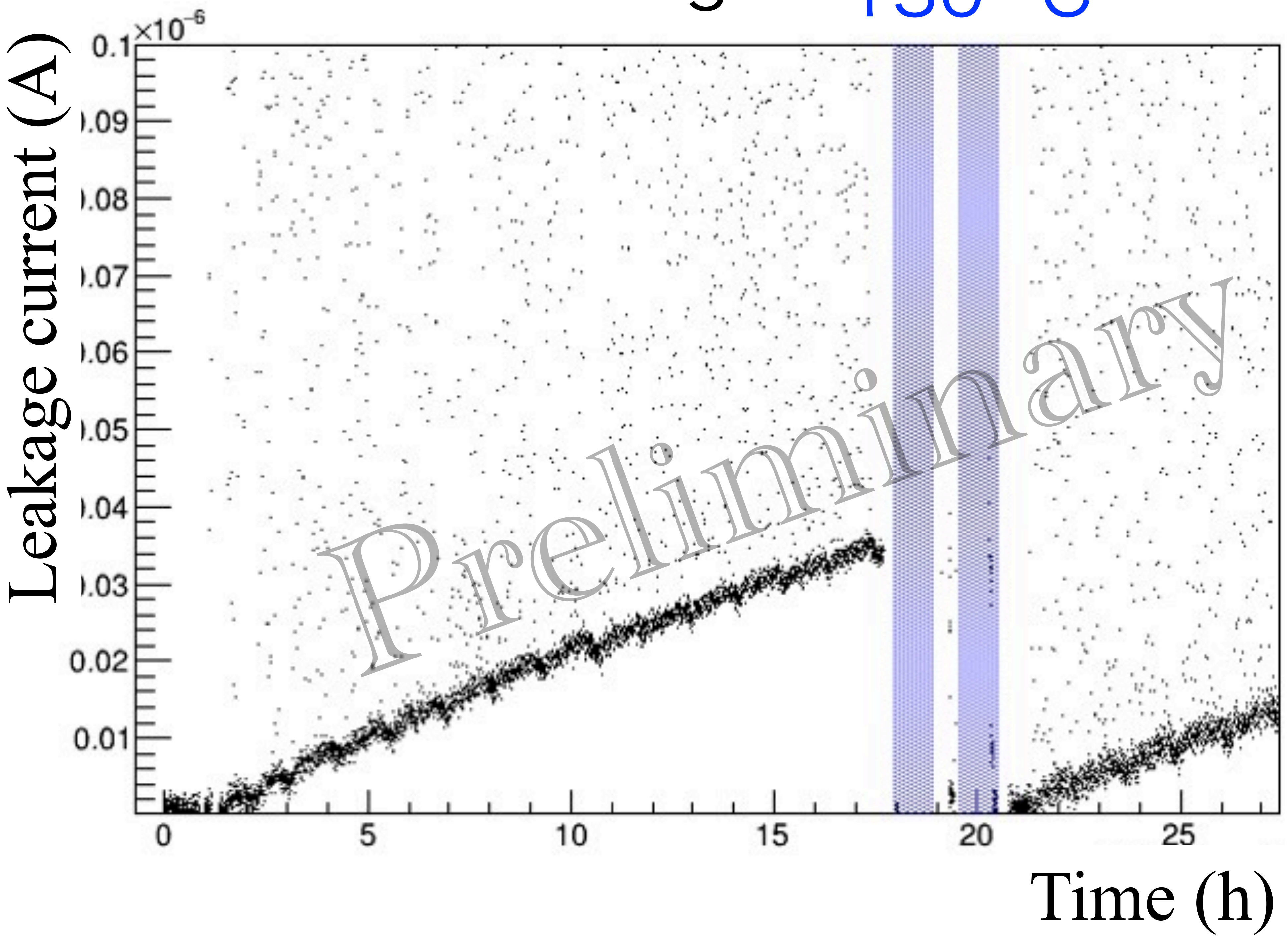
Radiation damage and recovery for the 2 μm thick CIGS 2



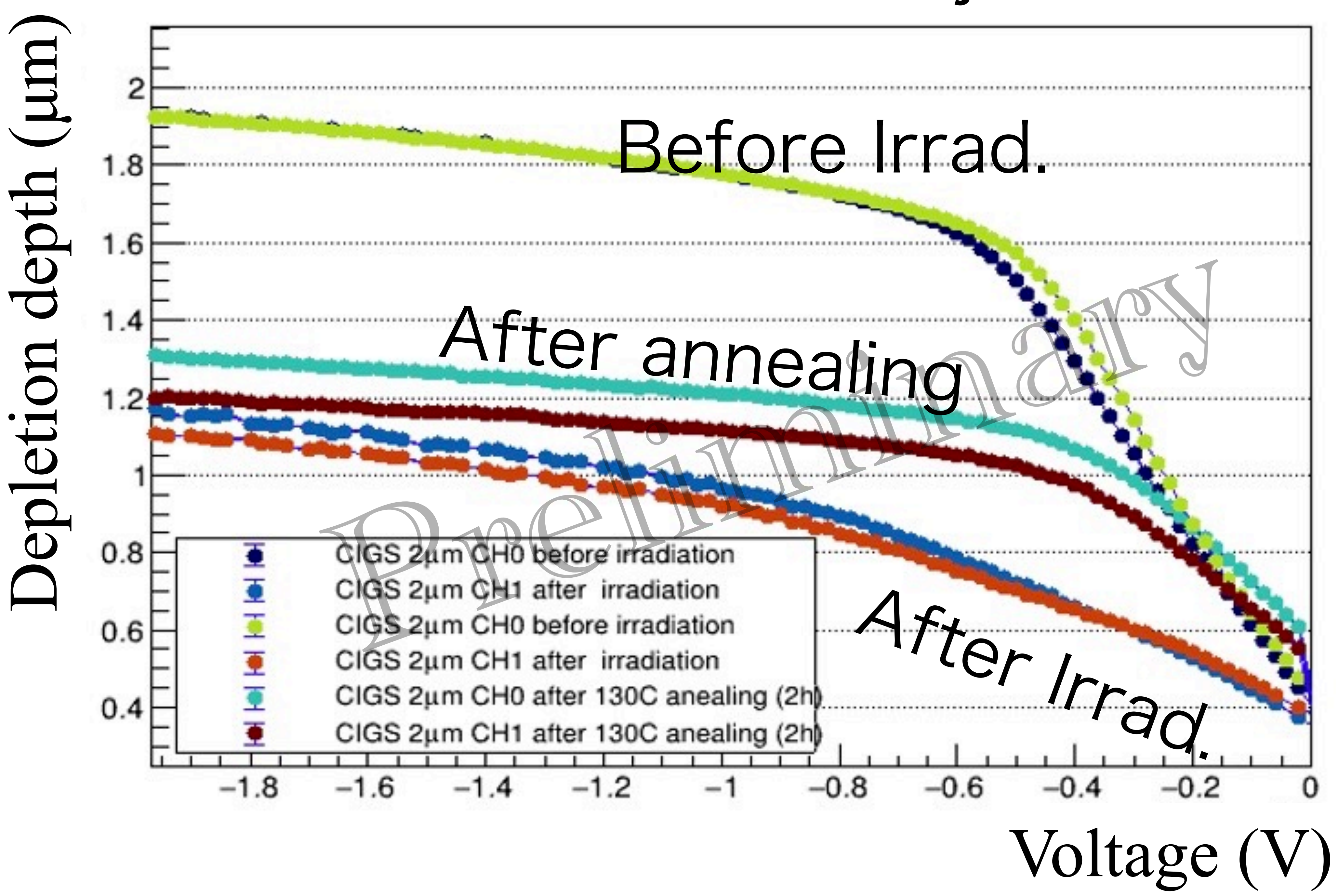
- Recovery by 130 ^{0}C annealing is confirmed up to 0.8 MGy
  - Repeatable
  - Strong temperature dependence between 90 - 130 ^{0}C

Leakage current and depletion depth

Annealing 130 ^{0}C



Evaluated by CV scan



- Leakage current : Recovered to be the value before irradiation
  - “Critical defects” for charge collection and leakage current may be almost recovered by annealing

- Depletion depth : Partially Recovered
  - Acceptor concentration may be increased.

Coming investigation

- Temperature and time dependence of recovery
  - CIGS solar cell.
- Detector performance after recovery from HL-LHC level damage.
  - CIGS detector

Future investigation

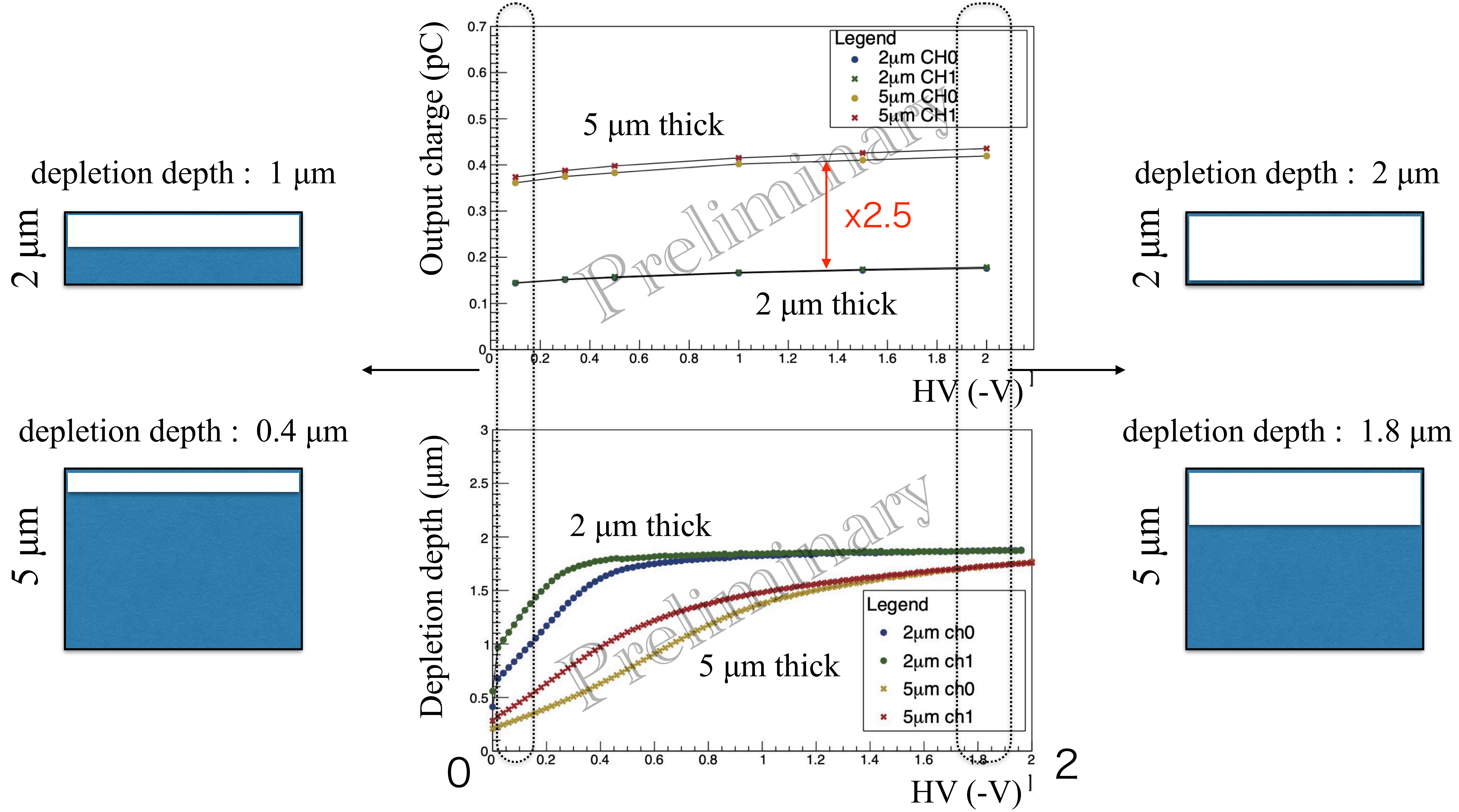
- Basic investigation
  - Compensation mechanism
  - Acceptor behavior after irradiation
- Gamma and neutron irradiation
  - To separation of NIEL and TID damage
- Future fabrication
  - Thicker CIGS detector : So far investigated up to 5 μm thick
  - Strip/Pixel type electrodes

Conclusion

- In recent high energy/intensity particle physics experiment, the radiation damage of silicon detector is being serious.
  - The CIGS semiconductor which has recovery feature shed new light to the super radiation hard detector.
- The CIGS detector has been evaluated with heavy ions at HIMAC
  - It is confirmed to detect single particle and the recovery of radiation damage up to 0.8 MGy.
  - Temperature / Time dependences has been investigated.
  - Understanding of acceptor behavior are important.

Backup

Charge collection

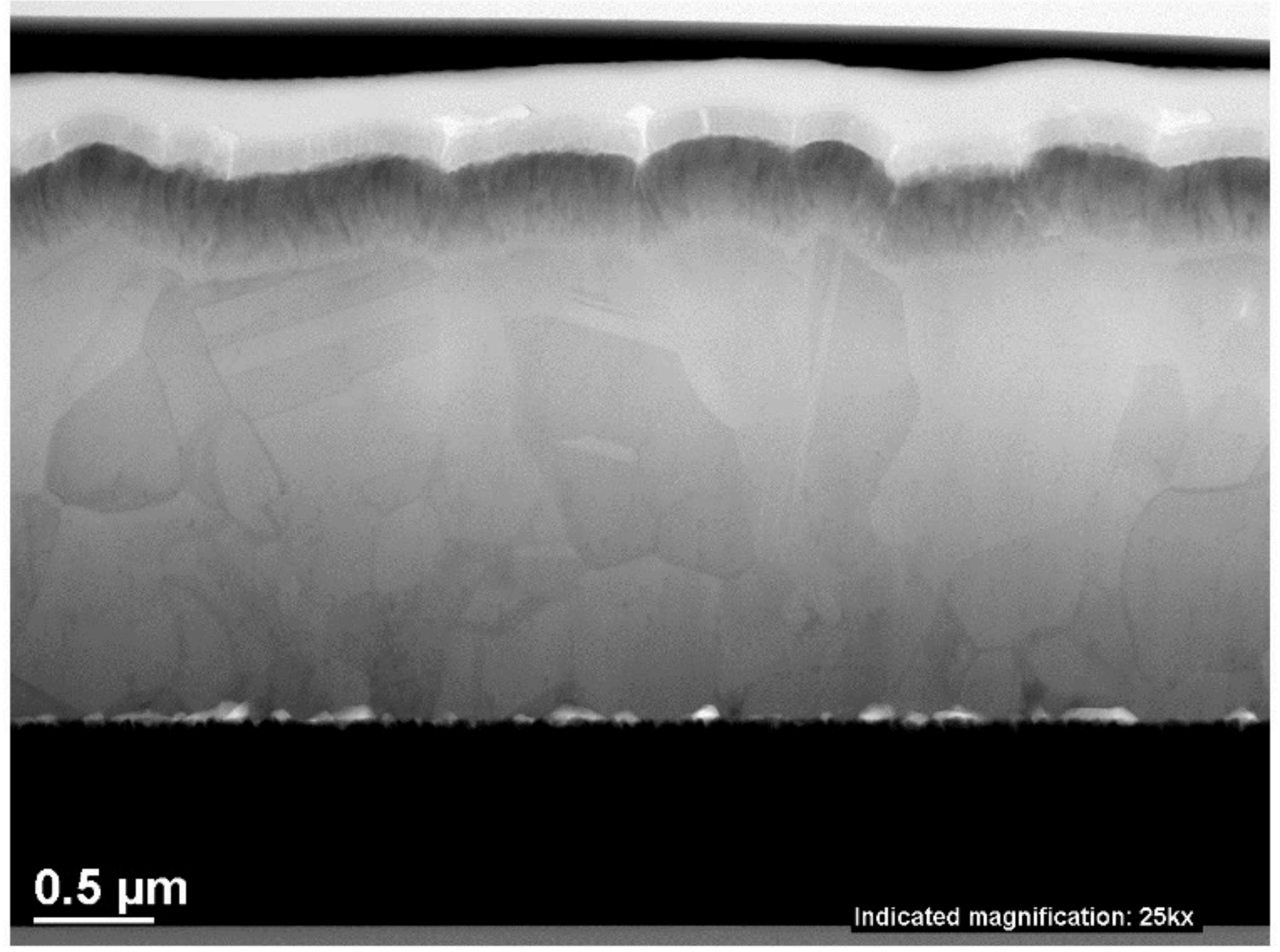


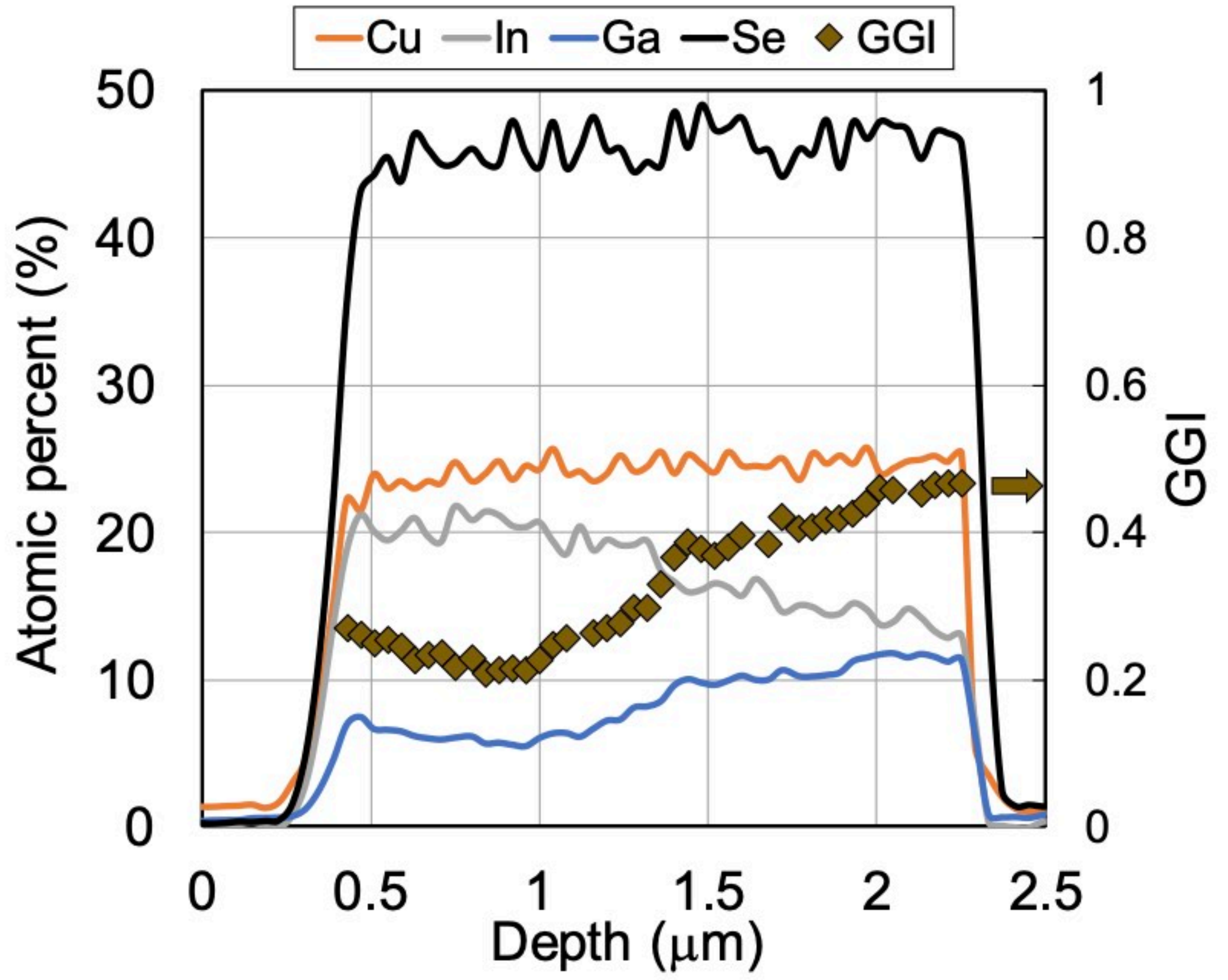
The charge collection does not depend on depletion depth.

cf. collection charge is proportion to the depth of depletion depth.

Consideration : Drifting by slope of band gap

$Cu(In,Ga)Se_2$ の構造

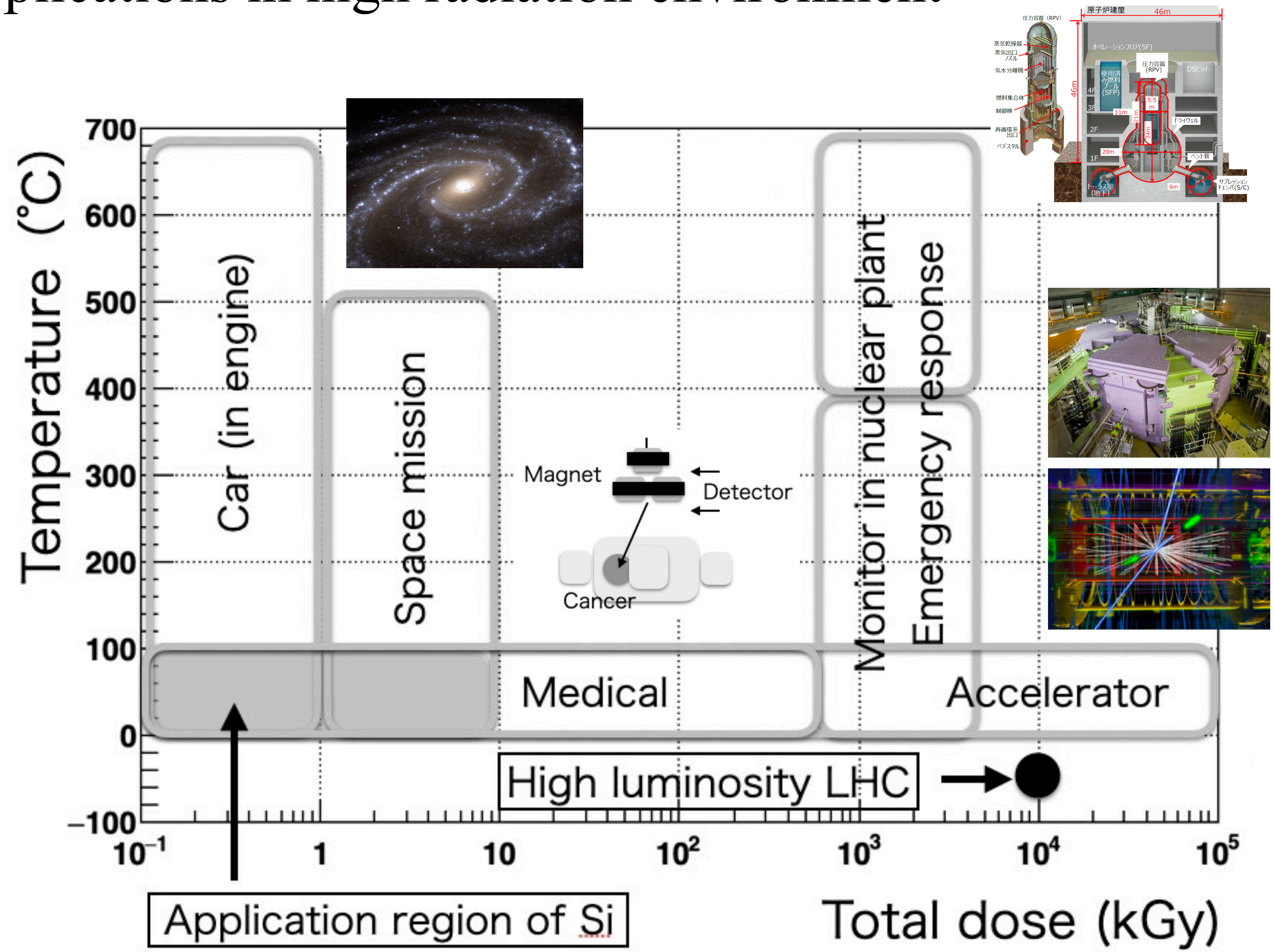




Band Gap
CIS : 1.0 eV
CGS : 1.7 eV

- CIGS is mixed of CIS and CGS
  - Band gap slope due to the mixing shade along the depth cause drifting
    - Like SiGe semiconductor (Si : 1.1 eV, Ge : 0.6 eV)
- Non or Low voltage operational detector would be developed.
- Wide-gap type CIGS can be possible increasing CGS ratio

Applications in high radiation environment



Toward single charged particle detection

Bethe-Bloch on PDF

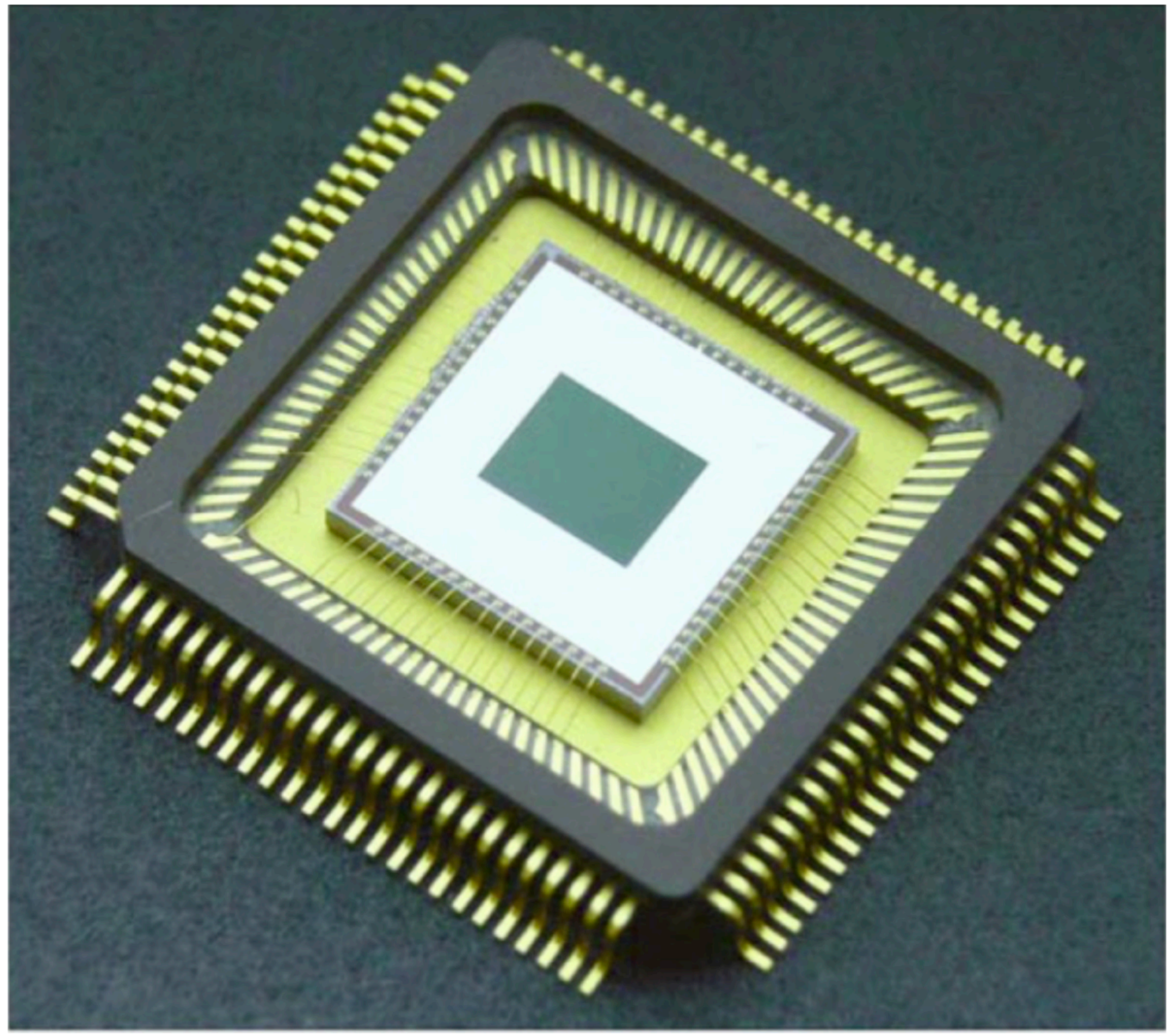
$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] . \qquad \frac{dE}{dx} \propto \rho$$

	Band Gap (Mean excitation)	Density	#e-h pairs (Si normarized)
Si	1.1 (3.6)	2.33	1 ← 22,400 e-h / 300 um
SiC	3.2 (7.8)	3.21	0.64
C (Diamond)	5.5 (12)	3.5	0.45
CIGS	1.2 (BGx2.5 ?)	5.7	(2.93)
AlN	6.2 (15.3)	3.26	0.33
Ga_2O_3	4.8 (BGx2.5 ?)	6.44	(0.83)
GaN	3.4 (8.9)	6.15	1.07

50 um thick silicon <-> 17 um thick CIGS >> 10-20 umCIGS

* Charge collection efficiency needs to be considered.

CIGS imaging sensor



https://www.aist.go.jp/Portals/0/resource_images/aist_j/aistinfo/aist_today/vol08_01/vol08_01_p27.pdf

- Joint development of AIST and Rohm developed at 2008
  - High sensitivity infrared camera
- 10x10 um^2 pixel CCD
  - 352x288 pixels
- Deposition on the read out CMOS
  - No bump bonding is necessary

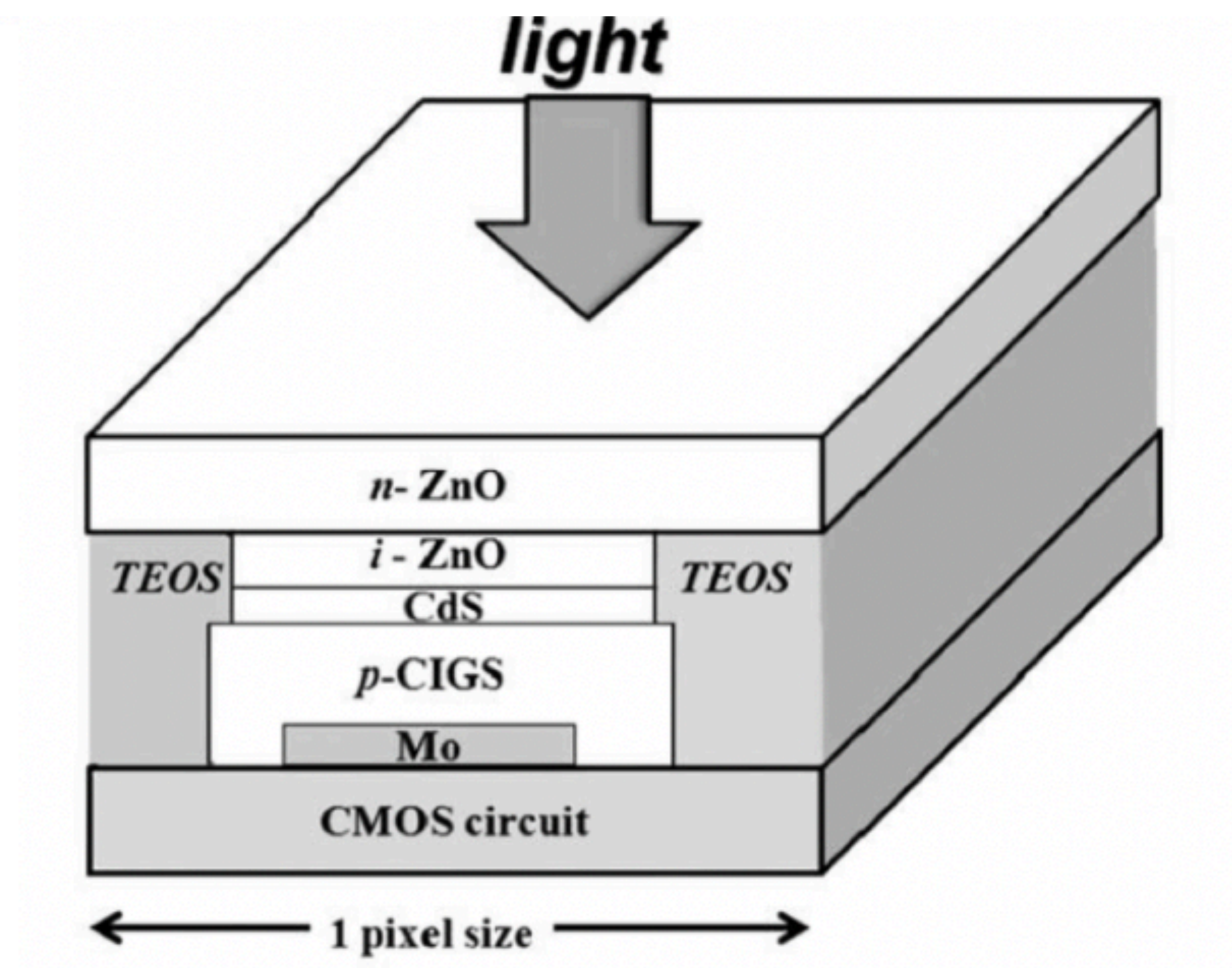


Fig. 2. A schematic structure of one pixel of the CIGS-based image sensor.

Achievement of pixel detector

*産総研、Rohm株式会社

Use in the heavy ion experiment

RIKEN : TadaAki Isobe

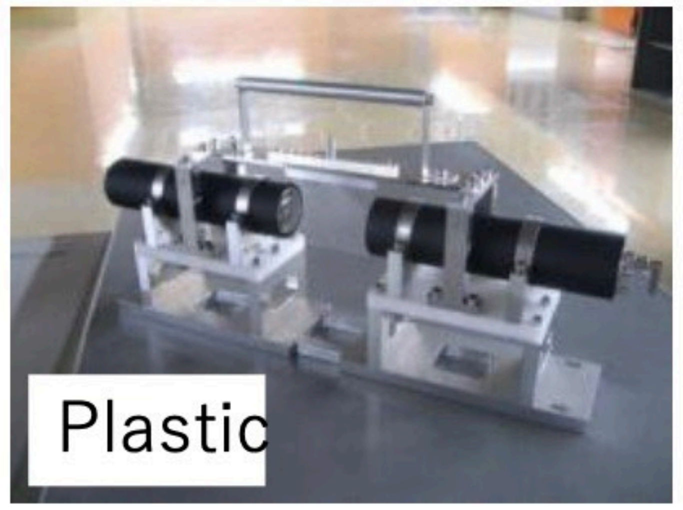
- RIKEN RIBF : Creation of heavier nuclei and neutron rich nuclei
  - Identification of created particle is important.

TOF-$B\rho$-ΔE method with track reconstruction → Improve $B\rho$ and TOF resolution

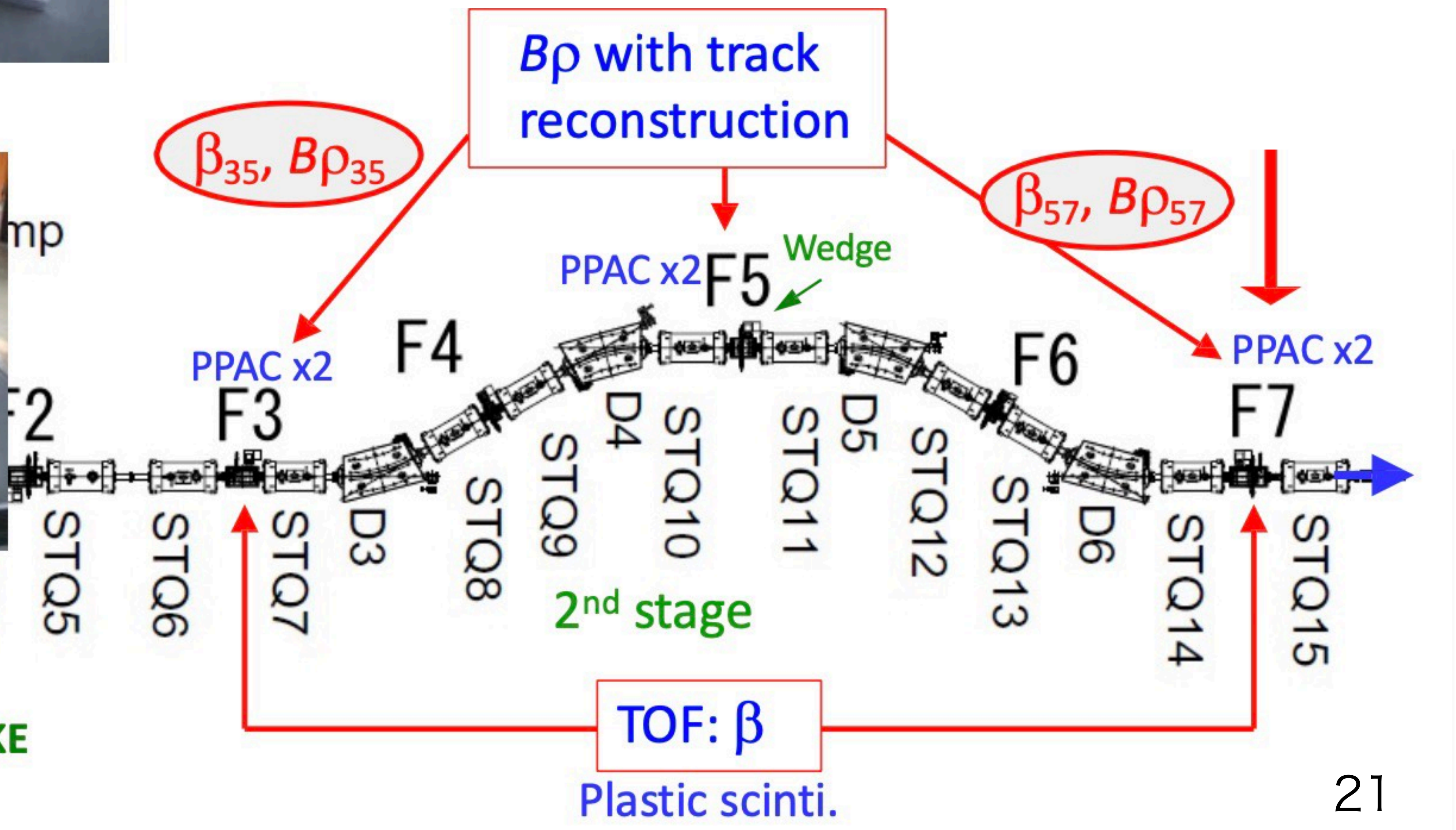
$$\frac{A}{Q} = \frac{B\rho}{\gamma\beta}\frac{c}{m_{\mathrm{nucl}}}$$

$$Z \leftarrow \Delta E = f(Z, \beta)$$

Scintillator :
:) Reduction of output



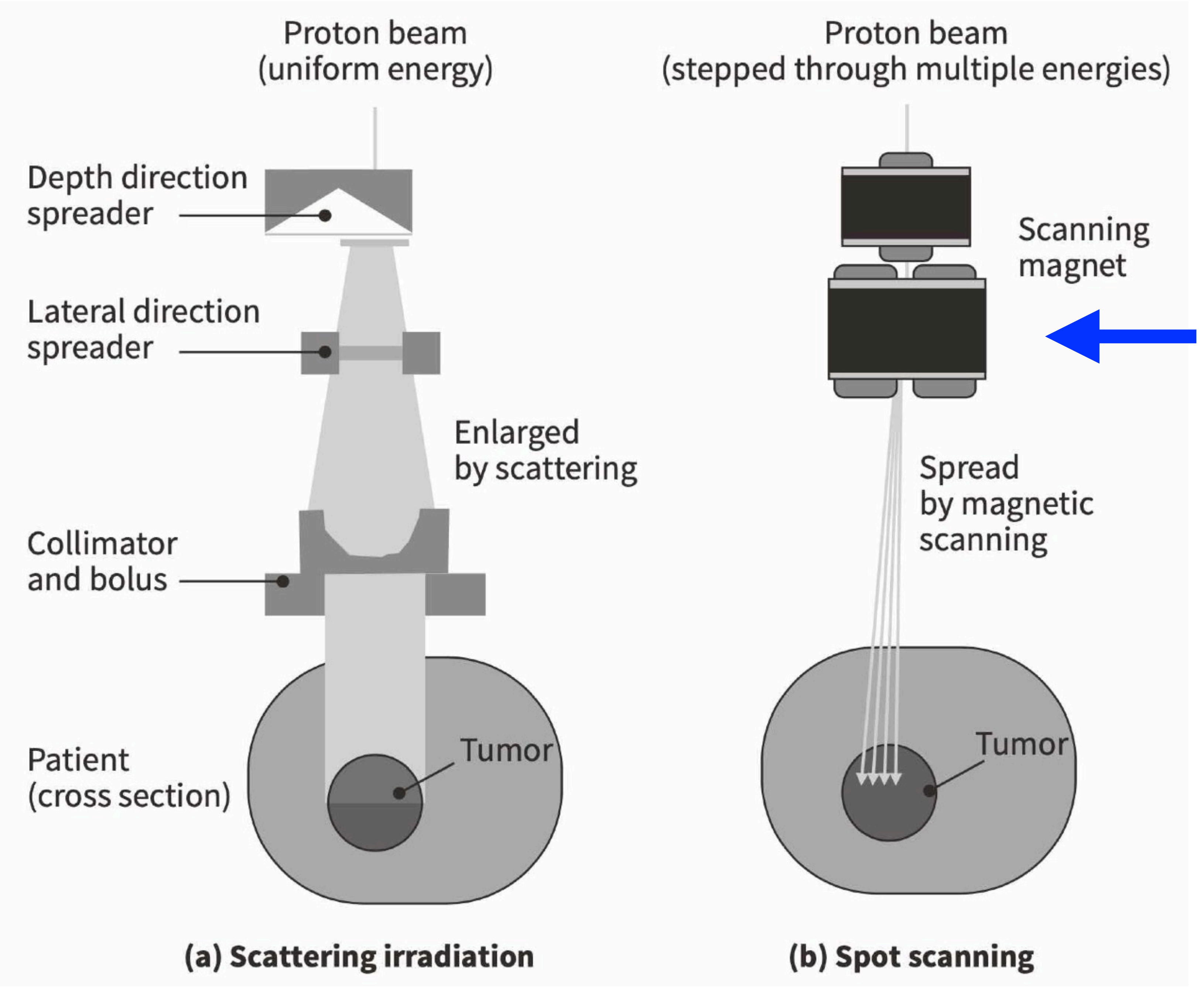
Gas chamber :
:) The gas can be purged in case of rad. damage.
:(Remnant in case of high intensity beam



Expecting of rad. hard semiconductor detector to replace them.

Application of spot scanning

Proton spot scanning



https://www.hitachi.com/rev/archive/2019/r2019_03/03a04/index.html

Detector for tracking

- Gas chamber has been used
  - Less position resolution
  - Remnant happens due to slow response in case of high intensity.

New semiconductor detector improves position resolution and intensity tolerance.
-> Reduction of the system QA and also treatment time.