ATLAS ITk Strip ASICs Irradiation

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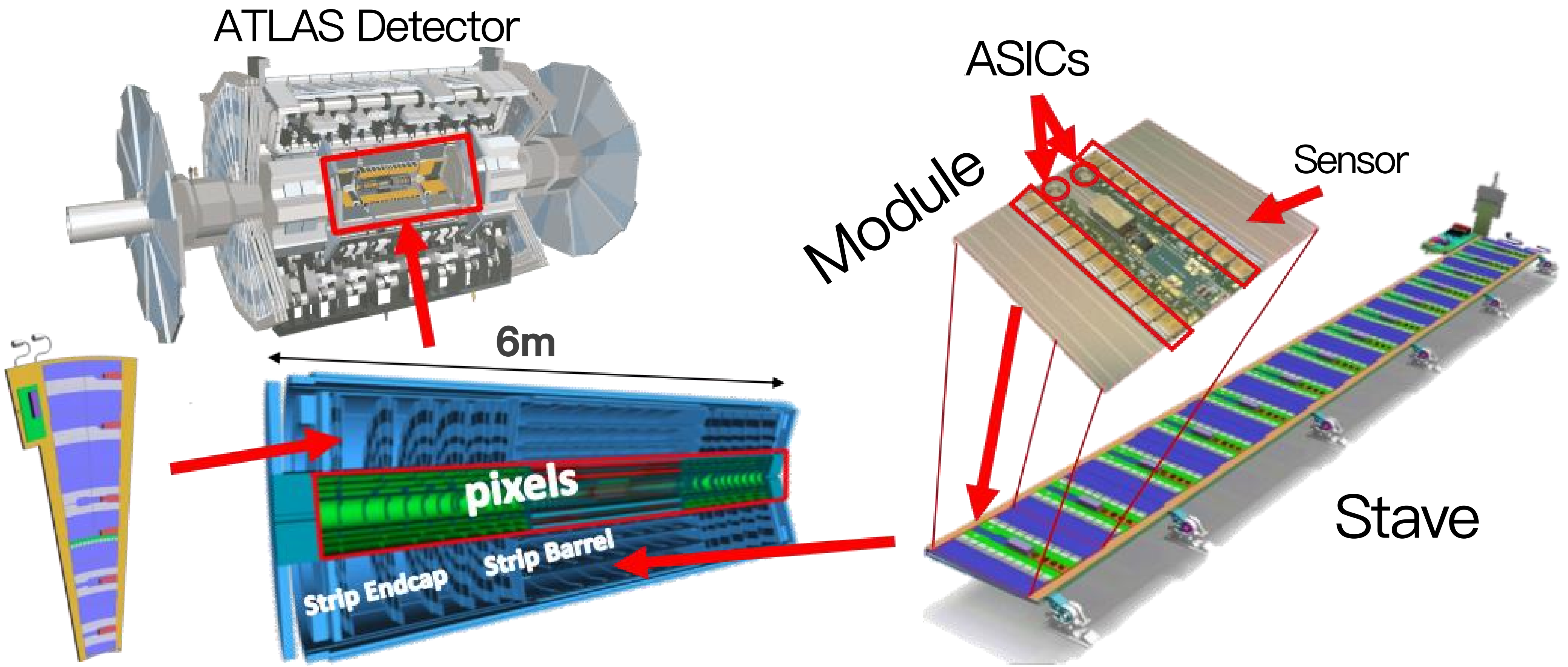
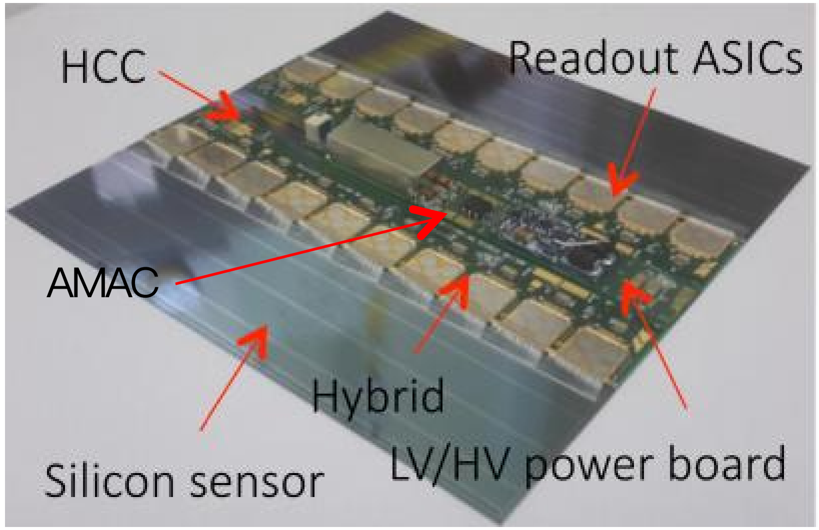
ITk upgrade

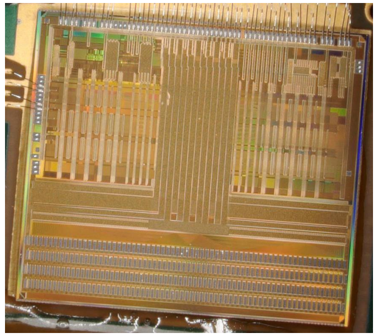
- Many ASICs are used in ATLAS ITk Strip phase II upgrade. We did a series of irradiation test for those chips.

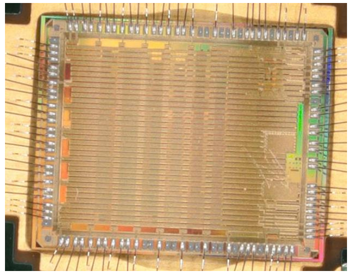


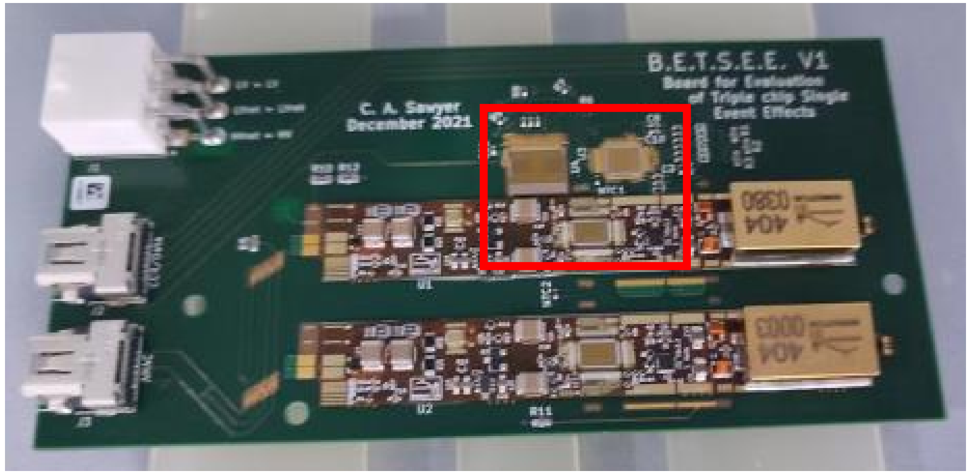
ASICs in Module

- The main ASICs includs ABC, HCC and AMAC.
- Also did BETSEE(Board for Evaluation of Triple chip Single Event Effect) that test the irradiation performance with all three chips at the same time.



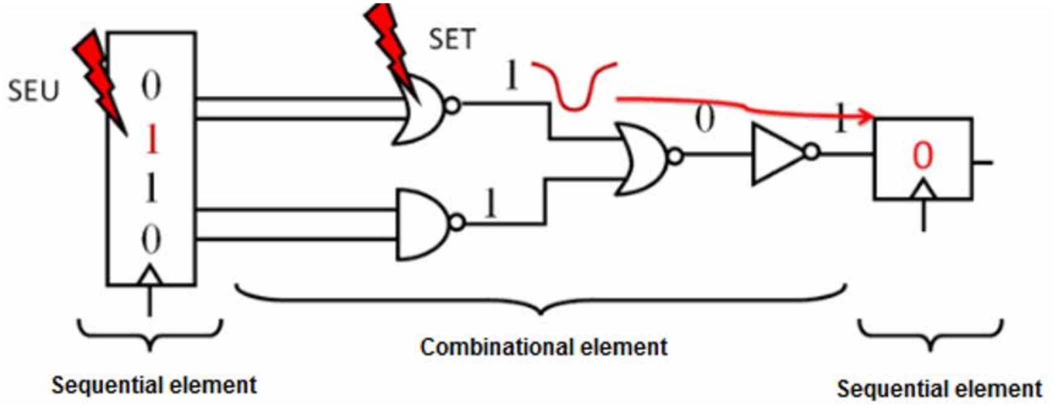






Irradiation effects

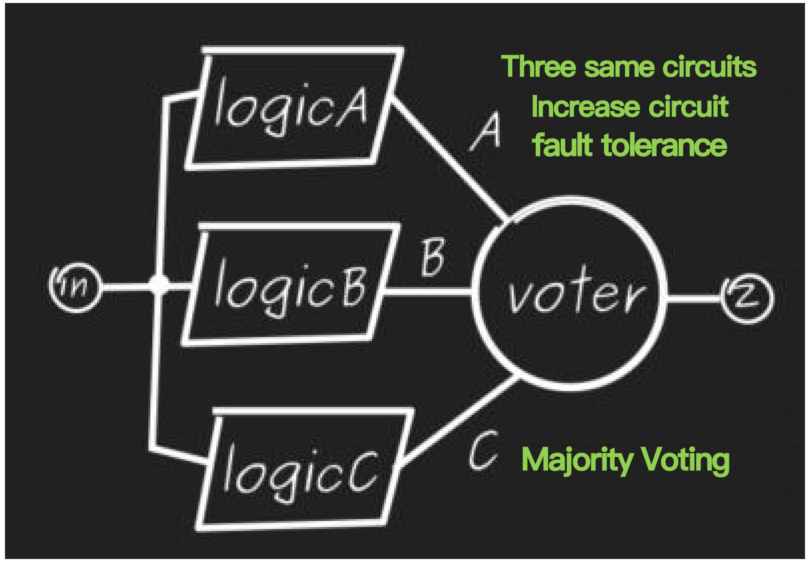
- Single Event Effects(SEE): Caused by a single interact with high-energy particle, that lead to bit flips happen in chips.



- Total Ionizing Dose(TID): Summation of the overall accumulated dose, shown as increase in digital current during irradiation.

Measures in ASIC

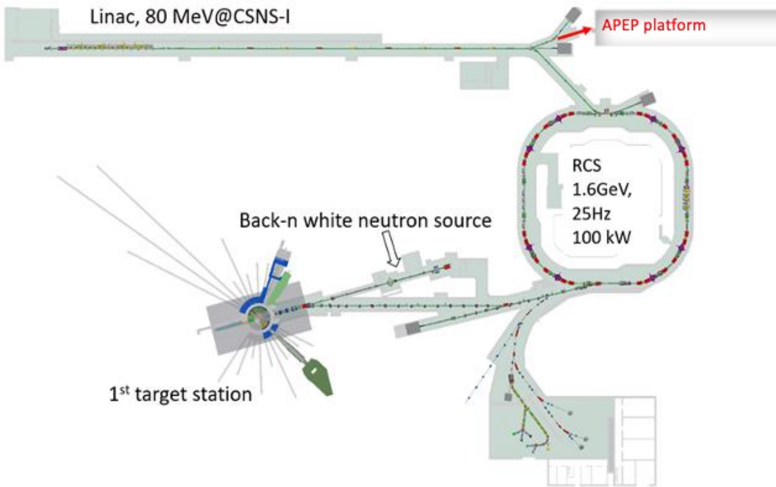
- All ASICs have used TMR design(Triple Modular Redundancy) to protect against SEEs.
- Also pre-irradiation to avoid TID bump.
- Still need to be tested before they finally installed on ITk detector.

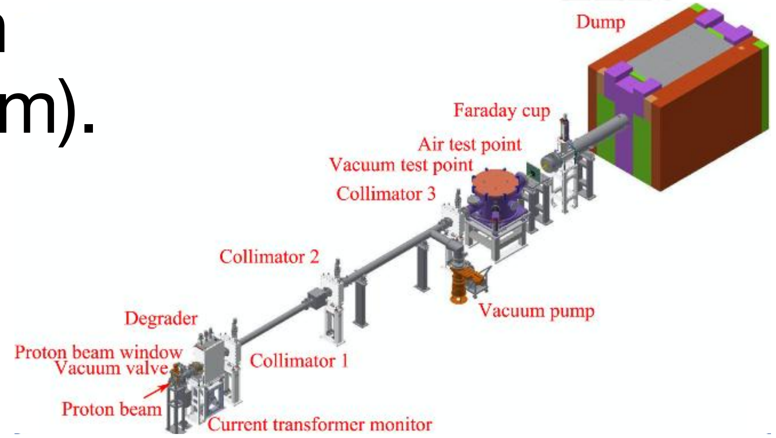


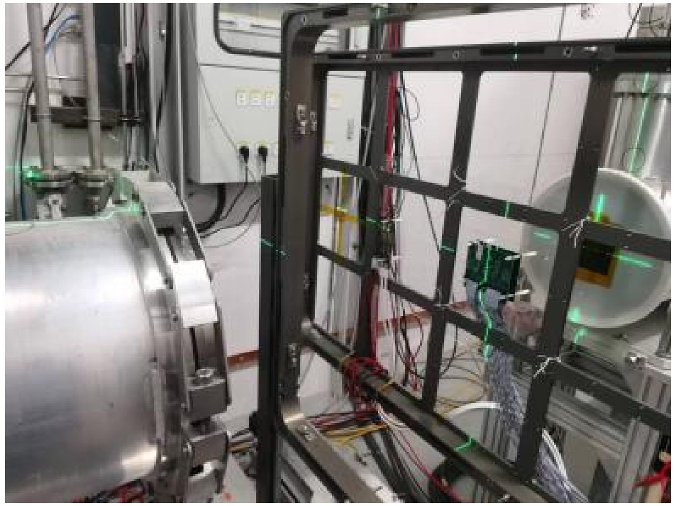
- Finish single chip test for ABC and HCC, calculate SEE Cross Section.
- Finish BETSEE test and find some issues on AMAC.

Beam test at CSNS

- All tests was done at CSNS(China Spallation Neutron Source) with 80 MeV proton beam on APEP(Associated Proton Experimental Platform).
- Used lead bricks to protect other part of readout system from background irradiation.



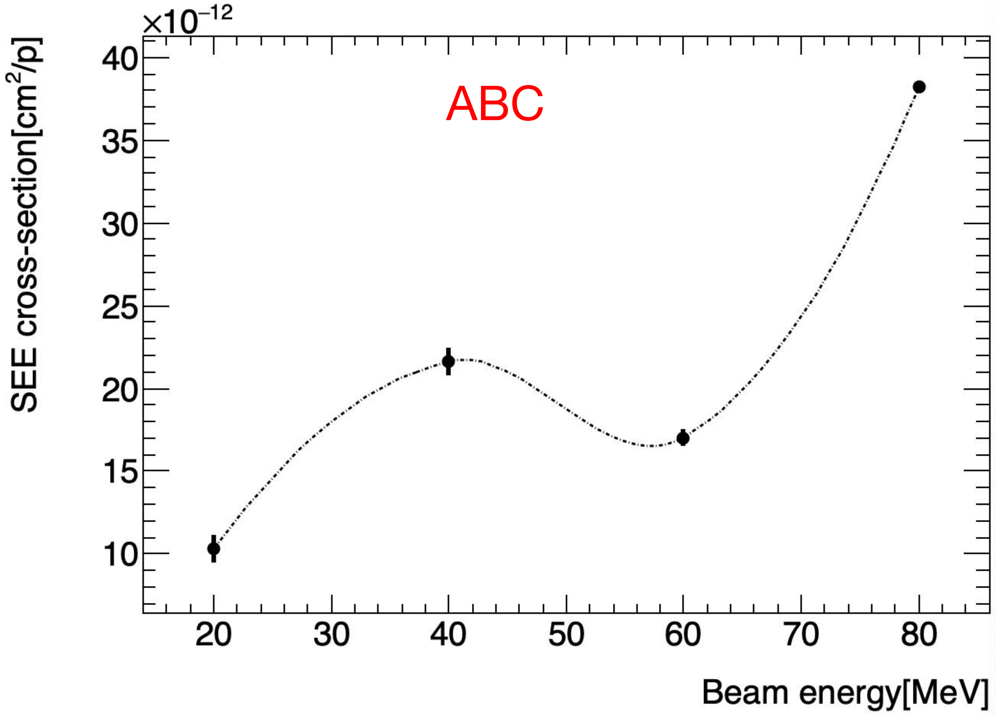


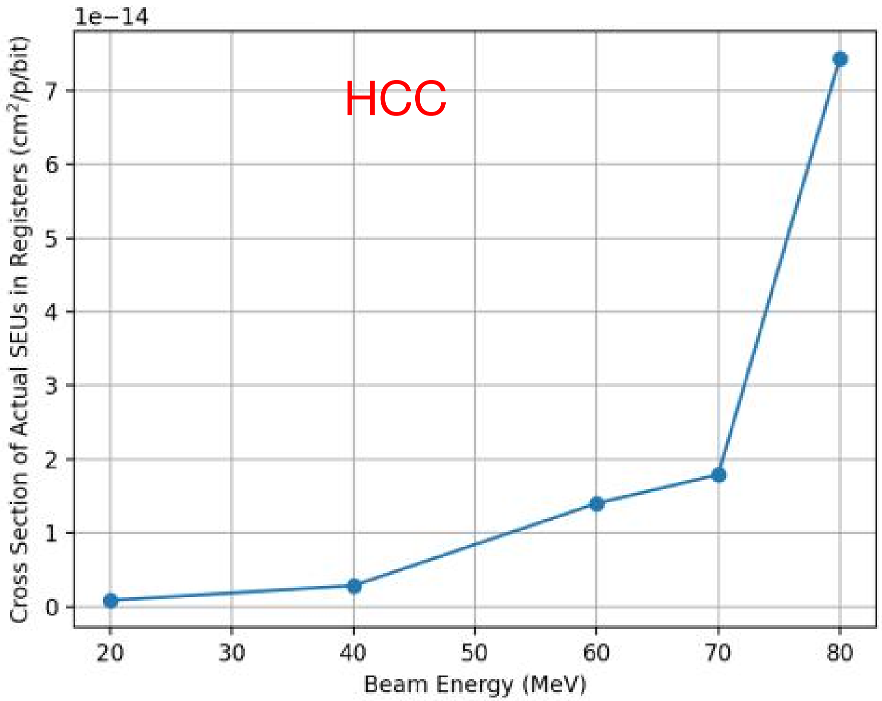


Single chip test result

- Tested different energy points about ABC/HCC chip SEE effect.

$$\sigma_{SEE} = (\frac{1}{N_{bits}})\frac{N_{flips}}{\Phi_{total}}$$





Prediction

- Make prediction about SEE frequence during HL-LHC period.
- Have a worst estimation of ATLAS irradiation flux:

$$\Phi_{proton} = O(10^7) p/cm^2/s$$

- In ABC physics packet:

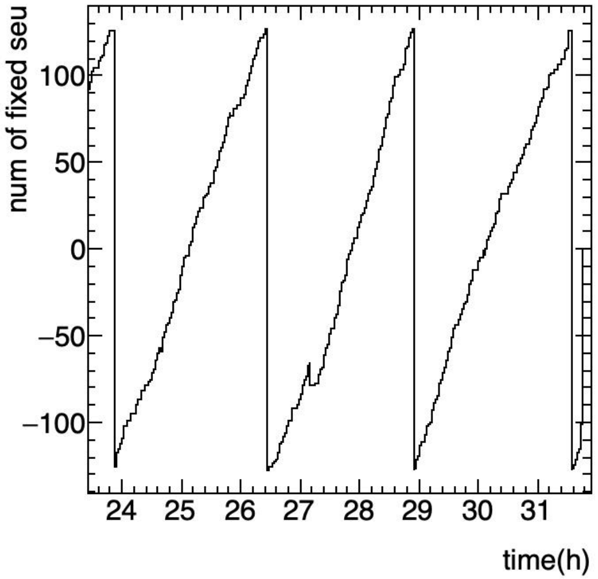
$$Rate_{packet} = \Phi_{proton} \times \sigma_{SEE} \times \left(\frac{< time\ in\ pipeline >}{packet} \times \frac{packets}{events}\right) = O(10^{-9})/event$$

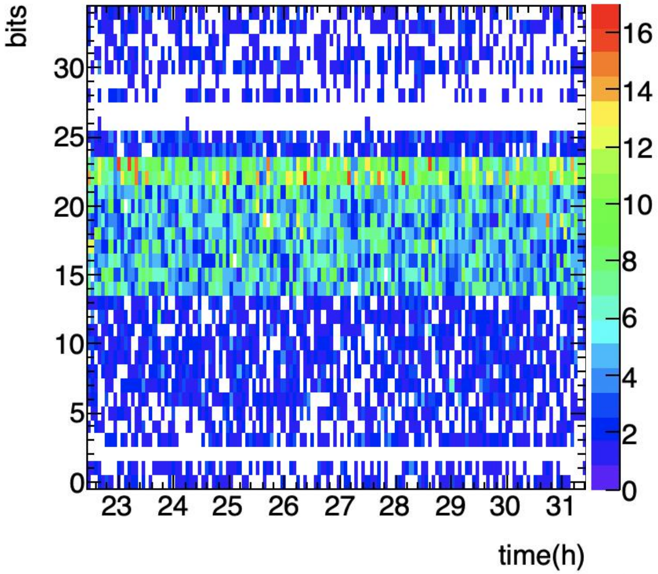
- In HCC register:

$$Rate_{register} = \Phi_{proton} \times \sigma_{SEE} = O(10^{-5})/s$$

BETSEE test result

- Only one bit flip found for ABC/HCC. Consistent with Single chip test result.
- Both are ADC_Enable bit changes from 0->1.

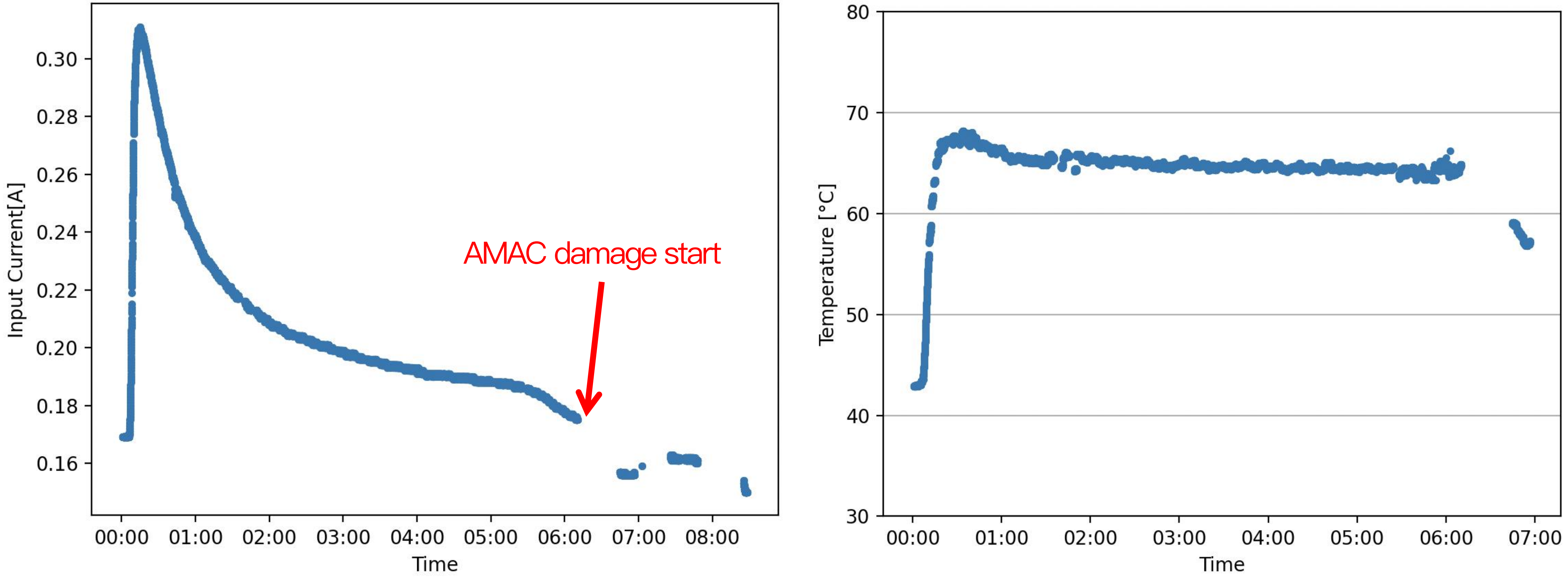




- Also checked corrected SEE. Shows TMR make a good protection.

TID effect

- Reach the top at 0.311A after 8 minutes (about 0.35Mrad), which makes the temperature too high.

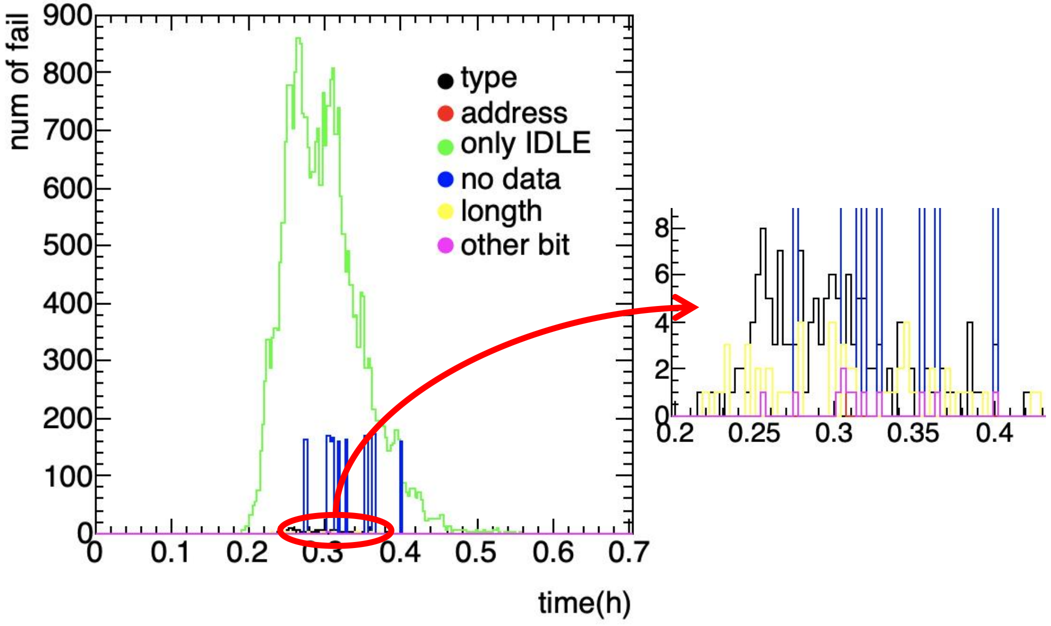


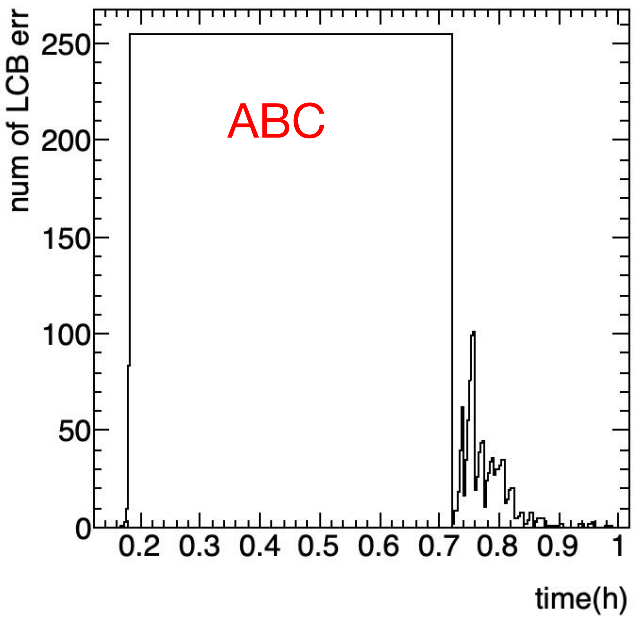
AMAC damage

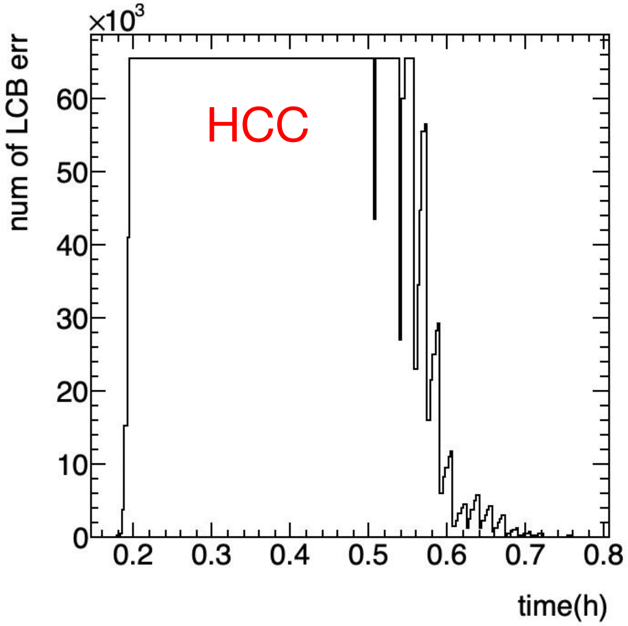
- Found AMAC have a bad performance under a high flux.
  - Endeavour communication broken after about 21 Mrad.
  - The power also have issues after about 23 Mrad.
- After damage happened:
  - All communication fails once beam is on.
  - Power output is related to the flux. In a dose rate range from 2.60 Mrad/h to 0.57 Mrad/h, the power output would be cut off while in a high flux, however would also automatically restore when reducing the dose rate.

Syetem unstable in TID period

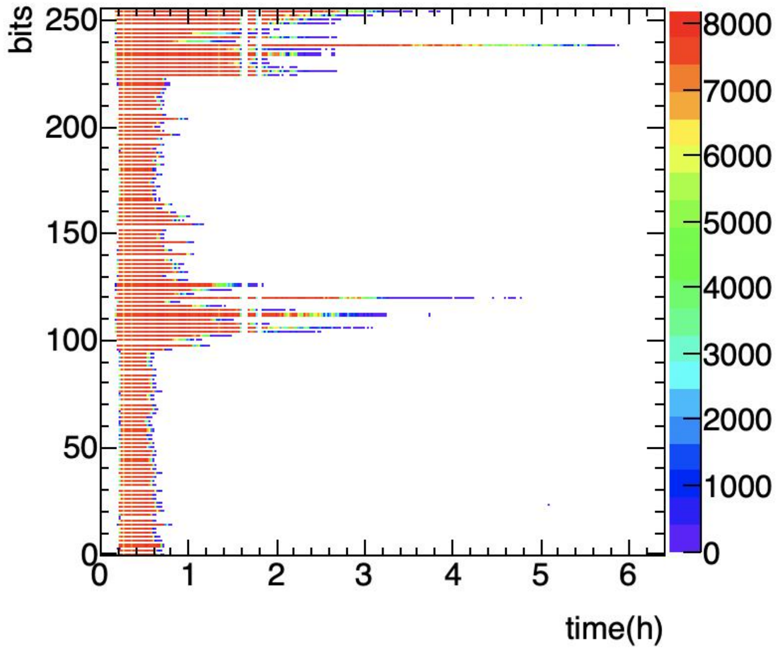
- Lots of failures discoverd during TID period.
- Including Packet error, LCB error(ASIC internal signal), SEE effect.

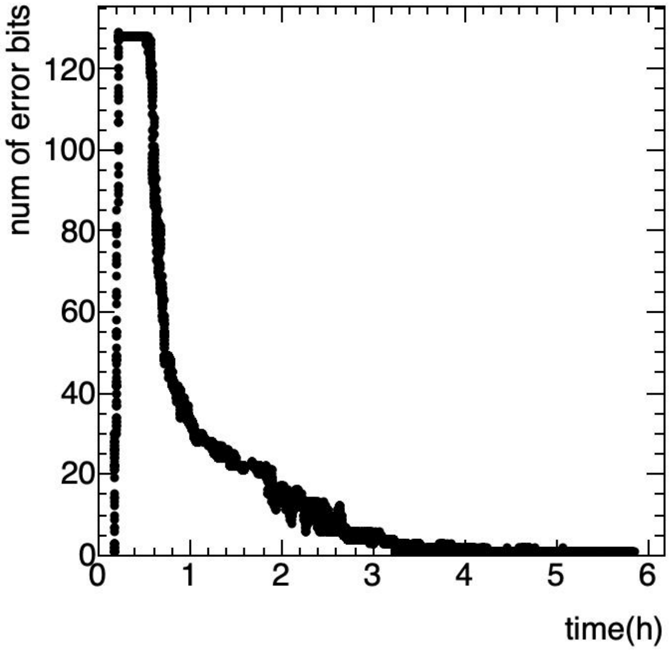






- 1 bit flip about output channel threshold found on AMAC at 21 minutes, from 1->0.
- Physic packet SEE effect happened a lot.





Conclusion

- Finished different beam test for about 30 Mrad. For the first time did ASIC irradiation at CSNS.
- Paper published: https://doi.org/10.1016/j.nima.2024.169531
- From BETSEE test, found powerboard have issues under a high flux irradiation and hybrid run unstable when TID current goes too high.
- Tested as a small module, we could clame the damage on AMAC have no obvious influence on hybrid.

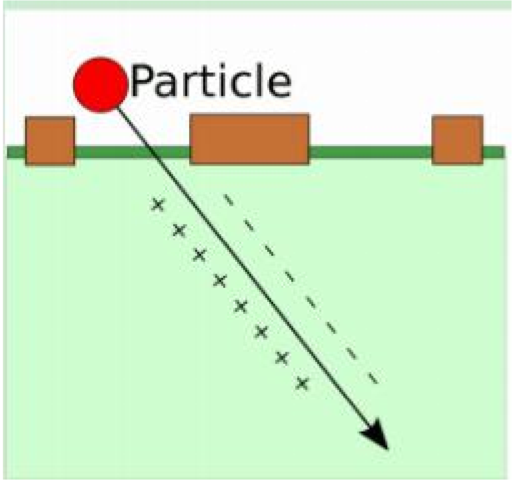
- All result has been reported to ATLAS ITk group and make a good contribution in further ITk production.

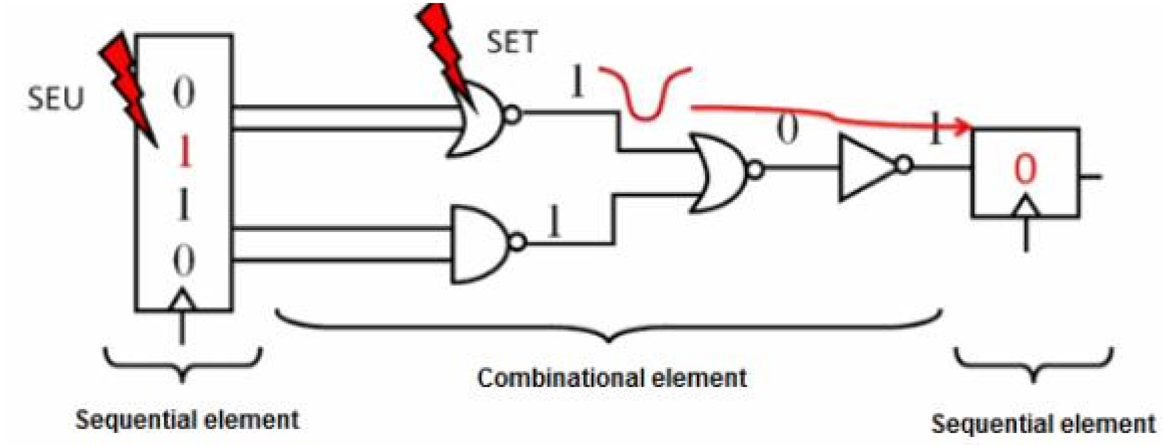
THANKS FOR LISTENING!

Backup

SEEs

- Single Event Effects (SEEs) – electrical disturbance of an electronic device interacts with high-energy particle
  - **Single Event Upset (SEU)** – affects both dynamic and static memory registers storing logic states by collecting charge → **voltage change** → bit flips happen
  - **Single Event Transient (SET)** – a transient pulse produced by a charged particle in a circuit → **temporal disorder** → bit flips happen

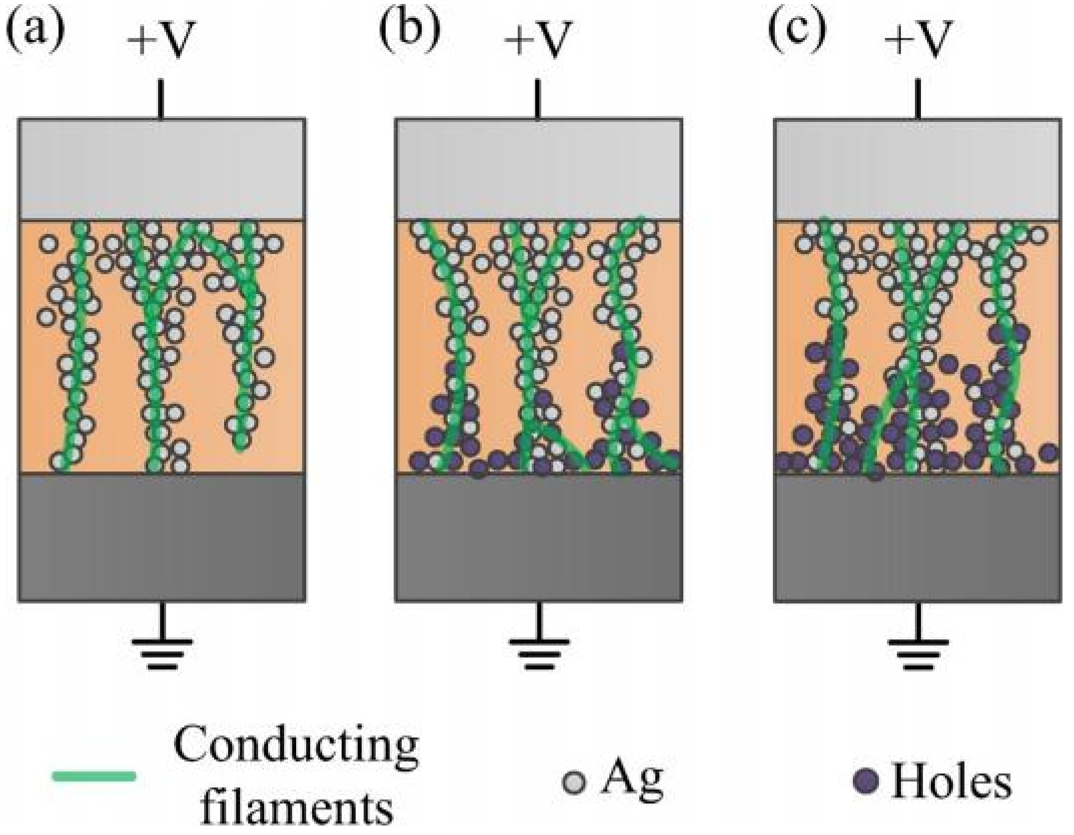




Figures: de Aguiar Y Q, Zimpeck A L, Meinhardt C. Reliability Evaluation of Combinational Circuits from a Standard Cell Library[J].

Total Ionzing Dose (TID)

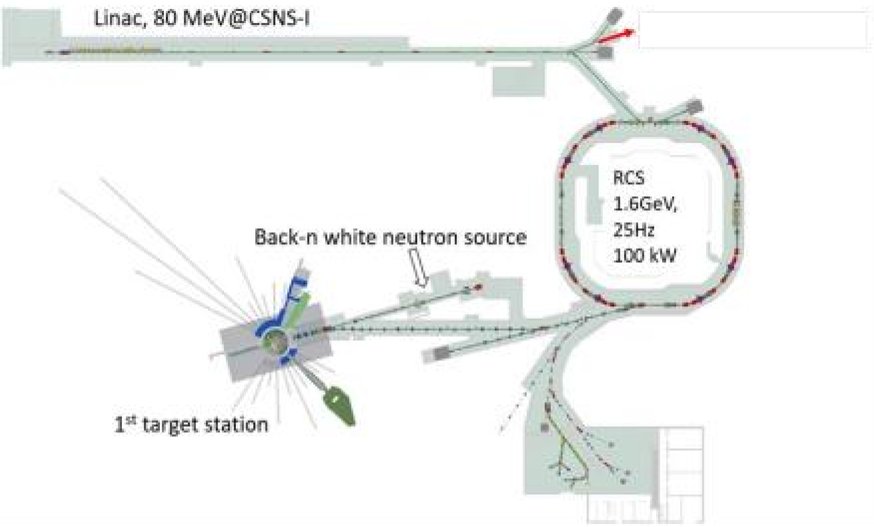
- An **increase in digit current** when chips exposed to ionizing doses of radiation
  - Interaction between particle and electron-hole pairs (produce electron-hole pairs)
- Up to **approximately 1 Mrad**
- Continued exposure gradually reduces the current back towards **normal value**
- Refers to the cumulative amount of radiation
- The sensitivity of microelectronics to TID can impact reliability and functionality
- Pre-irradiation to avoid TID bump



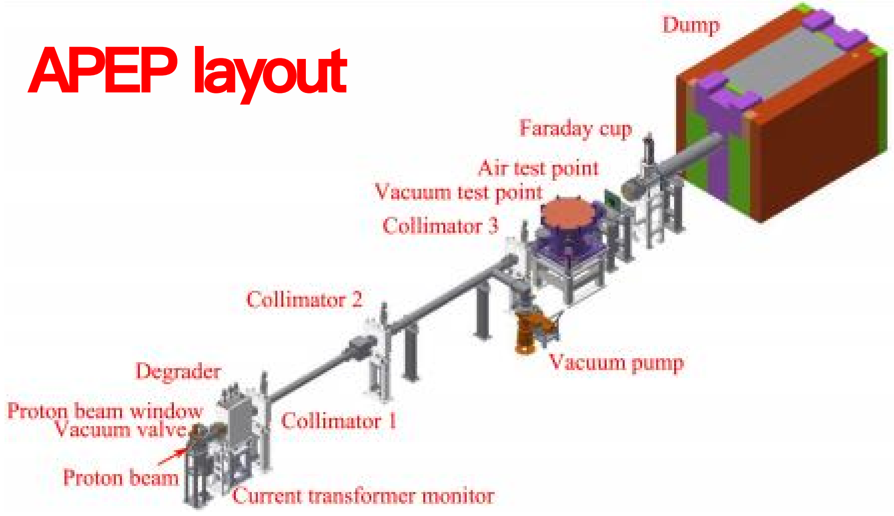
Figures: Yuan F, Zhang Z, Wang J C, et al. Total ionizing dose (TID) effects of γ ray radiation on switching behaviors of Ag/AlO x/Pt RRAM device[J]. Nanoscale research letters, 2014, 9: 1-6.

Proton beam in ABCStar at CSNS

- We utilize the **Associated Proton Experimental Platform (APEP platform)** to have irradiation on ABCStar chips at the end of the CSNS linac
- To validate the performance of ABCStar ASICs V1 and V0, irradiated **2 campaigns:**
  - May 2022: 80MeV, **one V0 chip**
  - April 2023: 20MeV ~ 80MeV, **four V1 chips**
- Beam spot → **20mm × 20mm**
- Flux: $1.16 \times 10^{7} \rightarrow 2.66 \times 10^{9}$ p/cm²/s
- Fluence: $1.24 \times 10^{14} \rightarrow 3.63 \times 10^{14}$ p/cm²
- Dose: ~ 40 Mrad
- **~ 170 hours** totally

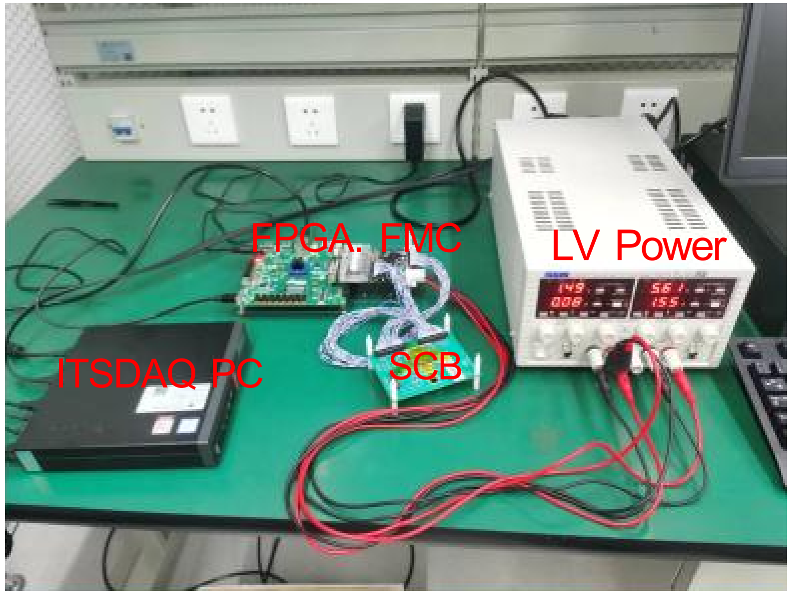


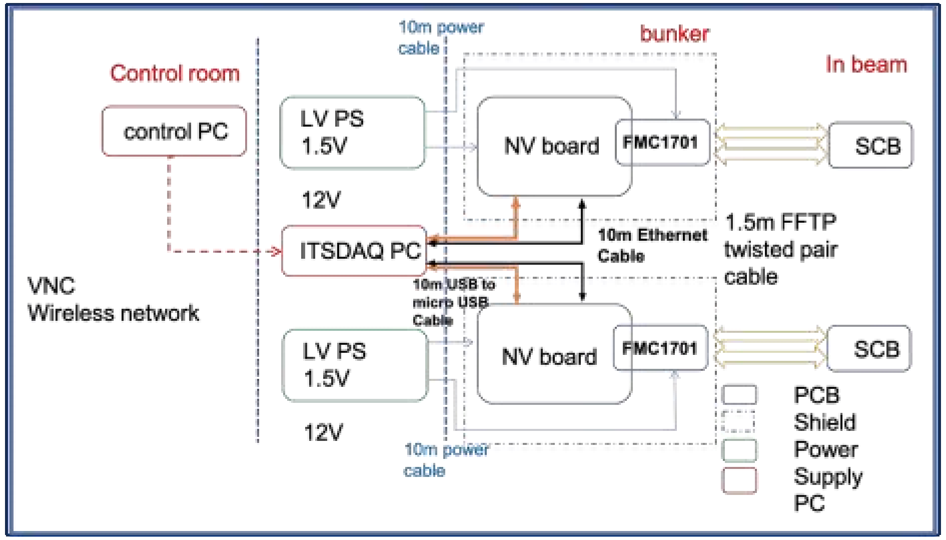
APEP layout



Proton beam in HCCStar at CSNS

- We utilize the **Associated Proton Experimental Platform (APEP platform)** to perform the irradiation of HCCStar chips at the end of the CSNS linac
- To validate the performance of HCCStars, irradiated **3 campaigns:**
  - February 2022 : heavy ions, one chip @ UCLouvain
  - May 2022: 480 MeV protons, two chips @ TRIUMF
  - October 2023: 20MeV $\sim$ 80MeV protons, **two V1 chips @ CSNS**
- Beam spot $\rightarrow$ **$20mm \times 20mm$**
- Flux: $4.64 \times 10^7 \rightarrow 5.32 \times 10^9$ p/cm^2/s
- Fluence: $\sim 7.06 \times 10^{14}$ p/cm^2
- Dose: $\sim$ 24 Mrad, equivalent to roughly 48% of HCC lifetime (radiation tolerant to a TID of 50 MRad)
- **~ 37 hours** totally





ABCStar — hit errors rate

- The rate of hit errors due to SEUs in physics packet clusters, Rate_{SEU} is given by:

$$\text{Rate}_{\text{SEU}} = \left(<\mu> \times \frac{fluence}{collision} \times \frac{collisions}{second} \times \frac{<time\ in\ pipeline>}{packet}\right) \times \frac{packets}{event} \times \sigma_{\text{SEU}}$$

$$= \left(200 \times \mathcal{O}(10^{-3}) \times (40 \times 10^{6}) \times \mathcal{O}(10^{-5})\right) \times 1.1 \times \mathcal{O}(10^{-11})$$

$$= \mathcal{O}(10^{-9})\ \text{bit flips/event/ABCStar}$$

- For ～230K ABCStars in the tracker, the entire system would need to be read out **～4000 times to see a SEU**
- There are **～230,000 ABCStar ASICs** in the ITk strip tracker and assuming a trigger rate of 1MHz, which means 。**(200) hit errors/s** during normal operation

HCCStar CBFs rate at the HL–LHC

- Follow ABC paper calculation
- The rate of CBFs, $Rate_{CBFs}$ is given by:

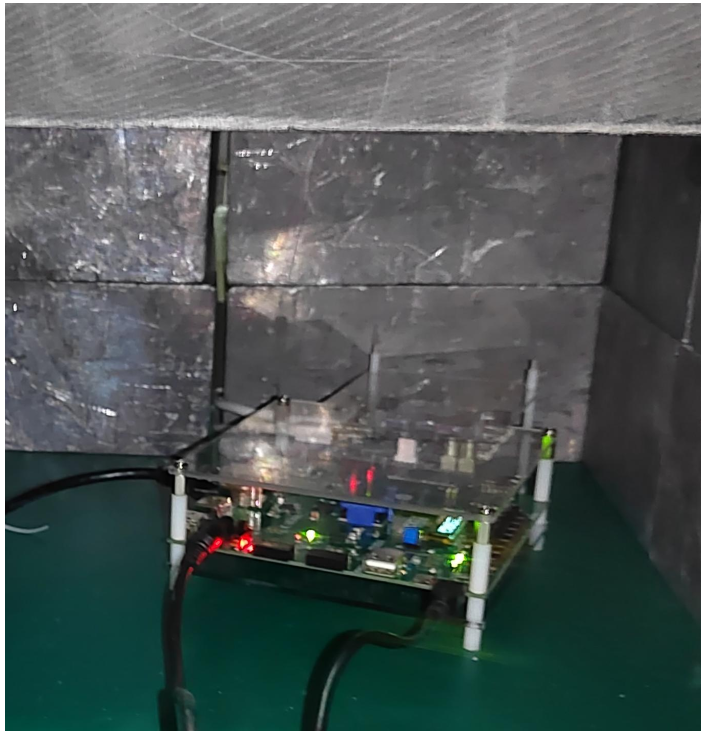
$$Rate_{CBFs} = O(10^7)\frac{hadrons}{cm^2\ s} - \frac{\sigma_{SEU}}{chip} - \frac{10^7 seconds}{year} \text{ (4 months per year continuous running)}$$

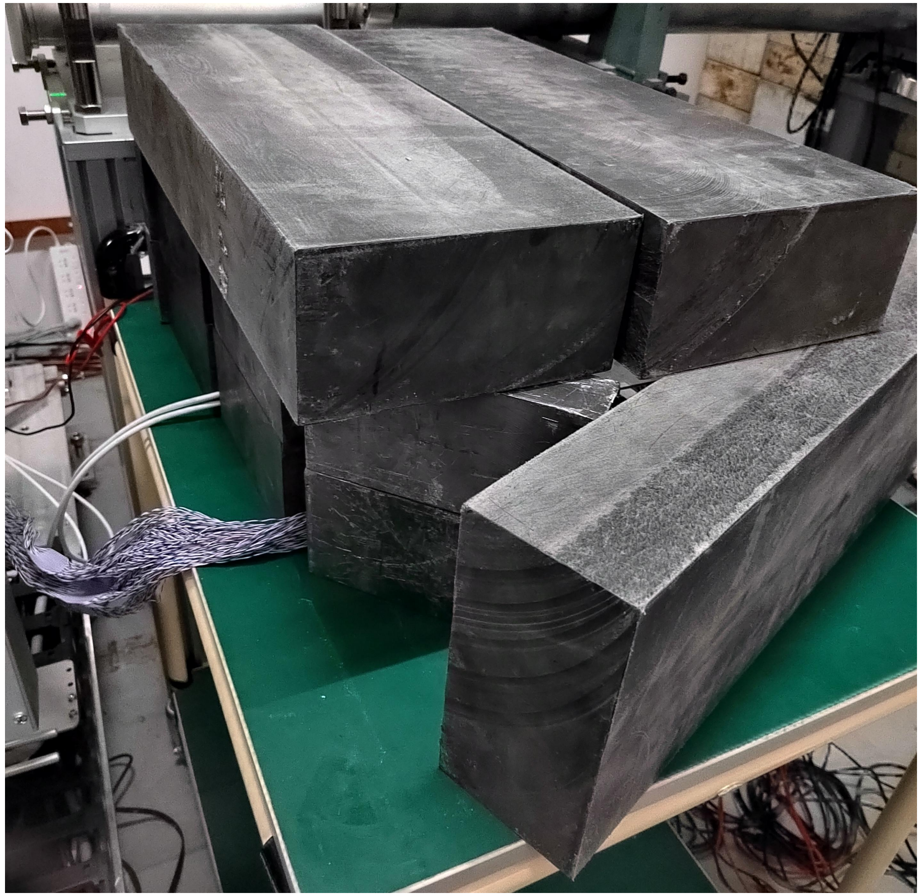
$$= O(10^7)\frac{hadrons}{cm^2\ s} - O(10^{-13})\frac{cm^2}{bit} - \frac{10^7 seconds}{year}$$

$$= O(10) \text{ CBFs/year/HCC}$$

Setup

Beam size: 3×3 (cm)



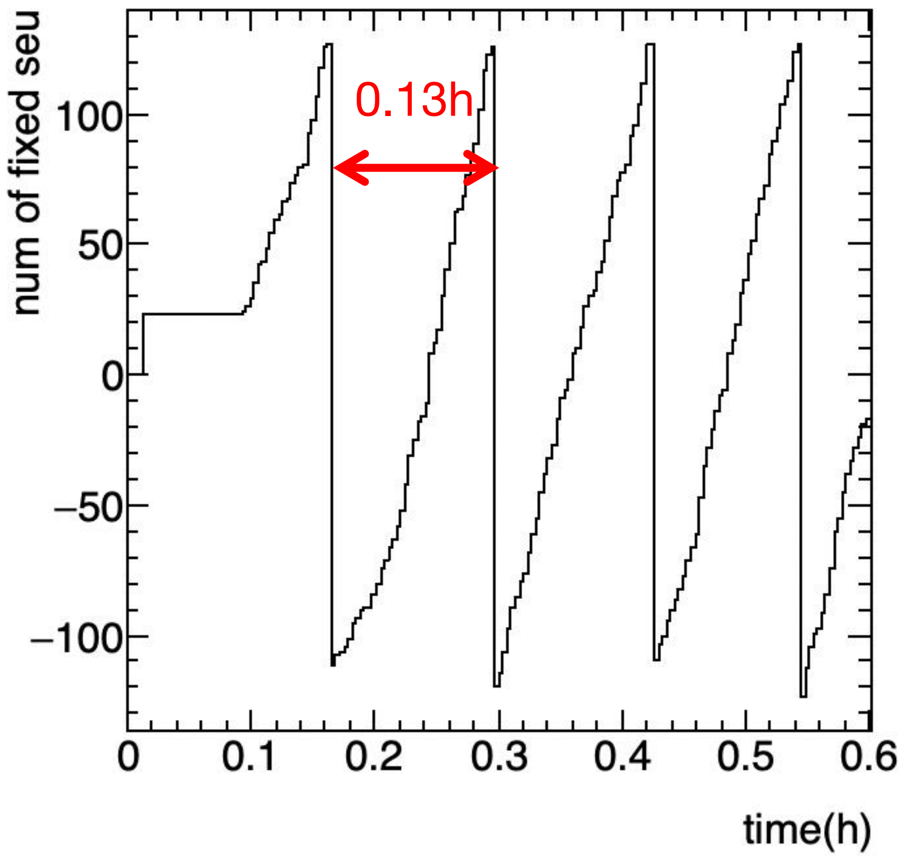


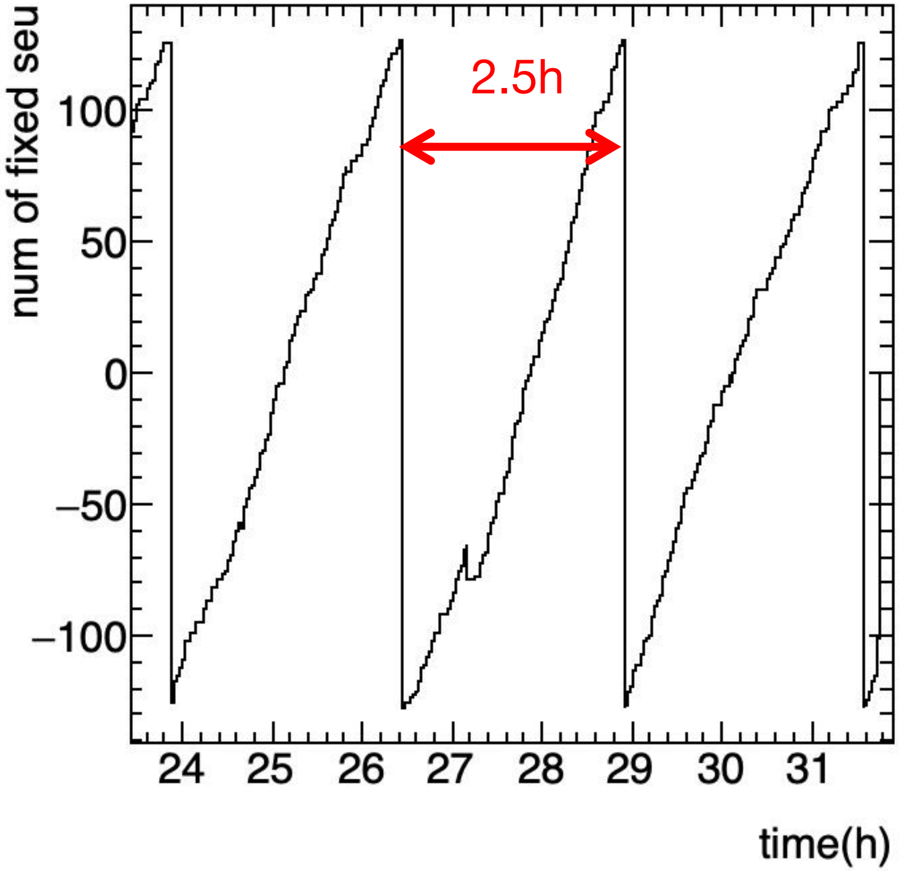
- Using lead bricks to protect the FPGA and FMC board.

- Flux: 6.6e9 → 1.3e9 (p/cm²·s)
- Dose rate: 2.6 → 0.57 (Mrad/h)
- Fluence: 1.9e14 → 2.52e14 (p/cm²)
- Dose: 20.9 → 27.7 (Mrad)

SEU counter for ABC

- The SEU counter register increase as expected in different flux.





rate ratio: 20
flux ratio: 5