The HCCStar ASIC for the ATLAS ITk Silicon Strip Detector: Irradiation Testing

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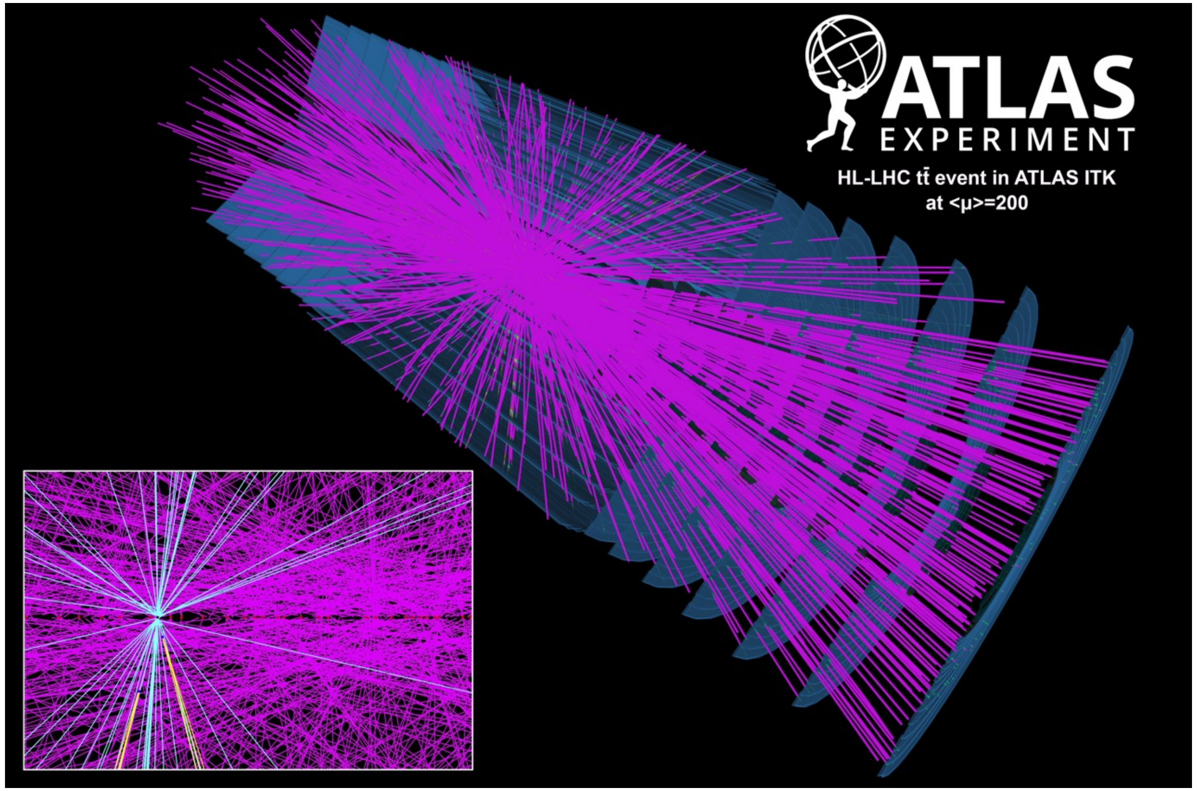
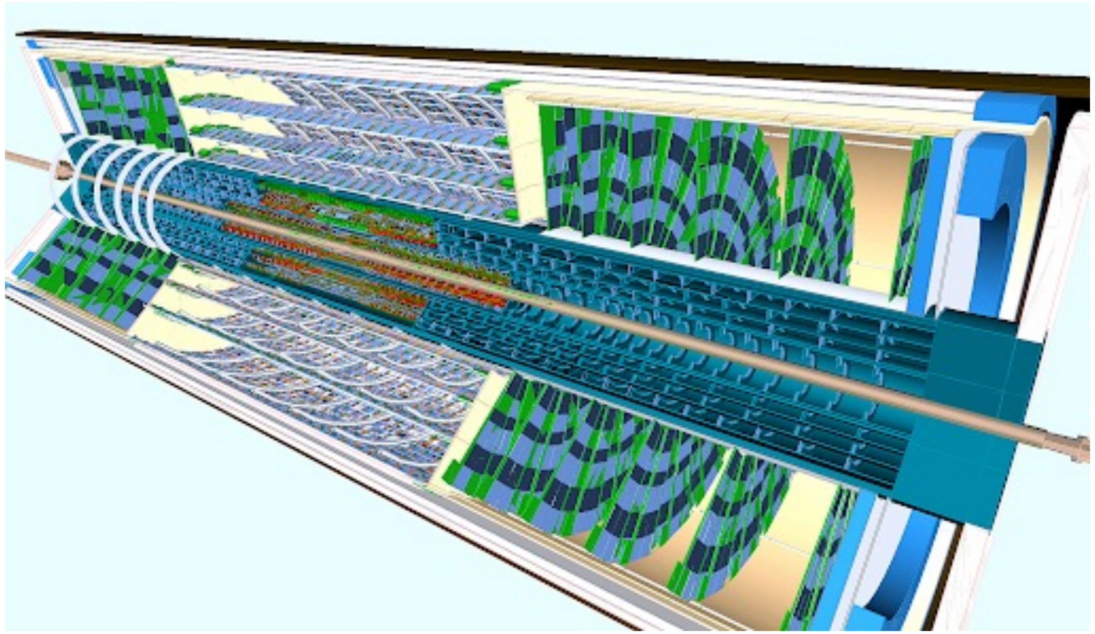
High Luminosity LHC: Detector Challenges

- With the planned upgrade to the High Luminosity LHC (HL-LHC), new challenges are introduced due to higher rate of data production
  - Data must be read out at a higher frequency
  - Detectors must have finer granularity
  - **Electronics must be radiation hard**

ATLAS ITk Workshop

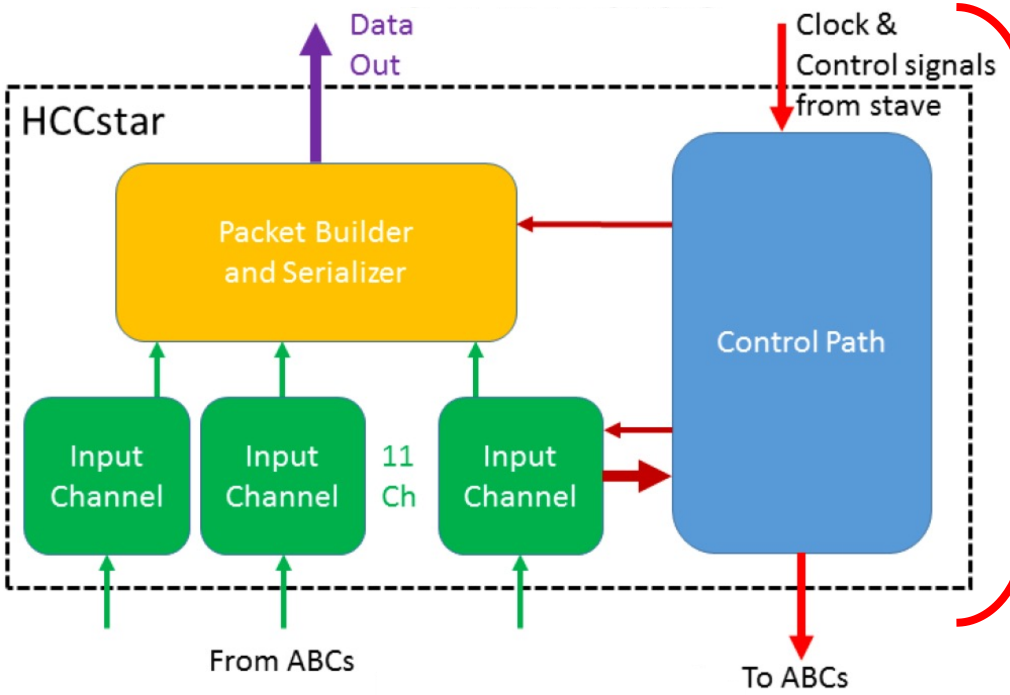




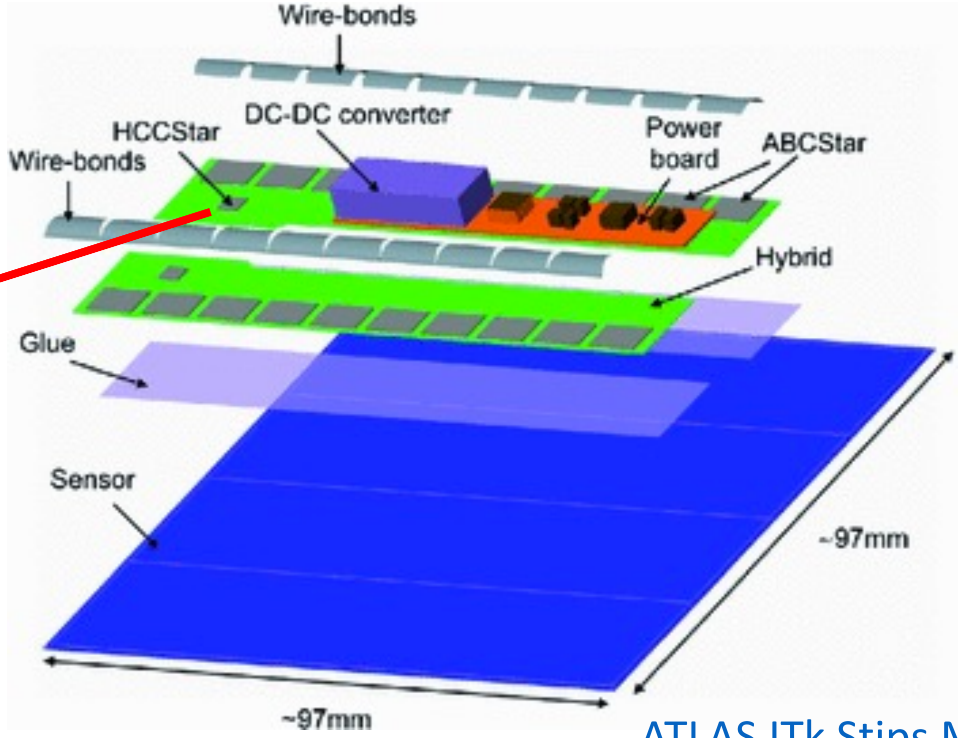
ATLAS ITk Strip TDR

Hybrid Controller Chip (HCCStar)

- The Hybrid Controller Chip (HCCStar) is one of three ASICs being developed for the ITk strips module
  - Sends control and trigger commands to ABCStars
  - Serializes event data from 5-11 ABCStar chips to send to off detector



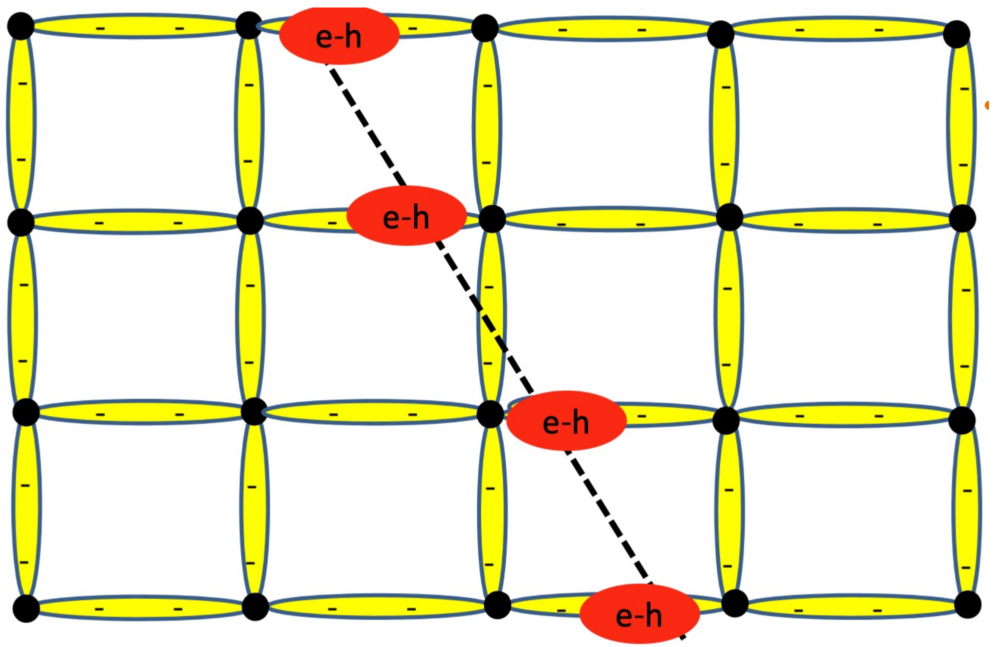
HCCStar Block Schematic



ATLAS ITk Stips Module

Single Event Effects: Overview

- Charged particles passing through electronics can ionize material
  - Higher charge particles are more destructive
- Charge build up can lead to corruption in stored data
- GOAL: Quantify effects of radiation on accuracy of our ASICs

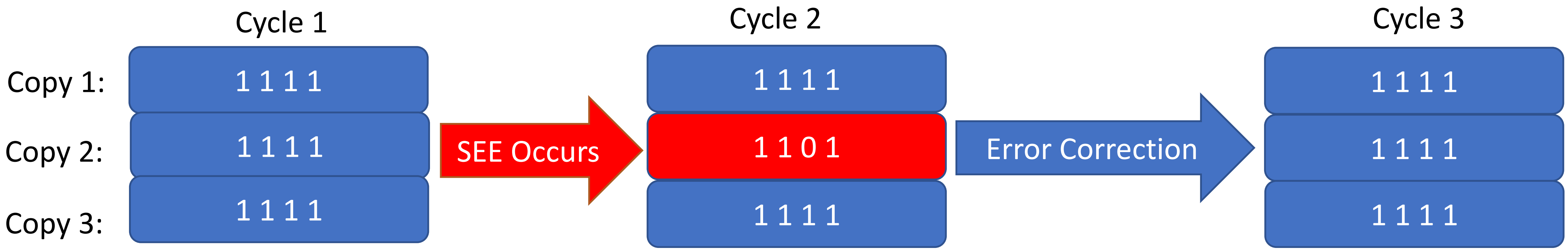


Charged particles passing through silicon, leaving electron-hole pairs

- Types of Irradiation:
  - Gamma: Low SEE rate; slowly affects current draw
  - Proton: Moderate SEE rate; tests vulnerability in design
  - Heavy Ion: Strongest ionizing capability

HCCStar Design: Error Correction

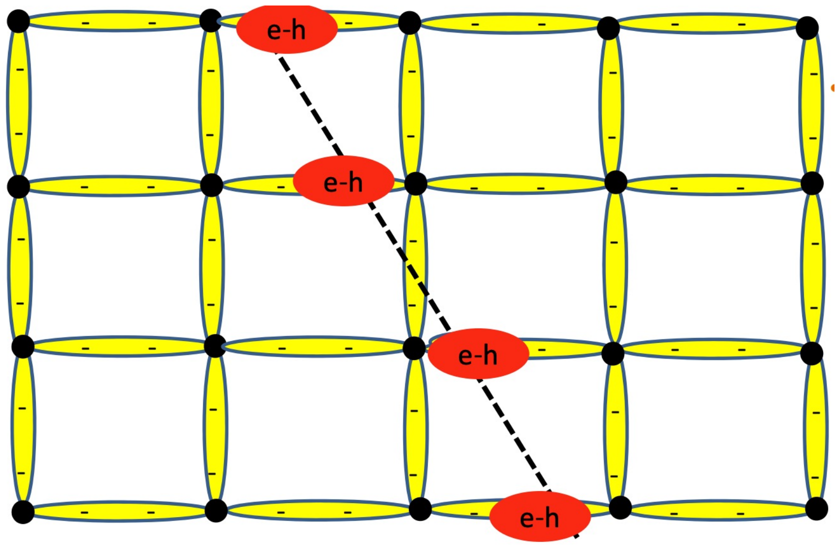
- HCCStar uses triplication to minimize destructive effects of radiation
  - Allows for recovery of states
  - Copies are physically separated on die
  - Majority Wins logic
- HCCStar records when it corrects an SEE, unlike other ITk Strips ASICs



Triplication allows recovery from SEE in single copy of register

Irradiation Testing

- Prototype HCCStar placed in beam line to test functionality in high radiation environment
- Three primary types of Irradiation were tested:
  - Gamma Irradiation: Measure current deviations and voltage regulation
  - Proton Irradiation: Test radiation vulnerability and measure SEE rate
  - Heavy Ion Irradiation: Observe SEE dependence on Linear Energy Transfer (LET)



Brookhaven National Laboratory

TRIUMF

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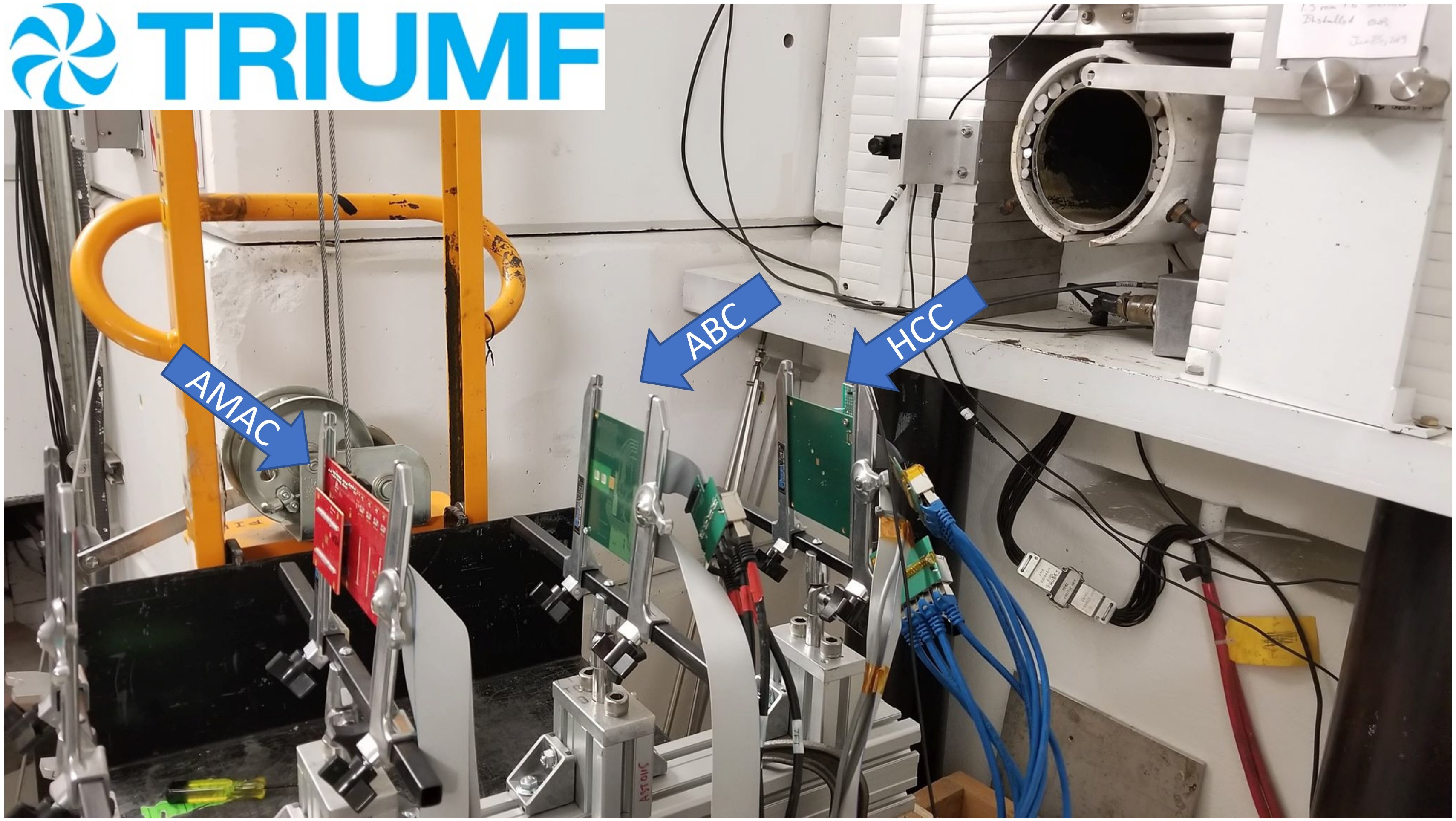
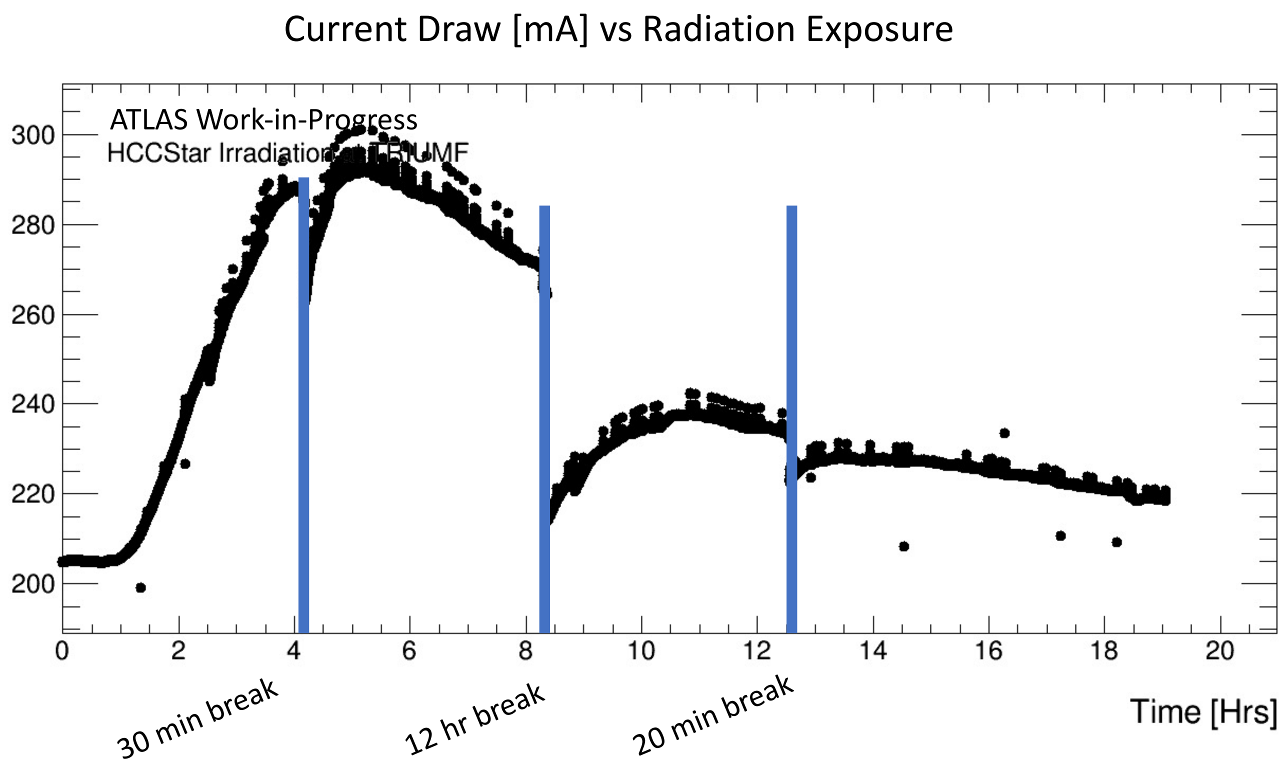
Proton Irradiation: Operational Setup

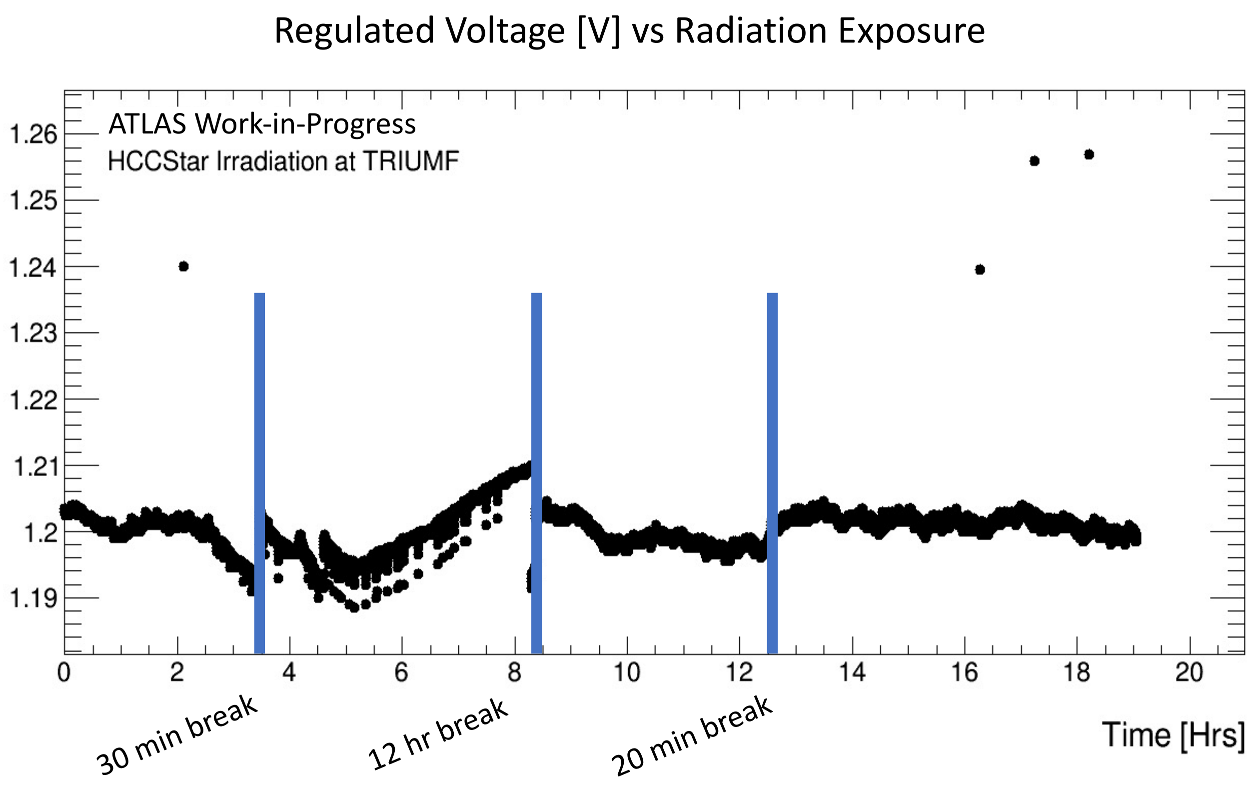
FPGAs control ASICs from a safe distance ☺



Chips are placed in a row and simultaneously irradiated for 24 hours

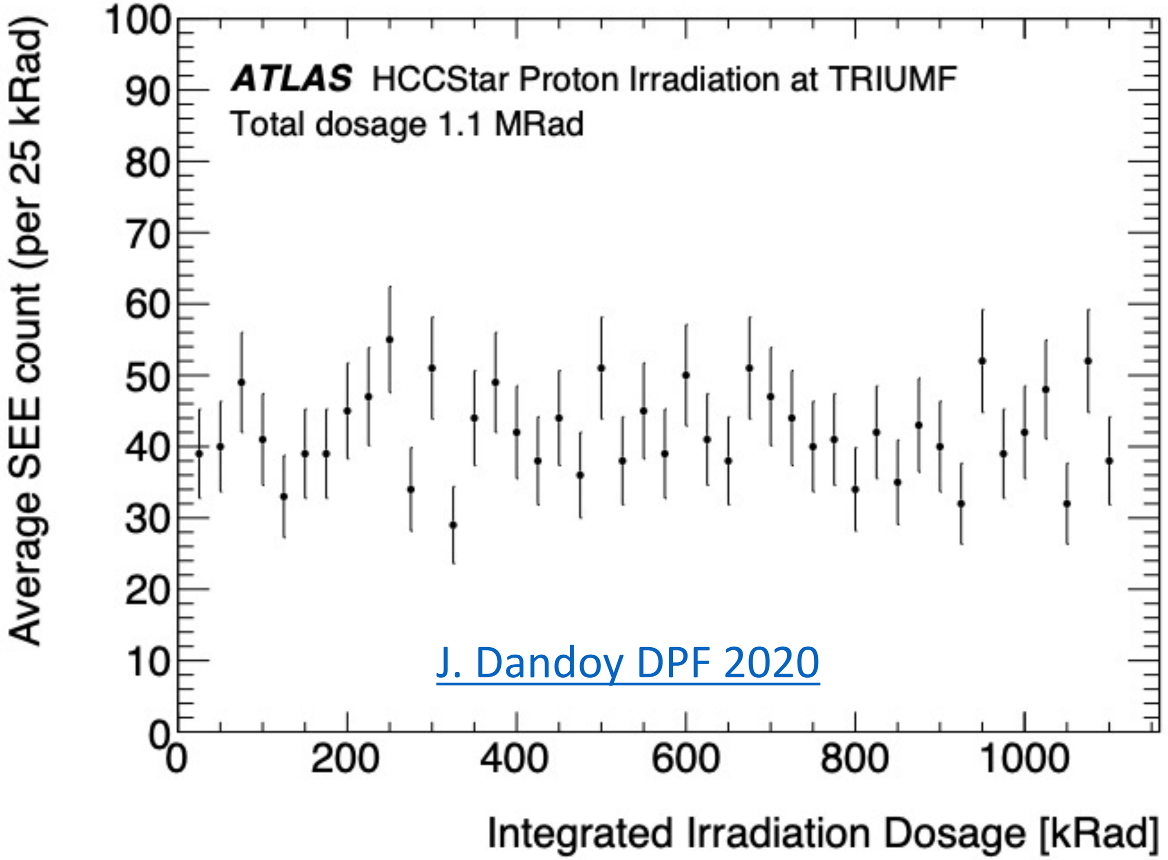
Proton Irradiation Results: Voltage Regulation





- Proton irradiation validated HCCStar ability to regulate voltage
  - Current increases by 50% while voltage is maintained within 0.01 Volts

Proton Irradiation Results: HL-LHC Extrapolation



J. Dandoy DPF 2020

- HCCStar expected to receive 1 kRad per hour in HL-LHC environment
- Expect 40 correctable SEEs per day under HL-LHC conditions
- Severe radiation vulnerabilities led to numerous chip resets
  - Long term damage + Power consumption

```
RegReadRetryTest: ERROR reading register 17, retrying.
Error: tried to read HCCStar register 32, but got packet with contents -1879048192 for register 17 instead.
RegReadRetryTest: ERROR reading register 32, retrying.
Error: tried to read HCCStar register 33, but got packet with contents 0 for register 32 instead.
RegReadRetryTest: ERROR reading register 33, retrying.
Error: tried to read HCCStar register 34, but got packet with contents 1717986918 for register 33 instead.
```

Register readout was non-functional during irradiation

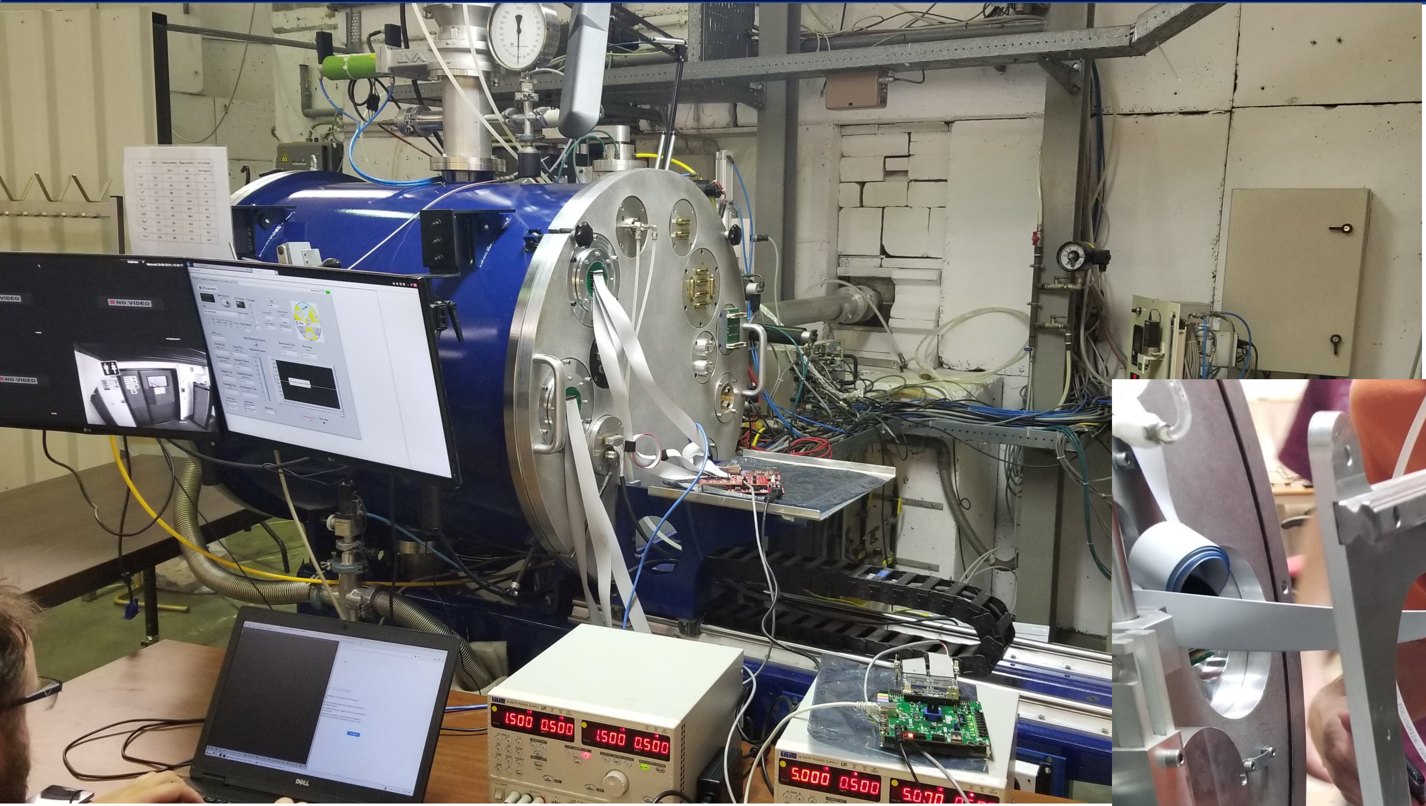
Heavy Ion Testing: Overview

- Heavy Ion testing probes Threshold Energy for SEUs and SEU Saturation
  - Proton Irradiation inspired updates to testing framework
- Irradiate HCCStar with different ions with unique Linear Energy Transfers (LETs)
  - HCCStar tested: ^{53}Cr, ^{26}Ar, ^{84}Kr, ^{124}Xe, ^{58}Ni

UCLouvain

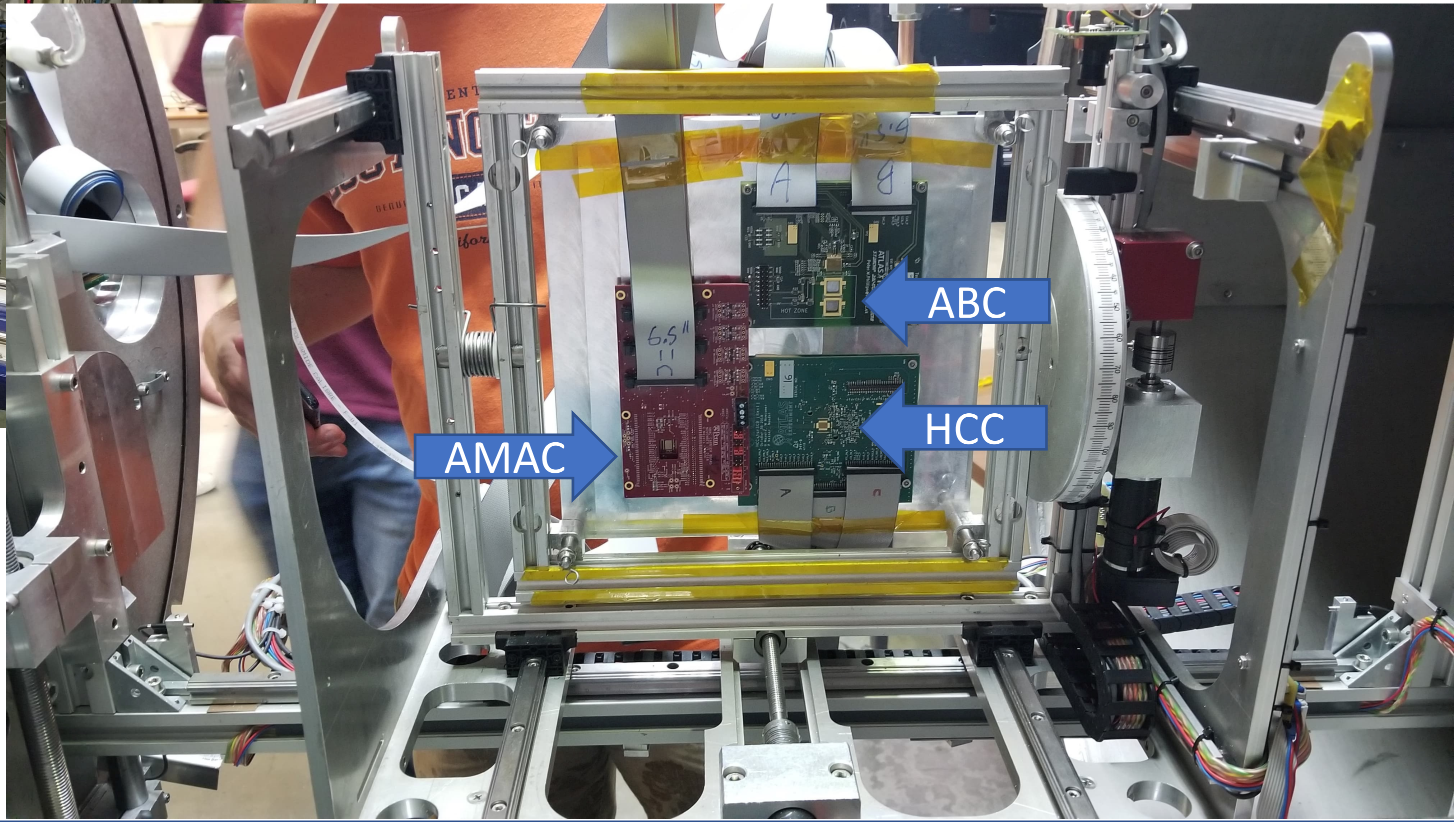
$$\mathrm{LET} = \frac{1}{\rho}\frac{dE}{dx}\left[\mathrm{MeV}\frac{\mathrm{cm}^2}{\mathrm{mg}}\right]$$

Heavy Ion Testing: Operational Setup



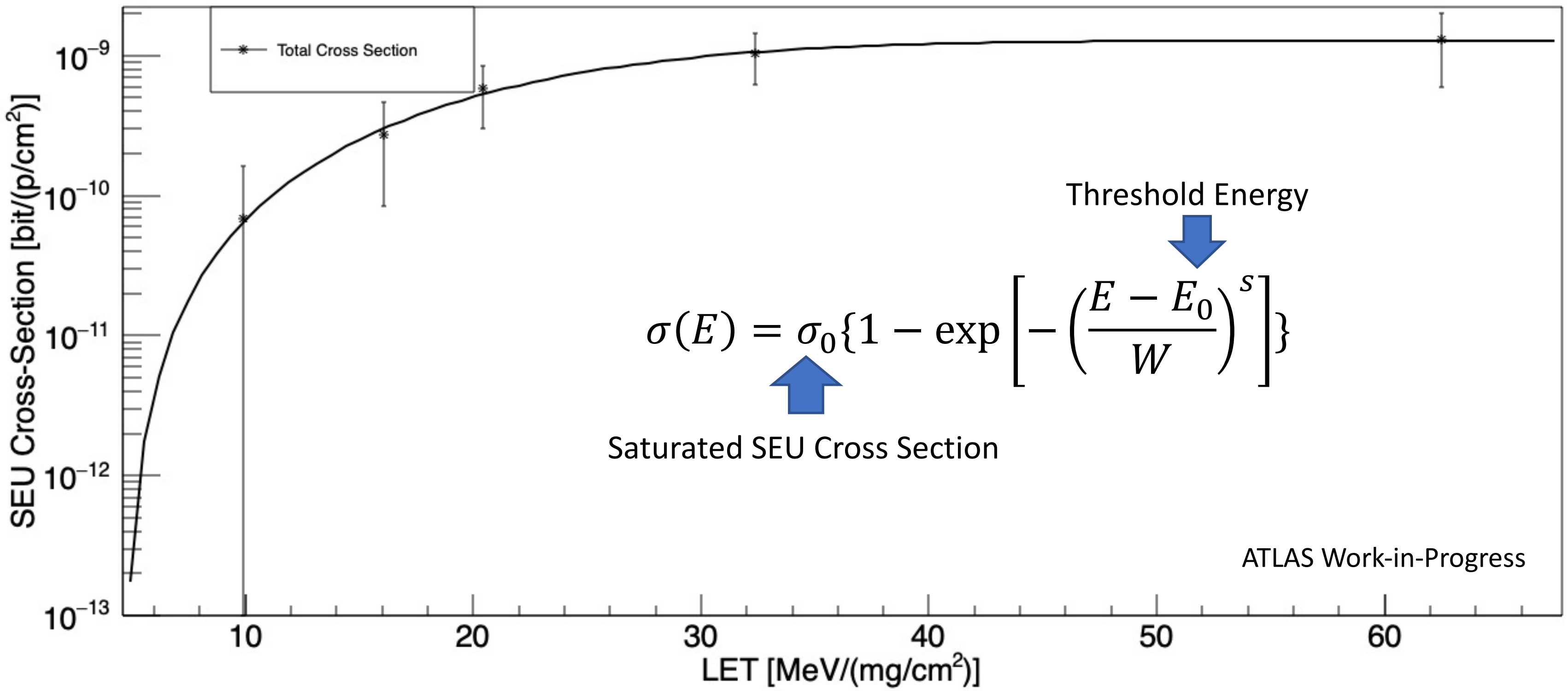
Chips are irradiated in vacuum chamber

ASICs are tested one at a time



Heavy Ion Results:

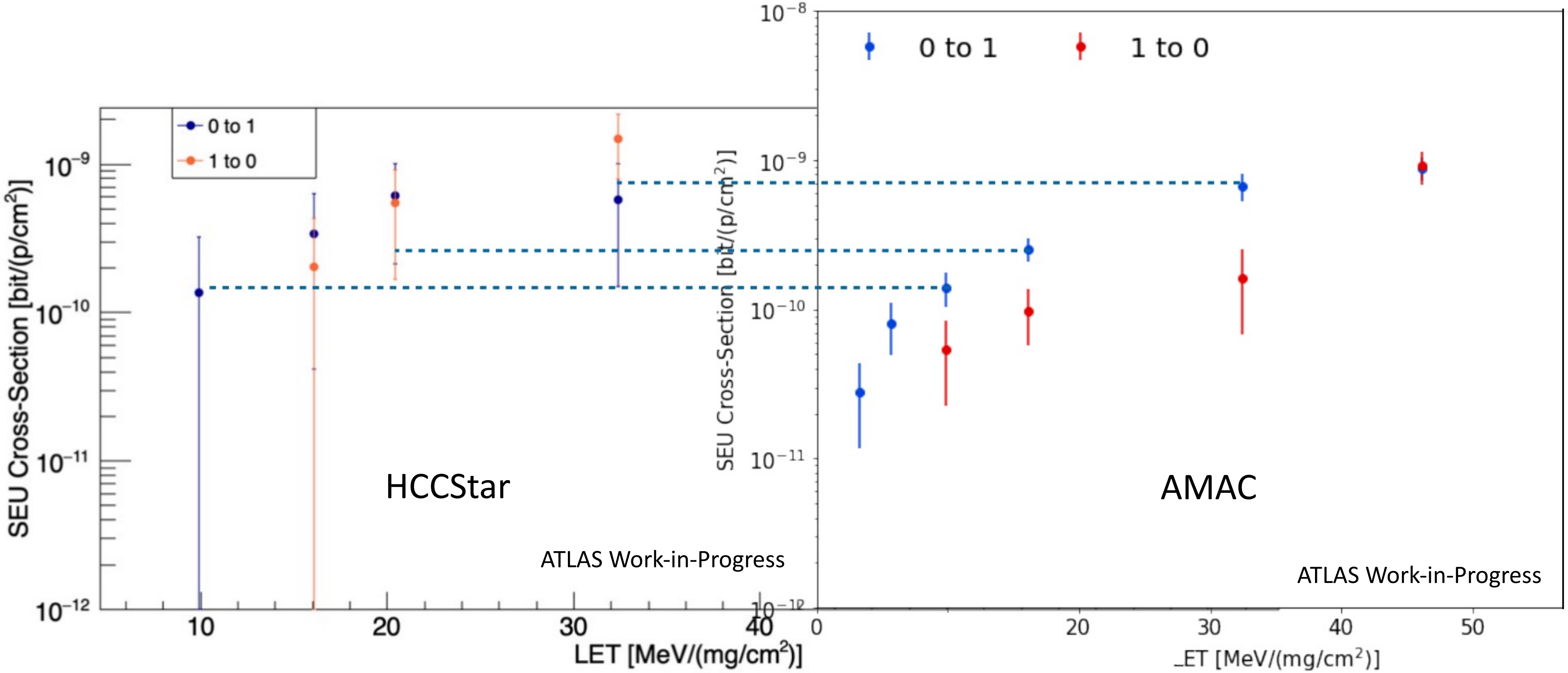
- Stats limitations became biggest problem with testing HCCStar
- Low SEU rate and fewer registers than other ASICs led to large uncertainties on measurement



$$\sigma(E) = \sigma_0\{1 - \exp\left[-\left(\frac{E - E_0}{W}\right)^s\right]\}$$

Heavy Ion Testing: AMAC comparison

- We see a similar cross section for AMAC and HCCStar, which share similar register design
  - Cross Section is split into “0 to 1” and “1 to 0” bit flips to observe bias



Conclusions and Ongoing Work

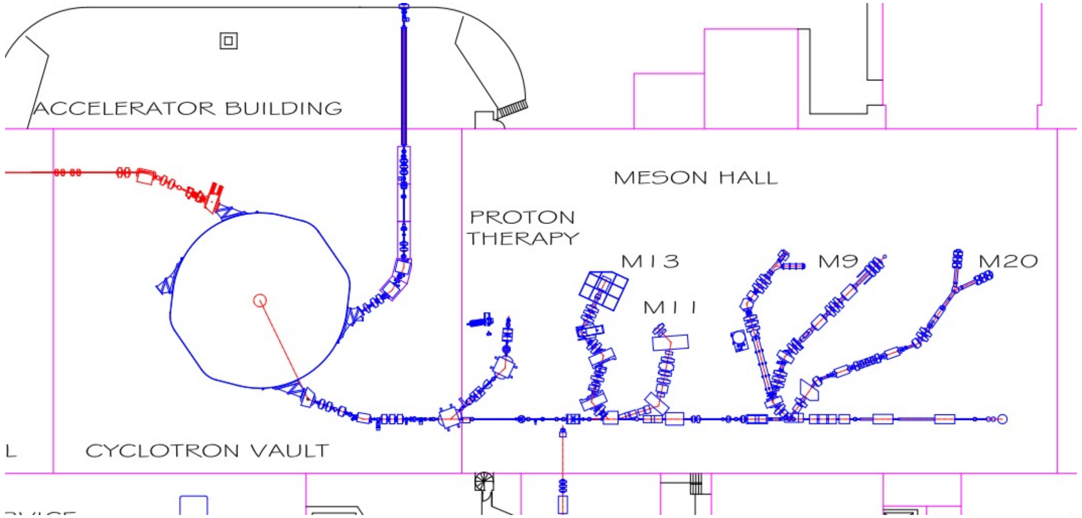
- HCCStar is responsible for controlling ABCStars and serializing physics event data from ABCStars
- HCCStar was able properly regulate voltage during substantial current increases
- During proton irradiation, HCCStar was found to be vulnerable to ionizing radiation
  - Stresses importance of doing irradiation testing early
- Problems encountered during proton irradiation led to many revisions to the chip design over the last year
  - Next talk by Ben Rosser will elaborate

Thanks ☺

Backup Slides

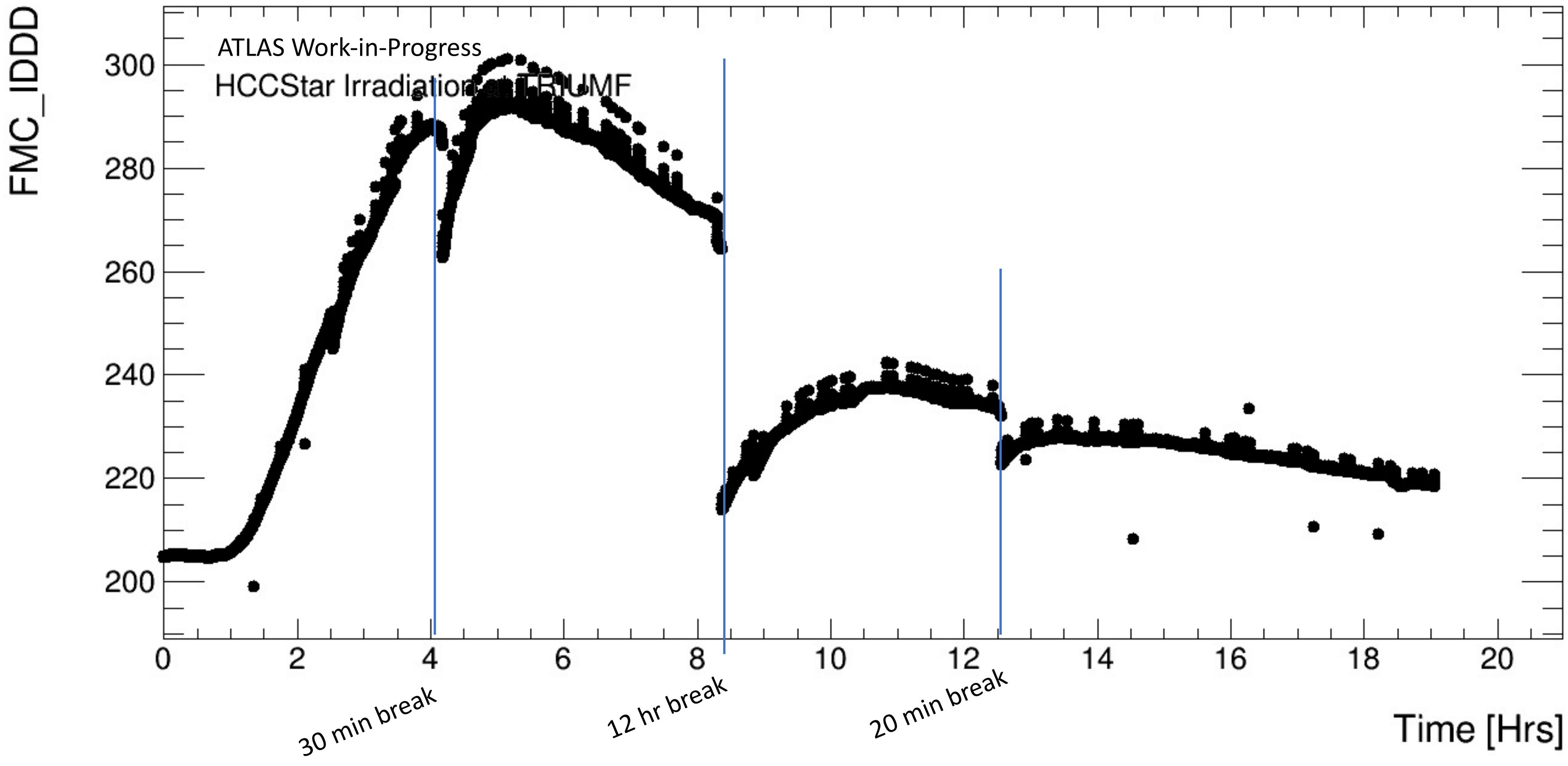
Proton Irradiation at TRIUMF

- Second round of ASIC irradiation was performed at TRIUMF from June 24-27 2019
- Had access to PIF (Proton Irradiation Facility) for approximately 21 Hrs
  - 480 MeV Proton beam off the second primary beamline
  - Fluence of $1.72\times10^{11}\ \frac{\text{protons}}{\text{cm}^2\text{s}}$



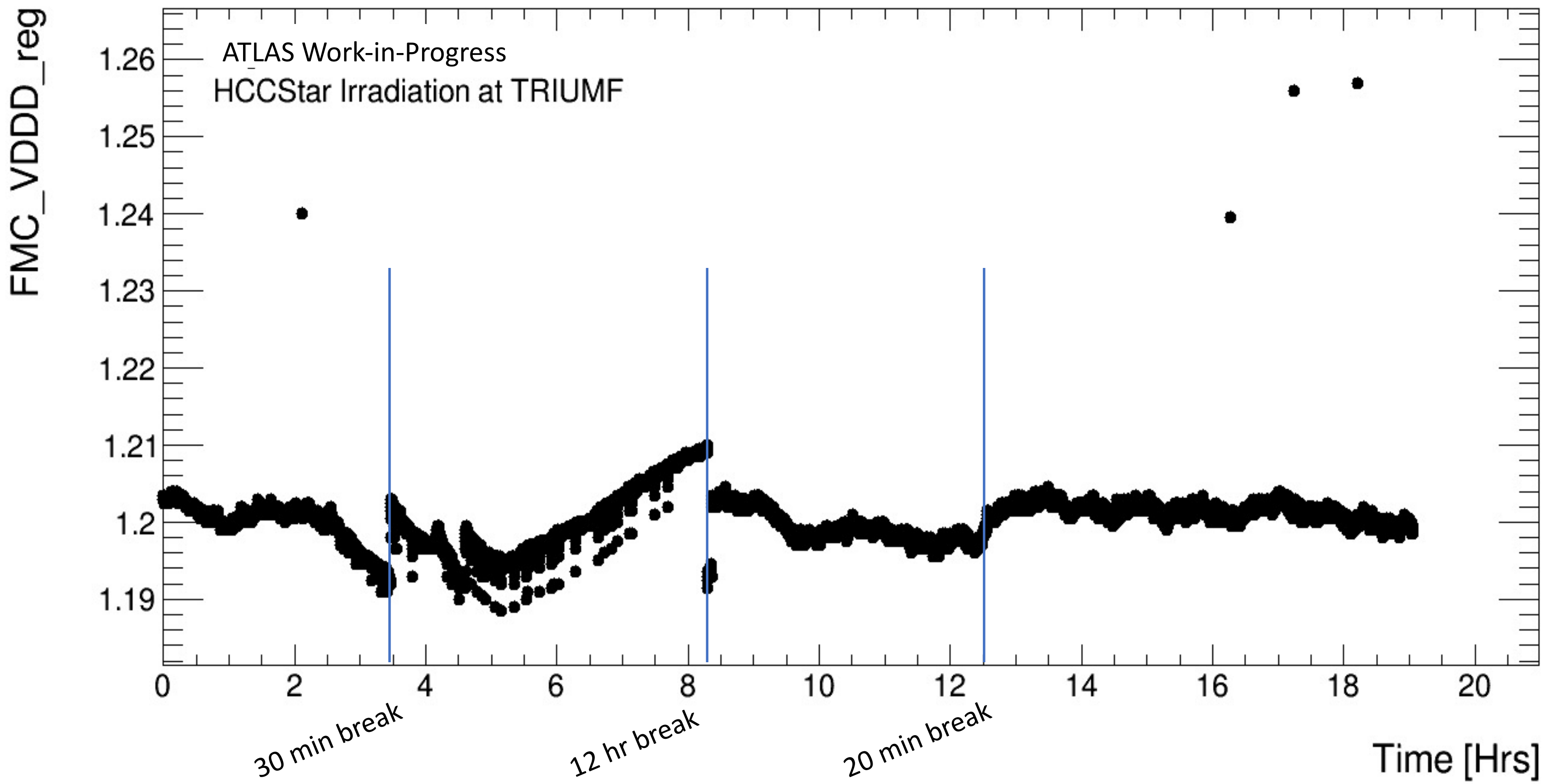
TRIUMF Results: Current vs TID

- The nominal current for the HCCStar is roughly 200mA
  - The current was observed to spike at 290mA at the TID peak



TRIUMF Results: Regulated Voltage vs TID

- The HCCStar voltage is regulated to be 1.2V
  - This was observed throughout the entire proton irradiation



Purpose of Proton Irradiation

- Large radiation doses are expected to alter the current/voltage draw of ASICs
  - Measure TID peak behaviors
  - Ensure the TID peak is still within safe/operable margins
- Measure the SEU cross section for proton irradiation
- Ensure HCCStar functions properly when hit with large amounts of radiation
  - Spoiler: Many things did not work

TRIUMF Results: SEU Cross Section

- Recently the results from TRIUMF were re-analyzed to try and unify the cross section calculation across the two data periods
- Key Differences in Setup:
  - Register default values are very close to 0x0
  - Many registers have similar/same default values
- What does this mean for SEU cross section calculation
  - It's difficult to determine if there is a register read problem or a true SEU
- Current event quality selection:
  - Reg17 (HCCID/eFuseID) was the correct value
  - Register value read out was NOT 0x0
  - The highest number of bit flips (double SEUs) in a given event is capped at 2
- Suggestions on how to proceed?

Heavy Ion Testing in Louvain

- Testing of SEE effects due to incident Heavy Ions was conducted at UC Louvain from Aug 28-29
- Louvain's facility capable of producing beams of 9 different Ions to irradiate the three ASICs being tested
  - HCCStar tested: ^{53}Cr, ^{26}Ar, ^{84}Kr, ^{124}Xe, ^{58}Ni

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Purpose of Heavy Ion Testing

- ASICs are expected to have different SEU cross sections depending on incident Ion
  - Each Ion has a characteristic Linear Energy Transfer (LET)
  - Higher LETs are expected to induce higher rate of SEUs
- **Goal**: Test many Ions on each chip to observe trend in SEU Cross Section vs LET

What Should We Expect to See?

- Studies done by NASA for their Proton Test Guideline have shown that the SEU cross section's dependence on LET is well modeled by:

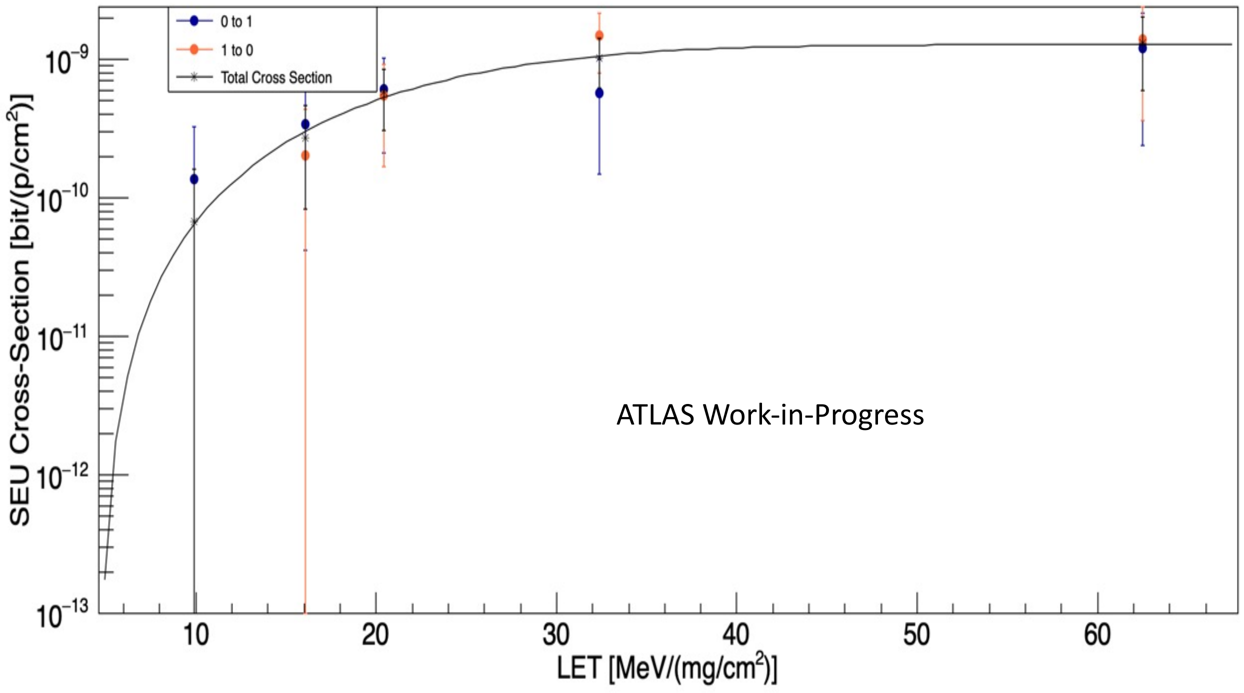
$$\sigma(E) = \sigma_0\{1 - \exp\left[-(\frac{E-E_0}{W})^s\right]\}$$

Where σ_0 is the saturated SEU cross section and E_0 is the minimum LET required to cause an SEU

HCCStar Heavy Ion Fit Results

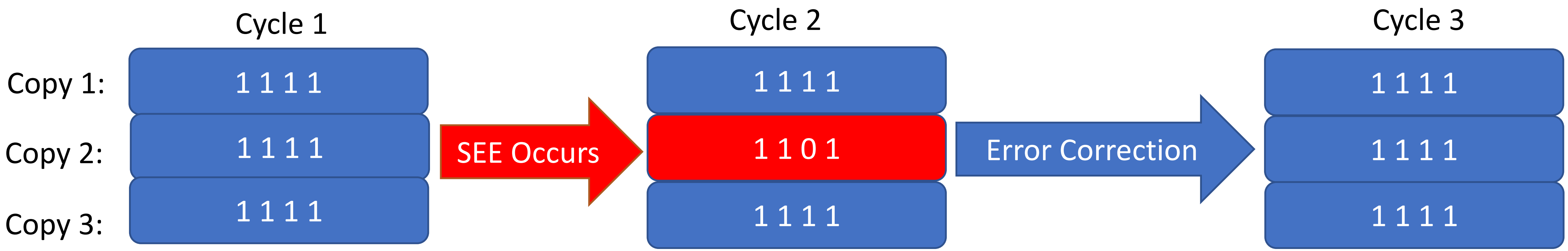
$$\sigma(E) = \sigma_0 \left\{1 - \exp\left(-\left[\frac{E - E_0}{W}\right]^S\right)\right\}$$

Fit Parameter	Total XS Fit Value	Uncertainty on Fit
σ_0 (Saturated XS)	$1.27 \times 10^{-9} \frac{\text{bit}}{\text{p}/\text{cm}^2}$	$7.7 \times 10^{-10} \frac{\text{bit}}{\text{p}/\text{cm}^2}$
E_0 (Threshold Energy)	4.63 MeV	17.5 MeV
W	21.24 MeV	16.56 MeV
S	2.13	3.27



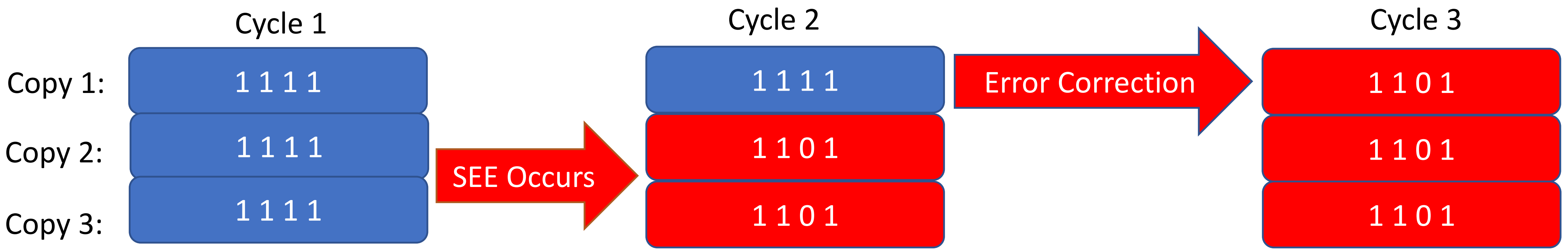
Error Correcting Code: Correctable SEUs

- Due to triplication, if a charged particle were to flip a single bit, the HCCStar would actively correct this problem
- On a given clock cycle, the HCCStar would notice a disagreement between copies of a given register
- Using a majority voting system, the incorrect bit would be fixed
- Since only one of the copies was corrupted, this error is completely <u>correctable</u>



Error Correcting Code: Uncorrectable SEUs

- If two copies of the same bit are flipped between cycles, it can lead to a change in majority
  - Termed “Double” SEU
- When we check what the value of this register is, we will now read out the wrong result
- In a real data collection environment, we don’t know what the “correct” value is, making this error <u>Uncorrectable</u>



Pictures of Setup!