Single Event Upsets in ATLAS SCT

Alex Dafinca, Jim Henderson & Tony Weidberg
(on behalf of the ATLAS SCT Collaboration)

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Single Event Upsets in ATLAS SCT

- Single Event Upsets (SEU) studied for ATLAS & CMS in test beams but this is first reported study of SEU in ASICs in LHC operation.
- Expectations for (SEU) from test beam data.
- SEU in SCT operation and comparisons with test beam
  - *p-i-n* diodes in TTC link.
  - DAC theshold registers in FE ASIC: ABCD.
- Mitigation for ATLAS operation.
- Mitigation strategy for SEUs at HL-LHC.

SEUs in SCT, how and where?

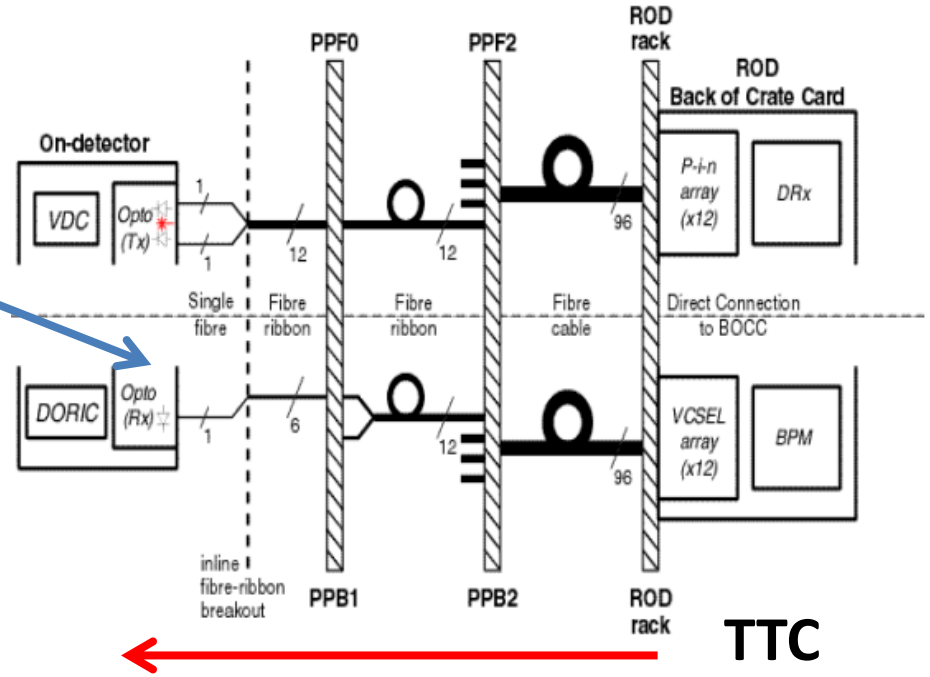
- Particles deposit sufficient charge in small region of silicon → bit error (SEU)
  - Typically needs nuclear interaction to deposit sufficient energy, i.e. MIPs are harmless.
- In *p-i-n* diode that receives optical TTC signal
  - Single bit error → loss of synchronisation of a FE module.
- In static registers in ABCD
  - Don't care about dynamic memory (pipeline) but static registers will stay wrong after an SEU until reset.
  - Look at effects in DAC threshold register.

SEU Studies

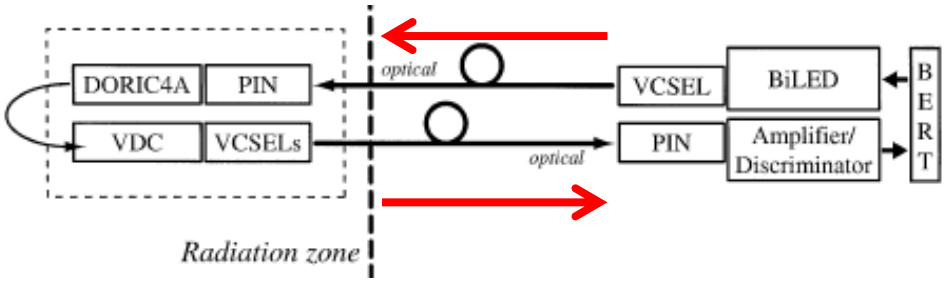
- Measure SEU rates for prototype in test beams:
  - Low energy π/p beams (mainly 200 – 500 MeV/c)
  - Extrapolate to LHC spectrum?
  - No synchronisation with beam bunches.
  - Angle of incidence.
- Measure actual SEU rates in ATLAS operation and compare with test beam based predictions.
  - Results shown for barrel SCT only.

SEU In SCT Optical Links

- On-detector *p-i-n* diode is Sensitive to SEU
  - Small electrical signal before amplifier stage.

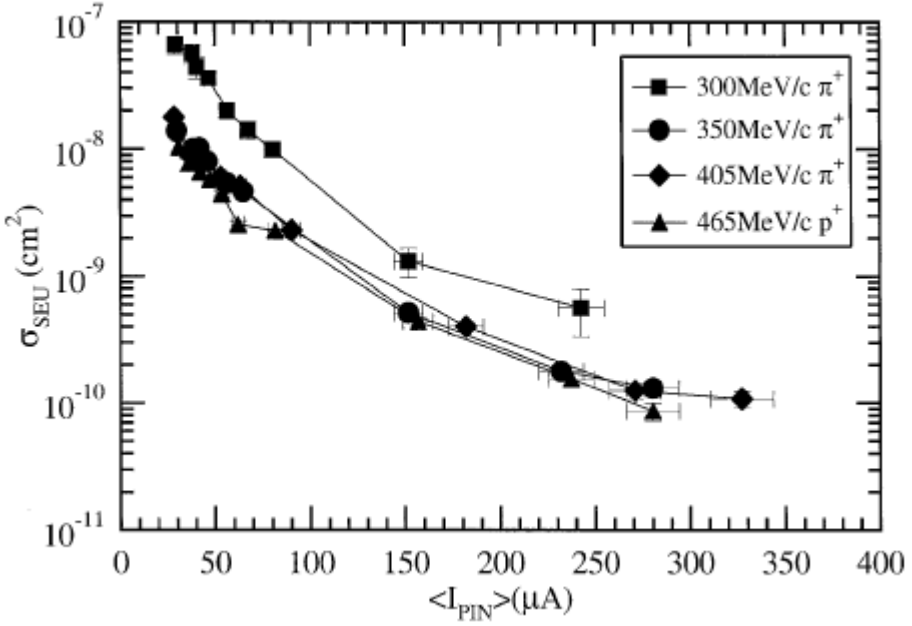


- Measure BER with loopback
  - With beam
  - Without beam
  - Difference ➔ SEU



SEU in *p-i-n* diode – Test Beam

- Measured SEU vs current in *p-i-n* diode I_{PIN} (simple loopback test) .
  - No errors with beam off.
  - No errors for MIPs.
  - Measured Bit Error Rate vs I_{PIN} with beam on.
  - ac coupled ➔ charge required to cause bit flip is proportional to I_{PIN} .
- σ higher for 300 MeV/c π because of Δ resonance ➔ large variation of σ with energy ➔ difficult to predict rates for LHC operation.



σ(SEU)=# bit errors/fluence

J.D. Dowell et al., Single event upset studies with the optical links of the ATLAS semiconductor tracker, Nucl. Instr. Meth. A 481 (2002) 575.

SEU in ATLAS Operation (1)

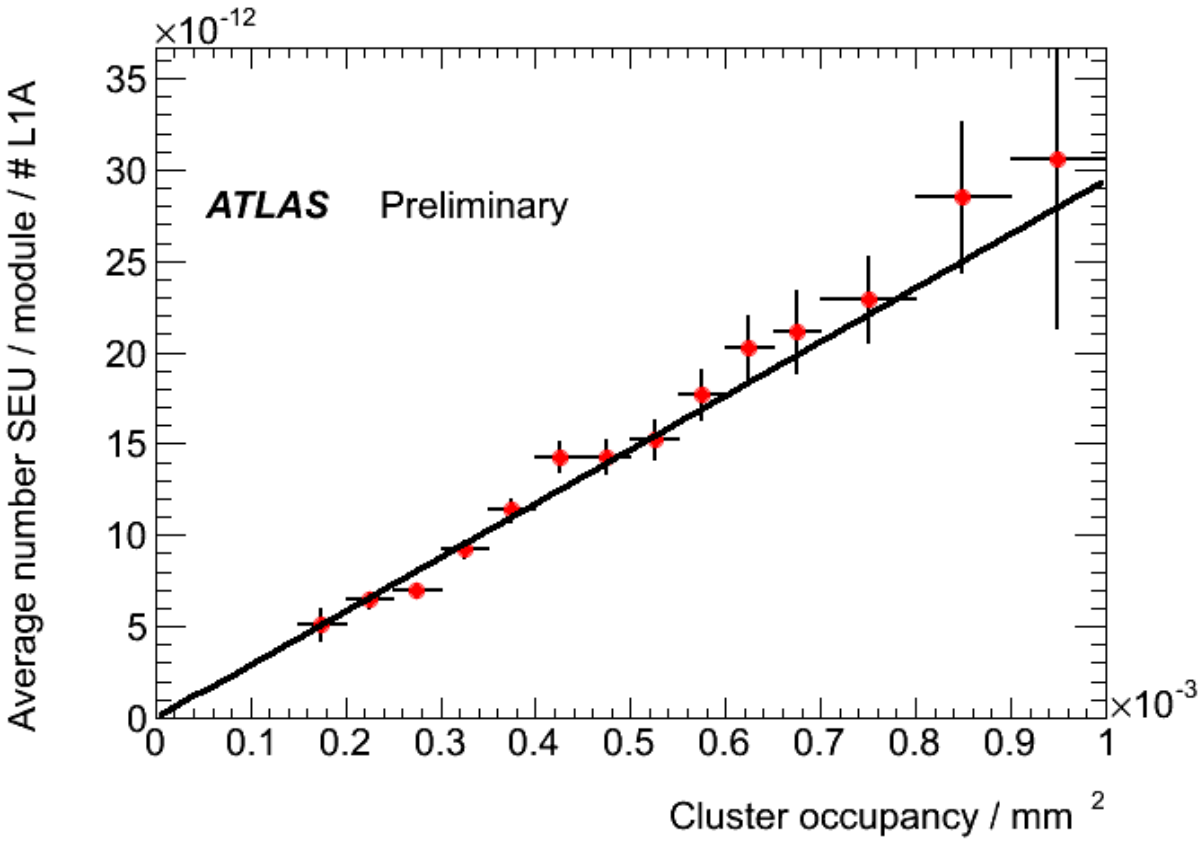
- *p-i-n* diode receives optical TTC signal.
- Indirect measurement BER
- Signature for SEU in *p-i-n* diode is loss of synchronisation for L1A trigger:
  - TTC sends
    - full L1A number to ROD: L1A(full)
    - L1A signal to detector FE via optical links.
  - On-detector 4 bit counter counts L1A and returns 4 LSBs in data stream: L1A(4)
  - SEU causes 0→1 can cause loss of L1A on-detector.
  - Compare L1A(full) with L1A(4). Persistent discrepancy is SEU.
- No errors seen in "physics mode" running with no beam ➔ suspect that these errors during beam are due to SEU.

SEU in ATLAS Operation (2)

- L1A signal is 110
- Short code vulnerable to single bit error (minimize latency).
- Assume 0→1 transitions more probable than 1→0 because of high value of I_{PIN}.
- Most probable error “110” ➔ “111”
- In ATLAS energy deposition synchronised to bunch crossing, unlike test beam
- Creates large uncertainties in extrapolating test beam cross section to ATLAS operation.

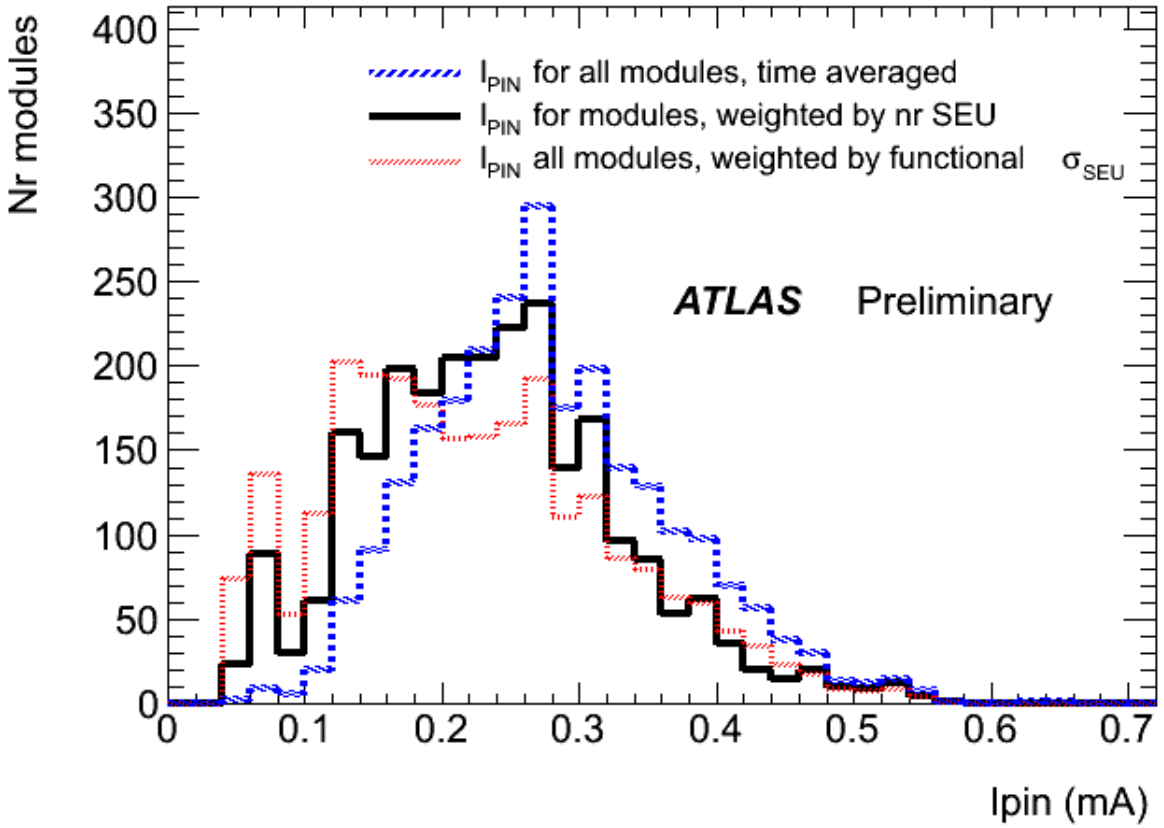
Are errors really SEU (1) ?

- SEU rate should scale with module occupancy (proxy for particle flux).
- Occupancy changes from luminosity variations and decreases as radius of barrels increase
- Shows expected linear behaviour



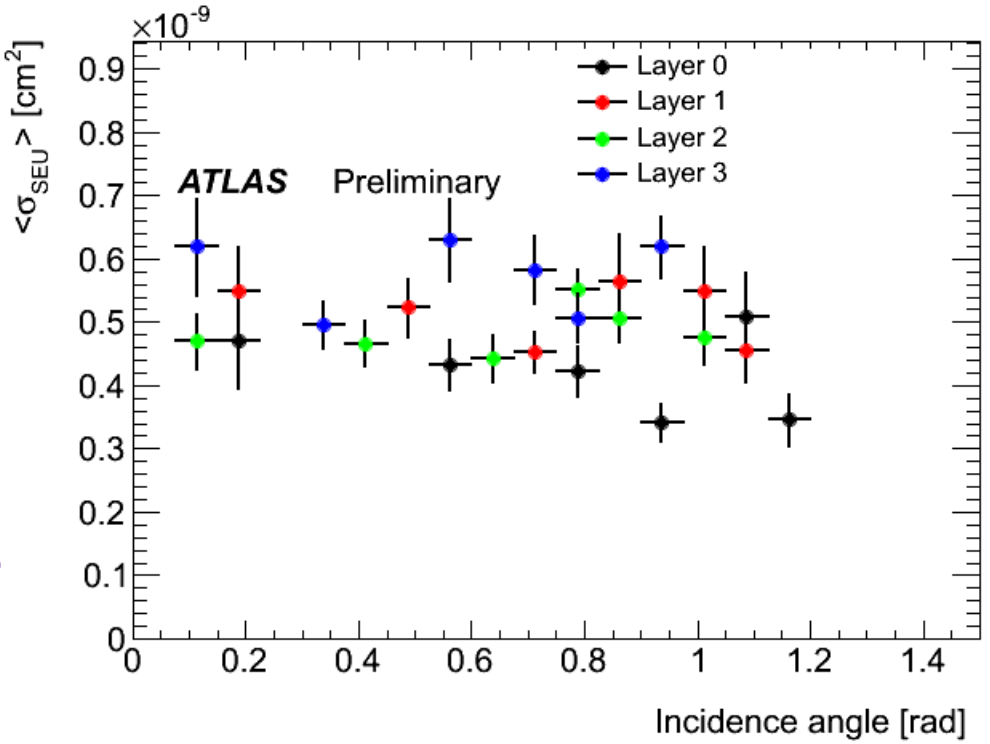
Are errors really SEU (2) ?

- **SEUs should be biased towards modules with low vales of $_{IPIN}$**
- **Compare:**
  - **All modules**
  - **Weighted by SEU**
  - **Model prediction based on exponential fit to test beam σ(SEU).**



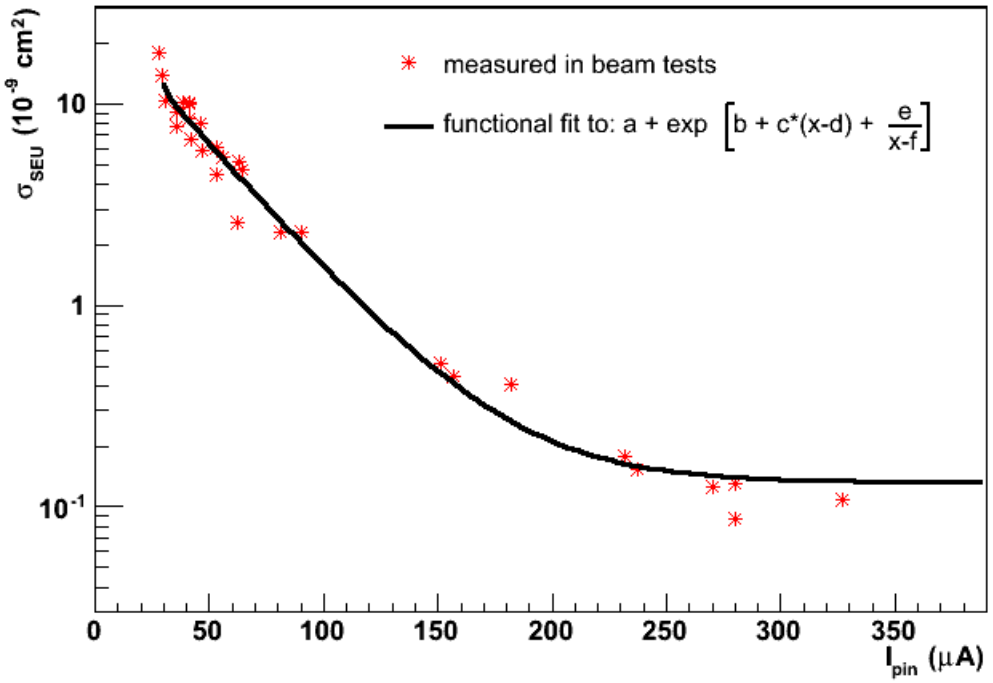
Angular Dependence?

- Normalise SEU rate by cluster occupancy (flux).
- Look at normalised rates vs incident angle in 4 barrel layers.
- No significant effect.
- Possible explanation:
  - High Ipin → large energy threshold for SEU → rate volume of active region (*p-i-n* diode is a micro-calorimeter).



Absolute Rates (1)

- Many uncertainties
  - Fit to σ(SEU) vs I_{PIN} (ignore data at 300 MeV/c)
  - Don't know how to make extrapolation to ATLAS particle spectra ➔ large uncertainty
  - Different beam conditions
    - ATLAS r/o synchronised to bunch crossings
    - Test beam asynchronous



Absolute Rates (2)

- Naïve prediction:
  - N(SEU) = σ(SEU) * Fluence
  - Ignore variation in σ(SEU) with LHC spectrum.
  - Corrected for variation of σ(SEU) with I_{PIN}.
  - Fluence: use <module occupancy>
  - Reject long SEU bursts (>60s) 13% uncertainty
  - Reject modules with multiple errors in one run: 5 to 6% bias.
- Number SEU in data set
  - Luminosity 7.81 fb^{-1}
  - Measured: 2504
  - Predicted : 1949
  - Good agreement within large uncertainties.

SEU in ABCD DAC registers

- **Test beam studies:**
  - **PSI 200 MeV/c π^+ angle of incidence 79°.**
- **No simple read/write test for registers in ABCD.**
  - **Indirect determination using mask register at o/p of pipeline.**
  - **Assume SEU rate in mask register same as DAC.**
  - **Measured 0 →1 errors but expect cross section for 1→0 to be larger (according to ABCD chip designer).**
- **Fluence/SEU = 3.7 10^{13} π/cm^2/SEU**
  - **Some batch to batch variations**

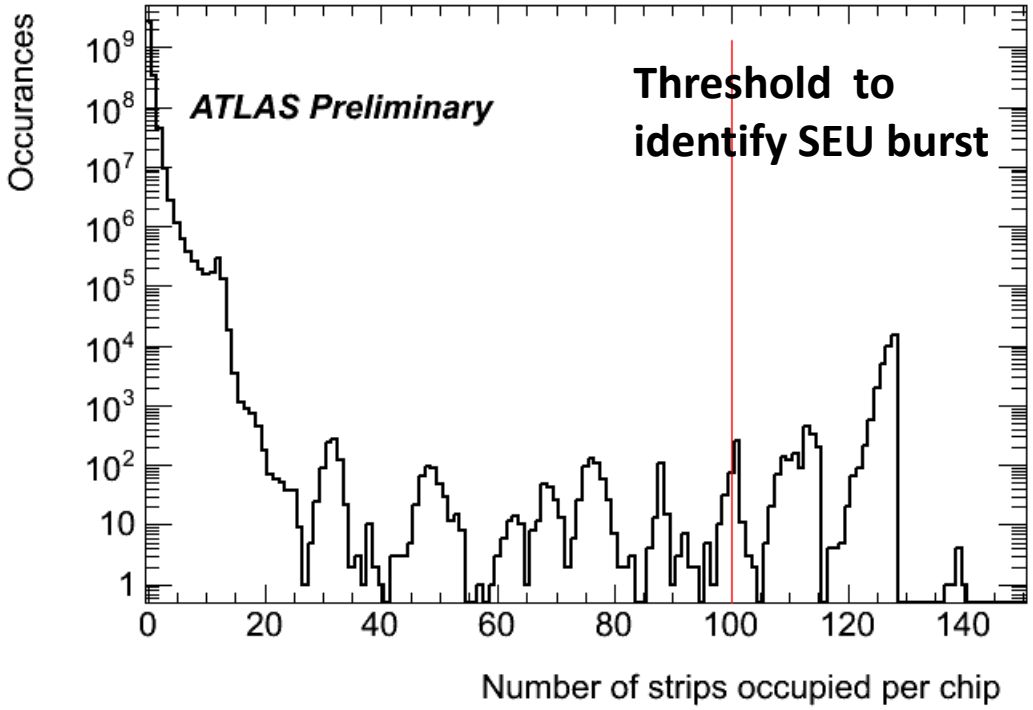
- L. Eklund et al., SEU rate estimates for the ATLAS/SCT front-end ASIC, Nucl. Instr. Meth. A 515 (2003) 415.

SEU in ATLAS Operation

- Indirect measure SEU.
- SEU in DAC threshold register change discriminator threshold for that ABCD:
  - (1) I→0 bit flip ➔ increase in chip occupancy
  - (2) 0→1 bit flip ➔ decrease in chip occupancy
  - In practice only sensitive to the 5th bit.
- Easier to look for effect (1) than (2).
- Effect should persist until module reset
  - Look for chips with persistently high occupancy.

Chip Occupancy

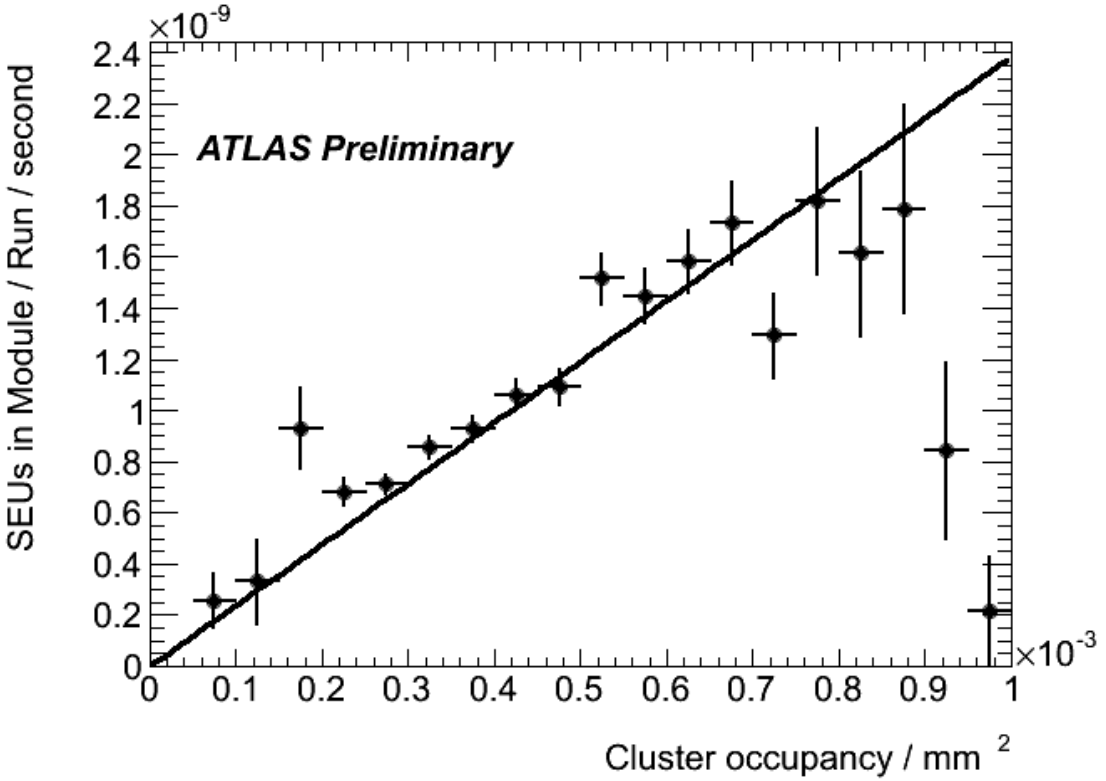
- 128 strips/chip
- Average over 10 events
- Mean occupancy very low as expected.
- Spike at 128 → every strip fires every event
- Also see rarer spikes from when all strips fire in 9 or 8 events (start or end of burst)



Note compressed log scale on y-axis
Vary threshold to identify start of burst but lower fixed threshold at 50 for end of burst.

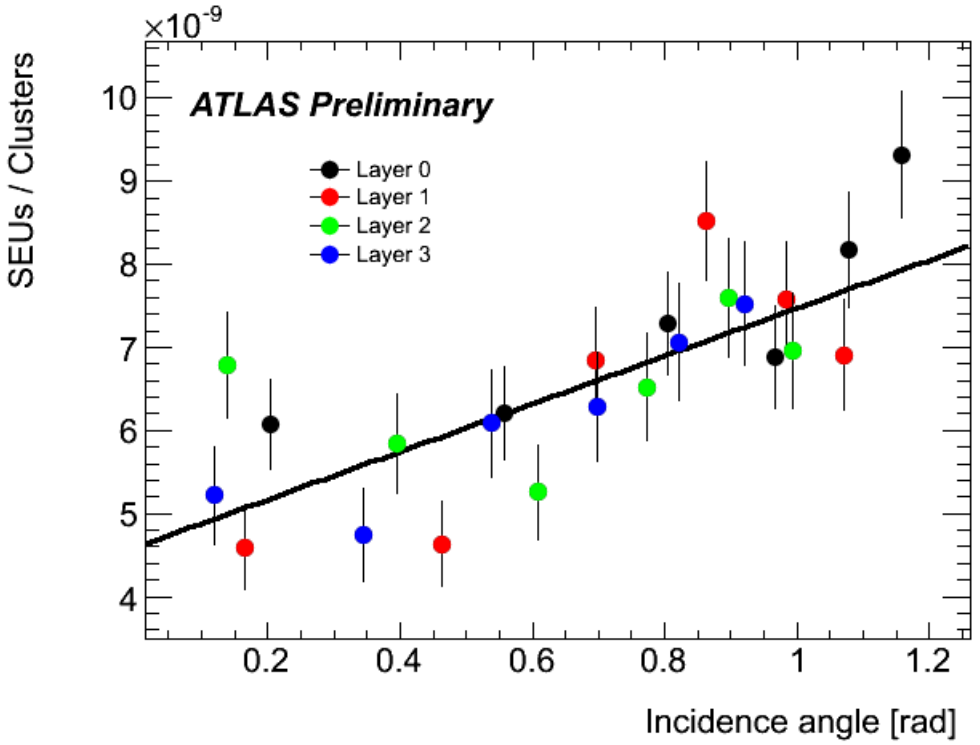
Are Errors Real SEU?

- Plot SEU rate vs chip occupancy per event (proxy for particle flux)
- See expected linear slope.



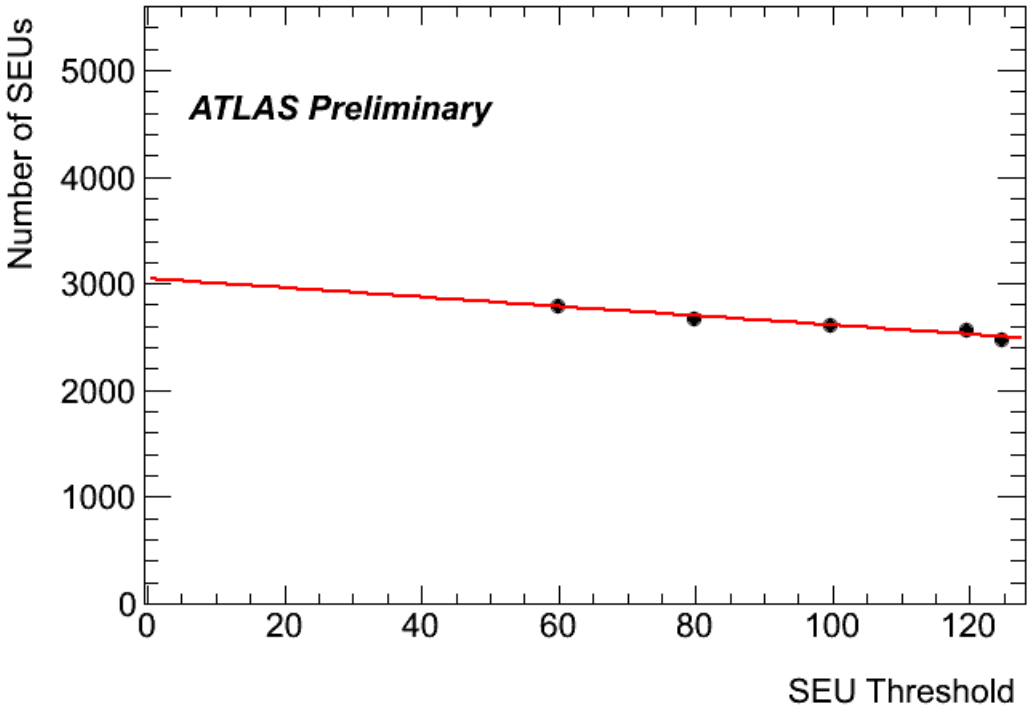
Angular Dependence

- Measure SEU/cluster occupancy vs incidence angle for barrel layers.
- See increase in rate with angle.
- Linear fit to compare PSI data at 79° with ATLAS data.



Absolute Predictions (1)

- Measure SEU rates as a function of threshold in number of hits/chip used to identify SEU bursts.
- Use fit to extrapolate to 0 threshold ➔measured # SEU.
  - 3% uncertainty from extrapolation.

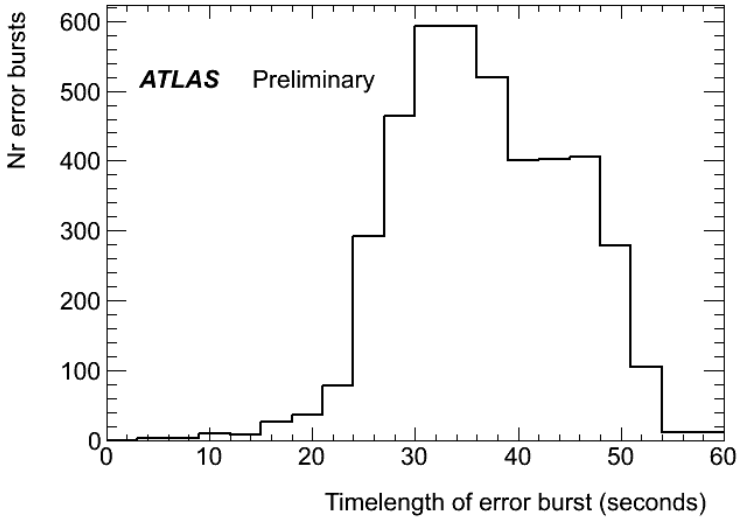


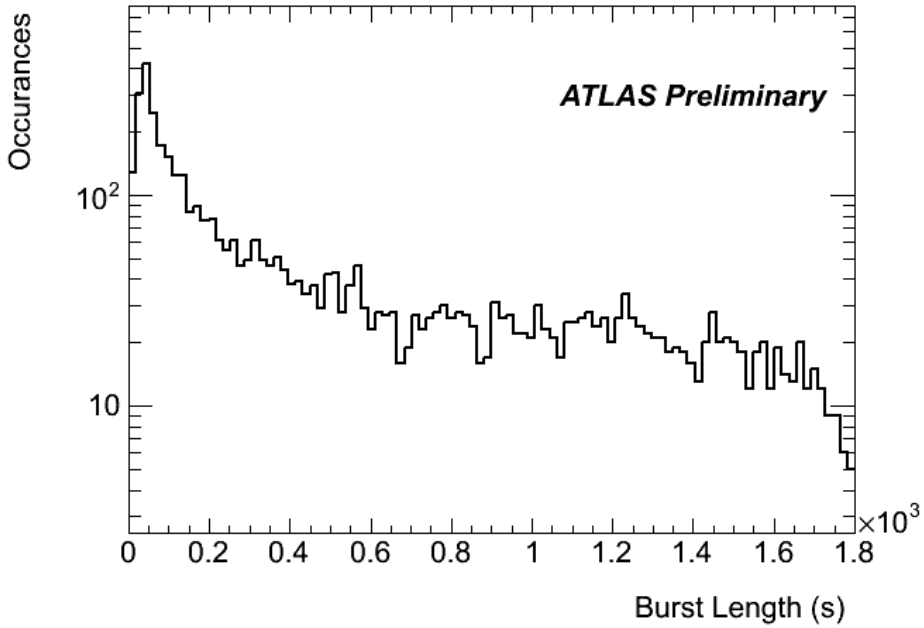
Absolute Predictions (2)

- Don't know how to scale σ(SEU) for π at 200 MeV/c to LHC spectrum ➔ large uncertainty
- Naïve model:
  - N(SEU) = σ(SEU) * Fluence
  - Fluence: FLUKA simulations scaled to luminosity
  - Results for inner barrel layer scaled to other layers using measured chip occupancies.
  - Corrected for angular dependence observed in data.
- # SEU in 23.4 fb^{-1}:
  - Measured: 3046
  - Predicted: 1090
- Understand rates to within a factor ~ 3.

Mitigation Strategies for ATLAS Operation

- SEU in TTC links
  - Use large values of I_{PIN} (> 100 μA) to reduce σ(SEU)
  - Reset pipeline in FE chips and all counters if this de-synchronisation detected by DAQ (20 to 50s).
- SEU in DAC register
  - Operator reset of module with high occupancy.
  - Full reset of all modules every 30 minutes.
- Mitigation strategies reduce effects of SEU to negligible level.



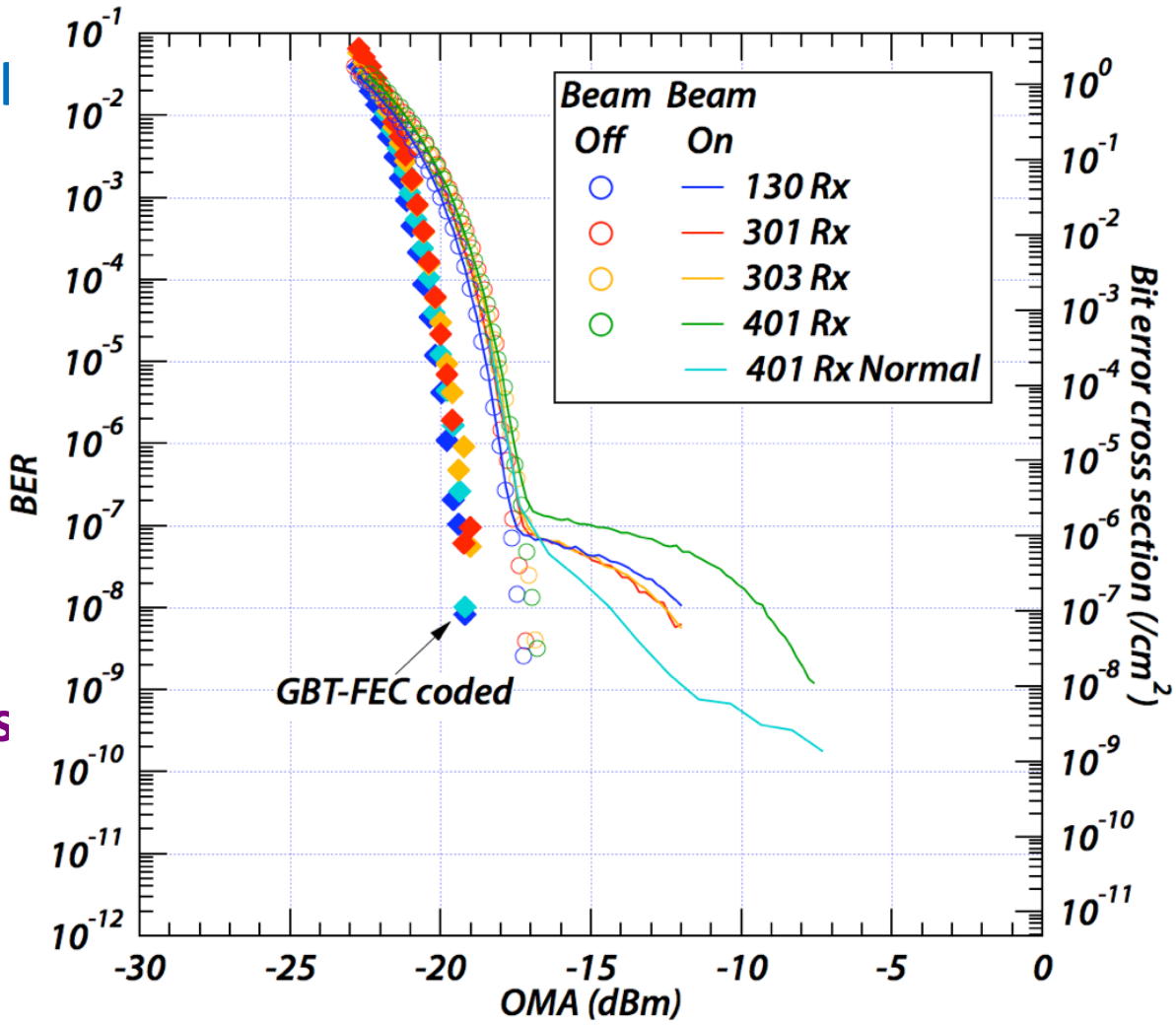


SEUs @ HL-LHC

- Expect SEUs to be more important @ HL-LHC because of higher Luminosity.
- What can we do to mitigate SEU?
  - Triple event redundancy in gates
  - Error correction on TTC link. P
  - Propose to correct for sequence of error bursts up to 16 bits long ➔ slide.

Versatile Link TTC SEU

- Measured BER vs optical power, Optical Modulation Amplitude (OMA).
- SEU killed by error correction (FEC)➔Error correction required for TTC links
- Tests to determine if it is also required for data



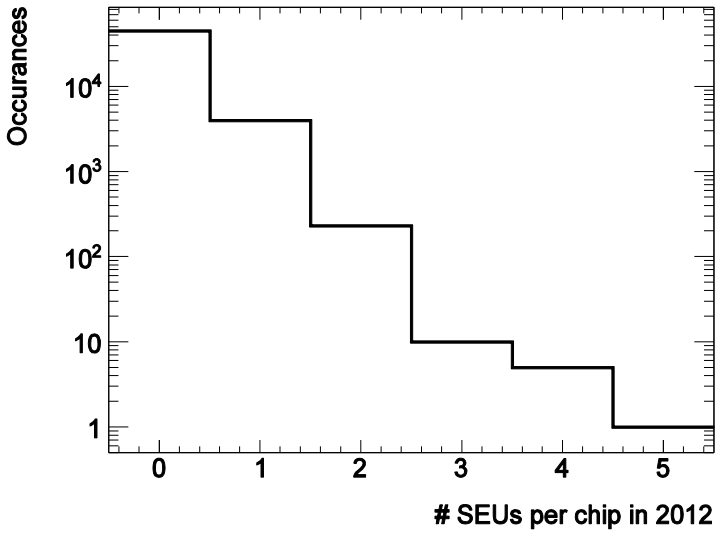
A. Jimenez Pacheco et al., Single-Event Upsets in Photoreceivers for Multi-Gb/s Data Transmission, IEEE Trans. Nucl. Sci., Vol. 56, Iss. 4, Pt. 2 (2009), pp. 1978 – 1986.

SEU Summary

- SEUs expected in SCT readout.
- Clear evidence of SEUs in ATLAS operation:
  - Predicted rates in ~ agreement with measurements.
  - Mitigation strategies work well.
- Mitigation strategies planned for HL-LHC should minimize impact of SEU.

Backup Slides

Number SEUs/chip



Burst Length SEU p-i-n