Studies of Beam Loss Effect on Silicon Strip Modules in ATLAS Detector

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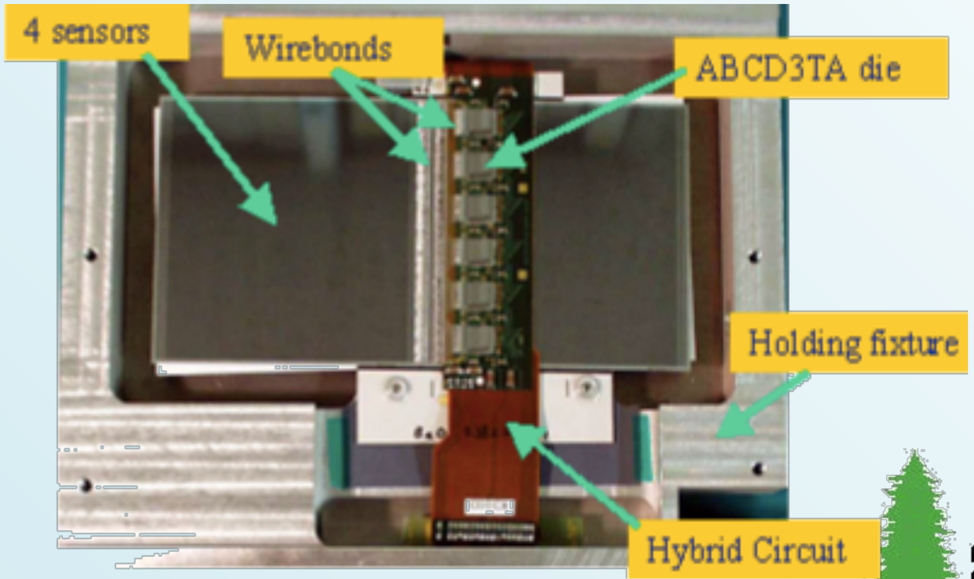
SCIPP - UCSC

Beam Loss Issues

- At design luminosity the LHC will contain ~10^{11} protons per bunch with a bunch spacing of 25 ns.
- If the beam becomes misaligned, it can scrape collimators or beam pipe, sending a spray of particles into the ATLAS detector.
- Before the beam loss monitors force a beam dump, the silicon strip detectors (the ATLAS SCT) may experience a large deposition of charge.
- Can this cause damage to the detector?



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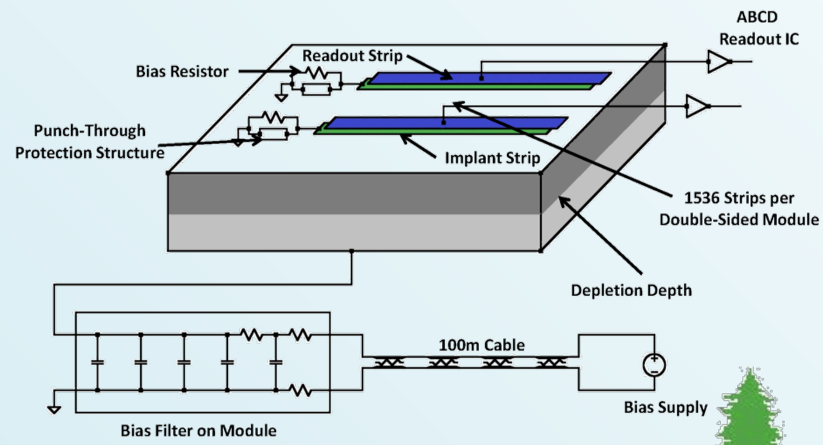
Vulnerabilities of the SCT Detector Module

- **Each SCT module is made up of the components shown in the picture below.**
- **All components inside the detector volume have been thoroughly tested for radiation hardness such that the extra radiation damage from a beam loss can be tolerated.**
- **Two components, however, may have a problem with a large instantaneous charge deposition.**
  - **A large current or voltage spike at the ABCD readout IC input may damage its first stage.**
  - **Large charge collection at the implant strip may cause breakdown of the coupling capacitor between the implant and readout strips.**
  - **Either may cause permanent damage.**

ATLAS SCT Module

Block Diagram



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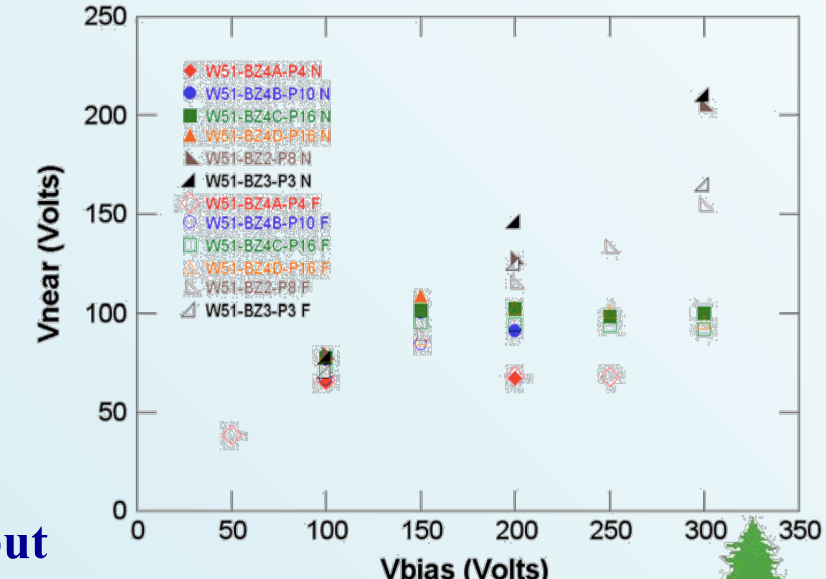
Previous Tests

- **Several tests have been conducted to test the limits of these two vulnerabilities:**
  - **The ABCD has an input spec limit of 450 V and 5 nC in 25 ns.**
    - **It was not clear how this compares to expected conditions of a realistic beam loss but this limit was tested on single channels and no failures were found up to the voltage limit & twice the charge limit. [1]**
  - **The dielectric forming the coupling capacitor between the implant strip and aluminum readout strip is spec'd to have a breakdown voltage ≥ 100 V. Exceeding this may cause the channel to fail.**
    - **Tests have been performed on sensor strips using lasers to emulate the charge deposition of minimum ionizing particles.**
    - **Voltages in excess of 100 V have been measured with charge deposition equivalent to ≥10^6 minimum ionizing particles (MIPs) per strip (spot size ~27 strips) without seeing breakdown, but damage has been seen at higher charge levels. [2,3]**



This Study

- This study attempts to incorporate the electrical contributions of the entire module and consider realistic beam loss scenarios with regard to expected charge deposition distributions.
- Given the difficulty in creating the expected high density spray of particles into a module, this study will rely on detailed simulations.
- However, the models we have used are based upon sensor and ASIC measurements we have made in our lab.

- This study is still in progress so the results are preliminary, however, they show some interesting features.

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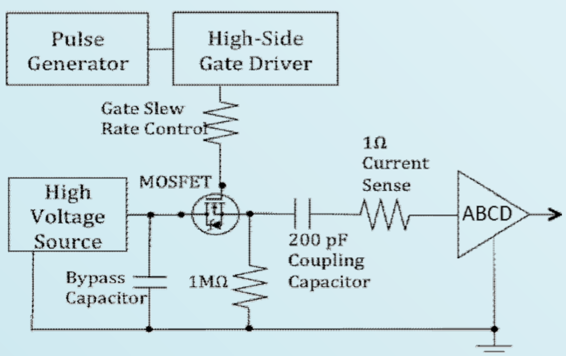
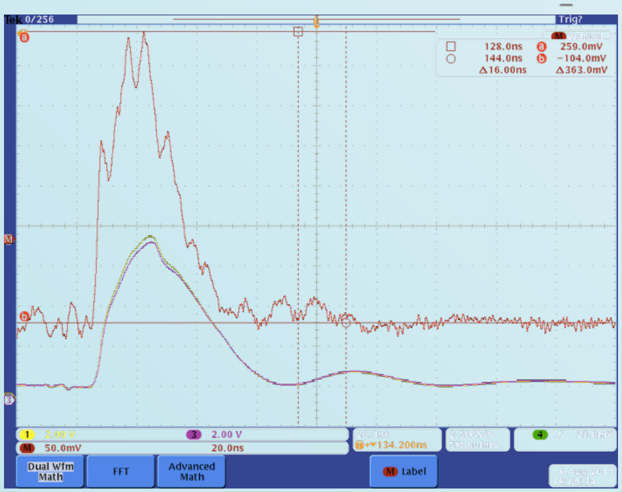
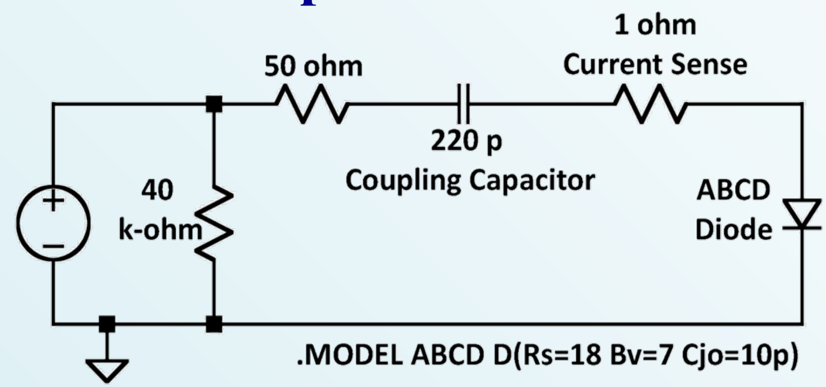
Tests & Simulations of ABCD Front-end

- **With the present ABCD IC, the base-emitter junction of the front transistor handles any excess current or voltage.**
  - **We then chose the simplest model to simulate the ABCD response, namely a diode with series resistance and breakdown voltage tuned to match the response we saw with our test setup.**

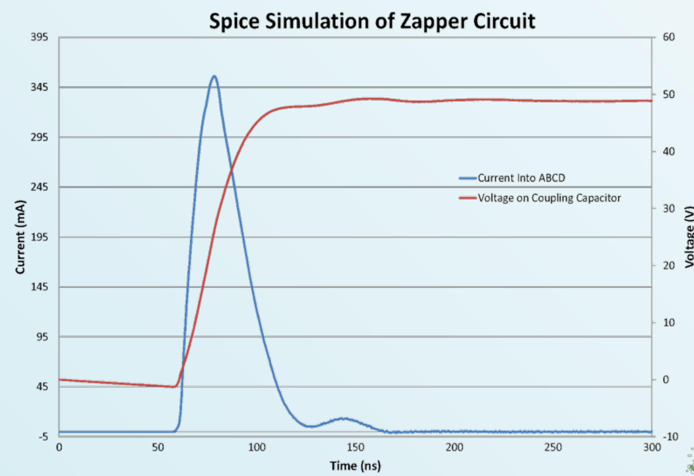


Tester to "Zap" ABCDs & Current Pulse into Front-end



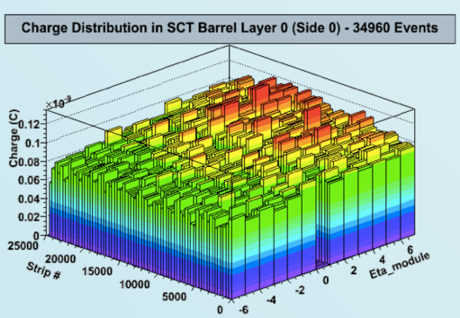


SPICE simulation of ABCD being "Zapped" & Current Pulse into Front-end

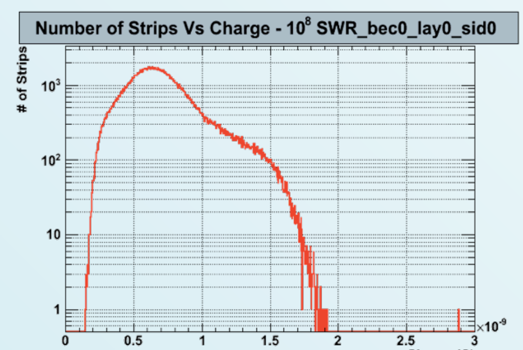


Expected Distribution of Charge Deposition

- **A group from University of Sydney has simulated the likely beam loss scenario as reported in an ATLAS note [4]:**
  - **They assumed 0.1% of the beam (10^8 protons) scraping the beam pipe or the TAS (Target Absorber Secondaries) collimator, tracking the resulting secondaries through the SCT.**
  - **The two plots below show the resultant distribution of charge across the inner SCT barrel for one beam bunch.**
  - **The charge deposition is fairly uniform; using a scale of 3.5 fC/MIP, their results equate to a distribution of incident particles ranging from ~0.4×10^5 MIPs to 0.5×10^6 MIPs with 0.2×10^6 MIPs most probable.**



7 TeV TAS collimator scrape scenario
for 35k fully simulated events



10^8 scaled sampling for 7 TeV TAS scrape scenario.
Plot of number of strips for given charge on Inner Barrel

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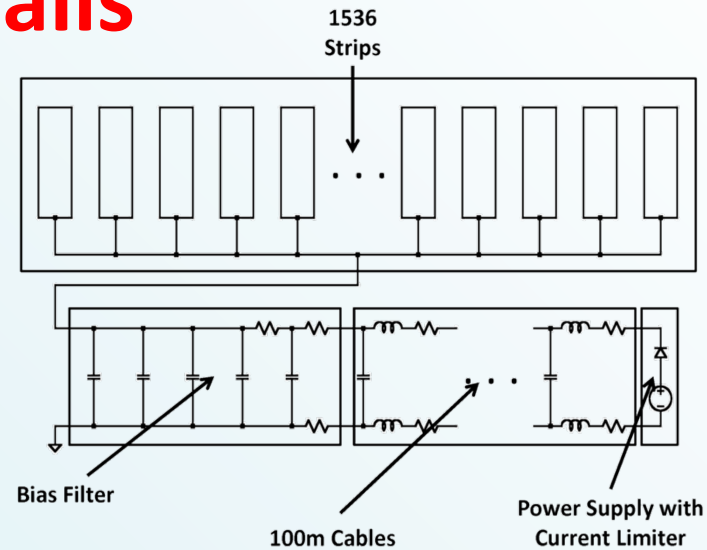
Beam Loss Timing

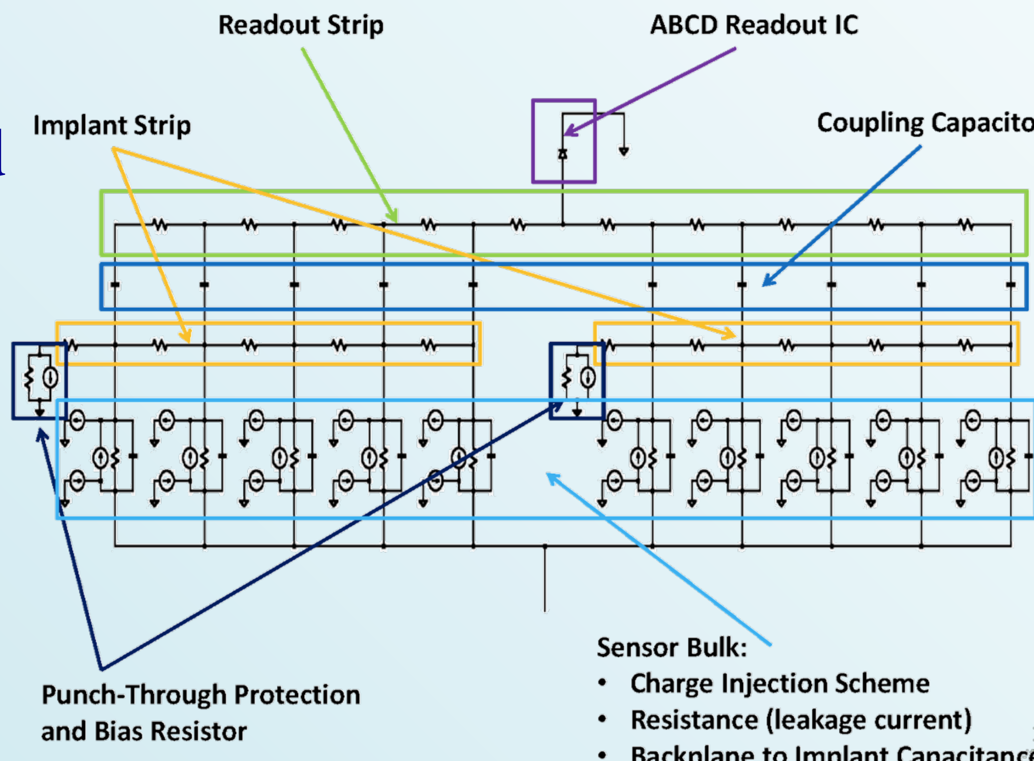
- An LHC bunch will pass every 25 ns with each bunch scraping the obstruction.
- Many timing sequences are possible.
- We assume for now a drift of the beam gradually scraping more of the bunch fringe until the beam abort is activated.
  - Then one cycle of the complete ring to send all bunches to the dump.
- An increasing number of MIPs will then hit a module every 25 ns until the beam is cleared, which takes ~90 µs.

Simulation Details

- We used SPICE to simulate the response of a full SCT module to such a beam loss scenario.



- Each strip was modeled as a distributed circuit using SPICE components.



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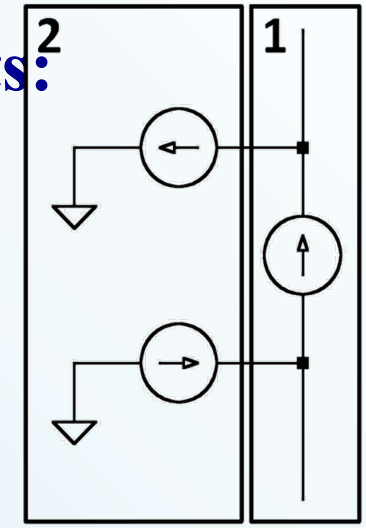
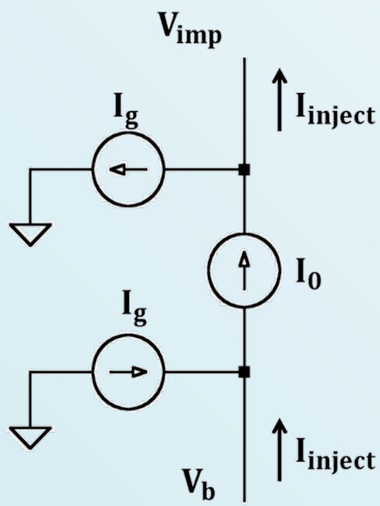
Details of Sensor Behavior are Included

- **The charge injection scheme has two components:**
  - **Component 1 models the timing structure of the beam.**
  - **Component 2 models the dependence of the charge collection on the bias voltage.**



  - **For bias voltages below the full depletion value, the amount of collected charge decreases due to smaller depletion depth.**

- **Also, charge collection time increases with increasing deposition as $Q^{1/3}$.**



For $(V_b - V_{imp}) > V_{fd}$:
-> $I_{inject} = I_0$
->$I_g = 0$

For $(V_b - V_{imp}) \leq V_{fd}$:
-> $I_{inject} = I_0\sqrt{(V_b - V_{imp})/V_{fd}}$
->$I_g = I_0 - I_{inject}$

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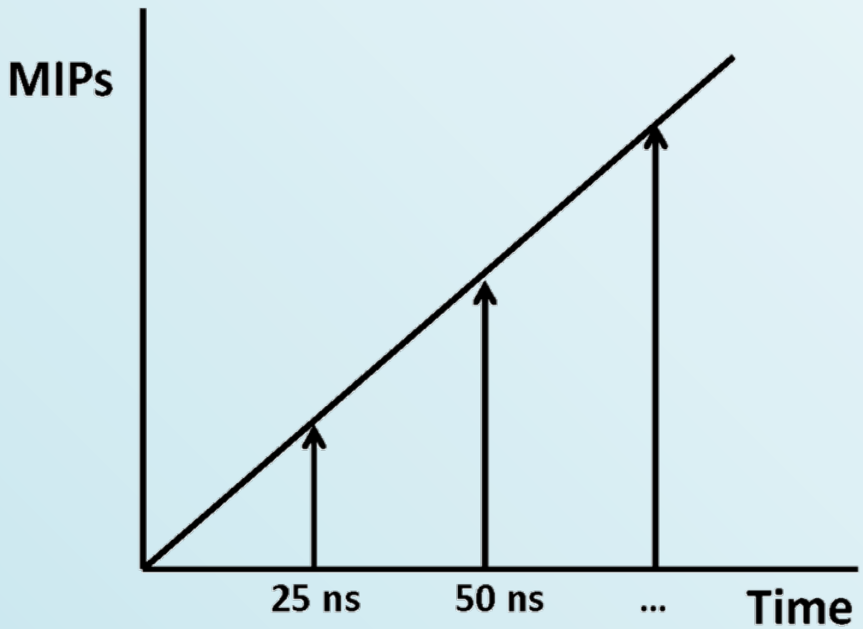
Simulation Sequence

Assumptions -> Maximum charge collected per strip = 2 nC = 5.4 $* 10^5$ MIPs
-> Beam loss occurs linearly over various time profiles (100 ms, 10 ms, … , 0.01 ms)
-> Bunch spacing is 25 ns



Every 25 ns:

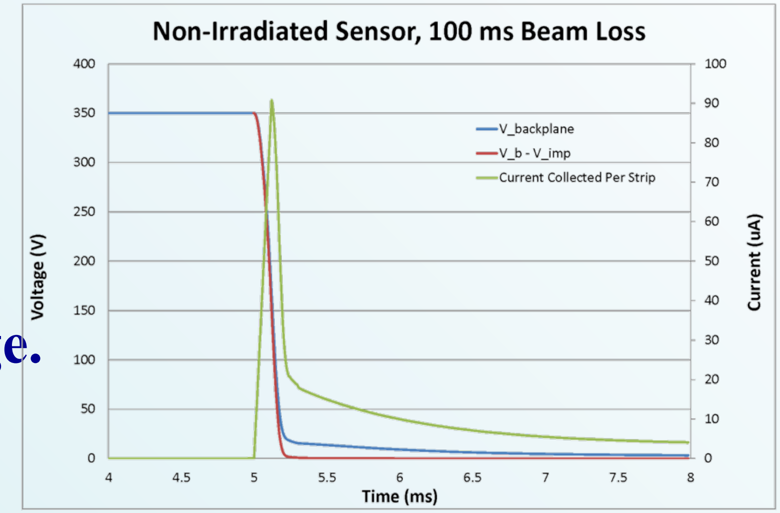
- Read number of MIPs, $MIPs$
- Calculate corresponding charge, Q
- Calculate charge collection time, t_{cc}
- Calculate average current, $I_{avg} = Q/t_{cc}$
- Add I_{avg} to existing value in each time bin
- Result : Array with each index corresponding to a time in the simulation, and the array value corresponding to the total current at that time.
- Use this array to print a PWL file

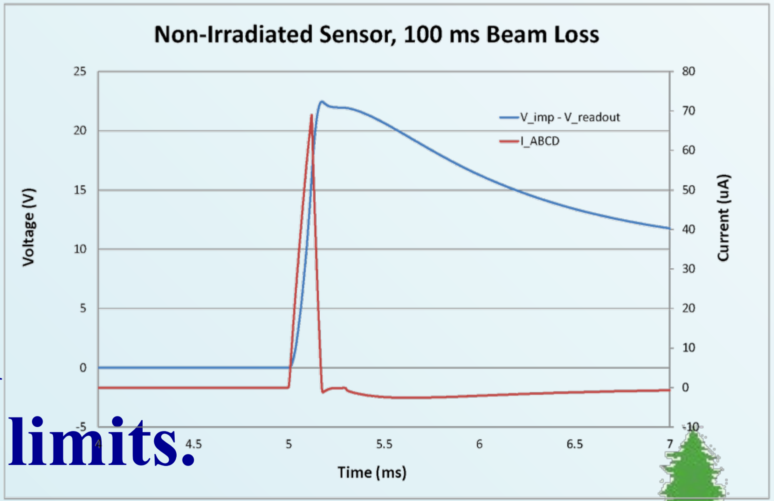
$$Q = MIPs * 80\frac{e^-}{\mu m} * 289.5\ \mu m * 1.6 * 10^{-19}\frac{C}{e^-}$$

$$t_{cc} = 10\ ns\ * \sqrt[3]{MIPs}$$

Electrical Response of Module to "Slow" Beam Loss

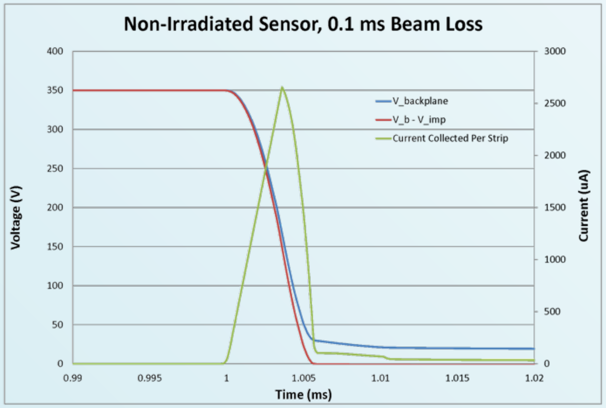
- **Simulation results for beam loss and dump in 100 ms reaching a peak of 0.54×10^6 MIPs/strip/25ns.**
  - **Note that the bias voltage quickly drops as the charge is injected.**
  - **This is because the capacitance of the bias filter is depleted of charge and the power supply cannot maintain the voltage.**
  - **This drop in bias voltage and field shielding by the large amount of charge deposited greatly limits the charge collection.**

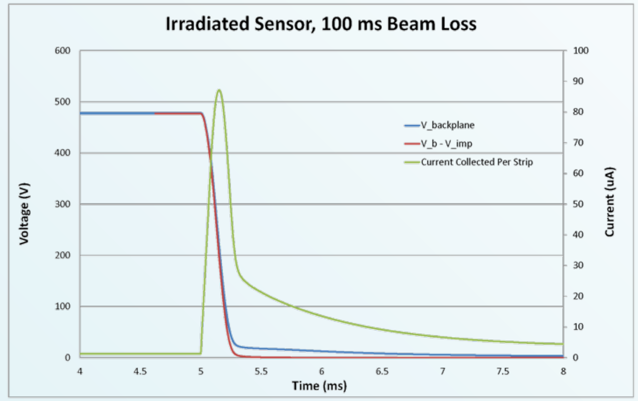


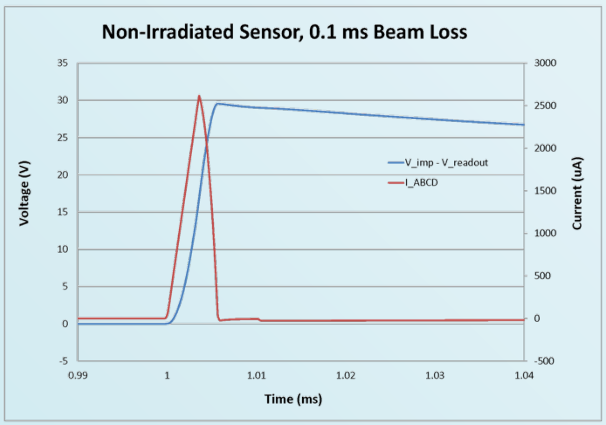


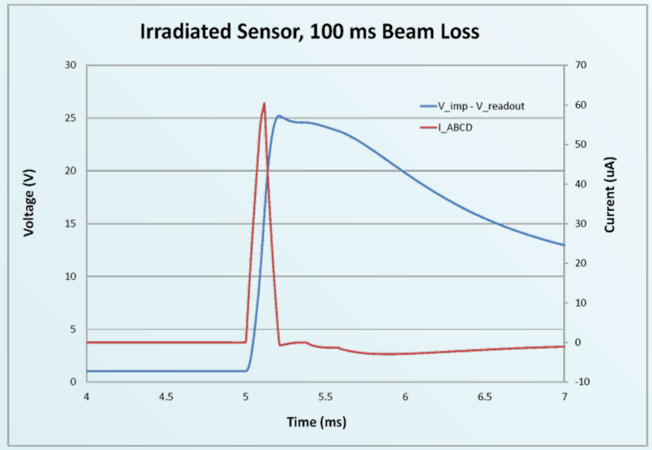
- **The voltage across the coupling capacitor remains < 25 V and the ABCD input current remains <70 µA (1.8 pC/25 ns) – both well below spec limits.**

Electrical Response for Two Other Conditions









0.1 ms Scenario **100 ms Scenario with Irradiated Sensor**

- **Even with a 0.1 ms scenario, the bias still drops quickly enough to limit the charge collection keeping the coupling capacitor voltage and ABCD current within a safe range.**

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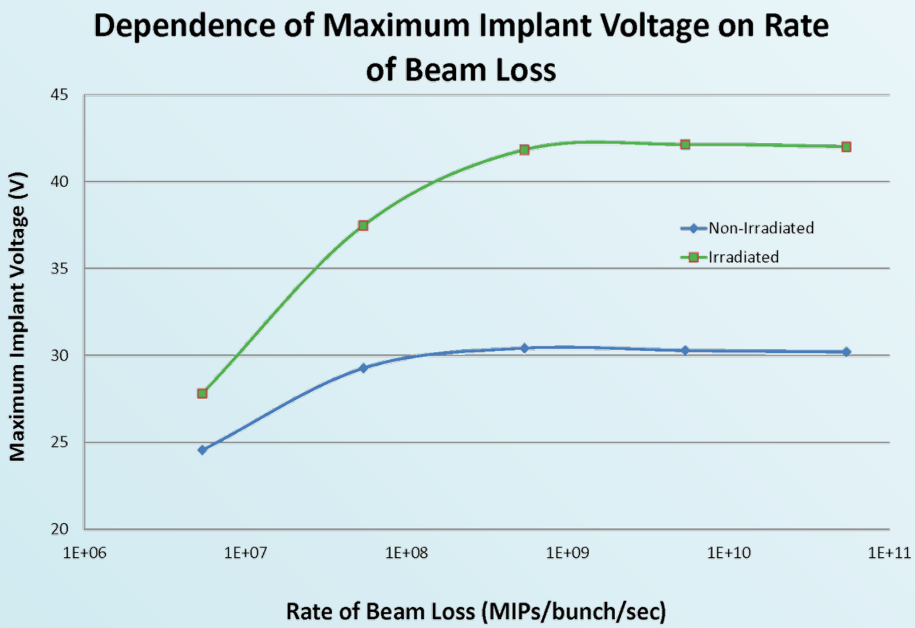
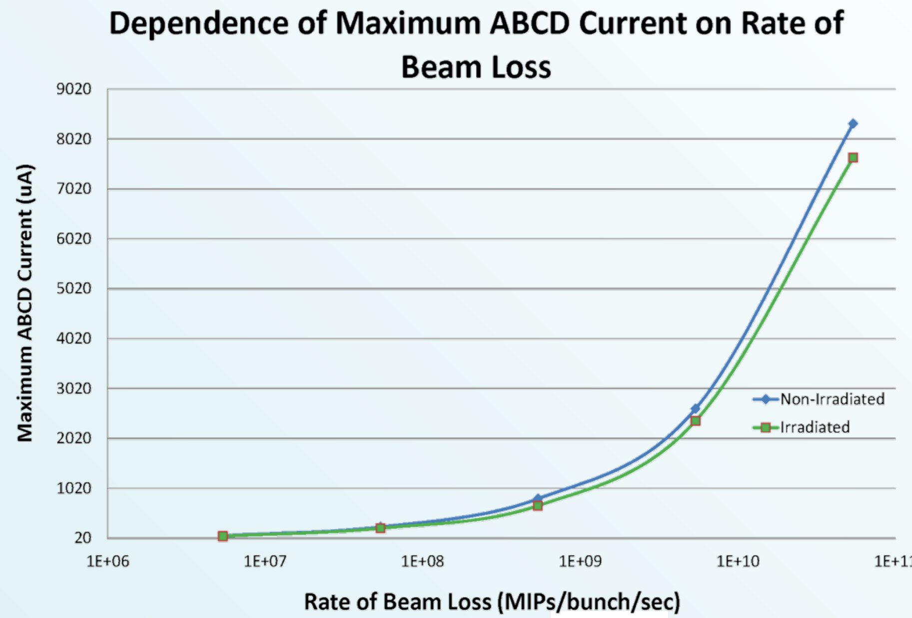
Electrical Response for Several Time Evolutions

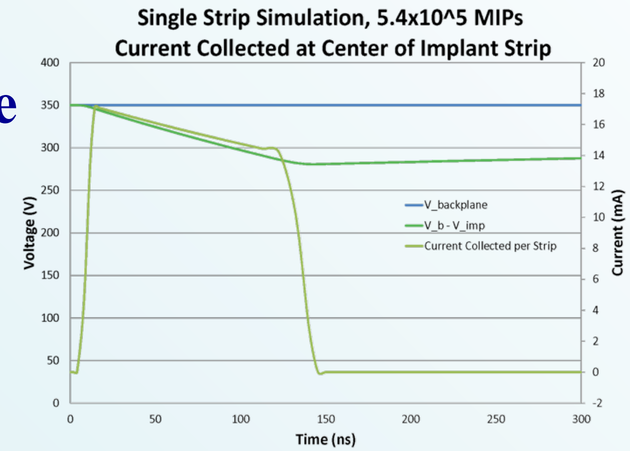




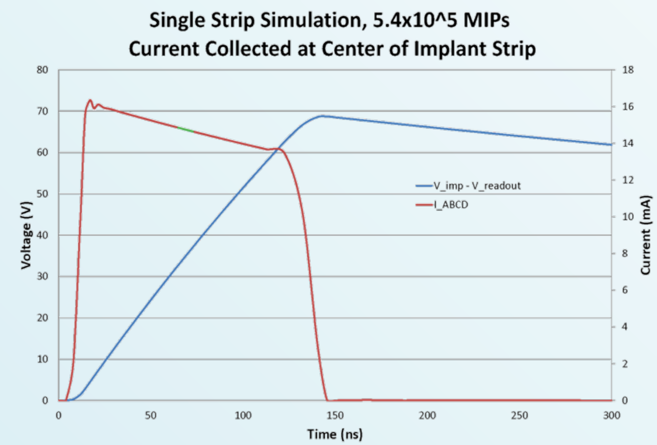
- **These plots show the electrical response of the module for the same peak loss of 5.4×10^5 MIPs/bunch but varying the speed at which the loss evolves.**
  - **The data points span full evolution times of 100 ms to 0.01 ms**
- **Even with the fastest rate, the implant voltage and the ABCD input current remain in very safe ranges.**

Careful if Limiting Charge Deposition to One Strip

- Here are the results of simulating a laser pulse hitting a single strip with the same intensity.
  - Note that the backplane voltage (blue curve above) does not decrease and the effective bias voltage (green curve above) only decreases slightly since the implant voltage is increasing.

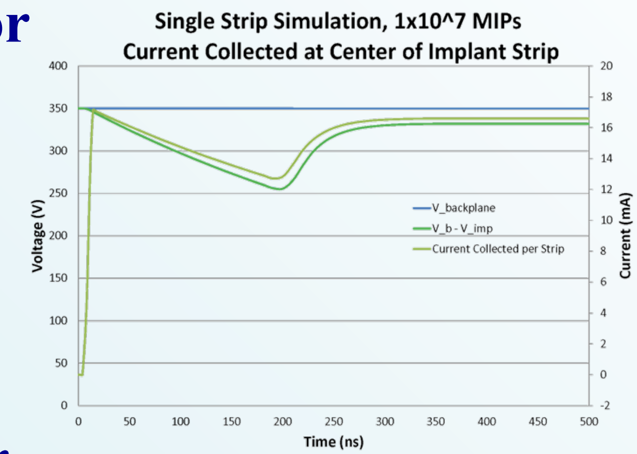


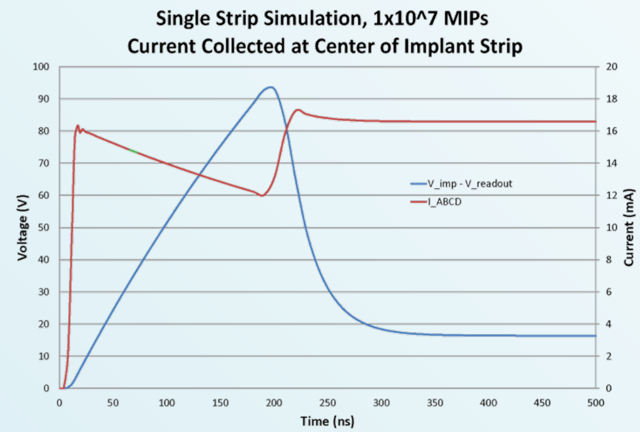
  - The voltage across the coupling capacitor (blue curve below) now reaches 70 V (> 2x the full module case) and the ABCD input current (red curve below is 6x greater.



Larger Charge Deposition onto One Strip

- **Here is the case of $1x10^7$ MIPs on one strip.**
  - **Now the voltage across the coupling capacitor (blue curve below) exceeds 90 V and the ABCD input current (red curve below) reaches 17 mA – still within spec limits but much closer to the maximum allowable.**
  - **Actually, the voltage across the coupling capacitor would have reached a much higher voltage but the simulation included a model for capacitor breakdown at 100 V, which activated.**
    - **We're not sure why the voltage appears to limit at 90 V instead of 100 V. This needs further study.**





Conclusions & Continuing Work

- We expect beam loss scenarios to deposit large amounts of charge across the entire sensor.
- Depending upon the time evolution, this distribution of charge results in several mitigating phenomena:
  - Charge collection time increases.
  - Bias voltage decreases due to the finite charge stored on the filter capacitors and to the 2 mA current limit of the the bias supply thus reducing the amount of charge collected.
- Depending upon the time evolution of the beam loss, the resulting module response may provide some self-protection.
- Subjecting only a small number of strips to large charge deposition may show very different results. Are they realistic?
- More variations of beam loss intensities along with time evolutions must be simulated to search for limits of safe operation.
- Upgraded detectors must take care with biasing so as not to lose these self-protection aspects of the full system.

References

1. A. Kuhl, V. Fadeyev, A.A. Grillo, F. Martinez-McKinney, J. Nielsen, E. Spencer, M. Wilder, ATLAS ABCD hybrid fatal charge dosage test, 2011 JINST 6 C12021.
2. H. F.-W. Sadrozinski *et al.*, Punch-through protection of SSDs, *Nucl. Instrum. Meth*ods A699 31 (2013).
3. K. Hara *et al.*, Beam splash effects on ATLAS silicon microstrip detectors evaluated using 1-w Nd:YAG laser, *Nucl. Instrum. Meth*ods A541 15 (2005).
4. N. Patel *et al.*, Charge deposition in the SCT due to beamloss, ATLAS Note ATL-INDET-PUB-2013-002.