Simulation of the ATLAS SCT Barrel Module Response to LHC Beam Loss Scenarios

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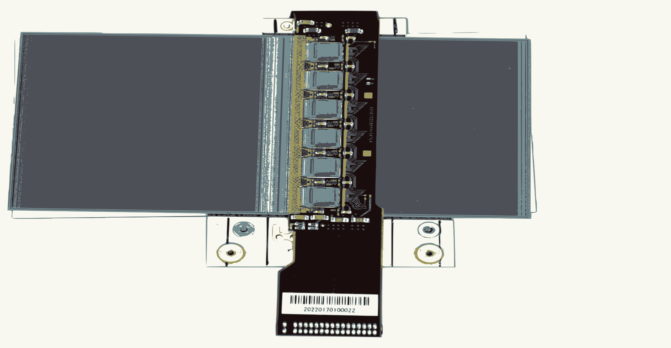
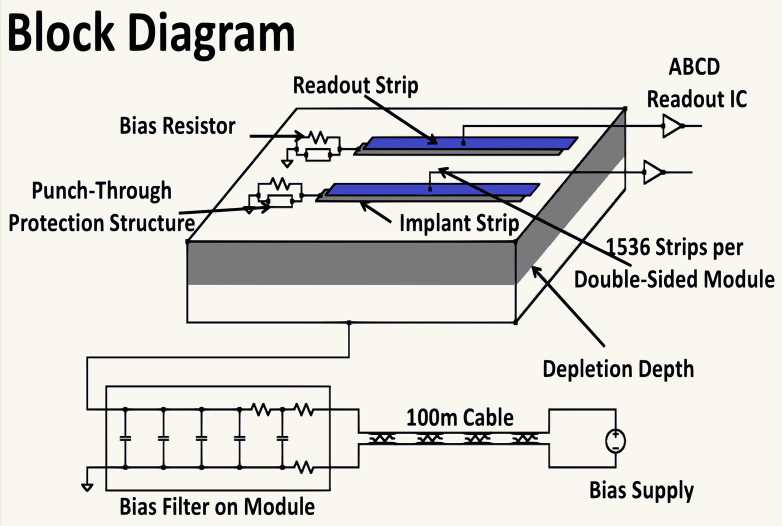
Abstract:

In the event of beam loss at the LHC, ATLAS Inner Detector components nearest the beamline may be subjected to unusually large amounts of radiation. Understanding their behavior in such an event is important in determining whether they would still function properly. We built a SPICE model of the silicon strip module electrical system to determine the behavior of its elements during a realistic beam loss scenario. We found that the power supply and bias filter characteristics strongly affect the module response in such scenarios. In particular, the following self-limiting phenomena were observed: there is a finite amount of charge initially available on the bias filter capacitors for collection by the strips; the power supply current limit reduces the rate at which the bias filter capacitors' charge can be replenished; the reduced bias voltage leads to a smaller depletion depth which results in less collected charge. These effects provide a larger measure of safety during beam loss events than we have previously assumed.

The ATLAS SCT Barrel Module:

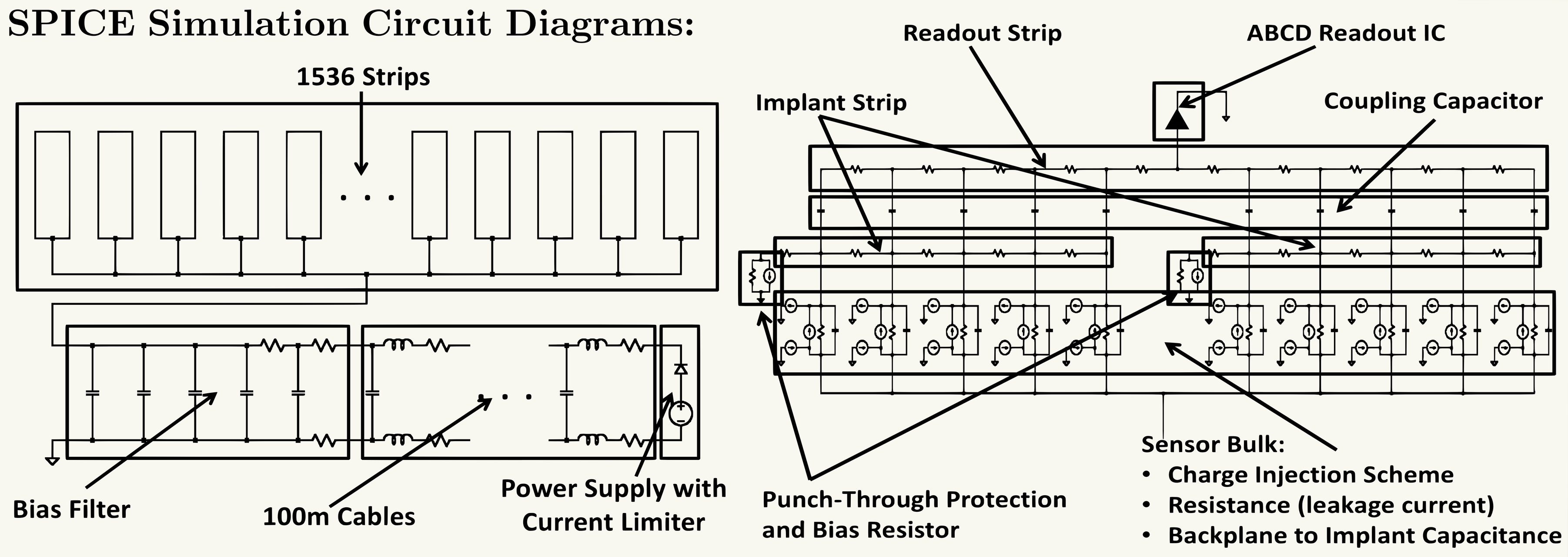


Block Diagram



The ATLAS [1] SemiConductor Tracker (SCT) is one component of the ATLAS Inner Detector, which tracks charged particles resulting from proton-proton collisions at the LHC. The SCT contains both barrel [2] and endcap regions, with 2112 modules comprising the barrel region. There are four silicon strip sensors per double-sided barrel module, each containing 768 individual strips. The strips on each side of a given module are daisy-chained together on the readout electronics to make an effective combination of 1536 12-cm strips per module. Previous simulations have shown that during the most likely beam loss scenarios, the SCT barrel modules may experience a large particle flux of up to 5.4 x 10^5 MIPs per strip per bunch crossing [3]. 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. However, both the ABCD readout IC [4] and the coupling capacitors between the implant and readout strips may experience problems from a large instantaneous charge deposition. The ABCD is rated to handle up to 5 nC in 25 ns, but previous tests have shown that it can withstand at least twice that amount [5]. The coupling capacitor is rated to 100 V, but again, higher values have been observed with no apparent damage [5,6]. However, since all sensors have only been systematically tested up to 100 V, this is still considered the safe limit. Here, we simulate the response of the ATLAS barrel modules to the most likely beam loss scenarios to determine which further tests, if any, need to be performed, and we determine what conditions are necessary to exceed the safe operating conditions.

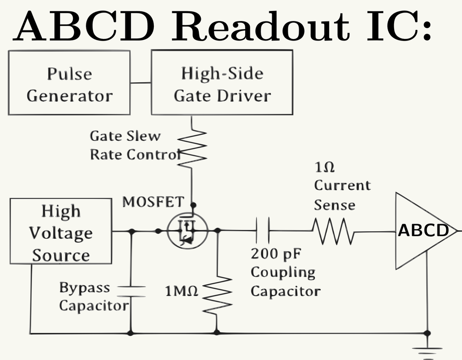
SPICE Simulation Circuit Diagrams:



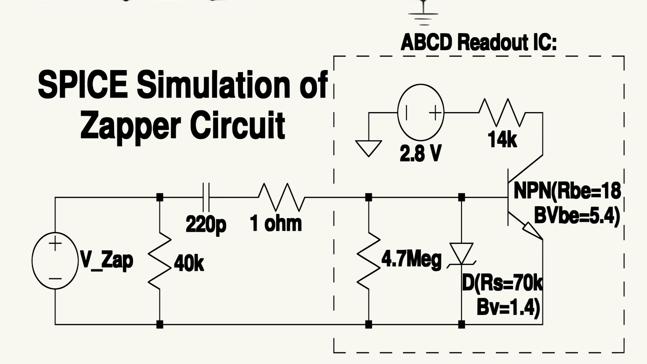
Each strip was modeled as a distributed circuit. We simulated 1536 individual strips, plus the power supply, cables, and bias filter. Component values are based on measurements of four production SCT sensors at our SCIPP sensor lab.

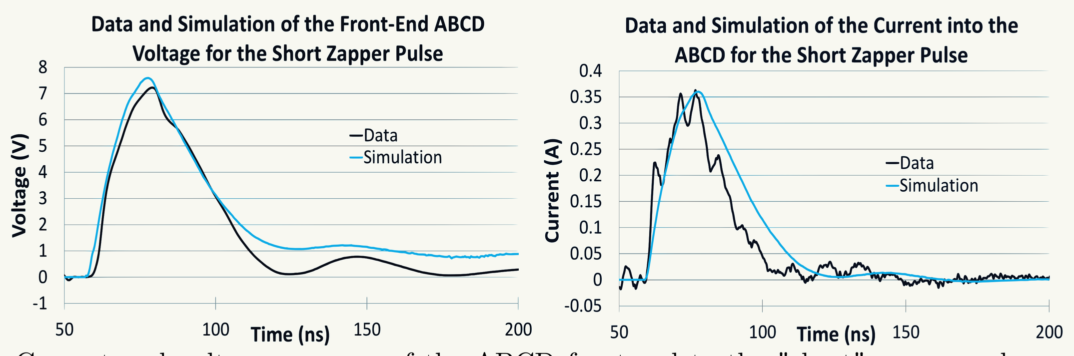
A Detailed Look at Components of Our Model:

ABCD Readout IC:



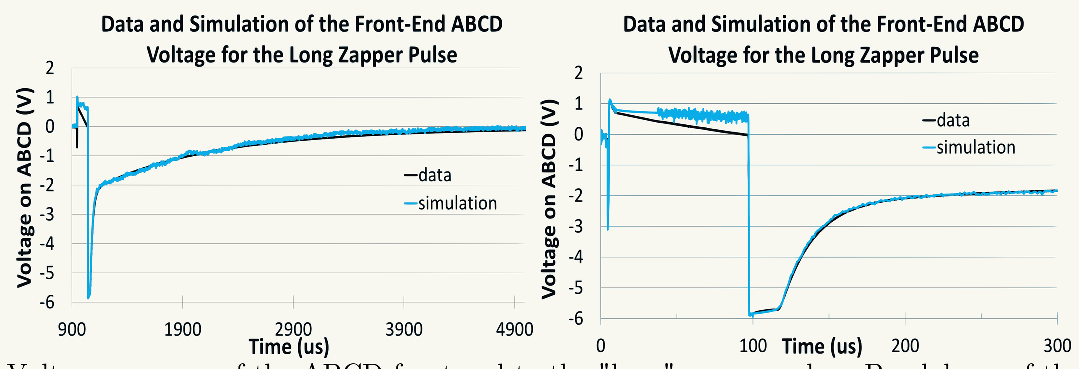
The ABCD response to voltage signals was measured using the "zapper" circuit (left) in our SCIPP sensor lab. The circuit is able to deliver both a "short" and a "long" pulse. The "short" pulse is capable of an 80 V step with a 40 ns transition time. It can deliver the equivalent of 10 nC in 25 ns to an ABCD channel. The "long" pulse is capable of a 450 V step with a 1 μs transition time [5].





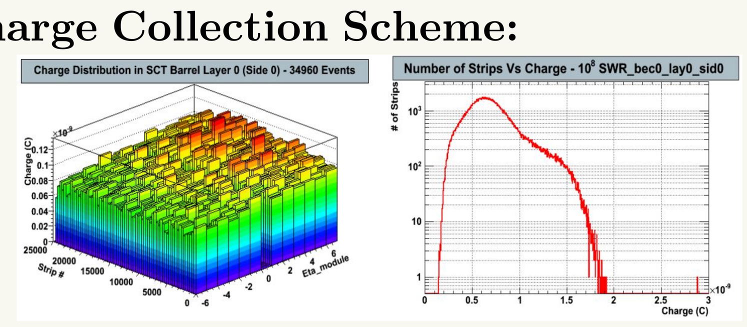
Current and voltage response of the ABCD front-end to the "short" zapper pulse. Data taken in our SCIPP sensor lab are shown in dark blue and the simulated response from our ABCD model is shown in light blue.

Our model for the ABCD front-end includes an NPN transistor, a zener diode, and a large resistor. The base-emitter junction of the transistor models the ABCD response to the "short" zapper pulse. Transistor parameters are largely based on the real DMILL model for the ABCD front-end transistor. We adjusted the base-emitter resistance value to match the response seen in the "short" zapper pulse data. The zener diode models the quick breakdown recovery to -2 V seen in the diagrams to the right; the large resistor models the slow breakdown recovery from -2 V to 0 V. The actual path of the breakdown current in the real ABCD is not well understood. Our model is motived by the fact that it can accurately reproduce the available data.



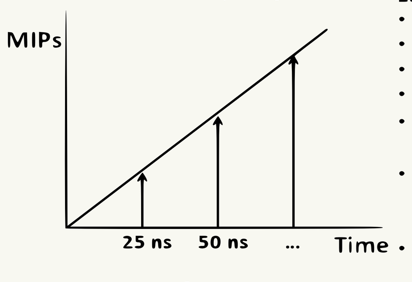
Voltage response of the ABCD front-end to the "long" zapper pulse. Breakdown of the transistor base-emitter junction occurs on the trailing edge of the input voltage pulse. **Left:** recovery from breakdown occurs in two stages: an inital quick return to -2 V is observed, followed by a slower return to 0 V. **Right:** a second higher resolution data set and simulation zooms in on the inital response.

Charge Collection Scheme:



A group from the University of Sydney simulated the most likely beam loss scenario [3]. The left plot shows a fairly uniform distribution of charge across the innermost SCT barrel layer. The right plot shows the distribution of maximum charge collected per strip per bunch crossing.

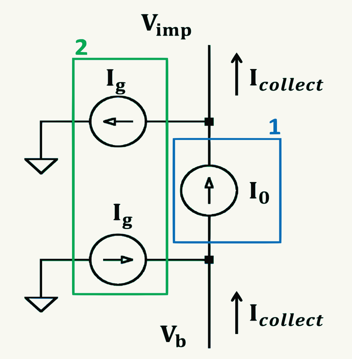
Assumptions -> Particle flux increases linearly from 0 to 5.4x10^5 MIPs per strip per bunch crossing until the beam is dumped
-> Beam loss occurs over various time profiles (100 ms, 10 ms, 1 ms, ...)
-> Beam dump occurs over a 90 μs interval, during which the particle flux continues to increase linearly
-> 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, and each value corresponding to the current at that time
- Use this array to print a PWL file

$Q = MIPs * 80\frac{e^-}{\mu m} * 289.5\ \mu m * 1.6 * 10^{-19}\frac{C}{e^-}$ $\qquad t_{cc} = 10\ ns * \sqrt[3]{MIPs}$

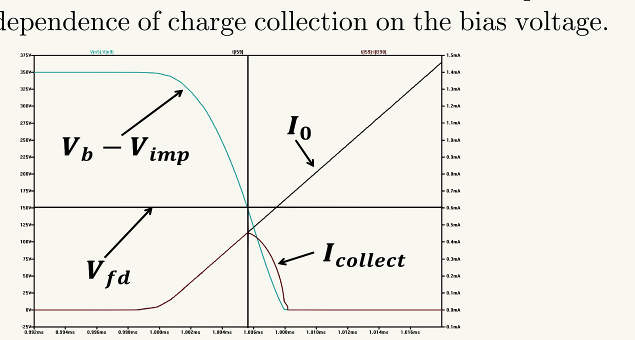
Calculation of the current through source 1.



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

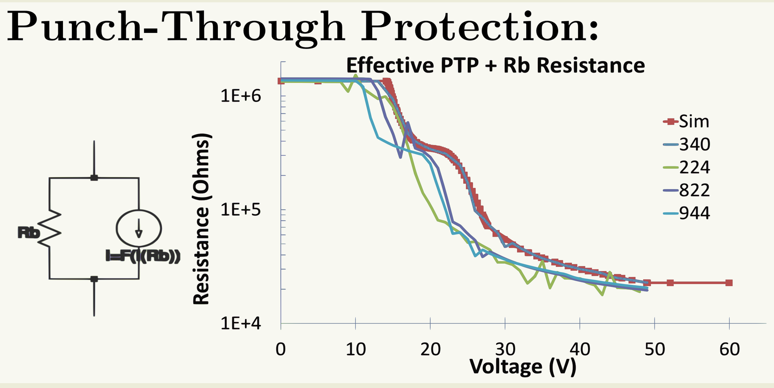
For $(V_b - V_{imp}) \leq V_{fd}$:
-> $I_{collect} = I_0\sqrt{(V_b - V_{imp})/V_{fd}}$
-> $I_g = I_0 - I_{collect}$

Our charge collection mechanism consists of three current sources. Component 1 models the timing structure of the beam, and its current is calculated outside of SPICE. Components 2 model the dependence of charge collection on the bias voltage.



For bias voltages below the full depletion value, the amount of collected charge decreases due to a smaller depletion depth. This excess current through source 1 is taken from and deposited back into ground so as to not affect other components in the simulation.

Punch-Through Protection:

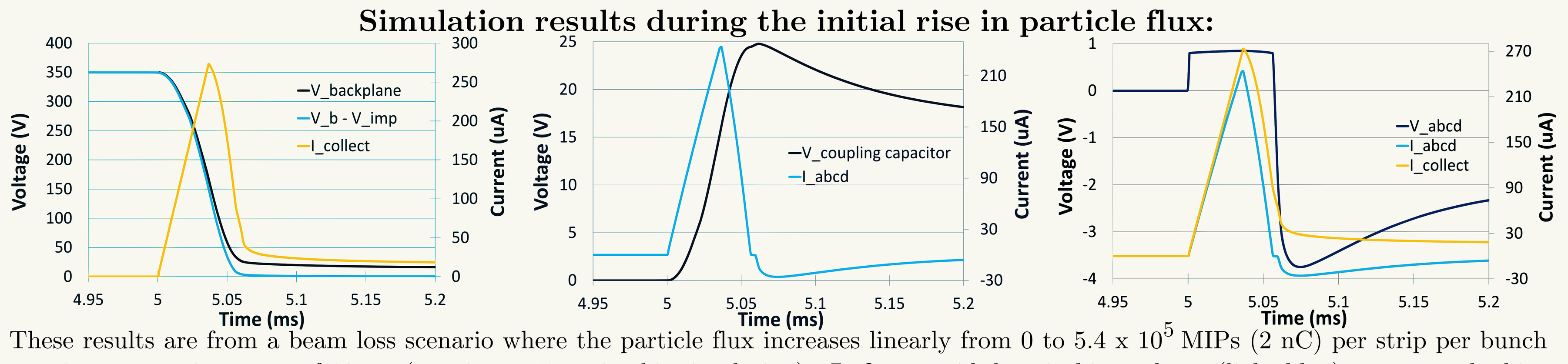


The punch-through protection (PTP) [7] structure is designed to limit high voltages on the implant strip. For voltages above a certain threshold, there is a voltage-dependent resistive path from one end of the implant strip to ground. In our SPICE simulations, the PTP structure is implemented as a current-dependent current source. We have characterized the effective resistance of PTP in parallel with the bias resistor for four different SCT production sensors at our SCIPP sensor lab. The worst-case measurement is modeled in our simulations.

Results:

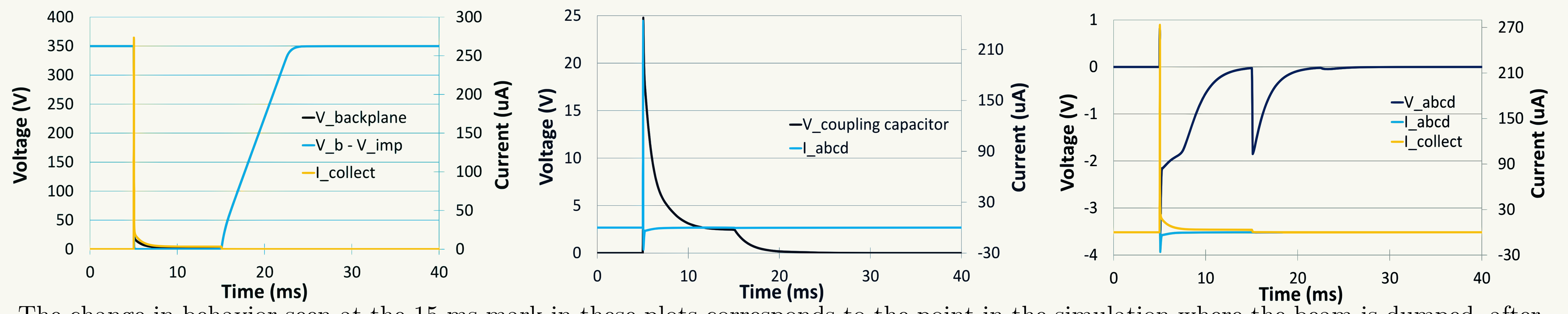
10 ms Beam Loss Scenario for Non-Irradiated Sensors:

Simulation results during the initial rise in particle flux:



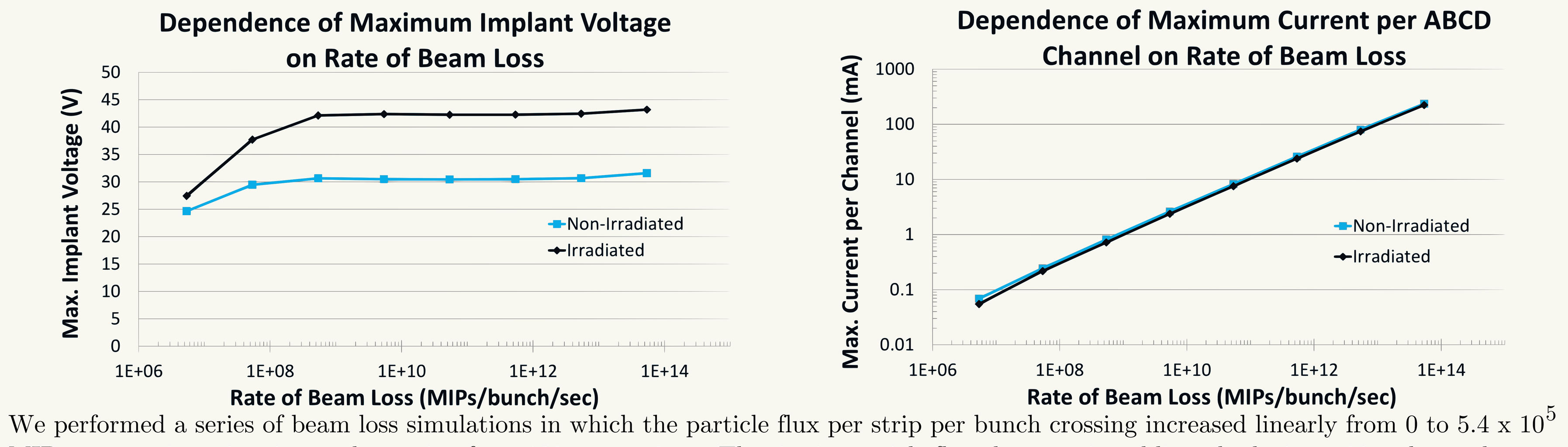
These results are from a beam loss scenario where the particle flux increases linearly from 0 to 5.4 x 10^5 MIPs (2 nC) per strip per bunch crossing over a time span of 10 ms (starting at 5 ms in this simulation). **Left:** a rapid drop in bias voltage (light blue) occurs as the bias filter capacitors are drained of their charge. This drop in bias voltage leads to a smaller depletion depth in the sensor. Consequently, the amount of charge collected per strip (orange) reaches a maximum rate of 273 μA before eventually falling back to 3.5 μA. **Center:** the ABCD current per channel (light blue) follows the time derivative of the coupling capacitor voltage (dark blue). The average coupling capacitor voltage reaches a maximum of 25 V, which is well below the 100 V specification. **Right:** breakdown of the ABCD front-end can be observed in the dark blue trace. This plot also shows that the ABCD current per channel (light blue) is less than the current collected per strip (orange). This excess current escapes to ground through the PTP structures. The maximum ABCD current per channel of 244 μA corresponds to 6.1 pC of charge in 25 ns, which is well below the 5 nC in 25 ns specification. We do not expect to see damage to the SCT barrel modules for this beam loss scenario.

Full simulation results:



The change in behavior seen at the 15 ms mark in these plots corresponds to the point in the simulation where the beam is dumped, after which the strips no longer collect charge. At this time, the bias voltage (left, light blue) and coupling capacitor voltage (center, dark blue) begin returning to their pre-beam loss values. The ABCD voltage (right, dark blue) experiences a second breakdown due to the abrupt drop in the coupling capacitor voltage. At 25 ms, 20 ms after the onset of beam loss, the module returns to its initial state.

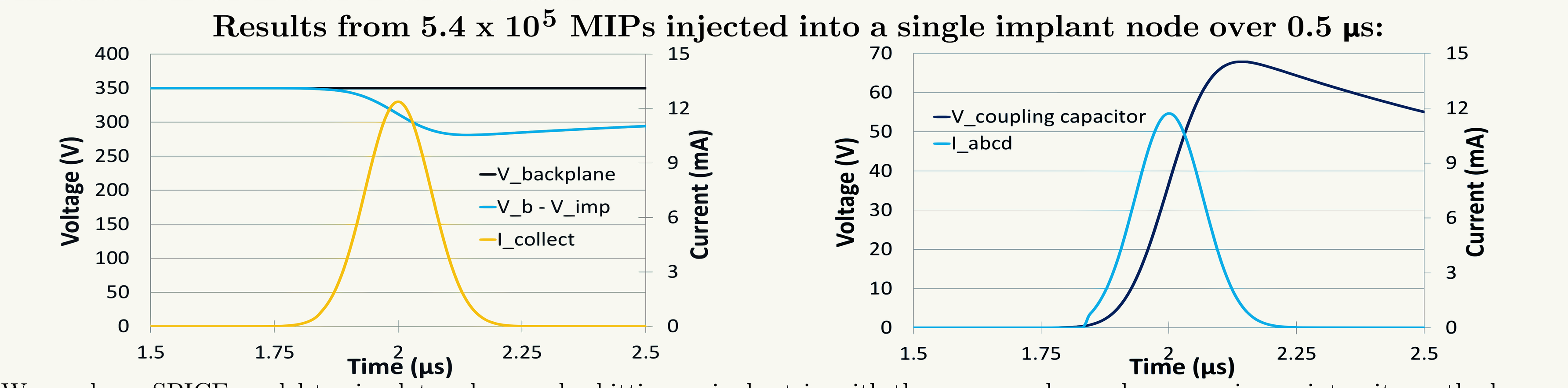
Summary of Beam Loss Simulations Over Various Time Profiles:



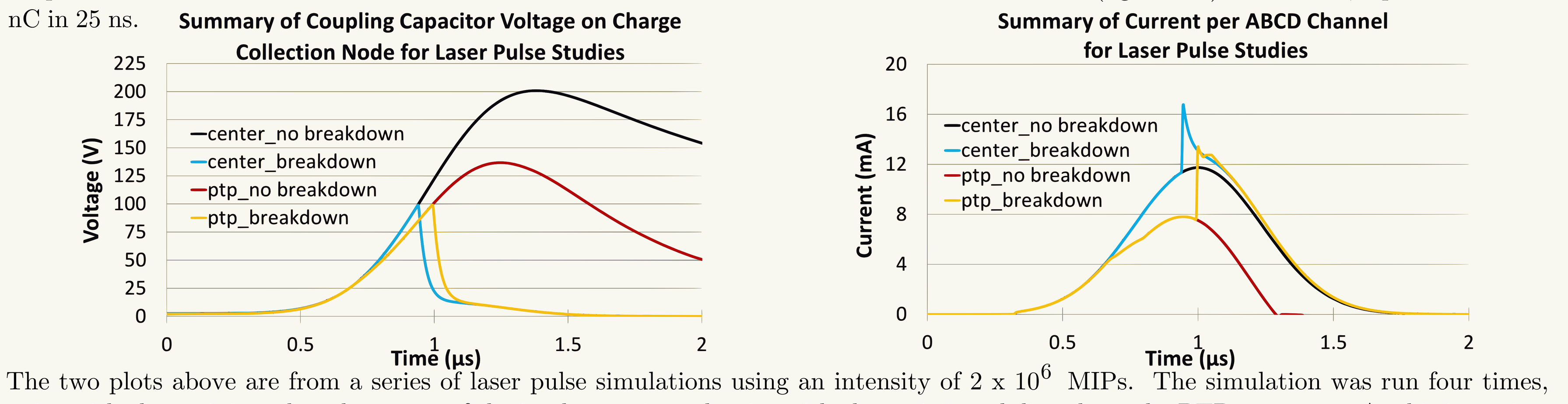
We performed a series of beam loss simulations in which the particle flux per strip per bunch crossing increased linearly from 0 to 5.4 x 10^5 MIPs over various time intervals ranging from 100 ms to 10 ns. The rise in particle flux then continued linearly during a 90 μs beam dump. These simulations were performed for both irradiated sensors and non-irradiated sensors. In each case, the shapes of the voltage and current traces were qualitatively similar to those from the 10 ms scenario. From these simulations, we extracted the two primary values of interest: the maximum coupling capacitor voltage on the node furthest from the PTP and the maximum current per channel into the ABCD front-end. These are shown in the two summary plots above. **Left:** the maximum implant voltage reaches a plateau, which varies with the operational bias voltage, due to the finite amount of charge stored on the bias filter capacitors. **Right:** the maximum current per ABCD channel rises with increasing rates of beam loss. The observed relationship is given by, $I \propto \sqrt{rate}$.

Simulation of Laser Pulse Studies:

Results from 5.4 x 10^5 MIPs injected into a single implant node over 0.5 μs:



We used our SPICE model to simulate a laser pulse hitting a single strip with the same pre-beam dump maximum intensity as the beam loss simulations. **Left:** with only one strip collecting charge, the drop in backplane voltage (dark blue) is negligible. The bias voltage on the charge collection node (light blue) decreases due to the increasing voltage on the implant node, but still remains above the full depletion value. **Right:** the voltage across the coupling capacitor at the charge collection node now approaches 70 V. This is much closer to the 100 V specification than in the beam loss simulations. The maximum ABCD current in this channel (light blue) is 11.7 mA, equivalent to 0.3 nC in 25 ns.



The two plots above are from a series of laser pulse simulations using an intensity of 2 x 10^6 MIPs. The simulation was run four times, twice with charge injected at the center of the implant strip and twice with charge injected directly at the PTP strucutre. At this intensity, the coupling capacitor reaches the 100 V breakdown specification, so two of the simulations were run with an additional breakdown mechanism that shorts the implant node to the readout strip though a 1 kΩ resistor when the coupling capacitor surpasses 100 V. **Left:** without the breakdown mechanism, the coupling capacitor voltage reaches 200 V when charge is injected at the center of an implant strip (dark blue), and it reaches 137 V when charge is injected directly at the PTP structure (red). **Right:** when the coupling capacitor breaks down, there is a surge of current into the ABCD channel. The magnitude of this current surge depends on the assumed value for the breakdown resistance of the coupling capacitor (1 kΩ in these simulations).

Conclusions and Future Work:

Our simulations show that during the most likely beam loss scenarios, namely, when the particle flux across an ATLAS SCT barrel module is rather uniform, there exist inherent self-protection features in the barrel module electrical system. These self-protection features are the finite amount of charge stored on the bias filter capacitors and the power supply current limit. Because of these features, the bias filter is unable to maintain a sufficient bias voltage during these beam loss scenarios, and the amount of charge collected by the implant strips is limited due to a reduced depletion depth in the sensors. We found that during these beam loss scenarios, the coupling capacitor voltage never approaches its breakdown specification, and the current per ABCD channel only reaches its specified limit for beam loss rates in excess of 5.4 x 10^{13} MIPs/bunch/second. In cases where only a fraction of the strips on a given SCT module are suscepted to a large particle flux, for example when a single strip is zapped by a laser, these self-protection features are not actuated, and the observed behavior of the module is very different. Therefore, these sorts of studies may not be an effective way to evaluate potential damage of SCT strips during beam loss. However, since small variations in particle flux across the strips in a single SCT module may exist, it would be useful to investigate what effect, if any, these variations have on the observed behavior of the modules.

References:

[1] ATLAS Collaboration, 2008 JINST 3 S08003.
[2] A. Abdesselam et al., The barrel modules of the ATLAS semiconductor tracker, Nucl. Instrum. Methods A568 642 (2006).
[3] N. Patel et al., Charge deposition in the SCT due to beamloss, ATLAS Note ATL-INDET-PUB-2013-002.
[4] F. Campabadal et al., Design and performance of the ABCD3TA ASIC for readout of silicon strip detectors in the ATLAS semiconductor tracker, Nucl. Instrum. Methods A552 292 (2005).
[5] A. Kuhl et al., ATLAS ABCD hybrid fatal charge dosage test, 2011 JINST 6 C12021.
[6] K. Hara et al., Beam splash effects on ATLAS silicon microstrip detectors evaluated using 1-w Nd : YAG laser, Nucl. Instrum. Methods A541 15 (2005).
[7] H.F.-W. Sadrozinski et al., Punch-through protection of SSDs, Nucl. Instrum. Methods A699 31 (2013).

Acknowledgements:

-> Special thanks to J. Kaplon from the CERN microelectronics group for helpul consultations, C. Haber from LBL for providing the SCT sensors, and the U. of Sydney group for discussions regarding their simulations.
-> Work supported by the U.S. Dept. of Energy under grant DE-FG02-13ER41983.

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TWEPP 2013
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