Status and Plans for ATLAS Radiation Damage Simulation

November 3, 2019

By the end of Run 2, the ATLAS IBL has experienced fluences of up to 10^{15} (1 MeV) n_{eq}/cm^2, and radiation damage effects can already be observed from measurements of charge collection efficiency and Lorentz angle [1]. A model to study these radiation damage effects has been implemented into the Athena digitizer, and this presentation highlights some of the recent updates to this effort.

1 Radiation damage implementation in the Athena digitizer

The algorithm for simulating radiation damage within the ATLAS Athena digitizer is as follows:

- After simulation, the digitizer takes in information such as the charge and position of the various particles, as well as global information such as the electric field profile after radiation damage
- This original charge is split into many subcharges, propagated separately under the electric field
- Effects such as Lorentz drift and thermal diffusion are applied
- Each subcharge is considered trapped if the time for it to drift to an electrode is greater than a fluence dependent trapping time.
- The final position of each subcharge is calculated. The induced charge on the electrode is then determined by a Ramo potential, and the initial and final charge positions

The electric fields for the planar (3D) sensors are computed from TCAD simulations with the Chiochia [2] (Perugia [3]) model. To save time, many quantities derived from the electric field (such as the time for a charge to drift to an electrode) are also precomputed and saved as maps. Further details can be found in [1].

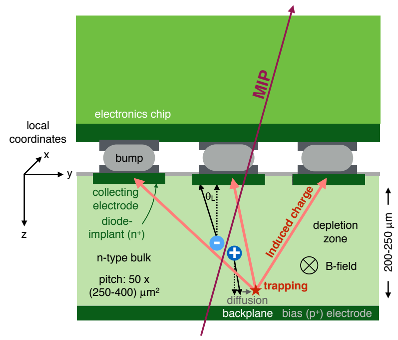

Figure 1: An illustration of the digitization process for the planar sensors

2 E-field interpolation algorithm

The two main parameters for generating maps are the fluence and the bias voltage. Typically, the electric field is computed only for a few benchmark pair, but it is of course not feasible to precompute all possible combinations. Recently, a new method has been developed to produce E-field maps for any (fluence, voltage) pair on the fly within the digitizer by interpolating existing E-field maps. This takes advantage of the fact that the E-field at a fixed sensor depth varies smoothly with fluence and voltage.

Given a desired (fluence, voltage) pair, an interpolation with cubic splines is first done on the fluence to obtain various samples with the correct fluence but different voltages. Using these new samples, the interpolation is repeated, this time on the voltage, to obtain the correct (fluence, voltage) target.

Closure tests on this interpolation method were performed by comparing the precomputed maps with the interpolated maps. Example distributions of the E-field and dE/dx in figure 2 show good agreement between the two. The E-field interpolation has now been added to the Athena digitizer for planar sensors.

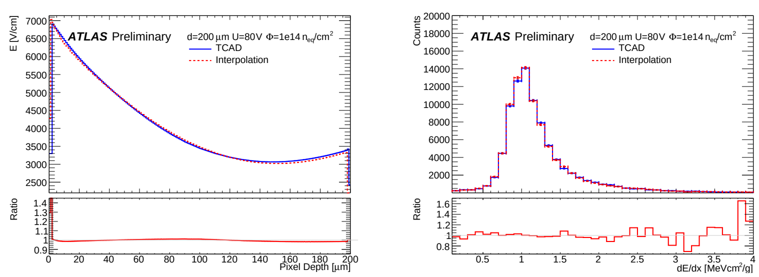

Figure 2: Comparisons of the E-field and dE/dx for the interpolated maps and the maps generated directly from TCAD.

3 Update on new E-field parameters

Previously, the E-field profile used relatively old silicon parameters, which agreed well with data for lower fluences but not for higher fluences. After discussions with CMS, a new set of parameters has been determined which work well for both low and high fluences, as shown in Figure 3. These new parameters are:

- Bandgap energy at 300K = 1.12415 eV
- Effective density of states in conductive band at 300K $= 2.825 * 10^{19}\text{cm}^{-3}$
- Effective density of states in valence band at 300K $= 3 * 10^{19}\text{cm}^{-3}$
- Effective electron mass = 0.32713
- Effective hole mass = 0.55865

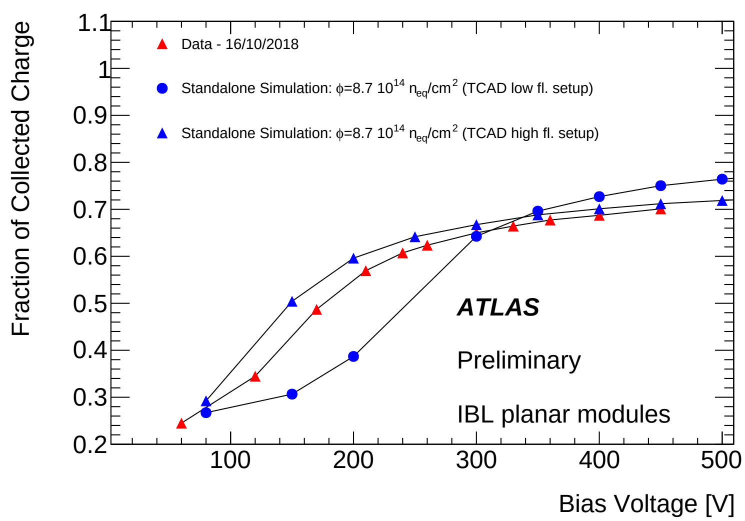

Figure 3: Comparisons of the charge collection efficiency for data, the old low fluence simulation setup, and the new high fluence simulation setup.

4 Update on 3D sensors

In addition to the more common planar pixel sensors, ATLAS also has 3D pixel sensors located at high η in the IBL. Recently, a radiation damage implementation for 3D sensors has also been added to Athena. This implementation is very similar to that of the planar sensors, despite the differing geometry.

To validate the Athena implementation, a muon particle gun is used to simulate hits in the 3D sensors, with the planar sensors disabled. The average dE/dx is plotted for a series of benchmarks, with fluences ranging from 0 to $10^{16} n_{eq}/\mathrm{cm}^2$. Figure 4 shows that the results from Athena agree well qualitatively with the results from standalone AllPix simulation, which itself has been validated against real test beam data.

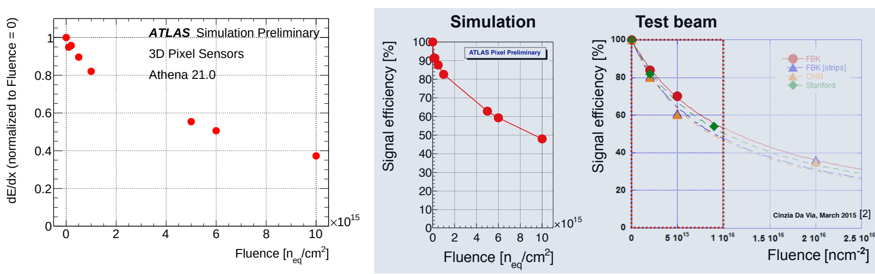

Figure 4: Comparison of the charge collection efficiency vs. fluence for the Athena simulation, the standalone AllPix simulation, and real test beam data.

5 Plans for Run 3 and the HL-LHC

For future ATLAS physics in Run 3 and the HL-LHC, understanding radiation damage effects will be crucial. One possibility is to make the radiation damage digitizer a default component of the ATLAS simulation. Future challenges include deciding the exact fluences to use as simulation inputs, and also ensuring that the digitizer will run fast enough for bulk simulation production.

References

[1] M. Aaboud, G. Aad, B. Abbott, D.C. Abbott, O. Abdinov, D.K. Abhayasinghe, S.H. Abidi, O.S. AbouZeid, N.L. Abraham, H. Abramowicz, and et al. Modelling radiation damage to pixel sensors in the atlas detector. *Journal of Instrumentation*, 14(06):P06012–P06012, Jun 2019.

[2] V. Chiochia, M. Swartz, Y. Allkofer, D. Bortoletto, L. Cremaldi, S. Cucciarelli, A. Dorokhov, C. Hörmann, D. Kim, M. Konecki, D. Kotlinski, K. Prokofiev, C. Regenfus, T. Rohe, D.A. Sanders, S. Son, and T. Speer.

A double junction model of irradiated silicon pixel sensors for lhc. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 568(1):51 – 55, 2006. New Developments in Radiation Detectors.

[3] F. Moscatelli, D. Passeri, A. Morozzi, R. Mendicino, G. . Dalla Betta, and G. M. Bilei. Combined bulk and surface radiation damage effects at very high fluences in silicon detectors: Measurements and tcad simulations. *IEEE Transactions on Nuclear Science*, 63(5):2716–2723, Oct 2016.