Radiation Damage Monitoring in the ATLAS Pixel Detector

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Abstract

We describe the implementation of radiation damage monitoring using measurement of leakage current in the ATLAS silicon pixel sensors. The dependence of the leakage current upon the integrated luminosity is presented. The measurement of the radiation damage corresponding to integrated luminosity 5.6 fb^{-1} is presented along with a comparison to the theoretical model.

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1. Introduction

The innermost detection system of the ATLAS Detector [1] at the Large Hadron Collider is a silicon pixel-based tracking and vertexing detector configured in 3 cylindrical barrels and 2×3 endcap disks, spanning $|\eta| < 2.5$. The proximity of the detector to the interaction region (the innermost layer, called Layer 0, has radius 50.5 mm; the outermost, 149.6 mm) implies a harsh radiation environment. Radiation damage incurred by silicon in the pixel region is primarily due to displacement damage and other point defects caused by non-ionizing energy loss of charged particles. Damage-induced recombination or generation centers increase the reverse leakage current, leading to increased power consumption and degrading the signal-to-noise ratio. Charge trapping centers diminish charge collection efficiency, resulting in diminished hit efficiency and track resolution. Acceptor centers change the effective doping concentration, causing the depletion voltage to increase and ultimately leading to type inversion. The innermost layer of this silicon system, based on n^+ -on- n technology, is expected to undergo type inversion after about 10 fb^{-1} of collision data have been received. To allow experimenters to respond to these changes, the radiation damage sustained by detector elements must be monitored.

Radiation-induced change ΔI in silicon sensor leakage current has been shown to vary directly with fluence Φ_{eq} through $\Delta I = \alpha \Phi_{\text{eq}} V$ [2], where V is the bias voltage and α is a temperature-dependent universal constant for silicon with value $(3.99 \pm 0.03) \times 10^{-17} \text{ A/cm}$ at 20° C after 80 minutes' annealing at 60° C . For convenience of comparison, fluences of various particle species and energies are typically converted to the fluence of 1 MeV neutrons that would produce an equivalent amount of displacement damage; this is the Φ_{eq} .

A system has been implemented to measure the leakage current in a representative sample of ATLAS Pixel Detector sensors to infer in real time the radiation profile received by the detector. Results presented here were measured for integrated luminosity approximately 5.6 fb^{-1} delivered during 2010-11. The sensors have active thickness (i.e., excluding passivation) of $250.6 \pm 0.3 \mu\text{m}$ and 46080 channels with granularity $50 \times 400 \mu\text{m}^2$. They are combined with their readout electronics into 1744 nearly identical modules. During the period described here, the average operational temperature was maintained at -13° C through evaporative cooling, except during a few documented cooling interruptions. The intrinsic resolution of the Pixel Detector, which includes approximately 80 million channels, is $10 \mu\text{m}$ in $r\phi$ and $115 \mu\text{m}$ in rz . The starting bias voltage for each device is 150 V. The Pixel Detector inner layer is designed to tolerate a radiation dose of 500 kGy or $10^{15} \text{ 1 MeV n}_{\text{eq}} \text{ cm}^{-2}$.

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2. Sensor Current Monitoring in the ATLAS Pixel Detector

High Voltage Patch Panel 4 (HVPP4), located in the ATLAS Detector caverns, distributes high voltage, including sensor bias, to the ATLAS Pixel Detector. The pixels use ISEG power supplies, which can distribute power at voltage V_{DC} up to 700 V and current $I \leq 4\text{mA}$. During the initial operational period of the detector, when leakage current is low, each ISEG supplies 6 or 7 pixel modules. The modularity will be reconfigured to 1 ISEG per 2-3 detector modules as currents rise.

The Current Measurement (CM) system monitors the leakage current on individual pixel modules. To assure precision results throughout the lifetime of the Pixel Detector, and from representative sensors installed in all layers, the system must measure currents over the range $0.01\text{ }\mu\text{A}$ to 1 mA . Figures 1 and 2 show the circuit and a photograph of its implementation. A current-frequency converter circuit is optically coupled to a frequency-voltage converter. Two digital readout ranges are available per channel, with different analog gains. Four circuits per board monitor selected modules through the radiation hard 64-channel Embedded Local Monitor Board (ELMB) [3]. The high gain channel reads out module leakage current in the range 10^{-8} to 10^{-5} A , and the low gain channel, in the range 10^{-6} to 10^{-2} A . The output voltage range is fixed by the standard ELMB input ranges: at the outset of the run, the range $0 - 1\text{ V}$ was chosen. This will be changed to the $0 - 5\text{ V}$ range as the high gain channels saturate at pixel leakage currents above about 10^{-5} A . Channels are isolated in pairs from each other and from the readout system. The frequency of the operating circuit is less than 100 kHz . The measured current values are digitized and transmitted from the CM board (which is attached to the HVPP4 Type II board) via CANbus to the Detector Control System (DCS) by the 16-bit analog-to-digital converter ELMB. PVSS software reads the data from the ELMB and downloads it to the DCS offline PVSS Archive Database. The resolution of the CM system is $(\text{ELMB range})/2^{16}$, implying a current measurement precision approaching 10 nA . The CM system comprises 22 boards for Layer 0, 16 boards for Layer 1, and 16 boards for Layer 2, and thus reads out 88 modules in Layer 0, 64 modules in Layer 1, and 64 modules in Layer 2, for a total of 216 barrel modules sampled uniformly in η and ϕ .

Figure 1: The Current Measurement circuit.

Figure 3 shows the two available ranges of output voltage versus input current that are available with this system. The system input calibration is made with a Keithley 237 High Voltage Source/Measure Unit in constant current mode. The calibration output voltage is measured through the ELMB with PVSS.

Figure 2: A sample Current Measurement Board.

3. Comparison of Data to the Model

Fluences at various points in the ATLAS Inner Detector have been predicted[4] for radii between 2 and 20 cm of the proton-proton collisions using the full ATLAS Monte Carlo simulation with packages PHOJET and FLUKA [5]. The response, including annealing, of silicon to particle interactions has been modeled [6, 7].

For the comparison, recorded currents are corrected for pedestal current and scaled to 0°C by the formula $I(T_{\text{ref}}) = I(T) \left(\frac{T_{\text{ref}}}{T} \right)^2 \exp \left[-\frac{E_g}{2k_B} \left(\frac{1}{T_{\text{ref}}} - \frac{1}{T} \right) \right]$. Here E_g is the silicon band gap, 1.21 eV [8], and k_B is the Boltzmann constant. Correction for beam-induced ionization current is made by subtracting $I_{\text{hit}} = N_b \cdot \nu_{\text{LHC}} \cdot Occ \cdot C_{\text{hit}}$, where N_b is the number of colliding bunches per train (this increased throughout the period examined, with a maximum of about 1330 at the end of 2011); ν_{LHC} is the LHC revolution frequency (value approximately $1.4 \times 10^8 \text{ sec}^{-1}$); Occ is the pixel hit occupancy per module (typically 10^{-6}), and C_{hit} is the deposited charge per hit (of mean value 20,000 electrons).

Figure 4 shows the corrected leakage current in Pixel barrel Layer 0 as a function of luminosity. The prediction of the model is superimposed. The agreement is good, and the annealing periods are prominent. The approximately linear correlation with integrated luminosity confirms that the fluence is dominated by proton-proton collisions.

4. Conclusions and Outlook

Leakage current observed in the ATLAS Pixel Detector's Layer 0 has been compared to a theoretical model and found to agree well for proton-proton collision integrated luminosity up to 5.6 pb^{-1} . This information can be used to validate the model, which includes charge trapping, electric field modification, and signal induction on the electrodes, and make predictions about the response of LHC detectors to future operation scenarios.

Figure 3: Output voltage versus input current to a representative board in the Current Measurement system. The high and low gain ranges are evident.

Figure 4: Points indicate measured corrected leakage current at Layer 0 as a function of integrated luminosity. The theoretical model [7] is also shown.

References

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