CMS Pixel Radiation Damage Measurements

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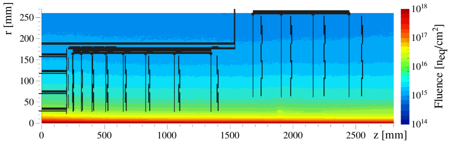
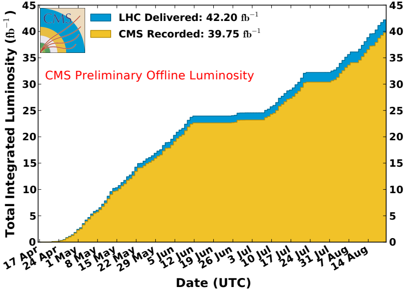
CMS Pixel Barrel

- Radiation damage during CMS operation
- Continuous degradation of detector properties
- Focus on
  - Leakage current I_{leak}
  - Full depletion voltage V_{depl}
- These properties need to be
  - Measured
  - Compared to models
  - Predicted
- Taking into account operation conditions (temperature)



1 MeV n-equivalent in silicon, 3000 fb^{-1}

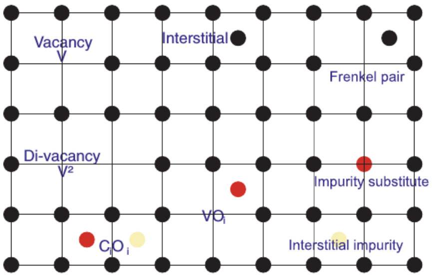


Two Types of Radiation-Induced Damage

- Ionizing energy loss - reversible, but not in SiO_2 ⇒ **surface damage**
- **N**on-**I**onizing **E**nergy **L**oss (NIEL) - displacing atoms ⇒ various types of **bulk defects**

Bulk Defects

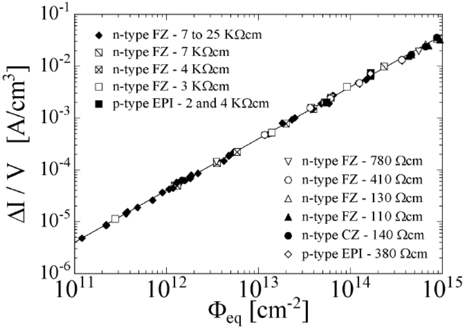
- Introduce new states in the band gap
  - Close to the conduction or valence band – donor or acceptor like defects ⇒ change the effective doping concentration
  - Shallow levels – trapping of electrons and holes
  - Close to the midgap ⇒ generation of leakage current
- May interact (annealing) so the concentrations of these defects may change in time



Introduction – Leakage Current Modeling

Leakage Current Model from M. Moll

- Change in leakage current due to irradiation
  $\Delta I_{leak} = \alpha \Phi_{eq} V$
- Φ_{eq} is the neutron equivalent fluence
- V is the volume
- α is the current related damage rate
  $\alpha(t, T) = \alpha_0(T) + \alpha_I e^{-\frac{t}{\tau_I(T)}} - \beta ln(\frac{t}{t_0})$
  subject to annealing
- All relevant parameters given in M. Molls thesis

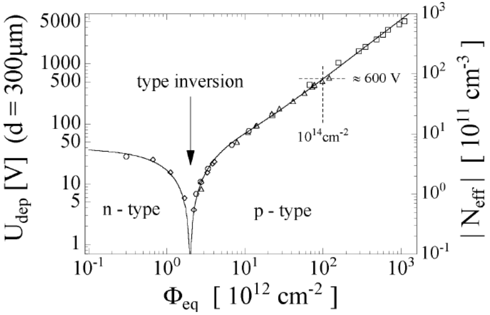


(for annealing 80 min at 60 °C)

Introduction – Full Depletion Voltage Modeling

Hamburg Model

- Change in the effective doping concentration $\Delta N_{eff}(\Phi_{eq}, t, T) = N_{C,0}(\Phi_{eq}) + N_A(\Phi_{eq}, t, T) + N_Y(\Phi_{eq}, t, T)$
- $N_{c,0}$ is the constant term
- N_A is the beneficial (short term) annealing
- N_Y is the reverse (long term) annealing
- There are several parameter sets available "RD48 oxy" and "CB-oxy" relevant for oxygenated Si
- In addition saturation of N_Y implemented



(measured as irradiated)

Introduction – Simulation Procedure

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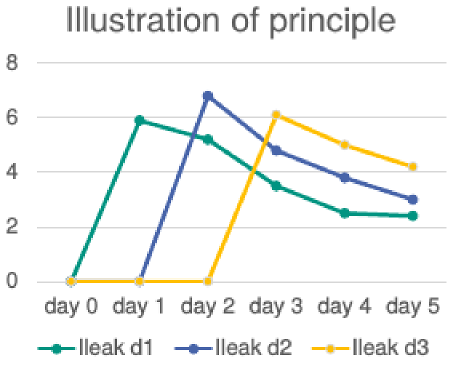
Input

- Full irradiation and temperature history

Radiation Damage Model

- Hamburg or α parameters
- FLUKA fluence predictions*
- Sensor position and geometry
- Thermal contacts*

* these introduce significant uncertainties



Procedure

- Each days deposited dose is annealed respecting the temperature history
- Previous days contributions are superimposed for leakage current or depletion voltage predictions

Simulation vs. Measurements – Leakage Current Layer 1

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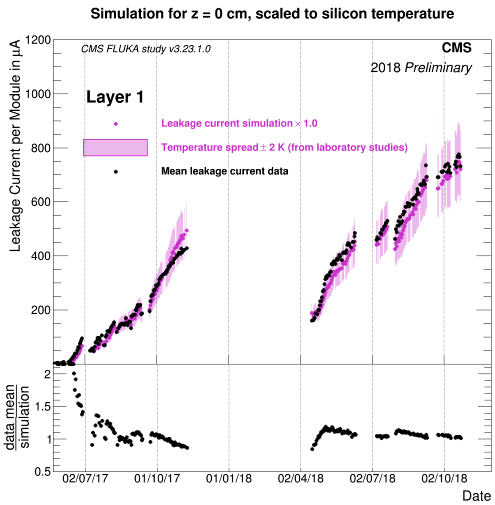
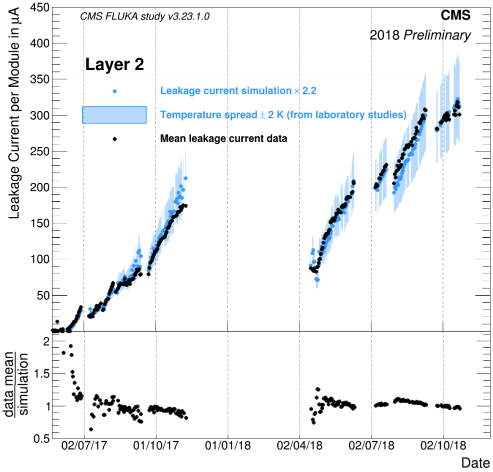
- Data granularity: Per sector, not resolved in z
- Temp measured near cooling loops ≈ −11.5 °C
  If detector on: Add an offset ⇒ Si at ≈ -8.5 ± 2 °C
- Leakage current simulations are corrected by a factor of 1.0
- Final fluence from FLUKA: $\approx 7.9 \times 10^{14}\ n_{eq}/cm^2$



Simulation vs. Measurements – Leakage Current Layer 2

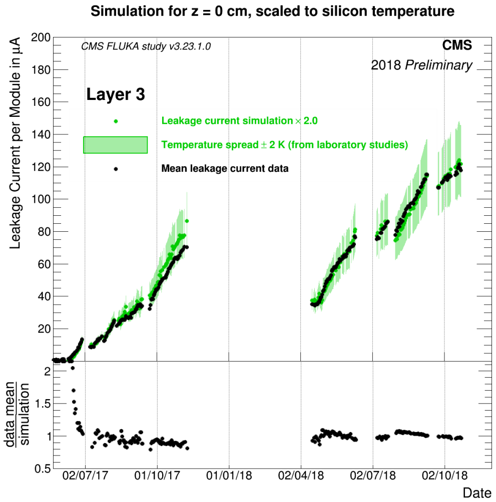
- Data granularity: Per sector, not resolved in z
- Temp measured near cooling loops $\approx -11.5\,^{\circ}$C
  If detector on: Add an offset $\Rightarrow$ Si at $\approx$ -8.5 $\pm$ 2 °C
- Leakage current simulations are corrected by a factor of 2.2
- Final fluence from FLUKA: $\approx 1.8 \times 10^{14}\ n_{eq}/cm^2$

Simulation for z = 0 cm, scaled to silicon temperature



Simulation vs. Measurements – Leakage Current Layer 3

- Data granularity: Per sector, not resolved in z
- Temp measured near cooling loops ≈ −11.5 °C
  If detector on: Add an offset ⇒ Si at ≈ -8.5 ± 2 °C
- Leakage current simulations are corrected by a factor of 2.0
- Final fluence from FLUKA: $\approx 9 \times 10^{13}\, n_{eq}/cm^2$



Simulation vs. Measurements – Leakage Current Layer 4

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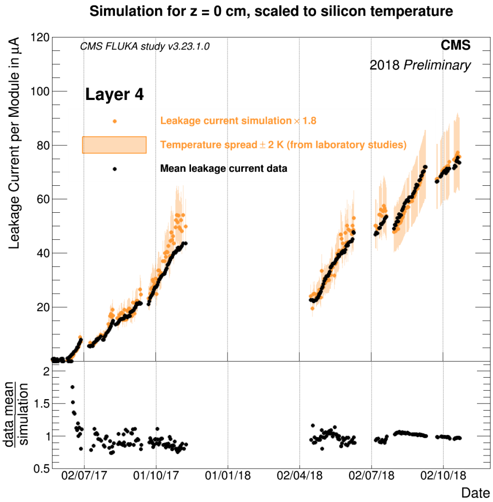
- Data granularity: Per sector, not resolved in z
- Temp measured near cooling loops $\approx -11.5\,^\circ$C
  If detector on: Add an offset $\Rightarrow$ Si at $\approx$ -7.5 $\pm$ 2 $^\circ$C
- Leakage current simulations are corrected by a factor of 1.8
- Final fluence from FLUKA: $\approx 5 \times 10^{13}\, n_{eq}/cm^2$



Simulation vs. Measurements – Full Depletion Voltage

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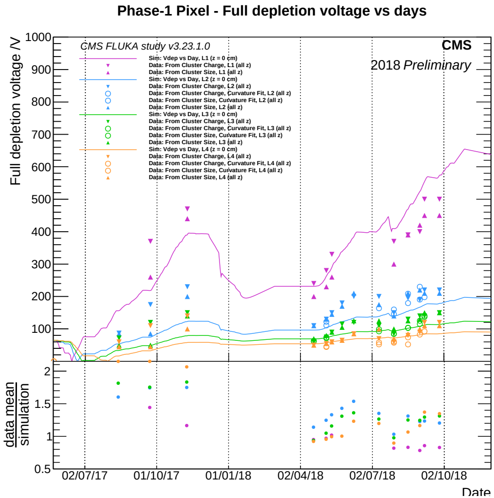
- Get N_{eff} from the simulation
- Calculating full depletion Voltage:

$$V_{dep} = N_{eff}\frac{qd^2}{2\epsilon\epsilon_0}$$

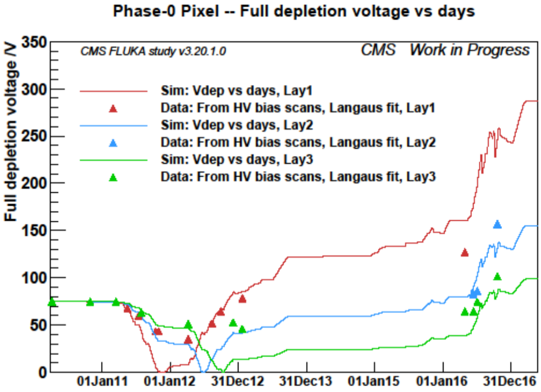
- Data from HV scan during operation:
  - Avg. cluster charge and size are determined as a function of bias voltage
  - The full depletion voltage is estimated from the kink in the respective curves
- For Layer 1 ($\approx 1.8 \times 10^{14}\ n_{eq}/cm^2$) double junction effects limit model accuracy



Simulation vs. Measurements – Last Years Results

Mayor Step With Respect to Last Year

- Last year, only full depletion voltage results for Phase-0 were shown
- For Phase-1 especially the high fluence for new Layer 1 is a challenge
- Modeling approach improved over the past year, especially our temperature assumptions
  - For the on-state of the detector, offsets between the temperature sensor and the silicon have been deduced from a mock-up of the pixel barrel
  - Scaling leakage current measurements to the temperatures at the time of measurement



Z-Dependence of Leakage Current – Measurements

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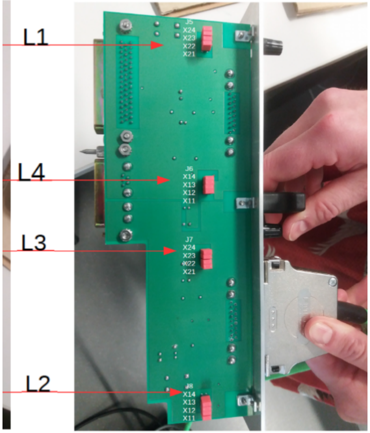
- HV channels group modules with the same ϕ region in the detector. Individual cables group modules in z. By disconnecting cables from power supply backplanes in the CMS experimental cavern it was possible to isolate individual (layer 1) and groups of modules on same z-positions.
- The detector was at nominal operating temperature with a CO_2 set point of $-22\,^{\circ}C$.
- The measurements were taken after the end of the 2018 heavy ion run.



Z-Dependence of Leakage Current – Layer 1 - I

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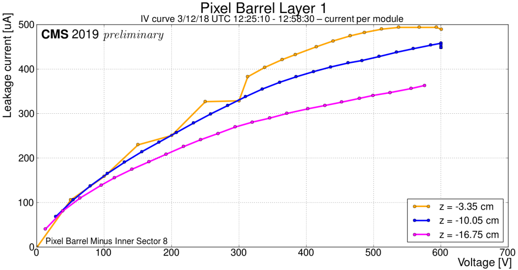

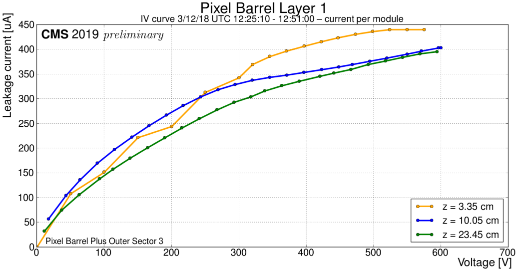

- Z-position measured mid of each module
- Measured volume 0.299 cm^3 (16 ROCs)
- Fluence $7.9 \times 10^{14}\ n_{eq}/cm^2$ (FLUKA, at z=0)
  Dose 41 Mrad (from occupancies)

- Different z, I_{leak} differs up to ≈ 150 µA
- Between sectors I_{leak} differs up to ≈ 50 µA
- Larger leakage currents towards smaller z, not fully consistent between all measured sectors (one outlier)

Z-Dependence of Leakage Current – Layer 1 - II

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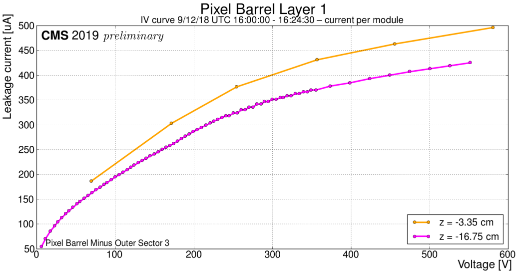
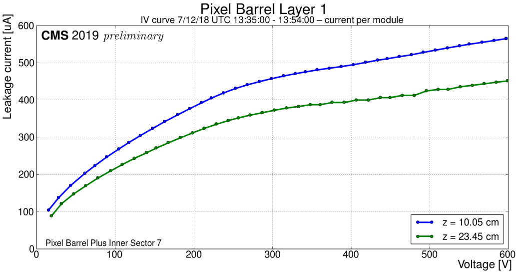
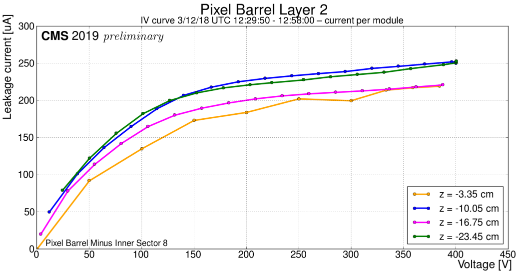


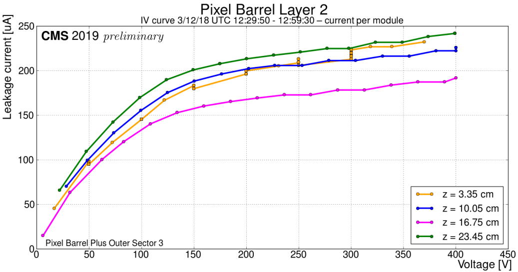


- Z-position measured mid of each module
- Measured volume 0.299 cm^3 (16 ROCs)
- Fluence $7.9 \times 10^{14}\,\mathrm{n_{eq}/cm^2}$ (FLUKA, at z=0)
  Dose 41 Mrad (from occupancies)

- Different z, I_{leak} differs up to $\approx$ 150 µA
- Between sectors I_{leak} differs up to $\approx$ 50 µA
- Larger leakage currents towards smaller z, not fully consistent between all measured sectors (one outlier)

Z-Dependence of Leakage Current – Layer 2

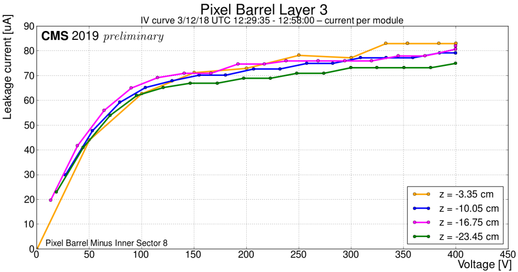


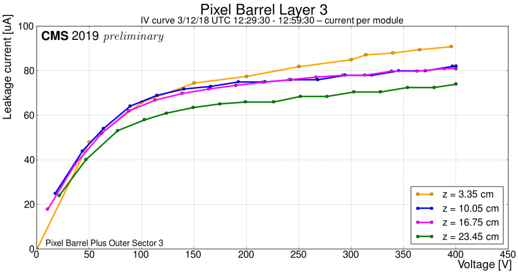


- Z-position measured mid of each module
- Measured volume 0.598 cm^3 (32 ROCs)
- Fluence $1.8 \times 10^{14}\, n_{eq}/cm^2$ (FLUKA, at z=0)
  Dose 8.6 Mrad (from occupancies)

- Different z, I_{leak} differs up to $\approx 60\,\mu A$
- Variations are not following a trend in z-direction
- No z-dependence for layer 2

Z-Dependence of Leakage Current – Layer 3

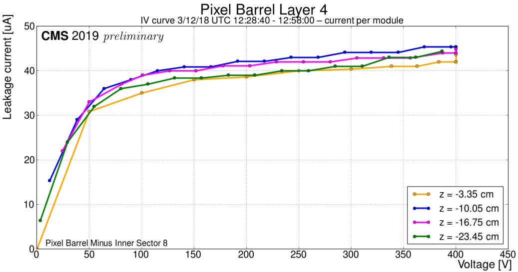


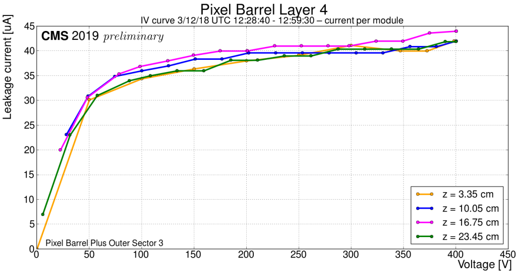


- Z-position measured mid of each module
- Measured volume 0.598 cm^3 (32 ROCs)
- Fluence 9×10^{13} n_{eq}/cm^2 (FLUKA, at z=0)
  Dose 5.3 Mrad (from occupancies)

- Different z, I_{leak} differs up to ≈ 50 µA
- Variations are not following a trend in z-direction
- Good agreement between the sectors

Z-Dependence of Leakage Current – Layer 4





- Z-position measured mid of each module
- Measured volume $0.598\,\mathrm{cm}^3$ (32 ROCs)
- Fluence $5 \times 10^{13}\,\mathrm{n_{eq}/cm^2}$ (FLUKA, at $z=0$)
  Dose 2.9 Mrad (from occupancies)

- Different z, I_{leak} differs up to $\approx 20\,\mu\mathrm{A}$
- No evidence for z-dependence of the leakage current in layer 4
- Good agreement between the sectors

Summary and Conclusion

- Leakage current measurements and simulation
  - For Layer 1: Decent agreement between measurements and simulation
  - Layer 2,3 and 4: Measurements and simulation differ by a factor of ≈ 2 – only partially understood
- Full depletion voltage measurements and simulation
  - For Layer 1: at ($\approx 1.8 \times 10^{14}\,\mathrm{n_{eq}/cm^2}$) double junction effects limit model accuracy
- Z-dependency of leakage current
  - For Layer 1: Larger leakage currents towards smaller z, not fully consistent between all measured sectors (one outlier)
  - Layer 2,3 and 4: No z-dependency observed

Simulation vs. Measurements

Data Point Calculation

- Leakage current measurements are taken for each fill **20 min** into stable beam condition (previously 10 min)
  - Granularity: Per layer and sector
  - Normalization: Average per ROC
- **Exclude short/ small bunch fills** (previously for all fills)
- **Measurements are averaged for one layer** excluding bad sectors (previously all sectors were shown separately)
- Measurements are scaled by 16 (# ROCs per module)

Simulation Point Calculation

- For each day calculate the product of
  - Simulated α – the current related damage rate – taking into account temperature history since that day
  - N_{eq} fluence at respective day
    - Using FLUKA ($z = 0$, per layer)
    - And the delivered luminosity
  - Module Volume $0.0285 \cdot 6.48 \cdot 1.62$ cm^3
- Sum over all days in the past
- **Scale to temperature at measurement** (previously the average temperature of the day was used)

Bold = new with respect to previous approved version (link here)