Evolution of Silicon Sensor Characteristics of the CMS Strip Tracker

Workshop Bad Liebenzell, 2012

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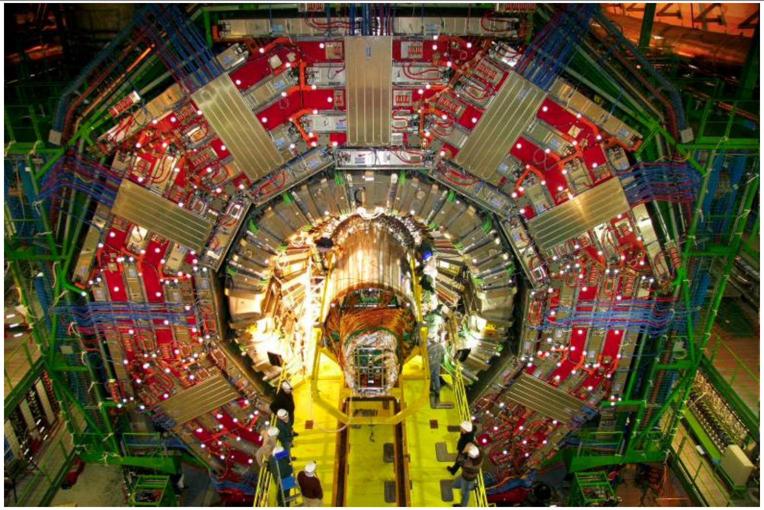
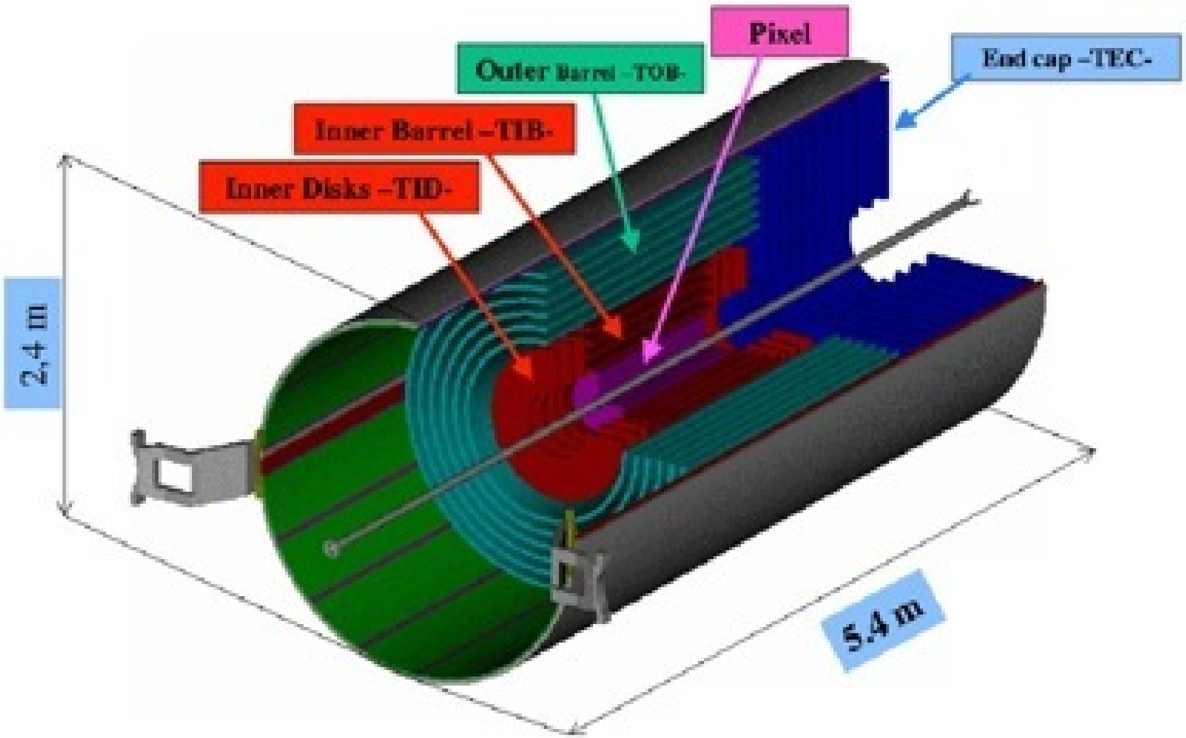


The CMS strip tracker

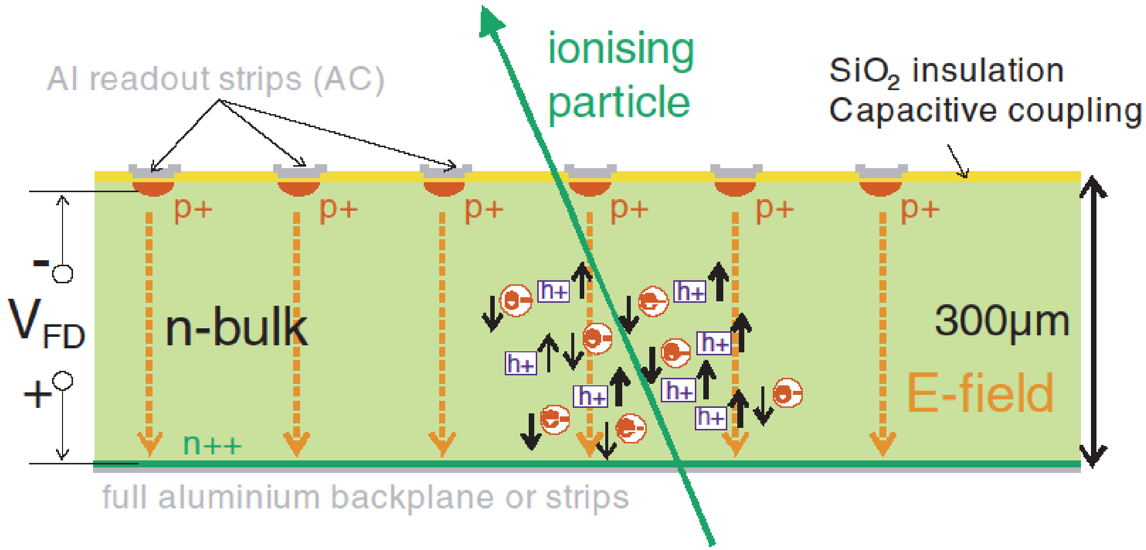
- 200 m^2 active silicon sensor area
- About 6000 sensors of 300 µm

  20000 sensors of

  500 µm
- Currently operated at 300V bias voltage
- Expected fluence exposure: up to $2x10^{14}$ 1MeV neutron equivalent



Reminder: silicon strip sensor working principle at CMS



- Traversing charged particles ionize the material along their trajectory, creating electron-hole-pairs.
- The charge is transported due to the electric field to the borders of the sensor.
- The readout is done via capacitive coupling at the Al readout strips.

- The bulk of the sensor is n-type doped silicon
- The strips are p type implants forming the p-n-junction.
- A bias voltage in reverse direction is applied to the p-n-junction in order to increase the size of the depletion width to cover the whole volume.
- A SiO_2 layer decouples the readout from DC.

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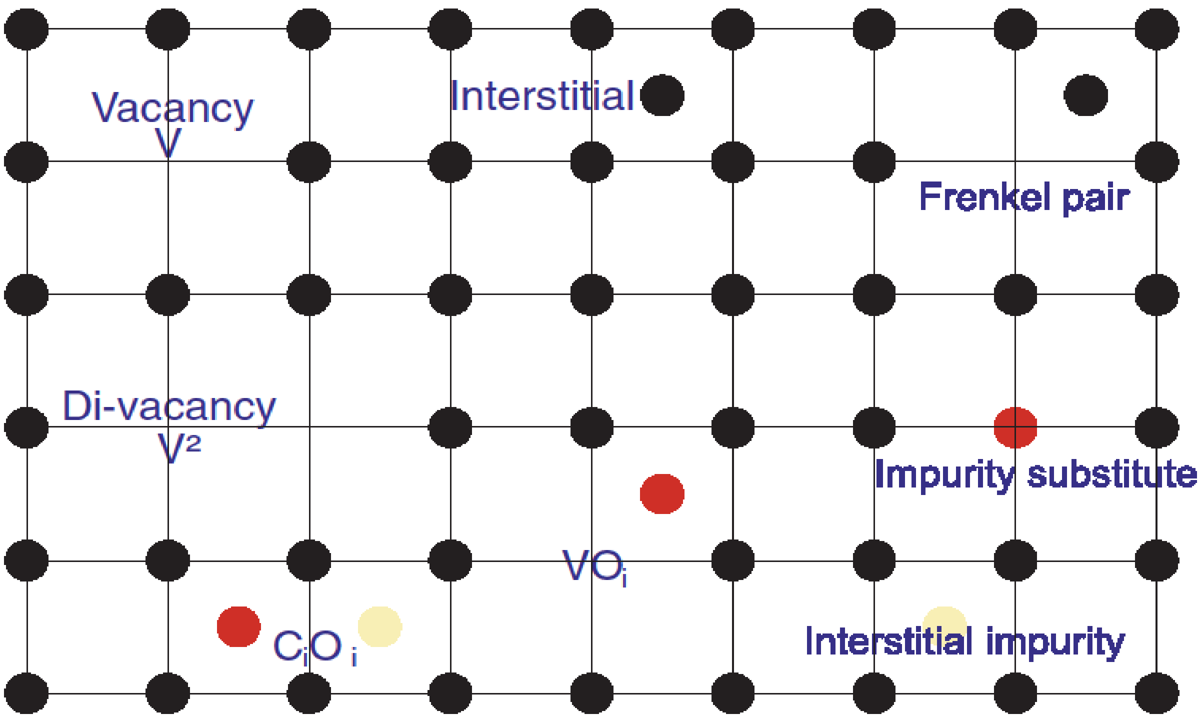
Why are we interested in the evolution of sensor properties?

- The silicon properties have a direct impact on the data quality
  - Decrease in signal, increase in noise

- The silicon properties strongly influence the power consumption and thus heat dissipation within the detector .
  - A reliable estimation for future evolution is important for the planing of the cooling improvements during the long shutdowns.

- At some point the silicon is not operational anymore.
  - We need to know when this will happen, and if we can do anything to delay this as much as possible.

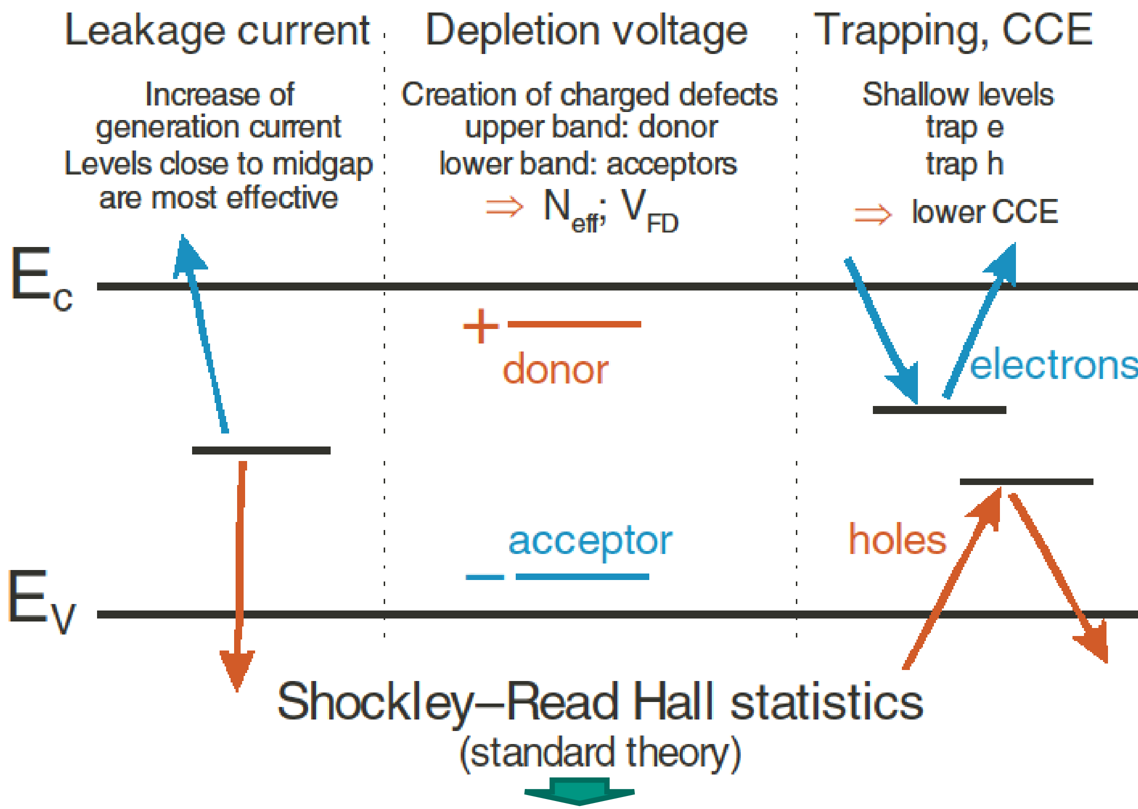
How do the properties change?



- Particles traversing the silicon material do not only interact with via ionization with the bulk, but also create defects in the crystal.

Defect impact on macroscopic properties

- High I_{leak}
- increases the noise
- Increases heat generation
- Power supply limitations



- Trapping
- Reduces signal strength

- V_{FD} needs to be kept small
  - Power supply limitations
  - Sensor breakthrough
  - Heat generation

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The leakage current

How can we describe this quantitatively?

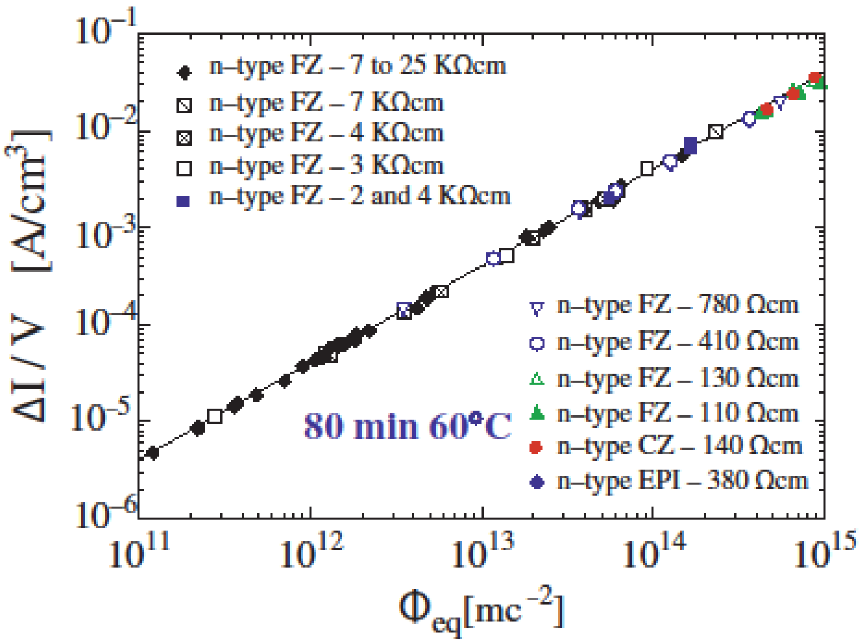
- Leakage current
  - Thermical induced current -> main dependency is the temperature

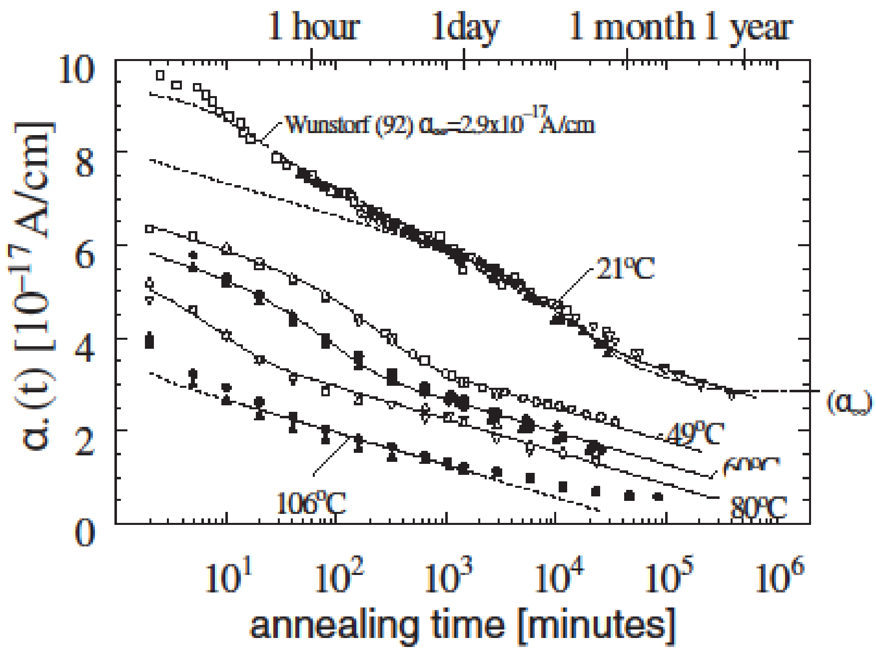
$$I_{leak} = I_0 \cdot \left(\frac{T}{T_0}\right)^2 \exp\left[\frac{E_{effg}}{2k_B}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right]$$

  - Radiation dependence is usually expressed in a radiation related damage rate:

$$\Delta I = \alpha(T,t) \cdot \Phi_{eq} \cdot V$$

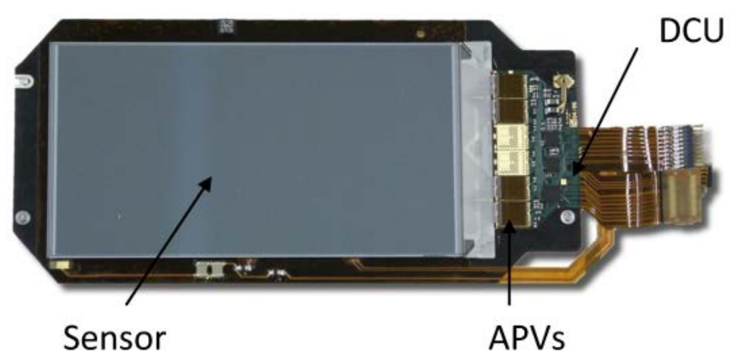
Radiation induced leakage current & annealing

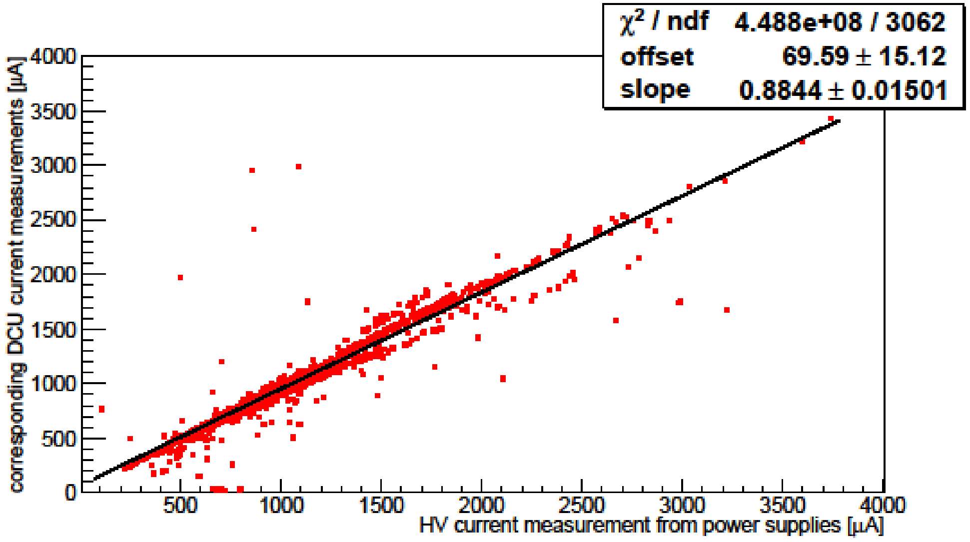




- Damage factor not material dependent and well known
- Annealing behaviour slightly more ambigous

Measuring leakage current and temperature





- The DCU aka detector control unit is a dedicated ASIC sitting on each of the tracker modules, with the ability to measure the temperature at different positions of the module as well as the leakage current and voltages applied
- Each high voltage line of our power supply system is connected to 3-12 modules, if we want to achieve higher granularity we need to use the DCU

Temperature distribution within the CMS strip tracker

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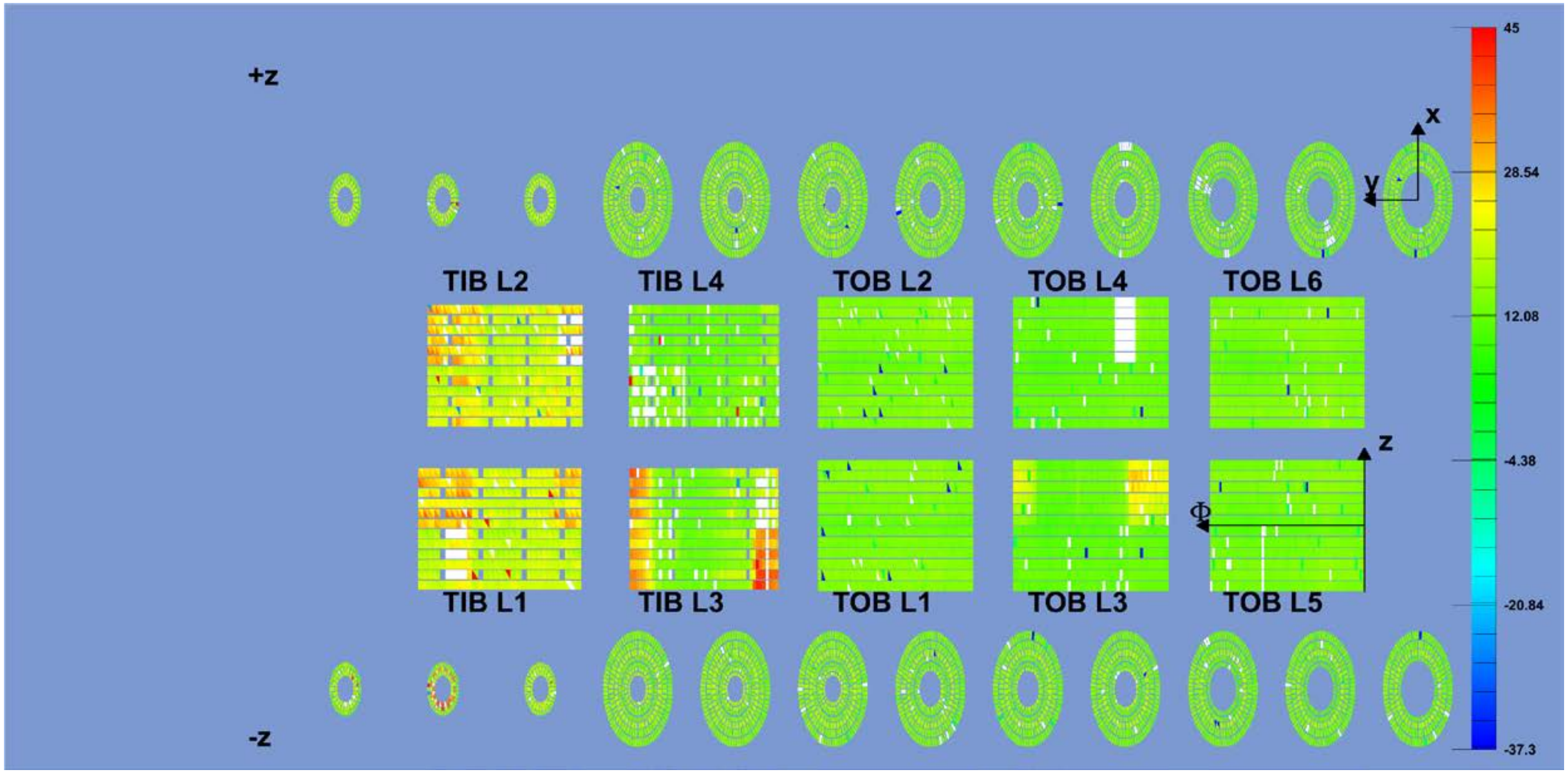
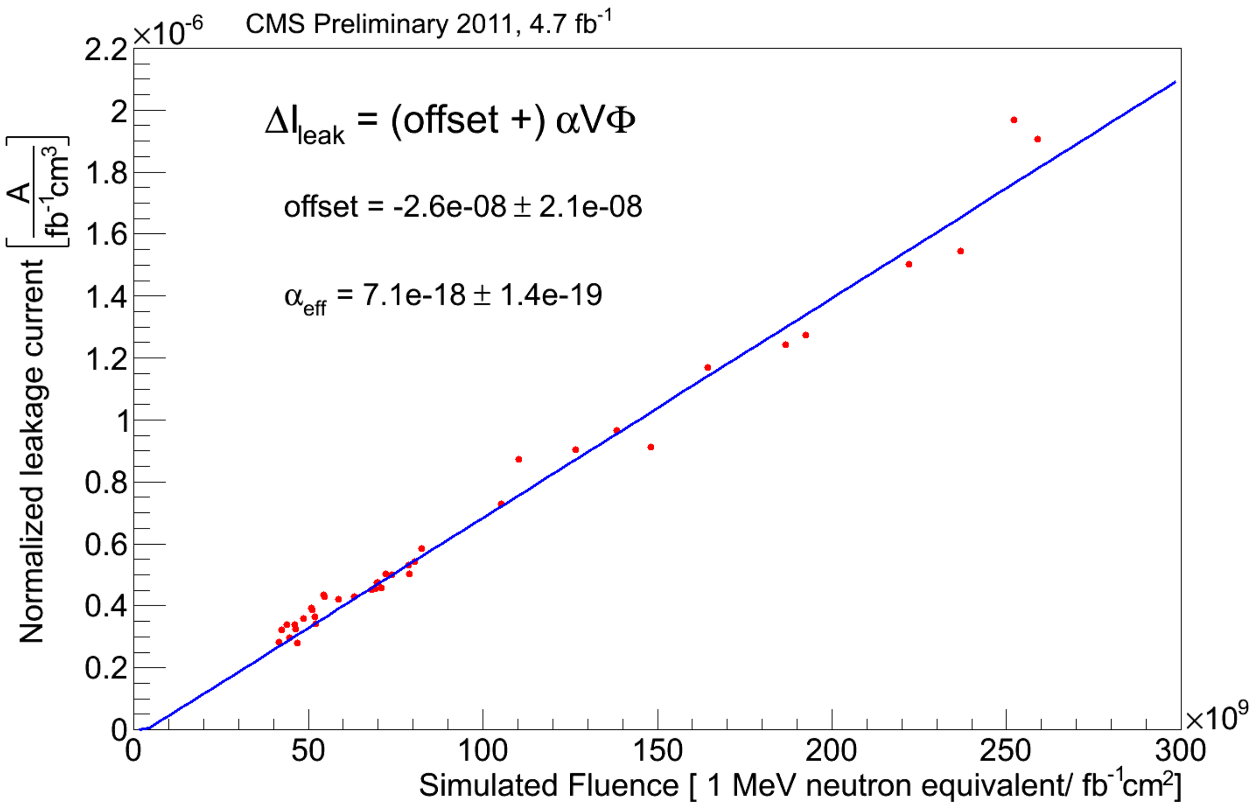


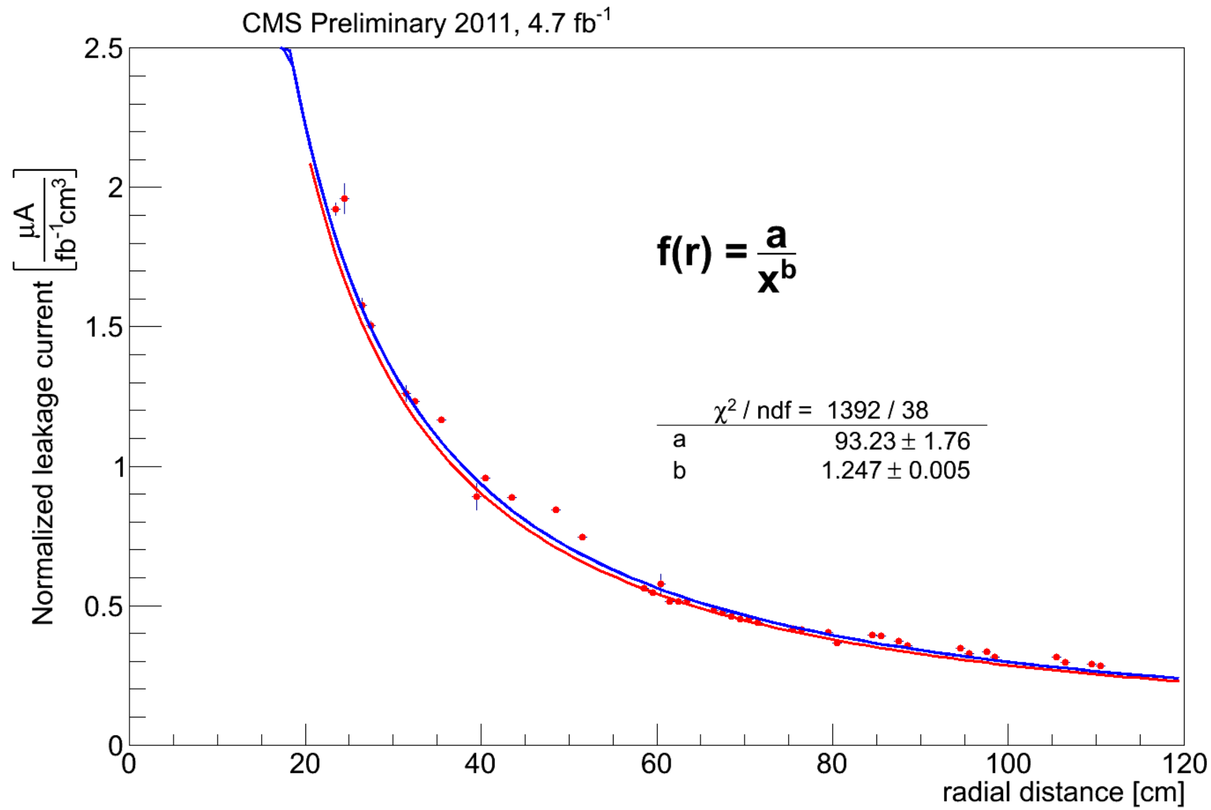
- Quite high temperature spread within the tracker (some elements un-cooled)
  - Current normalization is needed to allow comparison
  - Simulate the leakage current (+ V_{FD}) on module granularity
  - Radiation damage and annealing processes are simultaneously present

Measured alpha factor for the barrel region on the CMS strip tracker



- The leakage current have been normalized to 0°C, $1cm^3$ and $1fb^{-1}$ of integrated luminosity
- The corresponding fluence is taken from Fluka simulations of the particle interactions and transports in the tracker

Measured leakage current vs. fluence



- The measured leakage current normalized to 0°C and 1 cm^3 dependency in r matches very well with the simulated fluence expectations within the tracker volume.

Simulating tool

Inputs:

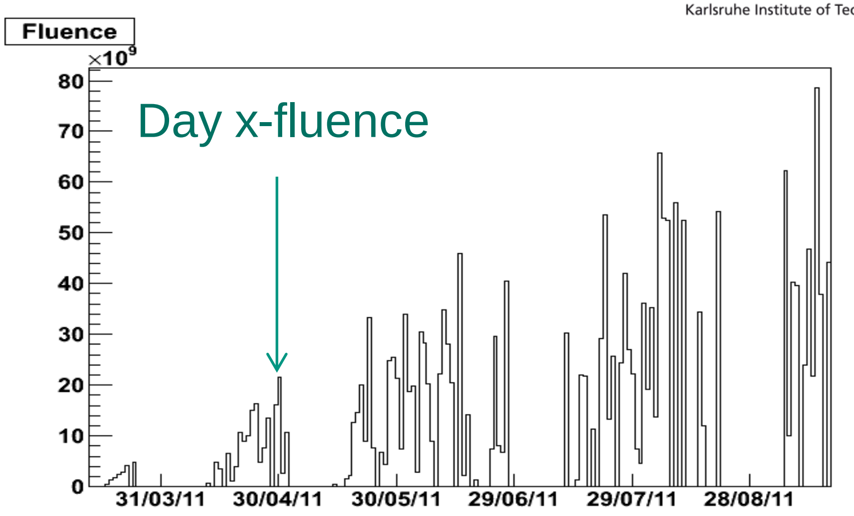
- Fluence at the module position
  - Linear interpolation of Fluka grid values (& integrated luminosity)
- Temperature of the modules
  - Measured by DCU

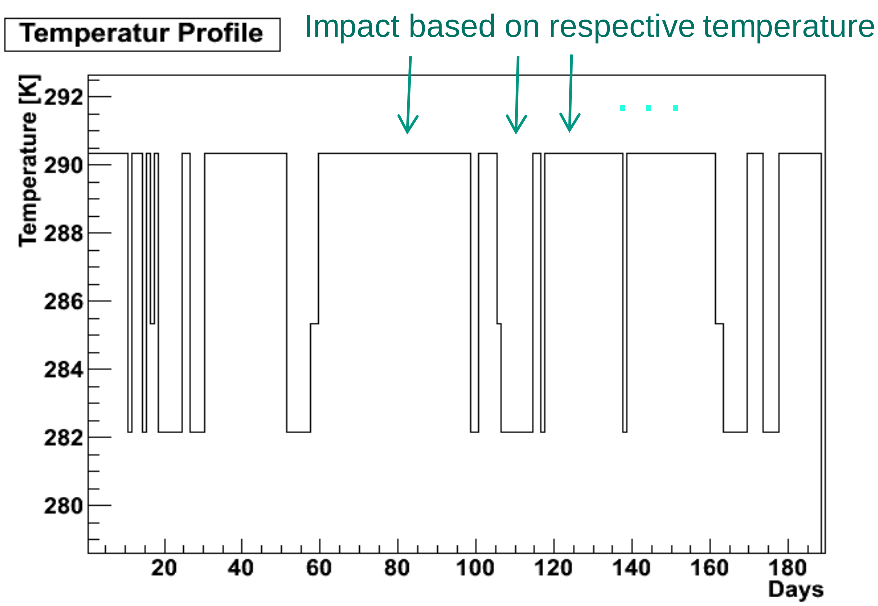
Method/Tools:

- Histograms filled with one bin per day for the temperatures and fluences
- Afterwards the impact of each day's fluence to all consecutive days is computed with the annealing time constants based on the given temperature at the respective day.
- The integrated sum over all days gives the result

Output:

- Leakage current
  - Leakage current of modules for comparison
    - Measured by DCU, cross checked by PS values
- Depletion voltage
  - Tools to determine Vdep in-situ exists





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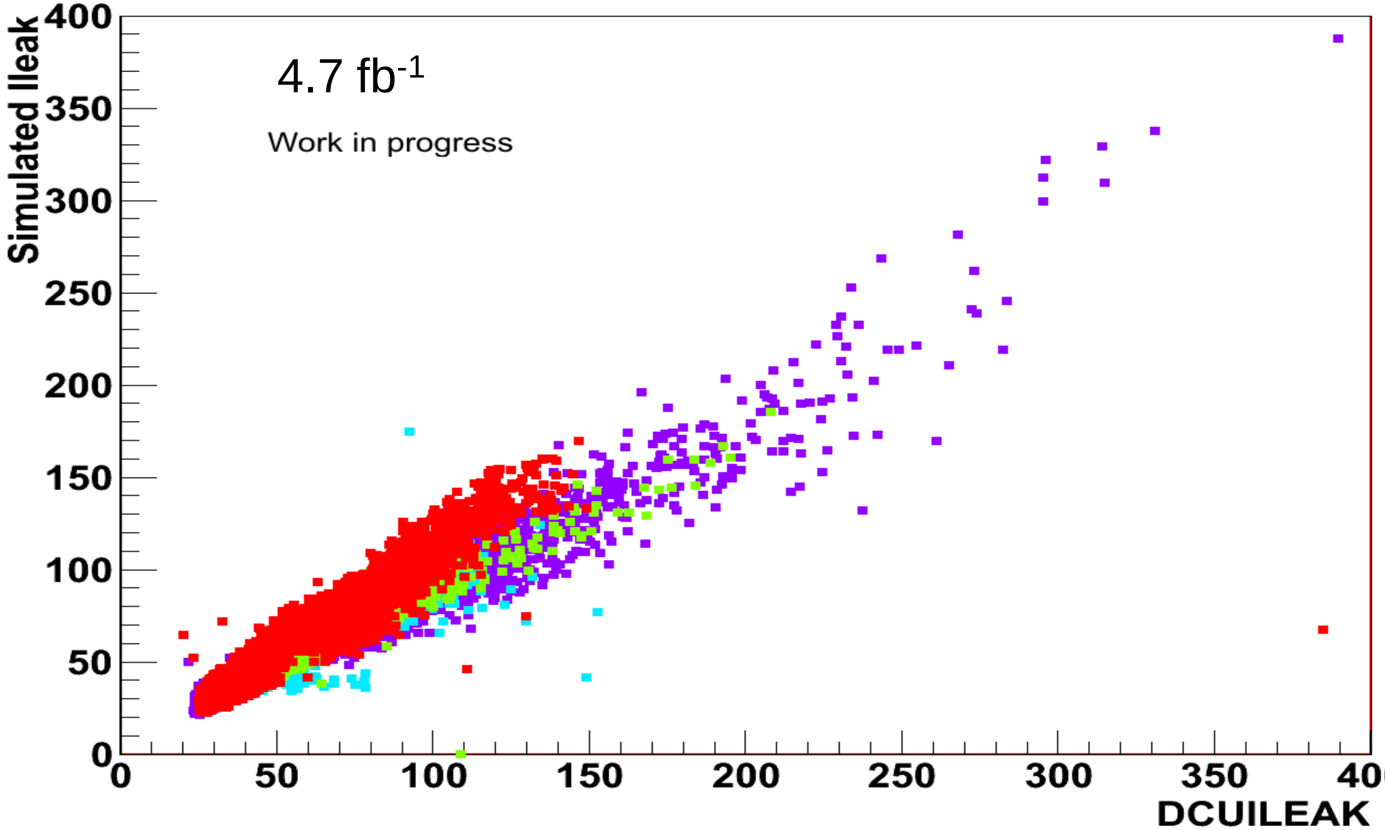
Comparison between simulation and measurement



- Simulation inputs:
  - Simplified temperature history based on on/off times (module granularity)
  - Measured integrated luminosity (per day)

Full Depletion Voltage

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Radiation induced change in full depletion voltage

- Described by Hamburg Model:

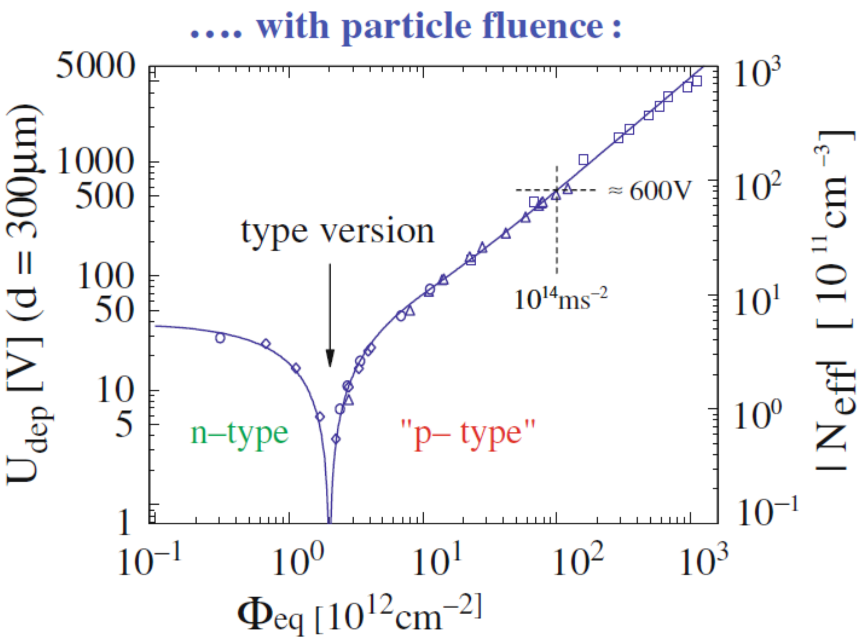
$$\Delta V_{FD} \propto \Delta N_{eff} = N_A(\Phi_{eq}, t, T) + N_C(\Phi_{eq}) + N_Y(\Phi_{eq}, t, T)$$

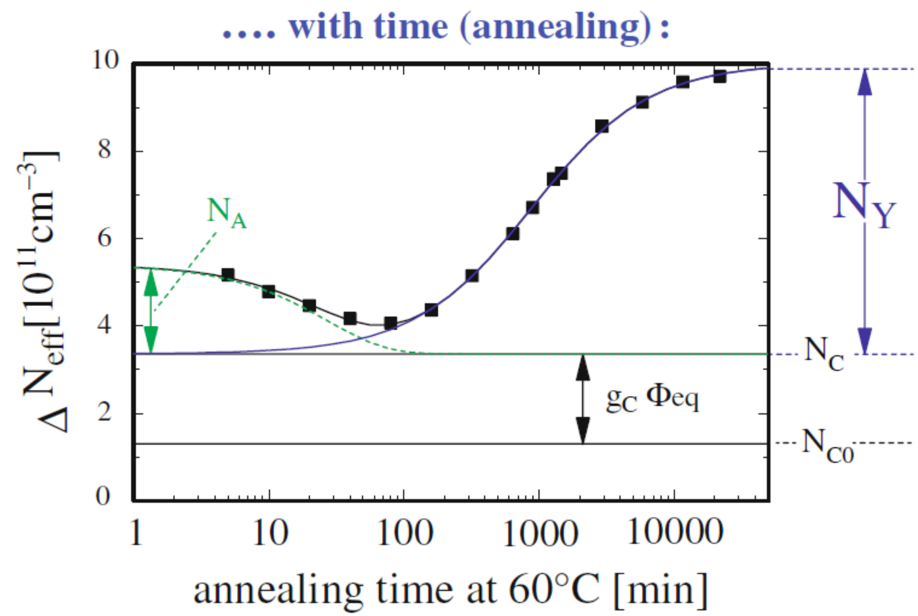
- Short term annealing
  - Low time constant
  - Beneficial with respect to effective doping concentration
- Defects anneal to less harmfull structures

- Stable damage term
  - Temperature and time independent
  - No annealing process taking place (in the considered temperature regime)

- Long term annealing
  - High time constant
  - Annealing is reverse with respect to short term annealing
- Defects anneal to more harmfull structures

Radiation induced change in full depletion voltage





- N-type silicon bulk material undergoes type inversion.
- Annealing has significant impact on V_{FD} change.

Depletion voltage measurement approaches

- Two Measurement types under development:
  - Noise Bias Scan
    - Using only module intrinsic noise, performed during interfill periodes for the whole tracker.
  - Signal Bias Scan
    - Using particle tracks recorded during stable beam collisions.
      - 2 – 3 times per year for the whole tracker.
      - Monthly for a small subset (5 PGs) without significant impact on data quality.

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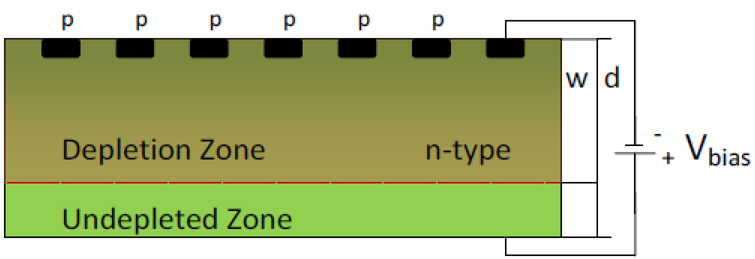
Noise method spotlight



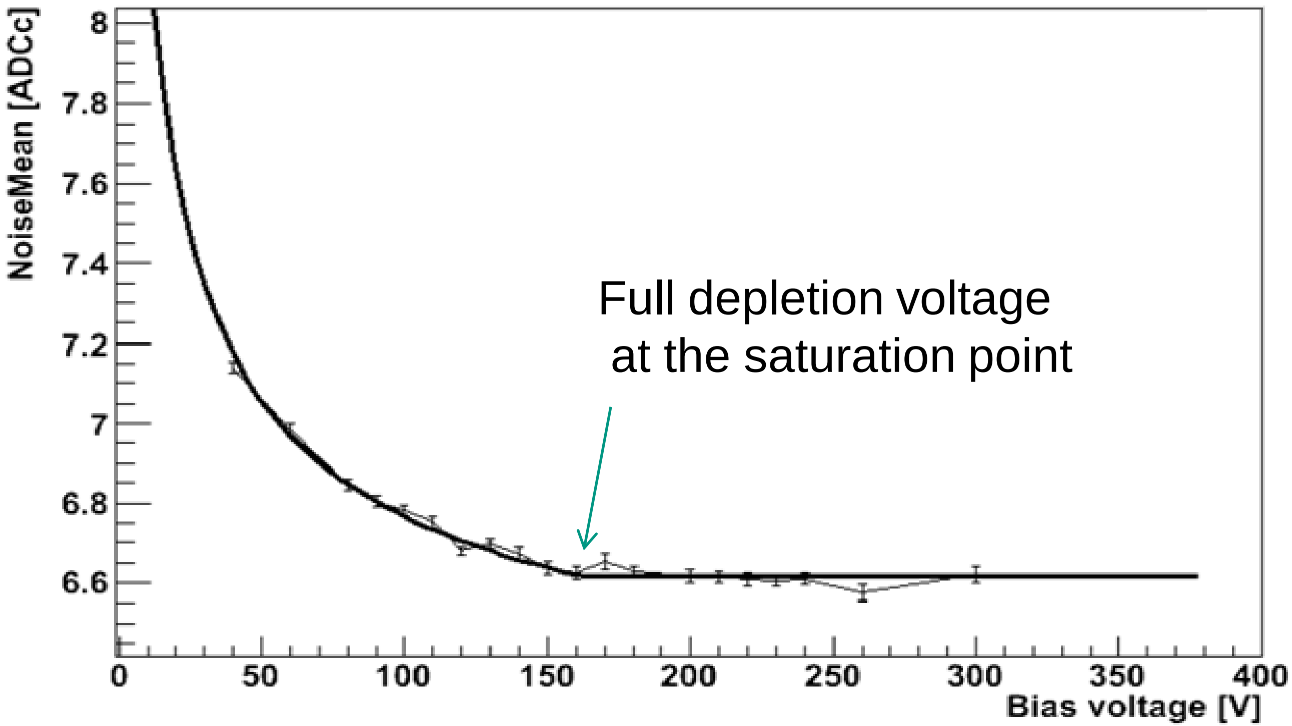
The width of the depletion zone is $w = \sqrt{\frac{2\epsilon_{Si} V}{q|N_{eff}|}} = d\sqrt{\frac{V}{V_{depl}}}$ this leads to

$$C = C_0\sqrt{\frac{V_{depl}}{V}} \quad for \quad V < V_{depl}$$
$$C = C_0 \quad for \quad V \geq V_{depl}$$

this leads with the readout electronic specific parameters A and B to

$$n = \sqrt{(A + B \cdot \sqrt{\frac{V_{depl}}{V}})^2 + others^2} \quad for \quad V < V_{depl} \quad ; \quad n = n_0 \quad else$$

Fitting noise data



- Fit is working reliable for moderate full depletion voltage values.
- With increasing full depletion voltage values, the fit becomes less and less accurate.

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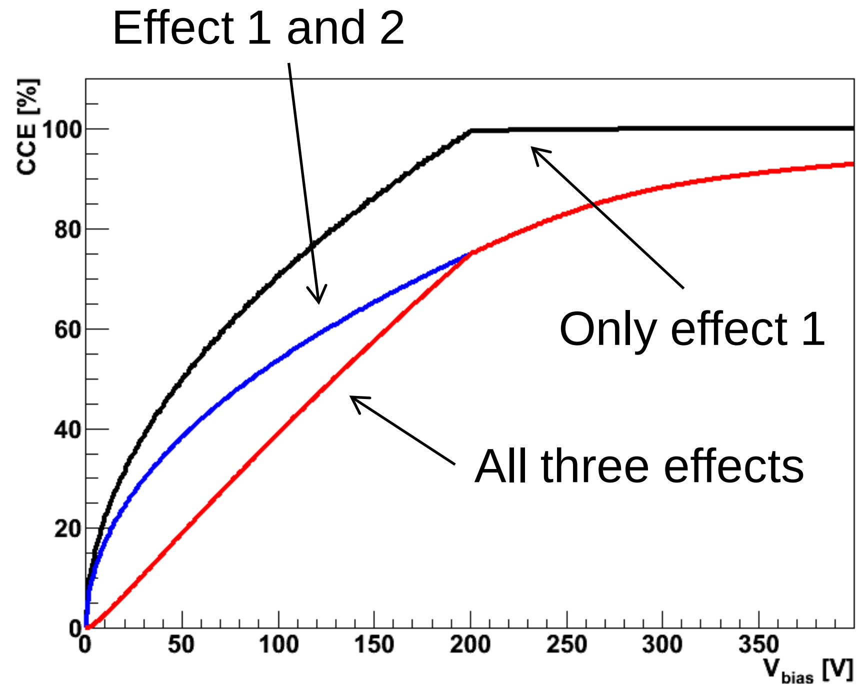
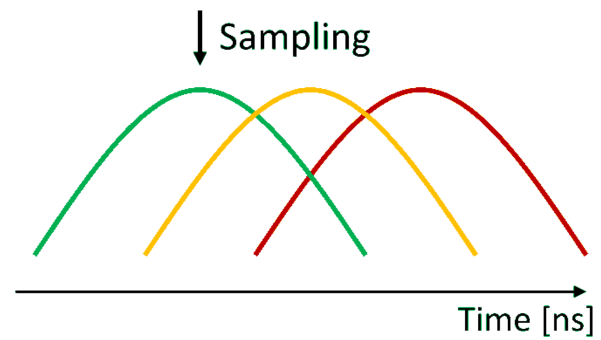
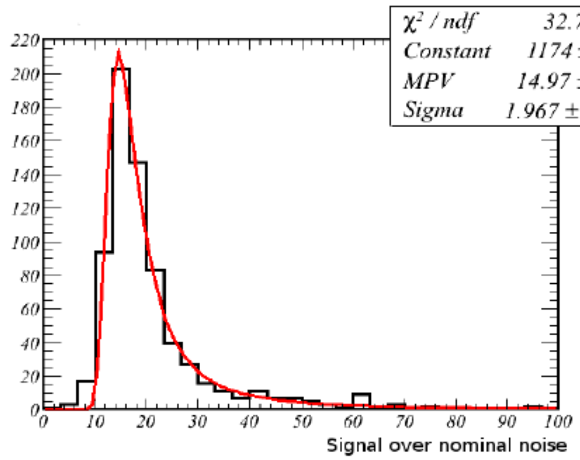
Signal method spotlight

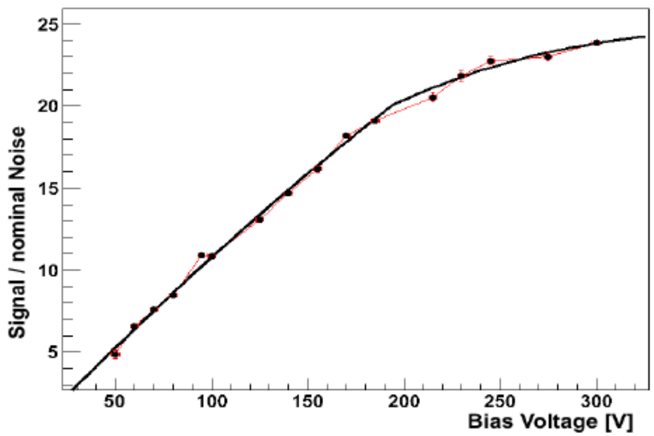
- Three effects are taken into account with our model:
  - Variation of depletion zone width.
  - Change in the mobility of charge carriers.
  - Change in the load capacitance of the APV leading to a suboptimal sampling.





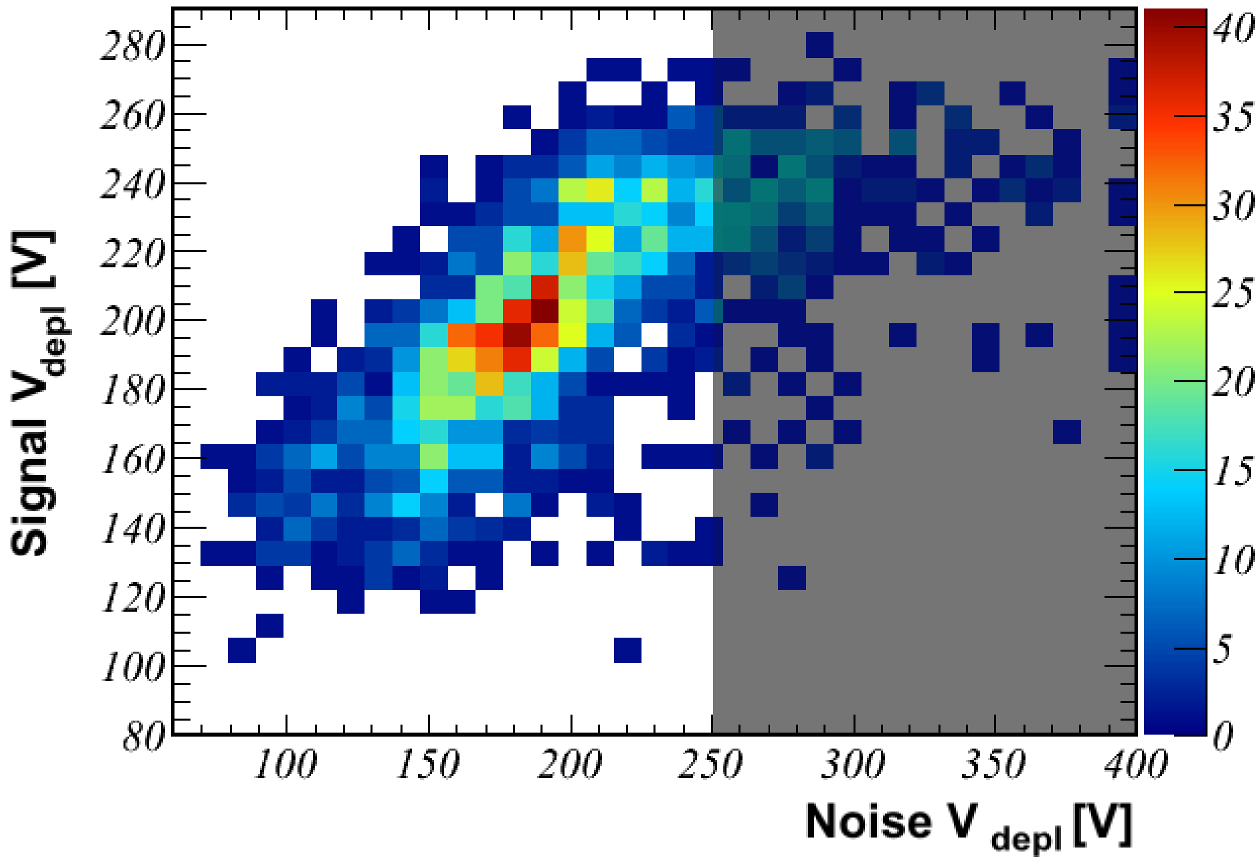
Analysis of signal bias scan





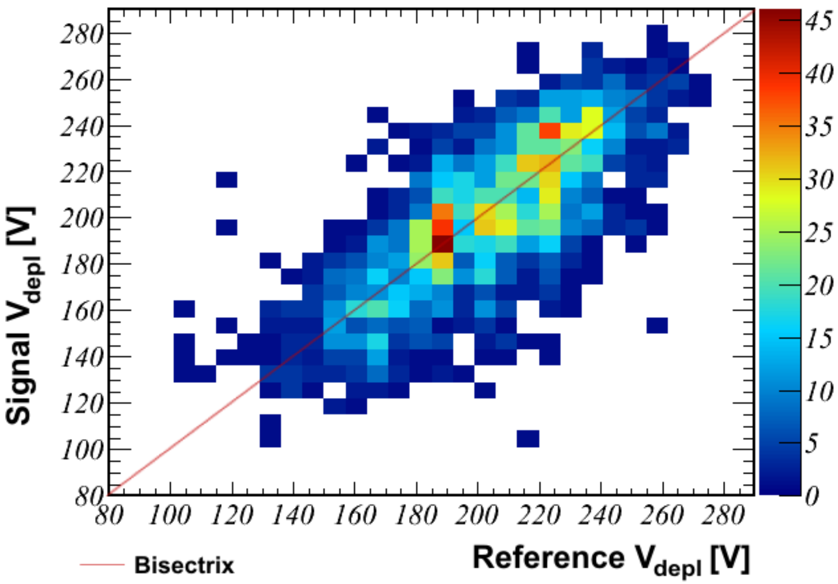
- For each given bias voltage the distribution of the collected charge per hit is analyzed
- This distribution is fitted with a Landau, resulting in a peak and an error
- We use only hits from good tracks ($\chi^2 < 5$) as well as MPVs with an error smaller than 5
- The graph is fitted with the corresponding curve obtained through simulation

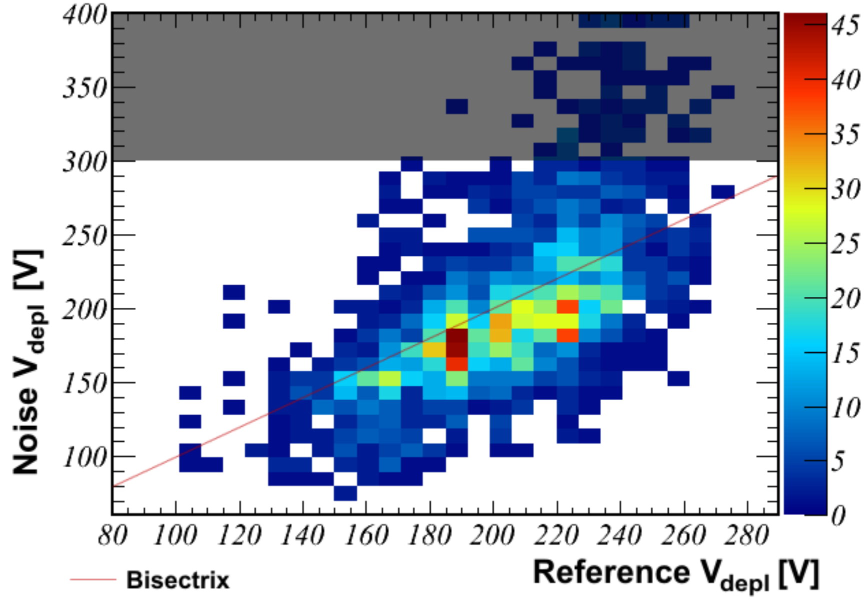
Method compatibility



- Correlation plot between the results of the signal method vs. the noise method in the tracker outer barrel partition.

Comparison between laboratory CV measurement and in situ approaches





- Correlation to CV measurements performed during the production of the strip tracker.

Summary

- Tools have been developed to simulate leakage current and depletion voltage.
  - Radiation damage, annealing, self-heating are taken into account.
  - Tool uses historic daily information and the “integrates” on a day-by-day basis.
- We validated the tool against the measured leakage currents.
- Work is on-going to validate also together with our LHC colleagues – (inter-experiment working group).
- We developed tools to determine the depletion voltages in-situ.
  - Interfill – Noise vs. bias.
  - Stable Beam – Signal vs. bias.
  - Results matching the CV measurement during production.
    - No detailed analysis of V_{FD} evolution possible with current fluence & accuracy of the measurement.

No time for . . .

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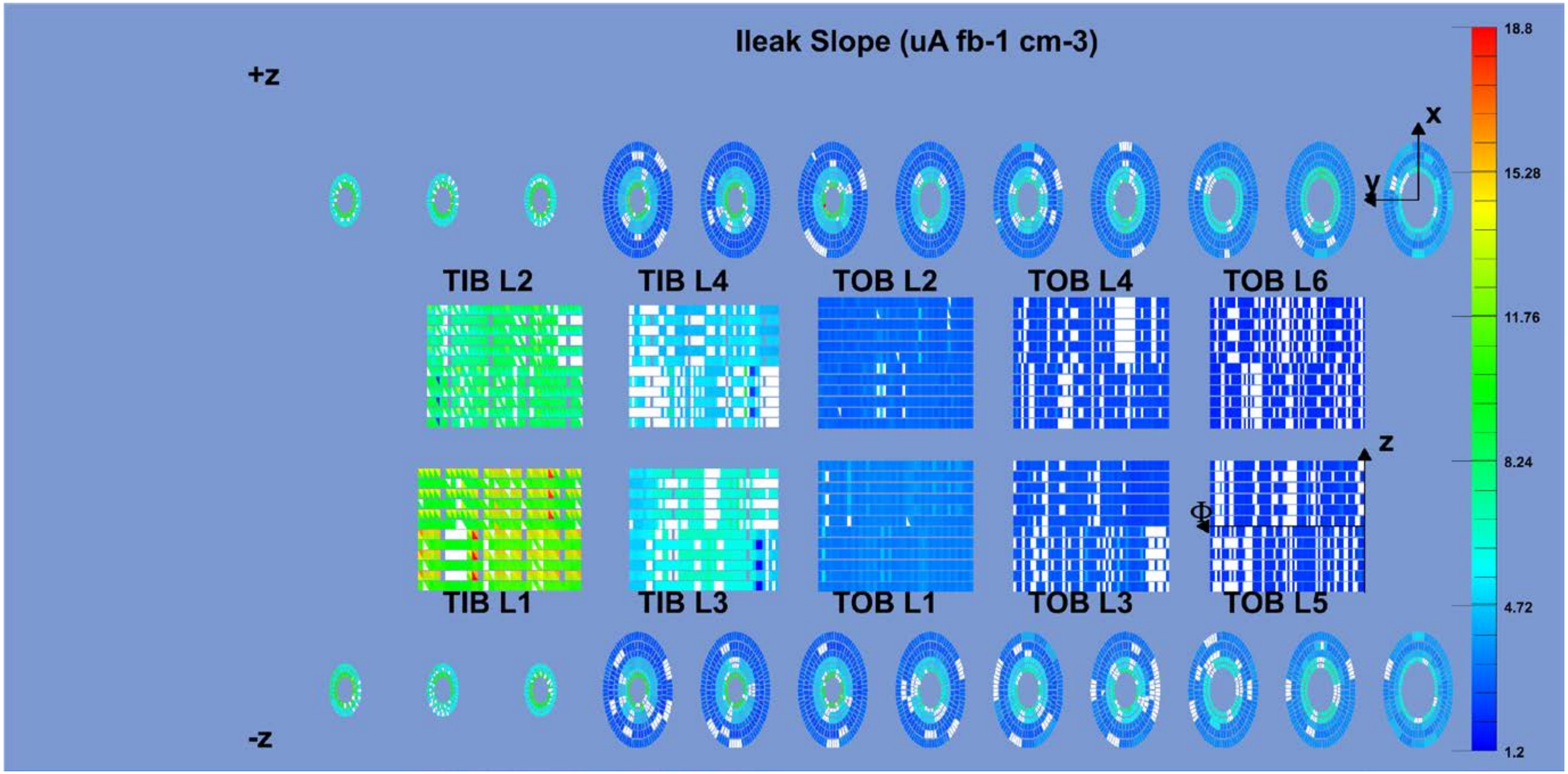
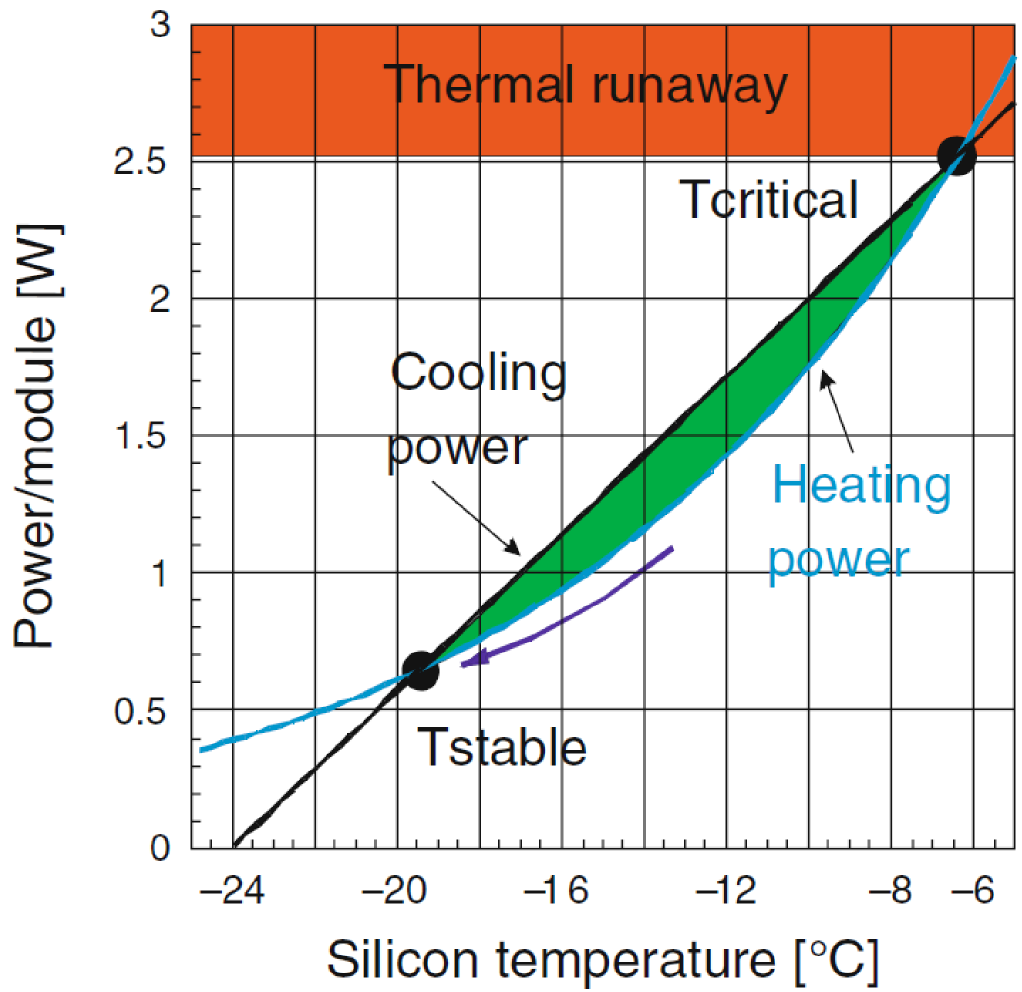
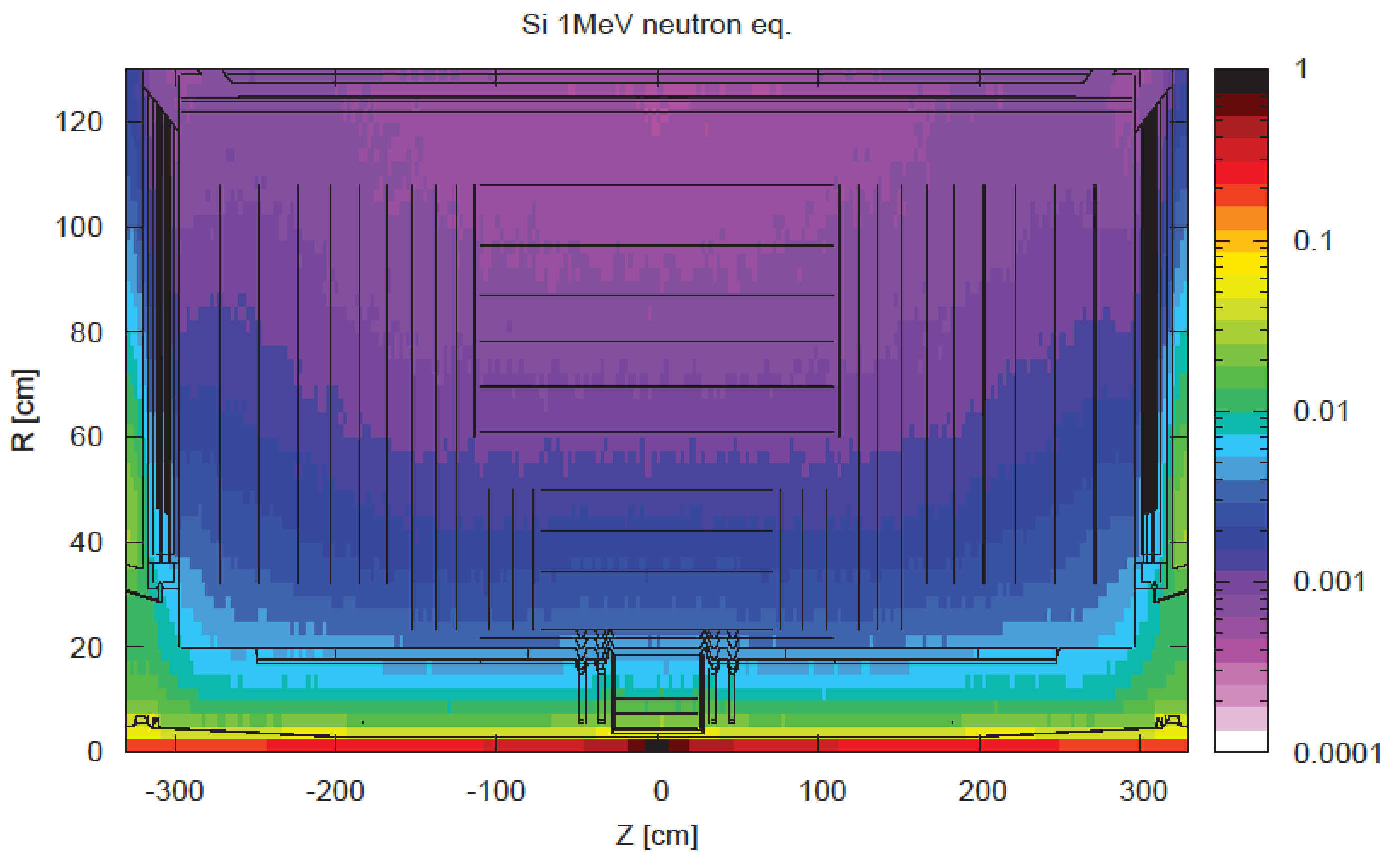
Tracker map of normalized leakage current



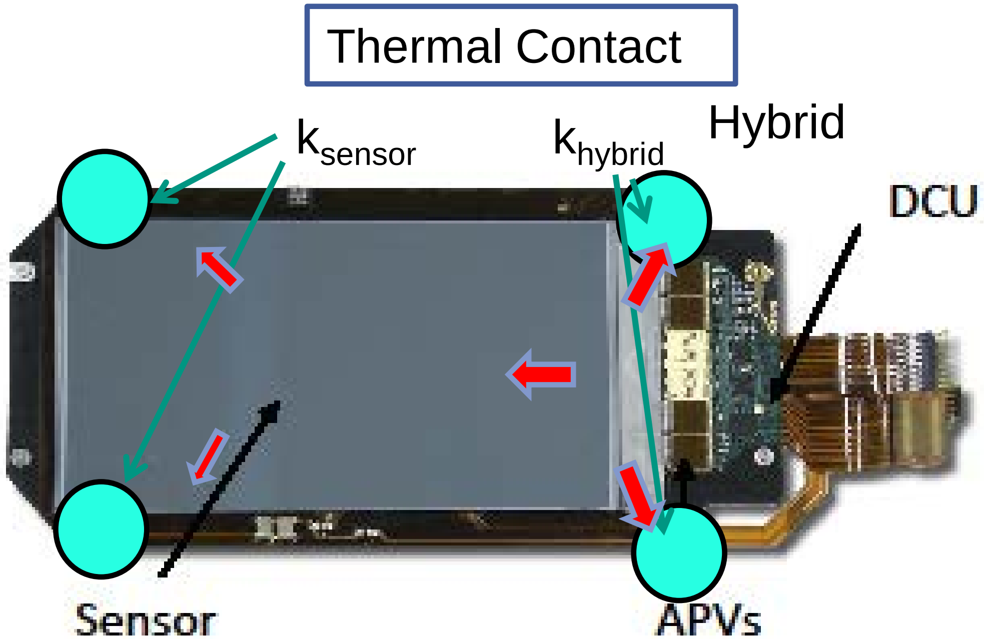
Thermal runaway



Fluka simulation



Power scan



TDR

End-cap

$$T_{Si} = 5.5\,\frac{\mathrm{K}}{\mathrm{W}} \cdot P_{Si} + 2.5\,\frac{\mathrm{K}}{\mathrm{W}} \cdot P_{Hyb} + T_{coolant}.$$

Barrel

$$T_{Si} = 5.7\,\frac{\mathrm{K}}{\mathrm{W}} \cdot P_{Si} + 2.2\,\frac{\mathrm{K}}{\mathrm{W}} \cdot P_{Hyb} + T_{coolant},$$

- Changing the power on the hybrid via VPSP results in a Temperature change on the hybrid
- This dT/dP is taken as an approximation for the dT/dP of the sensor
- FEA is planed to improve the approximation taking also the Tsil into account

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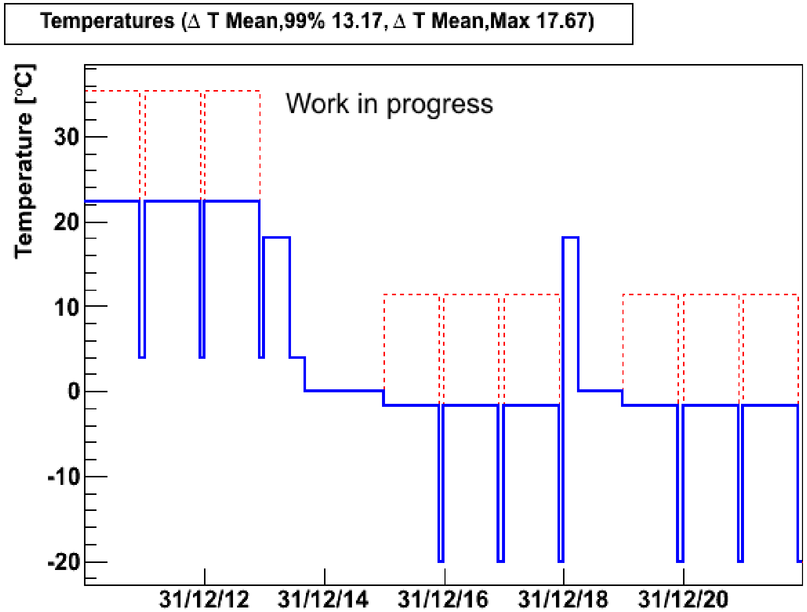
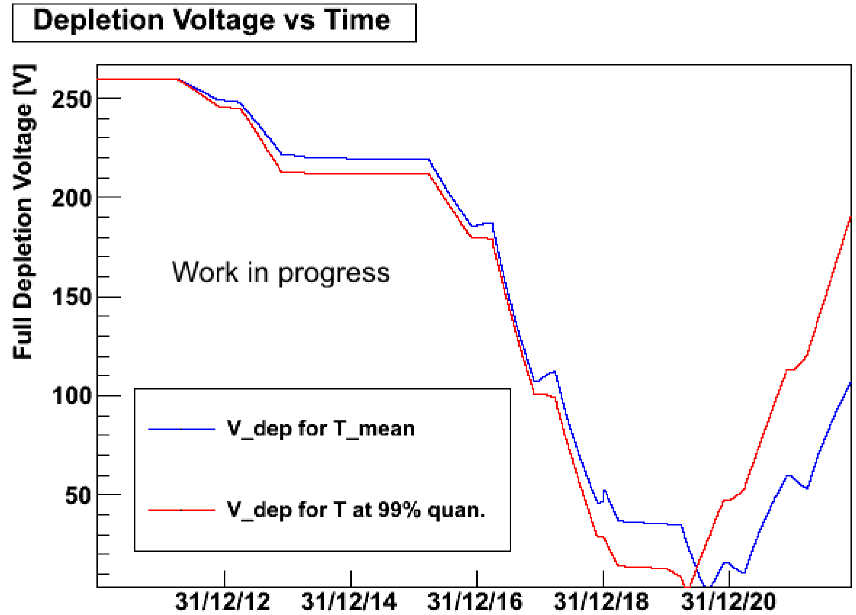
Full depletion projection





- Simulation for Tracker Inner Barrel Layer 1 with:
  - **High temperatures**
  - **High fluence exposure** (nearest to IP at r=24cm)
- Using a scenario with a total luminosity of 400fb^{-1} using the model & constants proposed in M. Moll's Ph.D. Thesis chap. 5 (**DESY-THESIS-1999-040**, December 1999, ISSN 1435-8085)
- The tracker specific constants used in the plot is presented in A. Dierlamm's Ph.D. Thesis chap. 3 (IEKP-KA/03-23)

NIEL – Non ionizing energy loss