Lorentz Angle Measurement in irradiated CMS Pixel Sensors

Setup and Results

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**Introduction**
- CMS Experiment
- Lorentz Angle
- Measurement principle

**Results**
- Bias Scan
- Lorentz Angle
CMS Detector

- General purpose detector at the LHC to measure the processes of high energetic particle collisions
- 3.8 T magnetic field
- Precision particle tracking with silicon sensors
CMS Phase I Pixel Detector

• The innermost part of the CMS Detector is the Pixel Detector
• The Pixel Detector measures the particles track for information on
  - The particle momentum
  - Vertex measurement (even more important for high pileup)
  - Secondary vertices → B tagging
• Phase I Pixel Detector, commissioned in 2017
  - **4 Barrel Layers** + 3 Endcaps
  - Expected irradiation of
    \[ \Phi_{eq} = 1.5 \times 10^{15} \text{ n/cm}^2 \]
    for the innermost layer
CMS Phase I Pixel Detector

- The CMS Phase I BPix detector module

Twisted pair cable

HDI (High Density Interconnect, signal and power handling)

n⁺-in-n silicon sensor

16 readout chips, bump bonded to sensor

Base strips for mounting

Sensor:
- n⁺-in-n sensor technology
- 285 um thickness
- 150 x 100 um pitch
- 52 x 80 = 4160 pixels/ROC
- 16 ROCs → 4160 x 16 = 66560 pixels/module
Lorentz Angle

- Charge carrier drift inside the sensor without magnetic field:
  \[
  \frac{d\vec{r}}{dt} = -\mu \vec{E}
  \]

- Charge carrier drift inside the sensor with magnetic field:
  \[
  \frac{d\vec{r}}{dt} = \frac{\mu \left(-\vec{E} + \mu r_H \vec{E} \times \vec{B} - \mu^2 r_H^2 \left(\vec{E} \cdot \vec{B}\right) \vec{B}\right)}{1 + \mu^2 r_H^2 |\vec{B}|^2}
  \]

- Effective Lorentz (deflection) angle: \( \tan(\theta_L) = r_H \mu B \)

- For optimal charge sharing between two rows and/or columns:
  - Charge carriers are deflected by one pixel’s pitch: \( \tan(\theta_L) = w/d \)
  - Optimal resolution \( \sigma \ll w/\sqrt{12} \)

\( \mu(\vec{E}) \): Electron mobility  
\( r_H \): Electron Hall factor  
\( w \): Pixel pitch  
\( d \): Sensor thickness
Lorentz Angle

- Charge carrier drift inside the sensor without magnetic field:
  \[
  \frac{dr^2}{dt} = -\mu \vec{E}
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- Charge carrier drift inside the sensor with magnetic field:
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Simulation: AllPix²
Measurement principle

- 2D scan:
  - Incidence angle (turn modules)
  - Magnetic field

- Find the track incidence angle resulting in the minimum horizontal cluster size for different magnetic fields
DESY II Test Beam Facility [1]

- Free positron or electron beams created from bremsstrahlung
- Energy: 1 – 6 GeV
- Particle rate: < 50 kHz (energy dependent)
- Three beam lines available
- This measurement:
  - TB 21
  - 5.6 GeV positrons
  - ~ 1 mrad angular spread
  - 1.35 T dipole magnet

[1]: http://testbeam.desy.de
CMS Pixel Detector Module Telescope

- CMS Pixel Module Telescope for use in the Test Beam:
  - 4 modules, 32 mm spacing
  - 19° tilt (optimal charge sharing, y), 0° or 27° turn (optimal charge sharing, x)
  - Cut out module handles for the reduction of material budget
  - Rotatable around y-axis (turn) and movable along x-axis
  - Use of non-magnetic materials
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  - **Isolation and ethanol cooling for last module**
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Results

Bias Scan
Lorentz Angle Measurements
Tested Modules

- Irradiated Module:
  - Fluence: $\Phi_{eq} = 4 \times 10^{14}$ n/cm$^2$ (25 MeV protons @ KIT)
  - Tested and calibrated → One ROC faulty
  - Result of the Bias Scan

- Eff. Lorentz angle measured at the following conditions:
  - Unirradiated:
    - +20°C, 150 V
    - -14°C, 150 V
    - -14°C, 250 V
    - -14°C, 350 V
  - Irradiated:
    - -14°C, 200 V
    - -14°C, 400 V
    - -14°C, 600 V

Thanks to T. Weiler et al. @KIT for providing the irrad. module!
Analysis

- Analysis per run (each angular / B-Field step of every scan):
  - Convert raw data to pixel hits, form clusters and calculate the hit position
  - Find tracks (corresponding hits in all planes) and perform a General Broken Lines (GBL) fit [2]
  - Alignment via Millepede II (after prealignment from residuals) for B = 0 T
  - Get isolated tracks with good GBL fits and apply charge cuts
  - Extract number of columns per cluster in the last plane
- Repeat this for the whole scan of the 2D matrix (B-Field / angle)
- Extract eff. Lorentz angle:
  - Calculate the incidence angle for each run from …
    - The modules turn angle
    - The predicted deflection caused by the magnetic field before reaching the telescope (propagation simulation)
  - Perform fit (number of columns vs angle) for each magnetic field strength to yield the shift of the angle with the minimum cluster size

[2]: C. Kleinwort, General broken lines as advanced track fitting method
Results

- Unirradiated, -14°C, 150 V Bias

- Fit for each magnetic field
  \[ f(x) = p_0 + \sqrt{p_1^2 + p_2^2(x - x_{\text{min}})^2}, \quad x = \tan(\theta) \]

- Measured Lorentz Angle \( \theta_L(1.27 \, \text{T}) \) = \( (7.44 \pm 0.05) ^\circ \)

- Extrapolated to CMS operational conditions \( (3.8 \, \text{T}) \):
  \[ \theta_L(3.8 \, \text{T}) = (21.34 \pm 0.45) ^\circ \]

- Comparison to CMS data \( (2011, 150 \, \text{V}, 0^\circ \, \text{C}) \): [3]
  \[ \theta_L(\text{CMS}) = (21.74 \pm 0.05) ^\circ \]

- Fits the angle for the optimal charge sharing
  \[ \Rightarrow \text{Optimal resolution} \]
Results

- Overview over all scans performed

- Increase in bias voltage
  - Decrease in eff. Lorentz angle
    \[ \tan(\theta_L) = r_H \mu B \]

- Mobility is a function of the electric field
  \[ \mu(E) = \frac{\mu_0}{\left(1 + \left(\frac{\mu_0 E}{v_{sat}}\right)^\beta\right)^{1/\beta}} \]

- \( \mu(E) \): Electron mobility
- \( r_H \): Electron Hall factor
- \( v_{sat} \): Saturation drift velocity
- \( \beta \): Free parameter (\( \approx 1 \))
Results

- Overview over all scans performed

- Increase in temperature
  - Decrease in eff. Lorentz angle
    \[ \tan(\theta_L) = r_H \mu B \]
  - Mobility is a function of temperature
    \[ \mu(T) \approx A \cdot T^{-2.42} \]

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\( r_H \): Electron Hall factor
\( v_{sat} \): Saturation drift velocity
\( \beta \): Free parameter (\( \approx 1 \))
Results

- Overview over all scans performed

- Increase in irradiation fluence
  - Increase in eff. Lorentz angle
    \[ \tan(\theta_L) = r_H \mu B \]
  - Radiation damage leads to a non-linear electric field in the bulk
  - More sophisticated models needed to describe the Lorentz drift in silicon sensors

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- Similar behavior can be seen in measurements at the previous CMS Pixel detector [3]
  - Trend in eff. Lorentz Angle vs. integrated luminosity

Bias Voltage 150 V → 200 V

Figure: CMS Preliminary 2016 Run I + Run II

Integrated luminosity [fb⁻¹]

[3]: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PixelOfflinePlots2016
Conclusion

• CMS Pixel Module Telescope was upgraded with cooling mechanics and isolation
  − High temperature stability and realistic operational conditions
  − Enables measurements with irradiated sensors

• Measurement of the effective Lorentz angle under various conditions
  − Lorentz angle in unirradiated sensor matches the results yielded with the previous CMS Pixel Detector and the requirement for optimal resolution
  − Measured the effects of temperature, bias voltage and irradiation

• Outlook:
  − Comparison to models and simulation
Backup

Restricted Area
CMS Module Telescope – Triggering and DAQ

- CMS Pixel Detector Telescope TDAQ:
  - External scintillator as particle trigger
    - Particles are only allowed during an 11 ns time window inside the 25 ns clock
  - 4 DTBs as DAQ boards
  - EUDAQ as DAQ software
    - Each plane runs as a producer
    - Raspberry Pi controller and NIM coincidence unit instead of TLU:
      - GPIO pins are connected to a NIM coincidence unit (GPIO→LEMO)
      - RPi Controller switches on (off) the triggers when all producers are ready (are still running)
CMS Module Telescope – Images

- 27° tilted module mounting
- Module handle cutouts
Magnetic field map – Big Red Magnet

DESY test beam 21, dipole MD (365 mm gap), long. field profile
Results – no cooling applied

- Two scans performed:
  - Around $\alpha = 0^\circ$
  - Around $\alpha = 27^\circ$

\[
f(x) = p_0 + \sqrt{p_1^2 + p_2^2(x - x_{\text{min}})^2}, \quad x = \tan(\theta)
\]

\[
\theta_L(1.27 \text{ T}) = (5.84 \pm 0.14)^\circ
\]

\[
\tan(\theta_L) = r_H \mu B
\]