X/X₀ measurements at the CERN SPS test beam 2014

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[Logos of Georg-August-Universität Göttingen and Volkswagen Stiftung]
**X/X₀ Measurement at CERN**

**first step: Calibration on metal grid**
- calibrated angle reconstruction error $\sigma^*_\text{err} = \lambda \cdot \sigma_{\text{err}}$, $\lambda$: calibration factor
- core width of multiple scattering (MSC) projected angle distribution is then given by
  \[
  \sigma = \sqrt{\sigma_{\text{measured}}^2 - \lambda^2 \cdot \sigma_{\text{err}}^2}
  \]
- Calculate $X/X₀(\sigma)$ by using an appropriate MSC model
- optimize $\lambda$ by comparing the measured values to the grid

**second step: Measurement on DEPFET**
- Use this optimal $\lambda$ in the DEPFET $X/X₀$ measurements
Peaks in kink angle distributions
Caused by digital readout of M26 pixels and discretization of hit position

No smearing

<table>
<thead>
<tr>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>6243</td>
<td>1.01e-06</td>
<td>4.038e-05</td>
</tr>
</tbody>
</table>

Effects dependent on:
- width of the MSC angle distribution → beam energy
- telescope setup
- $(\gamma)$ misalignment of the telescope planes
- size of the measurement area
Peaks in kink angle distributions
Caused by digital readout of M26 pixels and discretization of hit position

2 µm smearing

Entries 12492
Mean 5.959e-07
RMS 4.562e-05

effects reduced by:
- merging distributions of both projected angles
- adding artificial gaussian noise to the reco hit position (smearing)
Effects of adding artificial noise

The addition of gaussian noise also increases the covariances of the hit position. This effectively worsens the spatial and kink angle resolution.

General problem at CERN: \( \sigma / \sigma_{err} \) is very small

- \( \sigma_{err} \) should be of the same order as \( \sigma \)
  - \( \rightarrow \) smearing \( \geq 4 \)
  - shouldn’t be used
- Smearing of \( \approx 2 \mu m \)
  - seems to be a good choice
MSC models

Highland (HL) model

\[
\sigma = \frac{0.0136 \cdot q[e]}{\beta \cdot p[GeV]} \cdot \sqrt{\frac{X}{X_0}} \left(1 + 0.0038 \ln \left(\frac{X}{X_0}\right)\right)
\]  

(1)

V. L. Highland, *Some practical remarks on multiple scattering*, Nuclear Instruments and Methods, 1975

Frühwirth model

\[
\sigma = \sqrt{\mu_2(d')} \cdot \sqrt{(0.851 + 0.0331 \ln d' - 0.001825(\ln d')^2)}
\]  

(2)

with \[\sqrt{\mu_2(d')} = \sqrt{225 \cdot 10^{-6} \cdot d'/p^2}, \]

\[d' = \frac{X}{h(Z) \cdot X_0}\]

and \[h(Z) = \frac{Z + 1}{Z} \cdot \frac{\ln (287 Z^{-1/2})}{\ln (159 Z^{-1/3})}\]

Aluminum grid

- 0.5 mm thick aluminum layers, with different hole configurations
- taped to M26 frame
- increase of material budget by 0.56% per hole
Selection of measurement areas

X/X0 map of run 169, 170 and 171

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X/X0 measurements at the CERN SPS test beam 2014
Calibration (HL model)

- Comparison between measured and real $X/X_0$ values via $\chi^2$ test

![Graph showing measured $X/X_0$ values (Highland model)
lambda=1.000]

Global fit: chi2=69.656202
measured $X/X_0$ values
aluminum $X/X_0$ values
Calibration (HL model)

- Comparison between measured and real $X/X_0$ values via $\chi^2$ test
- best fit: $\lambda = 1.010 \pm 0.002$
Comparison between measured and real $X/X_0$ values via $\chi^2$ test

- best fit: $\lambda = 1.010 \pm 0.002$
Calibration (HL model)

- Comparison between measured and real $X/X_0$ values via $\chi^2$ test
- Best fit: $\lambda = 1.010 \pm 0.002$
- But linear fit: slope $= (0.63 \pm 0.01)\%$ → too large
- → Use Frühwirth model
Calibration (Frühwirth model)

- best fit:
  \[ \lambda = 1.008 \pm 0.002 \]
Calibration (Frühwirth model)

- best fit:
  \[ \lambda = 1.008 \pm 0.002 \]

- large \( X/X_0 \) difference for area 3 → 4 and area 6 → 7
Calibration (Frühwirth model)

- best fit: \( \lambda = 1.008 \pm 0.002 \)
- large \( X/X_0 \) difference for area 3 \( \rightarrow \) 4 and area 6 \( \rightarrow \) 7
- Linear fit: slope=(0.56\( \pm \)0.01)\% \( \rightarrow \) very close to expected value

Calibration results

Use this MSC model and \( \lambda=1.008\pm0.002 \) for further \( X/X_0 \) analysis
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$X/X_0$ measurements at the CERN SPS test beam 2014
Preliminary DEPFET $X/X_0$ measurements

PCB fit

$X/X_0 = (2.67 \pm 0.11)\%$

Expected: $0.45\%$

$X/X_0$ difference

$X/X_0 (\text{PCB-thinSI}) = 1.29 \pm 0.15\%$

Expected: $\approx 1.4-1.5\%$
Preliminary DEPFET $X/X_0$ measurements

**thick Si $X/X_0$**

$X/X_0$(thickSi) = 0.93±0.22%

expected: 0.45 %
Preliminary DEPFET $X/X_0$ measurements

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$X/X_0(\text{thickSi}) = 0.93 \pm 0.22\%$

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Preliminary DEPFET $X/X_0$ measurements

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X/$X_0$ measurements at the CERN SPS test beam 2014
Conclusion

- Radiation length resolution of $\Delta X/X_0 = 0.1\%$ using bins of $(500 \ \mu m)^2$ at a beam energy of 120 GeV
- Calibration via aluminum grid works well, differences between Highland and more sophisticated MSC models can be seen
- Main problem of $X/X_0$ analysis at CERN: Gaps in kink angle distributions caused by digital readout of M26 telescope sensors
- Gaussian smearing of the hit position is a temporary solution of this problem
gaussian smearing of hit position worsens the angle resolution and should be eventually replaced by another procedure → more detailed study of the effects of digital readout

- calibration measurements can be used to study difference between MSC models
- Reapeat calibration measurements at lower beam energies of 3-4 GeV (DESY) → $\Delta X/X_0$ will get even smaller
Thanks for your attention!
Backup Slides
Reconstruction of MSC angles in a EUDET teleskop

- Reconstruct angles on the DEPFET
- Particle crosses sensor $\rightarrow$ hits

Forward-backward Kalman Filter (KF) pair on hits

hit on DEPFET not needed $\rightarrow$ maps

Take MSC in air gaps into account

$\theta_p$ calculated from $(m_u, m_v)$

Reco error $\sigma_{reco}$ from error propagation
Reconstruction of MSC angles in a EUDET teleskop

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\[ \theta_p \text{ calculated from } (m_u, m_v) \]

Reco error \( \sigma_{\text{reco}} \) from error propagation

23mm 27mm 111mm 67mm 28mm 27mm

Mimosa Pixel Sensoren
Pixel Pitch 18.4 µm

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X/X₀ measurements at the CERN SPS test beam 2014
Reconstruction of MSC angles in a EUDET teleskop

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**Mathematical Formulas**

$\eta = (u, v, m_u, m_v)$

TrackState $C$ Cov. Matrix $C$

Forward KF In-State $(\eta_f, C_f)$

Backward KF Out-State $(\eta_b, C_b)$

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$X/X_0$ measurements at the CERN SPS test beam 2014
Example of a reconstructed angle distribution

Composition of the Reco Distribution

Reconstructed MSC angle distribution is a convolution between the truth MSC distribution and a Gaussian noise distribution caused by the reconstruction errors.

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X/X₀ measurements at the CERN SPS test beam 2014
alu grid pictures
alu grid pictures
Small deviations from real calibration factor can have large effects on $X/X_0$ measurements
multiple scattering models