DEPFET Testbeams 2006 and 2007: Challenges, Methods and Results

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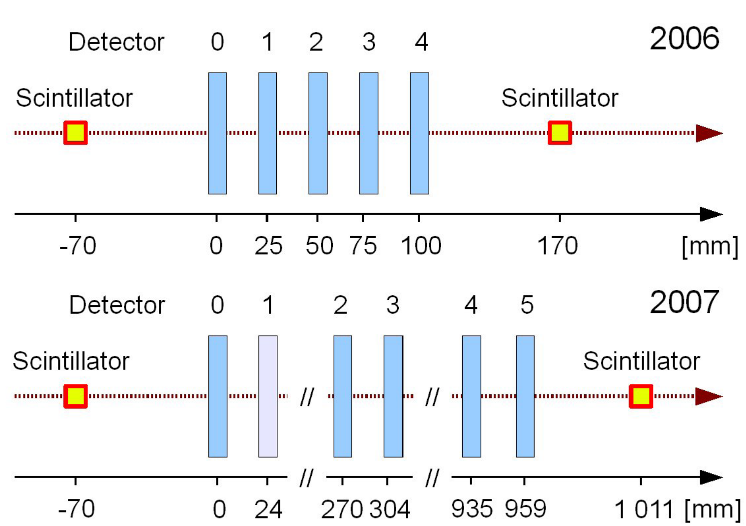
Outline

- DEPFET beam tests at CERN in 2006 and 2007
  - basic data, tasks and challenges
- Analysis overview
  - Track filtering, fitting and alignment, detector resolutions
  - Error determination: bootstrap resampling
  - Simulations
- Hit reconstruction
  - Towards a 2D eta correction: when is a 2D eta correction better than 2 1D corrections?
- Observations
  - Edge effects and eta-eta correlations

DEPFET beam tests 2006 and 2007: Basic information

- New modules and new data from the 2007 beam test, analyzed together with the data of the successful 2006 beam test.
- 180 GeV π^+ beam on SPS
- Two independent readouts on two PCs with recording of event numbers from TLU
- Very low efficiency: 1.5% tracks in events



Detector	X pitch (μm)	Y pitch (μm)
0	33	23.75
1	36	22
2	36	22
3	36	22
4	36	22

Detector	X pitch (μm)	Y pitch (μm)
0	32	24
1	-	-
2	24	24
3	33	23.75
4	36	22
5	36	22

Detector setup and pitch of detectors used in the 2006 (top) and 2007 (bottom) testbeam.

Analysis

- A standard analysis chain, comprising
  - i hit reconstruction
  - ii track identification
  - iii detector alignment and track fitting
  - iv calculation of detector resolutions
  - v reliability/sensitivity study on simulated data.
- There is another analysis

Velthuis, J. J. et al., *A DEPFET Based Beam Telescope With Submicron Precision Capability*, IEEE Transactions on Nuclear Science (TNS), 55 (2008) 662-666

- Several new methods:
  - i a track selection algorithm based on the principal components analysis (PCA)
  - ii robust linearized alignment
  - iii direct computation of detector resolutions based on a track model that explicitly takes into account multiple scattering

Analysis: Track identification

- Task:
  - Select good tracks from a set of track candidates (eg. formed by combining hits on individual planes).
- Challenges:
  - Several tracks per event due to long read-out cycle.
  - Volatile „hot“ zones on some planes that could not be masked out
- Algorithm: Iterative classifier
  1. **Within a starting set of tracks identify a pre-defined fraction *p* of tracks such that the selected tracks are mutually most similar**
  2. **Classify other tracks as similar or dissimilar to this group of tracks**
  3. **Iterate (back to 1)**
- To implement this, we need a measure of similarity

Analysis: Track identification

- Similarity is measured using principal components analysis (PCA) – ie, using the content of eigenvectors of the correlation matrix of the set of tracks.
- Except for position in space and direction, genuine tracks differ only by small Gaussian deviations due to measurement errors and multiple scattering.
- So we can construct cuts on the content of high principal components.
- The signature of fake tracks is high content of high eigenvectors
- The method will not work with high multiplicity of hits per event (5 and more), since the number of prototracks would become prohibitively high.

Analysis: Track identification

Equation of particle track

Lutz G.
Optimum track fitting in the presence of multiple scattering
Nucl. Instr. Meth. A 273 (1988) 349-361

$$
\begin{aligned}
x_k &= x_0 + a^{(x)} z_k + \sum_{j<k} (z_k - z_j)\, \epsilon_j^{(x)} + d_k^{(x)} \\
y_k &= y_0 + a^{(y)} z_k + \sum_{j<k} (z_k - z_j)\, \epsilon_j^{(y)} + d_k^{(y)} \\
k &= 1, 2, \ldots n
\end{aligned}
$$

Linear track — Multiple scattering — Measurement error

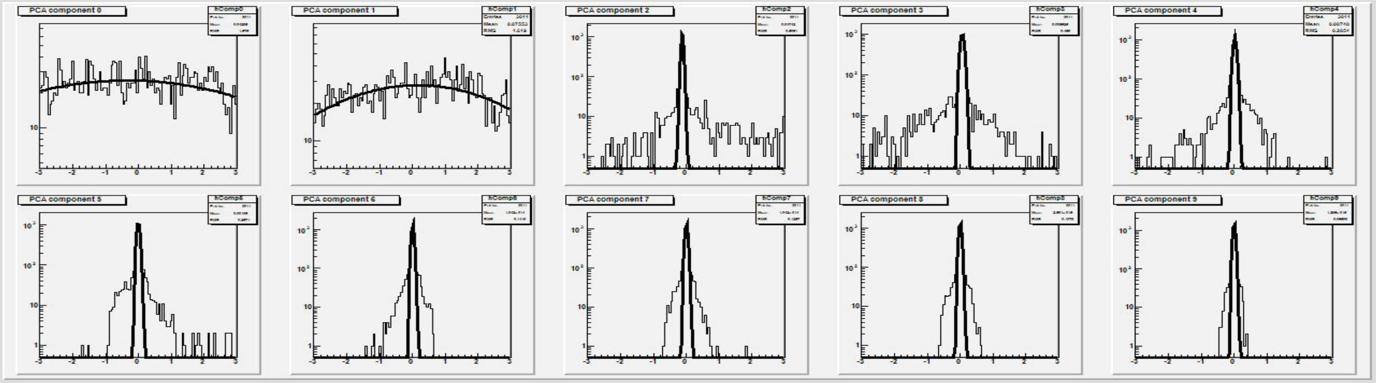
Form a matrix of tracks

$$
\mathbf{X} = \begin{pmatrix}
x_1^{(1)} & \ldots & x_n^{(1)} & y_1^{(1)} & \ldots & y_n^{(1)} \\
x_1^{(2)} & \ldots & x_n^{(2)} & y_1^{(2)} & \ldots & y_n^{(2)} \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
x_1^{(N)} & \ldots & x_n^{(N)} & y_1^{(N)} & \ldots & y_n^{(N)}
\end{pmatrix}
$$

Form correlation matrix and find its eigenvalues and eigenvectors

$$
\begin{aligned}
\mathbf{C} &= (\mathbf{X} - \langle \mathbf{X} \rangle)^T (\mathbf{X} - \langle \mathbf{X} \rangle) \\
\mathbf{C} &= \mathbf{U}^T \Lambda \mathbf{U}
\end{aligned}
$$

The signature of fake tracks is a high content of higher eigen-vectors



Analysis: Alignment and Track Fitting

- Line fits:
  - We use straight line fits to tracks since precise statistics is more essential for alignment and resolutions than precise predictions
  - „Kinked“ tracks are easy to fit once alignment is done and resolutions are calculated

- Alignment:
  - The goal is to have a robust alignment for simple setups.
  - We use a linearized alignment scheme based on the treatment of V. Karimaki. Shortly, we find first-order corrections to hit position in detector planes due to misalignment.
  - SVD is used to discard nuisance variables

Karimäki V. et al.
Sensor alignment by tracks
Computing in High Energy and Nuclear Physics, 24-28 March 2003, La Jolla, California;
arXiv:physics/0306034

Analysis: Calculation of Resolutions

- In detector resolution calculations we decompose track projection errors (fit residuals) into contributions of
  - **measurement error** (detector resolution)
  - **telescope error** (error of track projection on the detector)
  - contribution of **multiple scattering** to telescope error
- We use straightforward matrix inversion combined with quadratic programming or bootstrap resampling of the residual covariances to assure positivity of squared resolutions.
- In particular, with the method we don't need infinite energy extra-polation or telescopes with known resolutions.

Analysis: Calculation of Resolutions

- We however need tracks with a sufficient number of measurements per track (at least 5 per dimension). Otherwise the method provides a regularized MLS estimate – that is, a minimum-norm vector of detector resolutions.

The problem to be solved has the form

$$diag^{-1} cov\left(u^{(c)}\right) = \mathbf{M}_{\mathbf{\Delta}} \cdot \mathbf{\Delta}^2 + \mathbf{M}_{\mathbf{\Sigma}} \cdot \mathbf{\Sigma}^2$$

vector of diagonal elements of the matrix

covariance matrix of residuals (known from tracking)

Vector of squared detector resolutions

vector of mean square angular deflections

Matrices depending on the method of calculation - whether projections are calculated using the given detector or not

It can be solved by SVD inversion of $\mathbf{M}_{\mathbf{\Delta}}$, but we also have to assure that we obtain positive $\mathbf{\Delta}^2$. For this, quadratic programming or bootstrap resampling of residual covariances can be used.

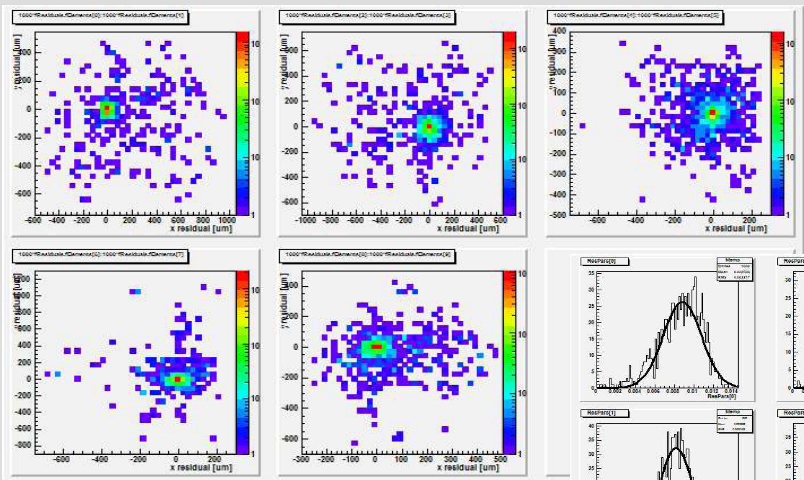
Analysis: Errors in alignment and resolutions

- Alignment and resolutions are calculated using linear algebra, but they contain inherent non-linearities. Therefore, linear regression error estimates are not usable and we have to use a different method of error calculation.
- Errors are calculated by **bootstrap resampling** of regression residuals:

1. **Generate a large number (several hundreds) of replicas of the original track set: combine parameters of each track with a set of residuals from another, randomly selected track.**
2. **Repeat the analysis for each replicated set**
3. **Determine errors from distributions of parameters**

- Though computationally intensive, the method is simple and reliable.

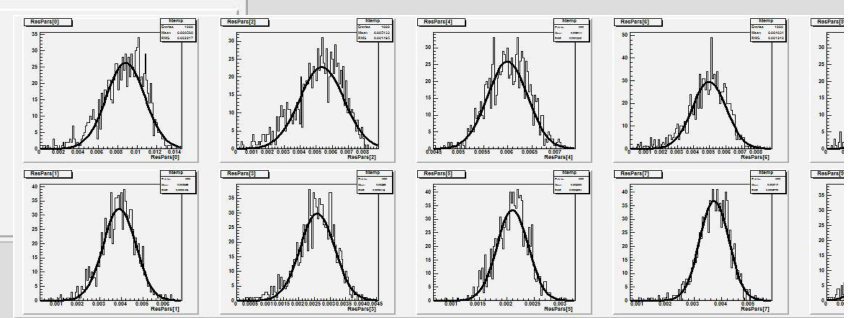
Results: Alignment



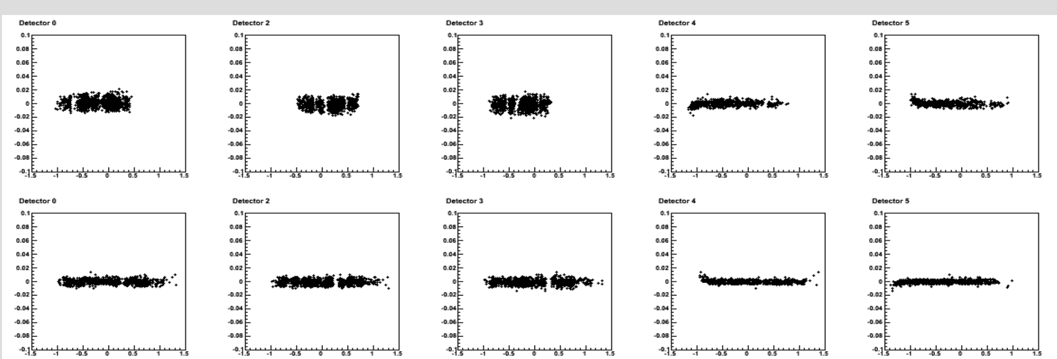
2D plot of residuals
Focused residuals are the first sign of a good alignment.

Alignment parameters
I show this table just to demonstrate the results of bootstrap error analysis used in these studies.

Number of tracks		308	
Parameter	Unit	Value	Error
		DETECTOR 1	
u shift	μm	-29.35	0.55
v shift	μm	-39.97	0.58
z rotation	mrad	-0.01	0.42
		DETECTOR 2	
u shift	μm	-39.72	0.63
v shift	μm	320.70	0.63
z rotation	mrad	0.00	0.51
		DETECTOR 3	
u shift	μm	168.46	0.78
v shift	μm	-166.45	0.51
z rotation	mrad	0.01	0.47
		DETECTOR 4	
u shift	μm	-87.51	1.16
v shift	μm	-459.47	0.62
z rotation	mrad	0.00	0.57
		DETECTOR 5	
u shift	μm	-9.54	0.71
v shift	μm	347.09	0.41
z rotation	mrad	-0.01	0.41



Bootstrap distributions of alignment parameters Clearly, the distributions show no anomalies or assymetries, so error estimation makes sense.



Alignment diagnostics:
Plots of residuals vs. position are a sensitive indicator of the quality of alignment. Residuals should form a band parallel to the x axis.

Results: Resolutions

Method	x resolution [μm]	y resolution [μm]
COG (no η)	4.35 ± 0.28	4.20 ± 0.16
beam test η	3.34 ± 0.27	3.40 ± 0.16
laser test η	3.41 ± 0.27	3.62 ± 0.17
telescope error	3.63 ± 0.13	2.11 ± 0.10
mult. scattering	0.71	0.71

Detector 2 (Prague), beam test 2007
The table reports resolutions for 3 methods of hit reconstruction. Telescope error and multiple scattering estimates are shown as well. Note the good performance of laser test based eta correction.

Detector	multiple scattering error, µm	
	2006	2007
0	0,16	1,62
1	0,06	0,71
2	0,09	0,77
3	0,06	0,3
4	0,16	0,37

1 µm resolutions appear consistently for the best detectors. Errors are bootstrap estimates.

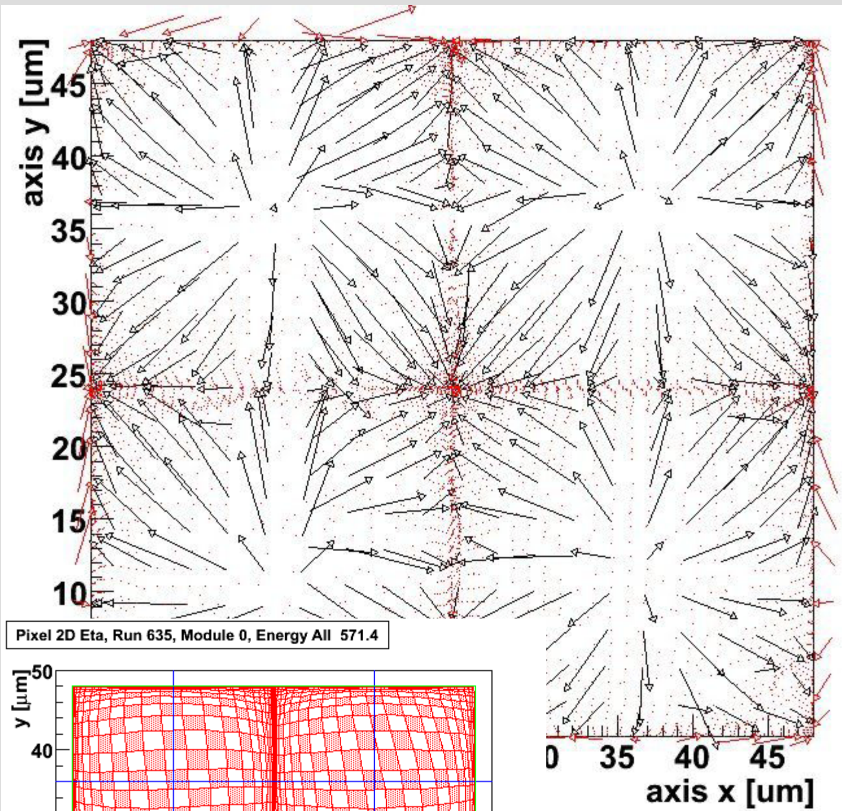
```
Resolutions in the fine coordinate:
        COG    EtaTB
Plane   res    res      error
1       4.34   4.97     0.38
3       1.63   1.49     0.55
5       1.19   0.93     0.18
7       2.37   2.11     0.28
9       1.76   2.12     0.64

Resolutions in the coarse coordinate:
        COG    EtaTB
Plane   res    res      error    pixelsize[um]
0       6.82   7.63     0.61     33
2       4.62   2.47     0.82     36
4       4.29   2.22     0.22     36
6       3.42   3.43     0.38     36
8       8.35   3.04     1.00     36
```

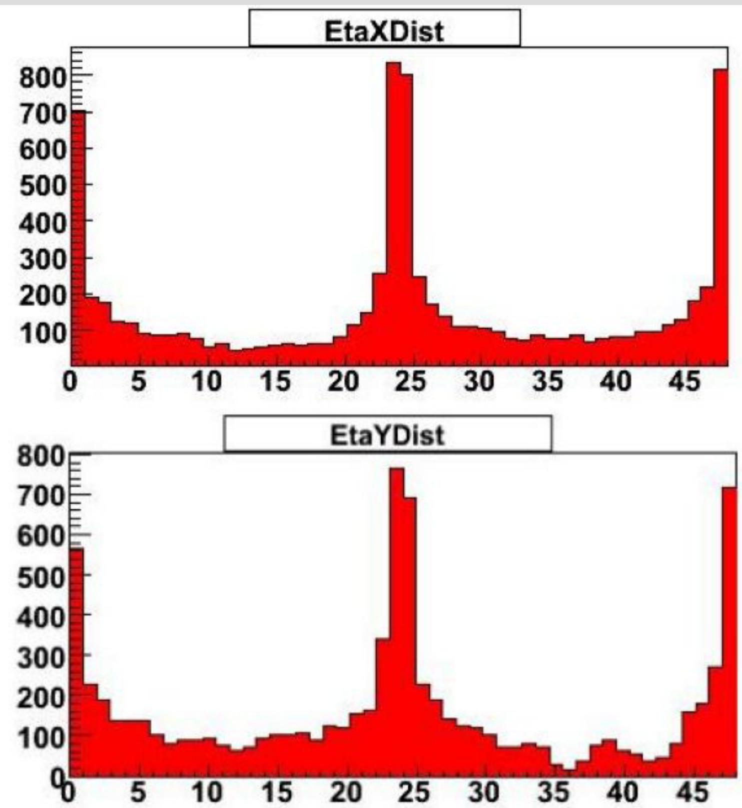
Multiple scattering effects in 2006 and 2007
Due to rotating stages, the detectors were much further apart in 2007 than in 2006. As a result, the multiple scattering contributed much more in 2007. This table quantifies the effect.

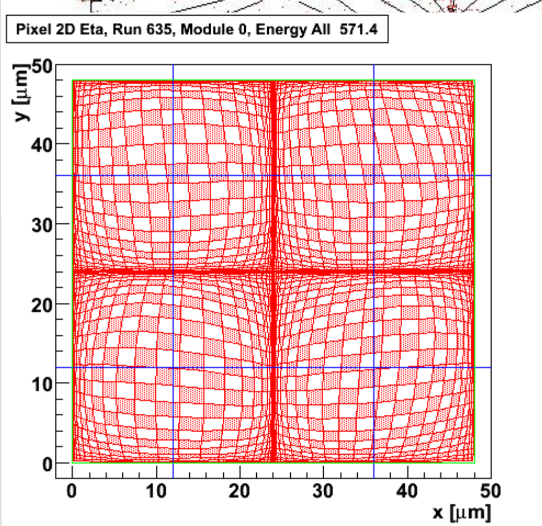
Hit reconstruction: all those η functions

- η correction is a method of correcting hit position for charge collection profile of the detector.
- The corrections for strip detectors (1D) are well understood and straightforward.
- For pixels, there is no generally accepted method of η correction.
- We don't have a final solution, just some data and methods to compare.
- Obvious solution: use 2 1D "projected" η corrections for the x and y coordinates.
- True 2D η correction cannot be computed using the recipe of 1D: while in 1D the requirement of uniformity uniquely defines the η function, in 2D it does not. However, cartographers have been doing 2D density corrections for years.
- Another option is to construct the correction differently: using laser tests, or using smoothed residual maps.

Hit reconstruction: all those η functions

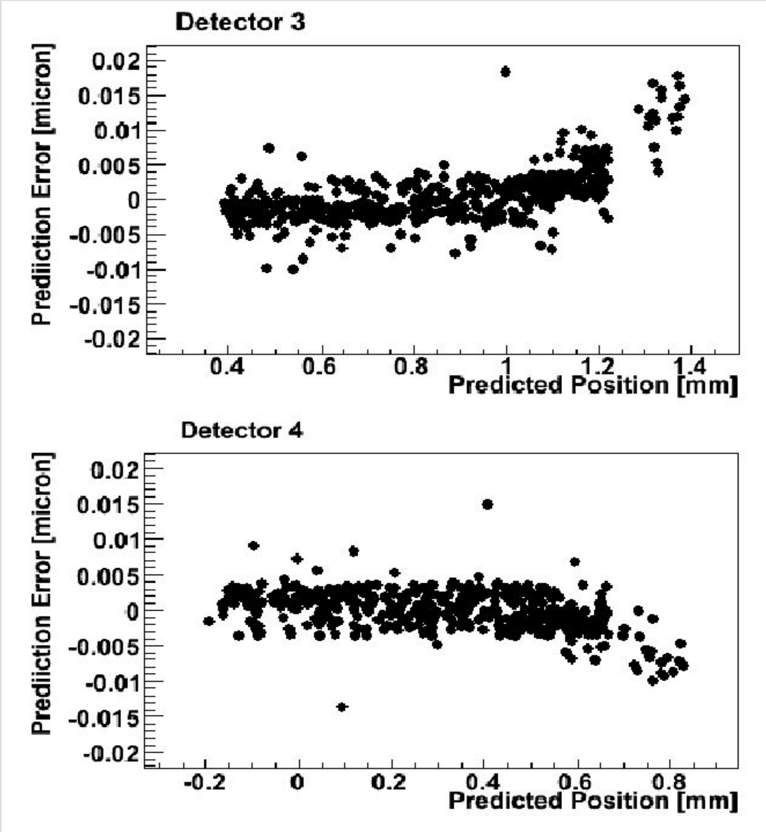






2D eta correction obtained from a laser scan (top left) has the form of a displacement field, with arrows pointing from actual positions to positions reported by the sensor. The field can be converted to two 1D projected eta functions (right), or processed to provide a 2D map of corrections (left). The same can be done using testbeam tracks, provided there is good statistics. Note that the elementary cell of a DEPFET matrix is 2x2 pixels.

Strange things 1: Edge effects

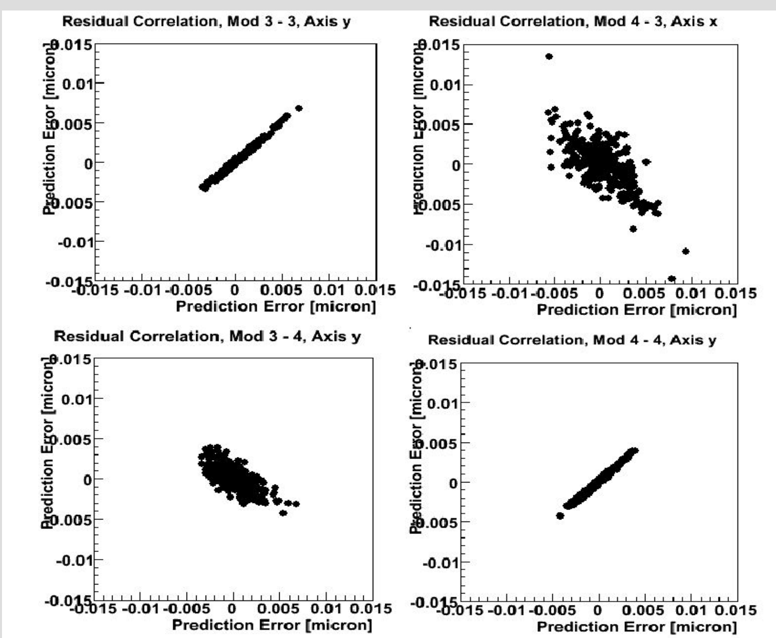


Prediction errors vs. position for two detectors in the 2007 setup: fine coordinate, detectors 3 and 4. About 250 µm at the perimeter are affected.

- The plot of residuals vs. position is a valuable alignment diagnostics tool. Here it reveals a clear systematic bias in residuals towards the edge of the sensor.
- A zone of about 250 µm around the perimeter is affected. Exclusion of this zone from the analysis makes alignment much more stable and improves resulting resolutions.
- Thus far, the cause of this effect is unclear.
- The moral of the story is that it is useful to look at regression diagnostics.

Strange things 2: Residual correlations

- We repeatedly see strong correlations between prediction errors on neighbouring detectors, iff
  - The detectors are of the same type = have the same pitch
  - The detectors are not far from each other.
- Where are residual correlations coming from?



  - **Multiple scattering**
  - **Eta-eta correlations:** When working with detectors of the same type, are we able to correctly determine eta corrections on all of them?

Matrix of residual correlations between detectors 3 and 4, 2006 setup. The correlations on the diagonal are trivial, while we see a strong correlation between prediction errors on neighbouring detectors.

Conclusions

- The DEPFET testbeams in 2006 and 2007 yielded a rich body of data, which is still being processed to test different analysis methods and approaches.
- The resolutions of DEPFET matrices is well reproducible and consistent between beam tests, with resolutions of the best detectors being around 1 micron.
- Based upon robust alignment and resolution estimates, we have a solid tool to study the quality of various hit reconstruction methods.
- Some of the methods await revision due to requirements of tracking using EUDET telescopes.

Thanks for your attention.