A 2008 overview of the 2006 and 2007 beam tests results

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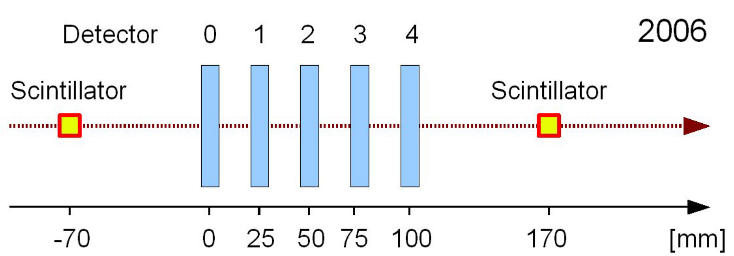
DEPFET meeting Heidelberg,
10-12 September 2008

* The presenter is supported by EU I3 contract 026 126-R II3 (EUDET)

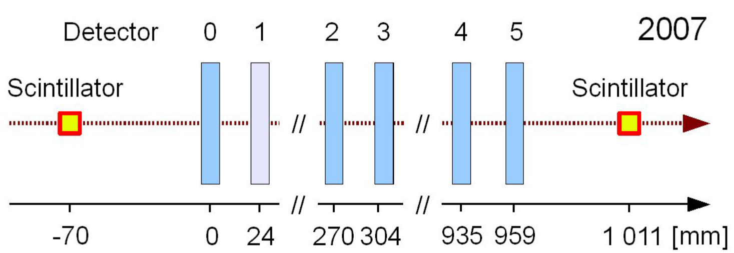
Outline

- DEPFET beam tests 2006, 2007, and 2008
  - Brief(est) overview
- Detector resolutions
  - Some data on the reliability of resolutions
  - The debate over the 2006 results: sub-micron or not?
  - Resolutions in the analysis of the 2008 beam test
- Hit reconstruction
  - Towards a 2D impact point correction: laser and tracking calibration of impact point correction

DEPFET beam tests 2006, 2007, and 2008



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



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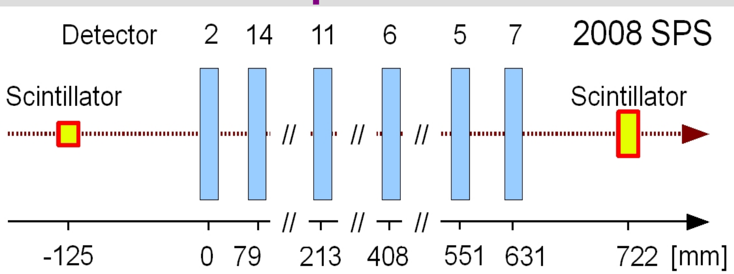
Detector setup and pitch of detectors used in the 2006, 2007 (top), and 2008 (bottom) beam tests.
Note that in 2008, we have – for the first time – a working 6-detector setup – AND HUGE STATISTICS !



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2	32	24
14	32	24
11	32	34
6	24	24
5	32	24
7	32	24

- 180 GeV π^+ beam on SPS
- Very low efficiency: 1.5% tracks in events
- We analyzed the data of 2006 together with those of 2007 (recovery of analysis software)
- So some new results will follow.

Detector resolutions

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

We directly solve for resolutions:

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

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

Detector resolutions

- The debate over the 2006 beam test analysis:
  Do 4 DEPFET telescopes provide submicron precision at the DUT plane or not? The Prague and Bonn analyses gave different resolutions, with the Prague results being worse.
- In the meantime, we are getting confidence in our resolutions. We get same resolution for the same module in 2006 and 2007 beam test (different position and geometry), and resolutions do not change when detectors are swapped In the setup.

2006	9	1.46±0.60	7	2.05± 0.28
2007	9	1.42±0.53	11	2.31± 0.33
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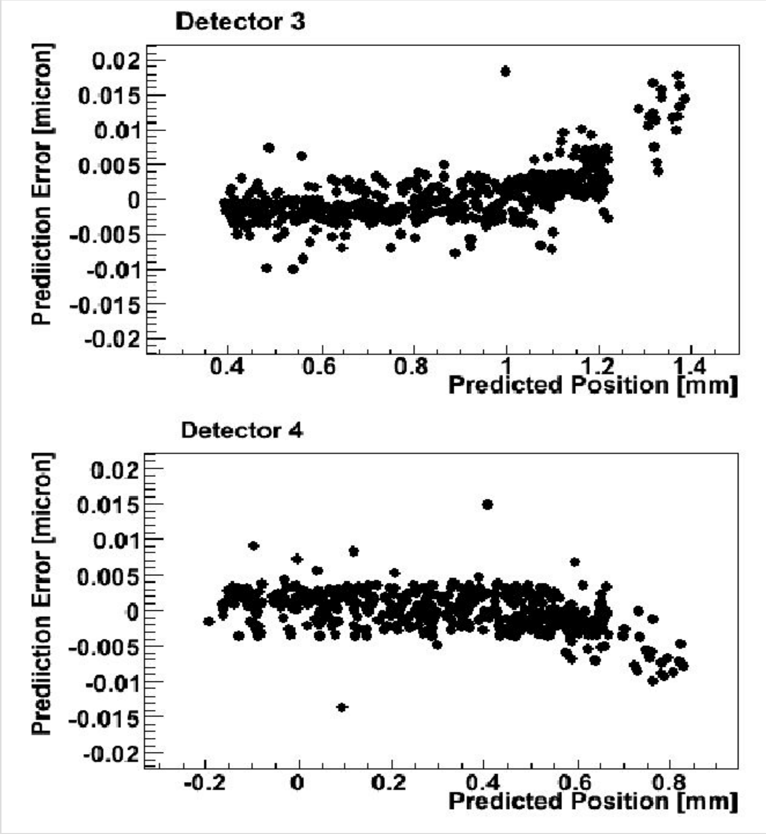
2006 plane 9 = 2007 plane 9 (HE, CCG, PXD4waf11, rsA, hyb 2b, T06, 0.036 x 0.022 mm)
2006 plane 7 = 2007 plane 11 and, after swap, plane 7 (HE, CCG, PXD4waf12,rsA hyb 7b, I12, 0.036 x 0.022 mm)

Detector resolutions

	2007 – Jaap		2007 – Prague		2008 – Prague	
	Resol.	Error	Resol.	Error	Resol.	Error
Detector 0						
coarse (µm)			8,4	0,9	7,5	0,7
fine (µm)			5,1	0,3	5,0	0,4
Detector 1						
coarse (µm)			6	0,5	2,6	0,8
fine (µm)	2,75	0,01	2,8	0,3	1,5	0,6
Detector 2						
coarse (µm)			5,3	0,2	2,2	0,2
fine (µm)	1,75	0,01	2,2	0,1	0,8	0,2
Detector 3						
coarse (µm)			4,3	0,5	2,8	0,5
fine (µm)	1,25	0,01	2,6	0,2	2,0	0,3
Detector 4						
coarse (µm)			8,2	0,7	4,1	0,9
fine (µm)			2,9	0,6	2,2	0,6

Detector resolutions

- Did we shave off some tracks to get better resolutions? YES. Here is one thing we improved (already shown in Valencia at the last DEPFET meeting)



- The plot of residuals vs. position reveals a systematic bias in track fit residuals towards the edge of the sensor.
- A zone of about 250 µm around the perimeter is affected. Its exclusion from the analysis stabilizes alignment and improves resulting resolutions.

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.

Detector resolutions – Questions to answer

Resolution maps

What precisely do our resolutions mean? We know that some areas in a pixel have worse resolution than others. How are these contributions weighted?

The best way is to map resolutions using high statistics data.

Correct treatment of multiple scattering

We have to be sure that our resolutions are consistent across beam energies – though GEANT simulations indicate they indeed are.

Why are detector resolutions so different?

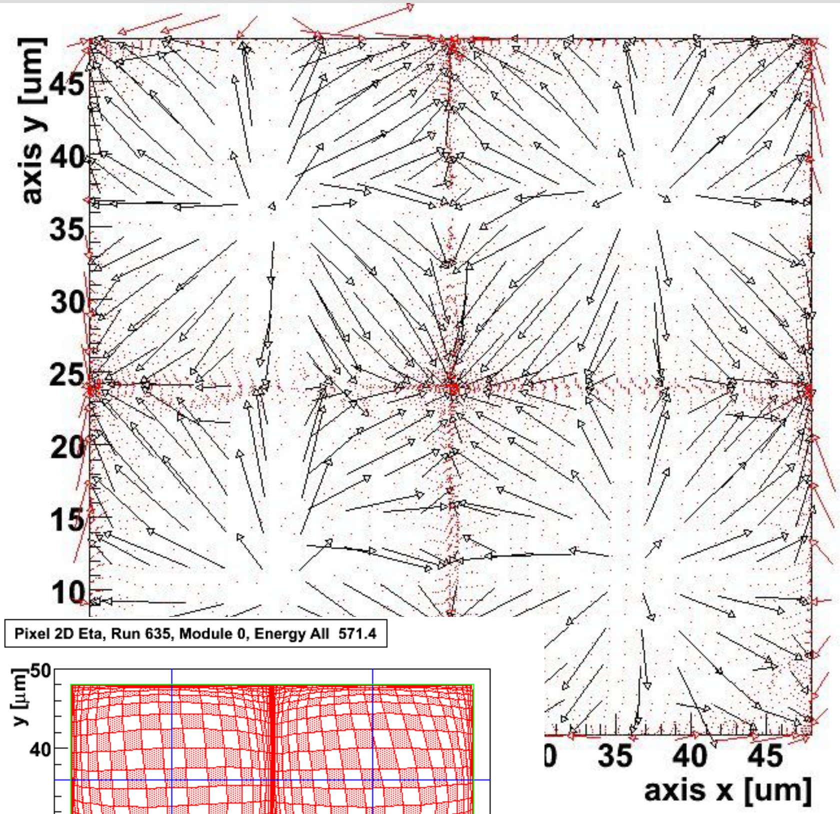
? slight inclinations of sensors, unseen by alignment

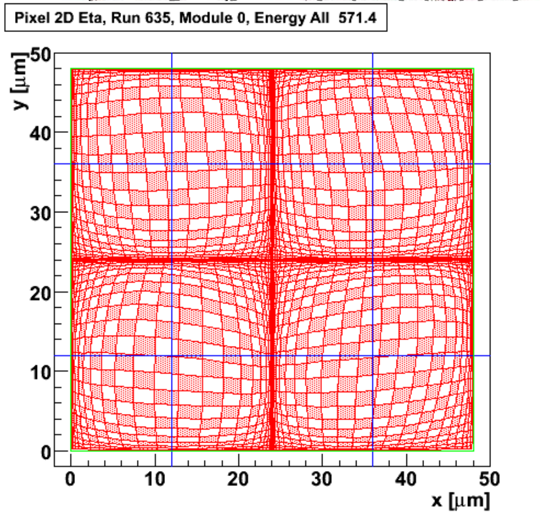
?- internal differences, causing different performance at equal powering settings

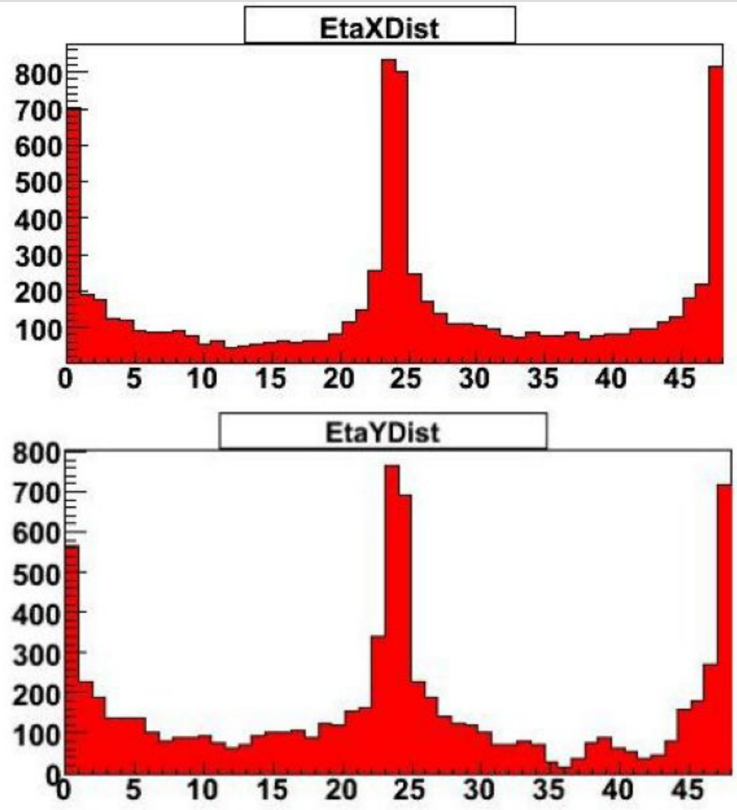
Hit reconstruction: towards a 2D impact point correction

- η correction is a method of correcting hit position based on equalization of the charge collection profile of a strip or pixel.
- The corrections for strip detectors (1D) are straightforward because **the correction map is uniquely defined** by the equalization condition..
- For pixels, there is no generally accepted method of η correction – maybe because **there's no unique method**.
- ... and also because the obvious shortcut – to use 2 1D "projected" η corrections for the x and y coordinates – is **very efficient**..
- Cartographers have been doing 2D density equalizations for years.
- Another option is to use experimental correction maps – ie, to use **calibration** instead of η correction. Such maps can be derived from laser tests or from tracking residuals.

Hit reconstruction: towards a 2D impact point correction







2D impact point calibration 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. With some generalization (smoothing), the calibration can be applied to hit positions instead of eta correction.

Hit reconstruction: towards a 2D impact point correction

- We hope we'll find good statistics to try this on the 2008 data.
- We can calculate reliable resolutions, so we have a tool to measure quality of corrections.

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 calibration	3.41 ± 0.27	3.62 ± 0.17
telescope error	3.63 ± 0.13	2.11 ± 0.10
multiple scattering	0.71	0.71

Table 1
Resolutions for the 2007 DEPFET beam test (CERN SPS) module in position 2 for different methods of impact point reconstruction. We also report the resolution of the telescope system at the DUT plane and the (RMS) contribution of multiple scattering to the telescope resolution.

Conclusions

- The DEPFET testbeams in 2006 and 2007 yielded a rich body of data, which helped us test and understand 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.
- Our resolution estimates provide us with a solid tool to study the quality of various hit reconstruction methods.
- **Looking forward to the 2008 data!!!**

Thanks for your attention.

Backup Slides

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

$$
\begin{aligned}
x_k &= \underbrace{x_0 + a^{(x)} z_k}_{\text{Linear track}} + \underbrace{\sum_{j<k} (z_k - z_j)\, \epsilon_j^{(x)}}_{\text{Multiple scattering}} + \underbrace{d_k^{(x)}}_{\text{Measurement error}} \\
y_k &= y_0 + a^{(y)} z_k + \sum_{j<k} (z_k - z_j)\, \epsilon_j^{(y)} + d_k^{(y)} \\
k &= 1, 2, \ldots n
\end{aligned}
$$

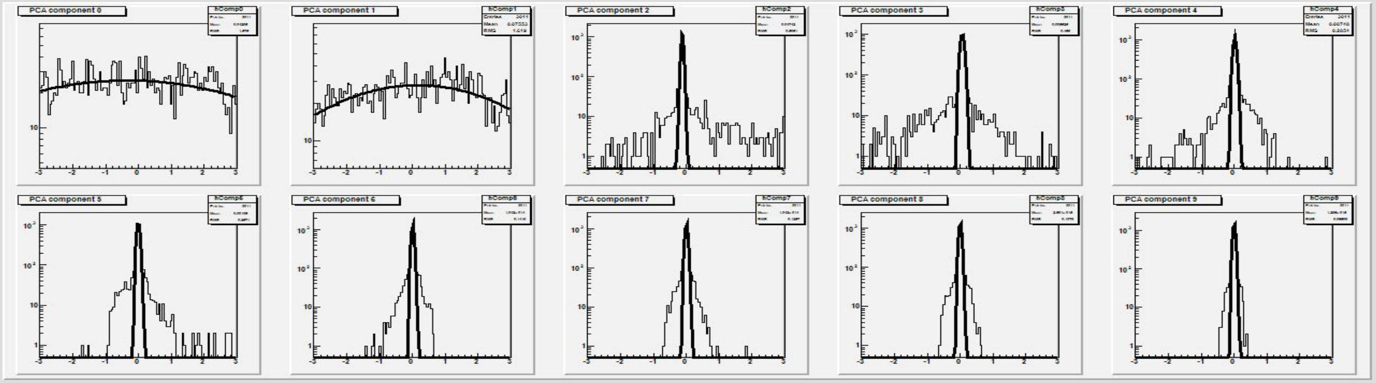
Form a matrix of tracks

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

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: 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:

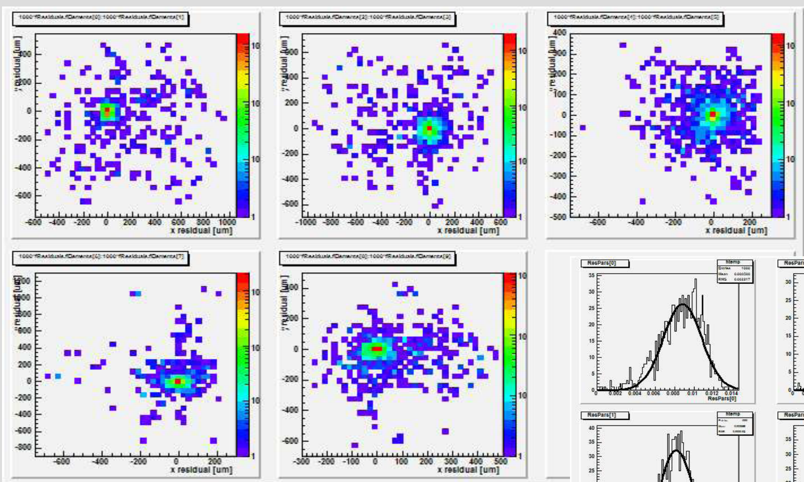
1. **Generate a large number (several hundreds) of replicas of the original track set: combine parameters of each track with a set of residuals from another, randomly selected track.**
2. **Repeat the analysis for each replicated set**
3. **Determine errors from distributions of parameters**

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

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.

Results: Alignment

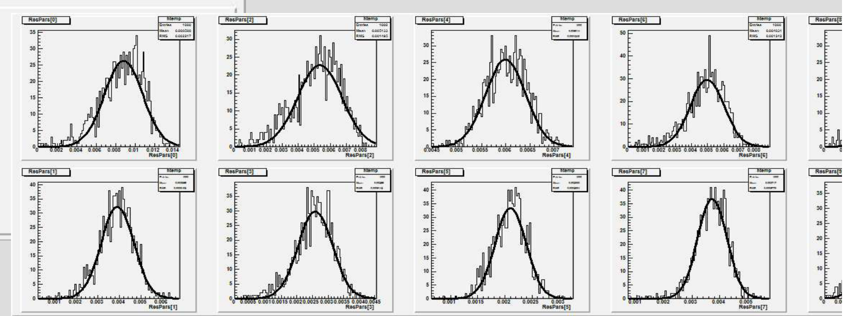


2D plot of residuals
Focused residuals are the first sign of a good alignment.

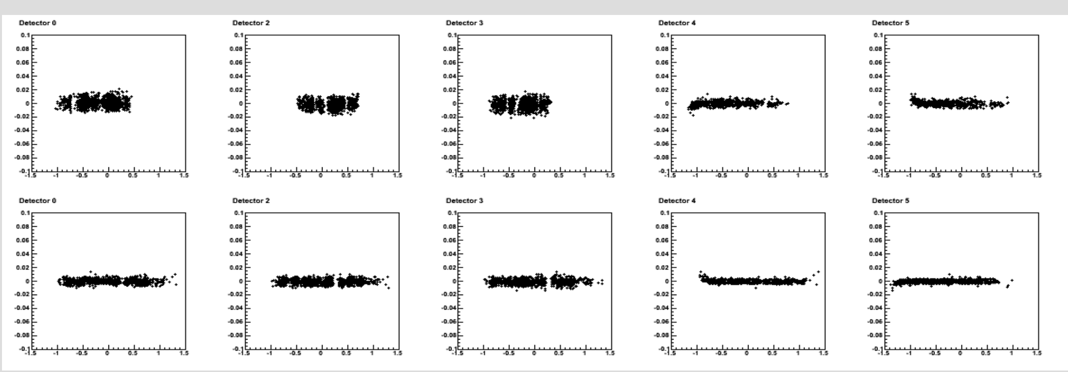
Alignment parameters

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
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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.

	multiple scattering error, µm	
Detector	**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.

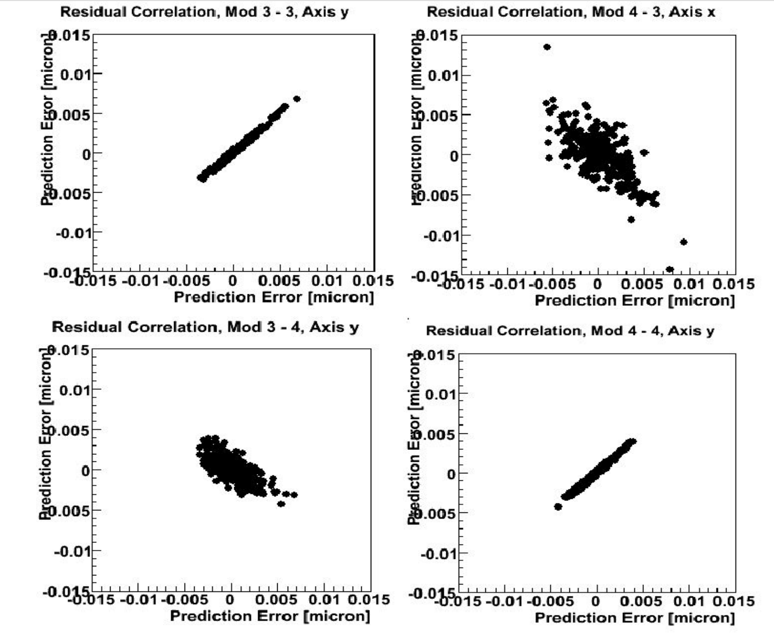
```
Resolutions in the fine coordinate:
      COG    EtaTB
Plane res    res     error
1     4.34   4.97    0.38
3     1.63   1.49    0.55
5     1.19   0.93    0.18
7     2.37   2.11    0.28
9     1.76   2.12    0.64

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.

One more strange thing: Residual correlations

- We repeatedly see strong correlations between prediction errors on neighbouring detectors, iff
  - The sensors have equal pitch
  - The detectors are close to each other.
- Where are the correlations coming from?

Why bother about such correlations?
They show that we can have better resolution!!



- Multiple scattering
- Eta-eta correlations

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.

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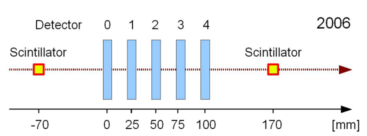

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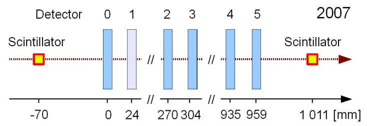

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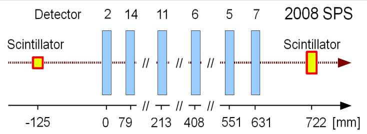

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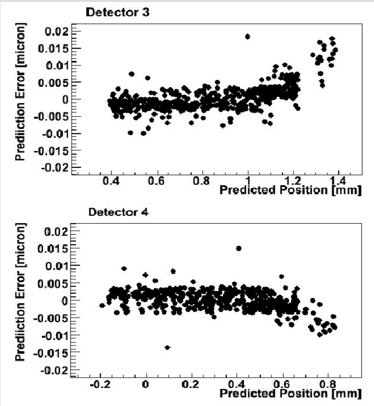

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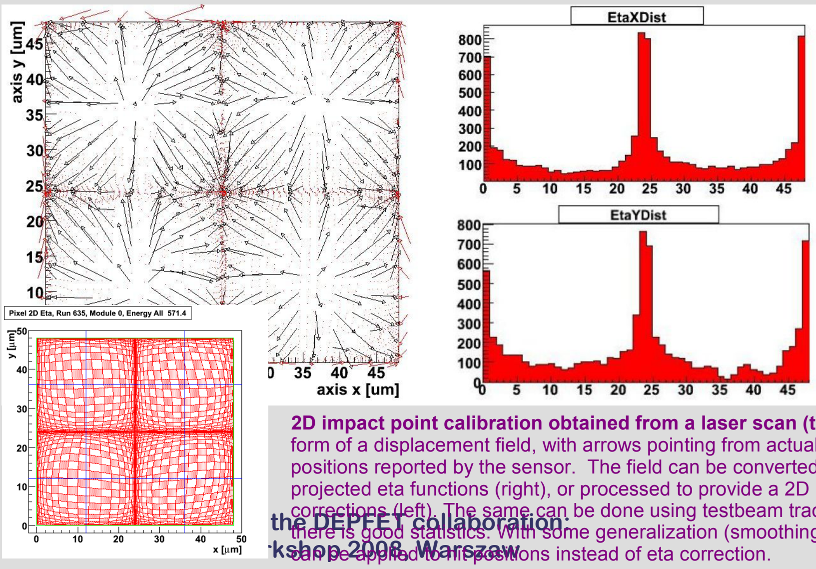
- Another option is to use experimental correction maps – ie, to use **calibration** instead of η correction. Such maps can be derived from laser tests or from tracking residuals.

Hit reconstruction: towards a 2D impact point correction



2D impact point calibration 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. With some generalization (smoothing), the calibration can be applied to hit positions instead of eta correction.

Hit reconstruction: towards a 2D impact point correction

- We hope we'll find good statistics to try this on the 2008 data.
- We can calculate reliable resolutions, so we have a tool to measure quality of corrections.

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

Table 1
Resolutions for the 2007 DEPFET beam test (CERN SPS) module in position 2 for different methods of impact point reconstruction. We also report the resolution of the telescope system at the DUT plane and the (RMS) contribution of multiple scattering to the telescope resolution.

Conclusions

- The DEPFET testbeams in 2006 and 2007 yielded a rich body of data, which helped us test and understand 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.
- Our resolution estimates provide us with a solid tool to study the quality of various hit reconstruction methods.
- **Looking forward to the 2008 data!!!**

Click to add title

Thanks for your attention.

Backup Slides

Click to add text

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

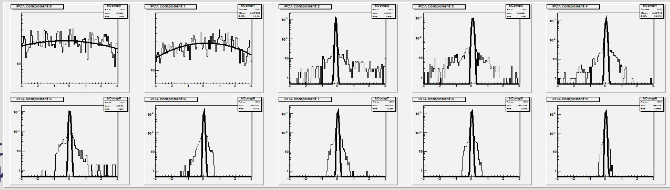
Form a matrix of tracks

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

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



Peter Kvasnicka & t
ILC ECFA Work

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: 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.

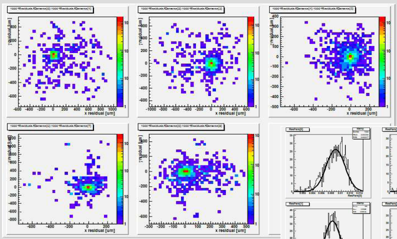
1. **Generate a large number (several hundreds) of replicas of the original track set: combine parameters of each track with a set of residuals from another, randomly selected track.**
2. **Repeat the analysis for each replicated set**
3. **Determine errors from distributions of parameters**

- Errors are calculated by **bootstrap resampling** of regression residuals.
- Though computationally intensive, the method is simple and reliable.

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.

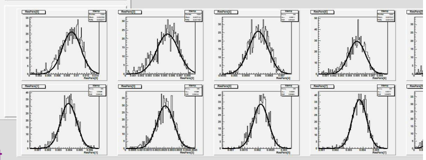
Results: Alignment



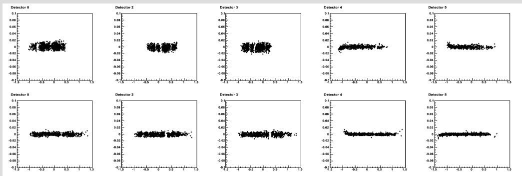
2D plot of residuals
Focused residuals are the first sign of a good alignment.

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.



on:

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.

	multiple scattering error, µm	
Detector	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.

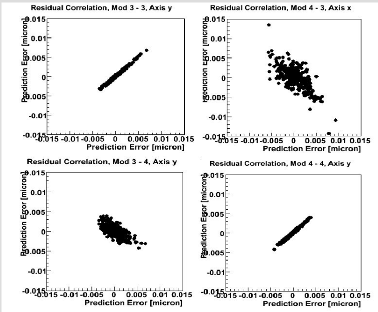
```
Resolutions in the fine coordinate:
       COG    EtaTB
Plane res     res      error
1      4.34   4.97     0.38
3      1.63   1.49     0.55
5      1.19   0.93     0.18
7      2.37   2.11     0.28
9      1.76   2.12     0.64

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.

One more strange thing: Residual correlations

- We repeatedly see strong correlations between prediction errors on neighbouring detectors, iff
  - The sensors have equal pitch
  - The detectors are close to each other.
- Where are the correlations coming from?

Why bother about such correlations?
They show that we can have better resolution!!



- Multiple scattering
- Eta-eta correlations

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.

collaboration:
, Warszaw