The Prague
Testbeam Resolutions Paper

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Introduction

- **Ringberg meeting: we promised to write a paper on measurement of detector resolutions based on data of TB 2009**
  - Ringberg plan: a general testbeam paper, and several specialized notes, focused, for example, on hit reconstruction, gains, pixel mapping etc., and on calculation of resolutions. (But so far there is none).
  - The first version of this paper appeared at the beginning of August, and underwent serious changes and improvements since then..

Current version: The most current version of the manuscript can be downloaded from
http://twiki.hll.mpg.de/twiki/bin/viewfile/DepfetInternal/TBResults2009PraguePage?rev=1;filename=201006_TBPrgResolution.pdf

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Introduction

What the paper says:

- Resolutions have been measured since 2006 (first attempts by Jaap), so there is some history behind us
- We want to describe some properties of resolutions estimators we are currently using, and demonstrate them on real testbeam data.
- The use of detector resolutions is twofold:
  - A measure of spatial discrimination power of a detector.

    We show how the resolutions are calculated, what are the properties of the estimates, what factors influence them, and how their reliability is tested.
  - A useful tool in studies of other detector properties

    We present 3 testbeam studies in terms of resolutions – bias scan, angle scan and energy scan.

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In this talk...

Intrinsic resolutions of DEPFET detector prototypes measured at beam tests

Laci Andricek[a], Javier Caride[b], Zdeněk Doležal[c], Zbyněk Drásal[c], Simone Esch[d], Ariane Frey[e], Julia Furletova[d], Sergey Furletov[d], Christian Geisler[e], Stefan Heindl[f], Carmen Iglesias[b], Jochen Kn... Kodyš[c1], Christian Koffmane[a,i], Christian Kreidl[g], Hans Krüger[d], Peter Kvasnička ... Malina[c], Carlos Mariñas[h], Jelena Ninkovic[a], Lars Reuen[d], Rainer Richter[a], Stefan ... Johannes Schneider[d], Benjamin Schwenker[e], Pablo Vazquez[b], Marcel Vos[h], Thomas ...

Author list:

- Who else wants to be on the author list?
- Do we want to impose any rules?

Purpose of the talk:

- (briefly) summarize the circumstances and ideas behind the paper manuscript
- give a “reading guide” to the paper
- (also briefly) summarize current status of the manuscript.

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...Compostela University, Spain
...lty of Mathematics and Physics, Charles University in Prague, ...Czech Republic
... University, Germany
...en University, Germany
[f] KIT Karlsruhe, Germany
[g] University of Heidelberg, Institute for Computer Engineering, Mannhei...
[h] IFIC, centre mixte Universitad Valencia/CSIC, Spain
[i] TU Berlin, Faculty of Electrical Engineering & Computer Science, Sensor & Actua...

Paper size:

- We kept the size of the paper at 8-9 pages. Anything that was not vital was stripped off.

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Overview: Section 1, Introduction

1 Introduction

Experiments in future colliders like the ILC or the super B factories require excellent vertexing performance. The DEPFET collaboration pursues the development of vertex detectors based on the concept of the depleted field effect transistor.

The concept (see Fig. 1) originated in the 1980s and has been published widely [1]-[4]. Briefly, each DEPFET pixel has an integrated p-FET transistor. Sideward depletion creates a potential minimum for electrons in the internal gate under the channel. Electrons collected in the internal gate modulate the transistor current. They can be removed from the internal gate via the clear contact.

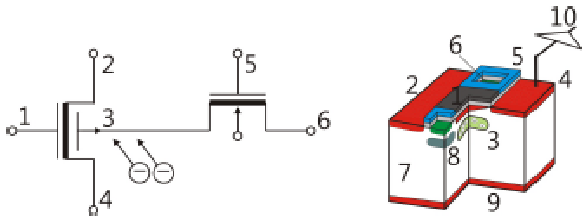

Figure 1: The principle of DEPFET. 1 - external FET gate, 2 - p^+ source, 3 - deep n-doped internal gate, 4 - p^+ drain with connection to external amplifier, 5 - clear gate, 6 - n^+ clear, 7 - depleted n-Si bulk, 8 - deep p-well, 9 - p^+ backside contact, 10 - amplifier

Currently, two major application areas for the DEPFET-based detectors are imaging systems of space based X-ray astronomy missions (XEUS, SIMBOLX, BepiColombo) and vertex detectors in high-energy physics colliders (the

forward procedure, though somewhat numerically subtle: the task is to decompose the tracking residuals to contributions of multiple scattering and measurement errors, based on known statistics of both.

We give a fairly extensinve description of beam test data analysis with a view to showing how individual steps of the analysis, such as hit reconstruction, alignment and tracking, mechanical instabilities, and irregularities in detector response, influence intrinsic detector resolutions. A few results of a MC simulation study illustrate the consistency of resolution estimates.

We illustrate the usefulness of detector resolutions by showing the results of beam energy scan, bias scan and angle scan in terms of detector resolutions. Some results on the variation of detector resolutions within the area of a detector pixel illustrate another useful application.

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- **Introduction: Standard stuff**
  - DEPFET, history and principles
  - What are spatial resolutions
  - Resolutions in testbeams: from Jaap to the present
  - Use of resolutions

Overview: Sections 2-5, Methods

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2 DEPFET beam test

The 2009 DEPFET beam test setup was built of 6 detectors as close to one another as allowed by the position stages to minimize the effects of multiple scattering. Particles were triggered by two scintillators in front of and behind the setup.

Five matrices of the same type were used as telesopes. Their parameters were kept constant during beam test experiments. The Detectors Under Tests (DUT) were three structures designed specially for the ILC conditions, with small pixels and high resolution. The thickness of all matrices was 450 μm. Eight matrices with 64×256 pixels, pixel pitch 20×20, 24×24 or 32×24 μm were used.

The geometry of the 2009 beam test is shown in Fig. 2. The DUT was placed in position 2.

Fig. 3 shows orientation of the (local) detector coordinate system relative to the layout of chips on a DEPFET hybrid.

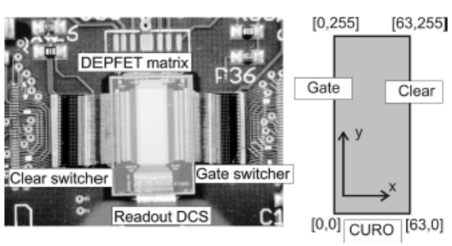

Figure 3: Layout of chips on a hybrid and the detector coordinate system

The six detectors of the setup were synchronized with a EUDET Trigger Logic Unit and operated from a Linux workstation.

We found tracks passing through all six detectors in ≈25% events, the inefficiency being mainly due to triggering by a 2.4×6.5 mm^2 scintillator at the front of the setup. Typical acquisition rate with 120 GeV pion beam was higher than 1000 events per minute.

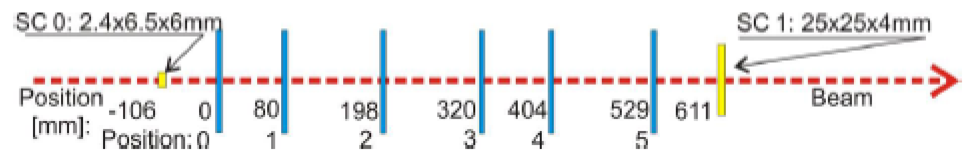

Figure 2: Arrangement of sensors in the 2009 beam test

- **Testbeam description (Section 2)**
  - Very brief, obligatory material
  - Would like to have a reference to a more detailed description in another paper. It would make things more complete and save some space.
  - Data-taking parameters and testbeam experiments – bias scan, angle scan (exception: from 2008) and energy scan

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Overview: Sections 2-5, Methods (cont'd)

The basic set of beam test studies comprised bias scan, 100 to 200 V; angle scan, ±4 deg tilt of the DUT around horizontal axis[2]; energy scan, 40 to 120 GeV, separate runs with electron beams with energies 40, 60, 80, and 100 GeV, and pion beams with energies 80, 100, and (default) 120 GeV.

3 Specific properties of DEPFET detectors

DEPFET detectors have some special features that have to be explained in order to understand the beam test analysis and its results.

3.1 Noise and intrinsic resolution

In DEPFET detectors, noise is dominated by the front-end electronics and was about 120 nA for all detectors where typical amplification in pixel is about 0.5 nA/e^-. Response to 120 GeV pions (110 keV deposited energy) was over 14.6 μA for the large pixel pitch (signal to noise ratio about 120), and 25.3 μA for the small pixel pitch (signal to noise ratio 200) [8]. In combination with fine pitch, the high S/N ratios result in intrinsic resolutions between 1 and 2 μm (see the Results section below). With these parameters, multiple scattering effects are very important at the nominal beam energy of the beam test, 120 GeV,

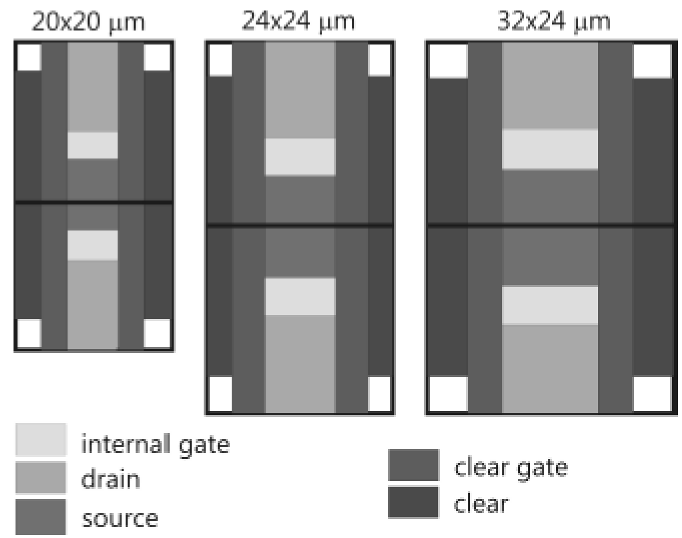

Figure 4: The design of a 1 × 2 pixels area for the smallest (left), small (center) and large (right) ILC pixel design.

- **Specific properties of DEPFET detectors (Section 3)**
  - Low noise and high intrinsic resolution
  - Pixel structure
  - Edge effect and other response distortions

are less pronounced and are corrected in the same way as

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Overview: Sections 2-5, Methods (cont'd)

CMN from frame data; estimate RMS channel noises as median absolute deviations of channel signals

White correction: estimate pixel gains using semi-parametric maximum-likelihood equalization of seed distributions; pixel gains are applied in hit reconstruction when a reliable value reliably different from 1 is available

Hit reconstruction: identify signal clusters; estimate hit positions using center of gravity and eta correction (see below in the list) based on groups of 2×2 (large pixel size) or 3×3 (small pixel size) highest signals of a cluster

Track formation: combine hits on various detectors into particle tracks using the Scott and Longuet-Higgins [9] similarity matrix deconvolution. Only tracks with exactly one hit in every sensor (and hits belonging to such tracks) are used in the following analysis

η corrections are calculated using only hits that belong to tracks; two one-dimensional η corrections [10] are calculated for the x and y projections of 2×2 pixels' area for each sensor

Track fitting and sensor alignment: parameterize particle tracks; estimate intersections of tracks with detectors; correct for detector misalignment. A cut of 250 μm around the perimeter of each detector was used to eliminate edge effects

Correction for mechanical movements: regularly update alignment to account for slow mechanical changes in detector positions (typical time scale tens of minutes). See

measurement errors and multiple scattering deflections. Therefore, residual covariance is a linear combination of measurement error covariance and multiple scattering covariance:

$$cov(\hat{u}^e) \equiv \left\langle (u^e - \hat{u}^e)(u^e - \hat{u}^e)^T \right\rangle = H(G\Sigma^2 G^T + \Delta^2)H \quad (1)$$

where:

u^e are local hit coordinates and $\hat{u}^e$ are local coordinates of track intersection with sensor plane

H is a projector to the residual space. If the track is fitted with a line, $u = F\beta$, with F the factor matrix

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tector resolutions in Δ in terms of (experimental) residual correlations and (theoretical) RMS multiple scattering deflections.

Formally, resolutions can be calculated by solving 1 for Δ.

- **Data analysis (Section 4)**
  - Data analysis chain – a brief and generic description of data analysis steps
  - Analysis software – here we note that there are several analysis groups using different tools for data analysis

Overview: Sections 2-5, Methods (cont'd)

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4.2 Analysis software

Two analysis groups (Bonn and Göttingen) used the ILC-Soft/EUTelescope [11] analysis package with special extensions for DEPFET sensors [12]. One group (Prague) used their own ROOT-based [13] analysis package allowing also intrinsic resolution calculations.

5 Notes on selected analysis methods

This section gives some more detail on selected steps of the analysis. The level of detail for individual steps was chosen in correspondence with the focus of the paper.

5.1 Calculation of detector resolutions

By *detector resolution* we mean the RMS error of position measurement in the detector. We calculate detector resolutions from the covariance matrix of track fit residuals. Each fit residual is a linear combination of detector

Another, more straightforward method is to find the resolutions by a maximum likelihood fit to the data using a non-linear fitter. Such estimate uses the full covariance matrix, but to-date it doesn't seem to be decisively better than the "diagonal" estimator. It is significantly more stable than the "diagonal" estimator in the large multiple scattering regime, but in that regime both estimators

- **Notes on selected analysis methods (Section 5)**

  Explanation how some important things are calculated.

  – Calculation of detector resolutions – minimalistic explanation

  – Mechanical stability and sliding alignment

  – Correction of edge effect and other response distortions

  – Subpixel analysis

  – Monte Carlo simulations

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Overview: Sections 6-8, Results and Discussion

6 Results and discussion I: Resolutions

Tracking residuals are key pre-requisites for the calculation of alignment (including corrections of mechanical movements), response distortion corrections, and resolutions. In this paper, "residuals" always mean "unbiased" residuals, that is, residuals from track fits using hits in all other modules except the module in question.

Table 1 shows a comparison between residuals fo[r] ... tors obtained in the analyses of the Prague an[d] ... gen groups. The analyses were carried out inde[pendently] using different algorithms (for example, for eta ... and for alignment) and different software (see se[ction] ... The agreement in residuals is apparent. We ... agreement in residuals means agreement in reso[lutions] ... the results presented in the following sections ... firmed by two independent analyses. For clarity ... in the following the Prague group values.

residuals [μm]	0	1	2	3	4
Göttingen x	2.39	1.52	1.46	1.81	1.97
Prague x	2.49	1.60	1.54	1.98	2.06
Göttingen y	2.24	1.27	1.42	1.55	1.60
Prague y	2.28	1.38	1.42	1.61	1.61

Table 1: Comparison of residuals for individual detectors obtained in two independent analyses by the Prague and Göttingen groups for all 6 modules. The analyses used 1600 events taken with DUT with pixel size 20 × 20 μm^2

Results and Discussion I: Resolutions

Resolution values, comparisons, properties.

- Comparison of residuals with Gottingen (thanks to the endurance of Christian Geisler)

residuals [μm]	0	1	2	3	4	5
Göttingen x	2.39	1.52	1.46	1.81	1.97	2.86
Prague x	2.49	1.60	1.54	1.98	2.06	3.24
Göttingen y	2.24	1.27	1.42	1.55	1.60	2.89
Prague y	2.28	1.38	1.42	1.61	1.61	2.86

Table 1: Comparison of residuals for individual detectors obtained in two independent analyses by the Prague and Göttingen groups for all 6 modules. The analyses used 1600 events taken with DUT with pixel size 20 × 20 μm^2 in position 2.

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Overview: Sections 6-8, Results and Discussion (cont'd)

Results and Discussion I: Resolutions

– Actual resolutions for 2 detectors – a DUT (20 x 20 μm) and a telescope (32 x 24 μm)

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6 Results and discussion I: Resolutions

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Table 1: Comparison of residuals for individual detectors obtained in two independent analyses by the Prague and Göttingen groups for all 6 modules. The analyses used 1600 events taken with DUT with pixel size 20 × 20 μm^2

[μm]	Module 2 (DUT) 20×20 μm^2		Module 3 (telescope) 32×24 μm^2	
	x	y	x	y
Residual	1.54	1.42	1.98	1.61
Resolution	1.10	1.00	1.60	1.20
Net Tracking Error	0.73	0.62	0.86	0.73
Multiple Scattering	0.76		0.79	

Table 2: Typical residuals and resolutions in x and y for 120 GeV pions. Systematic error is 0.1 μm. Residuals and resolutions are representative for several combinantions of conditions and algorithms.

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Overview: Sections 6-8, Results and Discussion (cont’d)

Results and Discussion I: Resolutions

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6 Results and discussion I: Resolutions

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Göttingen y	2.24	1.27	1.42	1.55	1.
Prague y	2.28	1.38	1.42	1.61	1.

Table 1: Comparison of residuals for individu obtained in two independent analyses by the Göttingen groups for all 6 modules. The a 1600 events taken with DUT with pixel size 2

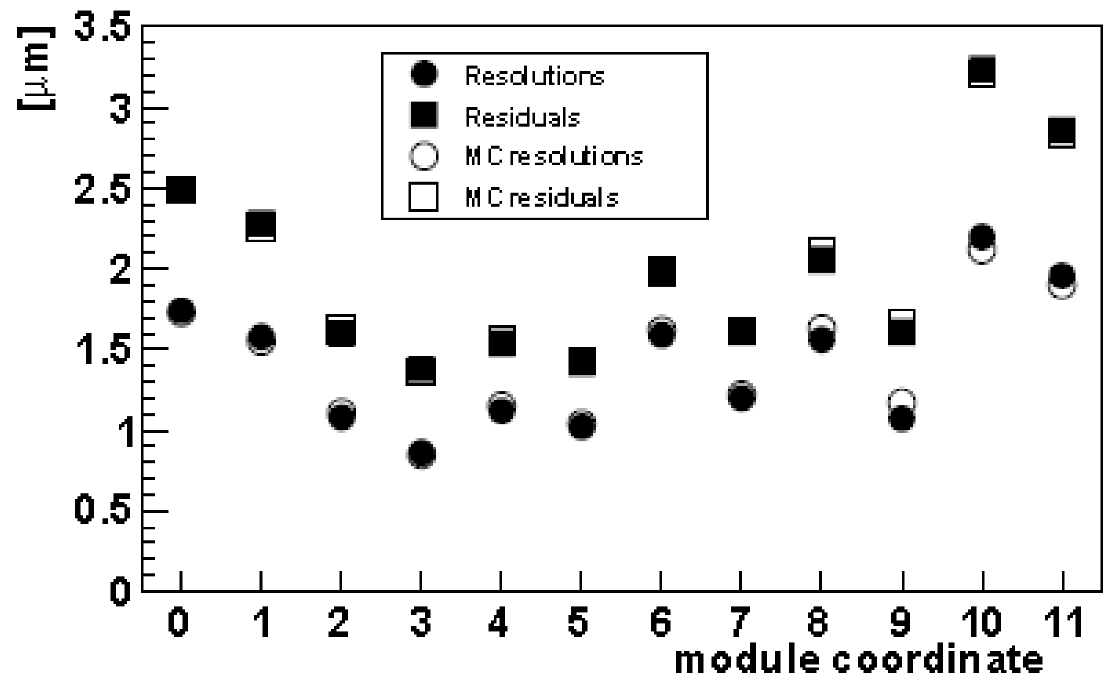

Figure 5: Comparison of residuals (squares) and resolutions (circles) from the analysis of beam test data (solid) and simulated data (hollow) with representative resolutions set for all detectors (120 GeV pion beam)

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Overview: Sections 6-8, Results and Discussion (cont’d)

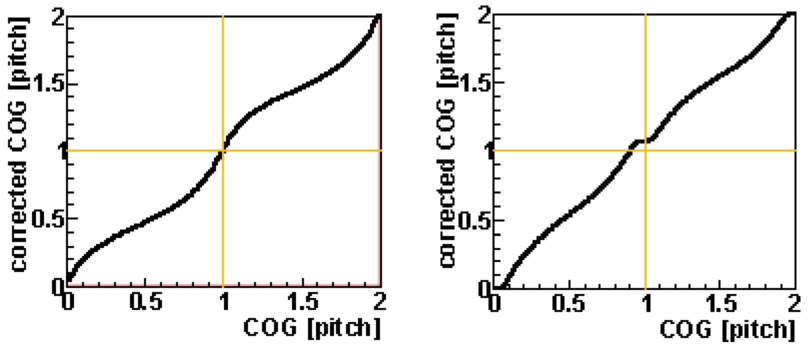

Figure 6: Example of η correction functions in x(left) and y (right) directions

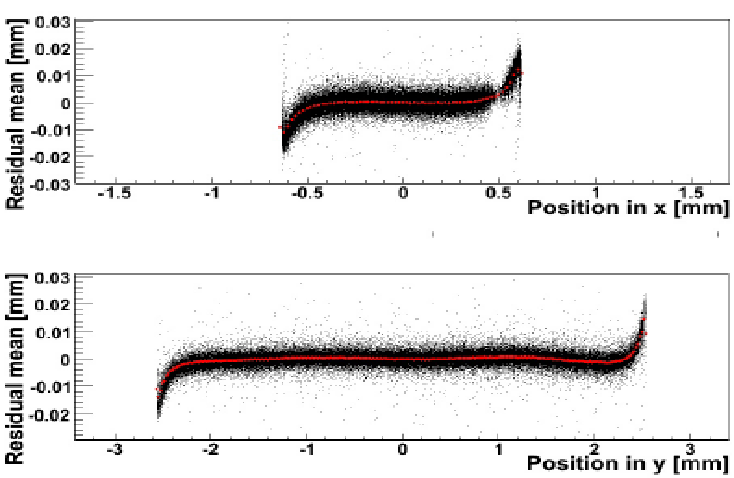

Figure 8: Residuals vs. hit position; positional response distortions before correction. Edge effect is clearly visible in both coordinates. The correction (light grey line) is based on median residuals at a given position.

- **Results and Discussion I: Resolutions**

  Factors influencing detector resolutions:

  - Gain correction
  - Hit reconstruction
  - Mechanical stability
  - Edge effect and other distortions

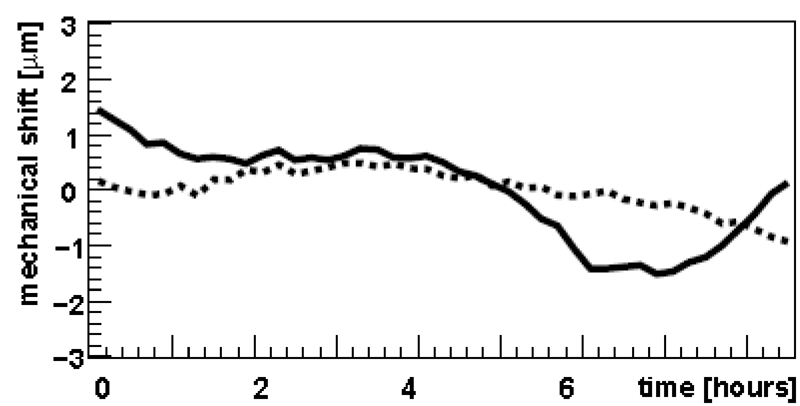

Figure 7: Mechanical shifts of Module 2 during an 8 hours’ run. The plots show median residuals before re-alignment vs. time. Solid - vertical, dotted - horizontal direction.

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Overview: Sections 6-8, Results and Discussion (cont'd)

- **Results and Discussion II: Studies using resolutions**:
  - Bias scan
  - Angle scan
  - Energy scan

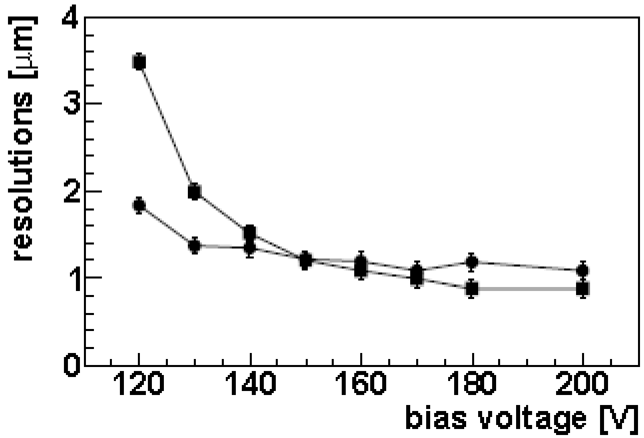

Figure 9: Bias scan: resolutions in x (circles) and y (squares) for the detector with pixel size 20×20 μm.

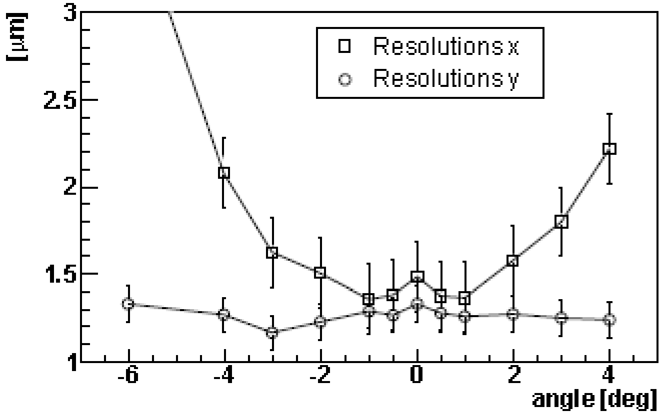

Figure 10: Resolution vs. incidence angle for the DUT with pixel size 24×24 μm in direction x (squares) and y (circles)

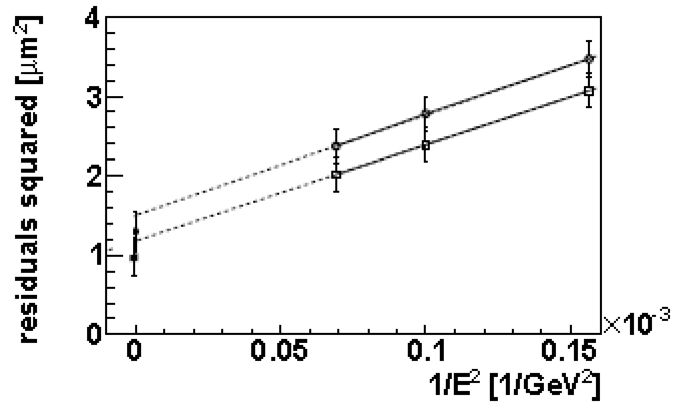

Figure 11: Squared residuals vs. squared inverse energy with extrapolation to infinite energy for pions: x, hollow circles; y, hollow squares. The solid marks at infinite energy are the respective intrinsic resolutions calculated directly.

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Overview: Sections 6-8, Results and Discussion (cont'd)

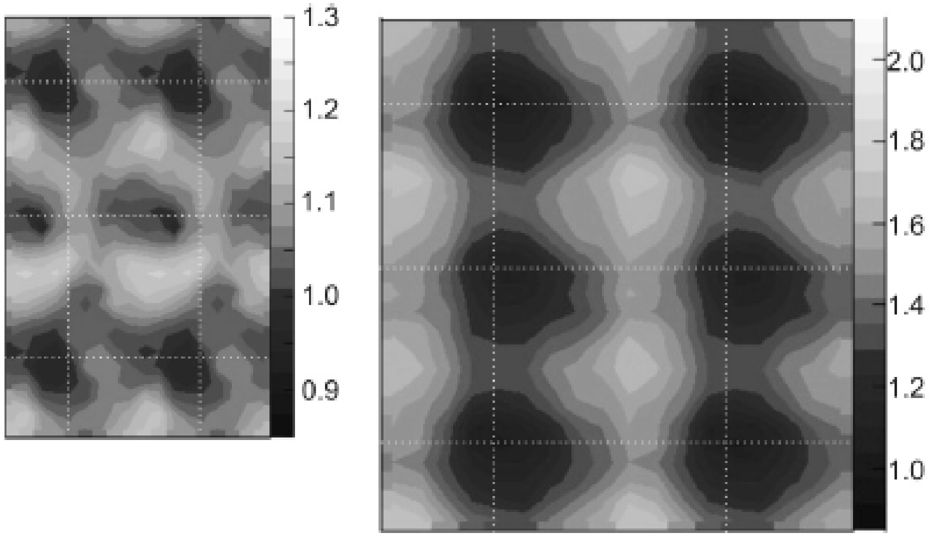

Figure 12: Maps of resolutions in pixel area (see also Table 3) for detector 2 (left, 20×20 μm pitch) and detector 3 (right, 32×24 μm pitch). Map dimensions correspond to pitch, but the grey scales are different.

Results and Discussion III: Resolution maps

- We only show resolution maps (i.e., not charge, seed, etc. maps). This part has undergone serious modifications in recent weeks.
- We want to show that for the small pixels, the variation of resolutions is much smaller than for the large pixels.

	Module	Approximate range, x	Apprixmate range, y
Residuals	20×20 μm	1.4 - 1.6	1.2 - 1.5
in μm	32×24 μm	1.5 - 2.4	1.4 - 1.85
Resolutions	20×20 μm	1.0 - 1.2	0.8 - 1.2
in μm	32×24 μm	1.0 - 2.0	0.9 - 1.5

Table 3: Pixel-scale variation of residuals and resolutions.

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Overview: Acknowledgements and References

Acknowledgement

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Acknowledgements

- Authors please send your acknowledgements to kodys@ipnp.troja.mff.cuni.cz or kvasnicka@ipnp.troja.mff.cuni.cz

References

[1] DEPFET homepage: www.depfet.org

[2] Kemmer, J., Lutz, G., *New detector concepts*, Nucl. Instrum. Meth. A, 253 (1987) 356

[3] Velthuis, J. J. et al., *DEPFET, a monolithic active pix sensor for the ILC*, Nucl. Instrum. Meth. A, 579 (2007) 685-689

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[5] Fischer, P. et al., *Progress towards a large area, thin*

References

- Write your paper so that we can reference it instead of writing one more time what you can write better!
- What are “representative” papers to cite for the previous testbeams? There are mostly conference proceedings.

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For discussion

Author list:

- Who else wants to be included?
- Do we impose some rules?

Text

- Any further suggestions?
- Have your suggestions been implemented ?

References

- What papers do we cite for previous testbeams?

Schedule

- Are there important issues still to be discussed?
- Do we have to wait for other papers?
- How much time is needed for another review round?
- Where do we publish?

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Acknowledgement again

Many thanks for all discussions, comments and suggestions!

Please help us again by re-reading the paper!

Thanks for your attention.