Spatial Resolution Analysis of Micron Resolution Silicon Pixel Detectors Based on Beam and Laser Tests

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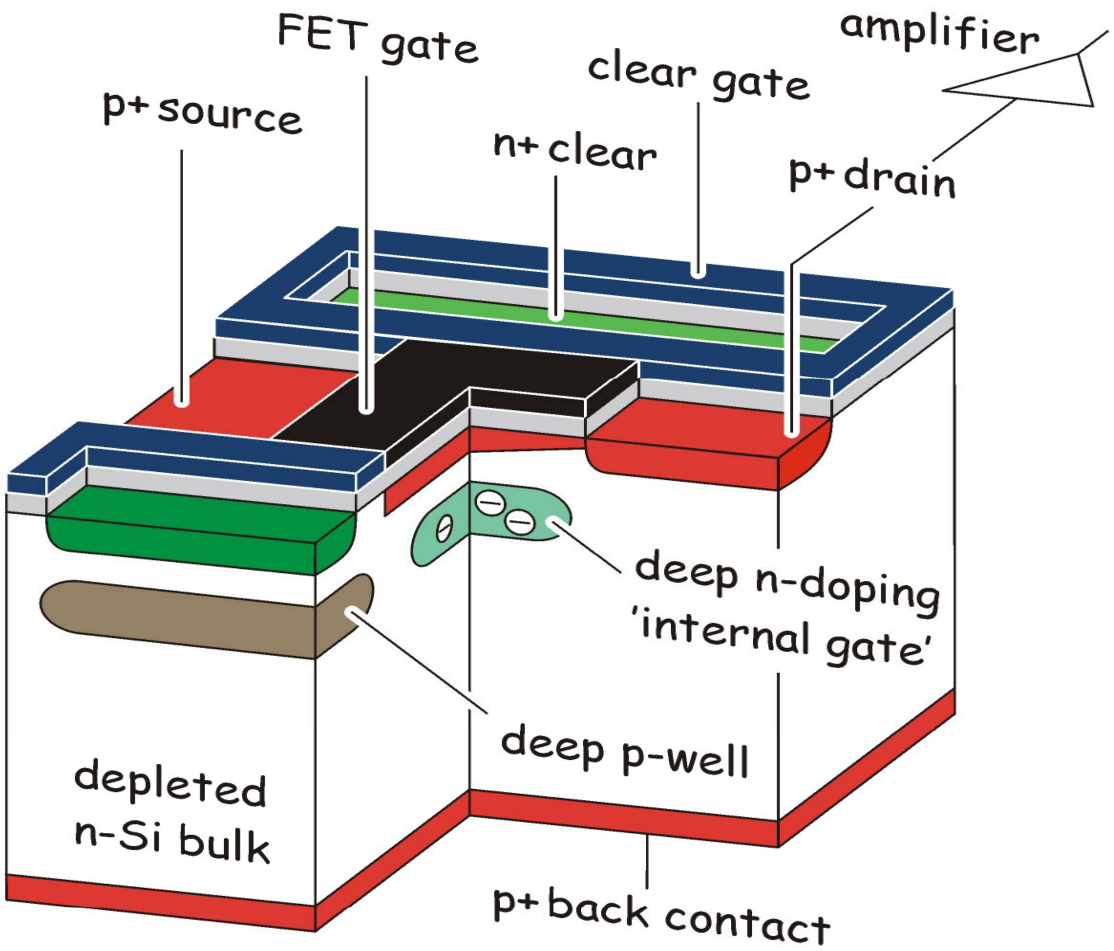
Introduction

1. A new generation of track detectors for high energy physics is being designed to allow track reconstruction with sub-micron precision. DEPFET structures are a good example.
2. With such precise detectors the determination of spatial resolution from beam test measurements becomes complicated because multiple scattering contributes significantly to tracking errors. This is further complicated if detectors with different (and unknown) resolutions are used as telescopes.
3. Similarly to strip detectors, positions of space points in pixel detectors are usually corrected using η-correction in both directions.
4. Firstly, it assumes independence of corrections in x on y and vice versa. Secondly, pixel detectors with integrated electronics on each pixel may contain areas with different charge-collecting properties.
5. We studied several hit reconstruction methods on a sample of beam test data and a series of laser scans.
6. Two methods of impact point position calibration based on beam test tracking and laser scan are compared with the traditional combination of η-corrections in both dimensions.

Methods – Detector Description

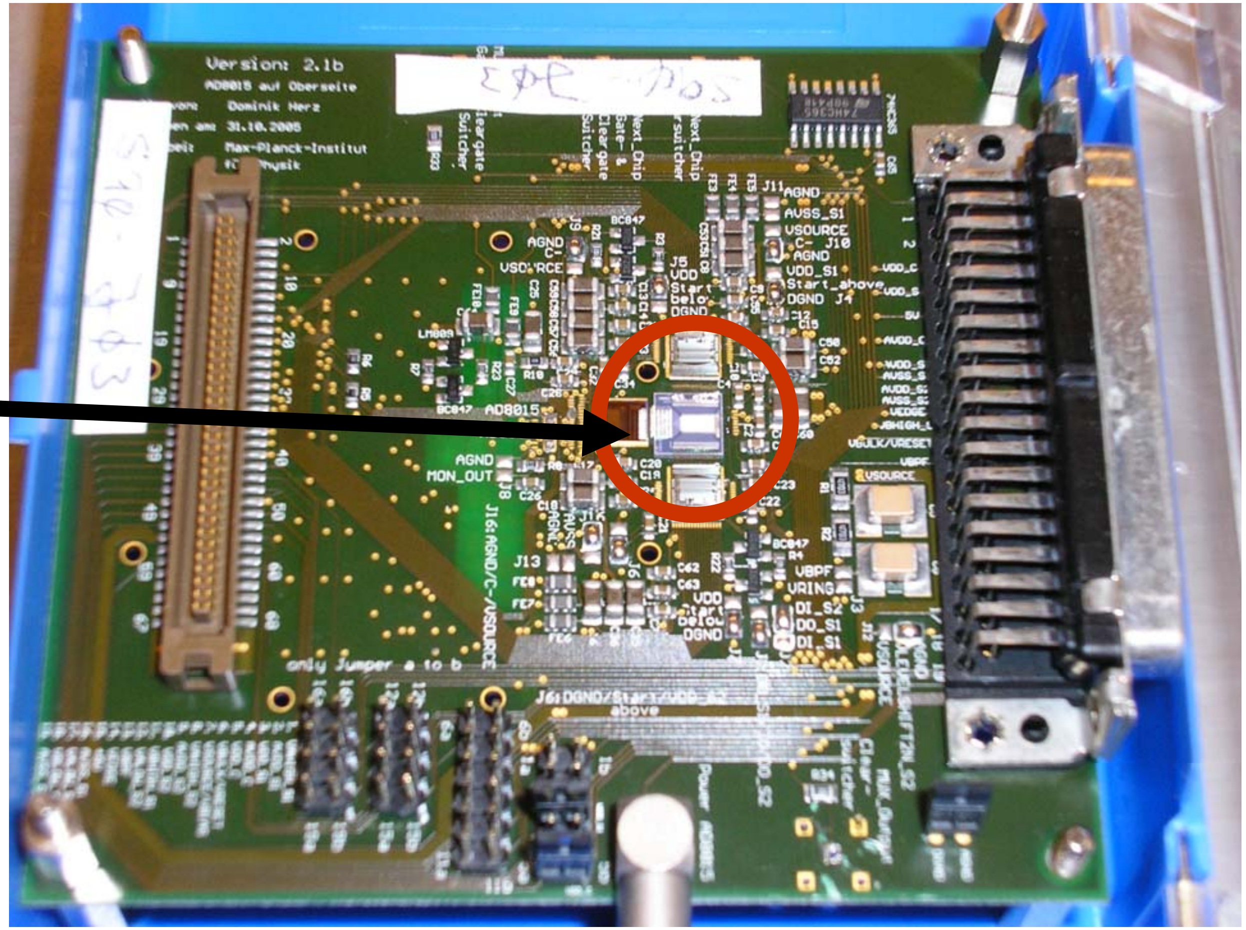


1. DEPFET sensors with active readout structures located on the sensor surface.
2. The tested sensors were test samples intended to verify the properties of different structures, so their resolutions differed and changed as their working settings were optimized.
3. Detectors produced with high and medium energy implantation technology.
4. Common clear gate version of DEPFET.
5. In some cases only a part of the sensor sensitive area was available.
6. Pixel structure 64 x 128 columns.
7. Thickness 450 μm.
8. Pixel size between 22 and 36 μm.
9. Bias voltage 200 V.
10. Same samples with the best resolution have S/N (cluster charge / pixel noise) higher than 110.

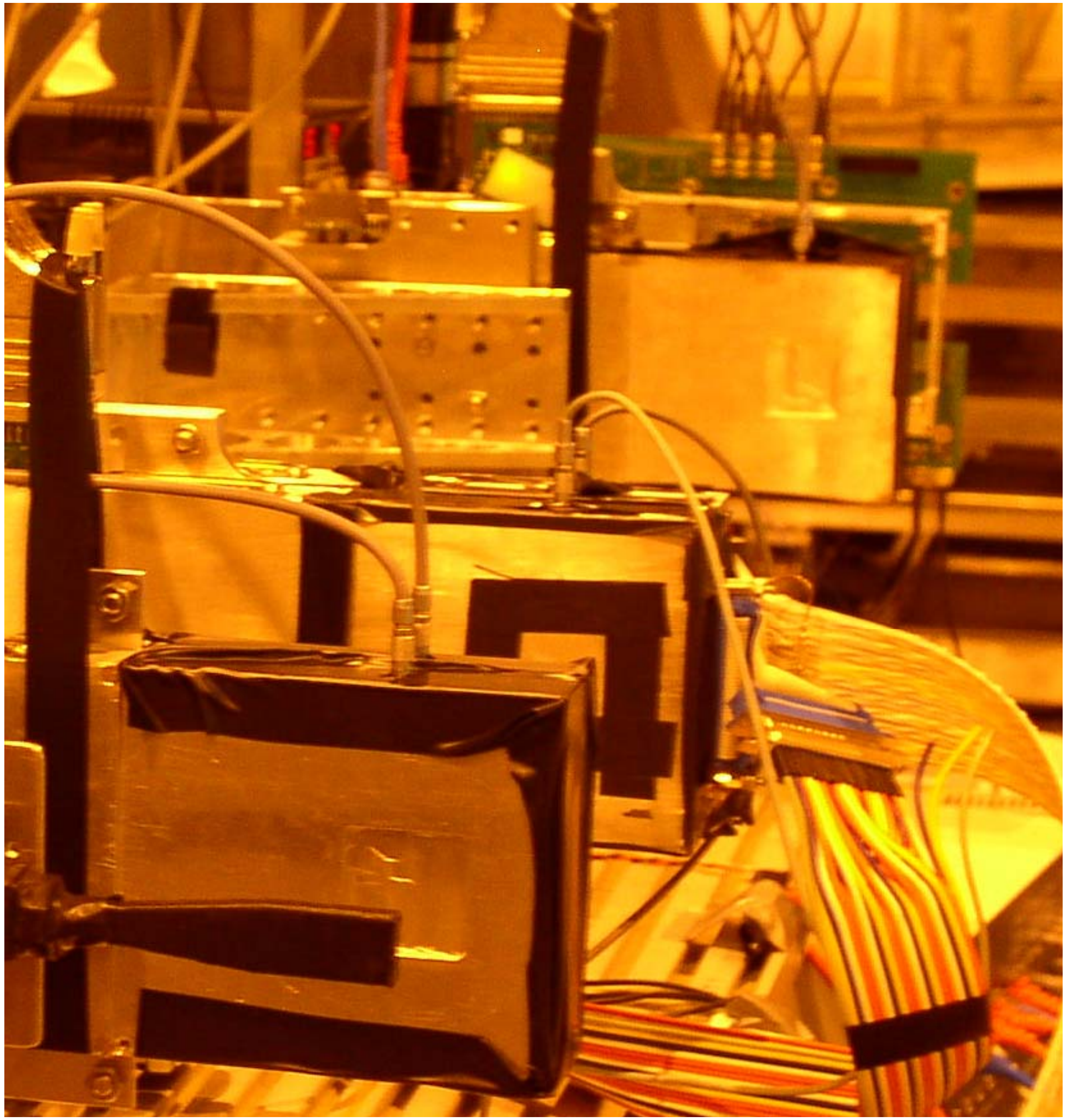
Methods – Detector Description

Back side of DEPFET with alumina lines for laser localization.

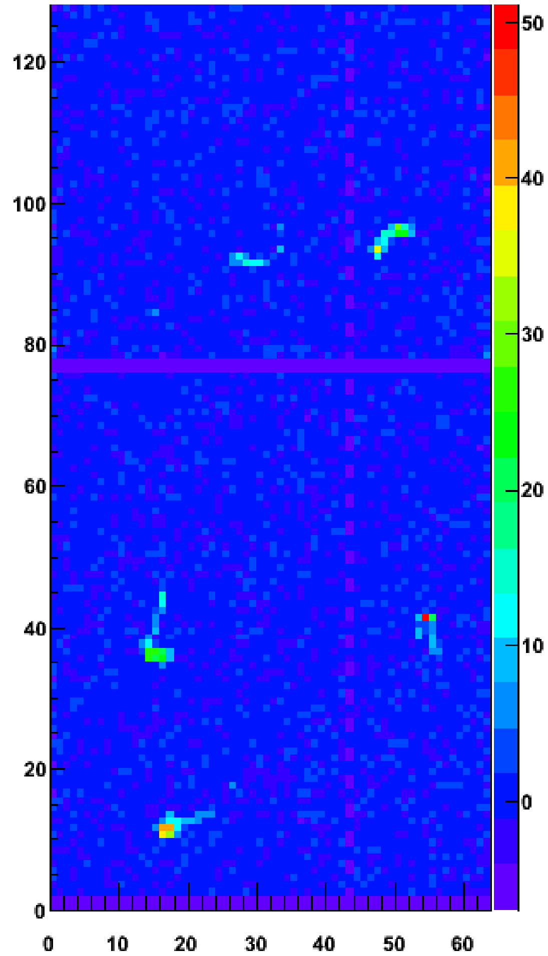
Location of the DEPFET sensor in readout electronics.



Methods – Detector Description



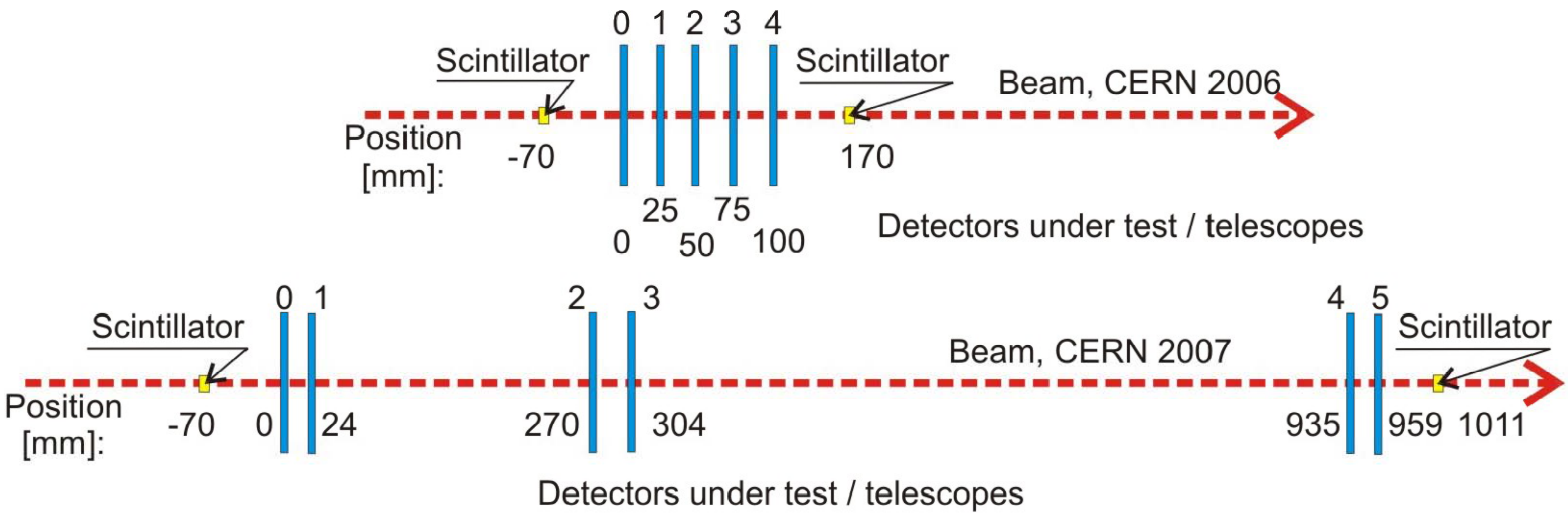
DEPFETs at beam test 2007.



Example of output from DEPFET with few particles impact points and δ-electron paths.

Methods – Beam Test

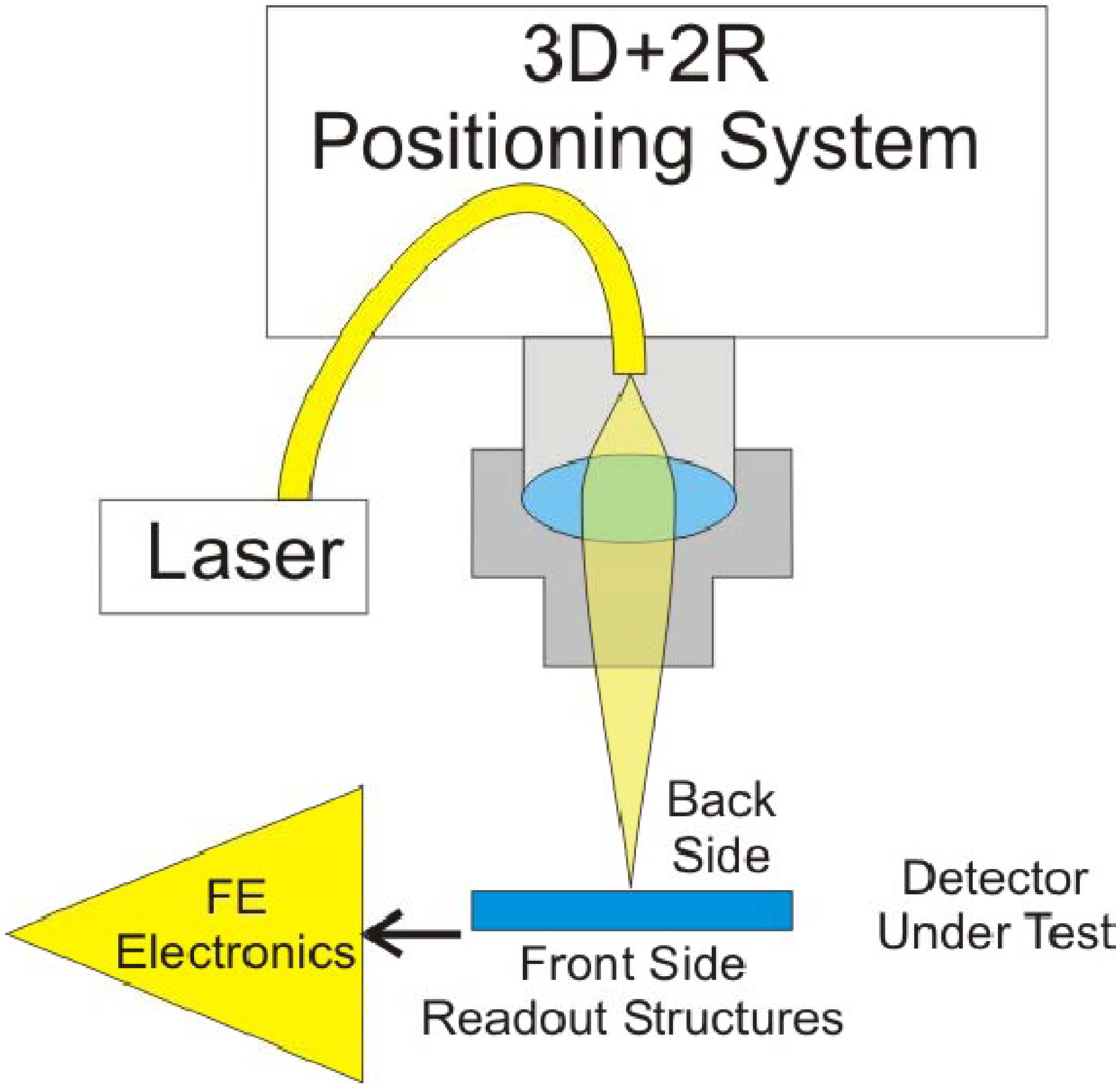
Two beam tests at CERN SPS with 180 GeV π^+ and with arrangements of 5 detectors.



Geometries of the CERN DEPFET beam tests in 2006 (top) and 2007 (bottom).

Methods – Laser Test

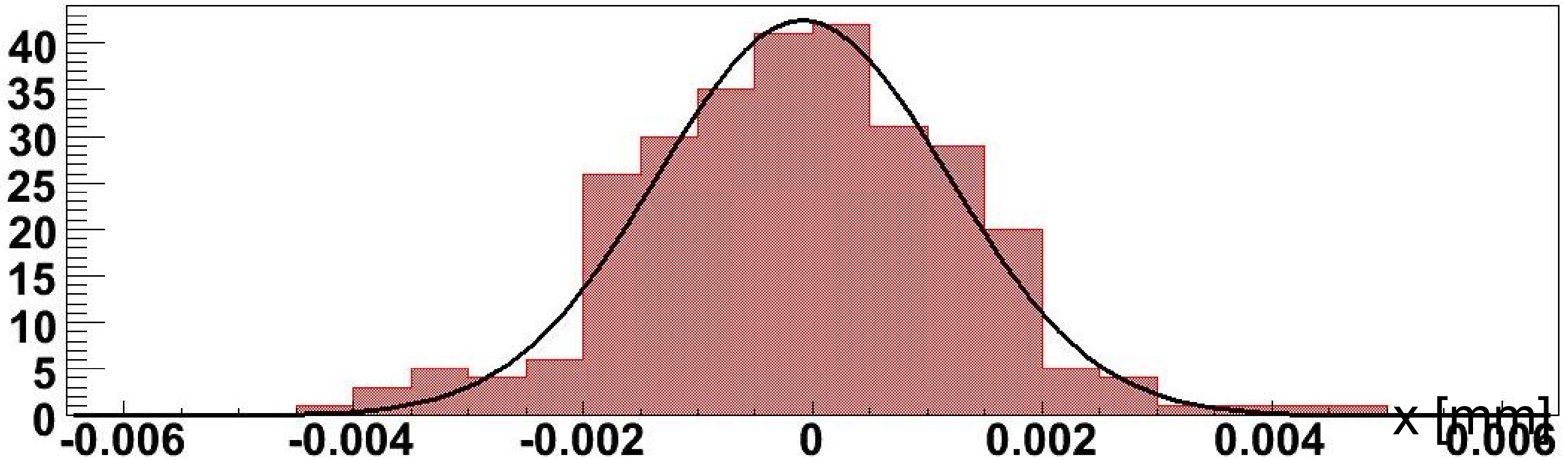
1. Laser tests were performed using a 682 nm semiconductor laser with calibrated beam power control system.
2. High statistics scans of 20 x 20 points on a grid of 2.5 µm for a wide range of laser beam powers.
3. Each point was probed by 50 pulses to eliminate laser noise and to obtain precise pixel response.
4. Laser power was controlled, monitored and calibrated to energies generating the same charge per laser pulse as a typical particle in a beam test.



Methods – Analysis

1. Several methods going beyond the standard beam test analysis.
2. Track finding using a PCA filter and robust alignment [*].
3. Resolution calculations taking into account multiple scattering and avoiding infinite energy extrapolation [*].
4. Several variants of impact point position correction:
   1. no η-correction, only center-of-gravity estimate
   2. standard one-dimensional η-corrections applied independently in both directions
   3. 2D impact point correction calibration based on laser test (for one detector)

[*]: Kvasnička, P.: Depfet beam test alignment and resolution analysis, EUDET Memo 2008-10, http://www.eudet.org/e26/e28/e615/e757/eudet-memo-2008-10.pdf



Example of residual plot: Histogram of track fitting residuals

Results and Discussion – Impact Point Reconstruction

1. In the absence of a feasible "full" 2D η-correction algorithm, the best available variant of η-correction applicable for pixel detectors is the combination of independent 1D η-corrections in both directions. This method is conceptually simple, but restrictive: it assumes that corrections in x and y are independent.

2. This η-correction remarkably (by more than 20%) improves detector resolutions for all detectors and both coordinates. For example, the correction reduced the resolution of the best detector in the 2006 beam test setup from

   $1.11 \pm 0.15\ \mu m$ to $0.83 \pm 0.18\ \mu m$.

Results and Discussion – Impact Point Reconstruction

1. A search for a method that could provide good impact point position correction for pixel detectors and, at the same time, be able to detect areas of charge collection in-efficiency within pixels, inevitably leads to methods which we call "impact point position calibration", to distinguish them from η-correction methods. These methods rely on experimental determination of corrections to centroid estimates.

2. Such determination can be based on tracking, where the corrections are calculated as mean difference between track intersection and centroid estimate for a given position on the detector, or on laser scans, where we have independent information about the position of laser beam.

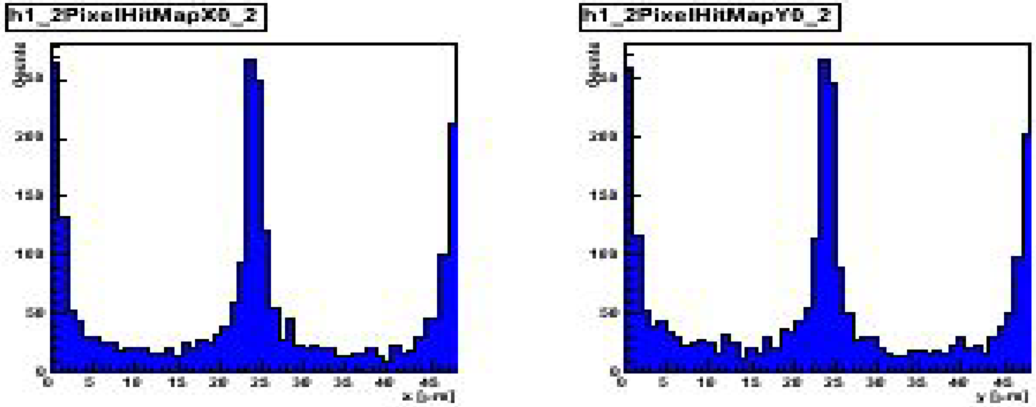
3. A special complication arises due to hits that do not induce charge sharing in one or both directions – these must be treated separately.

4. The basic advantage of laser calibration is a detailed information about response and local resolution from every point in a pixel, and very precise impact point correction due to cheaply achievable high statistics.

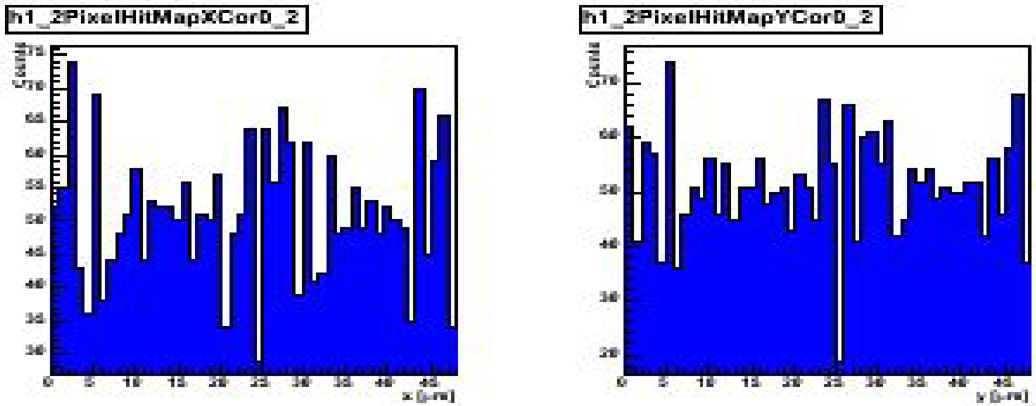
5. A disadvantage is a different mechanism of charge creation and, consequently, a slightly different profile of collected charge distribution, as described in the following slides.

Results and Discussion – Impact Point Reconstruction

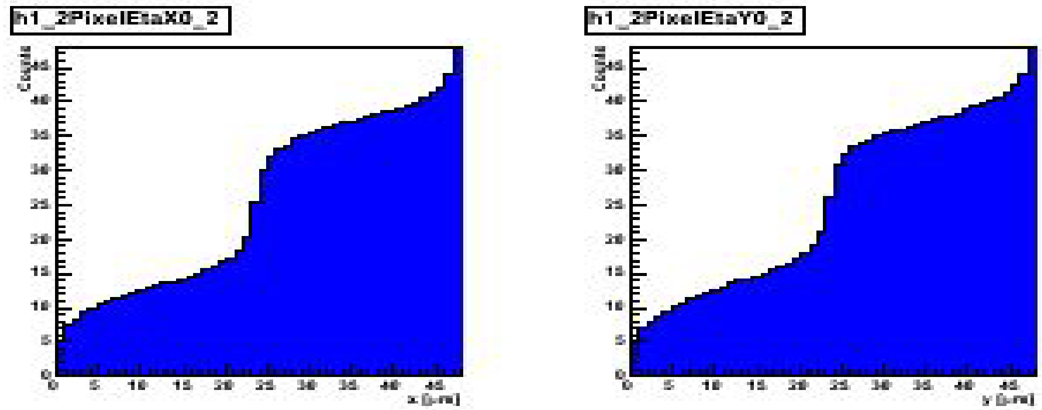
projections of hit distribution within 2 pixels



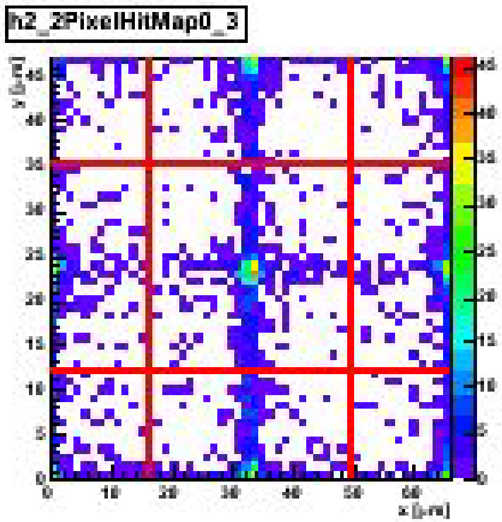
projections of hit distribution within 2 pixels after η-correction

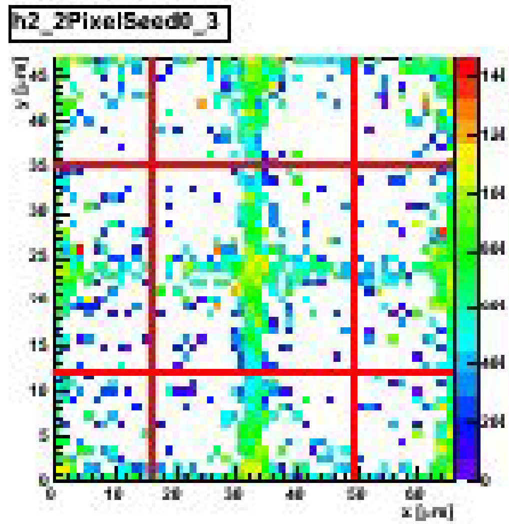


η-correction function



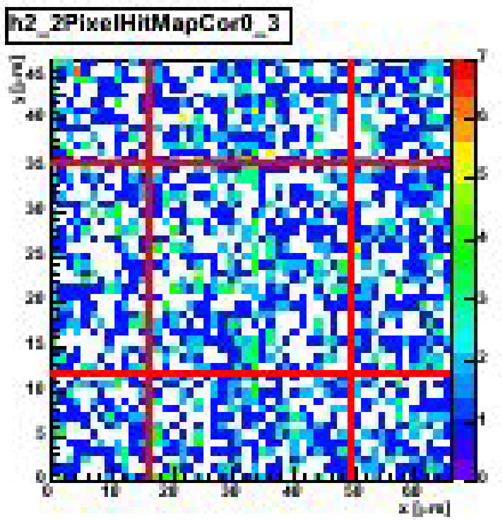
Results and Discussion – Impact Point Reconstruction

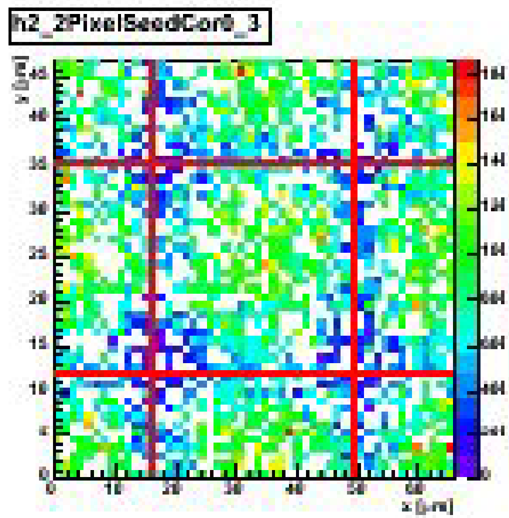




hit map

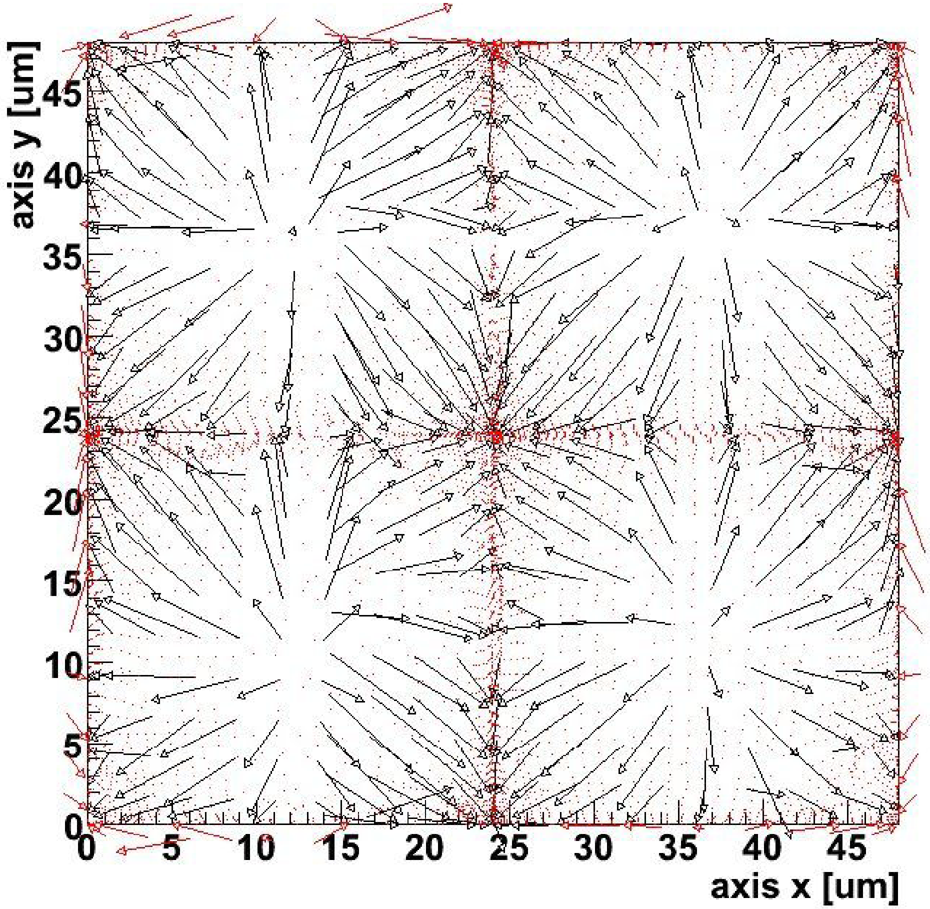
seed amplitude
distribution map

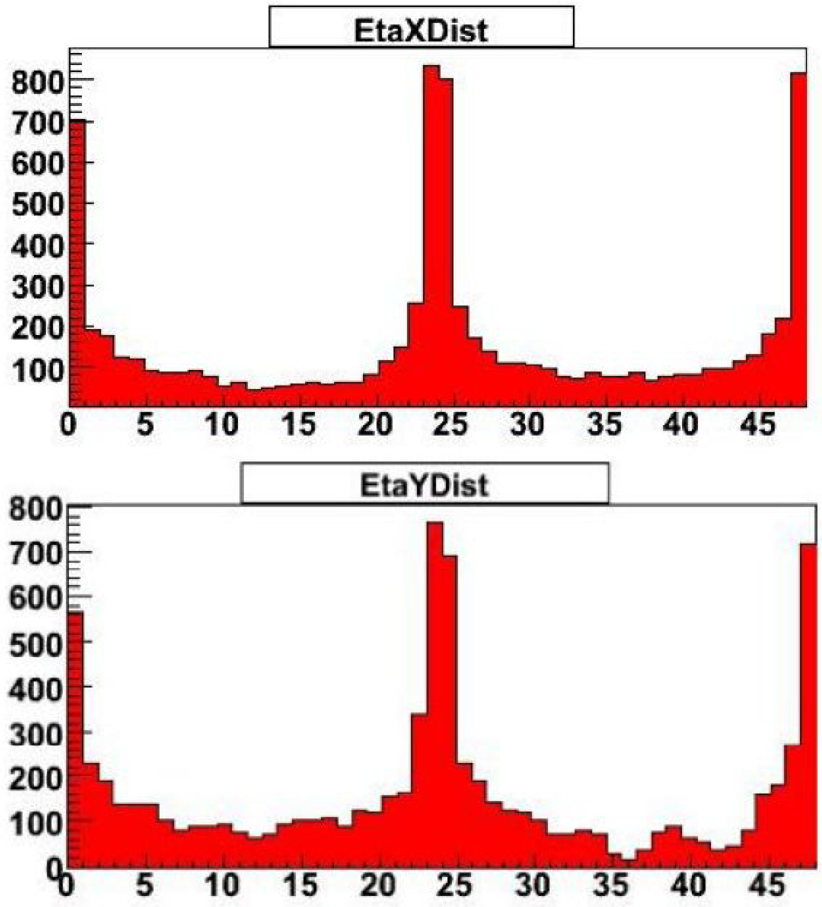




Example of a hit map a 2 x 2 pixels area before η-correction (only COG, top), and after η-corrections (bottom)

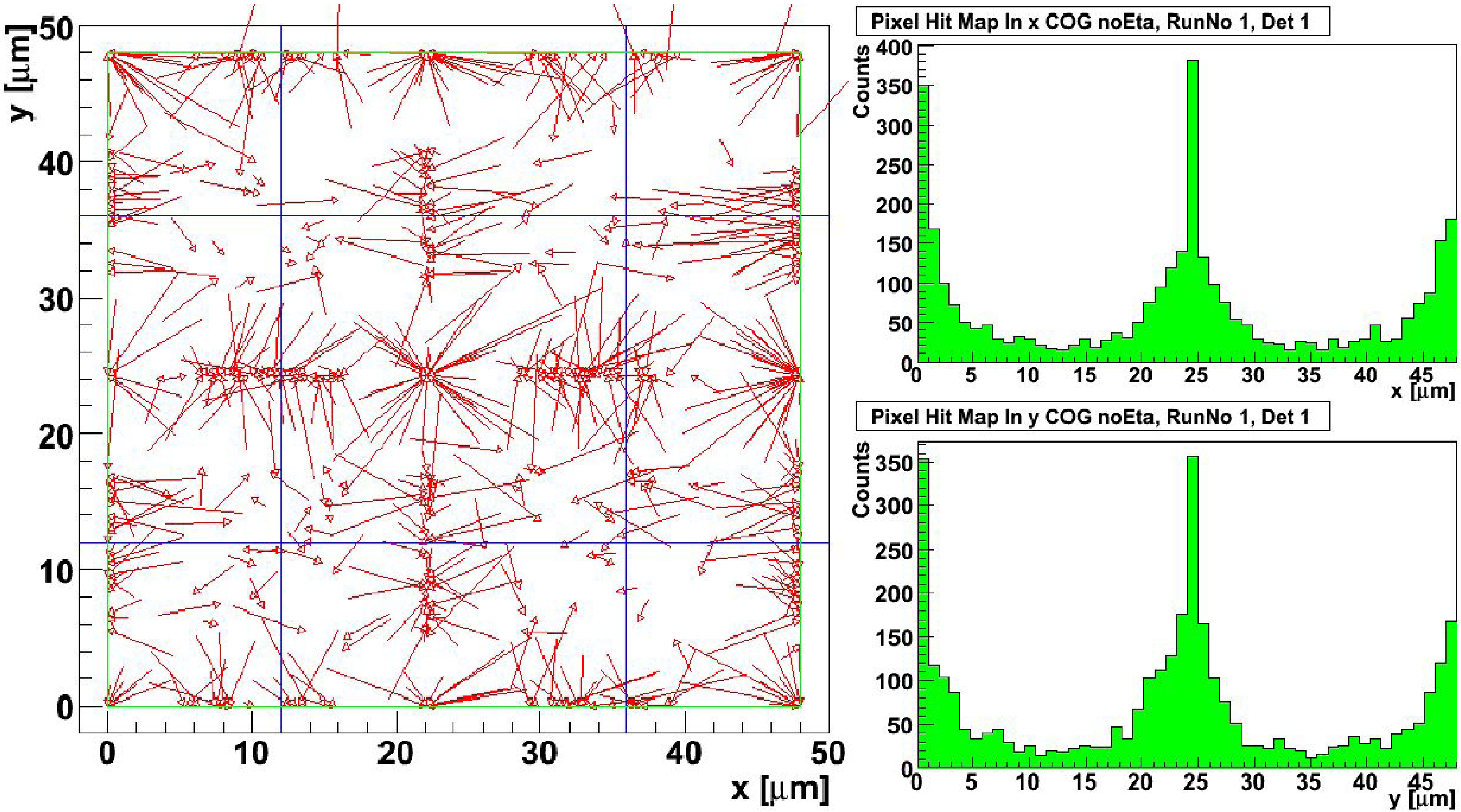
Results and Discussion – Impact Point Reconstruction





Laser test: an example of a 2D impact point correction field (left), X (top right) and Y (bottom right) projections of hit distribution within pixels.

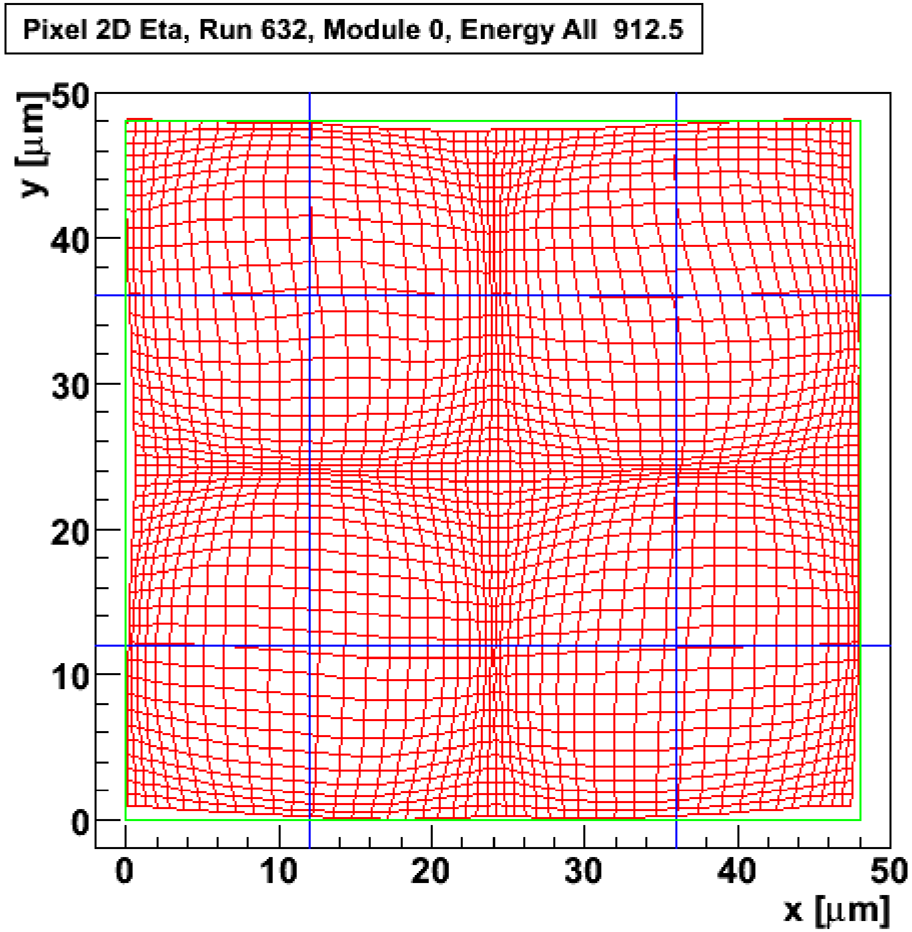
Results and Discussion – Impact Point Reconstruction



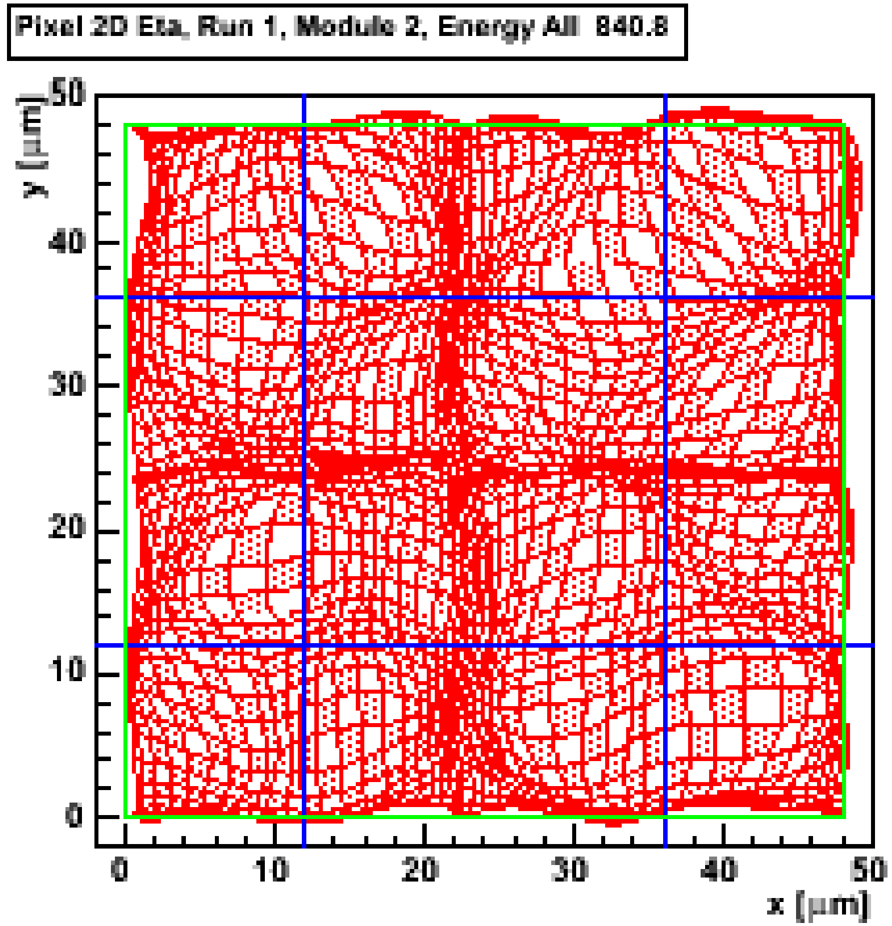
Beam test: an example of a 2D impact point correction field (left), X (top right) and Y (bottom right) projections of hit distribution within pixels.

Results and Discussion – Impact Point Reconstruction

From the 2D impact point correction field we construct a Delaunay triangulation of the correction map for x and y coordinates and find the correction for beam test hits by interpolating in the triangulated surfaces.



Correction obtained from laser test



Correction obtained from beam test (lower statistics of points for reconstruction)

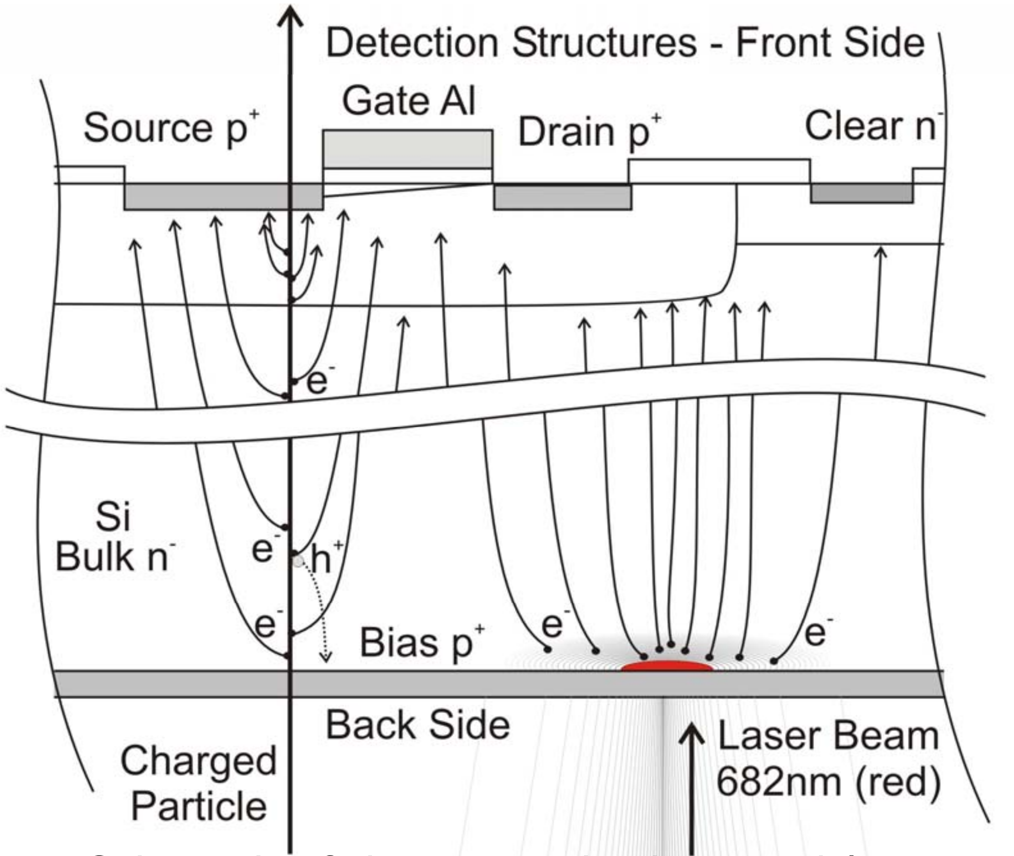
Results and Discussion – Detector Resolutions

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 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.

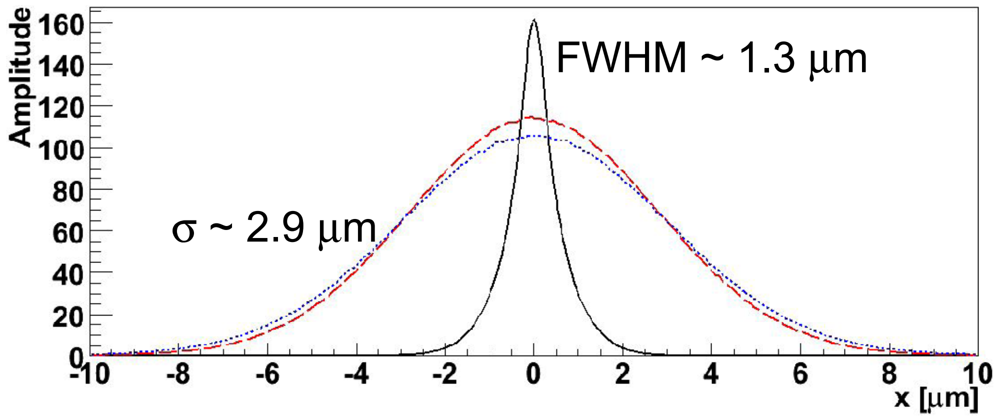
1. Stable values within experimental error.
2. Does not depend on geometry or detector position in the setup.
3. The resolutions for track calibration correction are not presented in Table 1, since we did not have sufficient statistics for the selected detector in the 2007 beam test.

Results and Discussion – Charge Distribution Calculations



Schematic of charge creation by a particle traversing a silicon detector (left) and by a red (682 nm) laser beam (right).

Charge distribution on the detecting surface generated by a particle traversing the detector (solid line), by a red (682 nm) laser beam (dashed line), and by an infrared (1065 nm) laser beam (dotted line). The particle track and laser beam are perpendicular to detector surface. The laser produces 4x more charge than the particle.



Conclusions

1. The studied methods of hit reconstruction using impact point position calibration from laser tests and reconstructed tracks from beams gives improvement of pixel detector resolution more than 20%. The best of the tested DEPFET structures consistently achieve sub-micron resolution in the fine coordinate.

2. The laser calibration function is a useful tool for mapping detector precision and could serve as a process quality monitoring tool in case of mass production of modules for a sub-micron semiconductor tracker.

3. A new promising DEPFET structures were tested in summer 2008 on PS and SPS beam tests (with high statistics collected), as well as in laser tests. We expect a confirmation of the presented analysis method.

Thank you for attention!

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