Simulation of Charge Collection in Microstrip Detectors

Z. Doležal, **Z. Drásal**, P. Kodyš, P. Řezníček

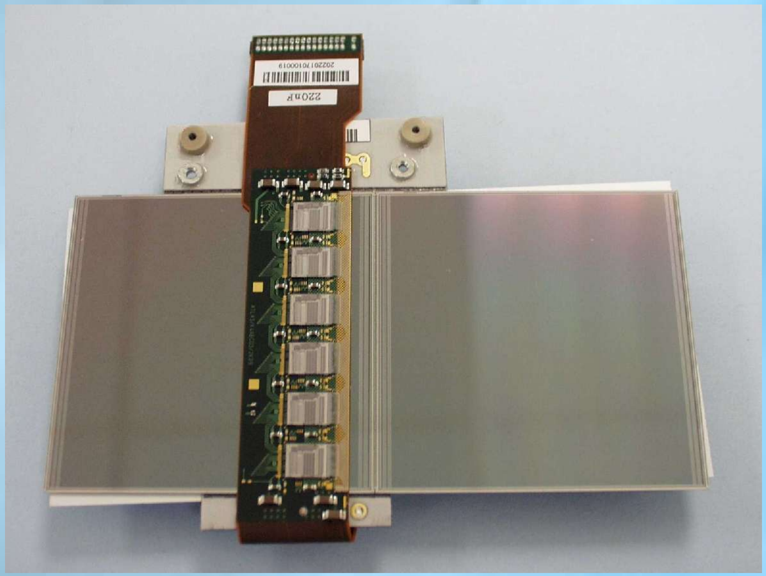
Institute of Particle and Nuclear Physics
Charles University, Prague

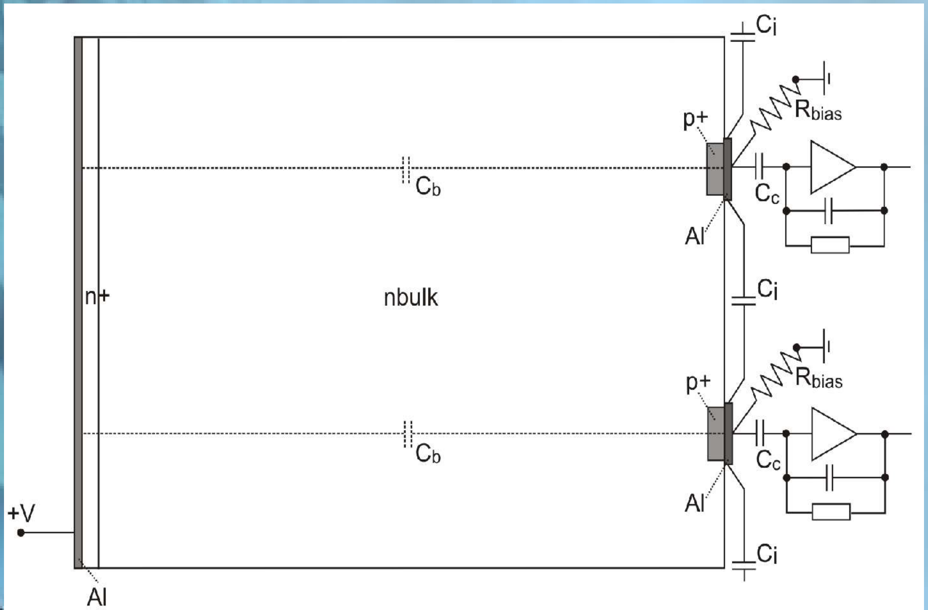
Simulation Conception

- Calculation of electric, resp. weighting field, in MAXWELL 2D simulation software, data export on a grid and conversion into hbook format
- Monte Carlo simulation
  - generation of e-h pairs
    - by a laserbeam incident at a certain angle
    - by a minimum ionizing particle (180 GeV/c pion) (Geant3) incident at a certain angle
  - e-h pairs propagation in a silicon bulk
    (Many thanks belong to N.Mazziotta, F.Loparco INFN Bari, see NIMA 533 (2004))
  - calculation of the current induced at time *t* by a moving carrier (e,h) on the k^{th} electrode (strip) via Shockley-Ramo theorem
  - results (histograms, graphs or ntuples) saved in hbook format (converted into ROOT format)
- Crosstalk simulation, further processing (ROOT)

SCT Detectors

- 2 p-n silicon wafers wire bonded (electrically connected) to each other
- 768 + 2 Al strips (Hamamatsu, CiS)
- stereo angle of 40 mrad
- spine – mechanical support for the wafers
- glass fan-in – forms connection between a sensor and a hybrid





- hybrid – 12 specially designed ABCD 3T chips, each reading 128 channels
- SCT electronics – uses binary read-out system (0 x 1)
- FE - front end electronics – AC coupled
- poly-silicon bias resistor $R_{bias} \approx 1.25M\Omega$ connected to guard ring

Barrel Detector Parameters

detector depth = 285 μm

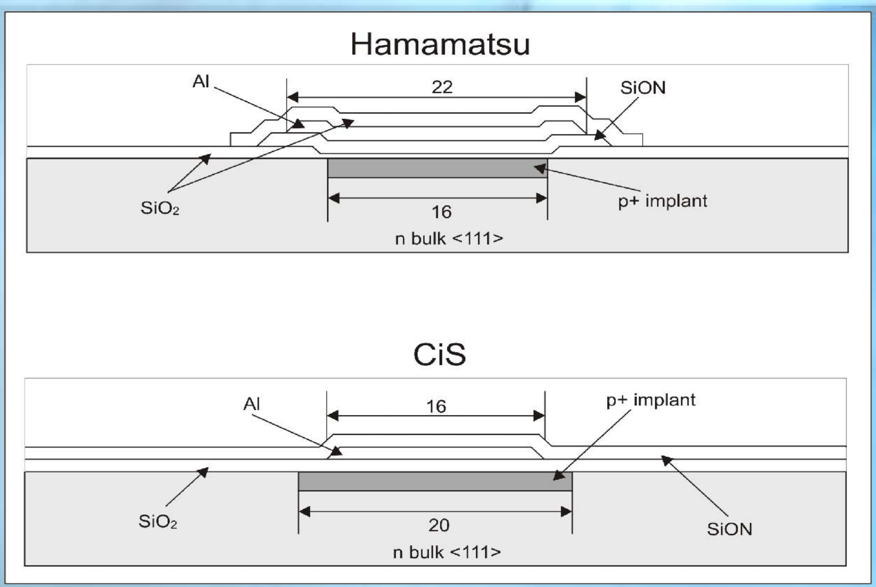
pitch = 80 μm

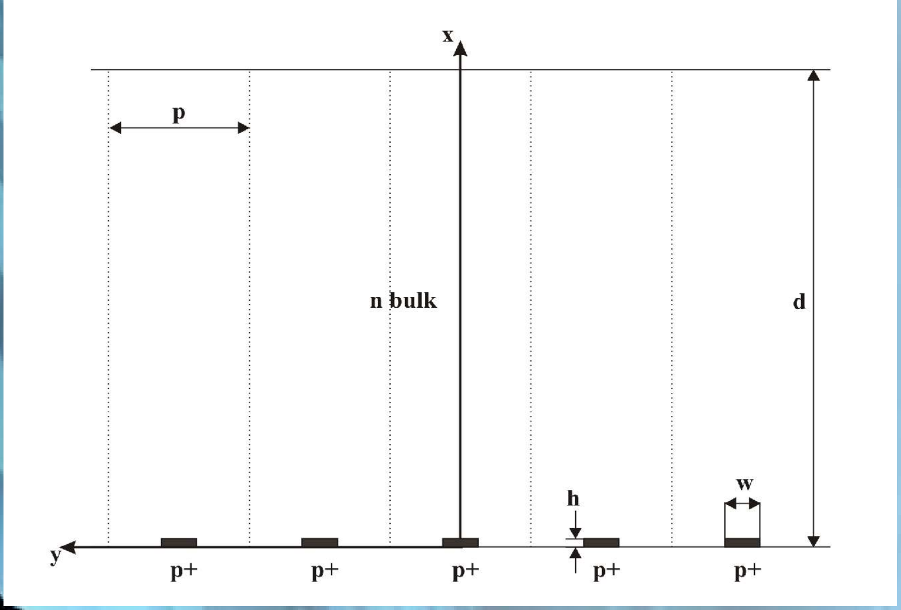
p^+ width = 16 μm

p^+ height ≈ 1 – 1.5 μm

Al width = 22 μm

Al height ≈ 1 μm





N_{donors} = 10^{12} cm^{-3}

$N_{acceptors}$ = 3.10^{19} cm^{-3}

$C_{interstrip}$ = 6 pF

$C_{backplane}$ = 1.77 pF

$C_{coupling}$ = 120 pF

ENC ≈ 1500 e ≈ 0.24 fC

bias voltage = 150 V

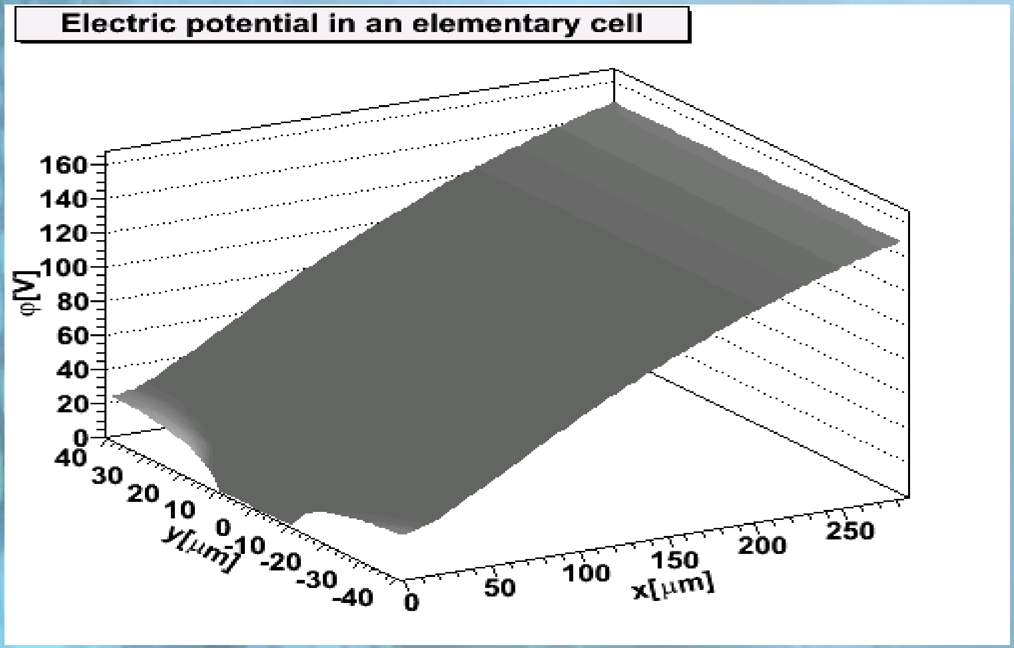
Simulation - electric field

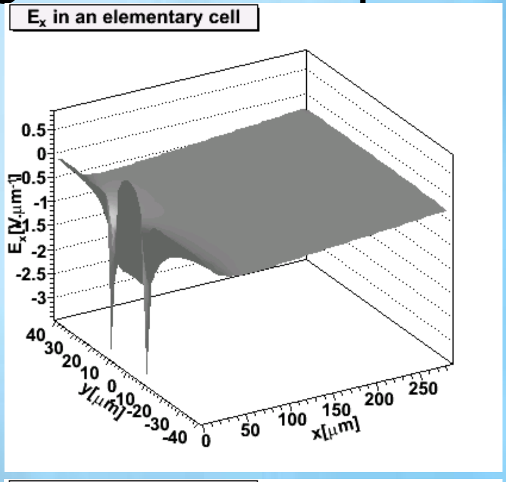
- Calculation of electric (resp. weighting field) - realized by dividing the detector volume into elementary cells and solving Poisson's equation with following boundary conditions:

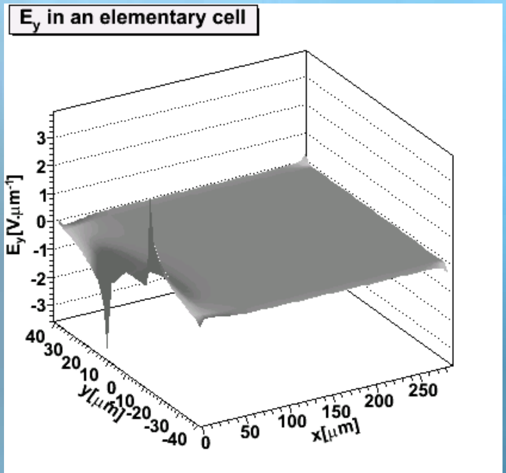
$$\varphi(x=d)=150\,V$$

$$\varphi(y=-p/2)=\varphi(y=+p/2)$$

$$\varphi(x=0,-w/2\leqslant y\leqslant+w/2)=0\,V$$





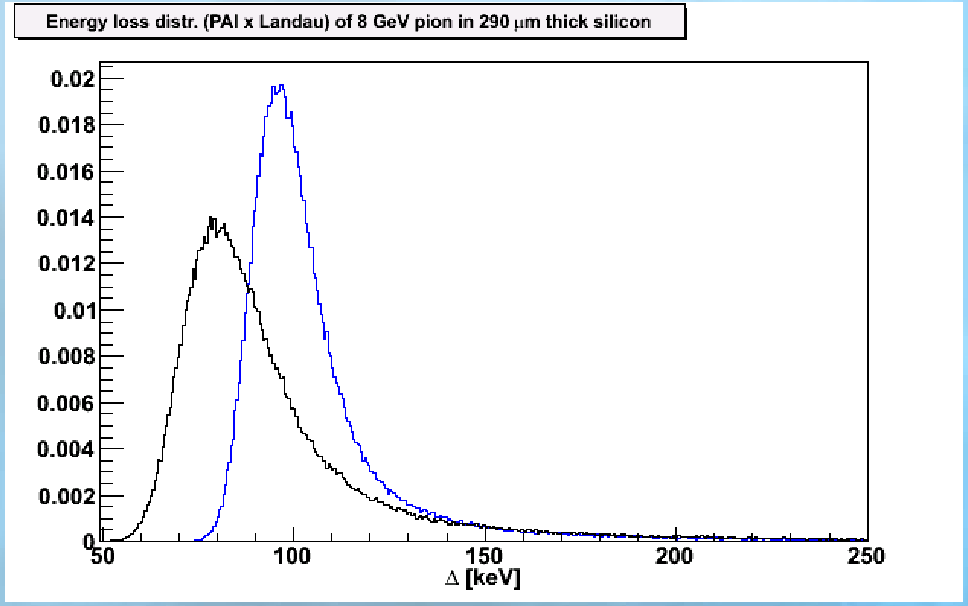


Simulation – e-h generation (Geant3)

- Energy loss distr. – Landau distribution **x** PAI model
  - for typical thickness (≈ 300 μm) of silicon wafers the Landau distribution (automatically set in Geant 3) is not adequate for description of energy loss distribution
  - PhotoAbsorption Ionization model (PAI model) is correct
  - automatic choice of model is connected with the significance parameter: $\kappa = \xi / T_{max}$ (Landau corresponds to $\kappa \leq 0.01$ for $\xi \gg I$)
  - the validity of Landau distribution is strongly dependent on: particle energy, Z_{med}, A_{med}, wafer thickness, mean ionization potential I
- 2 models of passage of ionizing particles (180 GeV/c pions) through the detector volume used:
  1. fast simulation without δ-electrons – generation of e-h pairs uniformly along the track, energy loss generated according to the Geant 3 energy loss distribution (PAI model, 1 e-h pair ≈ 3.65 eV)
  2. full simulation with δ-electrons, PAI model, STEMAX = 5 μm

Simulation – e-h generation (Geant3)

- energy loss distributions of 8 GeV/c pions in 290 μm Si (PAI model **x** Landau)
  - **PAI model** (black)
    - MPV ΔE = (79 ± 1) keV
    - width = (29 ± 1) keV
  - **Landau** (blue)
    - MPV ΔE = (96 ± 1) keV
    - width = (20 ± 1) keV
  - **Experimental values**
    - MPV ΔE = (79.43) keV
    - width = (29.24) keV



Simulation – e-h pairs propagation

- the drift of e-h pairs in electric field is described by:

$$\vec{v}(\vec{r}(t)) = \mu . \vec{E}(\vec{r})$$

- the mobility is strongly dependent on electric field and temperature:

$$\mu = \frac{v_m / E_c}{(1 + E / E_c^{\beta})^{1/\beta}}$$

- ODF solved numerically using Runge-Kutta method
  - with optimal space accuracy set as: $\varepsilon = 5$ µm
  - with integration step calculated as: $\delta t = \varepsilon / |\vec{v}(\vec{r}(t))|$
- the pairs are diffused during the motion by multiple collisions
  - the new distribution after time *t* is described by Gaussian law:

$$dN = \frac{N}{\sqrt{4\pi Dt(\vec{r})}} \exp\left(-\frac{\vec{r}^2}{4Dt(\vec{r})}\right) d\vec{r}$$

- the total simulation step: $\delta \vec{r} = \delta \vec{r}_{drift} + \delta \vec{r}_{diffusion}$

Simulation – weighting field

- the current induced at time *t* on the k^{th} electrode by a moving carrier can be evaluated using Shockley-Ramo theorem:

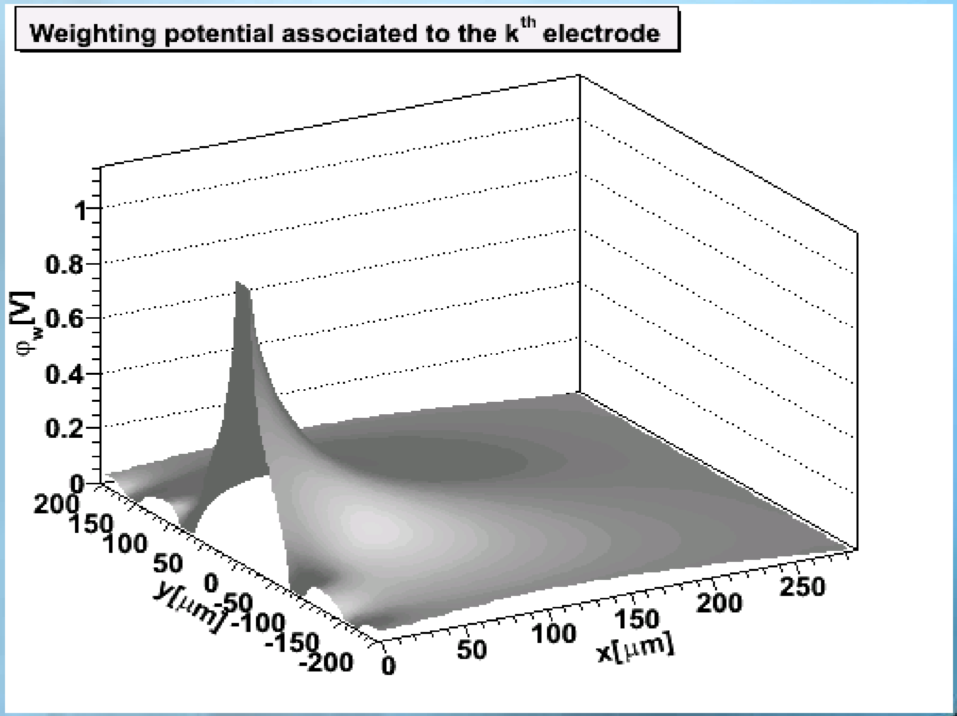
$$i_k(t) = -q\vec{v}\cdot\vec{E}_{wk}$$

- E_{wk} is the weighting field associated to k^{th} electrode
  - describes the geometrical coupling between a carrier and the electrode
  - obtained as a solution of Laplace equation with boundary conditions:

$$\varphi_{wk}(x=0, y=kp)=1 \quad k=0,\pm1,\pm2$$

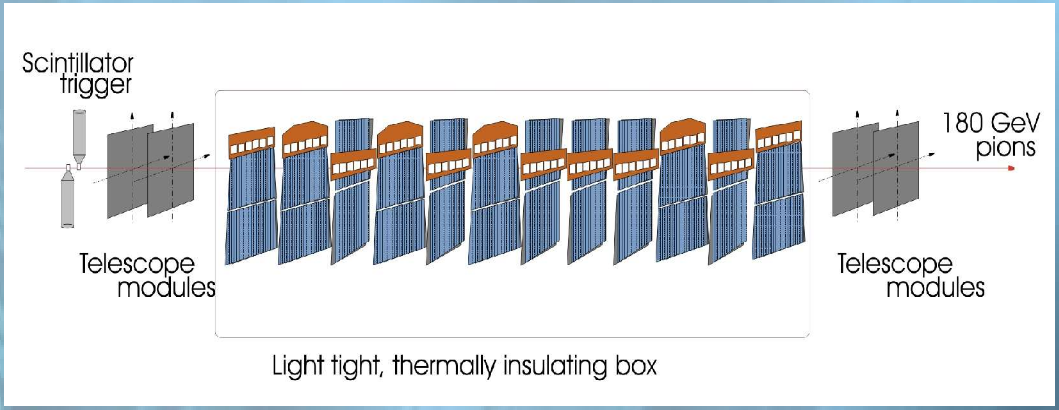
$$\varphi_{wi}(x=0, y=ip)=0 \quad i\neq k$$

$$\varphi_{w}(x=d)=0$$



SCT Beam Tests Simulations

- simulation of SCT detector response to a beam of 180 GeV/c pions (ATLAS CERN 2000–2004), comparison with the real experimental data and verification of simulation reliability:
  - for Hamamatsu barrel detector:
  - ENC 1500 e ≈ 0.24 fC
  - multiple scattering resolution $\sigma = 6$ μm
  - telescope resolution $\sigma = 5$ μm
  - discriminator threshold: 1 fC (detector efficiency higher than 99 %)
  - study of the influence of: δ–electrons, crosstalk (2 x 4.7 %), diffusion and weighting field



Beam Tests – median charge

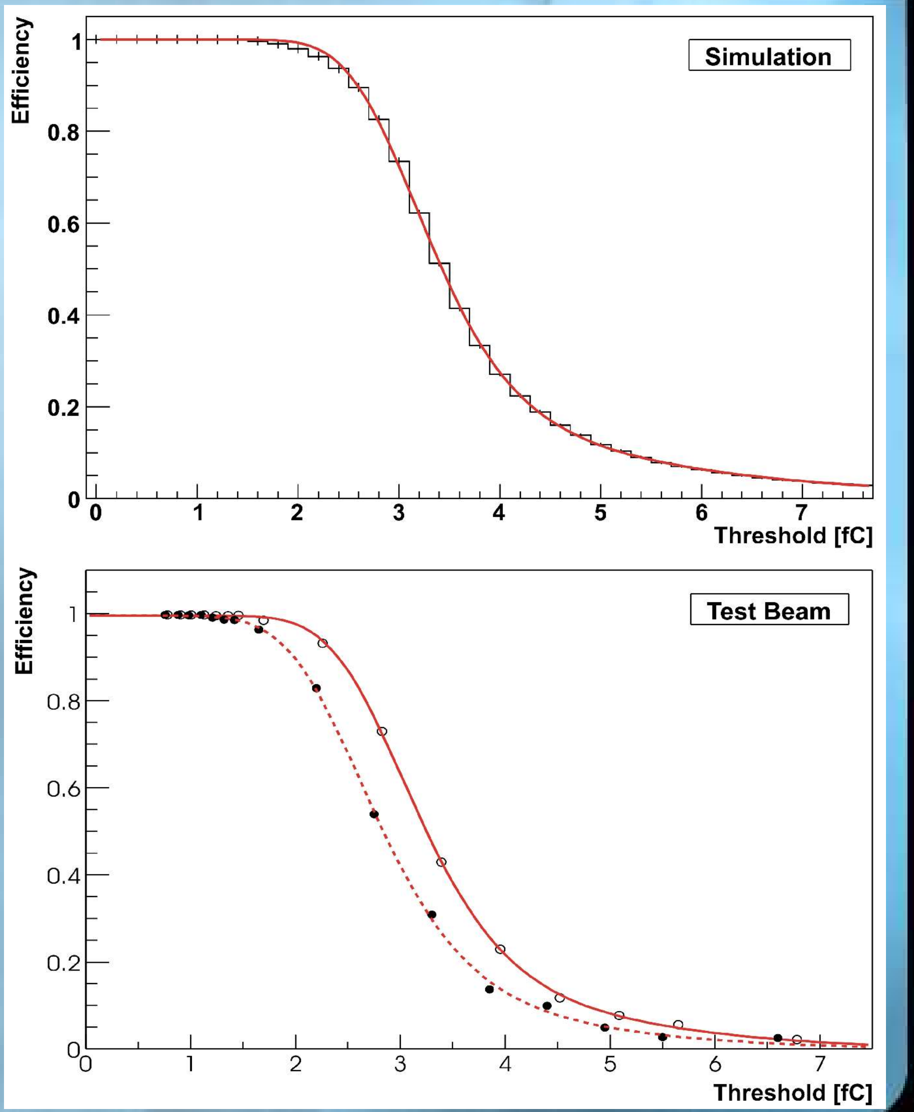
- **s-curve** measurements
- fit with a skewed error function:

$$\varepsilon = \varepsilon_{max}\, f\left(x\left[1+0.6\,\frac{e^{-\xi x}-e^{\xi x}}{e^{-\xi x}+e^{\xi x}}\right]\right)$$

$$x=(q_{thresh}-\mu)/\sqrt{2}\,\sigma$$

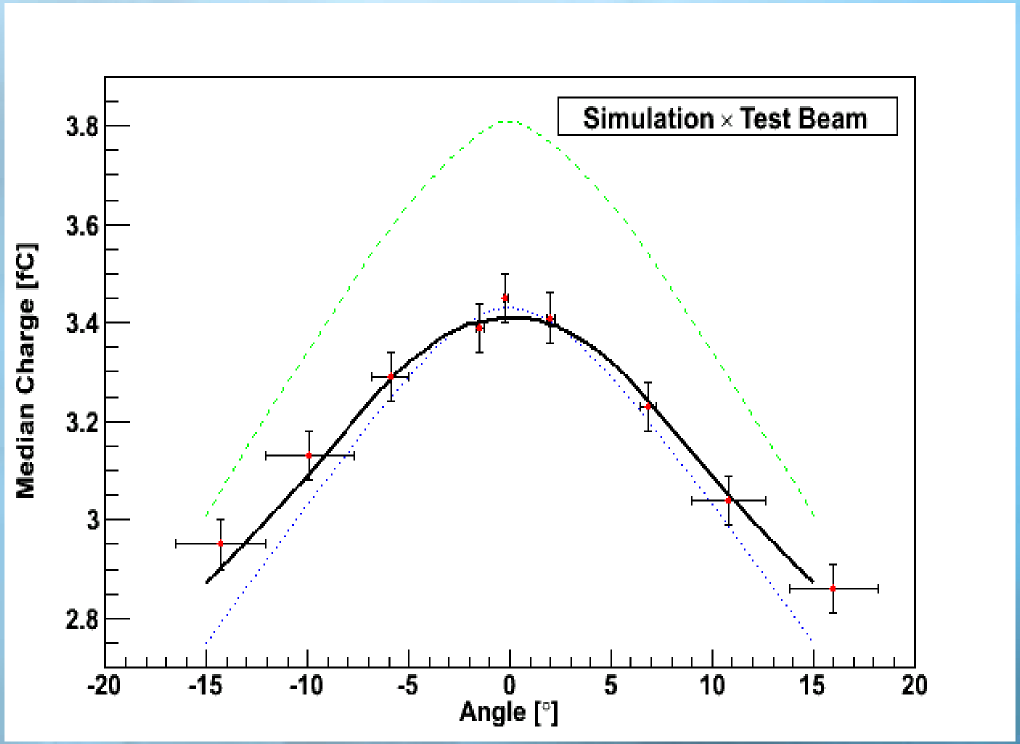
- **experiment:** (3.5 ± 0.1) fC
- **simulation:** (3.41 ± 0.04) fC

- mean ioniz. loss – PAI:	(3.91 ± 0.02) fC
- particle incident on a strip:	(3.94 ± 0.05) fC
- weight. poten., diffusion:	(3.81 ± 0.05) fC
- including crosstalk:	(3.43 ± 0.05) fC
- together with δ–electrons:	(3.41 ± 0.04) fC



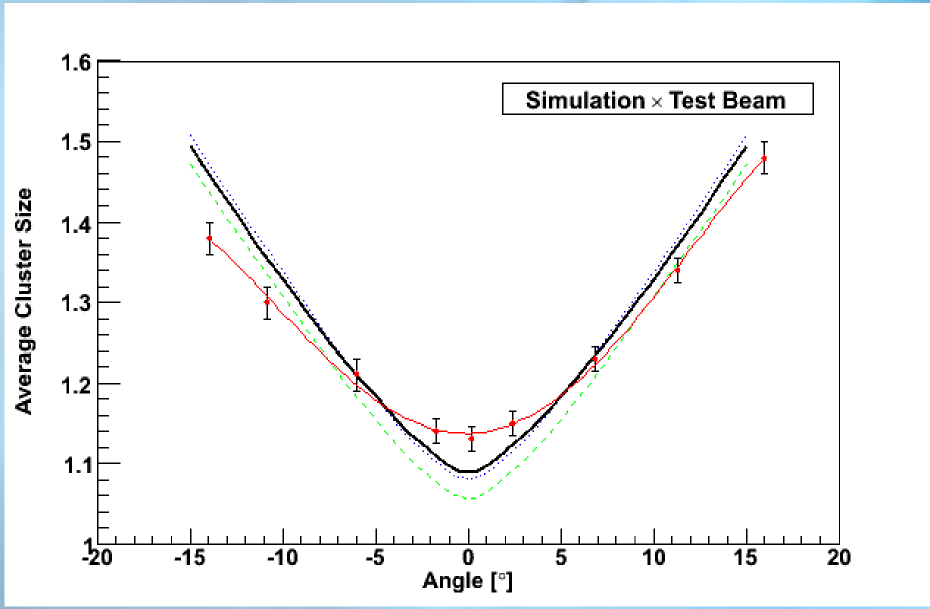
Beam Tests – incidence angle

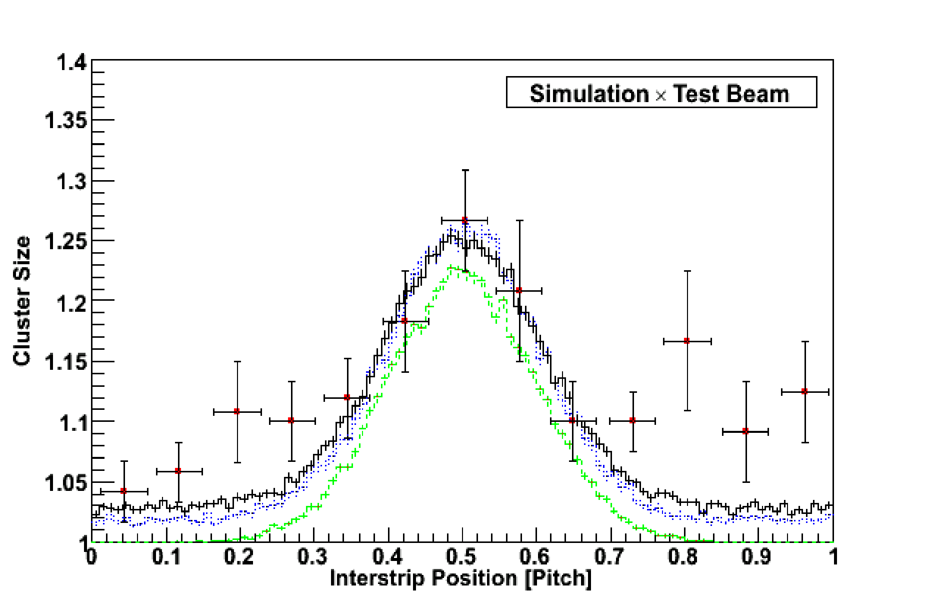
- median charge versus incidence angle
- **2 mutually opposite effects:** path length ≈ $1/\cos(\alpha)$ **x** charge sharing effect
- **simulation:**
  - green: weighting field effect and diffusion
  - blue: including crosstalk
  - black: together with δ–electrons



Beam Tests – cluster size

- **cluster size** = the number of strips that collect the charge when a particle crosses the detector volume
- **2 types of measurements** (dependent on**):**
  - angle of incidence
  - interstrip position

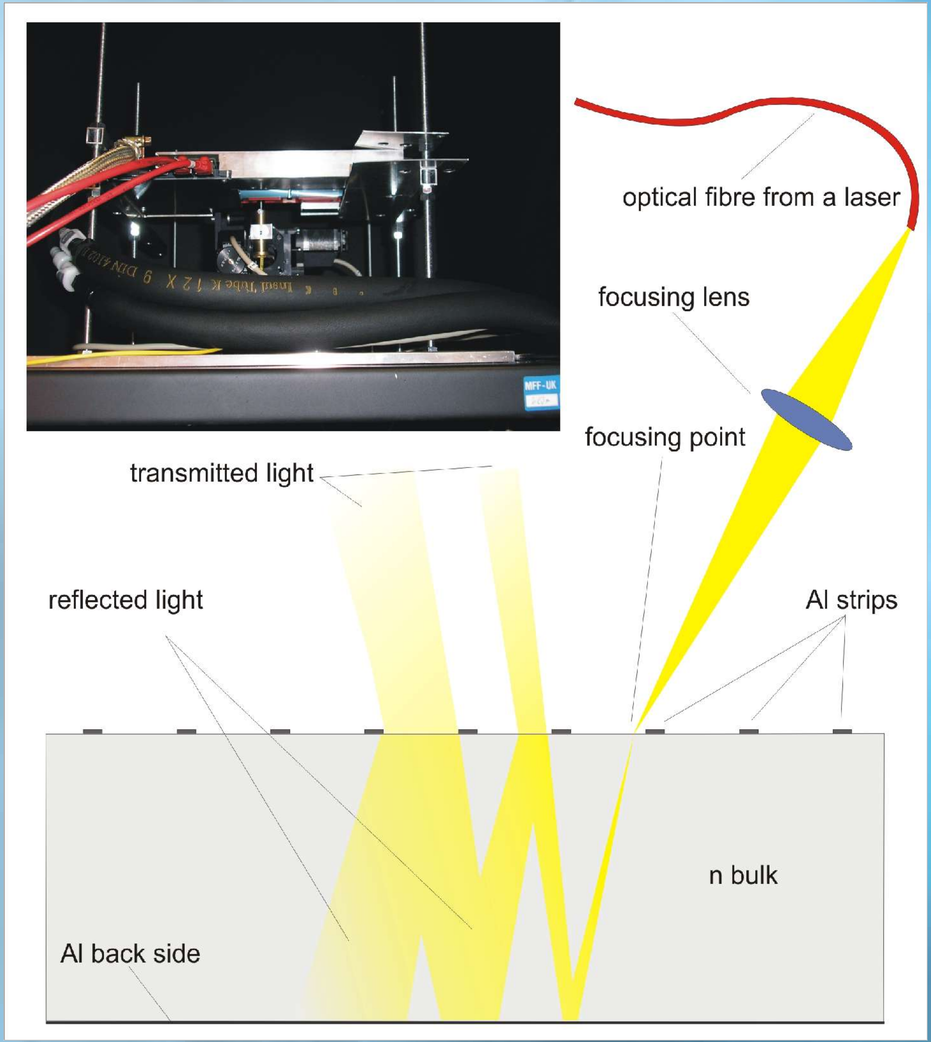




– **simulation:**
  - green: weighting field effect and diffusion
  - blue: including crosstalk
  - black: together with δ–electrons

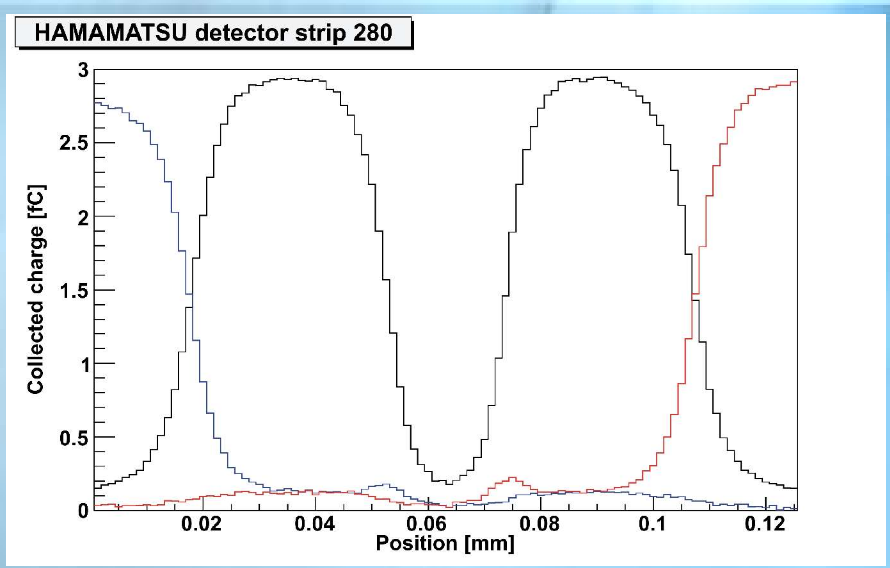
Simulation – laser beam

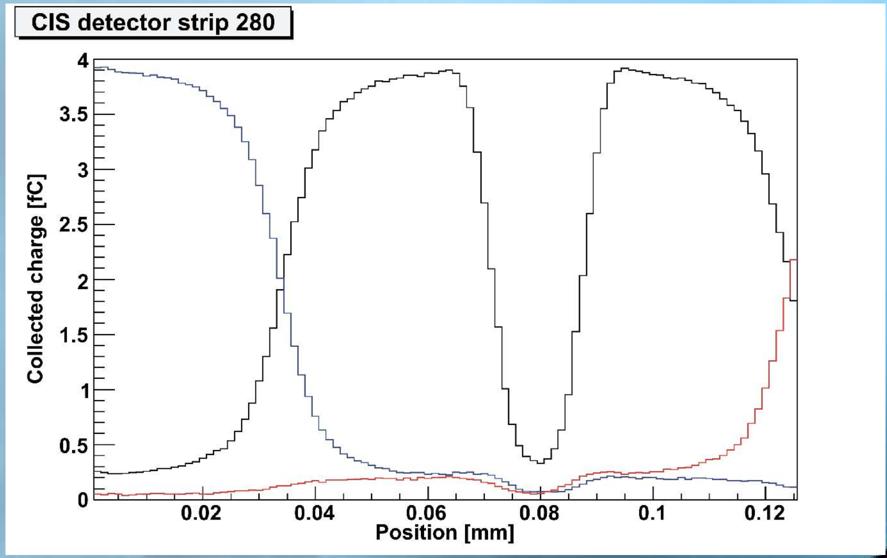
- Geometrical model of laser beam:
  - gaussian profile in plane perpendicular to the direction of motion $\sigma = 2.8\ \mu m$
  - beam divergency ≈ ±1° in direction of motion
  - exponential attenuation of the beam (untill intensity decreases below ~ 3%)
  - reflection on metal layers ≈ 90% and interface between air and Si ≈ 32%
  - each photon generates 1 e-h pair
  - equivalent generated charge 4 fC ≈ MIP
  - **wavelength**: $\lambda = 1060$ nm, $E_{ph} = 1.17$ eV
  - **attenuation length**: $\lambda_{att} = 894.2\ \mu m$
  - **refraction index**: n = 3.554



Experimental results – pitch

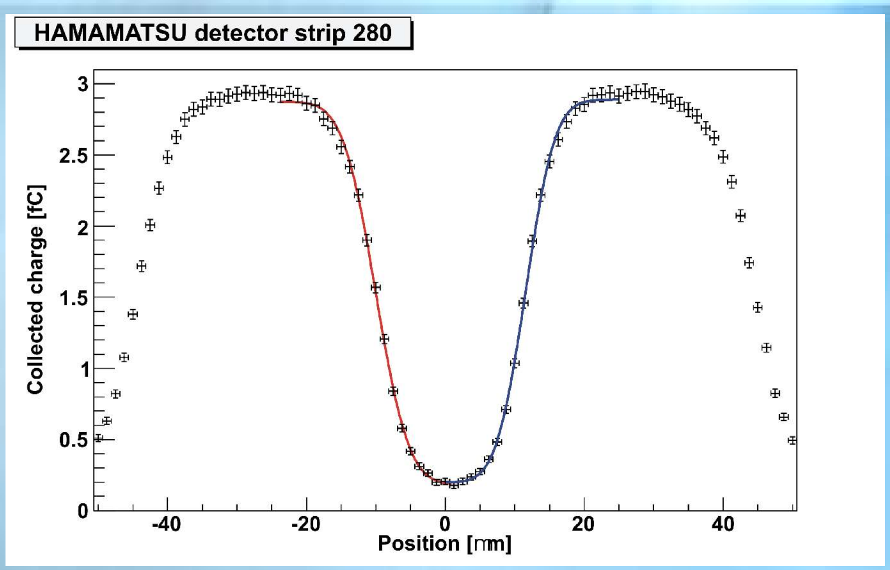
- detectors with 2 different technologies (Hamamatsu and CiS) measured
- end-cap modules measured
  - pitch$_{Ham}$ = 90.0 ± 0.5 μm
  - pitch$_{CiS}$ = 90.0 ± 0.5 μm

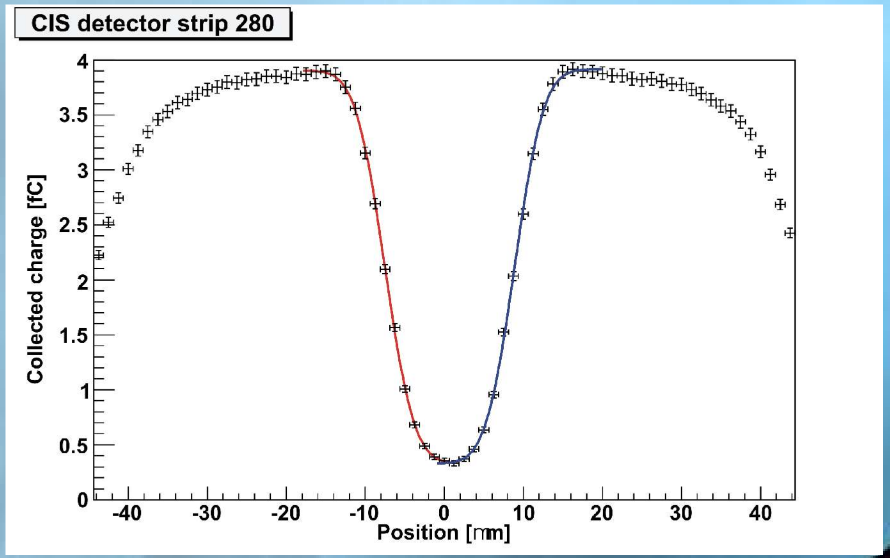




Experimental results – parameters

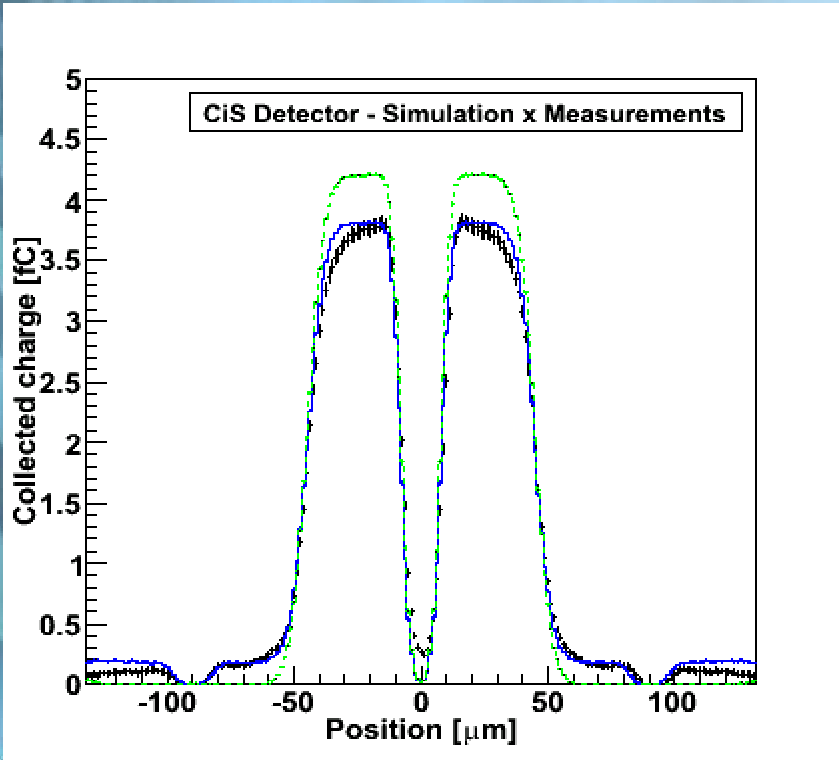
- detectors with 2 different technologies (Hamamatsu and CiS) measured
- fit with an error function and a complementary error function
  - Al strip width$_{Ham}$ = 21.6 ± 0.5 μm
  - Al strip width$_{CiS}$ = 16.1 ± 0.5 μm
  - $\sigma_{beam\ Ham}$ = 3.55 ± 0.10 μm
  - $\sigma_{beam\ CiS}$ = 2.86 ± 0.07 μm

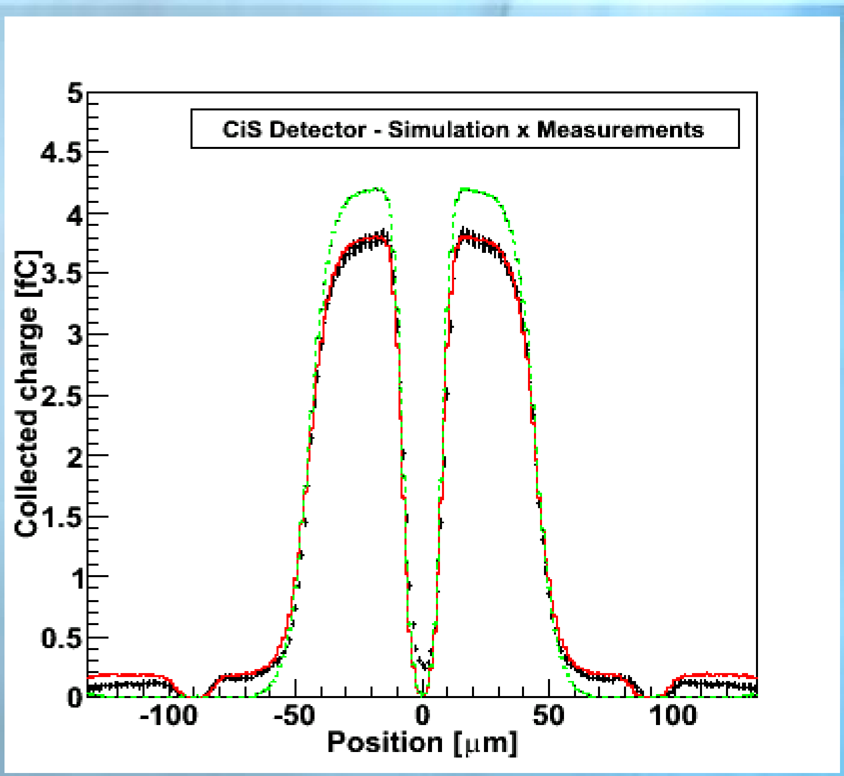




Comparison with Simulation – CiS

- $\sigma_{beam\ CiS} = 2.8\ \mu m$
- $divergency_{beam\ CiS} = \pm\ 0.5^{o}$ (blue)
- $divergency_{beam\ CiS} = \pm\ 1.25^{o}$ (red)
- simulation without crosstalk (green)

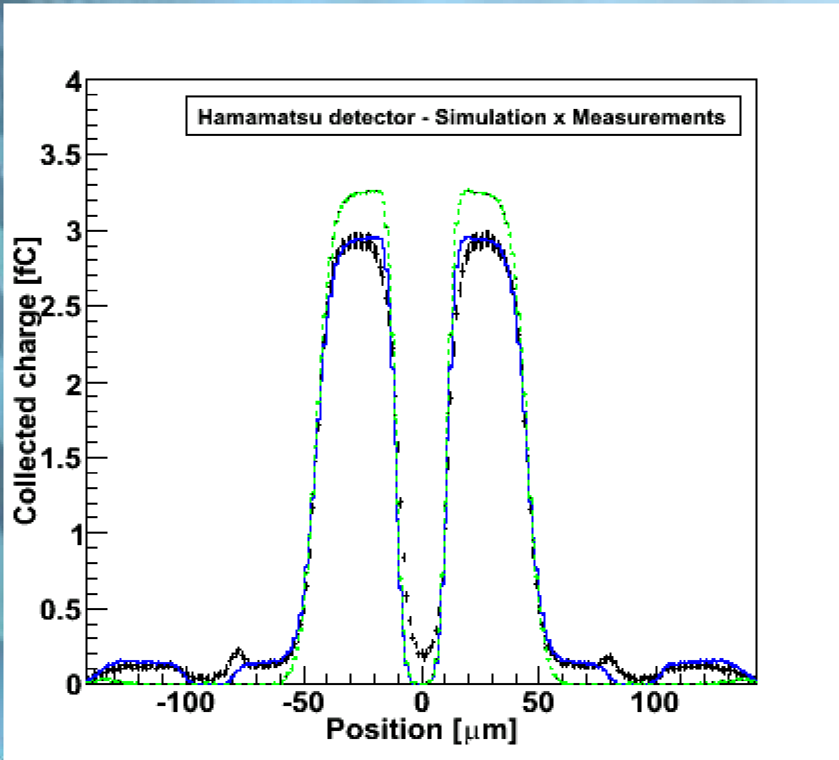


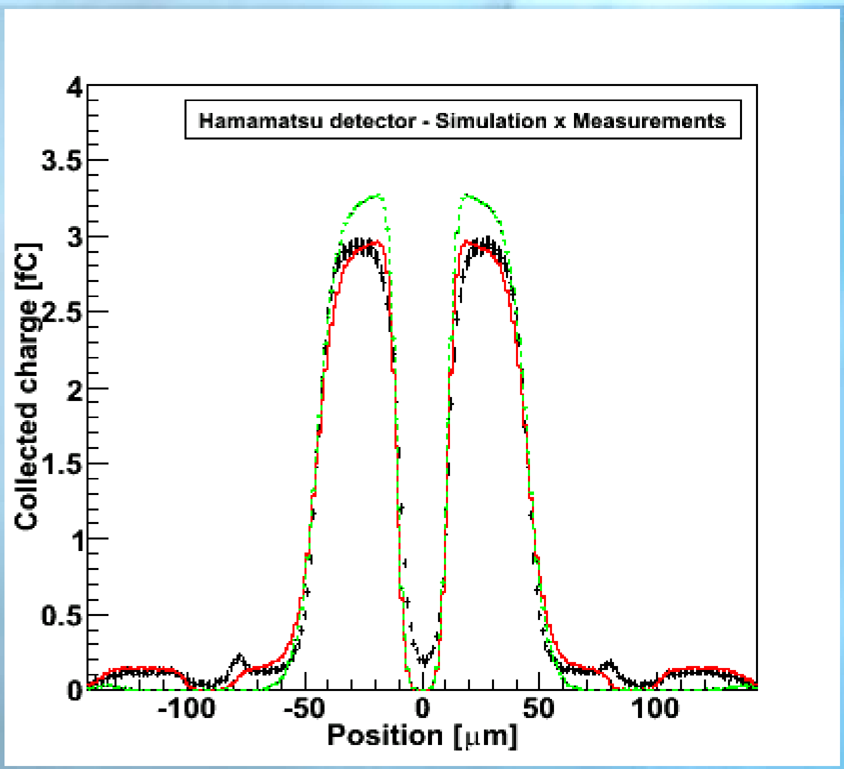


- **experiment**: (discrepancy in strip region)
  - 5 % of dep. signal ≈ 0.2 fC gets into the surface layer in strip area (protect. layer behaves as a waveguide)
  - 1 % dep. signal ≈ 0.04 fC "hallo" effect

Comparison with Simulation – Ham

- $\sigma_{\text{beam Ham}}$ = 2.8 µm
- $\text{divergency}_{\text{beam Ham}}$ = ± 0.5º (blue)
- $\text{divergency}_{\text{beam Ham}}$ = ± 1.25º (red)
- simulation without crosstalk (green)





- **experiment**: increase of signal at neighbouring strip ≈ 0.1 fC can be explained by getting of optical signal into the "waveguide" at the central region and diverting back at neighbouring strips

Conclusion

- Development of 2D Monte Carlo simulation of charge collection in microstrip detectors
- Implementation of simulation into Geant 3 framework
- Correctness verification on real experimental beam tests data (measured in CERN)
- Interpretation of physical results
  - study of dependence of detector response to individual physical results: δ–electrons, crosstalk, diffusion and weighting field
- Simulation of detector response to a laser beam
  - interpretation of experimental results based on comparison with the simulations
  - verification of geometrical model of laser behaviour in a strip detector
  - extraction of basic parameters of laser and detector from simulation and measurements
- www-ucjf.troja.mff.cuni.cz/diploma_theses/drasal_dipl.pdf