Sensor simulation and position calibration for the CMS Pixel detector

V.Chiochia[1], M.Swartz[2], E.Alagöz[1,3]

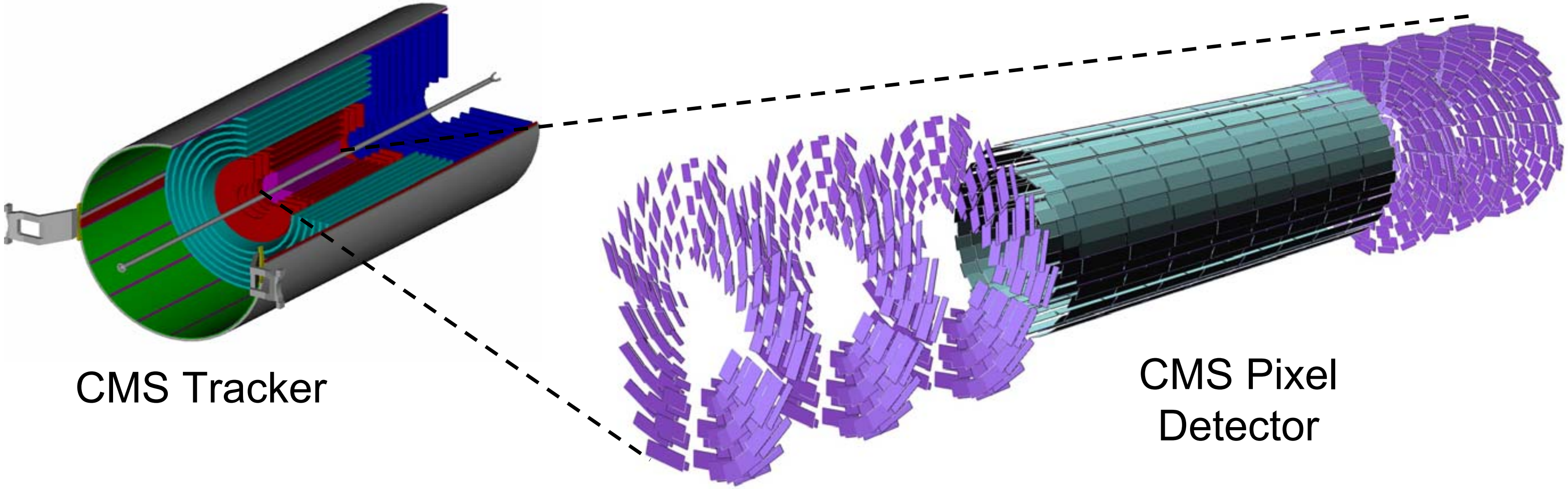
[1]Physik Institut der Universität Zürich-Irchel (Switzerland)
[2]Johns Hopkins University (USA)
[3]Paul Scherrer Institut, Villigen (Switzerland)

8th RD50 Workshop, Prague
June 26th, 2006

Outline

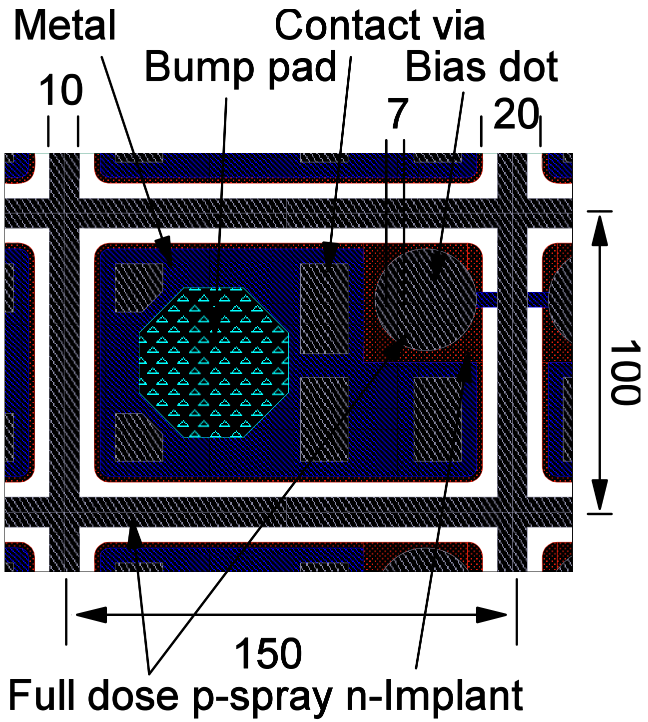
1. The CMS Pixel detector
2. Performance degradation with irradiation
3. Physical modelling of radiation damage
4. Position determination: template algorithm

CMS Pixel detector



- Hybrid pixel technology
- 3-d tracking with about 66 million channels
- Barrel layers at radii = 4.3cm, 7.2cm and 11.0cm
- Two endcap disks per side (baseline design)
- Pixel cell size = 100x150 μm^2
- 704 barrel modules, 96 barrel half modules, 672 endcap modules
- ~15,000 front-end chips and ~1m^2 of silicon

CMS Pixel sensors



CMS Pixel baseline sensors: Pitch 100×150 μm^2

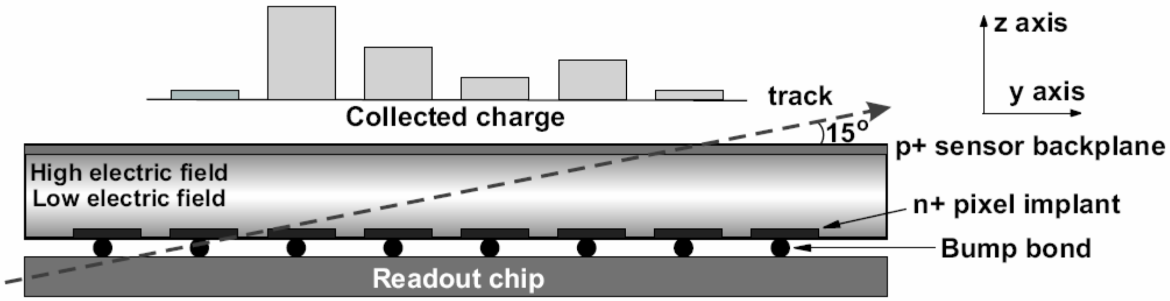
- *n*-in-*n* type with moderated p-spray isolation
- biasing grid and punch through structures (keeps unconnected pixels at ground potential, I-V tests possible)
- 285 μm thick <111> DOFZ wafer

Irradiated samples for tests: Pitch 125×125 μm^2

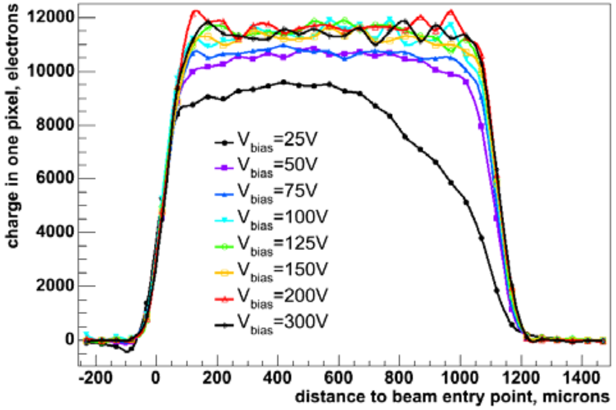
- Irradiated with 21 GeV protons at the CERN PS facility
- Fluences: $\Phi_{eq}=(0.5, 2.0, 5.9)\times 10^{14}\ n_{eq}/cm^2$
- Annealed for three days at +30º C
- Bump bonded at room temperature to non irradiated front-end chips with non zero-suppressed readout, stored at -20ºC

Charge collection measurements

Charge collection was measured using cluster profiles in a row of pixels illuminated by a 15º beam and no magnetic field

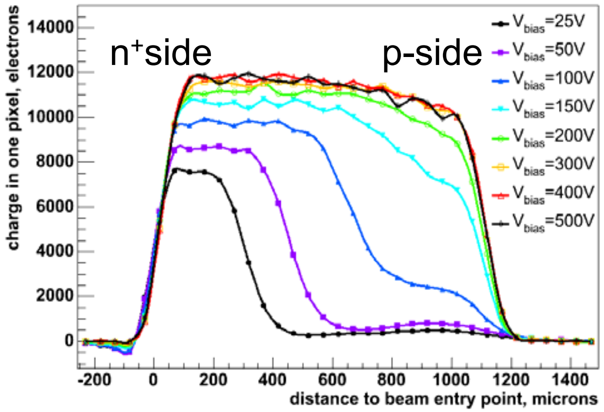


$\Phi_{eq} = 5\times10^{13}$ n/cm^2



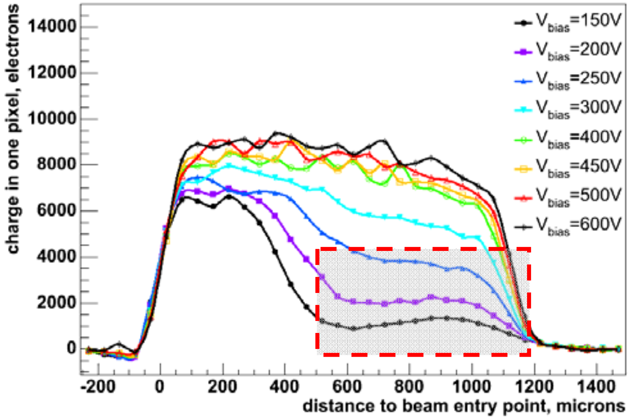
½ year LHC low luminosity

$\Phi_{eq} = 2\times10^{14}$ n/cm^2



2 years LHC low luminosity

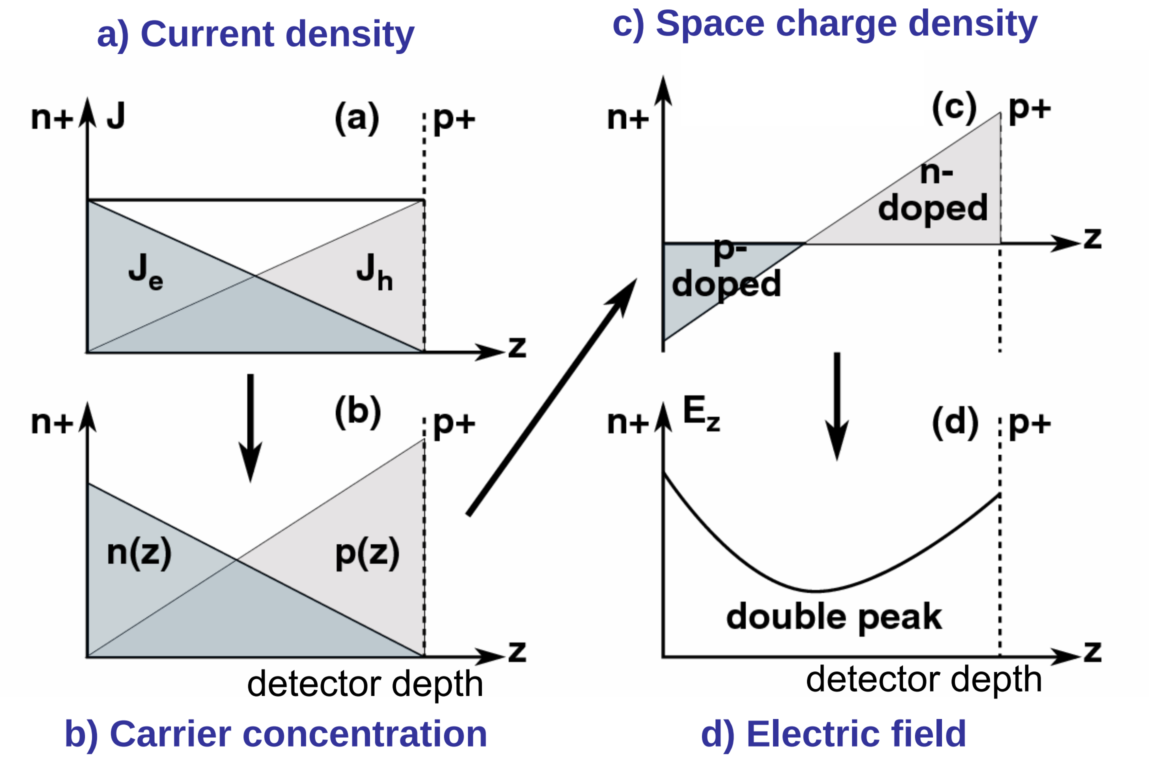
$\Phi_{eq} = 6\times10^{14}$ n/cm^2



2 years LHC high luminosity

AGEING

The double peak electric field

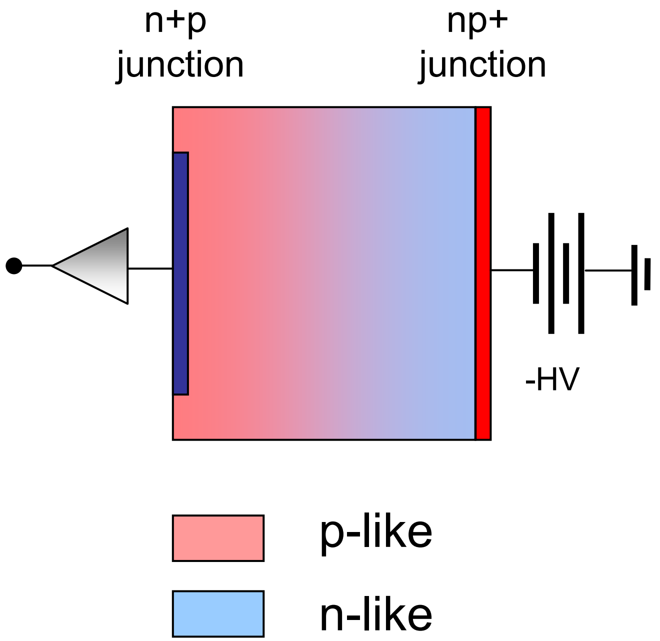


a) Current density

c) Space charge density

b) Carrier concentration

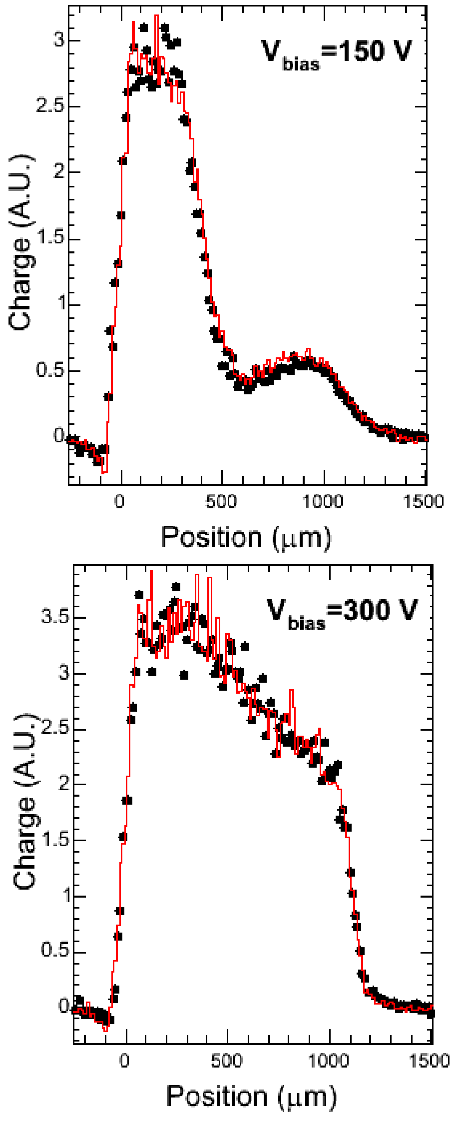
d) Electric field



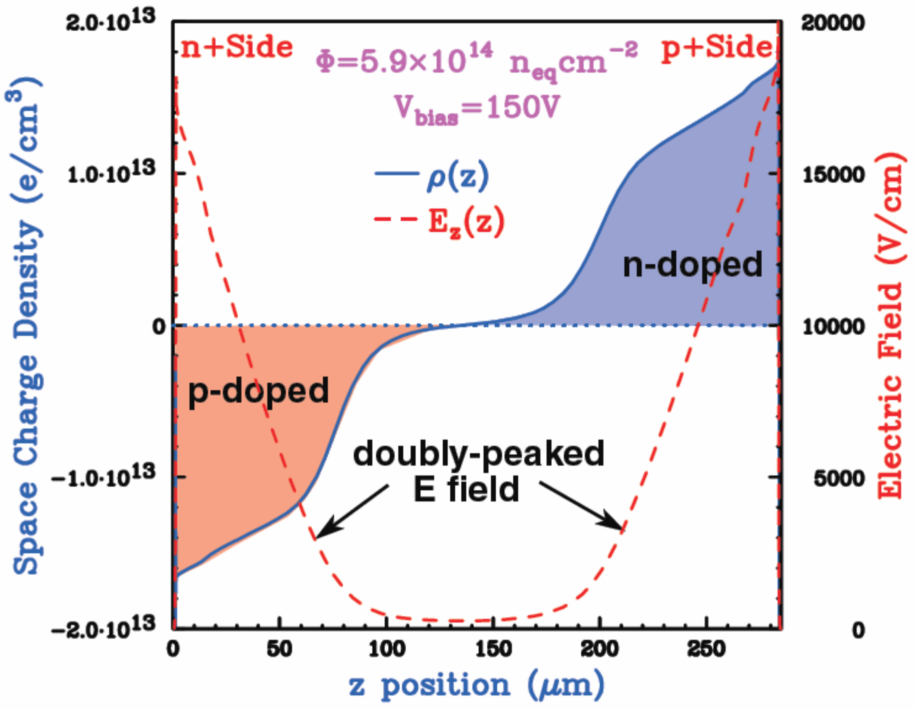
There are
P-N junctions at both
sides of the detector

V.Eremin *et al.*, NIM A 476 (2002) p476, NIM A 476 (2002) p537

Fit results



Electric field and space charge density profiles

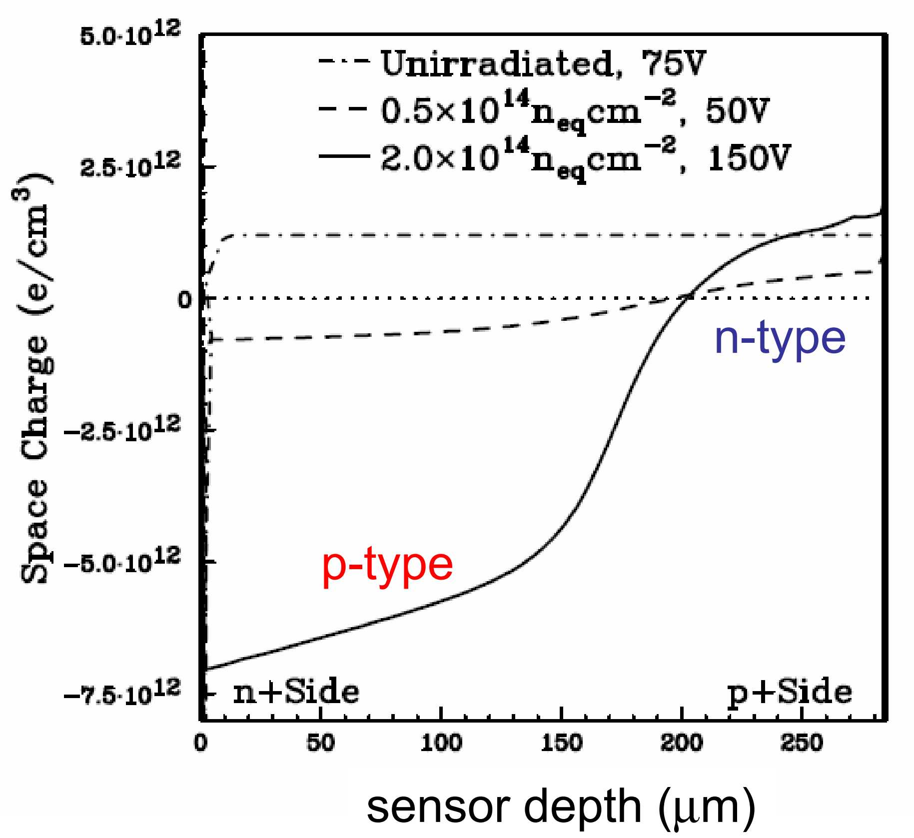


Φ_1=6x10^{14} n/cm^2
N_A/N_D=0.40
σ_h/σ_e=0.25

- ● Data
- — Simulation

NB: *Fits repeated for different fluences and bias voltages*
Results presented at past RD50 Workshops

Space charge across bulk

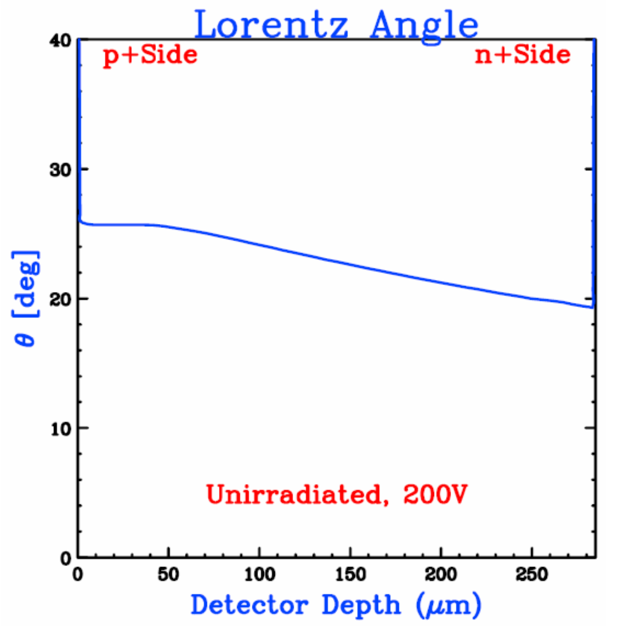


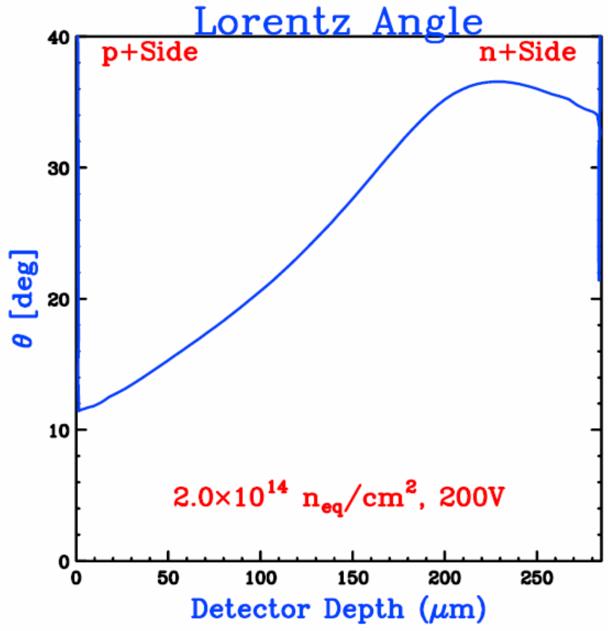
V.Chiochia, M.Swartz,et al.,physics/0506228

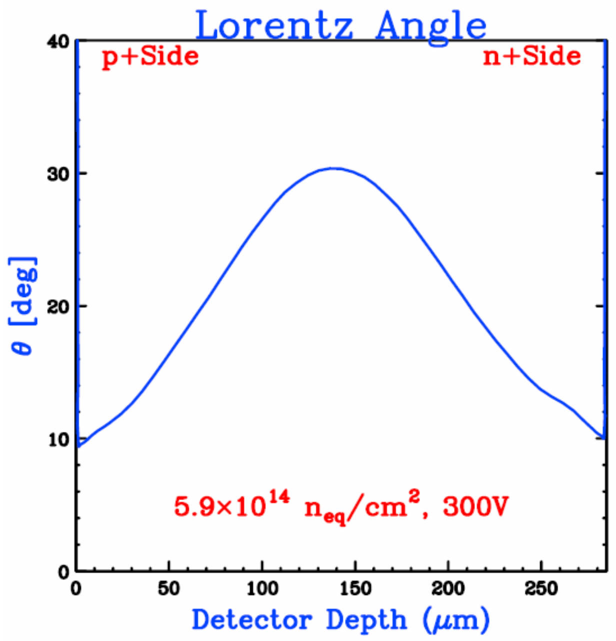
- Space charge density uniform before irradiation
- Current conservation and non uniform carrier velocities produce a non linear space charge density after irradiation
- The electric field peak at the p+ backplane increases with irradiation

Lorentz deflection

tan(θ) linear in the carrier mobility μ(E): $\tan\theta_L = r_H \mu(\vec{E}) B \sin\theta_{vB}$





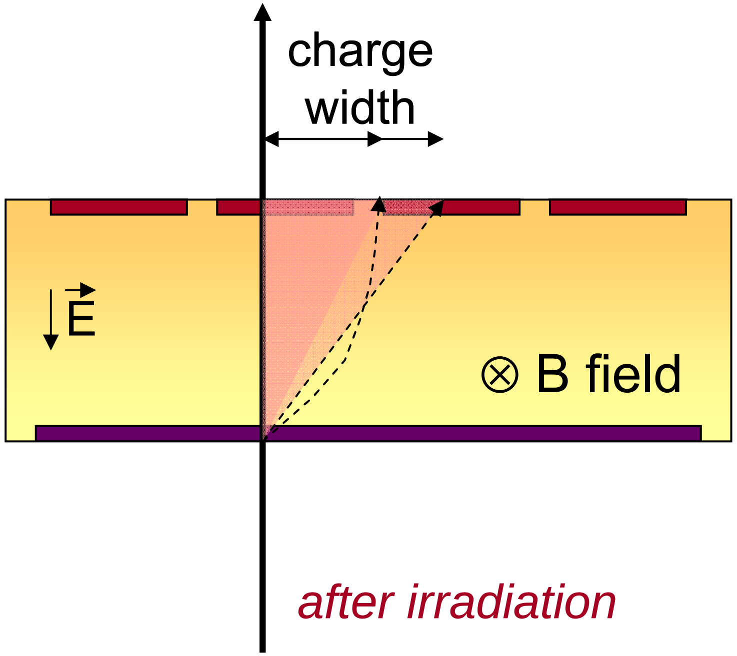


LHC startup | 2 years LHC low luminosity | 2 years LHC high luminosity

The Lorentz angle can vary a factor of 3 after heavy irradiation:
This introduces strong non-linearity in charge sharing

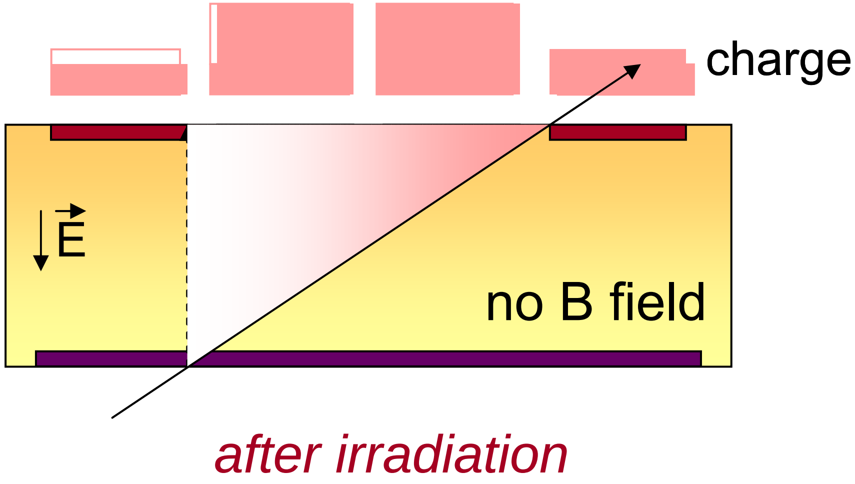
Impact on hit reconstruction

r-ϕ plane



Irradiation modifies
the electric field profile:
varying Lorentz deflection
(Pitch = 100 μm)

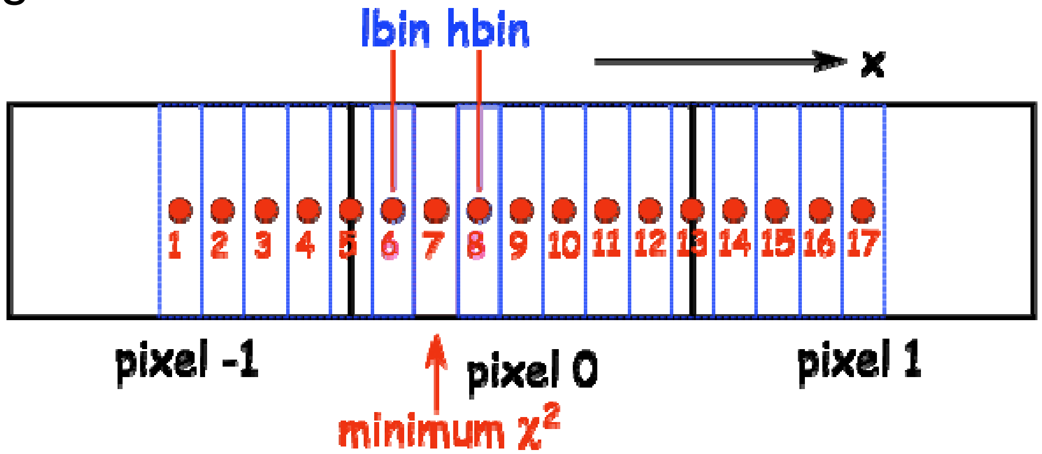
r-z plane



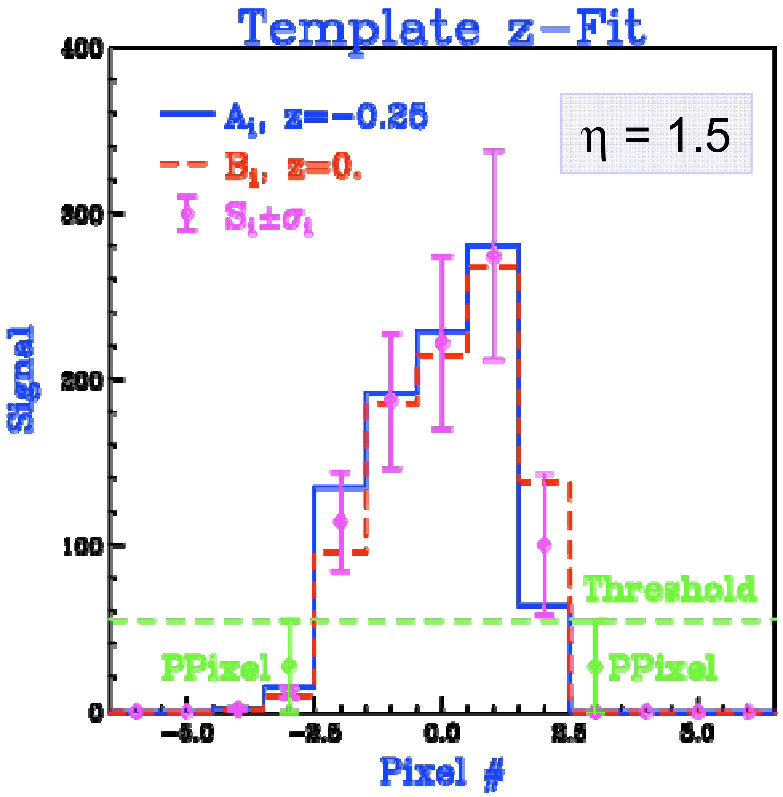
Irradiation causes
charge carrier trapping
(Pitch = 150 μm)

Template algorithm

- Goal:
  - Reconstruct with high precision the impact position after irradiation
- Current algorithms are prone to large errors for irradiated detectors
  - After irradiation also the signals of pixels within the cluster are position dependent, due to *trapping of carriers*
- Template algorithm:
  - Create average *cluster templates*
  - Position determination reduced to a linear interpolation between templates



Template algorithm



$\Phi_1 = 6 \times 10^{14}$ n/cm^2

measured signal

templates

$$\chi^2 = \sum_i \frac{\{nS_i - [(1-r)A_i + rB_i]\}^2}{\sigma_i^2}$$

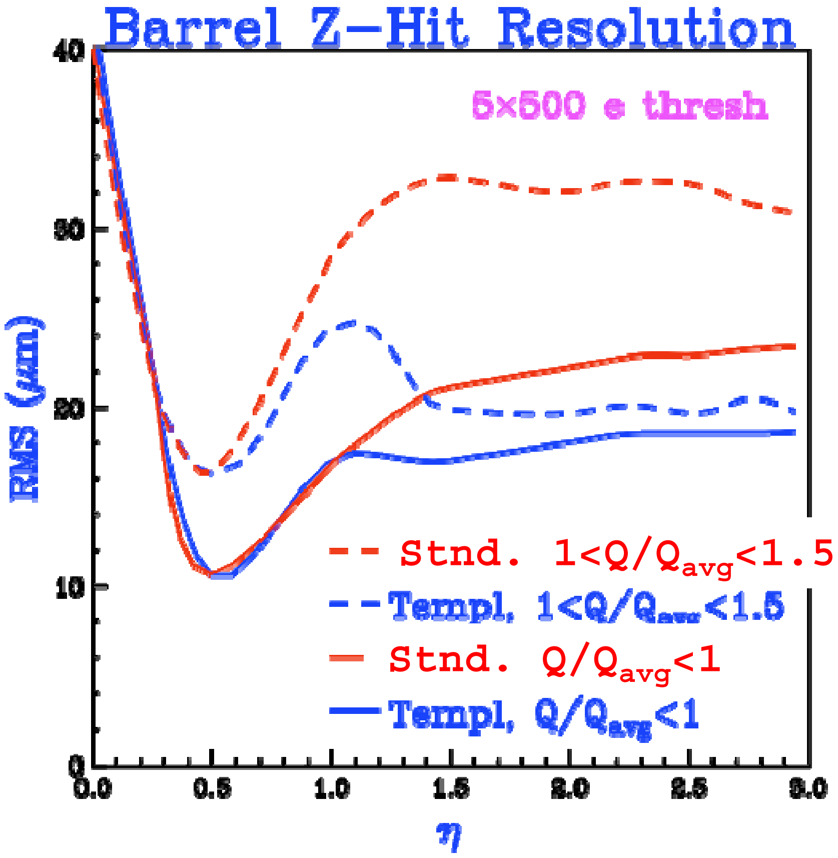
signal fluctuation

$$x = x(\mathrm{lbin}) + r\,[x(\mathrm{hbin}) - x(\mathrm{lbin})]$$

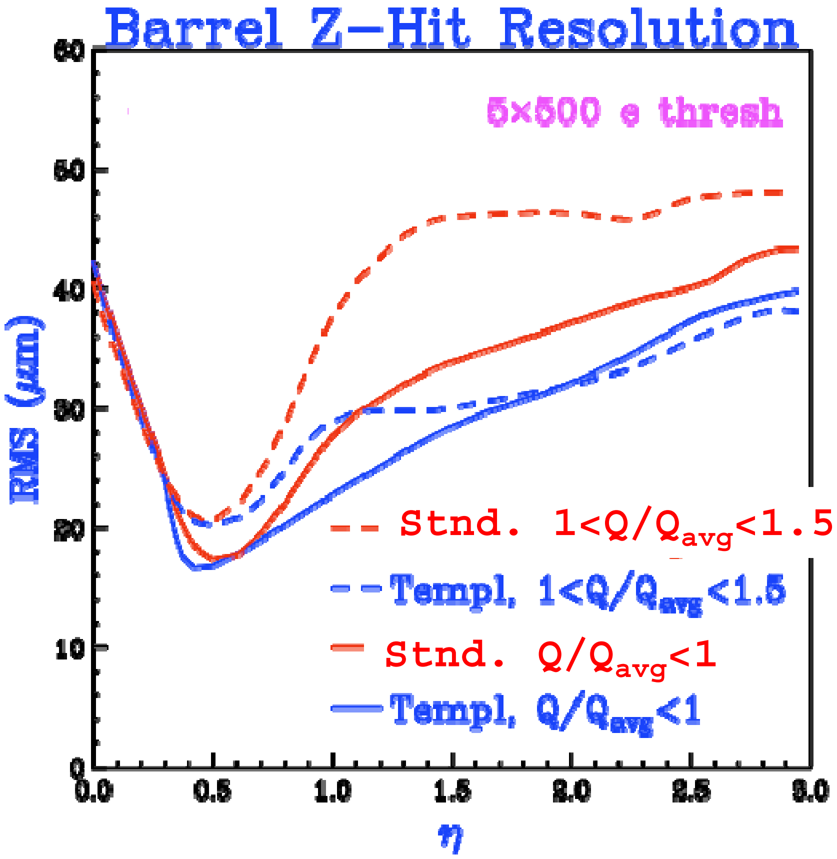
- n is a free normalization parameter
- r is the fraction of the bin size between templates A_i and B_i
- can calibrate irradiation effects by varying the templates A_i and B_i
- need to de-weight large pixel signals (fluctuations) with σ_i
- Solution: r-value which minimizes χ^2

Results: longitudinal plane

Unirradiated



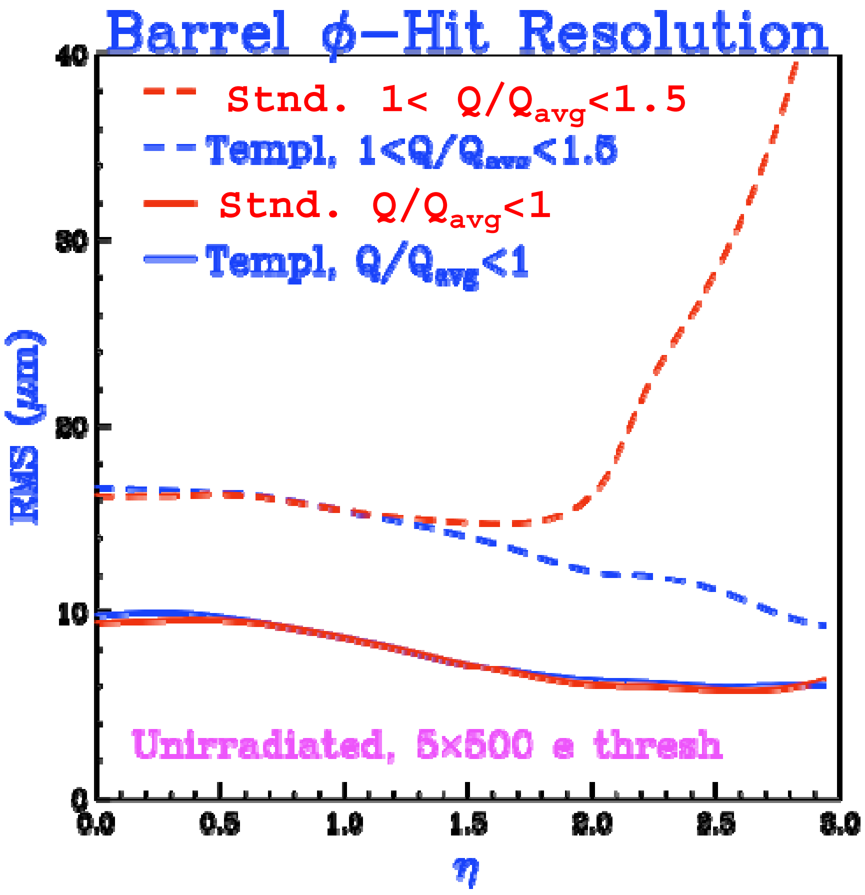
Φ_1=6×10^{14} n/cm^2



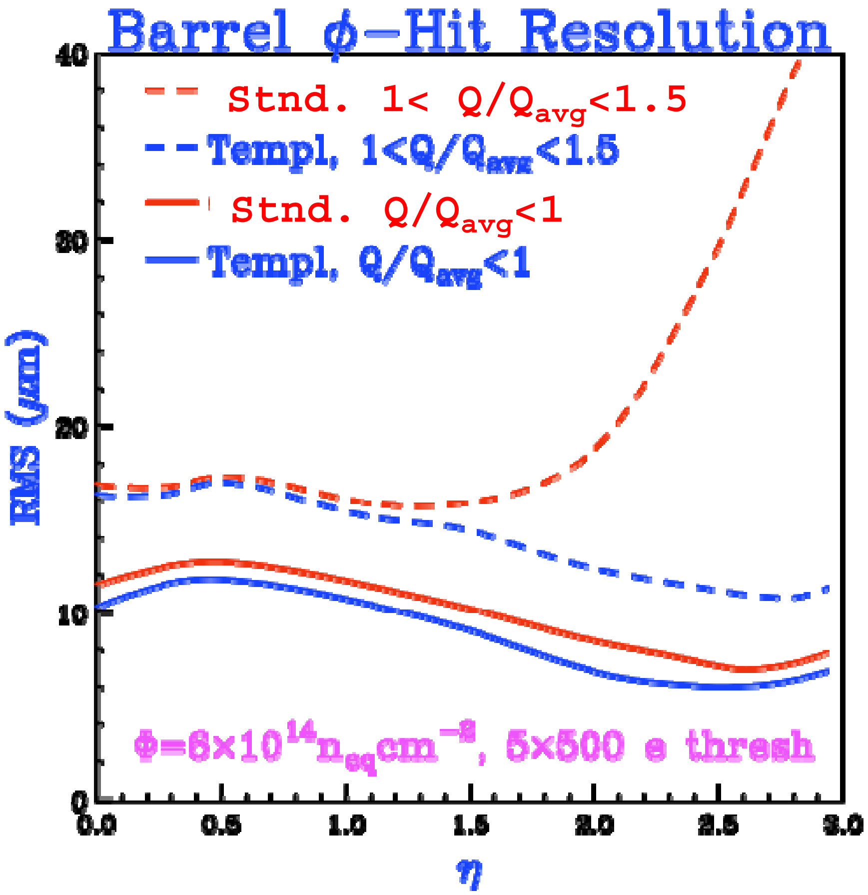
- Improvements for high rapidities (longer clusters)
- Larger improvements for clusters with high charge (delta rays)

Results: transverse plane

Unirradiated



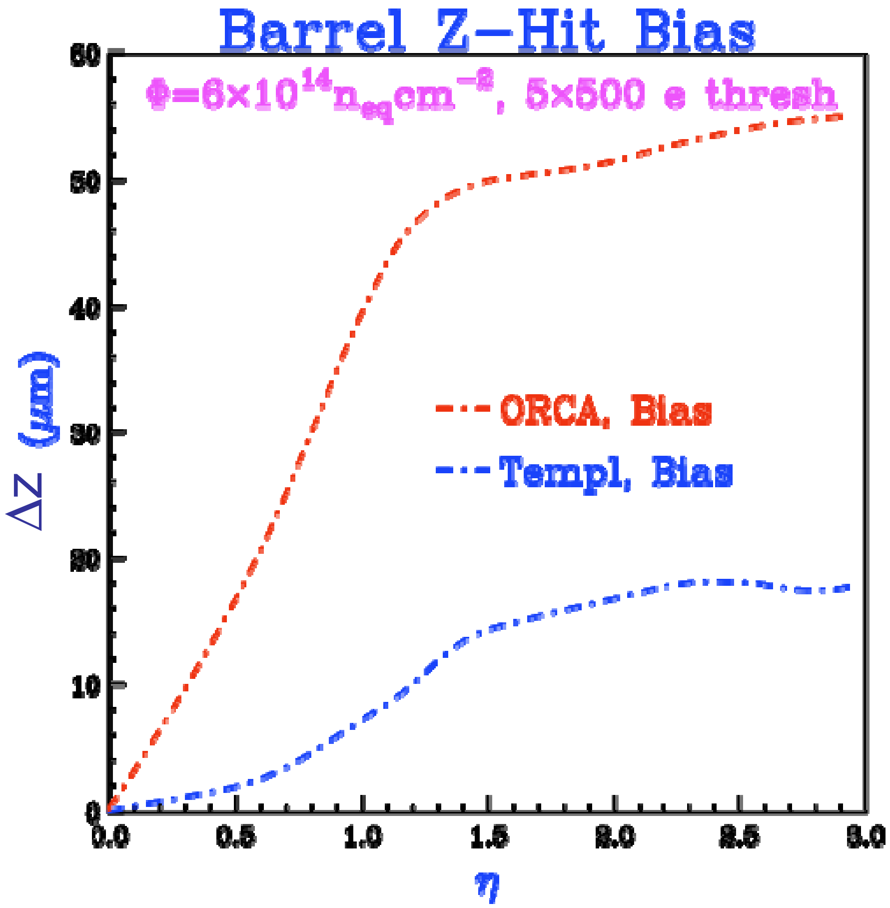
Φ_1=6×10^{14} n/cm^2



- for $Q/Q_{avg}<1$ (60% of all hits): Template is ~20% better
- $1<Q/Q_{avg}<1.5$ (30% of all hits): Template is comparable except for $\eta>1.5$ where it is much better

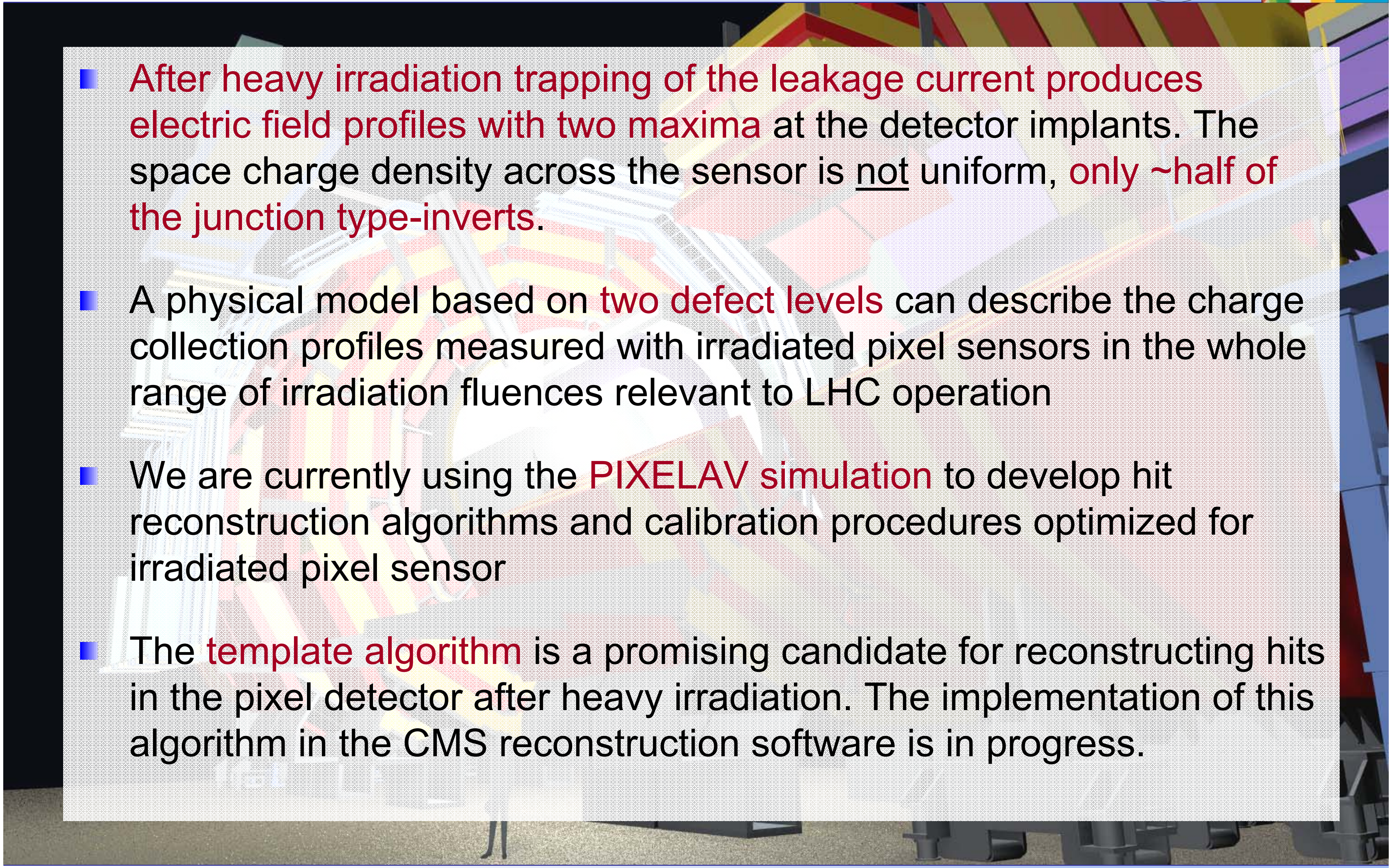
Results: systematic shift

$\Delta z = < z_{rec} - z_{true} >$



- Large systematic shifts in the reconstructed position caused by trapping.
- Template algorithm can significantly reduce the shift
- Calibration needed for ultimate precision

Summary



- After heavy irradiation trapping of the leakage current produces electric field profiles with two maxima at the detector implants. The space charge density across the sensor is not uniform, only ~half of the junction type-inverts.

- A physical model based on two defect levels can describe the charge collection profiles measured with irradiated pixel sensors in the whole range of irradiation fluences relevant to LHC operation

- We are currently using the PIXELAV simulation to develop hit reconstruction algorithms and calibration procedures optimized for irradiated pixel sensor

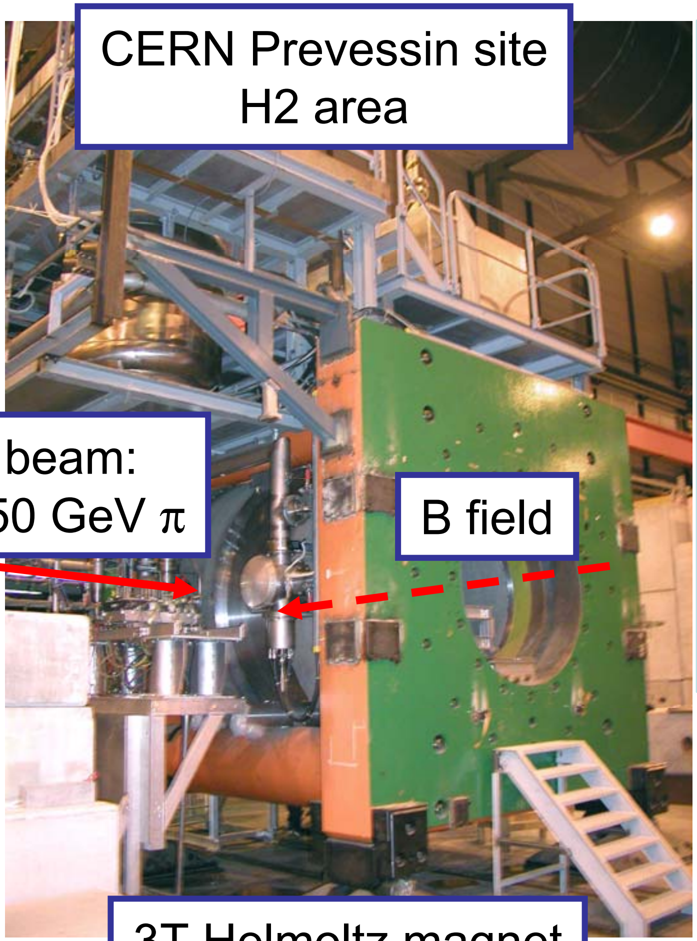
- The template algorithm is a promising candidate for reconstructing hits in the pixel detector after heavy irradiation. The implementation of this algorithm in the CMS reconstruction software is in progress.

References

- PIXELAV simulation:
  - M.Swartz, “CMS Pixel simulations”, *Nucl.Instr.Meth*. A511, 88 (2003)
- Double-trap model:
  - V.Chiochia, M.Swartz et al., “Simulation of Heavily Irradiated Silicon Pixel Sensors and Comparison with Test Beam Measurements”, *IEEE Trans.Nucl.Sci*. 52-4, p.1067 (2005), eprint:physics/0411143
  - V. Eremin, E. Verbitskaya, and Z. Li, “The origin of double peak electric field distribution in heavily irradiated silicon detectors”, *Nucl. Instr. Meth.* A476, pp. 556-564 (2002)
- Model fluence and temperature dependence:
  - V.Chiochia, M.Swartz et al., “A double junction model of irradiated pixel sensors for LHC”, accepted for publication on *Nucl. Instr. Meth.A,* eprint:physics/0506228
  - V.Chiochia, M.Swartz et al., “Observation, modeling, and temperature dependence of doubly-peaked electric fields in silicon pixel sensors”, Accepted for publication on *Nucl. Instr. Meth.A,* eprint:physics/0510040

BACKUP SLIDES

Test beam setup at CERN

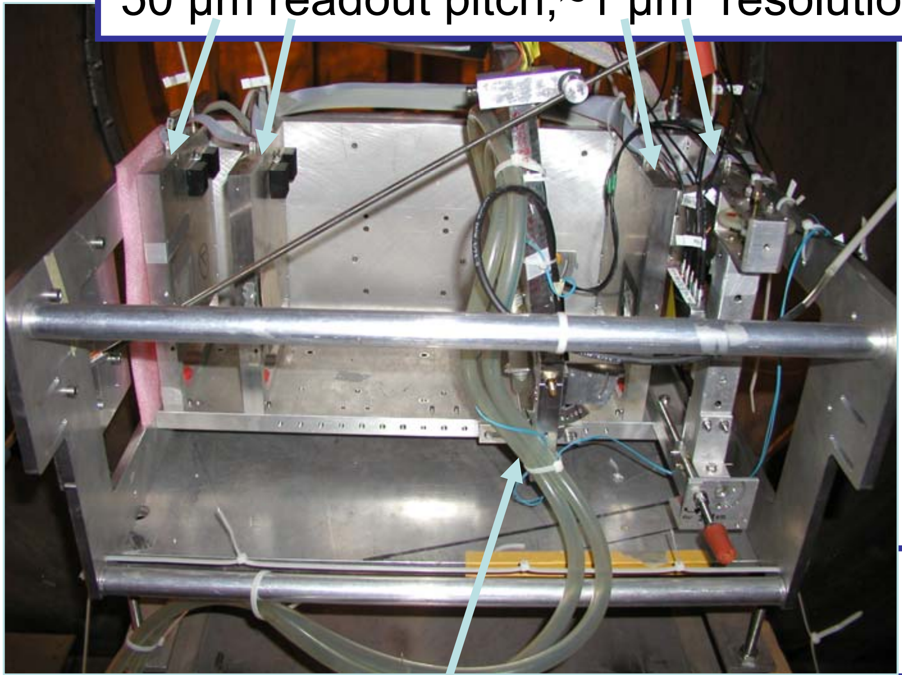


CERN Prevessin site
H2 area

beam:
150 GeV π

B field

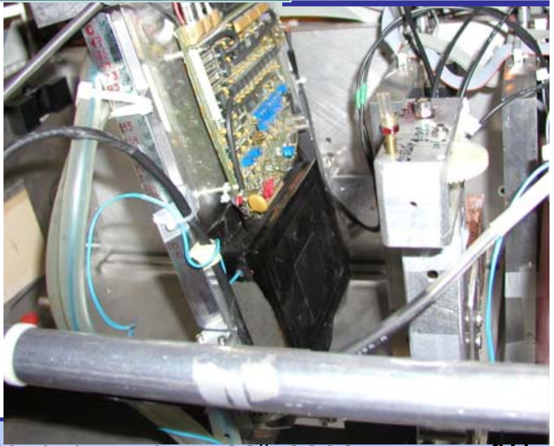
3T Helmoltz magnet



Silicon strip beam telescope:
50 µm readout pitch,~1 µm resolution

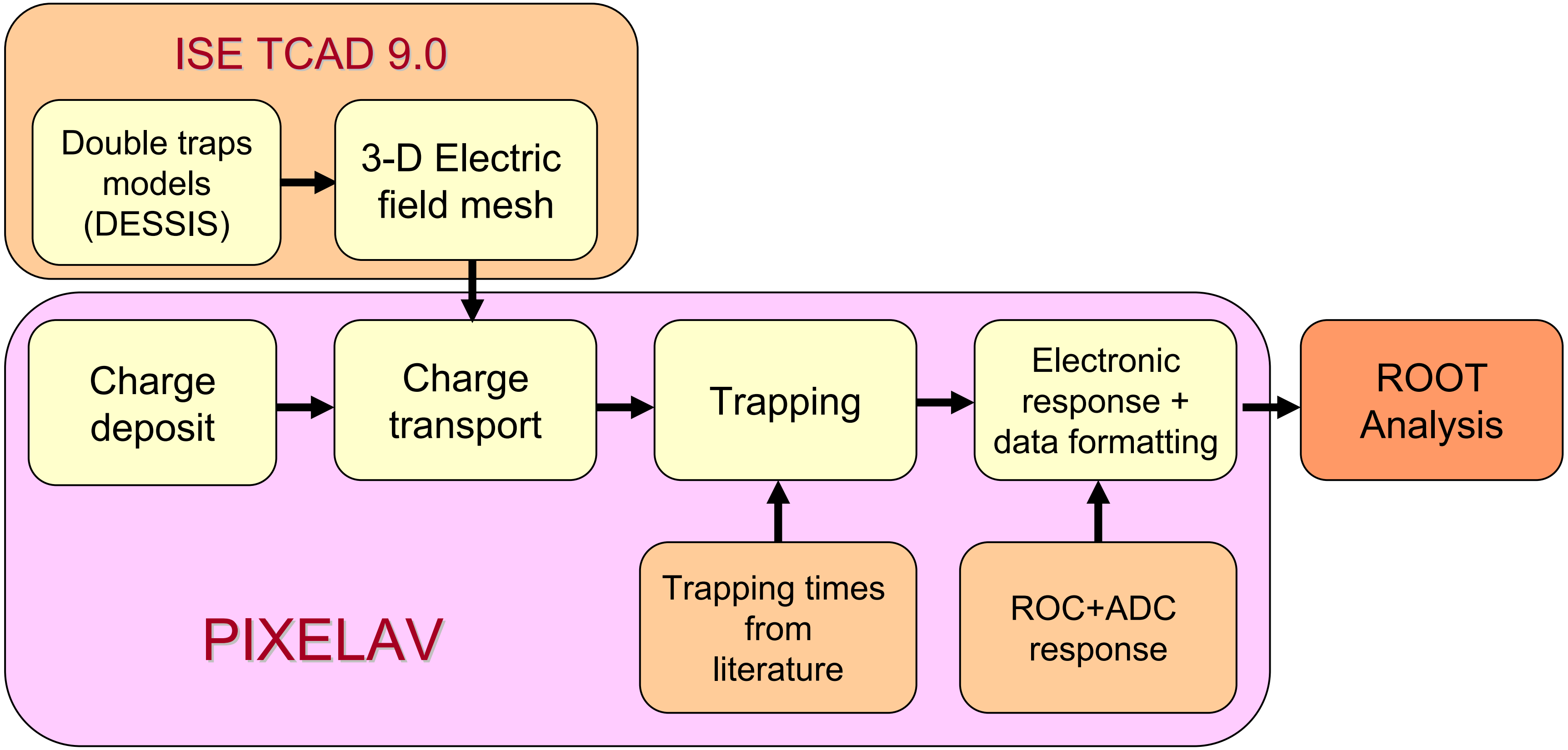
Cooling circuit
T =-30 ºC or -10ºC

pixel sensor
support



Data collected at CERN in 2003-2004

Detector simulation


ISE TCAD 9.0

Double traps models (DESSIS)

3-D Electric field mesh

Charge deposit

Charge transport

Trapping

Electronic response + data formatting

ROOT Analysis

Trapping times from literature

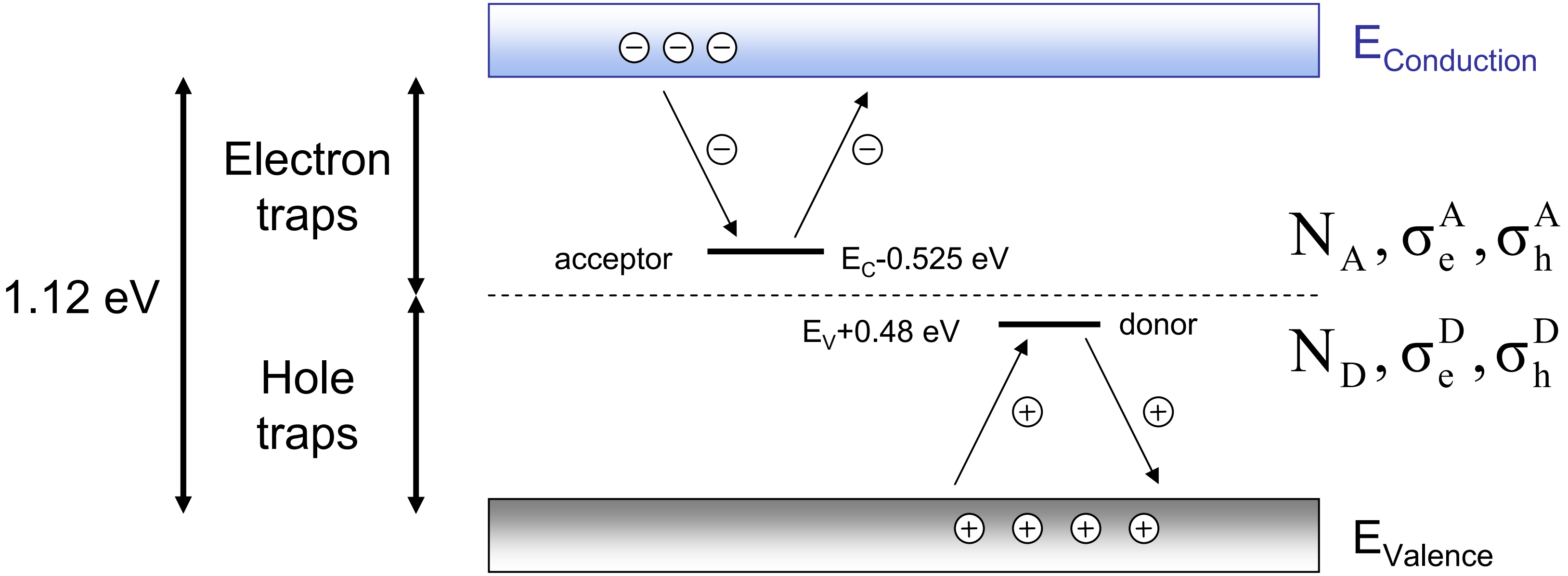
ROC+ADC response

PIXELAV

M.Swartz, *Nucl.Instr. Meth*. A511, 88 (2003);
V.Chiochia, M.Swartz et al., *IEEE Trans.Nucl.Sci*. 52-4, p.1067 (2005).

Two-traps effective models

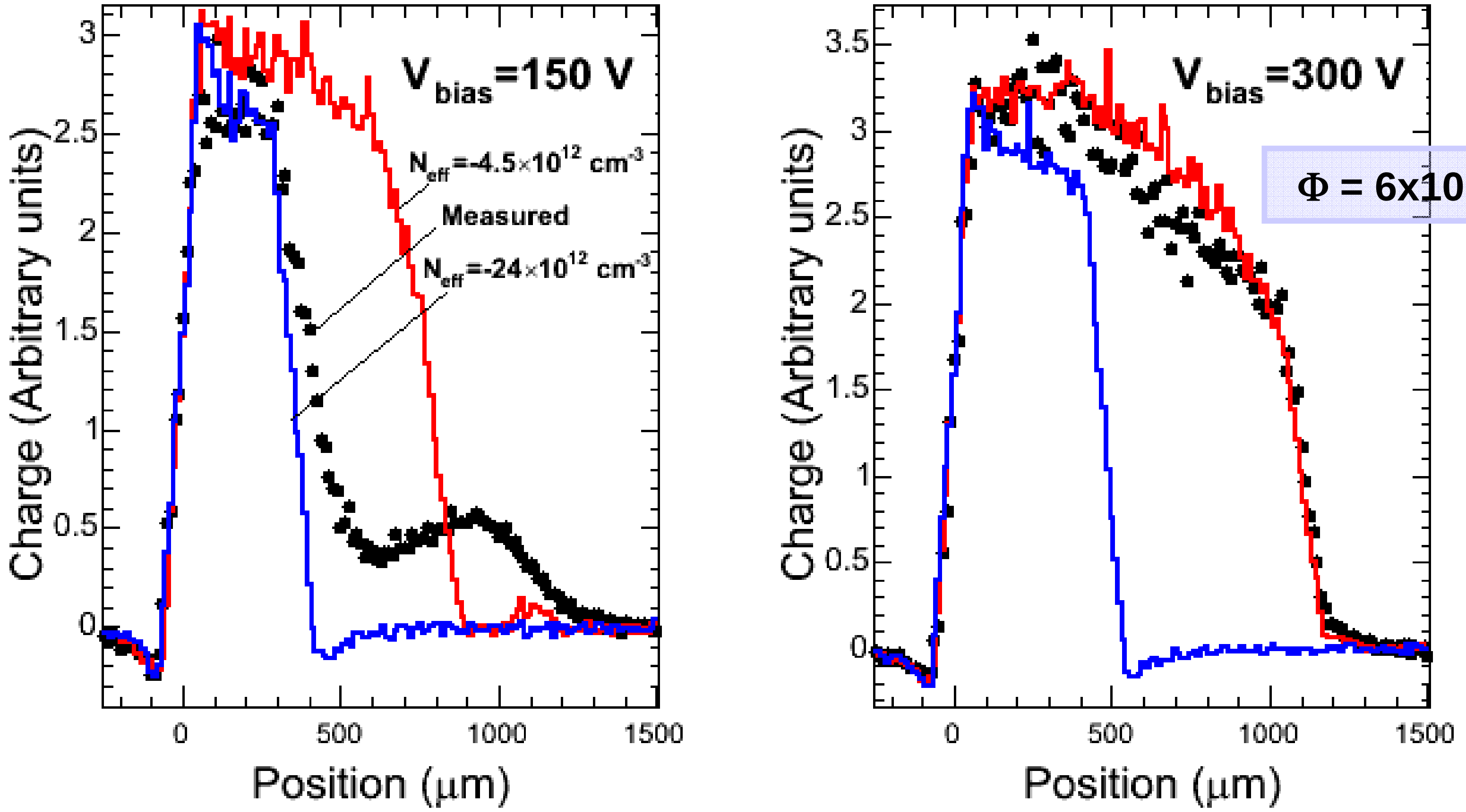
A physical model of radiation damage was included in the sensor simulation an compared to the test beam data



Model parameters (Shockley-Read-Hall statistics):

$E_{A/D}$ = trap energy level		fixed
$N_{A/D}$ = trap densities		extracted from fit
$\sigma_{e/h}$ = trapping cross sections		extracted from fit

Models with constant N_{eff}



Φ = 6x10^{14} n/cm^2

A model based on a type-inverted device with constant space charge density across the bulk does not describe the measured charge collection profiles

Model constraints

- Idea: extract model parameters from a fit to the data
- The two-trap model is constrained by:

1. Comparison with the measured charge collection profiles
2. Signal trapping rates varied within uncertainties

$$Q_{e,h}(t) = Q_{0e,h}\exp\left(-\frac{1}{\tau_{e/h}}t\right)$$

$$\Gamma_e = 1/\tau_e = \beta_e\Phi_{eq} \cong v_e\sigma_e^A N_A$$

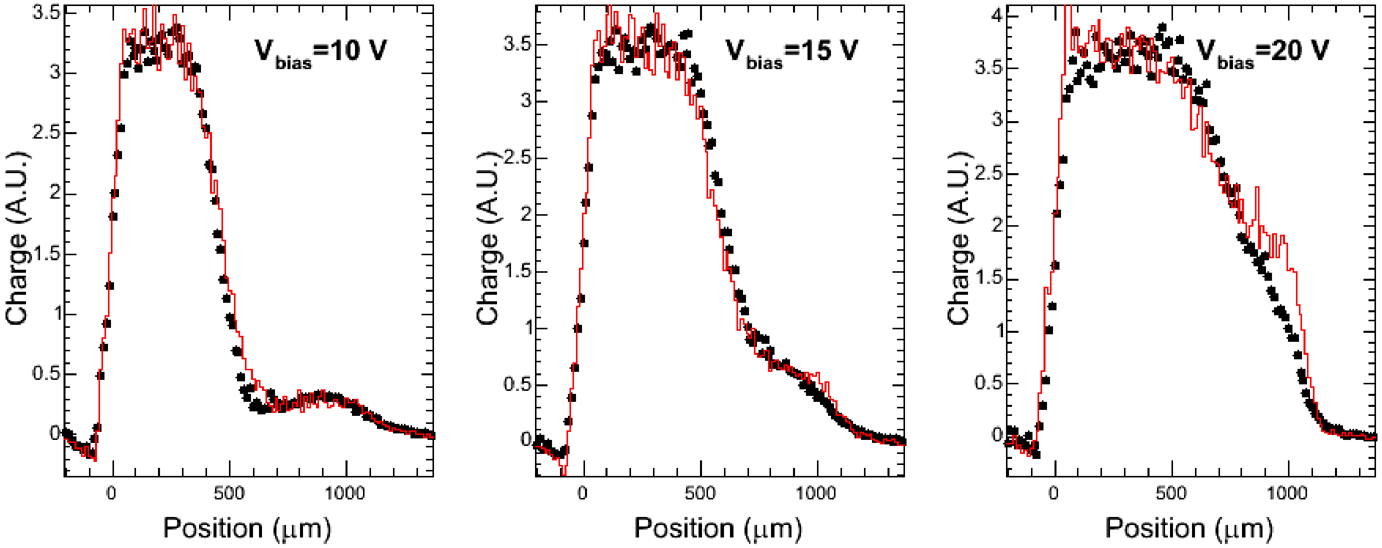
$$\Gamma_h = 1/\tau_h = \beta_h\Phi_{eq} \cong v_h\sigma_h^D N_D$$

3. Measured dark current

$$I = \sum_{j=D,A} \frac{v_h v_e \sigma_h^j \sigma_e^j N_D (np - n_i^2)}{v_e\sigma_e^j(n + n_i e^{E_j/kT}) + v_h\sigma_h^j(p + n_i e^{-E_j/kT})}$$

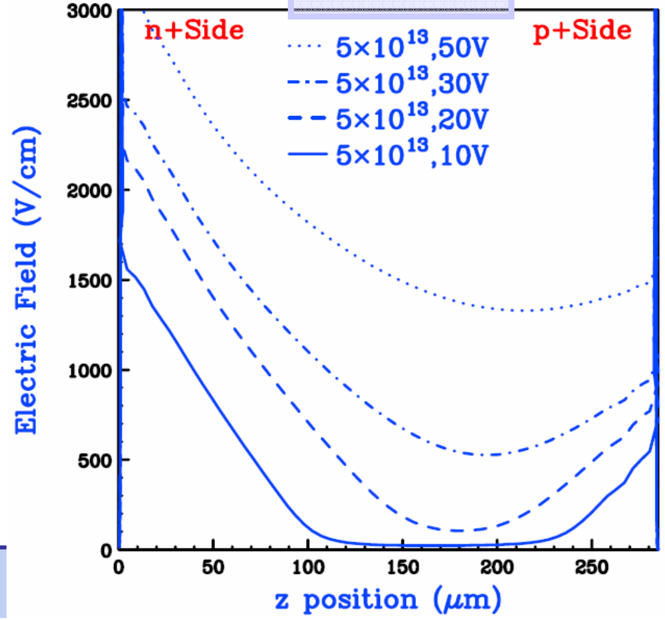
Typical fit iteration: (8-12h TCAD) + (8-16h PIXELAV)xV_{bias} + ROOT analysis

Scaling to lower fluences



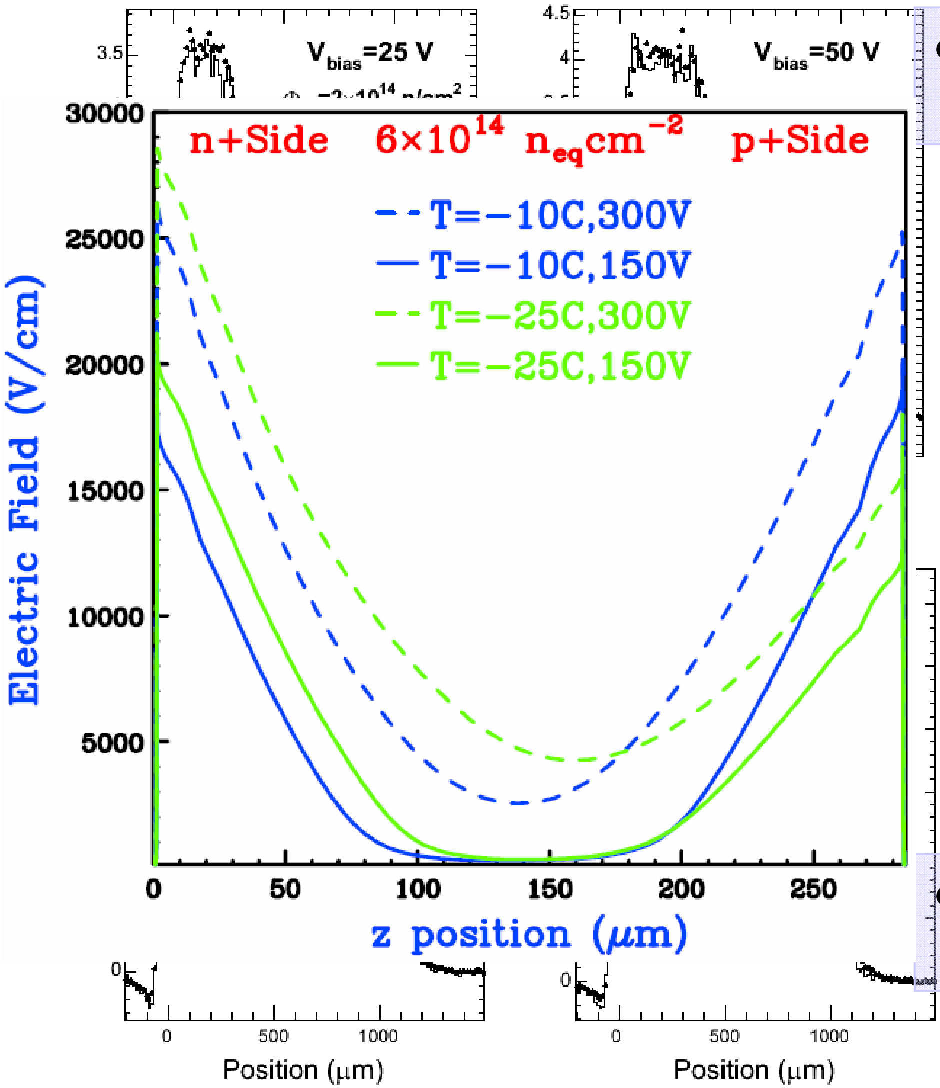
Φ_3=0.5x10^{14} n/cm^2
N_A/N_D=0.75
σ^A_h/σ^A_e=0.25
σ^D_h/σ^D_e=1.00

$\vec{E}$ field



- Near the 'type-invesion' point: the double peak structure is still visible in the data!
- Profiles are not described by thermodynamically ionized acceptors alone
- At these low bias voltages the drift times are comparable to the preamp shaping time (simulation may be not 100% reliable)

Temperature dependence



$\Phi_2=2\text{x}10^{14}$ n/cm^2
T=-25° C

- Comparison with data collected at lower temperature T=-25° C.
- Use temperature dependent variables:
  - recombination in TCAD
  - variables in PIXELAV
- The double-trap model is predictive!

$\Phi_1=6\text{x}10^{14}$ n/cm^2
T=-25° C

V.Chiochia, M.Swartz,et al., physics/0510040