Sensor Simulations in CMS

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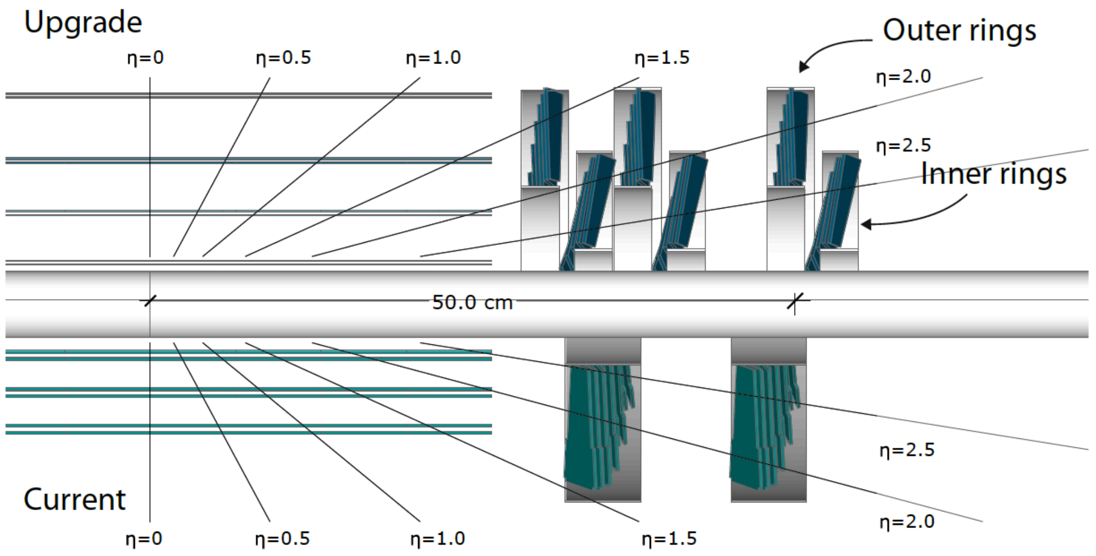
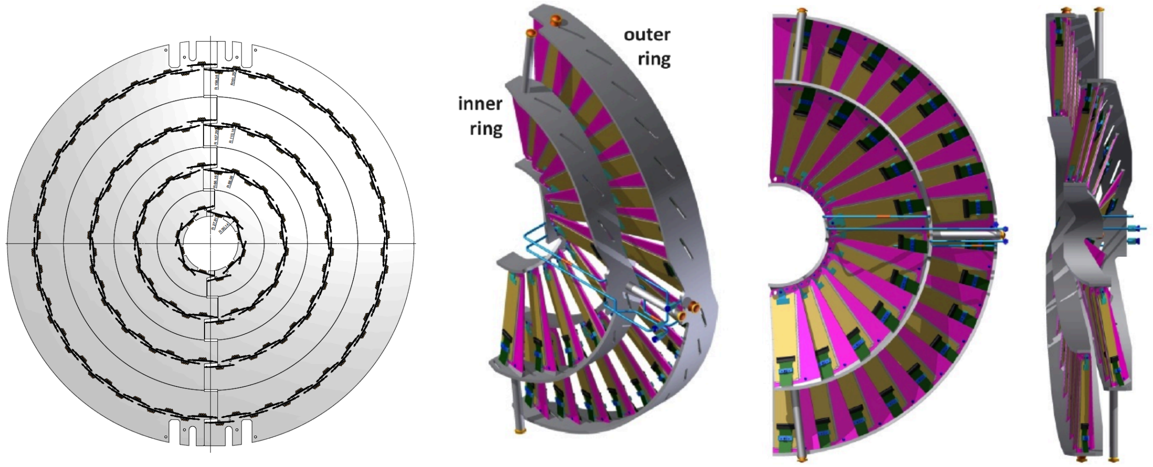
Phase 1 Pixel Detector

- Upgrade Pixel detector: 4 barrel layers (instead of 3) and 3 forward disks on each side (instead of 2)
- Installation: during extended winter shutdown in 2016/17

Bpix: 1184 modules, 48M->79M pixels
L1 r= 30mm, 96 modules, 2×TBM09, 4 links
L2 r= 68mm, 224 modules, TBM09, 2 links
L3 r=109mm, 352 modules, TBM08, 1 link
L4 r=160mm, 512 modules, TBM08, 1 link
Fpix: 672 modules, 18M->45M pixels
3 Disks r=45-161mm, 6×112 modules, TBM08, 1 link
Outer ring rotated by 20° (turbine like)
Inner ring rotated by 20° and tilted by 12° with respect to IP

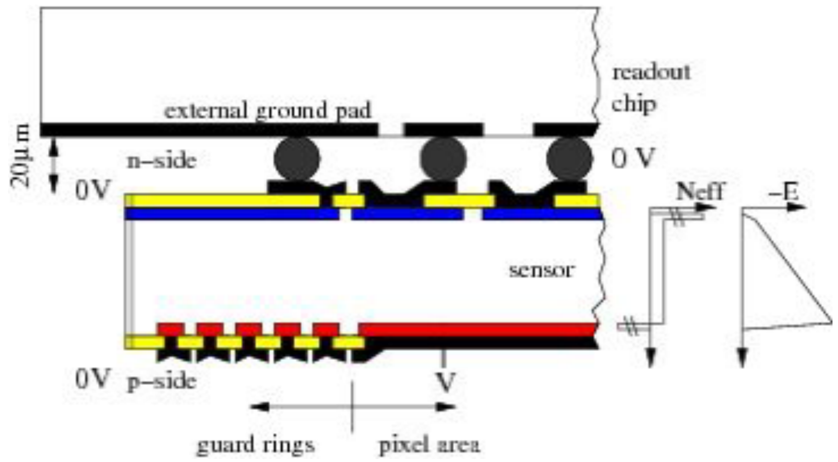


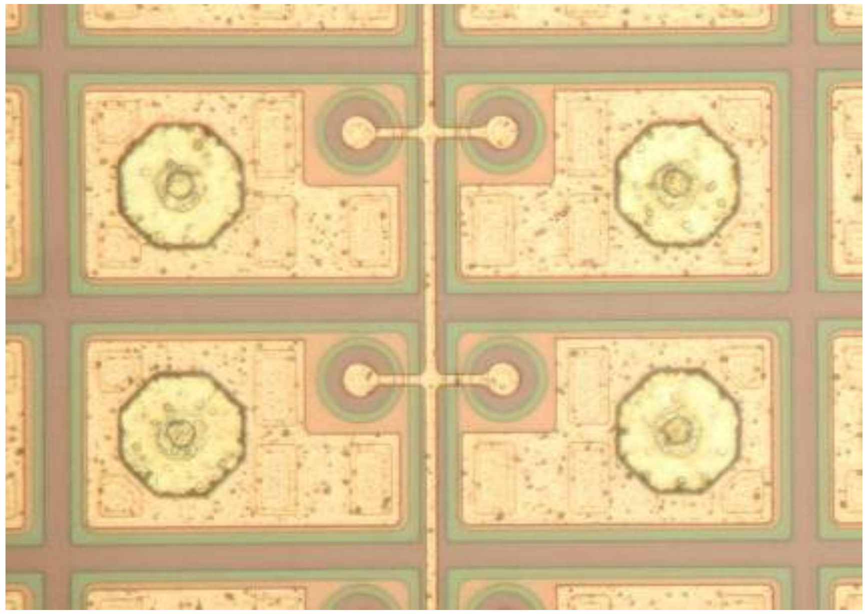


- New 4 layer barrel [BPix] and 3 disk forward [FPix] detectors
  - new digital ROCs for BPix L2-4/FPix and BPix L1
  - mixed phase CO2 cooling
  - DC - DC powering

Sensors

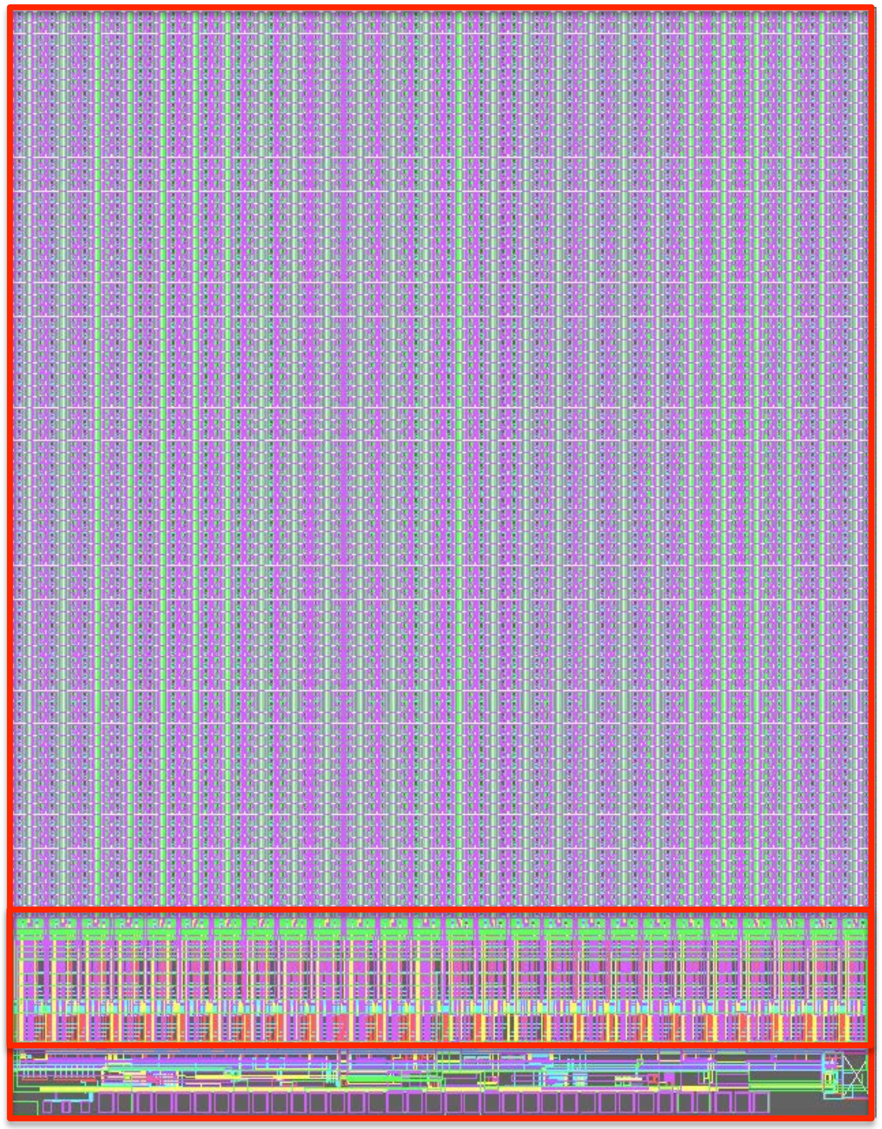
- BPix Sensors [CiS]
  - ✳ same modified p-spray design as for Phase 0
  - ✳ 100x150 um cell size
  - ✳ bias grid with punch though resistors
  - ✳ DOFZ <111> substrate
  - ✳ resistivity 5±0.5 kΩcm
  - ✳ polished to 285 μm thickness
- FPix Sensors [Sintef]
  - ✳ modified Phase 0 p-stop design
    - ‣ better HV performance
  - ✳ 100x150 um cell size
  - ✳ resistivity ~8 kΩcm
  - ✳ 290 μm thickness





Readout Chips

- PSI46DIGI: BPix L2-4, FPix
  - 8-bit digital charge info [analog in Phase 0]
  - Readout speed 160Mbit/s [40 MHz]
  - Time stamp buffer size 24 [12]
  - Data buffer size 80 [24]
  - Six metal layers [5]
  - In time threshold <2000e [3500e]
  - Data loss 1.6%@150MHz/cm^2 [5-6%]
- PROC600: BPix L1
  - Dynamic Cluster Column Drain [2x2 pixels]
  - Transfer speed increased 20->40 MHz
  - Deadtime free data buffer management
  - Data loss 2.5%@585MHz/cm^2



Radiation Exposure during 2017

The absolute charged particle fluences were detemined from Fluka and independently from counting clusters at a large enough radius 10 cm to minimize track angle effects. The relative fluences come from measuring the total cluster charge/volume in different subdetectors

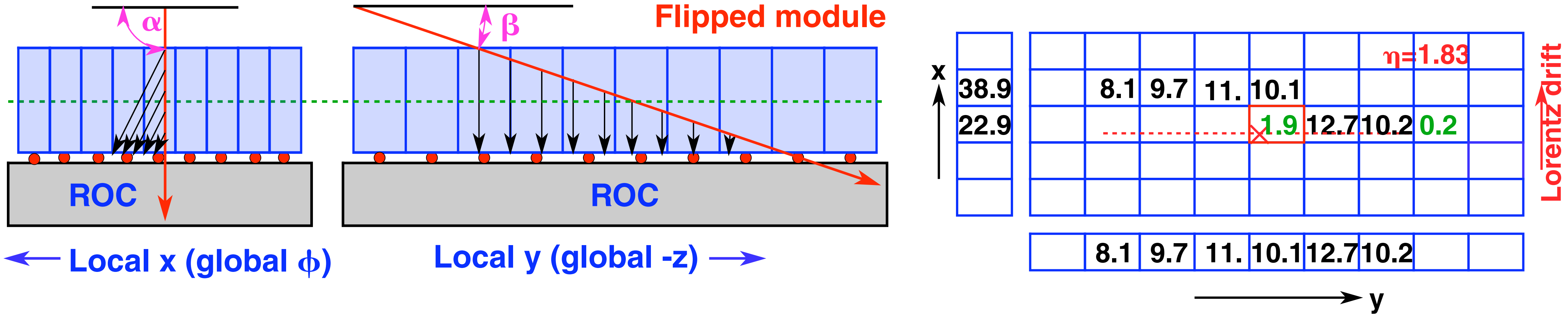
- BPix L1 saw over 5x10^{14} cm^{-2}
  - multiply by 0.6 to get Φ_{neq}?
  - effects of neutrals?
- BPix L2 and FPix R1 are quite similar
  - same fluence in each FPix disk
- BPix L3 and FPix R2 are also quite similar
  - same fluence in each FPix disk

Layer	Charged fluence
BP L1	10x10^{12} cm^{-2}/fb
BP L2	2.6x10^{12} cm^{-2}/fb
BP L3	1.4x10^{12} cm^{-2}/fb
BP L4	0.8x10^{12} cm^{-2}/fb
FP R1	3.1x10^{12} cm^{-2}/fb
FP R2	1.4x10^{12} cm^{-2}/fb

The appropriate hardness factor will actually be quite important in determining the longevity of the detector …

Hit Reconstruction

Tracks deposit distinct patterns of charge on the pixel sensors



- Hit position estimation is based on 1D projections of the 2D cluster
  - factorizes due to field configurations and cell periodicity
  - projected shapes depend upon the projected angles a and b
  - reconstruction algorithms use angle information iteratively
- Two techniques used in track reconstruction
  - “Generic” technique is h-like, uses end pixel charges of projection
    - faster, less precise algorithm used for all but last tracking pass
    - needs external Lorentz drift calibration [from detailed simulation]
  - “Template” technique fits projections to simulated profiles
    - slower, more precise algorithm used for final fitting pass
    - needs full cluster shape calibration
    - generates probabilities that test the consistency of the shapes

Pixelav Detailed Simulation

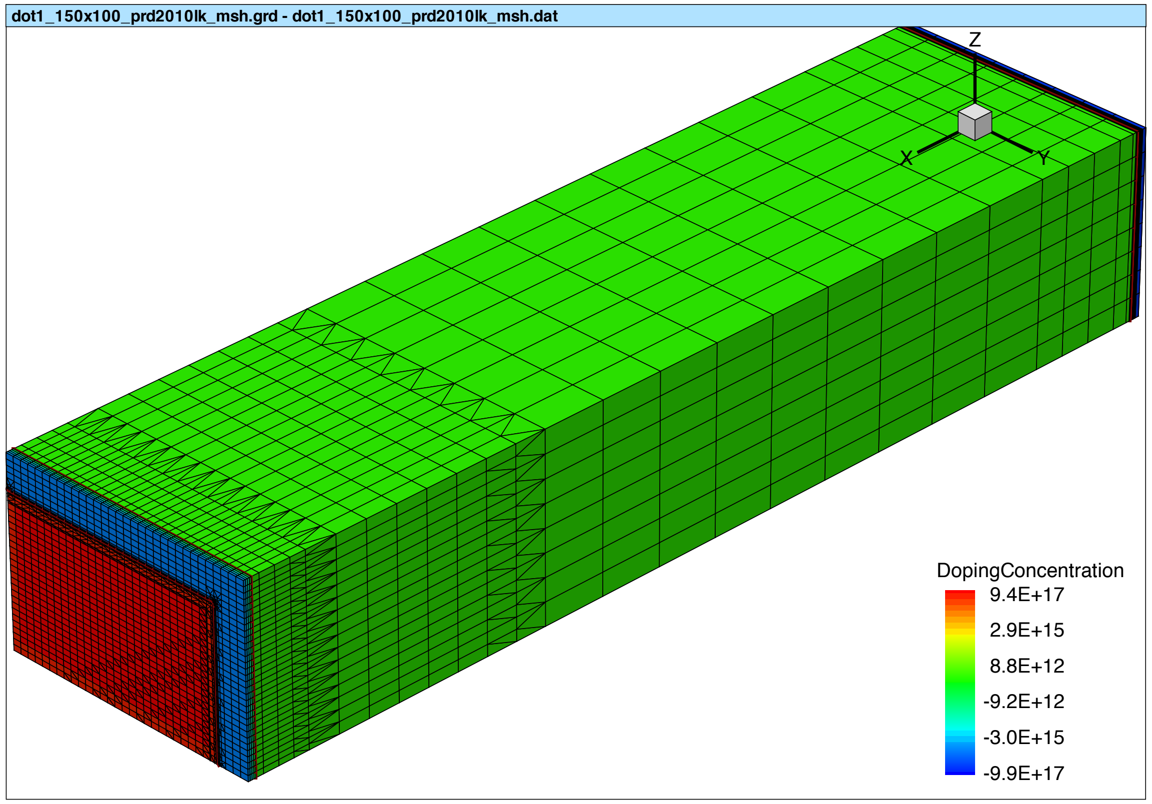
Created to interpret beam tests of irradiated sensors, now used to perform Lorentz calibrations and generate template profile shapes:

- charge deposition model based on Bichsel π-Si x-sections
- delta ray range: Continuous Slowing Down Approx + Nist Estar dedx
- plural scattering and magnetic curvature of delta ray tracks
- carrier transport from Runge-Kutta integration of saturated drift

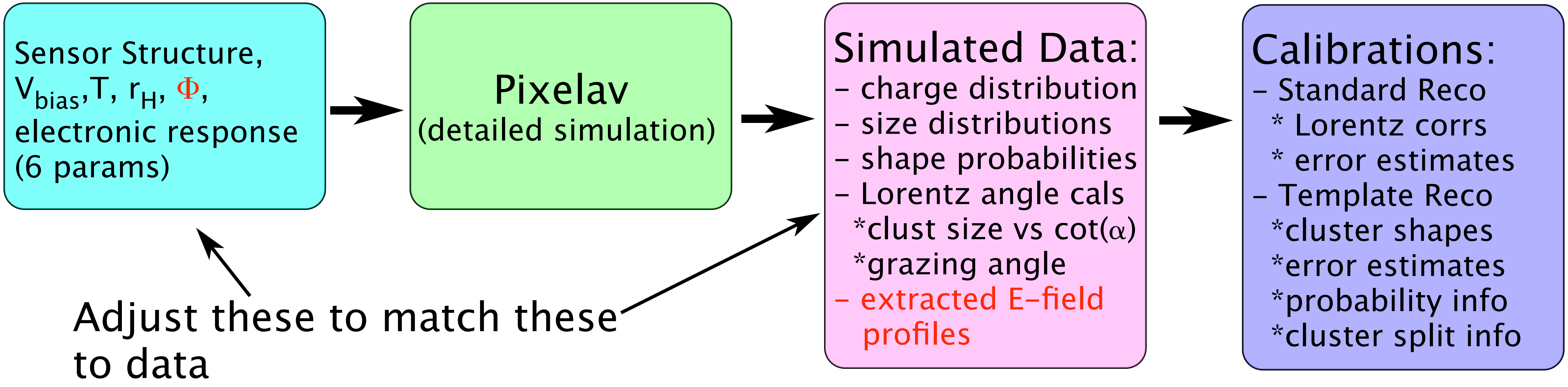
$$\frac{d\vec{x}}{dt} = \vec{v} = \frac{\mu\left[q\vec{E} + \mu r_H \vec{E} \times \vec{B} + q\mu^2 r_H^2 (\vec{E}\cdot\vec{B})\vec{B}\right]}{1 + \mu^2 r_H^2 |\vec{B}|^2}$$

  - ✳ electric field map from ISE TCAD simulation of pixel cell
  - ✳ includes diffusion, trapping, and charge induction on implants

- Electronic Simulation: noise, linearity, thresholds, mis-calibration



Calibration of Reconstruction Algs



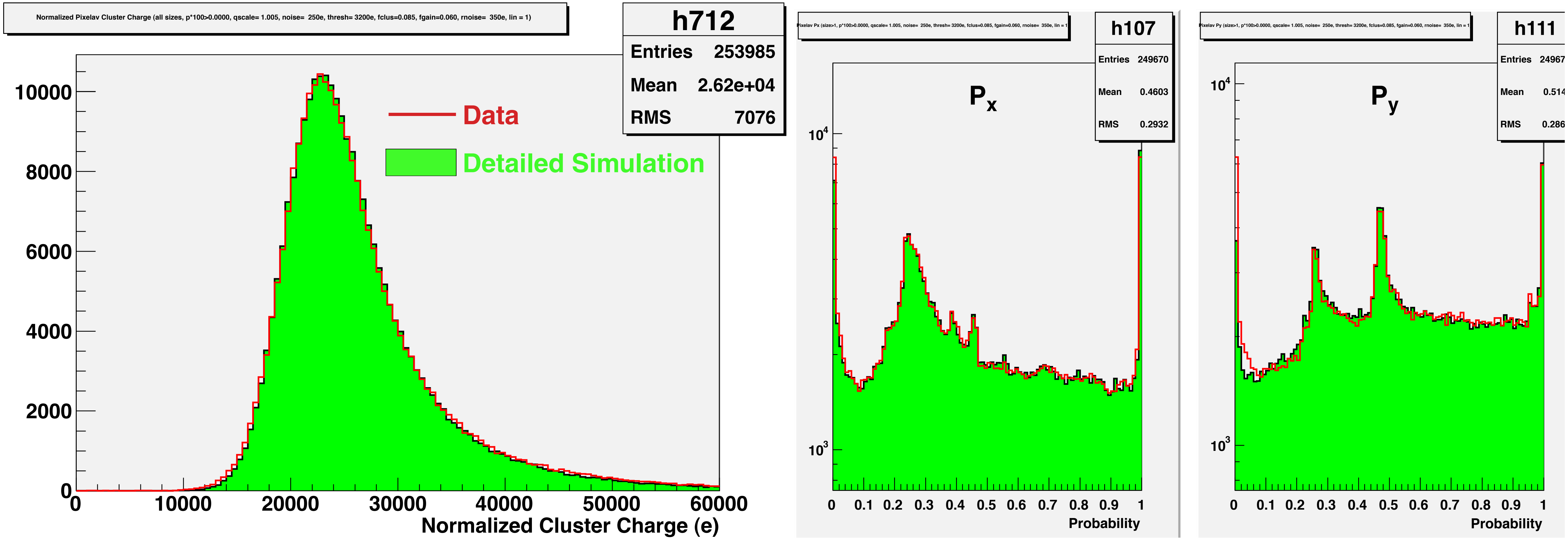
Sensor Structure, V_{bias},T, r_H, Φ, electronic response (6 params)

Pixelav
(detailed simulation)

Simulated Data:
- charge distribution
- size distributions
- shape probabilities
- Lorentz angle cals
  - *clust size vs cot(α)
  - *grazing angle
- extracted E-field profiles

Calibrations:
- Standard Reco
  - * Lorentz corrs
  - * error estimates
- Template Reco
  - *cluster shapes
  - *error estimates
  - *probability info
  - *cluster split info

Adjust these to match these to data

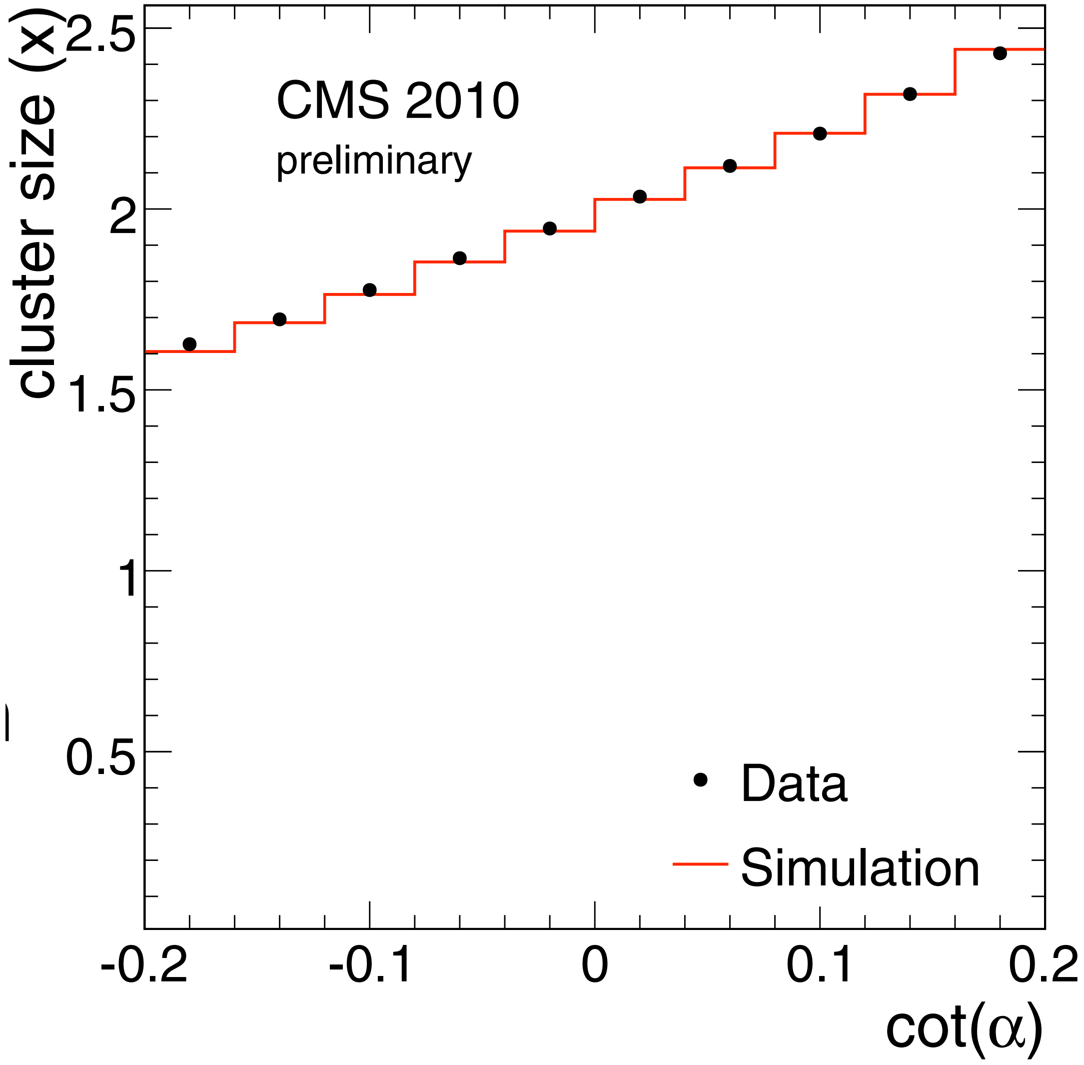


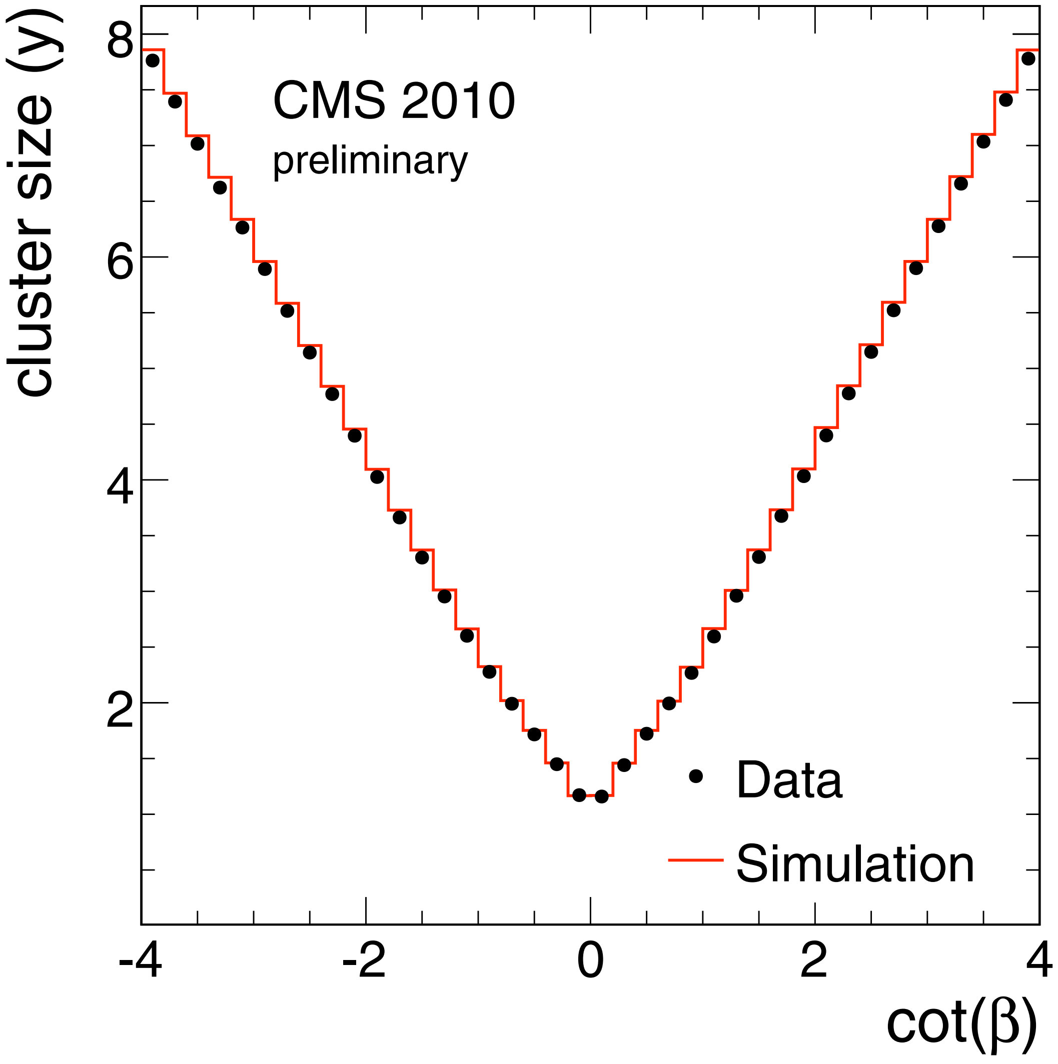
Simulated and measured charge scales typically within 1% for new detector.

Calibration of “In-Time” Thresholds

The average x/y cluster sizes for each bin in cot(α)/cot(β) depend upon the effective threshold.

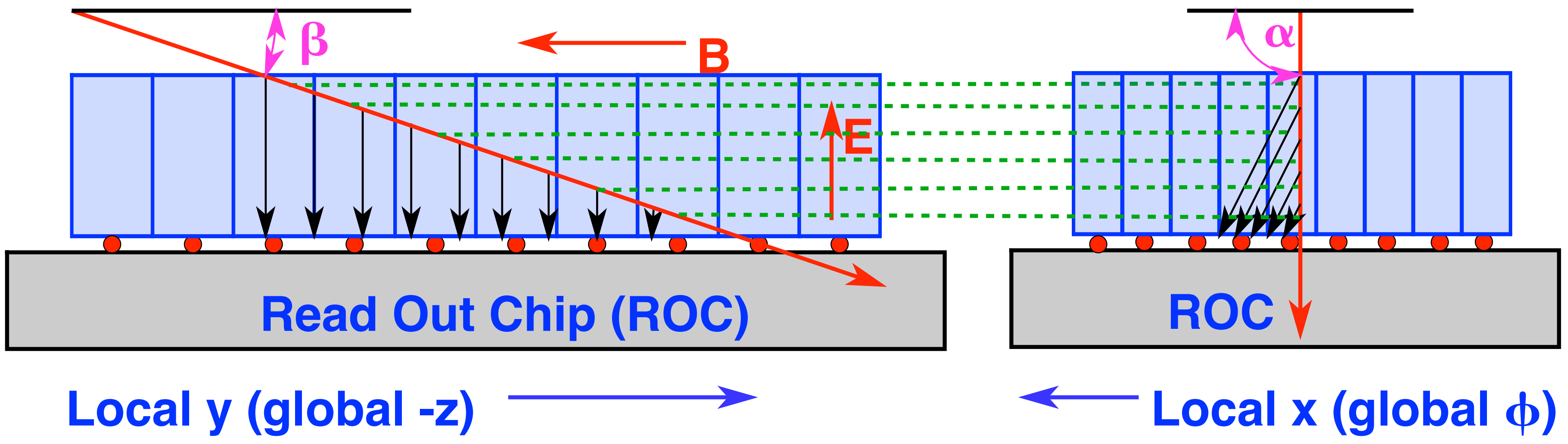
- Simulate the same track angles, momenta as reconstructed in the data
  - charge per unit cot(α/β) is same for simulated/measured samples
- Adjust threshold to achieve best agreement
  - x-size vs cot(α) is also sensitive to the Lorentz angle (meas separately)
  - thresholds vary from ~1600e [L3/4] to ~2500e [L2] to 3500-5000e





Old E-field Calibration Technique

Use signal trapping as a function of pixel column [depth] to probe E-field shape across the substrate of irradiated sensors

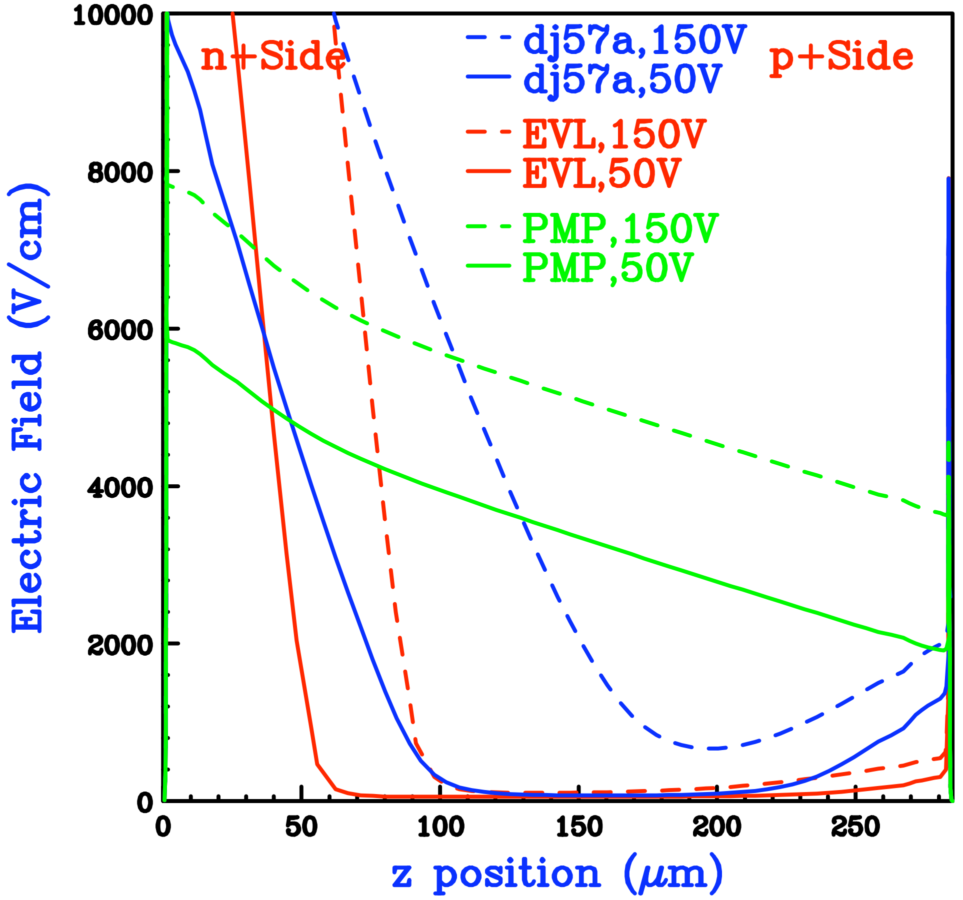


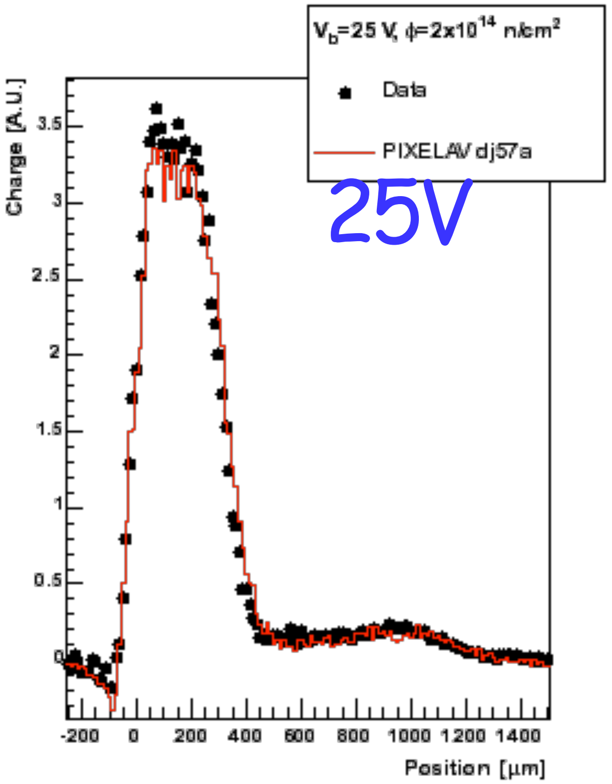
- Need to run at a series of low bias voltages
- 2003-2005 beam tests used a ROC with no zero suppression
  - ✴ could see very small [even wrong sign] signals
- Model results using TCAD with SRH statistics and 2 midgap defects [Eremin, Verbitskaya, Li]
  - ✴ TCAD defects model the E-field shape
  - ✴ Pixelav signal trapping independently adjusted

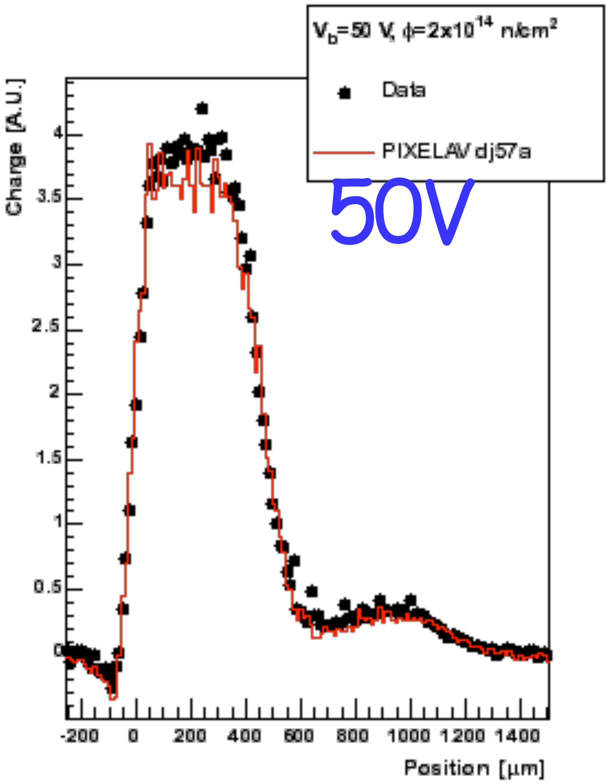
From RD50 Workhop 6 [2005]

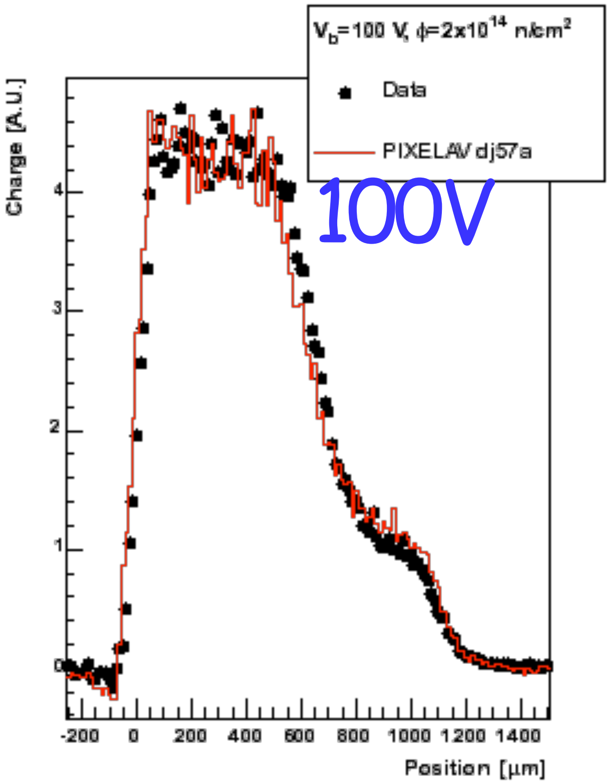
Best fit to 2.0x10^{14} n_{eq}/cm^2: labelled dj57a

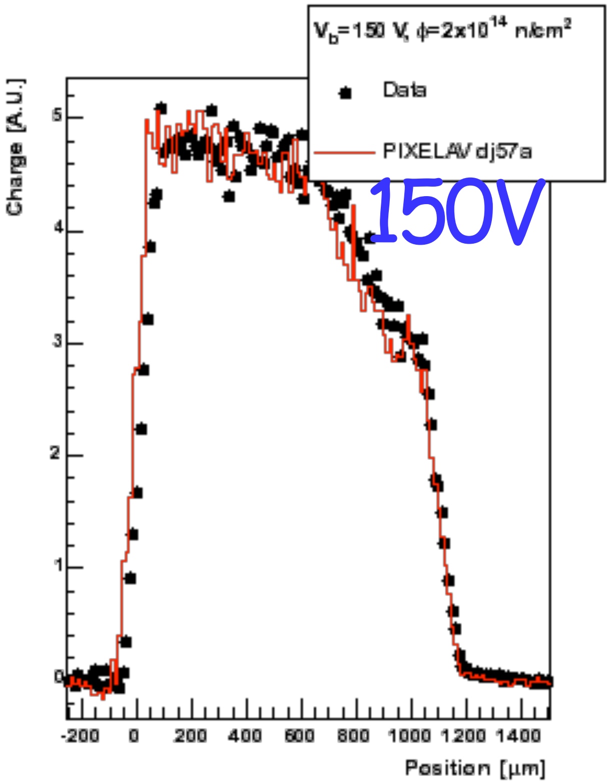
- N_A/N_D=0.68
- $\Gamma_{e/h}$ = 0.8 * Ljubljana trapping rates
- σ_{Ah}/σ_{Ae}=0.25, σ_{Dh}/σ_{De}=1.00,
- E-field still doubly-peaked





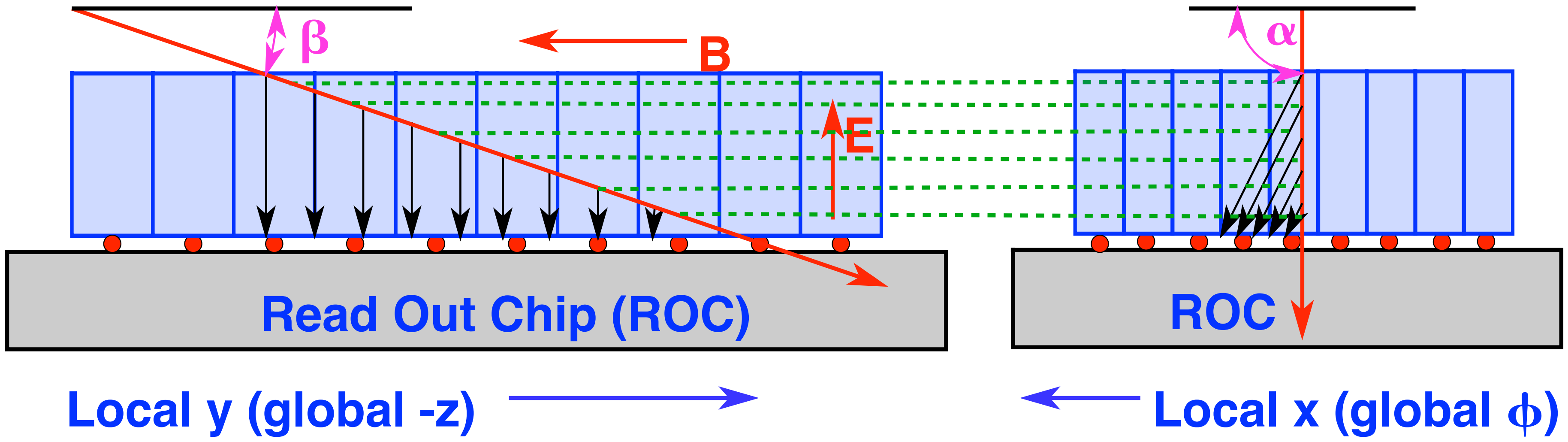




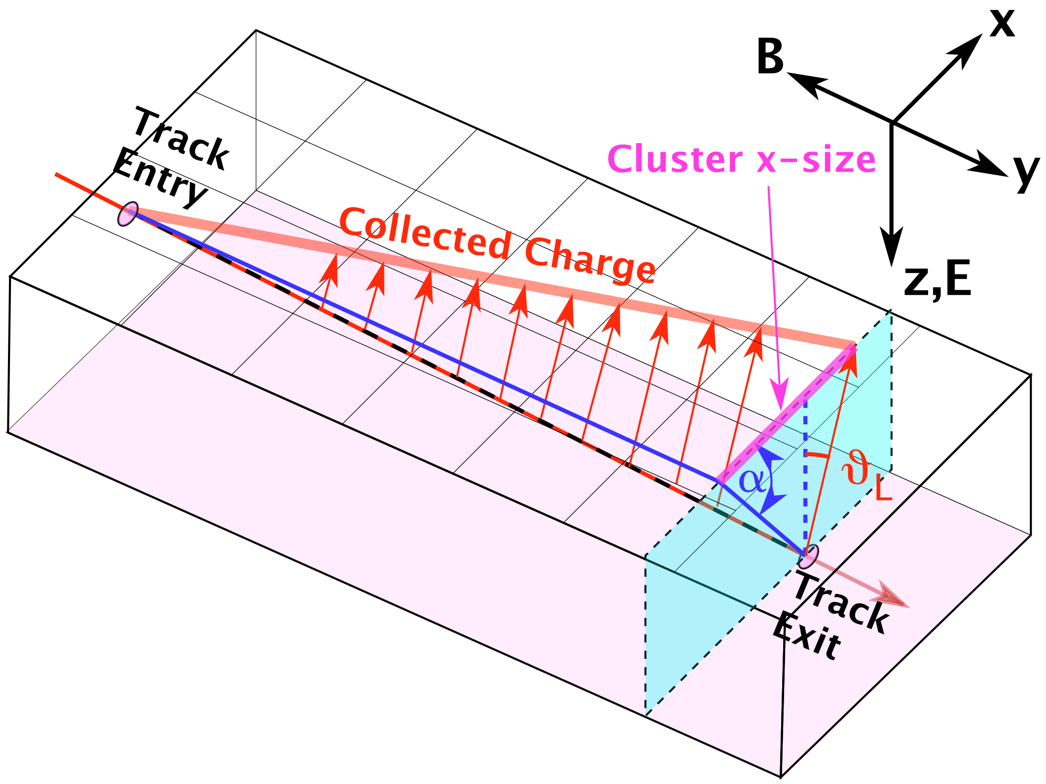


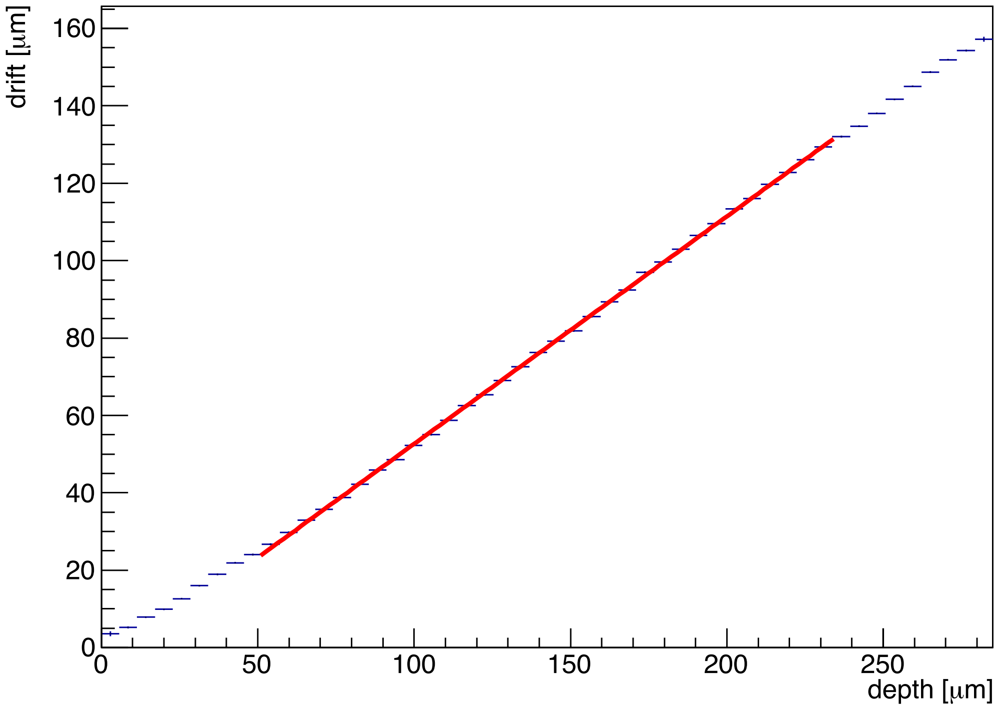
Lorentz Angle Calibration

Drift vs depth [grazing angle technique] was developed by UniZ colleagues to calibrate the Lorentz angle



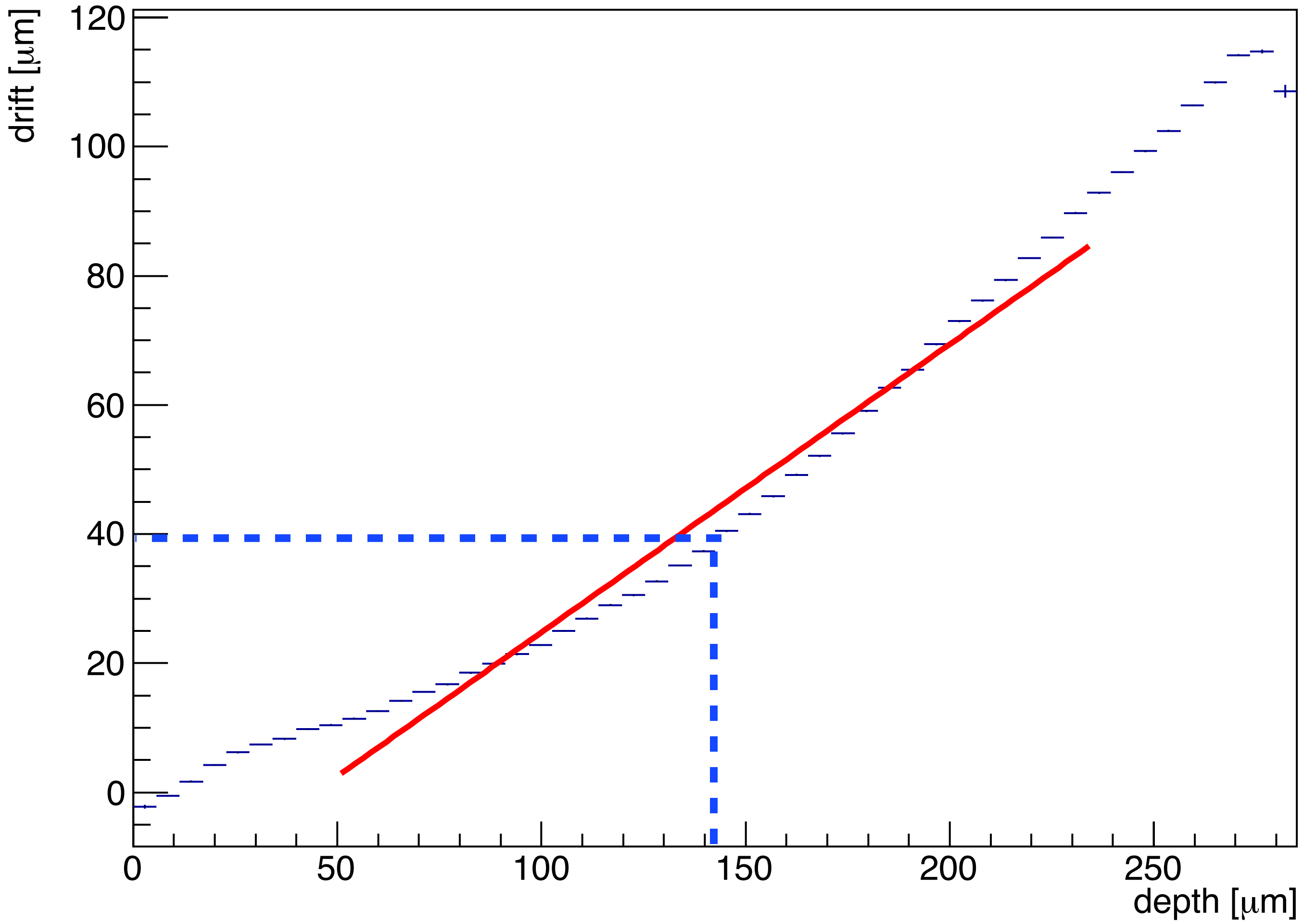
Accumulate the charge centroid [drift] vs depth for a sample of highly inclined tracks. The angle is the average Lorentz angle





Lorentz Angle Calibration

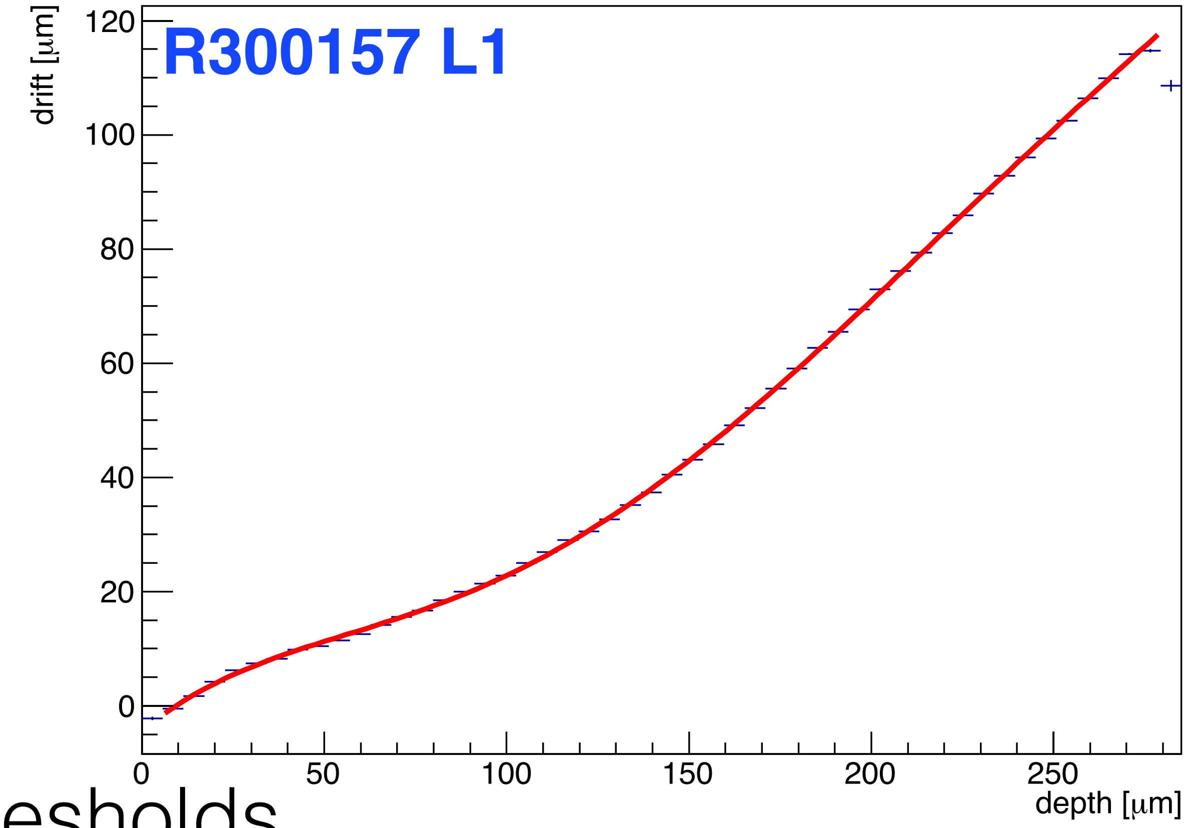
When the detector is irradiated, this technique is not useful



- the slope becomes steeper, but the actual offset from Lorentz drift [needed for eta-like reco] becomes smaller
  - ✴ Lorentz drift correction is the offset at the detector midplane
  - ✴ steeper slope would imply a larger drift correction
- we need a better method to calibrate the sensor simulation

E-Field Measurement and Template/LA Calibration

Take our drift (x) vs Depth (D) data, fit to a polynomial [5th order] and then calculate a local slope [Lorentz Angle] vs D. We then convert it to an E vs D curve from the expression

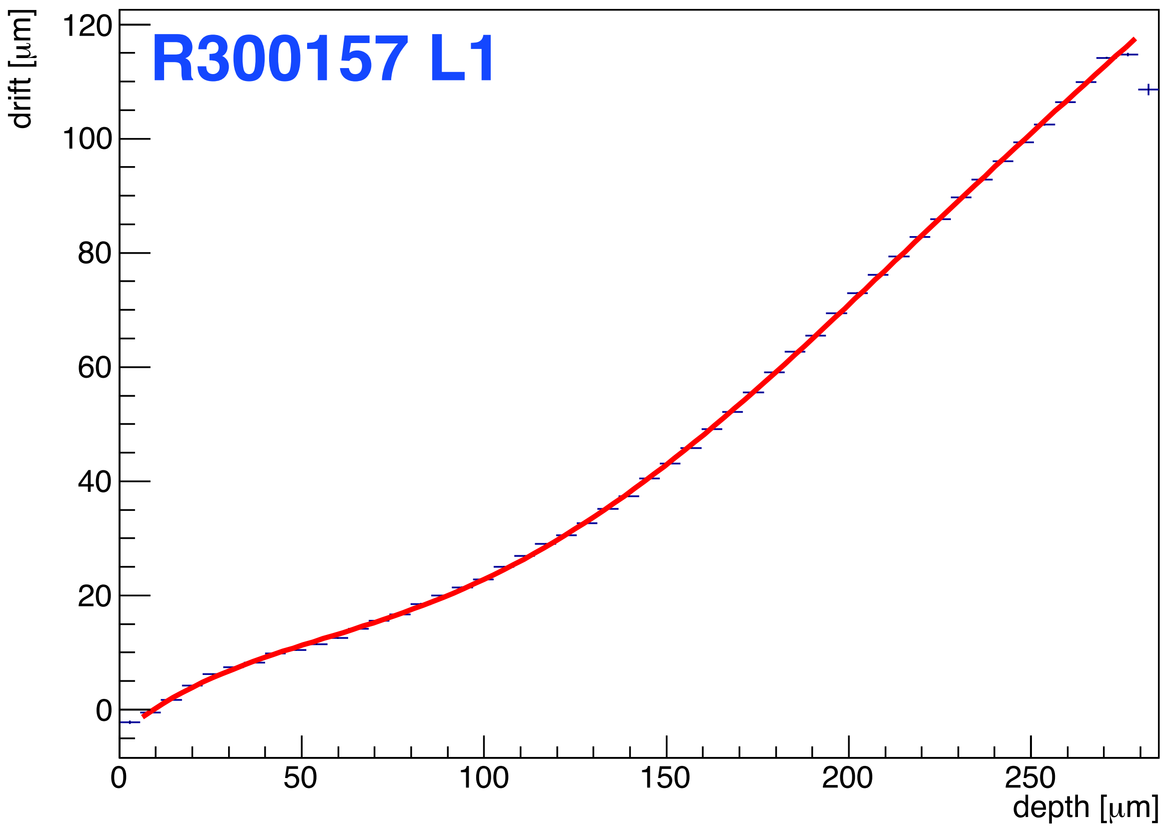


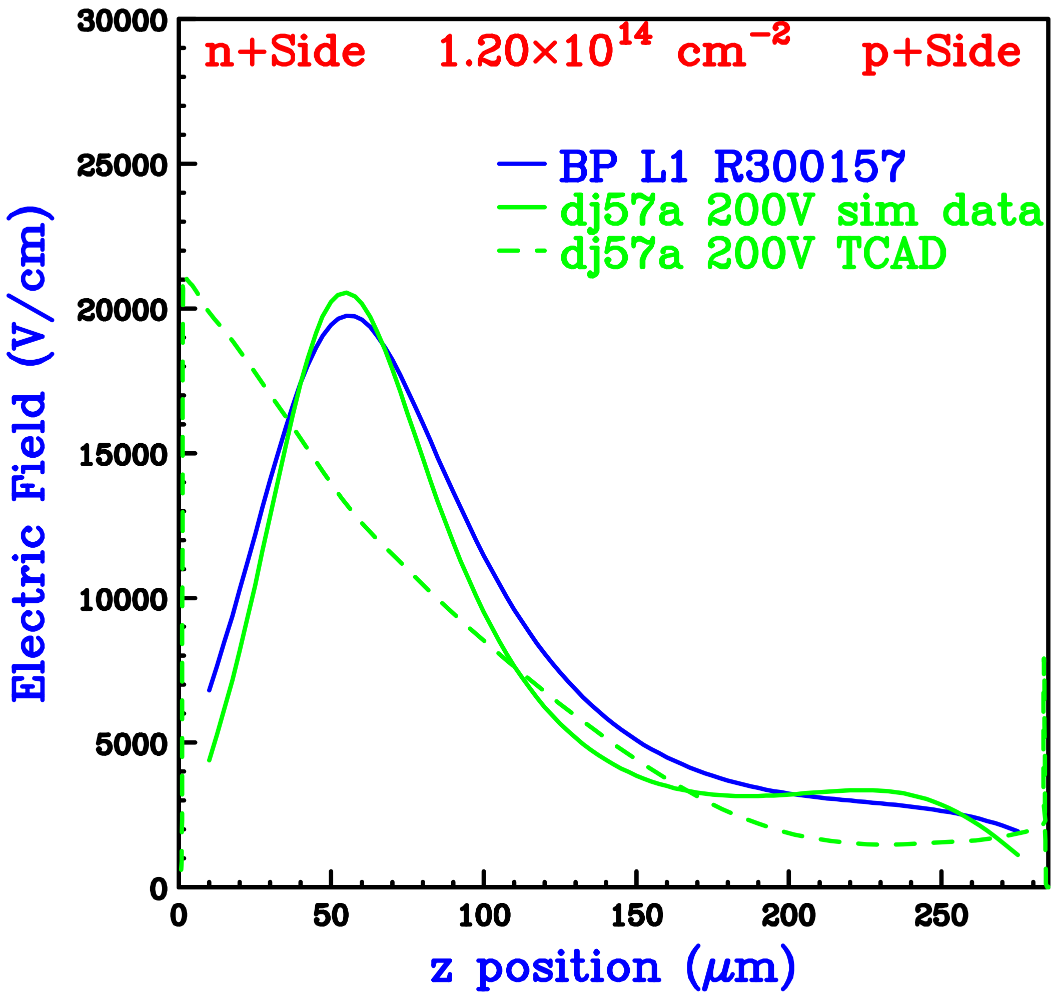
$$\tan\theta_L = \frac{dx}{dD} = r_H \mu(E) B_y$$

$$\rightarrow E = \mu^{-1}\left(\frac{1}{r_H B_y}\frac{dx}{dD}\right)$$

- depends upon the slope dx/dD
  - ✳ insensitive to alignment effects
- insensitive to the knowledge of thresholds
- insensitive to trapping [displacement is measured at fixed depth]!
- can be done at operating voltage: no need for bias scans
- extracts information that is sort of comparable to the simulated E-field
  - ✳ still need to simulate the extracted fields in this procedure
- Q vs D distributions can then be used to independently adjust the trapping rates for e/h

The extracted electric field profile is distorted by focusing near the n+ implant and other systematic effects. The good news is that we can simulate them [mostly]:





- Run 300157 was taken after 11.8 fb^{-1}: $\Phi_Q = 1.2\text{x}10^{14}$ cm^{-2}
  - ✳ the neutron equivalent flux [0.6 hardness] $\Phi_{eq} = 0.72\text{x}10^{14}$ cm^{-2}
  - ✳ the electric field is well described by our old model dj57a?
    - ‣ it was from a sensor that had been exposed to $\Phi_{eq} = 2\text{x}10^{14}$ cm^{-2}

Differences

Beam Test

- Sensors are irradiated in a short time [hours/days]
  - ✴ defect-defect interactions occur at rates ~ density^2
- Sensors are "standard annealed"
  - ✴ in 2003, sensors warmed to 30C for 30 hours?
    - ‣ they were always kept cold after that

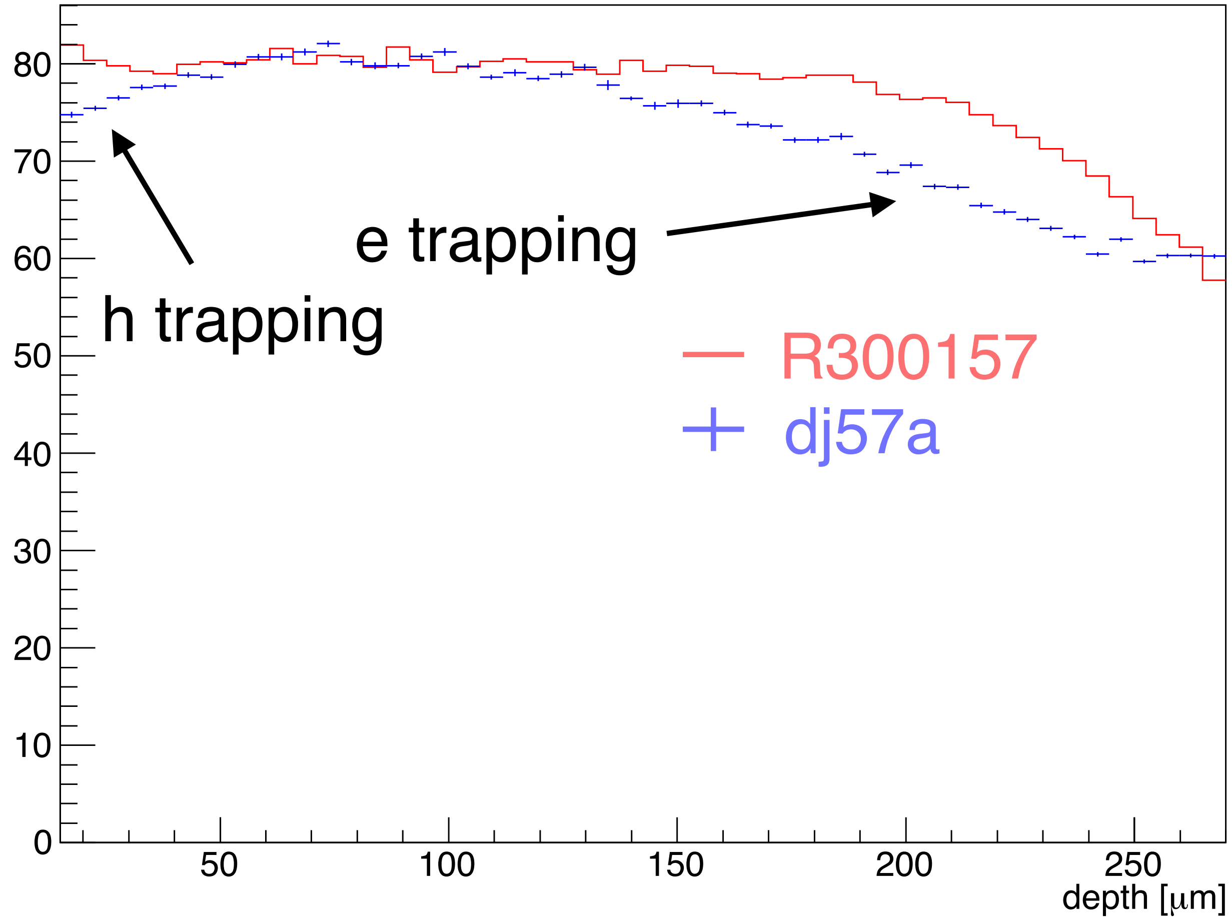
Operation

- Sensors are irradiated in a long time [months]
  - ✴ defects have more time to interact with impurities
- Sensors are not annealed at all
  - ✴ in CMS, everything has been kept at -10C [ROCs generating heat] or -20C [readout off]
    - ‣ there will be some annealing when maintenance is done if not before

Could these differences affect the evolution of the sensor E-fields and trapping rates?

Trapping Measurement

Compare the measured depth profile with the simulated profile



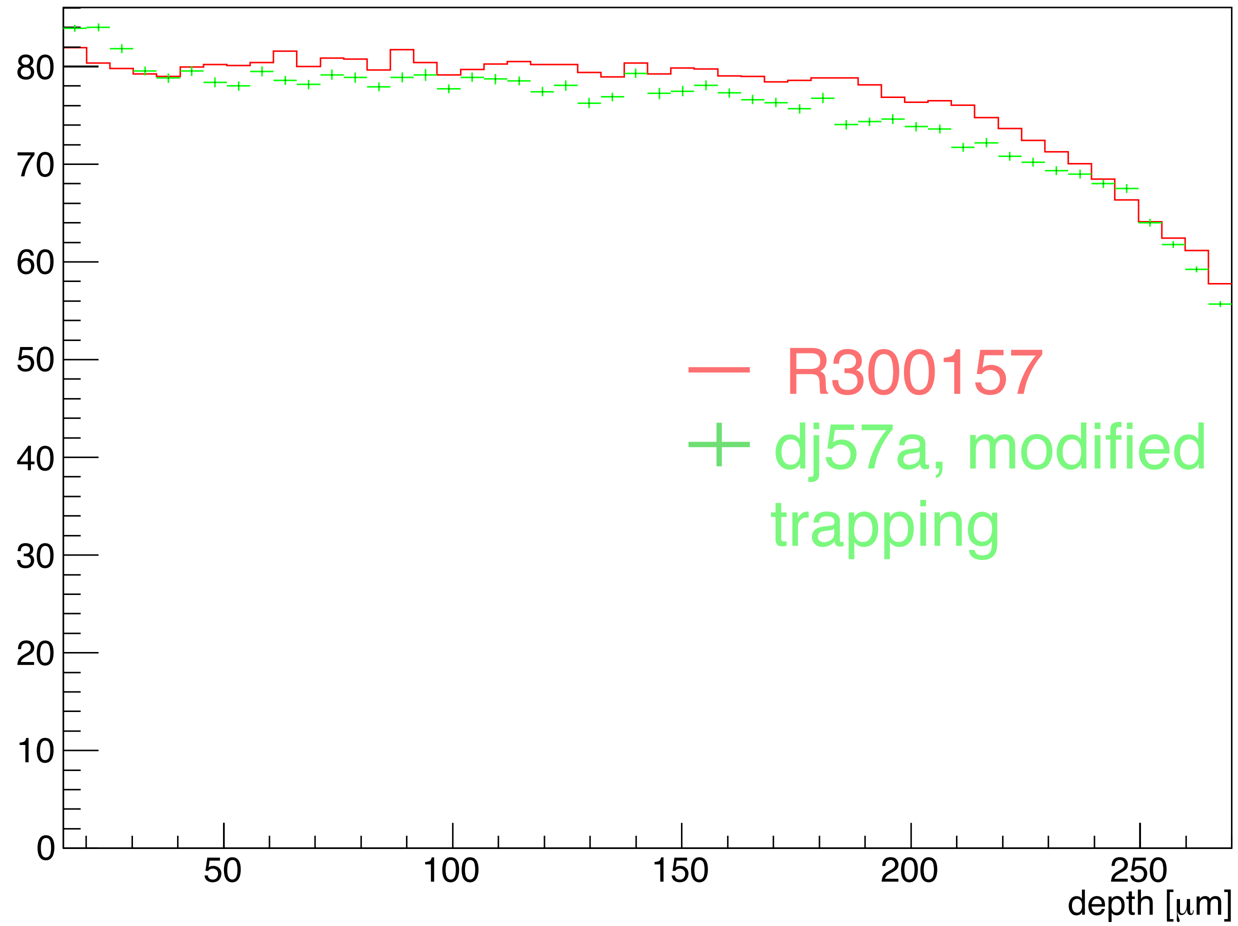
The trapping rates for e and h are both too large!

How much trapping do we expect for $\Phi_Q = 1.2 \mathrm{x} 10^{14}$ cm^{-2} ?

In our test beam models, the trapping rates should scale as $0.8\Phi_{eq} = 0.48\Phi_Q = 0.6\mathrm{x}10^{14}$ cm^{-2} ?

Trapping Measurement

Simulate the dj59a E-field with trapping rates corresponding to 0.6x10^{14} cm^{-2}



- The electric field is evolving faster [differently] than expectations from the beam test models
- Trapping rates appear to be evolving according to the fluence calculation with a hardness factor of 0.6
- The slower evolution of the trapping rates has important consequences for the longevity of the detector

Summary

- Sensor modeling is a key element in the calibration of CMS’ pixel hit reconstruction
- Lorentz drift vs depth provides information that is used in tuning the sensor models
  - ✳ it is performed with full bias voltage collision data
- The space charge effects have onset more quickly than might have been expected from beam test data
  - ✳ the effects differ from beam test expectations
  - ✳ could be due to different radiation profiles or different annealing history
- The signal trapping effects seem to be behaving according to expectations from beam test data