Double Junction Simulation of CMS Pixel Test Beam Data

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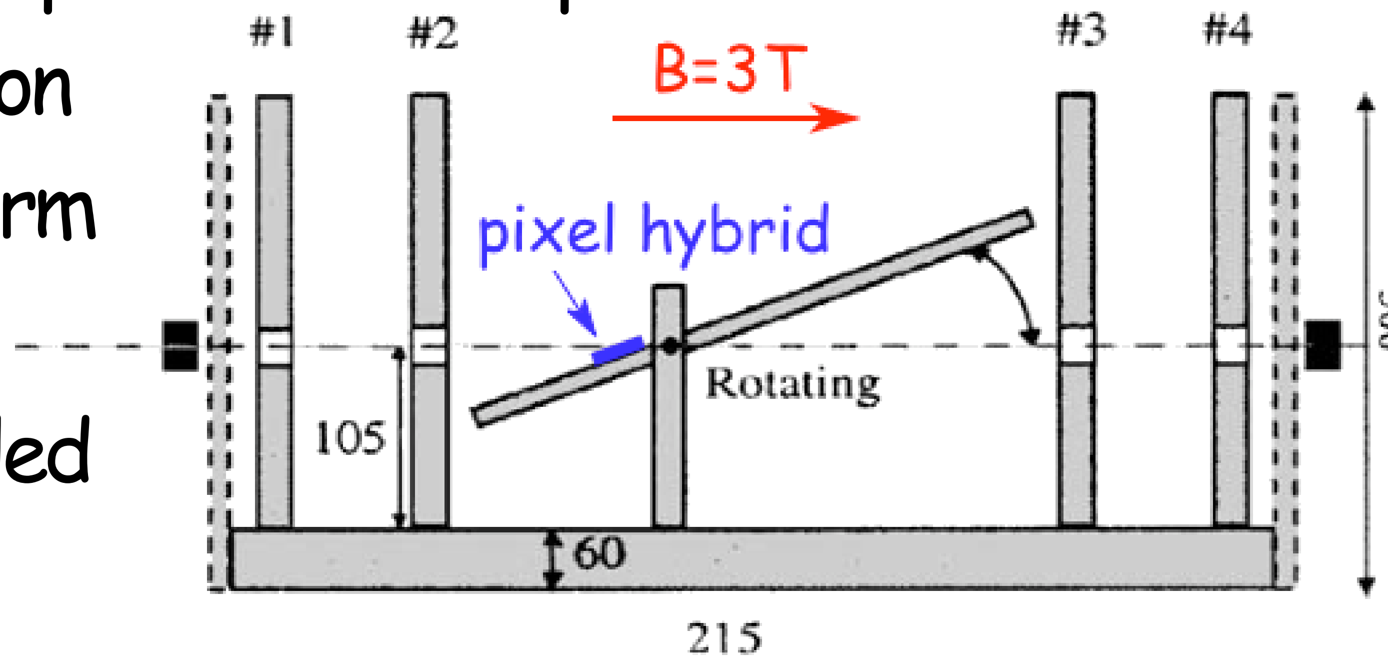
Test Beam Layout

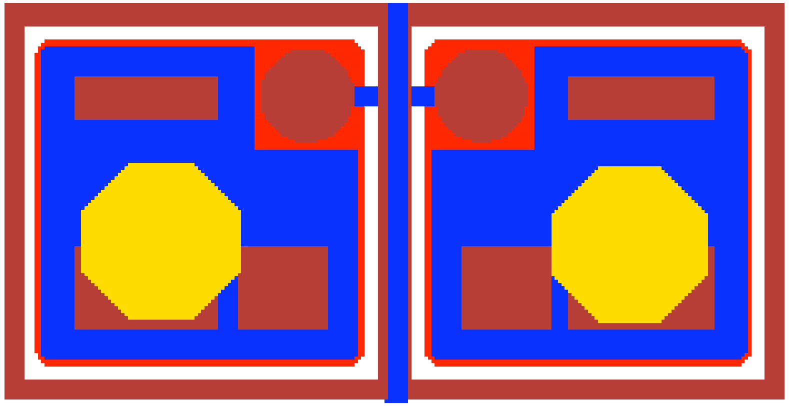
Beam tests performed in SPS H2 beam:

- 150-225 GeV π^+/p
- 3T open geometry magnet with field along beam axis
- 4xy plane Si strip beam telescope
  - 1 μm resolution
  - hybrid platform rotates
  - platform cooled to -20°C
  - heat load from ROC increases sensor temp to ~-10°C



Sensors

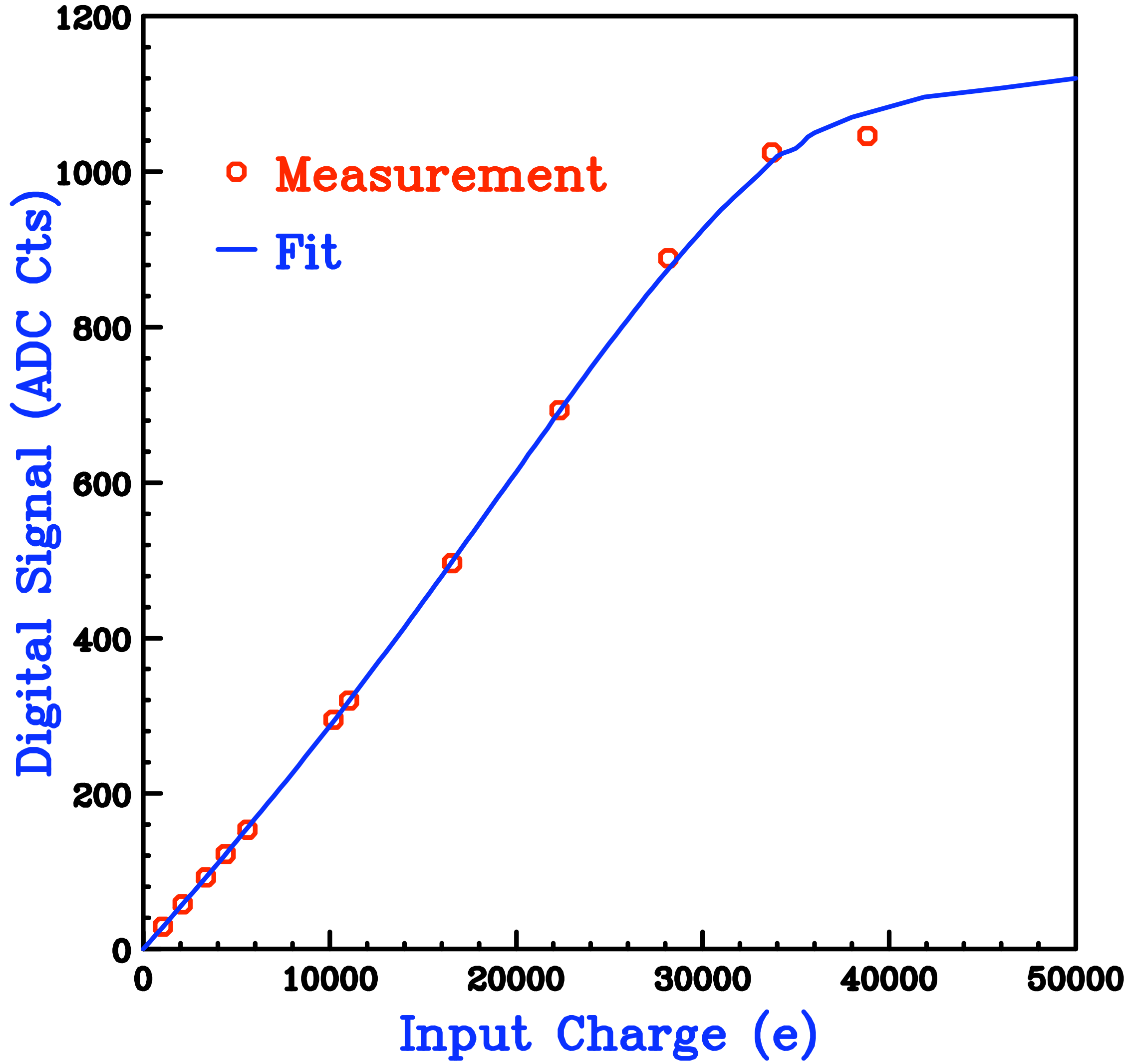
All results are based upon 125μmx125μm CiS pspray test sensors:



- 22x32 cells on each chip
- 285μm thick dofz substrate from Wacker
  - n- doped with ρ=2-5 kΩ-cm, <111> orientation
- irradiated with 21 GeV protons at PS to fluences:
  - 6×10^{14} n_{eq}/cm^2 nominal: $(8.1 \pm 0.7) \times 10^{14}$ n_{eq}/cm^2 actual
  - 9×10^{14} n_{eq}/cm^2 nominal: $(1.0 \pm 0.1) \times 10^{15}$ n_{eq}/cm^2 actual
- irradiated/bump-bonded at ~30°C, stored at -20°C

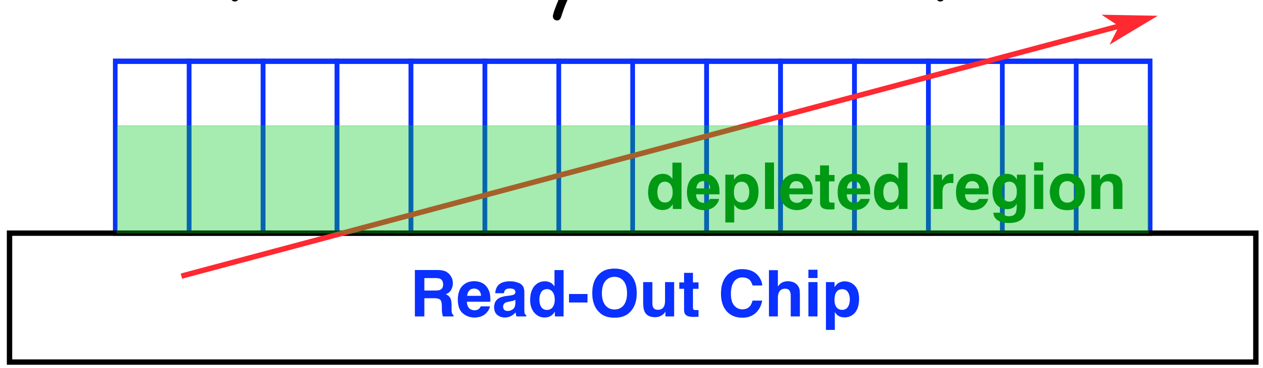
Readout Chip

- sensors bump-bonded to PSI30 ROC from Honeywell
  - doesn't sparsify data, permits readout of small signals
  - good linearity to 30k e (at 15°, mp charge deposit is ~10k e)
  - not very rad-hard
- irradiated sensors bump-bonded "cold" to unirradiated ROCs



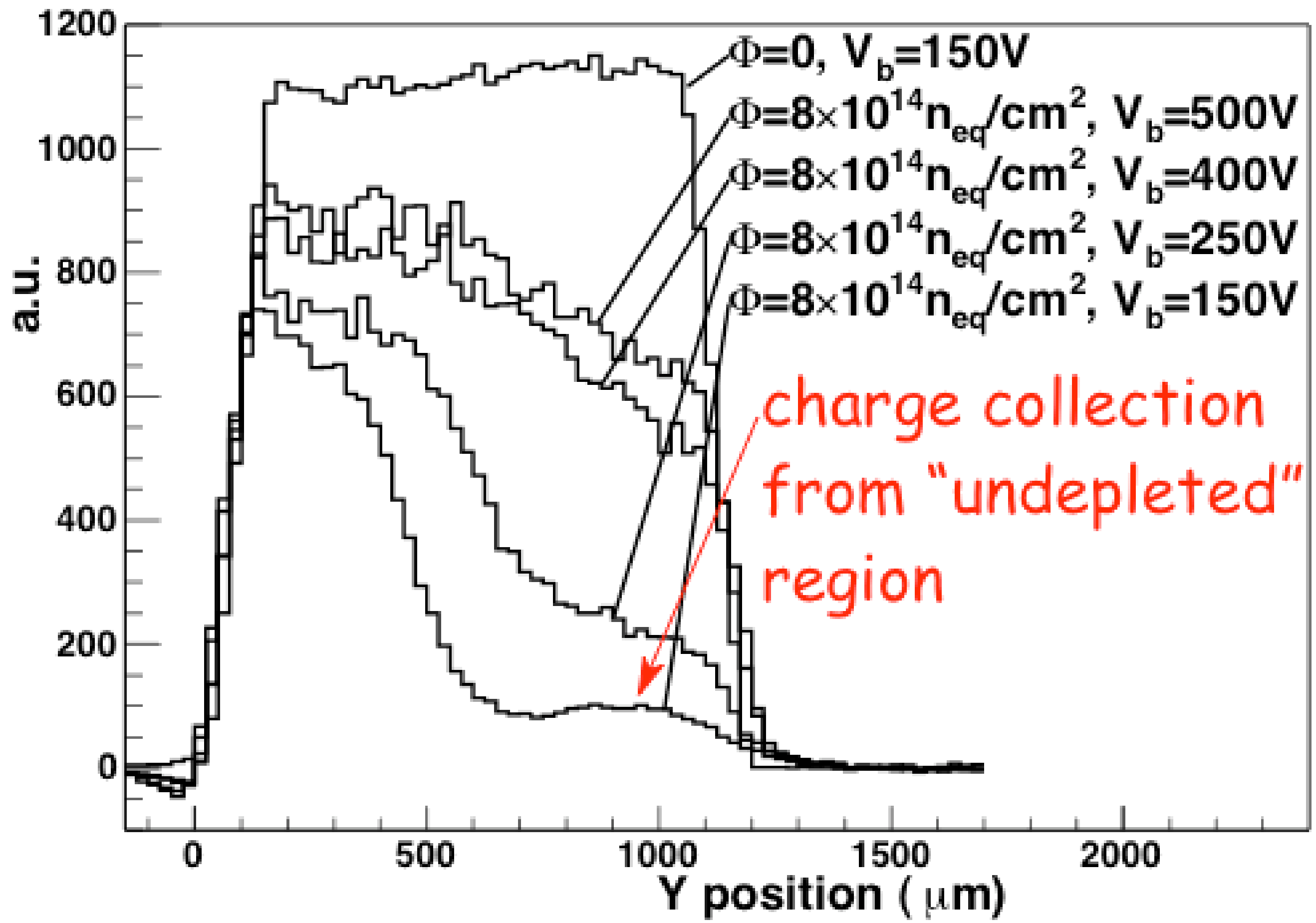
Charge Collection Studies

Charge collection was studied from the signal profiles in a row of pixels illuminated by a 15° beam and B=0,



- each pixel samples charge deposited at a different depth
- precise beam telescope info is used to refine profile
- collected charge profiles are sensitive to trapping
  - trap rates measured by Ljubljana + Dortmund groups
  - need a simulation to interpret the data

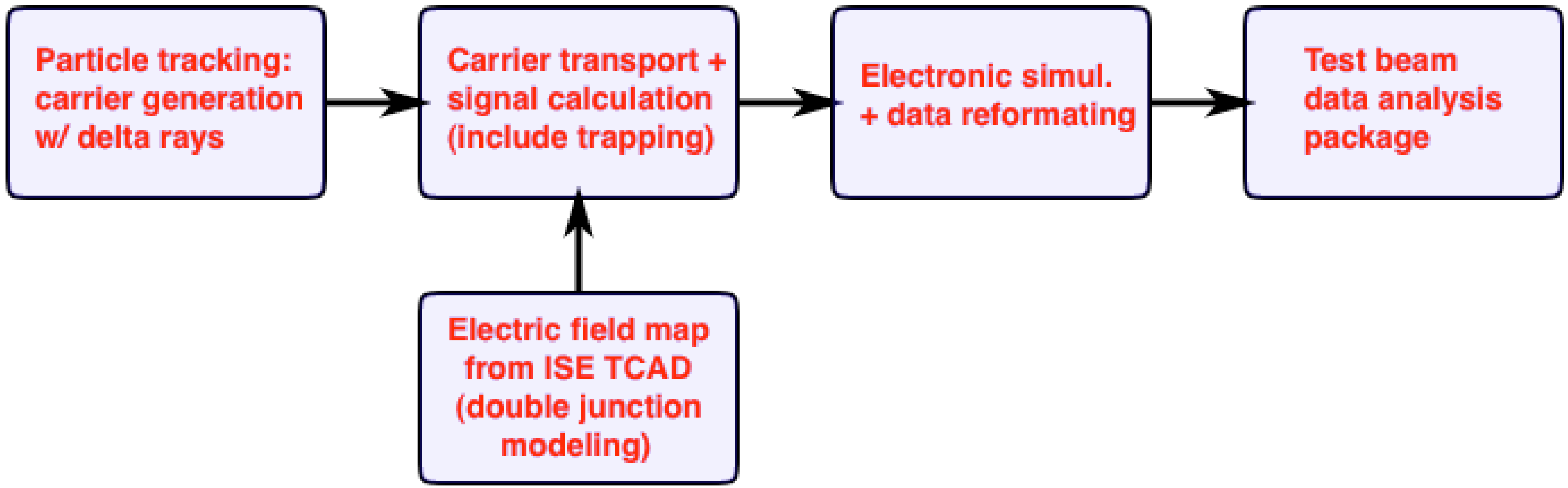
The charge collection profiles for a fully depleted unirradiated sensor and for a heavily irradiated sensor at several bias voltages show interesting features:



- field across the entire junction at low bias
- Q(300V)/Q(150V) = 2.1, faster than $(2)^{1/2}$

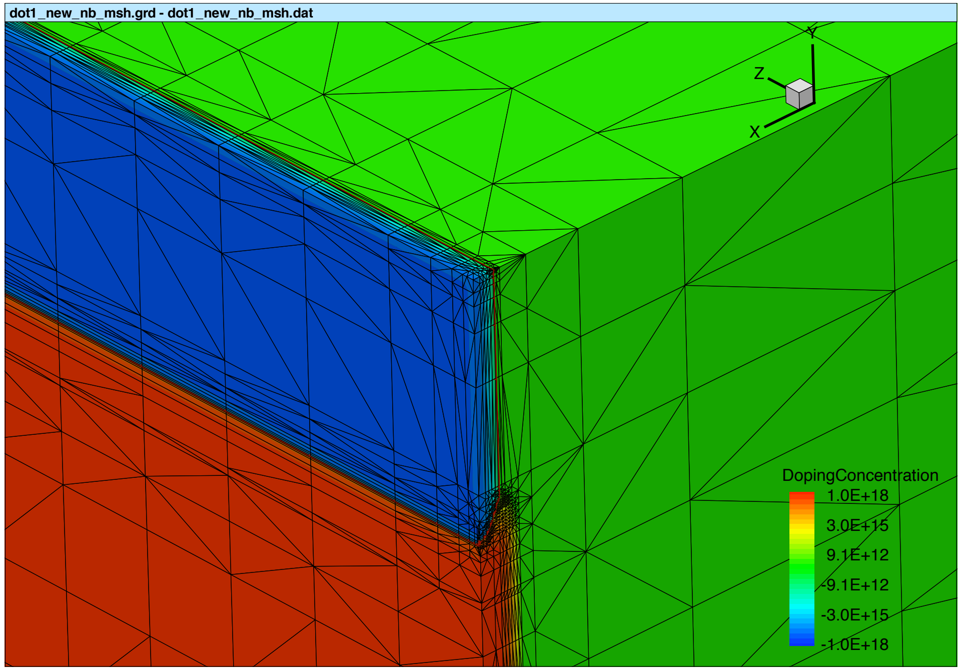
Simulation

Over the last several years, we have constructed a detailed sensor simulation, Pixelav [NIM A511, 88 (2003)]

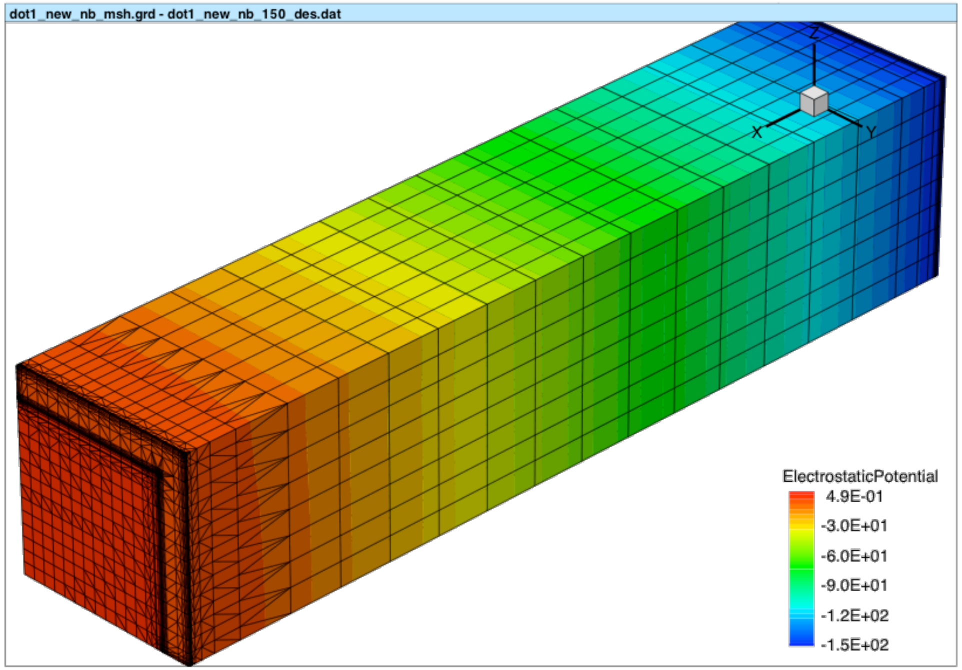


- Particle tracking: e-h pairs are generated according to x-sections of Bichsel [RMP 60, 663 (1988)]
  - E<1 MeV delta rays propagated according to range/energy relation (density of e-h pairs from dE/dx)

- Electric field calculation: uses ISE TCAD software
  - simulate 1/4 pixel cell to keep mesh size ~25,000 nodes. This requires 4-fold symmetry (no bias dot)
  - no process simulation, use MESH w/ analytic doping profiles to generate grid and doping files



doping profiles



potential distribution

- Transport calculations are done by integrating the fully saturated equation of motion for the carriers

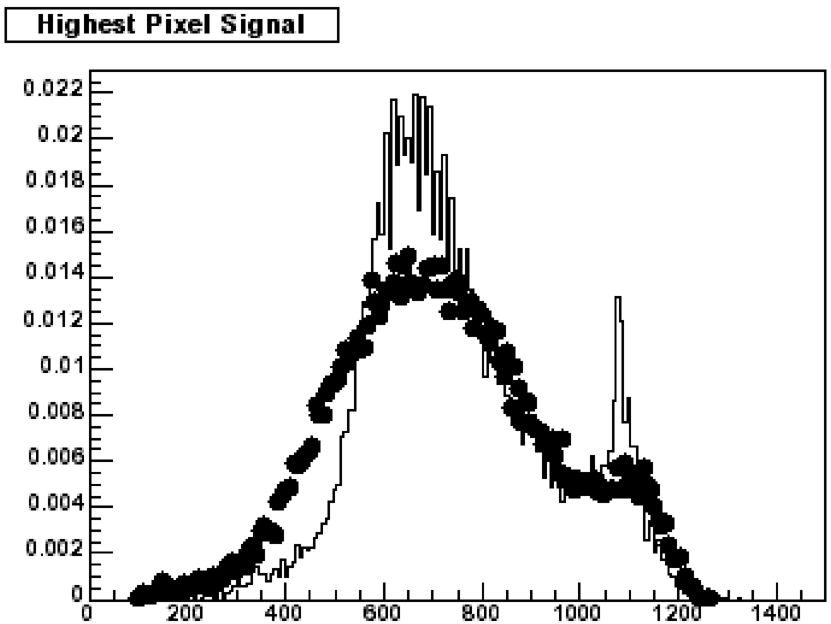
$$\frac{d\vec{r}}{dt} = \frac{\mu\left[q\vec{E} + \mu r_H \vec{E}\times\vec{B} + q\mu^2 r_H^2(\vec{E}\cdot\vec{B})\vec{B}\right]}{1+\mu^2 r_H^2 B^2}$$

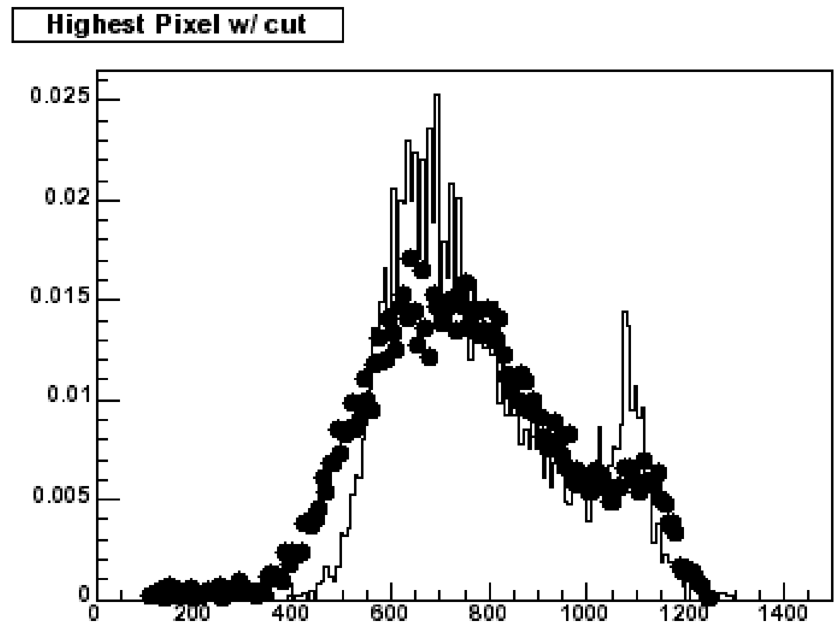
  - 4th-order R-K calc is vectorized for G4 processor
  - incorporates diffusion and trapping
  - signal induced from displaced, trapped charge is calculated from segmented parallel plate cap. model
- Electronics Simulation:
  - includes leakage current and electronic noise
  - readout chip analog response from measurements
  - ADC digitization
  - reformat data to look like test beam data

Unirradiated Data

Simulation is checked by comparing w/ unirradiated data:

- Pulse height distributions:

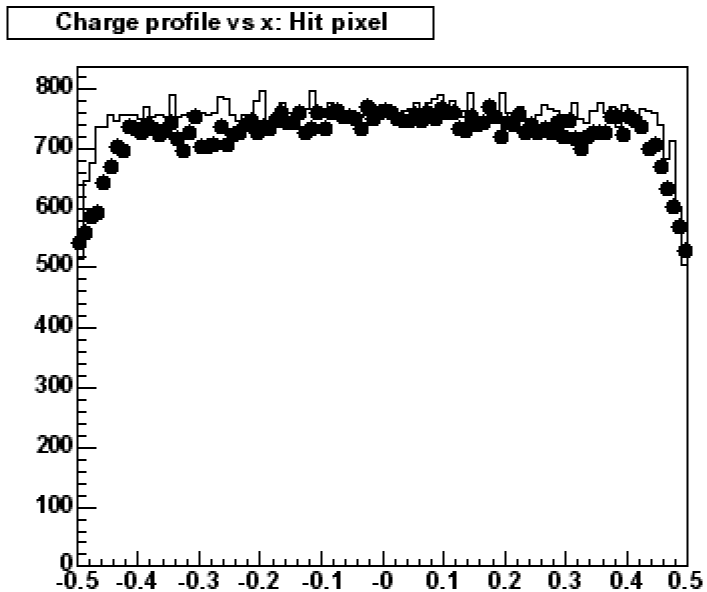


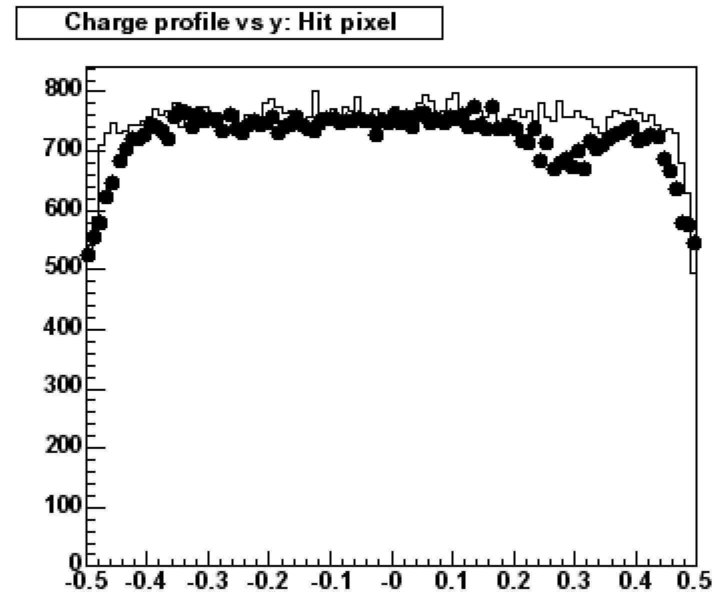


  - mean agrees well with data
  - too few low charges in simulation
  - too many simulated large charge events

➡ bias dot doesn't collect charge and is not simulated!

- Diffusive charge sharing for normally incident tracks:





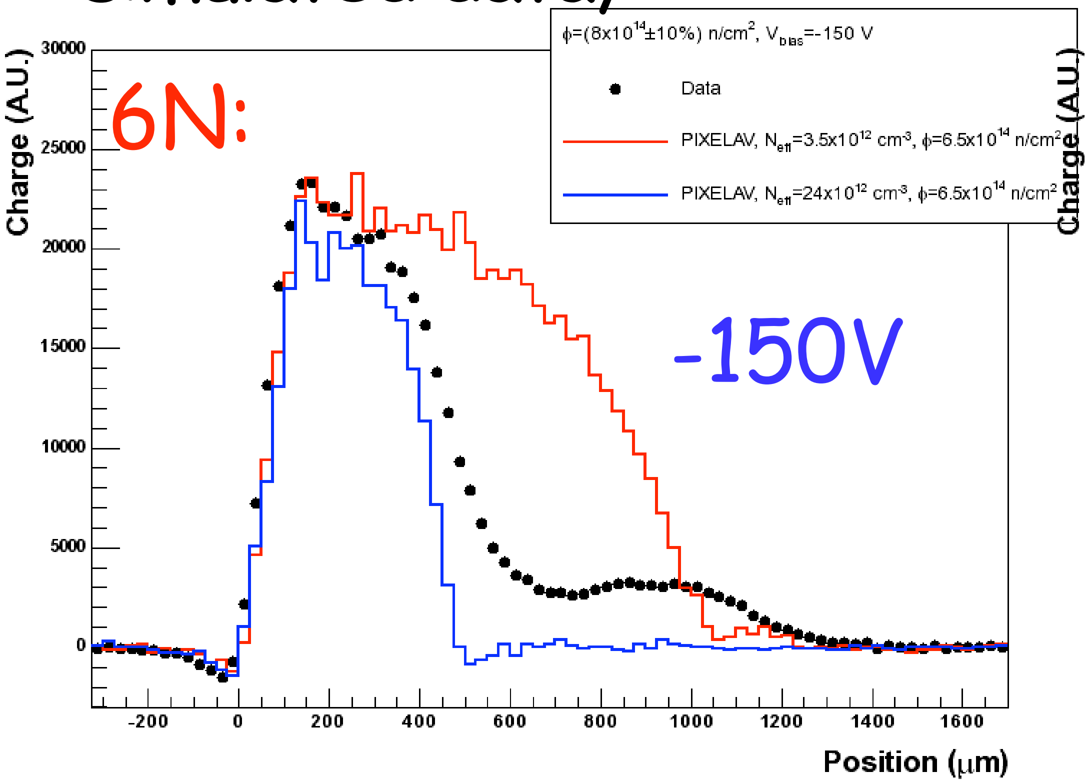
  - charge loss due to bias dot is visible in data
- Lorentz angle:
-

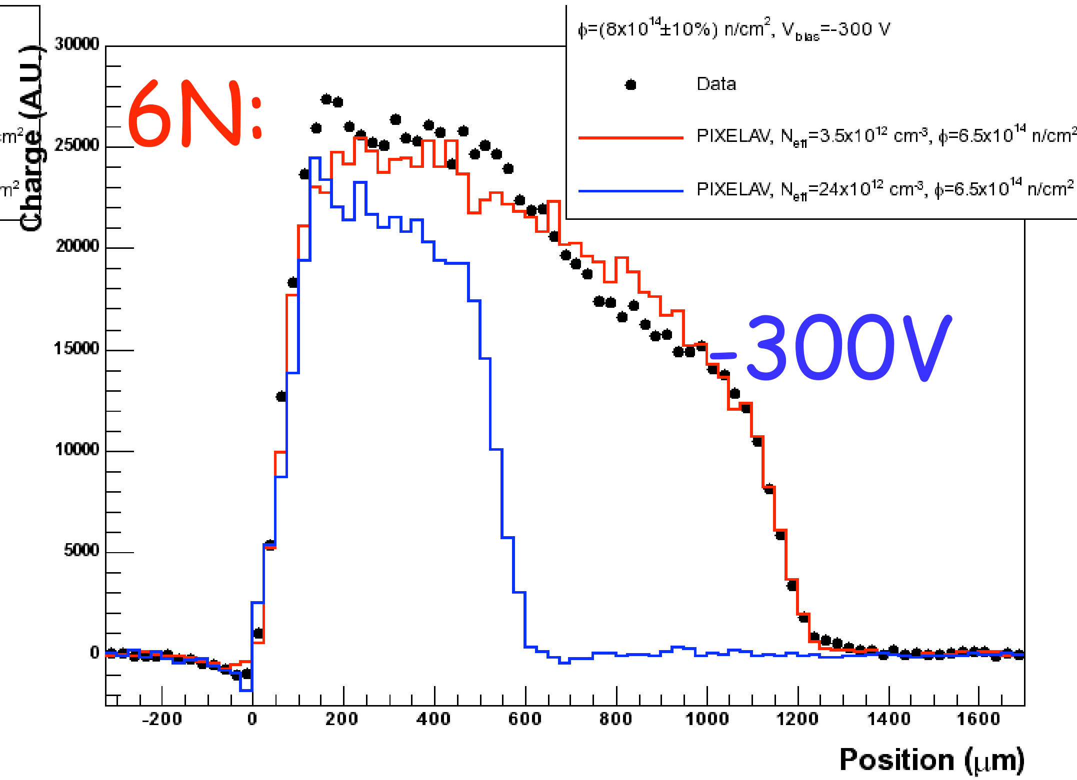
Bias (V)	Data (deg)	Simulation (deg)
150	22.8±0.7	24.7±0.9
300	14.7±0.5	17.4±0.9
450	11.2±0.5	12.0±0.9

➡ Simulation does a reasonable job describing the data

Irradiated Data vs Sim.

Comparing the charge collection profiles of real and simulated data,





- -300V data are well described by N_{eff}=$3.5\times10^{12}cm^{-3}$ p-
- width of -150V peak requires N_{eff}=$24\times10^{12}cm^{-3}$ p-
  - tail not described

Double Junctions

There has been experimental evidence of a double peaked electric field in heavily irradiated silicon detectors since 1992 [Li+Kramer]. Eremin, Verbitskaya, and Li have recently modeled this effect using a pair of midband traps: 1 e-trap and 1 h-trap [see 3rd RD50 workshop, NIM A476, 556 (2002), etc]. The EVL model is based on SRH statistics and generates the effective charge density from the trapping of leakage current,

$$\rho_{\text{eff}} = e\left[N_D f_D - N_A f_A\right] + \rho_{\text{dopants}}$$

where N_D and N_A are the densities of h- and e-traps and f_D and f_A are the trap occupation probabilities. Note that trap energies are far enough from the quasi-Fermi levels that they are not thermodynamically ionized.

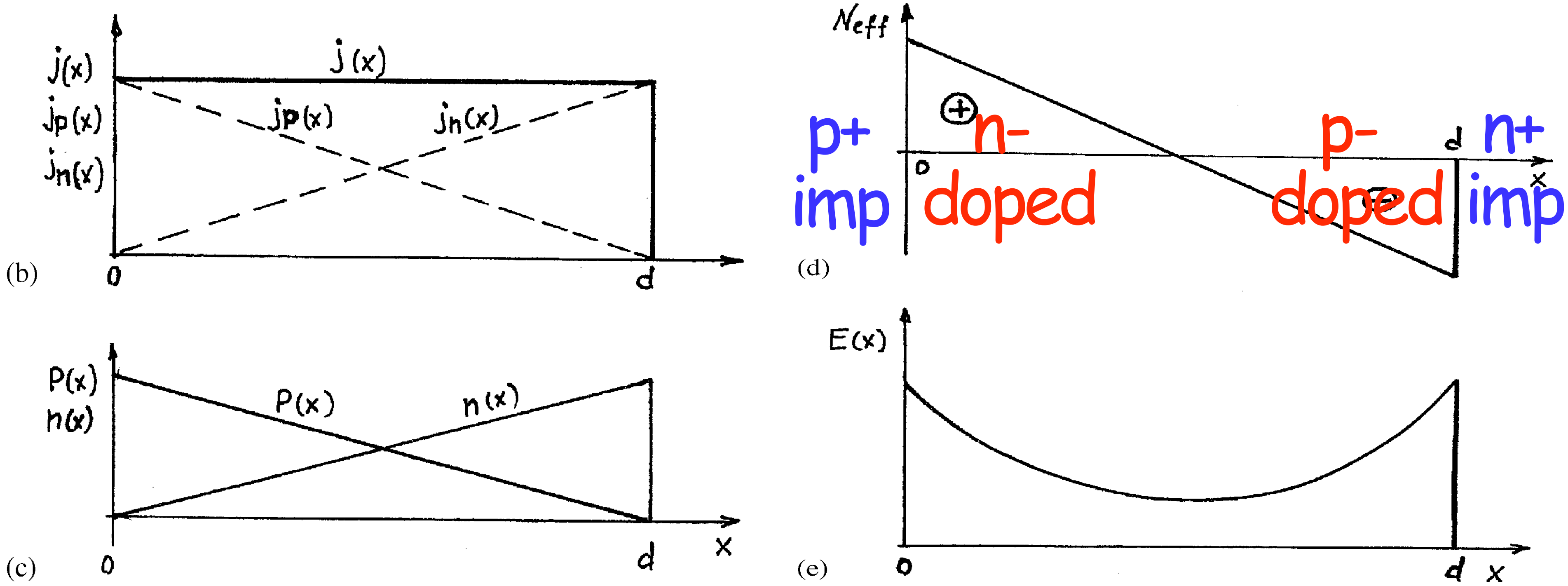
The occupation probabilities are given in terms of the usual SRH quantities:

$$f_D = \frac{v_h \sigma_h^D p + v_e \sigma_e^D n_i e^{E_D/kt}}{v_e \sigma_e^D (n + n_i e^{E_D/kt}) + v_h \sigma_h^D (p + n_i e^{-E_D/kt})}$$

$$f_A = \frac{v_e \sigma_e^A n + v_h \sigma_h^A n_i e^{-E_A/kt}}{v_e \sigma_e^A (n + n_i e^{E_A/kt}) + v_h \sigma_h^A (p + n_i e^{-E_A/kt})}$$

- E_D, E_A are defined relative to the mid-bandgap energy
- σ_e and σ_h are not well-known in general
- rescaling $\sigma_{e/h} \Rightarrow r\sigma_{e/h}$ leaves f_D and f_A invariant. They depend upon σ_h/σ_e only! [key point]

EVL creates double junctions from the trapping of the generation current,



- the trap parameters (3rd RD50 Workshop) are:

trap	E (eV)	g_{int} (cm^{-1})	σ_e (cm^{-2})	σ_h (cm^{-2})
donor	E_V+0.48	6	1×10^{-15}	1×10^{-15}
acceptor	E_C-0.525	3.7	1×10^{-15}	1×10^{-15}

- EVL model creates the generation current from SRH-based parameterization,
  - the mechanism that creates the leakage current is assumed not to affect ρ_{eff}

As we analyzed our test beam data, it became clear that a mechanism like EVL generates an internal E-field that has the qualitative features needed to describe our data:

- E-field minimum can act like a "gate" at low bias
  - reduces charge collected from p+ side (due to trapping)
- at larger bias, the "gate" lifts, allowing much more charge collection

Does this idea quantitatively describe our data?

DJs in ISE DESSIS

The implementation of the EVL model in DESSIS device simulator is complicated by the fact that EVL separates the trap dynamics from the leakage current. In Dessis, any attempt to add current-generating defects also traps charge. Two possible solutions:

- use the "Physical Model Interface" to replace the entire trapping/SRH formalism with a modified one
- rescale $\sigma_{e/h} \Rightarrow r\sigma_{e/h}$ (leaves f_D, f_A invariant) but increases SRH generation current by a factor of r,

$$U = \frac{r v_h v_e \sigma_h^D \sigma_e^D N_D (np - n_i^2)}{v_e \sigma_e^D (n + n_i e^{E_D/kt}) + v_h \sigma_h^D (p + n_i e^{-E_D/kt})} + \frac{r v_h v_e \sigma_h^A \sigma_e^A N_A (np - n_i^2)}{v_e \sigma_e^A (n + n_i e^{E_A/kt}) + v_h \sigma_h^A (p + n_i e^{-E_A/kt})} = rU_0$$

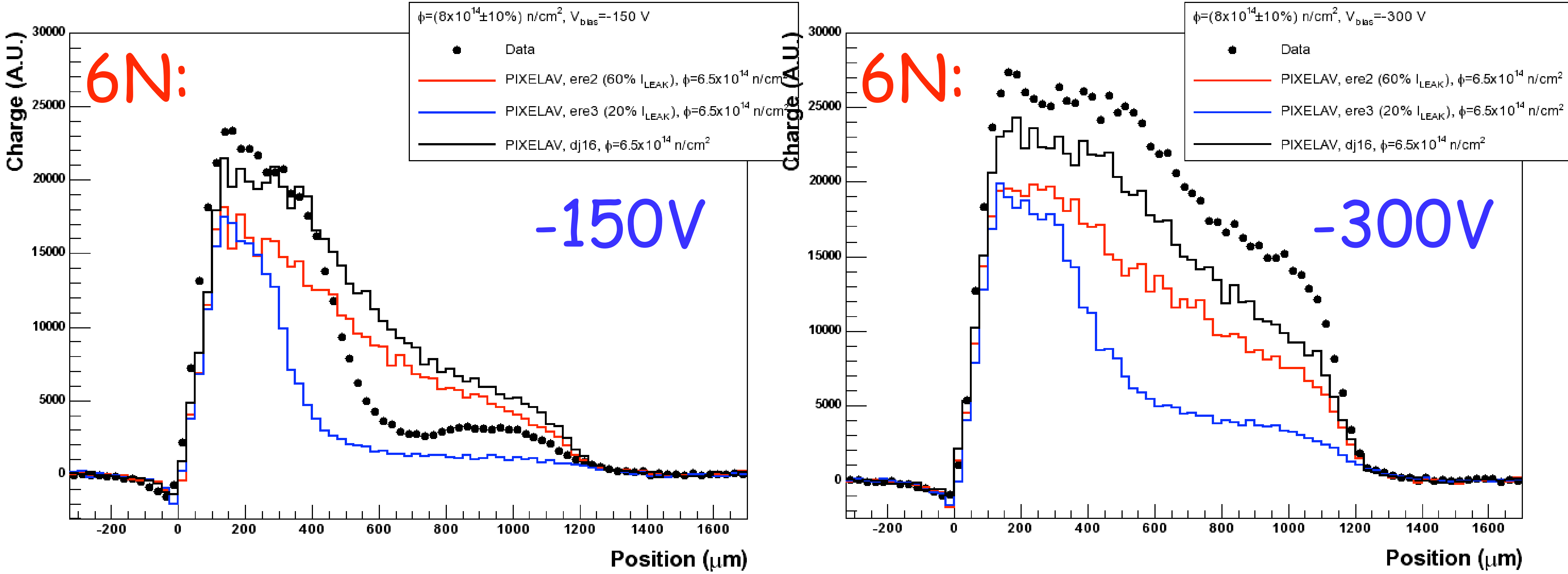
- can adjust leakage current without appealing to external sources
- EVL fix $\sigma_e = \sigma_h = 10^{-15}$ cm^{-2}, keeping $\sigma_e = \sigma_h$ is mathematically equivalent
- adjusting r does affect n and p which have 1st-order effects on f_D, f_A, ρ_{eff} (which we want)
- should reproduce EVL model

What current should we use? After bump-bonding, I increases by factor 2

$\Phi = 8\times10^{14}$ n_{eq}/cm^2:

bias	$\alpha = I(20C)/(V\Phi)$ [cm^{-1}]
-150V	15×10^{-17}
-300V	19×10^{-17}
-450V	25×10^{-17}

Expect $\alpha_0 \sim 4\times10^{-17}$ cm^{-1}, adjust r to try several values of I



- Model ere2 is normalized to produce 60% of I_{obs}
- Model ere3 is normalized to produce 20% of I_{obs} (saturates $\alpha=\alpha_0$)
- Model dj16 scales the introduction rates to 12.5% of the nominal ones and sets current to 55% of I_{obs}

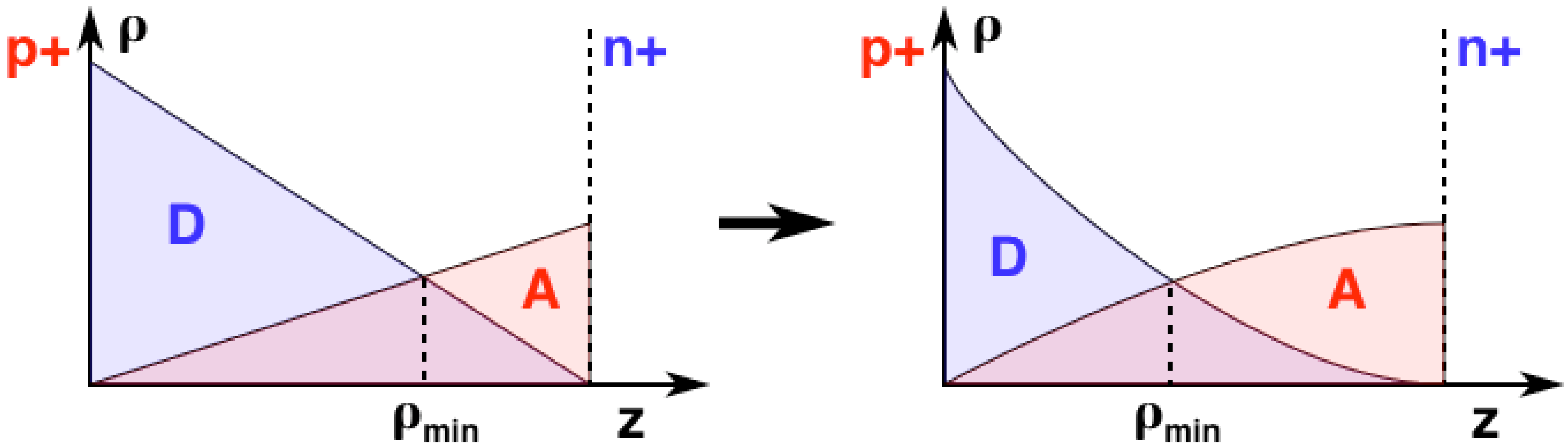
None of these can describe -150V AND -300V data!

"Fitting" the Data

The EVL model may have the correct qualitative features to describe the charge collection data. In order to adjust it quantitatively, the parameters $N_A, N_D, \sigma^A_e, \sigma^A_h, \sigma^D_e, \sigma^D_h$ were varied keeping the same E_A, E_D as EVL. Additionally, the signal trapping rates Γ_e, Γ_h are uncertain (±10% level due to Φ uncertainties and ±30% level due to possible annealing) and were also varied in the procedure:

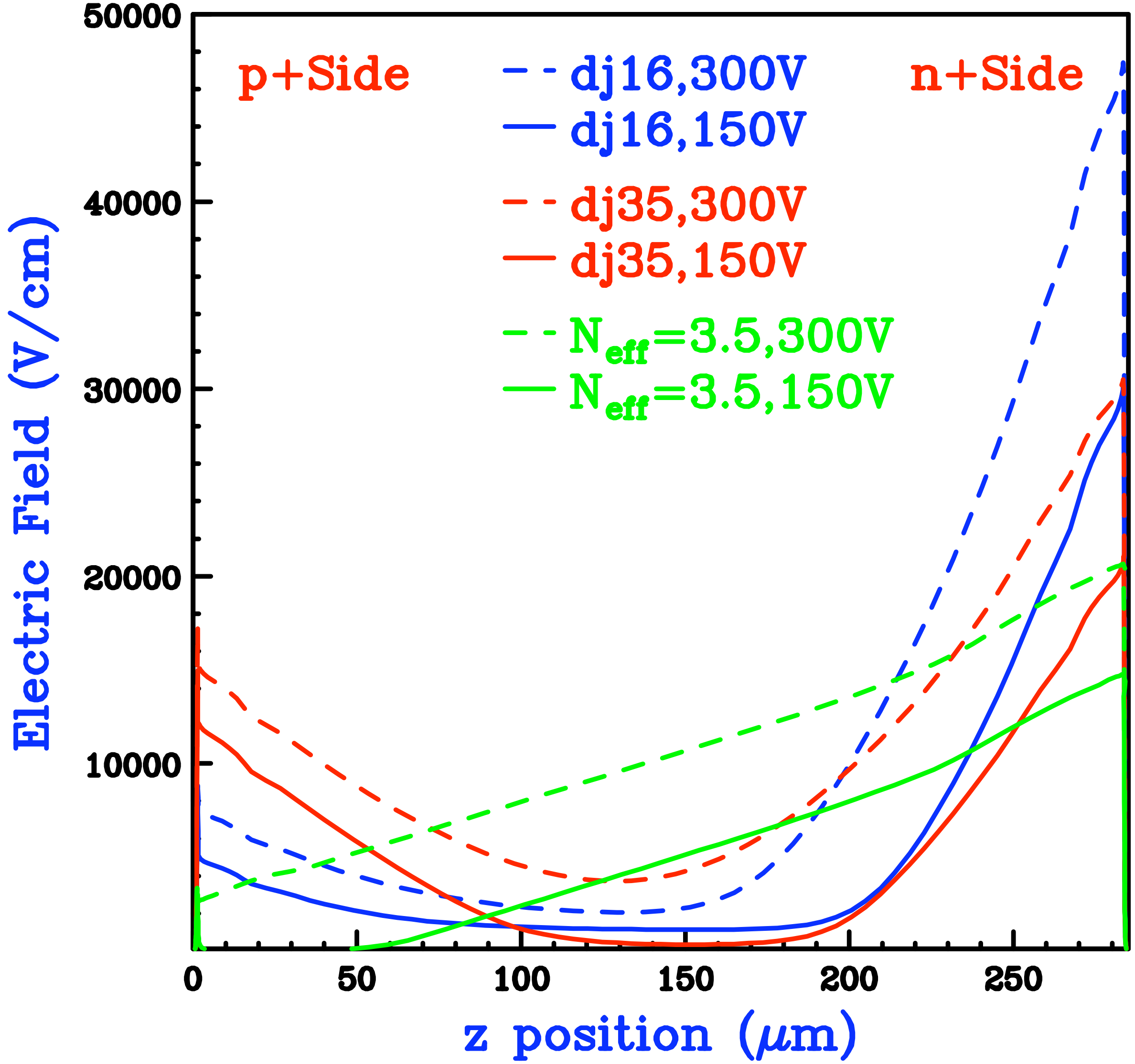
- very slow and tedious: 8hr TCAD run + 2x16hr Pixelav runs + test beam analysis
  - 5 months to produce 36 iterations: dj01 to dj36
- "eyeball" fitting only - no χ^2 or error matrix
- strong correlations between parameters

None of the EVL models has enough electric field on the p+ side of the detector to describe the data. The p+ side field can be increased by increasing N_D (h-trap density) relative to N_A(e-trap density). Unfortunately, this makes the high-field region on the n+ too narrow (at -150V):

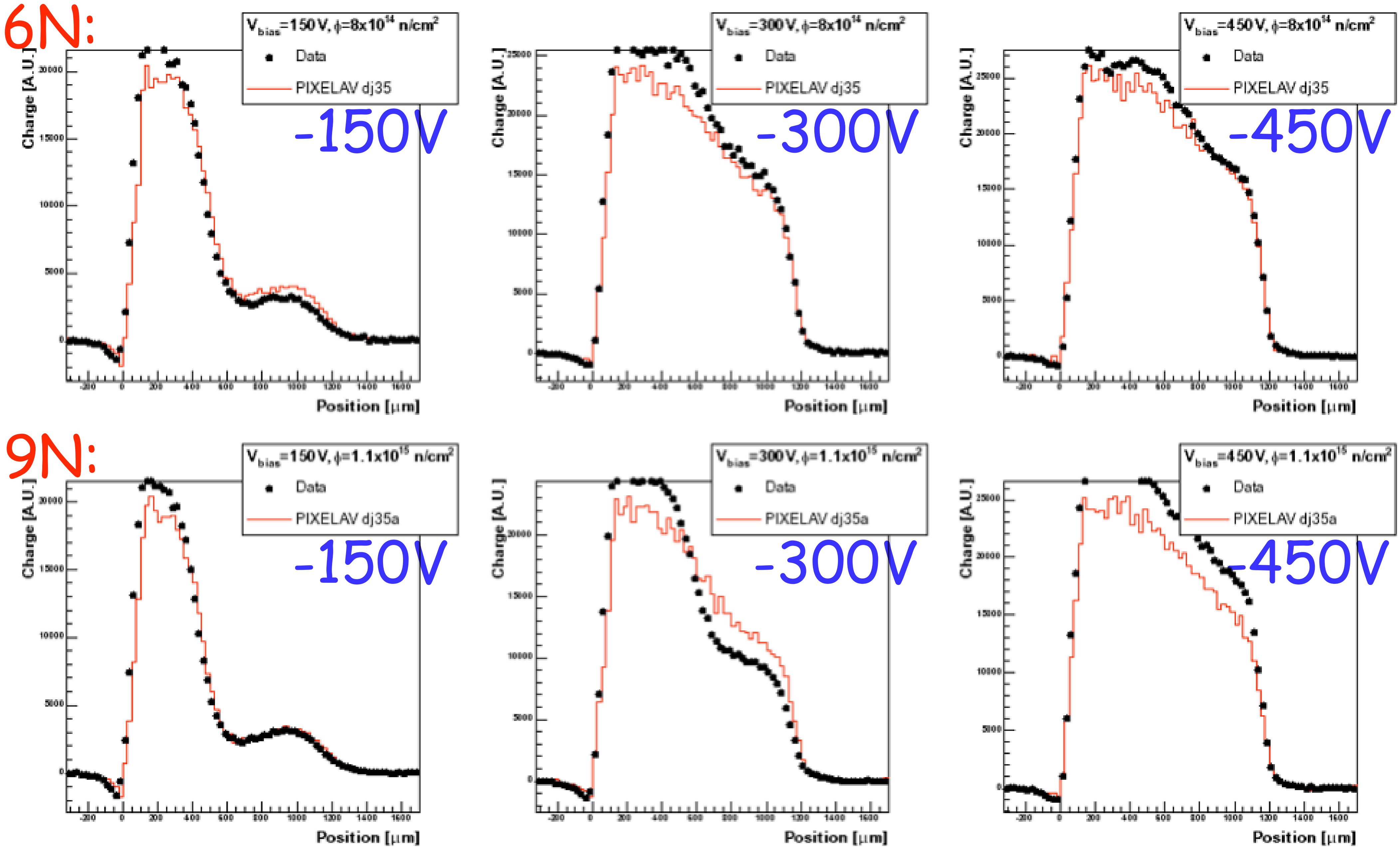


- solution is to adjust the ratios $\sigma_h^A=0.3\sigma_e^A$; $\sigma_h^D=0.3\sigma_e^D$
  - adjusting both σ_h^A and σ_h^D minimizes E at ρ_{min}
- best current fit to data has $N_A=0.4N_D$

- dj16 is a rescaled EVL model
- dj35 is the current "best fit" to the lower fluence data
  - low field "gate" is essential to explain large increase in signal with V
- N_{eff}=3.5x10^{12} cm^{-3} shown for reference



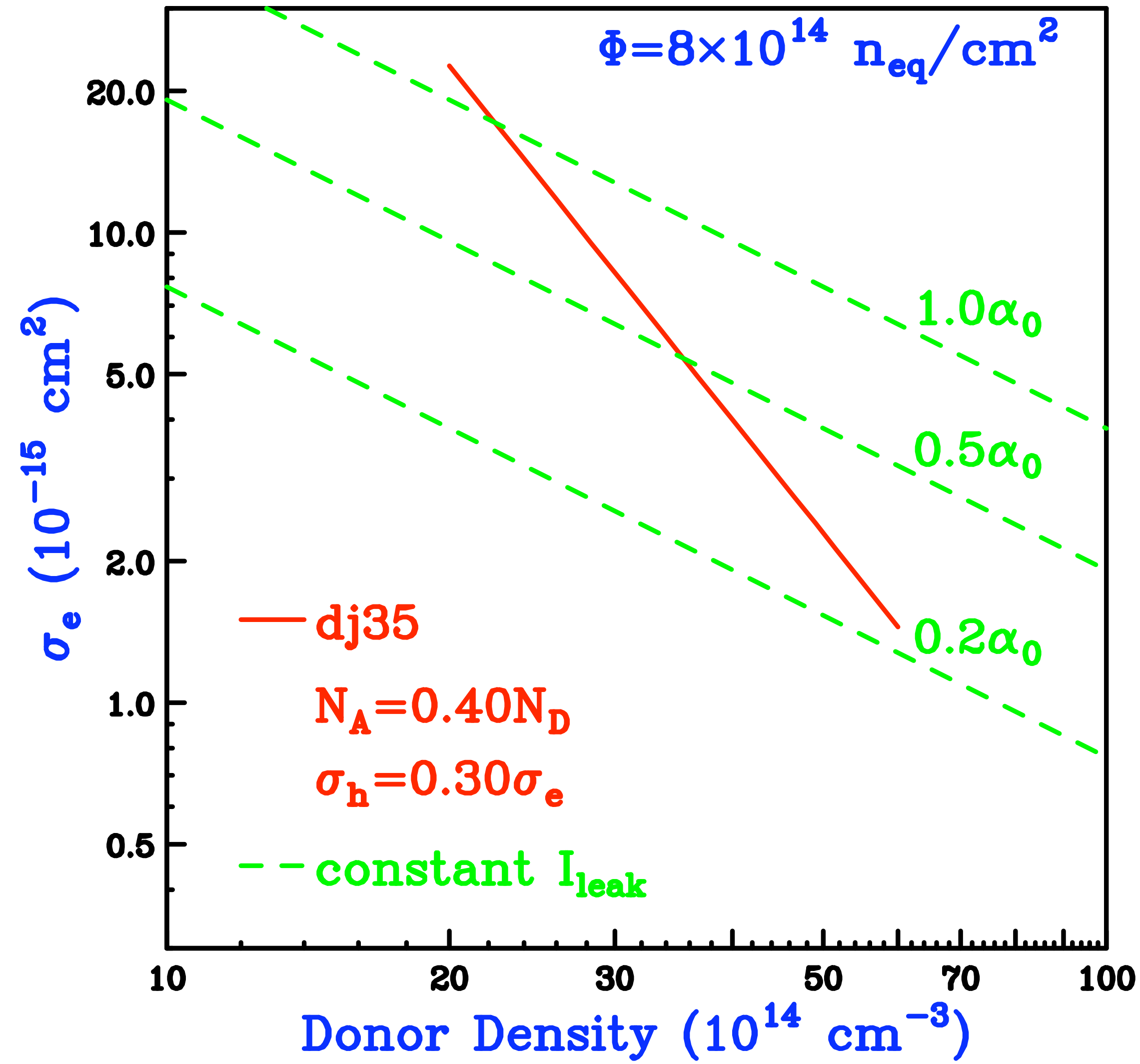
To fit the charge collection data, it was also necessary to scale Γ_e by 0.8 (data aren't very sensitive to Γ_h),



- high Φ model is a scaling of N_A, N_D, Γ_e, Γ_h by Φ_{9N}/Φ_{6N}
- Pixelav bug ⇒ mistuned ISE simulation, better soon

There is a contour in N_D vs σ_e space ($\sigma_e \sim N_D^{-2.5}$) that produces (more or less) the same efield in the detector:

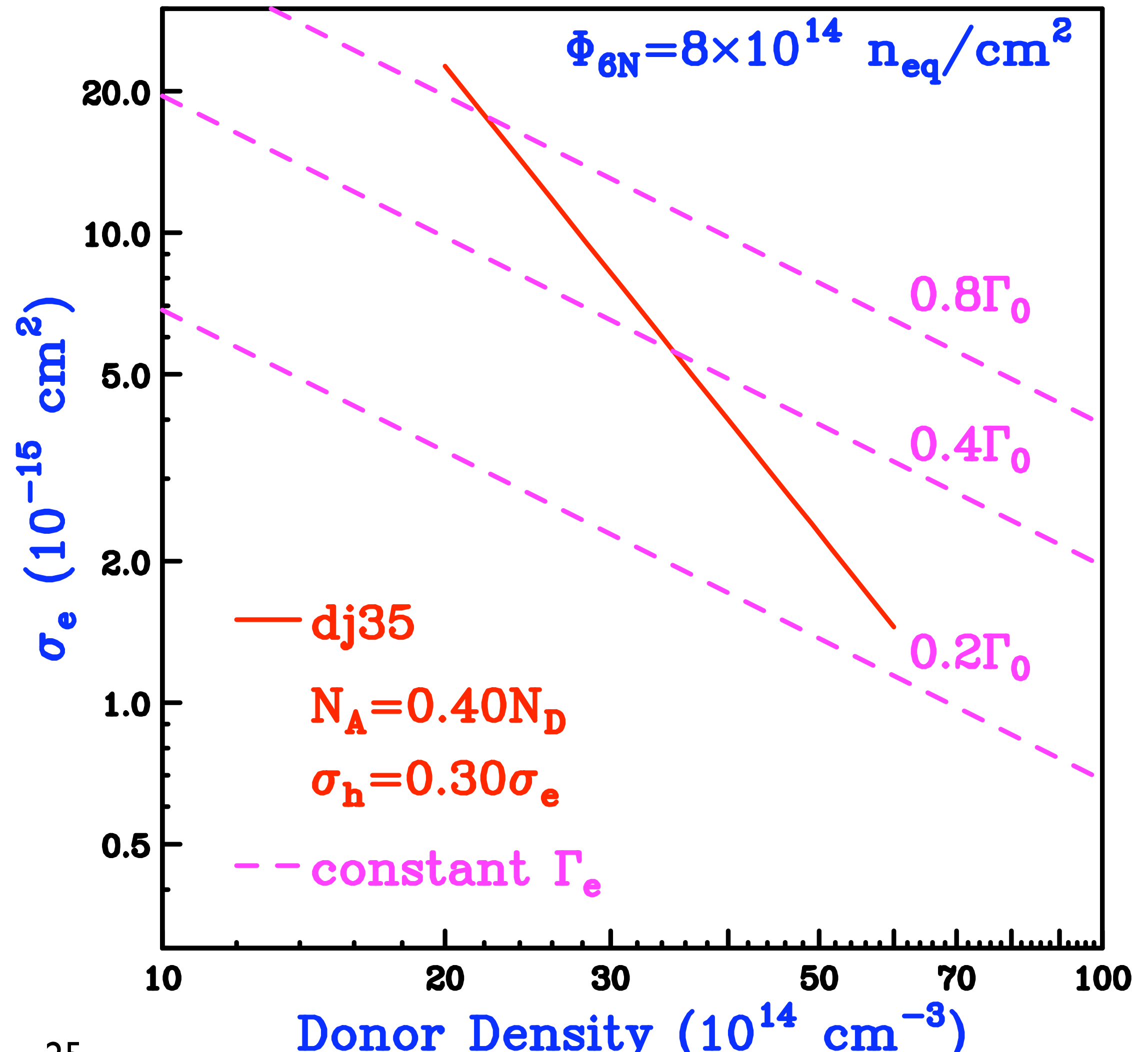
- large z, -150V tail becomes too large at small N_D ($N_D < 20\times10^{14}$)
- large z, -300V signal becomes too small at large N_D ($N_D > 50\times10^{14}$)
- $I \propto N_D \sigma_e$ so virtually any I up to α_0 fits data ($\alpha=\alpha_0$ is still too small to account for meas I)



The defects could also contribute to the effective signal trapping rates. Assuming that f_D and f_A are small,

$$\Gamma_e = v_e\left[\sigma_e^A N_A(1-f_A) + \sigma_e^D N_D f_D\right] \simeq v_e \sigma_e^A N_A$$
$$\Gamma_h = v_h\left[\sigma_h^D N_D(1-f_D) + \sigma_h^A N_A f_A\right] \simeq v_h \sigma_h^D N_D$$

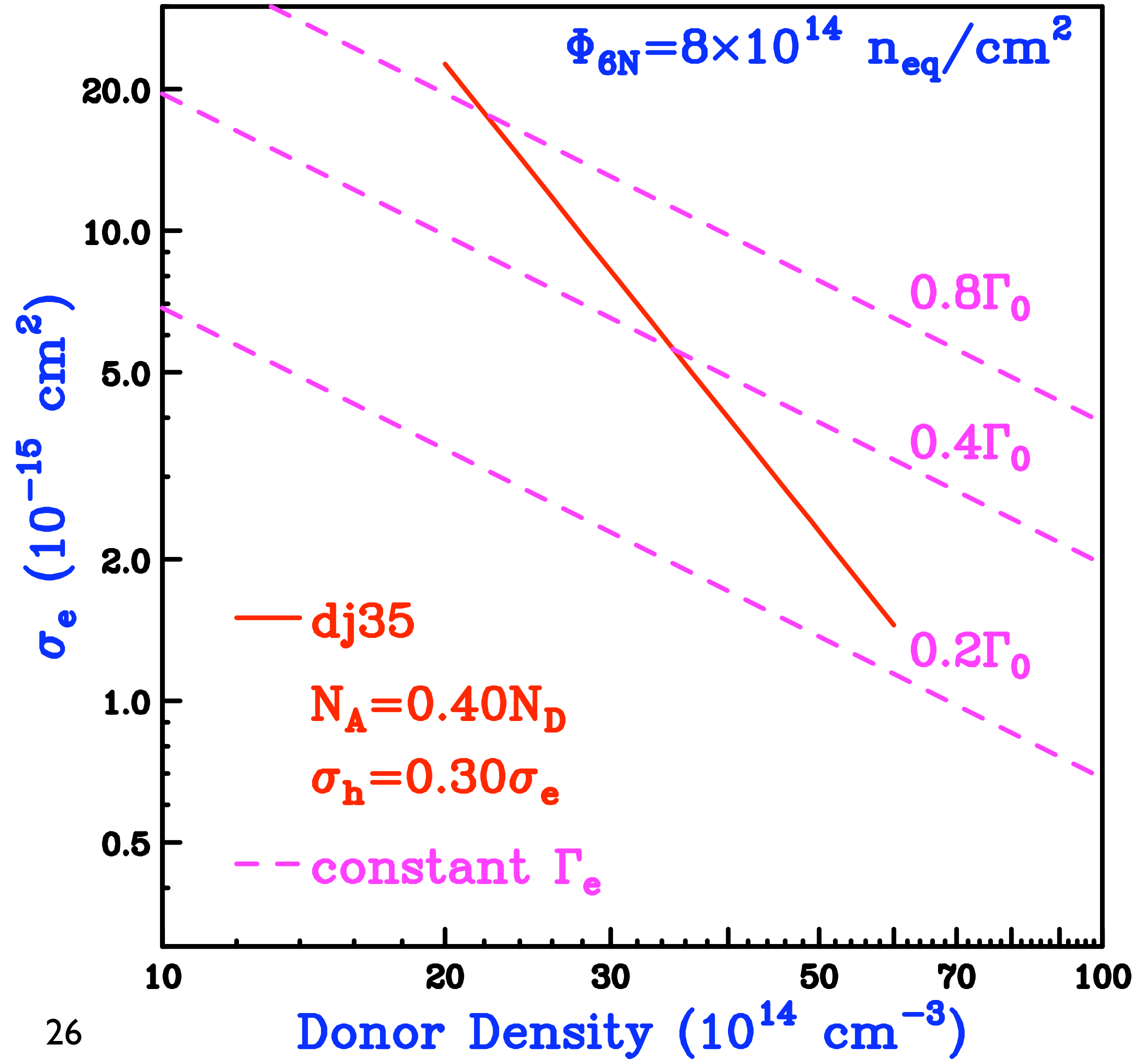
- since $v_e \sim v_h$, dj35 predicts $\Gamma_e \sim \Gamma_h$
- $\Gamma_e = v_e N_A \sigma_e \propto N_D \sigma_e$ so virtually any Γ_e up to $0.8\Gamma_0$ fits data (Γ_0 is rate expected for Φ_{6N})
- can account for all signal trapping that we see!



The same plot also suggests a solution to the apparent contradiction that ρ_{eff} is sensitive to O_2 whereas $\Gamma_{e/h}$ are not. We can add another donor/acceptor pair (suppressed by added O_2) which have large $N_{D/A}$ but small $\sigma_{e/h}$:

➡ could have large effect on ρ_{eff} and small effect on $\Gamma_{e/h}$

- ρ_{eff} is affected equally by large-σ "fast" traps and small-σ "slow" traps
- $\Gamma_{e/h}$ are affected only by large-σ "fast" traps



Conclusions

- It is clear that a two-peak electric field is necessary to describe our charge collection data
- A two-trap double junction model can be tuned to provide reasonable agreement with the data
  - can describe any I up to theoretical value (smaller than observed value)
  - can account for trapping rate up to observed value
  - suggests mechanism for O_2 dependence of $\rho_{eff}+\Gamma_{e/h}$
  - more tuning in near future: min χ^2 hyperspace also includes some contours in N_A/N_D vs σ_h/σ_e
- Model is undoubtedly too simple - could still be thermodynamically ionized defects and more traps