Contributions of Electrons and Holes to Total Collected Charge in Heavily Irradiated Si Pad and Strip/Pixel Detectors: A Comparison Simulation Study

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Outline

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   analytical solutions for collected charge

2. Simulation Results in Analytical Forms and plots

3. Increased Hole Contribution in Collected Charge in Heavy Irradiation Environments

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5. Summary

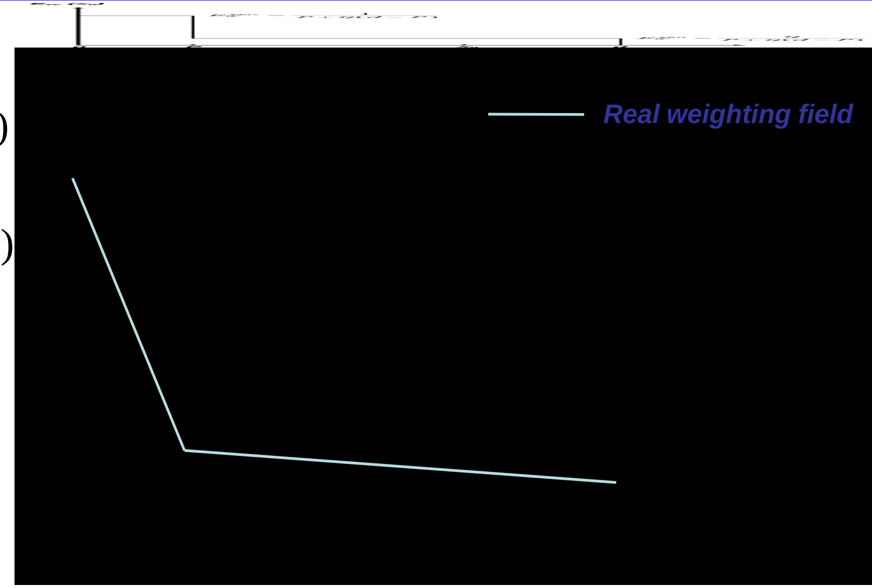
Simplified Model of Electric and Weighting Fields

analytical solutions for collected charge

Weighting field:

$$E_W(x_0) = \begin{cases} \dfrac{1}{P+\eta(d-P)} & (0 < x_0 < P) \\ \dfrac{\eta}{P+\eta(d-P)} & (P < x_0 < d) \end{cases}$$

$$0 \le \eta \le 1$$



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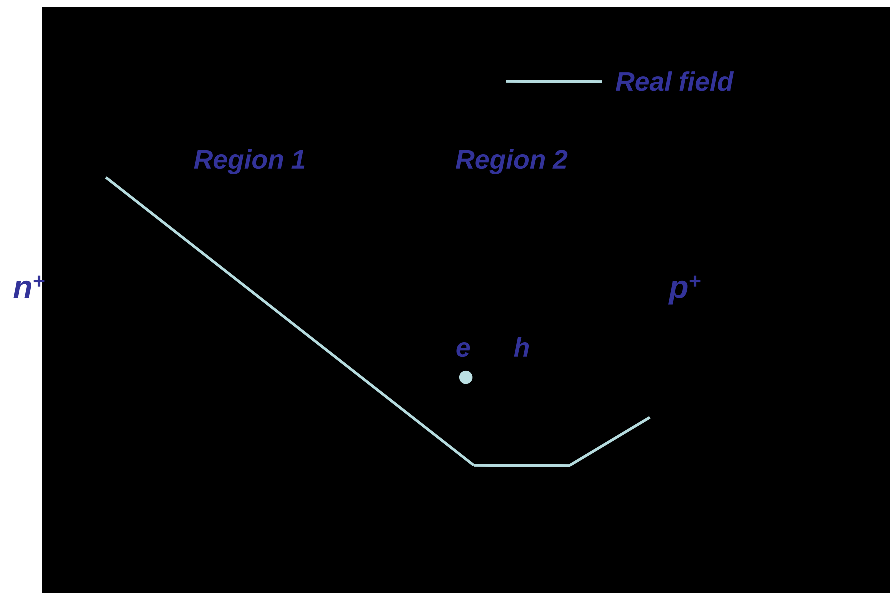
P is the segmentation pitch

d the detector thickness, or depletion depth

Electric Field:

$$E(x_0) = \begin{cases} \mathrm{E}_0 & (0 < x_0 < L) \\ \xi\,\mathrm{E}_0 & (L < x_0 < d) \end{cases} \qquad (\xi > 0)$$

$$E_0 = \frac{V}{L+\xi(d-L)}$$



Simplified Model of Electric and Weighting Fields

Two typical cases:

Strip/pixel front, Junction front (SFJF)

Strip/pixel front, Junction back (SFJB)

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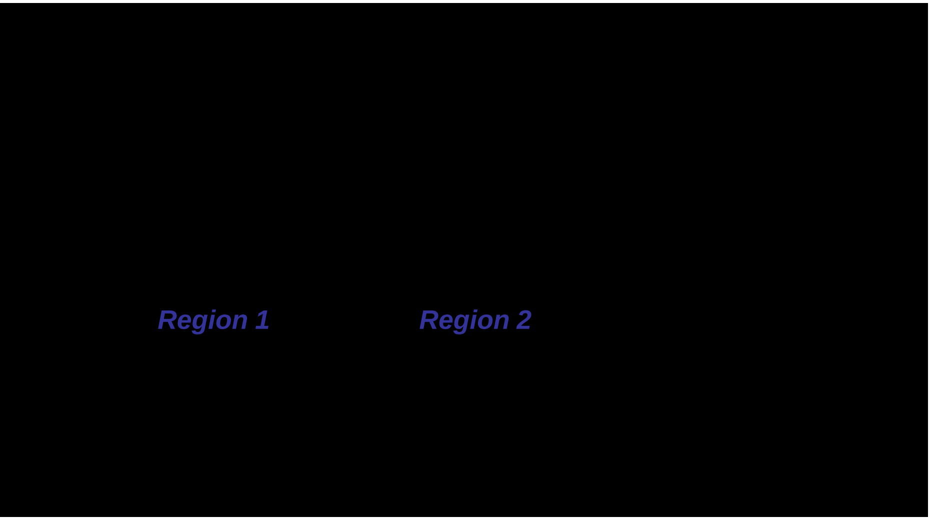

Simplified Model of Electric and Weighting Fields

Basic equations

Carrier drift velocity:

$$v_{dr}(x(t)) = \frac{dx(t)}{dt} = \frac{\mu E(x(t)}{1+\mu E(x(t)/v_s}$$

Depletion Depth:

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$$w = \sqrt{\frac{2\varepsilon\varepsilon_0 V}{eN_{eff}}}, \qquad N_{eff} = 0.02 \cdot \Phi_{n_{eq}}$$

Trapping time constant:

$$\frac{1}{\tau_t} = \eta \cdot \Phi_{n_{eq}} = 5\times 10^{-7}\, cm^2/s \cdot \Phi_{n_{eq}}$$

Induced current by a Charge layer $\frac{Q_0}{d}\Delta x_0$ at x_0:

$$di^{e,h}(t) = \frac{Q_0}{d}\Delta x_0 \cdot E_W \cdot v_{dr}^{e,h} \cdot e^{-\frac{t}{\tau_t}} = 80\,\text{e's}/\mu\text{m} \cdot \Delta x_0 \cdot E_W \cdot v_{dr}^{e,h} \cdot e^{-\frac{t}{\tau_t}}$$

Total collected charge:

$$Q = \int_0^d 80e's/\mu m \cdot dx_0 \cdot [\int_0^{t_{dr}^e} E_W \cdot v_{dr}^e \cdot e^{-\frac{t}{\tau_t}}\, \text{dt} + \int_0^{t_{dr}^h} E_W \cdot v_{dr}^h \cdot e^{-\frac{t}{\tau_t}}\, \text{dt}]$$

Simulation Results

Solutions

We can obtain analytical solutions for collected charges:

Electrons:

$$Q^e = 80e's/\mu m \cdot v^e_{dr,1}\tau_t \frac{P - v^e_{dr,1}\tau_t(1-e^{-\frac{P}{v^e_{dr,1}\tau_t}})}{P+\eta(d-P)} +$$

$$80e's/\mu m \cdot v^e_{dr,1}\tau_t \frac{\eta[(L-P) - v^e_{dr,1}\tau_t(1-e^{-\frac{L-P}{v^e_{dr,1}\tau_t}})] + v^e_{dr,1}\tau_t[(1-e^{-\frac{L-P}{v^e_{dr,1}\tau_t}}) - (e^{-\frac{P}{v^e_{dr,1}\tau_t}} - e^{-\frac{L}{v^e_{dr,1}\tau_t}})]}{P+\eta(d-P)} +$$

$$80e's/\mu m \cdot \frac{\eta v^e_{dr,2}\tau_t[(d-L) - v^e_{dr,2}\tau_t(1-e^{-\frac{d-L}{v^e_{dr,1}\tau_t}})] + \eta v^e_{dr,1}\tau_t[v^e_{dr,2}\tau_t(1-e^{-\frac{d-L}{v^e_{dr,2}\tau_t}})(1-e^{-\frac{L-P}{v^e_{dr,2}\tau_t}})] + v^e_{dr,1}\tau_t[v^e_{dr,2}\tau_t(1-e^{-\frac{d-L}{v^e_{dr,2}\tau_t}})(e^{-\frac{L-P}{v^e_{dr,1}\tau_t}} - e^{-\frac{L}{v^e_{dr,1}\tau_t}})]}{P+\eta(d-P)}$$

$$(L > P)$$

Holes:

$$Q^h = 80e's/\mu m \cdot \frac{\eta v^h_{dr,2}\tau_t}{P+\eta(d-P)} \cdot [(d-L) - v^h_{dr,2}\tau_t(1-e^{-\frac{d-L}{v^h_{dr,2}\tau_t}})] +$$

$$80e's/\mu m \cdot \frac{\eta}{P+\eta(d-P)}\{v^h_{dr,1}\tau_t[(L-P) - v^h_{dr,1}\tau_t(1-e^{-\frac{L-P}{v^h_{dr,1}\tau_t}})] + v^h_{dr,2}\tau_t[v^h_{dr,1}\tau_t(1-e^{-\frac{L-P}{v^h_{dr,1}\tau_t}})(1-e^{-\frac{d-L}{v^h_{dr,2}\tau_t}})]\} +$$

$$80e's/\mu m \cdot \frac{1}{P+\eta(d-P)}\{v^h_{dr,1}\tau_t[P - v^h_{dr,1}\tau_t(1-e^{-\frac{P}{v^h_{dr,1}\tau_t}})] + \eta v^h_{dr,1}\tau_t[v^h_{dr,1}\tau_t(1-e^{-\frac{P}{v^h_{dr,1}\tau_t}})(1-e^{-\frac{L-P}{v^h_{dr,1}\tau_t}})] +$$

$$+\eta v^h_{dr,2}\tau_t[v^h_{dr,1}\tau_t(e^{-\frac{L-P}{v^h_{dr,1}\tau_t}} - e^{-\frac{L}{v^h_{dr,1}\tau_t}})(1-e^{-\frac{d-L}{v^h_{dr,2}\tau_t}})]\} \qquad (L > P)$$

Where: $v^{e,h}_{dr,1} = \mu^{e,h} \cdot E_0,\ v^{e,h}_{dr,2} = \mu^{e,h} \cdot \xi E_0$ $\qquad E_0 = \frac{V}{L+\xi(d-L)}$

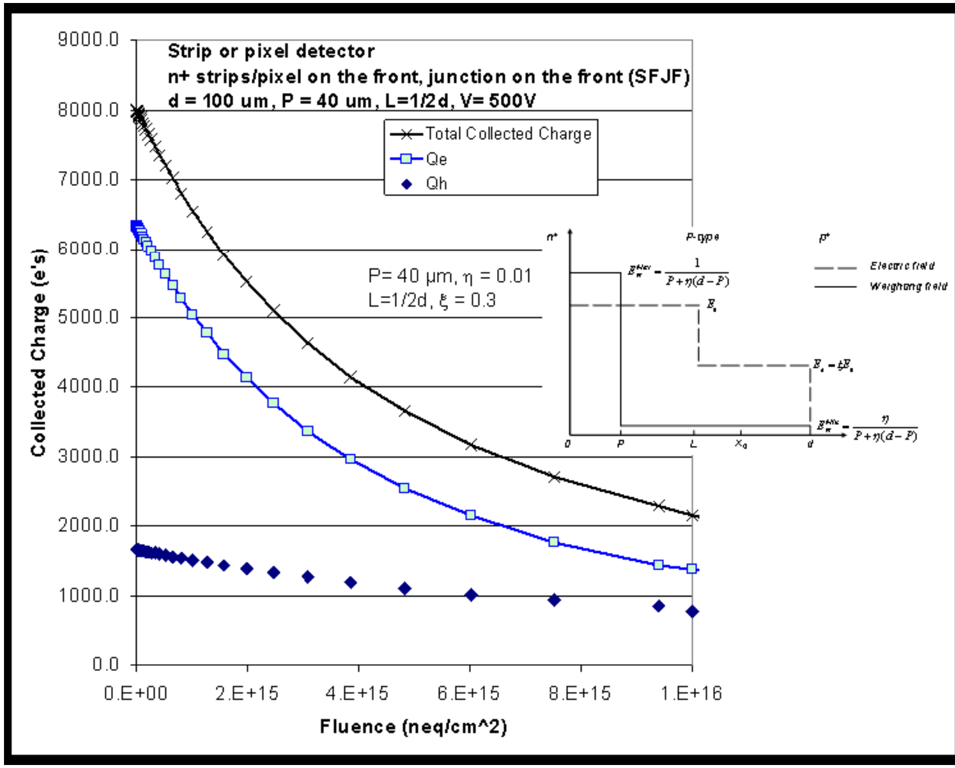
$$Q = f(P, \eta, L, \xi, V, d(or\ w)), \mu^e, \mu^h)$$

Simulation Results

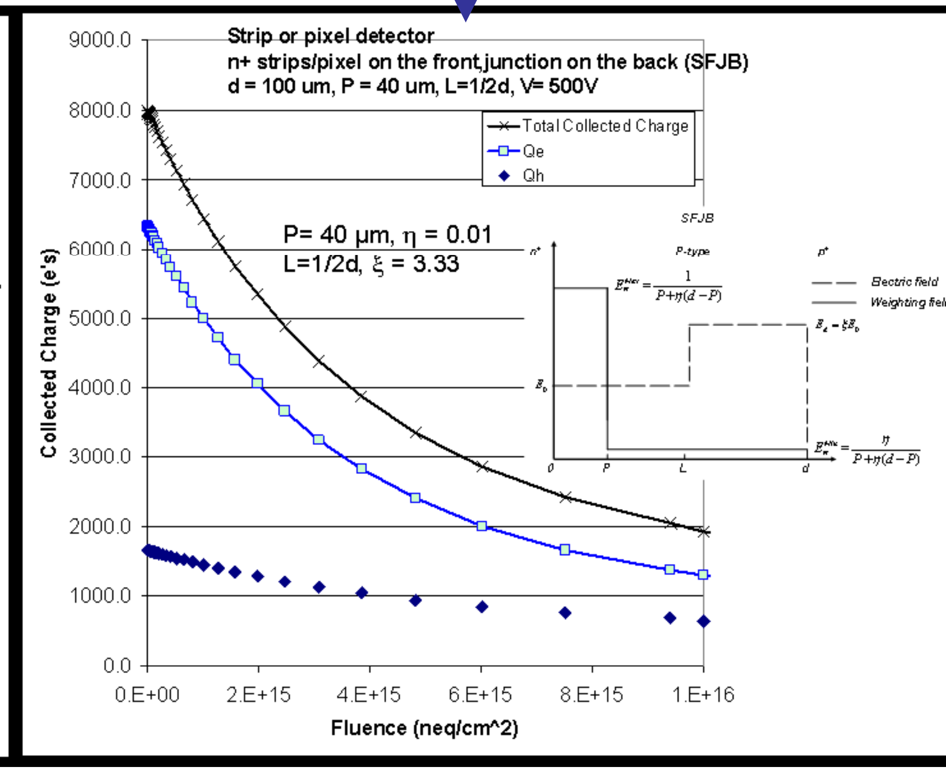
Plots

We can make some plots for some typical cases:

The total collected charge is a little bit lower, but not by much if the low E-field region at the strip side is not too low.



a) SFJF



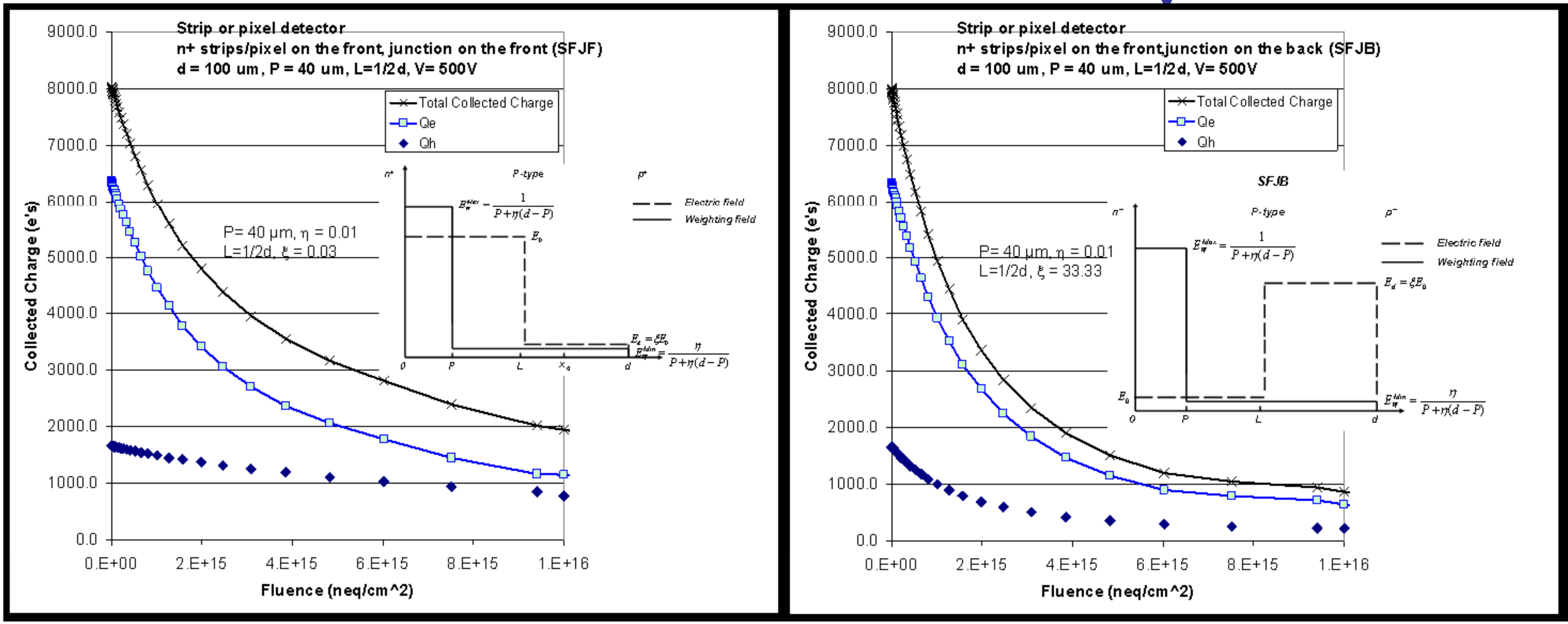
b) SFJB

Fig. 5 Collected charges for a strip or pixel detector with a) junction on the strip side (SFJF), and, b) junction on the backside (SFJB). The high-weighting field is 100 times more than the low one (η = 0.01), and high-electric field is 3 times more than the low one (ξ = 0.3 for JF, and 3.333 for JB).

Simulation Results

Plots

The total collected charge much lower if the low E-field region at the strip side is very low.



a) SFJF **b) SFJB**

Fig. 5 Collected charges for a strip or pixel detector with a) junction on the strip side (SFJF), and, b) junction on the backside (SFJB). The high-weighting field is 100 times more than the low one (η = 0.01), and high-electric field is 30 times more than the low one (ξ = 0.03 for JF, and 33.33 for JB).

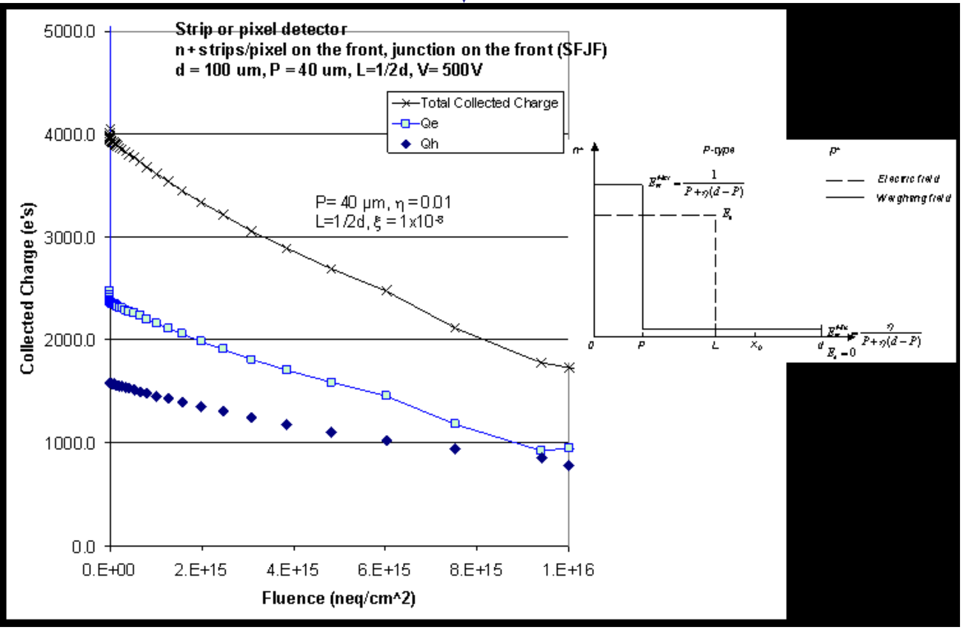
Simulation Results

Plots

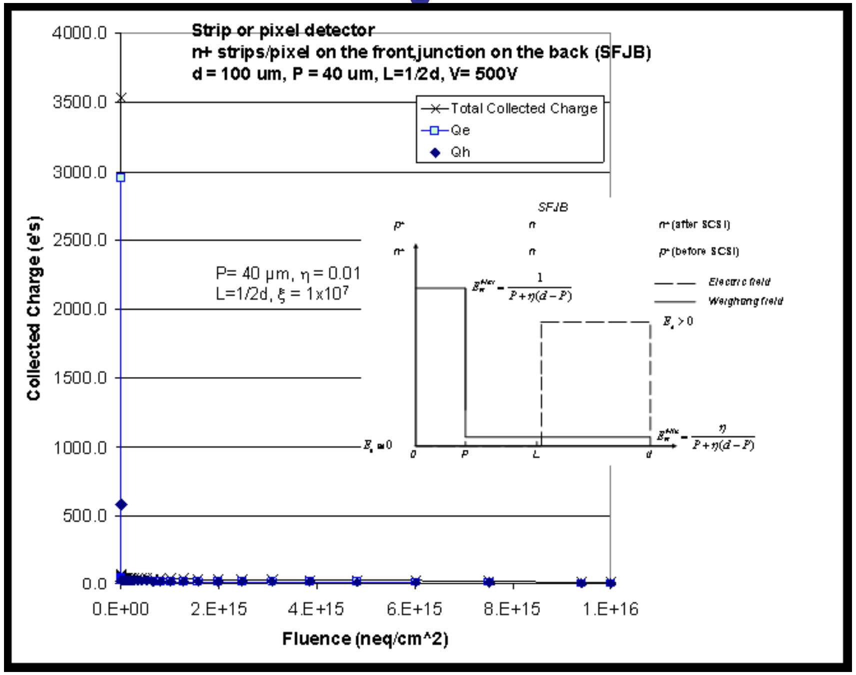
Partial depletion cases:

Half of total collected charge if only half of the detector is depleted.

Zero total collected charge if there is no E-field near the strip side.



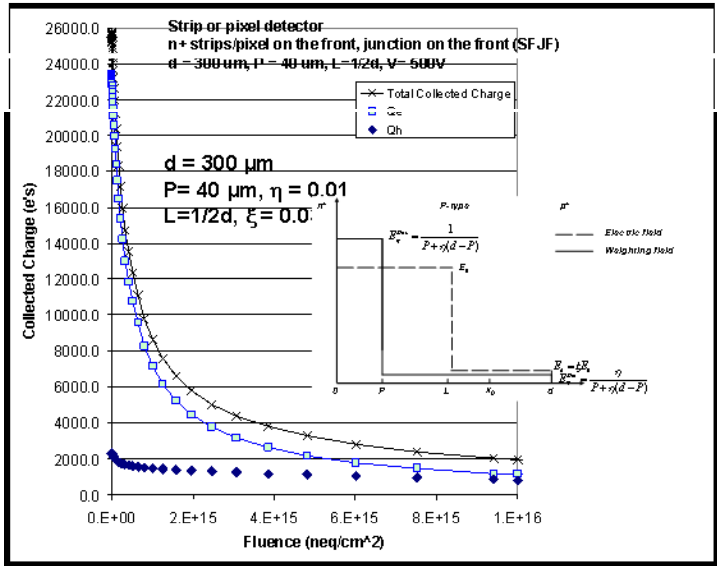
a) SFJF

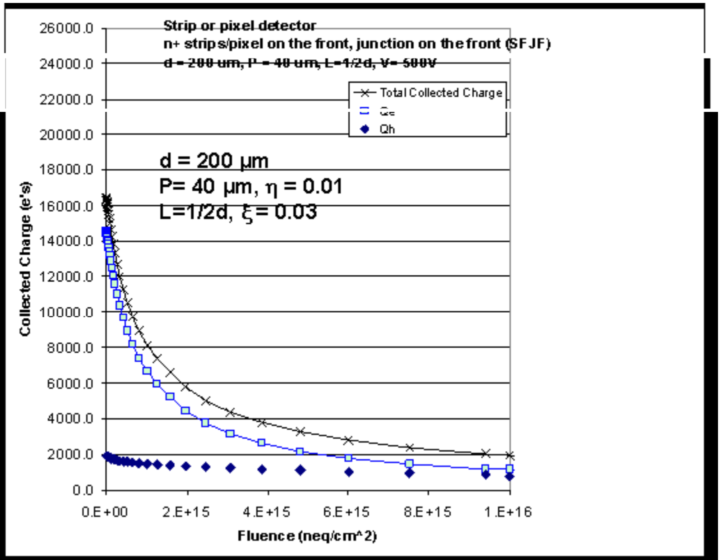


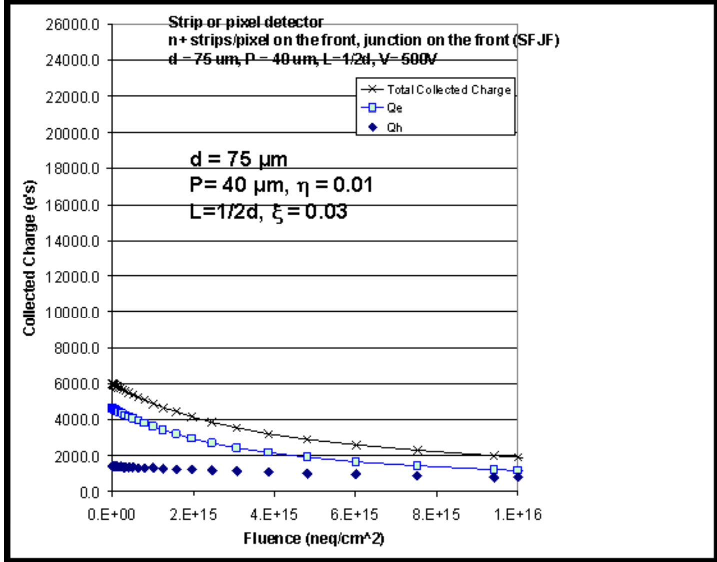
b) SFJB

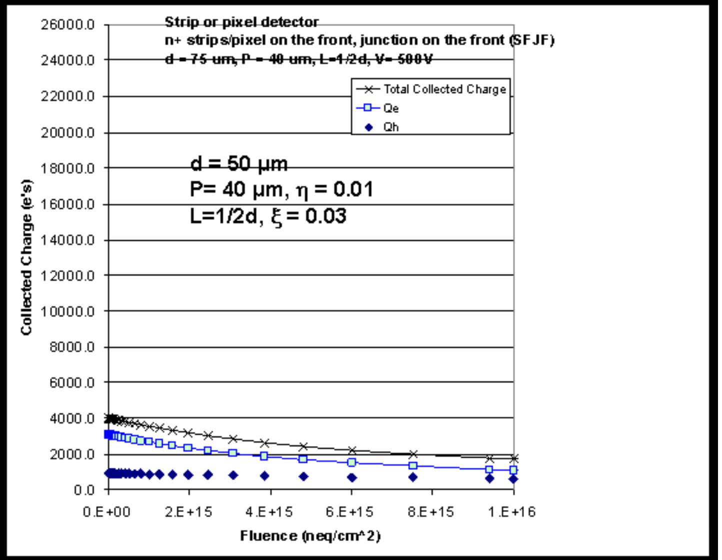
Simulation Results

Detector thickness dependence:







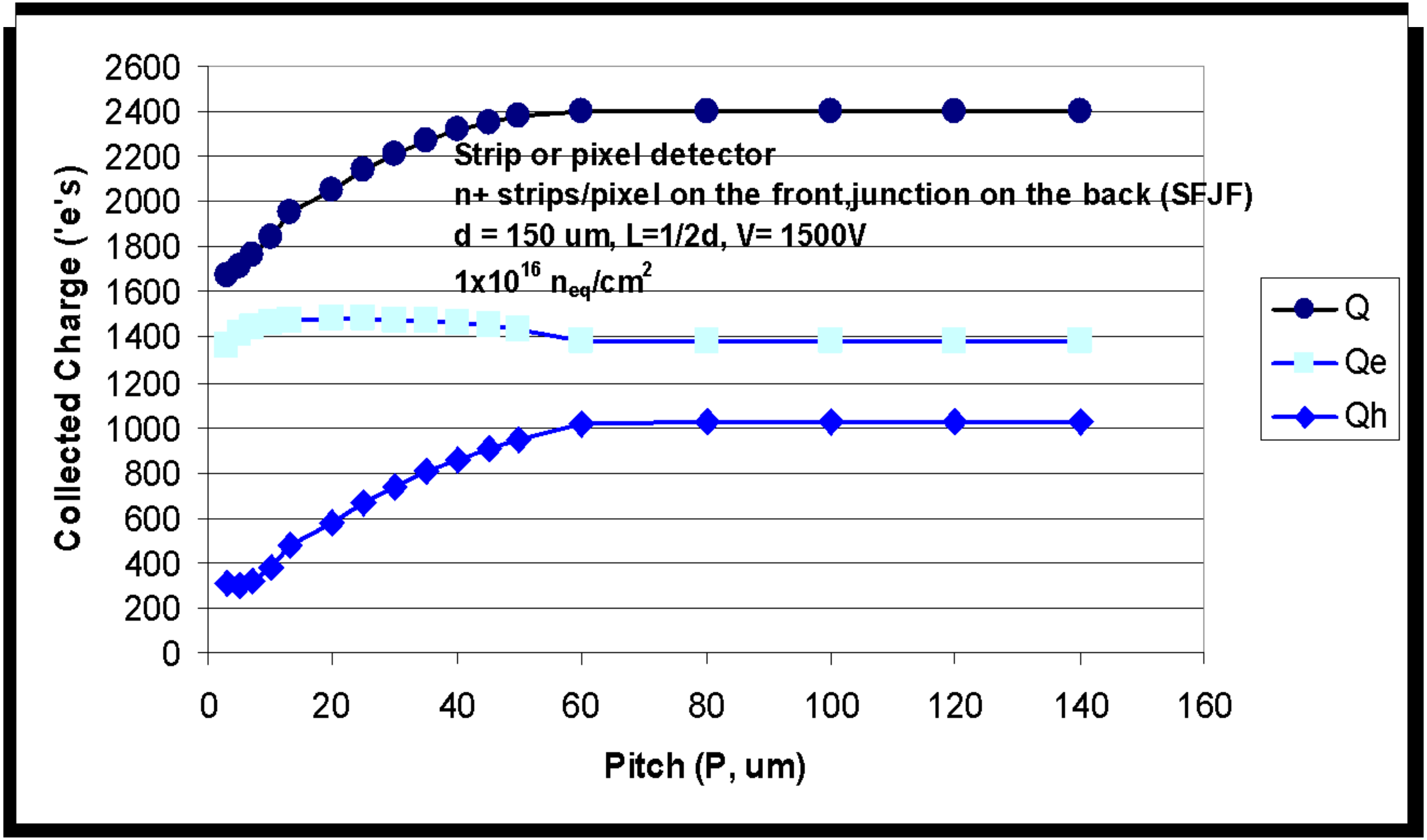


The thickness the detector, the more contribution of e's to Q at low fluences

At high fluences (>5x10^{15}n$_{eq}$/cm^2), total collected charge are almost the same and contribution by holes are approaching those of e's for all thickness >P.

Increased Hole Contribution in Collected Charge in Heavy Irradiation Environments

Detector segmentation/pitch dependence:

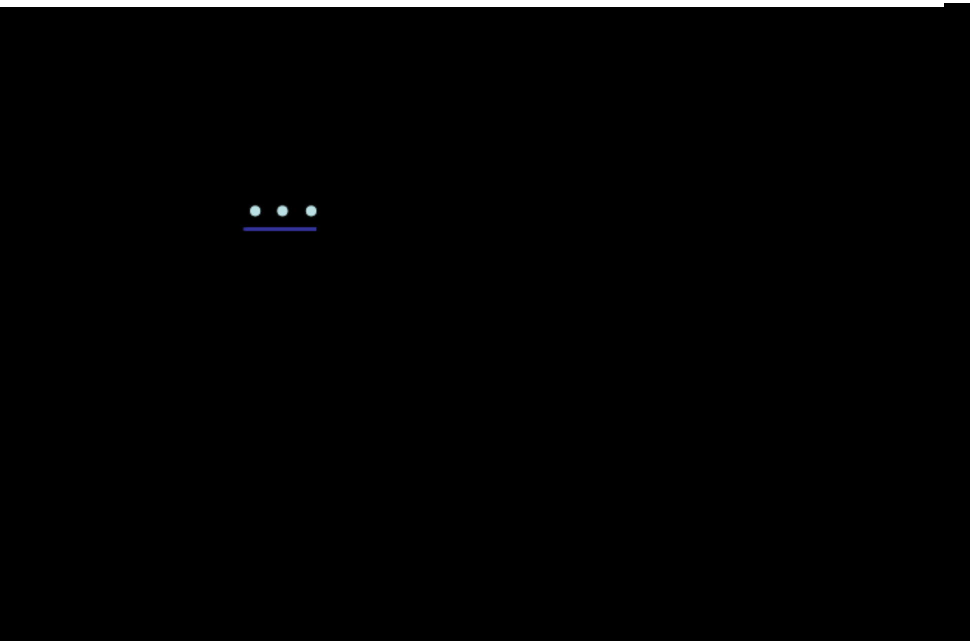


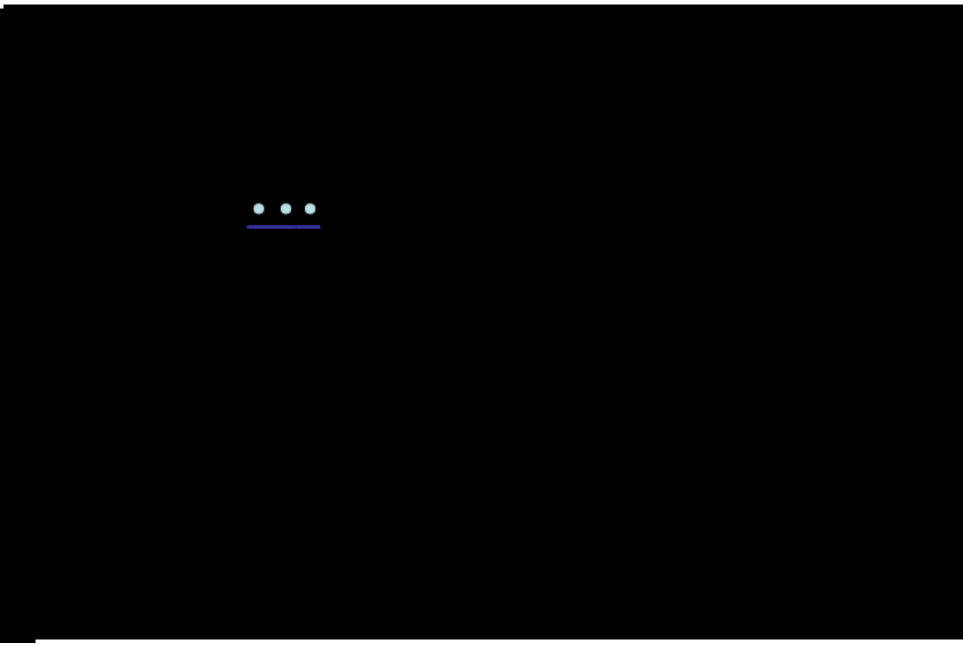
For P ≥ 60 µm, the hole contribution is about 43% due to P >> d_{CCE} or d_t

$$d_{CCE}\ (\text{or } d_t) = v_{dr} \cdot \tau_t \le v_s \cdot \tau_t$$

For P < 60 µm, the hole contribution decreases as the P approaches d_{CCE} or d_t

Detector segmentation/pitch dependence: Explanations





For P >> d_{CCE} or d_t,

(cases of high radiation, or large pitch)

hole contribution is compatible to that of electron

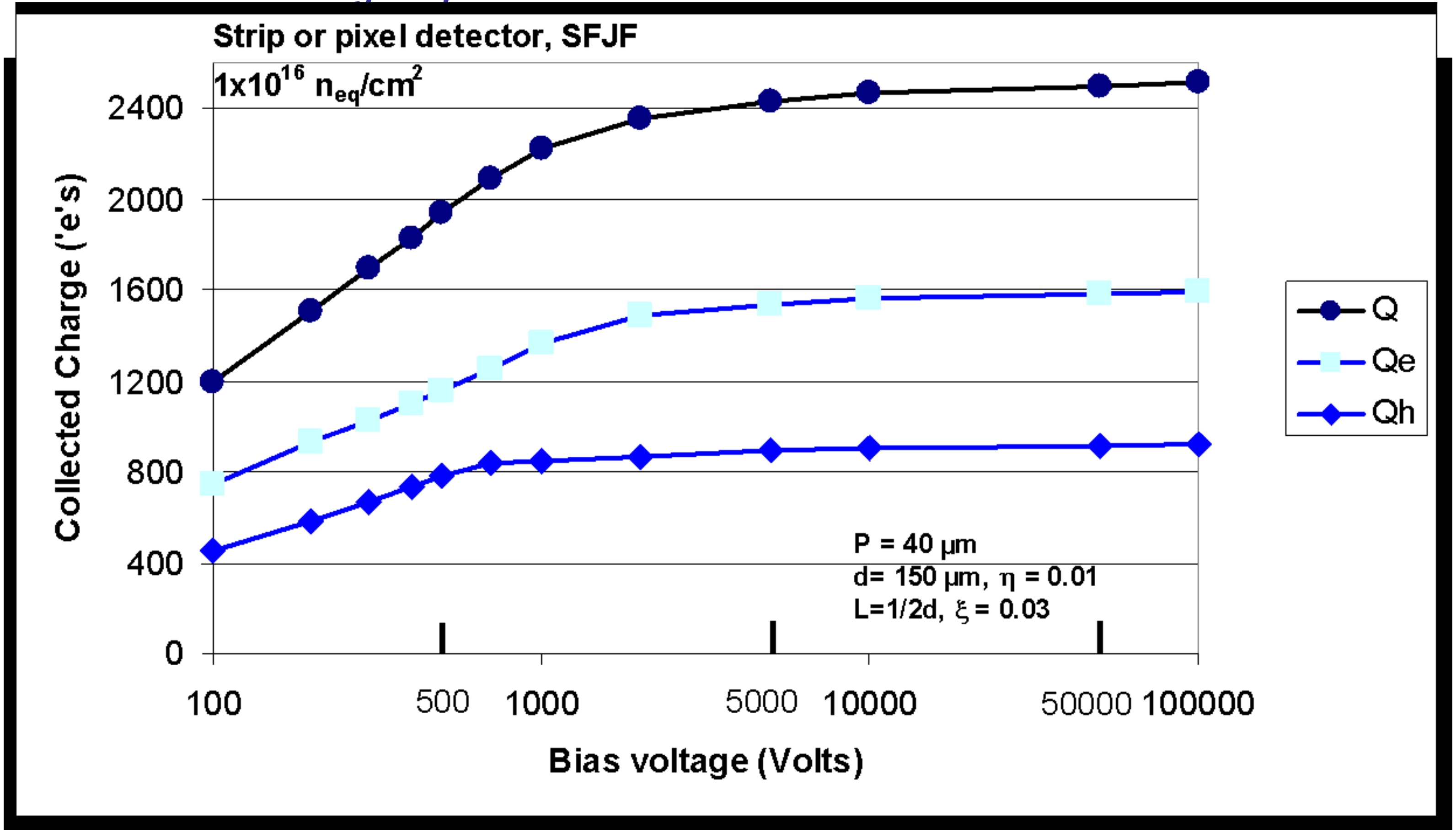
For P $\leq$ d_{CCE} or d_t,

(cases of low radiation, or very small pitch)

hole contribution is much smaller than that of electron

Increased Hole Contribution in Collected Charge in Heavy Irradiation Environments

Detector bias voltage dependence:



For V ≥ 1000 volts, Q reaches more than 90% of the maximum

For P = 40 µm, the hole contribution is about 36%

Some Approximations

Partially depleted detector: E-field in region 2 is zero (ξ=0), w = L

$$Q^e = 80e's/\mu m \cdot v^e_{dr,1}\tau_t \frac{P - v^e_{dr,1}\tau_t(1-e^{-\frac{P}{v^e_{dr,1}\tau_t}})}{P+\eta(L-P)} +$$

$$80e's/\mu m \cdot v^e_{dr,1}\tau_t \frac{\eta[(L-P) - v^e_{dr,1}\tau_t(1-e^{-\frac{L-P}{v^e_{dr,1}\tau_t}})] + v^e_{dr,1}\tau_t[(1-e^{-\frac{L-P}{v^e_{dr,1}\tau_t}}) - (e^{-\frac{P}{v^e_{dr,1}\tau_t}} - e^{-\frac{L}{v^e_{dr,1}\tau_t}})]}{P+\eta(L-P)} +$$

$$(L > P)$$

$$Q^h = 80e's/\mu m \cdot \frac{\eta}{P+\eta(L-P)} v^h_{dr,1}\tau_t[(L-P) - v^h_{dr,1}\tau_t(1-e^{-\frac{L-P}{v^h_{dr,1}\tau_t}})] +$$

$$80e's/\mu m \cdot \frac{1}{P+\eta(L-P)}\{v^h_{dr,1}\tau_t[P - v^h_{dr,1}\tau_t(1-e^{-\frac{P}{v^h_{dr,1}\tau_t}})] + \eta v^h_{dr,1}\tau_t[v^h_{dr,1}\tau_t(1-e^{-\frac{P}{v^h_{dr,1}\tau_t}})(1-e^{-\frac{L-P}{v^h_{dr,1}\tau_t}})]\}$$

$$(L > P)$$

Some Approximations

At high fluences (SLHC):

$$Q^e = 80e's/\mu m \cdot v^e_{dr,1}\tau_t = 80e's/\mu m \cdot d^e_{CCE}$$

$$Q^h = 80e's/\mu m \cdot v^h_{dr,1}\tau_t = 80e's/\mu m \cdot d^h_{CCE}$$

$$Q = 80e's/\mu m \cdot (d^e_{CCE} + d^h_{CCE})$$

At $1x10^{16}$ n_{eq}/cm^2: d_{CCE} = 20 µm:

Q ~ 3200 e’s

Some Approximations

At low fluences ($\leq 10^{15}\ n_{eq}/cm^2$)

For pad detectors:

$$Q_{pad} \cong Q_0[1 - \frac{1}{6}(\frac{L}{v^e_{dr,1}\tau_t} + \frac{L}{v^h_{dr,1}\tau_t})]$$

For fully depleted pad detectors:

$$Q_{pad} \cong Q_0[1 - \frac{1}{6}(\frac{d}{v^e_{dr,1}\tau_t} + \frac{d}{v^h_{dr,1}\tau_t})] = Q_0[1 - \frac{1}{6}(\frac{d}{d^e_{CCE}} + \frac{d}{d^h_{CCE\,t}})]$$

Summary

1. A simple model has bee developed to simulate segmentated Si detectors

2. Analytical solutions can be obtained for colleted charge $Q = f(P, \eta, L, \xi, V, d(or\ w)), \mu^e, \mu^h)$

3. Contribution of hole to the total colletected charge increases with radiation fluence in a n^+ segmentation Si detector

4. At SLHC fluences close to 1×10^{16} n_{eq}/cm^2, contribution of hole to the total colletected charge is comparable to that of electrons

5. At SLHC fluences, total collected charge can be appriximated as: $Q = 80e's/\mu m \cdot (d^e_{CCE} + d^h_{CCE})$

6. To improve radiation hardness, carrier trapping distance has to be increased --- e.g. by pre-filling of the traps, or decrease carrier drift distance (3D)

Collected charges simulated with real weighting field