Modelling and comparison with data of signal efficiency in 3D and planar devices

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Plus vital support from Prague, Bonn.
See Cinzia Da Via talk for full list of 3DC collaboration

- Some theory !
- Electric Field Calculation and Signal Calculation
- Simulation
- Data and theory comparison
- Conclusions

USE RAMO’s THEOREM

$\Delta S = q\,(V_c - V_x)$ Charge on collection electrode

Use weighting potential

$\Delta S/\Delta t = q\,(dV/\Delta x))\,(\Delta x/\Delta t) * \exp(-t/t_{eff})$

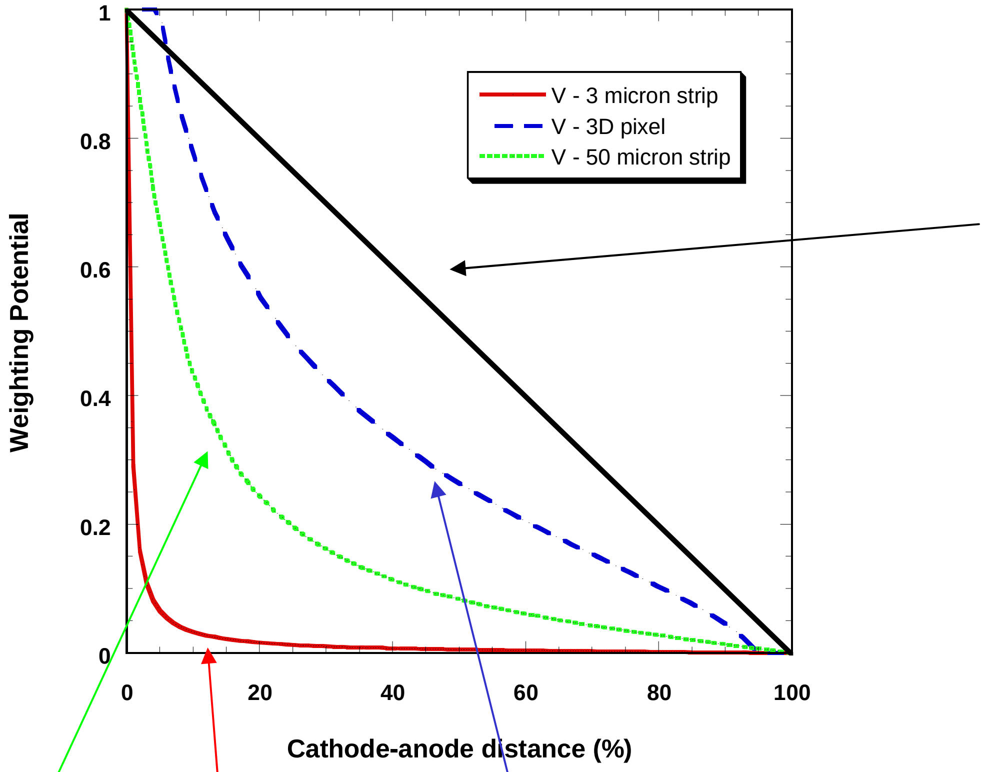
Weighting Field + Trapping

Thus, Current = $q\,E_w * V_{drift} * \exp(-t/t_{eff})$

Weighting Field – Geometry !

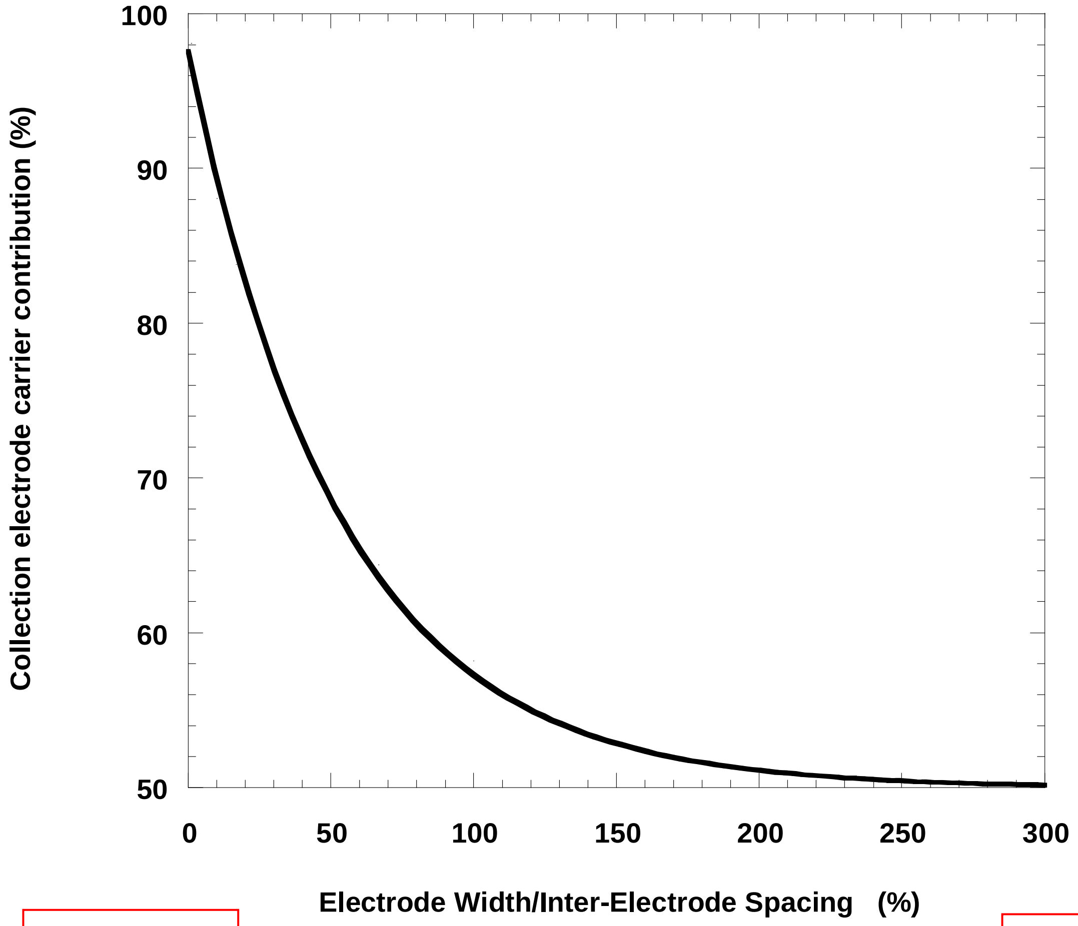
Measured by Kramberger et al.

Strip, pad, and 3D weighting potentials



Pad

- 50 micron and 3 micron strip with 300 micron inter-electrode spacing
- 3D 10 micron diameter electrode spaced 100 micron apart



For planar strip
detectors, signal
mainly due to

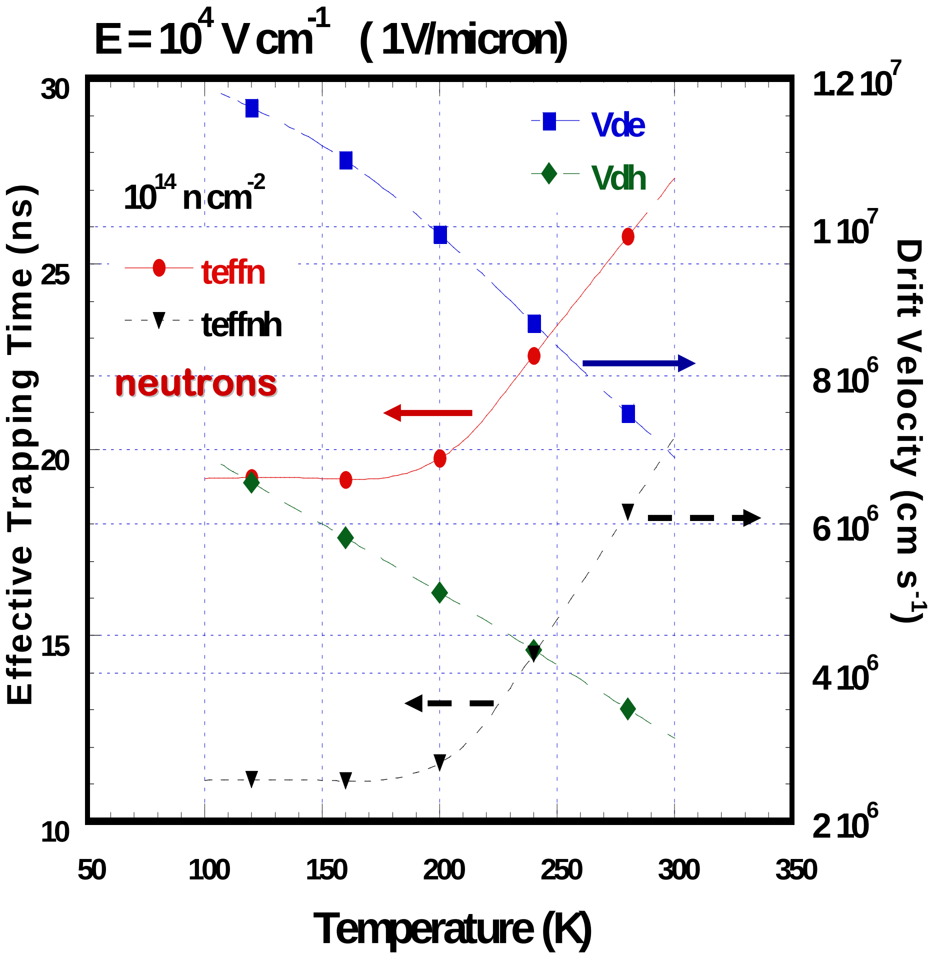
Electrons n on n
Electrons n on p
Holes p on n

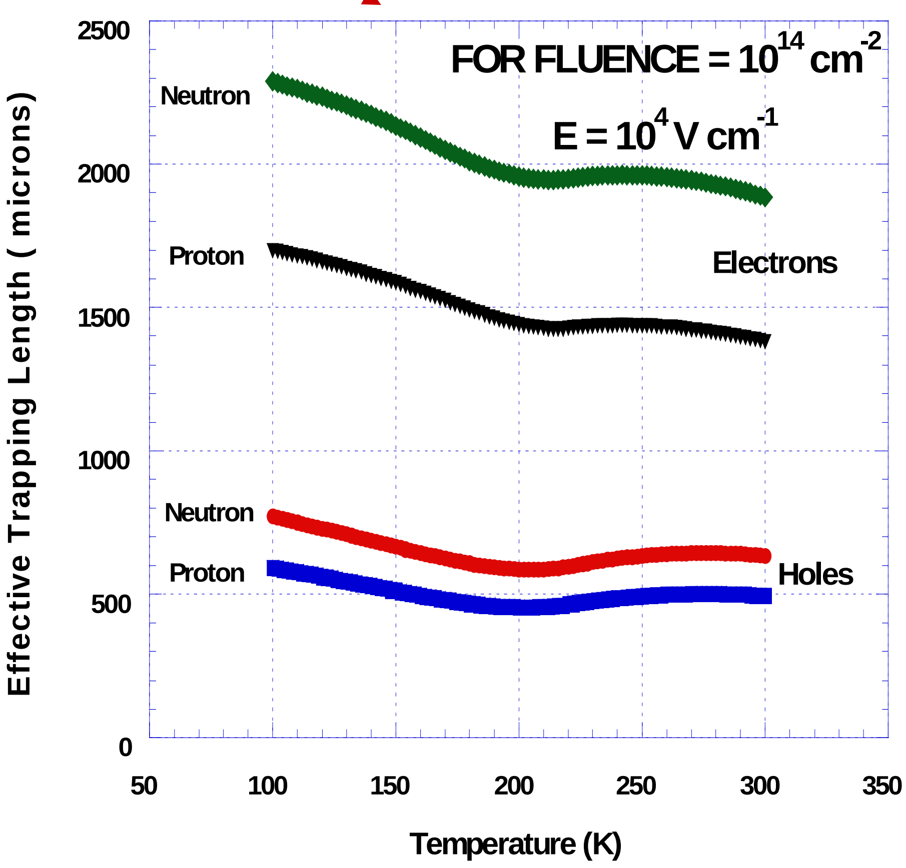
STRIP → PAD

Signal mainly created by carrier at collection electrode for small values of (electrode width/interelectrode distance).

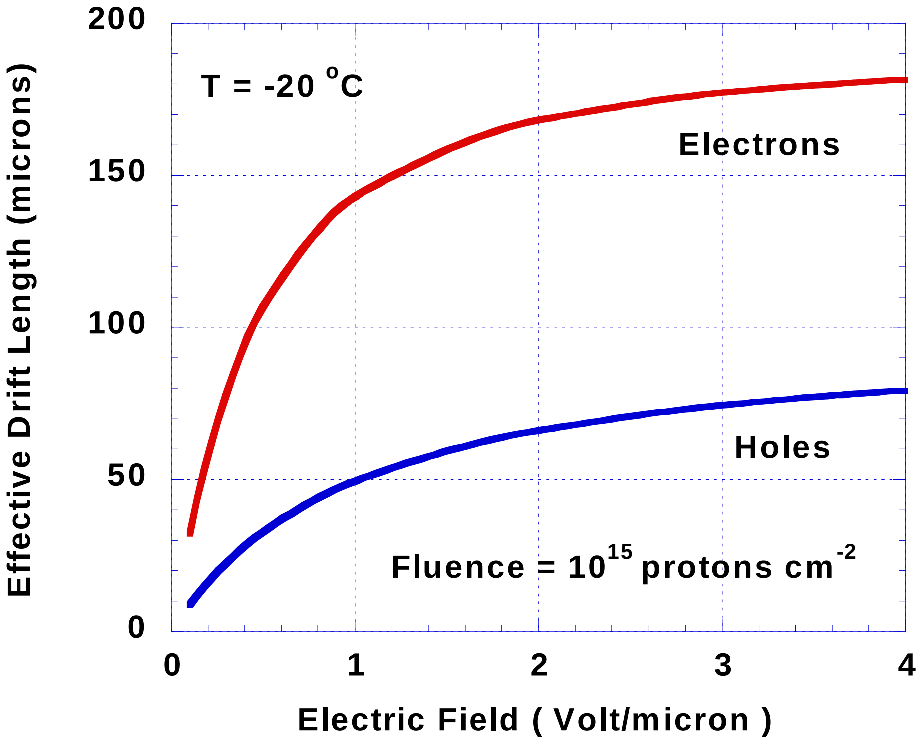
EFFECTIVE DRIFT LENGTH

$L_{eff} = \tau_{eff}$ x V_{drift}





Data for neutron and protons for effective trapping time 220K-300K from Kramberger et al



Effective drift length depends on field

Drift velocity saturates at

around 2 Volts/Micron

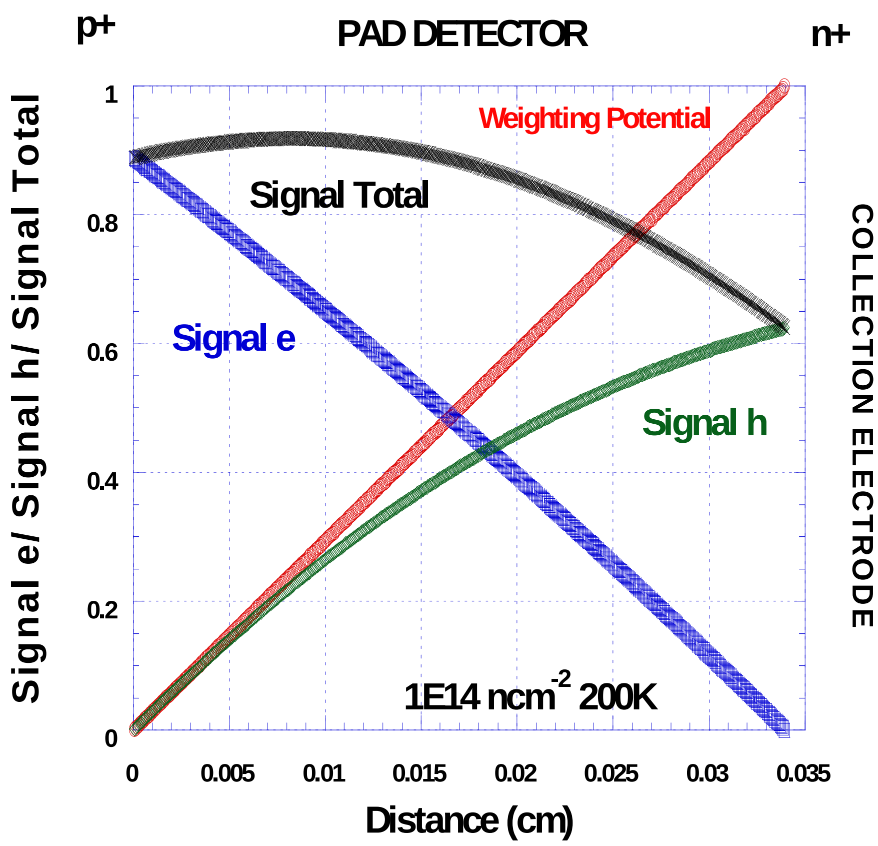
$$L_{eff} = \tau_{eff} V_D$$

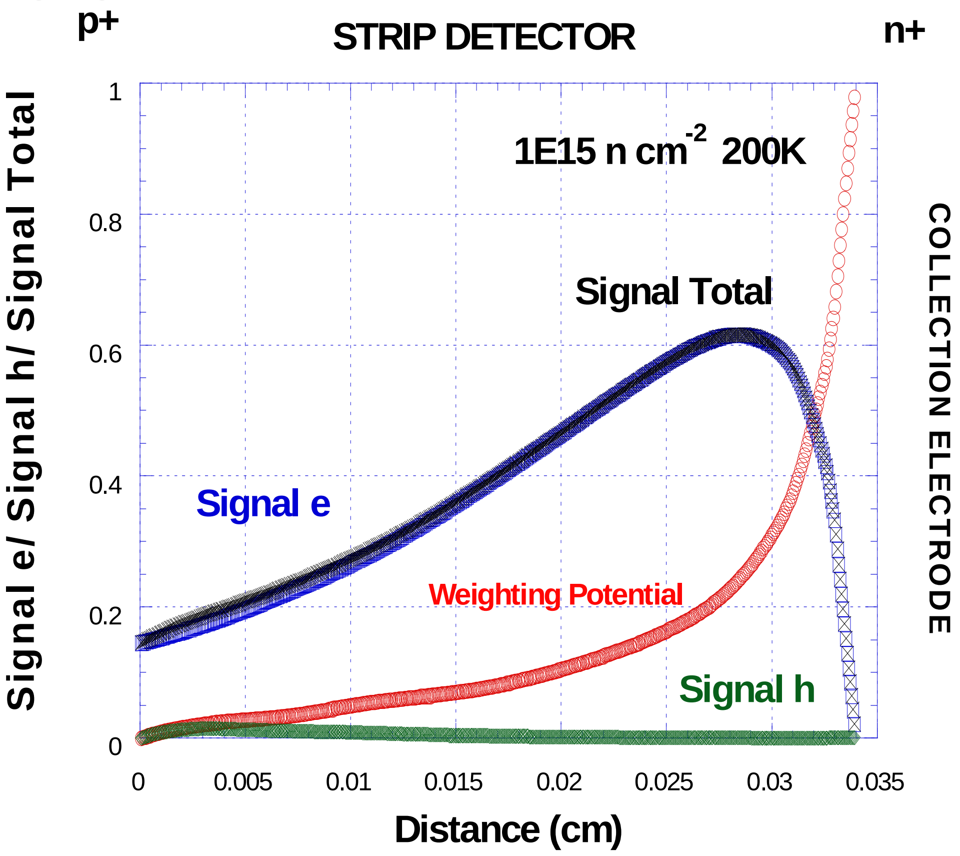
SIGNAL FORMATION - RAMO'S THEOREM

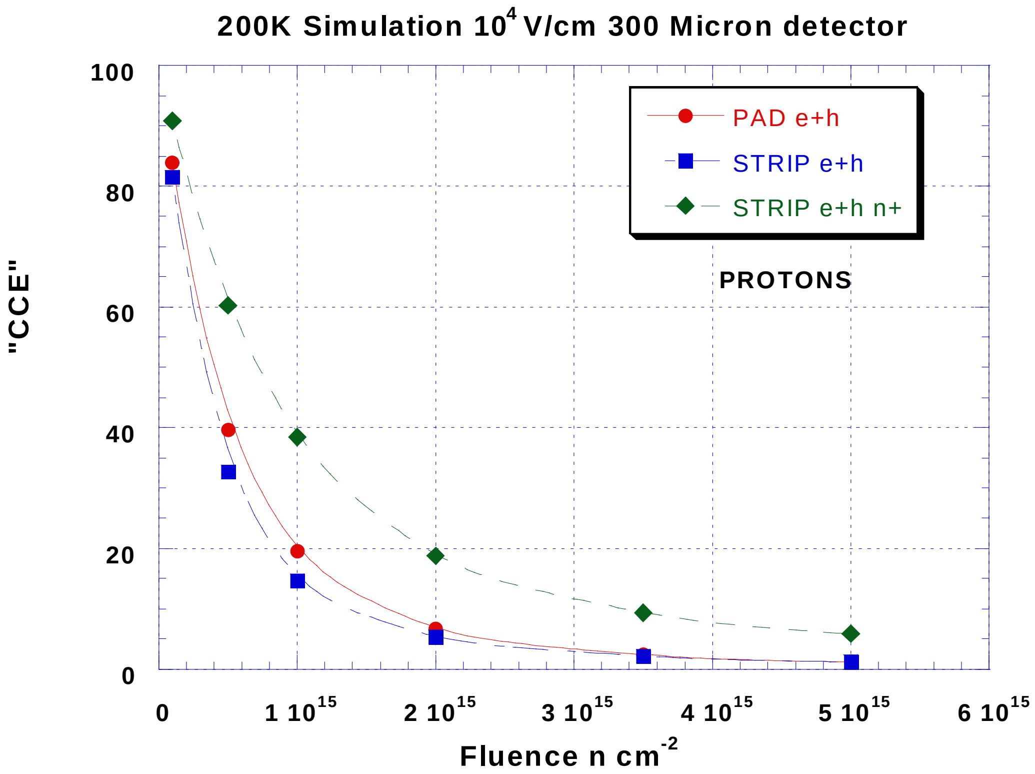
IMPORTANCE OF THE WEIGHTING POTENTIAL

PADS AND SEGMENTED DETECTORS ARE VERY DIFFERENT

← **Holes** **Electrons** →







CONCLUSION – collect electrons !!!!!

Is NOT linear in fluence - more graceful degradation
Effective trapping time is inversely proportional to fluence (1/Φ)
and even carriers that trap before getting to collection electrode produce signal

Electric Field and Weighting Field Calculation - script run by FLEXPDE

Input: Geometry, doping, voltage

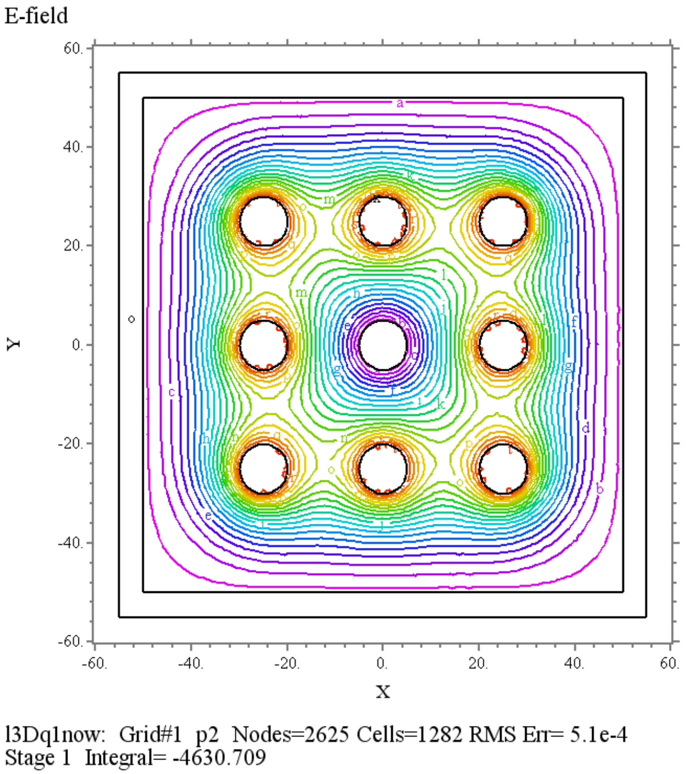
Calculate signal (current) from detector – SCALC .
Input: E, W, position in detector
Can also put in for trapping

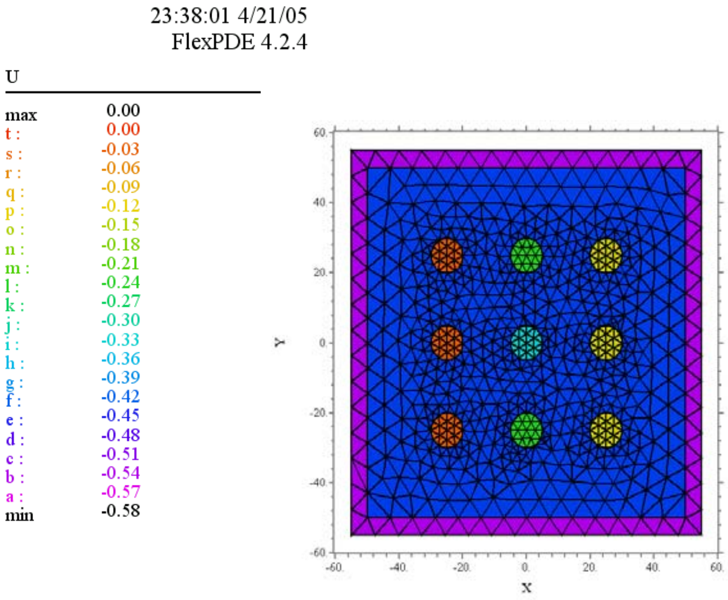
Answer – repeat for different Voltages and charge positions

Numerical Technique for 3D detectors

In some cases there is an analytical answer

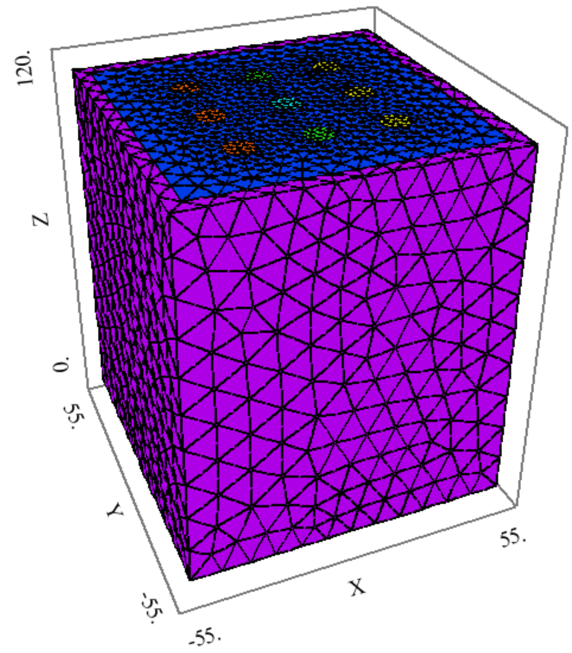
Device Modelling – e-field, weighting potential, signals and radiation damage.



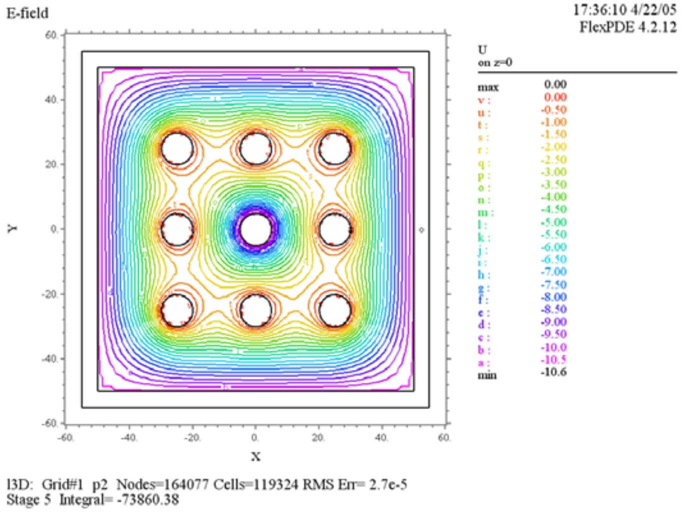


25 micron inter-electrode distance
p surrounded by n electrodes

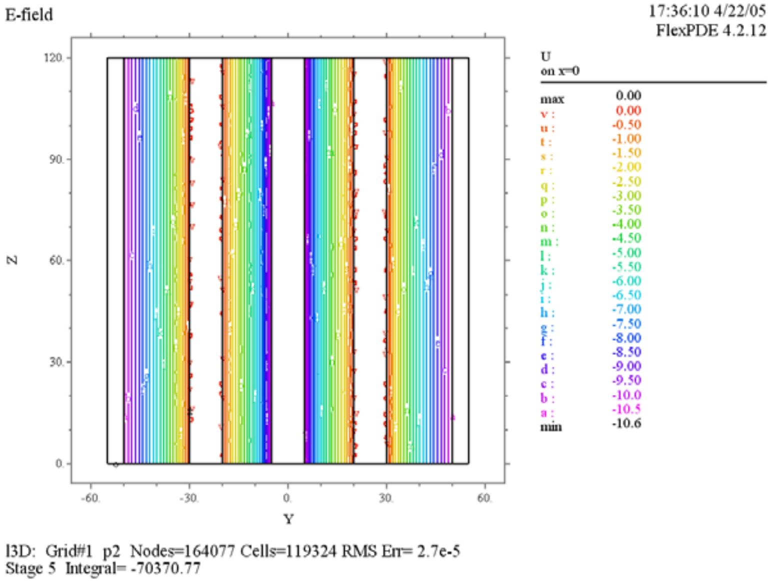
Use general PDE solver (FlexPDE) with modified Poisson equn. to calculate e-field in silicon (depleted/non-depleted).



Can solve in 3D if necessary

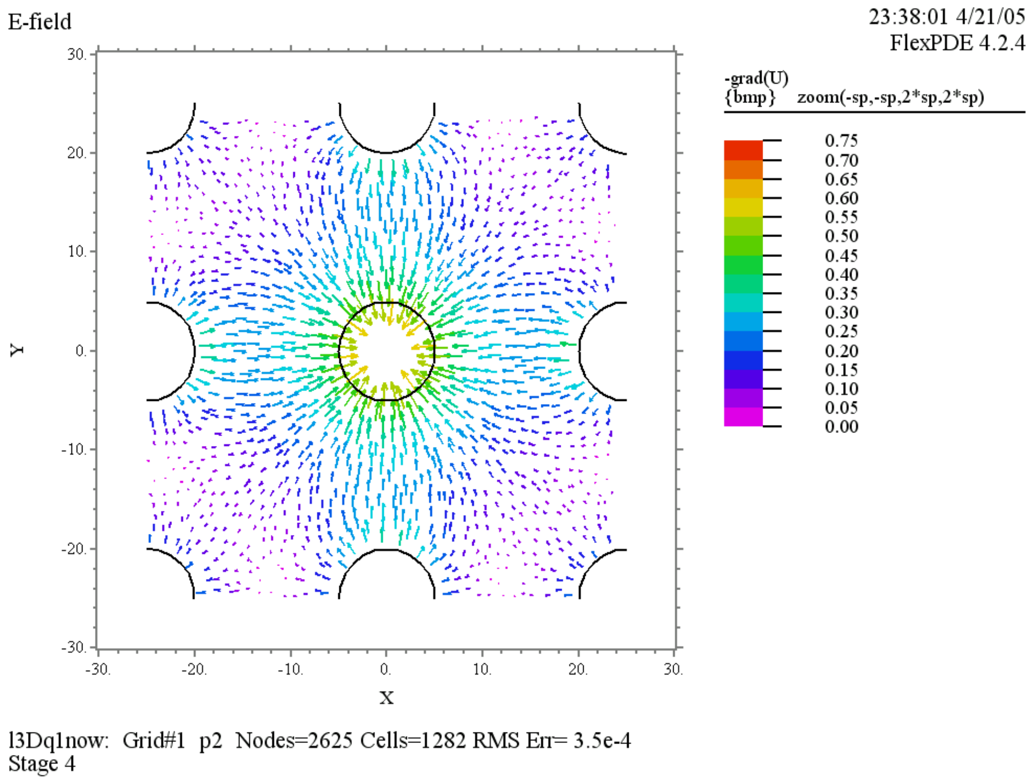


I3D: Grid#1 p2 Nodes=164077 Cells=119324 RMS Err= 2.7e-5
Stage 5 Integral= -73860.38



I3D: Grid#1 p2 Nodes=164077 Cells=119324 RMS Err= 2.7e-5
Stage 5 Integral= -70370.77

Electric field lines



This work

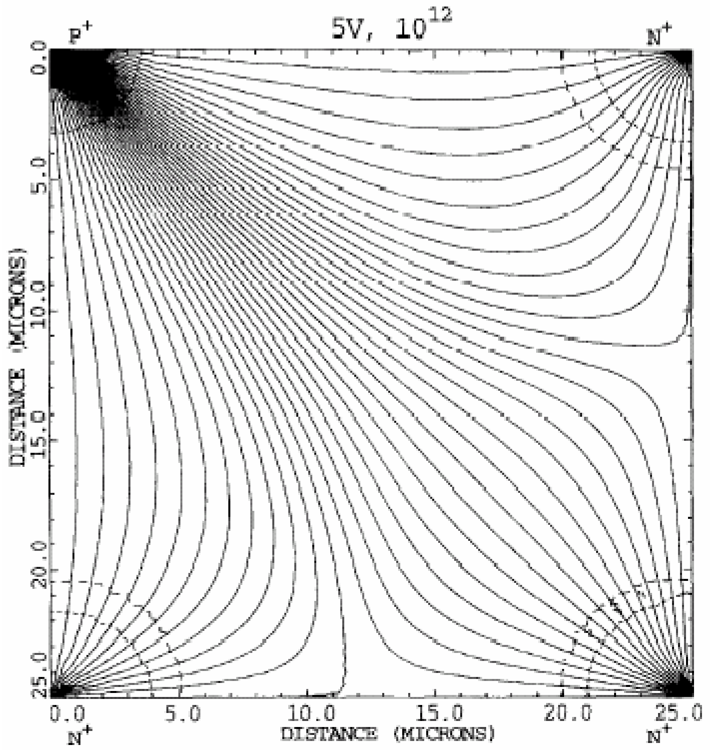
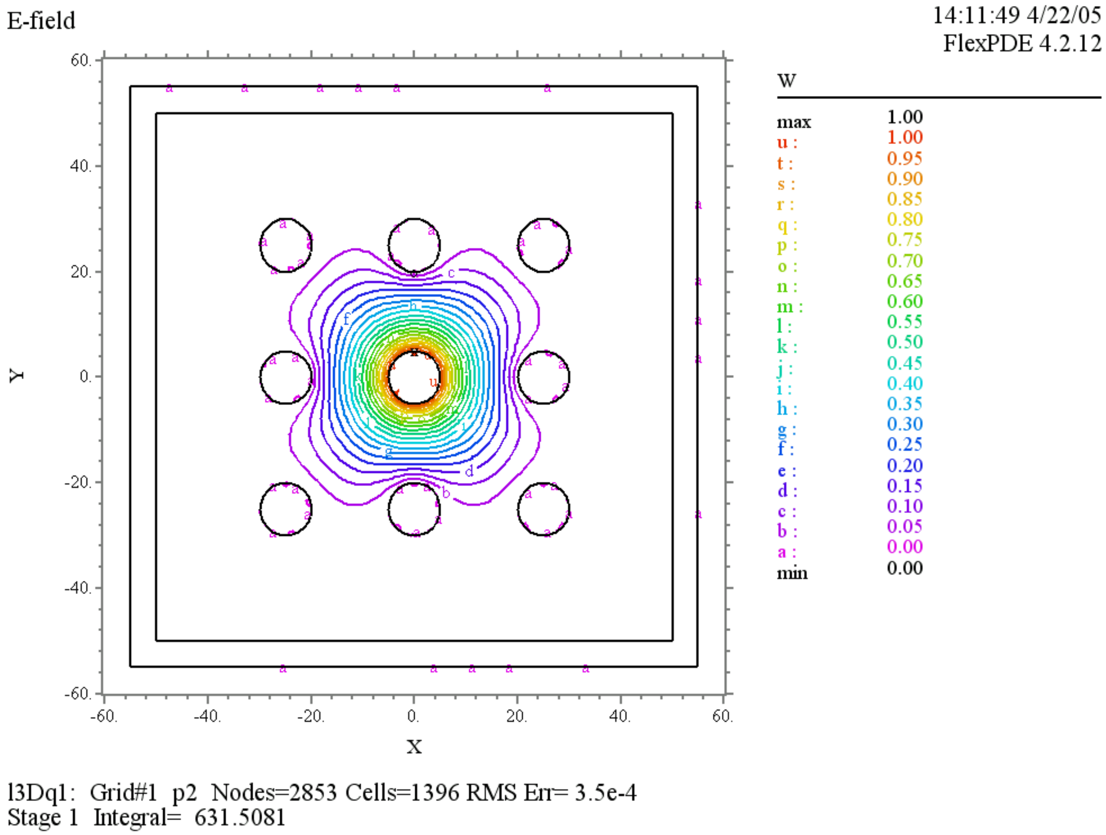
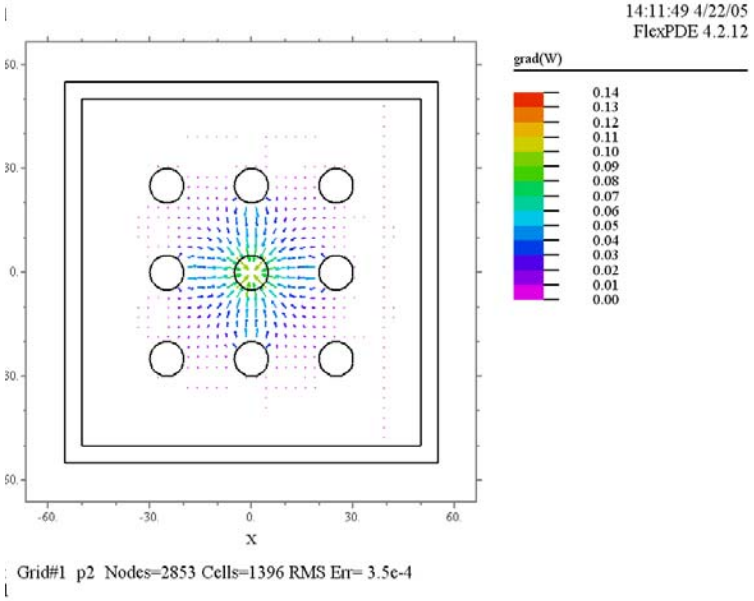


Fig. 3. Drift lines for Fig. 2(a): 10^{12} dopant atoms/cc and 5 V.

Sherwood Parker et al.
NIM A 395 (1997) 328.



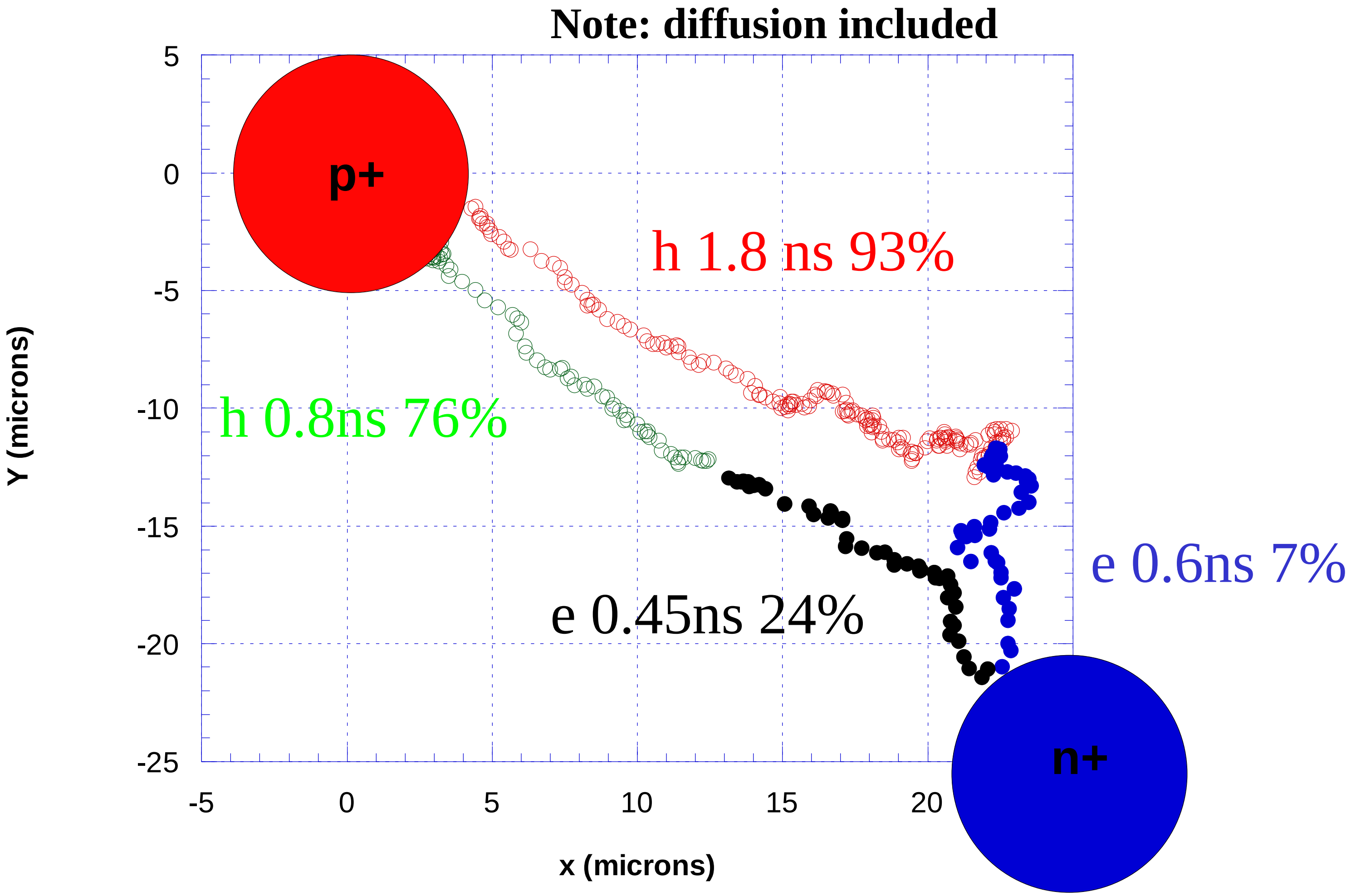
Weighting Potential
Charge Calculation



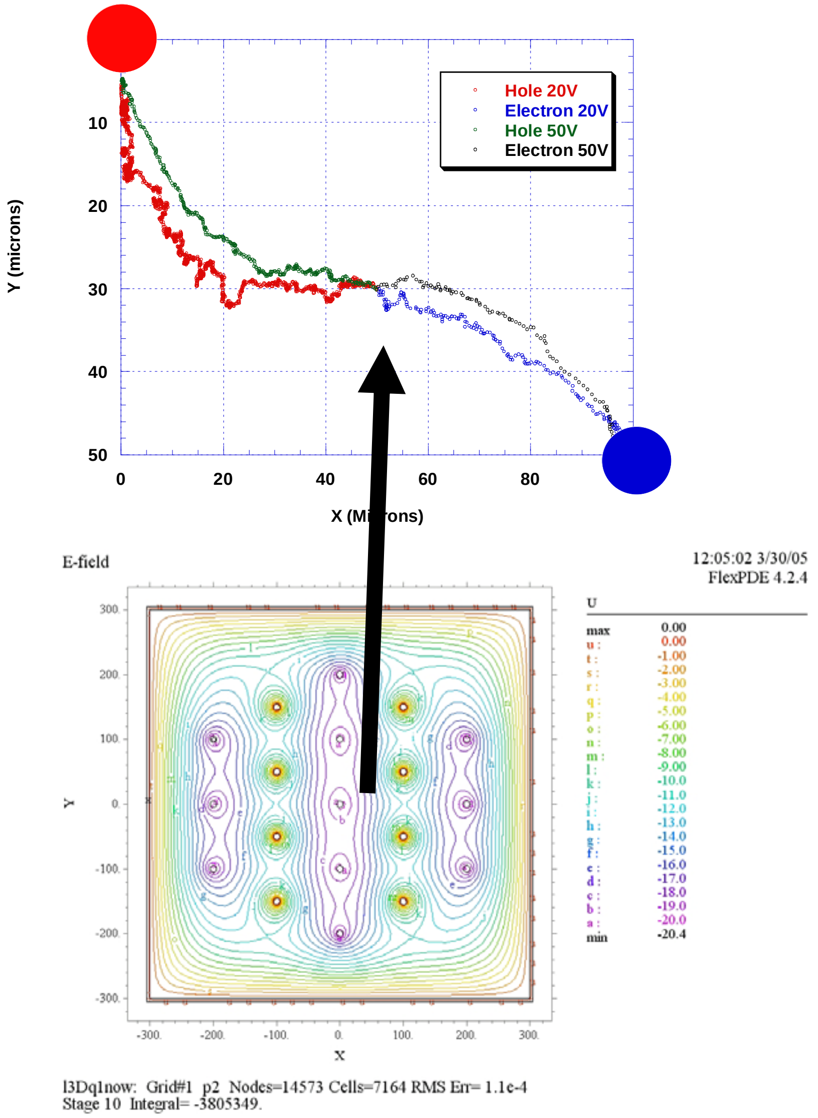
Weighting Field
Current Calculation

Charge in middle (12.5,-12.5) and null position (22,-12.5)

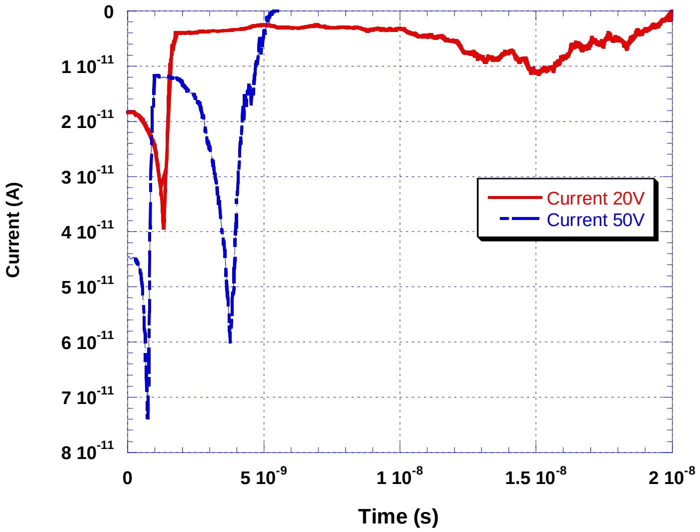
Calculate signal on p+ using Ramo's Theorem



e/h paths in device - includes diffusion



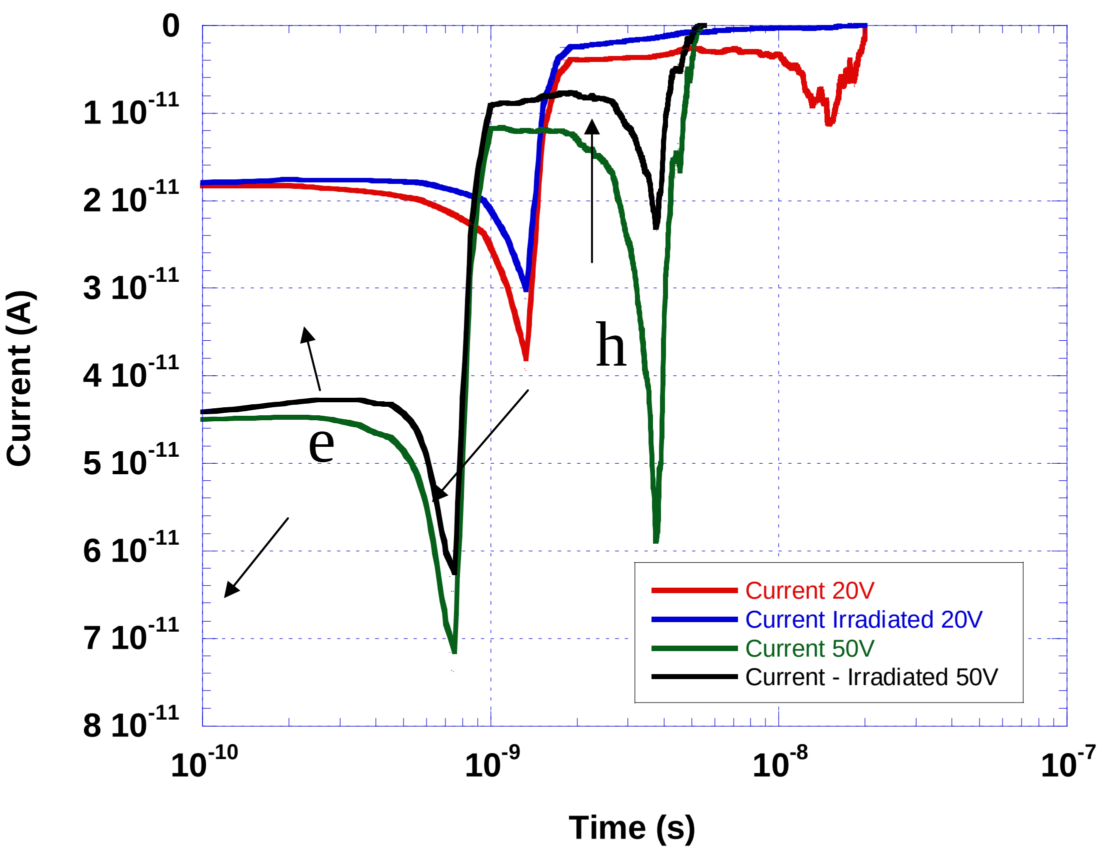
Current signal at p+



100 micron inter-electrode strip connection

Mainly affects fall time

With this method one can include trapping



1E15 High energy protons per sq. cm.
Log scale on time axis for clarity only.

Can solve exactly for a 1D PAD detector

$$\frac{dS}{dt} = q\frac{dV_w}{dx}\frac{dx}{dt}\exp\left(-\frac{t}{\tau_{eff}}\right) = q\frac{dV_w}{dx}\frac{dx}{dt}\exp\left(-\frac{x}{\lambda}\right)$$

Effective drift length = t_{eff} x drift velocity = λ

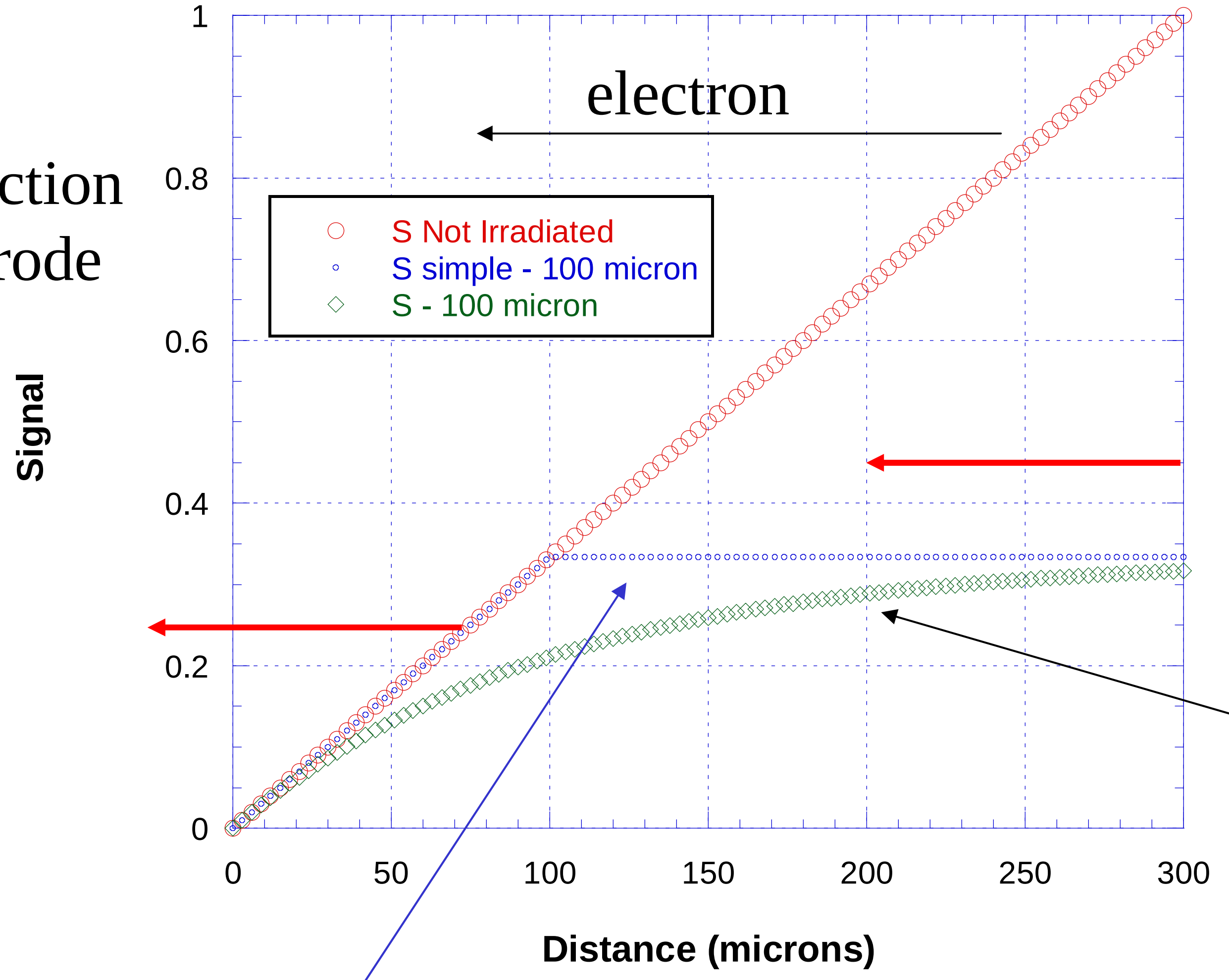
For a pad detector weighting field = -1/L

L is the inter-electrode spacing

$$S = \frac{\lambda}{L}\left[1 - \exp\left(-\frac{x}{\lambda}\right)\right]$$

Signal for a charge carrier at position x

Collection Electrode



100 micron effective drift length

Formula

Simple model…….

Drifts on average distance λ so signal = λ/L

If already within λ of collection electrode signal = x/L

DOES NOT NEED TO BE COLLECTED TO GIVE SIGNAL

USE TERM **SIGNAL EFFICIENCY**
NOT CHARGE COLLECTION EFFICIENCY

For MIP charge deposition – use S and integrate over distance

SE (electron or hole) = $\frac{\lambda}{L} - (\frac{\lambda}{L})^2 + (\frac{\lambda}{L})^2 \exp(-\frac{L}{\lambda})$

Exact solution for pad weighting field.
This is for one carrier (max =0.5)

Add SE for electrons and holes – different λ

For $\lambda/L < 1$ $SE = \lambda/L$

$1/t_{eff} = 1/t_0 + K_\tau\Phi$ Kramberger has measured this
Damage parameter for the effective trapping time

Note: 1/effective lifetime proportional to defect density

$1/L_{eff} = 1/L_0 + K_L\,\Phi$ $L_{eff} = V_D t_{eff}$ λ in previous slides

Effective drift length. V_D is the drift velocity

$K_L = K_\tau V_D$

After some algebra, can write $SE = 1/(1 + K_C\Phi)$

$K_c = 0.6L\,K_\tau/V_D$ For a pad detector. Will use this to fit data.

Comments

1) K_c proportional to L K_τ/V_D

Small value of K_c is better.
Means – small inter-electrode spacing, and high drift velocity

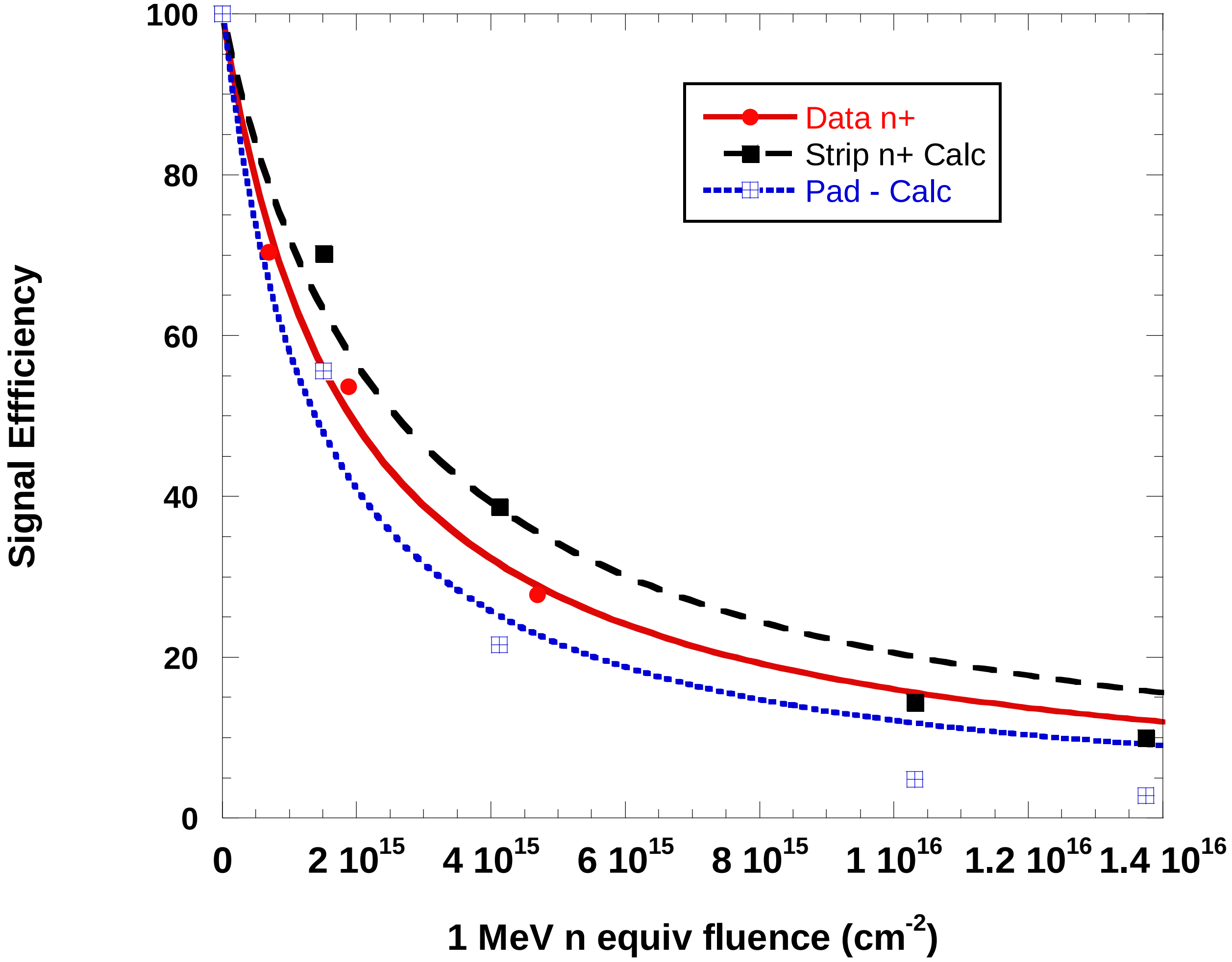
2) For a MIP in Si
Signal = SE x Length of track x 80 e/h per micron

$= \lambda/L \times L \times 80 = \lambda \times 80$ Planar Detector

$= \lambda/L \times$ Silicon Thickness $\times 80 = \lambda \times (2 - 5) \times 80$ 3D

Decouple inter-electrode spacing and device thickness in 3D !

Ultimately it is Signal/Noise that matters most………



$SE = 1/(1+K_c\ \Phi)$

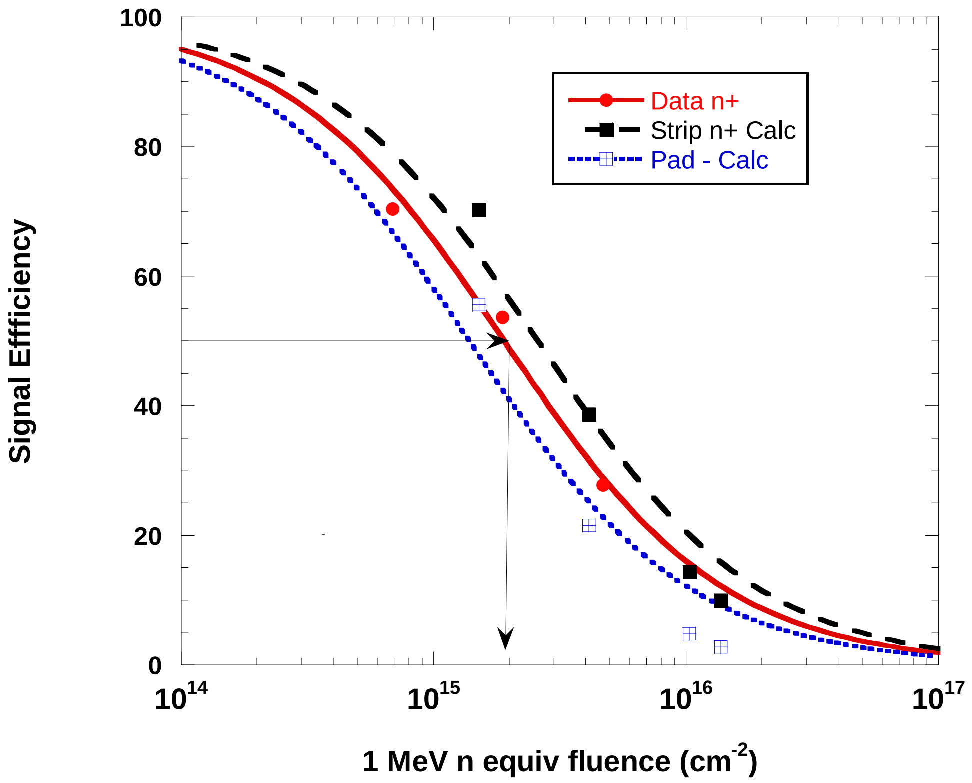
$\tau_{eff} = (1/\beta\Phi)$

β and K_c are related

Expect K_c

$10\mathrm{x}10^{-16}$ Holes
$4.4\mathrm{x}10^{-16}$ Electrons

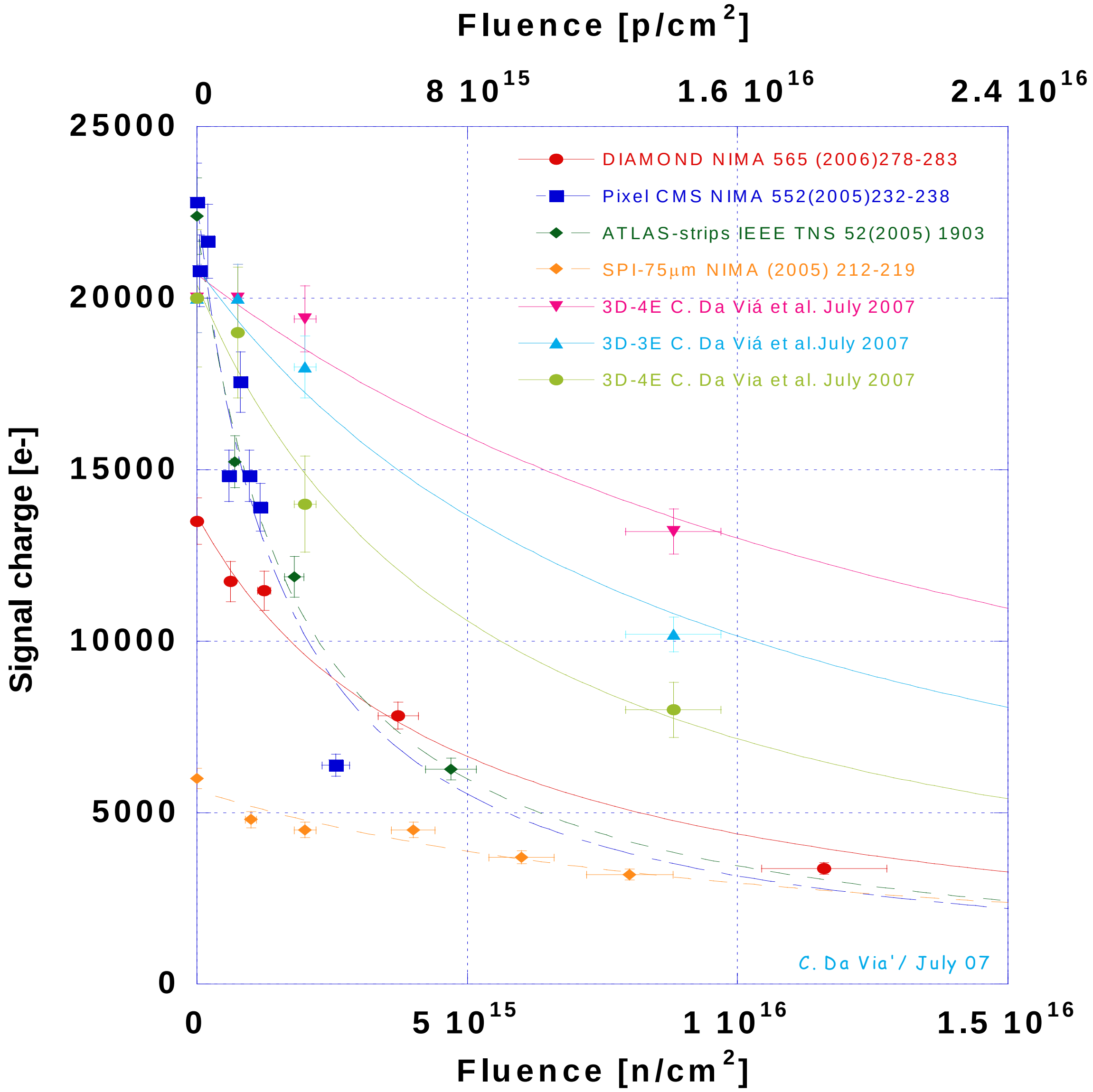
Data n+ in p (Liverpool) 280 micron 5.2 +/- 0.4 10^{-16} cm^2
340 micron strip num. calc. 3.9 +/- 0.5 10^{-16} cm^2
340 micron pad num. calc 7.2 +/- 1.4 10^{-16} cm^2

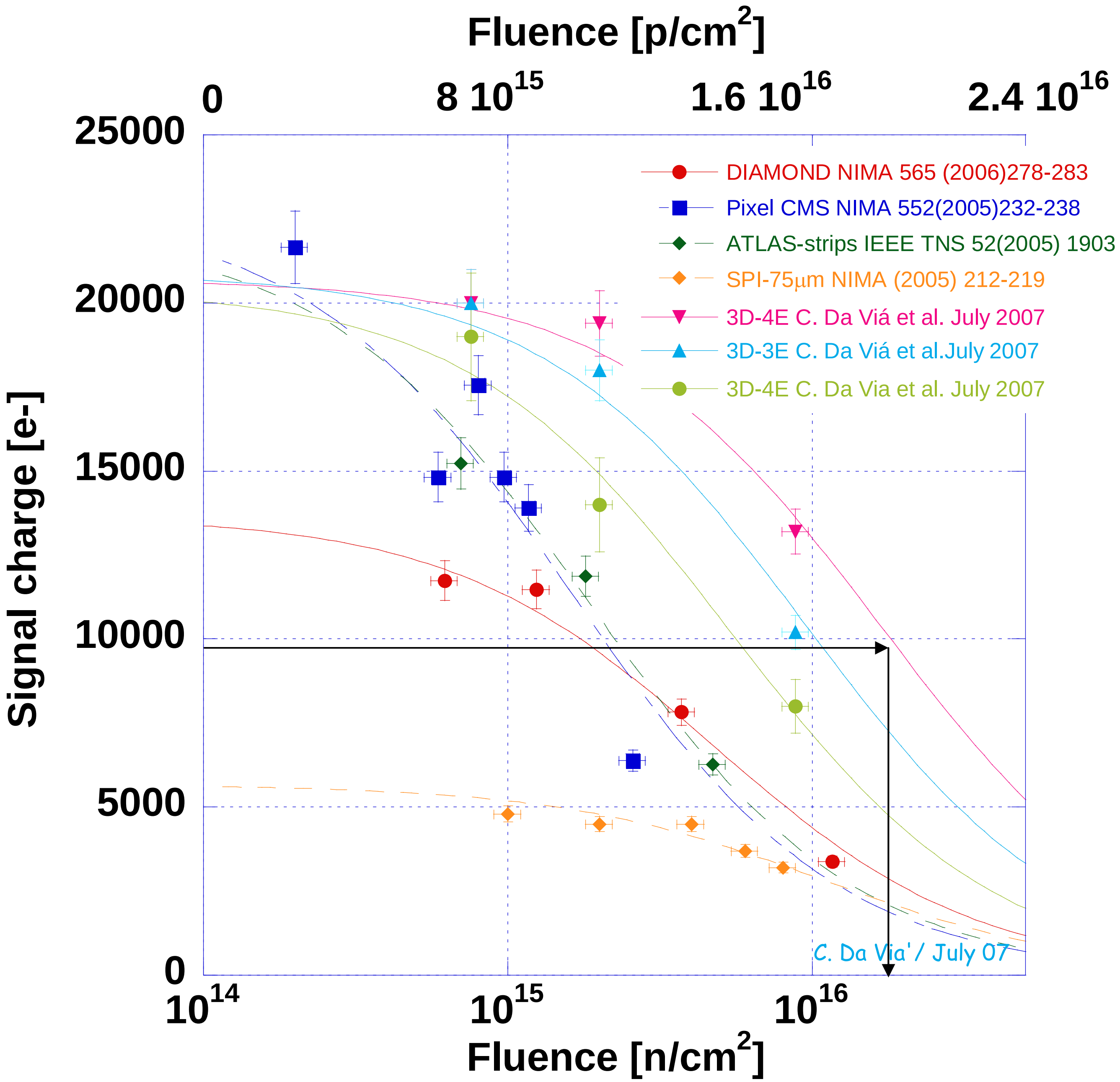


Alternatively, define fluence for SE=0.5

$\phi_{1/2} = 1/K_c$

Data n+ in p (Liverpool) $\phi_{1/2}$ = 1.92E15 cm-2
340 micron strip calc. 2.56E15
340 micron pad calc 1.4E15


Fluence [p/cm^2]
0
8 10^{15}
1.6 10^{16}
2.4 10^{16}
25000
20000
15000
10000
5000
0
Signal charge [e-]
DIAMOND NIMA 565 (2006)278-283
Pixel CMS NIMA 552(2005)232-238
ATLAS-strips IEEE TNS 52(2005) 1903
SPI-75μm NIMA (2005) 212-219
3D-4E C. Da Viá et al. July 2007
3D-3E C. Da Viá et al.July 2007
3D-4E C. Da Via et al. July 2007
C. Da Via'/ July 07
0
5 10^{15}
1 10^{16}
1.5 10^{16}
Fluence [n/cm^2]


Fluence [p/cm^2]
0
8 10^{15}
1.6 10^{16}
2.4 10^{16}
Signal charge [e-]
25000
20000
15000
10000
5000
0
DIAMOND NIMA 565 (2006)278-283
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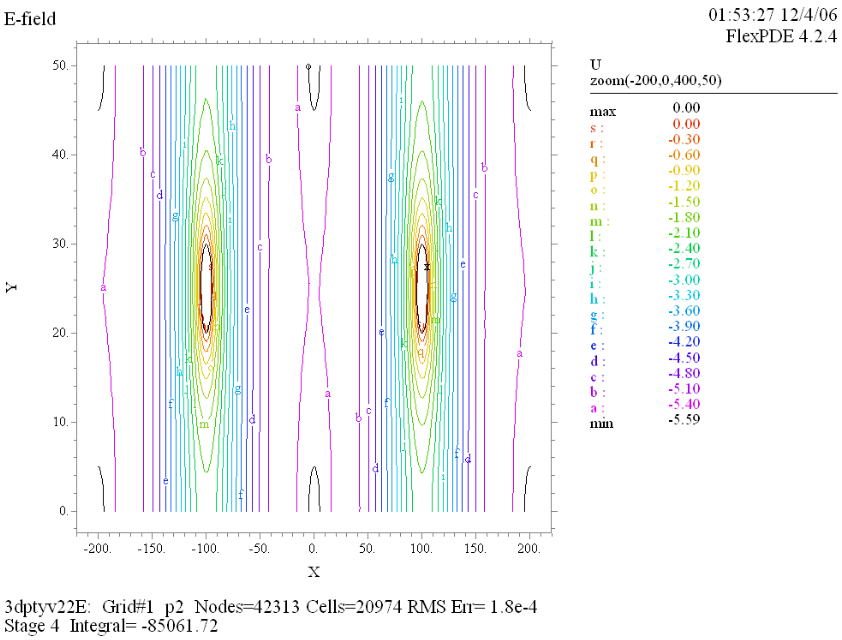
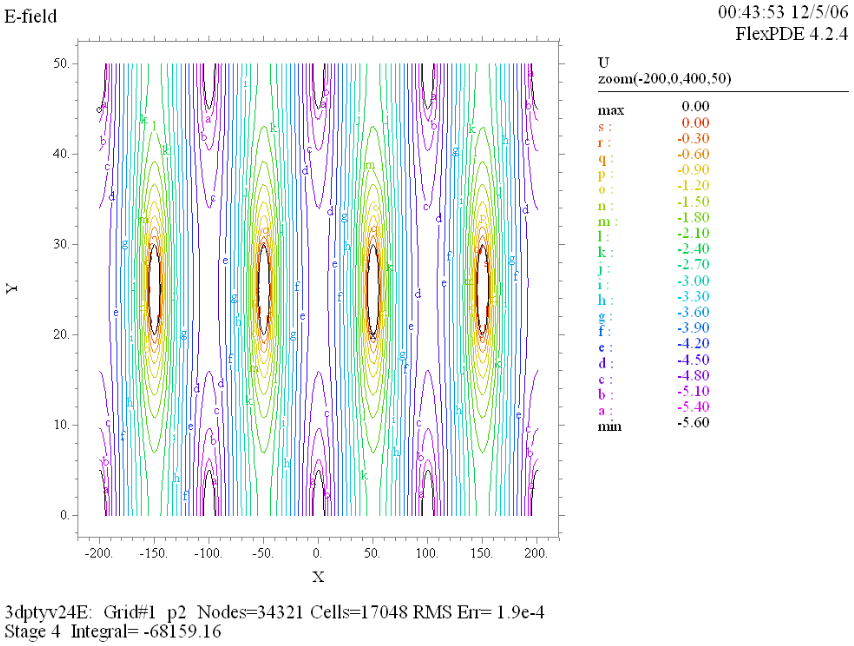
3D-4E C. Da Viá et al. July 2007
3D-3E C. Da Viá et al.July 2007
3D-4E C. Da Via et al. July 2007
C. Da Via' / July 07
10^{14}
10^{15}
10^{16}
Fluence [n/cm^2]

400 micron x 50 micron pixel cell



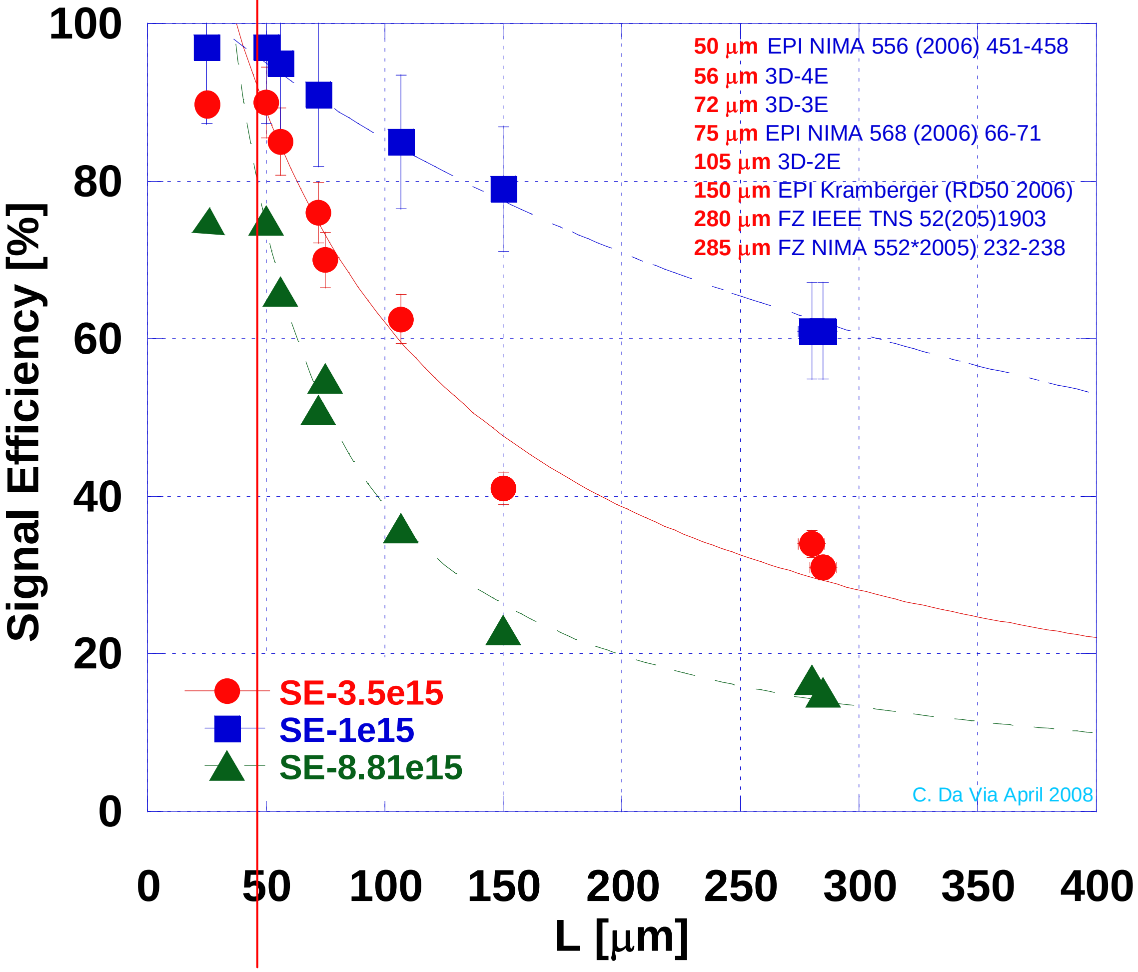


Equipotentials in 2E and 4E 3D detector

Only 5V bias !!!!!!

Detector	**K_c** **(10^{-16} cm^2)**	**$\Phi_{1/2}$** **(10^{15} cm^{-2})**	**Thickness/ Inter-electrode distance**
2E	1.74 +/- 0.24	5.75	2.4
3E	0.91 +/- 0.17	11.0	3.5
4E	0.51 +/- 0.1	19.6	4.5
Pixel CMS	6.21 +/- 1.3	1.6	1
n on p	5.4 +/- 0.64	1.85	1
Epi 150	4.2 +/- 0.07	2.4	1
Epi 75	0.92 +/- 0.2	10.9	1
CZ (Pad ?)	10.94 +/- 3.3	0.91	1
Diamond	2.11 +/- 0.3	4.7	1

Offset…



Signal Efficiency [%]
100
80
60
40
20
0
0
50
100
150
200
250
300
350
400
L [µm]
50 µm EPI NIMA 556 (2006) 451-458
56 µm 3D-4E
72 µm 3D-3E
75 µm EPI NIMA 568 (2006) 66-71
105 µm 3D-2E
150 µm EPI Kramberger (RD50 2006)
280 µm FZ IEEE TNS 52(205)1903
285 µm FZ NIMA 552*2005) 232-238
SE-3.5e15
SE-1e15
SE-8.81e15
C. Da Via April 2008

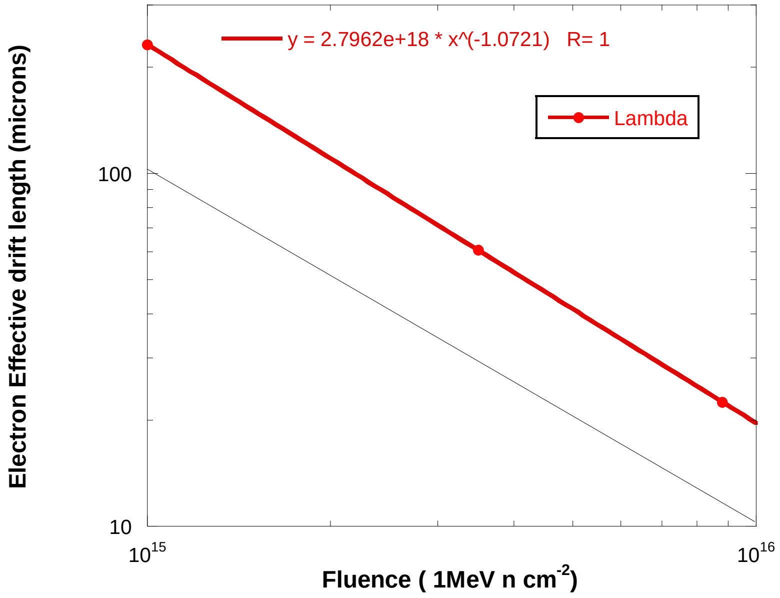
$$\frac{\lambda}{L} - \left(\frac{\lambda}{L}\right)^2 + \left(\frac{\lambda}{L}\right)^2 \exp\left(-\frac{L}{\lambda}\right)$$

Electron + Holes

Use this formula to fit the data on previous slide

λ for holes set to 0.4 of λ for electrons. One parameter fit.

Offset of 40 micron on the L – ideas why this is needed but more work and thought required.



Higher by factor 2 than expected. However – simple model so do not treat as exact. Fluence dependence is correct !!

CONCLUSIONS

- Signal efficiency (SE) is controlled by device geometry

  Inter-electrode distance.
  Electrode width to thickness (strips and pixels especially)

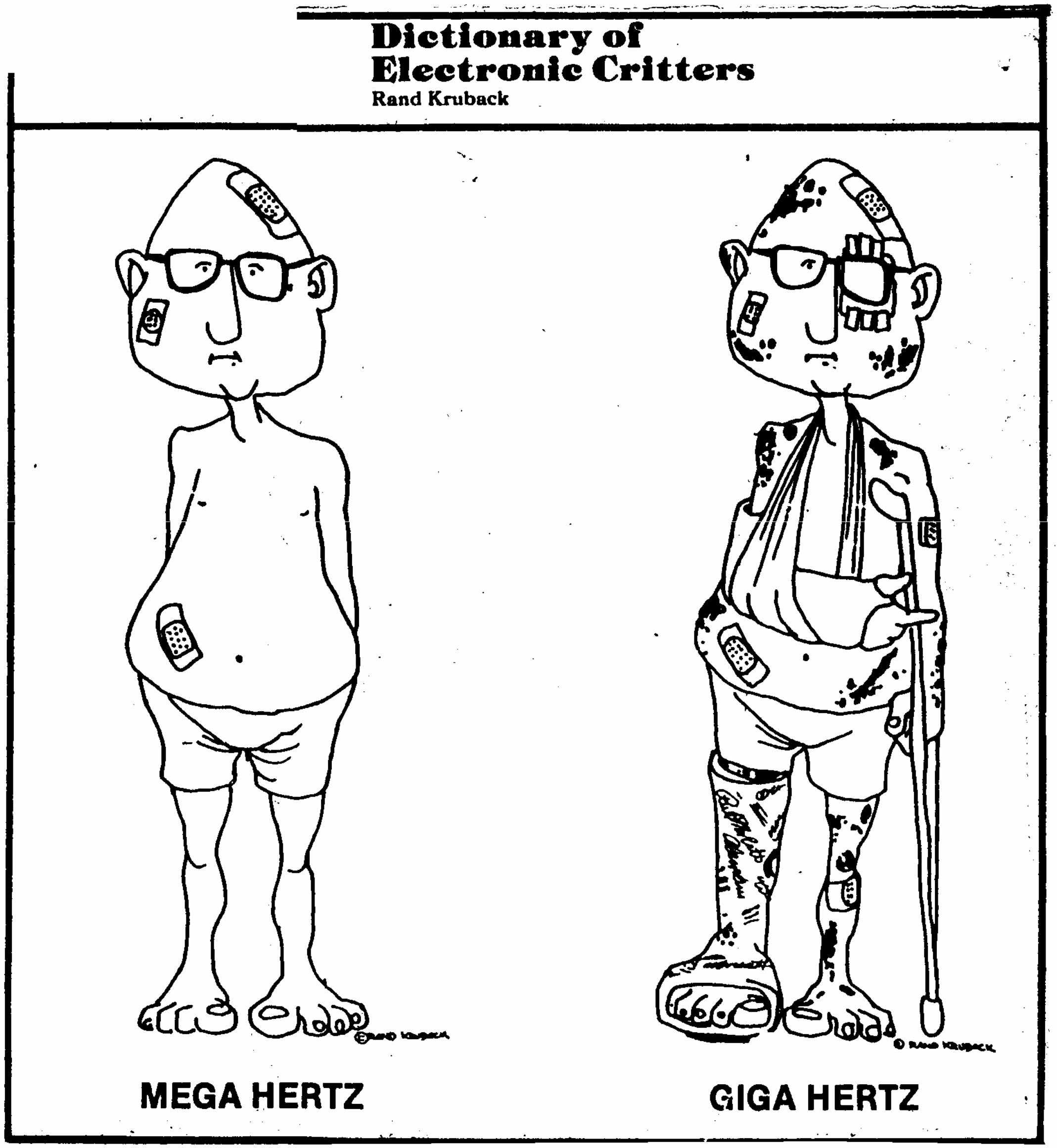
- Signal size proportional to
  Effective drift length x Thickness/inter-electrode distance

- Can define a damage constant for the SE, K_c

  $SE = 1/(1 + K_c\Phi)$

- To date, defect engineering has not altered the trapping. Can only control space charge and reverse annealing

Device engineering does work – 3D and collect electrons in segmented sensors



`3D 4E 1E16

3D 1E17 ???

Next challenge??