Experimental
Particle Physics

Simulations of 3D detectors with radiation damage up to $10^{16} n_{eq}/cm^2$

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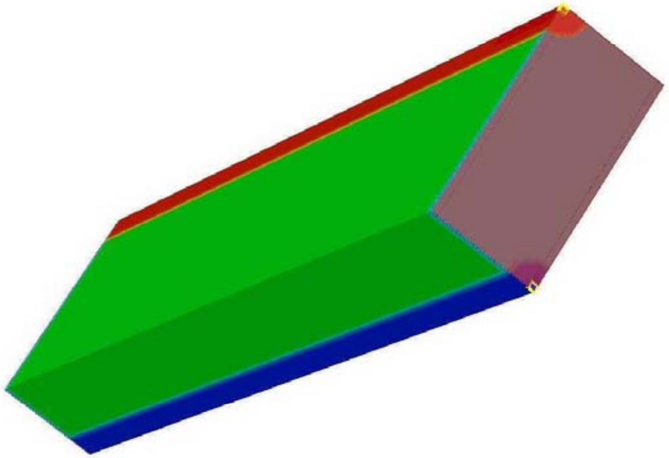
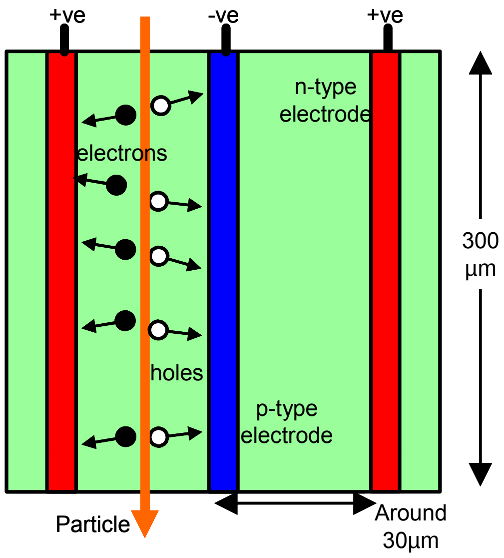
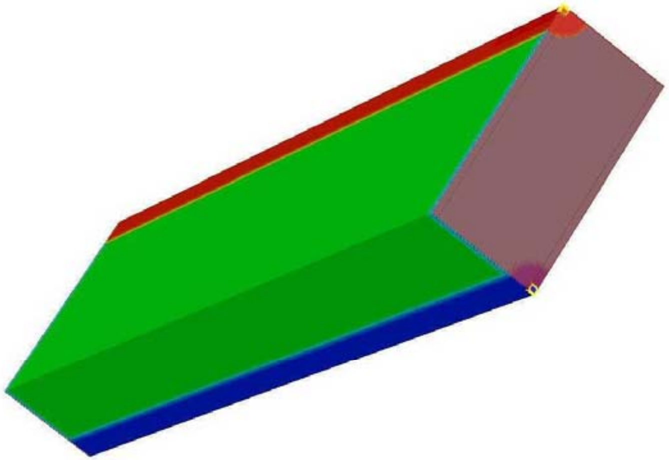




Overview

- Radiation damage model and comparison with experiment
- Behaviour of different ATLAS pixel 3D layouts
- Comparison of double-sided & standard 3D



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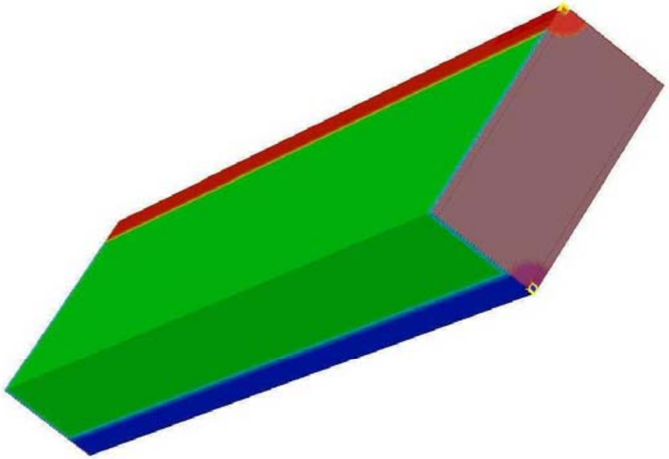


Simulation methods

- **See presentation from 10th RD50 meeting**
- Synopsis TCAD finite element simulation

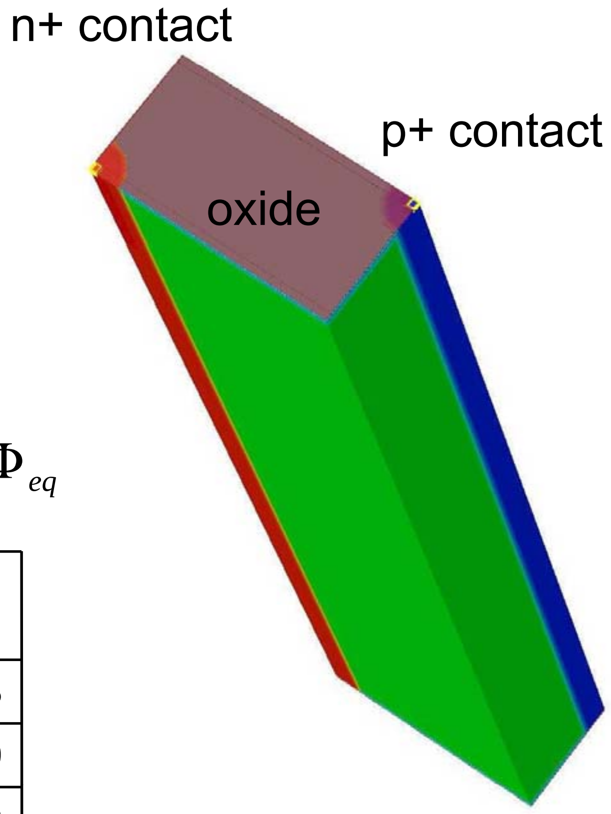
- **Damage model**
  - Trap dynamics modelled directly
  - P-type FZ material, proton irradiation
  - Based on work at Uni. Perugia – see M. Petasecca et al., *IEEE Trans. Nucl. Sci., vol. 53, pp. 2971–2976, 2006*
  - Modified to match experimental trap times (V. Cindro et al., IEEE NSS, Nov 2006)

$\beta_e = 4.0*10^{-7}\text{cm}^2\text{s}^{-1}$, $\beta_h = 4.4*10^{-7}\text{cm}^2\text{s}^{-1}$,

$$\frac{1}{\tau_e} = \beta_e \Phi_{eq}$$

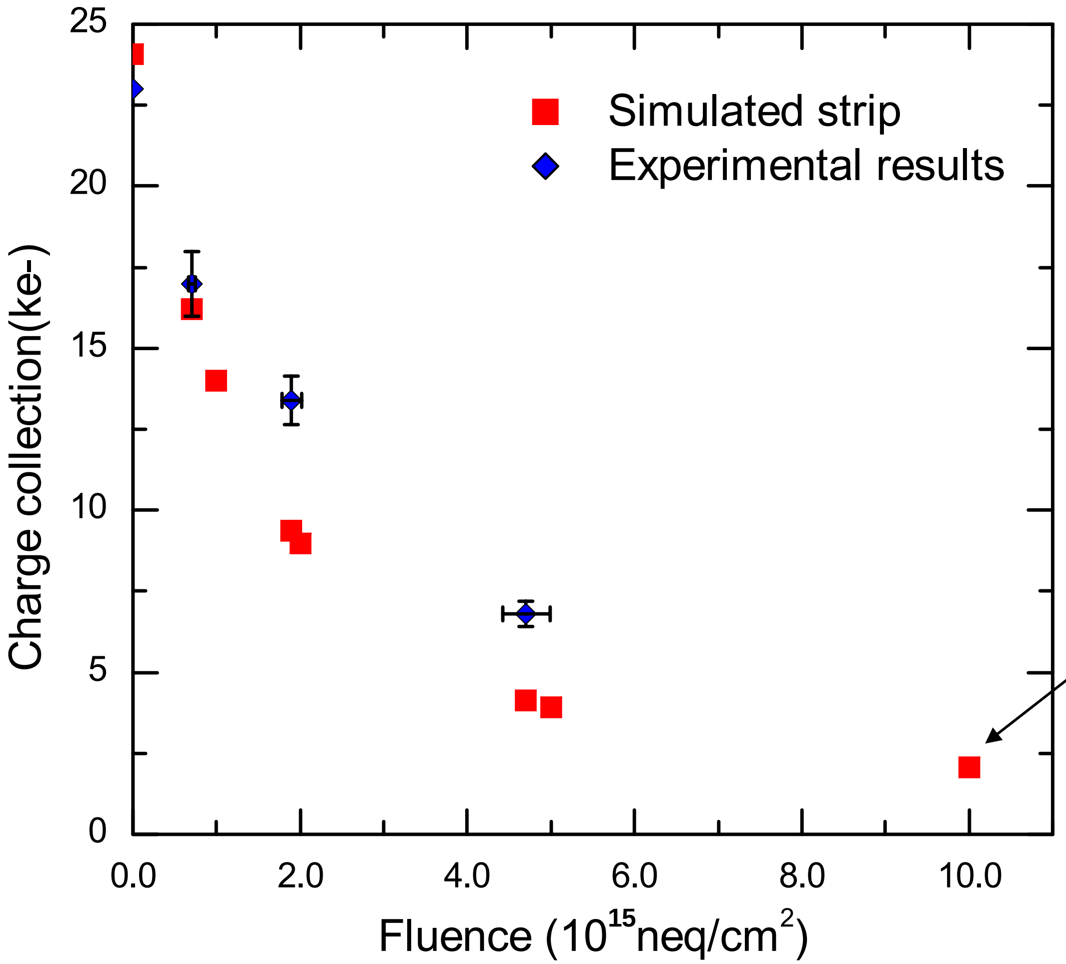
Type	Energy (eV)	Trap	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
Acceptor	Ec-0.42	VV	$9.5*10^{-15}$	$9.5*10^{-14}$	1.613
Acceptor	Ec-0.46	VVV	$5.0*10^{-15}$	$5.0*10^{-14}$	0.9
Donor	Ev+0.36	CiOi	$3.23*10^{-13}$	$3.23*10^{-14}$	0.9

Example of a simulated 3D structure



N+ on p strip detector: CCE

- At high fluence, simulated CCE is lower than experimental value
  - Trapping rates were extrapolated from measurements below $10^{15} n_{eq}/cm^2$
  - In reality, trapping rate at high fluence probably lower than predicted



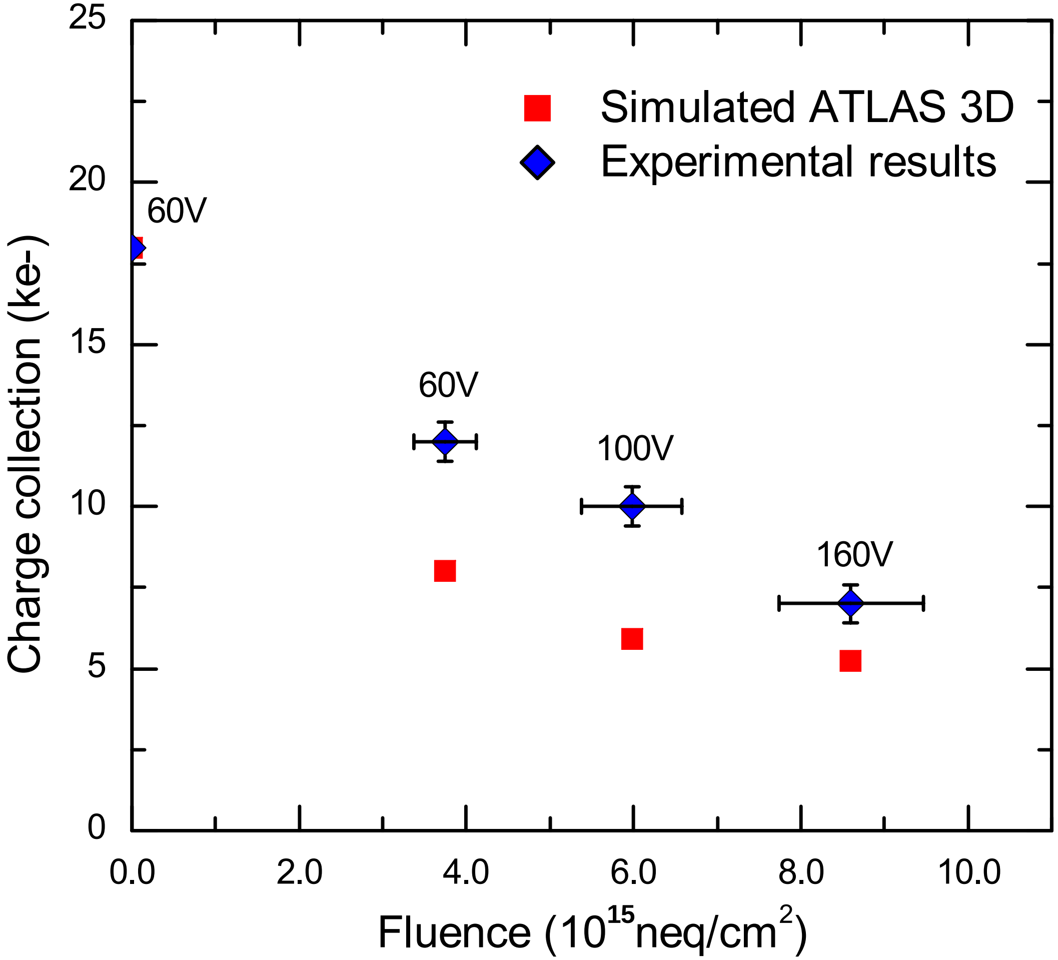
PP Allport et al., IEEE Trans. Nucl. Sci., vol 52, Oct 2005

900V bias,
280µm thick

From β values used, expect 25µm drift distance, 2ke- signal

ATLAS 3D detector: CCE

- Experiment used 230μm substrate, 3 n+ columns per ATLAS pixel
- Defocused IR laser pulse was used to flood the pixel with charge; the simulation mimics this
- Both experiment and simulation show improved CCE at high fluence



C. da Via et al., Liverpool ATLAS 3D meeting, Nov. 06

Detectors produced at Stanford

At high fluences, simulated CCE ~2/3 of experimental value (like with planar detector)

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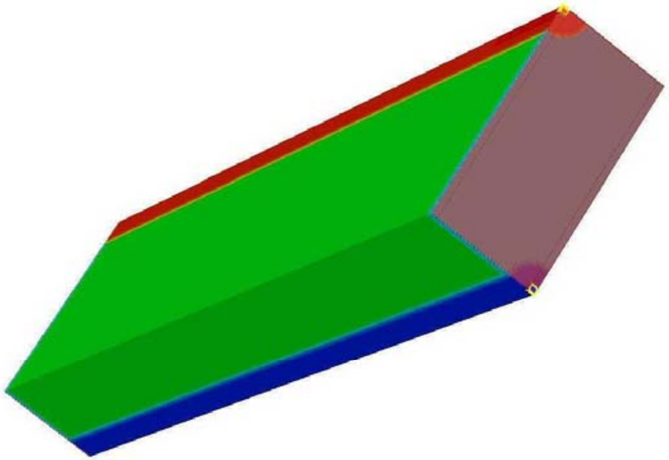
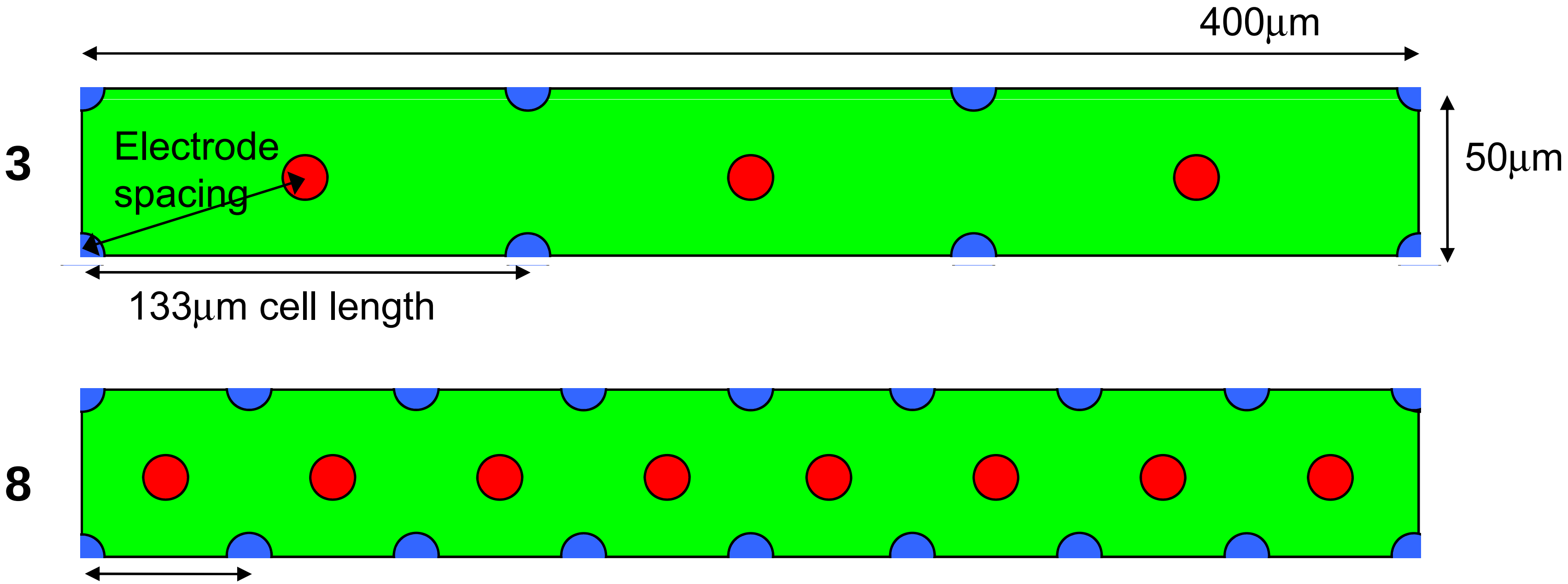
- Comparison of double-sided & standard 3D



ATLAS 3D simulations

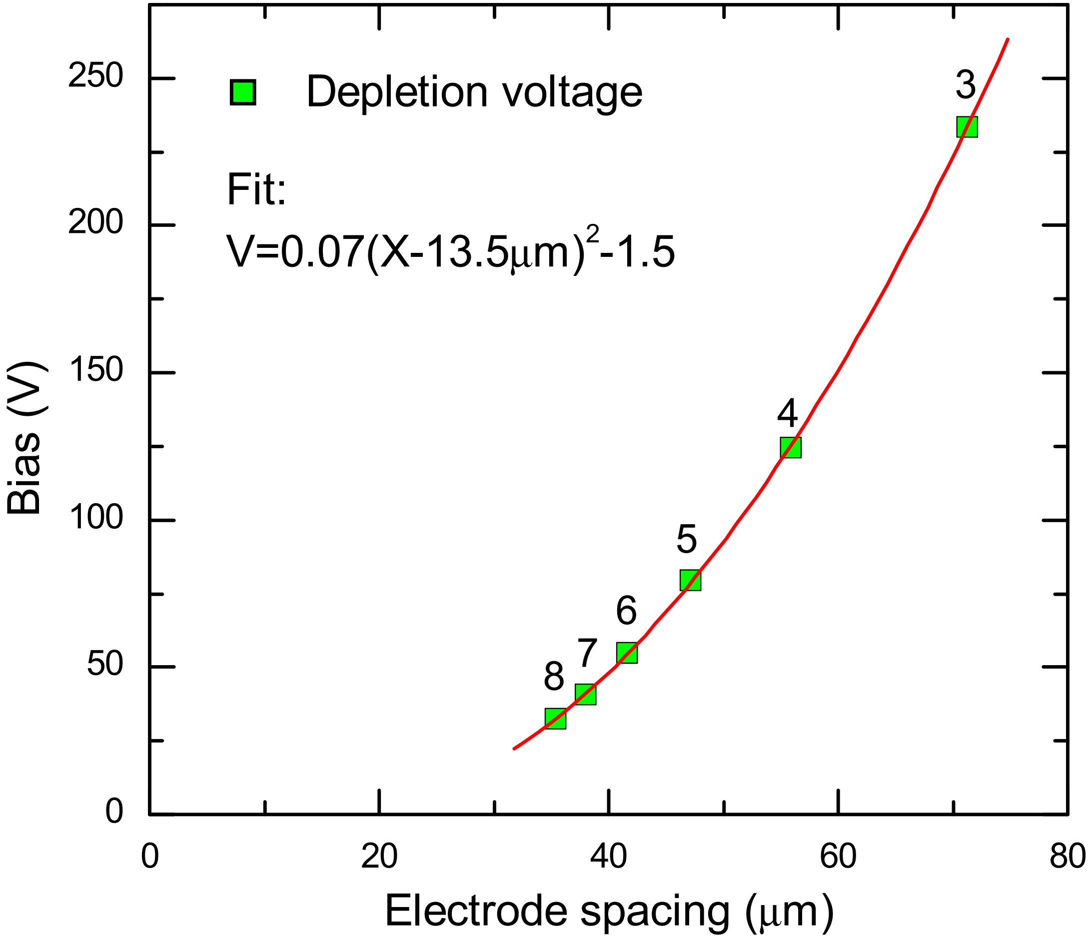
- ATLAS pixel (400µm * 50µm) allows layouts with different electrode spacing
  - No of n+ columns per pixel could vary from ~2-8
    - Previous ATLAS results shown used 3 columns
- Simulations use 230µm-thick p-type substrate, n+ readout
  - Columns have 5µm radius, with dopant profile extending ~2µm further
  - P-spray is used to isolate the columns



Note larger volume occupied by columns

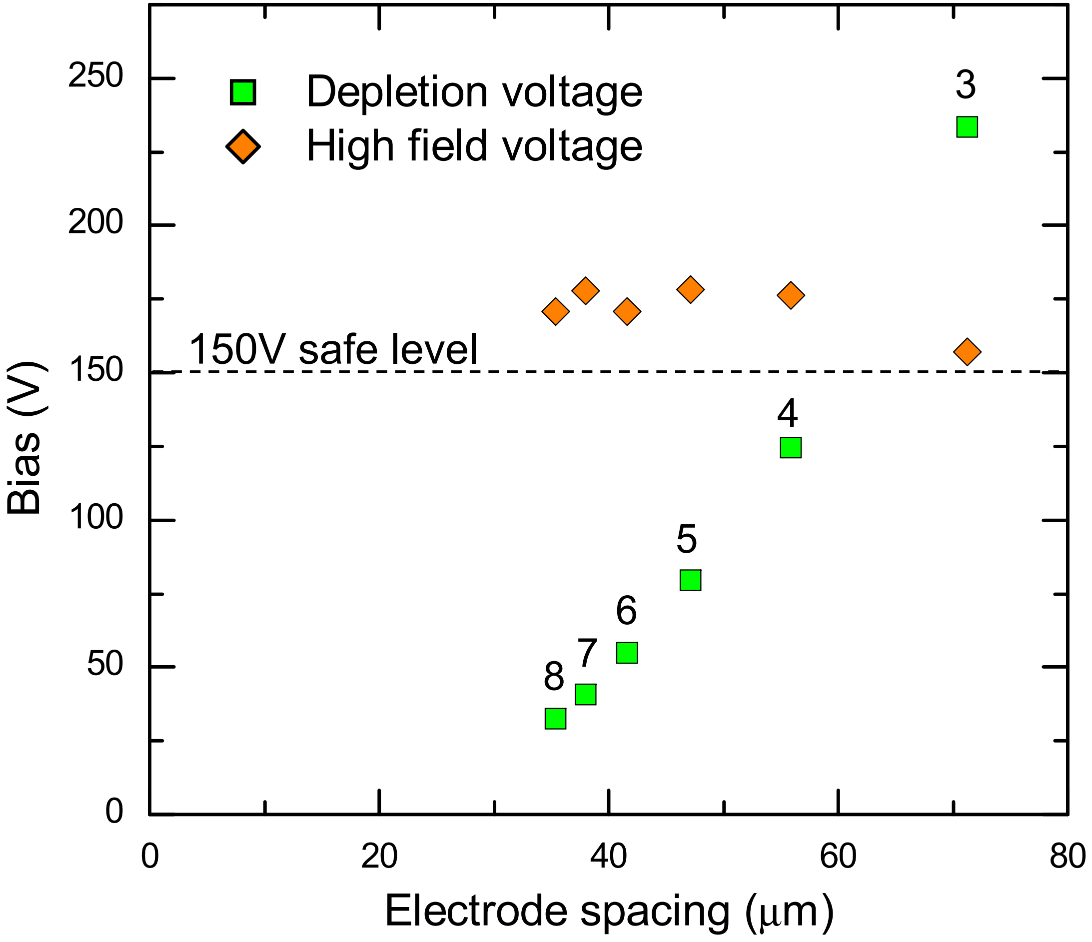
ATLAS 3D – Depletion voltage at $10^{16}n_{eq}/cm^2$

- Depletion voltage will depend on substrate material (this model matches p-type FZ, rather than oxygenated silicon)
- No. of n+ columns shown next to each data point
- V_{dep} proportional to depletion distance squared



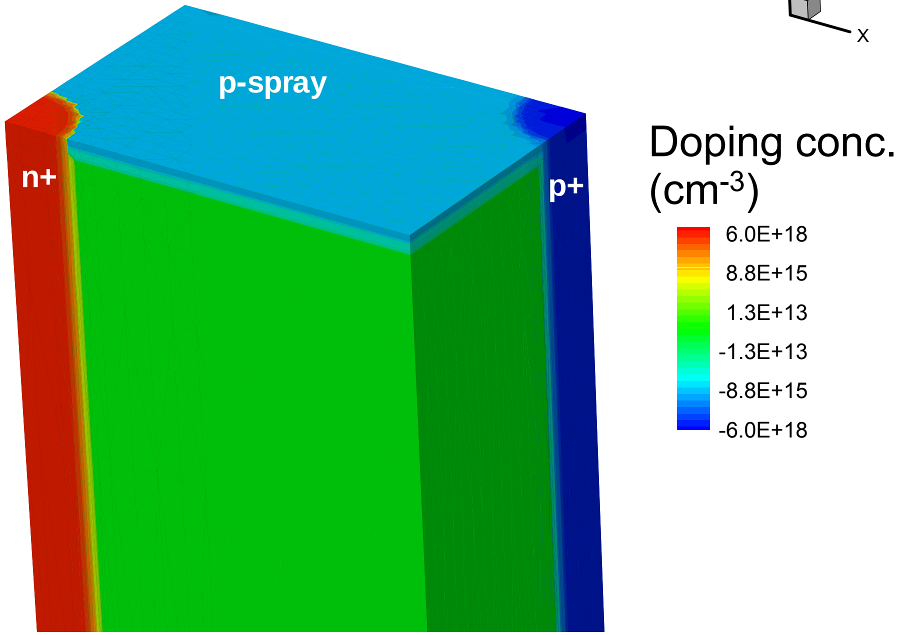
ATLAS 3D – high-field voltage at $10^{16} n_{eq}/cm^2$

- As an approximate judge of a "safe voltage", found the bias at which the maximum field in each device reached $2.5*10^5$V/cm
- Surprisingly, all the devices gave much the same results at $10^{16} n_{eq}/cm^2$
- Used 150V bias in following simulations

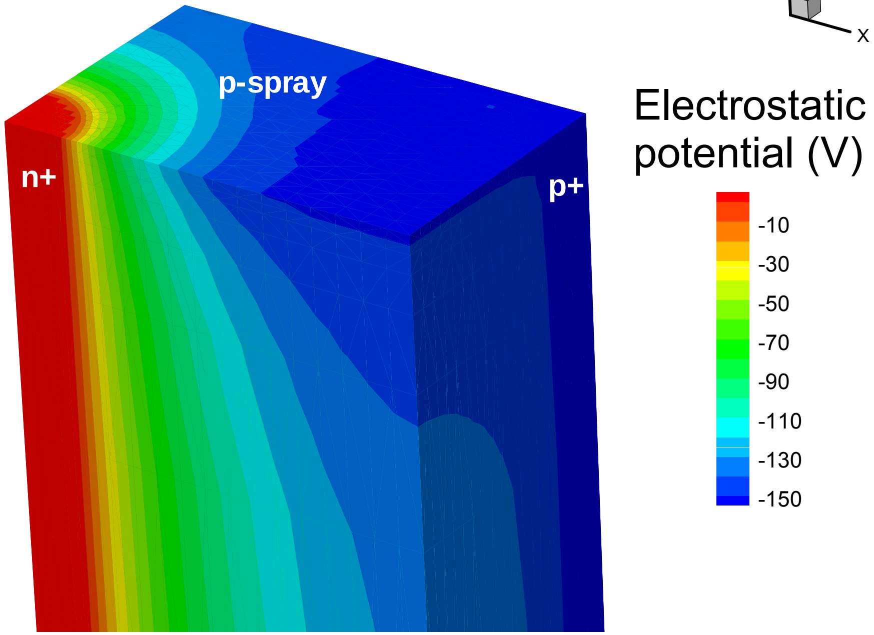


Device structure and high-field regions

- P-spray links p+ columns to n+
- So, the p-spray is at the same potential as the p+, resulting in high field at front surface where it meets the n+ columns
- This effect isn't strongly affected by the electrode spacing itself



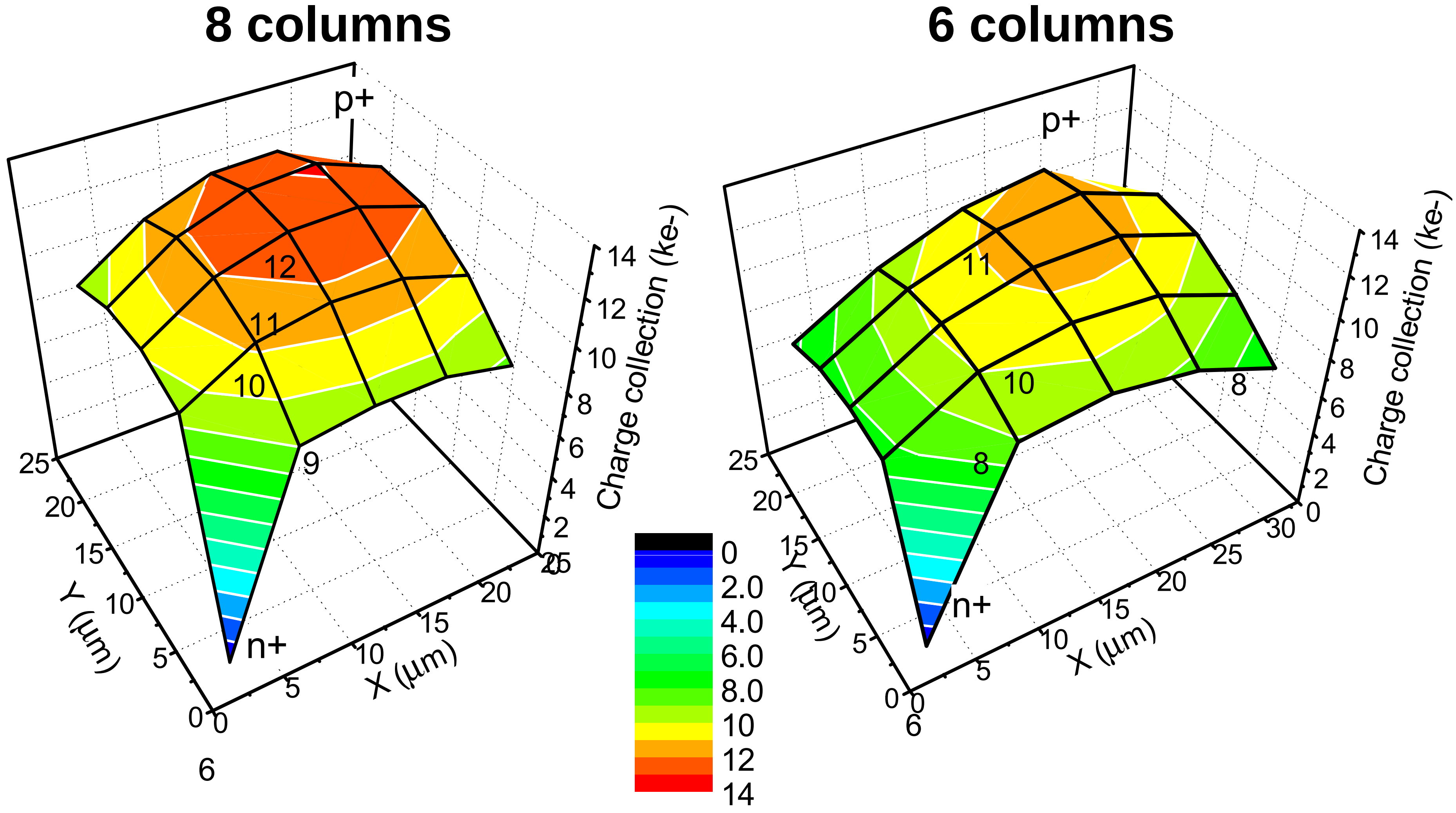
5-column ATLAS 3D, $10^{16} n_{eq}/cm^2$, 150V bias



5-column ATLAS 3D, $10^{16} n_{eq}/cm^2$, 150V bias

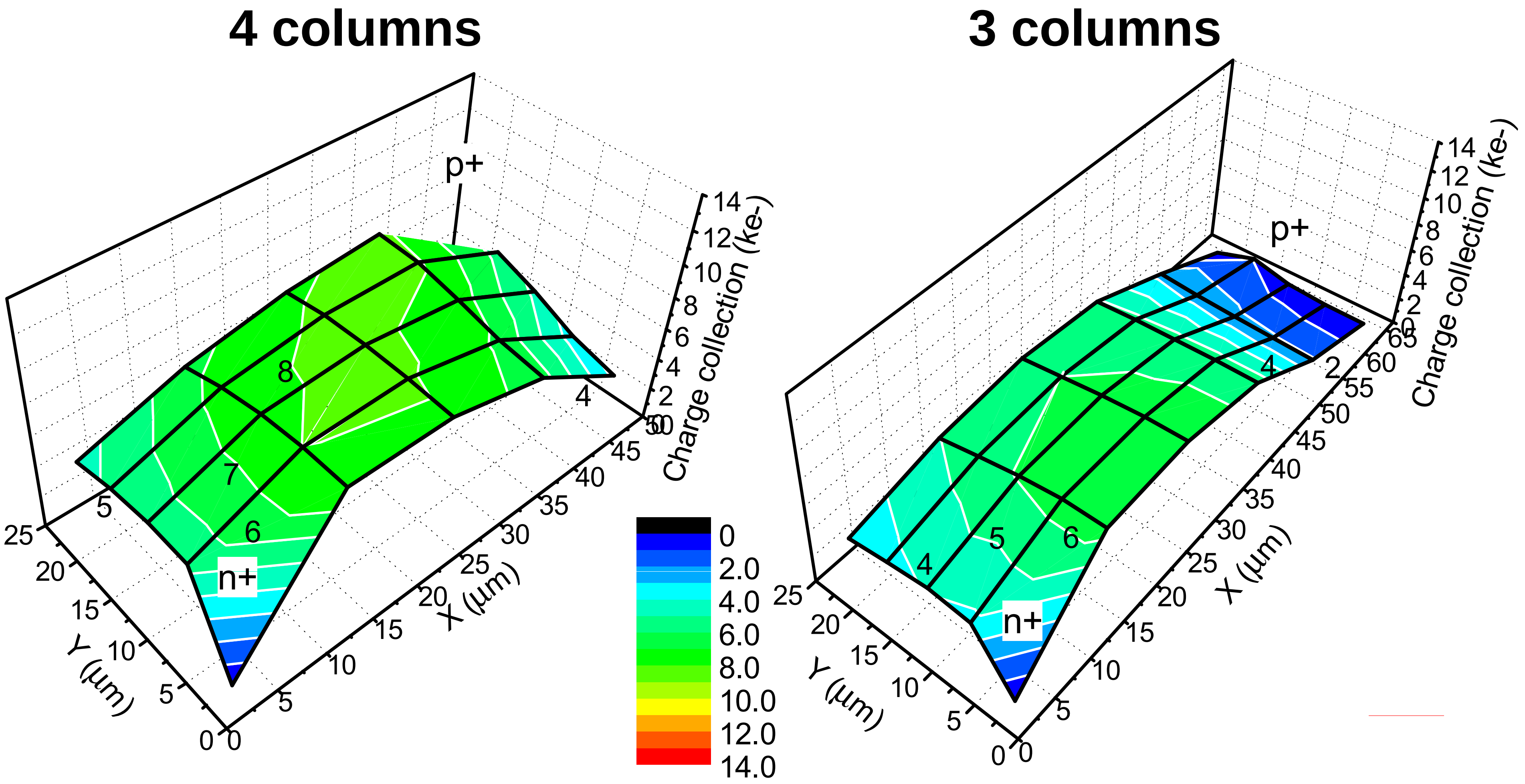
Charge collection vs position at $10^{16} n_{eq}/cm^2$

- Simulated MIPs passing through detector at 25 positions, to roughly map the collection efficiency. 150V bias. Charge sharing not taken into account.
- Low collection within n+ and p+ columns (seen experimentally)



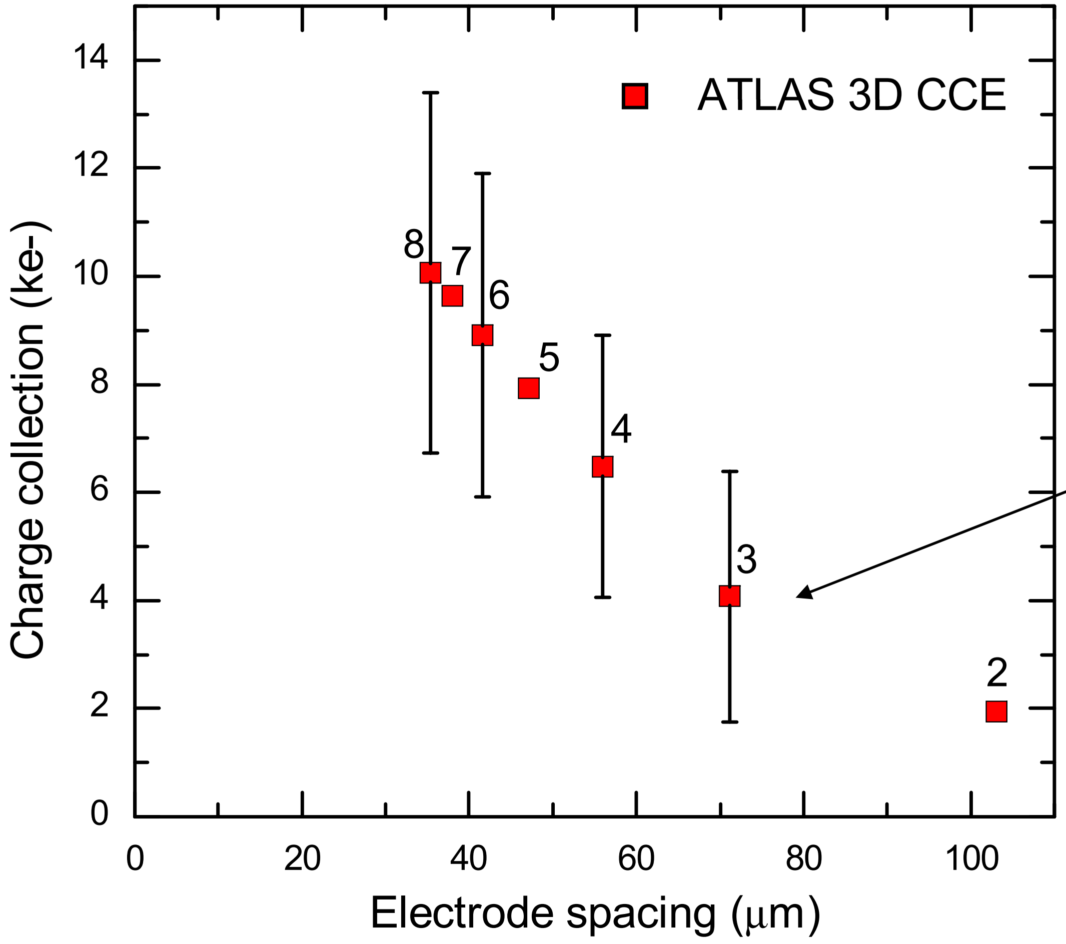
Charge collection vs position at $10^{16} n_{eq}/cm^2$

- Collection across active region is non-uniform
- This becomes more significant as the electrode spacing increases



Average ATLAS CCE at $10^{16} n_{eq}/cm^2$

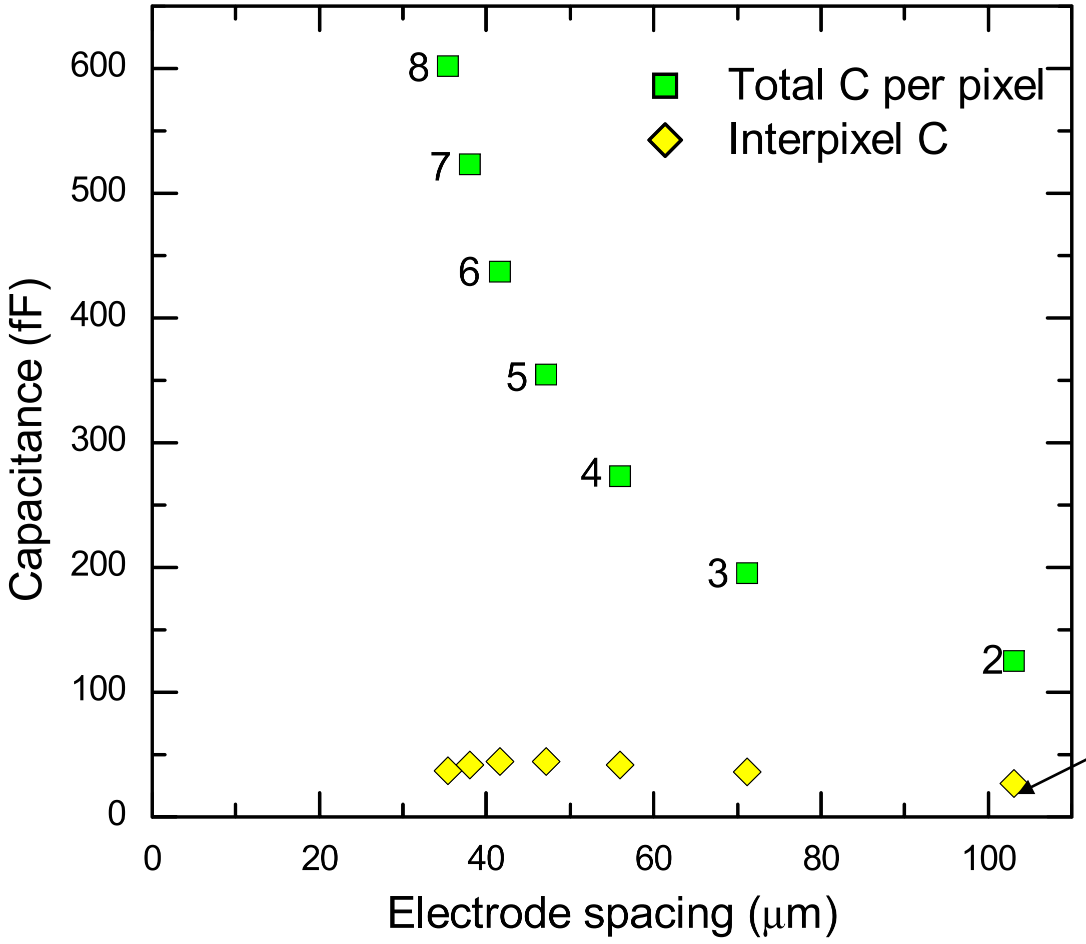
- Average CCE found by flooding entire pixel with charge. 150V bias.
- Previous simulations used to find RMS variation from average, as a measure of nonuniformity. Shown by "error bars".
- Collection in active region improves as electrode spacing is reduced



Variation in collection with position larger relative to CCE

Total capacitance seen at each ATLAS pixel

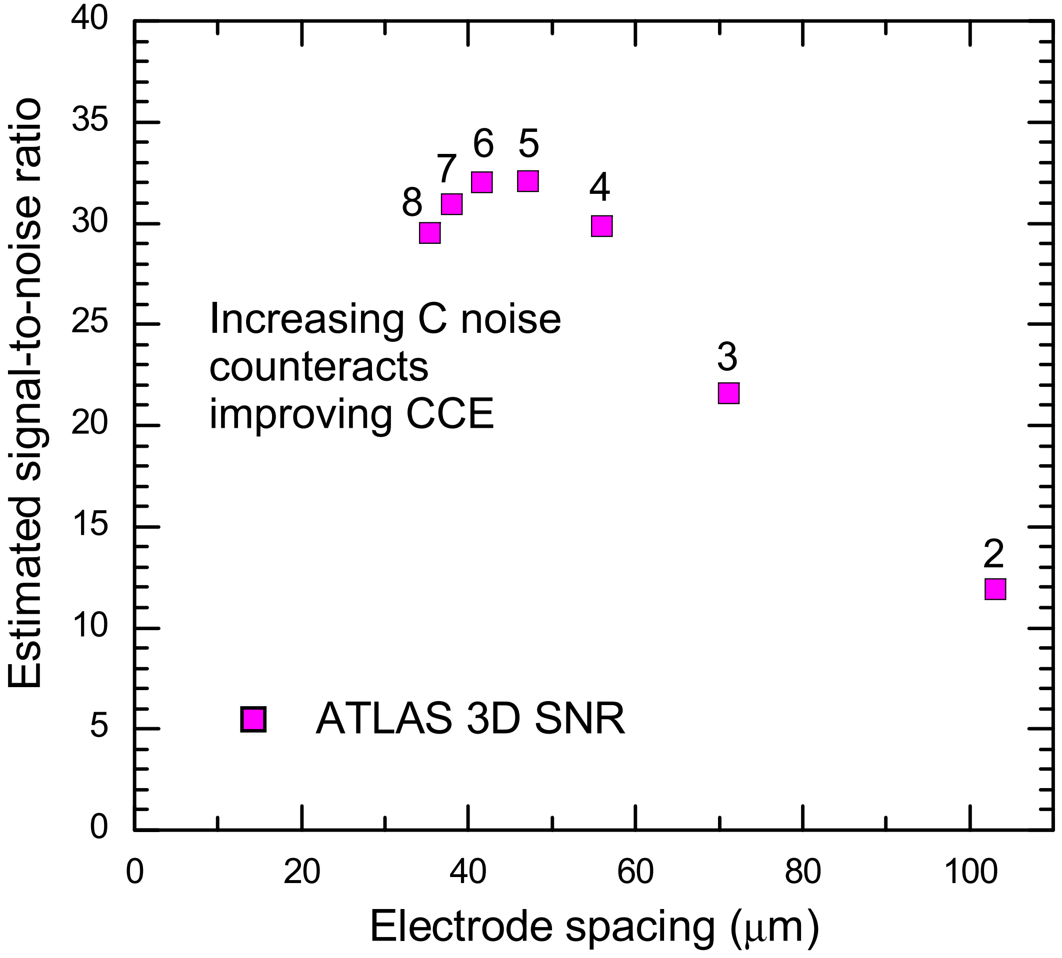
- The total pixel capacitance was found with 10^{12}cm^{-2} oxide charge (a typical saturated value) but *without* radiation damage.
- C increases rapidly with no. of columns – the column capacitances add in parallel, and the capacitance per column gets larger as spacing decreases.



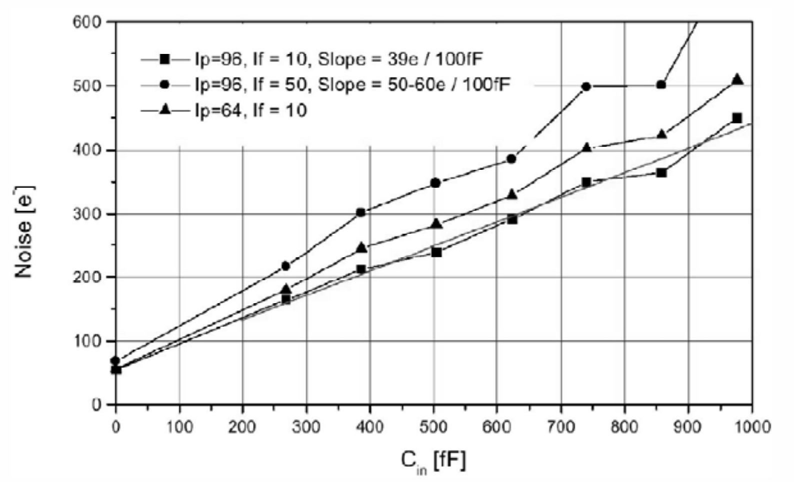
Unlike in planar detectors, interpixel C is only a small component of total

Signal to noise estimate at $10^{16} n_{eq}/cm^2$

- Uses noise vs. capacitance data from unirradiated ATLAS sensors (won't include high leakage current or damage to readout chip)
  - Assume 100fF from preamplifier input and bump bond
  - Also 70e- threshold dispersion


Increasing C noise counteracts improving CCE

Noise≈$60e^{-}+39e^{-}/100fF$



"Progresses on the ATLAS pixel detector", A. Andreazza, *NIMA* vol. 461, pp. 168-171, 2001

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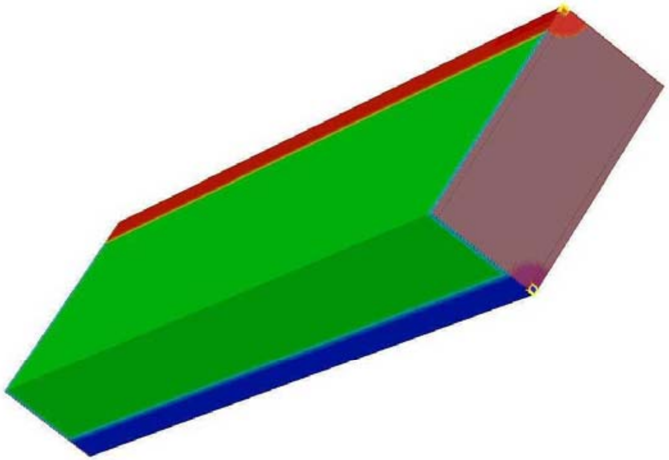
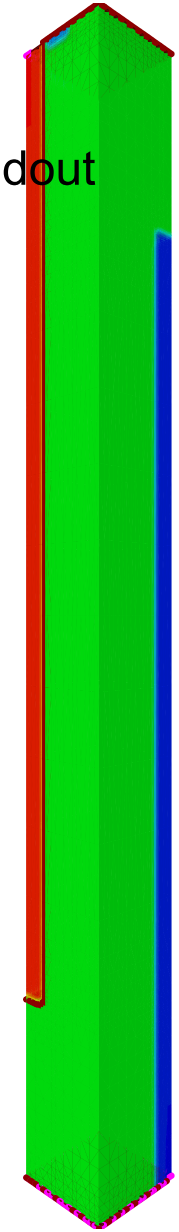
- Comparison of double-sided & standard 3D



Comparison of double-sided & standard 3D

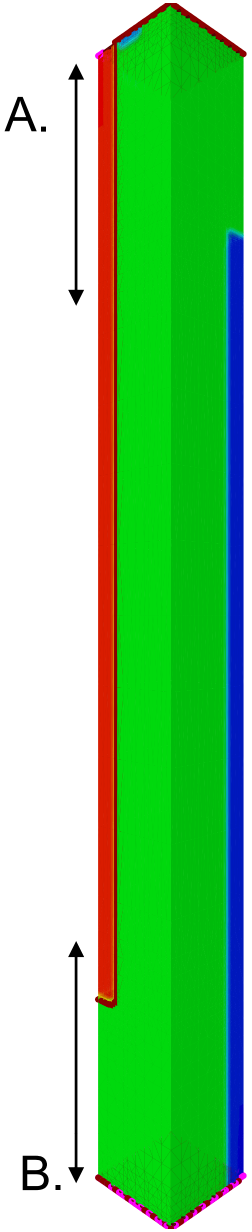


- Full 3D (Parker et al., Stanford, Sintef, ICEMOS)
- Double-sided 3D (CNM, Trento)
  - Readout columns etched from front surface
  - Bias columns etched from back surface
  - Columns don’t pass through full substrate thickness

- The maximum column depth that can be etched is about 250µm (with a 5µm radius)
  - Double-sided 3D simulation uses 250µm columns in a 300µm substrate
  - Full-3D device used for comparison is 250µm thick

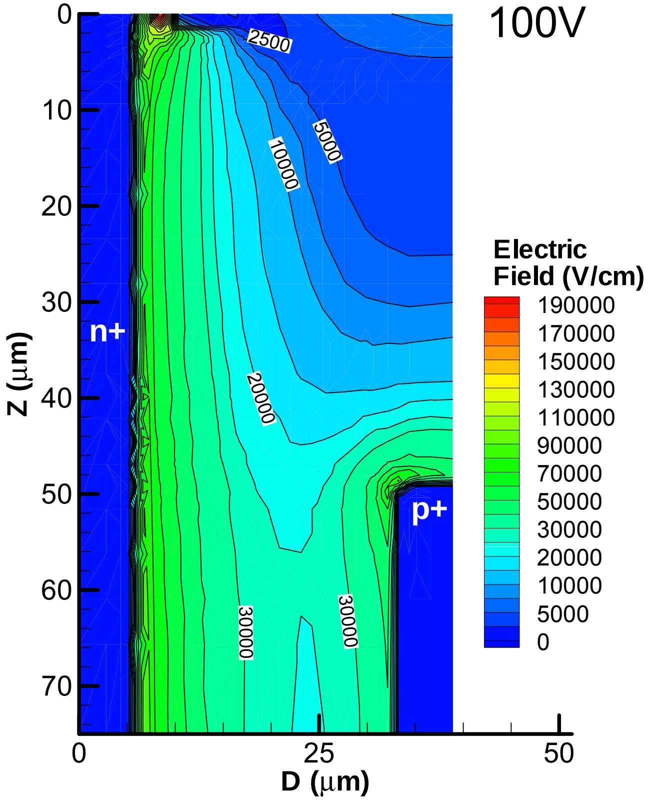
- Device structure used for comparison
  - N+ columns used for readout, p-type substrate
  - 55µm* 55µm pixel size (Medipix)
  - 100V bias

Double-sided 3D field and depletion

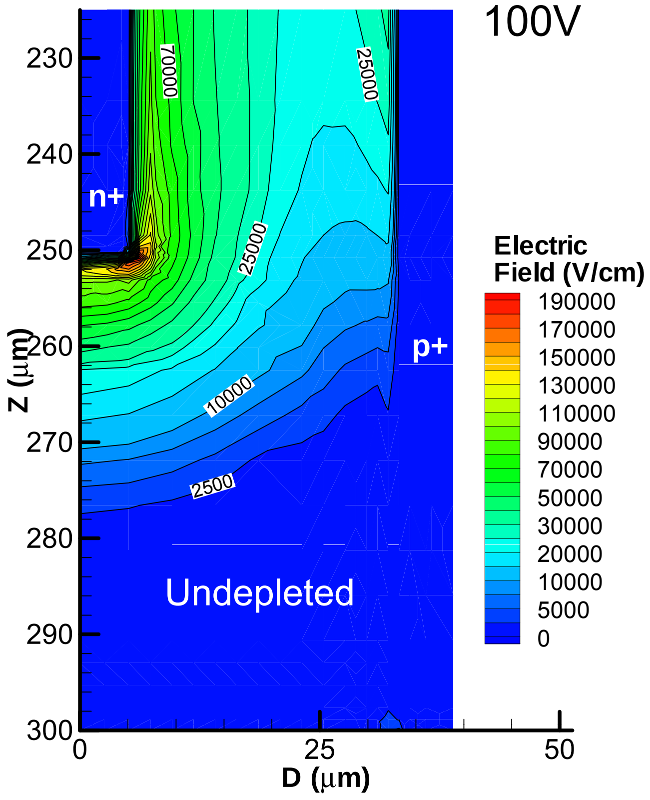


- Where the columns overlap, (from 50μm to 250μm depth) the field matches that in the full-3D detector
- At front and back surfaces, fields are lower as shown below
- Region at back is difficult to deplete at high fluence

A. $10^{16}n_{eq}/cm^{2,}$ front surface

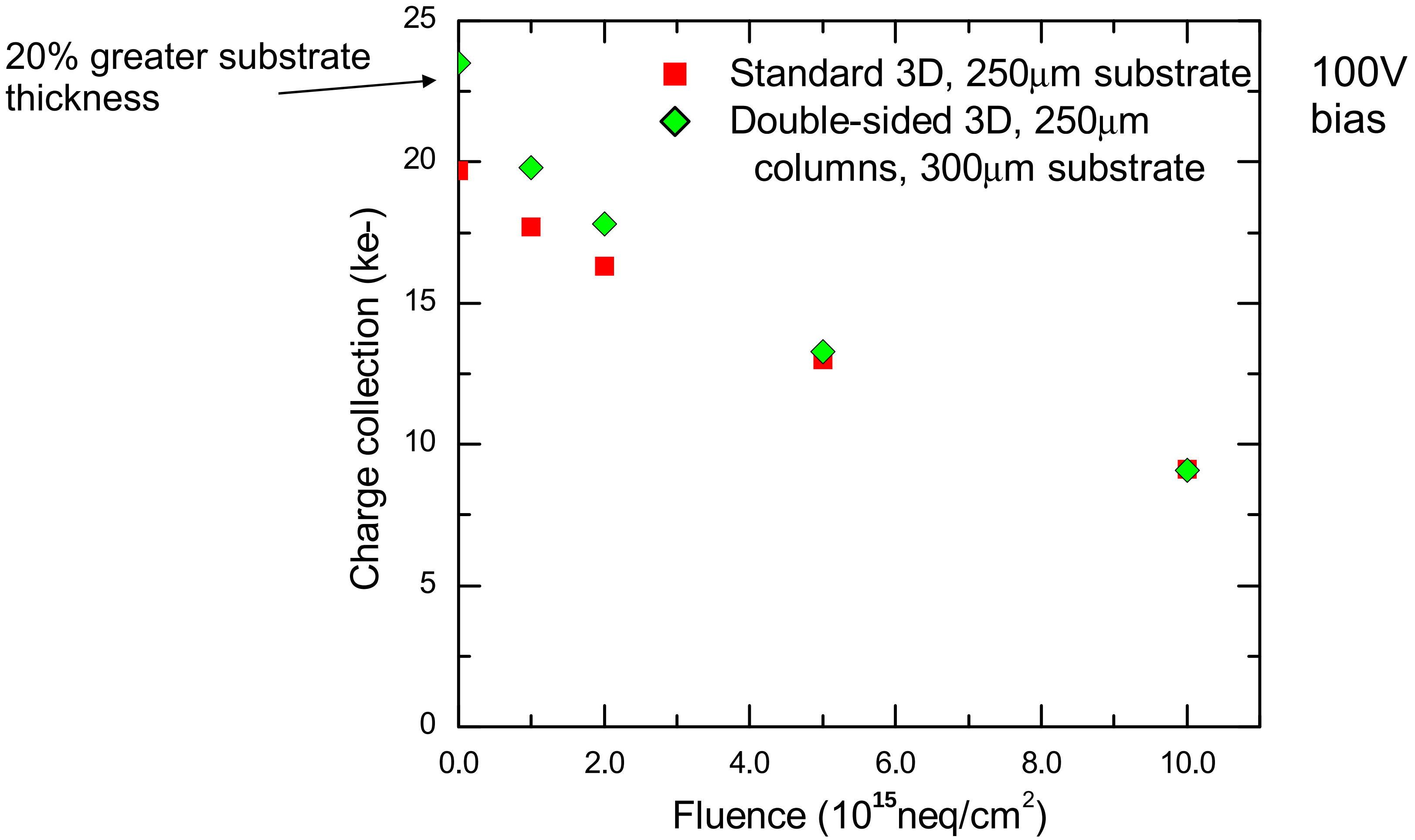


B. $10^{16}n_{eq}/cm^{2,}$ back surface



Collection with double-sided 3D

- Slightly higher collection at low damage
- But at high fluence, results match standard 3D due to poorer collection from front and back surfaces.

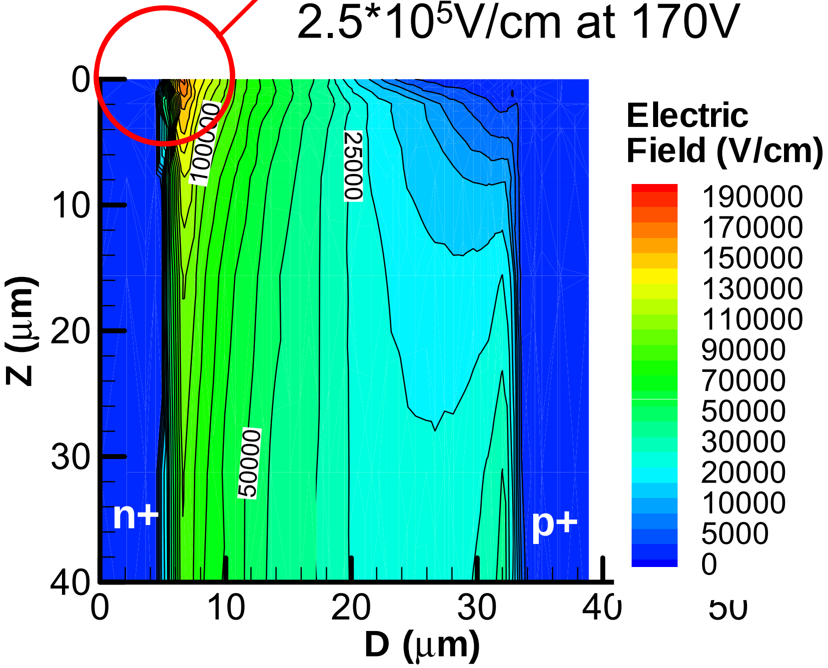


High-field regions in full and double-sided 3D

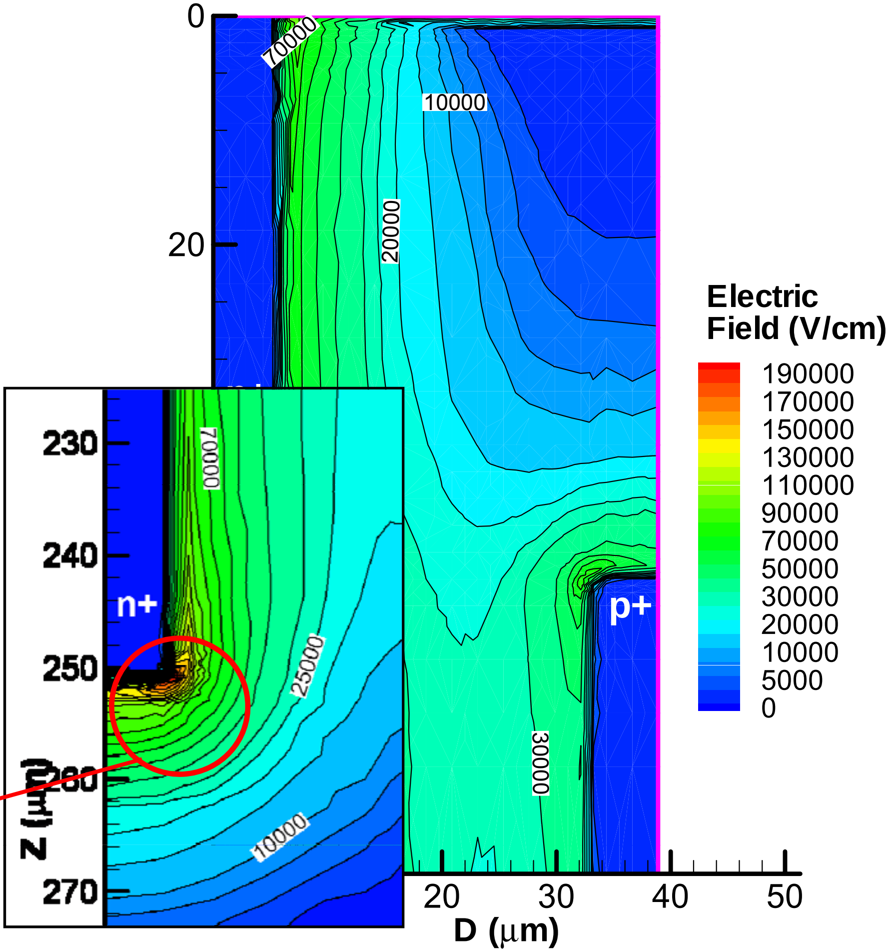
- Simulated full and double-sided 3D using p-spray isolation at 10^{16} n_{eq}/cm^2
- Double-sided 3D is less prone to surface effects because columns are etched from opposite sides, but high-field regions develop at n+ column tip.

Full 3D

Field reaches $2.5*10^5$V/cm at 170V



Double-sided 3D



Field reaches $2.5*10^5$V/cm at 130V

Conclusions

- ***Radiation damage model and comparison with experiment***
  - Simulation models effects of N_{eff} and charge trapping
  - Typically, charge collection results lower than experiment (simulated charge trapping rate is probably too high)

- ***Behaviour of different ATLAS pixel 3D layouts***
  - Devices with few n+ columns per pixel have high depletion voltage (without much improvement in breakdown behaviour), lower average CCE, and poorer CCE uniformity across the active region
  - However, with 6-8 n+ columns the high capacitance reduces SNR, and the volume occupied by the columns becomes larger
  - Need to find a compromise; 4-5 columns?

- ***Comparison of double-sided 3D & standard 3D***
  - Double-sided 3D has similar charge collection performance
    - Greater substrate thickness counteracts poorer collection from surfaces
  - Structure reduces high-field effects at front and back surfaces, but high fields develop at tips of n+ columns

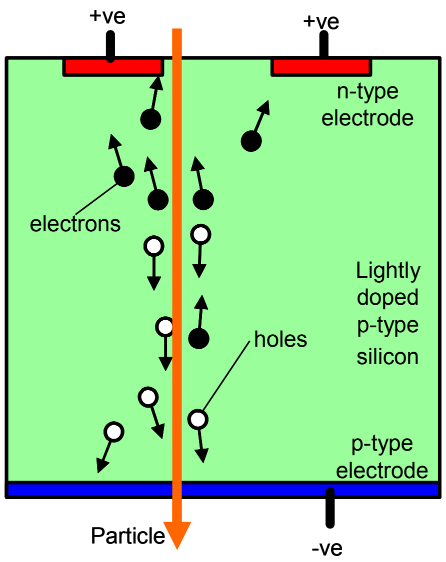
Thank you for listening

Additional slides

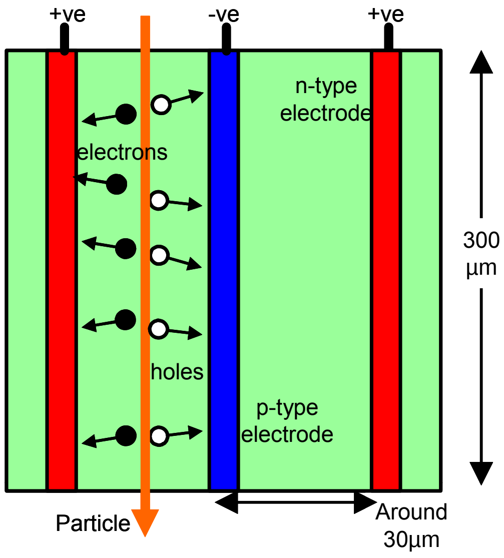
Introduction

- 3D detector structure
  - ~250µm substrate thickness
  - ~50µm electrode spacing
- Small electrode spacing gives:
  - Lower depletion voltage – counteracts increasing N_{eff}
  - Faster collection – counteracts carrier trapping by defects
- Candidate for pixel detectors at SLHC
  - Inner layer will receive $10^{16} n_{eq}/cm^2$ over the run-time of SLHC

Planar



3D



P-type FZ model – proton irradiation

Type	Energy (eV)	Trap	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
Acceptor	Ec-0.42	VV	$9.5*10^{-15}$	$9.5*10^{-14}$	1.613
Acceptor	Ec-0.46	VVV	$5.0*10^{-15}$	$5.0*10^{-14}$	0.9
Donor	Ev+0.36	CiOi	$3.23*10^{-13}$	$3.23*10^{-14}$	0.9

- **See presentation from RD50 June 2007**
- Based on work at Uni. Perugia – see M. Petasecca et al., *IEEE Trans. Nucl. Sci., vol. 53, pp. 2971–2976, 2006*
- Modified to give correct trapping times while maintaining depletion behaviour

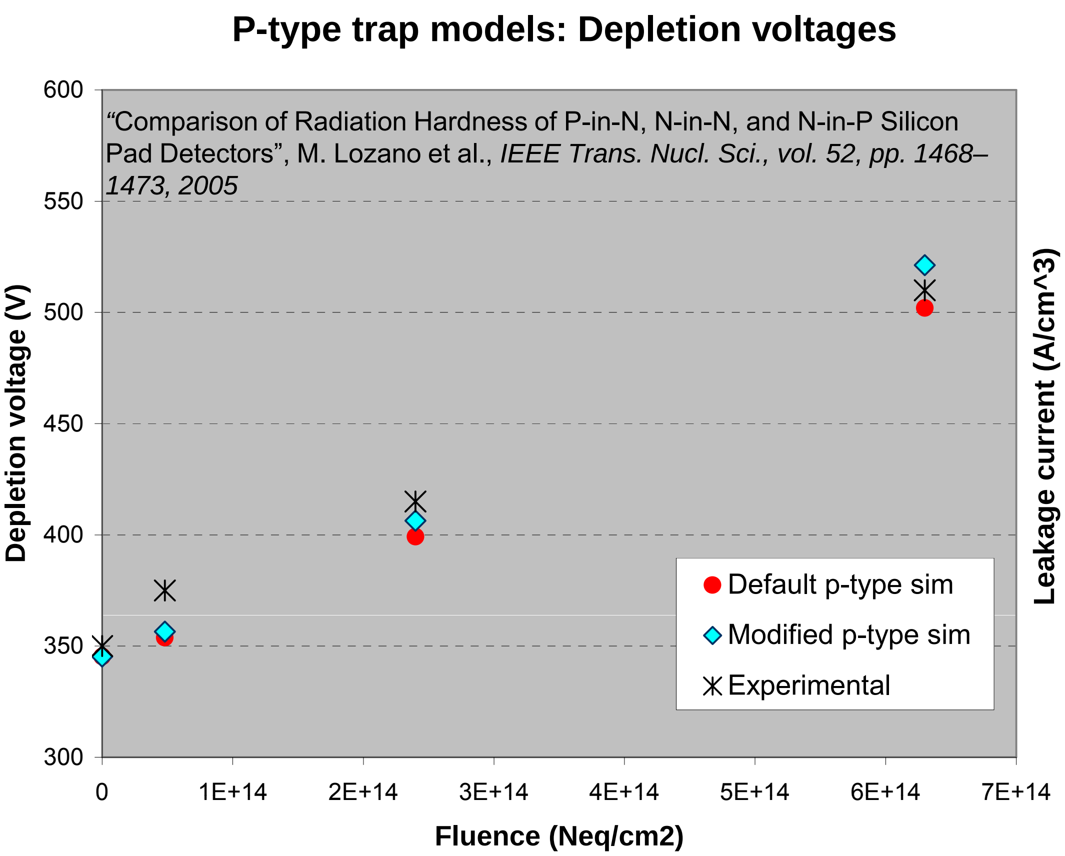
$$\frac{\partial n}{\partial t} = -n/\tau_e \qquad \frac{1}{\tau_e} = \beta_e \Phi_{eq} \qquad \beta_e = v_{th}{}^{e} \sigma_e \eta$$

- Experimental trapping times for p-type silicon (V. Cindro et al., IEEE NSS, Nov 2006) *up to $10^{15} n_{eq}/cm^2$*
  - $\beta_e = 4.0*10^{-7}$cm^{2}s^{-1} $\beta_h = 4.4*10^{-7}$cm^{2}s^{-1}

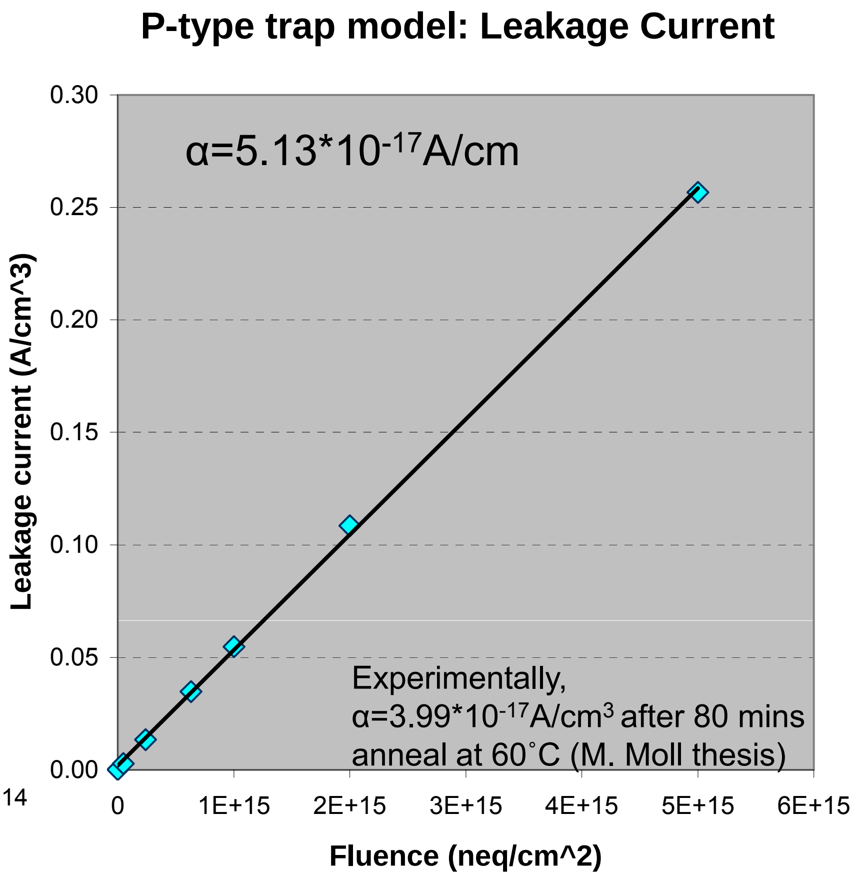
- *Assume these can be extrapolated to $10^{16} n_{eq}/cm^2$*

Comparison with experiment

- Compared with experimental results with proton irradiation
- Depletion voltage matches experiment
- Leakage current is higher than experiment, but not excessive



"Comparison of Radiation Hardness of P-in-N, N-in-N, and N-in-P Silicon Pad Detectors", M. Lozano et al., *IEEE Trans. Nucl. Sci., vol. 52, pp. 1468–1473, 2005*



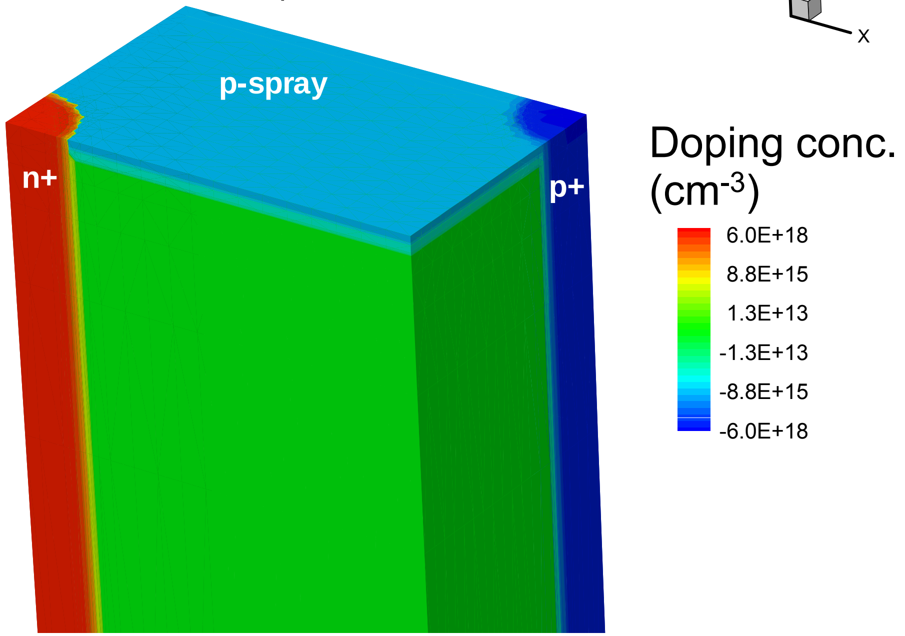
$\alpha=5.13*10^{-17}$A/cm

Experimentally,
$\alpha=3.99*10^{-17}$A/cm^3 after 80 mins anneal at 60˚C (M. Moll thesis)

Device structure and high-field regions

- P-spray links p+ columns to n+
- So, the p-spray is at the same potential as the p+, resulting in high field at front surface where it meets the n+ columnsAt higher bias the p-spray around the n+ column becomes depleted
- These effects won’t be greatly affected by the electrode spacing itself

5-column ATLAS 3D,
$10^{16} n_{eq}/cm^2$, 150V bias



5-column ATLAS 3D,
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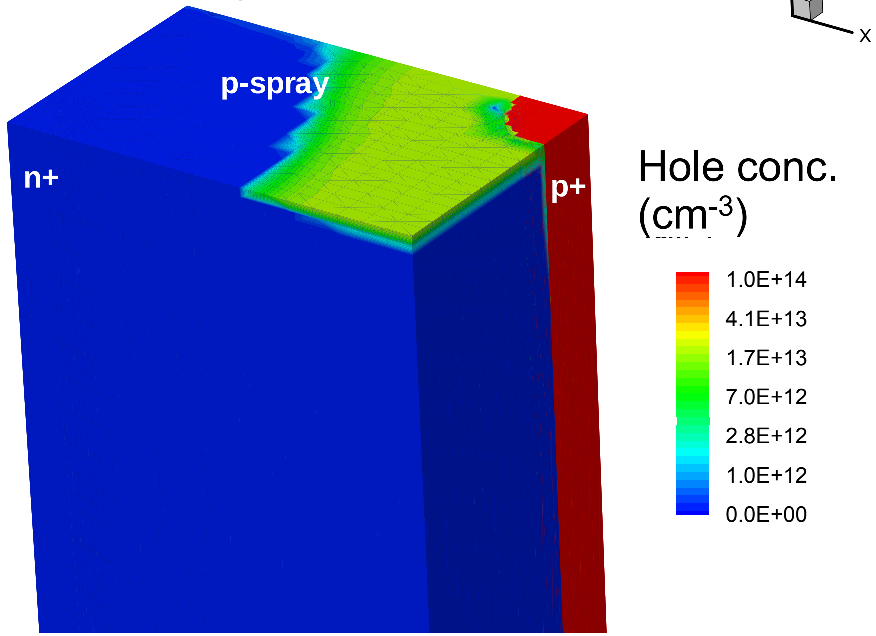
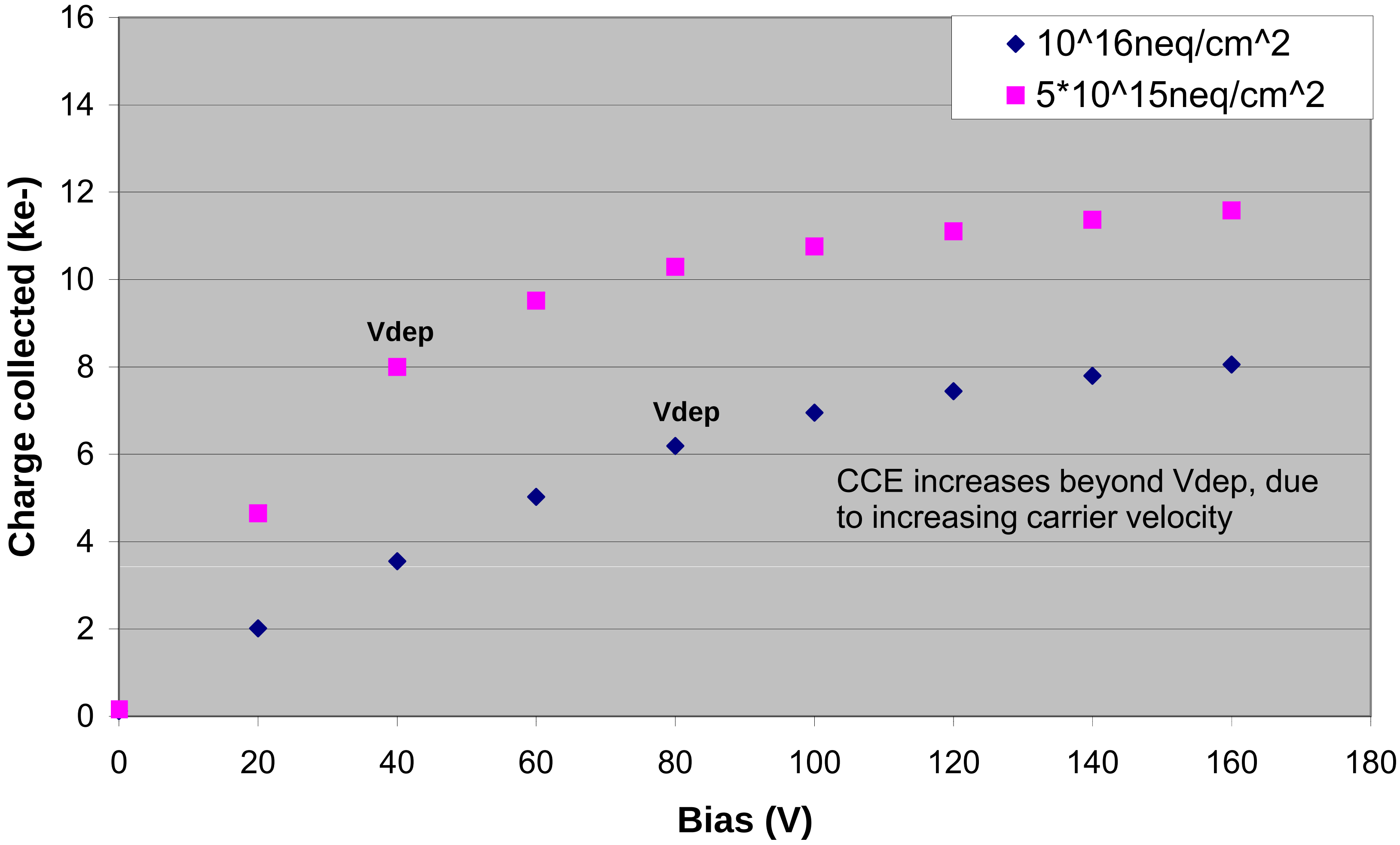


Example of CCE with varying bias

- CCE curves show a smaller gradient after depletion voltage is reached

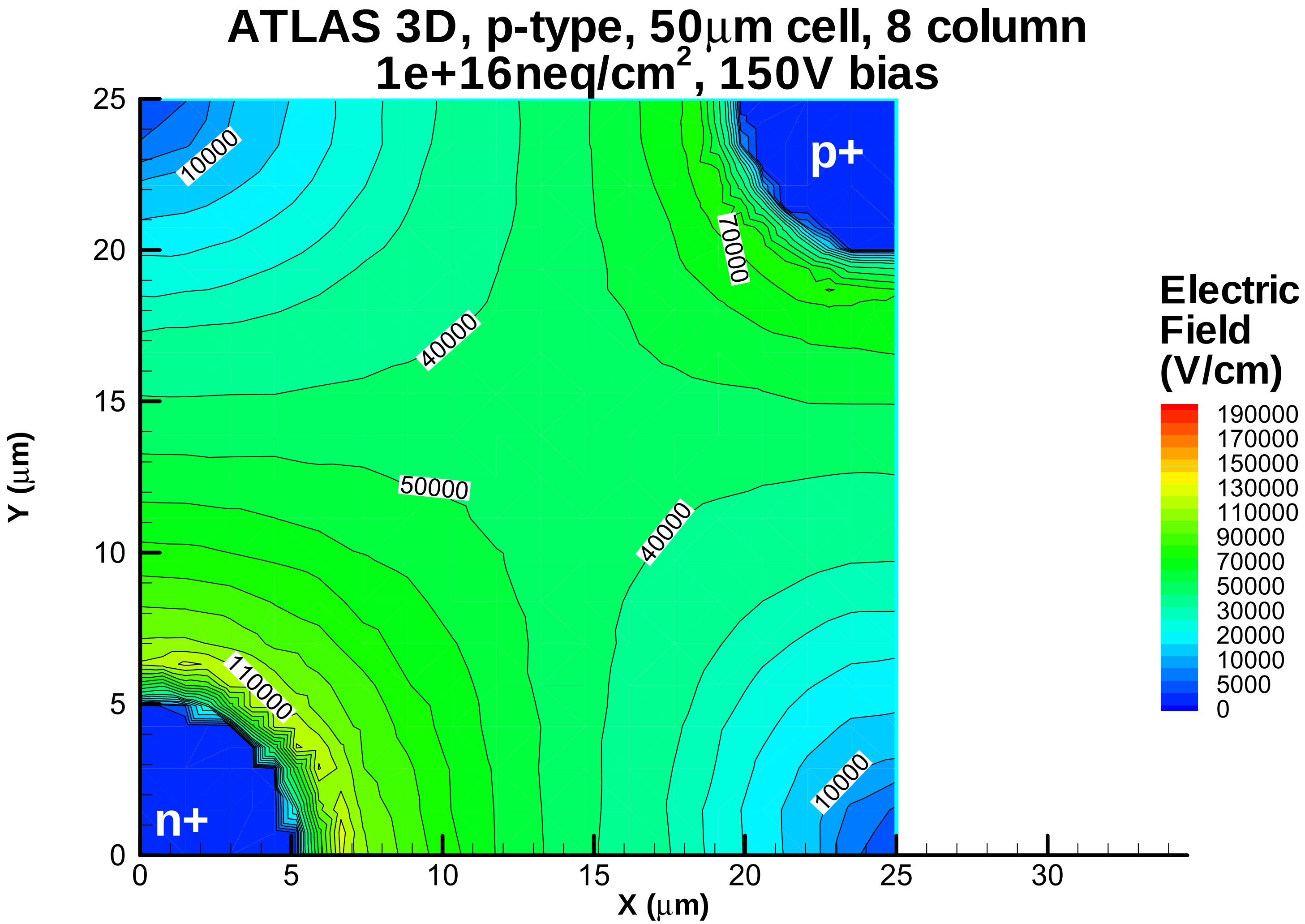
Collection vs bias in 5-column ATLAS



CCE increases beyond Vdep, due to increasing carrier velocity

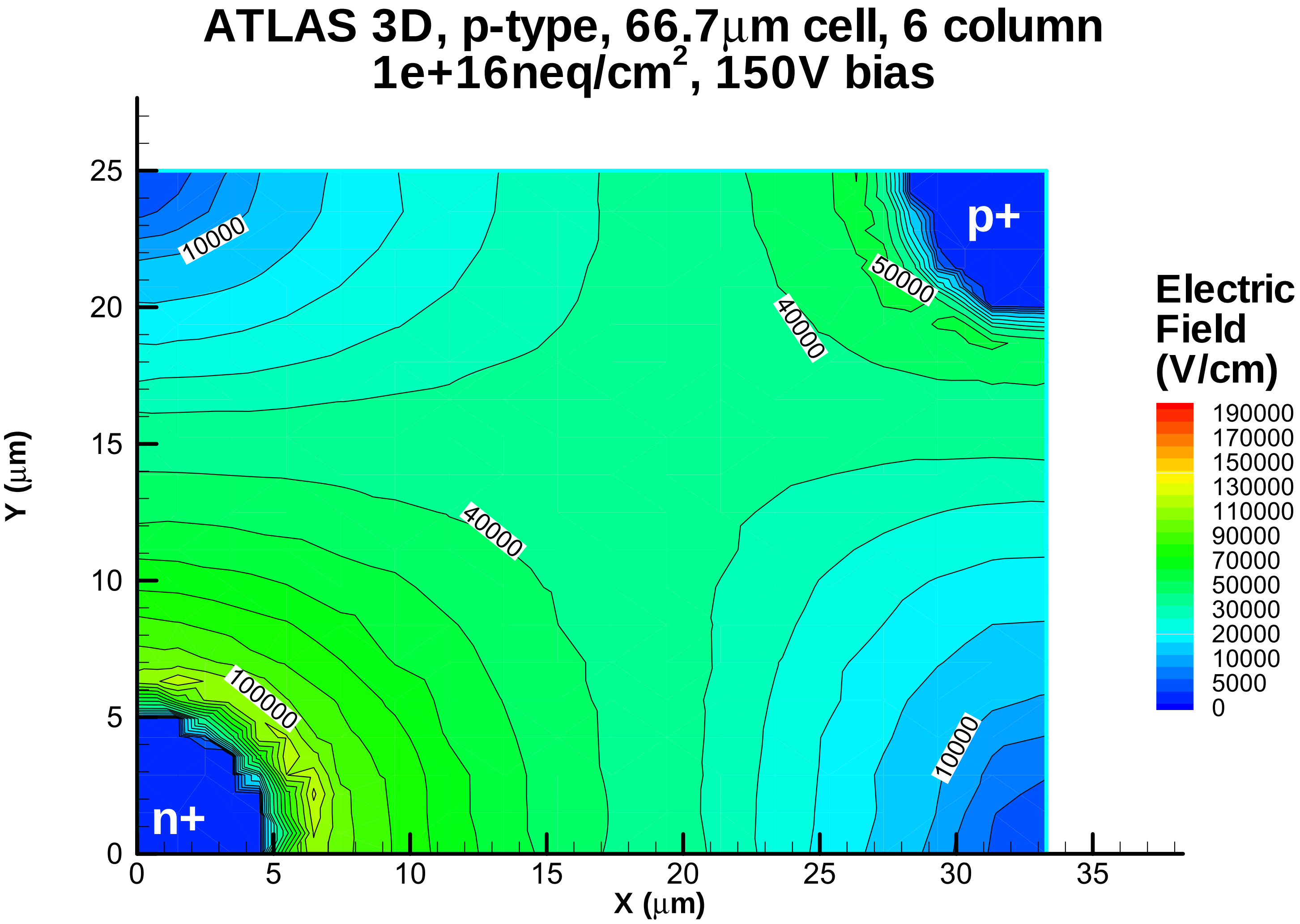
Electric field distribution – 8 columns per pixel

- The previous simulations showed an “average” CCE for the pixel, but the uniformity across the pixel is also important. The following slides show how the electric field distribution varies with the pixel layout



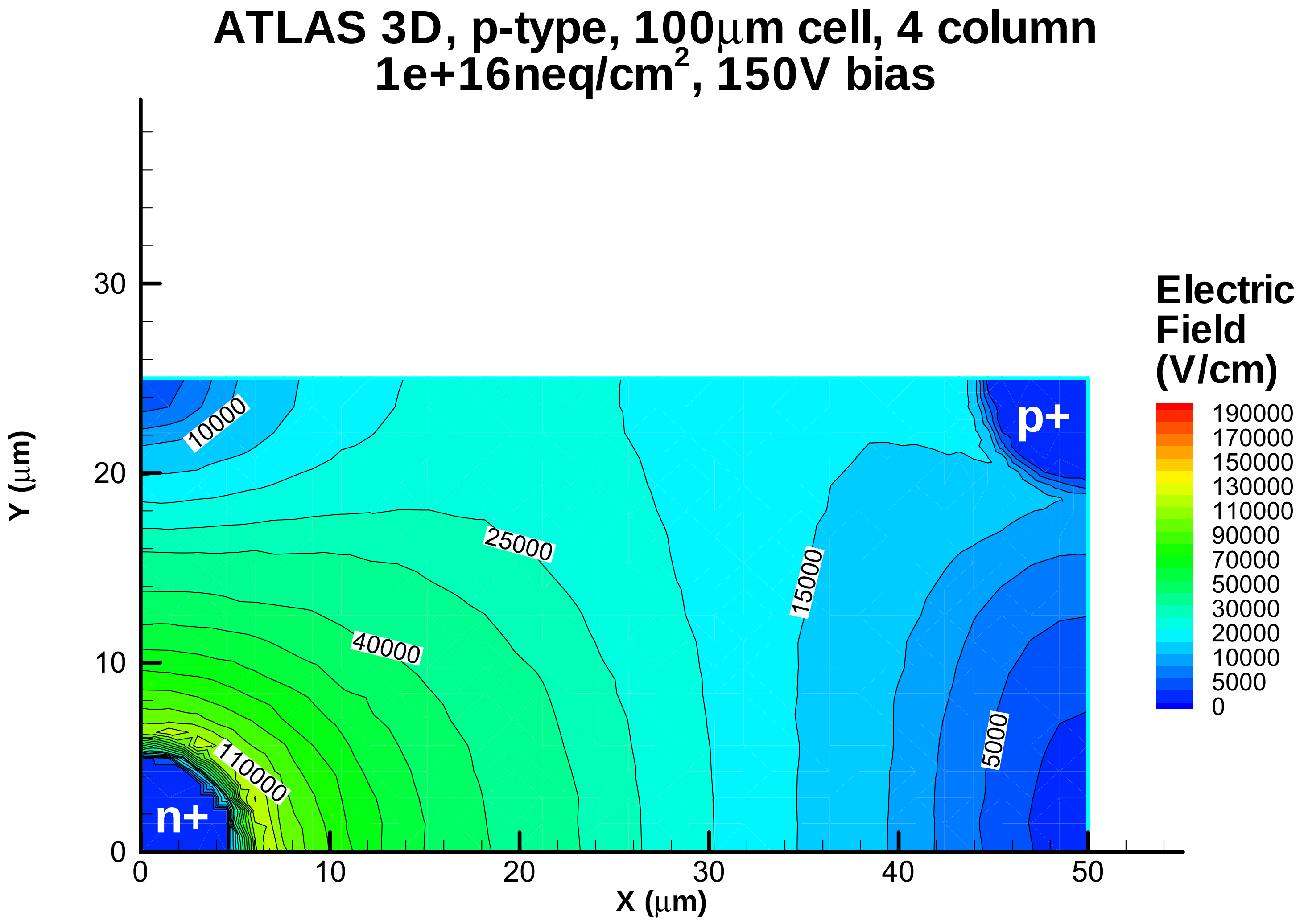
Electric field distribution – 6 columns per pixel

- Even at $10^{16} n_{eq}/cm^2$, the devices with 6-8 columns show a reasonably uniform electric field across the pixel, with the field being weakest at the null points at the corners



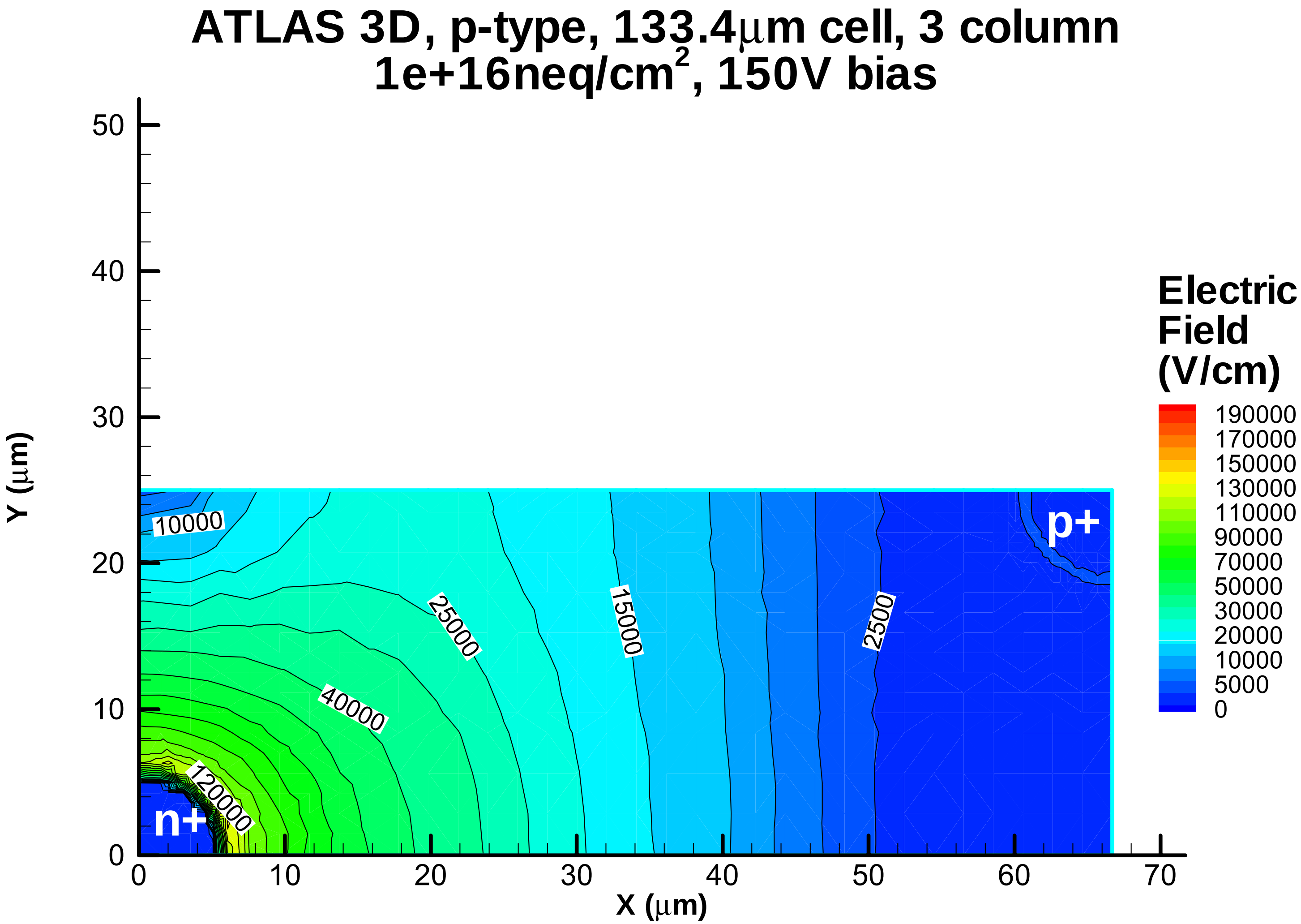
Electric field distribution – 4 columns per pixel

- As the length of the cell gets longer, the low-field regions become more substantial. Depending on where a track hits, the collection may be less than the “average” value calculated earlier.



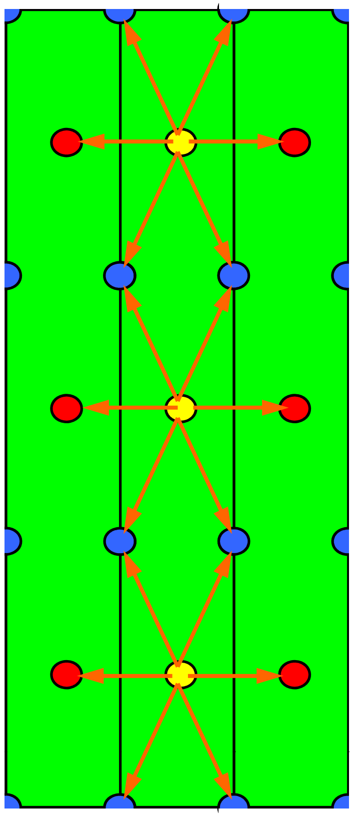
Electric field distribution – 3 columns per pixel

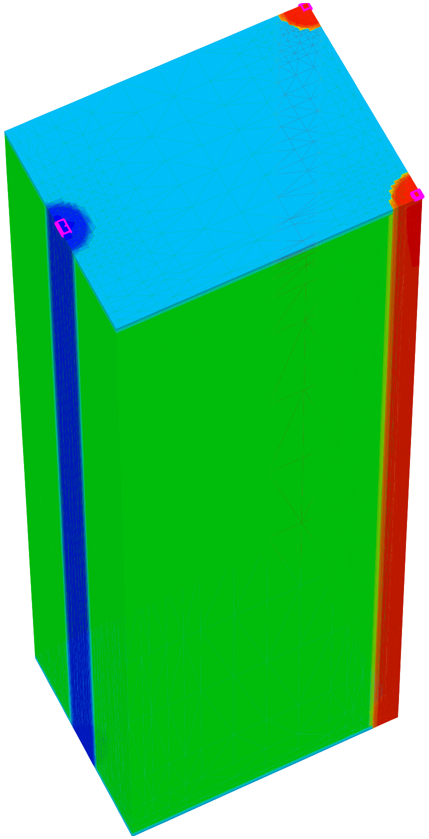
- If the longer pixel lengths are used, the region around the p+ has a weak field, and might not be depleted.



ATLAS 3D capacitance

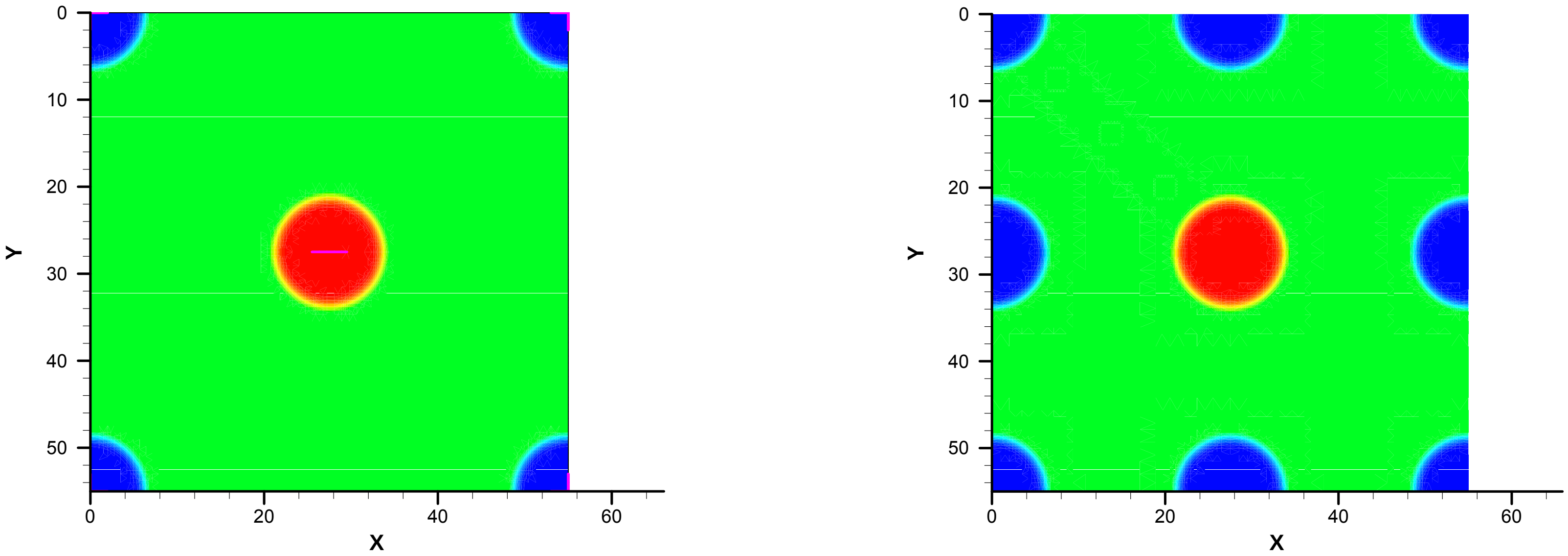
- The simulations will take into account nearest neighbouring p+ columns, and n+ columns in adjacent pixels.
- These simulations used saturated oxide charge (10^{12}cm^{-2}) but *no bulk damage*





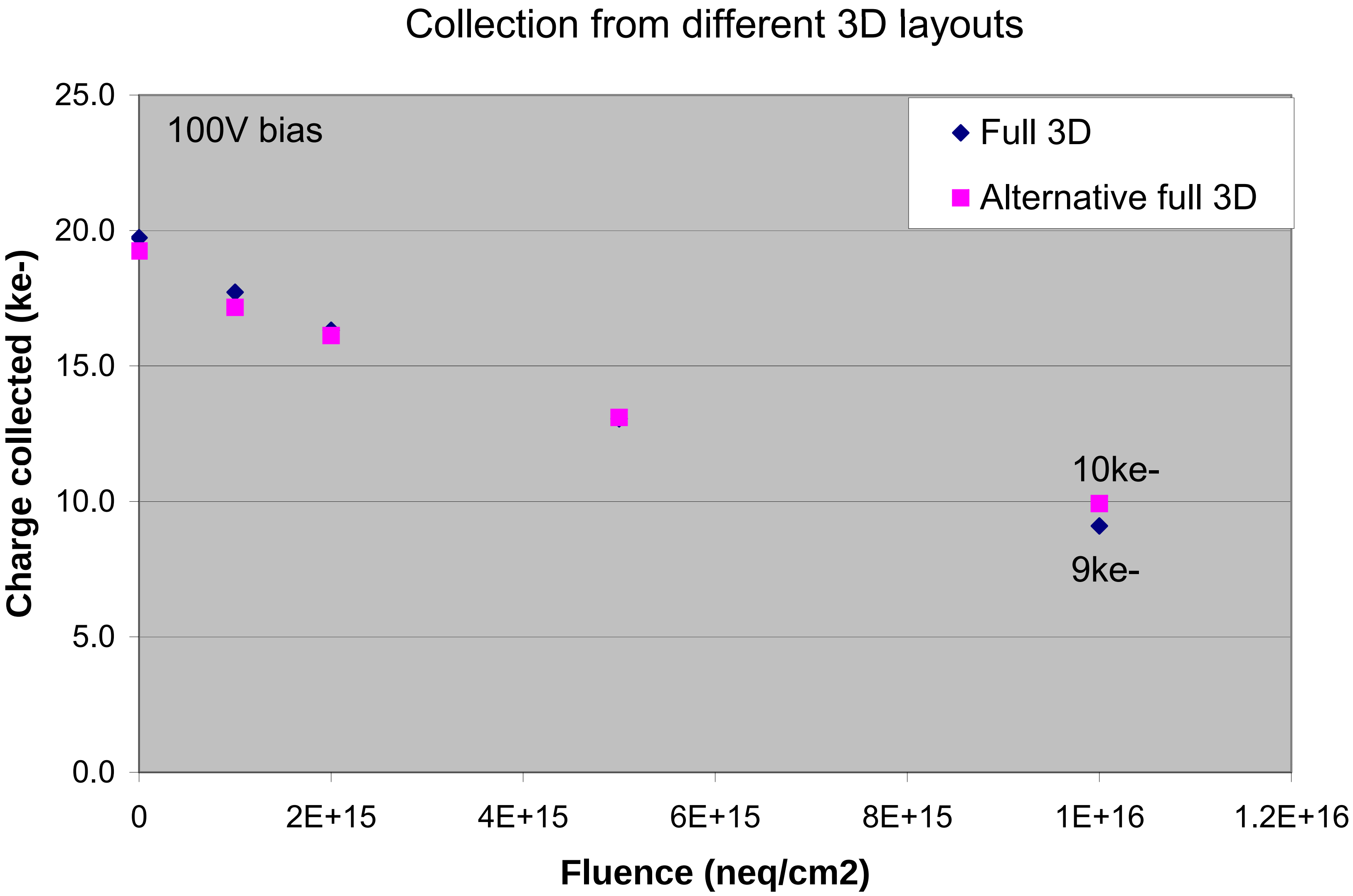
Design choices with 3D

- Choice of electrode layout:
  - In general, two main layouts possible



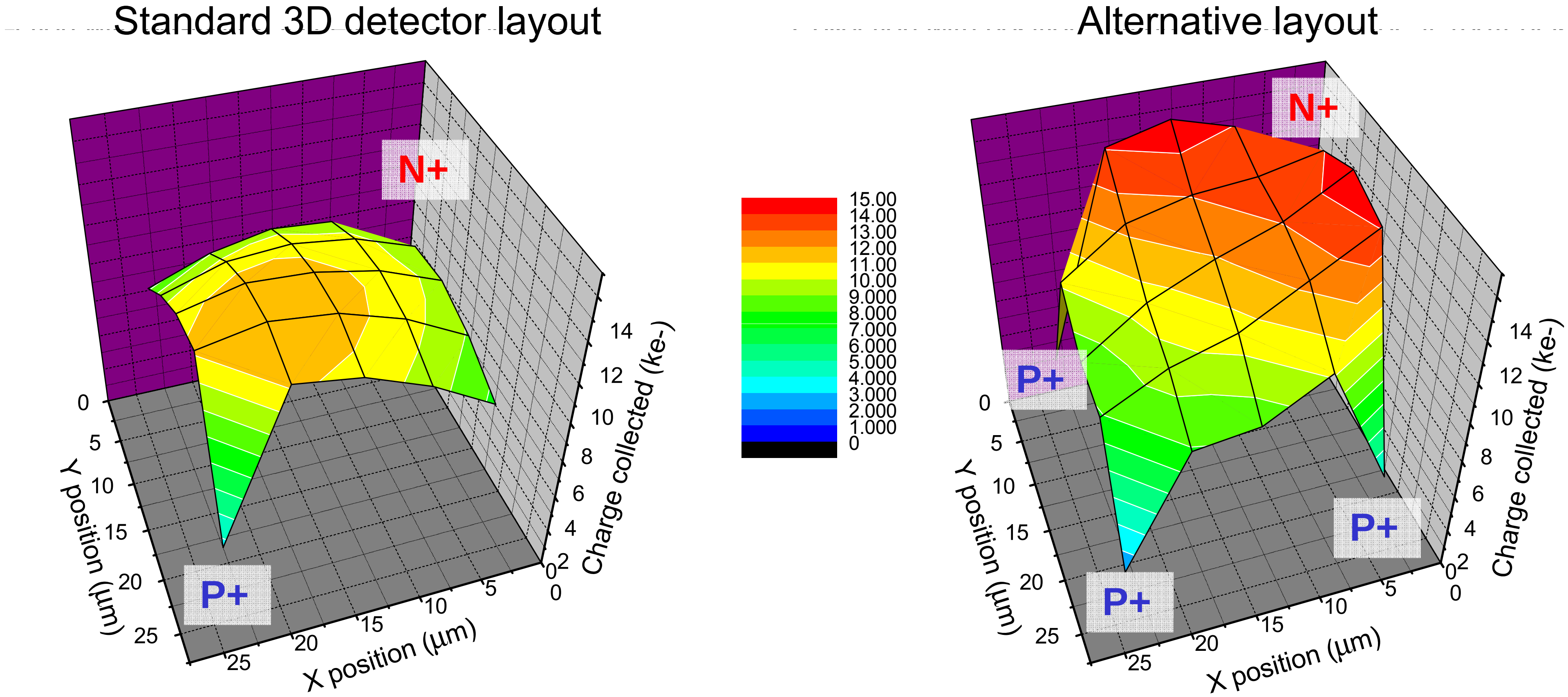
CCE with different 3D layouts

- Little difference in results
- Alternative structure has slightly better average CCE at $10^{16}n_{eq}/cm^2$



Comparison of layouts at $10^{16}n_{eq}/cm^2$

- Layout with 3 p+ columns per n+ gives slightly higher average CCE (10ke- compared to 9ke-) *but* CCE with position is much less uniform
  - Greater electrode volume, greater asymmetry in field & weighting field
  - Alternative structure doesn't appear worthwhile

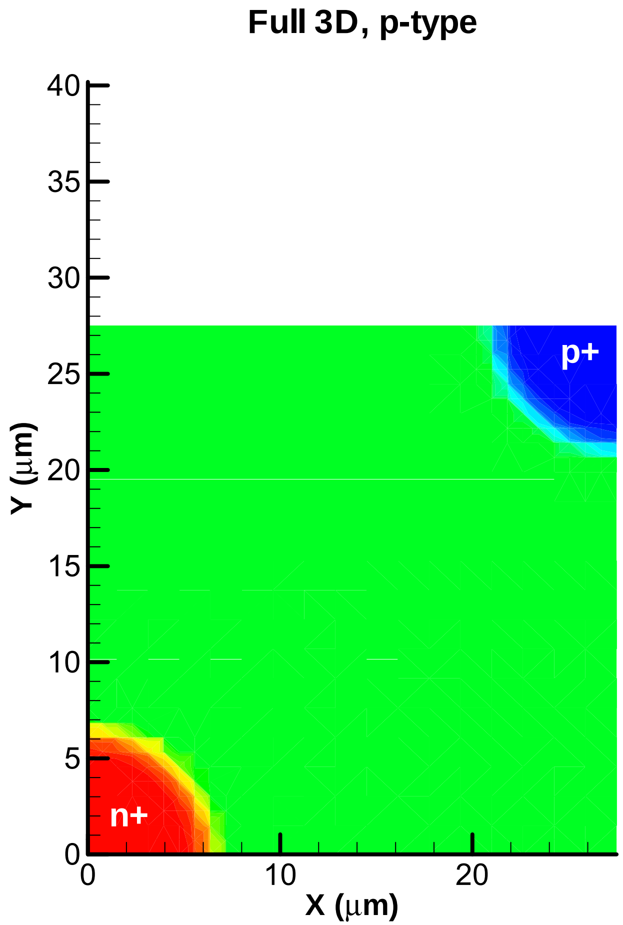


Standard 3D detector layout

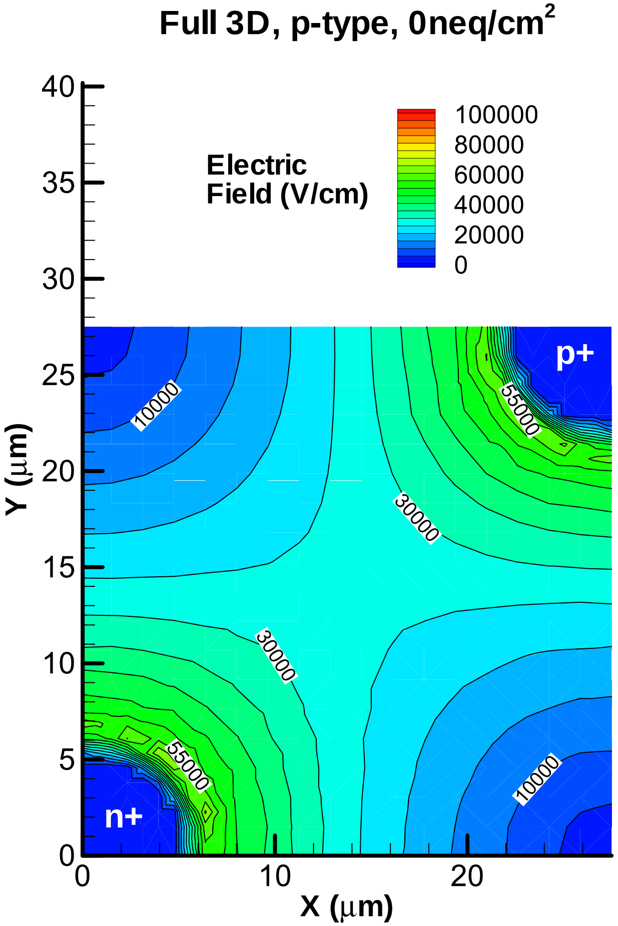
Alternative layout

Full 3D – electric field at 100V

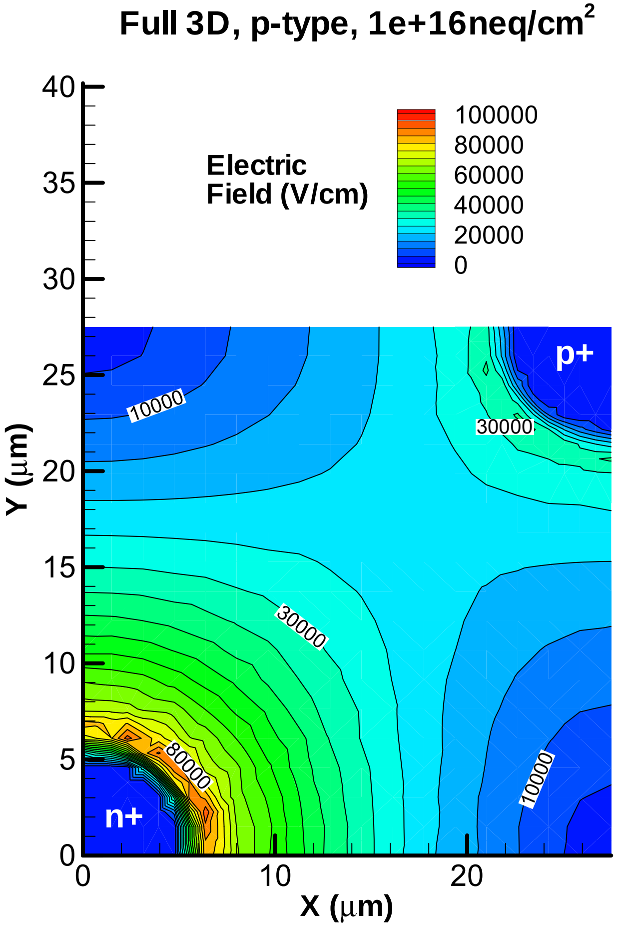
- Full depletion is achieved well under 100V, but electric field becomes less symmetric at high fluence



No damage

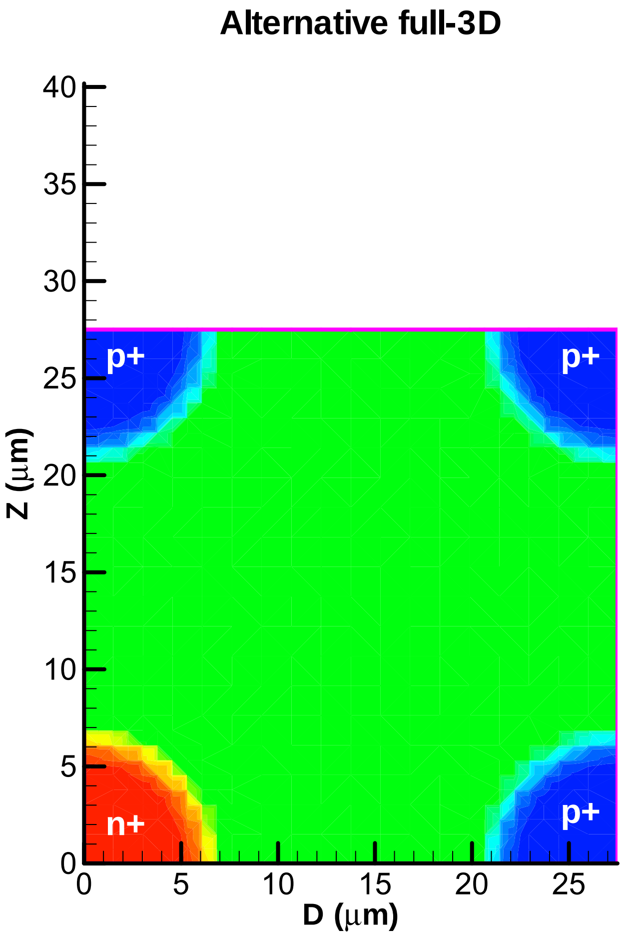


10^{16} n^{eq}/cm^2

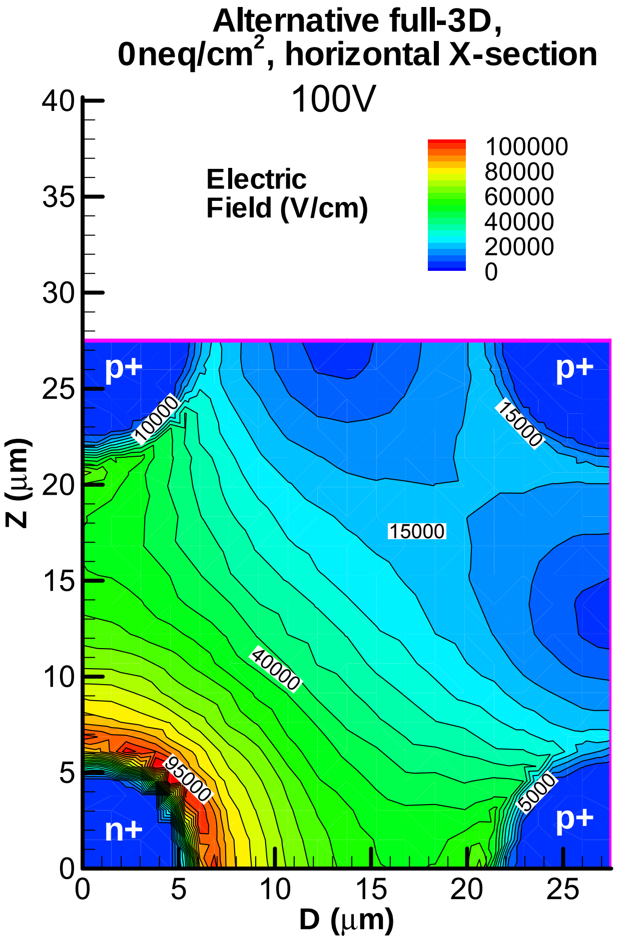


Alternative full-3D

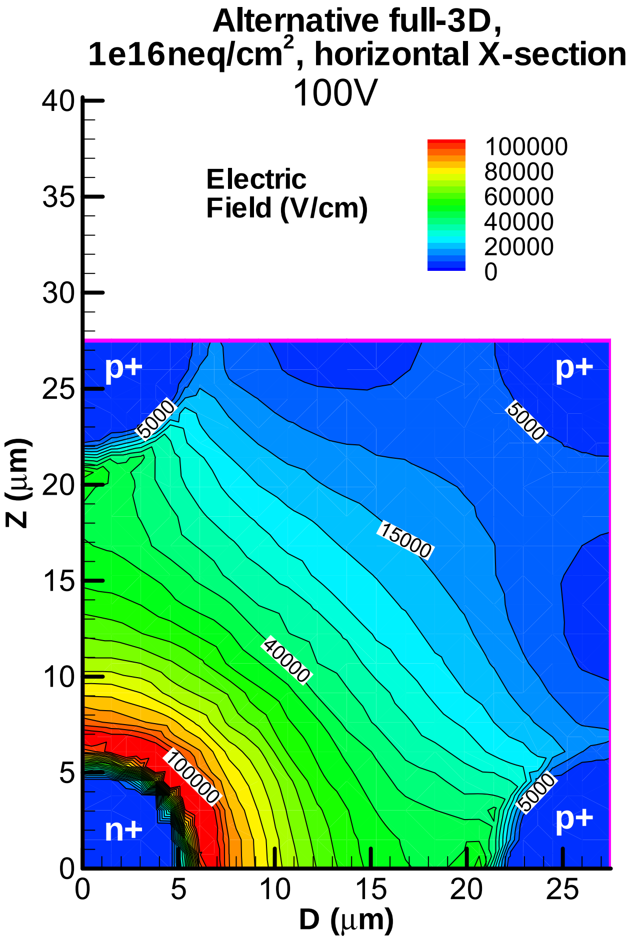
- 3 bias columns per n+ readout column
- Structure increases field around n+, reduces it around p+, particularly at high fluences



No damage



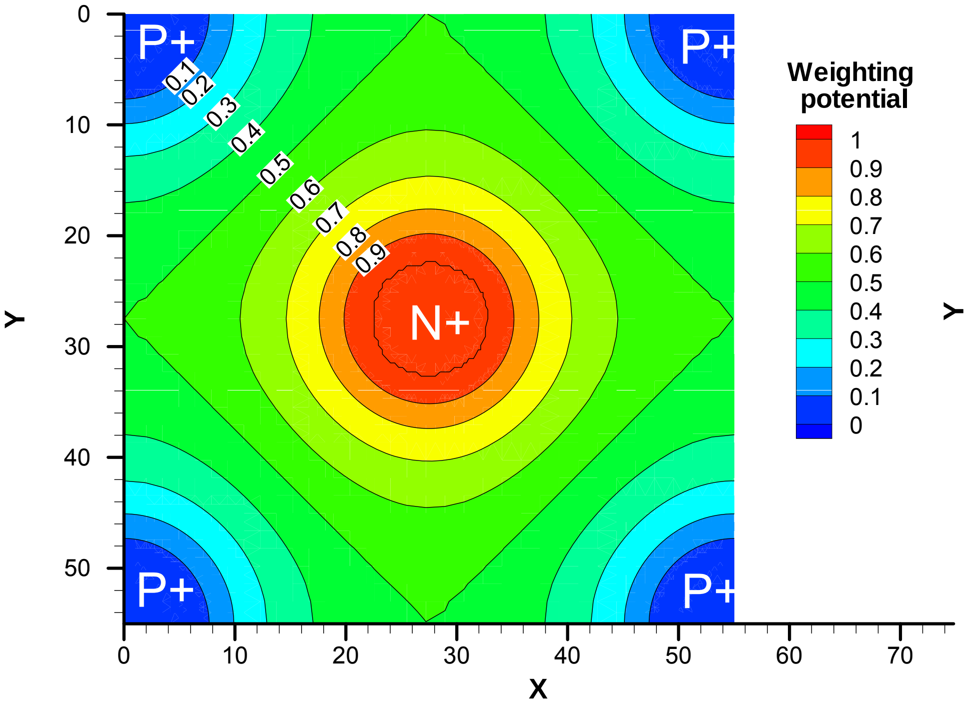
10^{16} n^{eq}/cm^2



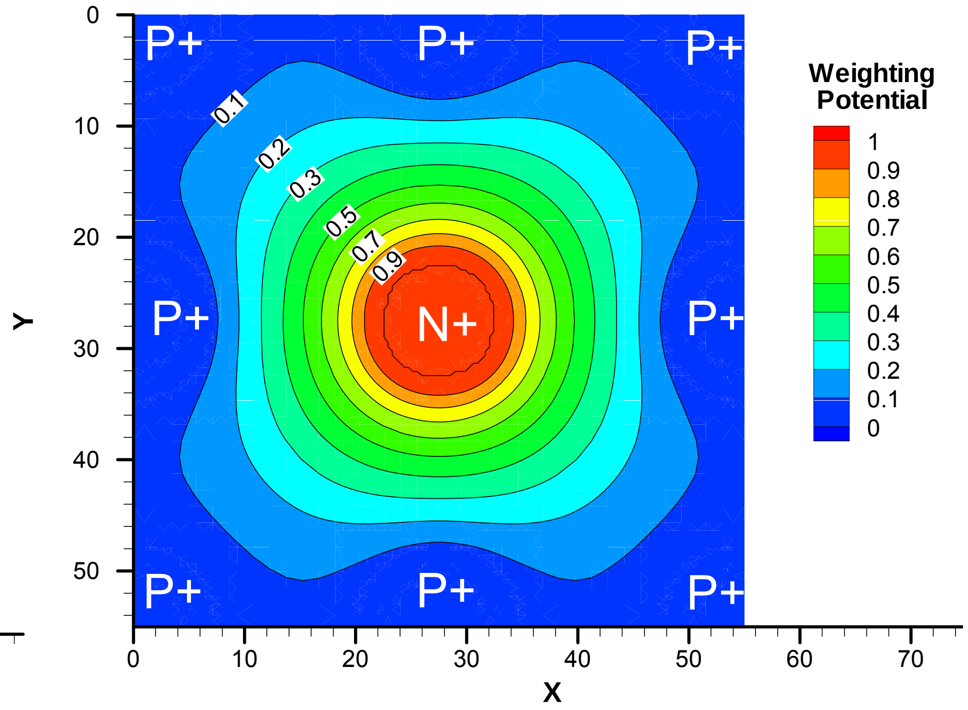
Weighting potentials

- These two layouts give different weighting potentials
- Standard full 3D: Symmetrical for both electrons and holes
- Alternative full 3D: Favours electrons
  - Possibly larger total signal
  - Poorer uniformity in response at different positions?

Standard layout

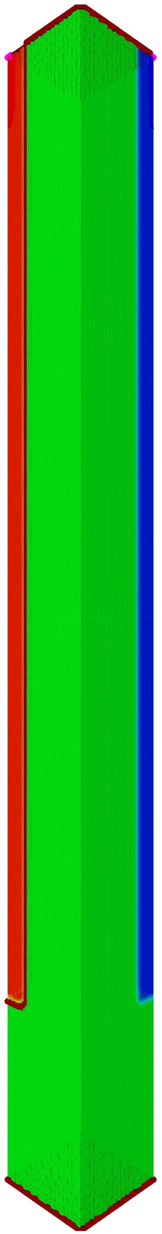


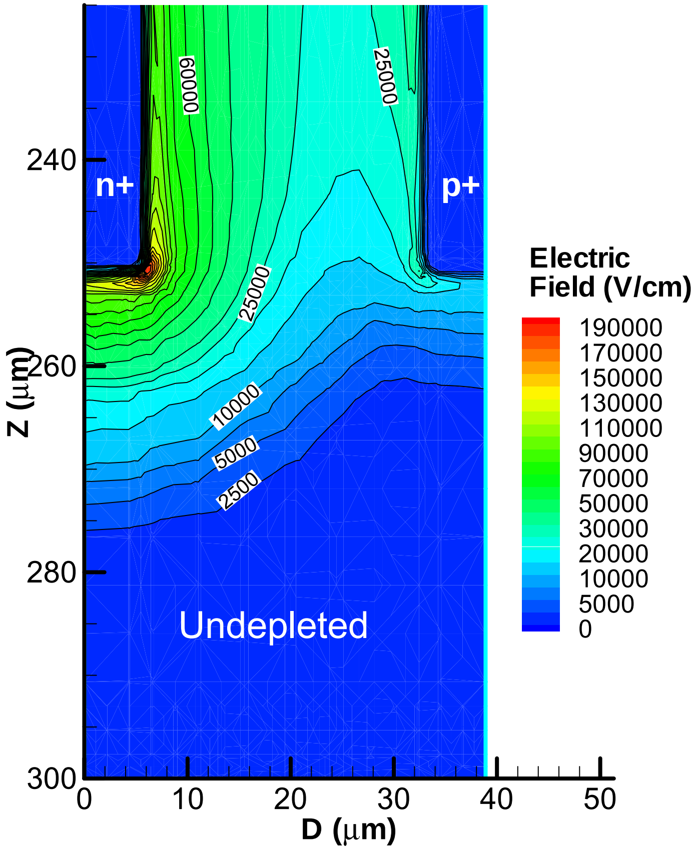
Alternative layout



Dual-column 3D (BNL)

- Columns etched from front partially through wafer
- Where columns overlap, field matches full-3D
- Back surface has lower field, difficult to deplete



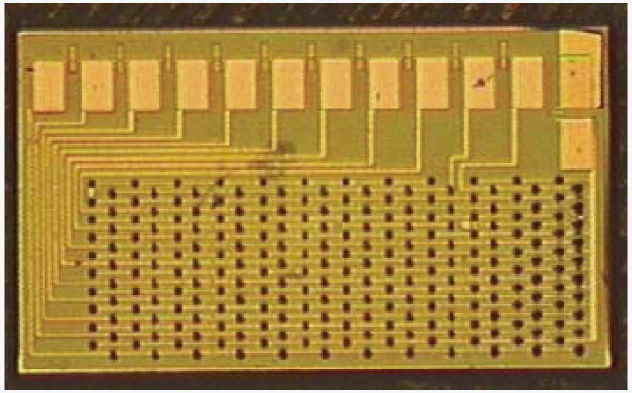


Dual-column 3D, p-type, 1e16neq/cm^2, back surface

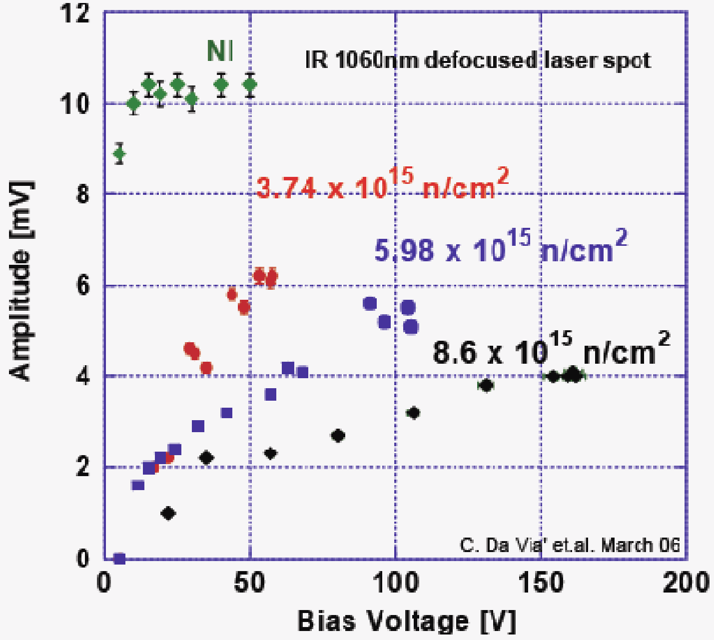
Cinzia Da Via' - Brunel/Manchester- Atlas 3D-pixel meeting Liverpool - December 2006

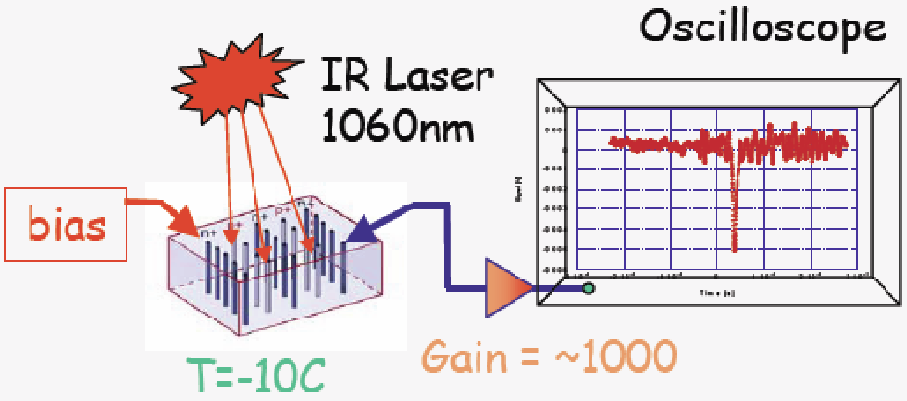
3D is radiation hard: Tests with baby-Atlas sensors

C. DaVia. J. Hasi, S Watts, (Brunel/Manchester),V. Linhart, T. Slavicheck,
T Horadzof, S. Pospisil (Technical University, Praha), C. Kenney (MBC), S. Parker (Hawaii/LBL)



- Volume = 1.2 x 1.33 x 0.23 mm³
- 3 electrode Atlas pixel geometry 71 µm IES
- n-electrode readout
- n-type before irradiation -12 kΩ cm
- Irradiated with reactor neutrons (Praha)





Oscilloscope

IR Laser 1060nm

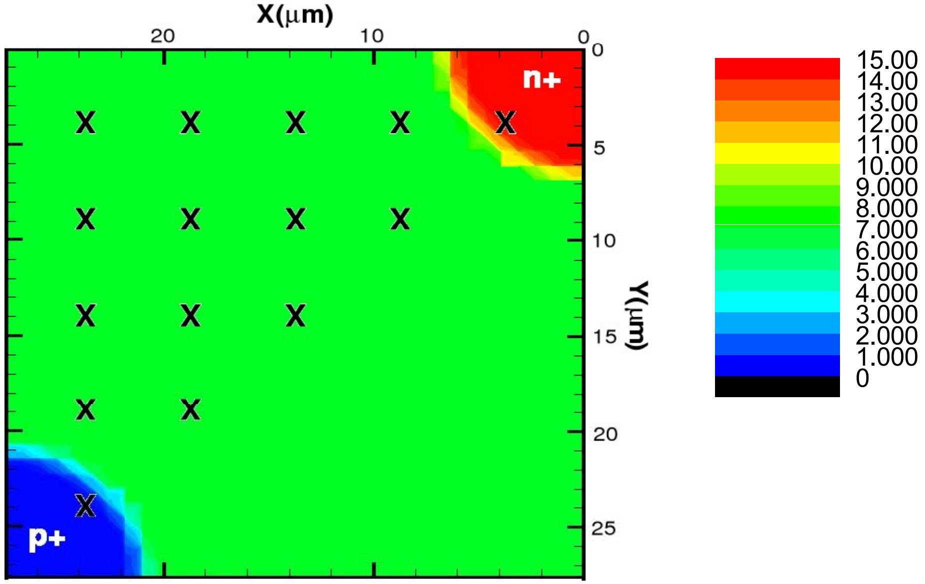
bias

T=-10C

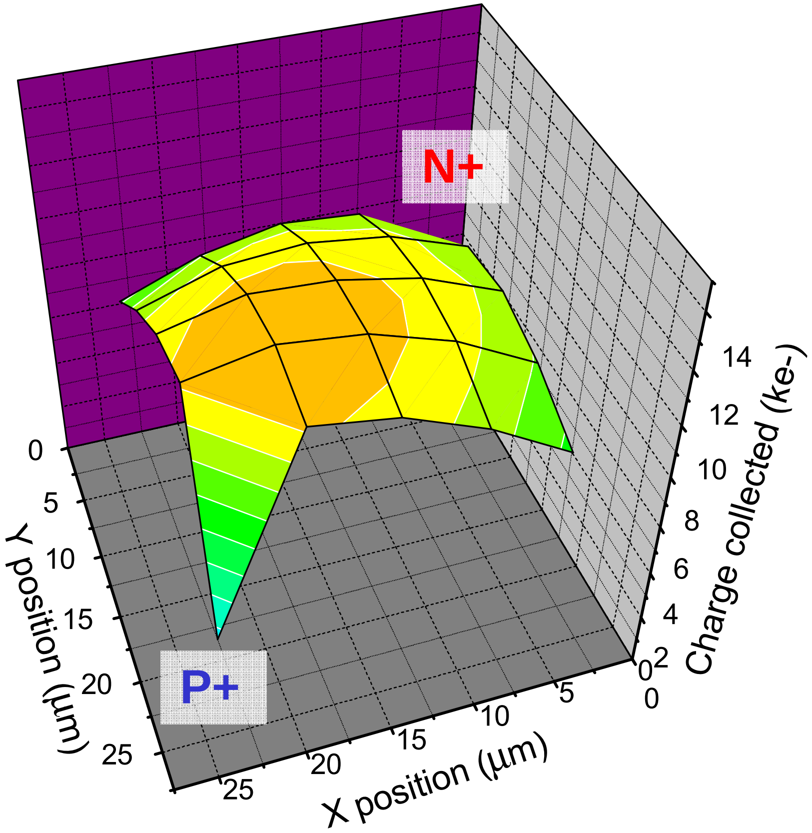
Gain = ~1000

Variation in CCE with position at $10^{16} n_{eq}/cm^2$

- Simulated a series of particle tracks passing through a standard full 3D detector at different positions (100V bias)
- Columns have low sensitivity
- Aside from this, charge collected varies from around 8-12ke-



Positions of particle tracks



Collection with position - 3D detector at 100V bias