UNIVERSITY of GLASGOW

EPSRC Engineering and Physical Sciences Research Council

diamond

Simulation results from double-sided and standard 3D detectors

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Overview

- Simulations of different 3D detectors in ISE-TCAD
  - Comparison of double-sided 3D and full-3D detectors before irradiation
  - Radiation damage models
  - Preliminary results of radiation damage modelling

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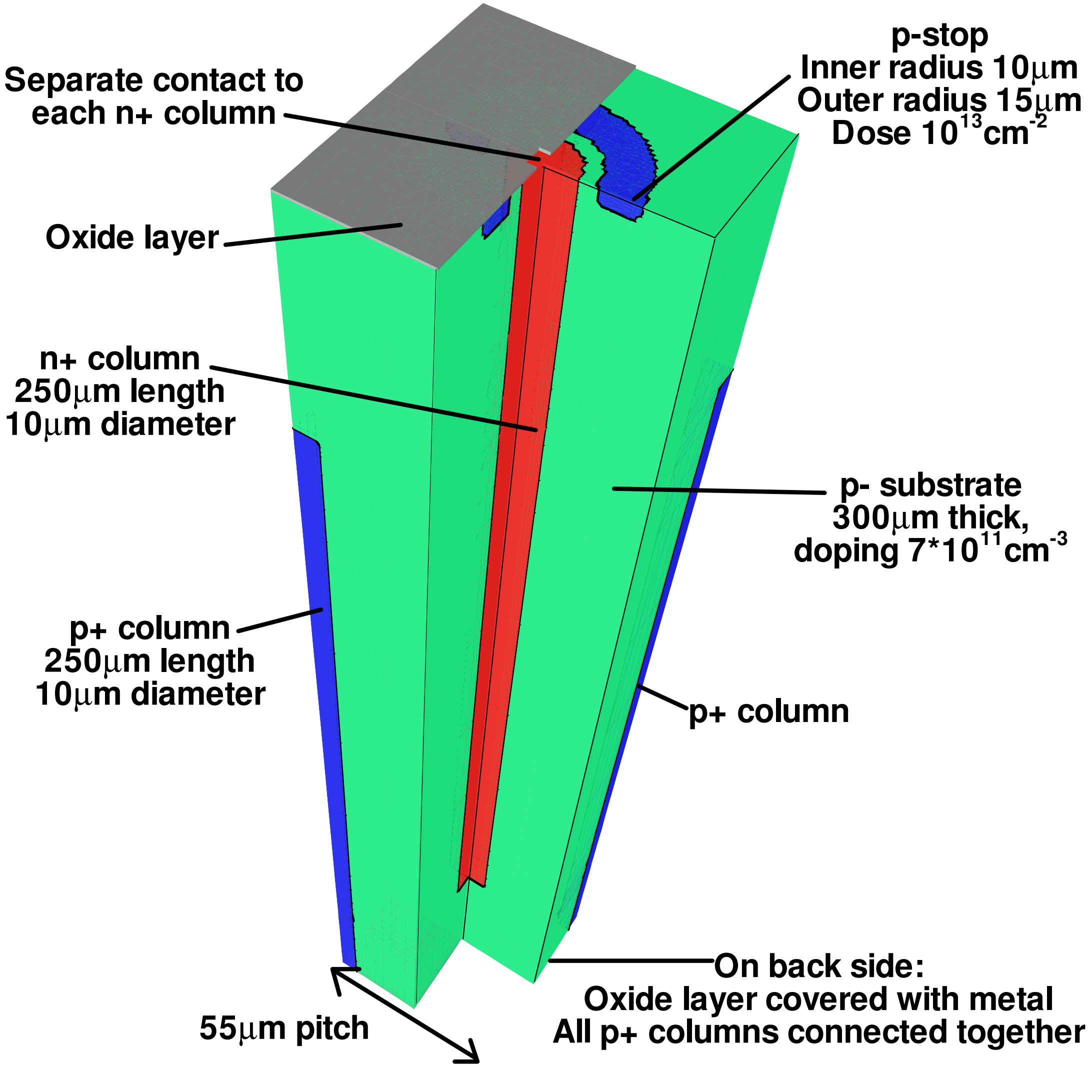
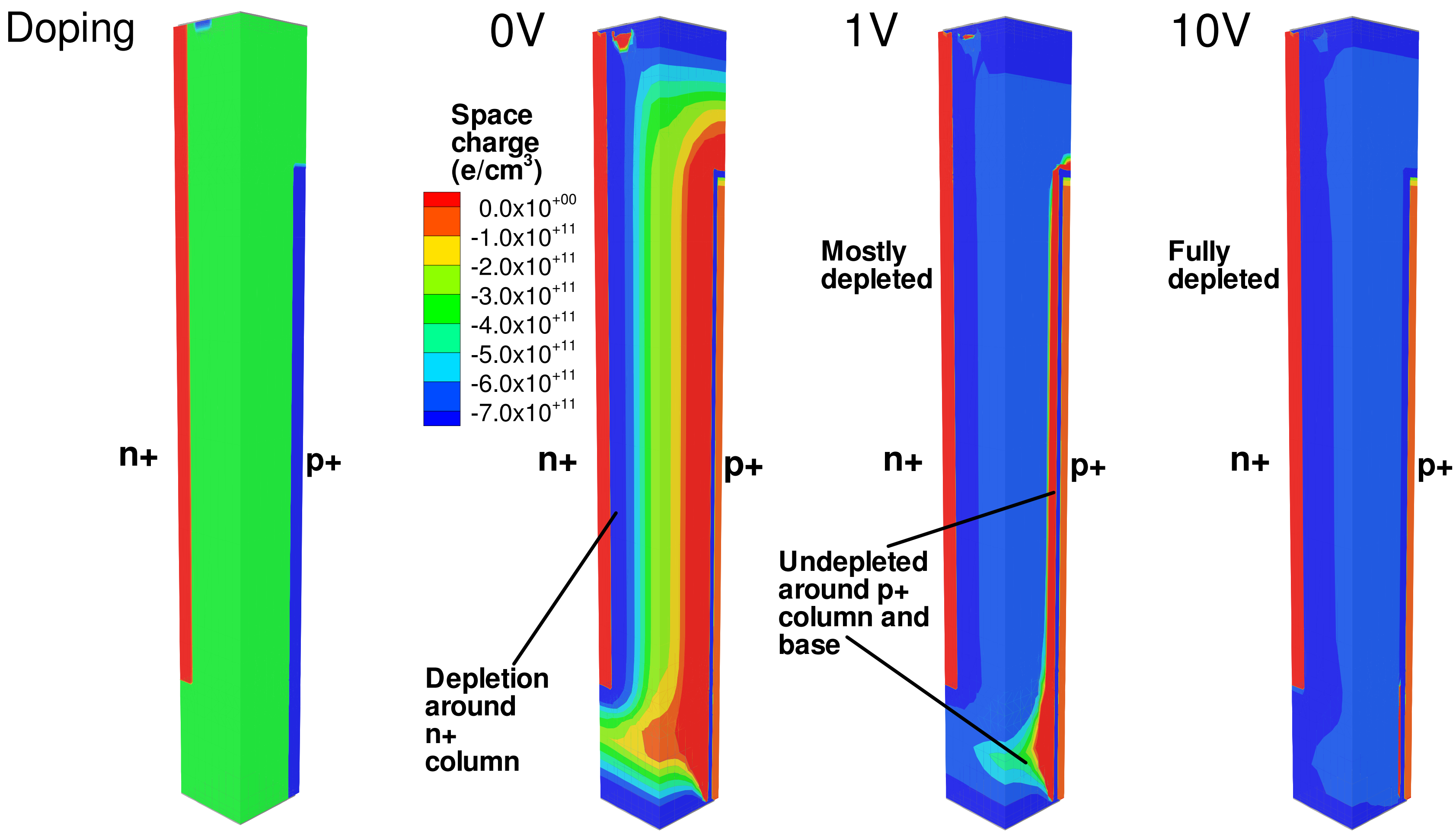
Double-sided 3D detectors

- Proposed by CNM, also being produced by IRST
- Columns etched from opposite sides of the substrate
- Metal layer on back surface connects bias columns
  - Backside biasing
- Medipix configuration (55µm pitch) and 300µm thickness

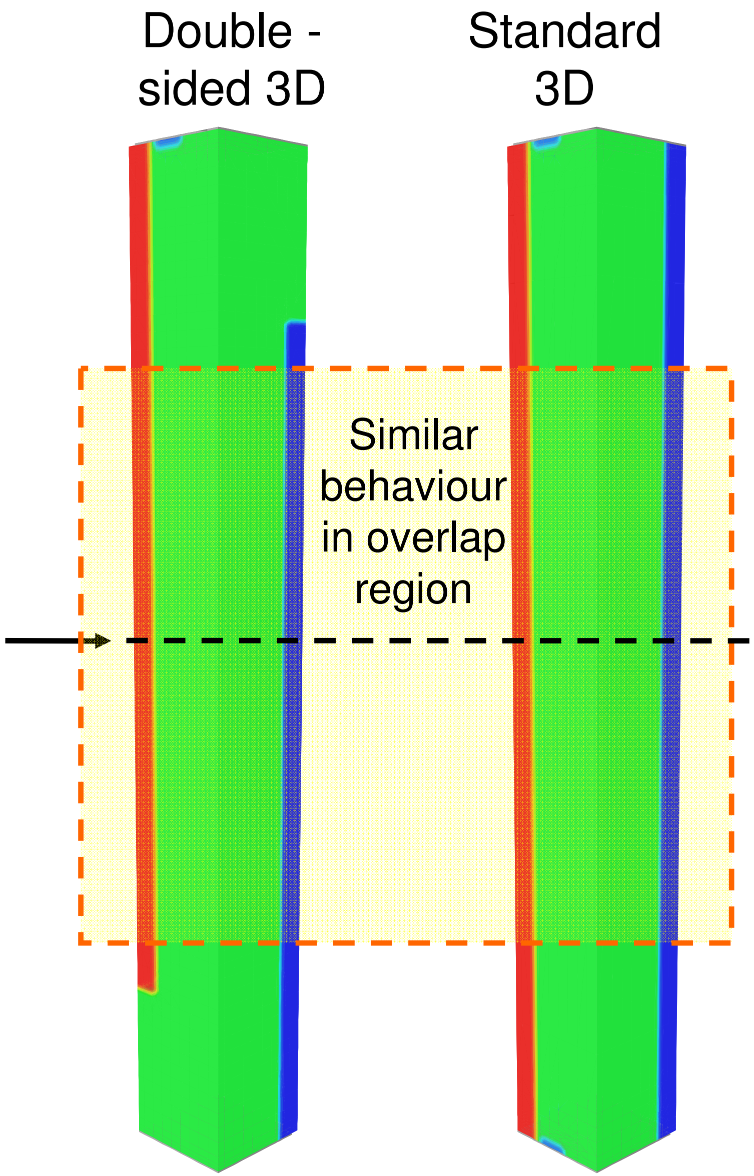


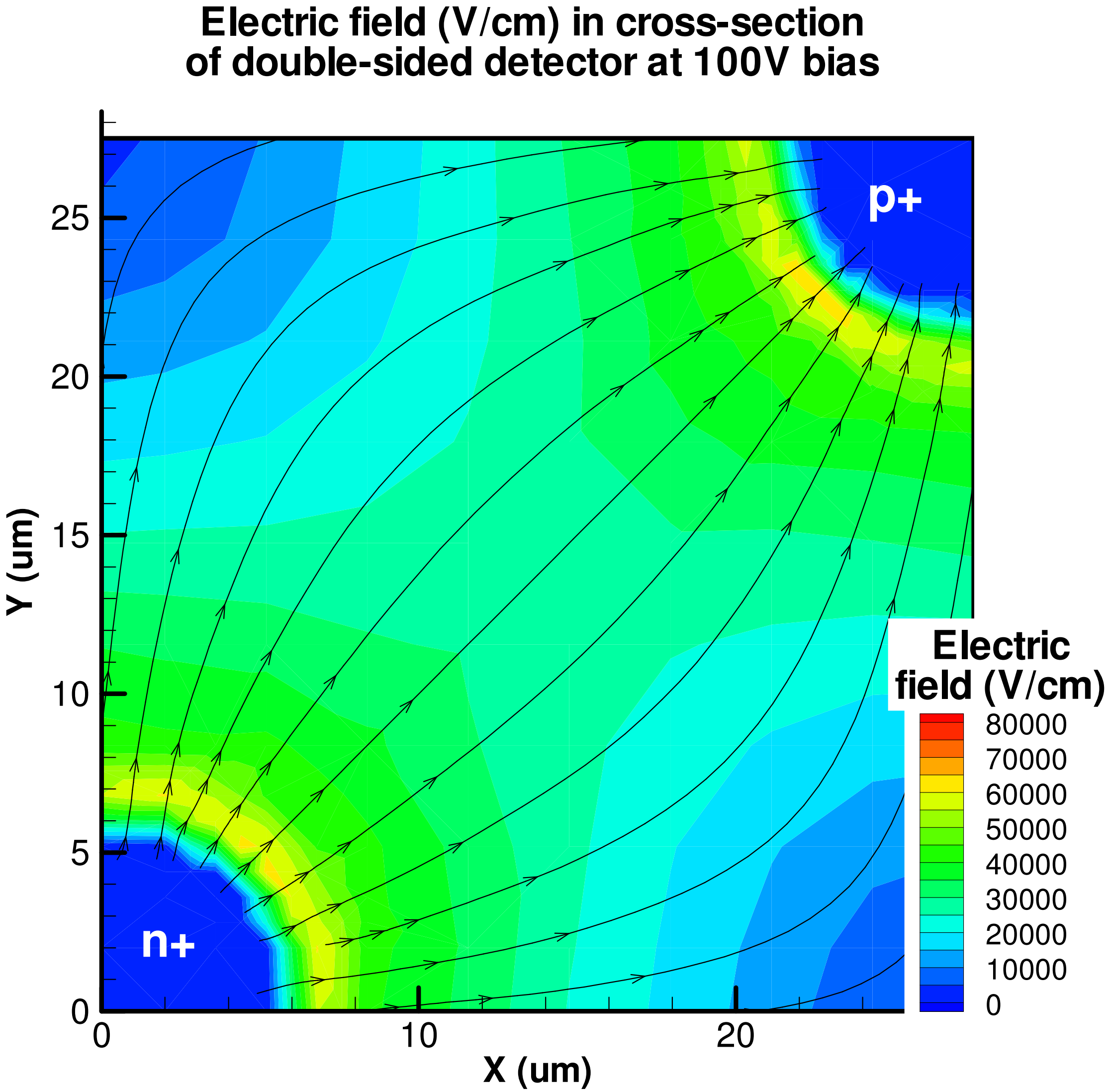
Double-sided 3D: Depletion behaviour

- ~2V lateral depletion (same as standard 3D)
- ~8V to deplete to back surface of device

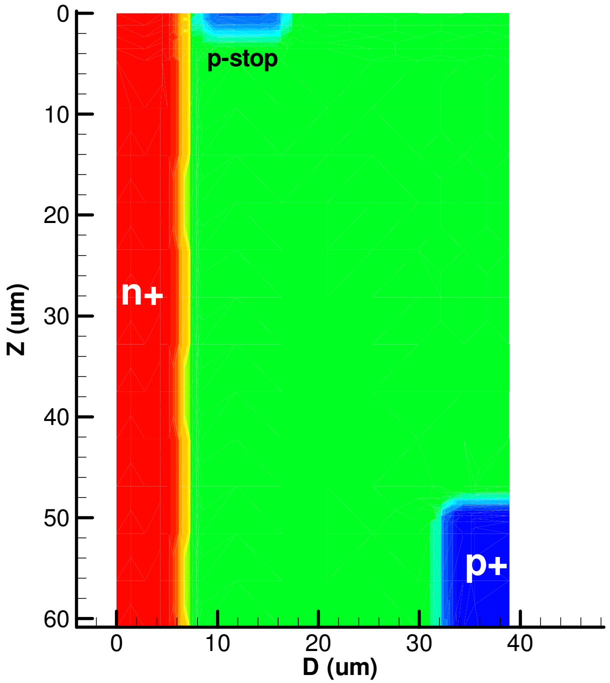


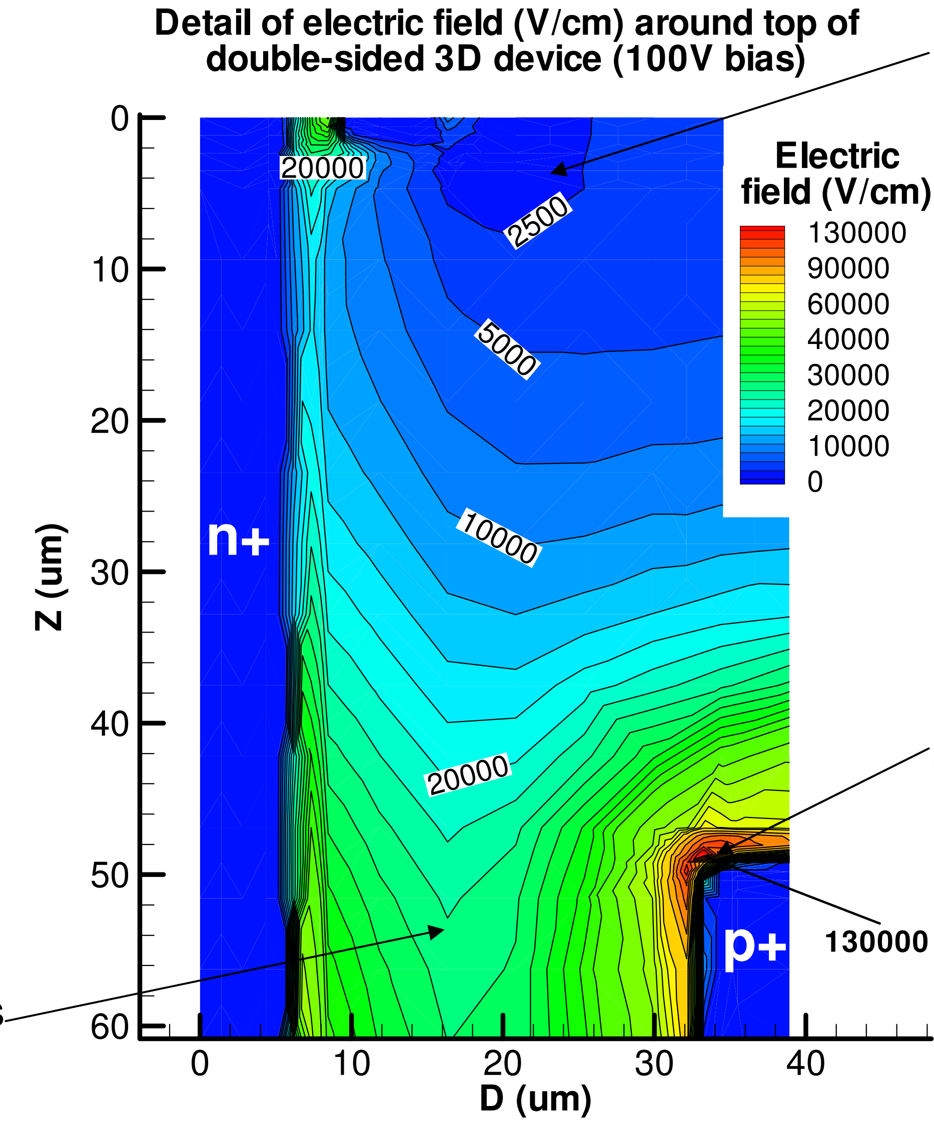
Double-sided 3D: Electric field





Double-sided 3D: Electric field at front





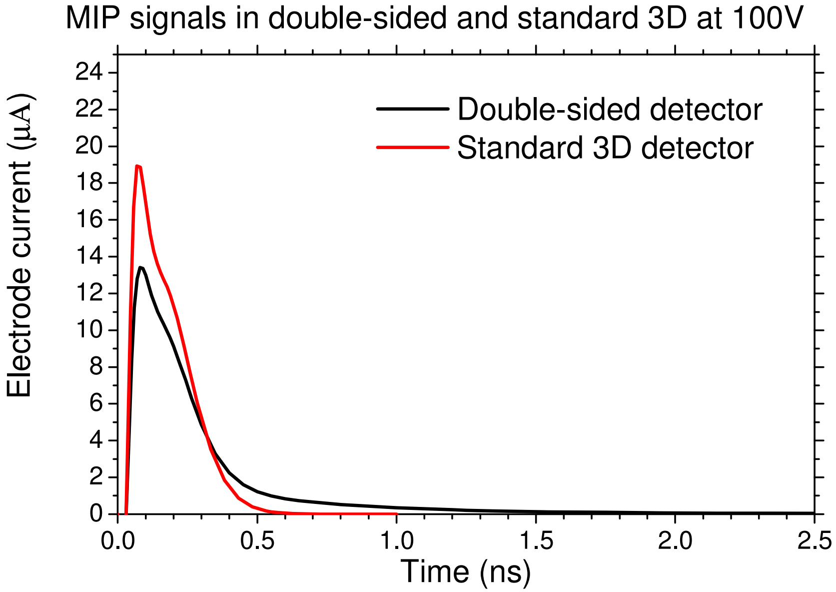
Low fields around front

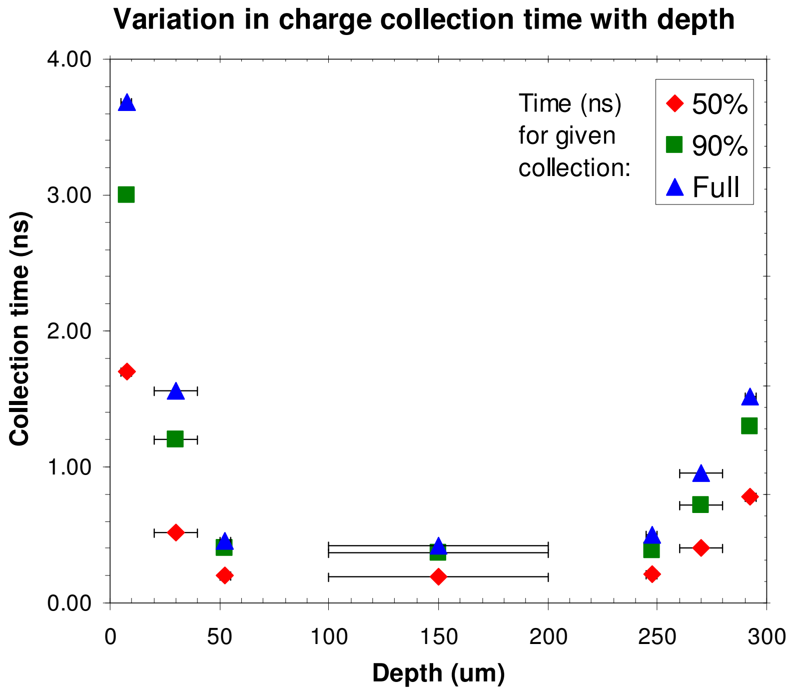
High field at column tip

Electric field matches full 3D where columns overlap

Double-sided 3D detectors: Collection time

Simulated particle track passing midway between n+ and p+ columns





Variation in charge collection time with choice of device structure

Detector	**Column length**	**90% collection**	**99% collection**
Double-sided 3D	250μm	0.75ns	2.5ns
Double-sided 3D	270μm	0.40ns	1.0ns
Double-sided 3D	290μm	0.35ns	0.5ns
Standard 3D	*300μm*	*0.35ns*	*0.5ns*

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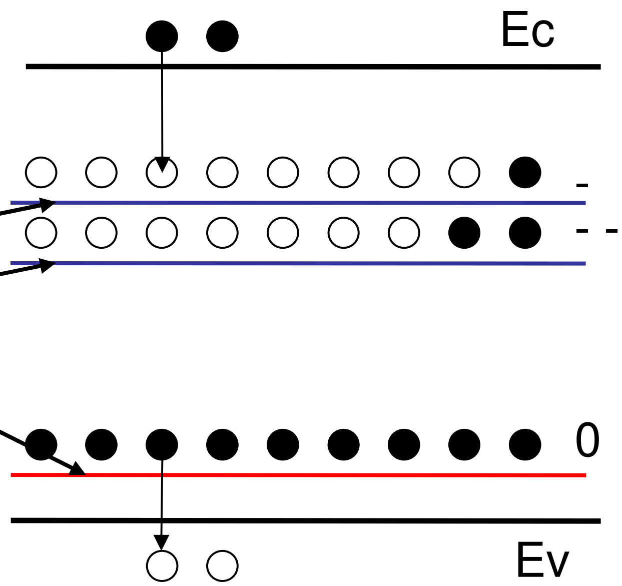
  - Radiation damage models
  - Preliminary results of radiation damage modelling

University of Perugia trap models

IEEE Trans. Nucl. Sci., vol. 53, pp. 2971–2976, 2006
"Numerical Simulation of Radiation Damage Effects in p-Type and n-Type FZ Silicon Detectors", *M. Petasecca, F. Moscatelli, D. Passeri, and G. U. Pignatel*

Perugia P-type model (FZ)

Type	Energy (eV)	Trap	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
Acceptor	Ec-0.42	VV	$2.0*10^{-15}$	$2.0*10^{-14}$	1.613
Acceptor	Ec-0.46	VVV	$5.0*10^{-15}$	$5.0*10^{-14}$	0.9
Donor	Ec+0.36	CiOi	$2.5*10^{-14}$	$2.5*10^{-15}$	0.9



- 2 Acceptor levels: Close to midgap
  - Leakage current, negative charge (N_{eff}), trapping of free electrons
- Donor level: Further from midgap
  - Trapping of free holes

University of Perugia trap models

- Aspects of model:
  - Leakage current – reasonably close to α=4.0*10^{-17}A/cm $\quad I/Vol = \alpha\Phi$
  - Depletion voltage – matched to experimental results (M. Lozano et al., *IEEE Trans. Nucl. Sci., vol. 52, pp. 1468–1473, 2005)*
  - Carrier trapping –
    - Model reproduces CCE tests of 300μm pad detectors
    - *But* trapping times don't match experimental results

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

Link between model and experiment

$$\beta_e = v_{th}{}^{e}\sigma_e \eta$$

- Experimental trapping times for p-type silicon (V. Cindro et al., IEEE NSS, Nov 2006) *up to $10^{15}n_{eq}/cm^2$*
  - β_e= 4.0*10^{-7}cm^{2}s^{-1} $\qquad$ β_h= 4.4*10^{-7}cm^{2}s^{-1}
- Calculated values from p-type trap model
  - β_e= 1.6*10^{-7}cm^{2}s^{-1} $\qquad$ β_h= 3.5*10^{-8}cm^{2}s^{-1}

Altering the trap models

- Priorities: Trapping time and depletion behaviour
  - Leakage current should just be "sensible": α = 2-10 *10^{-17}A/cm
- Chose to alter cross-sections, while keeping σ_h/σ_e constant

Carrier trapping:

$$\beta_{e,h} = v_{th}^{e,h} \sigma_{e,h} \eta$$

Space charge:

$$n_{e,Trap} = N_{trap} f_n \approx N_{trap} \exp\left(-E_t/kT\right)\left(\frac{n}{n_i} + \frac{\sigma_h v_{th}^h}{\sigma_e v_{th}^e} \exp\left[-E_t/kT\right]\right)$$

Modified P-type model

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
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Donor	Ec+0.36	CiOi	$3.23*10^{-13}$	$3.23*10^{-14}$	0.9

Modified P-type model and experimental data

Type	Energy (eV)	Trap	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
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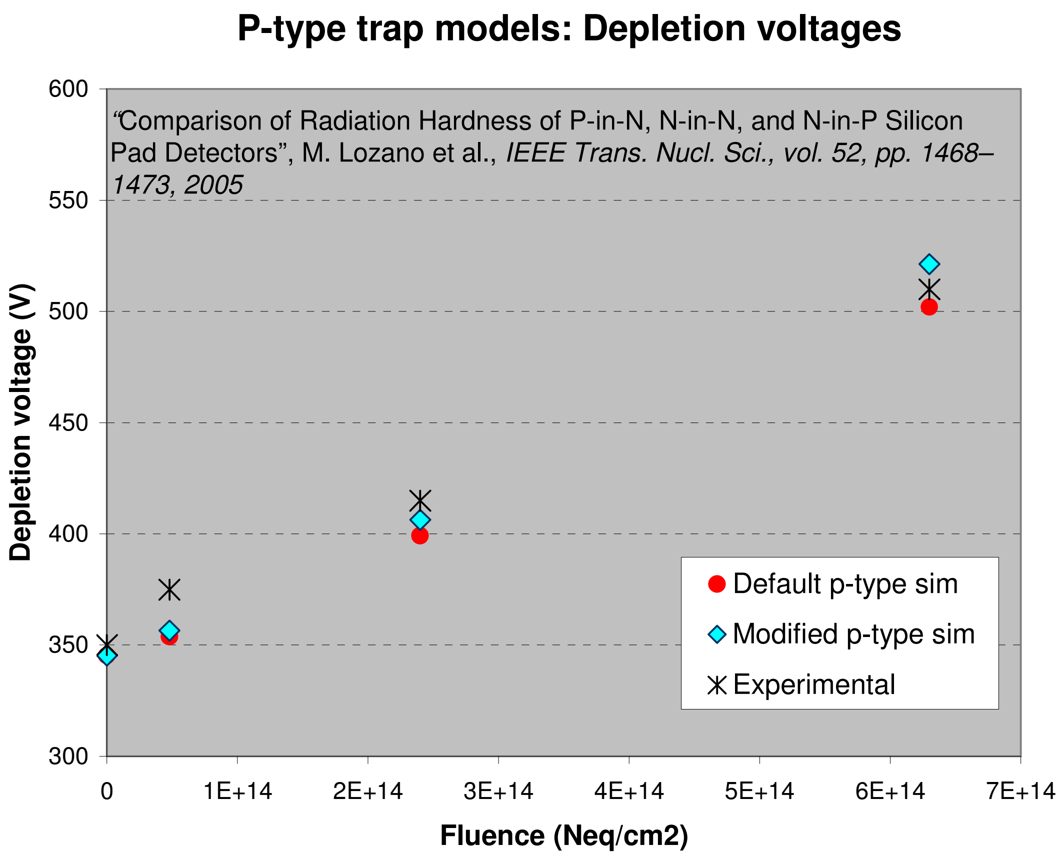

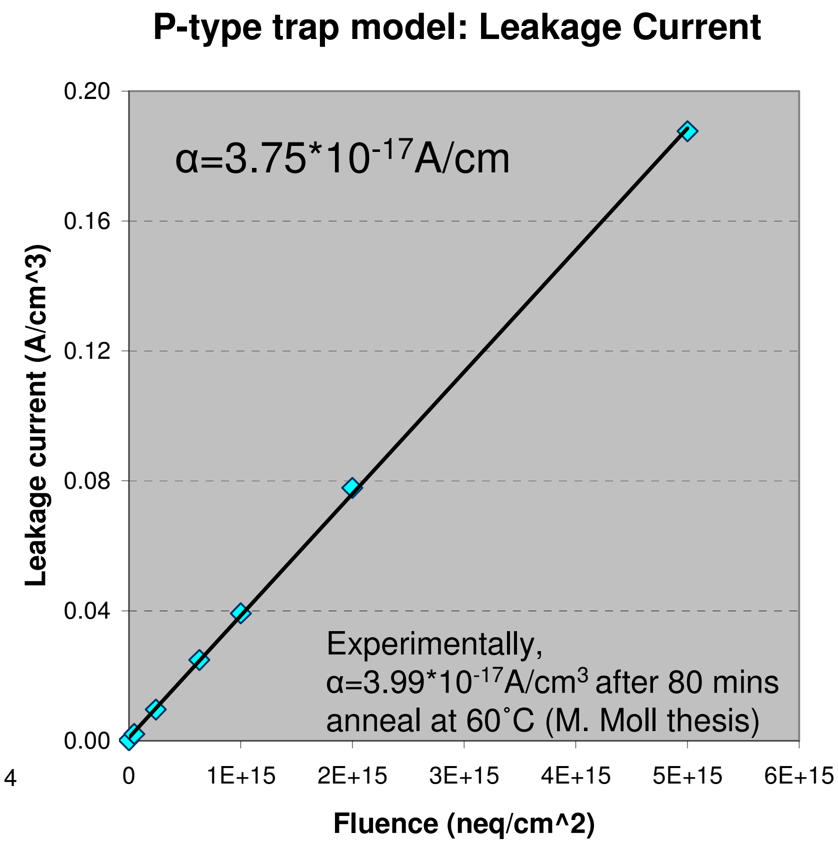

Perugia N-type model

Perugia N-type model (FZ)

Type	Energy (eV)	Trap	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
Acceptor	Ec-0.42	VV	$2.0*10^{-15}$	$1.2*10^{-14}$	13
Acceptor	Ec-0.50	VVO	$5.0*10^{-15}$	$3.5*10^{-14}$	0.08
Donor	Ec+0.36	CiOi	$2.0*10^{-18}$	$2.5*10^{-15}$	1.1

Donor removal

$$N_D = N_{D0} \exp(-c_D \Phi)$$

$$N_{D0} * c_D = K_C = const$$

$$K_C = (2.2 \pm 0.2) * 10^{-2} \text{cm}^{-1}$$

- Works similarly to the p-type model
- Donor removal is modelled by altering the substrate doping directly

- Experimental trapping times for n-type silicon (G. Kramberger et al., NIMA, vol. 481, pp297-305, 2002)
  - β_e= $4.0*10^{-7} cm^2 s^{-1}$ β_h= $5.3*10^{-7} cm^2 s^{-1}$
- Calculated values from n-type trap model
  - β_e= $5.3*10^{-7} cm^2 s^{-1}$ β_h= $4.5*10^{-8} cm^2 s^{-1}$

Modified N-type model

Type	Energy (eV)	Trap	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
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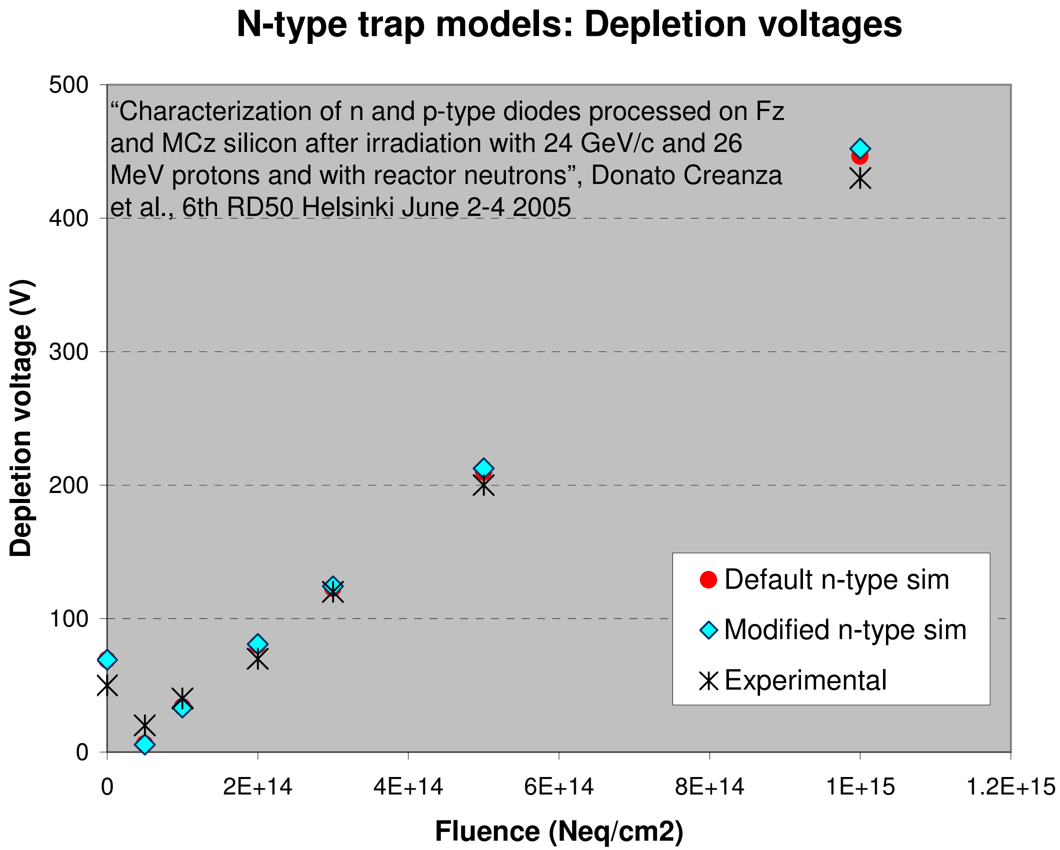
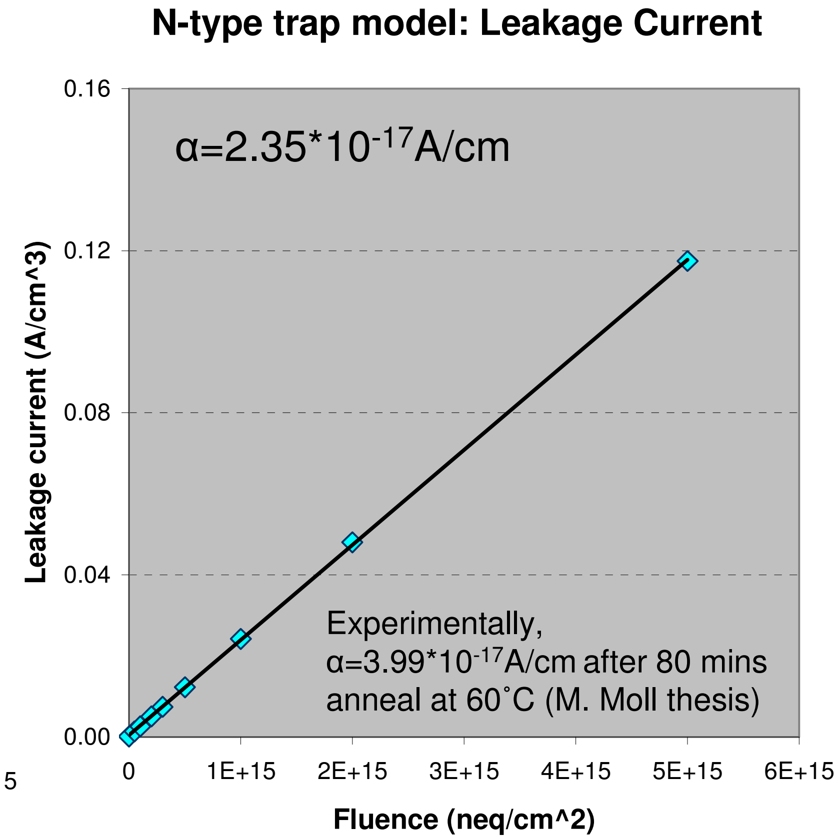
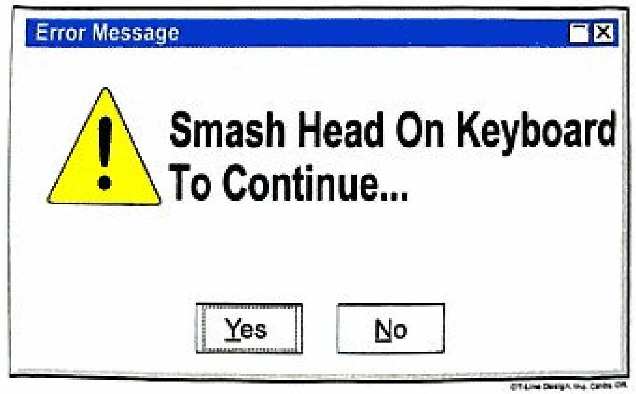
Acceptor	Ec-0.5	VVO	$5.0*10^{-15}$	$3.5*10^{-14}$	0.08
Donor	Ec+0.36	CiOi	**$2.5*10^{-17}$**	**$3.1*10^{-15}$**	1.1





Bug in ISE-TCAD version 7

- Currently using Dessis, in ISE-TCAD v7 (2001)
- Non time-dependent simulations with trapping are OK
- Error occurs in transient simulations with traps
  - Carrier behaviour in depletion region is OK
  - **Displacement current is miscalculated**
  - **This affects currents at the electrodes**



Correct behaviour: $\nabla.\underline{J}_{tot} = \nabla.\underline{J}_{disp} + \nabla.\underline{J}_{n} + \nabla.\underline{J}_{p} = 0$

Error: $\nabla.\underline{J}_{disp,error} = \nabla.\underline{J}_{tot} = q(R_{e,Trap} - R_{h,Trap})*(\sim)1.73$

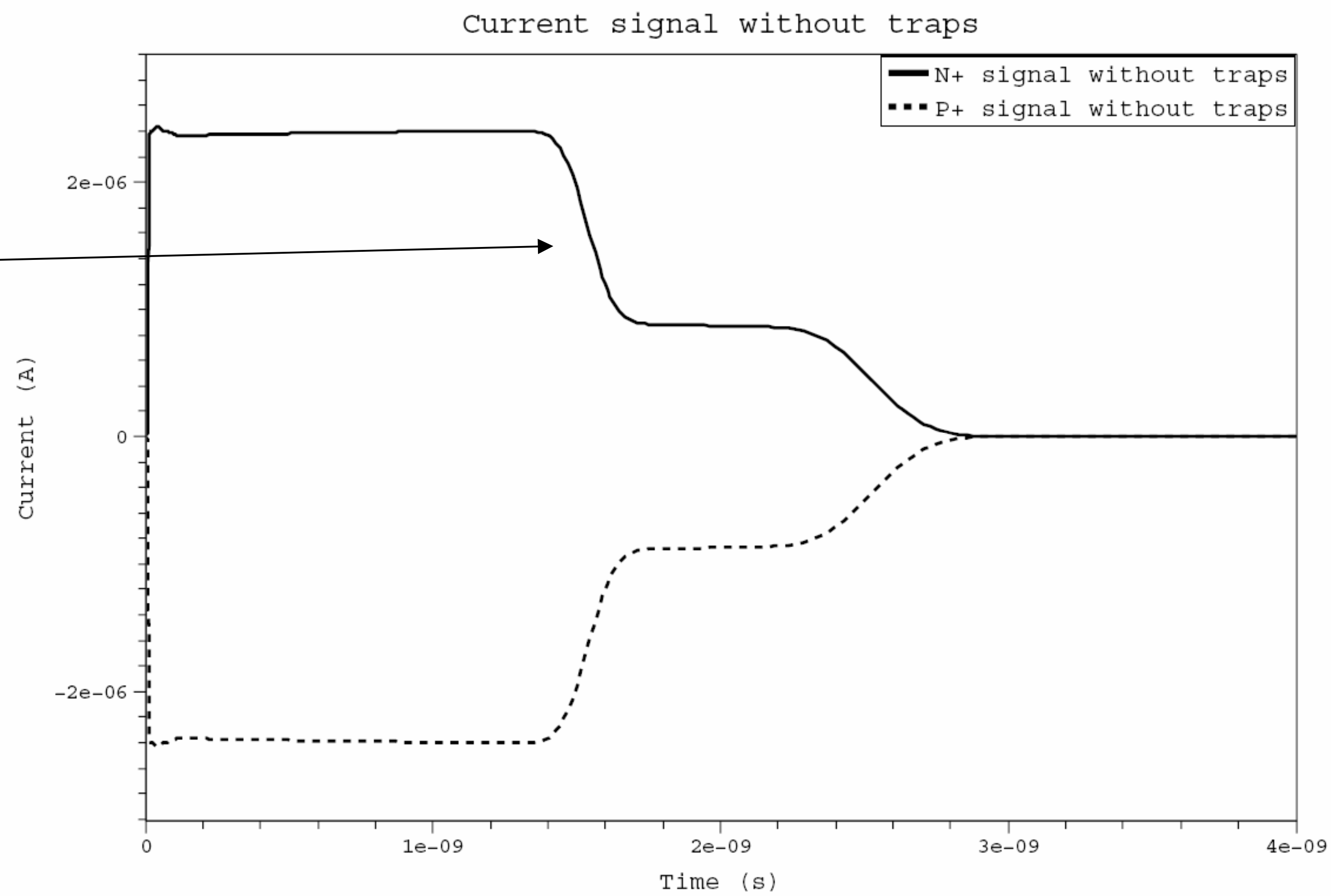
- This bug is not present in the latest release of **Synopsis TCAD** (2007)
  - Synopsis bought ISE TCAD, and renamed Dessis as “Sentaurus Device”
  - Don’t know which specific release fixed the problem

Test of charge trapping in Synopsis TCAD

- Simulated a simple diode with carriers generated at its midpoint

No traps

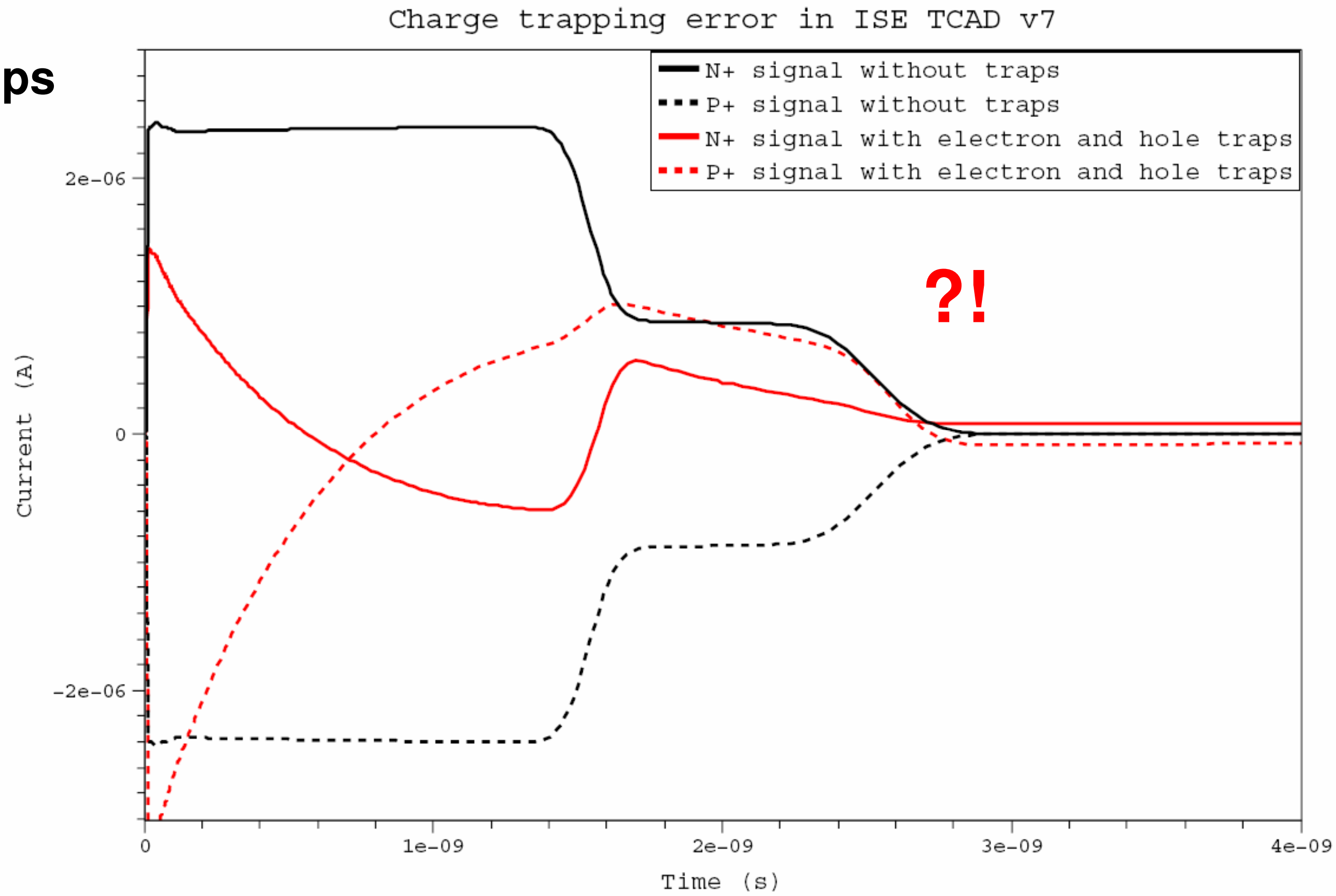
“Double step” seen because electrons are collected before holes



Test of charge trapping in Synopsis TCAD

- Simulated a simple diode with carriers generated at its midpoint
- Acceptor and donor traps *further from the midgap*
  - Produces charge trapping but little change in N_{eff}
  - Trap levels should give $\tau_e \approx \tau_h \approx 1\text{ns}$

ISE TCAD traps



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- Acceptor and donor traps *further from the midgap*
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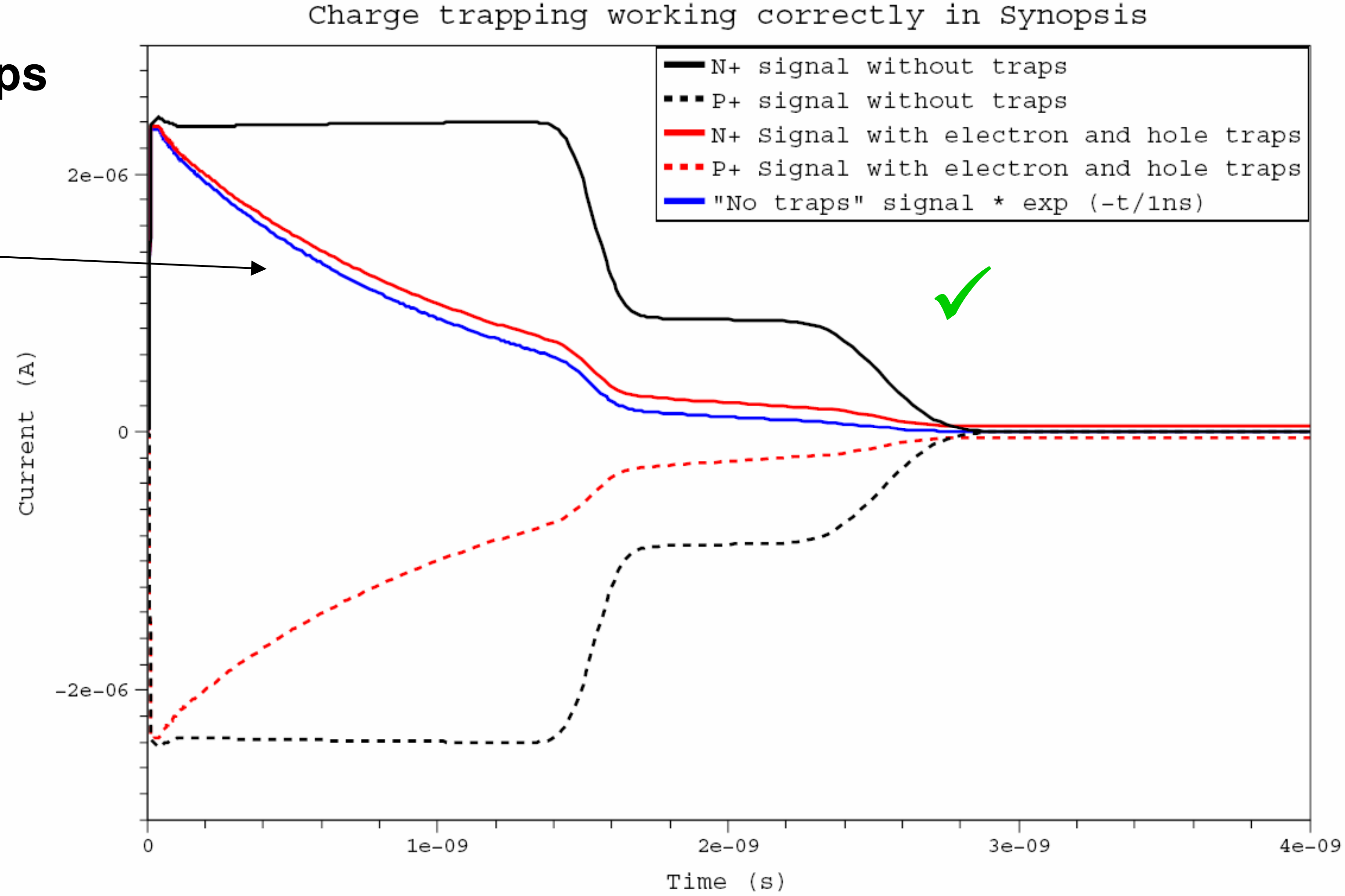
Synopsis traps

With traps, signal decays as exp (-t/1ns) as expected



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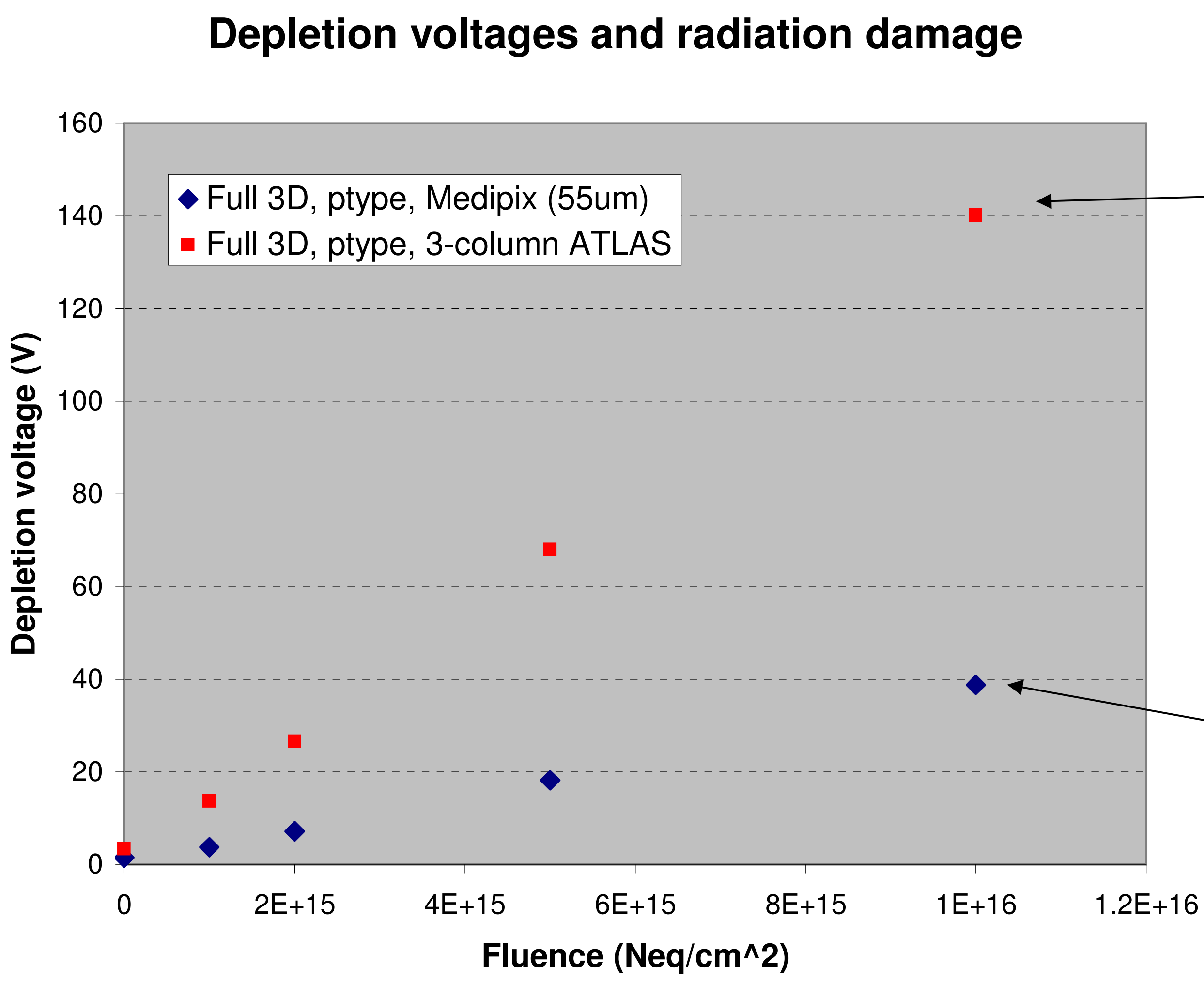
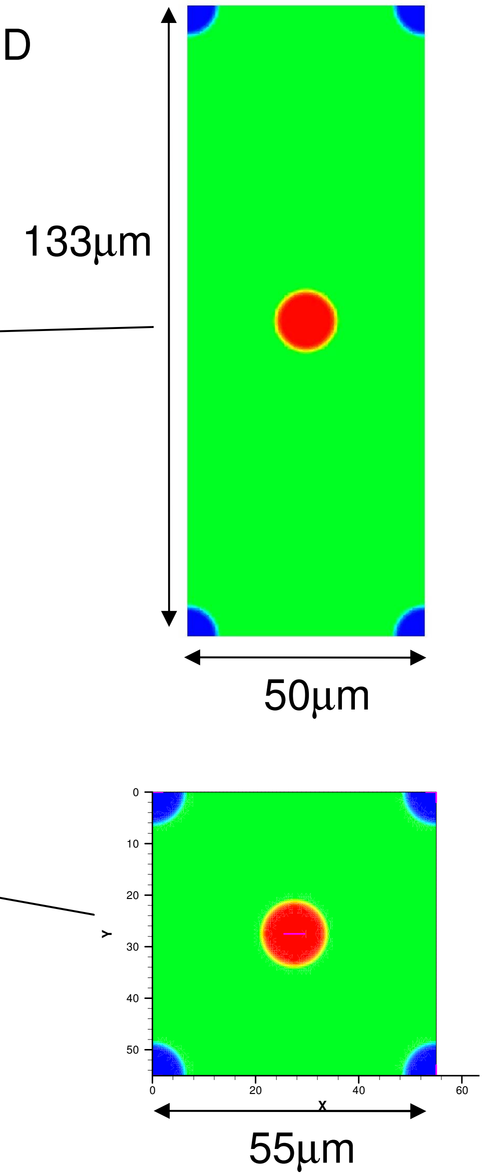
Full 3D – Depletion voltage (p-type)

- Depletion voltage is low, but strongly dependent on pitch
- Double sided 3D shows the same lateral depletion voltage as full 3D



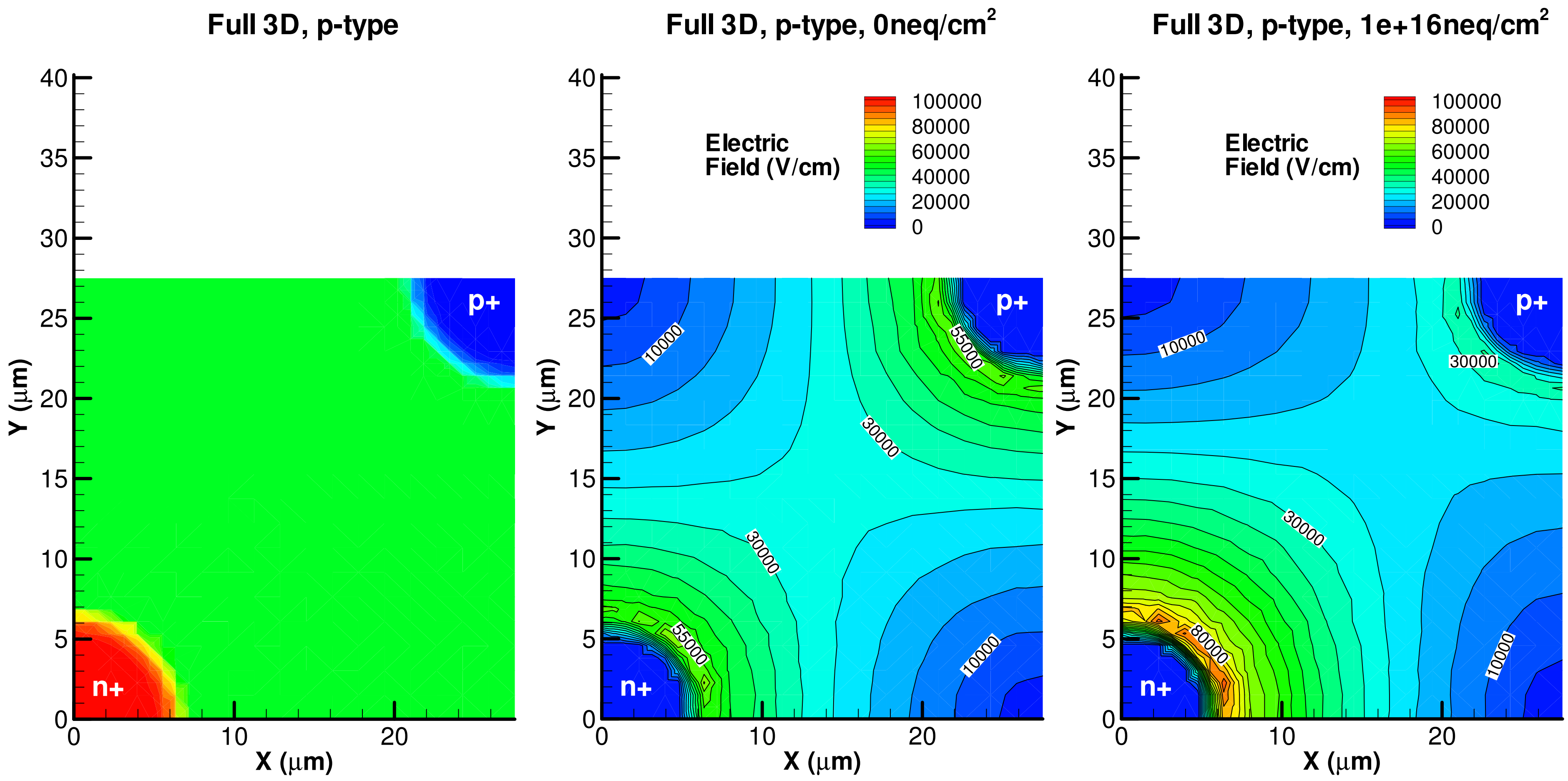


Full 3D – electric field at 100V

Full depletion is achieved well under 100V, but electric field is altered

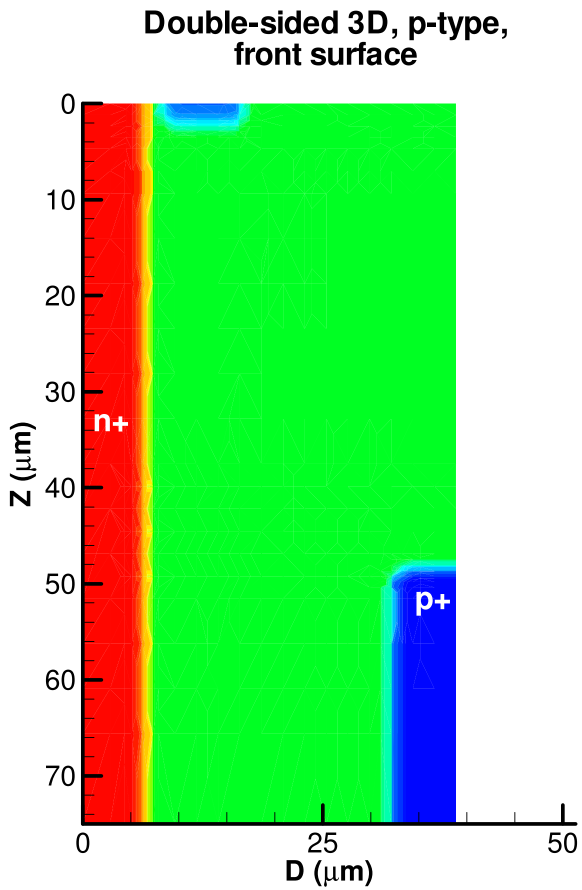
No damage

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

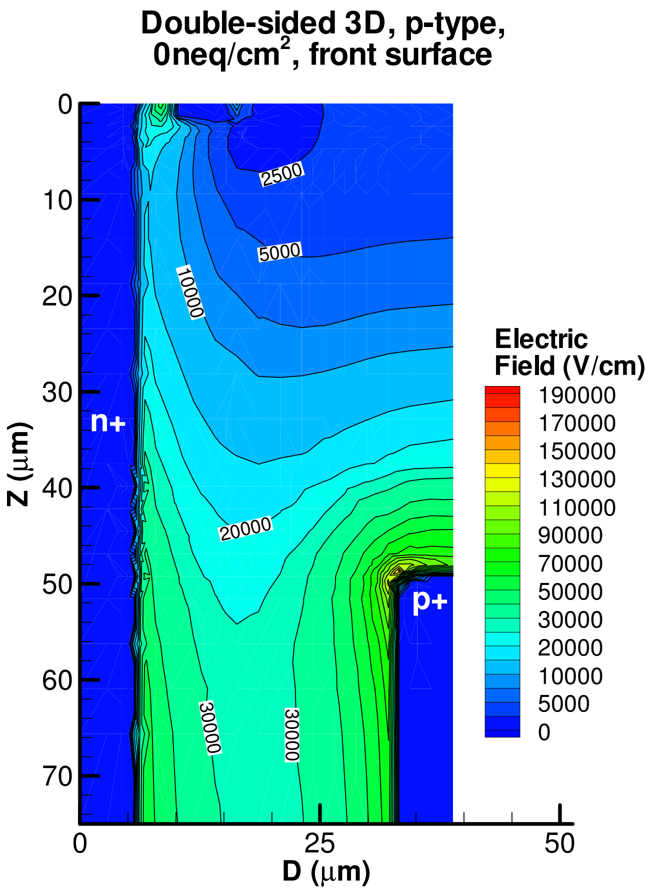


Double-sided 3D – front surface

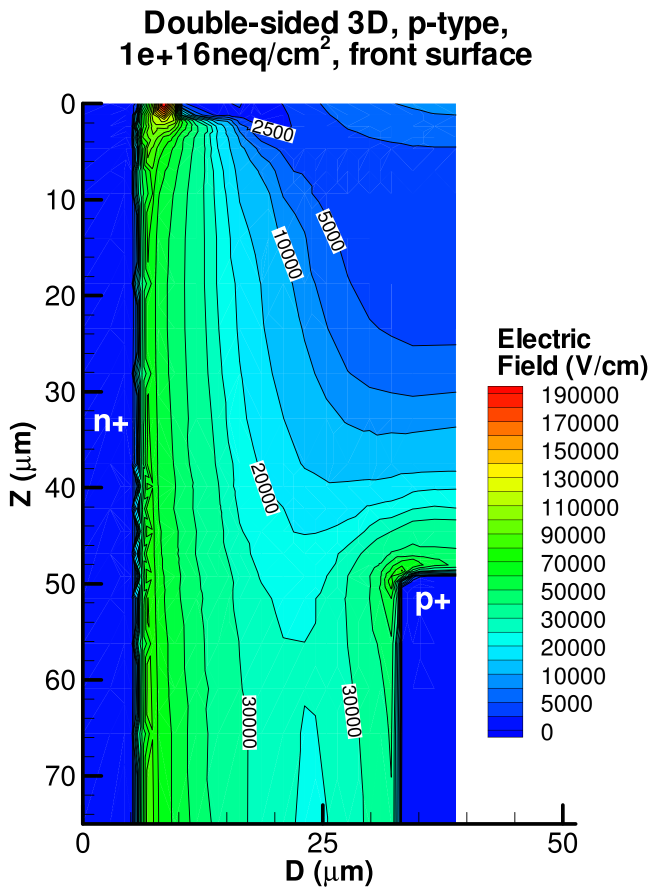
Once again, double-sided devices show different behaviour at front and back surfaces



No damage



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

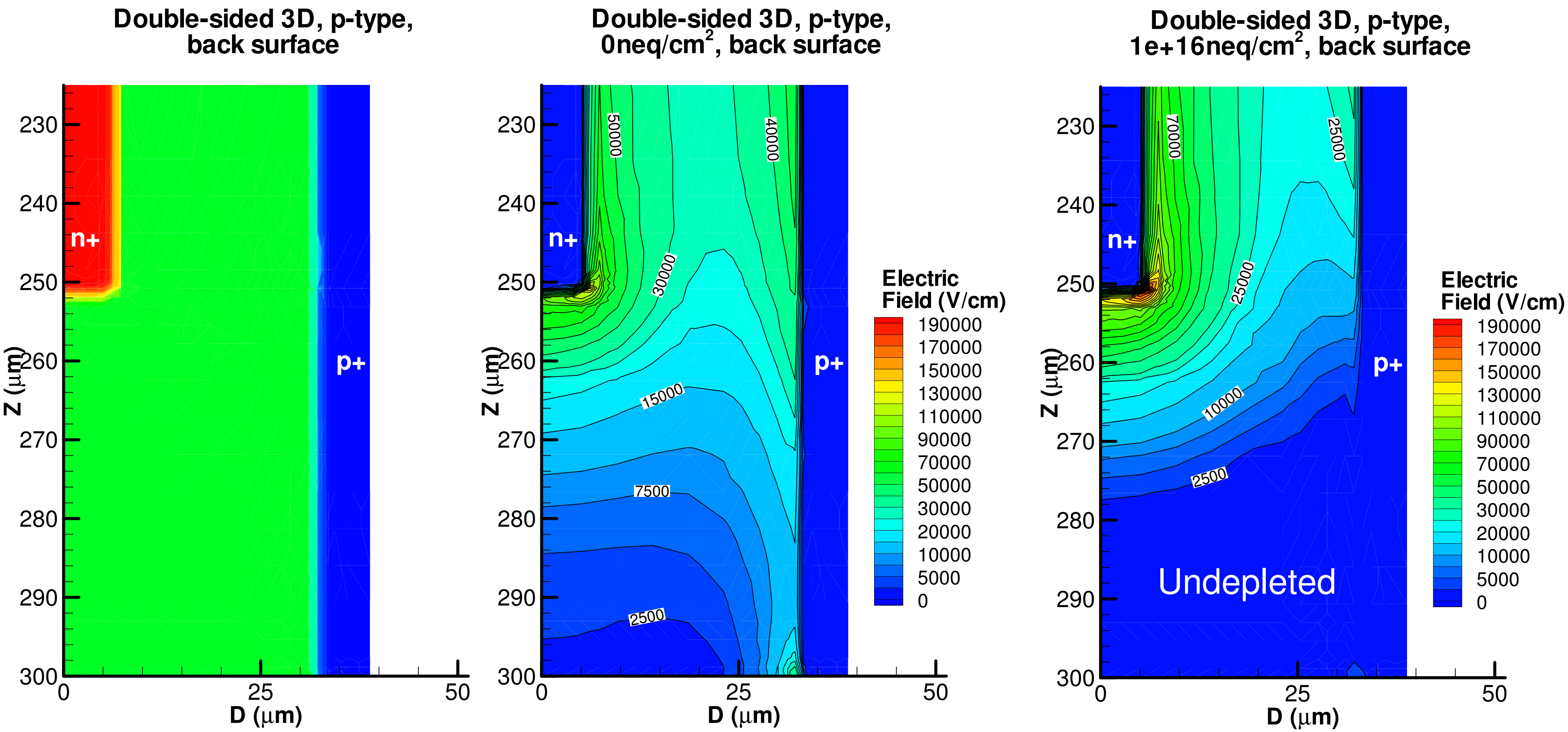


Double-sided 3D – back surface

Region at back surface depletes more slowly – not fully depleted at 100V bias

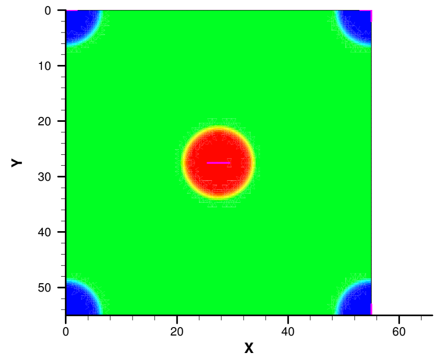
No damage

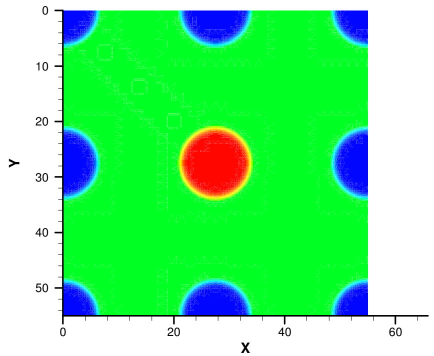
10^{16} neq/cm²

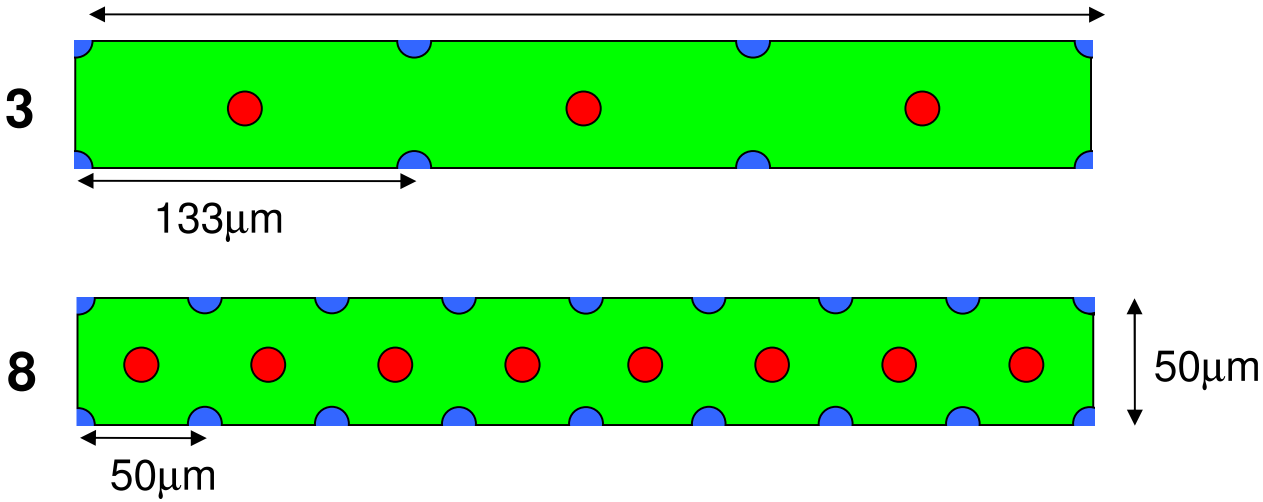


Further work

- Simulate charge collection!
- Consider effects of different available pixel layouts
  - CCE, depletion voltage, insensitive area, capacitance







Conclusions

- Double-sided 3D detectors:
  - Behaviour mostly similar to standard 3D
  - Depletion to back surface requires a higher bias
  - Front and back surfaces show slower charge collection

- Radiation damage model
  - Trap behaviour is directly simulated in ISE-TCAD
  - Trap models based on Perugia models, altered to match experimental trapping times

- Preliminary tests of damage model with 3D
  - Relatively low depletion voltages, but electric field pattern is altered
  - Double-sided 3D shows undepleted region at back surface at high fluences

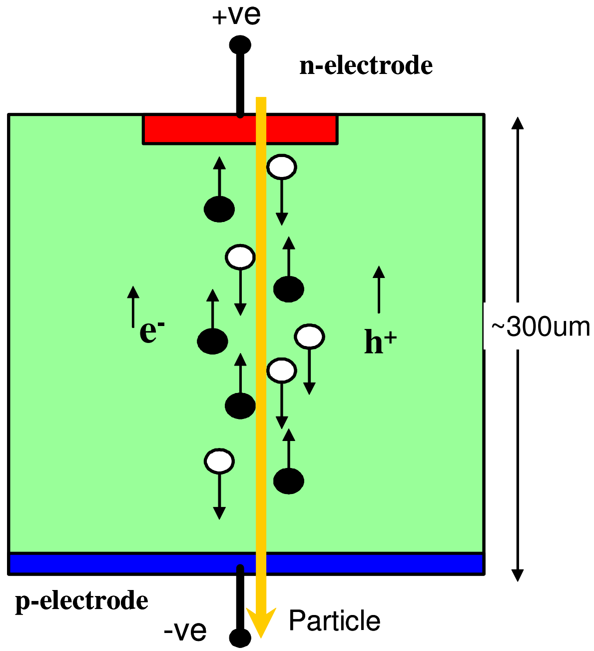
Thank you for listening

Additional slides

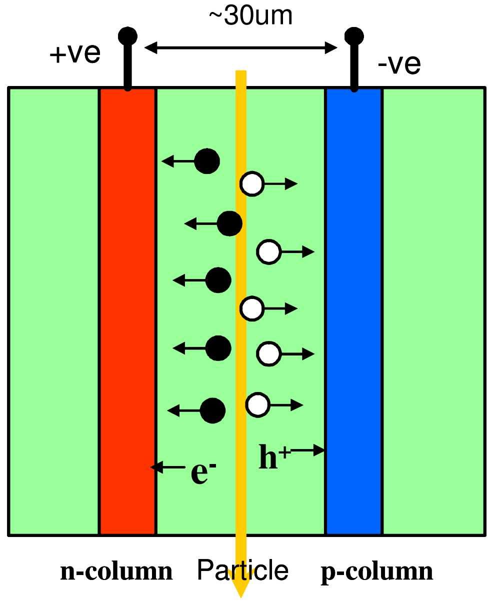
3D detectors

- N+ and p+ columns pass through substrate
- Fast charge collection
- Low depletion voltage
- Low charge sharing
- Additional processing (DRIE for hole etching)

Planar



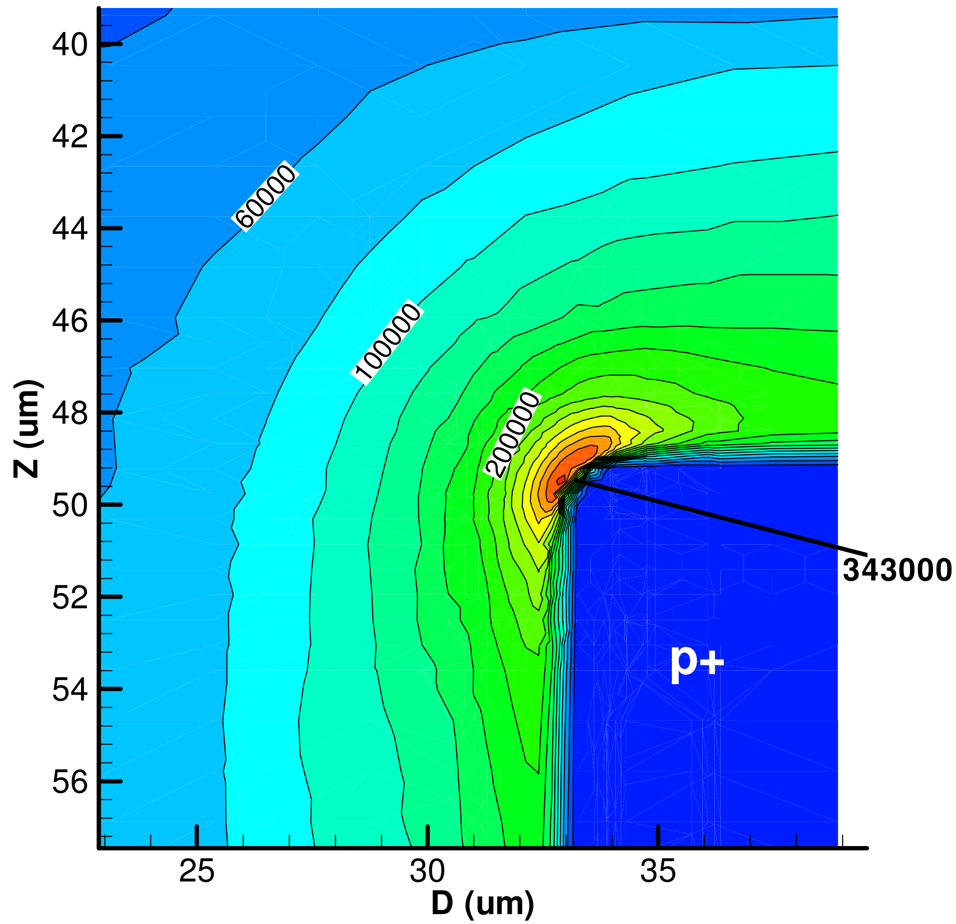
3D



Breakdown in double-sided 3D

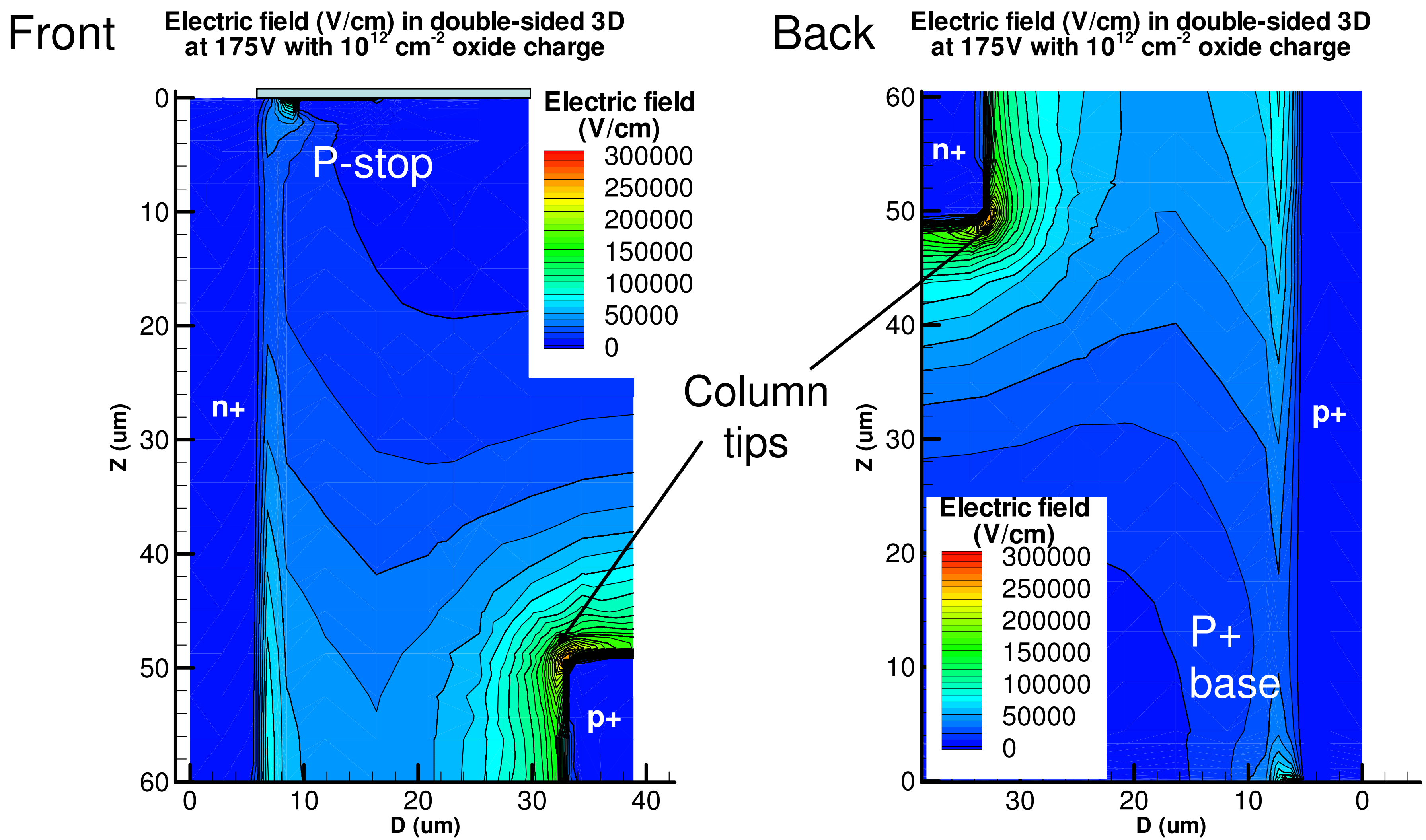
- Breakdown occurs at column tips around 230V
  - Dependent on shape, e.g. 185V for square columns

Electric field (V/cm) around tip of p+ column at 215V

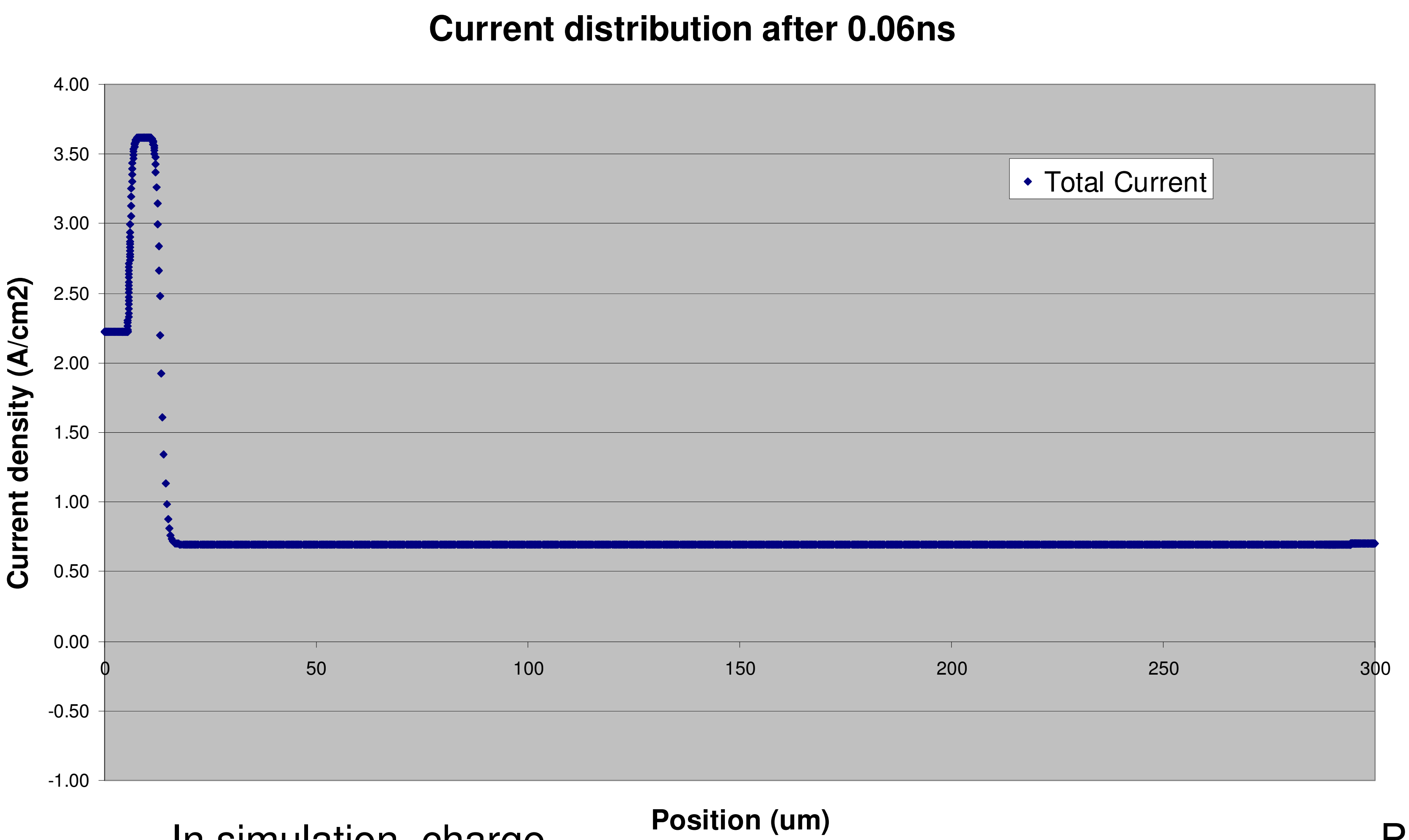


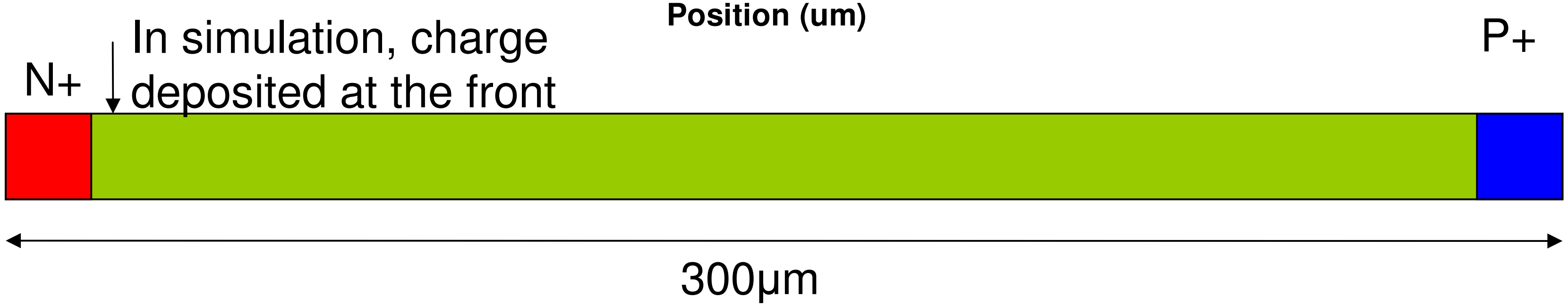
Breakdown in double-sided 3D

- With 10^{12}cm^{-2} charge, breakdown at 210V



Example of ISE TCAD bug





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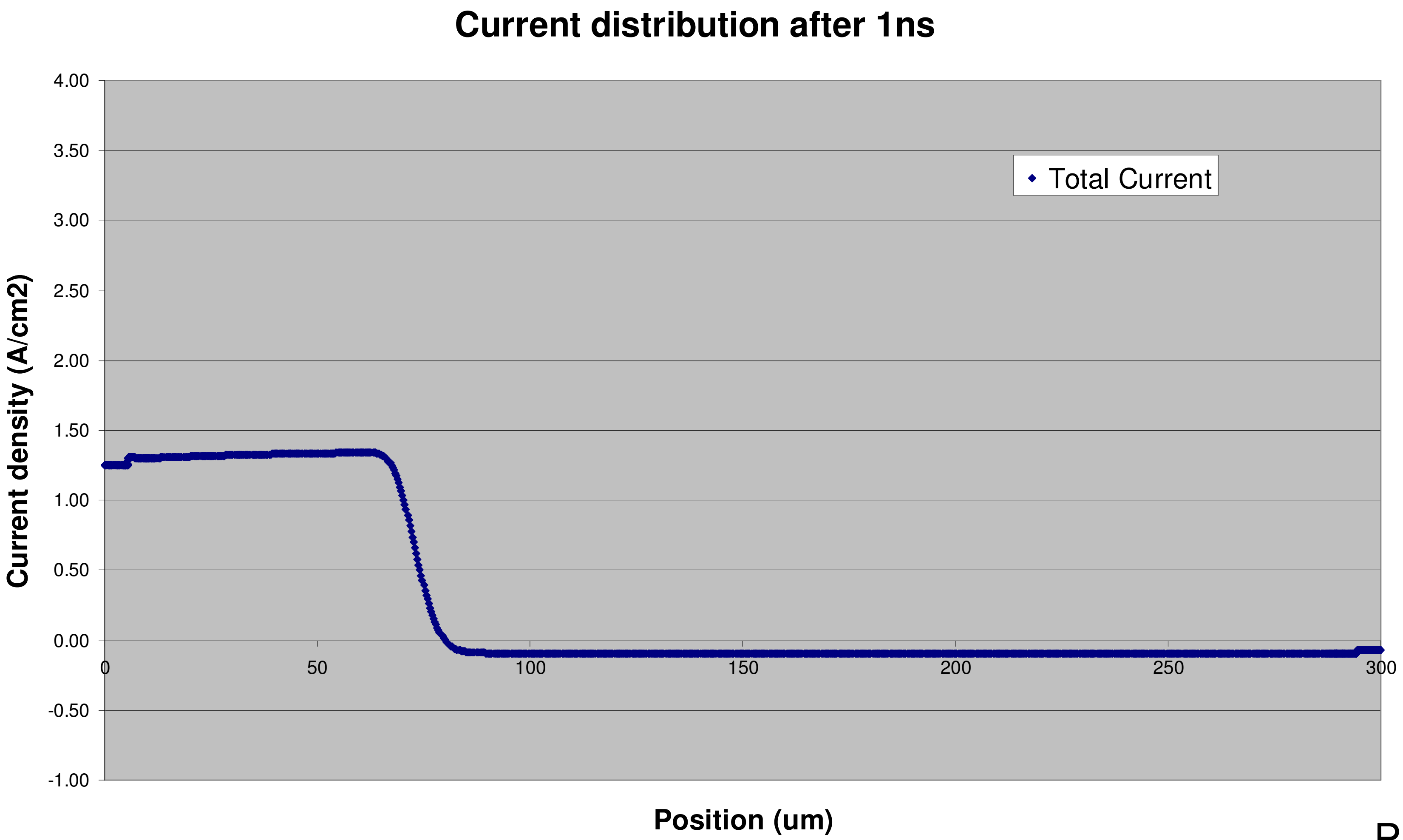

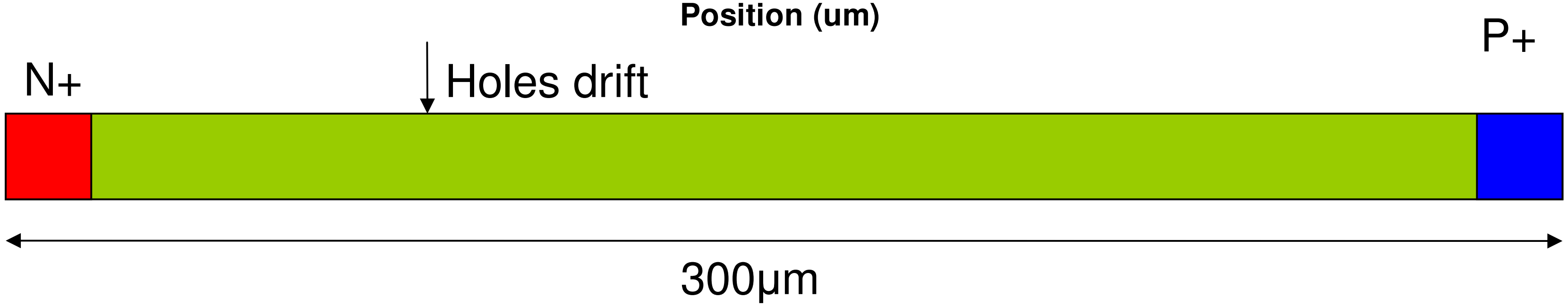

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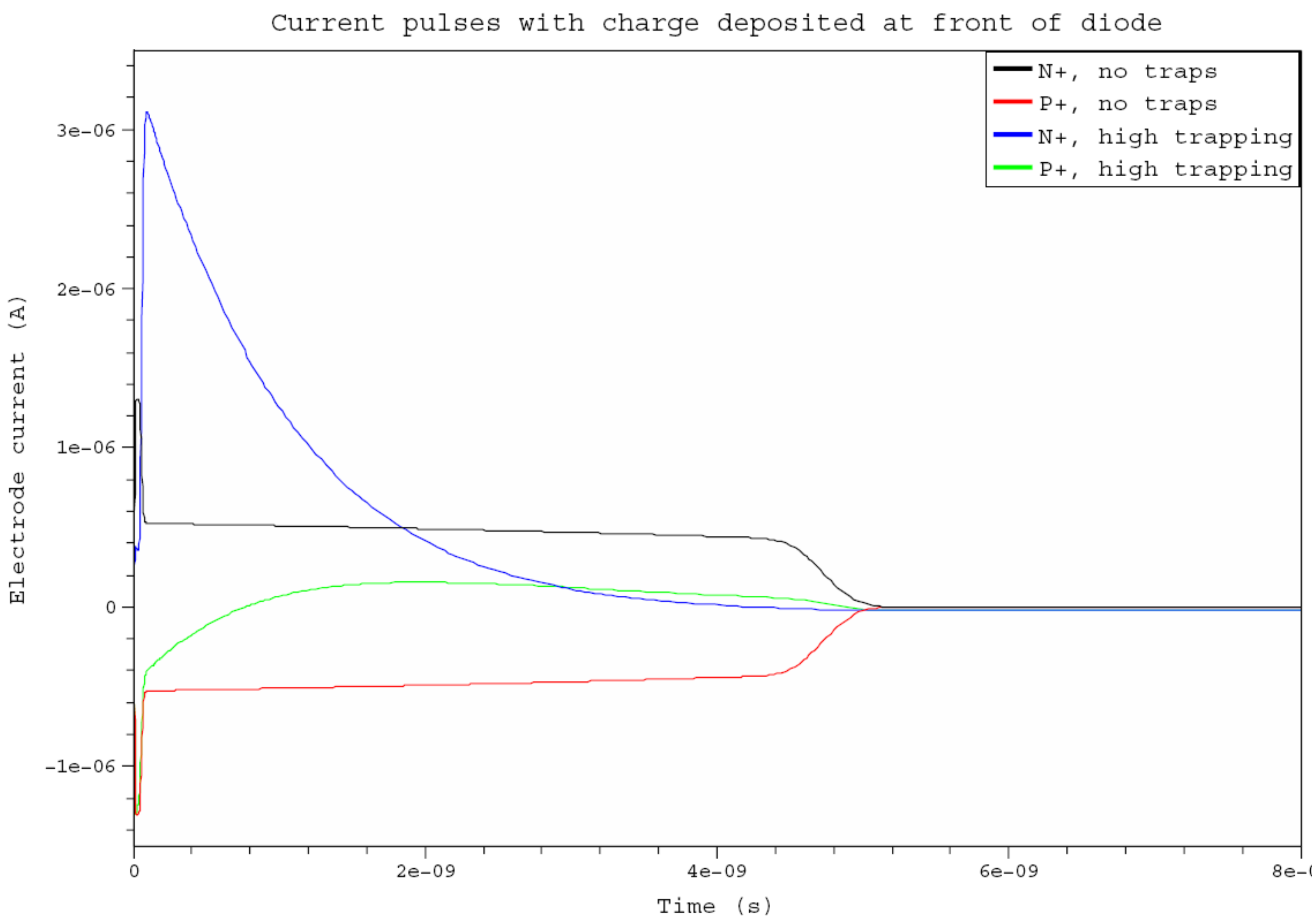
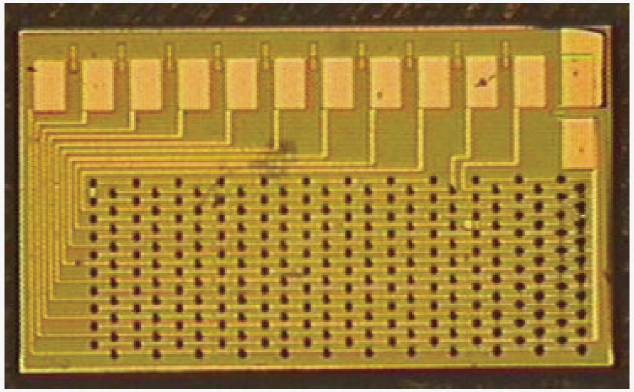
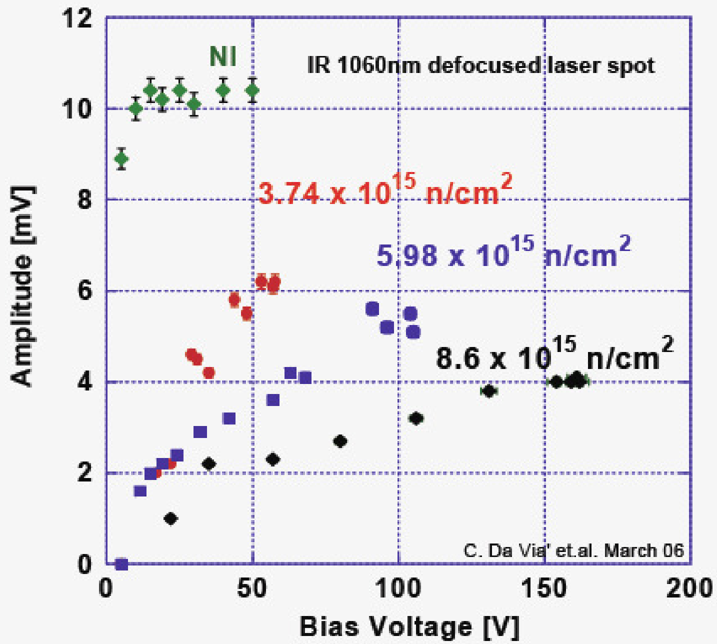


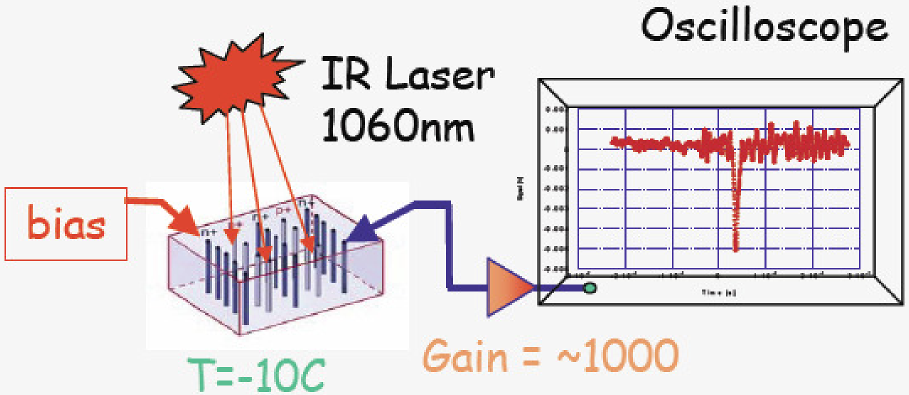
3D is radiation hard: Tests with baby-Atlas sensors

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 mm^3
- 3 electrode Atlas pixel geometry 71 μm IES
- n-electrode readout
- n-type before irradiation -12 kΩ cm
- Irradiated with reactor neutrons (Praha)





Full 3D – Depletion voltage (p-type)

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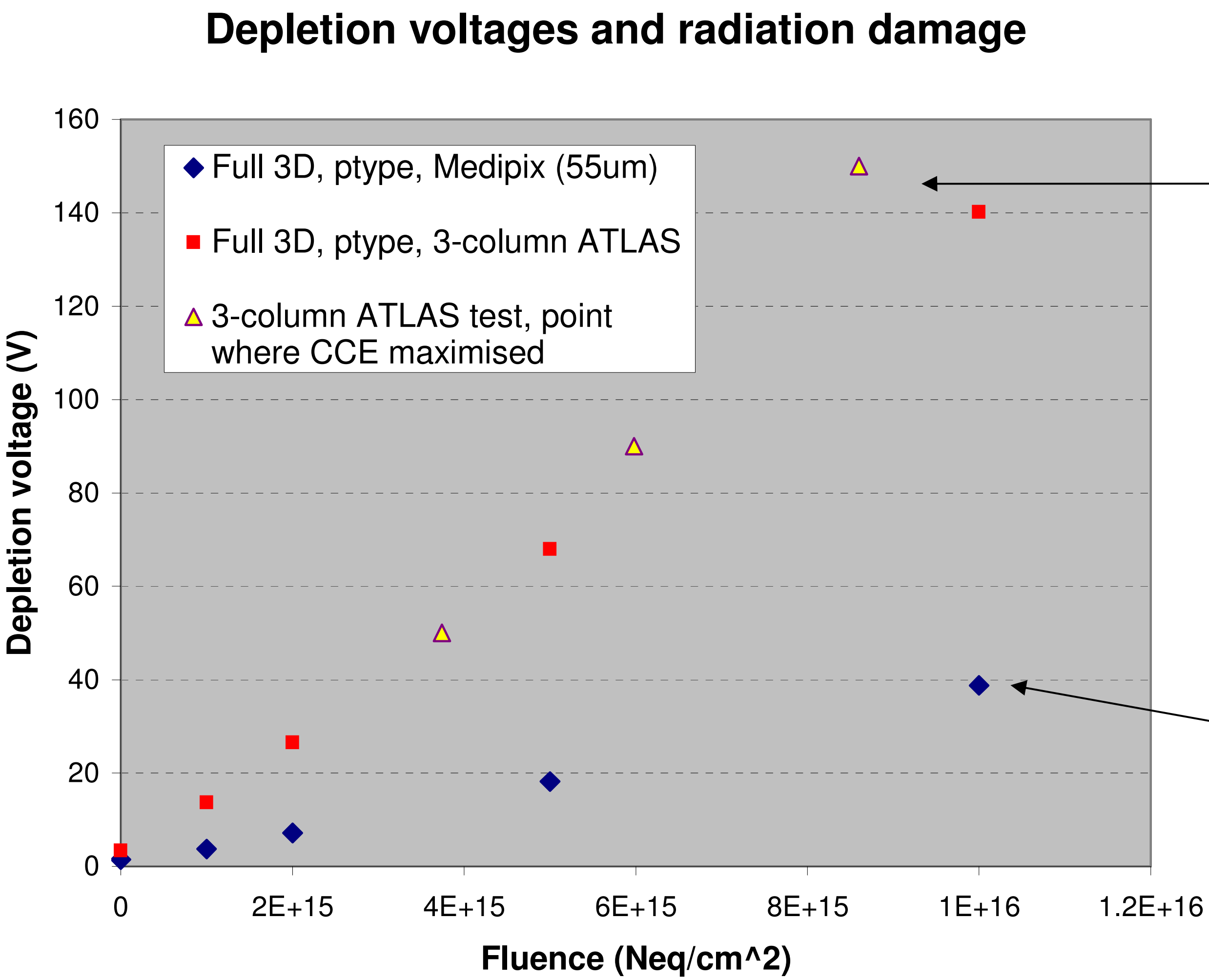
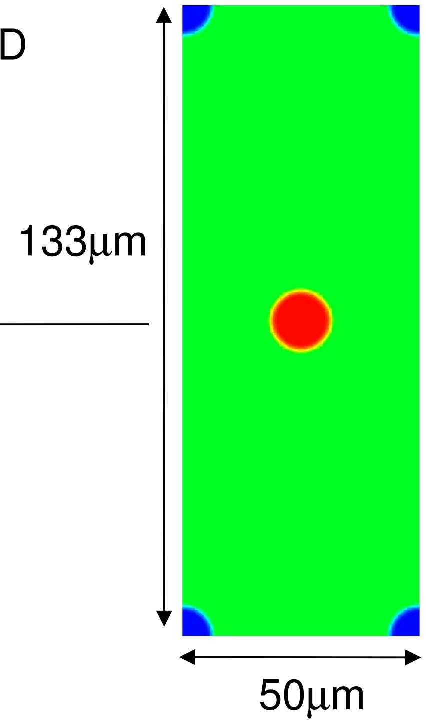
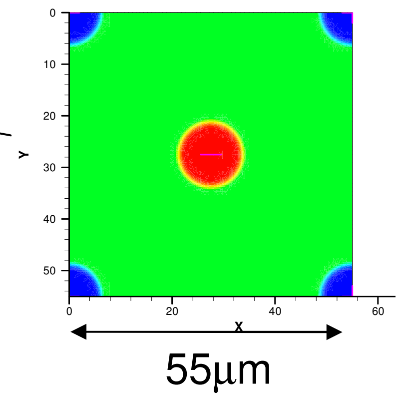
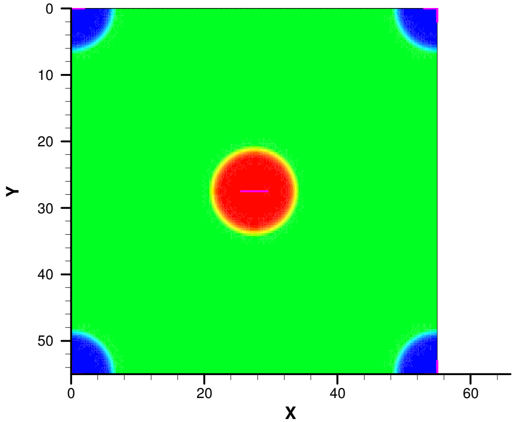




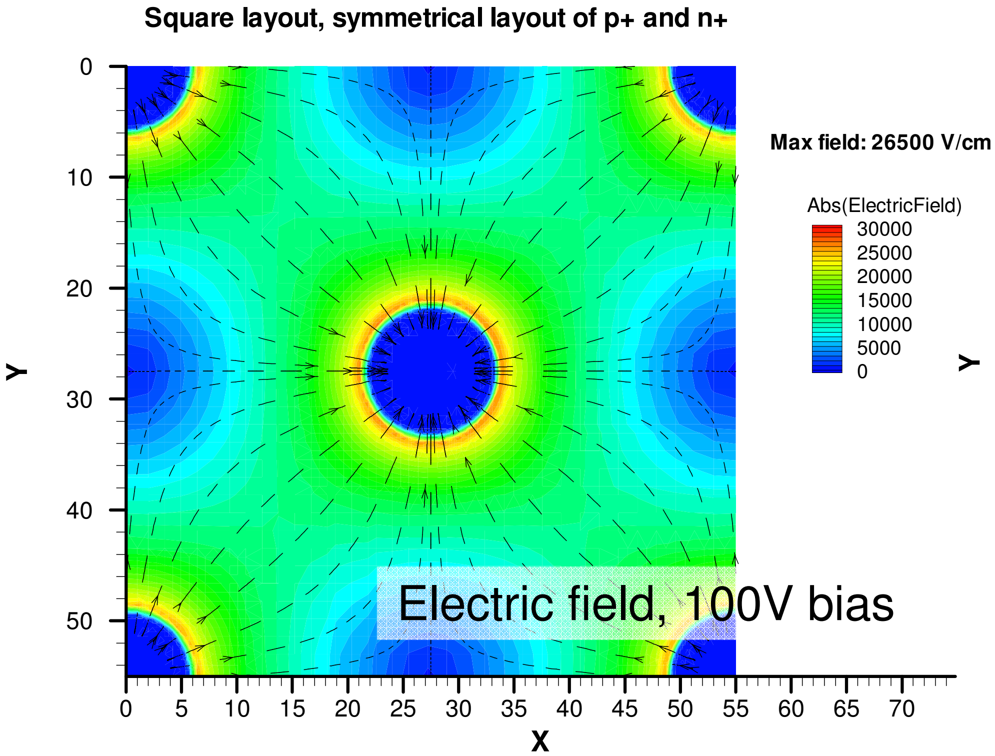


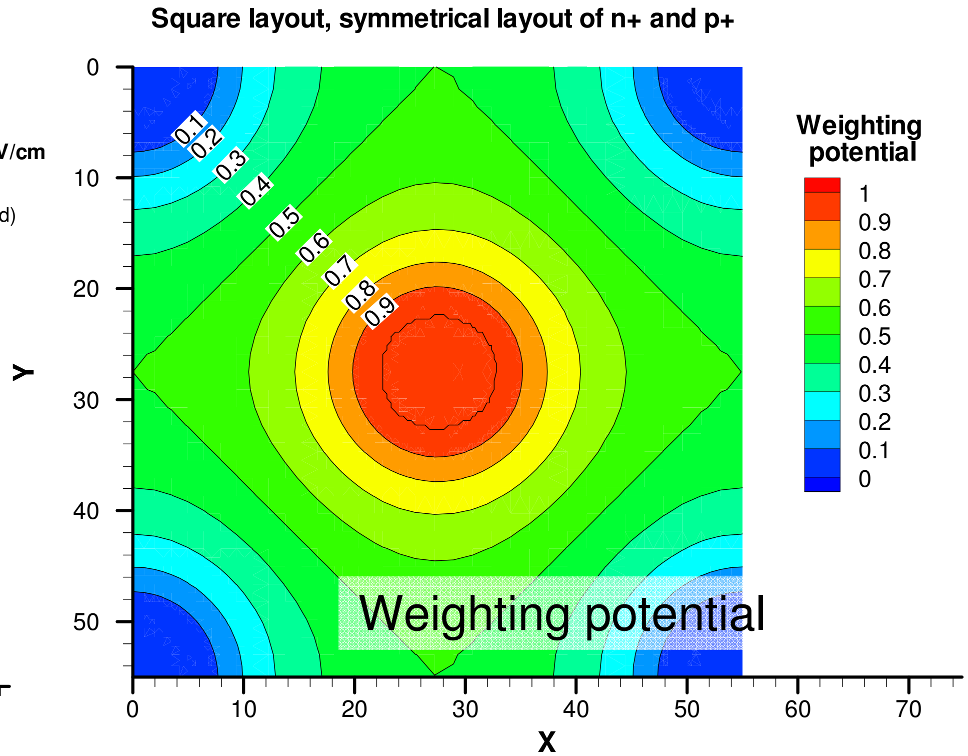
Weighting fields and electrode layouts



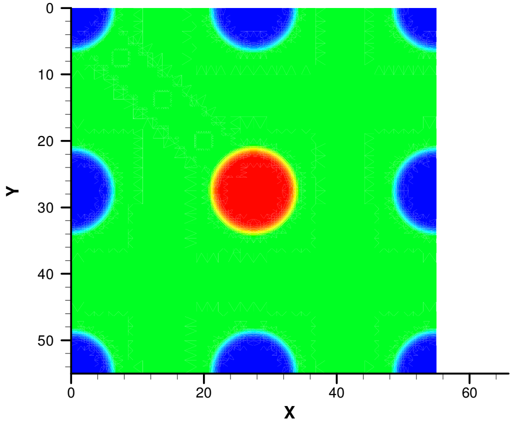
Symmetrical layout of n+ and p+

Weighting potential is the same for electrons and holes



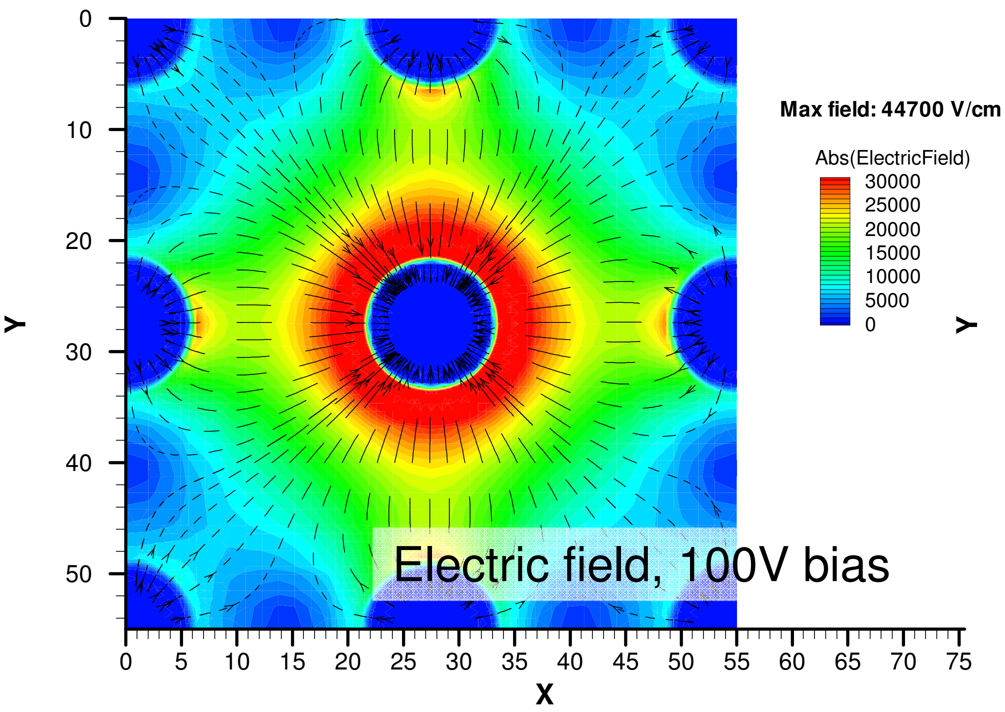


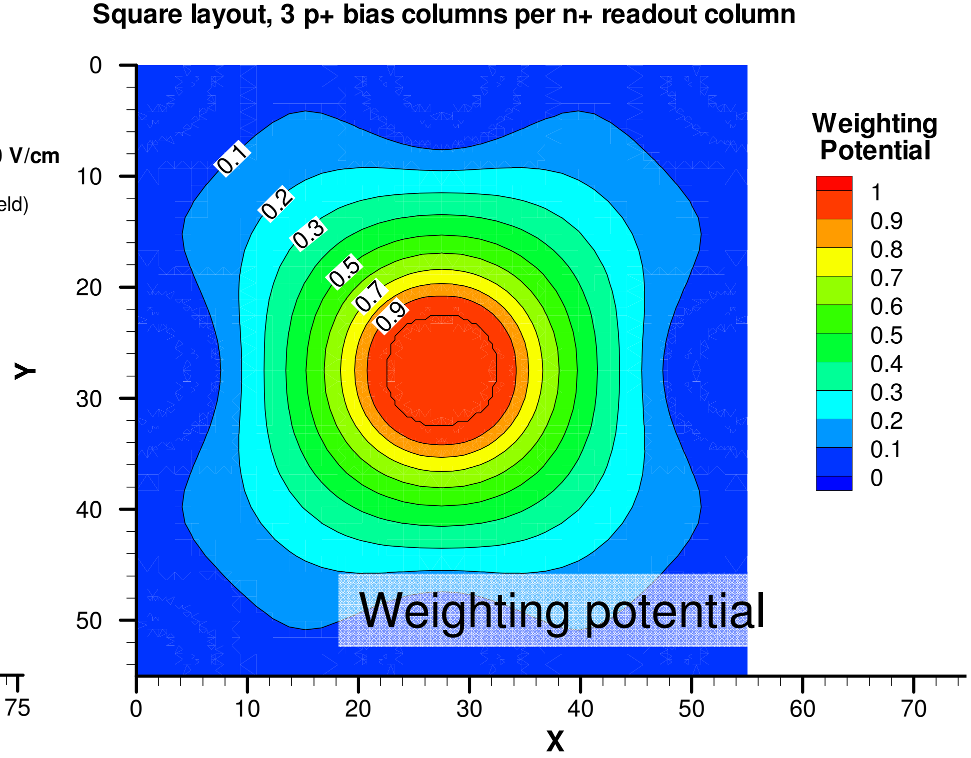
Weighting fields and electrode layouts



3 bias columns per readout column

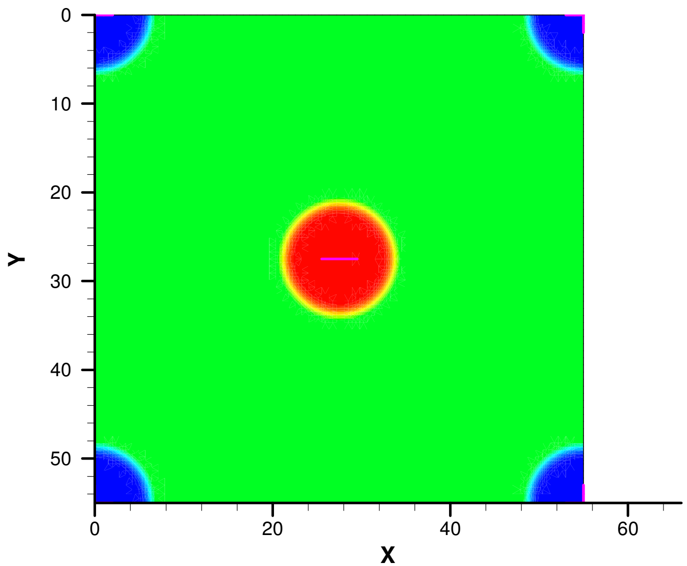
Weighing potential favours electron collection

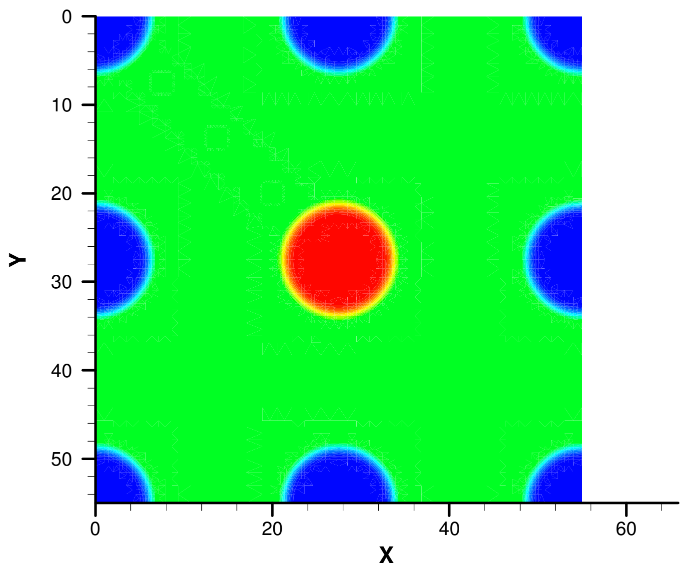




Future work – Design choices with 3D

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





  - Second option doubles number of columns
  - However, increasing no. of p+ columns means larger electron signal

Future work – Design choices with 3D

- **ATLAS pixel (400μm * 50μm) allows a variety of layouts**
  - **No of n+ electrodes per pixel could vary from ~3-8**
  - **Have to consider V_{dep}, speed, total column area, capacitance**
  - **FP420 / ATLAS run at Stanford already has different layouts**
- **CMS (100 μm * 150μm)**