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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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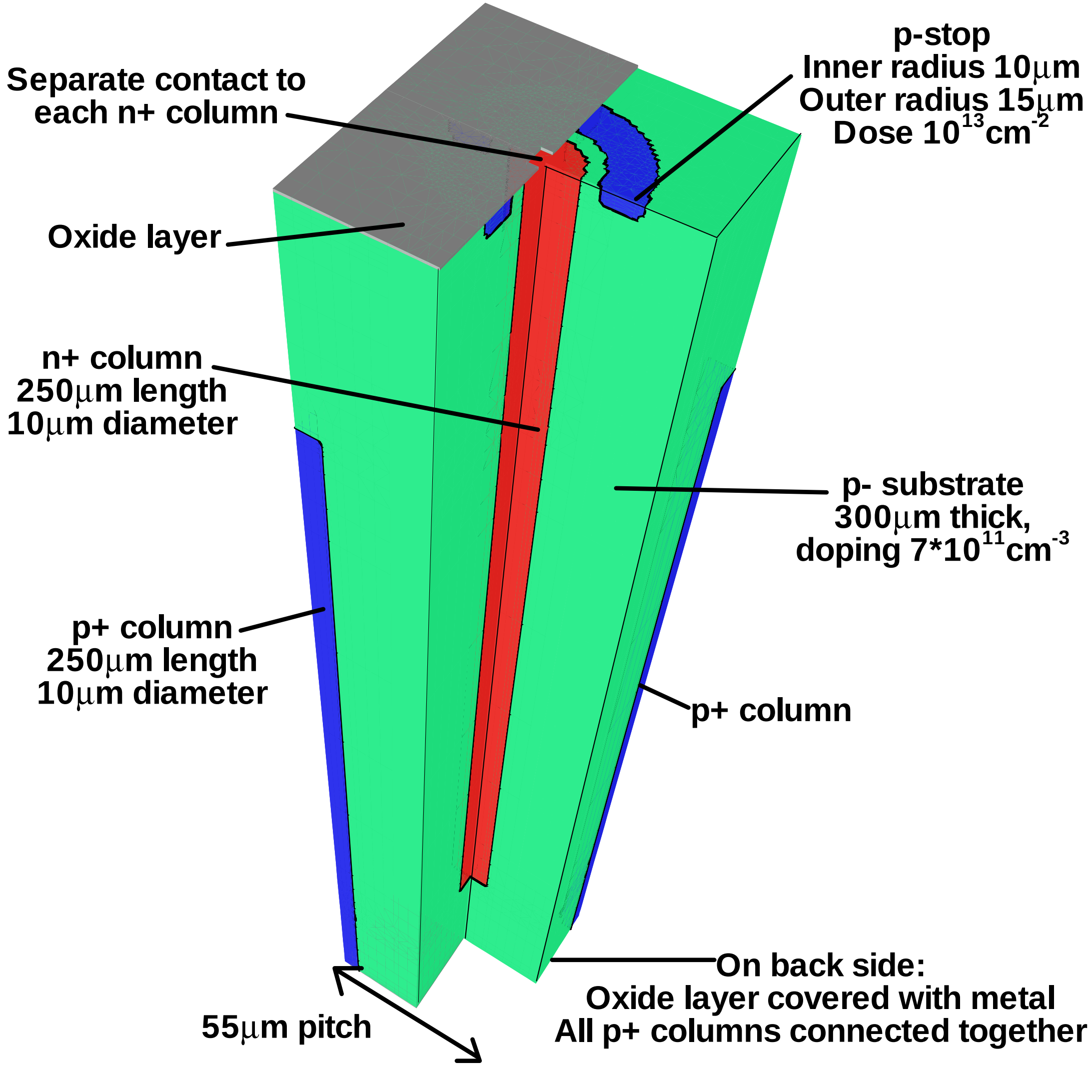
  - Preliminary results of radiation damage modelling

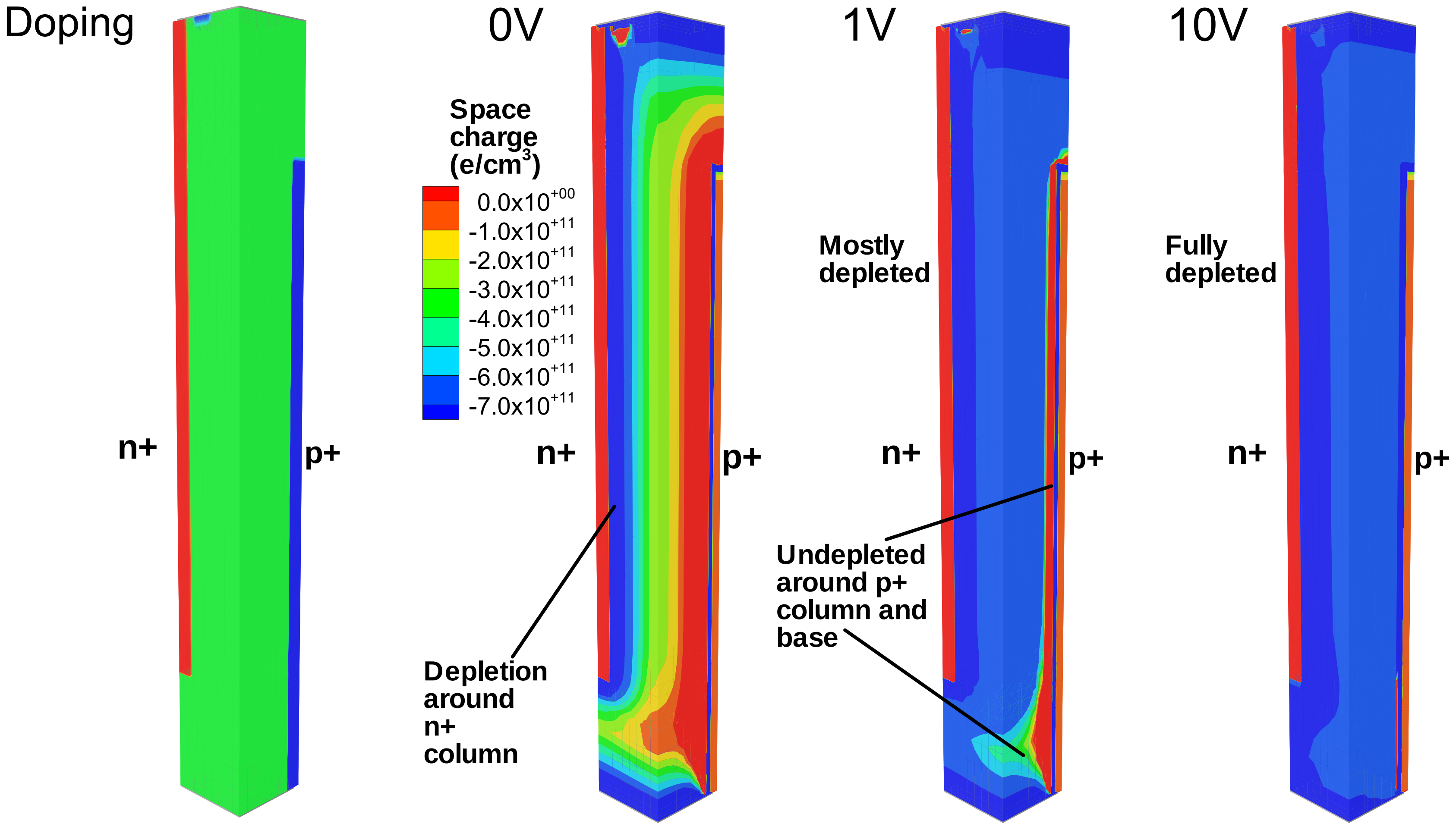
Double-sided 3D detectors

- 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

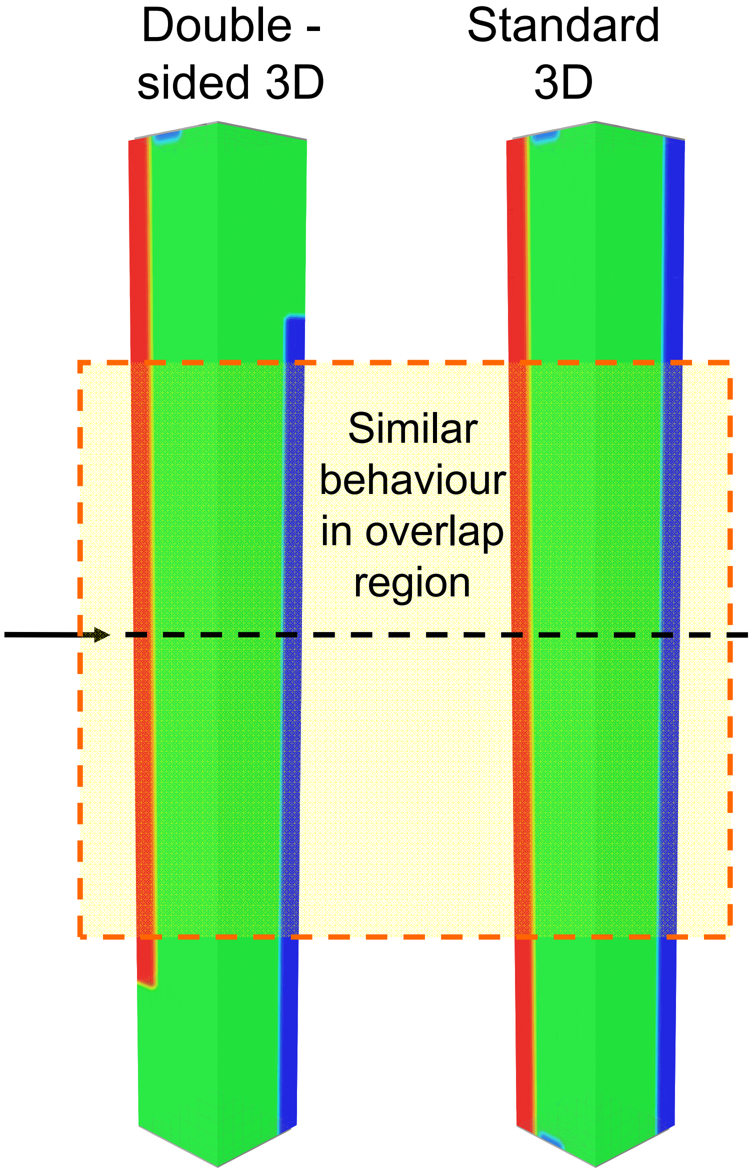


Double-sided 3D: Depletion behaviour

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



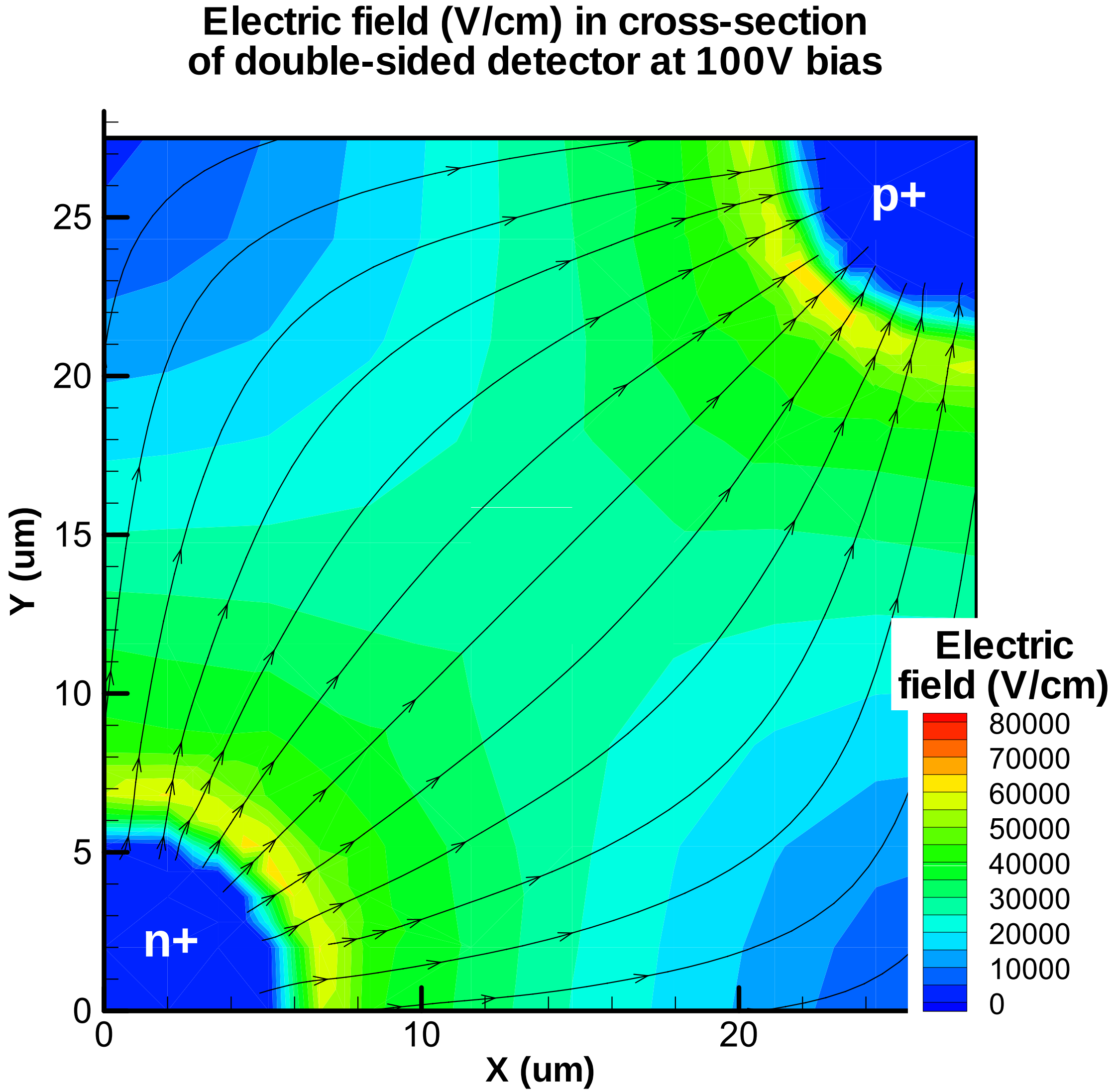
Double-sided 3D: Electric field



Double - sided 3D

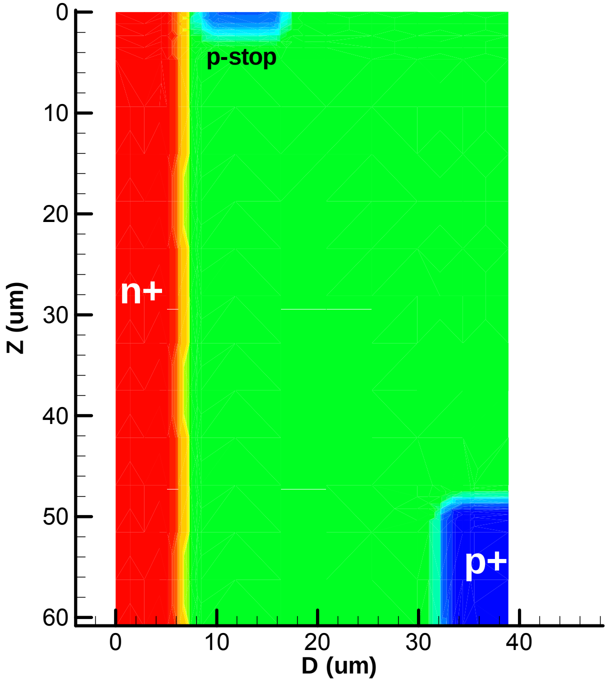
Standard 3D

Similar behaviour in overlap region



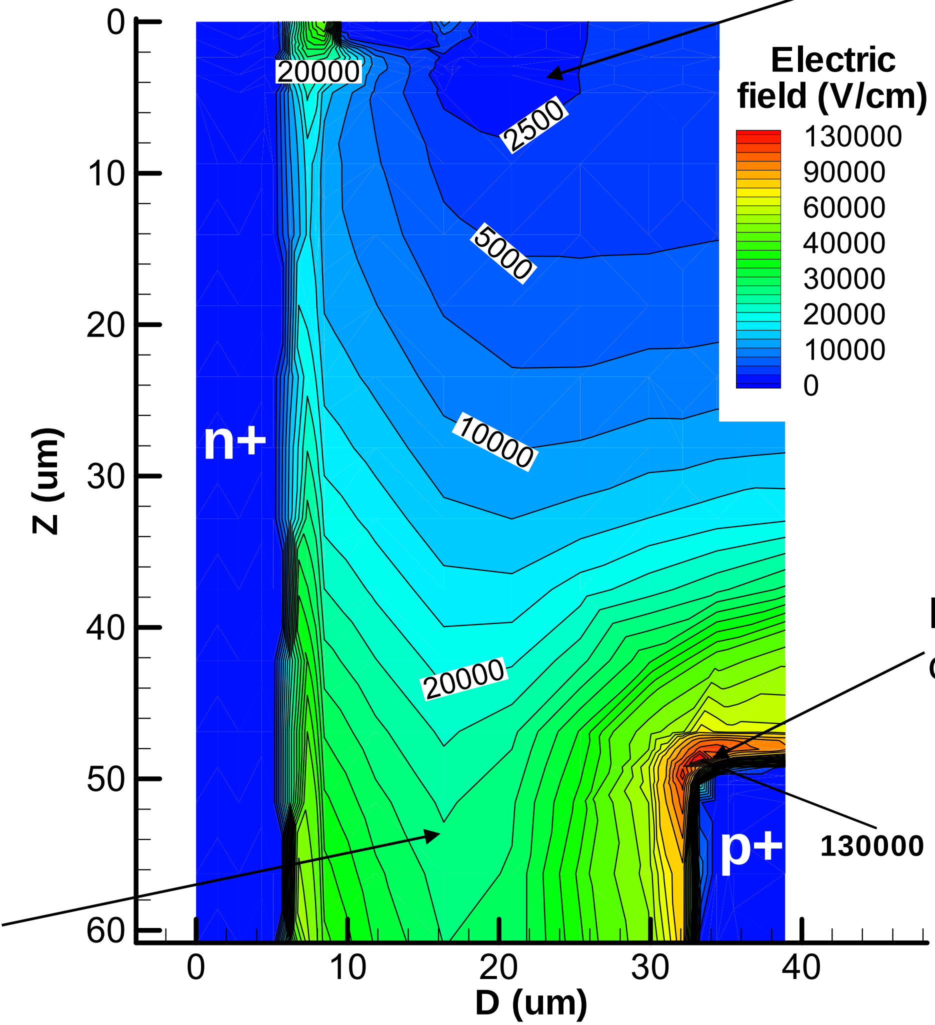
Electric field (V/cm) in cross-section of double-sided detector at 100V bias

Double-sided 3D: Electric field at front



Electric field matches full 3D where columns overlap

Detail of electric field (V/cm) around top of double-sided 3D device (100V bias)

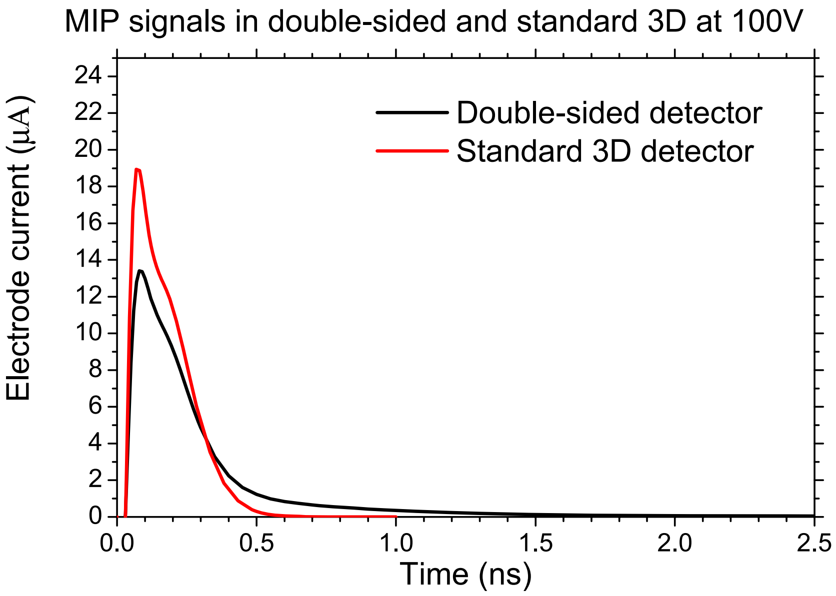


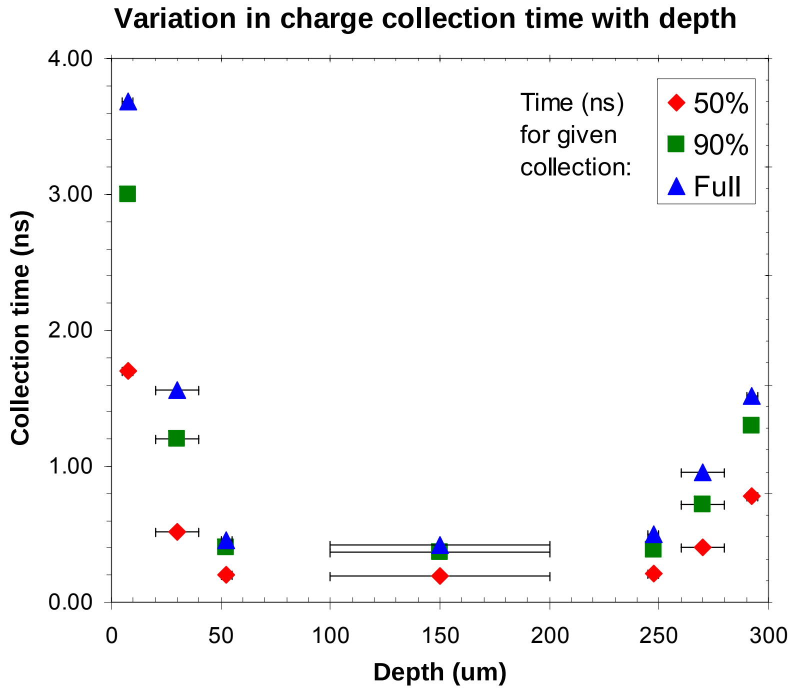
Low fields around front

High field at column tip

Double-sided 3D detectors: Collection time

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


MIP signals in double-sided and standard 3D at 100V


Variation in charge collection time with depth

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*

Overview

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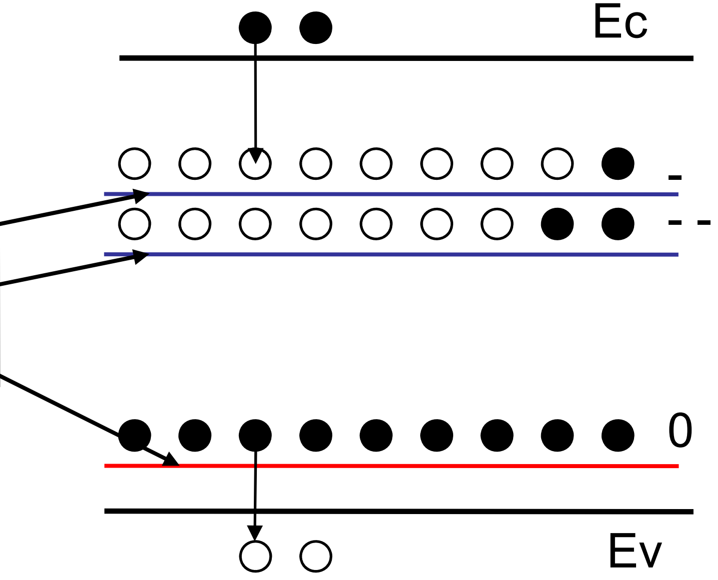
  - Comparison of double-sided 3D and full-3D detectors before irradiation
  - Radiation damage models
  - Preliminary results of radiation damage modelling

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 $I/Vol = \alpha\Phi$
  - 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

$$\frac{\partial n}{\partial t} = -n/\tau_e$$

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

$$\frac{1}{\tau_e} = v_{th}{}^{e} \sigma_e N$$
$$= v_{th}{}^{e} \sigma_e \Phi_{eq} \eta$$

Link between model and experiment

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

- 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} 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} 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:

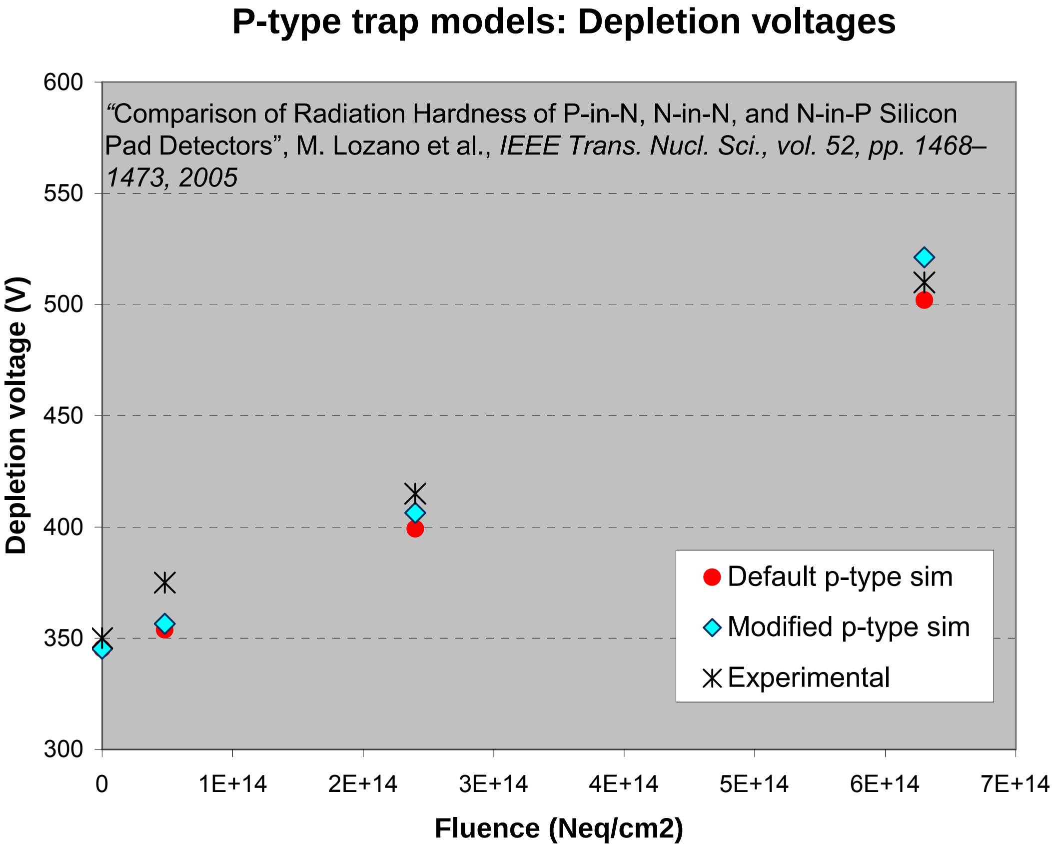
$$n_{e,Trap} = N_{trap} f_n \approx N_{trap} \exp\left(-E_t \big/ kT\right)\left(\frac{n}{n_i} + \frac{\sigma_h v_{th}^{h}}{\sigma_e v_{th}^{e}} \exp\left[-E_t \big/ kT\right]\right)$$

Modified P-type model

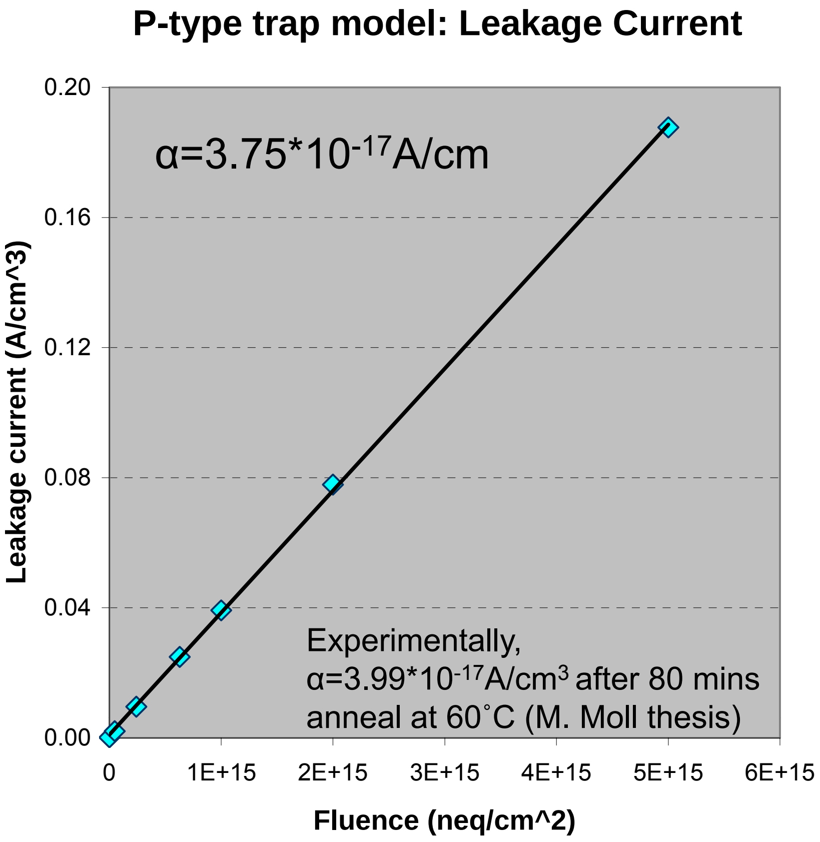
Type	Energy (eV)	Trap	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
Acceptor	Ec-0.42	VV	$9.5*10^{-15}$	$9.5*10^{-14}$	1.613
Acceptor	Ec-0.46	VVV	$5.0*10^{-15}$	$5.0*10^{-14}$	0.9
Donor	Ec+0.36	CiOi	$3.23*10^{-13}$	$3.23*10^{-14}$	0.9

Modified P-type model and experimental data

Type	Energy (eV)	Trap	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
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	Ec+0.36	CiOi	$3.23*10^{-13}$	$3.23*10^{-14}$	0.9



"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*



$\alpha=3.75*10^{-17}$A/cm

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

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

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

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

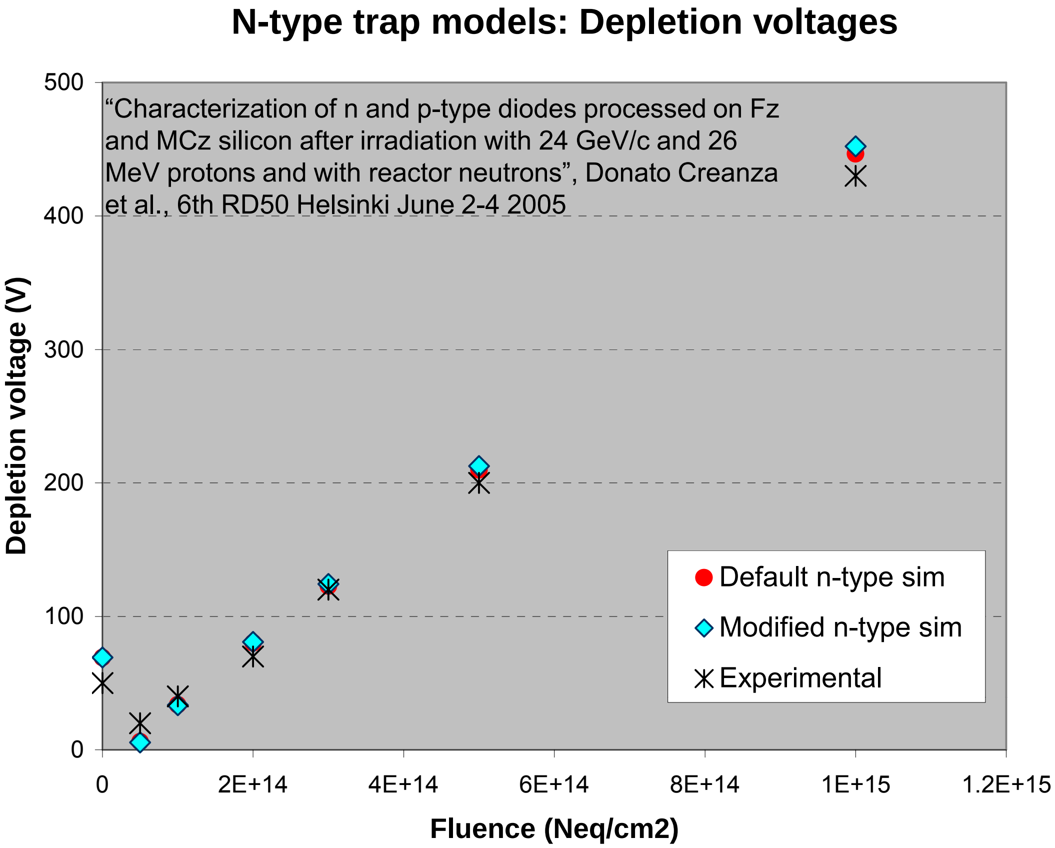
$$K_C = (2.2 \pm 0.2) * 10^{-2} \text{cm}^{-1}$$

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

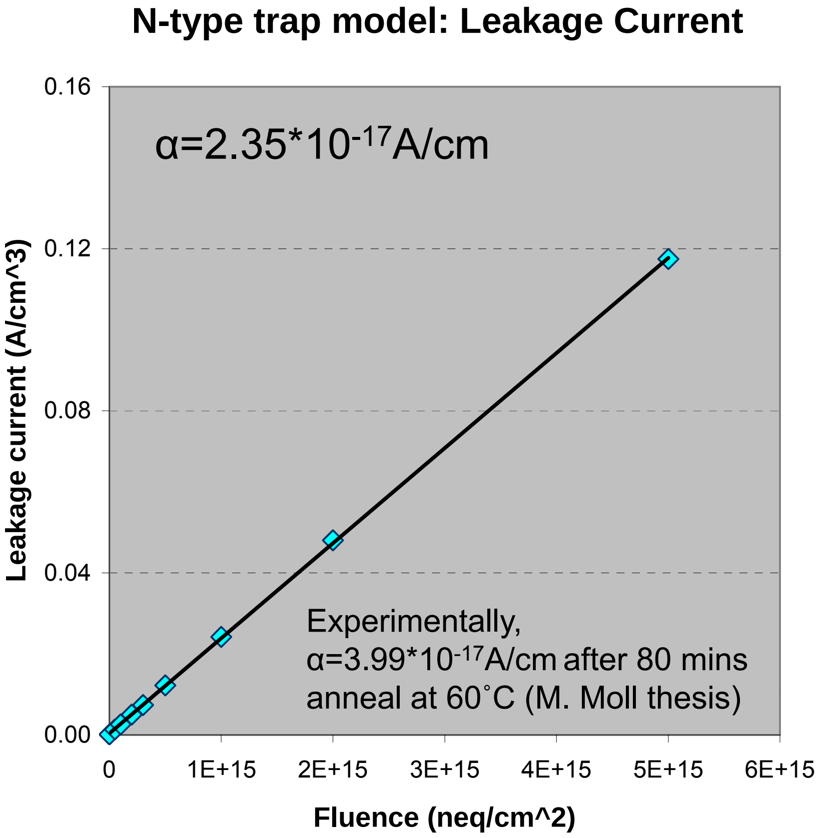
- Experimental trapping times for n-type silicon (G. Kramberger et al., NIMA, vol. 481, pp297-305, 2002)
  - $\beta_e = 4.0*10^{-7}\text{cm}^2\text{s}^{-1}$ $\beta_h = 5.3*10^{-7}\text{cm}^2\text{s}^{-1}$
- Calculated values from n-type trap model
  - $\beta_e = 5.3*10^{-7}\text{cm}^2\text{s}^{-1}$ $\beta_h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

Modified N-type model

Type	Energy (eV)	Trap	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
Acceptor	Ec-0.42	VV	**$1.5*10^{-15}$**	**$0.9*10^{-14}$**	13
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



"Characterization of n and p-type diodes processed on Fz and MCz silicon after irradiation with 24 GeV/c and 26 MeV protons and with reactor neutrons", Donato Creanza et al., 6th RD50 Helsinki June 2-4 2005

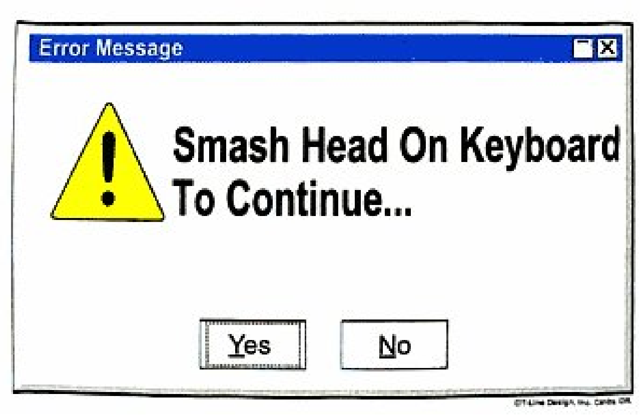


$\alpha=2.35*10^{-17}$A/cm

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

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**


Error Message

Smash Head On Keyboard To Continue...

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

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

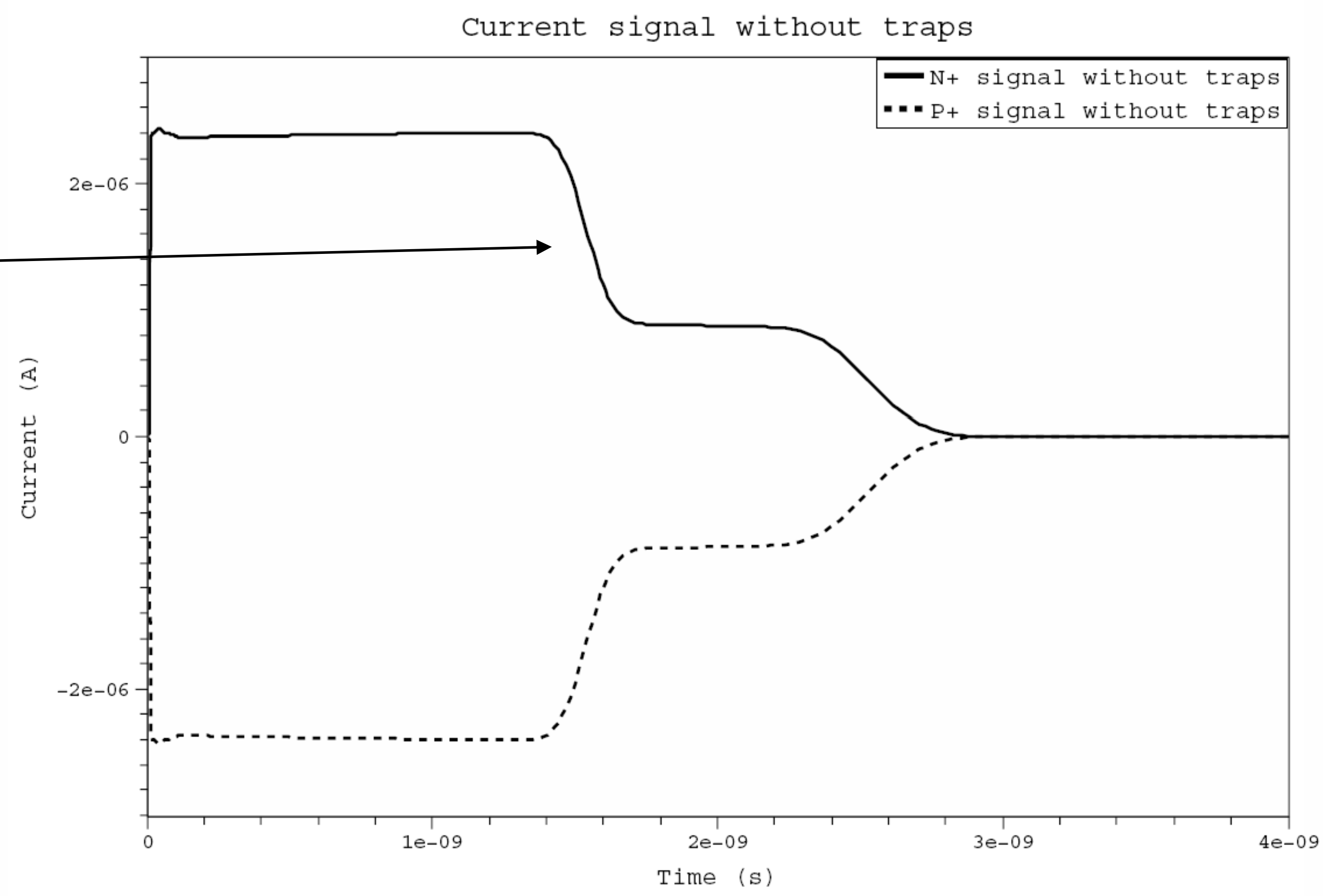
- This bug is not present in the latest release of **Synopsis TCAD** (2007)
  - Synopsis bought ISE TCAD, and renamed Dessis as “Sentaurus Device”
  - Don’t know which specific release fixed the problem

Test of charge trapping in Synopsis TCAD

- Simulated a simple diode with carriers generated at its midpoint

No traps

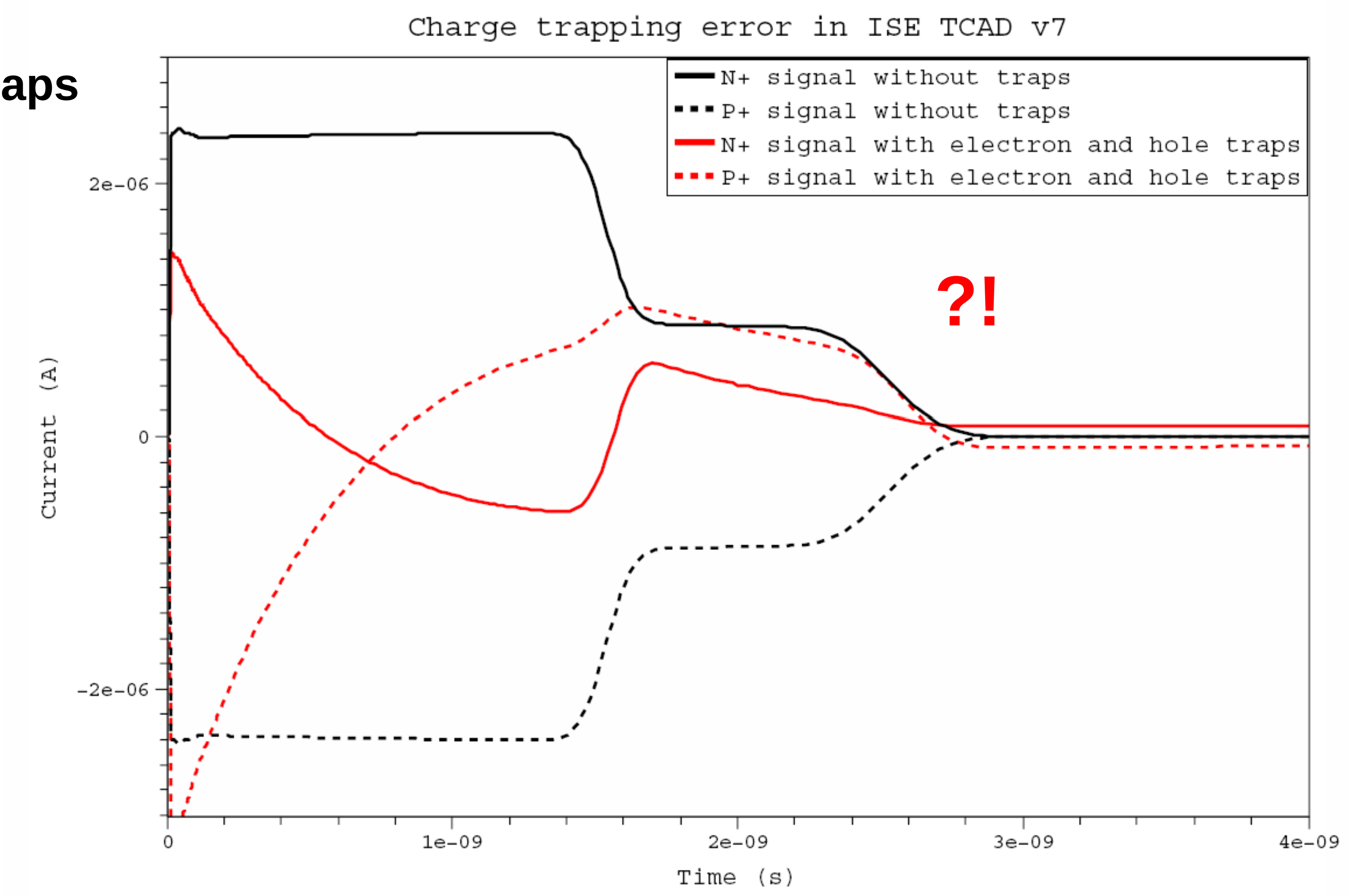
“Double step” seen because electrons are collected before holes



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

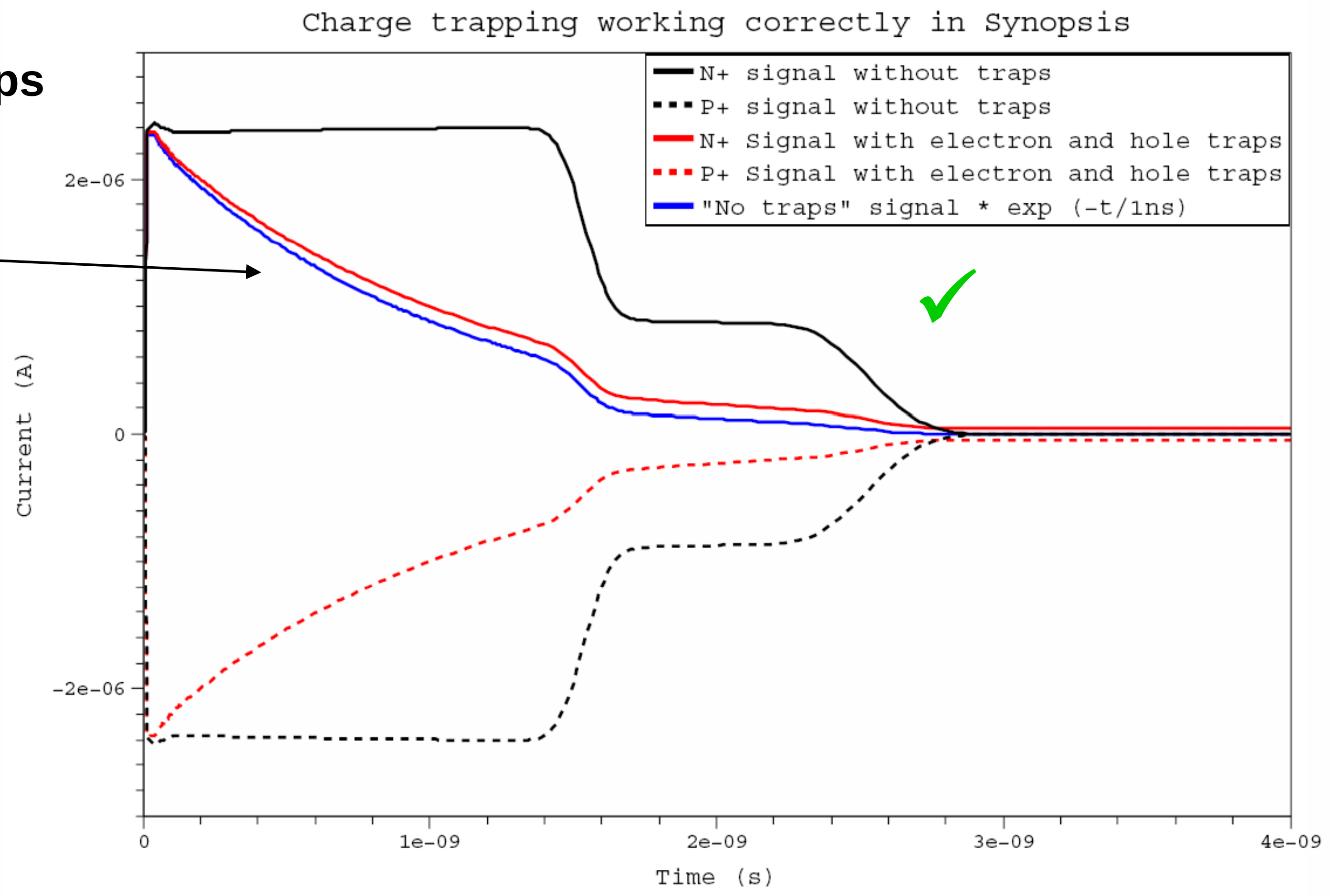


Test of charge trapping in Synopsis TCAD

- 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 $\tau_e \approx \tau_h \approx 1\mathrm{ns}$

Synopsis traps

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



Overview

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  - Comparison of double-sided 3D and full-3D detectors before irradiation
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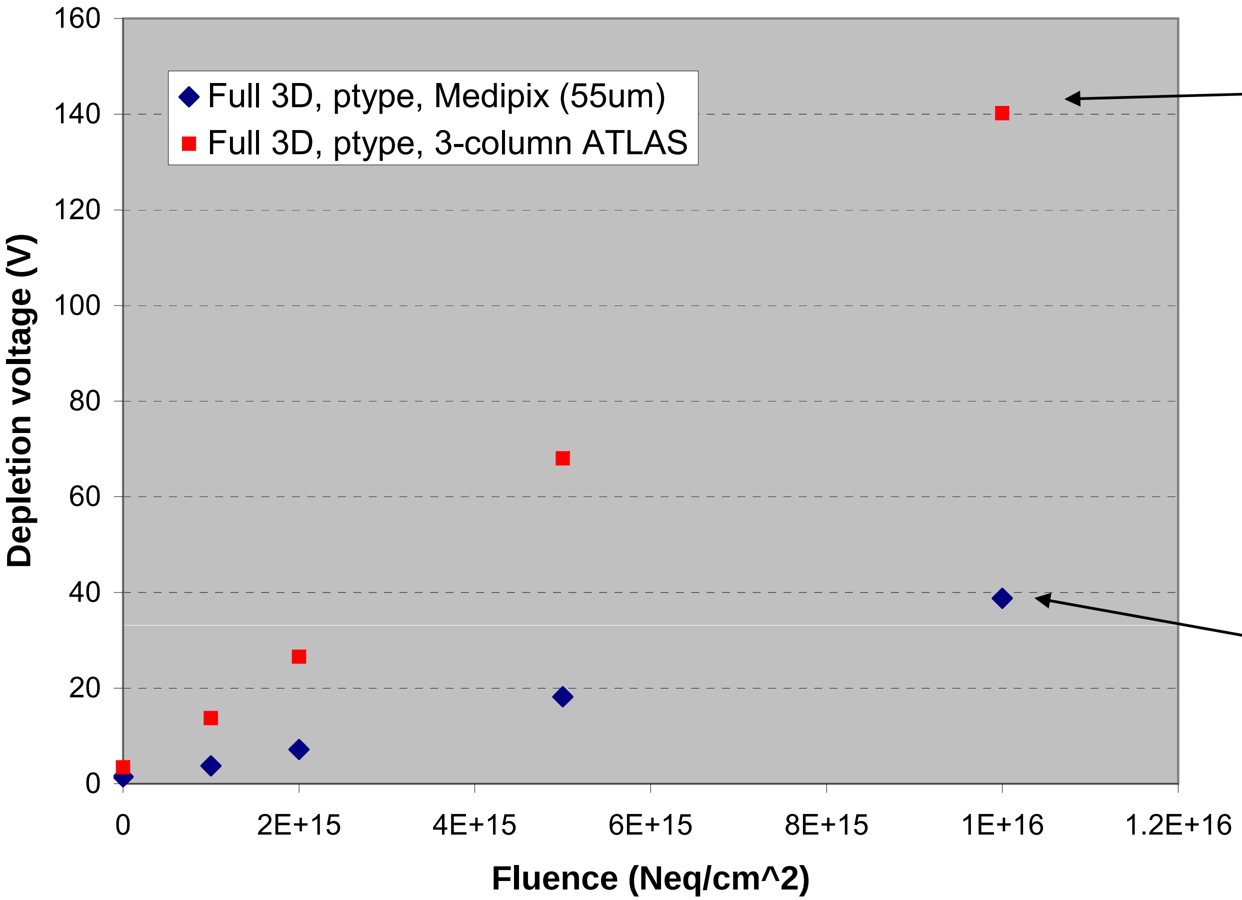
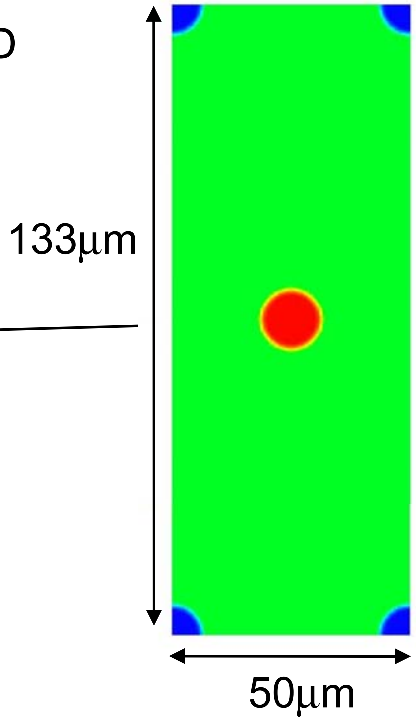
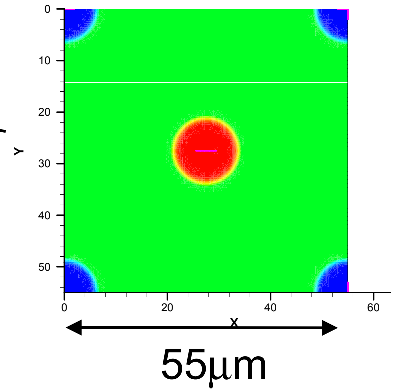
Full 3D – Depletion voltage (p-type)

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

Depletion voltages and radiation damage





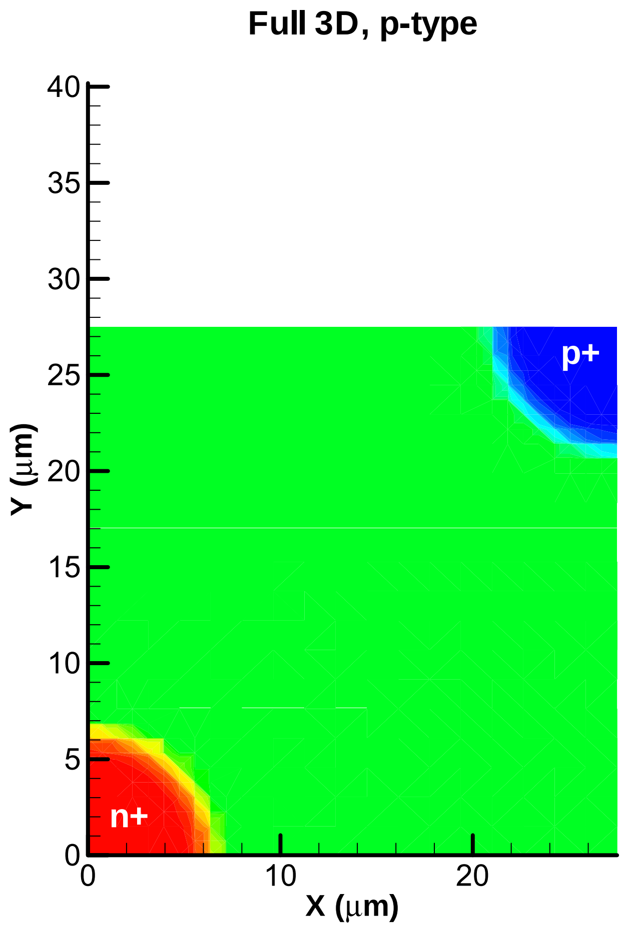


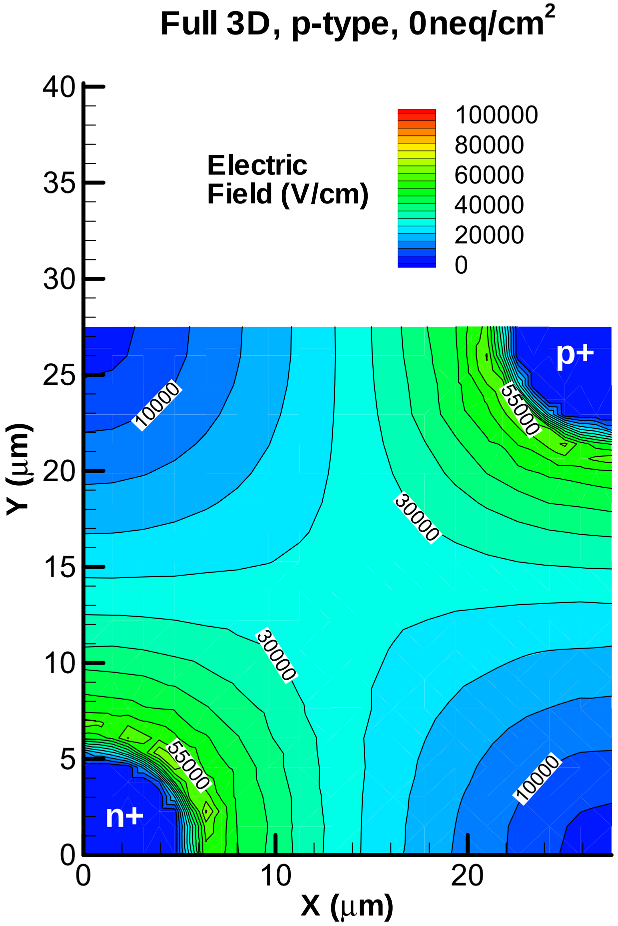
Full 3D – electric field at 100V

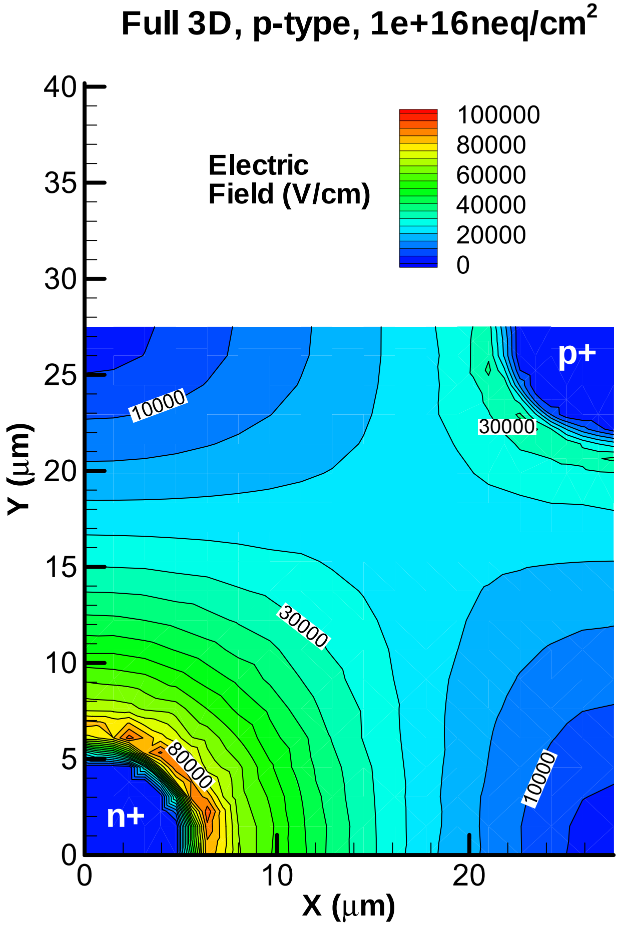
Full depletion is achieved well under 100V, but electric field is altered

No damage

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


Full 3D, p-type


Full 3D, p-type, 0neq/cm^2

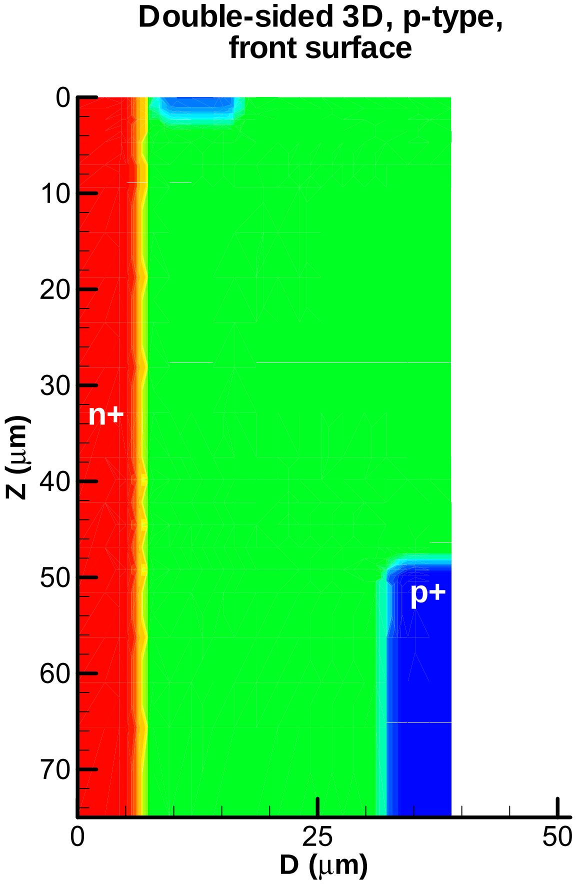

Full 3D, p-type, 1e+16neq/cm^2

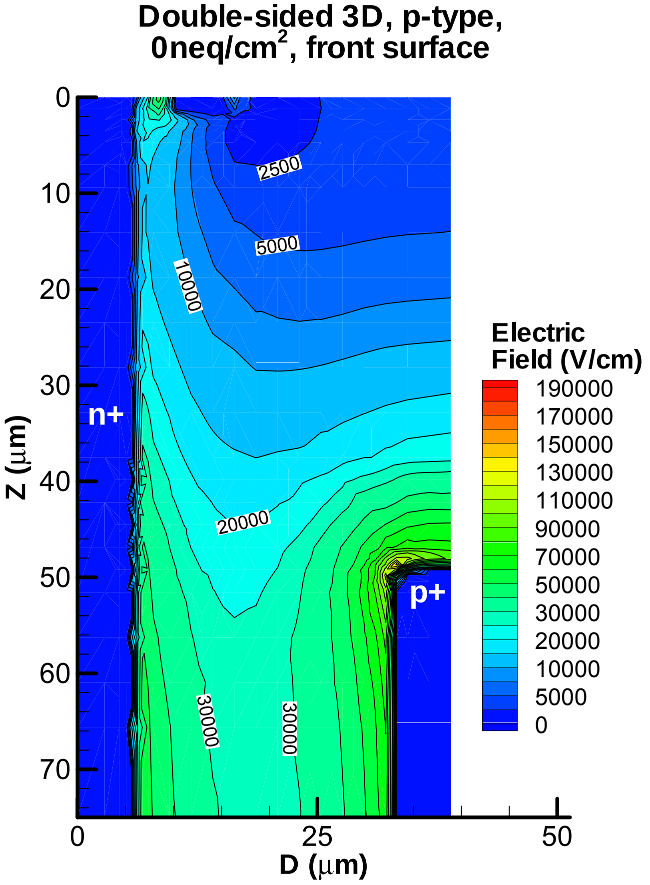
Double-sided 3D – front surface

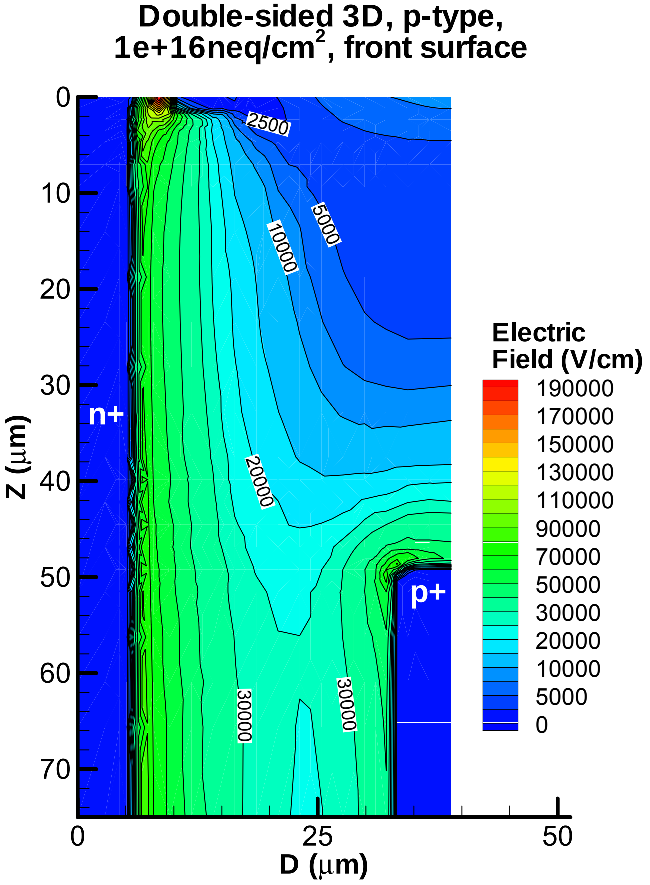
Once again, double-sided devices show different behaviour at front and back surfaces

No damage

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







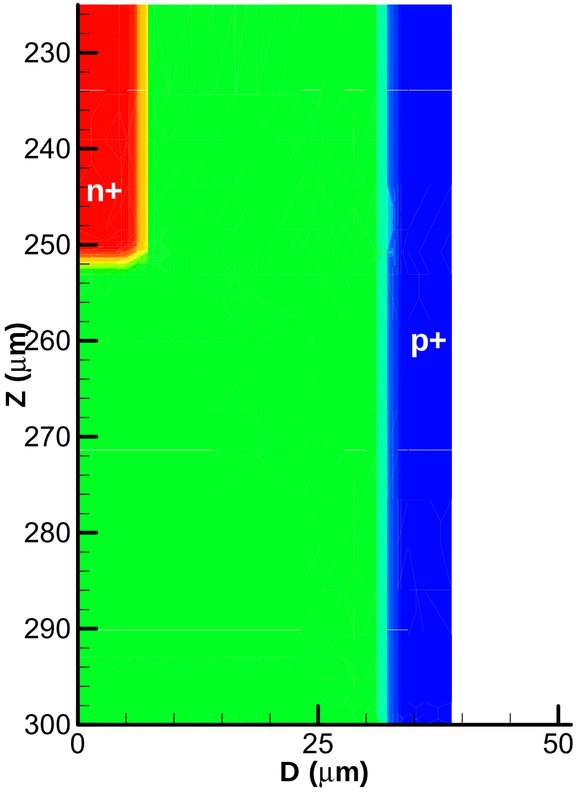
Double-sided 3D – back surface

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

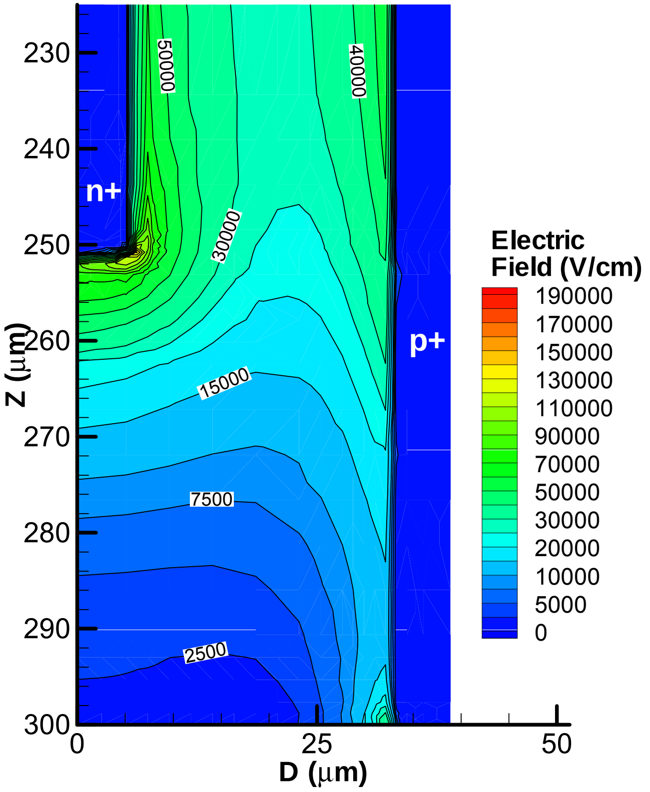
No damage

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

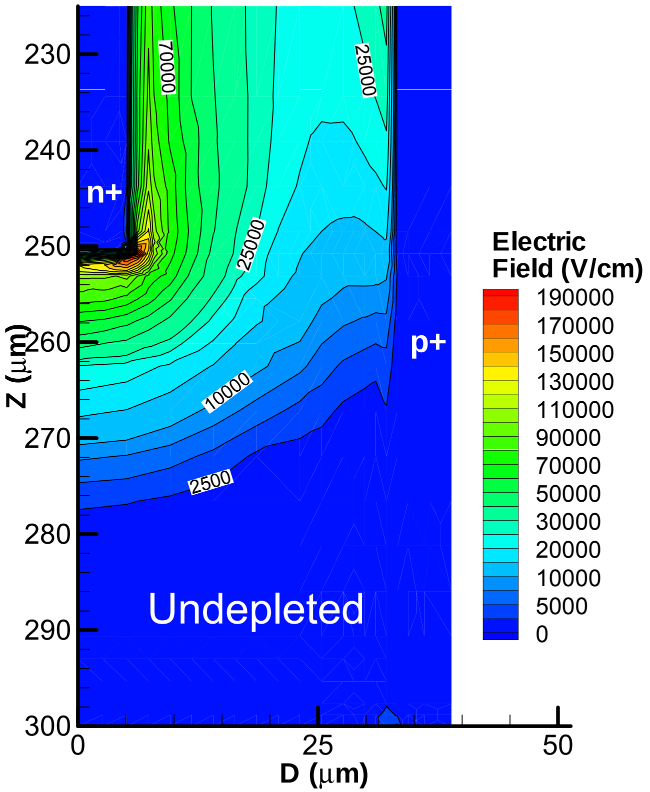
Double-sided 3D, p-type, back surface



Double-sided 3D, p-type, 0neq/cm^2, back surface

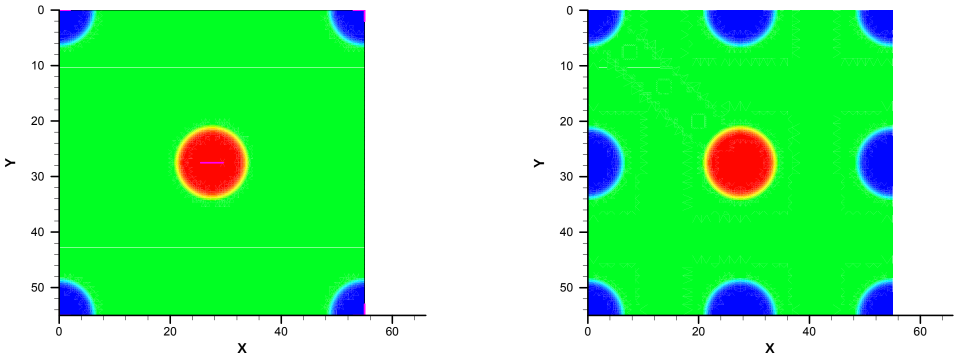


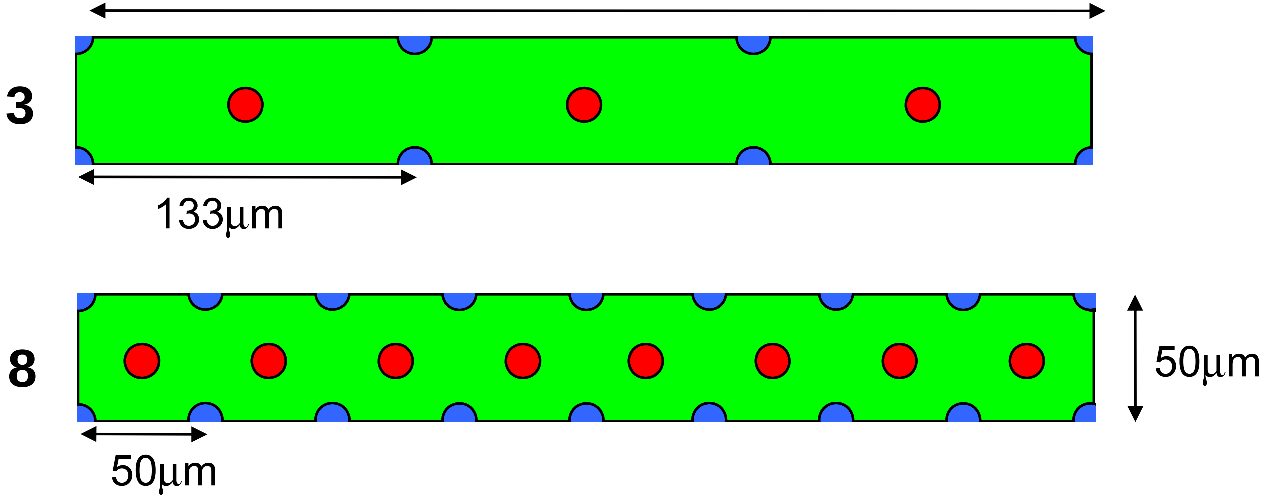
Double-sided 3D, p-type, 1e+16neq/cm^2, back surface



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

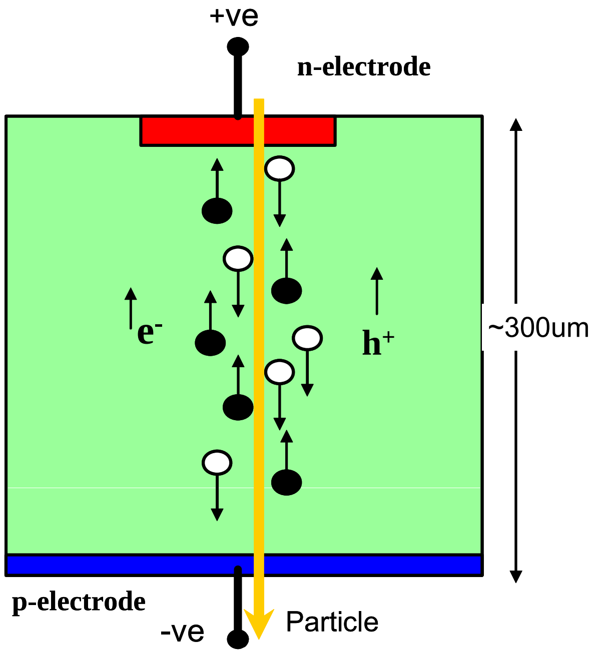
Thank you for listening

Additional slides

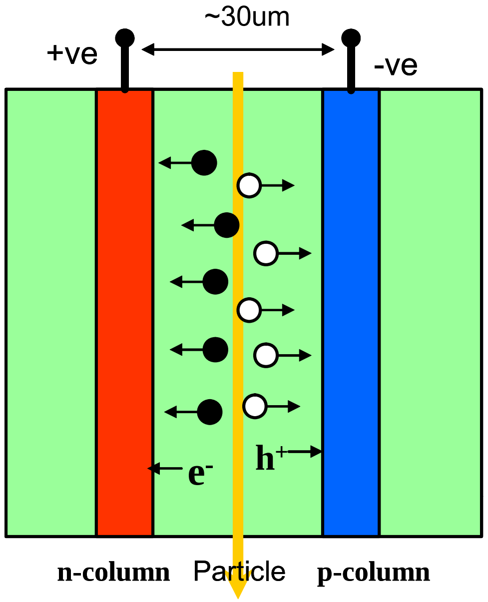
3D detectors

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

Planar



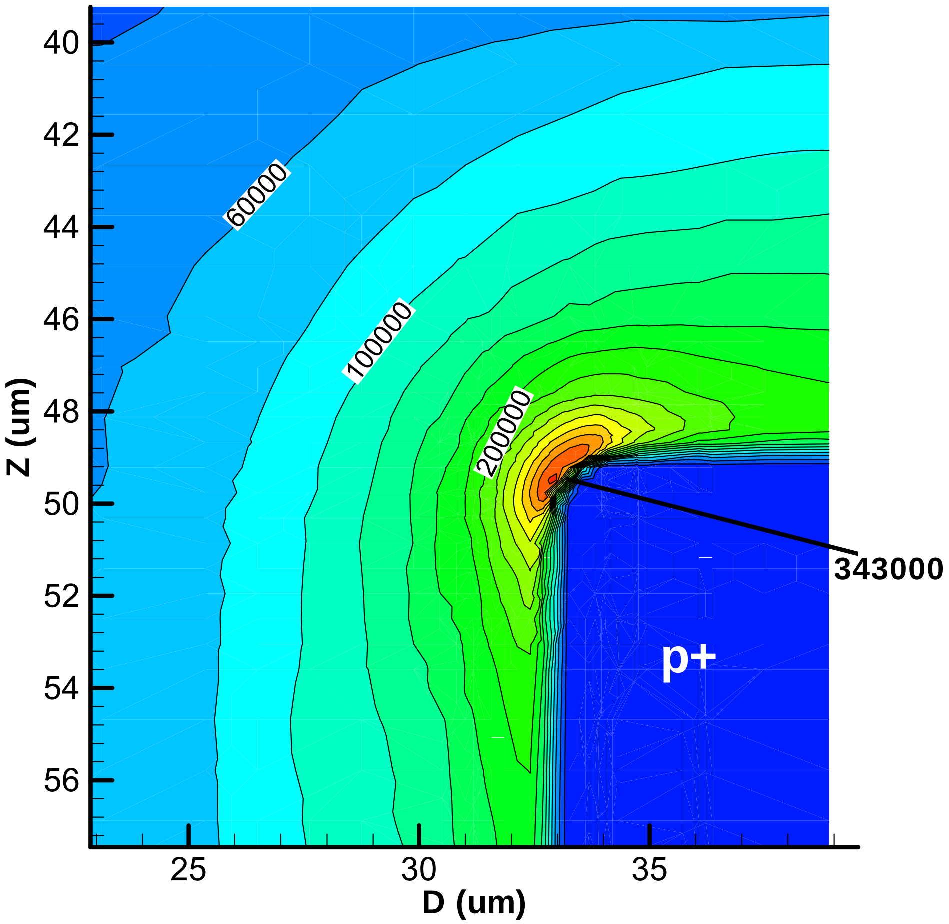
3D



Breakdown in double-sided 3D

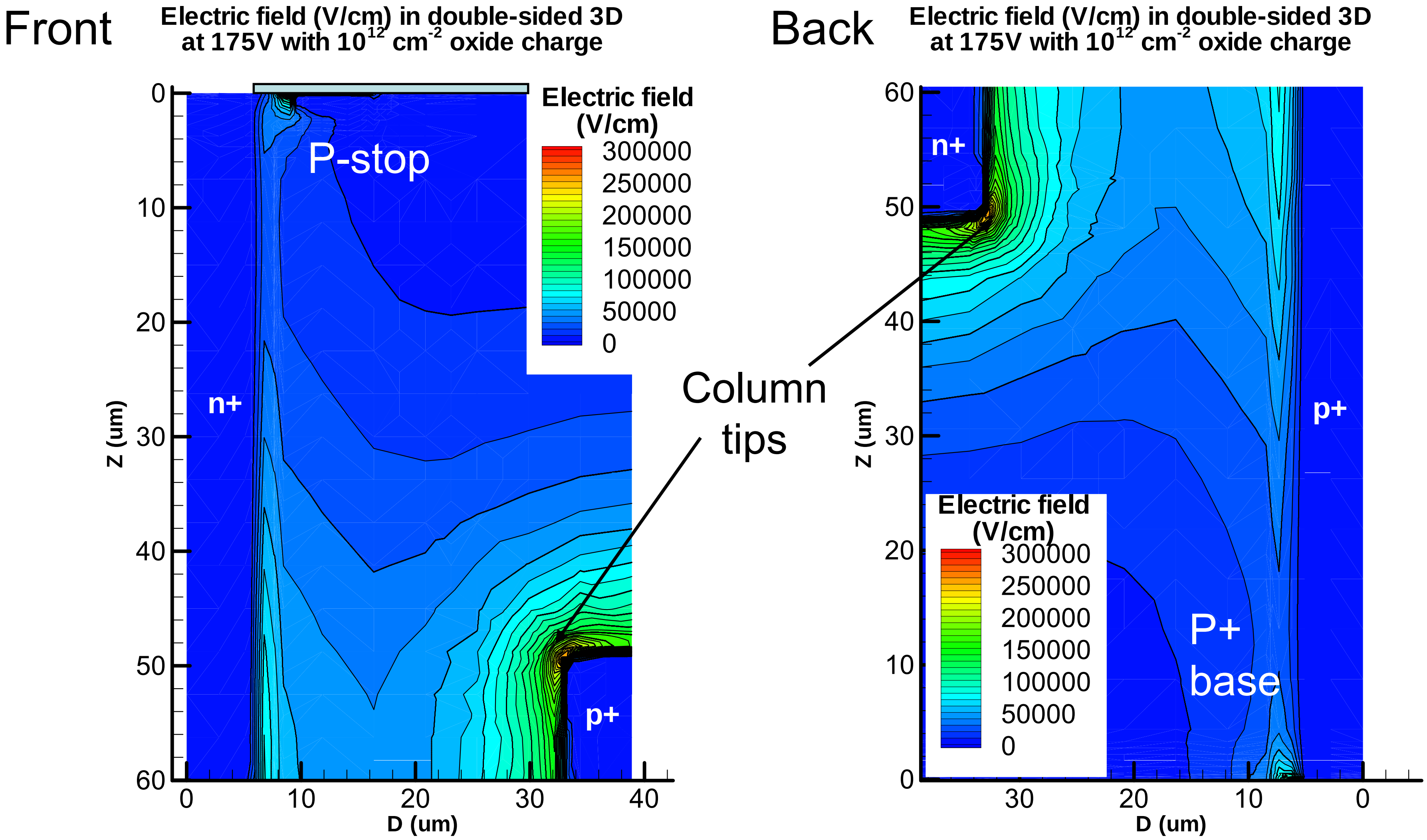
- Breakdown occurs at column tips around 230V
  - Dependent on shape, e.g. 185V for square columns

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


Front

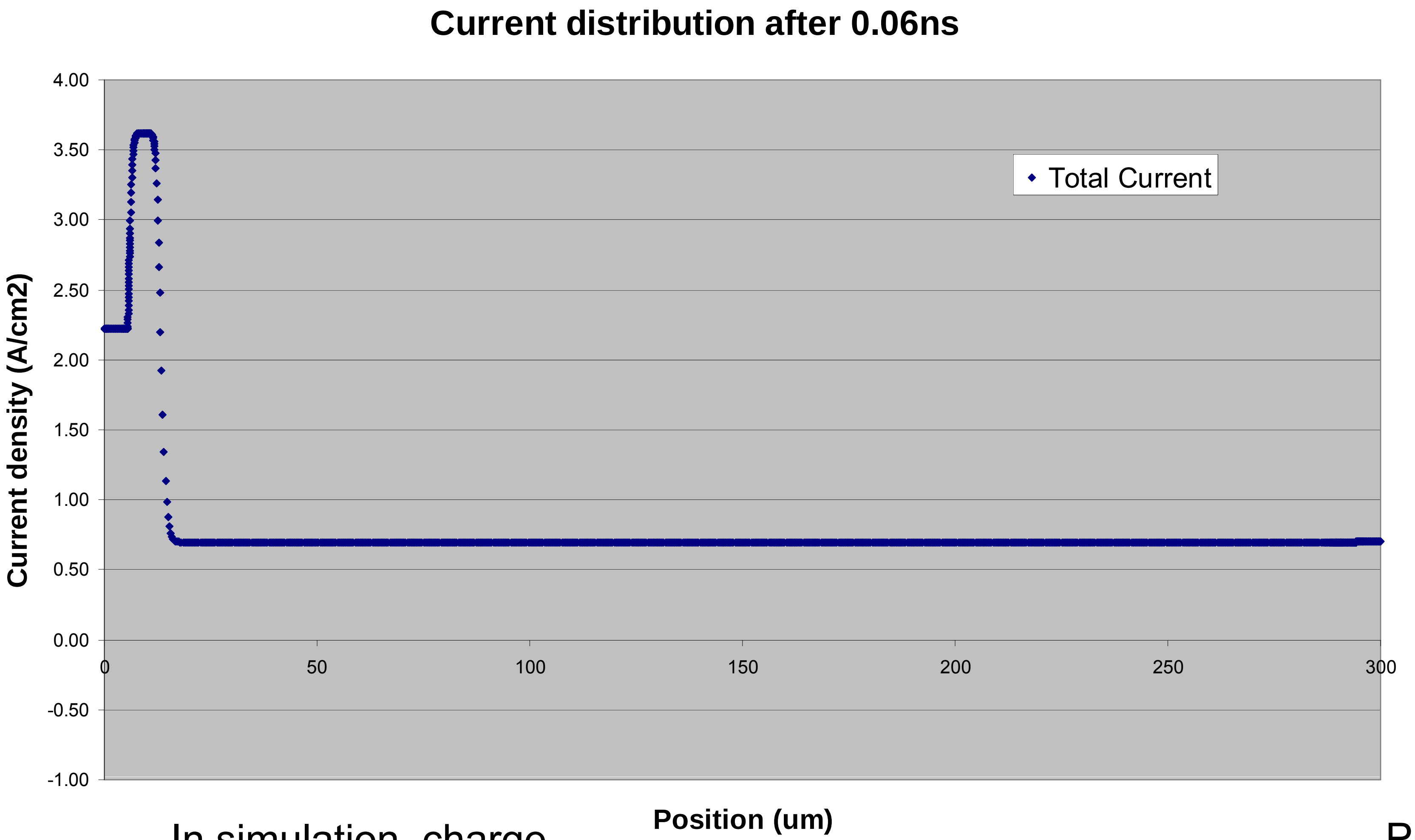
Electric field (V/cm) in double-sided 3D at 175V with 10^{12} cm^{-2} oxide charge

Back

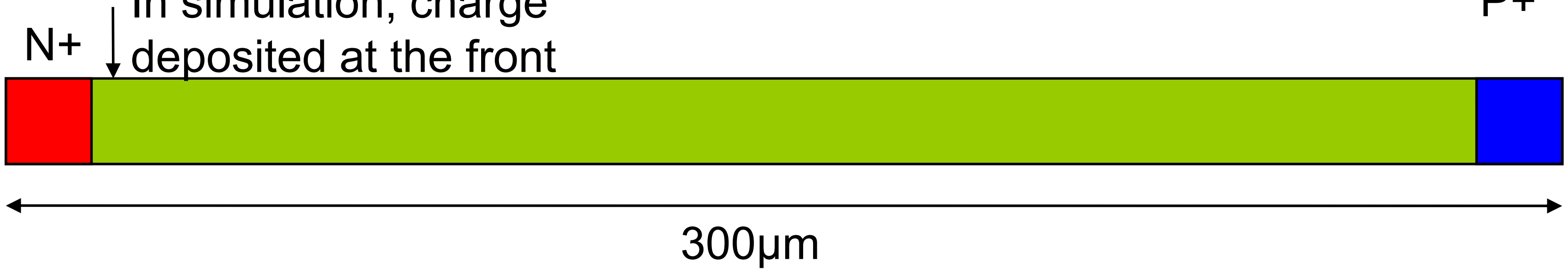
Electric field (V/cm) in double-sided 3D at 175V with 10^{12} cm^{-2} oxide charge

Column tips

Example of ISE TCAD bug

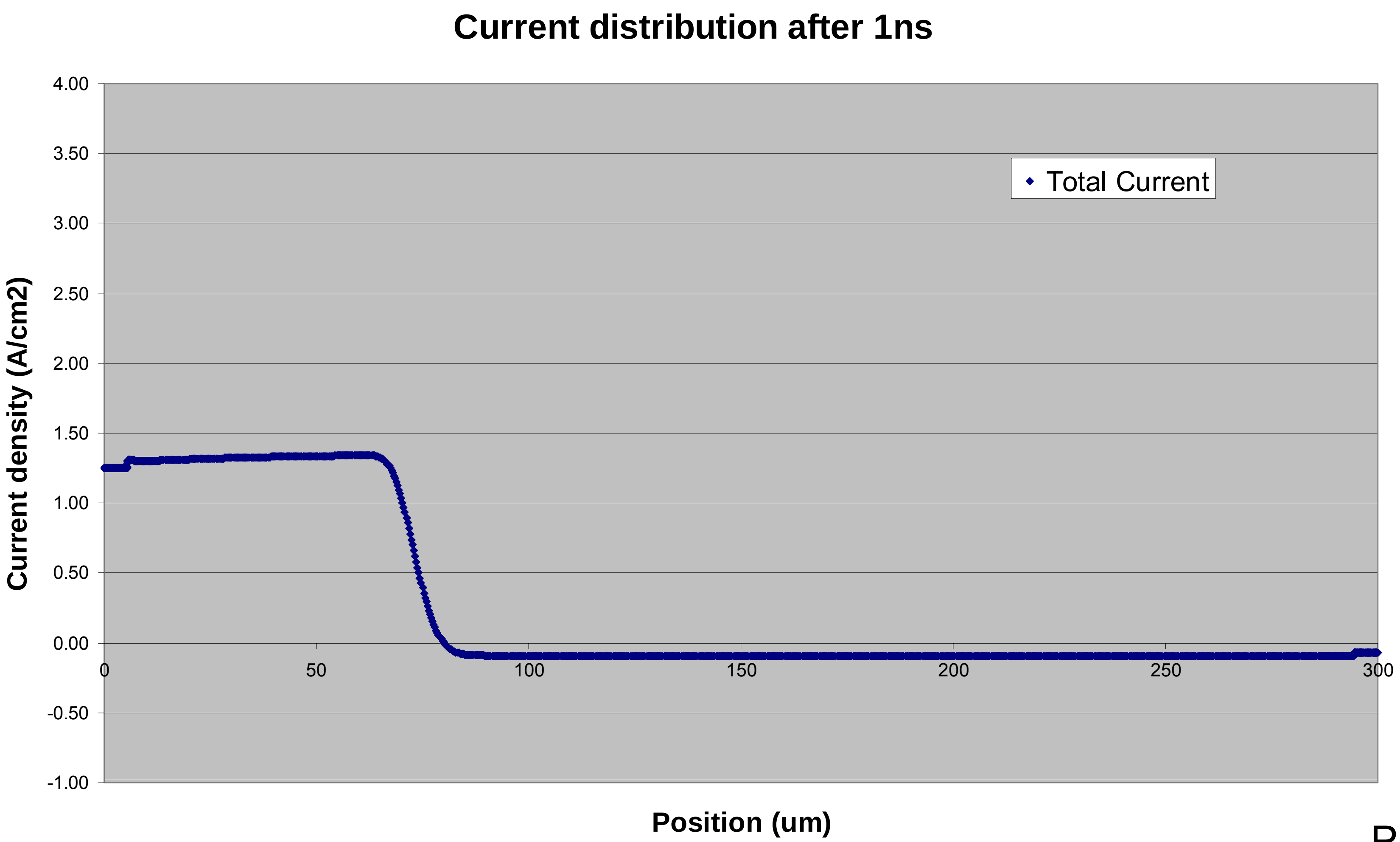


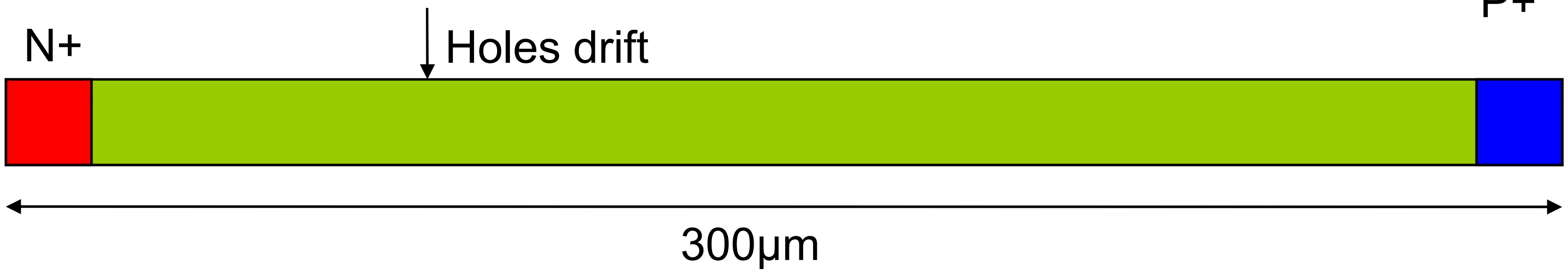
Current distribution after 0.06ns



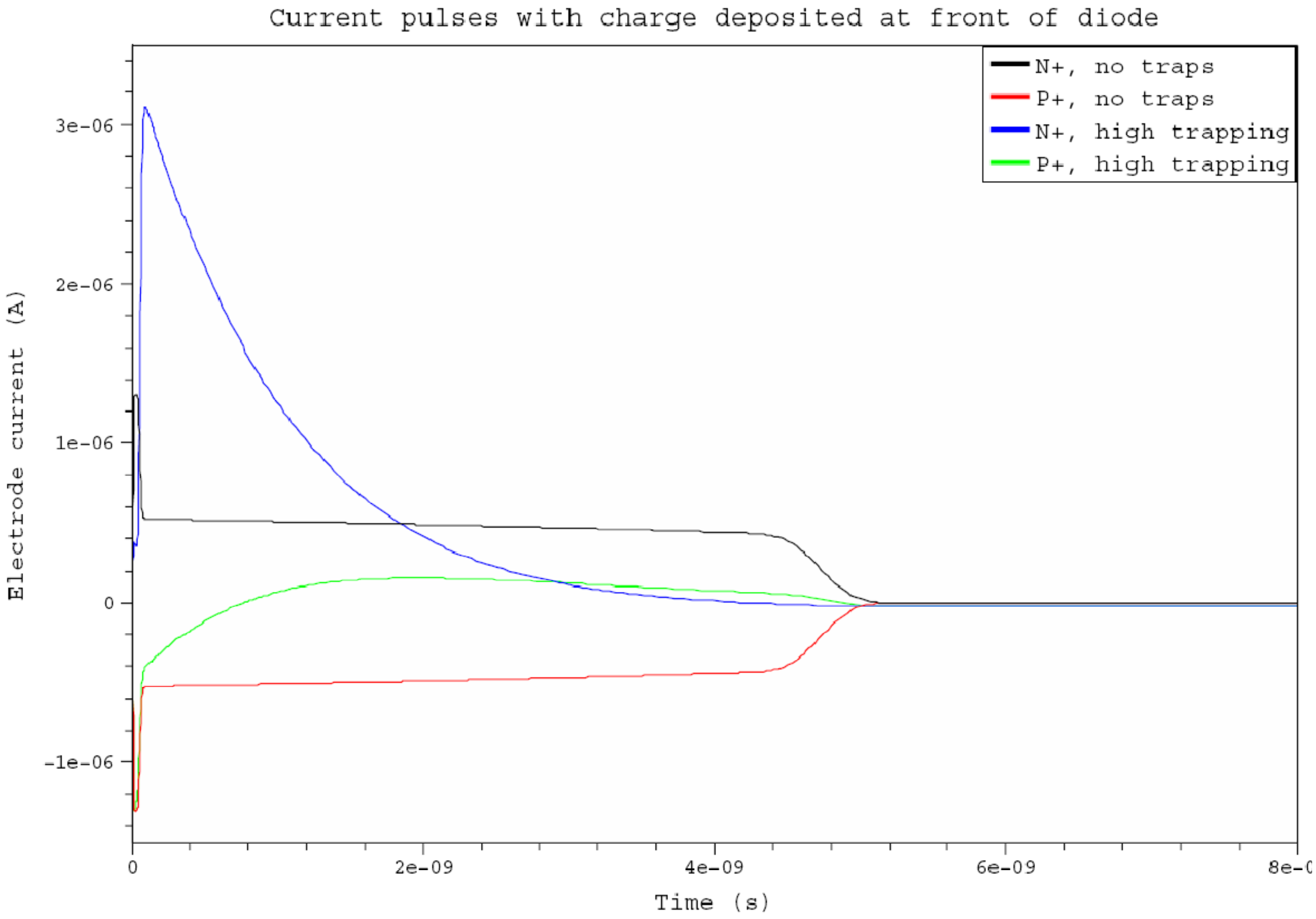
In simulation, charge deposited at the front

Example of ISE TCAD bug



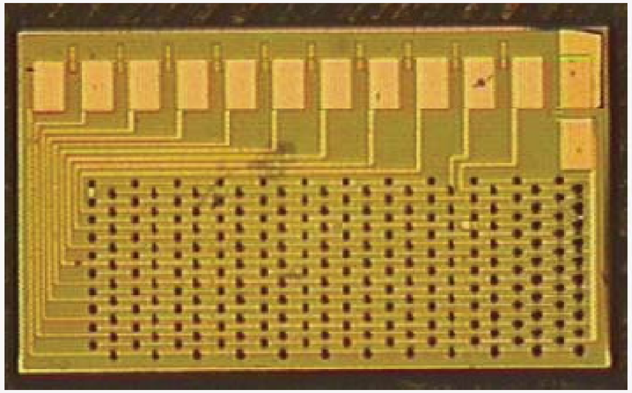


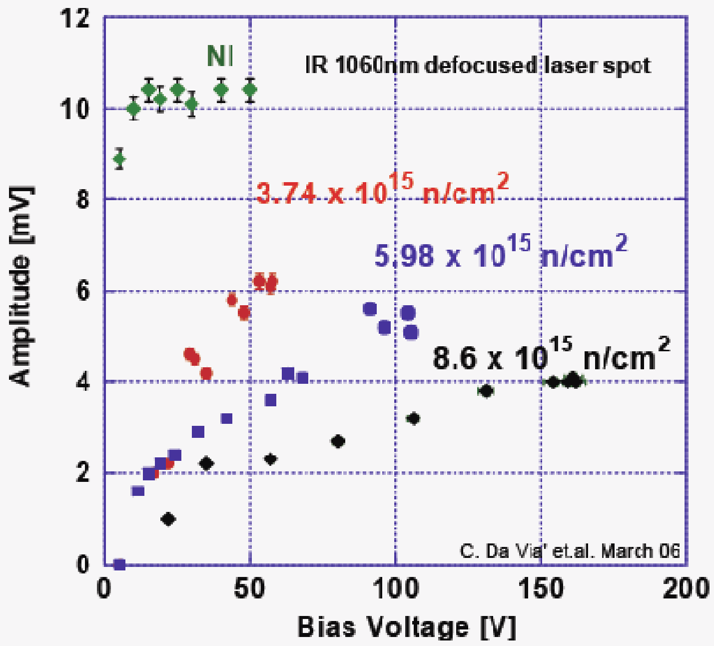
Example of ISE TCAD bug



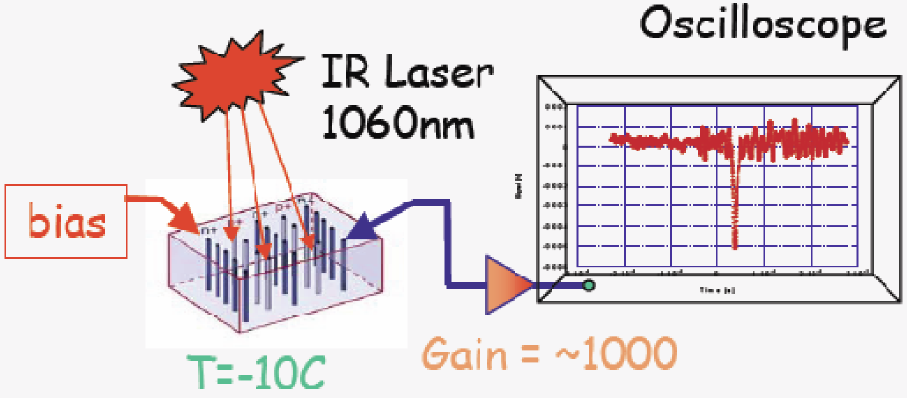
3D is radiation hard: Tests with baby-Atlas sensors

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 = $1.2 \times 1.33 \times 0.23$ 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)



Oscilloscope

IR Laser 1060nm

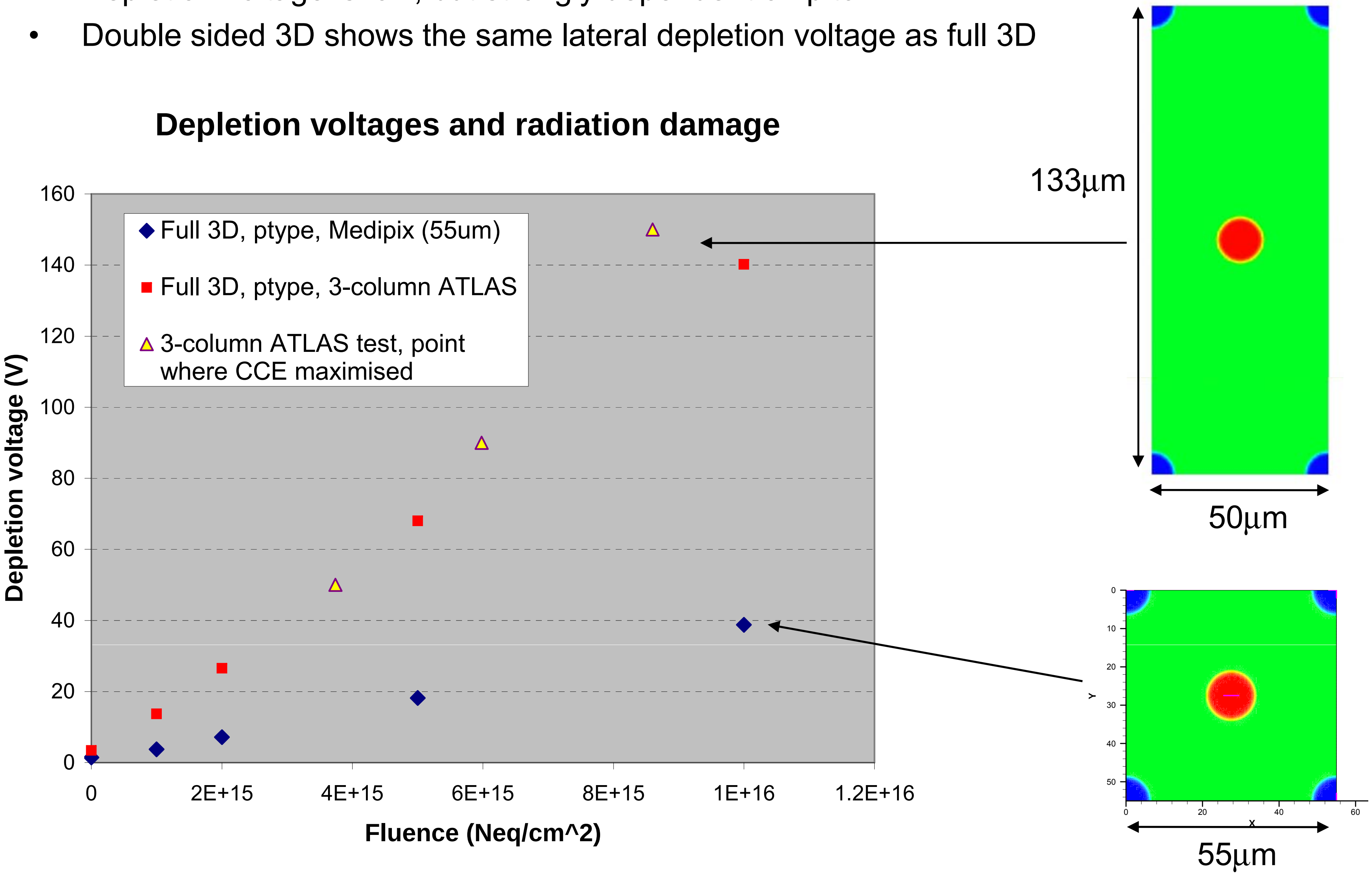
bias

T=-10C

Gain = ~1000

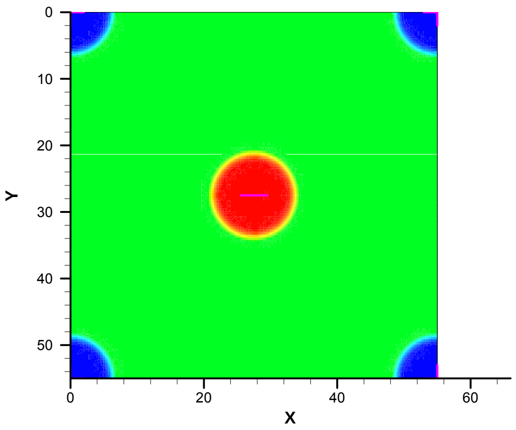
Full 3D – Depletion voltage (p-type)

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



Depletion voltages and radiation damage

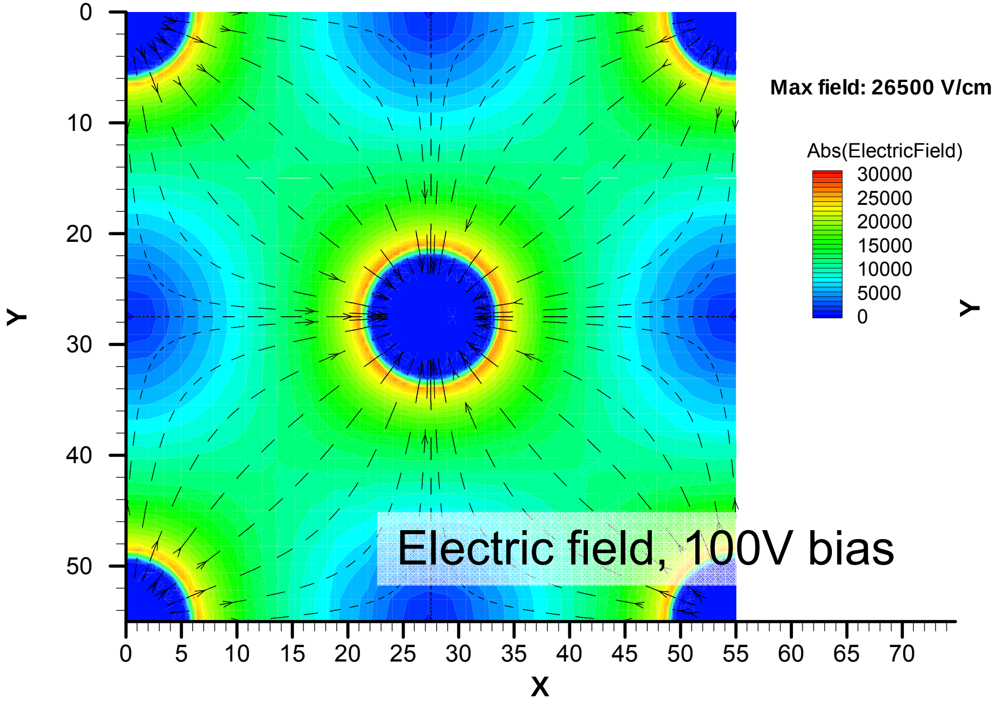
Weighting fields and electrode layouts



Symmetrical layout of n+ and p+

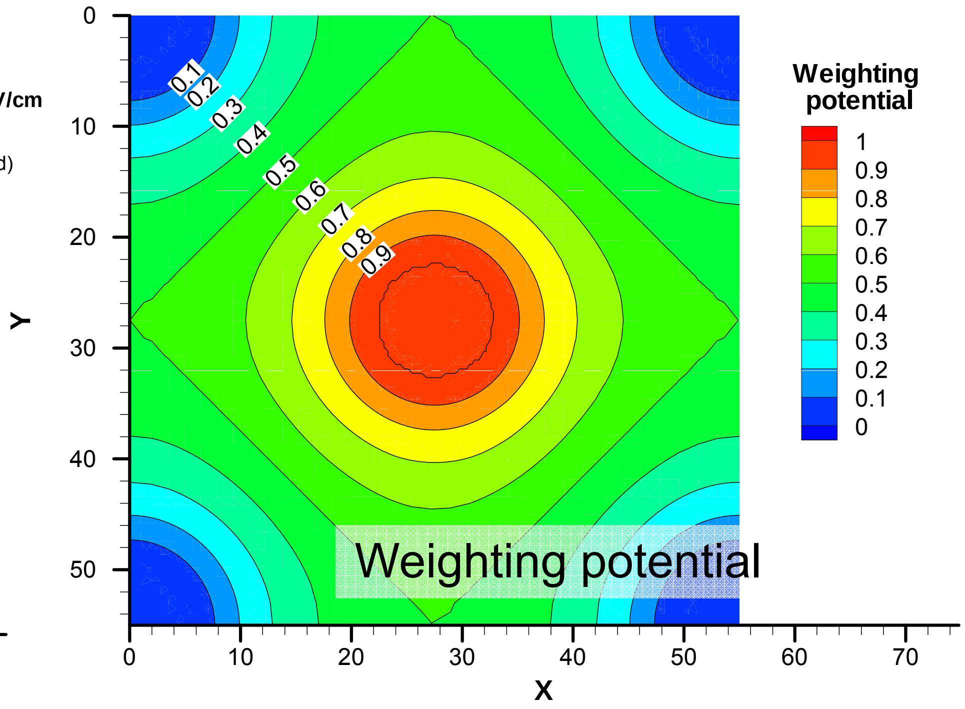
Weighting potential is the same for electrons and holes

Square layout, symmetrical layout of p+ and n+



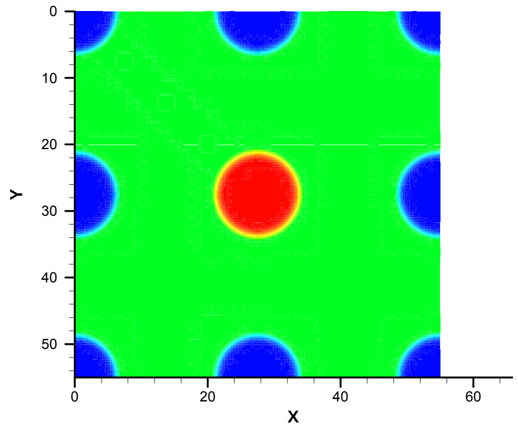
Electric field, 100V bias

Square layout, symmetrical layout of n+ and p+



Weighting potential

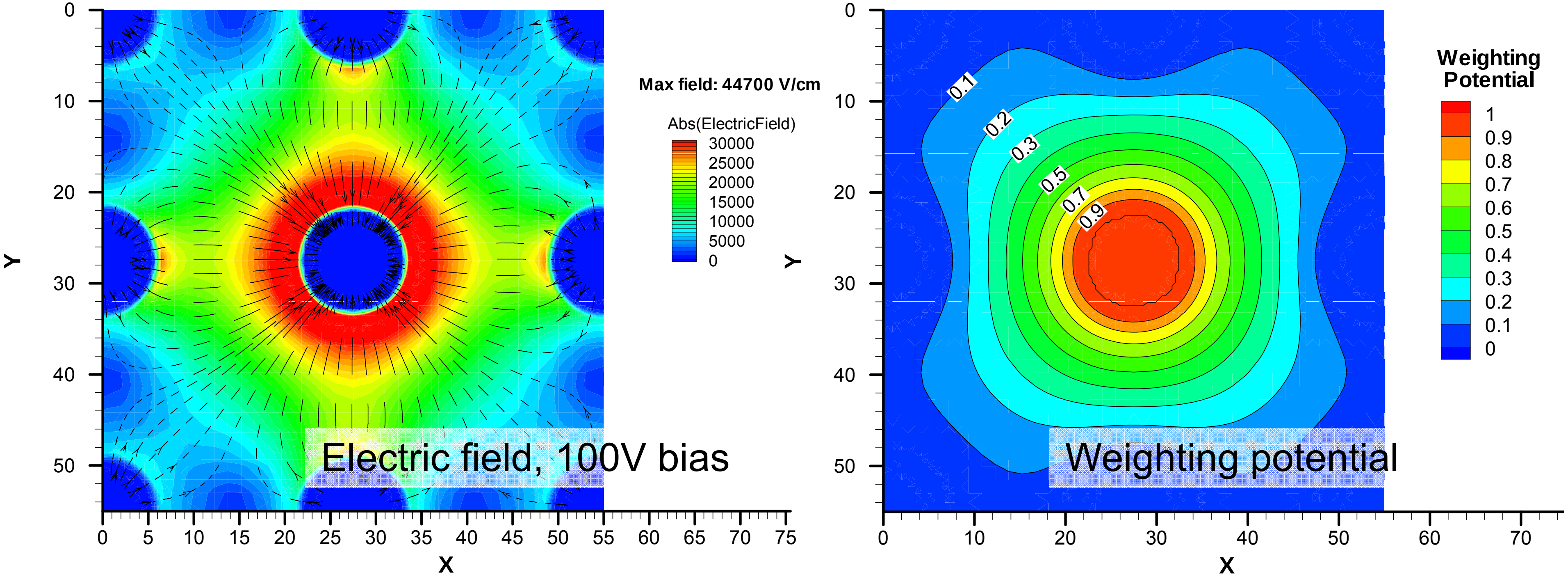
Weighting fields and electrode layouts



3 bias columns per readout column

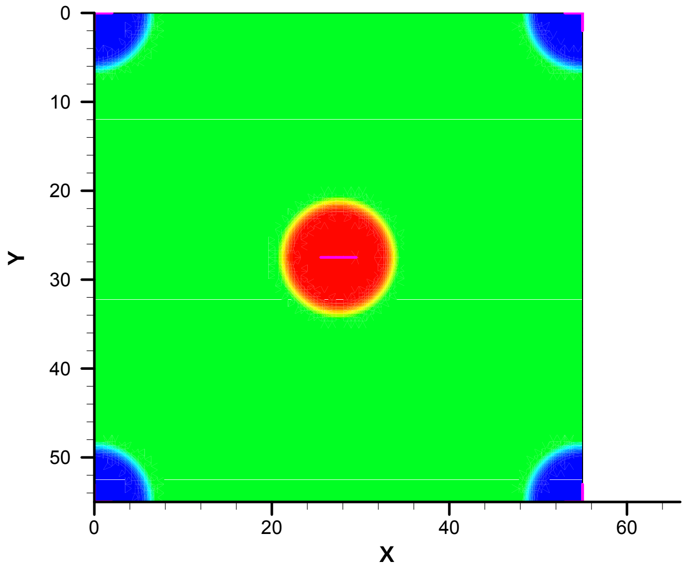
Weighing potential favours electron collection

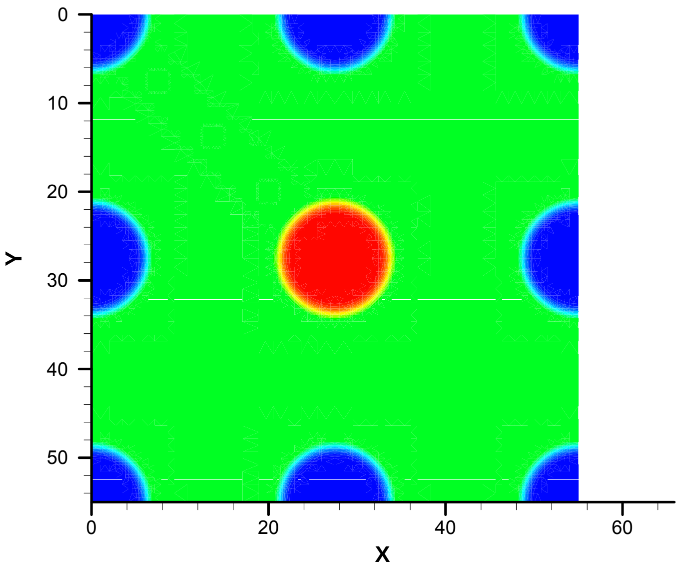
Square layout, 3 p+ bias columns per n+ readout column



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)