Radiation Damage TCAD Analysis of Low Gain Avalanche Detectors

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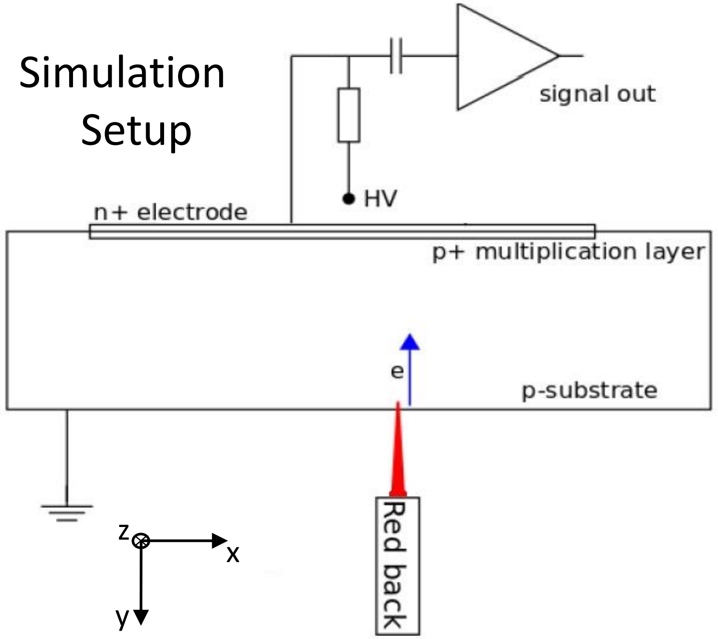
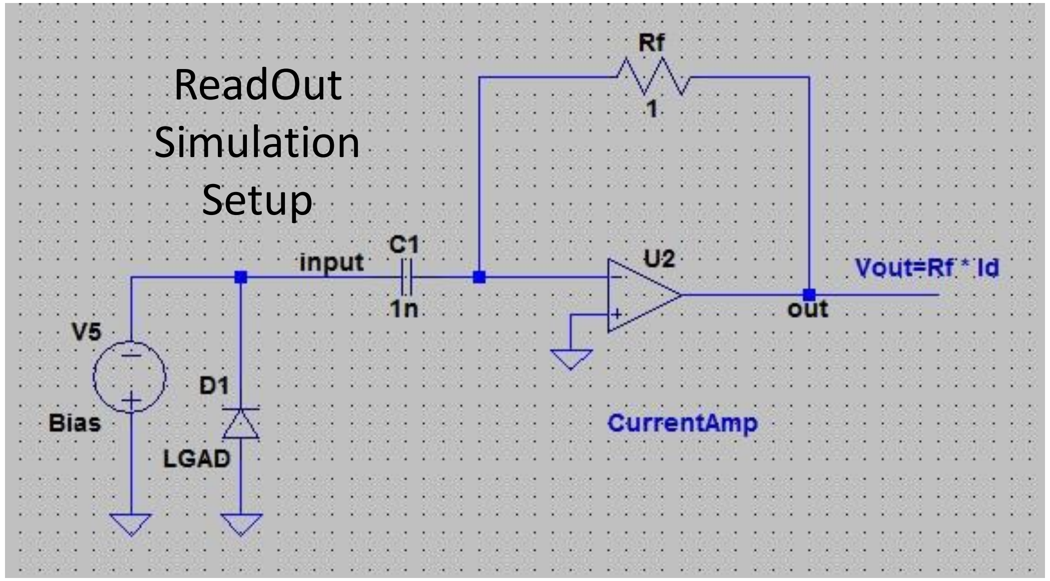
Sentaurus TCAD Simulation SetUp

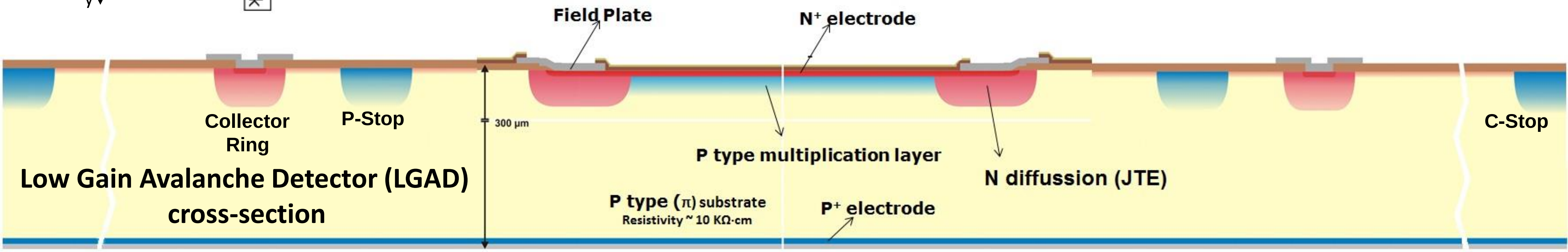
Simulation Setup



Mixed Simulation Setup:

- Red Pulsed Laser: 670 nm, 10 μm spot, 1e4W/cm², 50 ps, BackIllumination at Device Center
- ReadOut: gain unity current amplifier (Rf=1), AC (1 nF) coupled
- 2D detector model: 1 μm in Z direction, 3 mm in X direction, 300 μm in Y direction)

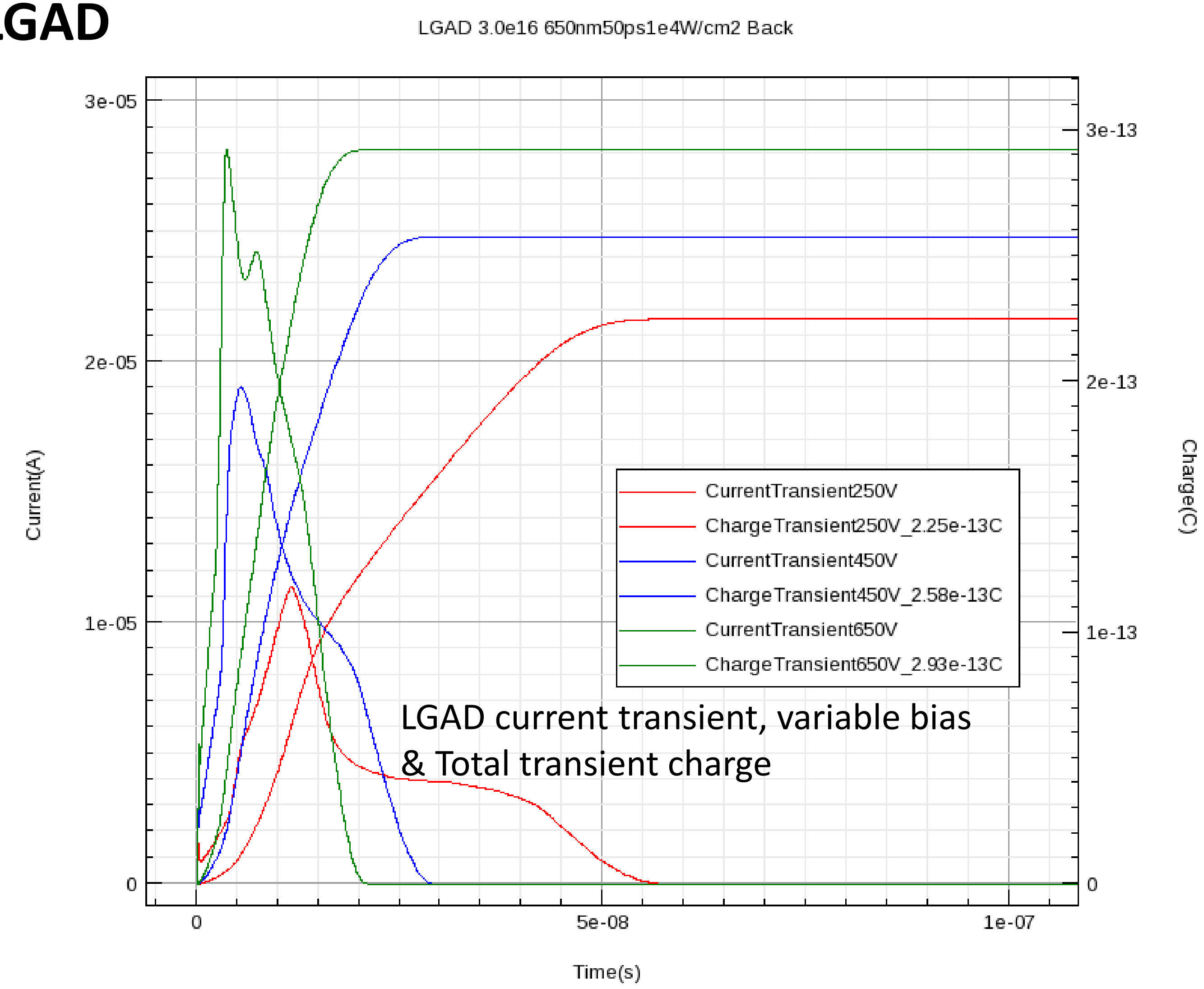


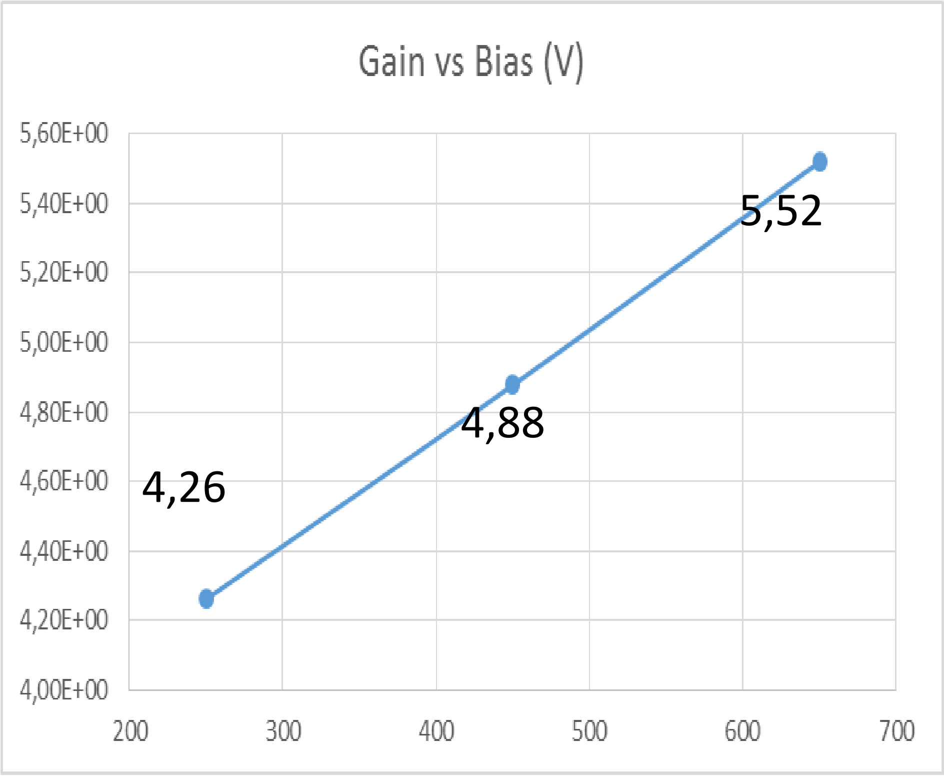


Low Gain Avalanche Detector (LGAD) cross-section

Doping profiles under confidenciality rules

LGAD





$Gain=(Q_{LGAD}/Q_{PiN})|_{bias}$

LGAD Bias Analysis: 250V, 450V, 650V, Gain shows a linear increase with bias

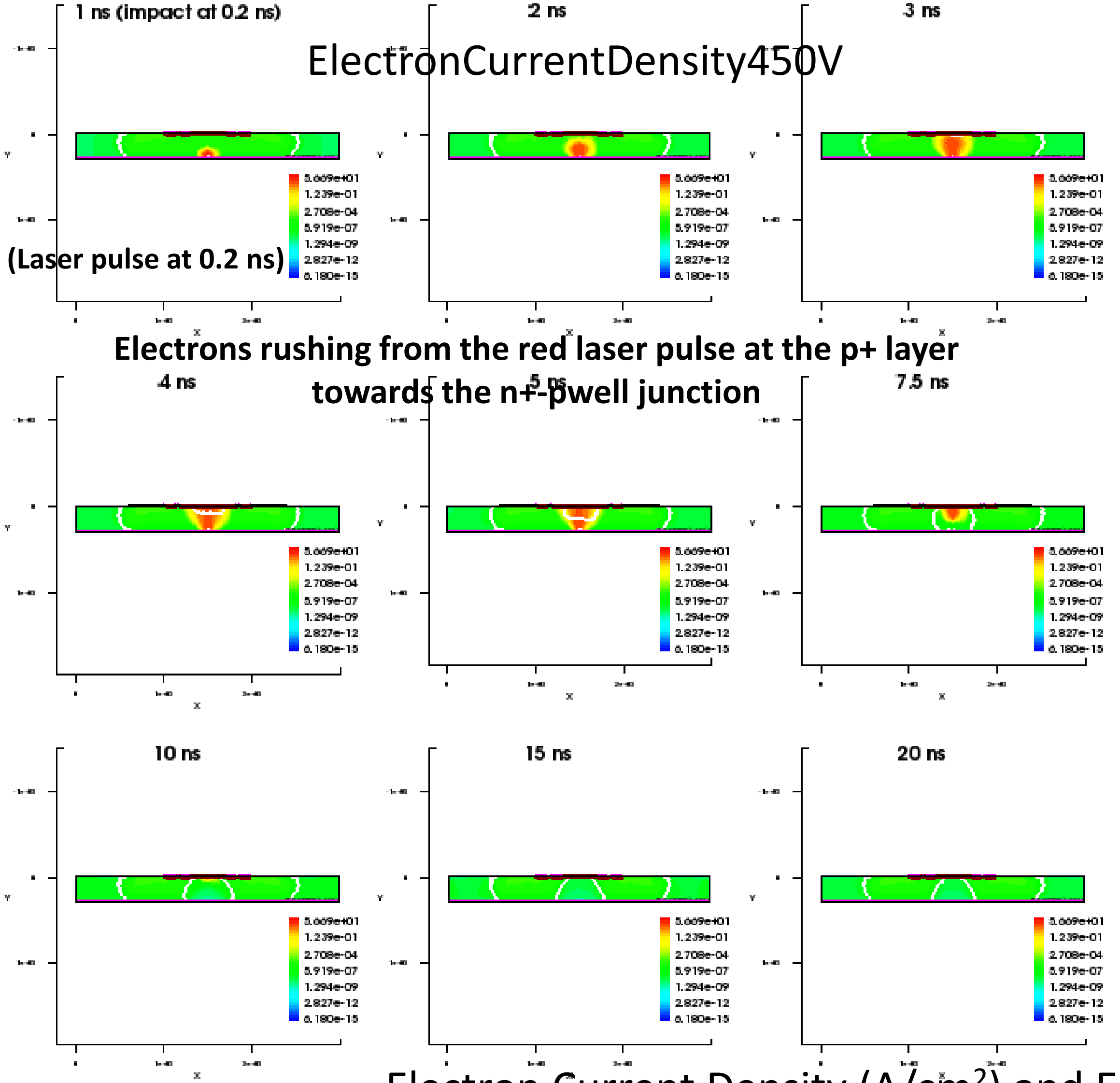
The equivalent PiN is an LGAD device without Pwell (gain well)

LGAD450V

ElectronCurrentDensity450V

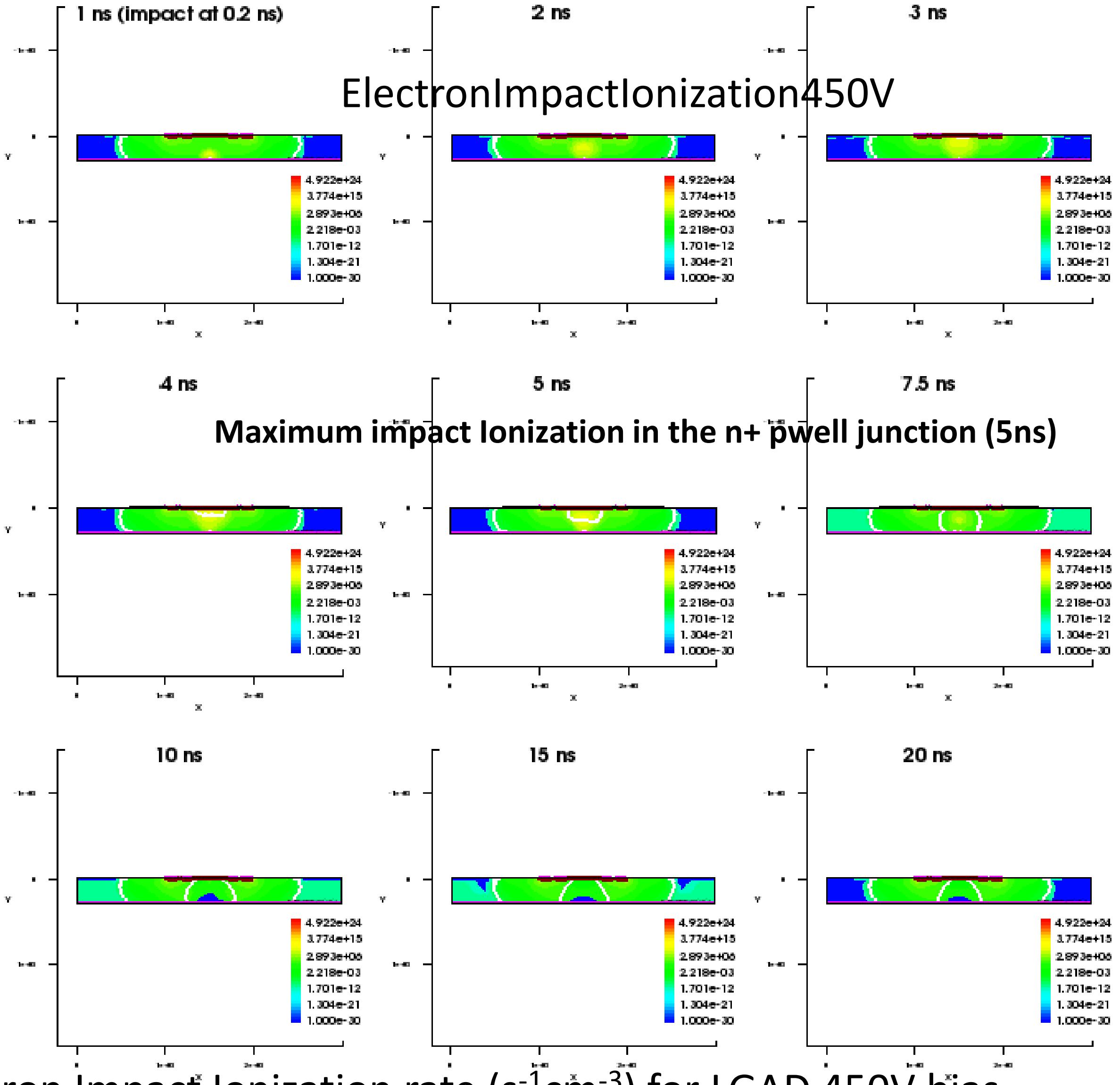
(Laser pulse at 0.2 ns)

Electrons rushing from the red laser pulse at the p+ layer towards the n+-pwell junction



ElectronImpactIonization450V

Maximum impact Ionization in the n+ pwell junction (5ns)



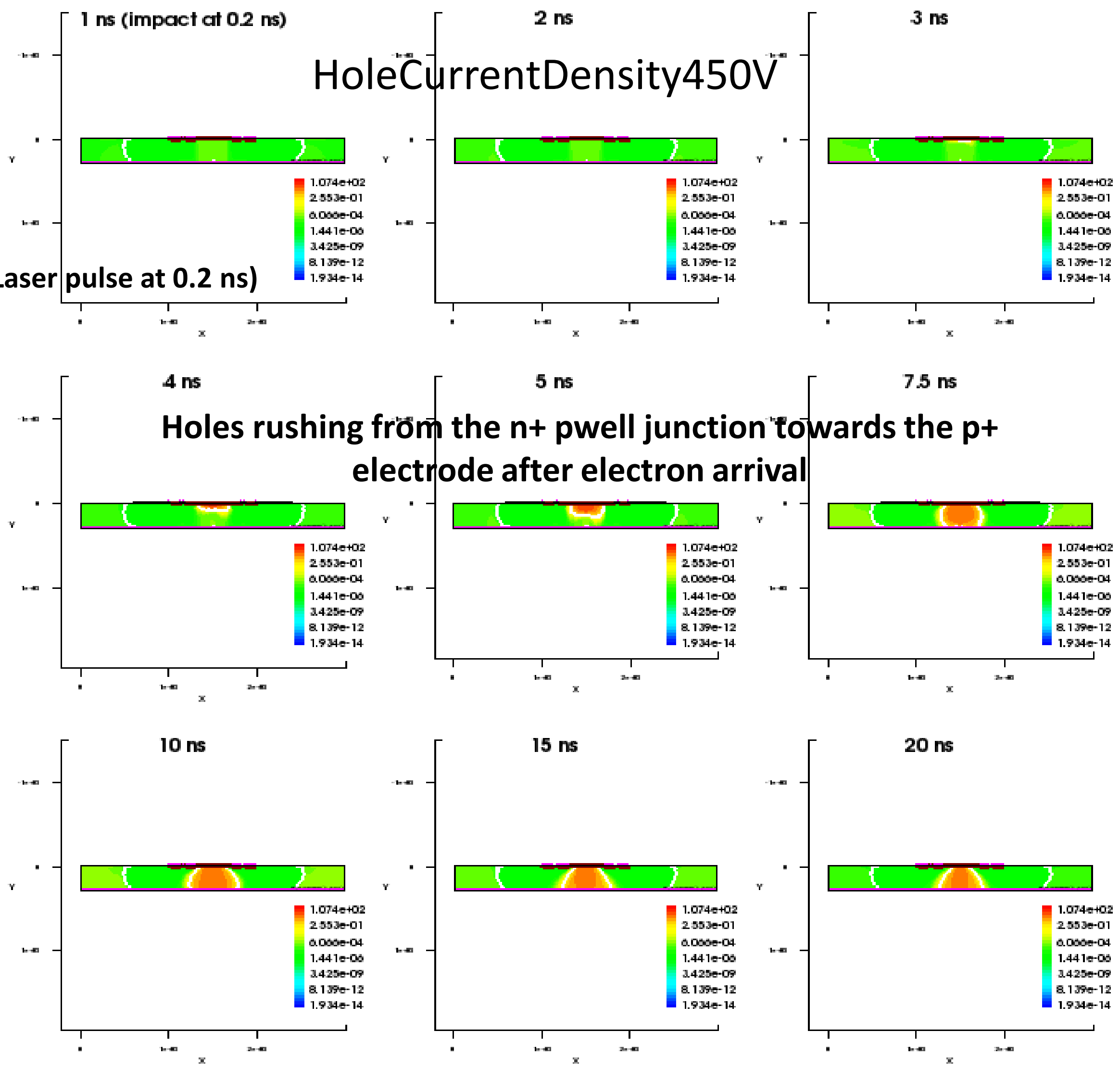
Electron Current Density (A/cm^2) and Electron Impact Ionization rate ($s^{-1}cm^{-3}$) for LGAD 450V bias

LGAD450V

HoleCurrentDensity450V

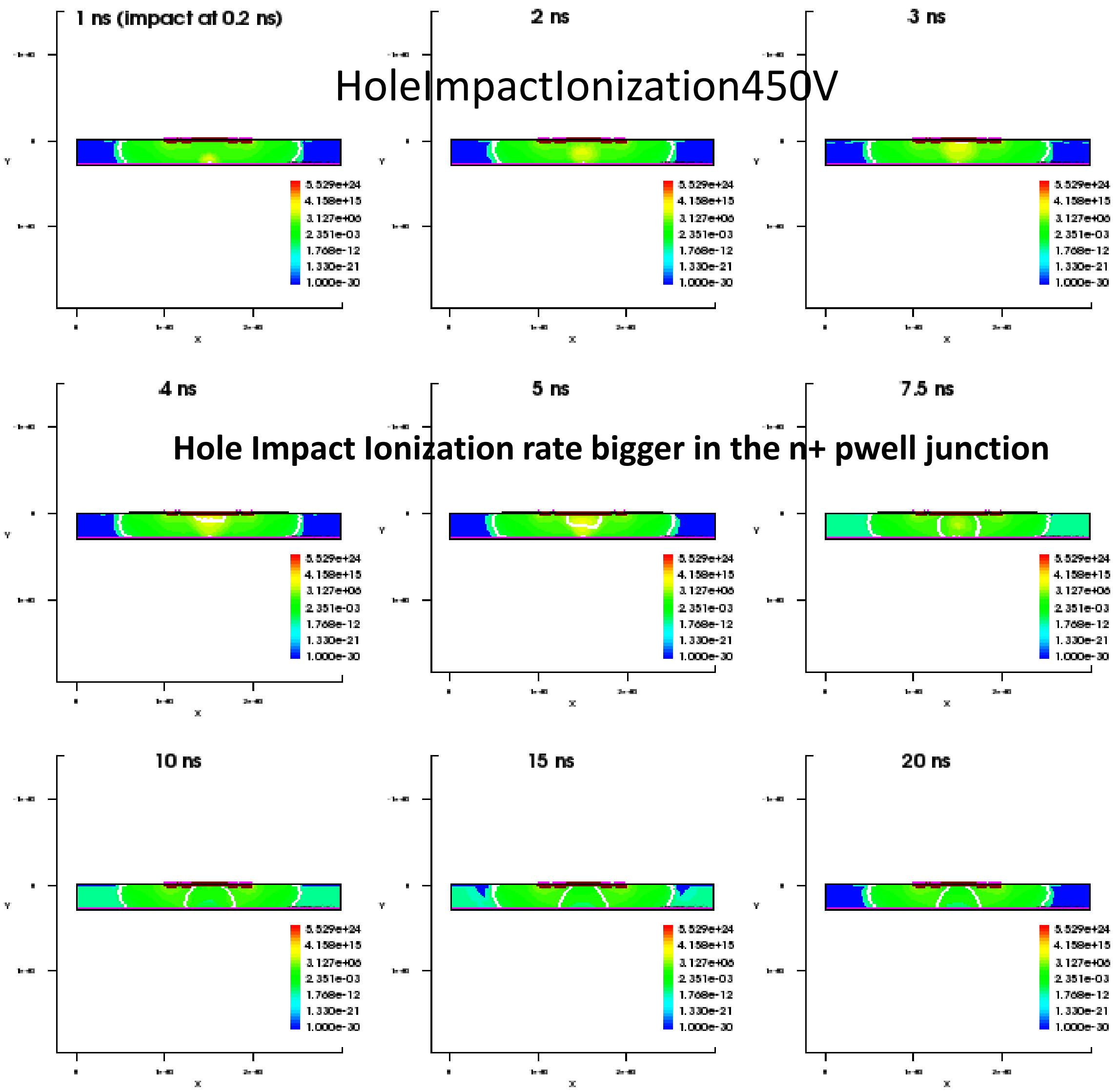
(Laser pulse at 0.2 ns)

Holes rushing from the n+ pwell junction towards the p+ electrode after electron arrival



HoleImpactIonization450V

Hole Impact Ionization rate bigger in the n+ pwell junction

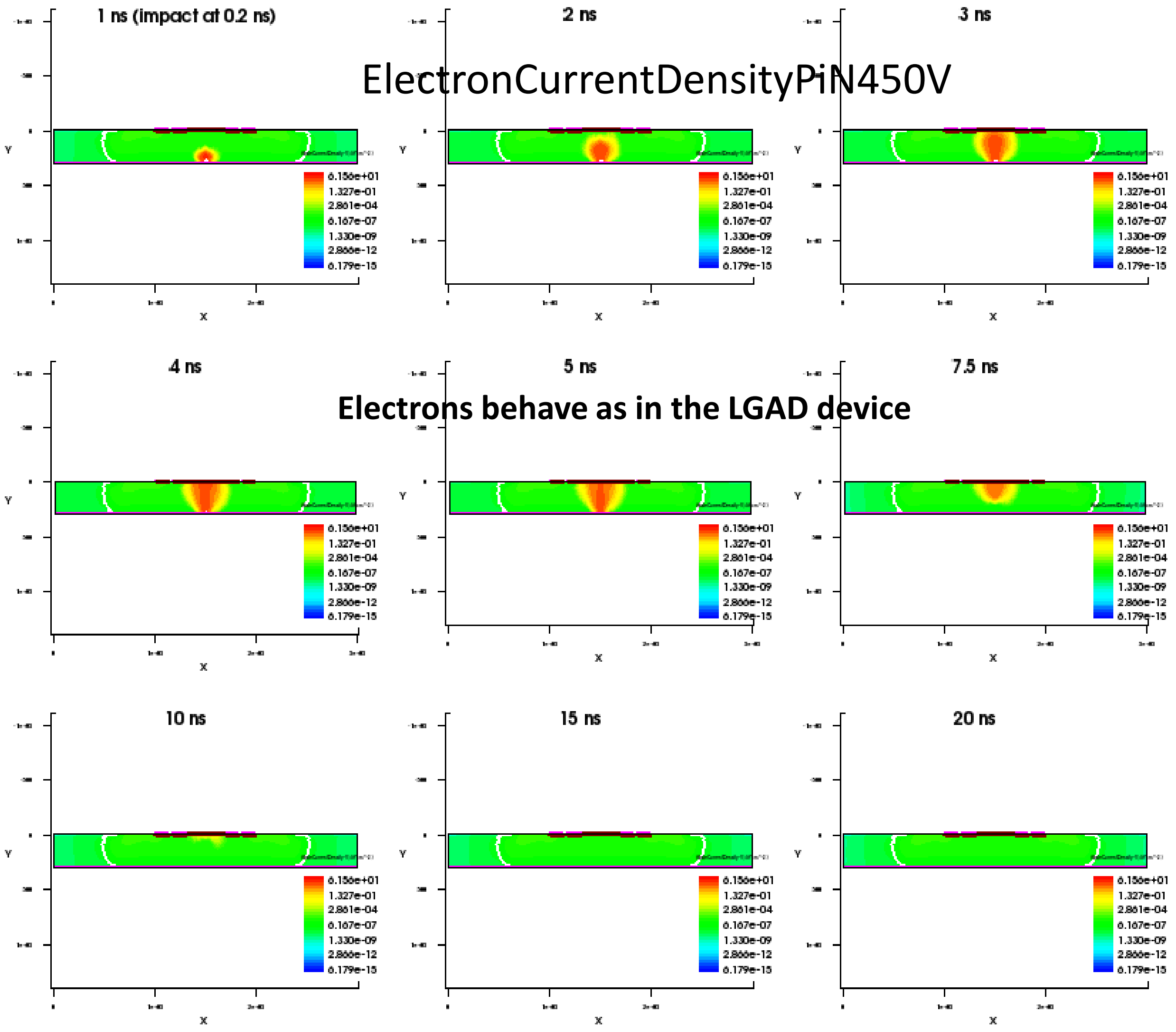


Hole Current Density (A/cm^2) and Holen Impact Ionization rate (s^{-1}cm^{-3}) for LGAD 450V bias

PiN 450V

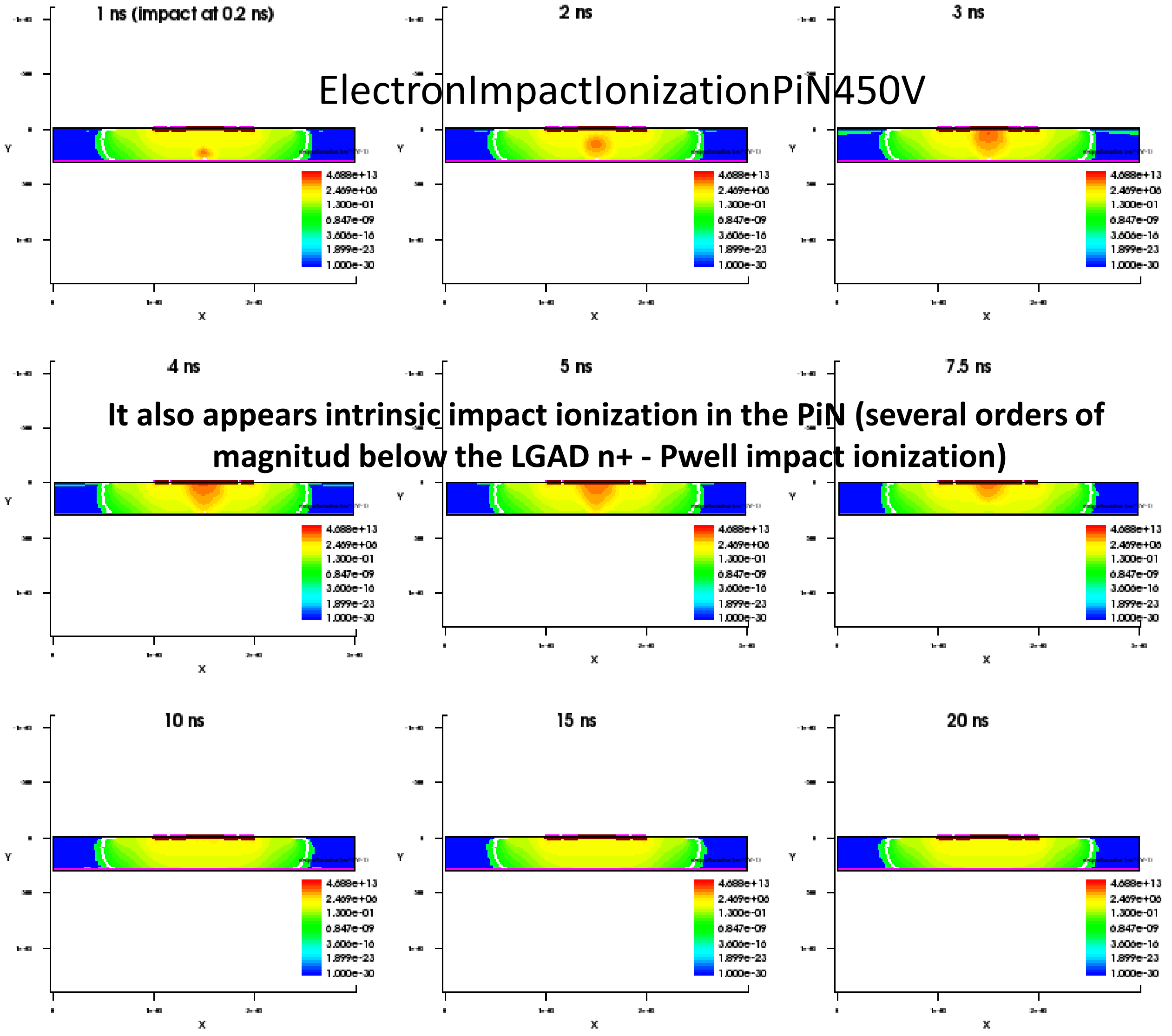
ElectronCurrentDensityPiN450V

Electrons behave as in the LGAD device



ElectronImpactIonizationPiN450V

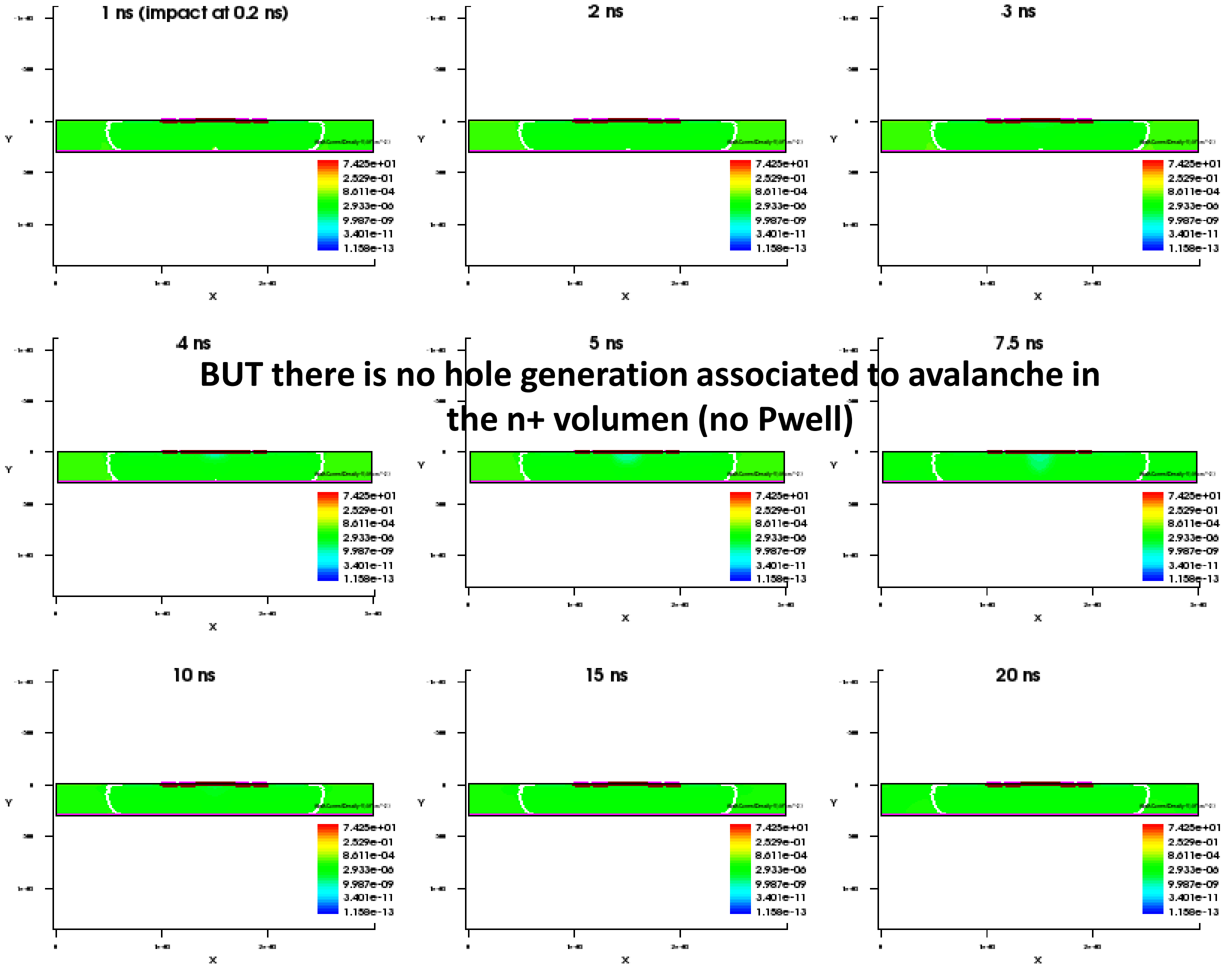
It also appears intrinsic impact ionization in the PiN (several orders of magnitud below the LGAD n+ - Pwell impact ionization)



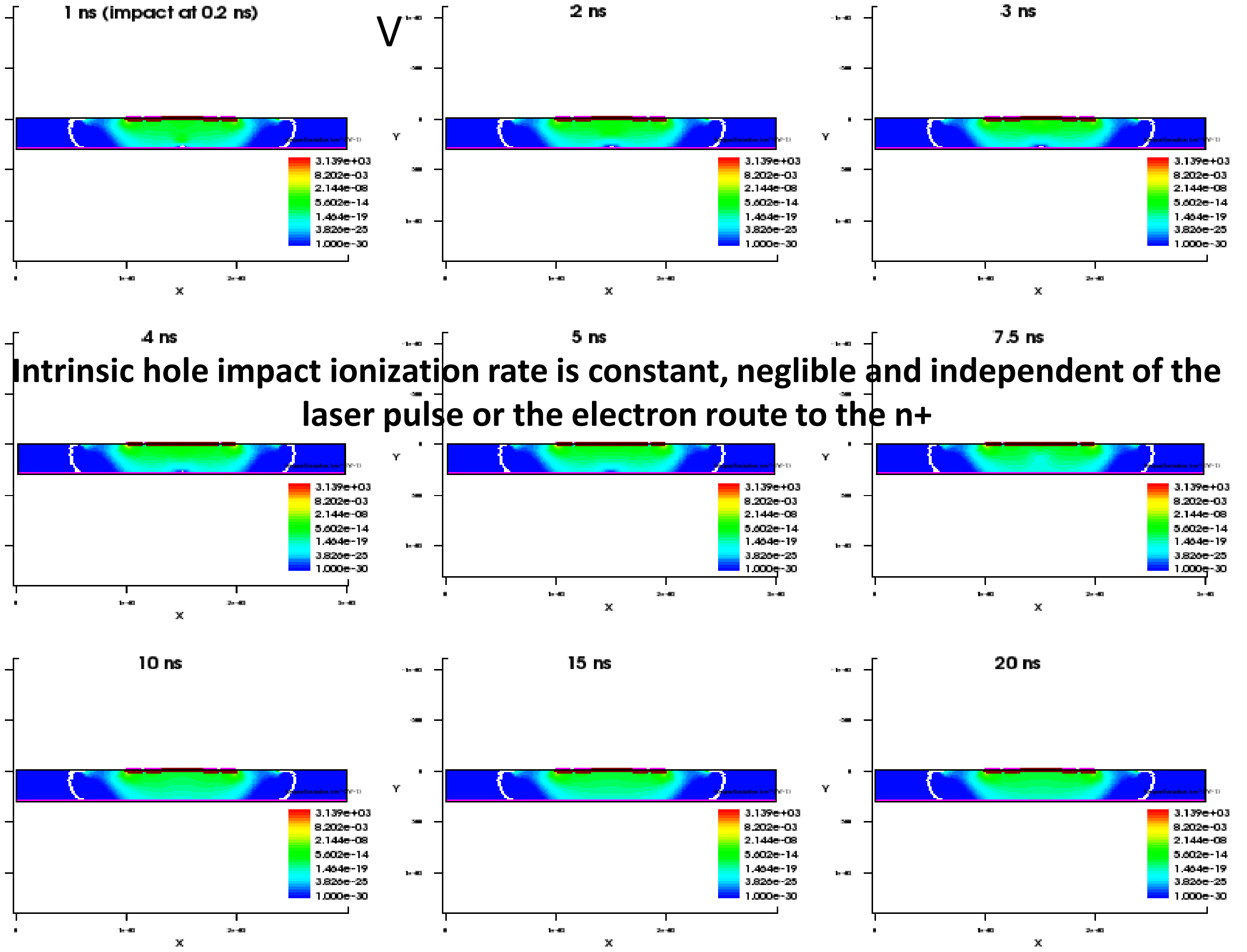
Electron Current Density (A/cm^2) and Electron Impact Ionization rate (s^{-1}cm^{-3}) for PiN 450V bias

PiN 450V

HoleCurrentDensityPiN450V



HoleImpactIonizationPiN450V



BUT there is no hole generation associated to avalanche in the n+ volumen (no Pwell)

Intrinsic hole impact ionization rate is constant, neglible and independent of the laser pulse or the electron route to the n+

Hole Current Density (A/cm^2) and Hole Impact Ionization rate (s^{-1}cm^{-3}) for PiN 450V bias

Radiation Damage Models

Three damage models

1. Pennicard Model ϕ =1e12 up to 1e14 n_{eq}/cm^2
2. CMS Proton and Neutron model ϕ = 1e14-1e15 n_{eq}/cm^2
3. Delhi Model Proton ϕ = 1e14-1e15 n_{eq}/cm^2

CMS Proton Model

Defect	Energy (eV)	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})	Concentration (cm^{-3})
Acceptor	$E_c - 0.525$	10^{-14}	10^{-14}	–	$1.189\times\Phi+6.454\times10^{13}$
Donor	$E_v + 0.48$	10^{-14}	10^{-14}	–	$5.598\times\Phi-3.959\times10^{14}$

CMS Neutron Model

Defect	Energy (eV)	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})	Concentration (cm^{-3})
Acceptor	$E_c - 0.525$	1.2×10^{-14}	1.2×10^{-14}	1.55	$1.55\times\Phi$
Donor	$E_v + 0.48$	1.2×10^{-14}	1.2×10^{-14}	1.395	$1.395\times\Phi$

Simulation of Silicon Devices for the CMS Phase II Tracker Upgrade
CMS Note 250887

Delhi Model $N(cm^{-3})=g_{int} \times \phi$

No.	Trap	Energy Level	g_{int} (cm^{-1})	σ_e (cm^{-2})	σ_h(cm^{-2})
1.	Acceptor	$E_c - 0.525$ eV	0.8	4×10^{-14}	4×10^{-14}
2.	Donor	$E_v + 0.48$ eV	0.8	4×10^{-14}	4×10^{-14}

Combined effect of bulk and Surface damage on strip insulation properties of proton irradiated n+-p silicon strip sensors, R.Dalal et al. JINST 2014 9 P04007

Pennicard Model $N(cm^{-3})=\eta_{int} \times \phi$

Type	Energy (eV)	Defect	σ_e (cm^2)	σ_h (cm^2)	η (cm^{-1})
Acceptor	$E_C - 0.42$	VV	$*9.5\times10^{-15}$	$*9.5\times10^{-14}$	1.613
Acceptor	$E_C - 0.46$	VVV	5.0×10^{-15}	5.0×10^{-14}	0.9
Donor	$E_V + 0.36$	C_iO_i	$*3.23\times10^{-13}$	$*3.23\times10^{-14}$	0.9

Simulations of radiation-damaged 3D detectors for the Super-LHC, D.Pennicard et al. NIMA 592(1-2), 2008, pp16-25

LGAD

Pulsed red laser transient, current amp readout (gain=1)

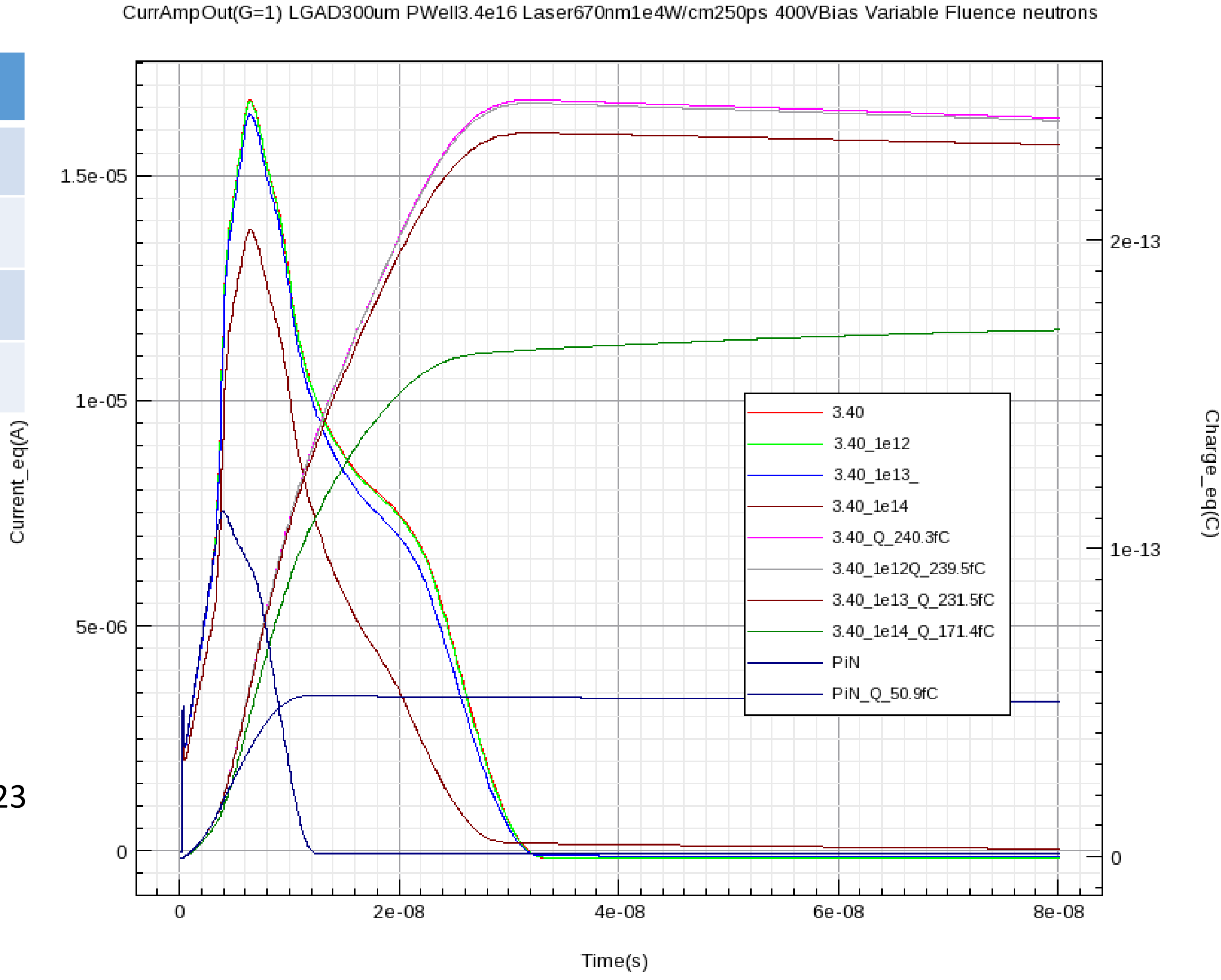
Pennicard Damage Model

Pennicard model valid up to 1e14 n_{eq}/cm^2. It shows that **LGAD does not experiment a significative gain reduction up to 1e14**. At 1e14, gain decreases 29%.

Fluence	Gain
0	4,80
1e12	4,72
1e13	4,54
1e14	3,36

```
##   Putting traps in Silicon region only
##   Trap concentrations found from Petasecca model and modified by
D. Pennicard, Fluence=1E14
Physics (material="Silicon") {
# Putting traps in silicon region only
# Modified Perugia model with trapping times at reported value
    Traps (
      (Acceptor Level EnergyMid=0.42 fromCondBand  Conc=1.1613E14
Randomize=0.29 eXsection=9.5E-15 hXsection=9.5E-14) #Conc=Fluence*1.1613
      (Acceptor Level EnergyMid=0.46 fromCondBand Conc=0.9E14 Randomize=0.23
eXsection=5E-15 hXsection=5E-14 ) #Conc=Fluence*0.9
      (Donor Level EnergyMid=0.36 fromValBand  Conc=0.9E14 Randomize=0.31
eXsection=3.23E-13 hXsection=3.23E-14 ) #Conc=Fluence*0.9
      )
}
```

LGAD 400V Bias



(Reference PiN Charge 50.9 fC)

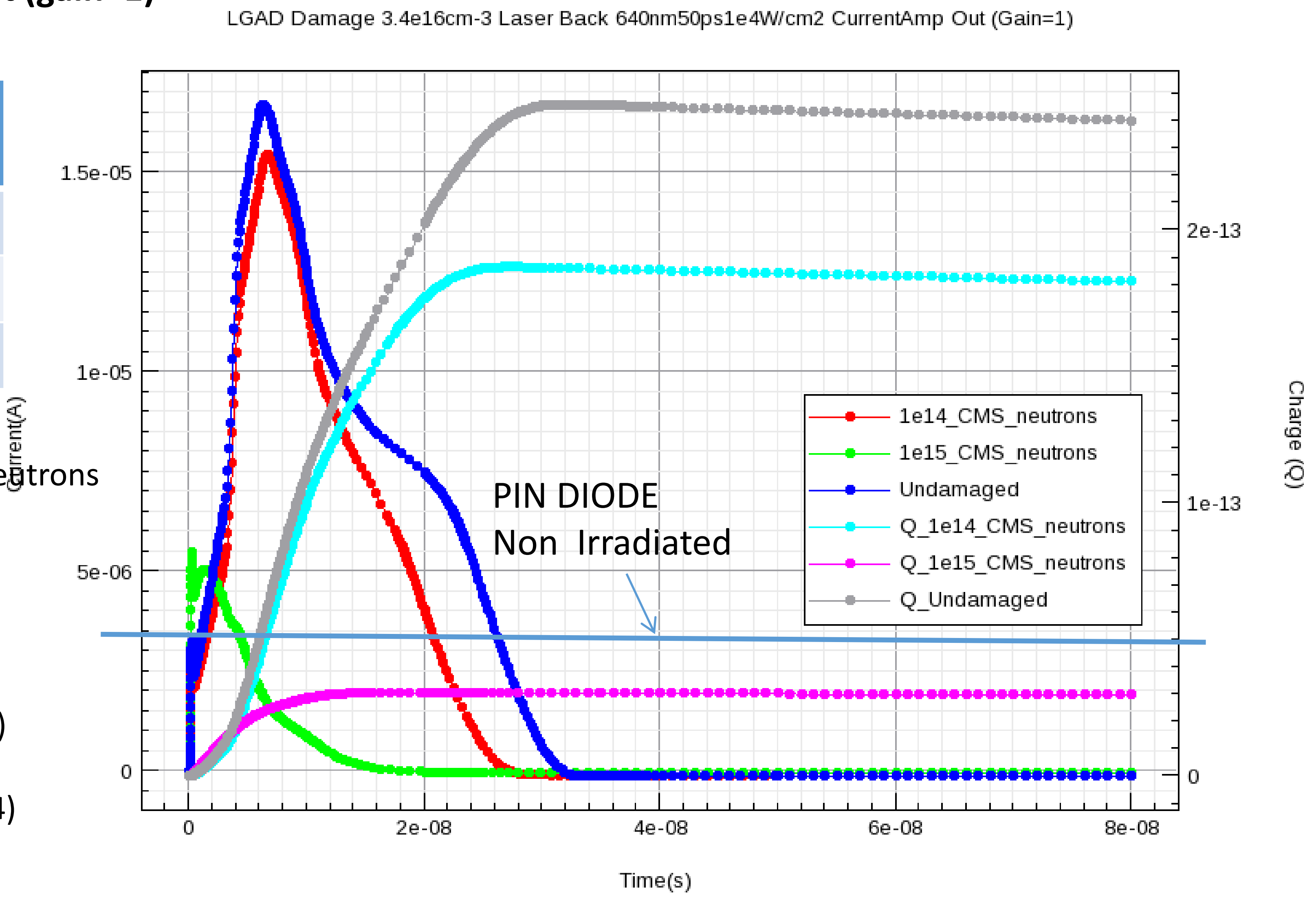
LGAD

Pulsed red laser transient, current amp readout (gain=1)

CMS Neutron Damage Model

Fluence	Charge (fC)	Gain
0	244,0	4,80
1e14	186,1	3,66
1e15	30,7	0,60

```
##   Putting traps in Silicon region only
##   Trap concentrations found from CMS Two level neutrons
#Fluence=1E14
Physics (material="Silicon") {
# Putting traps in silicon region only
    Traps (
      (Acceptor Level EnergyMid=0.525 fromCondBand
Conc=1.55E14  eXsection=1.2E-14 hXsection=1.2E-14)
      (Donor    Level EnergyMid=0.48  fromValBand
Conc=1.395E14 eXsection=1.2E-14 hXsection=1.2E-14)
      )
}
```



LGAD

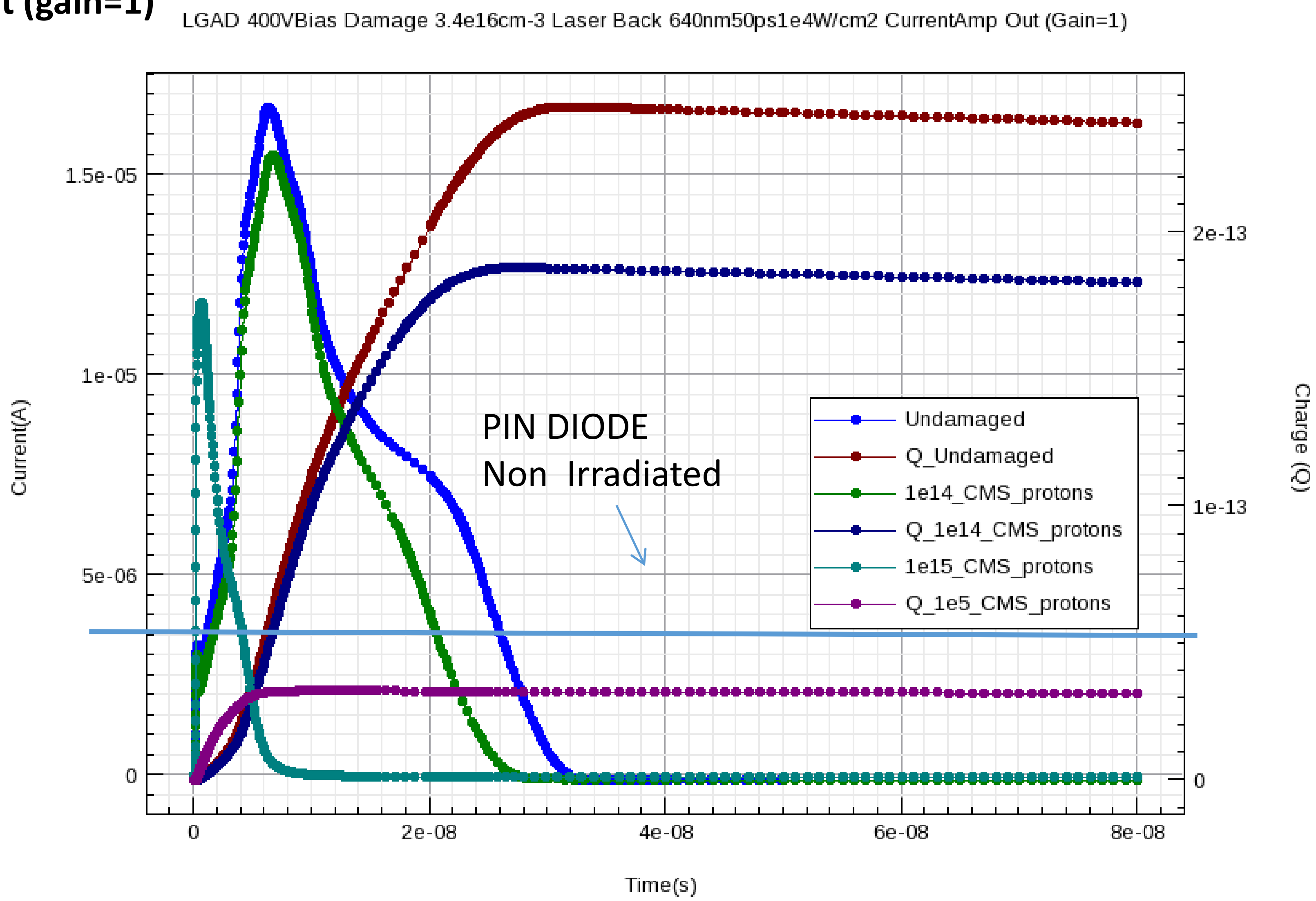
Pulsed red laser transient, current amp readout (gain=1)

CMS Proton Damage Model

Fluence	Charge (fC)	Gain
0	244,0	4,80
1e14	186,7	3,67
1e15	24,6	0,48

Putting traps in Silicon region only
Trap concentrations found from CMS Two level protons

```
#Fluence=1E14
Physics (material="Silicon") {
# Putting traps in silicon region only
   Traps (
     (Acceptor Level EnergyMid=0.525 fromCondBand
Conc=1.8344E14  eXsection=1E-14 hXsection=1E-14)
     (Donor    Level EnergyMid=0.48  fromValBand
Conc=1.6390E14 eXsection=1E-14 hXsection=1E-14)
     )
}
```



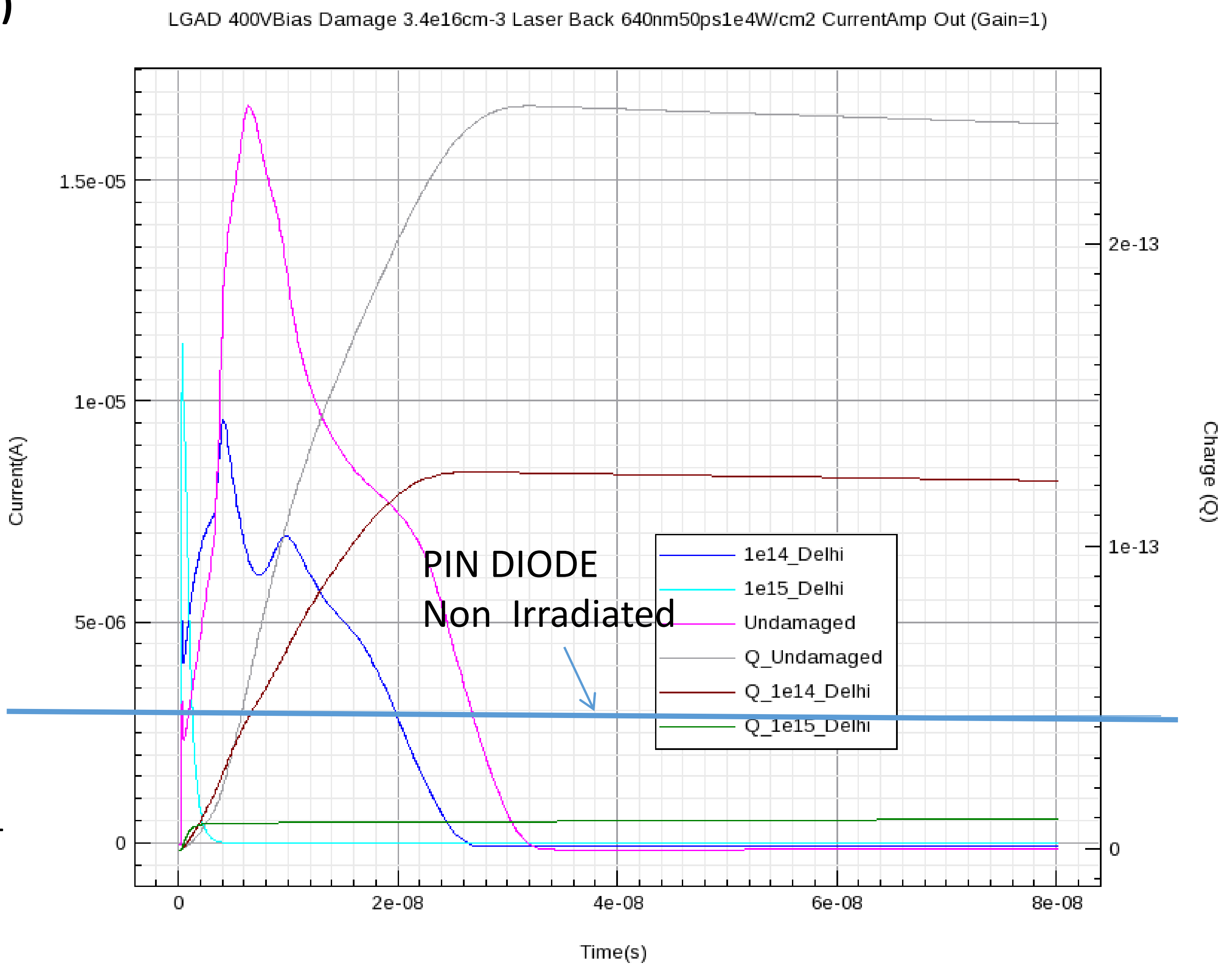
LGAD

Pulsed red laser transient, current amp readout (gain=1)

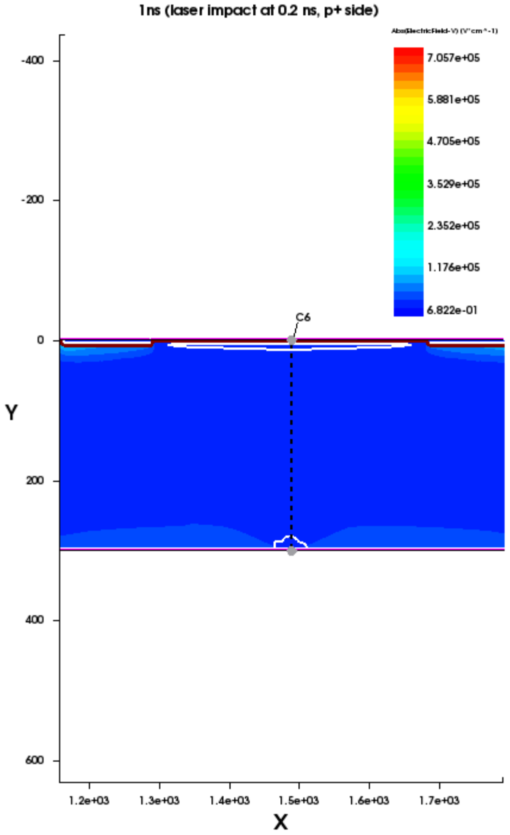
Delhi Damage Model

Fluence	Charge (fC)	Gain
0	244,0	4,80
1e14	124,6	2,45
1e15	9,4	0,18

```
##   Putting traps in Silicon region only
##   Trap concentrations found from Delhi Two level
#Fluence=1E14
Physics (material="Silicon") {
# Putting traps in silicon region only
    Traps (
      (Acceptor Level EnergyMid=0.51  fromCondBand
Conc=4E14 eXsection=2E-14 hXsection=3.8E-15)
      (Donor    Level EnergyMid=0.48  fromValBand   Conc=3E14
eXsection=2E-15 hXsection=2E-15)
      )
}
```

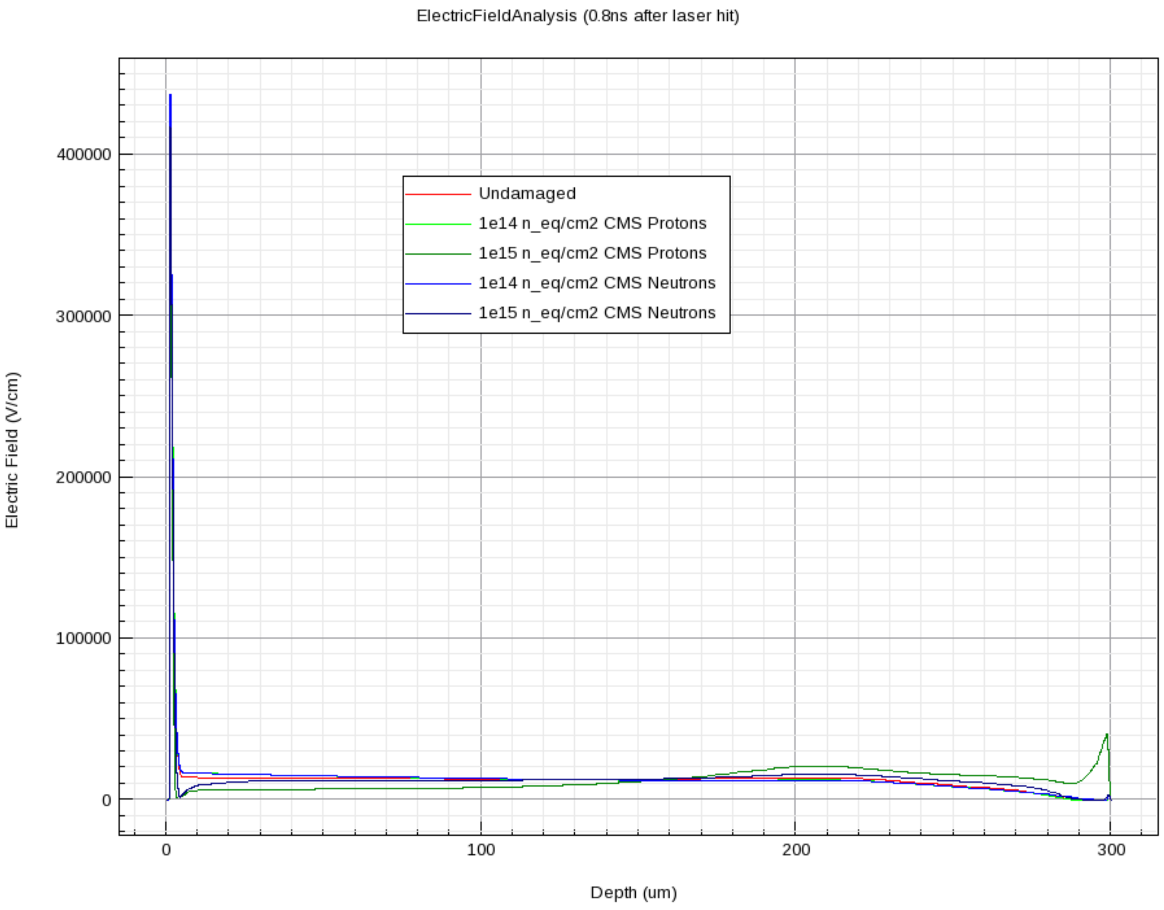


LGAD
CMS Models

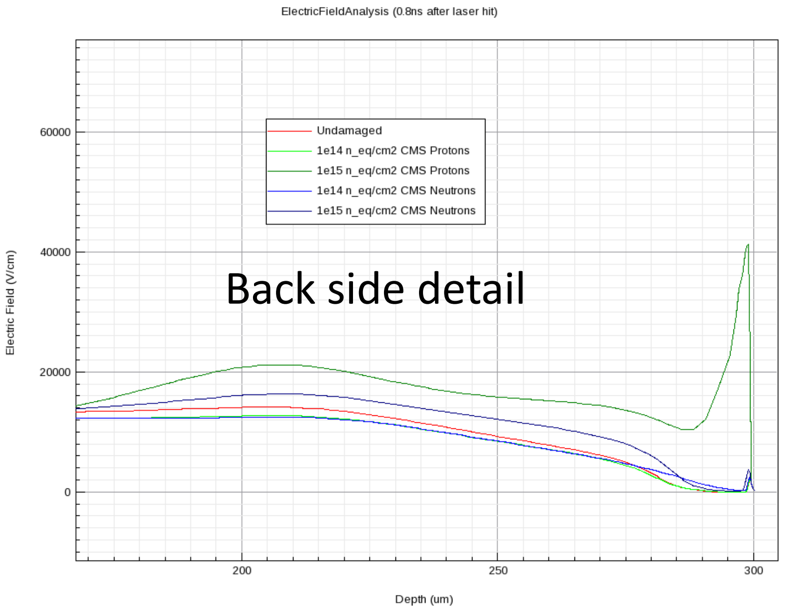


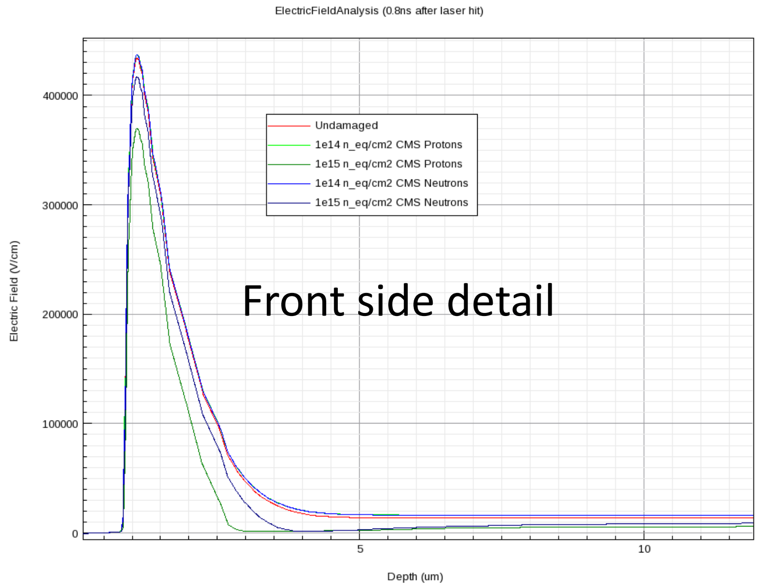
Electric Field Profiling

Electric Field along Y axis



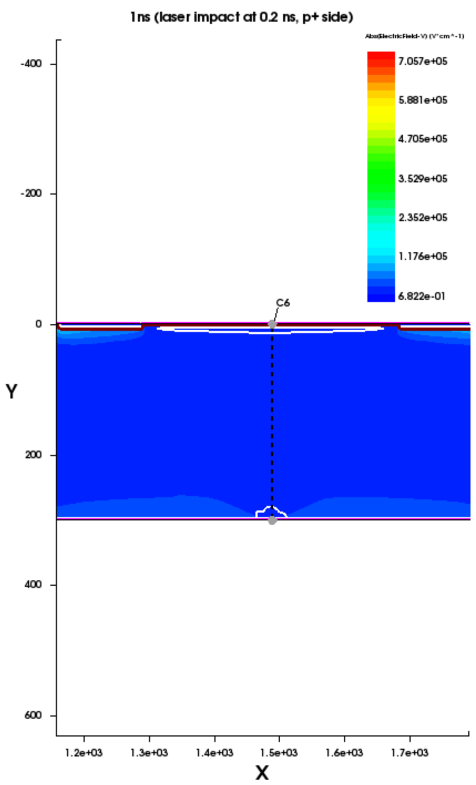
At 1e15 a double junction appears at P+ volume

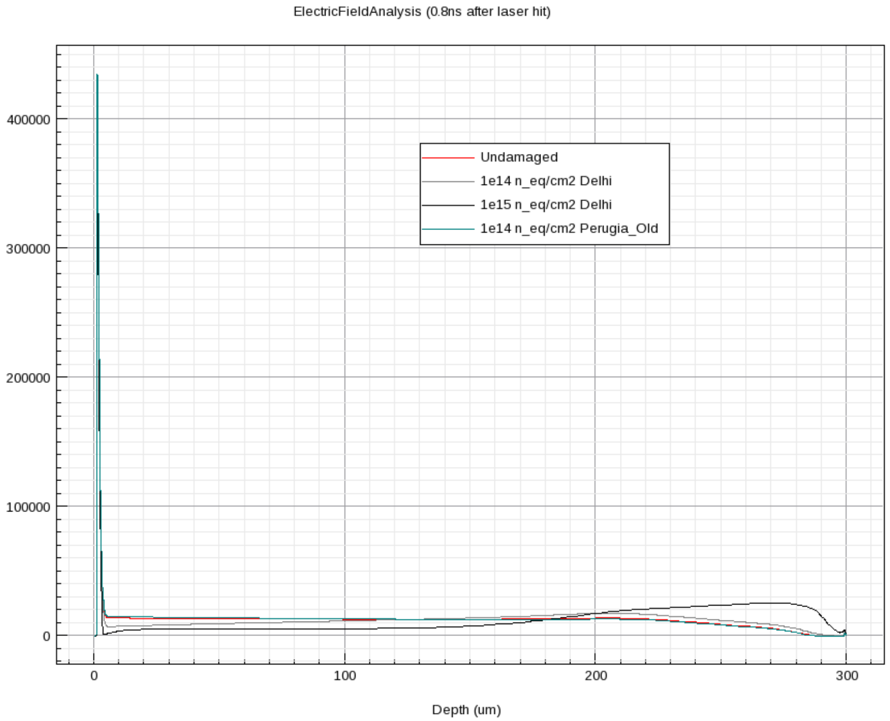


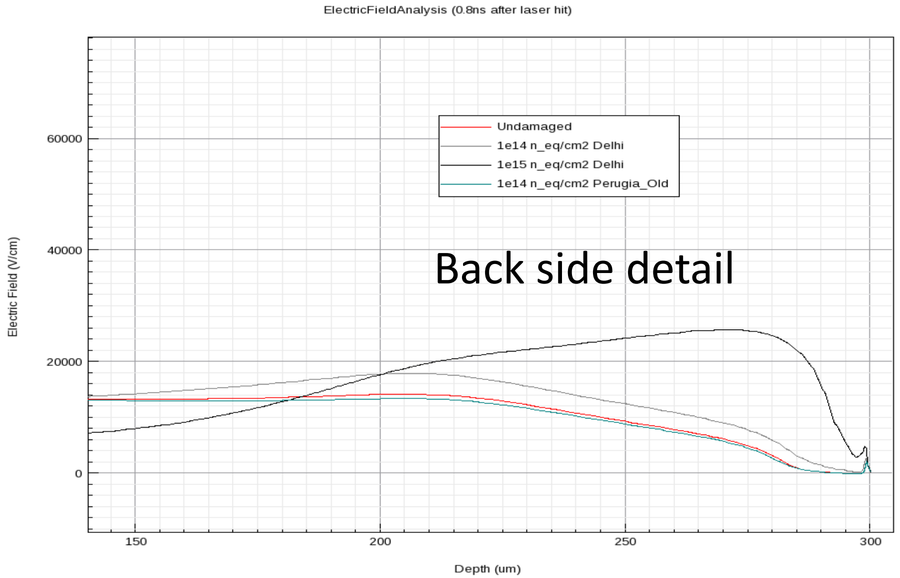


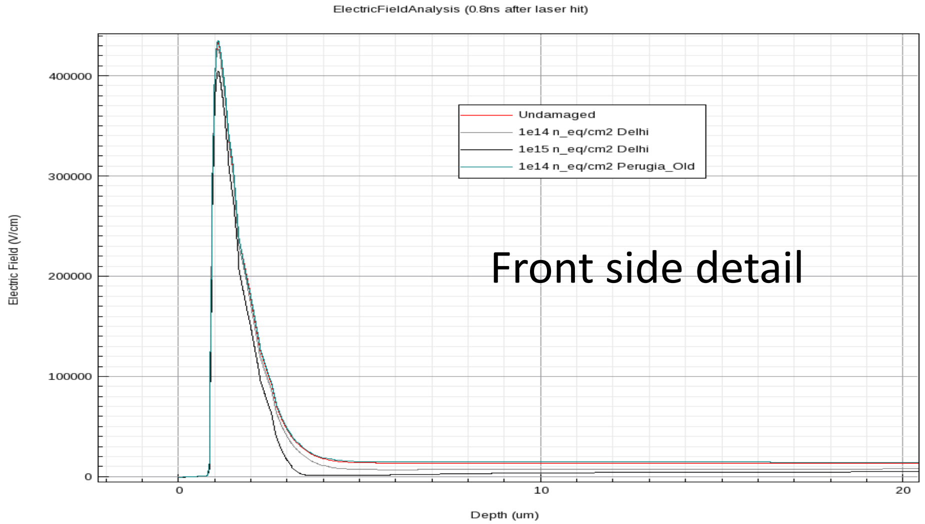
LGAD
Delhi Models

Electric Field along Y axis







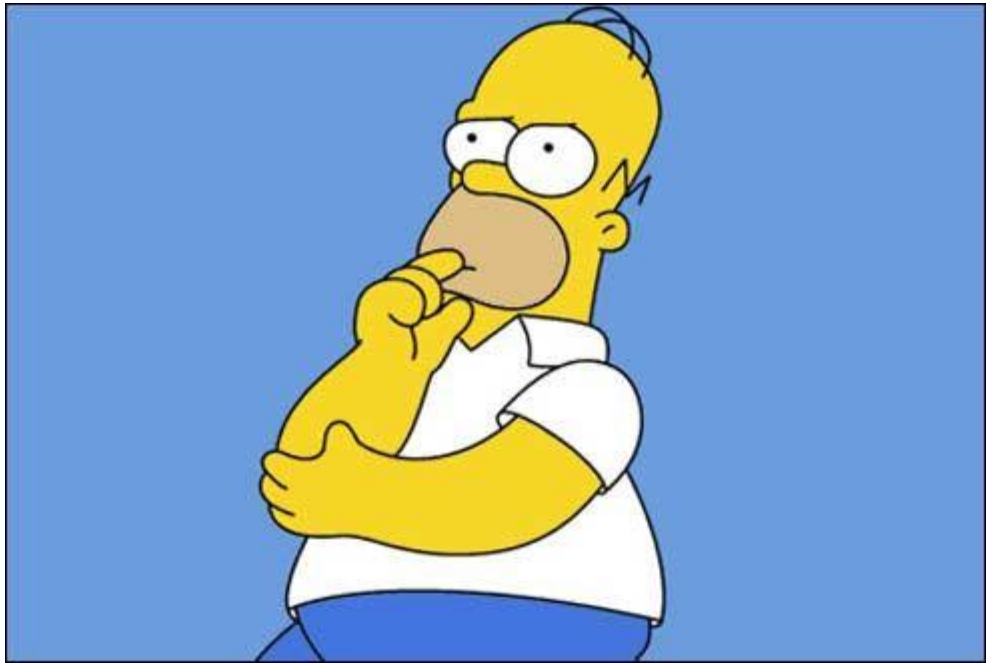


Electric Field Profiling

At 1e15 a double junction appears at P+ volume

Conclusions

- LGAD model from CNM, with JTE, guard rings, p-stops and c-stops
- The device withstand radiation damage up to 1e14 n_{eq}/cm^2
- Fails approaching 1e15 n_{eq}/cm^2
- Main fail mechanism: double junction



Thanks for your attention

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