LGAD Simulations with Ga doping: An Exploration

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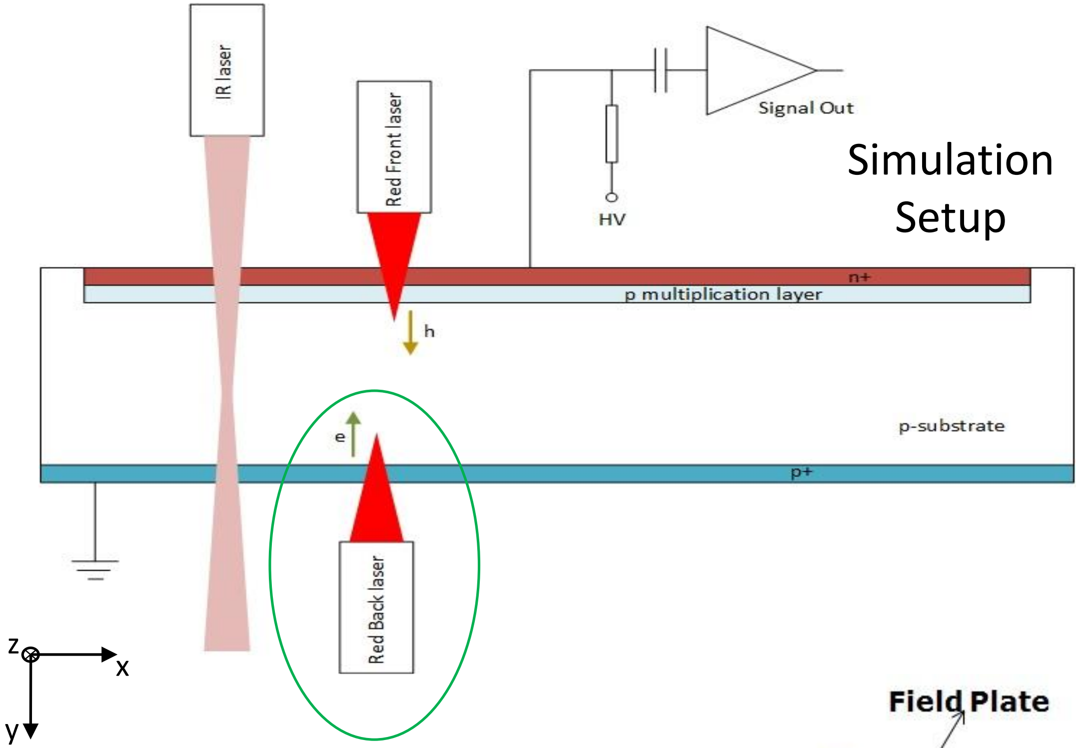
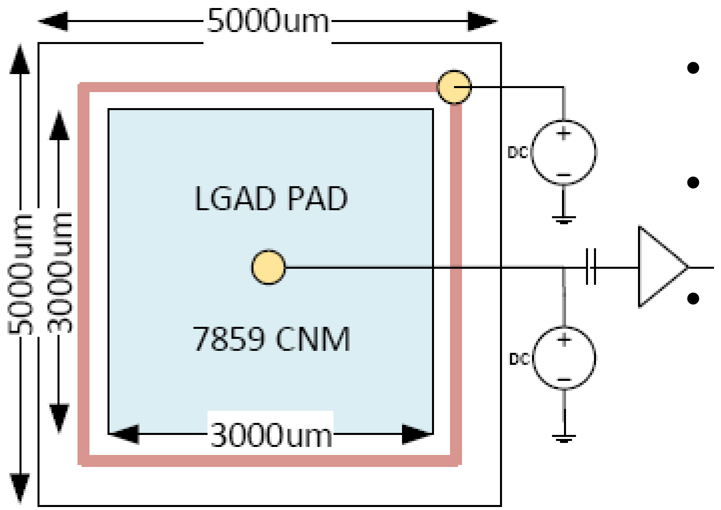
Introduction

1. Development of several LGAD models to test gain variation with bias and n+/pwell doping
2. Previous results (29th RD50 workshop, Nov 2016@CERN)
3. Analisis of radiation effects in LGAD Ga doped (a tentative): 300 um device
4. Analisis of radiation effects in LGAD Ga doped (a tentative): 50 um device

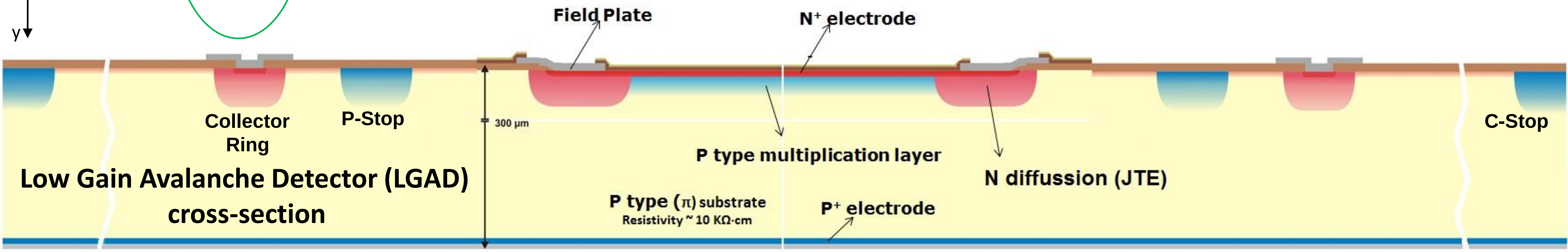
Sentaurus TCAD Simulation SetUp





Simulation Setup:

- Red Pulsed Laser: 670 nm, 10 μm spot, 50W/cm², 200 ps,
- BackIllumination at Device Center
- 2D detector model: 1 μm in Z direction, 5 mm in X direction, 300 μm in Y direction)



Low Gain Avalanche Detector (LGAD) cross-section

Doping profiles under confidenciality rules

From 29th RD50: Radiation Damage Models

Four 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. Two Level Model Proton ϕ = 1e14-1e15 n_{eq}/cm^2
4. New Perugia Model ϕ =1e12 up to 2e16 n_{eq}/cm^2

New Perugia

Parameters for fluences up to 7×10^{15} n/cm^2.

Defect	E (eV)	σ_e (cm^{-2})	σ_n (cm^{-2})	η
Acceptor	$E_c - 0.42$	1.00×10^{-15}	1.00×10^{-14}	1.6
Acceptor	$E_c - 0.46$	7.00×10^{-15}	7.00×10^{-14}	0.9
Donor	$E_v + 0.36$	3.23×10^{-13}	3.23×10^{-14}	0.9

Parameters for fluences within 7×10^{15} n/cm^2 and 2.2×10^{16} n/cm^2.

Defect	E (eV)	σ_e (cm^{-2})	σ_n (cm^{-2})	η
Acceptor	$E_c - 0.42$	1.00×10^{-15}	1.00×10^{-14}	1.6
Acceptor	$E_c - 0.46$	3.00×10^{-15}	3.00×10^{-14}	0.9
Donor	$E_v + 0.36$	3.23×10^{-13}	3.23×10^{-14}	0.9

Modeling of radiation damage effects in silicon detectors at high fluences HL-LHC with Sentaurus TCAD, D.Passeri et al, NIMA 824 (2016), 443-445

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}	—	$1.189 \times \Phi + 6.454 \times 10^{13}$
Donor	$E_v + 0.48$	10^{-14}	10^{-14}	—	$5.598 \times \Phi - 3.959 \times 10^{14}$

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

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	$*9.5 \times 10^{-15}$	$*9.5 \times 10^{-14}$	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	$*3.23 \times 10^{-13}$	$*3.23 \times 10^{-14}$	0.9

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

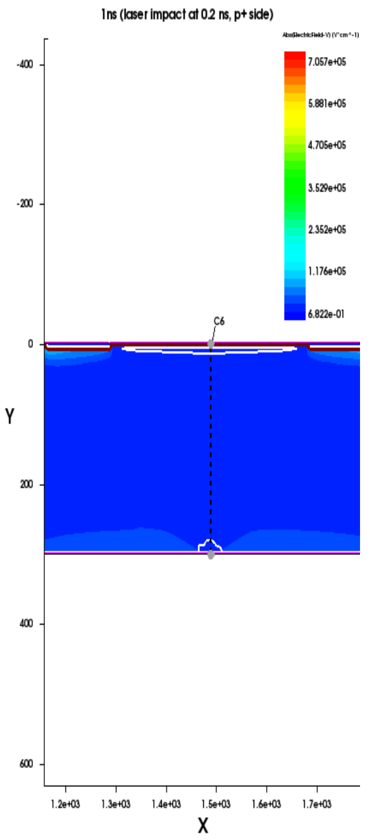
Eremin et al two level model*

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

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}

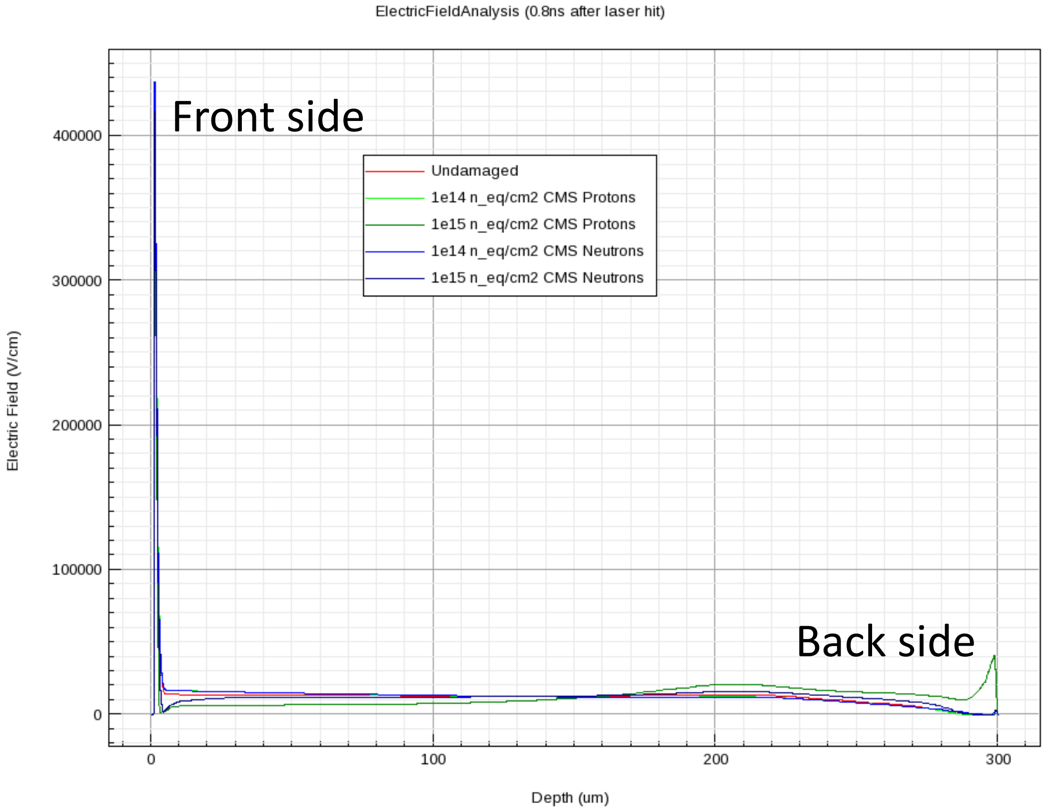
Combined effect of bulk and Surface damage on strip insulation properties of proton irradiated n+-p silicon strip sensors, R.Dalal et al. JINST 2014 9 P04007
*The origin of double peak electric field distribution in heavily irradiated silicon detectors, V.Eremin, E.Verbitskaya, Z.Li, NIMA 476 (2002) 556-564

From 29th RD50 LGAD:
All Models show a similar panorama, for example:
CMS Model

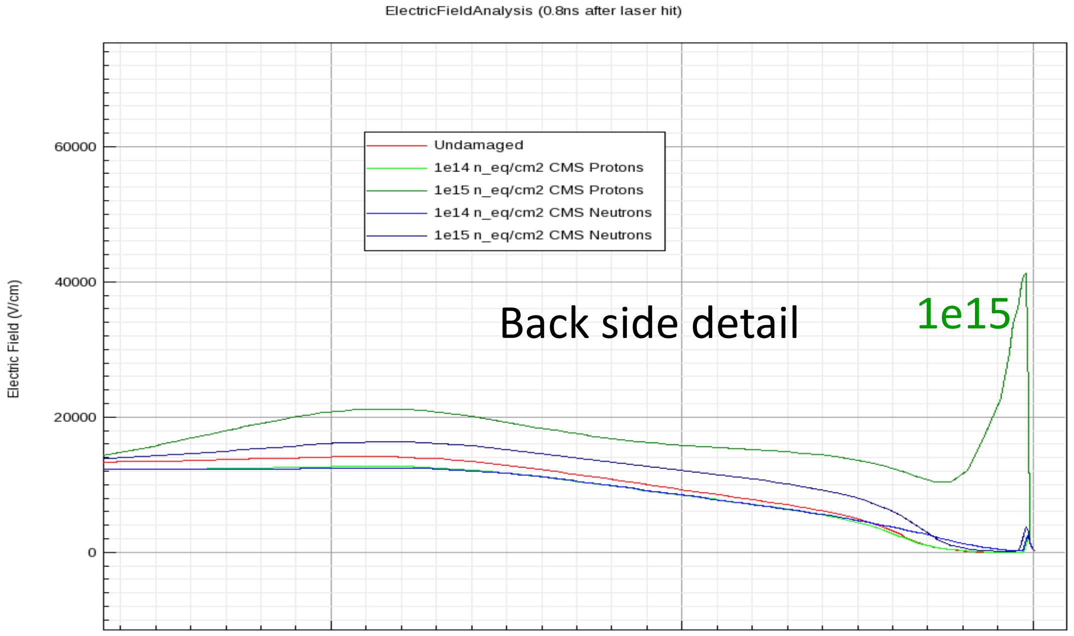


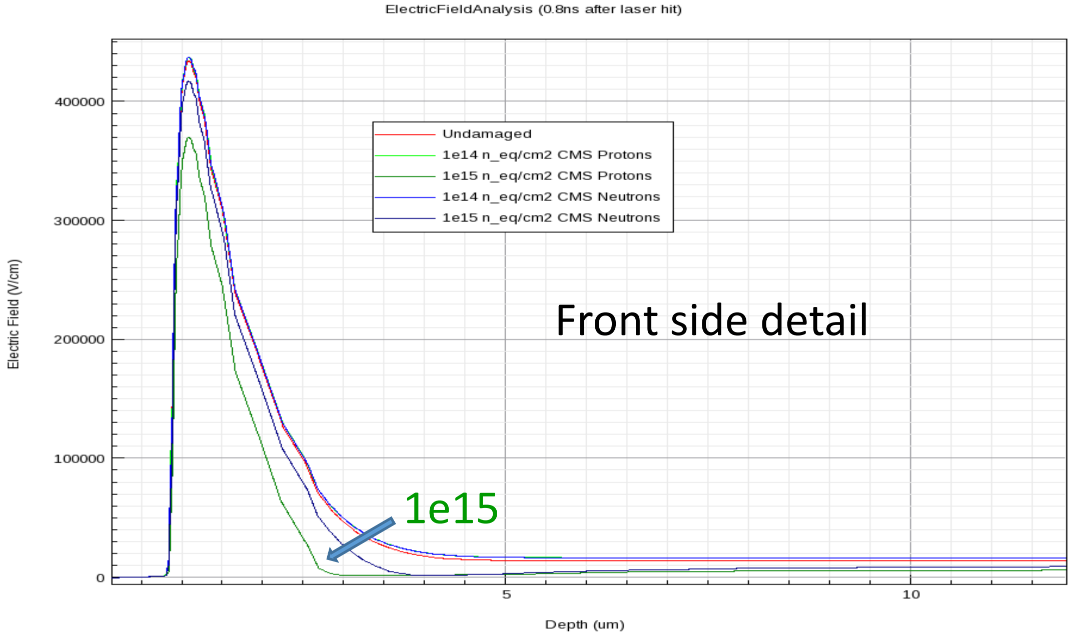
Electric Field Profiling

Electric Field along Y axis



At 1e15 a double junction appears at P+ volumen (device back side)





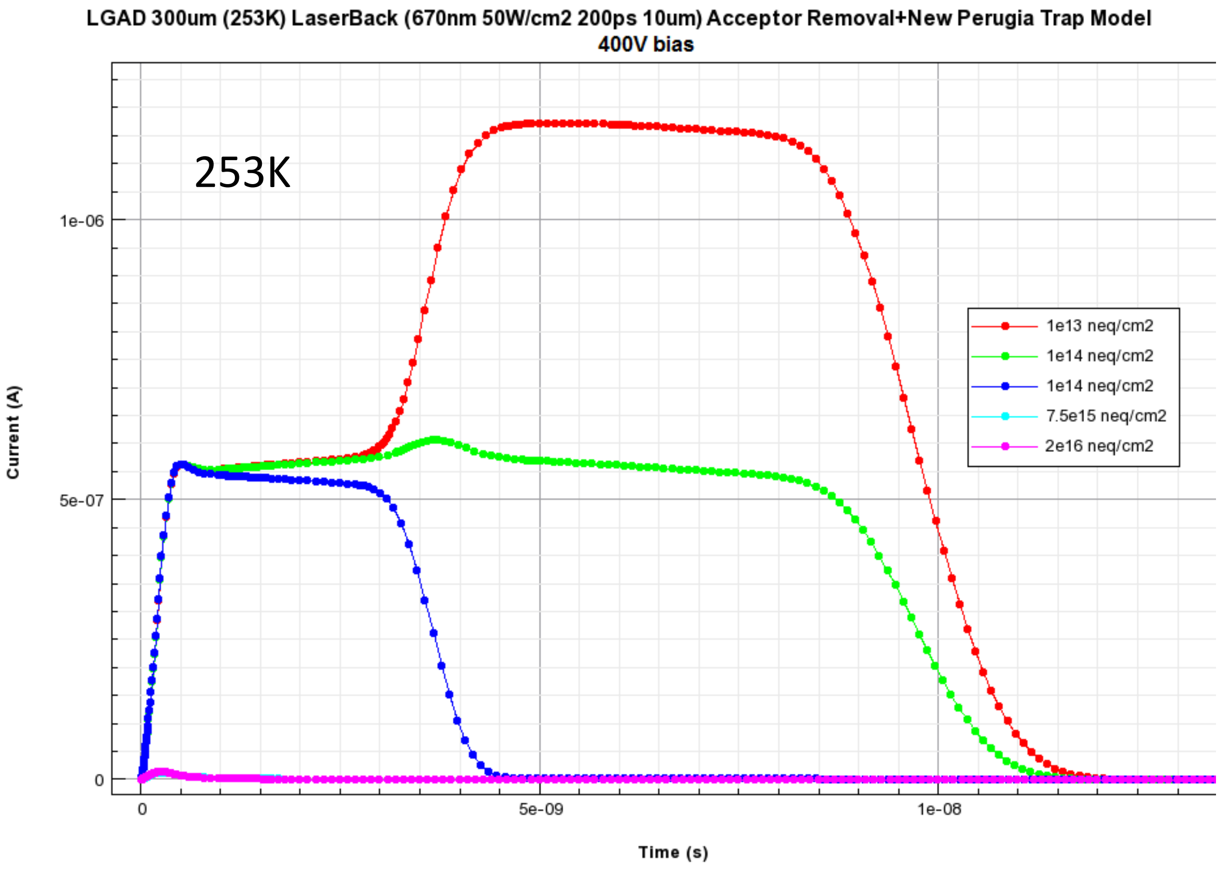
From 29th RD50: Acceptor Removal+Trap Model (New Perugia)

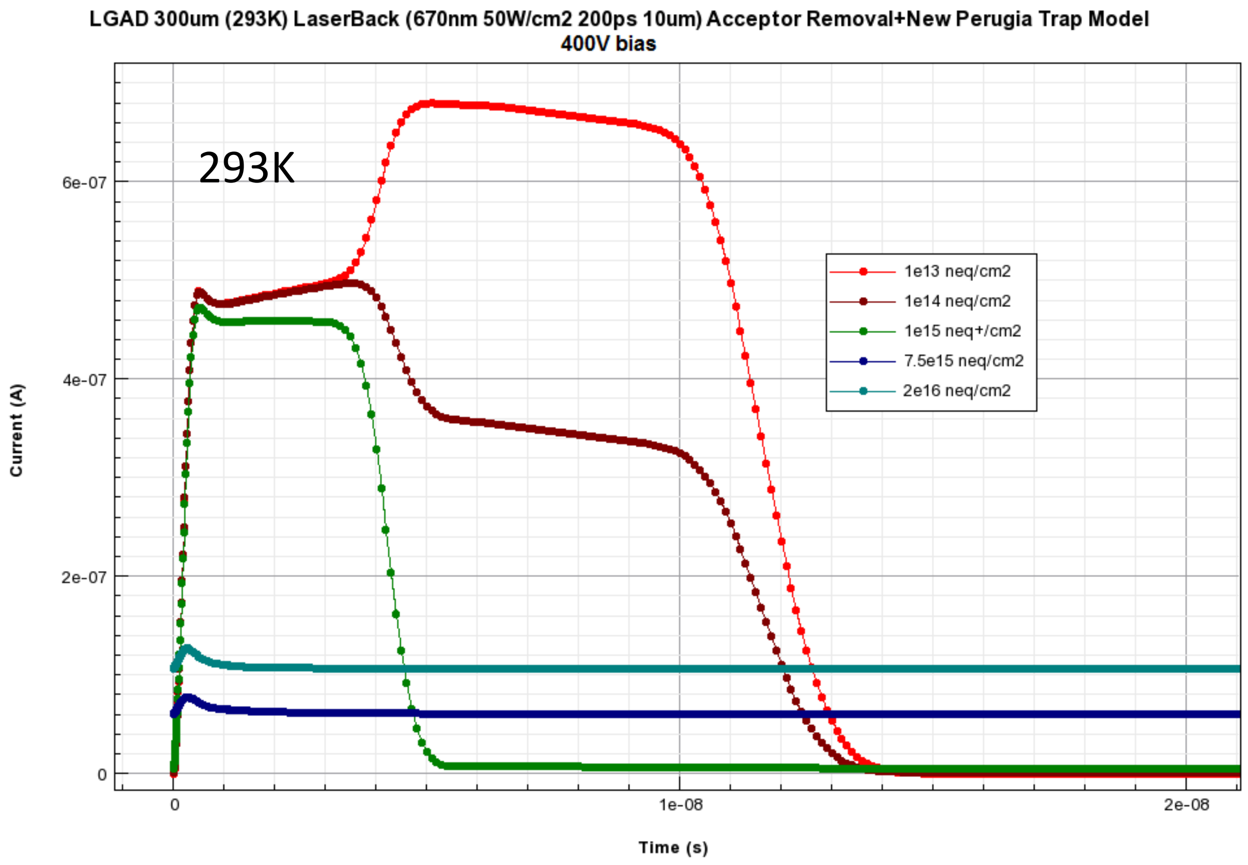
$$N_A = N_A e^{-c\phi}$$

c=10e^{-16} cm^{-2}

Boron Doping

Beyond 1e15 n_{eq}/cm^2 there is no p mult.layer for all practical purposes,





Radiation effects in Low Gain Avalanche Detectors after hadron irradiations, G.Kramberger et al., JINST 2015 10 P07006

Wafer Data (from Mar Carulla @ Trento Meeting)

$$\frac{dN_T^0}{dt} = -eN_T^0 \; ; \; e = \frac{\sigma \nu N_c T^2}{g} \exp\left(\frac{-E_a}{k_b T}\right) \; ; \; N_T^0 = N_T \exp(-et)$$

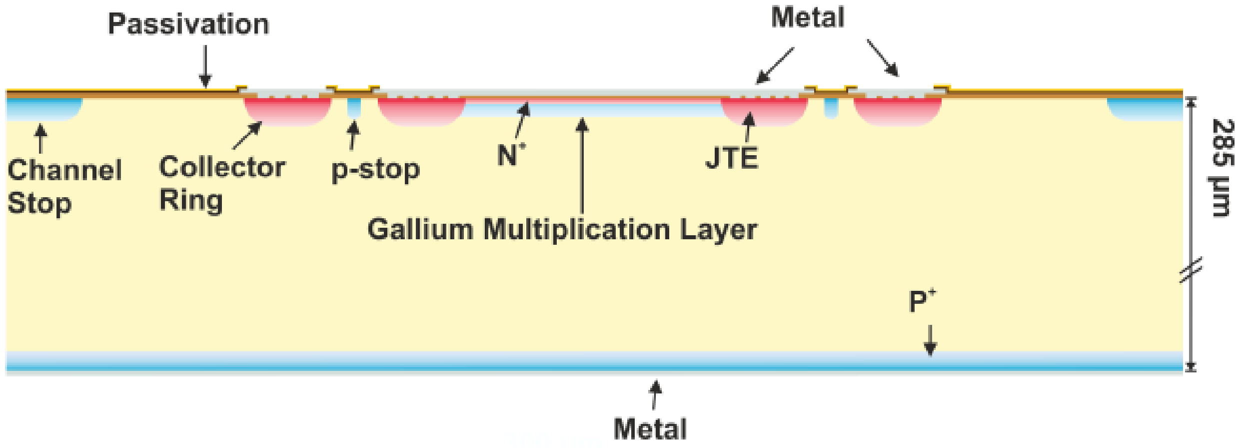
(1998 Yamaguchi)

$$N_A = N_A e^{-cA\phi}$$

(1999 Yamaguchi)

- We consider the acceptor removal model from literature (Watkins' removal mechanism)
- From Mar Carulla we extrapolate C_A=4e-16 cm^2 for a Kramberger's Paper type Gallium LGAD device, no T dependence as a first approach (also 2003 Kahn)
- We consider also the trap model (new Perugia)
- Simulation of Red Laser Back Transient
- Maximum fluence damage 2e15 n_{eq}/cm^2 compatible with CMS ETL (Endcap Timing Layer) see Cartiglia's talk

	Dopant	Doping(cm^{-3})	C_A (cm^2)
Wafer9 (Mar)	Ga	2,25E+16	6,90E-16
Kramb. Paper(2015)	B	5,00E+16	9,10E-16
Wafer10 (Mar)	Ga	1,00E+17	1,00E-16
Wafer11 (Mar)	Ga	2,30E+17	3,30E-16
Wafer14 (Mar)	B	3,00E+18	2,00E-17



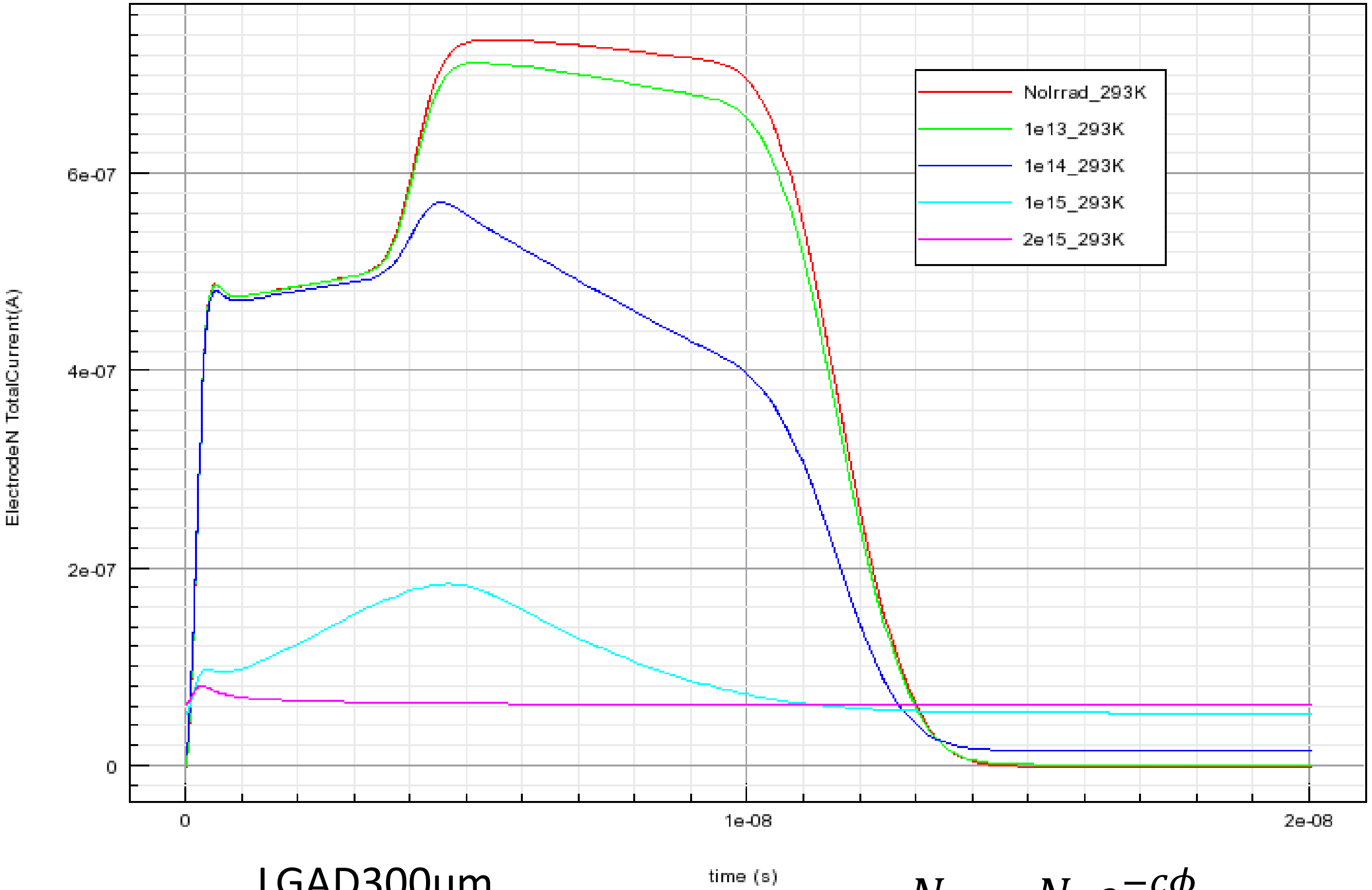
- Explanation for carrier removal and type conversión in irradiated silicon solar cells, T.Yamaguchi et al. Applied Physics Letters 72(10), 1998
- A detailed model to improve the radiation resistance of Si space solar cells, T.Yamaguchi et al. IEEE Trans on Electron Devices,46(10), 1999
- Strategies for improving radiation tolerance of Si space solar cells, A.Kahn et al. Solar Energy Materials & Solar Cells, 75, 271-276, 2003
- Defects in Semiconductors, L.Romano, V.Priviera, C.Jagadish, 2015 AP Elsevier publishers
- Radiation effects in Low Gain Avalanche Detectors after hadron irradiations, G.Kramberger et al., JINST 2015 10 P07006
- Last measurements and developments on LGAD detectors, Mar Carulla et al., 12th "Trento" Workshop February 2017

LGAD-Ga analysis, a tentative one

- We define a new LGAD with higher doping in the p multiplication layer
- NO Ga physics card in Sentaurus so:
  - We suppose that as a dopant, Ga behaves like B
  - We use the acceptor removal coefficients from the Mar Carulla analysis of the Ga doped wafers
- Tested several hypothetical devices, too high doping and the device goes to avalanche too soon
- The LGAD doping profile is a narrow Street
- From Mar Carulla wafer results, the acceptor removal coefficient goes down quickly
- We extrapolate the value c_A=4e-16 for the simulations, no T dependence (~worst case)
  - Probably the c_A value will be even lower if we consider the carbon interstitials effect (for the future)
- For sure, we need more experimental data
- First, we analyze the 300 um new LGAD device
- Second, we analyze a posible 50 um LGAD device
- Exploration of different damage fluences, trap & acceptor removal models, 293 & 253K, even variable bias
- Everything ready to inject new data from experiments and the T dependence of c_A

Acceptor Removal+Trap Model (New Perugia)

detector LGAD7859_Gallium_RedLaserBack_400V



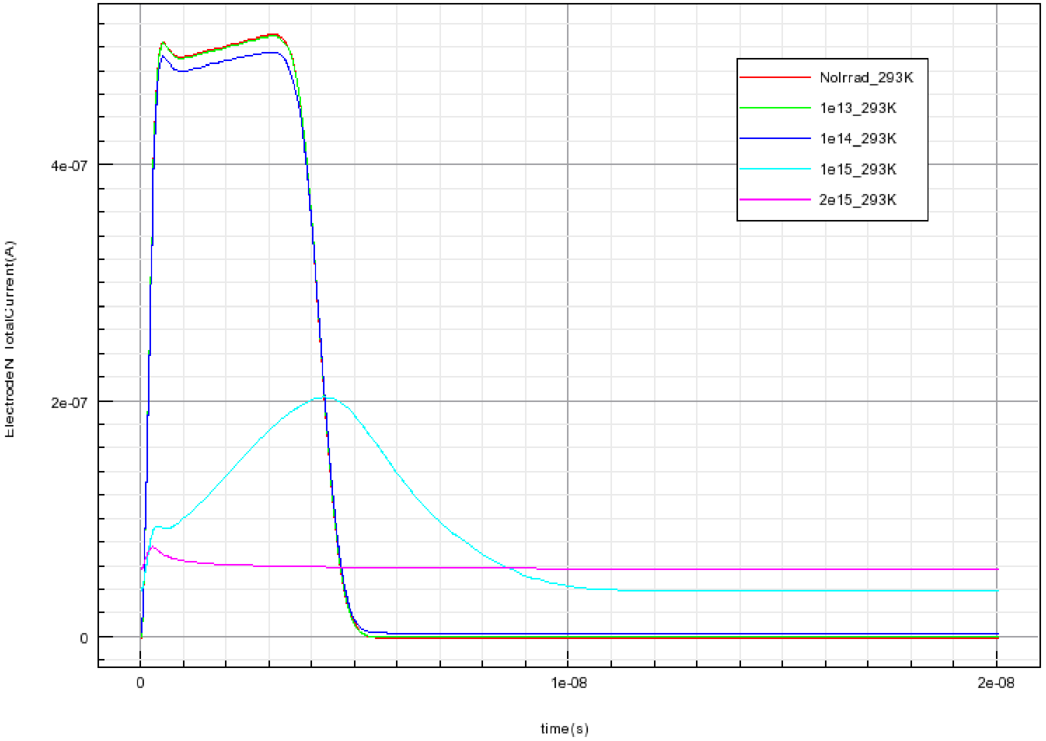
LGAD300um
Red Laser Back
400V Bias 293K
1e13-2e15 n_{eq}/cm^2

$$N_A = N_A e^{-c\phi}$$

$c=4x10e^{-16}\ cm^{-2}$

New Perugia Trap Model

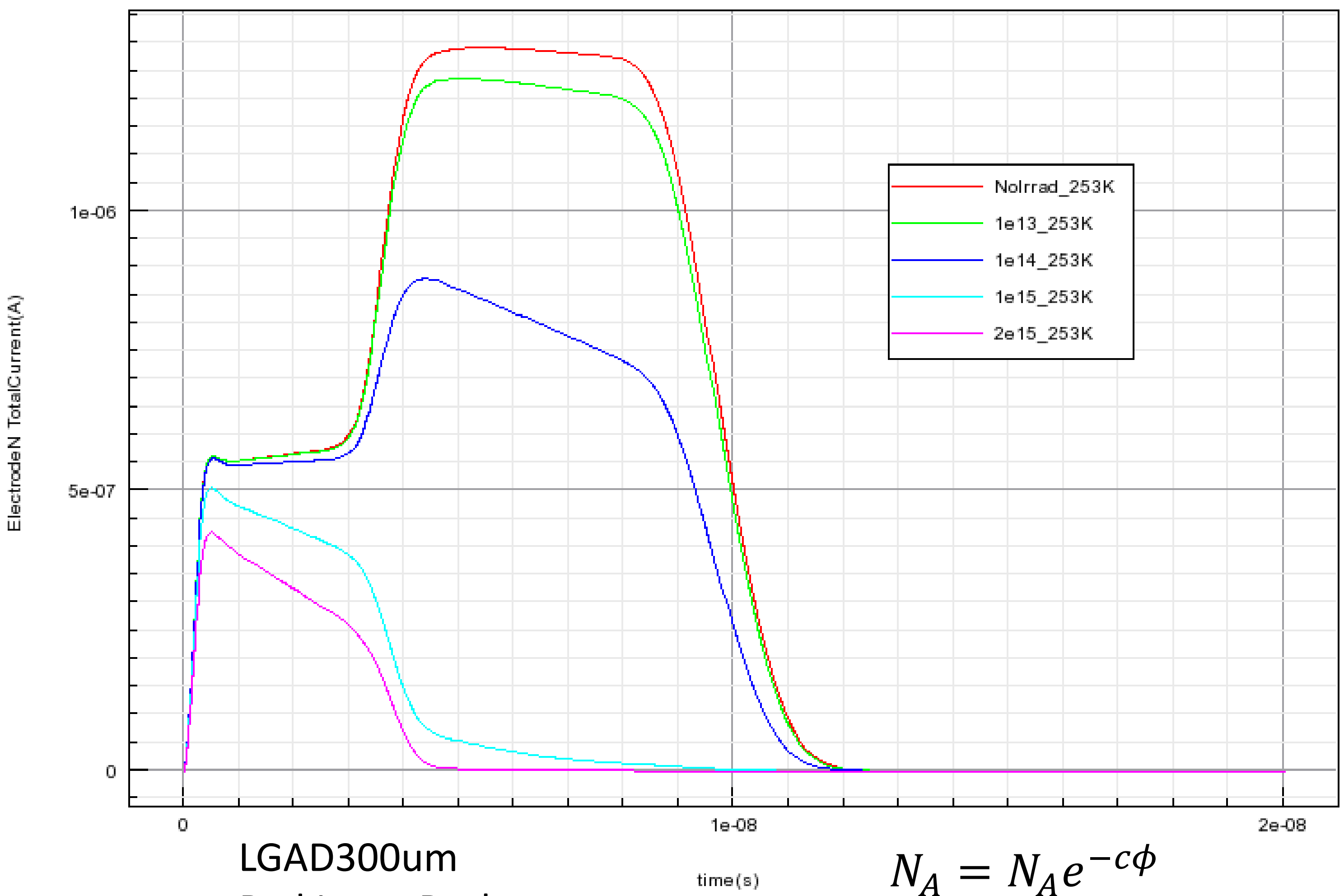
detector PINLGAD7859_Gallium_RedLaserBack_400V



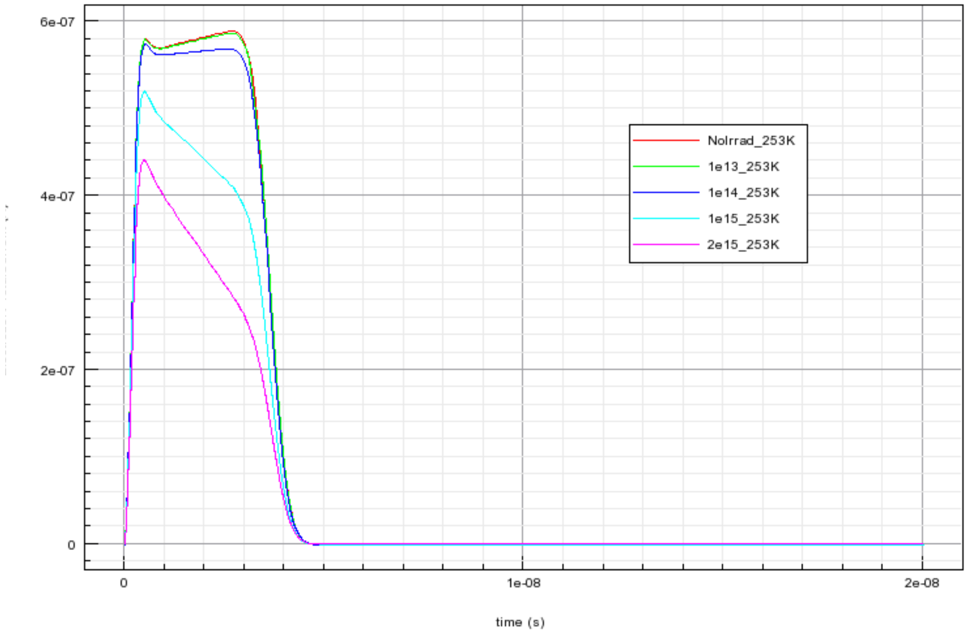
Fluence n/cm^2	Charge LGAD (C)	Charge PIN (C)	Gain Q_{lgad}/Q_{pin}
NoIrrad	7,42e-15	2,01e-15	3,689
1e13	7,19e-15	2,01e-15	3,581
1e14	5,6e-15	1,99e-15	2,818
1e15	1,86e-15	1,19e-15	1,563
2e15	1,28e-15	9,98e-16	1,284

Acceptor Removal+Trap Model (New Perugia)

detector LGAD7859_Gallium_RedLaserBack_400V



detector PINLGAD7859_Gallium_RedLaserBack_400V



LGAD300um
Red Laser Back
400V Bias 253K
1e13-2e15 n_{eq}/cm^2

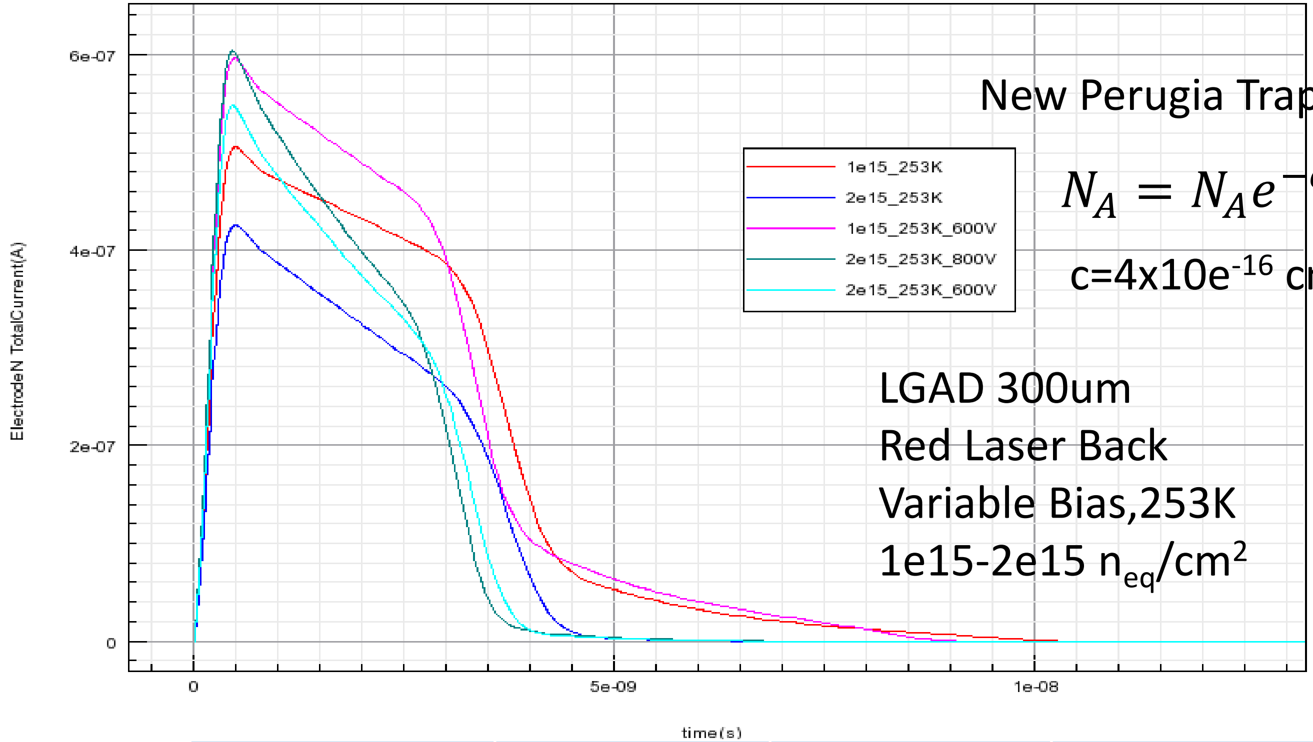
$$N_A = N_A e^{-c\phi}$$

$c=4x10e^{-16}\ cm^{-2}$

New Perugia Trap Model

Fluence n/cm^2	Charge LGAD (C)	Charge PIN (C)	Gain Q_{lgad}/Q_{pin}
NoIrrad	9,86e-15	2,01e-15	4,91
1e13	9,46e-15	2,00e-15	4,72
1e14	6,77e-15	1,95e-15	3,46
1e15	1,74e-15	1,22e-15	1,42
2e15	1,28e-15	1,19e-15	1,08

detector LGAD7859_Gallium_RedLaserBack_Variable Bias



New Perugia Trap Model

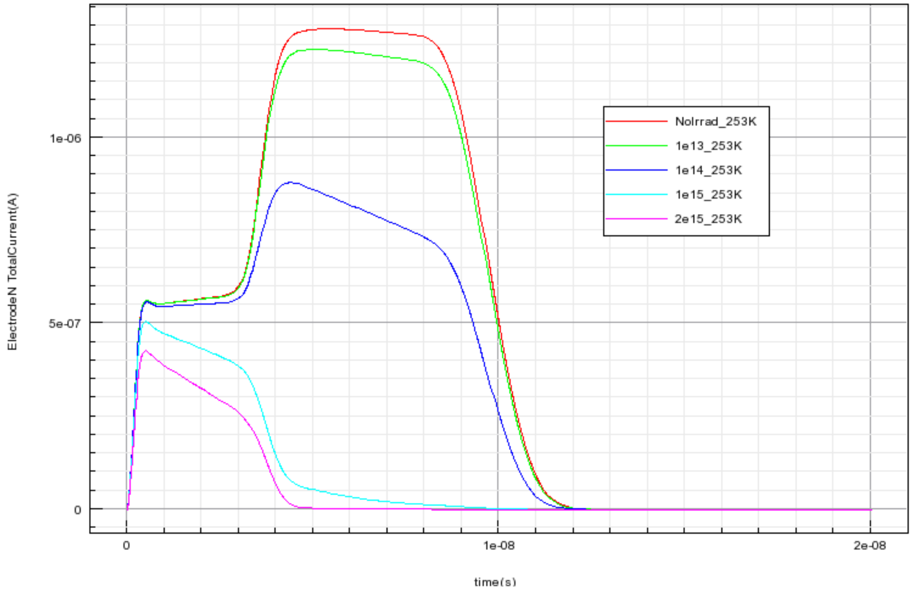
$$N_A = N_A e^{-c\phi}$$

c=4x10e^{-16} cm^{-2}

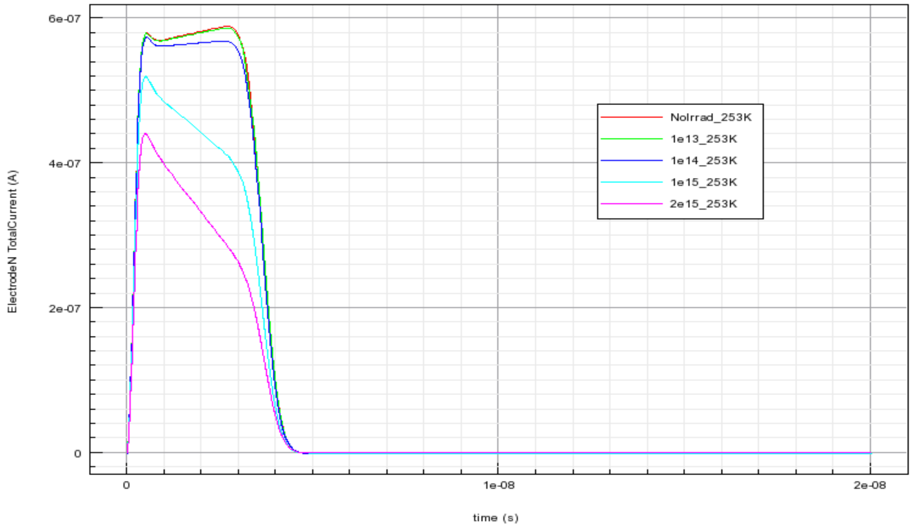
LGAD 300um
Red Laser Back
Variable Bias,253K
1e15-2e15 n_{eq}/cm^2

Fluence n/cm²	Charge LGAD (C)	Charge PIN (C)	Gain Q_{lgad}/Q_{pin}
NoIrrad	9,86e-15	2,01e-15	4,91
1e15(400V)	1,74e-15	1,22e-15	1,42
1e15(600V)	1,86e-15	1,22e-15	1,53
2e15(400V)	1,28e-15	1,19e-15	1,08
2e15(600V)	1,30e-15	1,19e-15	1,09
2e15(800V)	1,34e-15	1,19e-15	1,13

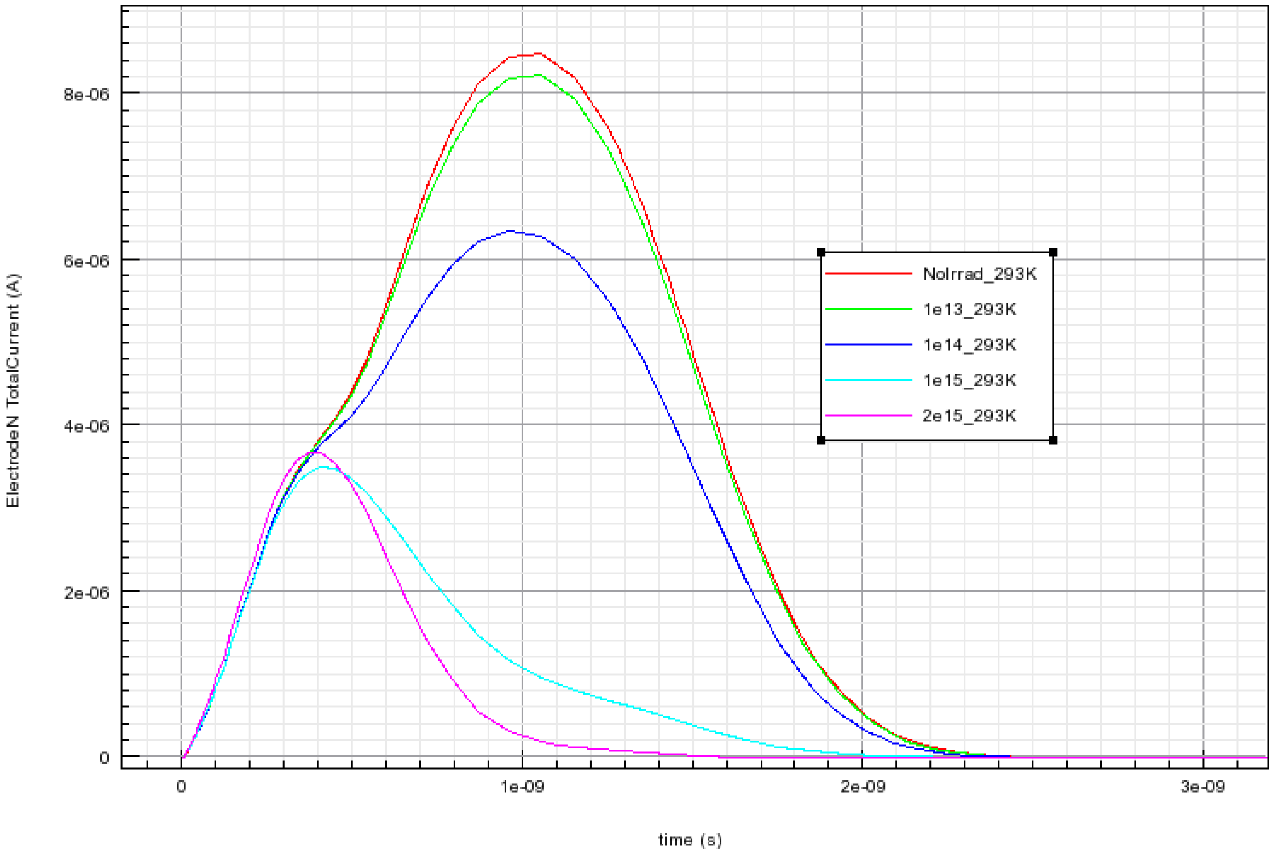
detector LGAD7859_Gallium_RedLaserBack_400V



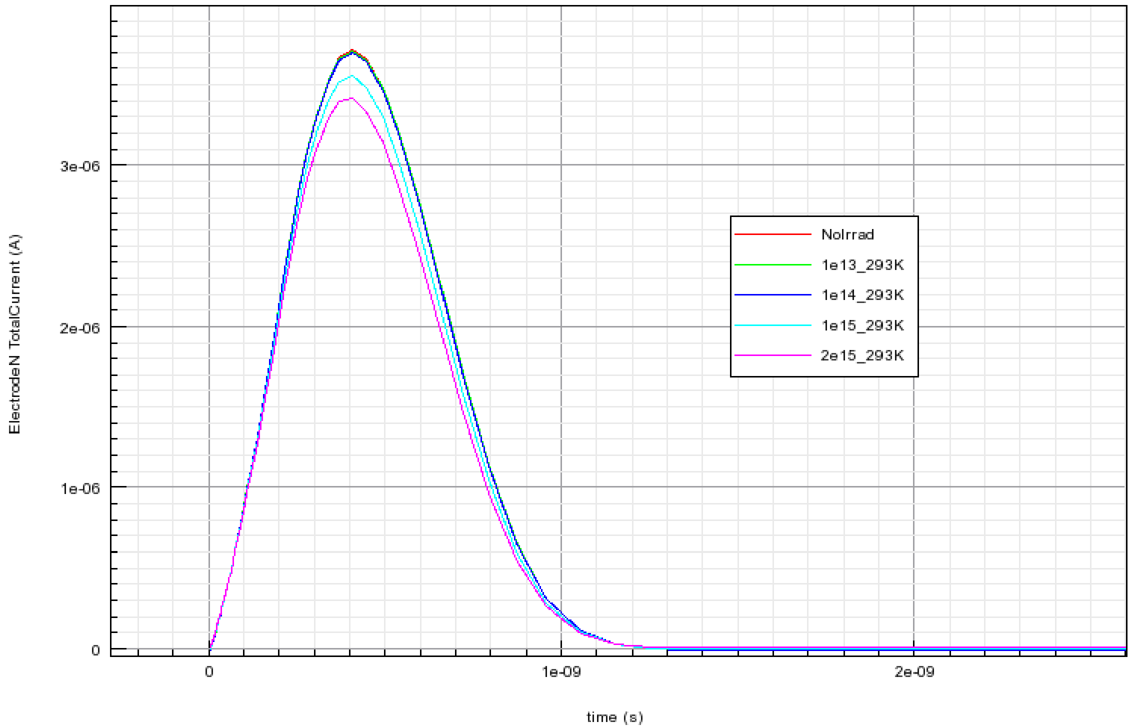
detector PINLGAD7859_Gallium_RedLaserBack_400V



detector LGAD7859_Gallium_RedLaserBack_150V



detector PINLGAD7859_Gallium_RedLaserBack_150V



LGAD50um
Red Laser Back
150V Bias 293K
1e13-2e15 n_{eq}/cm^2

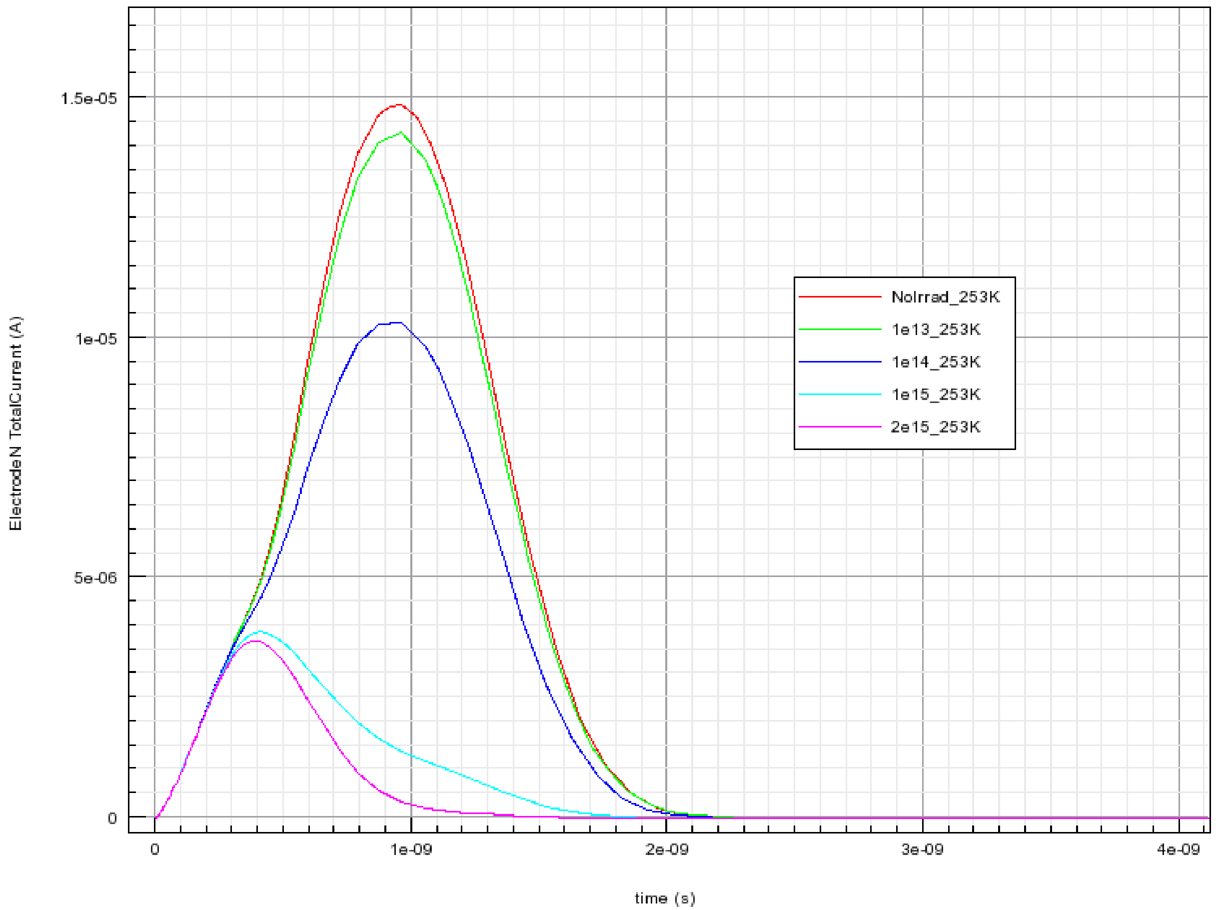
$$N_A = N_A e^{-c\phi}$$

c=4x10e^{-16} cm^{-2}

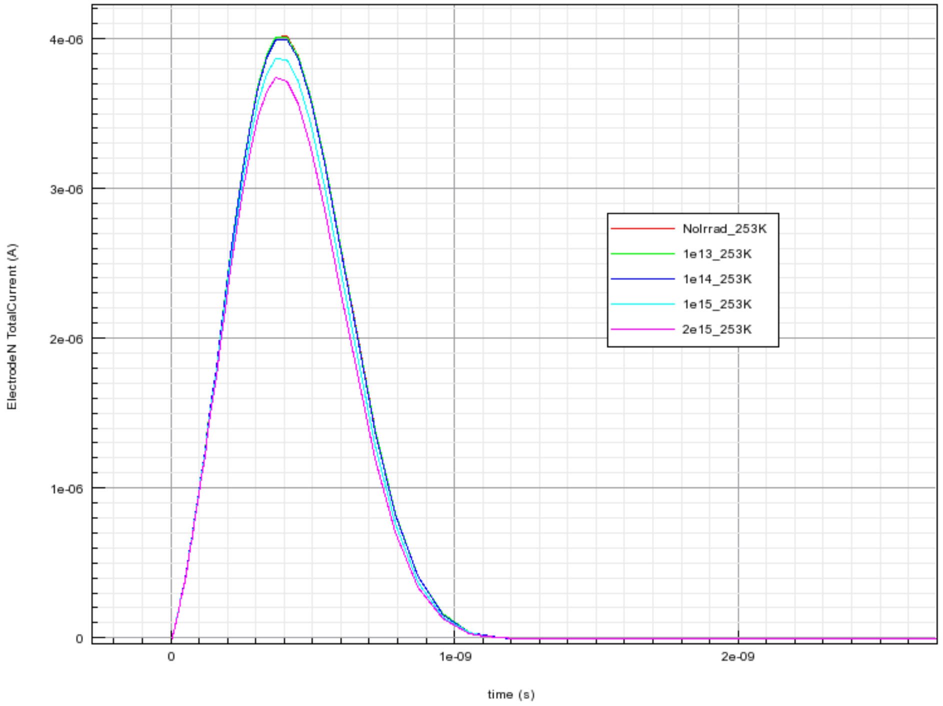
New Perugia Trap Model

Fluence n/cm^2	Charge LGAD (C)	Charge PIN (C)	Gain Q_{lgad}/Q_{pin}
NoIrrad	9,52e-15	2,02e-15	4,72
1e13	9,27e-15	2,02e-15	4,60
1e14	7,49e-15	2,02e-15	3,71
1e15	2,72e-15	1,92e-15	1,42
2e15	1,98e-15	1,84e-15	1,08

detector LGAD7859_Gallium_RedLaserBack_150V



detector PINLGAD7859_Gallium_RedLaserBack_150V



LGAD50um
Red Laser Back
150V Bias 253K
1e13-2e15 n_{eq}/cm^2

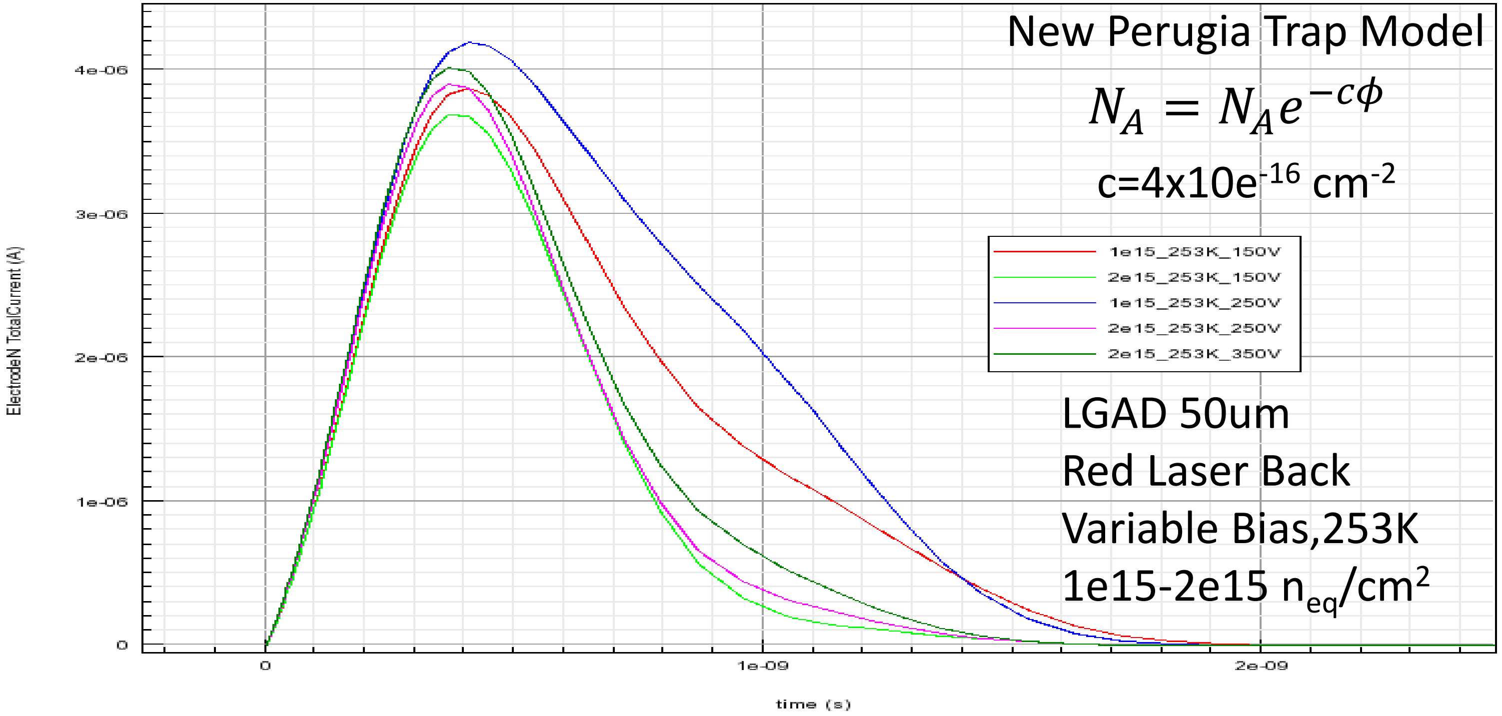
$$N_A = N_A e^{-c\phi}$$

$c=4x10e^{-16}\ cm^{-2}$

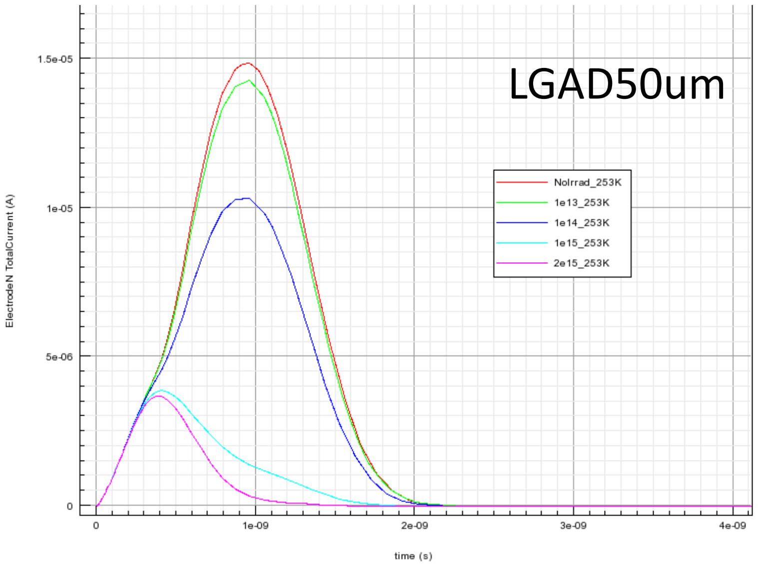
New Perugia Trap Model

Fluence n/cm²	Charge LGAD (C)	Charge PIN (C)	Gain Q_{lgad}/Q_{pin}
NoIrrad	1,37e-14	2,02e-15	6,78
1e13	1,32e-14	2,01e-15	6,54
1e14	9,94e-15	2,01e-15	4,96
1e15	2,84e-15	1,93e-15	1,47
2e15	1,98e-15	1,87e-15	1,05

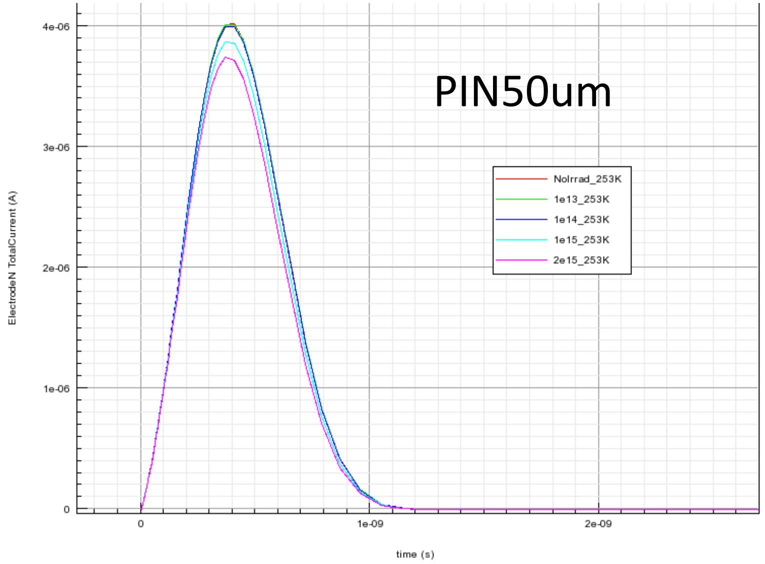
detector LGAD7859_Gallium_RedLaserBack_Variable Bias



detector LGAD7859_Gallium_RedLaserBack_150V



detector PINLGAD7859_Gallium_RedLaserBack_150V



Fluence n/cm^2	Charge LGAD (C)	Charge PIN (C)	Gain Q_{lgad}/Q_{pin}
NoIrrad	1,37e-14	2,02e-15	6,78
1e15(150V)	2,84e-15	1,93e-15	1,47
1e15(250V)	3,4e-15	1,93e-15	1,77
2e15(150V)	1,98e-15	1,87e-15	1,05
2e15(250V)	2,11e-15	1,87e-15	1,13
2e15(350V)	2,31e-15	1,87e-15	1,23

Conclusions

- New experimental data are desperately needed
- Ga and C doping could be the solution up to 2e15 n_{eq}/cm^2 damage (ELT@CMS)
- The simulation models are ready for the new data

Thanks for your attention

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