# Simulation of LGAD characteristics taking into account negative feedback in Si detectors with carrier multiplication

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## Goal

**Our vision of the processes in LGAD:
how to explain reduction of the gain and collected charge**

## Outline

♦ PTI model of $Q_c$ enhancement in irradiated Si detectors
♦ Restriction on collected charge arisen from negative feedback in irradiated Si strip detectors
♦ Fit of the experimental data
♦ $E(x)$ distribution in LGAD
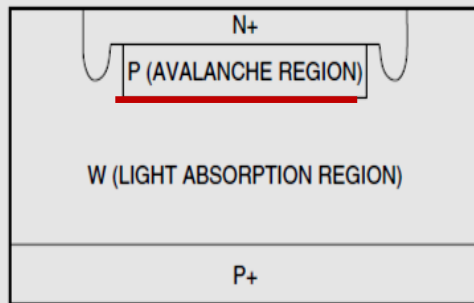♦ $Q_c$ vs. F dependences in LGAD and comparison with experimental data

  Conclusions

# *Comparison between LGAD and APD*

## Hamamatsu APD

Read structures
$I \sim 20$ pA ($\varnothing$ 1.5 mm)
$E$ – hundreds kV/cm



| N+ |
|---|
| P (AVALANCHE REGION) |
| W (LIGHT ABSORPTION REGION) |
| P+ |



(Typ. λ=800 nm)

♦ *E(x)* as in heavily irradiated detector (high *V*)
♦ carrier avalanche multiplication
   **but**
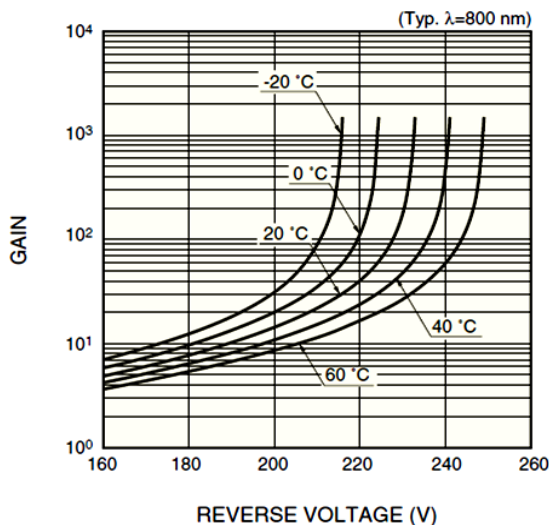♦ $\tau_{tr} = 1$ ms (no trapping of nonequilibrium carriers)

**Internal gain**

$G = Q_{am}/Q_o$

**Internal gain in APD ≥200**

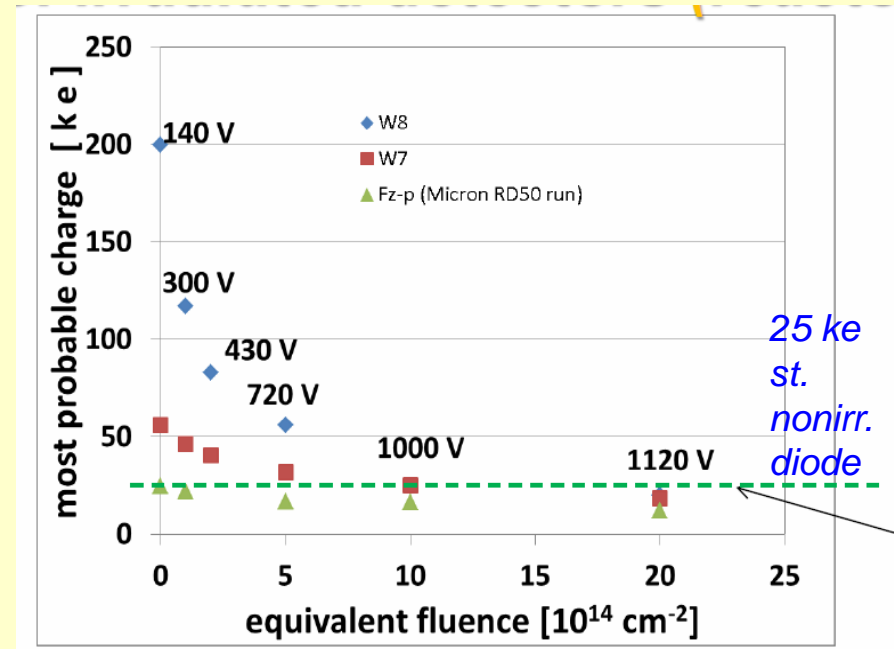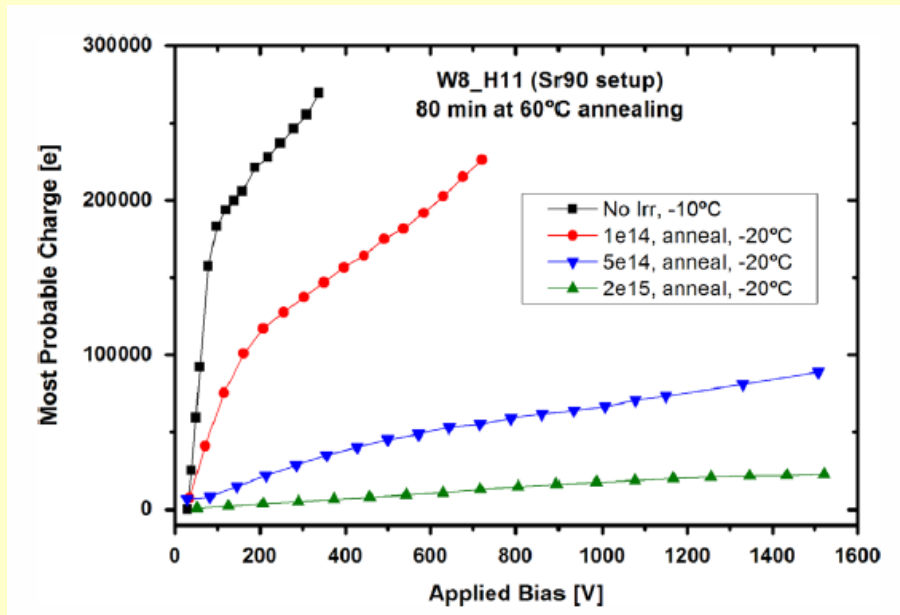$Q_o$ – induced signal without avalanche multiplication
$Q_{am}$ - signal measured or calculated in the same detector with avalanche multiplication

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# *Experimental results of RD50*

*Experimental data are taken in G. Pellegrini, et al., NIM A765 (2014) 12
and G. Kramberger, 24 RD50 workshop, June 2014*



**Gain in nonirradiated LGAD achieves 10-20
and goes down under irradiation being higher than in standard detectors**

# *Model of $Q_c$ enhancement due to avalanche multiplication in irradiated n-on-p Si strip detectors*

**The model considers**:

⋎ formation of Double Peak (DP) electric field profile – DP $E(x)$;

⋎ carrier impact ionization in high electric field;

⋎ avalanche hole generation near the $n^+$ contact, hole injection into the detector bulk, and hole trapping to radiation-induced deep levels defects

➜ give rise to the trapping-related **negative feedback** which stabilizes avalanche multiplication and total detector performance

**but restricts the gain**

Published/presented in
V. Eremin, et al., *14 and 15 RD50 workshops, 2009, Freiburg and Geneva*
V. Eremin, E. Verbitskaya, A. Zabrodskii, Z. Li, J. Härkönen, *NIM A 658 (2011) 145*
E. Verbitskaya, V. Eremin, A. Zabrodskii, 2012, J. Instrum., v.7, 2, ArtNo: C02061;
doi: 10.1088/1748-0221/7/02/C02061
E. Verbitskaya, et al., NIM A 730 (2013) 66

# *Negative feedback in irradiated n-on-p detectors*

♦ impact ionization near n$^+$ (e, h)
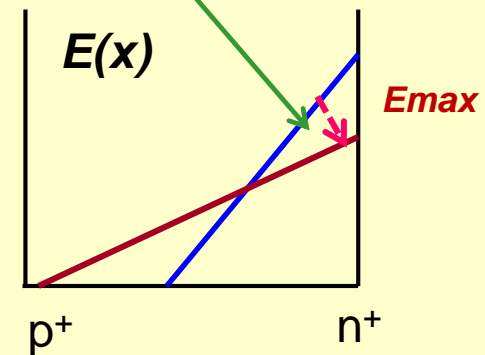♦ hole injection
♦ hole trapping to DLs

♦ reduction of $-N_{eff}$
♦ reduction of dE/dx
   and stabilization of $E_{max}$ at n$^+$
♦ **reduction of $\alpha_{e,h}$**

Trapping-related negative feedback:

♦ stabilizes avalanche multiplication
   and total detector performance

   BUT

♦ simultaneously restricts $Q_c$ enhancement

*E(x)*

*Emax*

p$^+$          n$^+$

**LGAD initially contain high doped built-in layer with E ~ 10$^5$ V/cm
DLs are introduced by radiation**

➔ **There is no reason to exclude the influence of negative feedback in LGAD**

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# Algorithm of E(x) and $Q_c$ simulation

**Processes considered**:

⩒ formation of a steady-state *E(x)* distribution:
  equilibrium carriers (bulk generation current) and avalanche generated carriers near
  $n^+$ contact, their trapping on radiation-induced DL defects;

⩒ charge collection in the detector bulk with a calculated *E(x)* profile;

⩒ e and h are generated by MIPs

**Procedure and main parameters**

♦ **numerical calculation – EXCEL MS Office**

♦ Poisson equation combined with the rate equation

♦ one-dimensional approach for detector geometry

♦ Effective deep levels: DA $E_c$ – 0.53 eV;   DD $E_v$ + 0.48 eV

♦ $1/\tau_{e,h} = \beta_{e,h} F_{eq}$;   $\beta_e = 3.2 \times 10^{-16}$ cm$^2$ns$^{-1}$, $\beta_h = 3.5 \times 10^{-16}$ cm$^2$ns$^{-1}$

♦ ionization rates $\alpha_{e,h} = A_{e,h} exp(-B_{e,h}/E)$

  *see also talk of V. Eremin*

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# Fitting of $Q_c(V)$ dependences
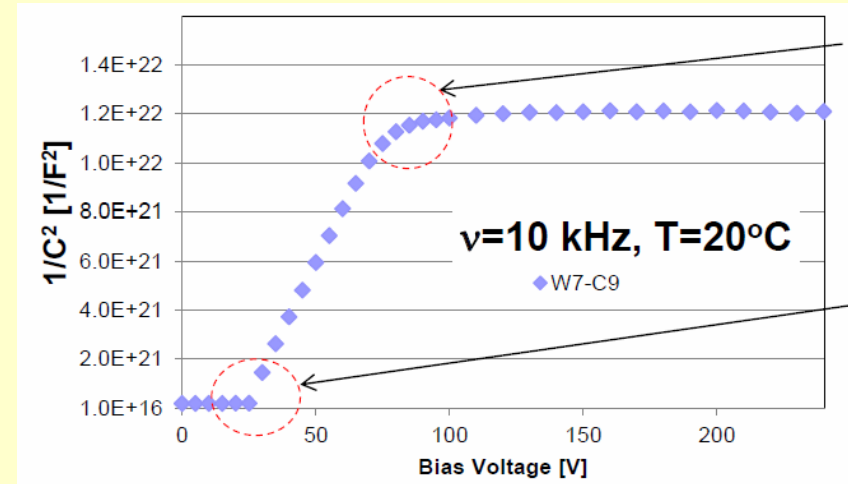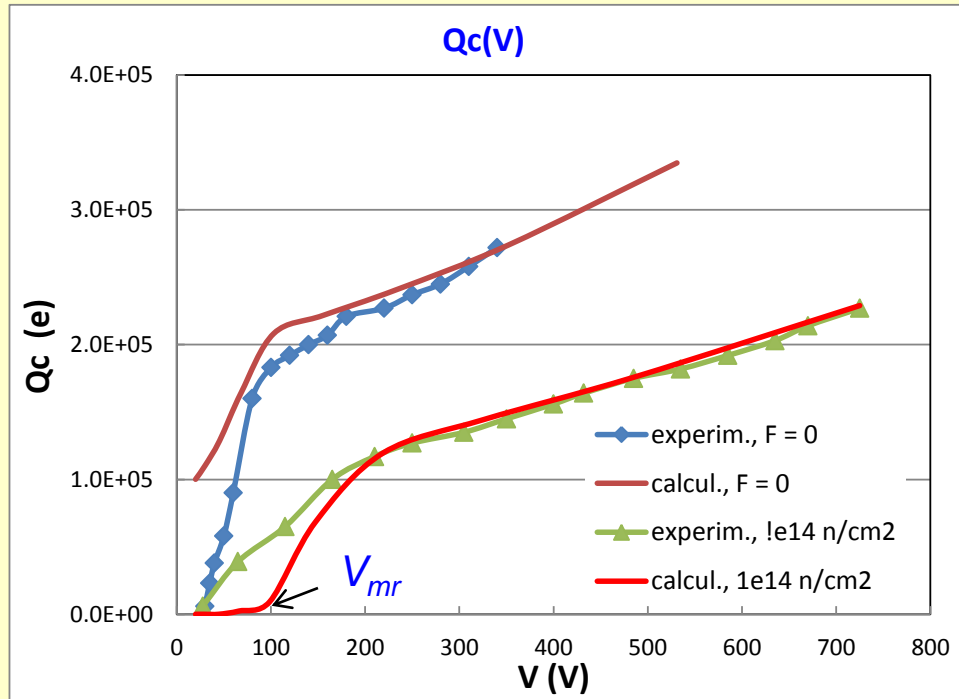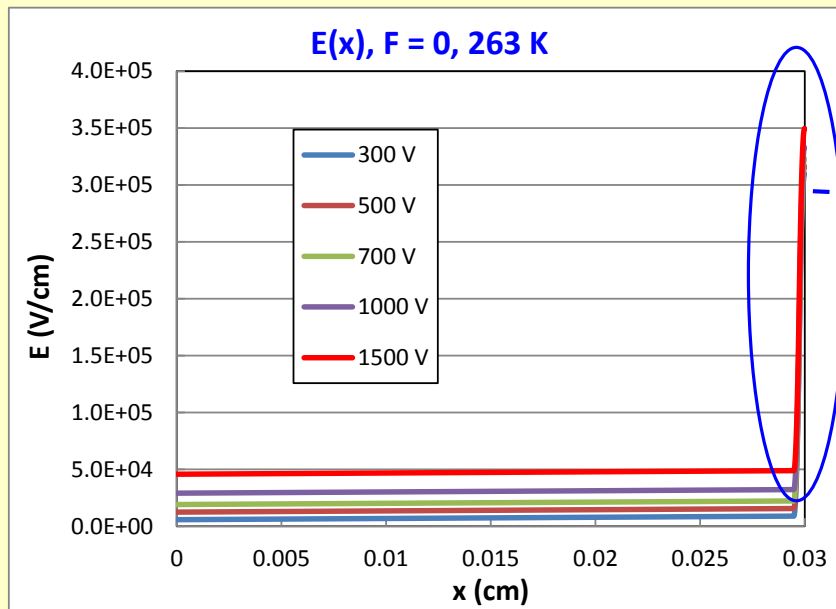


Implantation dose $2 \times 10^{12}$ cm$^{-3}$

**Similarity of calculated $Q_c(V)$ and experimental curves**

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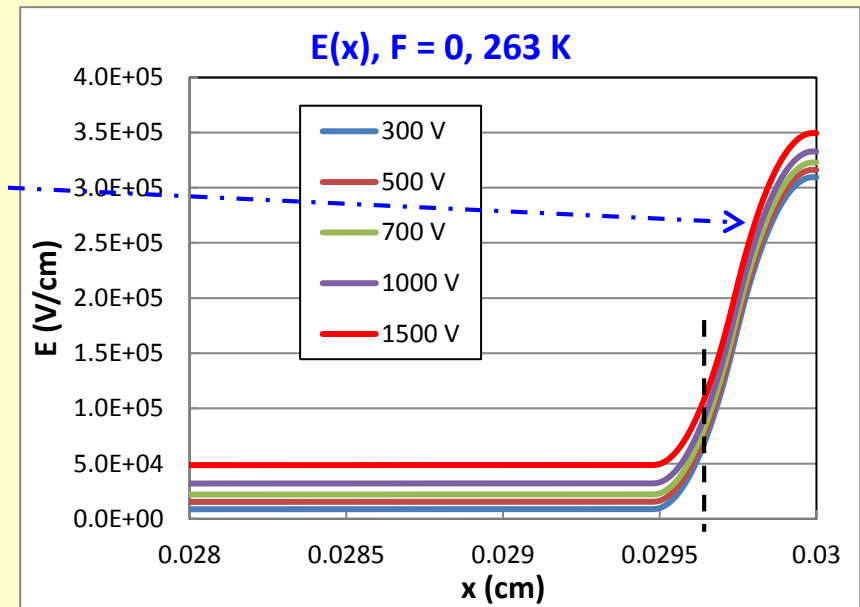# *Electric field distribution in LGAD*

E(x) distribution is a key factor for charge collection

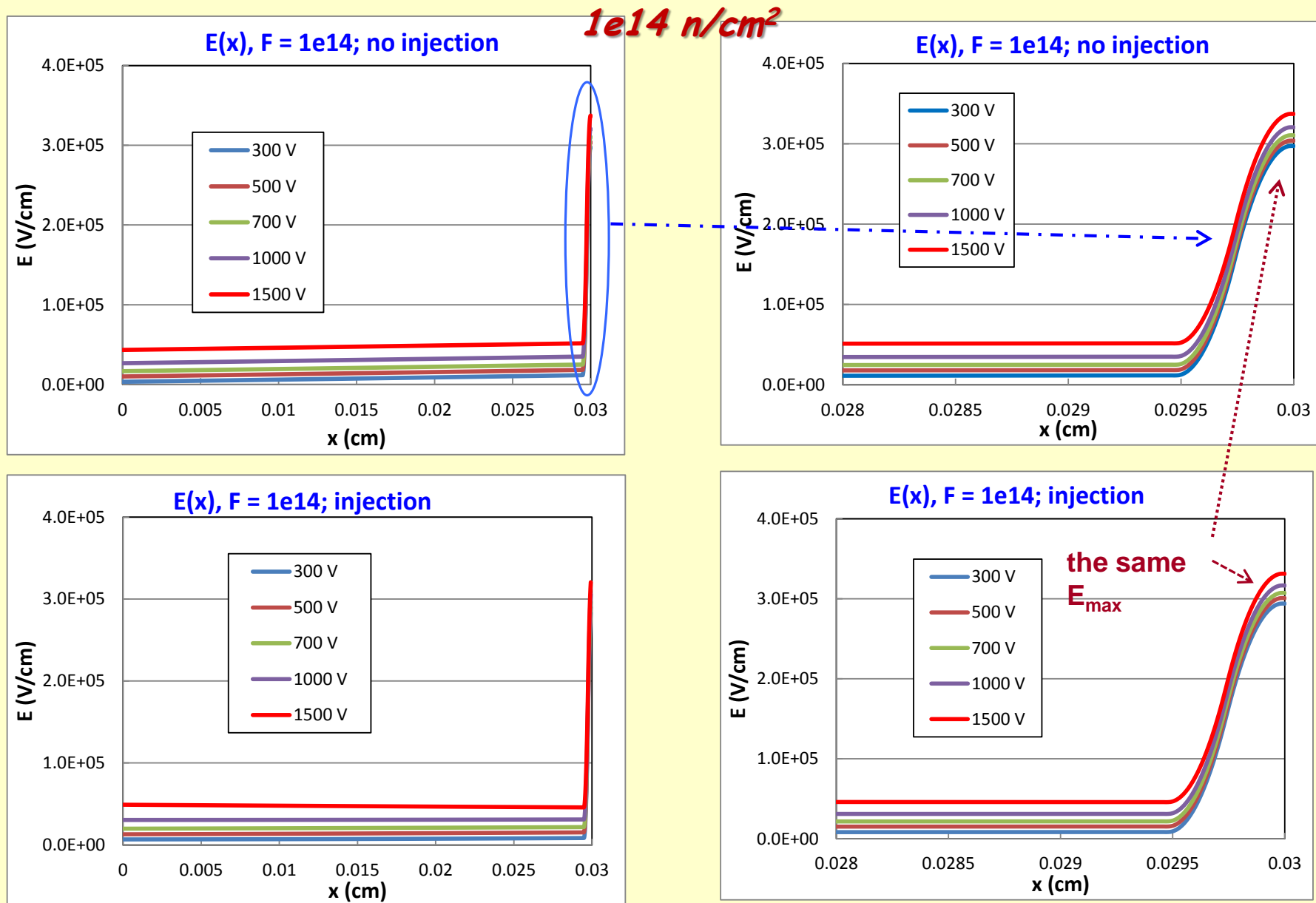Calculation: comparison between "no injection" and regarding injection
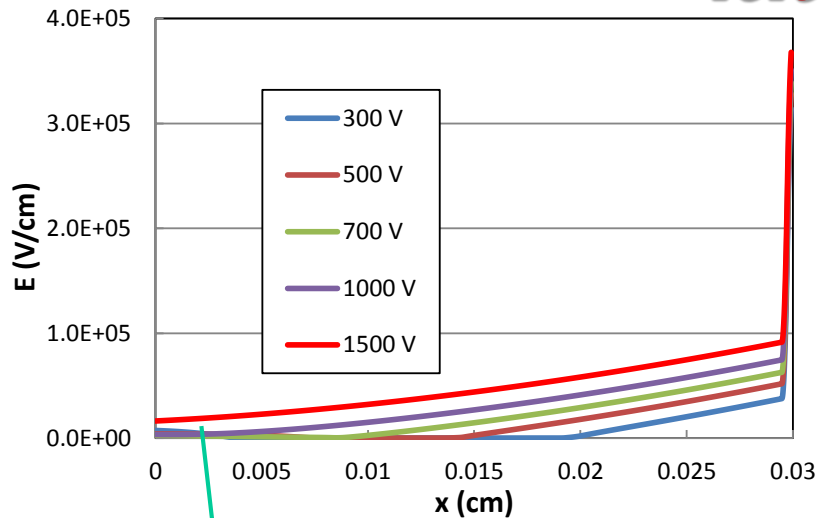
## Nonirradiated diode



n+

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# *Electric field distribution in irradiated LGAD*

**1e14 n/cm²**

**E(x), F = 1e14; no injection**

- 300 V
- 500 V
- 700 V
- 1000 V
- 1500 V

E (V/cm) vs x (cm)

**E(x), F = 1e14; no injection**

- 300 V
- 500 V
- 700 V
- 1000 V
- 1500 V

E (V/cm) vs x (cm)

**E(x), F = 1e14; injection**

- 300 V
- 500 V
- 700 V
- 1000 V
- 1500 V

E (V/cm) vs x (cm)

**E(x), F = 1e14; injection**

- 300 V
- 500 V
- 700 V
- 1000 V
- 1500 V

**the same $E_{max}$**

E (V/cm) vs x (cm)
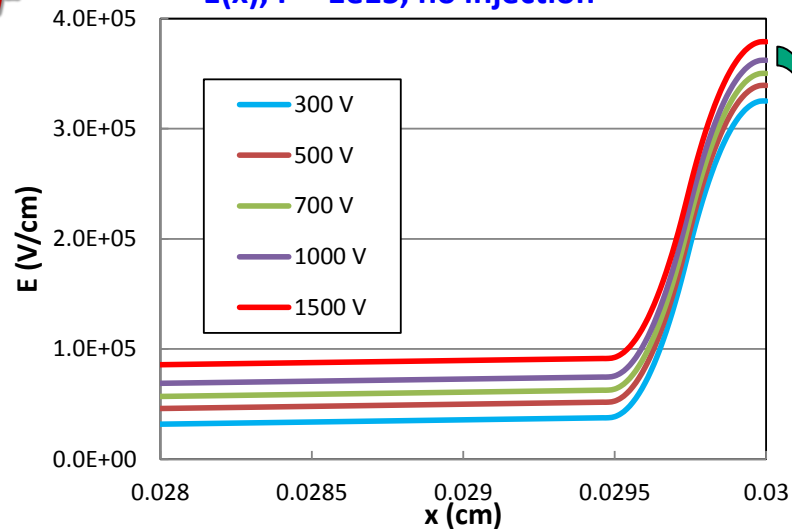
# Electric field distribution in irradiated LGAD
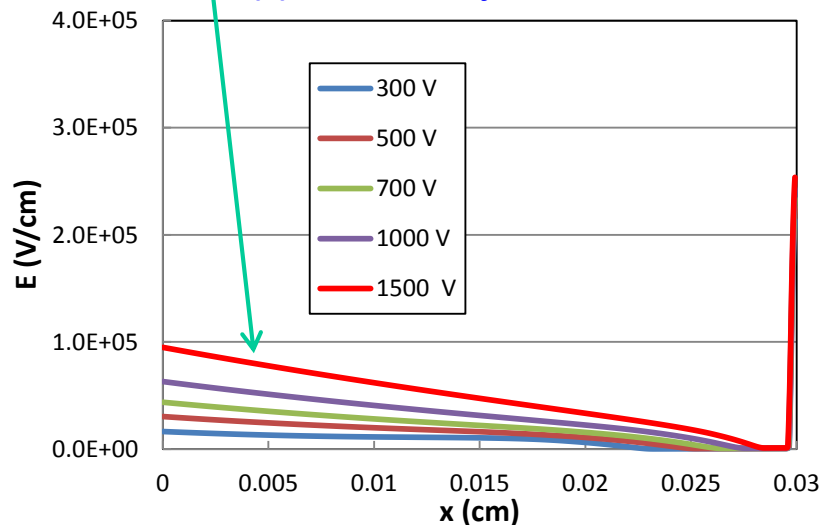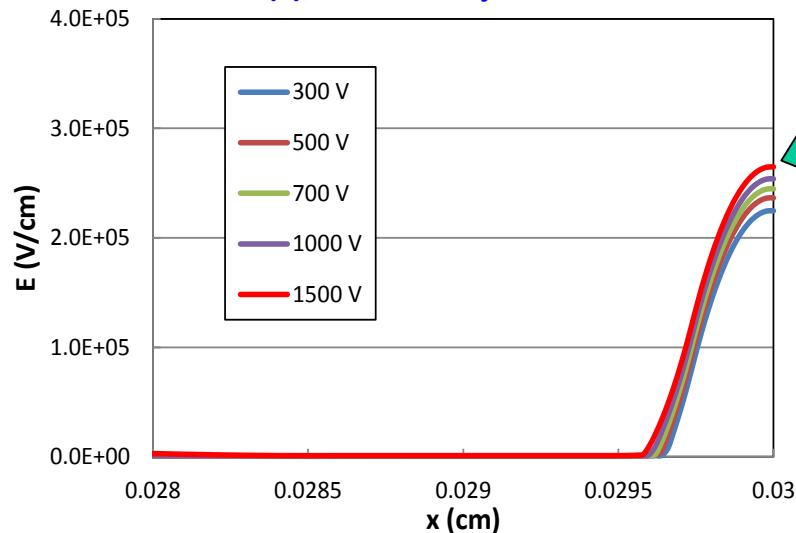
# *Evolution of electric field distribution under irradiation*
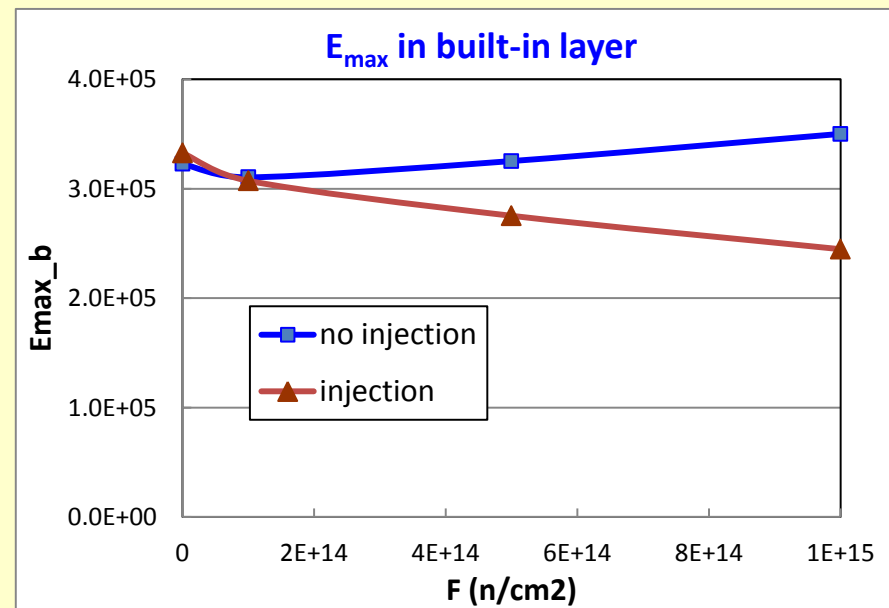


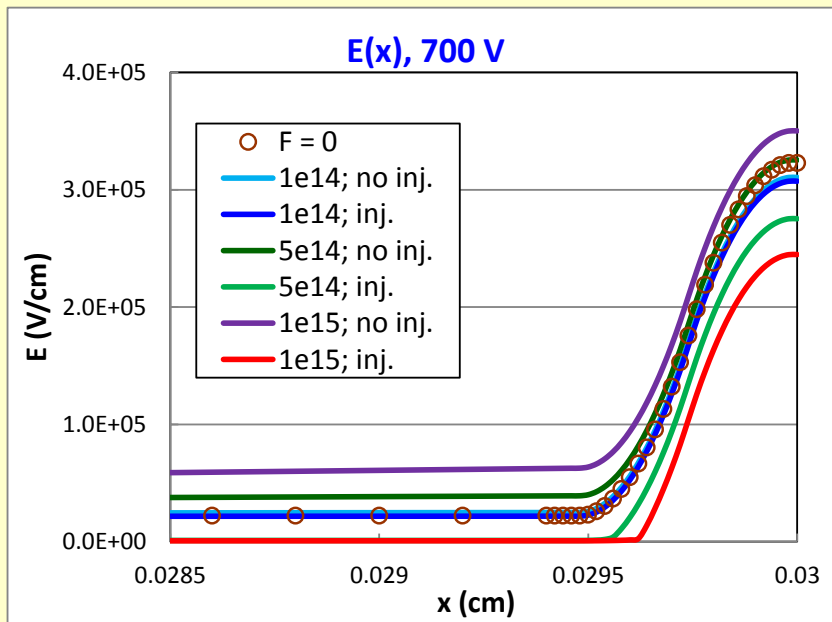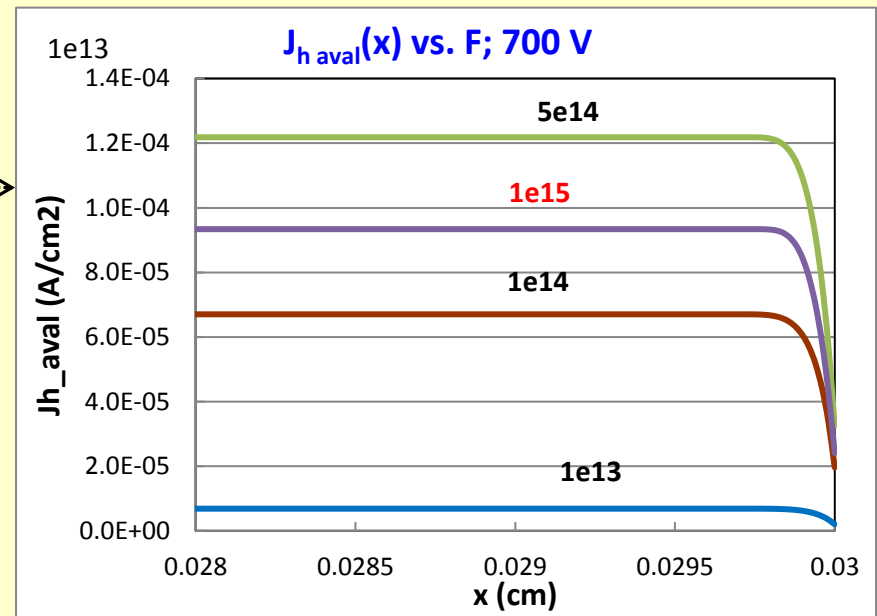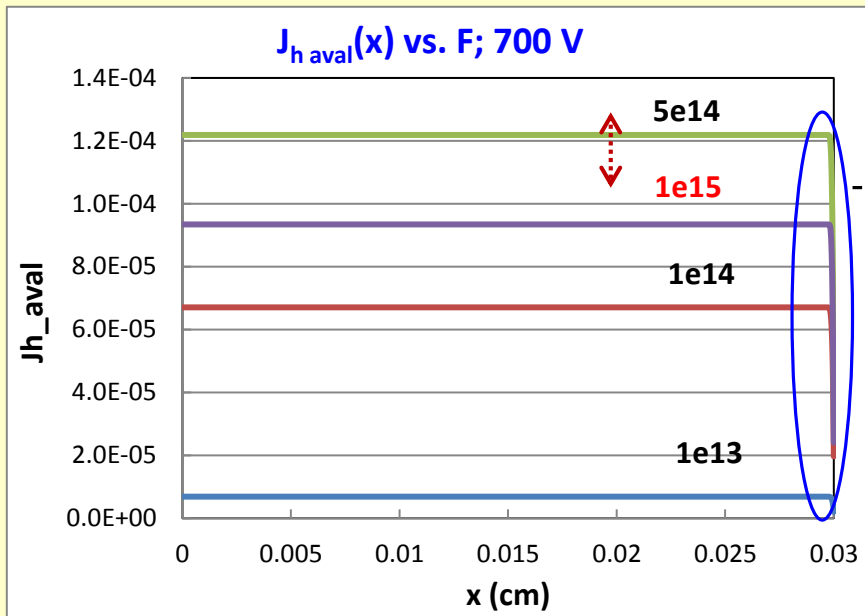- ⛉ Injection leads to potential redistribution and formation of high electric field region near the back contact
- ⛉ $E_{max-b}$ in a built-in $p^+$ layer goes down
- ⛉ Scale of reduction increases with fluence: the higher is the fluence, the lower is $E_{max-b}$
- ⛉ $E_{max\_b}$ drops down/disappears at high $F \sim 5 \times 10^{15}$ n/cm$^2$

# *Hole injection current distribution*



Left chart: $J_{h\,aval}(x)$ vs. F; 700 V — y-axis: Jh_aval; x-axis: x (cm); curves labeled 5e14, 1e15, 1e14, 1e13

Right chart: $J_{h\,aval}(x)$ vs. F; 700 V — y-axis: Jh_aval (A/cm2); x-axis: x (cm); curves labeled 5e14, 1e15, 1e14, 1e13

- Hole injection current – steady-state current of holes originated by impact ionization and drifting towards the back contact
- Holes are trapped on radiation-induces defects, which leads to potential redistribution and reduction of electric field in a buit-in p+ layer and current

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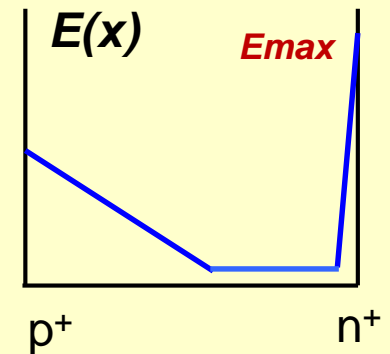# *Mechanism of negative feedback in LGAD*

**strip**
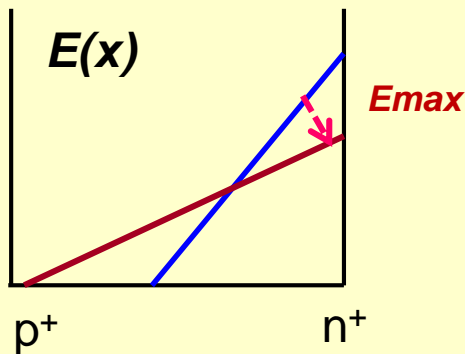
**LGAD**
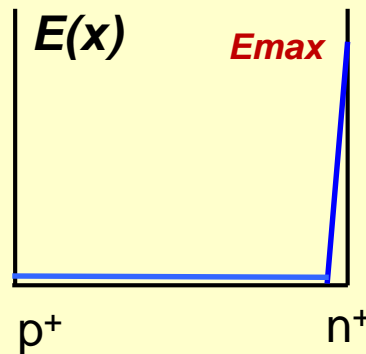


$10^{15}$ $n_{eq}/cm^2$

**LGAD**

E of $>1 \times 10^5$ V/cm is initially (at F = 0) and exists even at low V
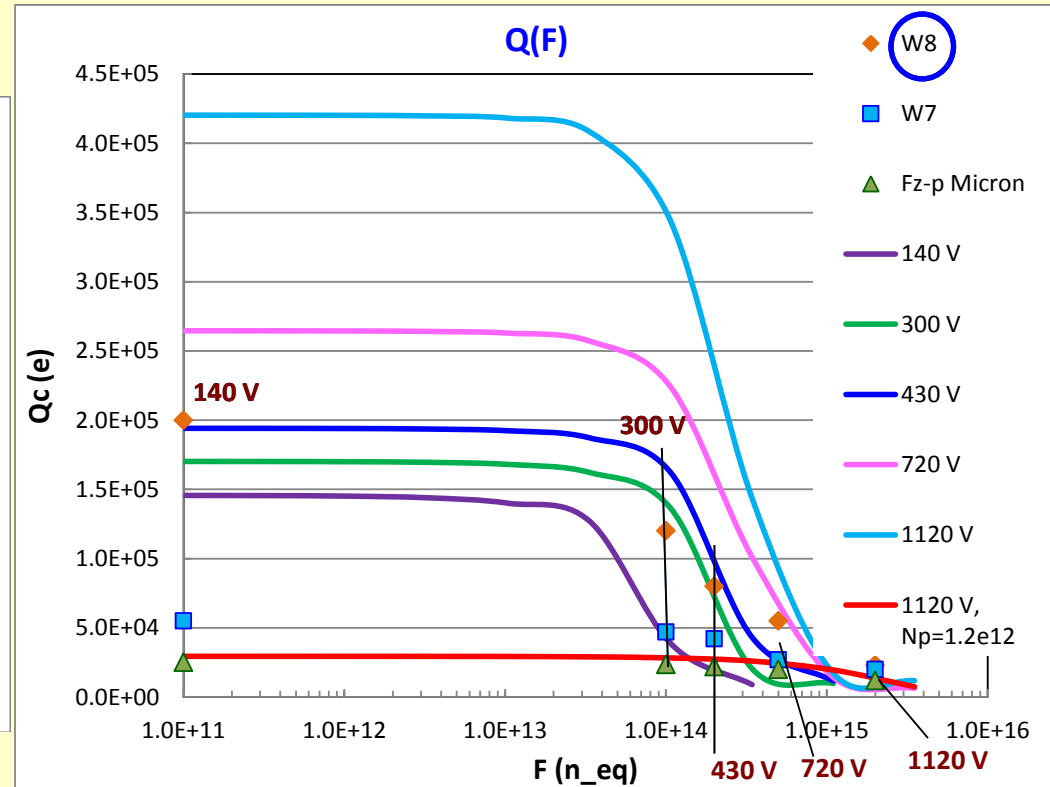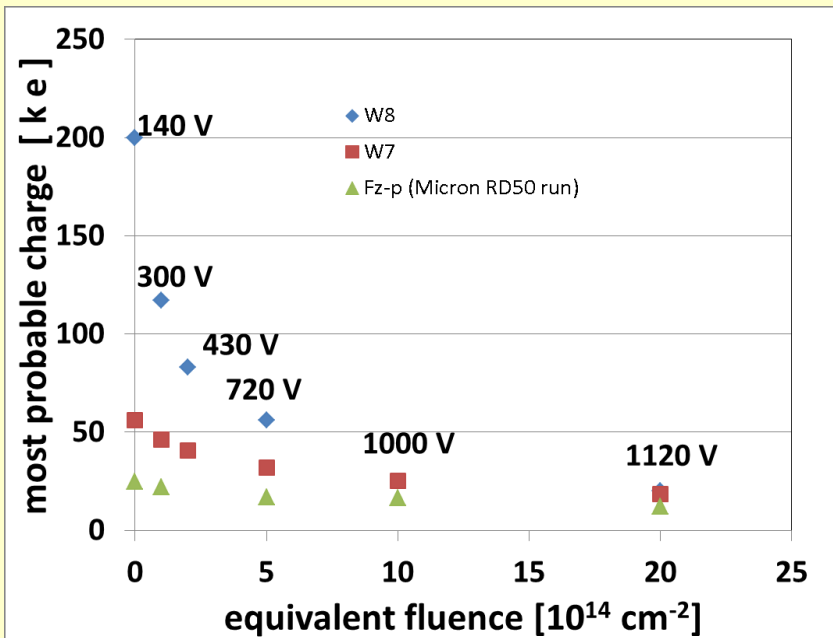
At $10^{15}$ $n_{eq}/cm^2$ high field regions are at both sides and maximal fields are comparable
→ avalanche at back contact, electrons flow to n+, impact ionization, and so on
→ self-consistent process which prevents breakdown

# Collected charge vs. fluence

Experiment for three different LGAD



Agreement is reasonable:
better for W8

Other options are available in the calculations program

# *Conclusions*

1. The factors which affect reduction of the gain in irradiated LGAD:

♦ Reduction of carrier trapping time constants,

♦ Trapping-related negative feedback which leads to:
   - redistribution of potential in LGAD bulk,
   - formation of high electric field region near the back contact
   - reduction of E in a built-in $p^+$ layer.

2. E near the back contact stays sufficient for impact ionization, which increases collected charge with respect to standard diodes.

3. However, this effect can only partially compensate reduction of the field in a built-in layer ➔
**The gain in LGAD is also restricted by negative feedback.**

# *Acknowledgments*

This work was made within the framework of CERN RD50 collaboration and supported in part by:

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*Thank you for attention!*

# PTI model of $Q_c$ enhancement via avalanche multiplication and negative feedback

| Equilibrium carriers | | | | High bias voltage | | Nonequilibrium carriers | | |
|---|---|---|---|---|---|---|---|---|
| source/ origin | process | characteristic /result | | process | characteristic /result | source/ origin | process | characteristic /result |
| Bulk genera- tion current | **Trapping to DLs** | $I_{bgen}$; **steady-state DP $E(x)$** | Junction region with high $E$; focusing | Impact **ioniza- tion**, carrier **injection** into the bulk, **trapping** to DLs | $I_{bgen}$ increase; Change of steady-state DP $E(x) \rightarrow$ **$E$ reduction** near the junction | Gene- rated by parti- cles | **Trapping to DLs during drift in $E(x)$** | $\tau_{tr}(F)$; pulse response, $Q_c$ (CCE) |
| | | | | **Trapping – related negative feedback** | | | | |

E. Verbitskaya,, et al., 27 RD50 workshop, Dec 2-4, 2015, CERN