Novel view on extraction of charge carrier transport parameters from the data of classical TCT

A. Shepelev, V. Eremin. E. Verbitskaya
Ioffe Institute, St. Petersburg, Russia

33rd RD50 Collaboration Workshop
CERN, Geneva, Nov 26-28, 2018

Motivation

TCT **is the unique method for investigation of electric field distribution in** ***heavily irradiated p-i-n*** **structures**

TCT goal:

$$i(t) \rightarrow E(x), N_{eff}(x)$$

Ramo's theorem:

$$i(t) = E_w Q(t) v_{dr}(t)$$

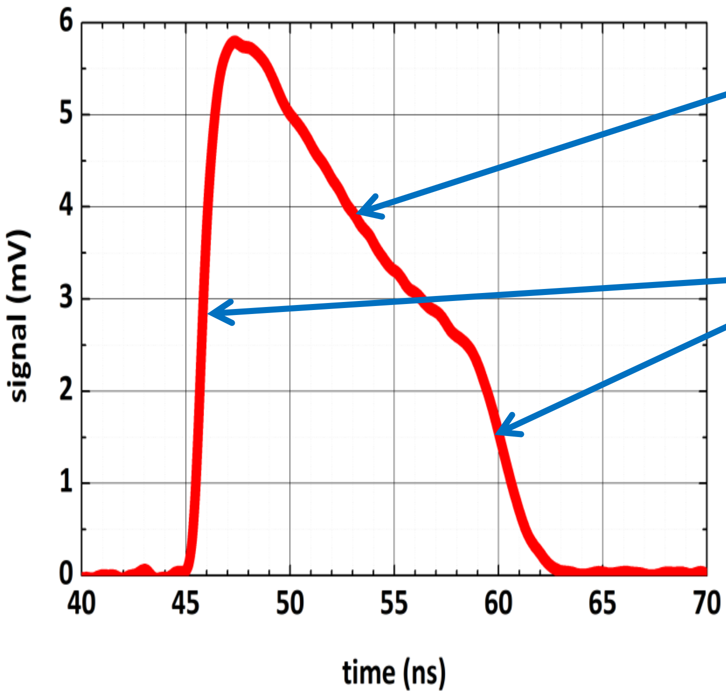
There are some *problems*:
Pulse shape is determined by a combination of a several factors:

- $E(x), \mu(E(x)) \rightarrow v_{dr} = E\big(x(t)\big) \times \mu[E\big(x(t)\big)]$
  Drift velocity is a function of a several variables
- **The charge of drifting carriers is not constant in time** $Q = Q(t)$
  Due to the carrier trapping on deep levels (τ_{tr})
- **Pulse edges distortions**
  Due to the nonuniformity of generated cloud of carriers, diffusion and response of the electric circuit

Outline

- ❖ Motivation
- ❖ Reconstruction of the physical response
- ❖ TCT Signal processing
- ❖ Numerical solution of the system of equations for the electric field
- ❖ Electric field reconstruction in nonirradiated detectors
- ❖ Electric field reconstruction in irradiated detectors
- ❖ Summary

TCT Pulse



Typical TCT pulse of nonirradiated detector

Current induced by electron drift

$$\boldsymbol{i}(t) = \frac{1}{d} \times \boldsymbol{Q}(x(t)) \times \boldsymbol{v}_{\boldsymbol{dr}}(x(t), E(x(t)))$$

Distorted **pulse edges**

*in this case, key condition: $\boldsymbol{Q}\left(\boldsymbol{x}(\boldsymbol{t})\right) \equiv \boldsymbol{Q}_0$

We want to obtain the electric field directly from the experimental data without a priori knowledge and any models

Main equations for Electric field reconstruction

The lateral size of the detector's contacts is much bigger than thickness of sensitive area:
1D geometry

Current response

$$i(t) = \frac{Q(t)}{d} v_{dr}(t)$$

Drift velocity

$$v_{dr}(t) = \mu\big(E(t)\big)E(t)$$

Mobility

$$\mu_{eff}(E) = \frac{\partial v_{dr}(E)}{\partial E}$$

Translation to coordinate scale

$$x(t) = \int_0^t v_{dr}(t')dt'$$

Collected charge

$$Q_0 = \int_0^{t_{dr}} i(t)dt$$

$\tau_{tr} \gg t_{dr}$ only!

Potential difference

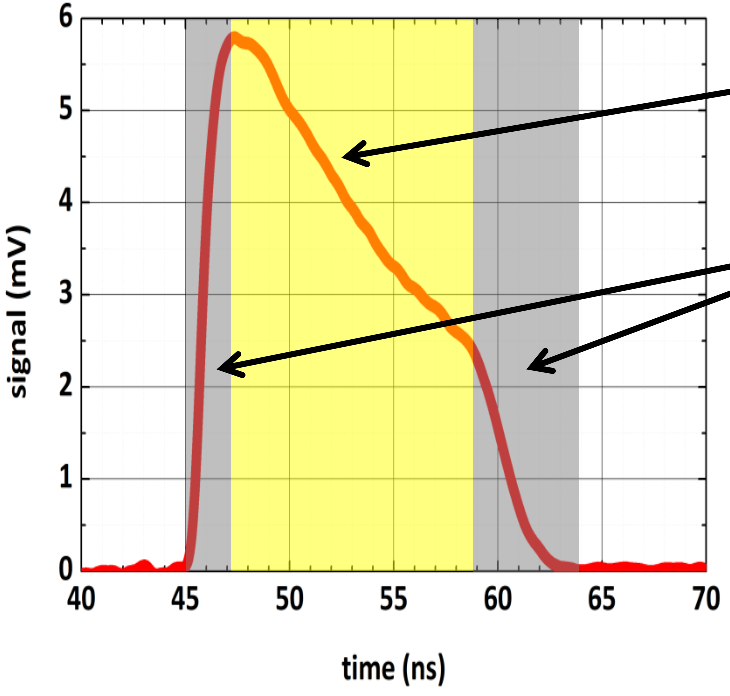
$$\Delta\varphi = \int_0^d E(x)dx = V_{bias}$$

Always!

All we need is solve this system...*but how?*

Simple criteria

Reconstruction of the E(x) in the assumption of negligible carrier trapping



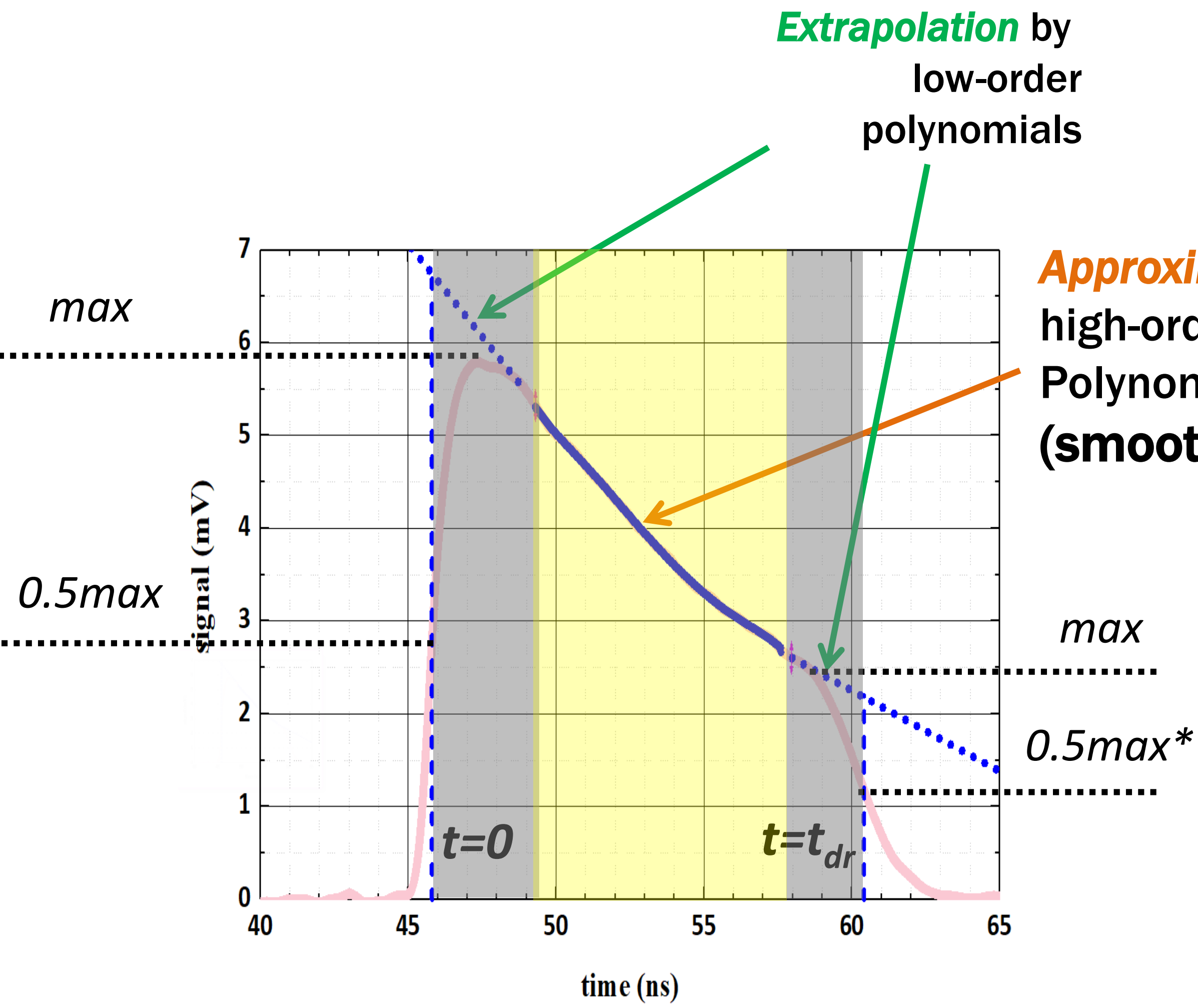
Current pulse response of the full-depleted detector

Gradual current reduction

*Current response shape is **strongly disturbed (gray regions)***

$$\tau_{tr} \gg t_{dr}$$

Data processing: reconstruction of physical response



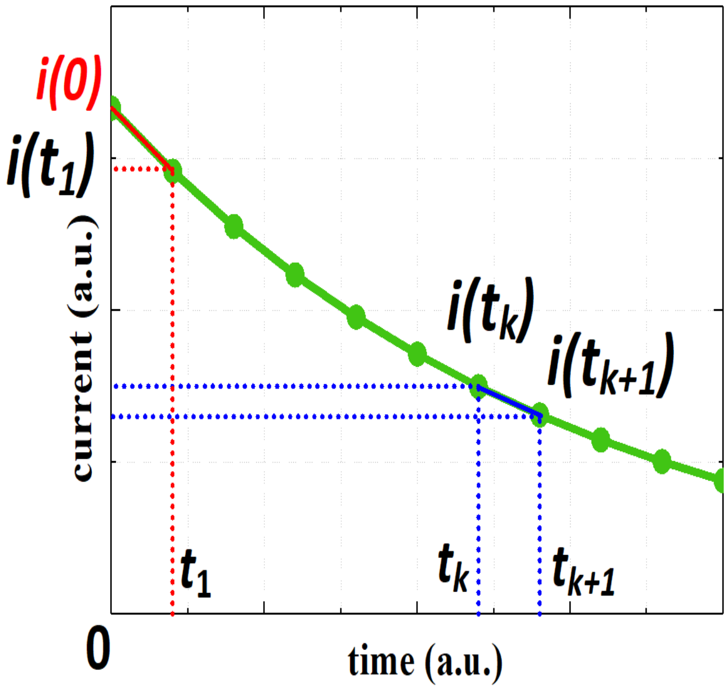
Criterion for the correctness:

$$Q_0^{exp} = Q_0^{phys}$$

In the case of mistake

t_{dr} can be moved

We have the physical response, what's next?



Approach to the reconstruction of the E(x) profile

$$E(0) = \frac{d}{Q_0 \times \mu} \times i(0)$$ **Initial condition**

$$E_{k+1} = \frac{d}{Q_0}[i(t_{k+1}) - i(t_k)]\mu_{eff}(E_k) + E_k,$$

$$k = 0 \ldots . N-1, \qquad t_N = t_{dr}.$$

$$x_k(t_k) = \int_0^{t_k} v_{dr}(t)dt \,,$$

N.B. $\mu_{eff} = const$ in the interval $[i_k, i_{k+1})$

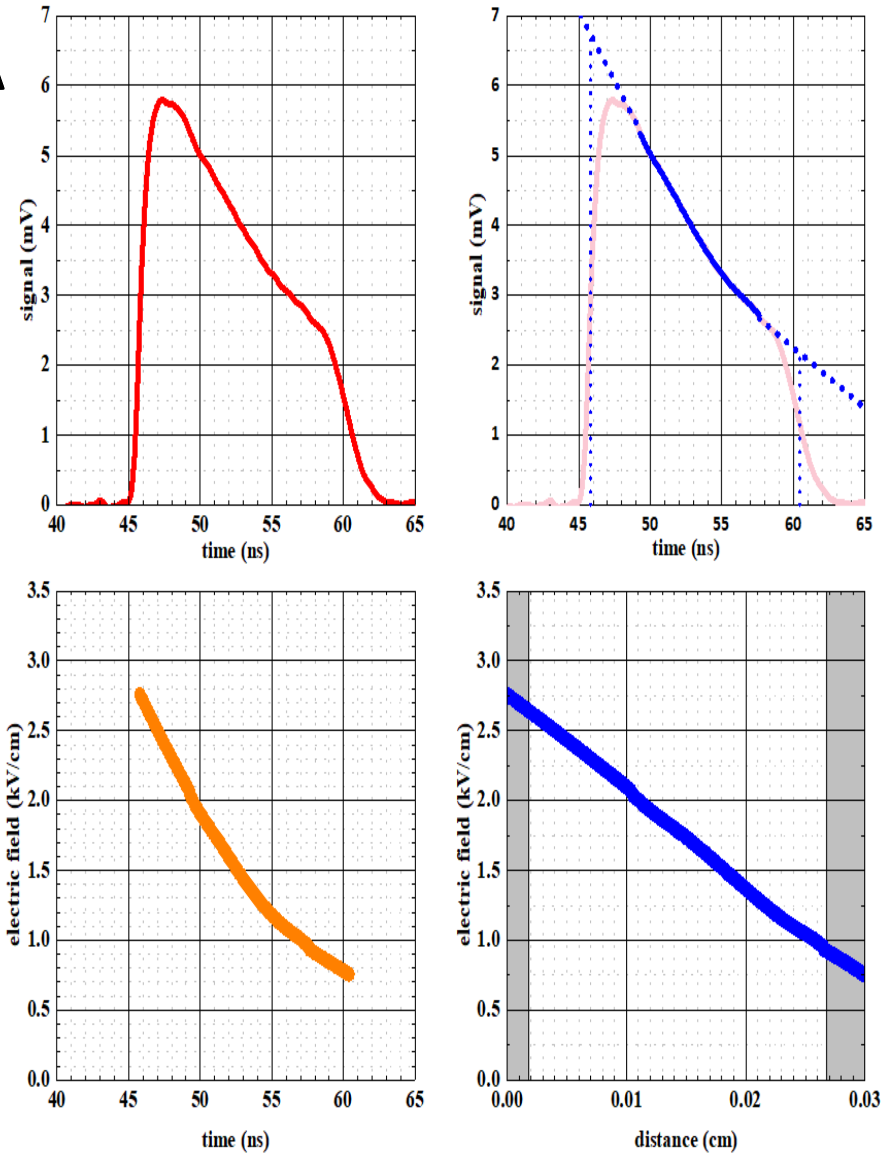
Reconstruction of E(x)

DATA

Physical response

E(t)

E(x)



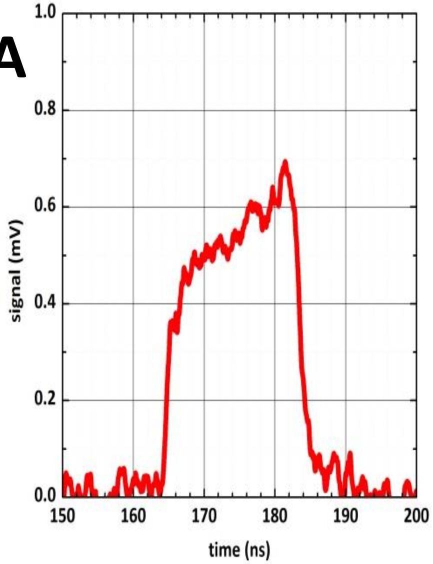
Correctness test:

$$\Delta\varphi = \int_0^d E(x)dx = 52.2\,V$$

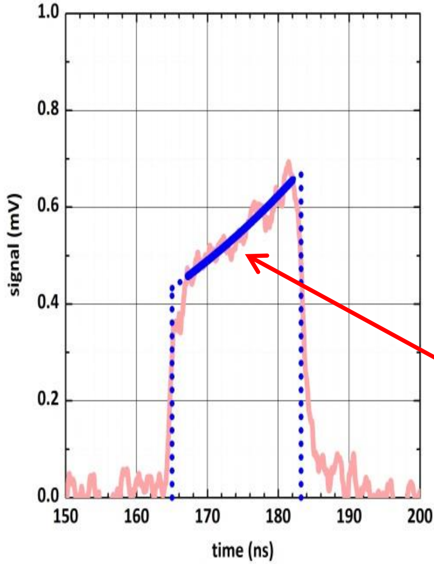
only 4% larger than applied bias of 50 V

Hole current response

DATA

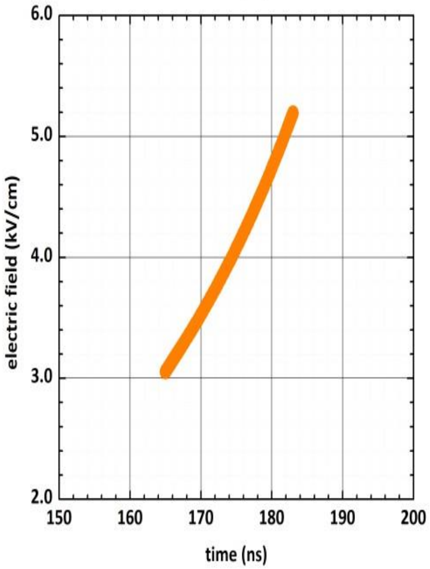


Physical response

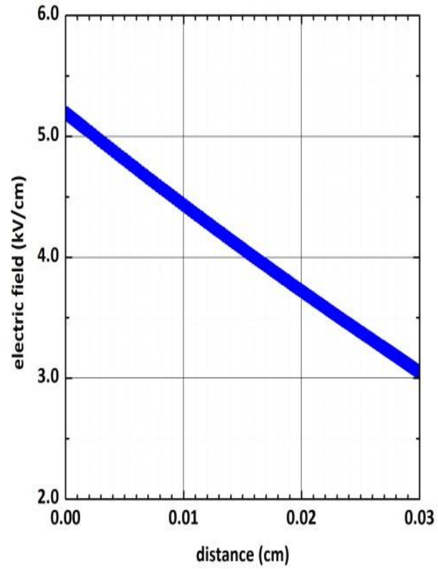


In this case, the correctness of smoothing is ***really important*** ***(suppression of fluctuations produced by noise)***

E(t)



E(x)



Correctness test:

$$\Delta\varphi = \int_0^d E(x)dx = 101.3\ V$$

only 1% larger than applied bias of 100 V

Effective concentration

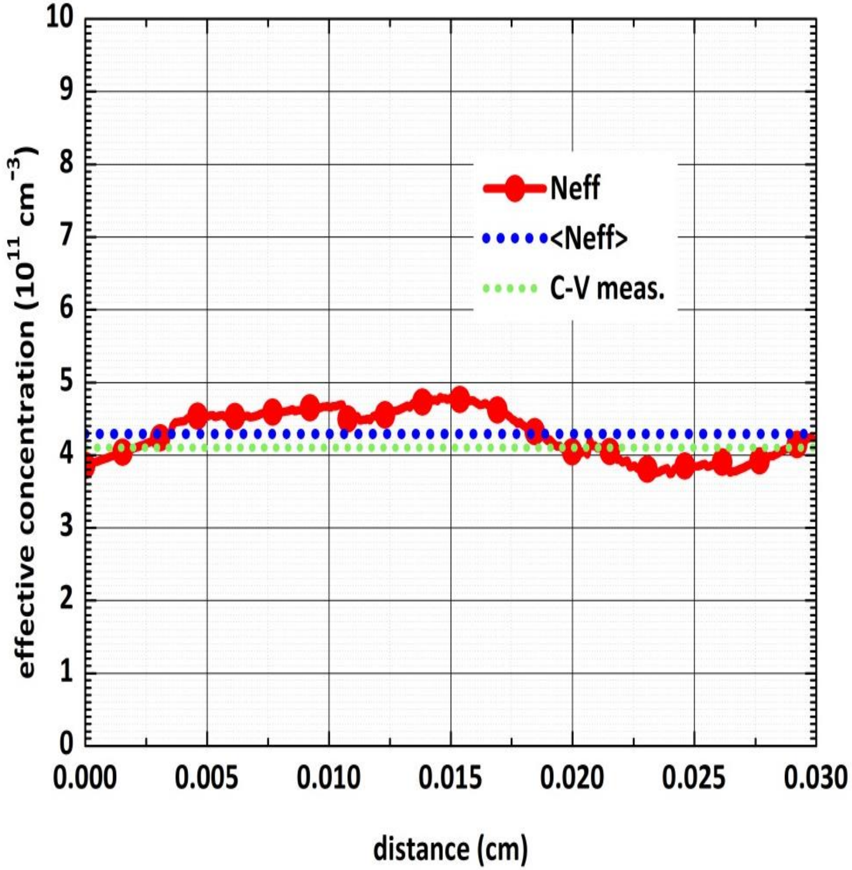
Poisson's eq.

$$E(x) \longrightarrow N_{eff}(x)$$

Method	Electron current response	Hole current response	C-V
N_{eff} (10^{11} см$^{-3}$)	4.3	4.0	4.1

Accuracy: σ = 5%!

The profile of the effective concentration is close to uniform



Carrier trapping

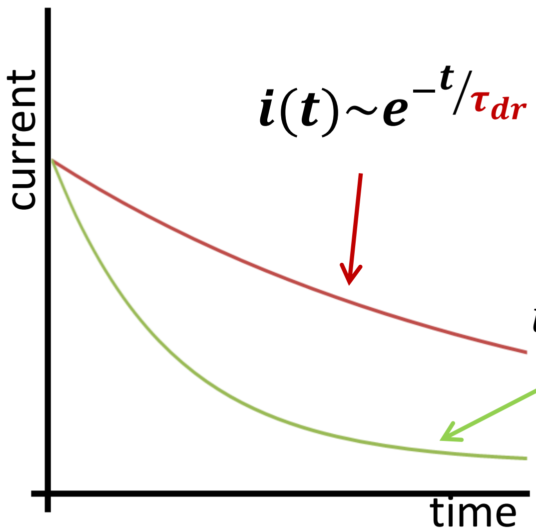
In irradiated *Si* detectors, the drifting charge decreases with time due to carrier *trapping* on the deep levels ☹

$$\frac{1}{\tau_{tr}} = \beta \times F$$

Trapping time constant — Proportionality constant — Fluence

$$i(t) \sim e^{-t/\tau_{dr}}$$

$$i(t) \sim e^{-t/\tau_{tr}} + e^{-t/\tau_{dr}}$$



However, the same procedure is applicable

TCT signal processing:

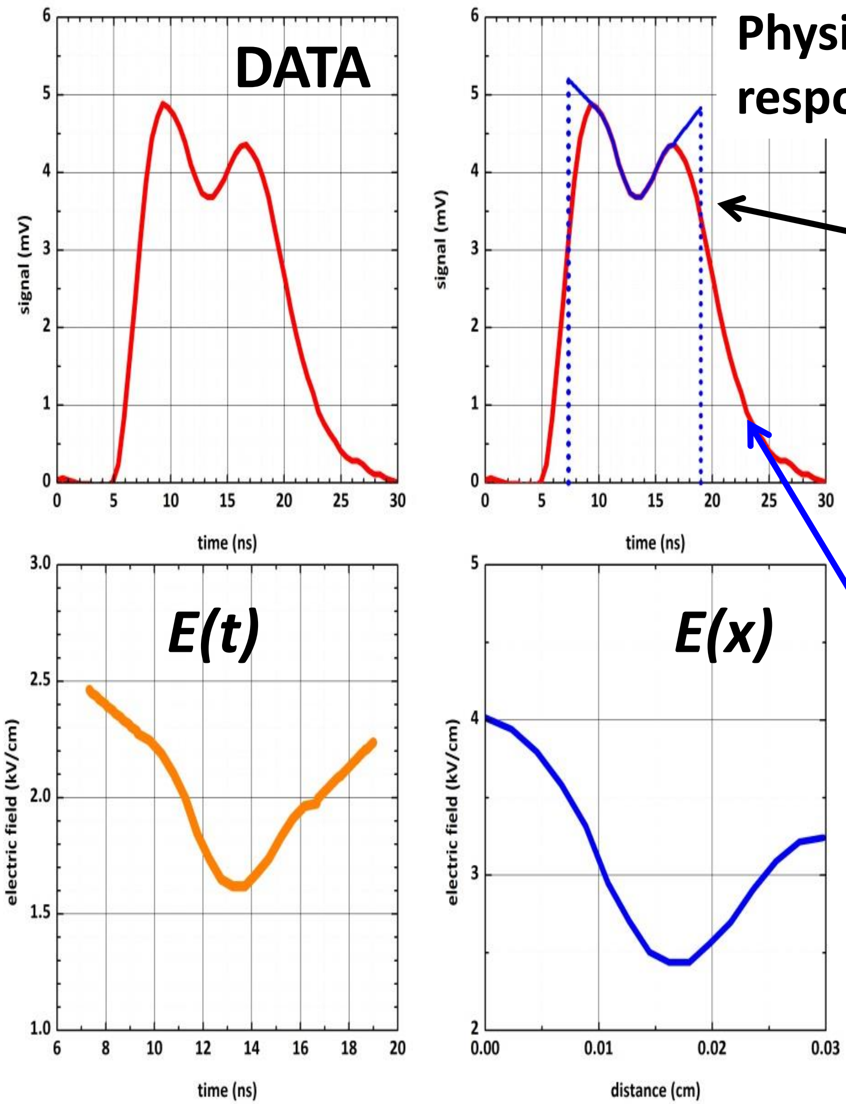
$$E_{k+1} = \frac{d}{Q_0 \exp(-\frac{t_{k+1}}{\tau_{tr}})}[i(t_{k+1}) - i(t_k)]\mu_{eff}(E_k) + E_k,$$

$$k = 0 \ldots . N-1, \qquad t_N = t_{dr}.$$

N is the number of experimental points

Different processes have a *similar effect* on the pulse shape !

The same steps to the E(x) reconstruction



In this case, ***we can't*** use a criterion of Q_0 and only $\Delta\varphi$ **isn't affected by charge trapping!**

$$d = \int_0^{t_{dr}} v_{dr}(t)dt$$

$$\int_0^{\int_0^{t_{dr}} v_{dr}(t)dt} E(x)dx = 80\,V \rightarrow t_{dr} = 12\,ns!$$

t_{dr} is not on the level of half-amplitude!

The long tail in the response is not connected with the carrier drift and can be explained by the fast trapping/detrapping.
The criterion of potential difference shows it!

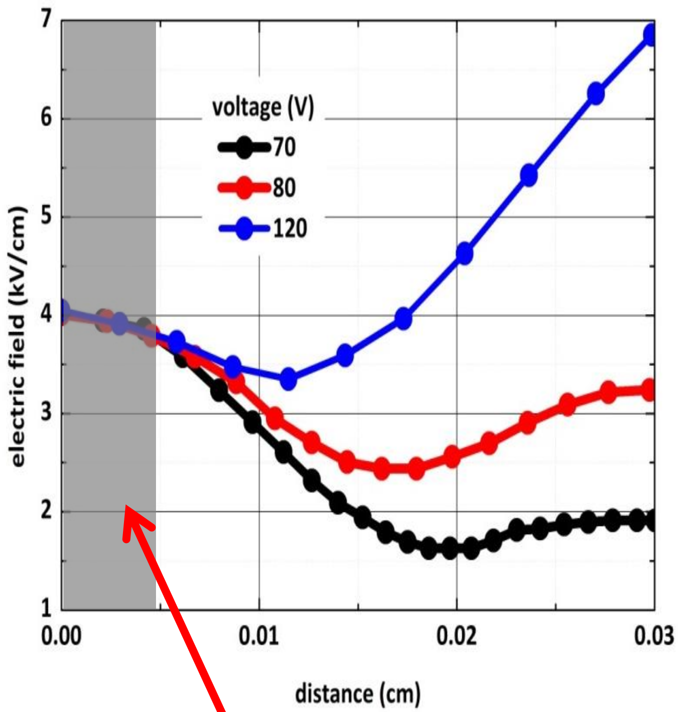
Irradiated Si detector

$p^+/n/n^+$ pad detector
$d = 300\ \mu m$
$N_D = 5 \times 10^{11} cm^{-3}$

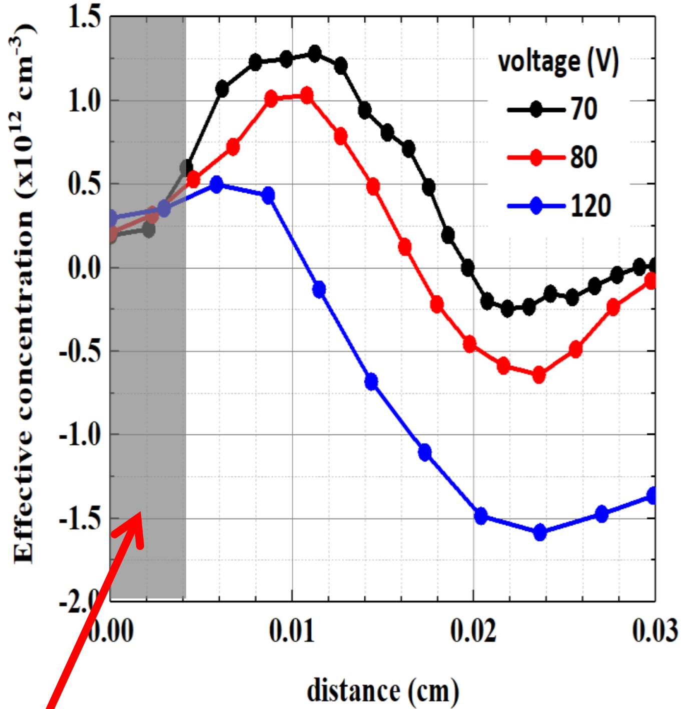
Irradiated by protons
$F = 4 \times 10^{14} cm^{-2}$

The described **algorithm was applied** for the treatment of pulse series recorded for the detector operated at **different bias voltages**

Electric field



Effective concentration



Area of uncertainty (area of extrapolation)

Summary

- The new approach is proposed for obtaining the $E(x)$ and $N_{eff}(x)$ from TCT data. It based on the reconstruction of physical response and numerical solution of the system of transport equations.
- In the case of nonirradiated detector, $E(x)$ and $N_{eff}(x)$ were obtained. They are close to uniform and their mean values equal with 5% accuracy to the results of the C-V measurements.
- The described algorithm was applied to responses of irradiated detectors. In this case, temporal resolution and pulse approximation is critical.

Thank you for attention!