Space charge sign inversion and electric field reconstruction in 24 GeV proton irradiated MCZ Si p^+-n(TD)-n^+ detectors processed via thermal donor introduction

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Outline

1. Background: specific features/advantages of p-type Si for development of radiation-hard detectors

2. Experimental: samples; measurement technique

3. Experimental results on TCT pulses after 24 GeV/c proton irradiation: **SCSI in p^+-n(TD)-n^+ detectors**

4. Approach for simulation of detector Double Peak response and E(x) profile reconstruction with a consideration of electric field in the “neutral” base

5. New method for E(x) reconstruction

6. Results on E(x) reconstruction in protons irradiated p^+-n(TD)-n^+ detectors

7. Comparison of E(x) profile reconstructed from TCT data and E(x) profile simulated with a consideration of carrier trapping

Conclusions

Specific features and advantages of p-type Si for development of radiation-hard detectors

Recently development of Si detectors based on the wafers from p-type Magnetic Czochralski (MCZ) silicon became an attractive way for radiation hardness improvement [1]. The main advantage is that the major signal arises from electron collection which leads to efficient detector operation [2], and the detector is non-inverting after irradiation. Along with this, a single sided process can be used to fabricate n^+-p-p^+ detectors that facilitate device fabrication.

1. J. Härkönen et al., Proton irradiation results of p^+-n-n^+ Cz-Si detectors processed on p-type boron-doped substrates with thermal donor-induced space charge sign inversion, NIM A 552 (2005) 43-48.

2.G. Casse et al., NIM A 518 (2004) 340.

Experimental

- **Samples**:

p-type MCZ Si, as-processed p^+-p-n^+ structure (processed at HIP)

Treatment:

annealing at 430 C, Thermal Donor (TD) introduction ➔

Conversion to p^+-n(TD)-n^+

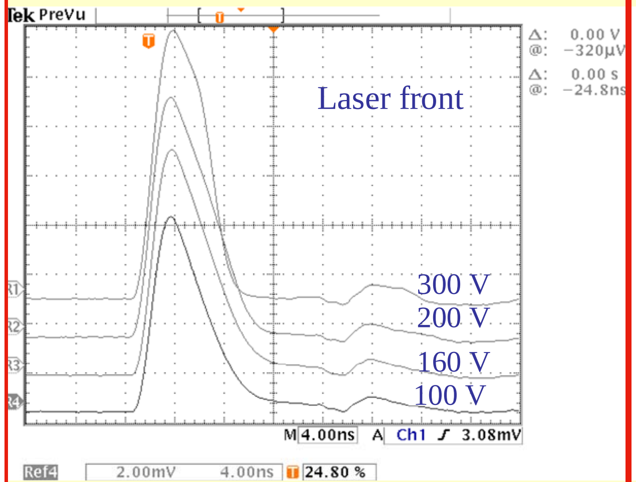
Irradiation: 24 GeV/c protons at CERN PS ***(Thanks to Maurice!)***
7 fluences ($8{\cdot}10^{12}$ p/cm^2 to $5{\cdot}10^{14}$ p/cm^2)

- **Experimental technique**: TCT (measured at BNL and PTI)

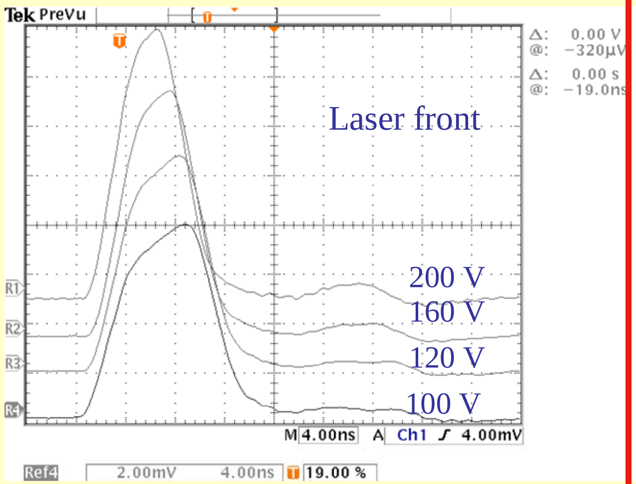
V. Eremin, N. Strokan, E. Verbitskaya and Z. Li, NIM A 372 (1996) 388-298

SCSI in MCZ p^+-n(TD)-n^+ detectors

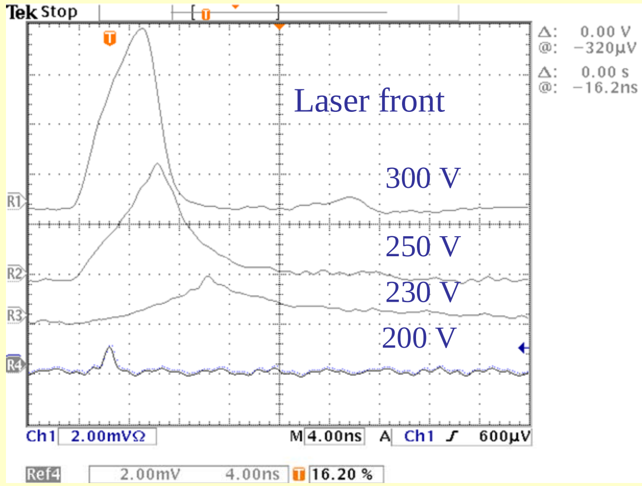
SC +



SC – (SCSI)



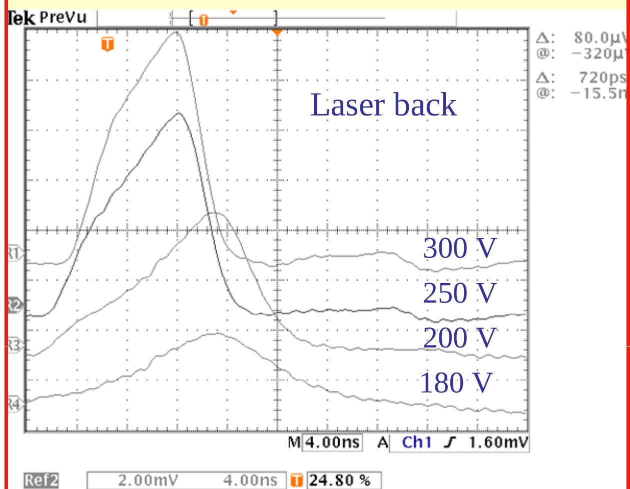
SC – (SCSI)

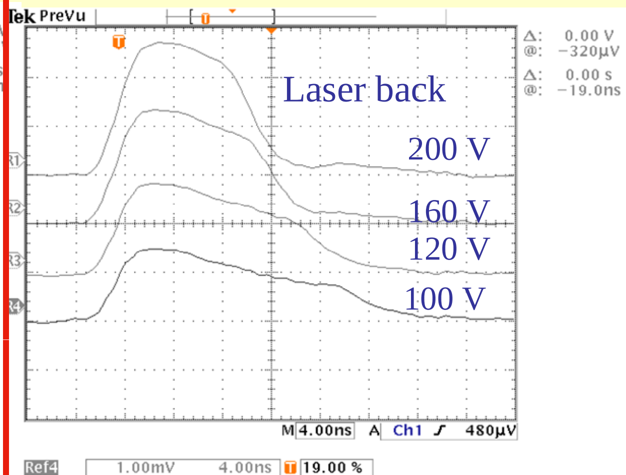


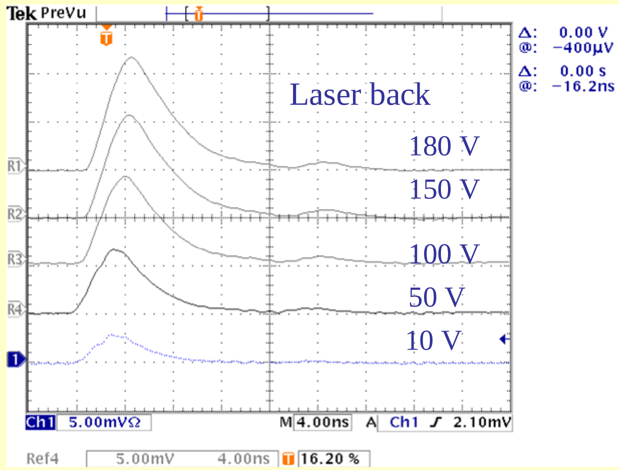
8x10^{12} p/cm^2

2x10^{13} p/cm^2

6x10^{13} p/cm^2

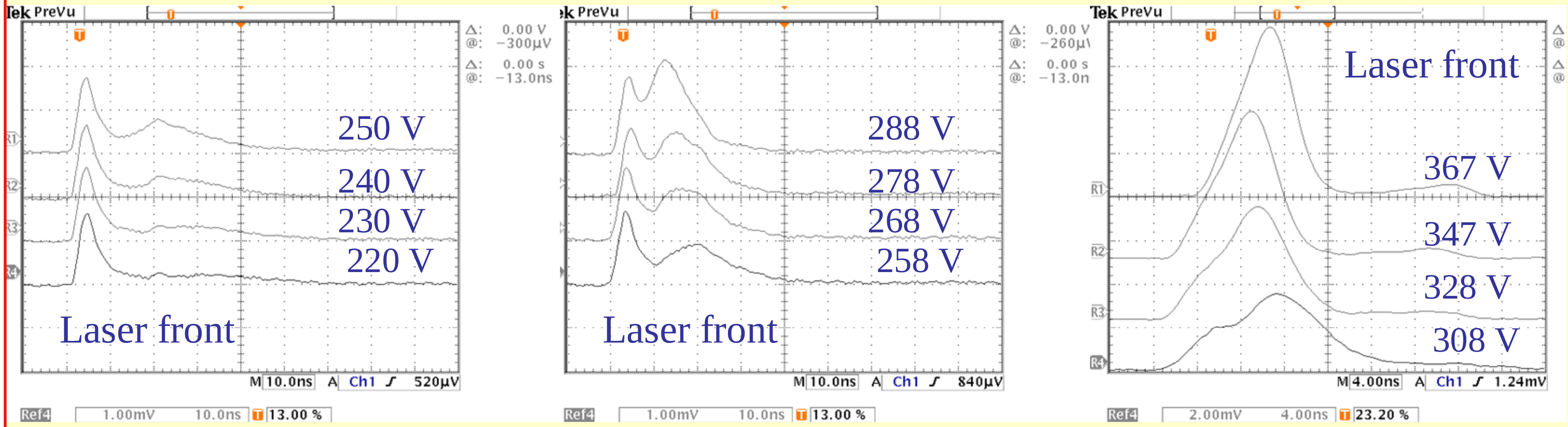


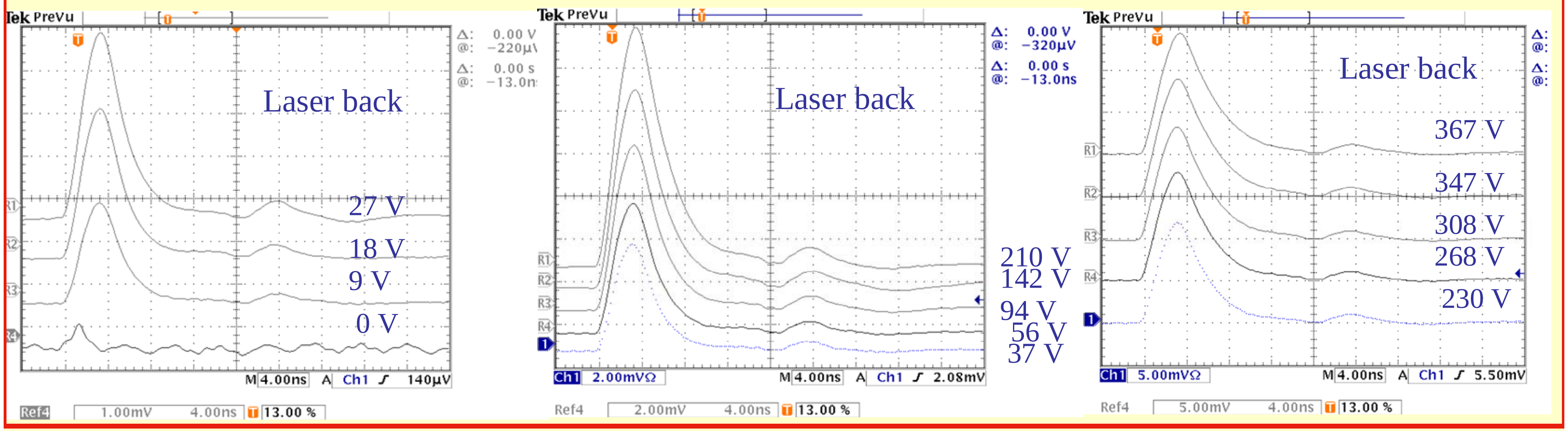




SCSI in MCZ p^+-n(TD)-n^+ detectors

2.14×10^{14} p/cm^2 DP, SC - (SCSI)

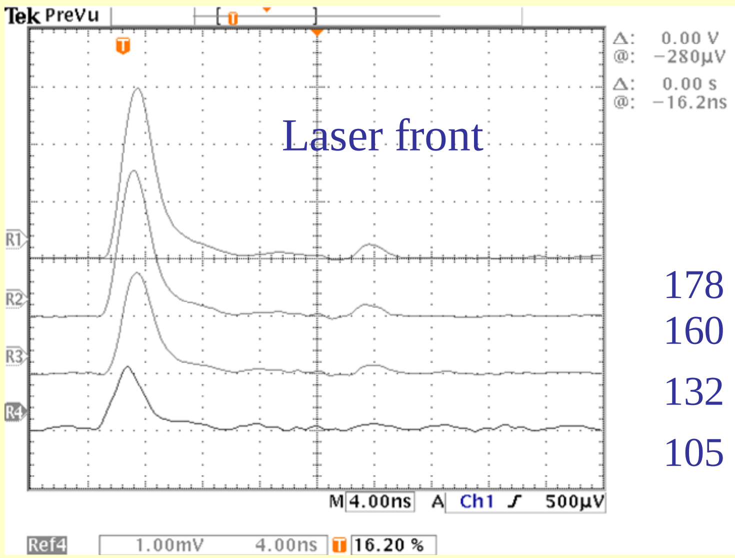




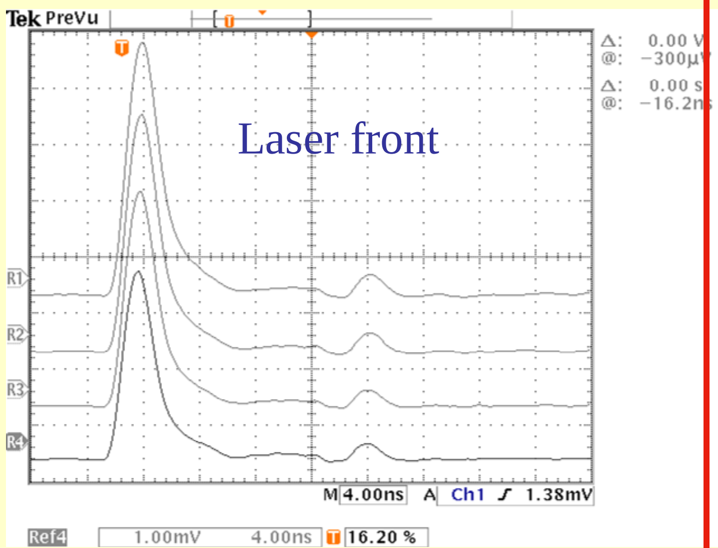
SCSI in MCZ p^+-n(TD)-n^+ detectors

4.2x10^{14} p/cm^2 DJ, SC - (SCSI), symmetrical TCT pulses

87 V
69 V
43 V
18 V



178 V
160 V
132 V
105 V



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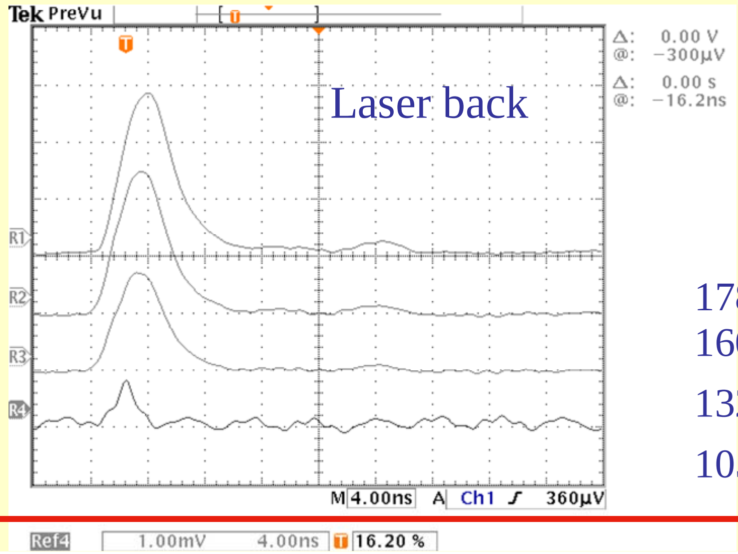

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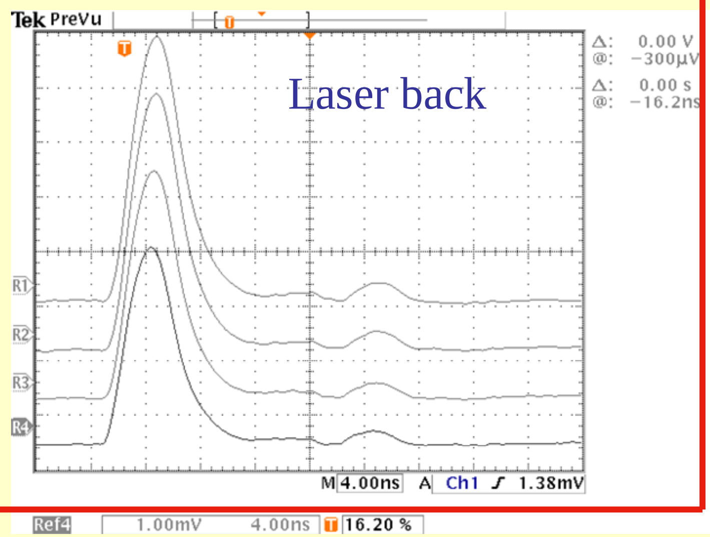
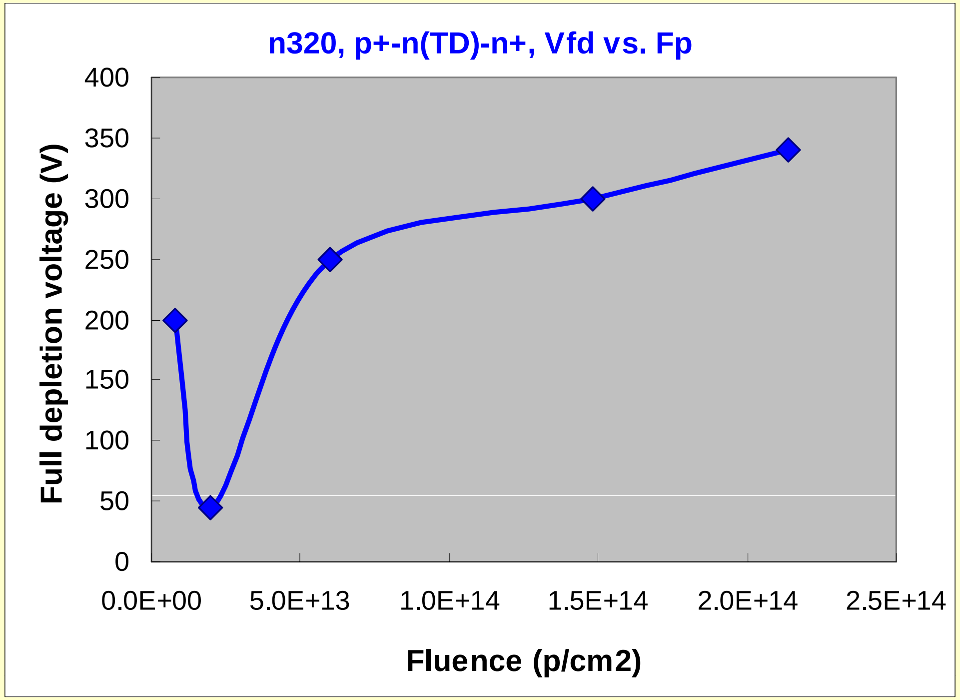


V_{fd} vs. F_p dependence

#	Fp (cm-2)	SC	V_fd (Q_V)
47	8.00E+12	positive	200
49	2.00E+13	negative	45
15	6.00E+13	negative	250
59	1.48E+14	DP to (-)	300
69	2.14E+14	DP to (-)	340
26	4.18E+14	DJ	
48	5.05E+14	DJ	

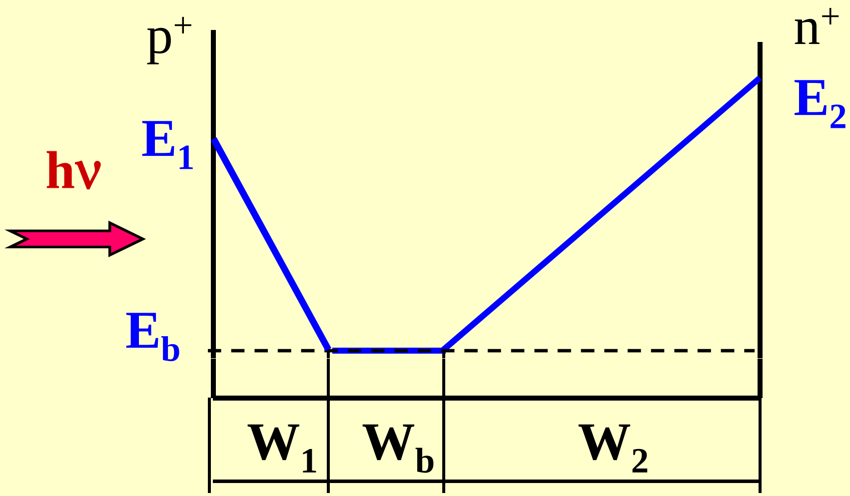


Approach for simulation of detector Double Peak response and E(x) profile reconstruction with a consideration of electric field in the "neutral" base

Initiated by PTI, developed in:

1) E. Verbitskaya et al. NIM A 557 (2006) 528;
2) E. Verbitskaya, pres. RESMDD'6, NIM A (in press)

- Three regions of heavily irradiated detector structure are considered
- **Reverse current flow creates potential difference and electric field in the neutral base**



Transient current:

$$i(t) = \frac{Q_o \mu E}{d} e^{-t/\tau_{eff}}$$

$$\tau_{tr} = \frac{1}{\sigma v_{th} N_{tr}} \qquad N_{tr} = f(F)$$

New method for DP E(x) profile reconstruction

Developed at BNL

Method:

- based on three region model;
- describes induced current pulse arisen from carrier drift

$$i(t) = \frac{Q_o v_{dr}}{d} \exp(-t/\tau_t) \qquad v_{dr} = \frac{\mu E(x)}{1+\mu E(x)/v_s}$$

- initial extraction of charge loss due to trapping ➔ "corrected" pulse response

$$i(t)_{corrected} = i(t) \cdot \exp\left(t/\tau_t(F_{neq})\right) = \frac{Q_o v_{dr}}{d}$$

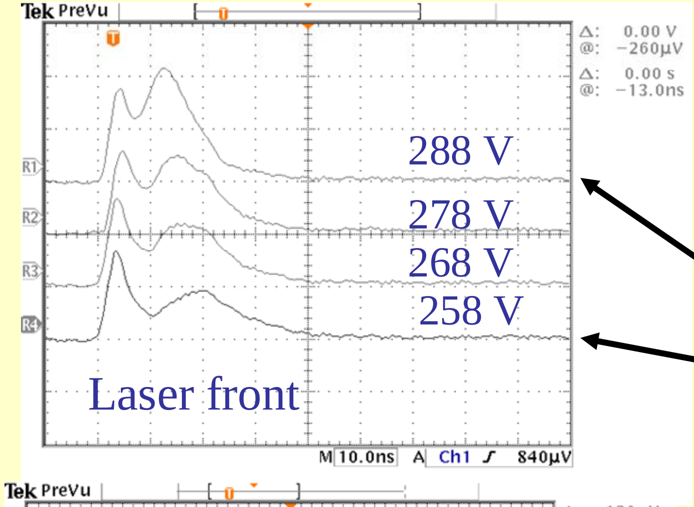
$\tau_t(F)$ – known from reference data (e.g. H.W. Kraner et al, NIM A326 (1993) 350-356, and G. Kramberger et al., NIM A481 (2002) 297)

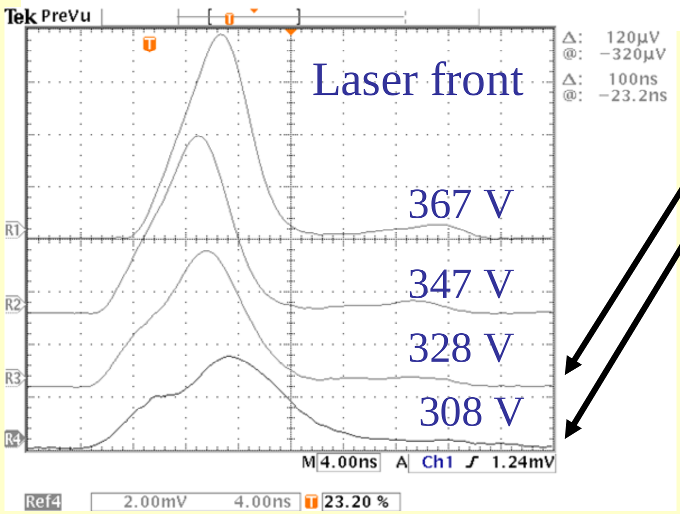
- fitting of the "corrected" current pulse response ➔
  best matches the "corrected" current pulse response in:

1) the heights of the two current pulse peaks;
2) the shape and position of the minimum;
3) the time interval between the two current pulse peaks.

Results on E(x) reconstruction in proton irradiated p^+-n(TD)-n^+ detectors: proof of SCSI

Laser front (p^+), e





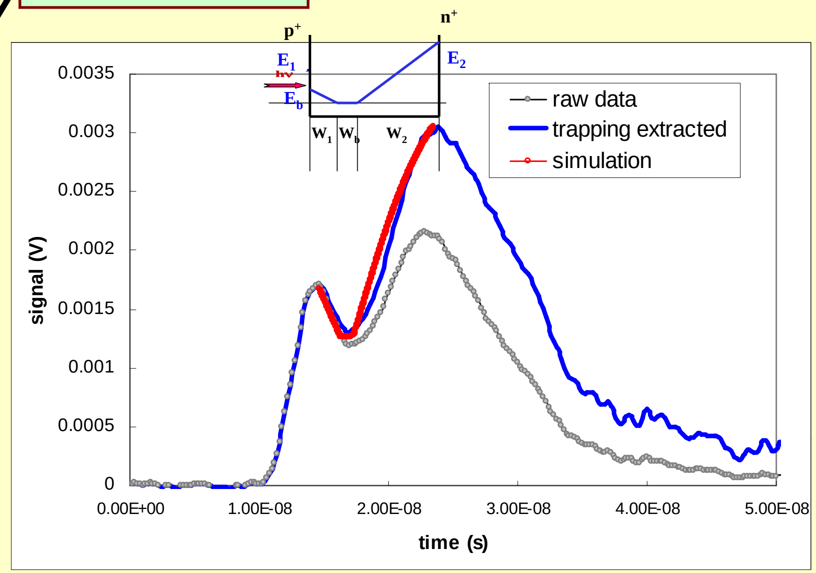
N320-69

$F_p = 2.14 \cdot 10^{14}$ cm^{-2}

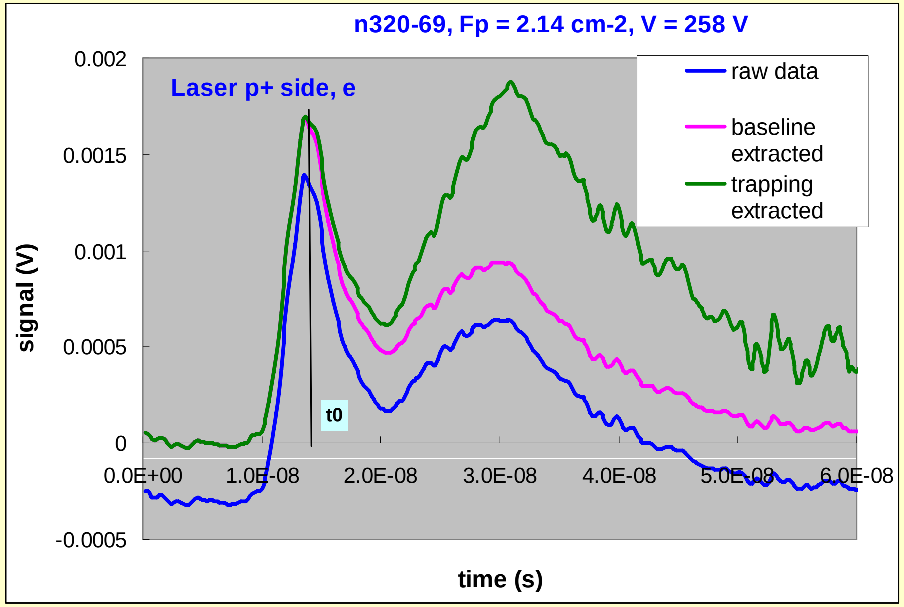
E(x) reconstruction is made for DP pulses

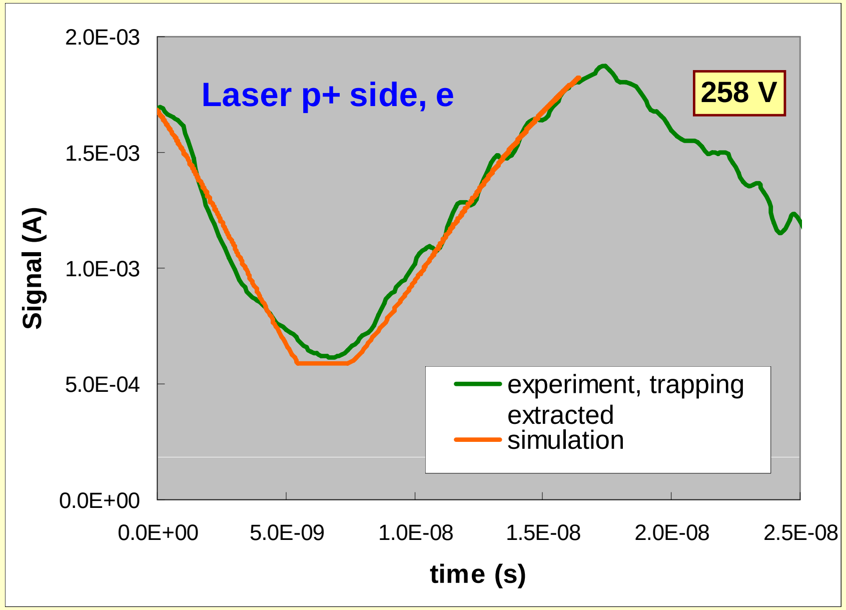
It gives the final proof of the sign of space charge (N_{eff})

Responses to be simulated



Procedure of E(x) reconstruction





Variable parameters:
E_1, E_2, E_b
W_1, W_b

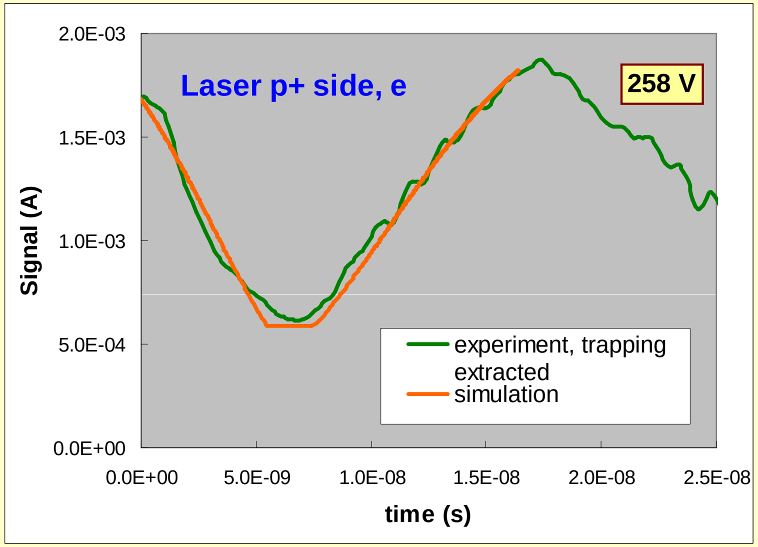
$$d = W_1 + W_b + W_2$$

$$\int E dx = V$$

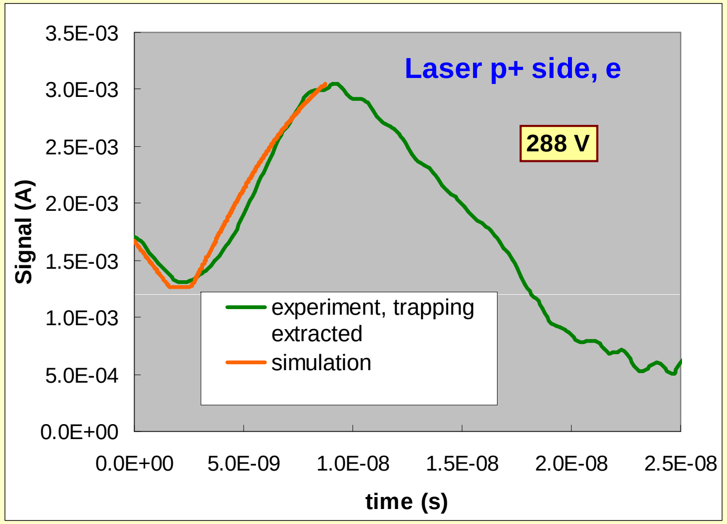
Fits of current pulse response at increasing bias voltage

N320-69
$F_p = 2.14 \cdot 10^{14}$ cm^{-2}

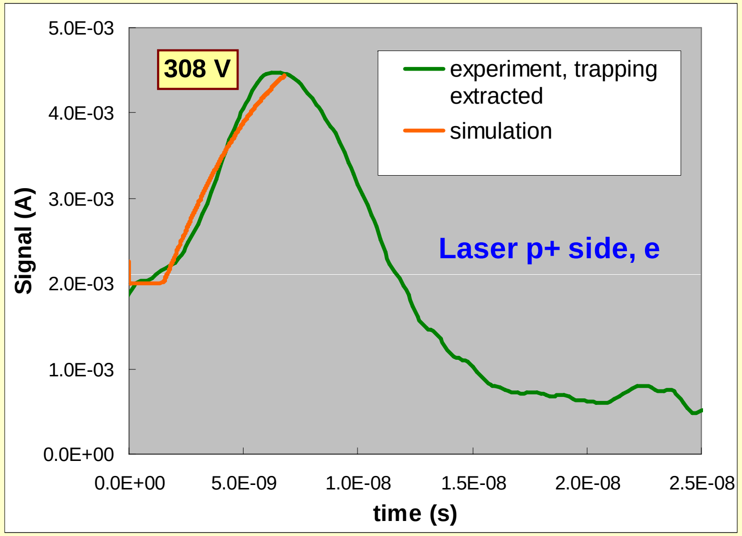
1



2



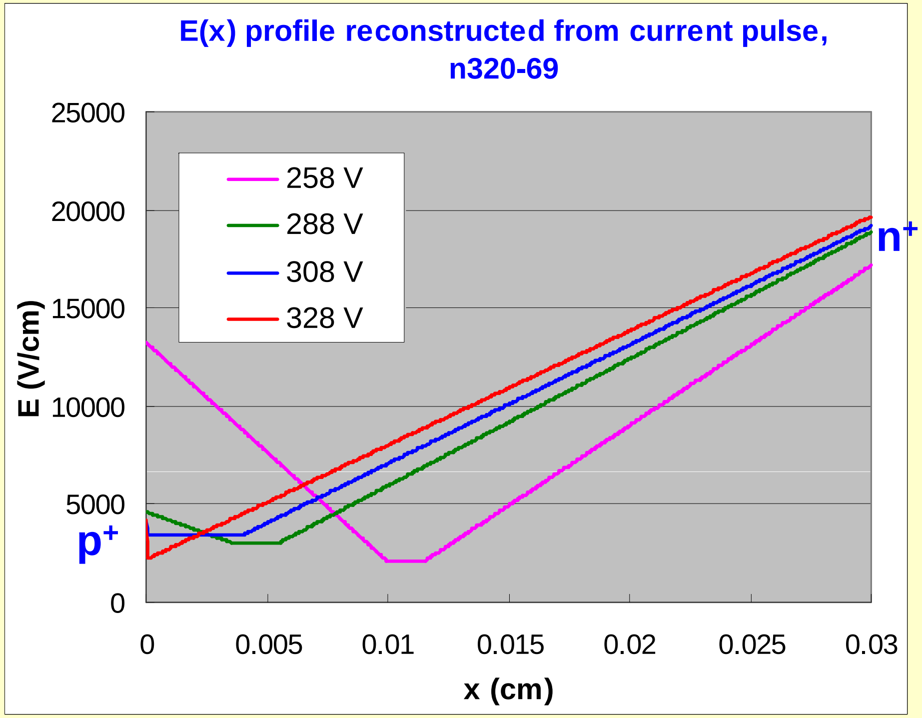
3



τ_t = 25 ns

Fits may be done:
- starting from pronounced Double Peak pulse shape
- up to its conversion to Single Peak Shape

Evolution of E(x) profile at increasing bias voltage



$F_p = 2.14{\cdot}10^{14}$ cm^{-2}

- At lower V maximal E is near the n$^+$ contact, and $W_2 \approx 2W_1$
- This asymmetric distribution becomes enhanced at higher V.
- Finally, positively charged region is immersed by a region with negative charge.

Simulation of DP E(x) profile with a consideration of carrier trapping to midgap energy levels: *E(x) and $N_{eff}(x)$ vs. V*

Parameters:

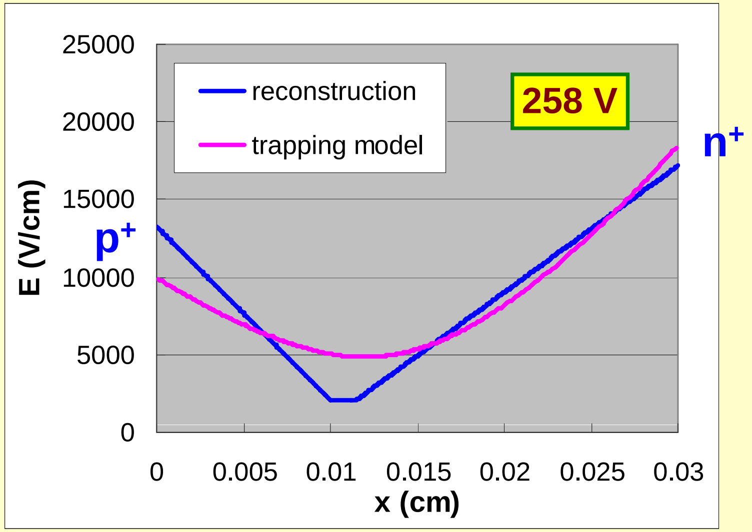
E. Verbitskaya
pres. RESMDD'6, NIM A (in press)

- introduction rate of generation centers m_j
- introduction rate of midgap deep levels, DA and DD
- concentration ratio $k = N_{DA}/N_{DD}$
- bias voltage V
- temperature T
- detector thickness d
- initial resistivity (shallow donor concentration N_o)

midgap DLs: ***DD**:* $E_v + 0.48$ *eV* — *simulation is based on*
DA: $E_c - 0.52$ *eV* — Shockley-Read-Hall statistics

Comparison between E(x) profile reconstructed from current pulse response and E(x) profile simulation considering thermal carrier trapping to midgap DDs and DAs

1



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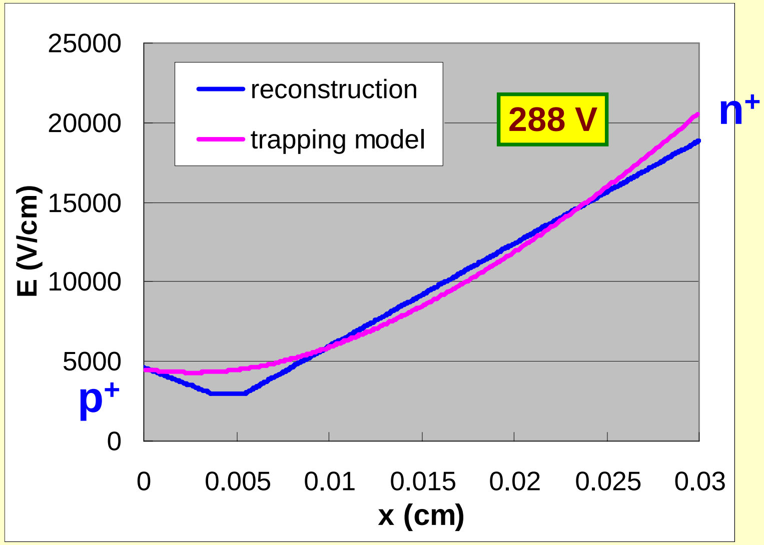
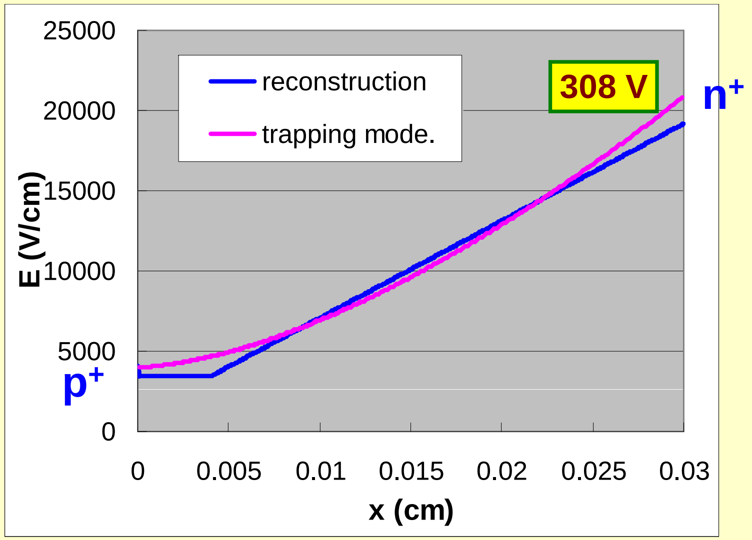


3

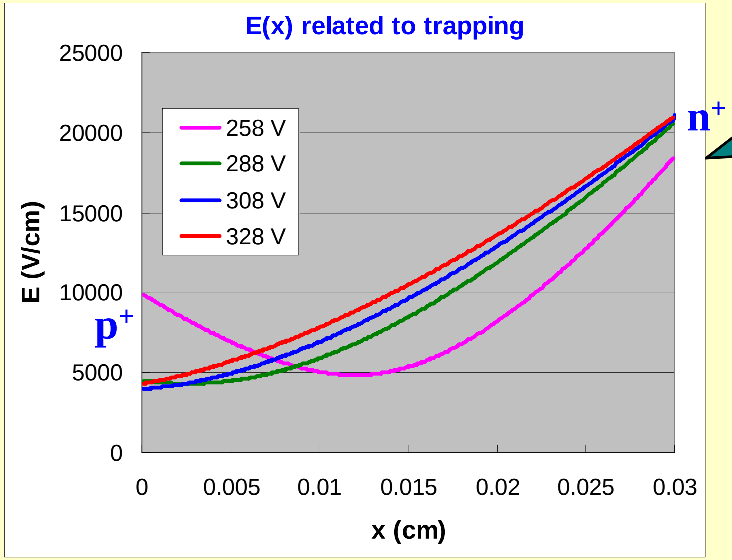


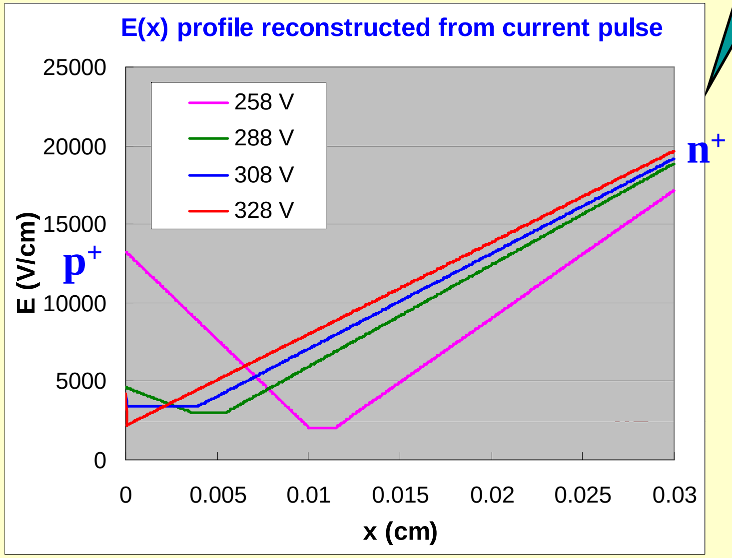
Boundary condition for simulation: electric field at the p^+ and n^+ contacts equals to the electric field obtained from E(x) reconstructed from TCT pulses

Good agreement between two profiles

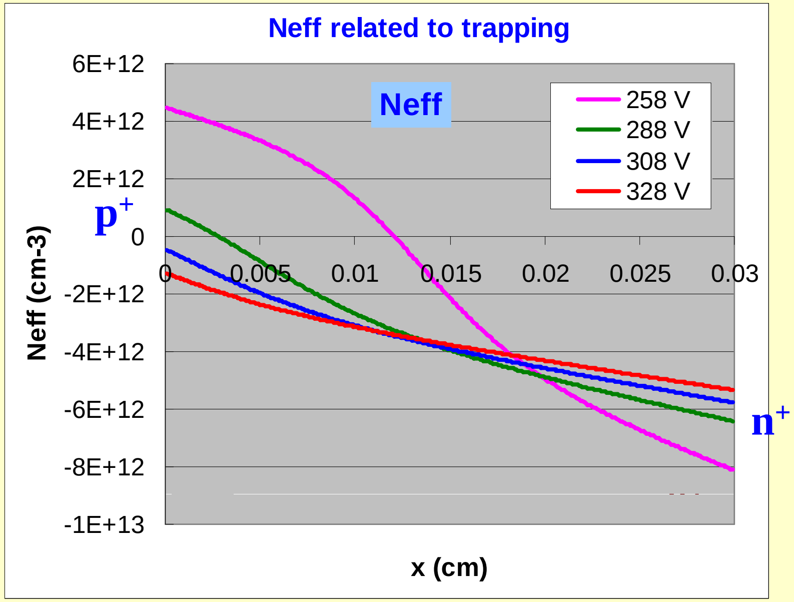
E(x) and N_{eff}(x) simulated considering free carrier trapping to midgap DDs and DAs

n320-69





Good agreement between E(x)



At V ≈ 300 V negatively charged region W_2 extends over the total detector thickness

Conclusions

SCSI does occur in 24 GeV/c proton-irradiated p^+n(TD)-n^+ MCZ detectors!

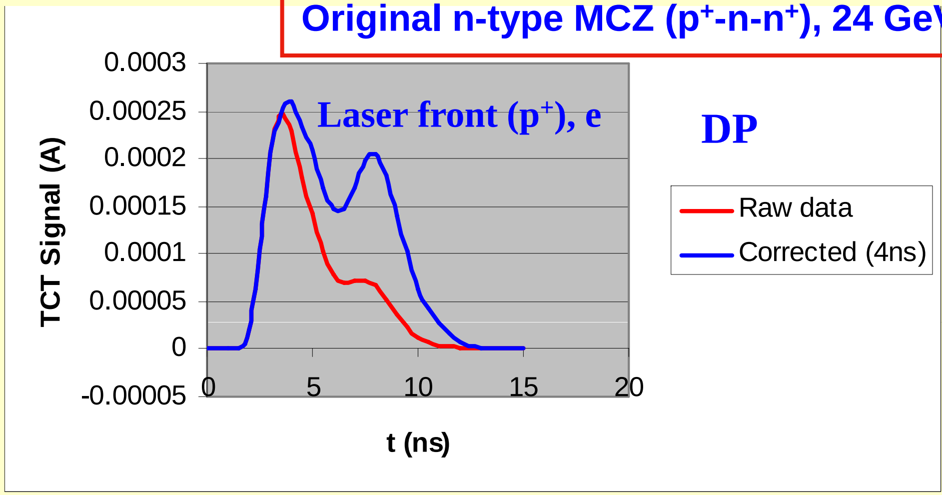
– similar to n-type FZ and DOFZ Si

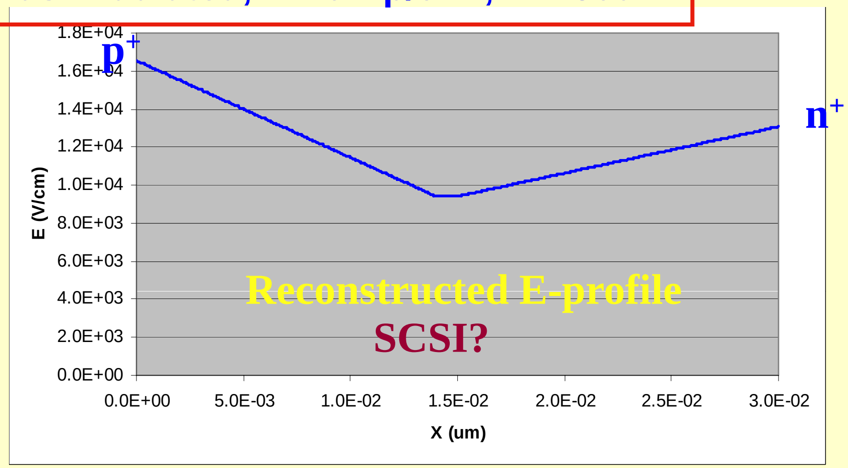
This finding reverts us to the “puzzle” of space charge sign in 24 GeV proton irradiated n-type MCZ Si detectors –

whether there is a dependence on the sample pre-history?

New method of E(x) reconstruction in heavily irradiated Si detectors allows to get nice agreement between experimental “corrected” response independent on fluence, and a simulated response arisen from the carrier drift in detector bulk with three regions of electric field profile

Original n-type MCZ (p^+-n-n^+), 24 GeV p as-irradiated, 1×10^{15} p/cm^2, V = 360V





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Thank you for your attention!