Electric field distribution in irradiated MCZ Si detectors

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9 RD50 Collaboration Workshop
CERN, Geneva, Oct 16-18, 2006

Outline

1. Background: E(x) distribution in heavily irradiated detectors
2. Approach for simulation of detector Double Peak response and E(x) profile reconstruction with a consideration of electric field in the “neutral” base
3. Comparison of experimental results on DP pulse response of MCZ Si detectors irradiated by 1 MeV neutrons and 24 GeV protons with F > 10^{14} cm^{-2} (detectors developed under “Technotest” sub-project)
4. Simulation of DP E(x) profile with a consideration of carrier trapping to midgap energy levels
5. Reconstruction of E(x) profiles in MCZ Si detectors

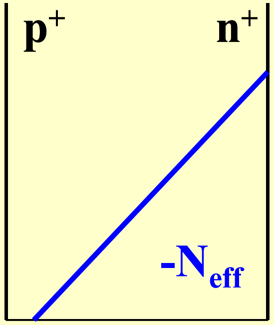
Conclusions

Models for electric field distribution in irradiated Si detectors

Standard model

N_{eff} = const, E(x) – linear,
V_{fd} derived from C-V curves

Valid for $F \leq 5 \cdot 10^{13}$ cm^{-2}



n-type Si
beyond SCSI
$-N_{eff}$

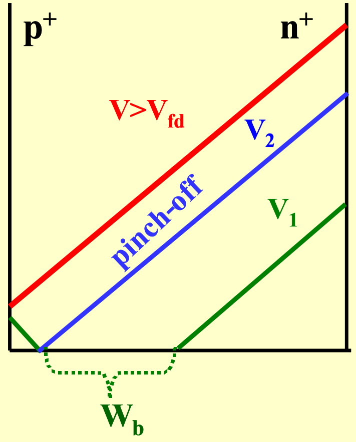
E. Verbitskaya et al., 9 RD50 Workshop, CERN, Geneva, Oct 16-18, 2006

Models for electric field distribution in heavily irradiated Si detectors

Bulk Si: n-type converts to high resistivity p-type

E. Borchi, M. Bruzzi et al, IEEE Trans. Nucl. Sci. 46 (1999) 834; M. Bruzzi, IEEE Trans. Nucl. Sci. 48 (2001) 960.

Detector: Double Junction structure:



- **Two depleted regions** at the sides of detectors irradiated beyond SCSI, **peaks of E at p^+ and n^+ contacts**

Z. Li, H. W. Kraner, IEEE TNS 39 (1992) 577

- **Two depleted regions and a neutral base *in-between***

D. Menichelli, M. Bruzzi, Z. Li, V. Eremin, NIM A 426 (1999) 135

- **Two depleted regions and a base *in-between* with electric field due to potential drop over high resistivity bulk**

E. Verbitskaya et al. Operation of heavily irradiated silicon detectors in non-depletion mode. Pres. RESMDD'05, Nucl. Instr. and Meth. A 557 (2006) 528-539

Experimental evidence of Double Peak electric field distribution

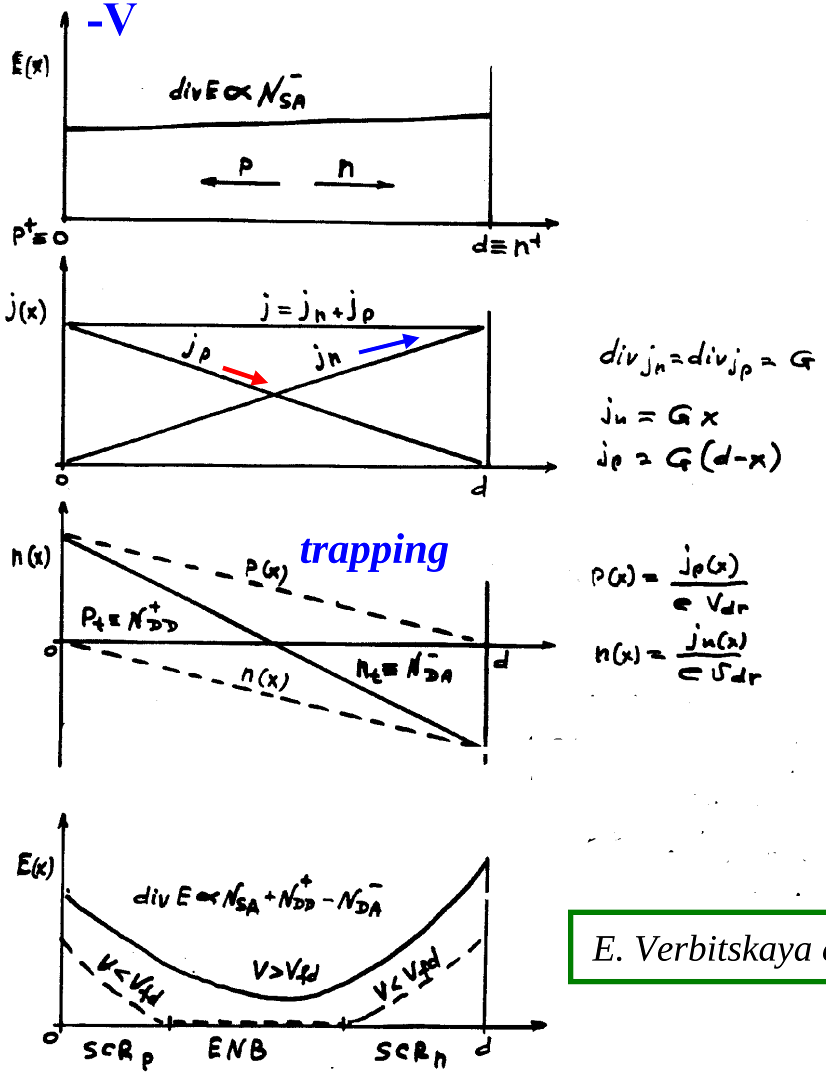
A. Castaldini, A. Cavallini, L. Polenta, F. Nava, C Canali, NIM A476 (2002) 550

- Measurements of OBIC and surface potential in non-irradiated and irradiated detectors
- Existence of two depletion layers adjacent to the contacts and separated by a layer inverted to p-type Si (close to intrinsic)
- Insignificant difference in E(x) near the p^+ contact in non-irradiated and irradiated Si detectors

Model of DP E(x) distribution:
ionization of DLs due to band bending near the contacts

Origin of Double Peak (DP) electric field distribution

V. Eremin, E. Verbitskaya, Z. Li. NIM A 476 (2002) 556



Trapping of free carriers
from detector reverse current
to Deep Levels leads to DP E(x)

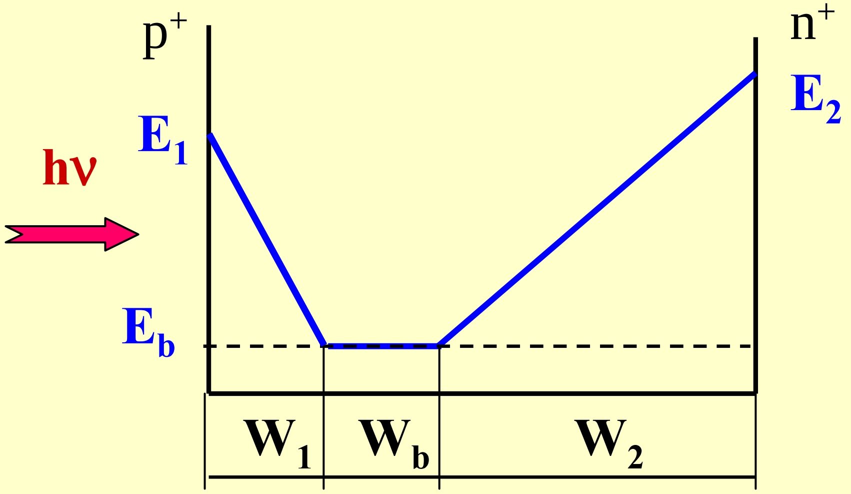
midgap DLs:

DD: E_v + 0.48 eV
DA: E_c – 0.52 eV

Approach for pulse response simulation and E(x) reconstruction with a consideration of electric field in the base

Goal: reconstruction of electric field profile from current pulse response, simulation of detector DP pulse response

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



Transient current:

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

$$\tau_{eff}^{-1} = \tau_{dr}^{-1} + \tau_{tr}^{-1}$$

$$\tau_{dr} = \frac{\varepsilon\varepsilon_o}{e\mu N_{eff}} \qquad \tau_{tr} = \frac{1}{\sigma v_{th} N_{tr}}$$

N_{eff}, N_{tr} = f(F)

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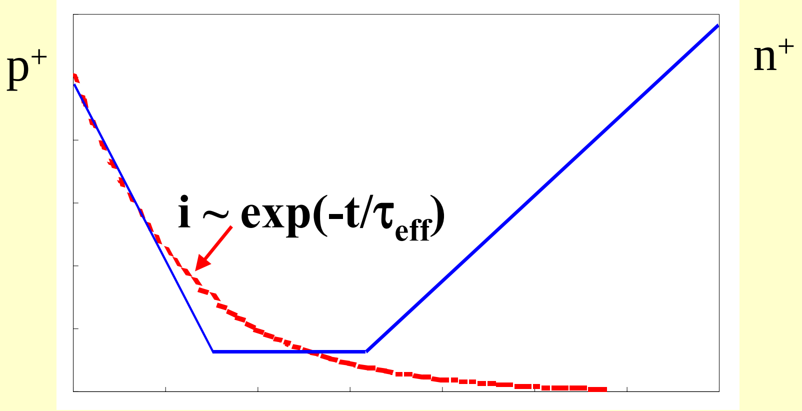
Pres. RESMDD'05, NIM
A 557 (2006) 528-539

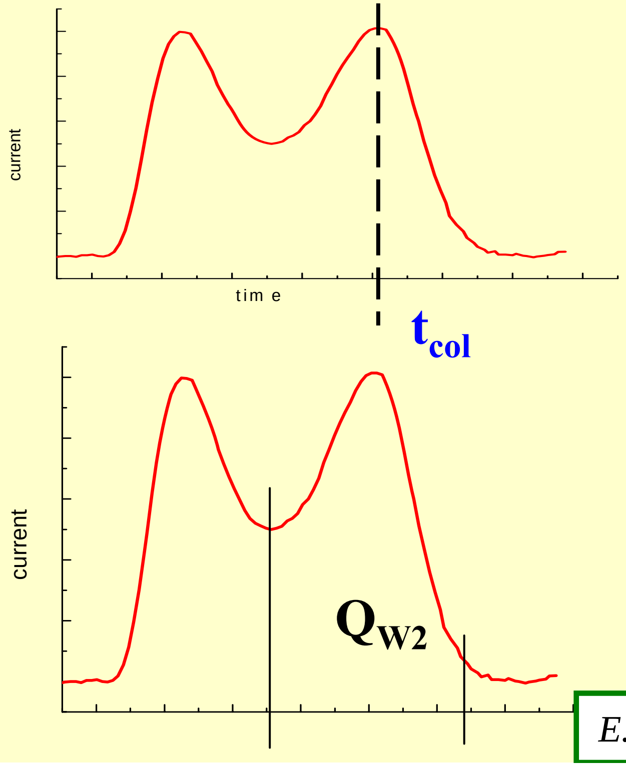
Simulation of pulse response for carrier generation from one side of detector



Signal due to carrier drift in W_1 is independent on the properties of W_b and W_2

$$i = i_1 \sim \exp(-t/\tau_{eff})$$

$$\boxed{\Rightarrow W_1,\ N_{eff1},\ E_1}$$



t_{col}: depends on E_b and W_b

$$\boxed{\Rightarrow E_b,\ W_b}$$

Charge collected inside W_2

$$Q_{W2} = Q_o(d - W_1 - W_n)/d$$

$$\boxed{\Rightarrow W_b,\ W_2,\ E_2,\ N_{eff2}}$$

$$\boxed{\int E dx = V}$$

Experimental tool for study of electric field distribution

- Transient Current Technique

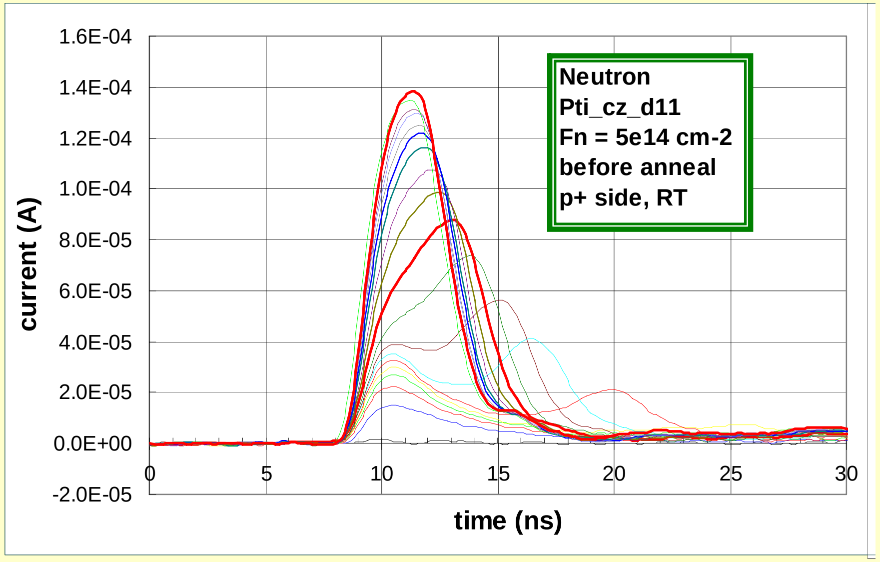
- Pulse Laser for generation of nonequilibrium carriers

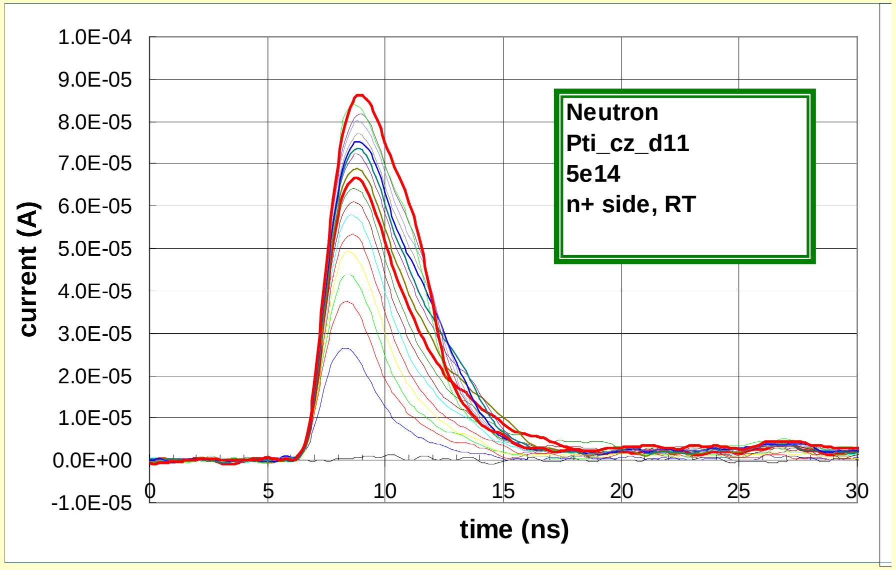
- Short wavelength of laser (e or h generation from one side and transport through detector bulk)

Experimental observations of DP current pulse response

1. 1 MeV neutron irradiation

MCZ Si, $F_n = 5{\cdot}10^{14}$ cm^{-2}

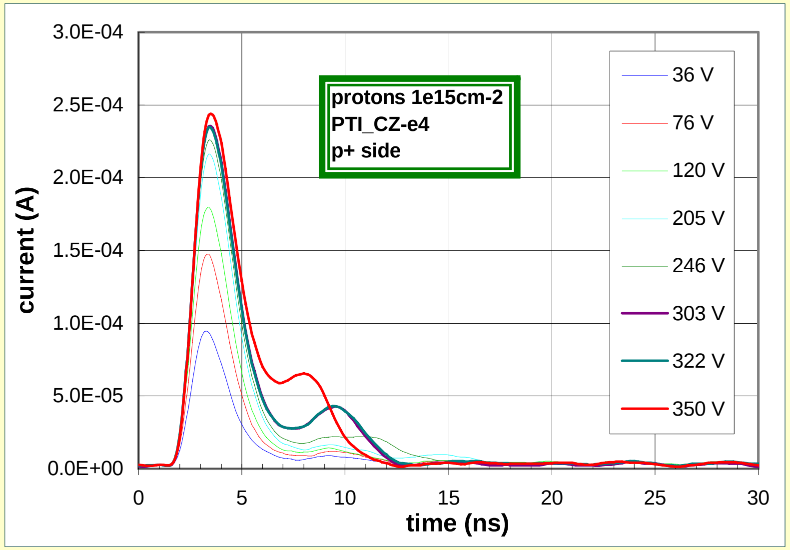




- **Electron collection (p+ side): second peak (H_2) increases with V: H_1/H_2 ↓**
- **Major junction at n^+ side: SCSI:**

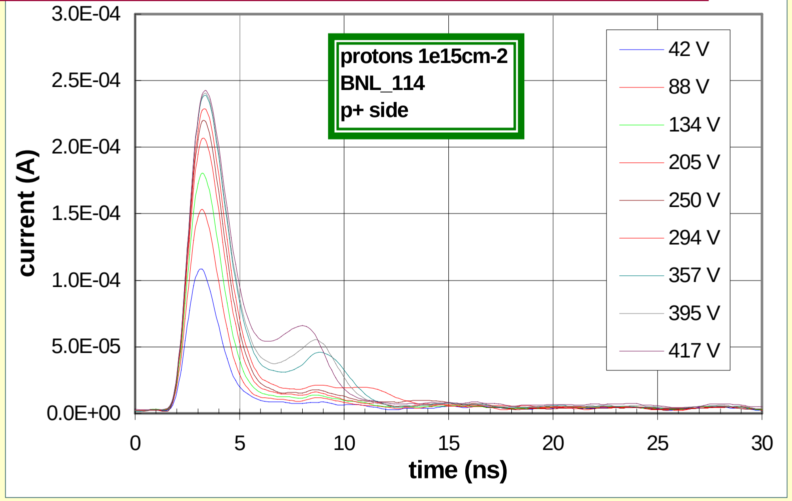
2. 24 GeV proton irradiation

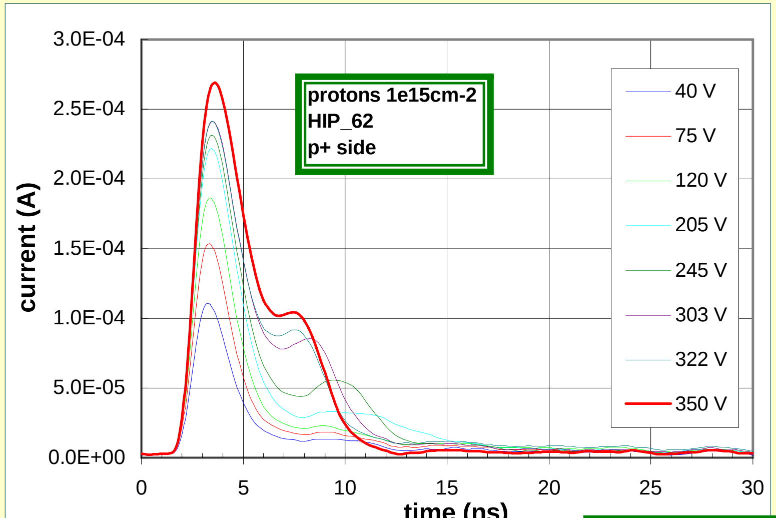
MCZ n-Si, $F_p = 1\cdot10^{15}$ cm^{-2}



Double Peak for all detectors at V > 200 V

1st peak dominates ($H_1/H_2>1$)





Influence of processing: difference in H_1/H_2

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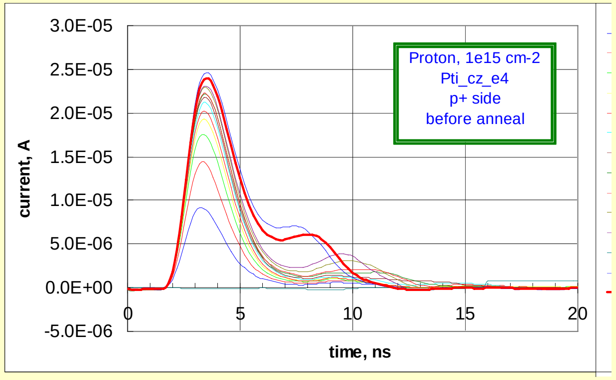
DP response under long term annealing

MCZ Si, $F_p = 1\cdot10^{15}$ cm^{-2}

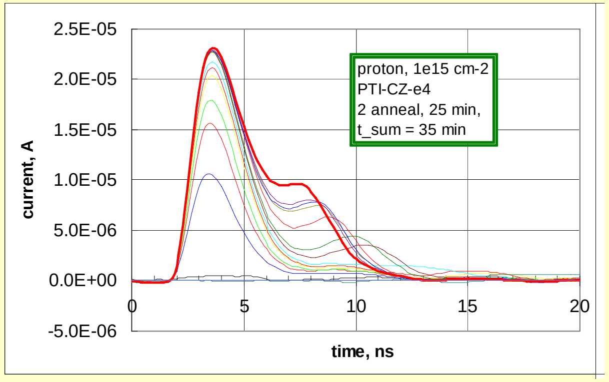
PTI-CZ-e4

T_{ann} = 80C, 7 steps

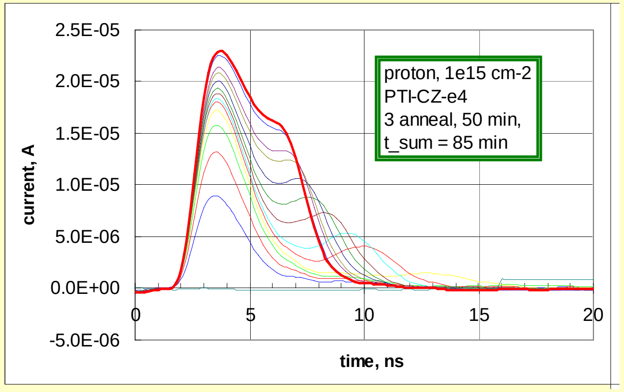
Before anneal



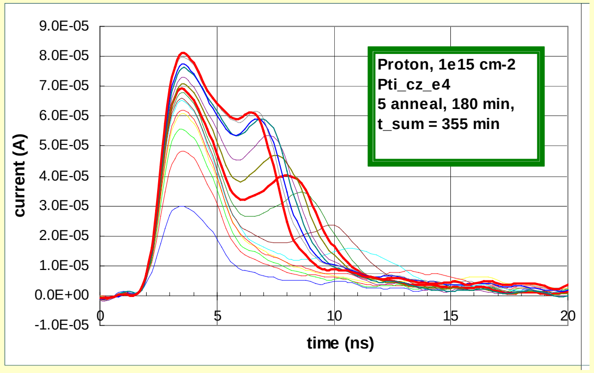
2: 35 min (total t_{ann})



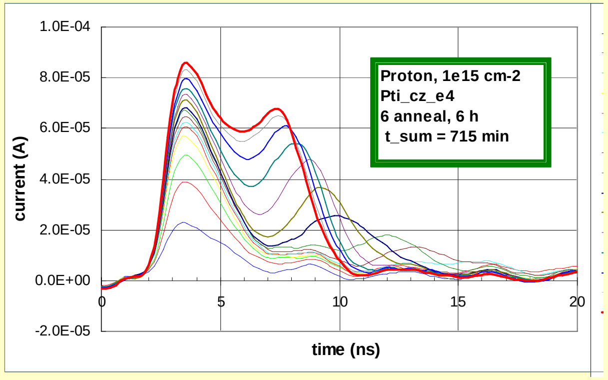
3: ~1.5 h



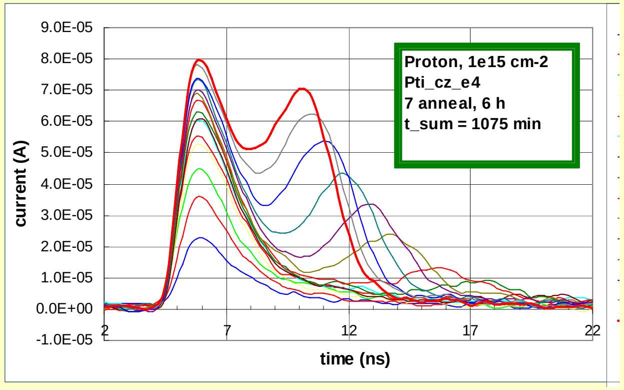
5: 6 h



6: 12 h



7: 18 h



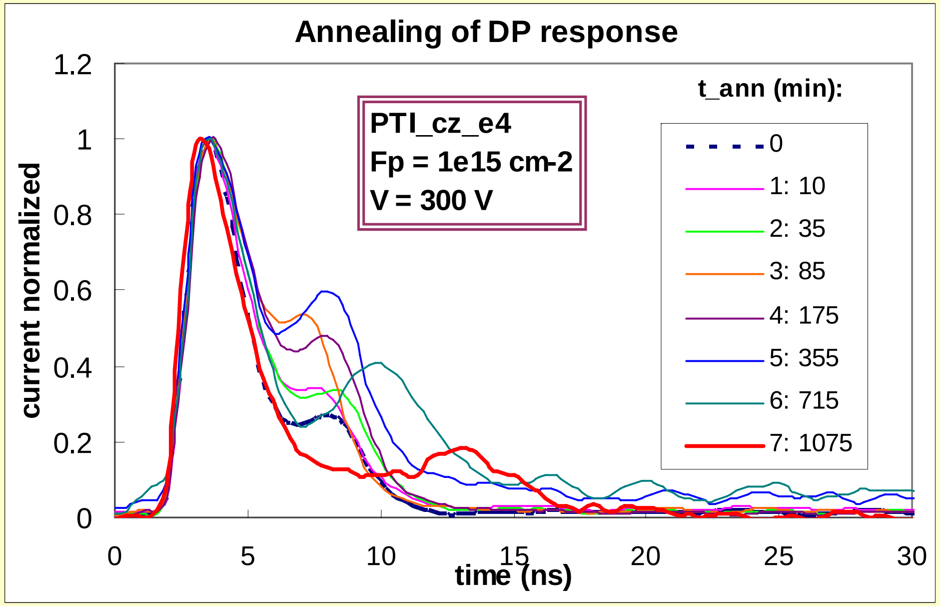
V = 40-440 V

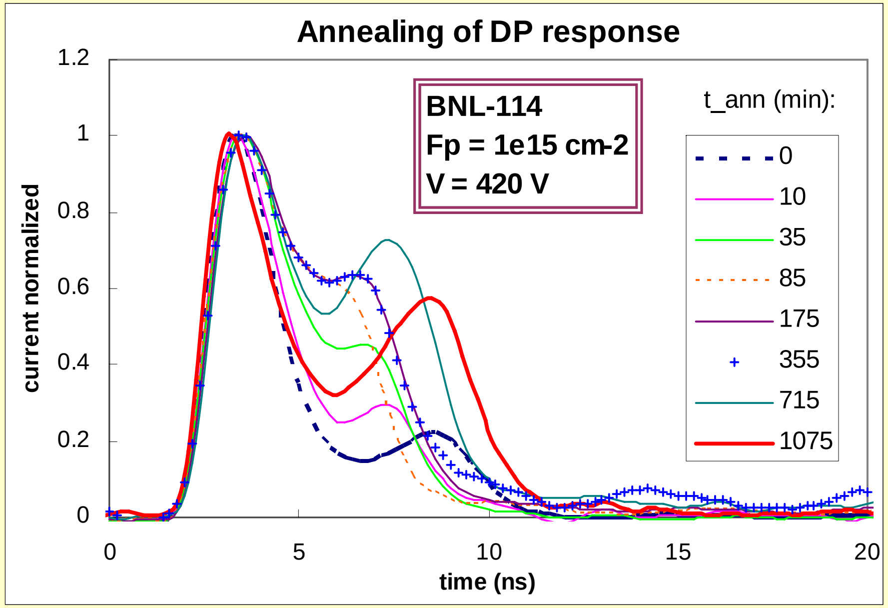
- **H_1 and H_2 rise at each step**
- **H_1/H_2 changes under annealing and → 1**

Evolution of Double Peak response under annealing,

MCZ Si, $F_p = 1{\cdot}10^{15}$ cm^{-2}

Normalized response





τ_{eff} doesn't change under annealing

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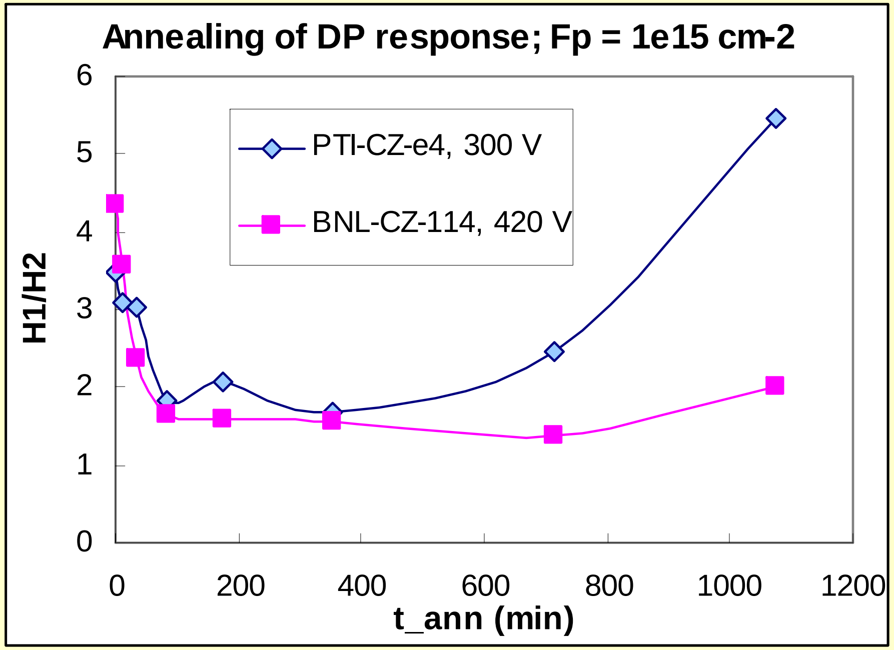
Amplitude ratio H_1/H_2 under annealing

MCZ Si, $F_p = 1\cdot10^{15}$ cm^{-2}



Stages of DP shape non-monotonous changes:

1. increase of H_1
2. increase of H_2

   ⇒ shape tends to single peak (E(x) ⇒ linear) at t_{ann} = 1.5-6 h
3. reduction of H_2 and increase of pulse width

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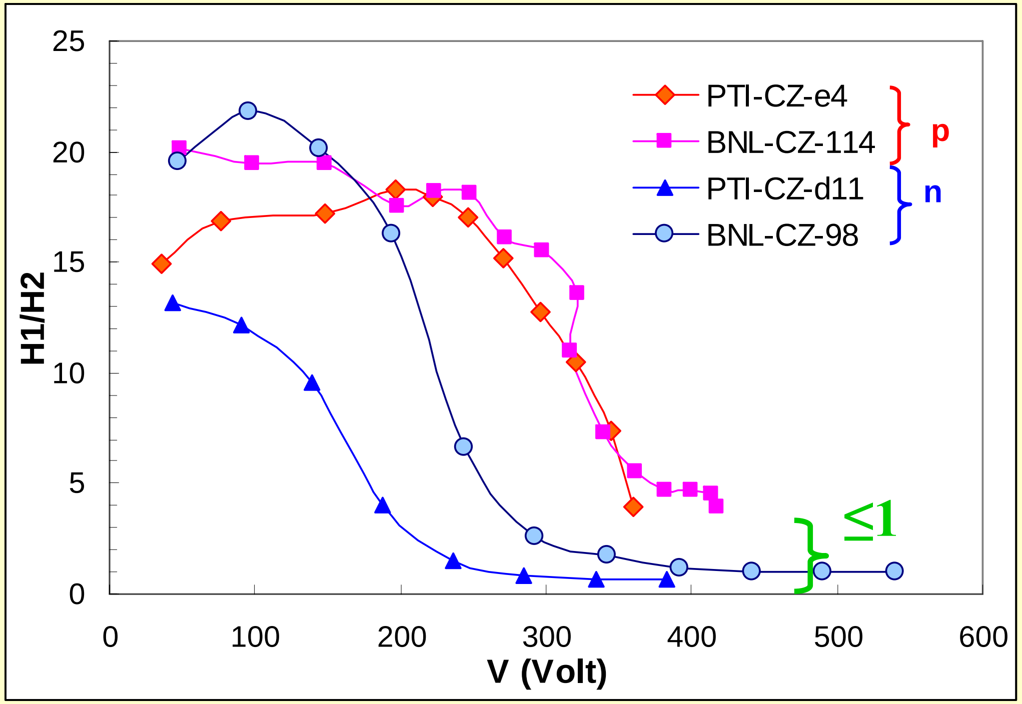
Comparison between n and p: amplitude ratio H_1/H_2 in DP response



Fluence:

$F_n = 5 \cdot 10^{14}$ cm^{-2}

$F_p = 1 \cdot 10^{15}$ cm^{-2}

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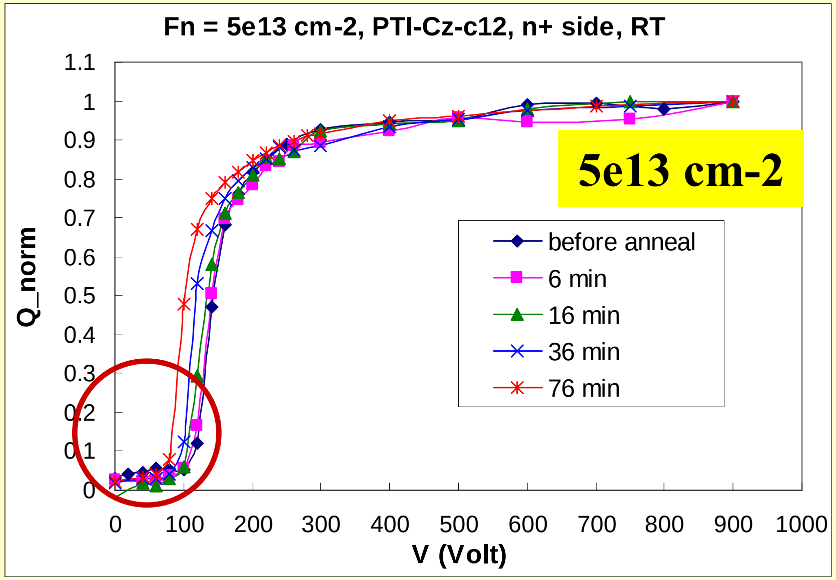
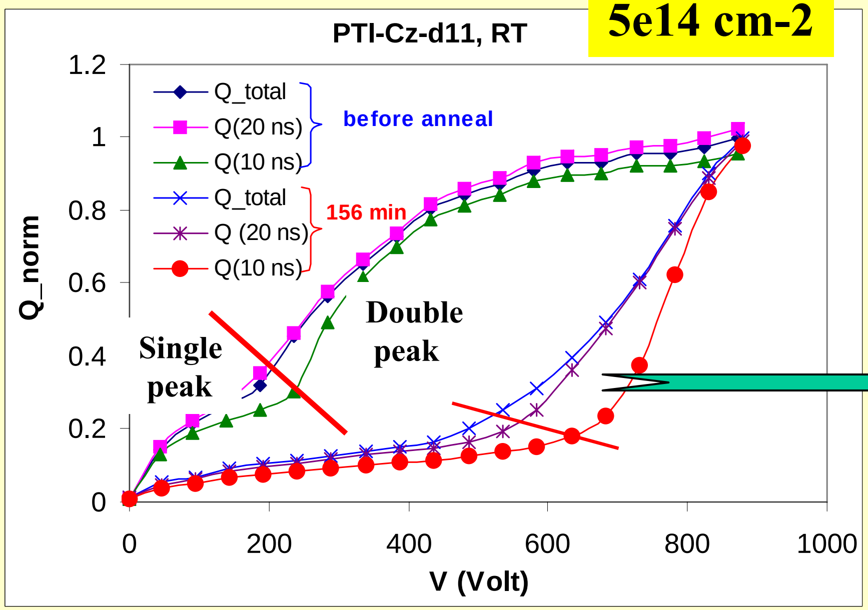
Comparison: MCZ Si, Q(V)

neutrons

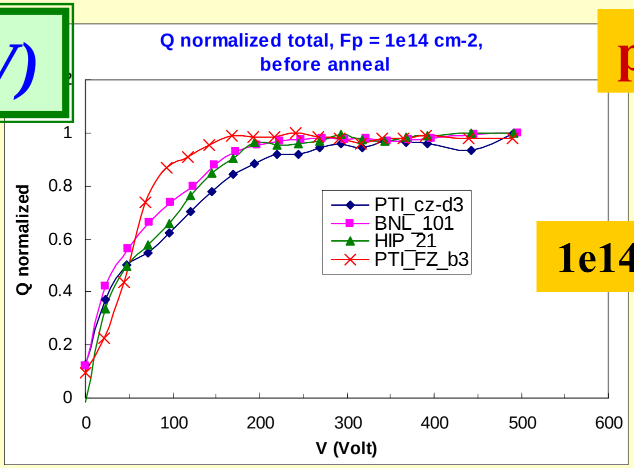


5e13 cm-2

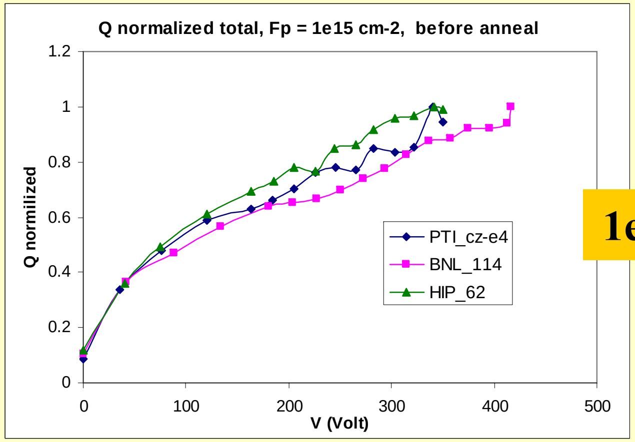


5e14 cm-2

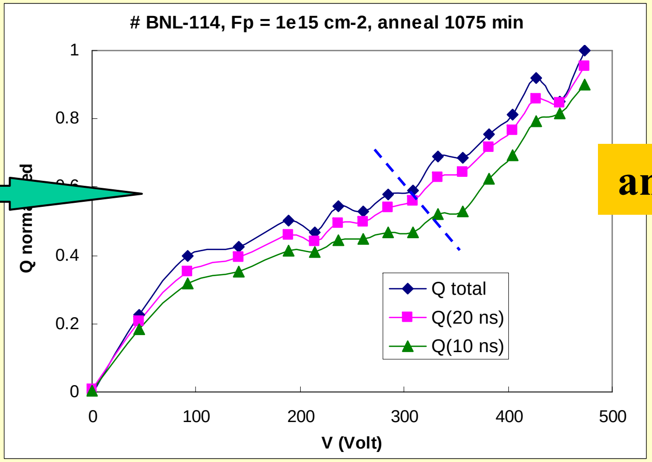
protons



1e14 cm-2



1e15 cm-2



annealing

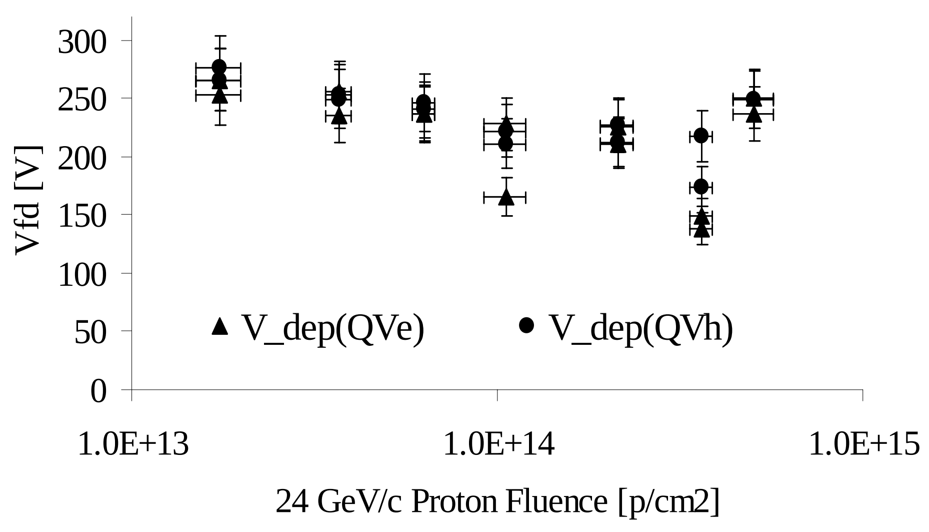
Experimental data on $N_{eff}(F)$ and V_{fd} dependence in MCZ Si detectors

β for neutrons and protons,
TCT data

FZ, n: 0.022

MCZ, n: 0.017
MCZ, p: 0.0045

Z. Li et al. Radiation hardness of high resistivity magnetic Czochralski silicon detectors after gamma, neutron, and proton radiations,
TNS- 51 (2004) 1901-1908



A. Bates and M. Moll. A comparison between irradiated Magnetic Czochralski and Float Zone silicon detectors using the Transient Current Technique. NIM A 555 (2005) 113

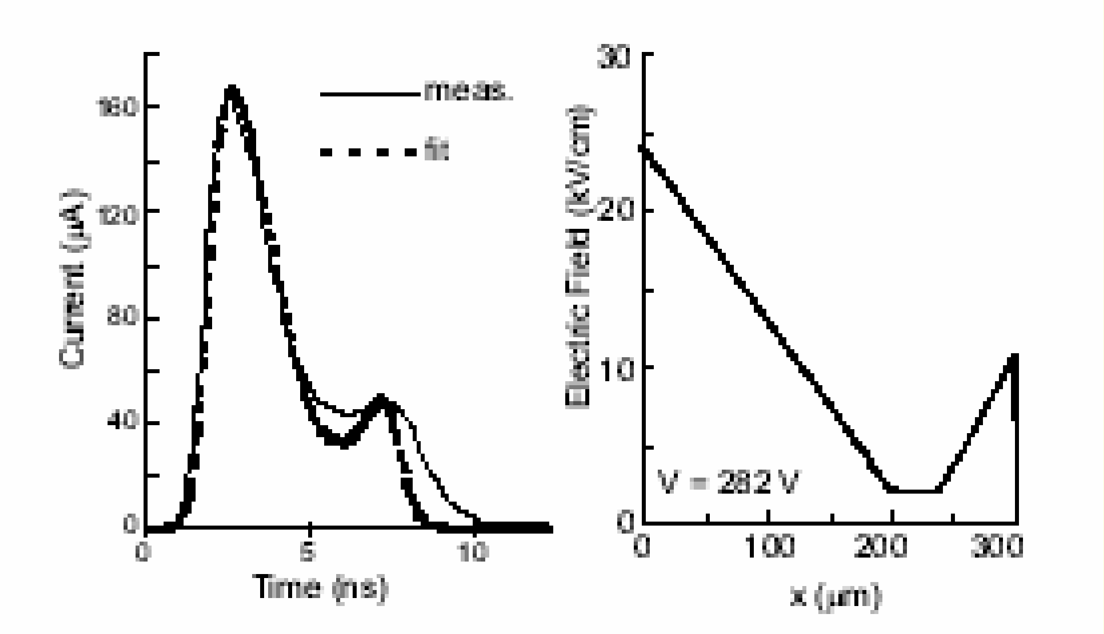
Depletion voltage has passed its minimum value without type inversion

E(x) profile in MCZ Si detectors irradiated by 24 GeV protons (earlier results)

Pulse response fit and E(x) reconstruction basing on three region structure

$F_p = 2.2 \cdot 10^{15}$ cm^{-2} **Electron collection (p+ side)** SMART detector

M. Scaringella et al. Localized energy levels generated in Magnetic Czochralski silicon by proton irradiation and their influence on the sign of space charge density. NIM A, in press; and N. Manna, pres. 8 RD50 Workshop, June 25-28, 2006, Prague



Wide region with positive space charge!

"Puzzle" –
Space Charge Sign
in MCZ Si
irradiated by 24 GeV
protons??

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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:

- 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

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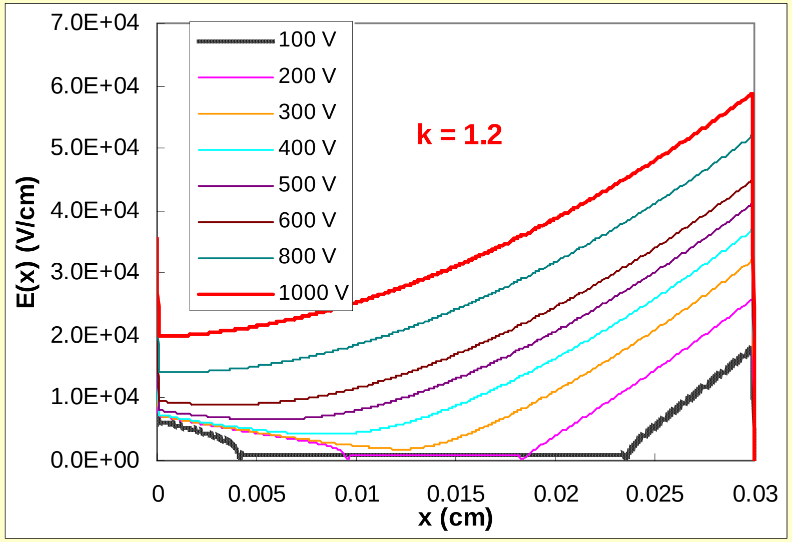
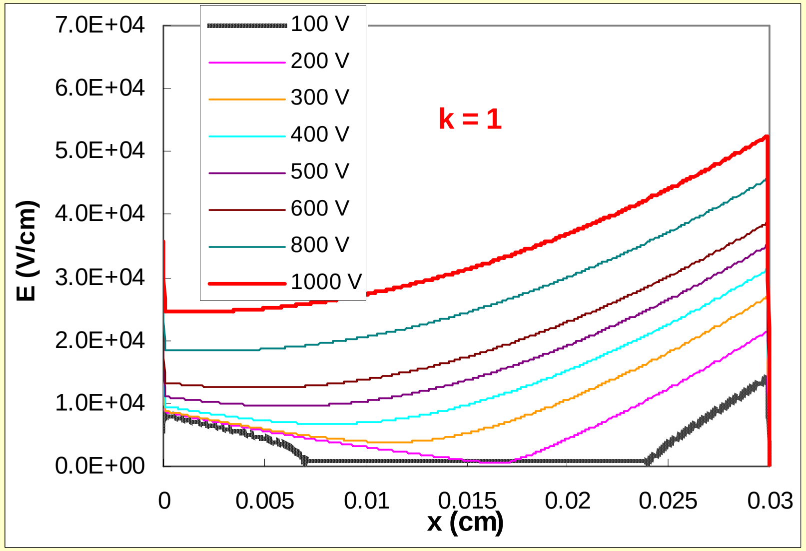
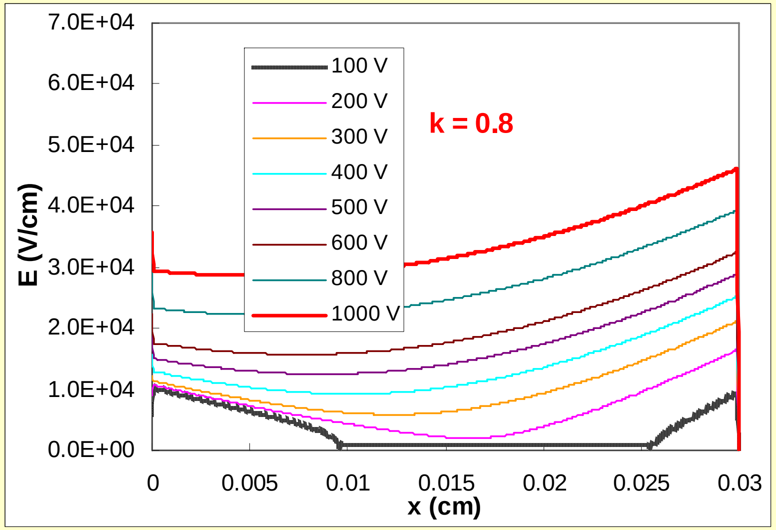
Simulation: Evolution of Double Peak E(x) at various N_{DA}/N_{DD}
$F_n = 5\cdot10^{14}$ cm^{-2}







V: 100-1000 V

$N_o = 1\cdot10^{12}$ cm^{-3}

d = 300 μm, RT

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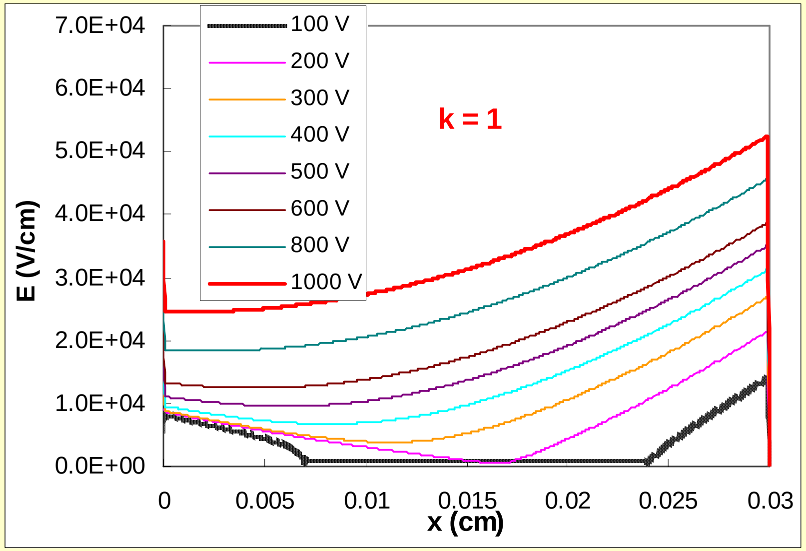
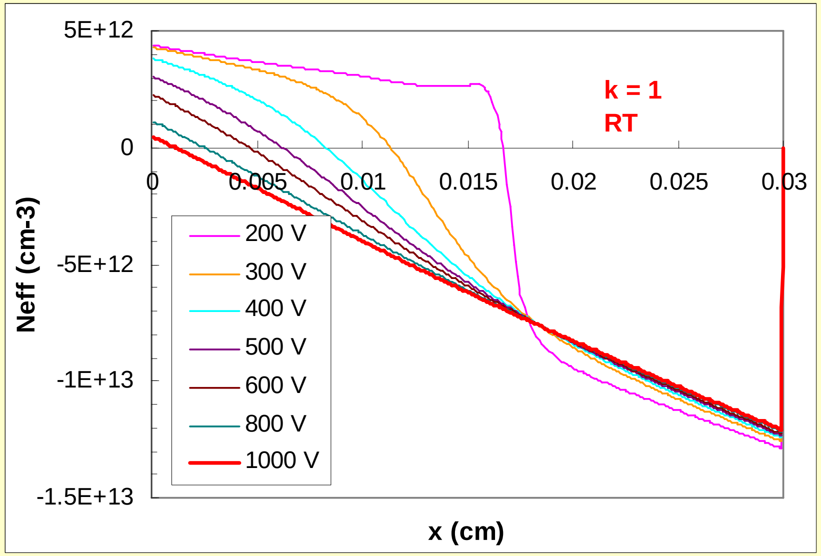
CERN, Geneva, Oct 16-18, 2006

E(x) and N_{eff} vs. V

$F_n = 5\cdot10^{14}$ cm^{-2}





N_{eff} is vastly non-uniform and E is non-linear even at maximal V of 1000 V

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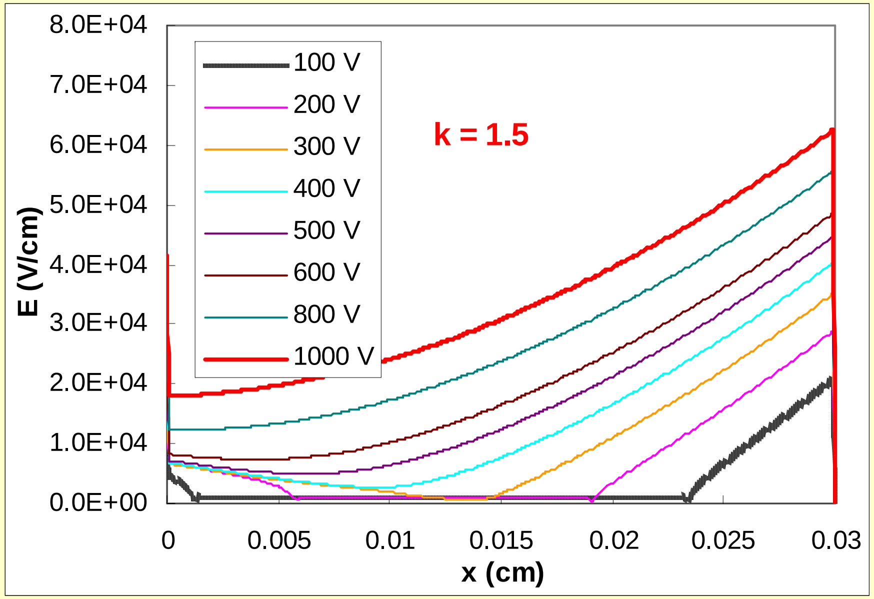
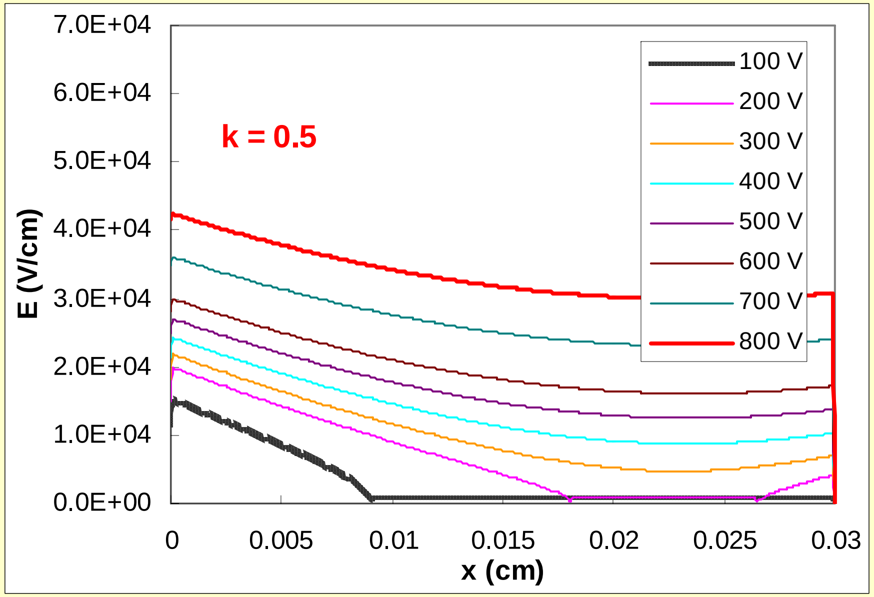
Evolution of Double Peak E(x) vs. N_{DA}/N_{DD}

$F_n = 5\cdot10^{14}$ cm^{-2}

MCZ Si

$N_o = 3.5\cdot10^{12}$ cm^{-3}
d = 300 mm, RT





**E at p^+ contact changes insignificantly:
correlates to neutron irradiation**

**Major junction at p^+ side:
correlates to proton irradiation**

Experimental results:
current response fit and E(x) reconstruction in MCZ Si detectors

Goal:

- simulation/fit of detector DP pulse response,
- **reconstruction of electric field profile from current pulse shape,**

considering detector structure with three regions: W_1, W_b and W_2

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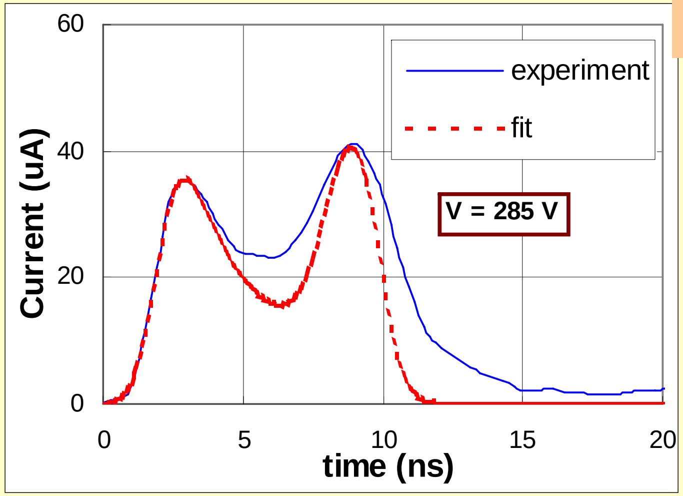
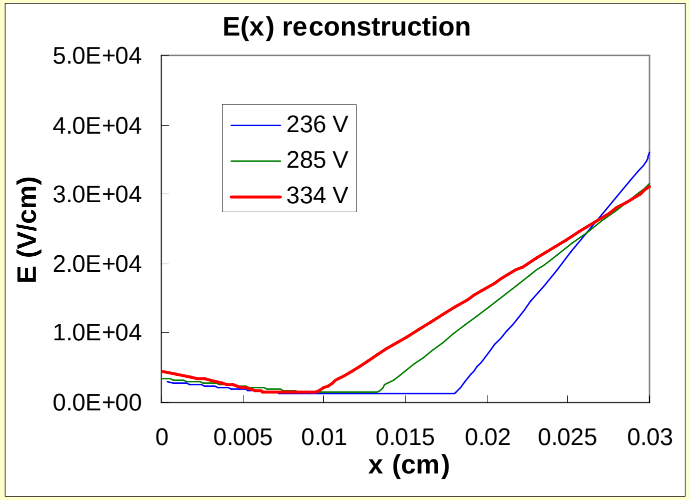
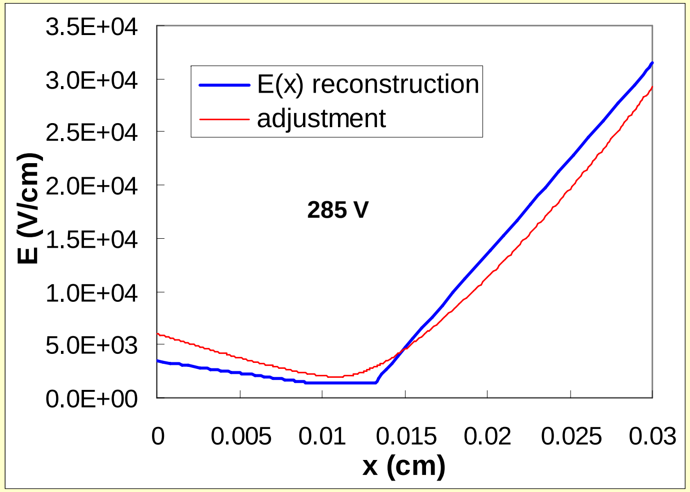
E(x) reconstruction and adjustment to midgap level model

Neutrons, $F_n = 5{\cdot}10^{14}$ cm^{-2}, MCZ Si

PTI-CZ-d11







At high F_n and V negative SCR extends inside detector bulk

Parameters derived by adjustment:

m_j = 0.7 cm^{-1}

DD E_v + 0.48 eV $5{\cdot}10^{14}$ cm^{-3}

DA E_c - 0.52 eV $6.75{\cdot}10^{14}$ cm^{-3}

k = 1.35

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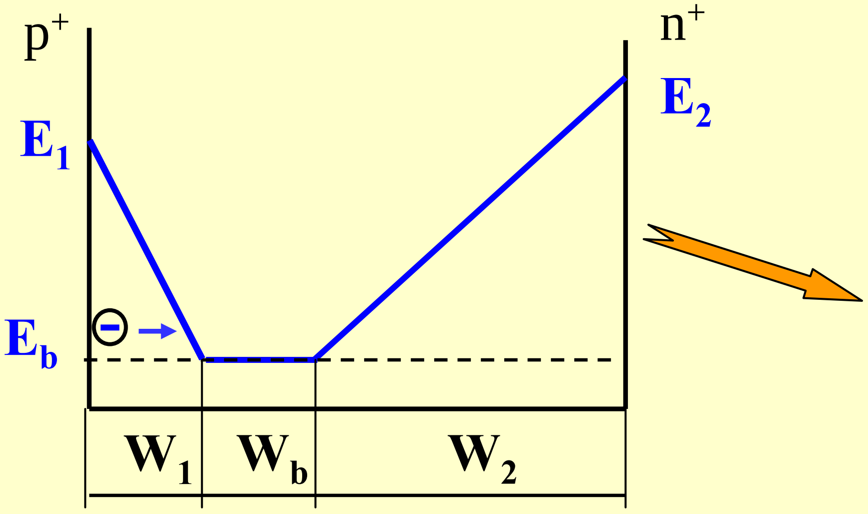
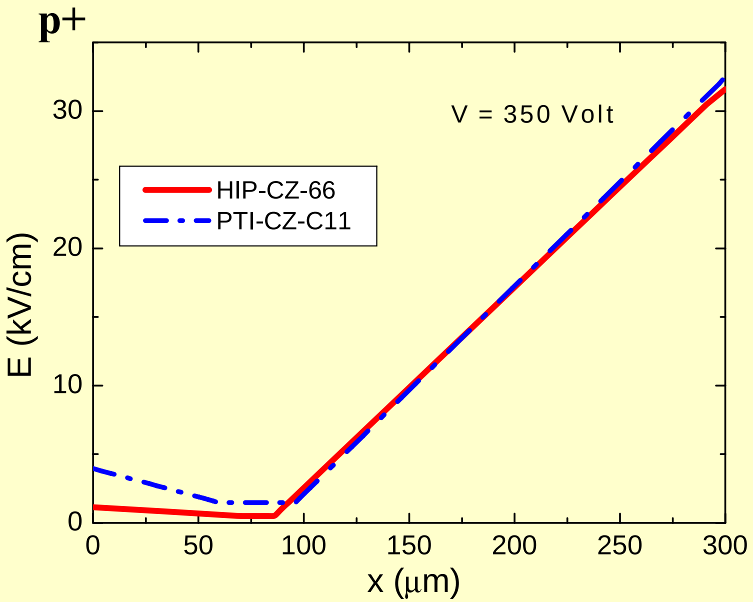
Reconstruction of E(x) from DP response: influence of processing

$F_n = 5\cdot10^{14}$ cm^{-2}

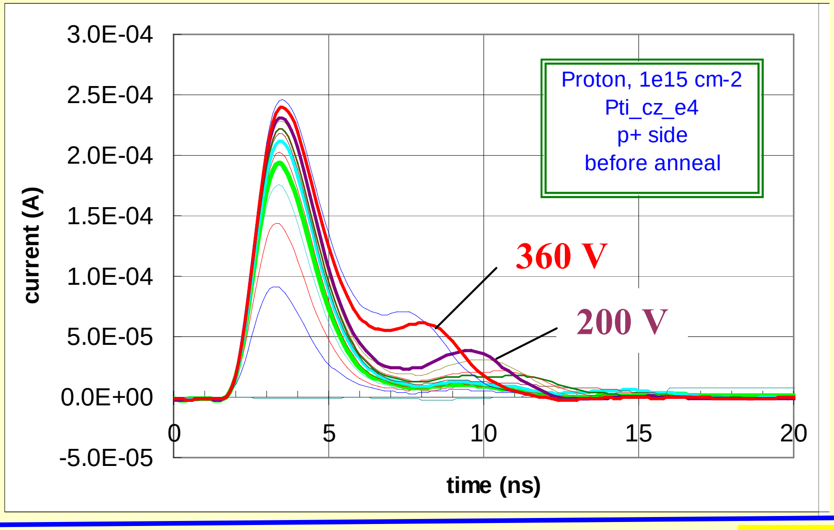


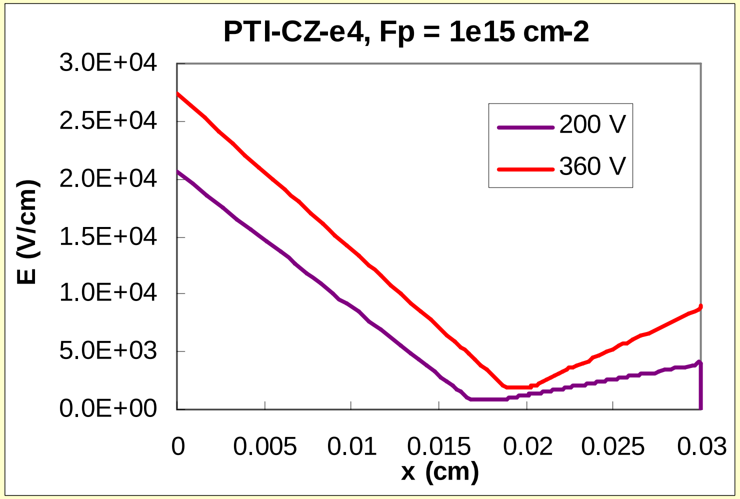


	HIP-CZ-66	**PTI-CZ-C11**
tau_e (ns)	4	5
Neff1 (cm-3)	1.41E+11	1.09E+12
Neff2 (cm-3)	9.46E+12	9.51E+12
E_b (V/cm)	500	1500

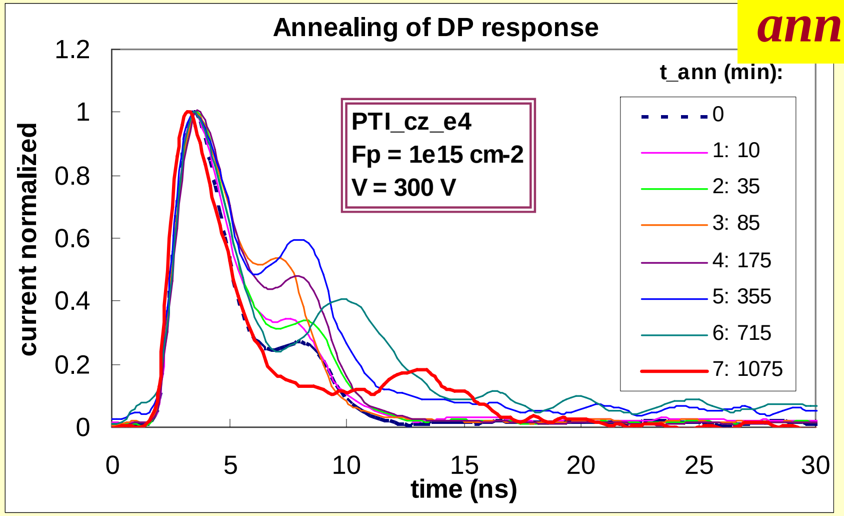
Electric field gradient dE/dx and N_{eff} in the region adjacent to p^+ contact are different and sensitive to detector processing

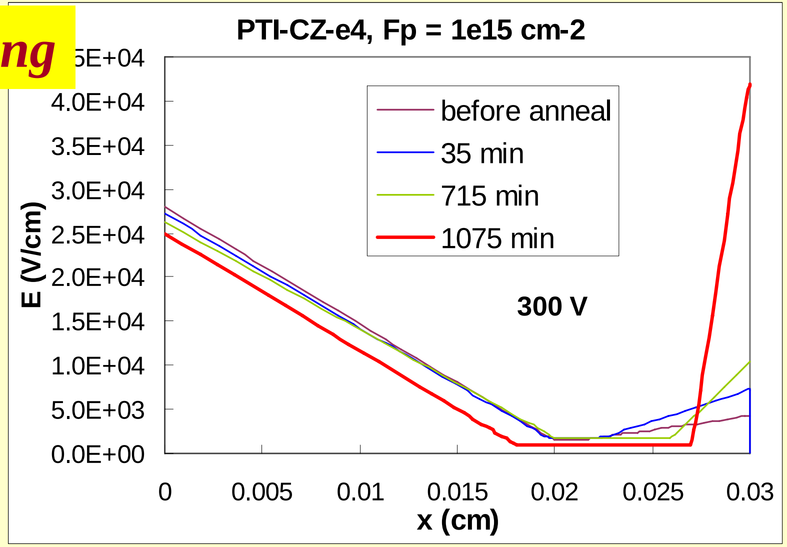
Reconstruction of E(x) from DP response:
<u>Protons</u>, $F_p = 1\cdot10^{15}$ cm^{-2}, MCZ Si + annealing





annealing





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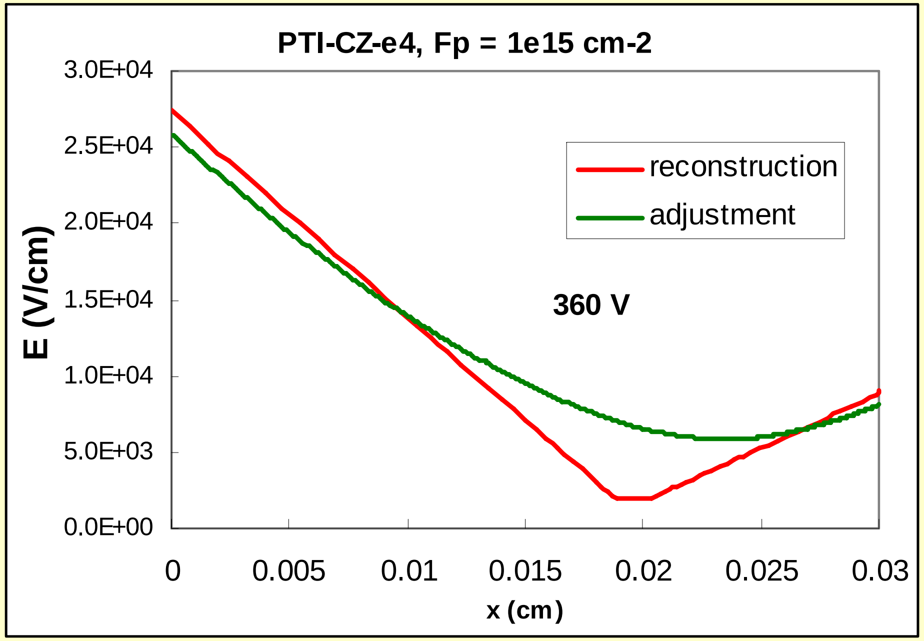
E(x) reconstruction and adjustment to midgap level model

$F_p = 5 \cdot 10^{14}$ cm^{-2}, MCZ Si, PTI-CZ-e4



Parameters derived by adjustment:

m_j = 0.7 cm^{-1} – like for neutrons

DD E_v + 0.48 eV $6.6 \cdot 10^{14}$ cm^{-3}

DA E_c - 0.52 eV $3 \cdot 10^{14}$ cm^{-3}

k = 0.45

$k(n)/k(p) \approx 3$

correlates to $\beta(n)/\beta(p) \approx 4$

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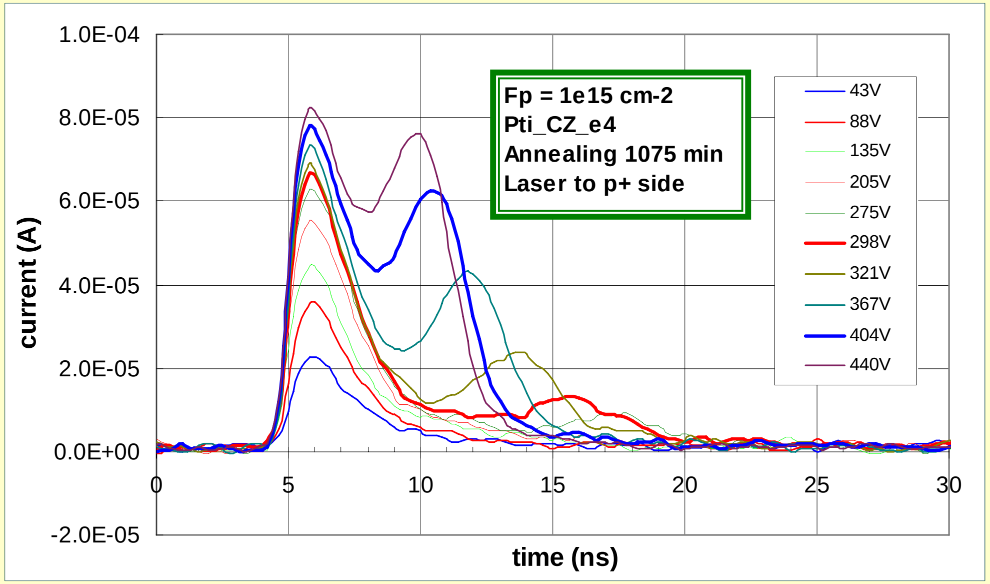
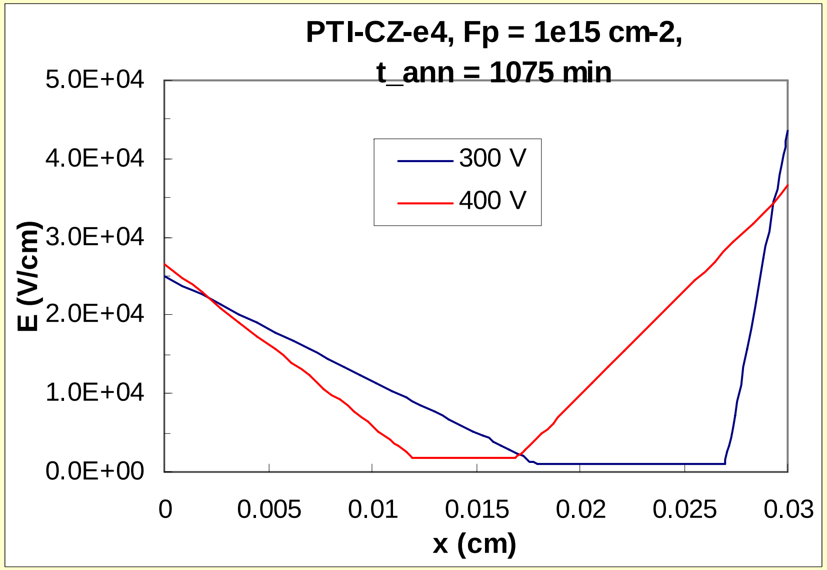
Protons, $F_p = 1 \cdot 10^{15}$ cm^{-2}, *MCZ Si, annealing*





- **In MCZ Si detectors irradiated by 24 GeV protons electric field extends over entire detector thickness. The major junction is at the p$^+$ contact and SCR is charged positively.**
- **Under annealing E(x) profile becomes more symmetric with increasing V.**

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Conclusions

- ✓ Approach of E(x) distribution with a consideration of electric field in the base region allows E(x) reconstruction in detectors irradiated by high F irrespective to the irradiation type.
- ✓ In heavily irradiated detectors electric field distribution is vastly non-uniform and shows double peak shape with positively and negatively charged regions. Full depletion implies that electric field extends over entire detector bulk and carrier collection is drift process.
- ✓ Different balance of DDs and DAs induced by neutrons and protons results in the essential difference of E(x) profile, pulse shape and collected charge at the same bias voltage.
- ✓ In neutron irradiated MCZ Si detectors E at the major junction (n^+ side) decreases with voltage that is favorable for detector operation.
- ✓ In MCZ Si detectors irradiated by 24 GeV protons the major space charge region is adjacent to the p+ contact and has a positive space charge.

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Thank you for your attention!