

*Operational conditions  
for enhancement of collected charge  
via avalanche multiplication  
in n-on-p Si strip detectors*

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20 RD50 Workshop  
Bari, May 30 - June 1, 2012

# *Outline*

- ◆ Goal
- ◆ Background
- ◆  $E(x)$  and  $Q_c(V)$  vs.  $T$  dependences
- ◆  $E(x)$  and  $Q_c$  vs.  $V$  and  $F$  dependences
- ◆ Influence of detector geometry
- ◆ Comparison with experimental results
- ◆ Considerations on defect energy levels
- ◆ Impact of avalanche multiplication on  $S/N$

## **Conclusions**

# *Goal*

- Simulation of  $Q_c$  enhancement:  
extension of quantitative PTI model
- Finding the conditions for observation of enhanced  
collected charge in n-on-p Si strip detectors
- Comparison with experimental data

## *Recent results on collected charge enhancement: main references*

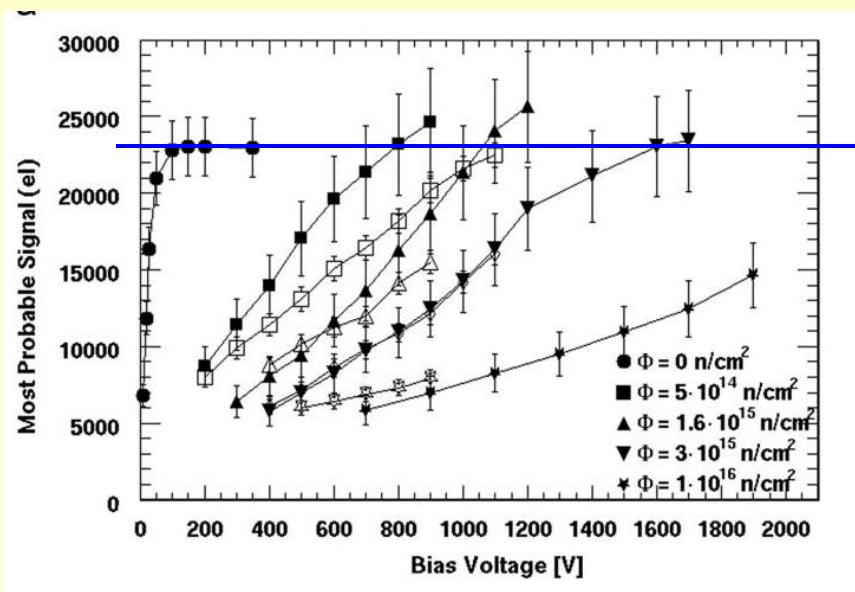
1. I. Mandić, V. Cindro, G. Kramberger, M. Mikuž, *NIM A* 603 (2009) 263
2. I. Mandić, A. Gorišek, G. Kramberger, M. Zavrtanik, *NIM A* 612 (2010) 474
3. A. Affolder, P. P. Allport, G. Casse, *Nucl. Instrum. Meth. A* 612 (2010) 470
4. G. Casse, *NIM A* 612 (2010) 464
5. G. Casse, et al., *NIM A* 624 (2010) 401
6. M. Mikuž, V. Cindro, G. Kramberger, I. Mandić, M. Zavrtanik, *NIM A* 636 (2011) 550
7. G. Casse, A. Affolder, P. P. Allport, H. Brown, I. McLeod, M. Wormald, *NIM A* 636 (2011) 556
8. I. Mandić, V. Cindro, G. Kramberger, M. Mikuž, *NIM A* 629 (2011) 101.
9. A. Dierlamm, *NIM A* 624 (2010) 395
10. J. Lange, et al., *NIM A* 622 (2010) 49 (*epi-Si*)
11. A. Affolder, et al., *NIM A* 658 (2011) 11 (3D)
12. I. Mandić, et al., *JINST* (2011) doi:10.1088/1748-0221/6/11/P11008
13. V. Eremin, E. Verbitskaya, A. Zabrodskii, Z. Li, J. Hätkönen, *NIM A* 658 (2011) 145

# Experimental results

- ◆ N-on-p microstrip detectors processed by Micron
- ◆ Neutron irradiation

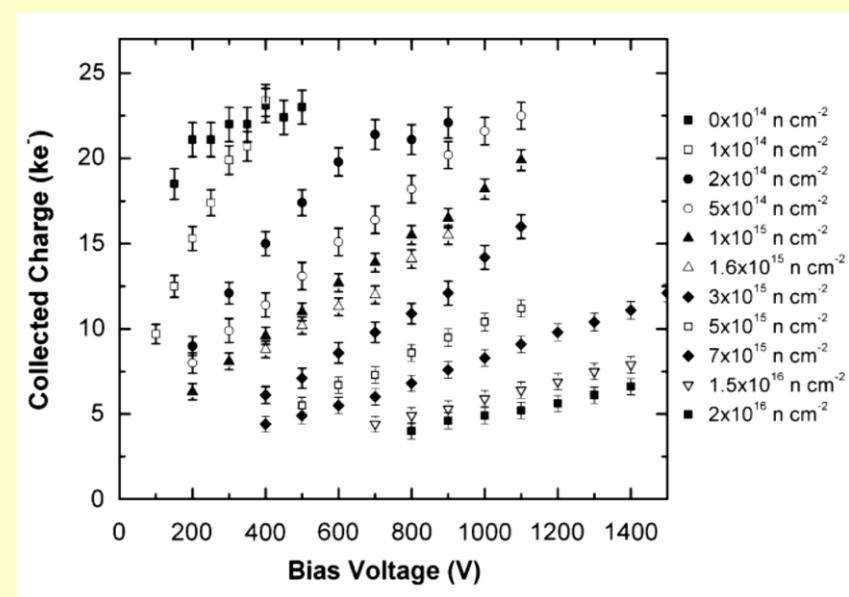
I. Mandić, et al., *NIM A 612 (2010) 474.*

-20°C (and -40°C for  $1 \times 10^{16} \text{ cm}^{-2}$ )



G. Casse, et al., *NIM A 636 (2011) 556.*

-25°C



# *Simulation of $Q_c$ enhancement*

**Most probable – carrier avalanche multiplication in high  $E$  of n<sup>+</sup>-p junction**

[www.cern.ch/rd50](http://www.cern.ch/rd50):

V. Eremin, E. Verbitskaya, Z. Li, J. Härkönen, *14 RD50 workshop, June 3-5, 2009, Freiburg*

V. Eremin, E. Verbitskaya, A. Zabrodskii, *15 RD50 workshop, Nov 16-18, 2009, Geneva, CERN*

V. Eremin, E. Verbitskaya, A. Zabrodskii, Z. Li, J. Härkönen, *NIM A 658 (2011) 145.*

**The PTI model considers:**

- ✓ competition of  $Q_c$  reduction due to carrier trapping to radiation induced deep level (DL) defects and charge increase arisen from avalanche multiplication;
  - ✓ formation of Double Peak electric field profile  $E(x)$ ;
  - ✓ focusing of the electric field and current near the collecting strips;
  - ✓ avalanche hole generation near the strips, the hole injection into the detector bulk, and the hole trapping to radiation induced deep levels defects
- gives rise to the **negative feedback**, which stabilizes the avalanche multiplication and total detector performance

# PTI model of $Q_c$ enhancement via avalanche multiplication

## Processes considered:

- formation of a steady-state  $E(x)$  distribution by considering the generation of equilibrium carriers (bulk generation current), avalanche generated carriers near the  $n^+$  strips, and carrier trapping by the radiation induced DLs;
- charge collection in the detector bulk with a calculated  $E(x)$  profile

## Procedure and main parameters

- ◆ Poisson equation combined with the rate equation
- ◆ one-dimensional approach for detector geometry
- ◆ Deep levels: DA  $E_c - 0.53$  eV; DD  $E_v + 0.48$  eV
- ◆  $1/\tau_{e,\eta} = \beta_{e,h} F_{eq}$ ;  $\beta_e = 3.2 \times 10^{-16} \text{ cm}^2 \text{s}^{-1}$ ,  $\beta_h = 3.5 \times 10^{-16} \text{ cm}^2 \text{s}^{-1}$  [2]
- ◆  $A$  and  $B$  from B. J. Baliga, *Modern Power Devices*, Hoboken, NJ; Wiley, 1987

## Extension in this study: variable parameters

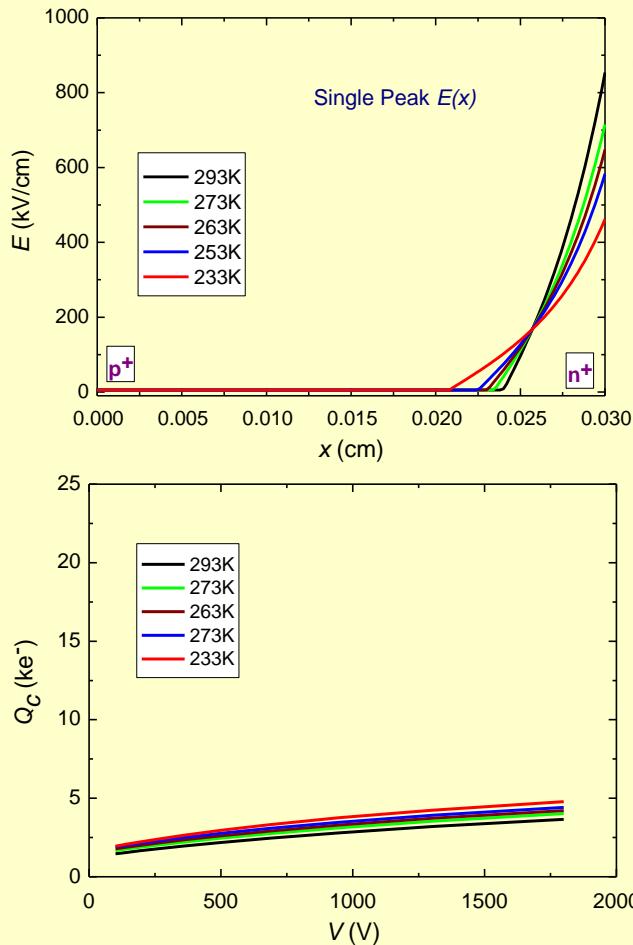
- ◆ detector bias voltage  $V$ ,
- ◆ temperature  $T$  in the LHC range,
- ◆ irradiation fluence  $F$ ,
- ◆ strip detector **geometry** (strip width, detector thickness)

**Starting point** – fit to the curve with maximal  $Q_c$  [2]:  $F = 3 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$ ,  $T = -20^\circ\text{C}$   
→ gives  $K_{DA} = 2$ ,  $K_{DD} = 0.07$

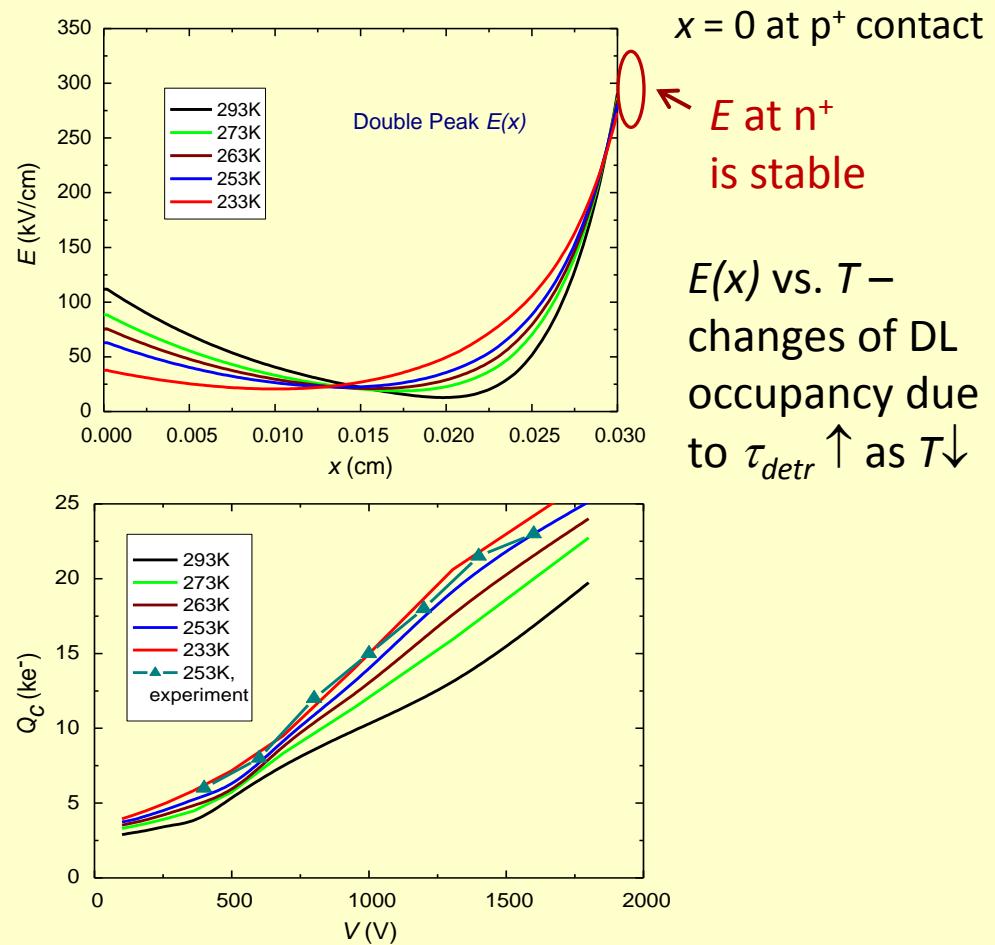
# $E(x)$ and $Q_c$ vs. $T$ dependences

n-on-p strip detector;  $d = 300 \mu\text{m}$ ; pitch/strip width 80/20 ( $\mu\text{m}$ )  $F = 3 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$

No avalanche multiplication

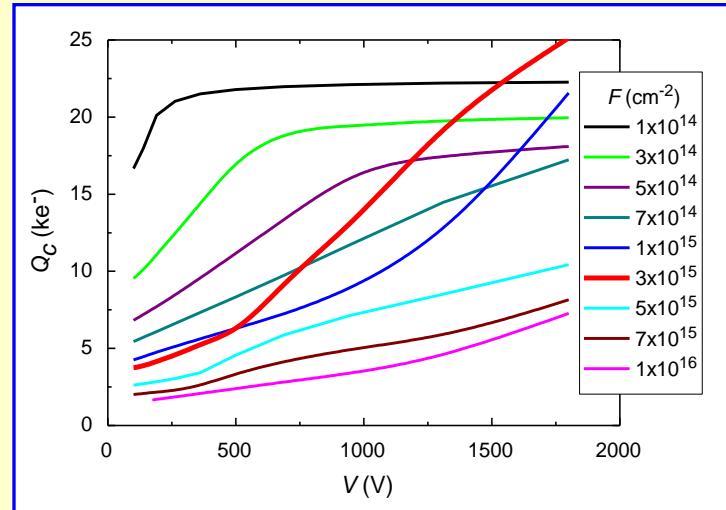
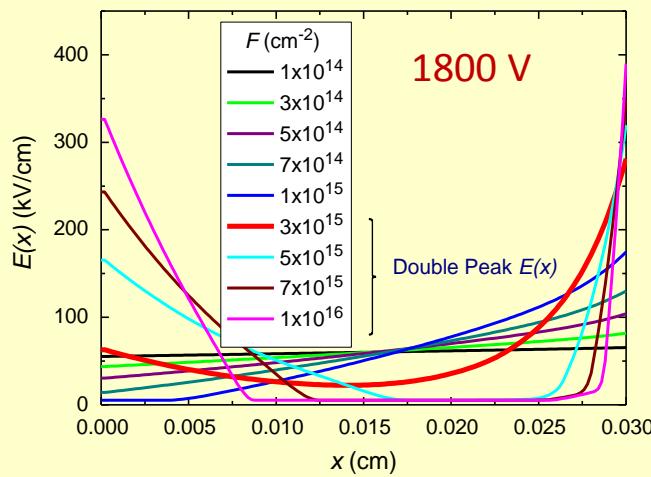
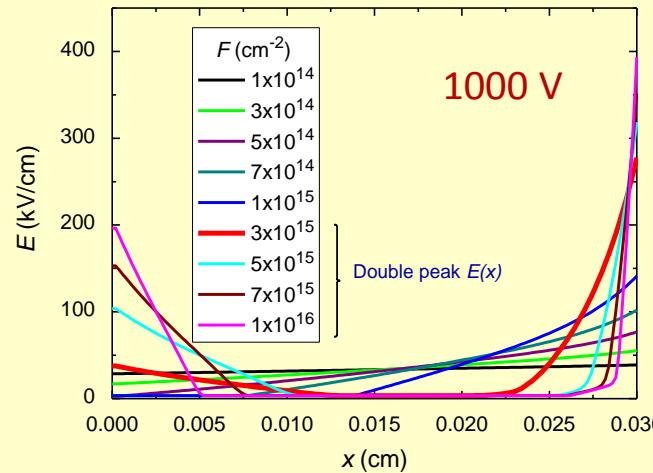
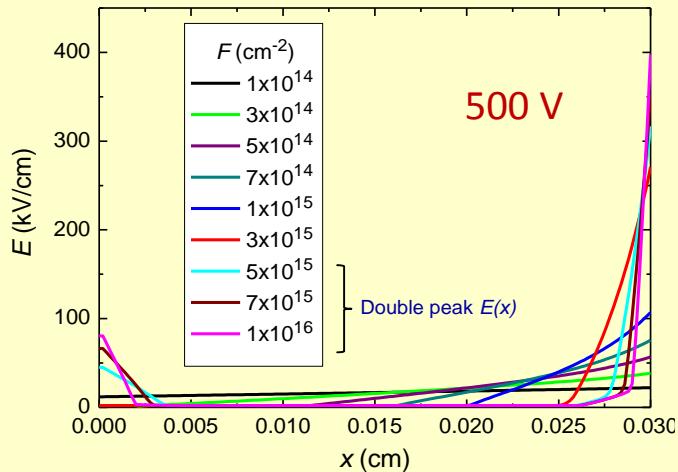


Avalanche multiplication is considered



# $E(x)$ and $Q_c(V)$ dependences at different $F$

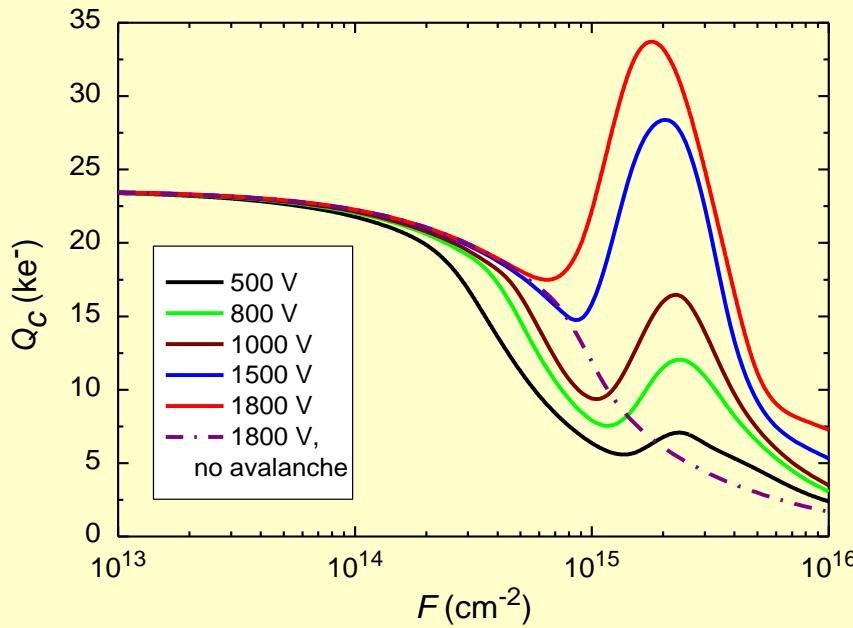
## Avalanche multiplication



$Q_c$  rise correlates with appearance of DP  $E(x)$   
Minimum  $V$  –  $500$  V

# Dependence of $Q_c(F)$ on $V$

T = 253K

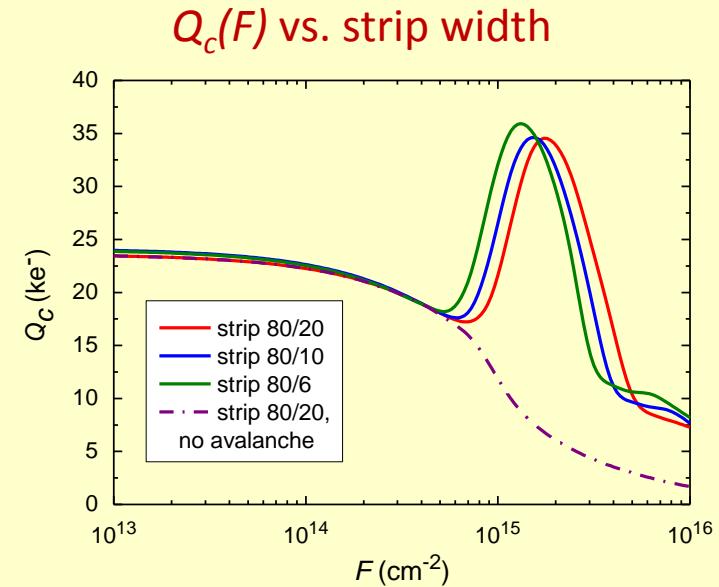
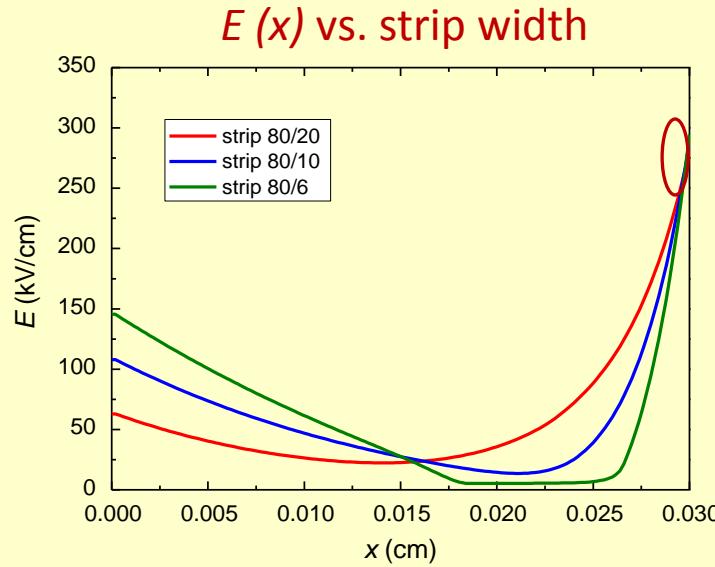


- ◆ competition of carrier trapping and avalanche multiplication  
→ non-monotonic behavior with a bump;
- ◆ at  $F \sim 10^{15} \text{ cm}^{-2}$  and 1800 V  $Q_c$  is close to  $25 \text{ ke}^-$ ;
- ◆ at  $V \geq 1500 \text{ V}$   $Q_{c\_max}$  is above  $24 \text{ ke}^-$ ;
- ◆ maximum  $Q_c$  of  $34 \text{ ke}^-$  at  $F \approx 2 \times 10^{15} \text{ cm}^{-2}$  and 1800 V

# Influence of detector geometry

## 1. Strip width $\rightarrow 20, 10, 6 \mu\text{m}$

Focusing of the electric field and current – special parameters vs. strip width



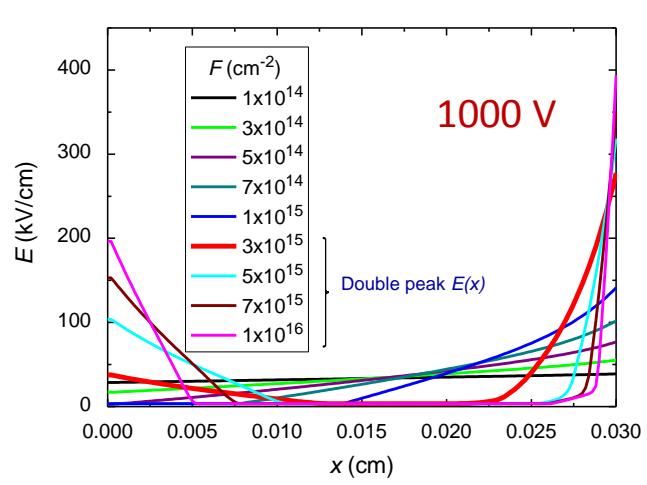
- ◆ Rise of the maximum  $Q_c$  due to focusing with strip width reduction  
→ the scale of the effect is rather small;
- ◆ Main effect - shift of  $Q_c$  enhancement towards lower  $F$

# Influence of detector geometry

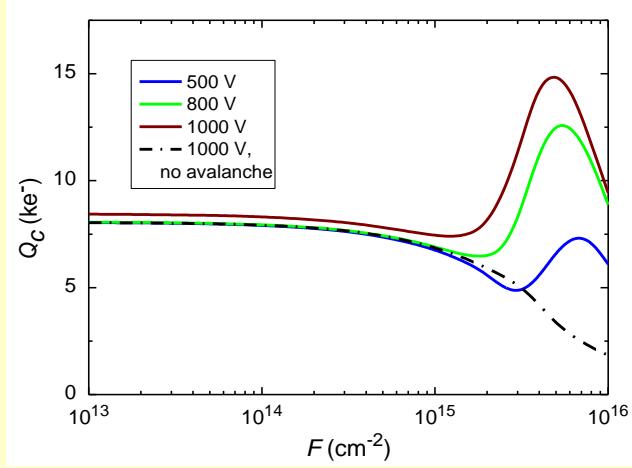
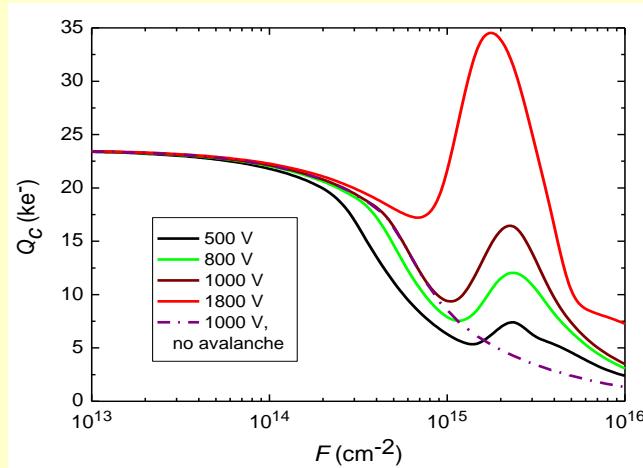
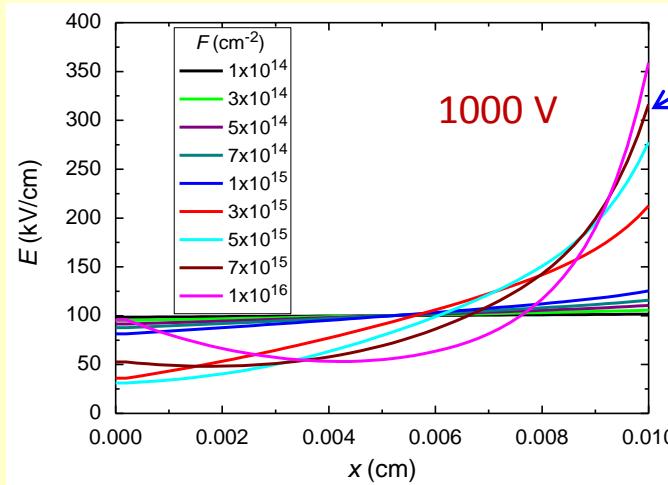
## 2. Different detector thickness → 300, 100 μm

1000 V, 253K

300 μm



100 μm

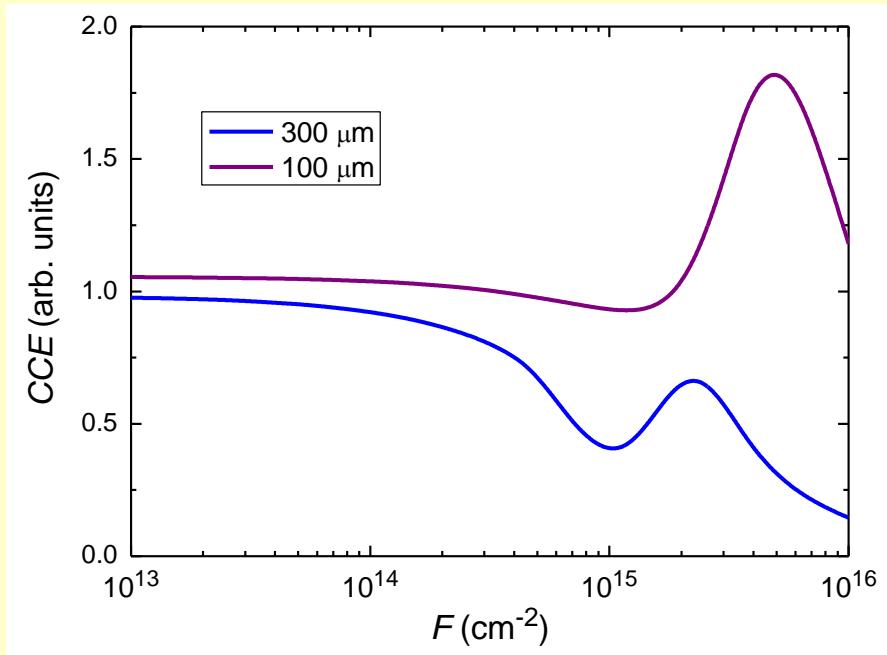


DP  
uniform

In thin detector  
 $DP E(x)$  and  
 $Q_{c\_max}$  are  
shifted to  
higher  $F$

# Influence of detector thickness on CCE

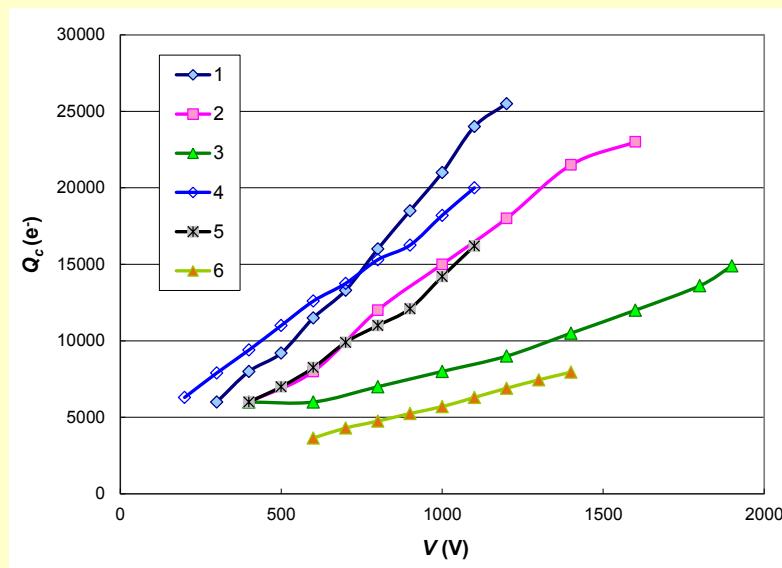
1000 V, 253K



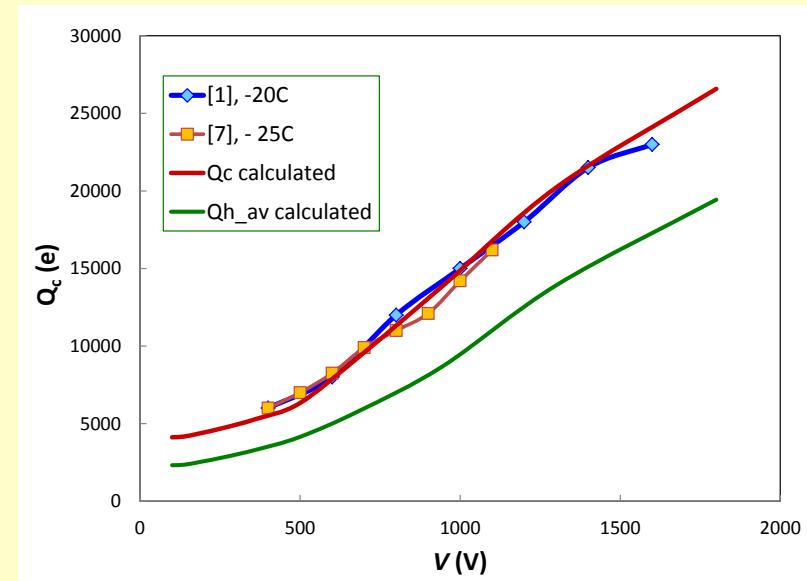
- ♦ Low electric field base region damps avalanche effect in 300  $\mu\text{m}$  detector
- ♦ **Reduction of the wafer thickness increases the collected charge more effectively than the electric field focusing at the strip with a smaller width**

# Analysis of experimental data

## Neutron irradiation



$$F = 3 \times 10^{15} \text{ n/cm}^2$$



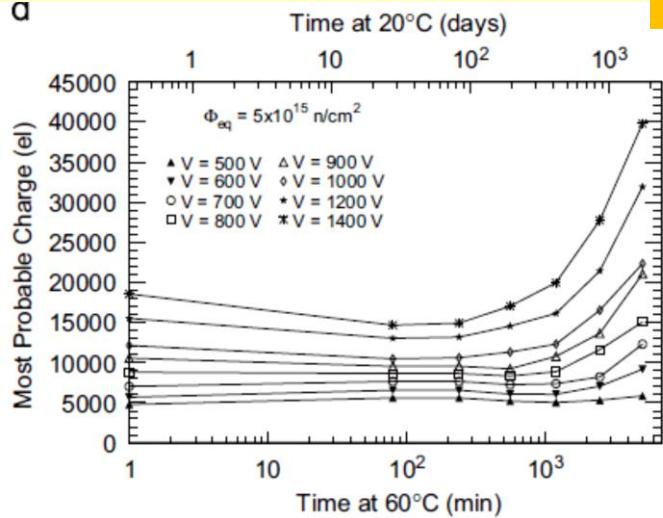
In legend:

- 1 - [2];  $1.6 \times 10^{15} \text{ cm}^{-2}$ ;  $-40^\circ\text{C}$
- 2 - [1];  $3 \times 10^{15} \text{ cm}^{-2}$ ;  $-20^\circ\text{C}$
- 3 - [2];  $1 \times 10^{16} \text{ cm}^{-2}$ ;  $-40^\circ\text{C}$
- 4 - [7];  $1 \times 10^{15} \text{ cm}^{-2}$ ;  $-25^\circ\text{C}$
- 5 - [7];  $3 \times 10^{15} \text{ cm}^{-2}$ ;  $-25^\circ\text{C}$
- 6 - [7];  $1.5 \times 10^{16} \text{ cm}^{-2}$ ;  $-25^\circ\text{C}$

- Nice agreement at  $3 \times 10^{15} \text{ cm}^{-2}$
- $Q_c$  enhancement is larger at lower  $T$  (*as in the model*)
- Agreement between experiment and simulation
- Dominant contribution of multiplied holes to  $Q_c$

# Very abnormal $Q_c$ enhancement

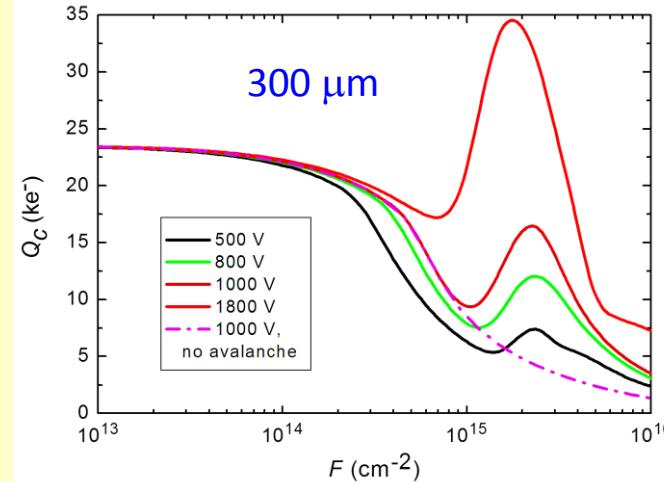
## Experiment



$$K_{enh} = Q_{c\text{-max}} / Q_{mip}$$

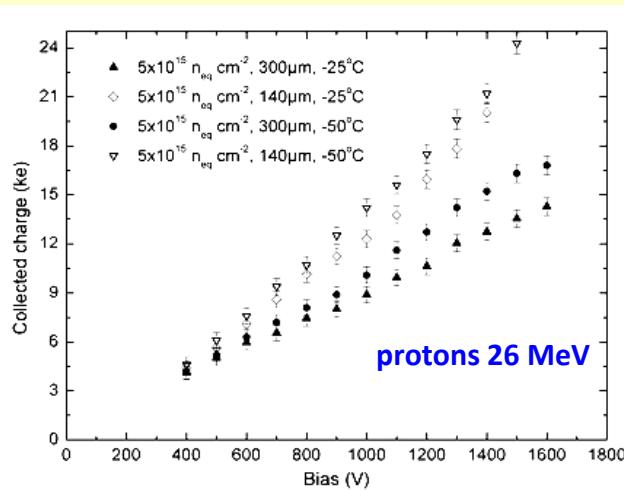
300  $\mu m$ :  
 $Q_{c\text{-max}} = 40 ke$   
 $K_{enh} = 1.7$  [8]

## PTI model



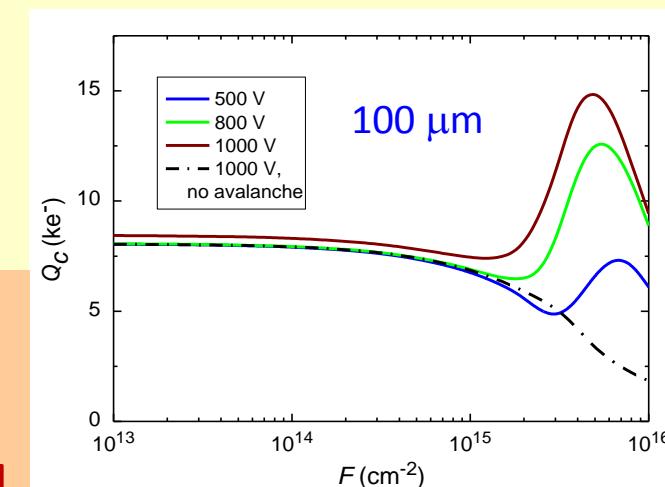
-20°C

300  $\mu m$ :  
 $Q_{c\text{-max}} = 35 ke$   
 $K_{enh} = 1.45$



140  $\mu m$ ; -25°C:  
 $Q_{c\text{-max}} = 20 ke$   
 $K_{enh} = 1.75$  [5]

3D detectors:  
 $Q_{c\text{-max}} = 42 ke$   
 $K_{enh} \approx 2$   
 $V = 200 V$  [11]



-20°C

100  $\mu m$ :  
 $Q_{c\text{-max}} = 15 ke$   
 $K_{enh} = 1.9$

# Consideration on trapping centers

PTI model: DD  $E_v + 0.48$  eV; DA  $E_c - 0.53$  eV

Defect Identity	method	Trap parameters	
		$E_t$ [eV]	$\sigma_{n,p}$ [ $\text{cm}^{-2}$ ]
V-O <sub>i</sub>	DLTS	$E_v - 0.169$	$1.0 \times 10^{-14}$
C <sub>i</sub> C <sub>s</sub>	DLTS	$E_v + 0.17$	
		$E_v + 0.171$	$1.44 \times 10^{-14}$
V <sub>2</sub> <sup>+</sup>	EPR	$E_v + 0.25$	
		$E_v + 0.21$	$2 \times 10^{-16}$
V <sub>2</sub> <sup>-</sup>	DLTS/TSC	$E_c - 0.246$	$4 \times 10^{-16} e^{-0.017/kT}$
		$E_c - 0.23$	$2 \times 10^{-16}$
C <sub>i</sub>	DLTS	$E_v + 0.3$	
		$E_v + 0.33$	$9 \times 10^{-14}$
C <sub>i</sub> O <sub>i</sub>	EPR		
	PL		
	DLTS	$E_v + 0.38$	$2.5 \times 10^{-15}$
	TCT	$E_v + 0.36$	$1.2 \times 10^{-15}$
V <sub>2</sub> <sup>+</sup>	EPR	$E_c - 0.4$	
	PL	$E_c - 0.4$	
	DLTS	$E_c - 0.41$	$2 \times 10^{-15}$
P-V	EPR		
	HE	$E_c - 0.4$	
	DLTS	$E_c - 0.456$	$3.7 \times 10^{-15}$
	DLTS	$E_c - 0.49$	$6.6 \times 10^{-16}$
	TSC	$E_c - 0.48$	$4 \times 10^{-15}$
Si <sub>i</sub> related No assessed identity	TCT	$E_c - 0.52$	
		$E_v + 0.48$	$5.5 \times 10^{-15}$
		$E_v + 0.51$	$1 \times 10^{-14}$
	DLTS/TCT		

M. Bruzzi, *IEEE Trans. NS-48* (2001) 960-971

## TCT:

$E_c - 0.52$  eV – electron trap  
 $E_v + 0.51$  eV – hole trap

*E. Fretwurst, V. Eremin, et al., NIM A 388 (1997) 356;  
Z.Li, C.J.Li, V.Eremin, E.Verbitskaya, NIM A 388 (1997) 297*

## TSC:

$E_v + 0.48$  eV (0.46) – hole trap

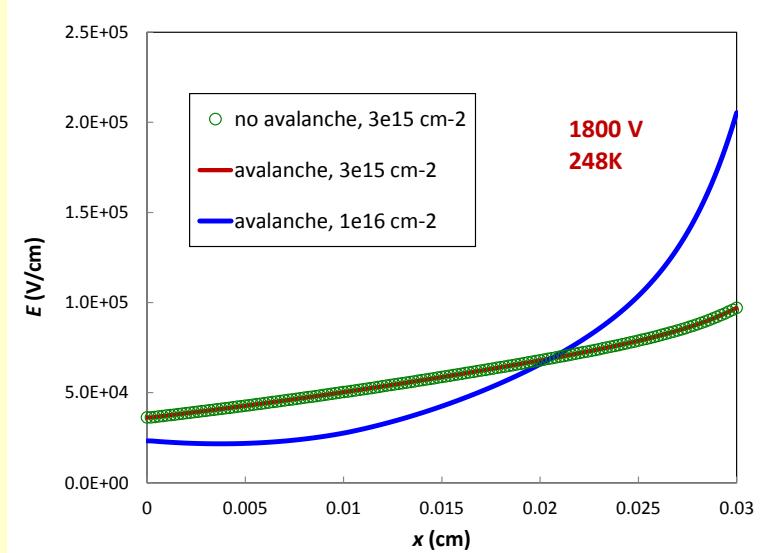
*U. Biggeri, E. Borchi, et al., NIM A 409 (1998) 176;  
M. Moll, Ph.D. dissertation, Univ. of Hamburg, Hamburg, Germany, 1999*

# Alternative traps

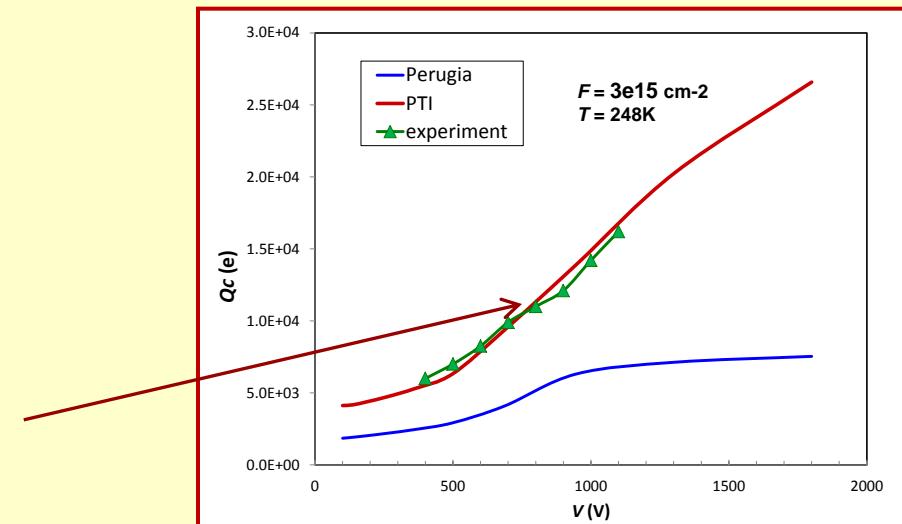
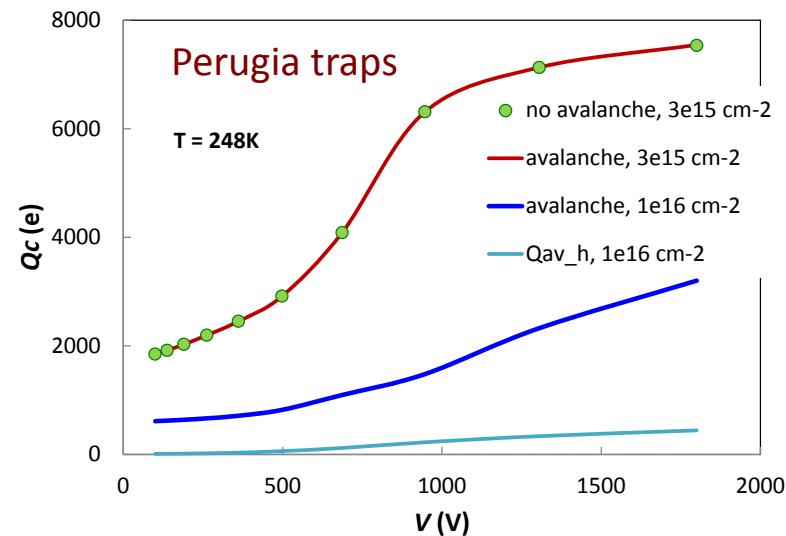
D. Pennicard, et al., NIM A 592 (2008) 16

Type	Energy (eV)	Defect	$\sigma_e$ (cm $^2$ )	$\sigma_h$ (cm $^2$ )	$\eta$ (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	$5.0 \times 10^{-15}$	$5.0 \times 10^{-14}$	0.9
Donor	$E_V + 0.36$	C <sub>1</sub> O <sub>1</sub>	$*3.23 \times 10^{-13}$	$*3.23 \times 10^{-14}$	0.9

Asterisks indicate the values that have been changed.



Agreement with experiment are obtained with midgap levels only



## *Signal to noise ratio*

Achieving of good performance →  $S/N$  should be above 8

$N \approx 1000$  ENC - strip detectors 320  $\mu\text{m}$  thickness, 6 cm length and 75  $\mu\text{m}$  pitch irradiated to  $(1-5) \times 10^{15} \text{ n}_{\text{eq}} \text{cm}^{-2}$  and connected to SCT128A readout ASIC [8]

$S/N \approx 8$  can be realized

at  $F = (1-5) \times 10^{15} \text{ n}_{\text{eq}} \text{cm}^{-2}$  - in avalanche mode at  $V \geq 1500 \text{ V}$  since  $Q_c > 11 \text{ ke}^-$

$F \approx 1 \times 10^{16} \text{ n}_{\text{eq}} \text{cm}^{-2}$  - the  $S/N$  ratio may go down

Conversely, with shorter strips and better electronics, an adequate  $S/N$  should be achievable at lower voltage

## *Conclusions*

In avalanche multiplication mode:

- ✓  $Q_c$  enhancement occurs when  $E(x)$  distribution transforms to a DP profile and results in self-stabilization of the electric field at the  $n^+$  strip at 300 kV/cm regardless of  $T$  and  $F$
- ✓ Minimal bias voltage at which  $Q_c$  rise starts is 500 V (at  $F = 3 \times 10^{15} \text{ cm}^{-2}$ )
- ✓ Maximal  $Q_c$  is above the charge collected in nonirradiated detector!

**PTI model gives an adequate description of the experimental results**

*Main results were presented at PSD9, Sept 2011  
and are published: E.Verbitskaya, V. Eremin, A.  
Zabrodskii, 2012, J. Instrum., v.7, 2 ArtNo: #C02061*

## *Acknowledgments*

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

- Fundamental Program of Russian Academy of Sciences  
on collaboration with CERN,
- RF President Grant # SS-3008.2012.2

*Thank you for attention!*