Silicon Sensors for HL-LHC Tracking Detectors
- RD50 Status Report

Igor Mandić
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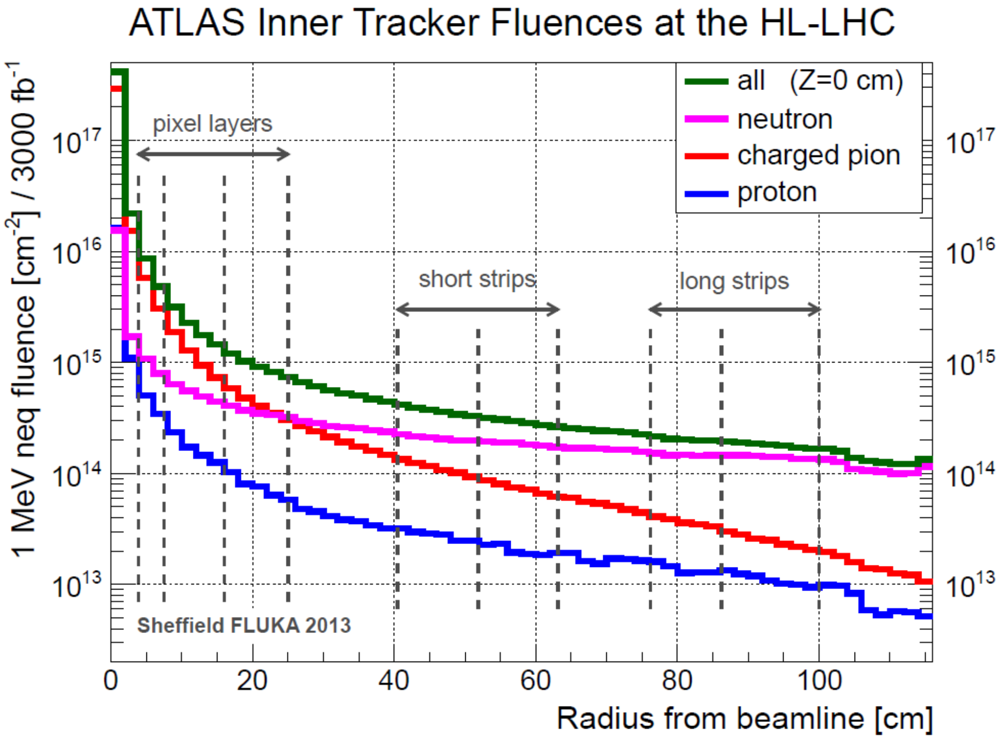
On behalf of RD50 collaboration

LHC Upgrade

- upgrade of the LHC to High Luminosity LHC (**HL-LHC**) after 2021
- expected integrated luminosity 3000 fb^{-1}



[I. Dawson, P. S. Miyagawa , Atlas Upgrade radiation background simulations]

Silicon detectors will be exposed to hadron fluences equivalent to more than 10^{16} n/cm^2
➔detectors used now at LHC cannot operate after such irradiation

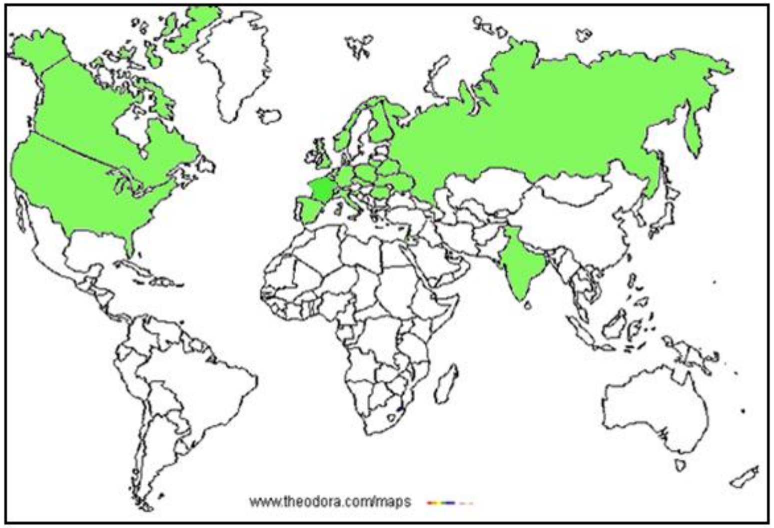
RD50 mission: development of silicon sensors for HL-LHC

RD50 Collaboration

- RD50: *49 institutes and 263 members*

39 European and Asian institutes

Belarus (Minsk), Belgium (Louvain), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), France (Paris), Germany (Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe, Munich), Italy (Bari, Florence, Padova, Perugia, Pisa, Trento), Lithuania (Vilnius), Netherlands (NIKHEF), Norway (Oslo)), Poland (Krakow, Warsaw(2x)), Romania (Bucharest (2x)), Russia (Moscow, St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona(2x), Santander, Valencia), Switzerland (CERN, PSI), Ukraine (Kiev), United Kingdom (Glasgow, Liverpool)



8 North-American institutes

Canada (Montreal), USA (BNL, Fermilab, New Mexico, Purdue, Santa Cruz, Syracuse)

1 Middle East institute

Israel (Tel Aviv)

1 Asian institute

India (Delhi)

Detailed member list: http://cern.ch/rd50

RD50 Collaboration

Co-Spokespersons

Gianluigi Casse **and** ***Michael Moll***

(Liverpool University) (CERN PH-DT)

Defect / Material Characterization

Mara Bruzzi

(INFN & Uni Florence)

Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation

- WODEAN: Workshop on Defect Analysis in Silicon Detectors (G.Lindstroem & M.Bruzzi)

Detector Characterization

Eckhart Fretwurst

(Hamburg University)

- **Characterization of test structures (IV, CV, CCE, TCT,.)**
- **Development and testing of defect engineered silicon devices**
- **EPI, MCZ and other materials**
- **NIEL**
- **Device modeling**
- **Operational conditions**
- **Common irradiations**
- New Materials (E.Verbitskaya)
- Wafer procurement (M.Moll)
- **Simulations** (V.Eremin)

New Structures

Giulio Pellegrini (CNM Barcelona)

- **3D detectors**
- **Thin detectors**
- **Cost effective solutions**
- **Other new structures**

- Semi 3D (Z.Li)
- Thinned detectors
- Slim Edges (H.Sadrozinski)
- Low Resistivty Strips(M. Ullan)

Full Detector Systems

Gregor Kramberger

(JSI Ljubljana)

- **LHC-like tests**
- **Test beams**
- **Links to HEP**
- **Links electronics R&D**
- **Comparison:**
  - **pad-mini-full detectors**
  - **different producers**

- Pixel Europe (T.Rohe)
- Pixel US (D.Bortoletto)
- Test beams (G.Casse)

Collaboration Board Chair & Deputy: G. Kramberger(Ljubljana) & J.Vaitkus (Vilnius), Conference committee: U.Parzefall (Freiburg)
CERN contact: M.Moll (PH-DT), Secretary: V.Wedlake (PH-DT), Budget holder & GLIMOS: M.Glaser (PH-DT)

Defect Characterization

- Identify radiation induced defects responsible for trapping, leakage current, change of N_{eff}
  → experimental tools:

  - C–DLTS: Capacitance Deep Level Transient Spectroscopy
  - I-DLTS: Current Deep Level Transient Spectroscopy
  - TSC: Thermally Stimulated Currents
  - PITS: Photo Induced Transient Spectroscopy
  - FTIR: Fourier Transform Infrared Spectroscopy
  - RL: Recombination Lifetime Measurements
  - PC: Photo Conductivity Measurements
  - EPR: Electron Paramagnetic Resonance
  - TCT: Transient Charge Technique
  - C-V/I-V

➔ Over 240 samples irradiated with protons, neutrons , electrons, ^{60}Co gamma

➔ … significant impact of RD50 results on silicon solid state physics – defect identification

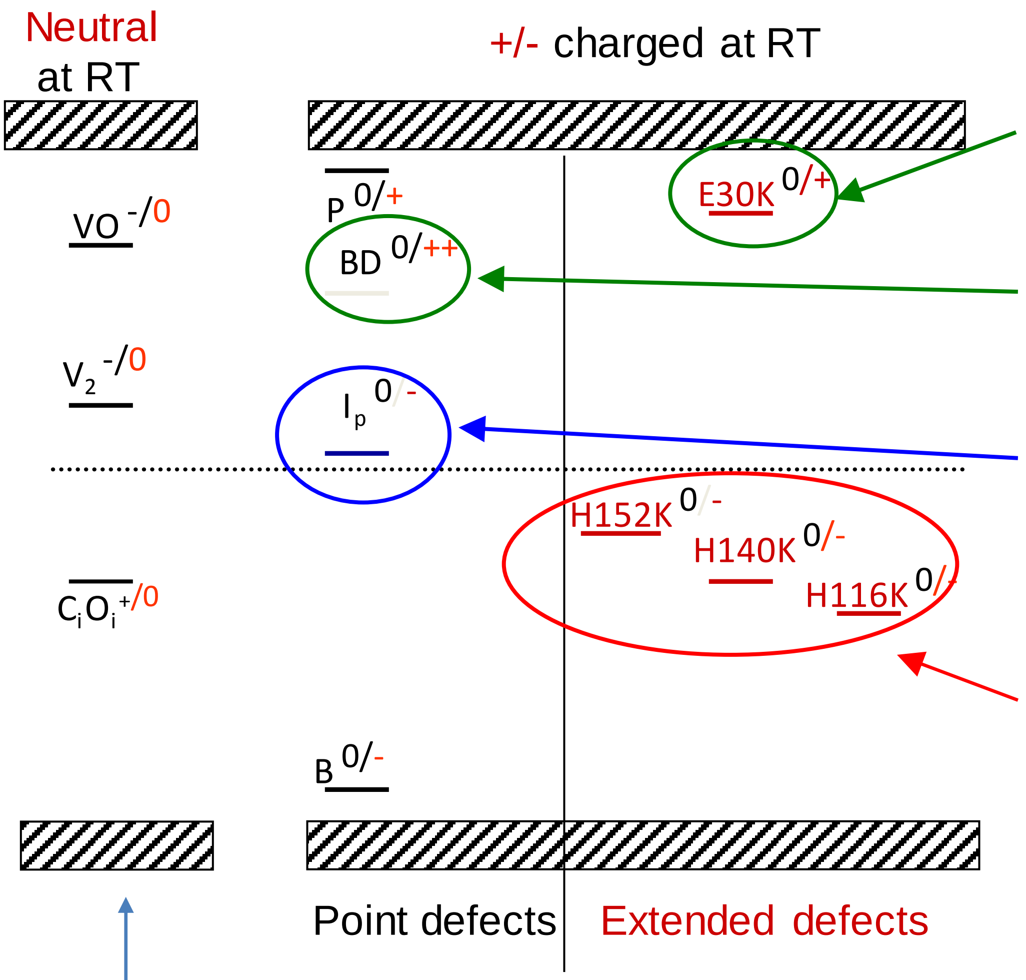
Defect Characterization

Point defects

- $E_i^{BD} = E_c - 0.225$ eV
  $\sigma_n^{BD} = 2.3 \cdot 10^{-14}$ cm^2
- $E_i^{I} = E_c - 0.545$ eV
  $\sigma_n^{I} = 1.7 \cdot 10^{-15}$ cm^2
  $\sigma p^{I} = 9 \cdot 10^{-14}$ cm^2

Cluster related centers (extended defects)

- $E_i^{H116K} = E_v + 0.33$eV
  $\sigma_p^{H116K} = 4 \cdot 10^{-14}$ cm^2
- $E_i^{H140K} = E_v + 0.36$eV
  $\sigma_p^{H140K} = 2.5 \cdot 10^{-15}$ cm^2
- $E_i^{H152K} = E_v + 0.42$eV
  $\sigma_p^{H152K} = 2.3 \cdot 10^{-14}$ cm^2
- $E_i^{E30K} = E_c - 0.1$eV
  $\sigma_n^{E30K} = 2.3 \cdot 10^{-14}$ cm^2



positive charge
(higher introduction after proton irradiation than after neutron irradiation)

positive charge
(high concentration in oxygen rich material)

leakage current + neg. charge
(current increase after γ irradiation)

Negative charge, reverse annealing
(neg. charge, concentration increases with annealing)

Neutral defects:
trapping centers decrease charge collection

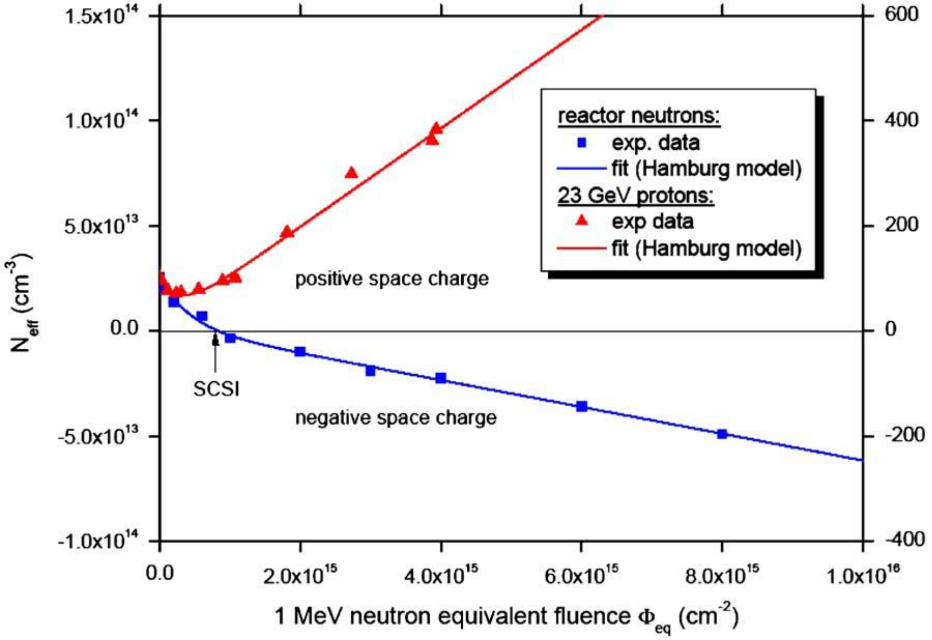
[Pintilie, Fretwurst, Lindstroem, Appl. Phys. Lett.92 024101,2008]
[Pintilie, Lindstroem, Junkes, Fretwurst, NIM A 611 (2009) 52–68]

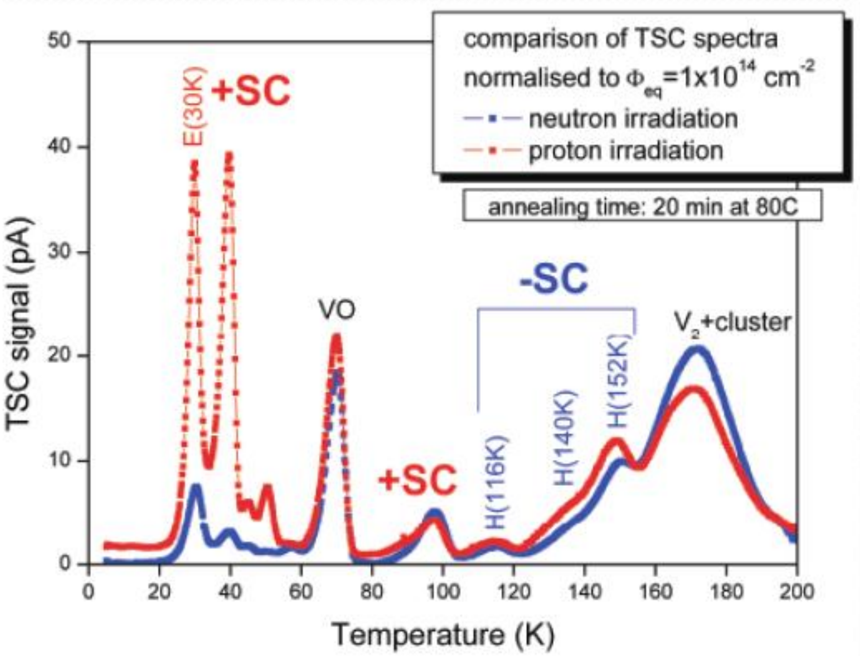
Defect Characterization: N_{eff} change

Example:

N_{eff} change in epitaxial silicon explained with TSC results

[RD50 collaboration (A. Affolder et al), NIMA 658 (2011) 11–16]





Epitaxial silicon:

- Space Charge Sign Inversion after reactor neutron irradiation
- no inversion after 23 GeV proton irradiation

➔ TSC spectra: much larger donor (E(30K)) generation after proton irradiation

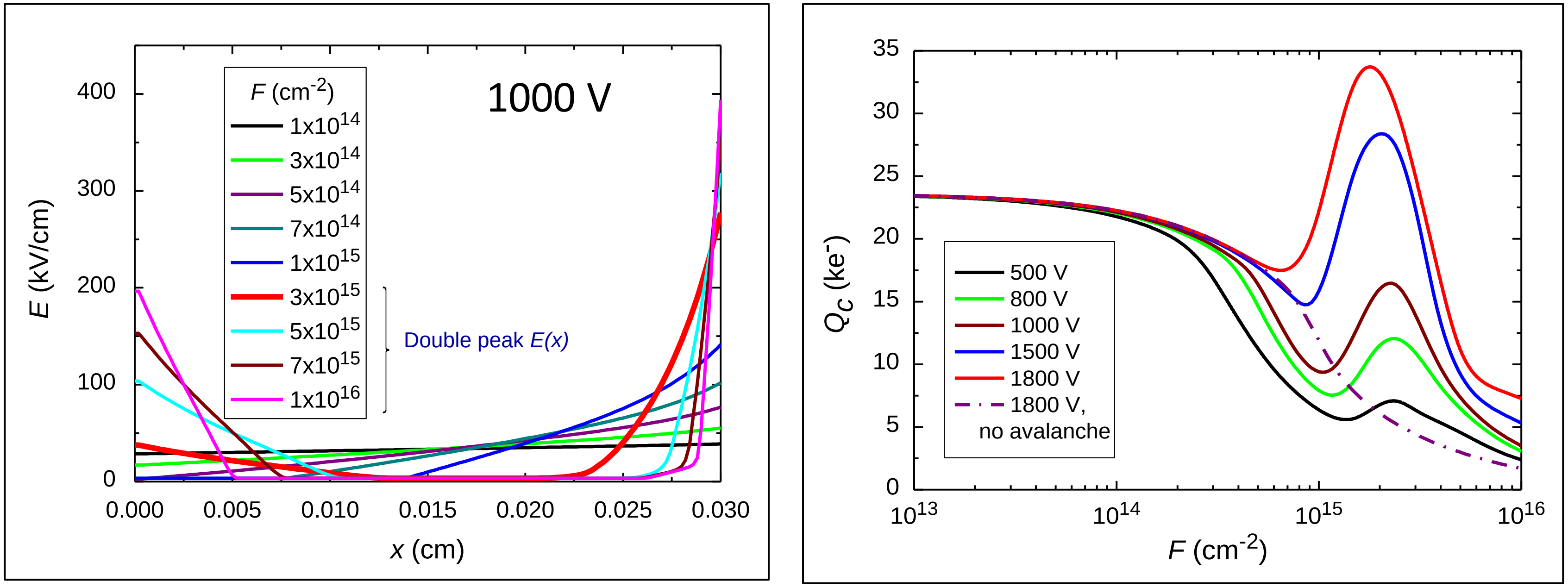
Simulation

Simulation task group formed in RD50 (lead by V. Eremin, Ioffe Inst.)

- ➔ use TCAD and/or custom made software
- ➔ simulate macroscopic behavior (electric field (TCT signal), charge collection, multiplication…)

Example (custom made simulation):

- n^+p strip detector; 300 μm thick; 20 μm strip width; 80 μm pitch
- two effective deep levels contribute to N_{eff} and trapping
- leakage current influences N_{eff} by charging the deffects
  - → predicts double peak electric field
  - → increase of collected charge at high fluences and bias voltages due to multiplication

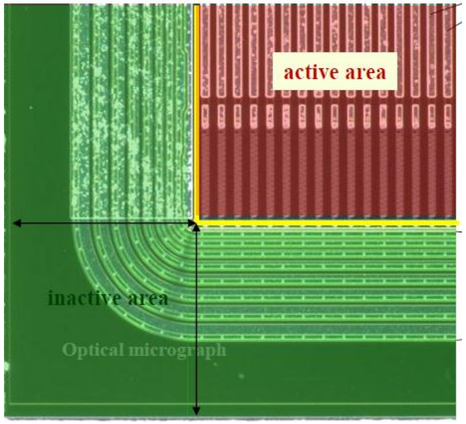


[E.Verbitskaya, 20th RD50 Workshop, Bari, 2012]

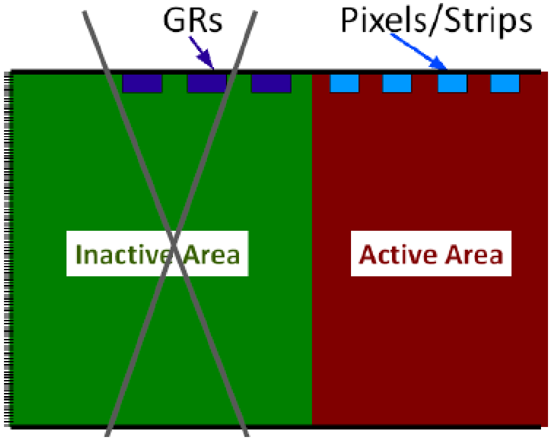
Slim Edges

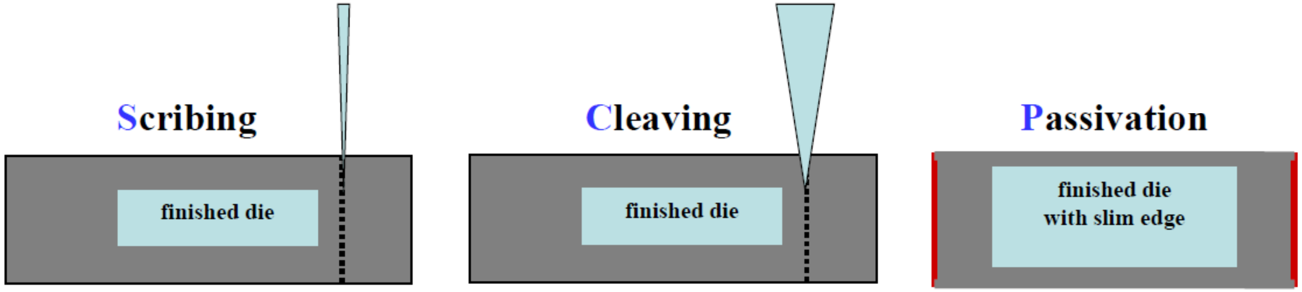
Reduce the inactive area of sensor

Example: **S**cribing **C**leaving **P**assivation (SCP) method



Guard Rings





Laser or
XeF2 etching

tweezers or
automated cleaving
machine

n-type: oxide
p-type: alumina (with ALD)

[V. Fadeyev, 20th RD50 Workshop, Bari, 2012]

- **work going on also on other methods to reduce inactive area: active edge, guard rings on back side in n-in-n type sensors**
  → see talk by A. Macchiolo at this conference

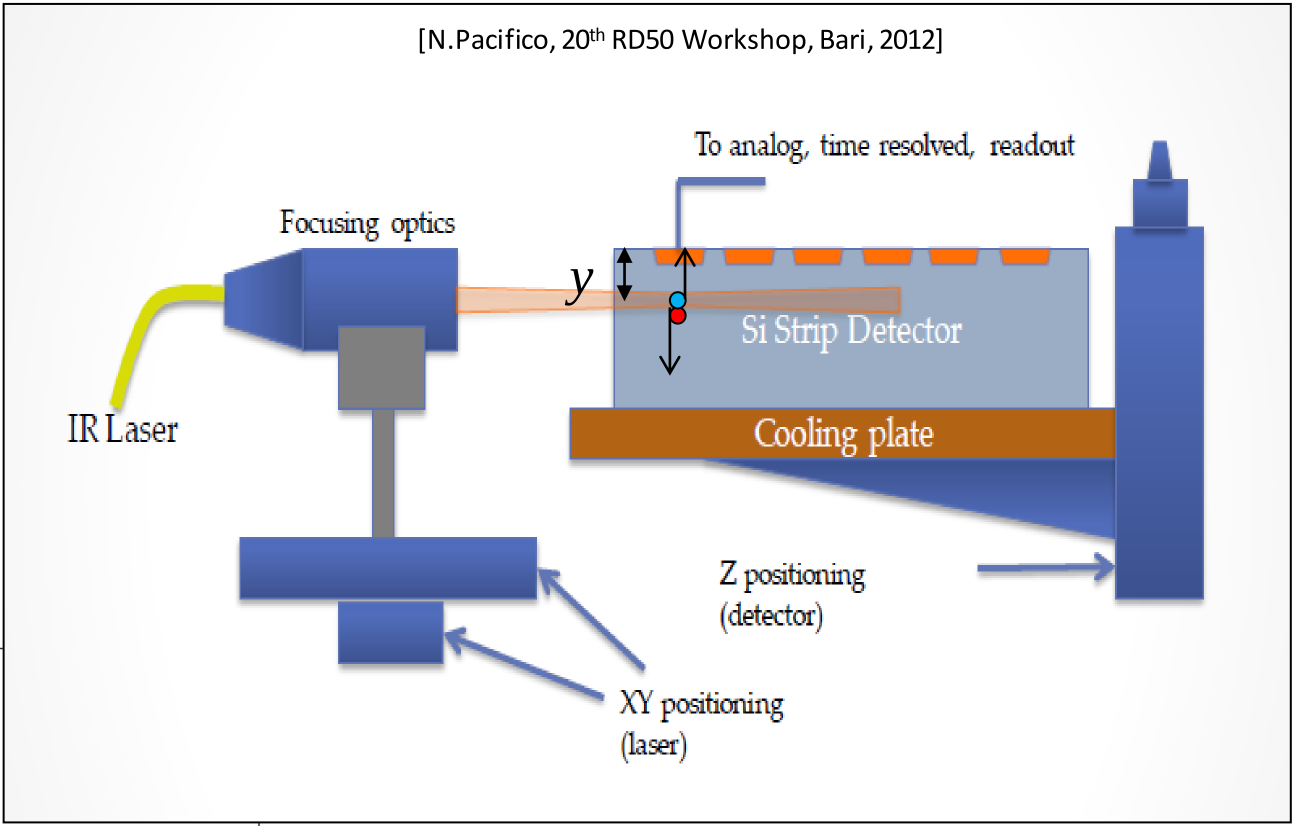
Edge – Transient Current Technique (Edge-TCT)

[G. Kramberger, IEEE TNS, VOL. 57, NO. 4, AUGUST 2010, 2294]

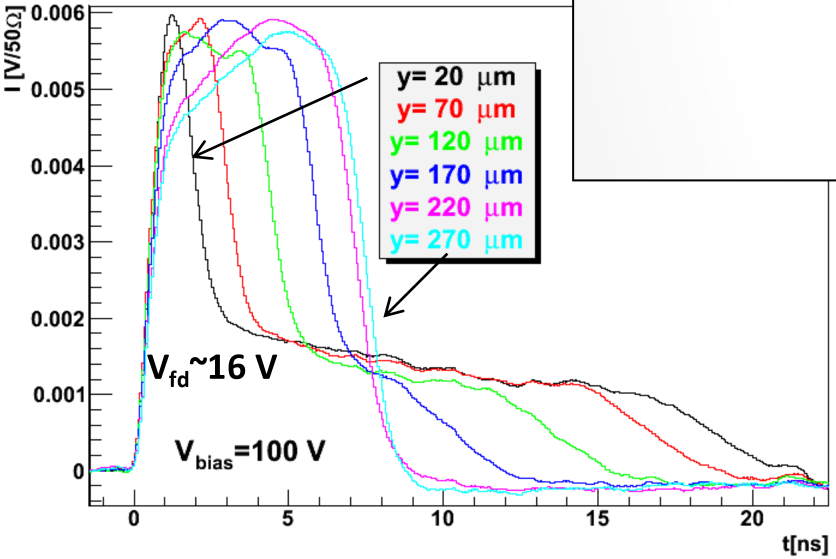
- Illuminate segmented sensor from the side with fast (sub-ns), focused (10 µm) infrared laser pulses

- Scan across the detector thickness

- Record current pulses as function of depth



[N.Pacifico, 20th RD50 Workshop, Bari, 2012]



G. Kramberger, 17th RD50 Workshop, 2010

Charge collection profile:

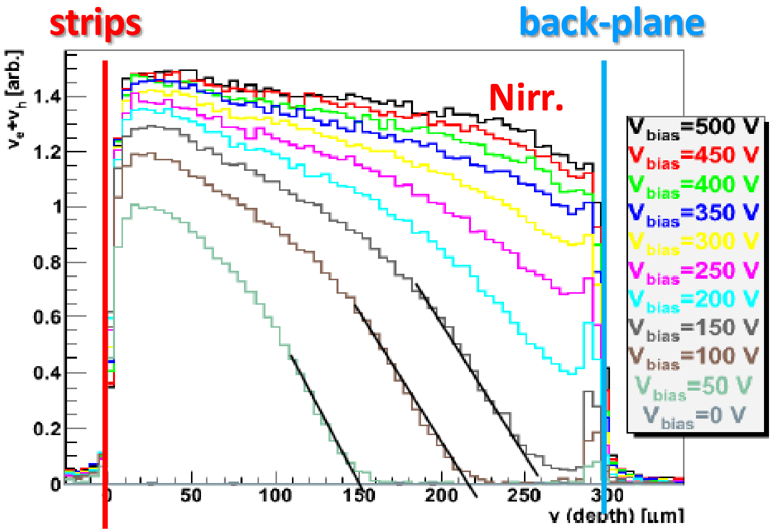
$$Q(y) = \int_{0}^{25ns} I(y,t)dt$$

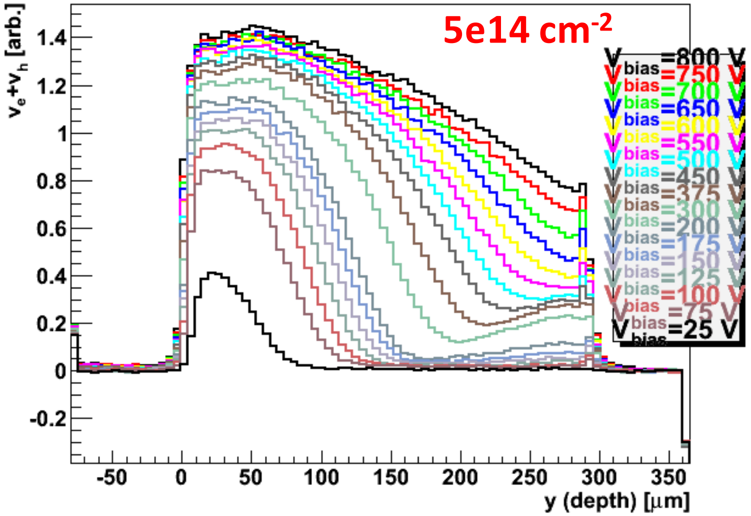
Velocity profile:

$$(v_e + v_h)(y, t \sim 0) \propto I(y, t \sim 0)$$

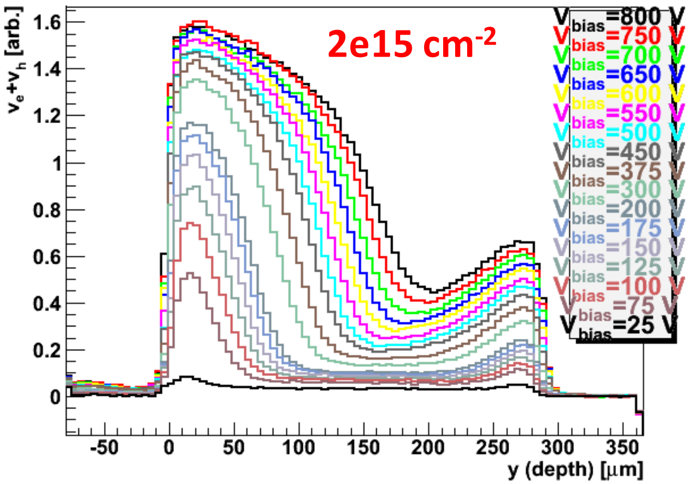
E – TCT, velocity profiles

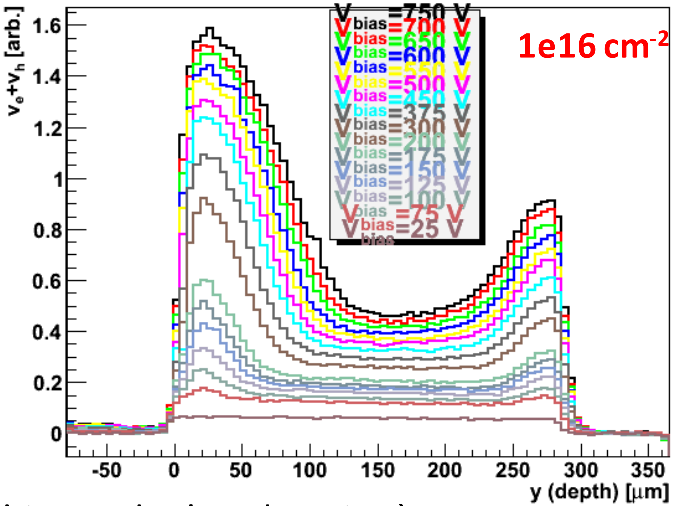
HPK, Fz-p, V_{fd}~180 V, strips at 80 um pitch, neutron irradiated, 80min@60°C, different bias voltages





[G. Kramberger, Vertex 2012]



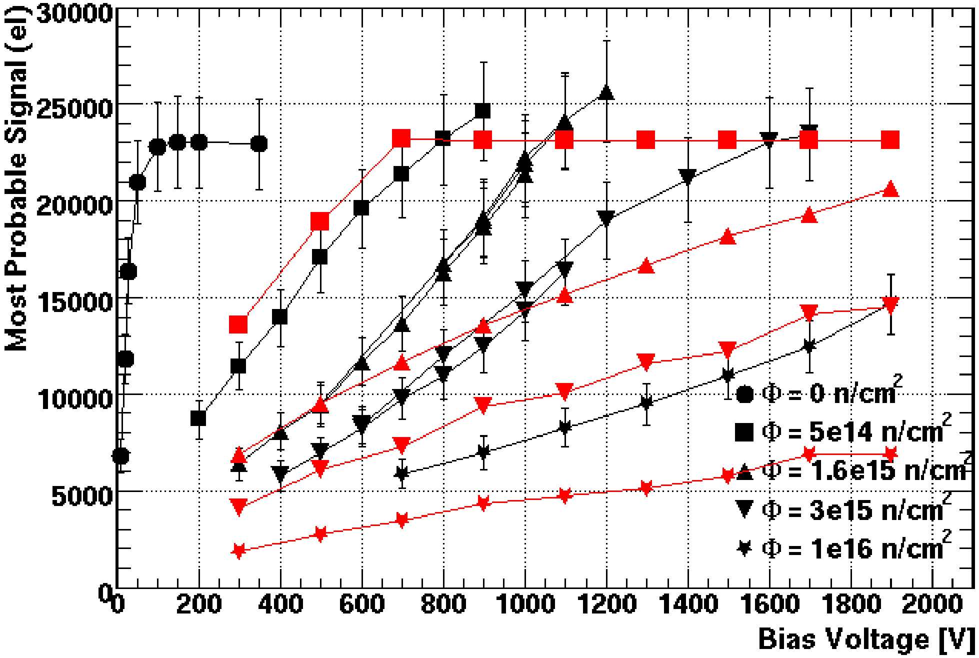


- Before irradiation: "standard" behaviour (V_{fd}, no field in un-depleted region)
- High fluences: non-zero carrier velocity in whole detector also at low voltages, **double peak**

➔ **electric field in whole detector although V_{fd} > 10000 V**

Charge Multiplication

- CCE measured with p-type Si microstrip detectors irradiated to high fluences and biased with high voltages shows evidence of charge multiplication effect: **100% CCE seen after 3x10^{15} n/cm^2, 15000 electrons after 10^{16}n/cm^2**



[RESMDD 2008., I. Mandić et al., NIMA 612 (2010) 474–477]

Red: calculations based on N_{eff} and trapping measurements at lower fluences

Black: measurements

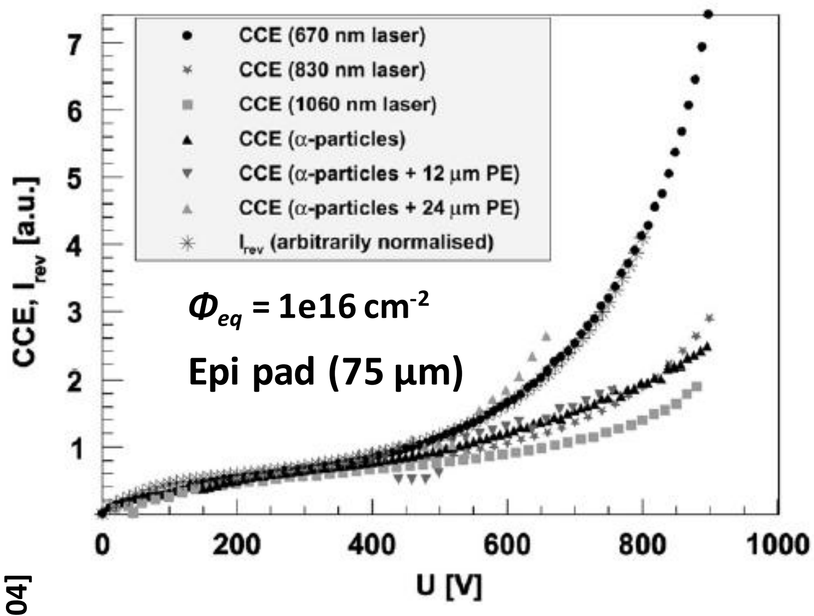
At high bias and high fluence:
measured >> **expected**

- high negative space charge concentration in detector bulk because of irradiation
  → high electric field close to the n-type strips
  ➔ **impact ionization!**

Charge Multiplication

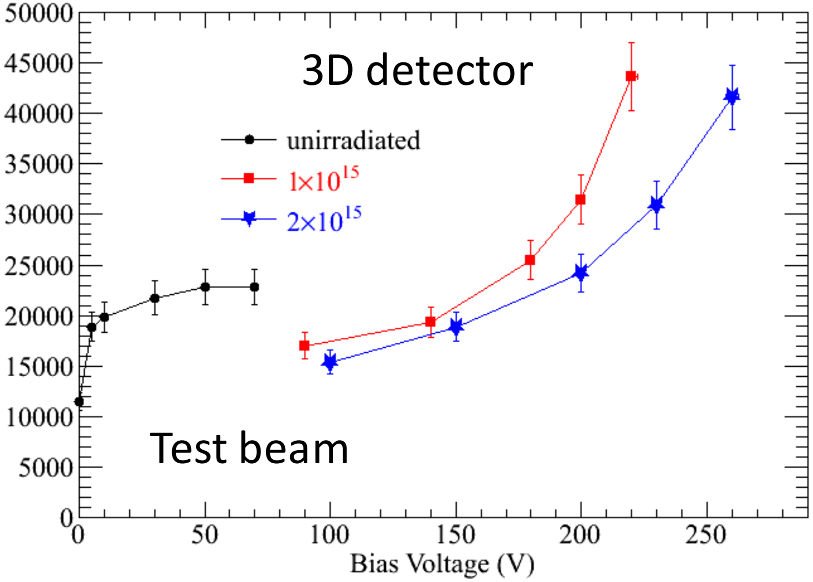
Charge Multiplication measured after high levels of irradiation with different techniques and in several different types of devices

[J. Lange et al., NIMA622 (2010) 49-58.]



Φ_{eq} = 1e16 cm^{-2}

Epi pad (75 µm)



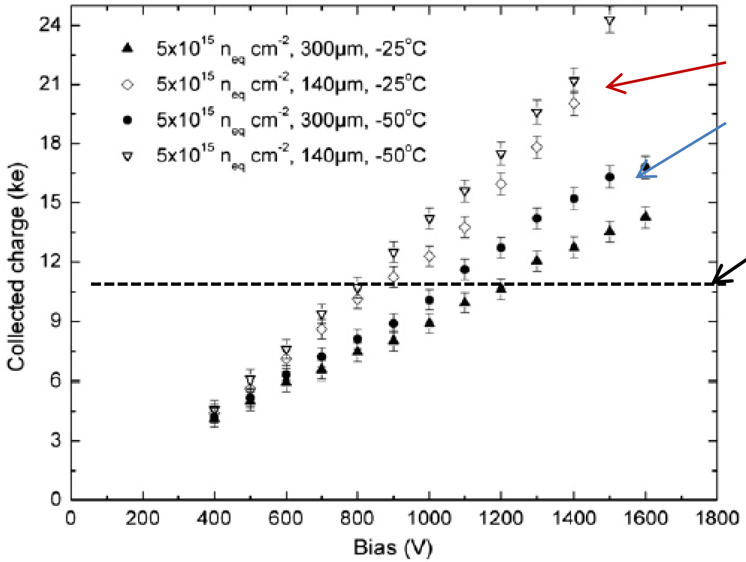
3D detector

Test beam

[M. Koehler et al., (2011) NIMA659 272-281]

[A. Affolder et al., (2011) NIMA658 11-16]

[G. Casse et al., NIMA 624, 2010, 401-404]



140 µm

300 µm

Full charge for 140 µm thick detector

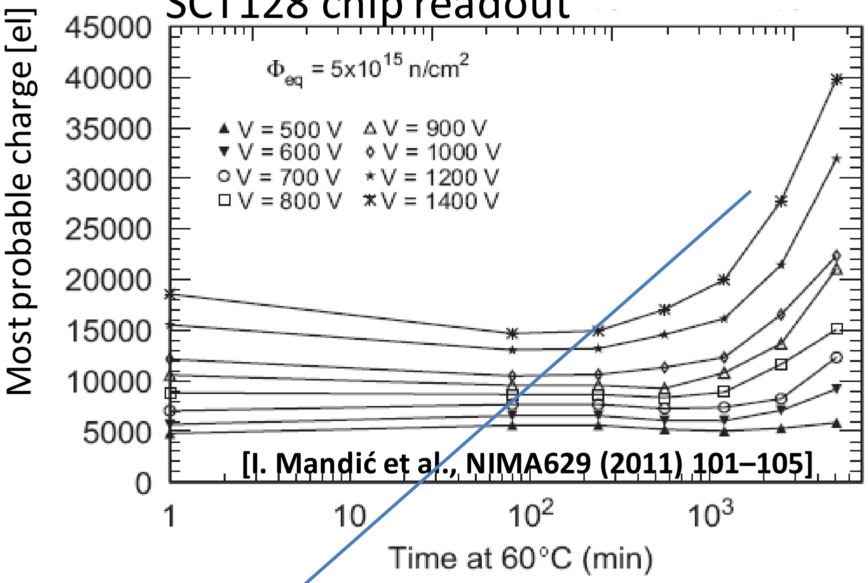
Strip detectors irradiated to Φ_{eq} = 5e15 cm^{-2}
^{90}Sr, alibava readout

Charge(140 µm) > Charge(300 µm)

➔thinner sensors give more charge at very high fluences

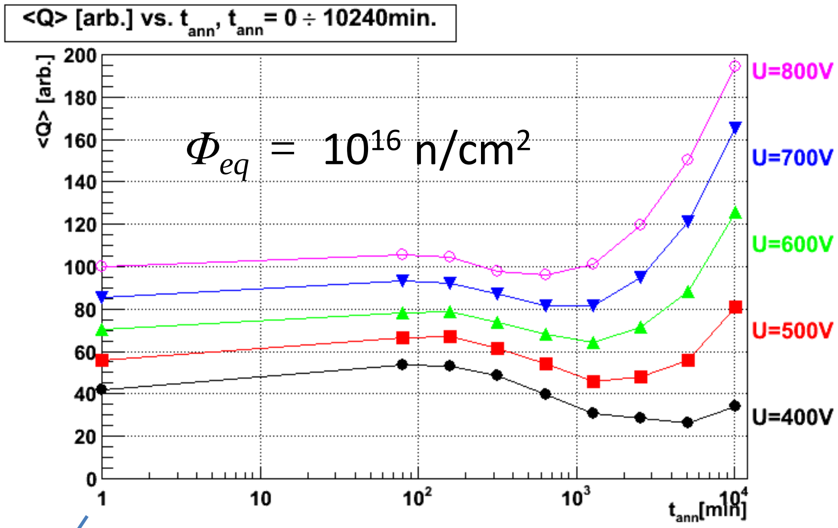
Charge multiplication: annealing

SCT128 chip readout

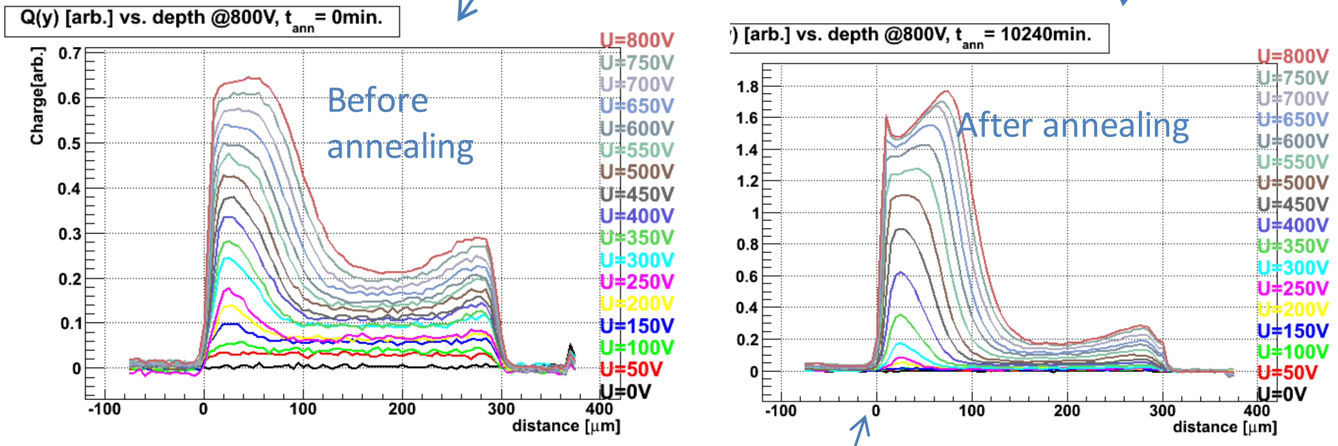


[I. Mandić et al., NIMA629 (2011) 101–105]

E-TCT



N_{eff} increases with long term annealing ➔ collected charge increases at high voltages because of multiplication



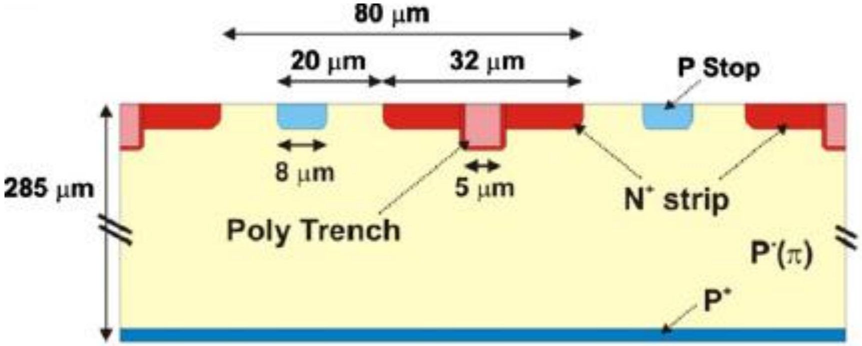
[M. Milovanović et al., 2012 JINST 7 P06007]

Increase of collected charge near strips → multiplication!

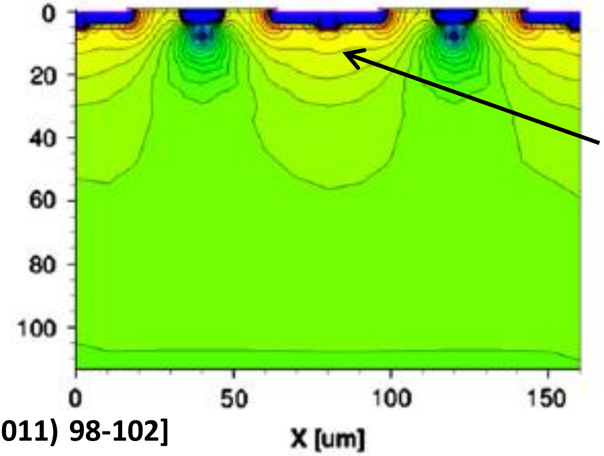
Charge multiplication: enhance the effect

Junction engineering :

- 5 µm wide trench in the middle of the implant
- depth of the trench: 5, 10 or 50 µm

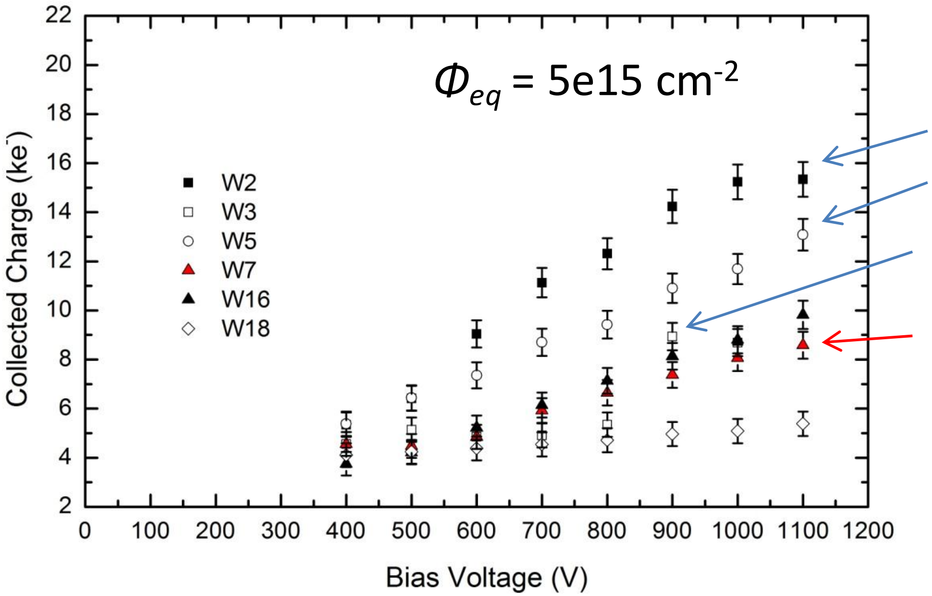


Calculation of E field, $\Phi_{eq} = 0$.



Increased electric field at the trench

[P. Fernandez –Martinez et al., NIMA 658 (2011) 98-102]



5 µm

50 µm

10 µm

standard

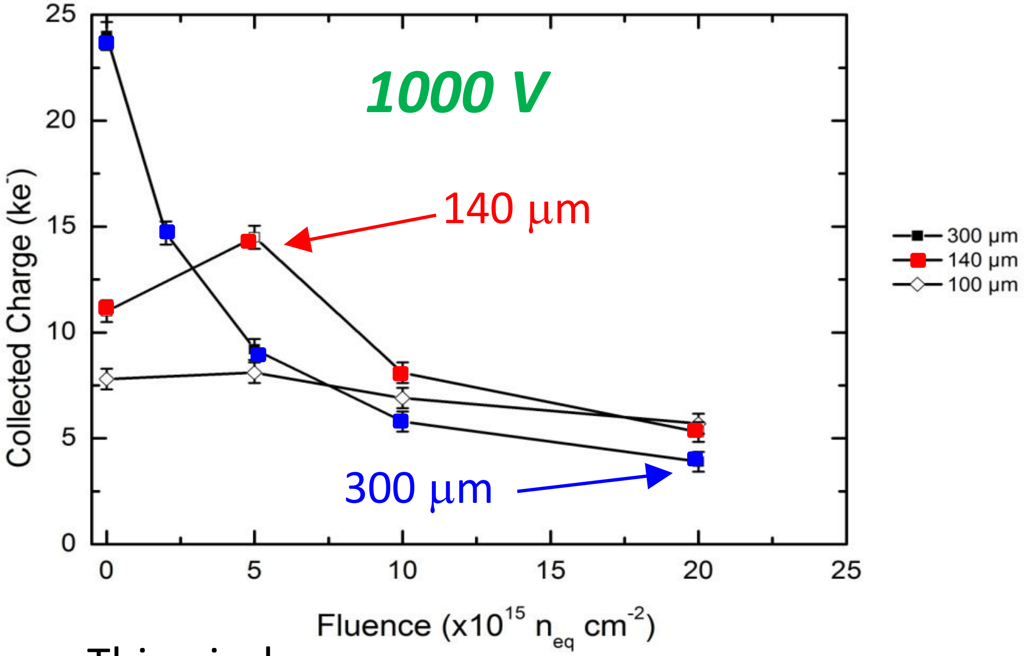
Large effect of 5 µm and 50 µm deep trench after irradiation!

[G.Casse, Trento Workshop, Feb.2012]

[G. Casse et al., NIMA 699 (2013) 9-13]

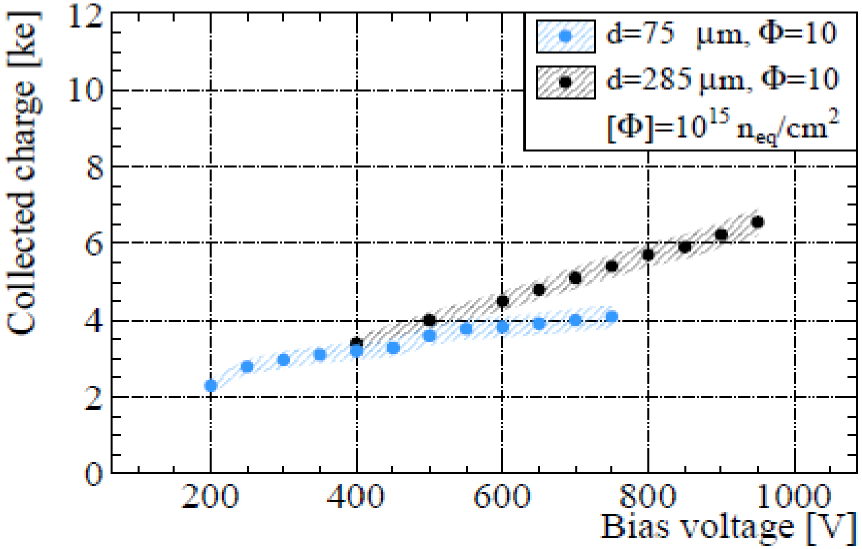
Thin sensors

[G.Casse, 20th RD50 Workshop, Bari, May 2012]



Thin strips detectors:
at extreme fluences more charge
with thin sensors

Thin pixels:



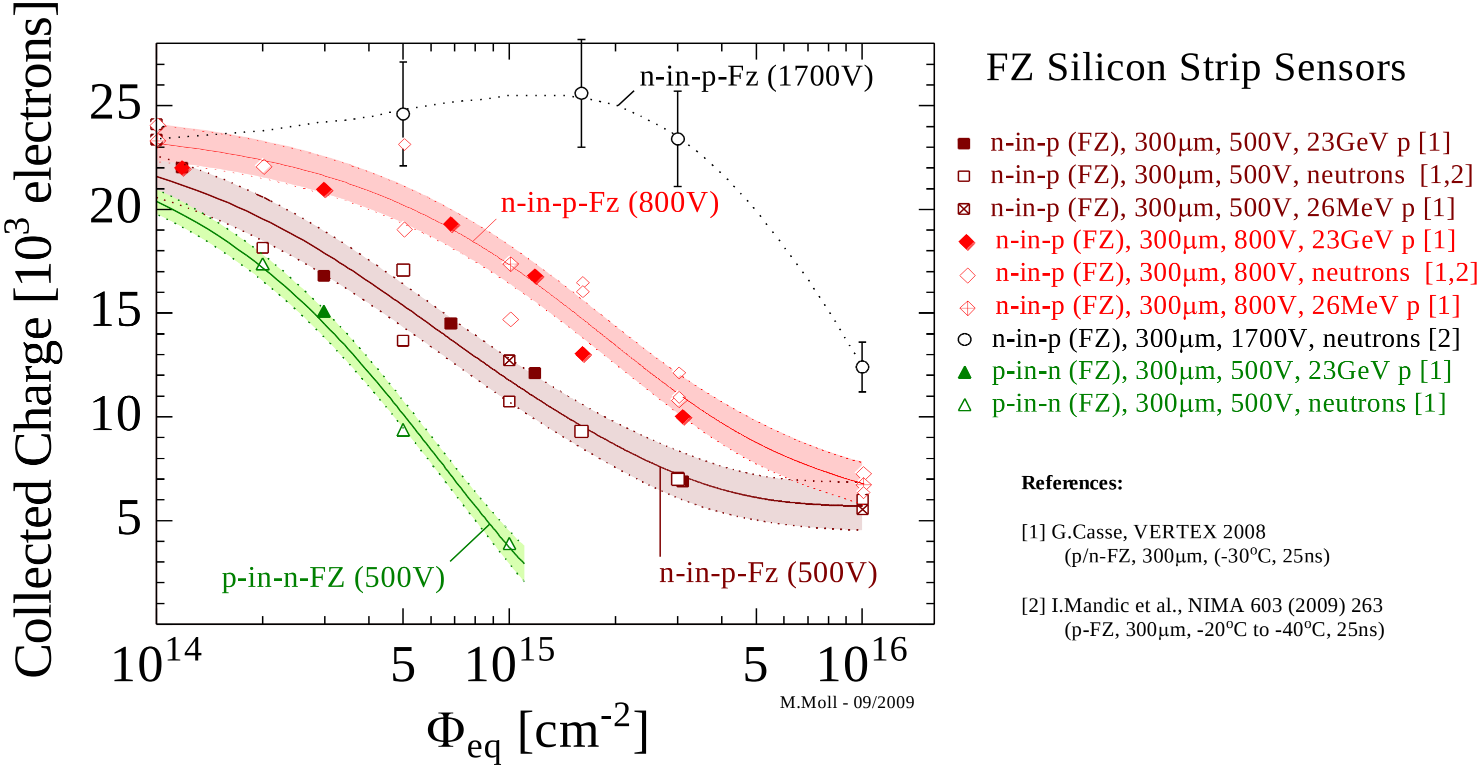
[S. Terzo, 21th RD50 Workshop, CERN, 2012]

Thin pixels: at very high fluences thick and thin give similar charge

Thin detectors -> less material

RD50: Sensors for HL-LHC, detector material

- **p-type silicon (brought forward by RD50 community)** - baseline for ATLAS Strip Tracker upgrade



M.Moll - 09/2009

References:

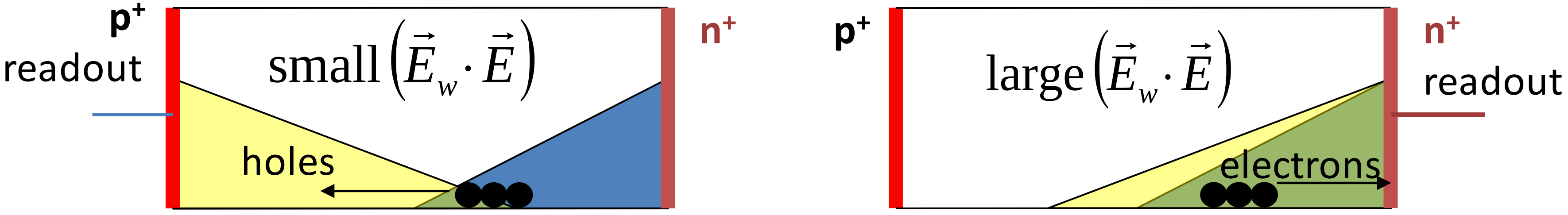
[1] G.Casse, VERTEX 2008
(p/n-FZ, 300µm, (-30°C, 25ns)

[2] I.Mandic et al., NIMA 603 (2009) 263
(p-FZ, 300µm, -20°C to -40°C, 25ns)

- **n-side readout natural in p-type silicon:**

→ favourable combination of weighting and electric field in heavily irradiated detector

→ electron collection, multiplication at segmented electrode



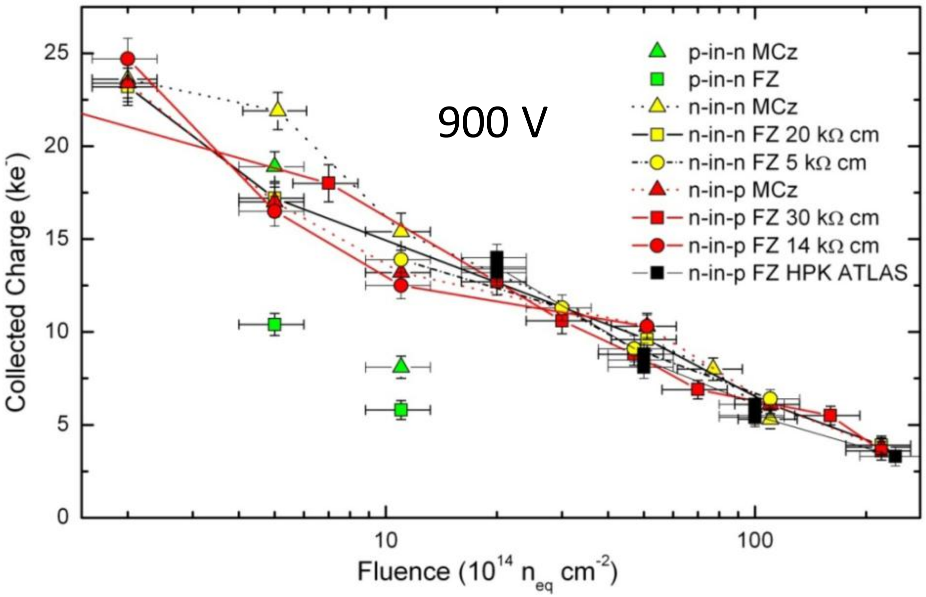
[G. Kramberger, Vertex 2012]

RD50: Sensors for HL-LHC, detector material

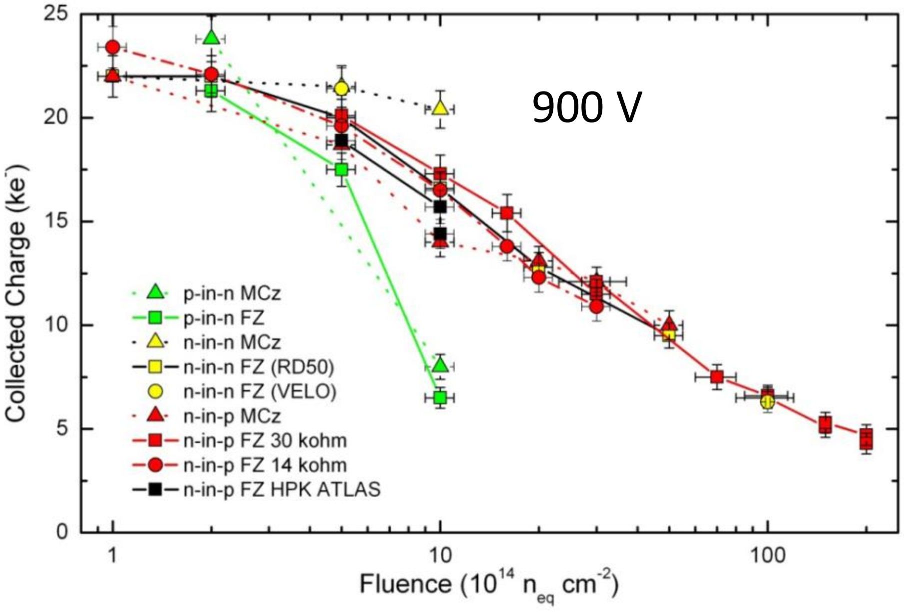
Comparison of detector materials:

➔ more charge with n-side readout at high fluences

26 MeV protons



Reactor neutrons



[P. Dervan, Pixel 2012]

Data points from:

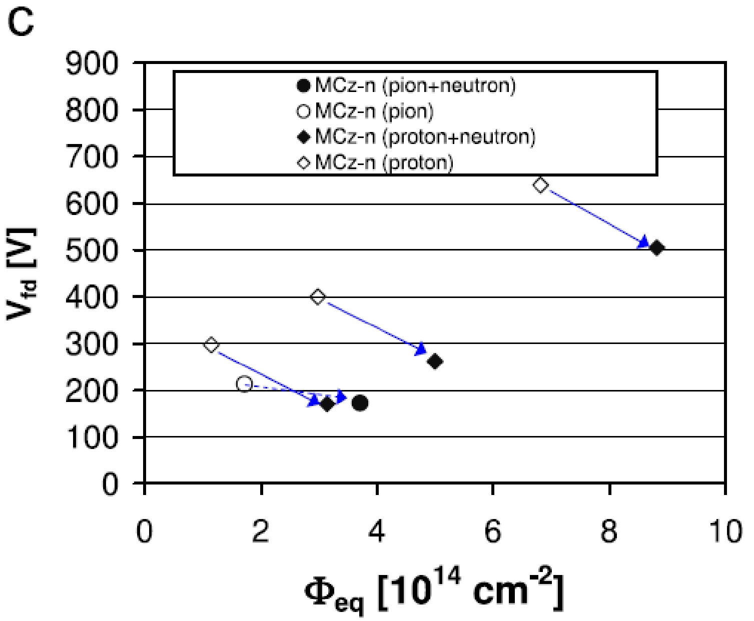
Micron Neutrons: A. Affolder, et. al., Nucl. Instr. Meth. A, Vol. 612 (2010), 470-473.

Micron 26 MeV Protons: A. Affolder, et. al., Nucl. Instr. Meth. A, Vol.623 (2010), 177-179.

HPK Neutrons: K. Hara, et. at., Nucl. Inst. Meth. A, Vol. 636 (2011) S83-S89.

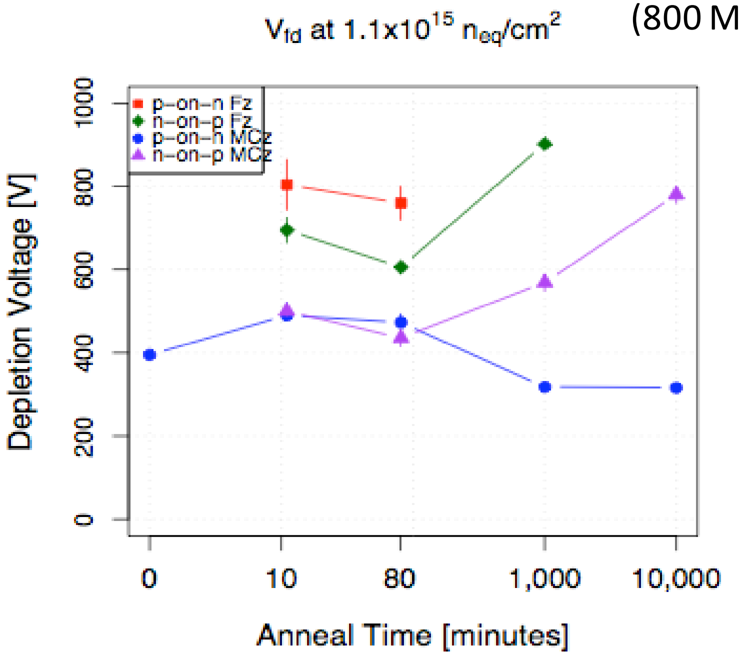
RD50: Sensors for HL-LHC, detector material

- n-MCz (introduced by RD50 community) might improve performance in mixed fields due to compensation of neutron and charged particle damage
  → interesting in mixed radiation field
  → p-in-n MCz detectors interesting also because of lower cost



[G. Kramberger et al. NIMA 609 (2009) 142–148]

Damage done by 24 GeV protons or 300 MeV pions compensated with damage caused by neutrons



(800 MeV protons)

J. Metcalfe, M. Hoeferkamp, S. Seidel

n-MCz less affected by annealing

- CCE > 50% at 500 V with p-in-n–type MCz detectors after Φ_{eq}=1e15 cm^{-2} (26 MeV p)
  [E. Tuovinen et al., NIMA 636 (2011) S39]

→ more about MCz and Epi material in talk by A. Junkes

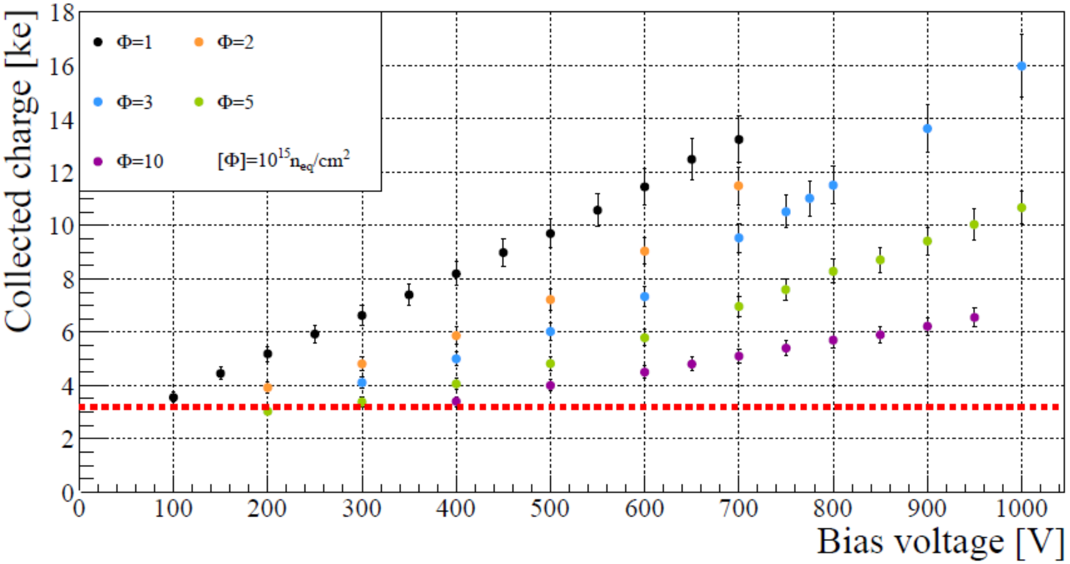
RD50: Sensors for HL-LHC, device type

Planar segmented detectors n-in-p or n-in-n

→ results on highly irradiated planar segmented sensors have shown that these devices are a feasible option for the innermost layers of LHC upgrade

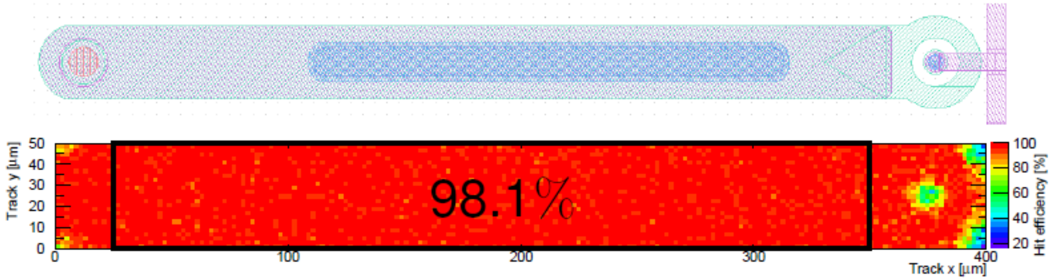
Example:

- 285 µm thick n-in-p FZ pixels
- FE-I3 readout
- sufficient charge also at $\Phi_{eq} = 1 \cdot 10^{16}$ n/cm^2



$\Phi_{eq} = 1 \cdot 10^{16}$ n/cm^2

- test beam, 120 GeV pions:
- perpendicular beam incidence
- bias voltage: 600V
- threshold: 2000 el



[S. Terzo, 21th RD50 Workshop, CERN, 2012]

➔ 97.2% hit efficiency (98.1% in the central region)

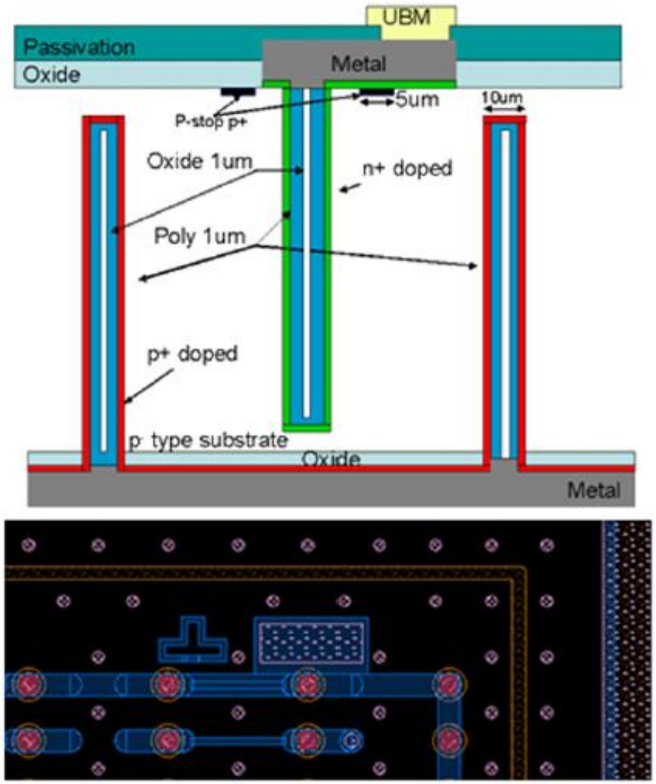
→ More about planar pixel results in the talk by A. Macchiolo!

RD50: Sensors for HL-LHC, device type

3D sensors:

- used in ATLAS IBL, excellent up to $\Phi_{eq} = 5\cdot10^{15}$ n/cm^2, promising results also for HL-LHC
- operation at lower voltage in innermost HL-LHC tracking layer(s)

➔ More in other presentations at this conference!

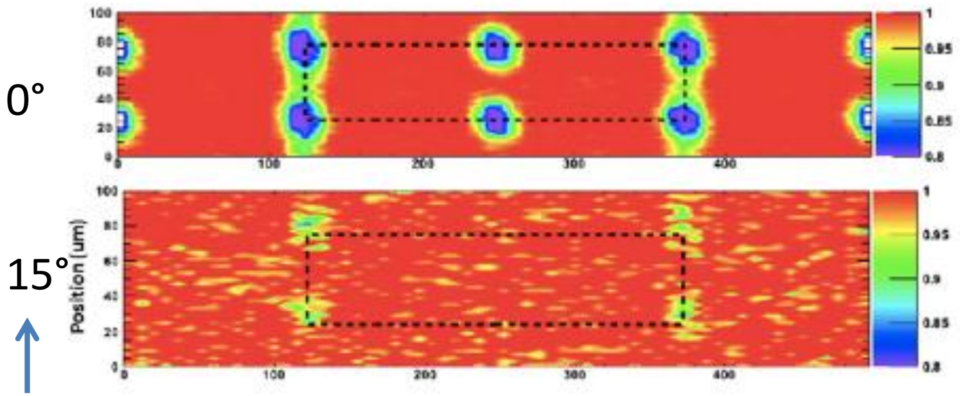


CNM 3D sensor

[G. Pellegrini, et al., NIMA 592 (2008) 38]

Work of ATLAS 3D Sensor R&D Collaboration:

test beam, CNM, sensors,
$\Phi_{eq} = 5\cdot10^{15}$ n/cm^2, Bias voltage = 160 V
Track efficiency > 98%



Track incidence angle

[ATLAS IBL collaboration, JINST (2012) 7 P11010]

Conclusion

RD50 recommendations for the silicon detectors to be used for LHC detector upgrades:

Innermost layers: fluences up to $2 \cdot 10^{16}$ $n_{\mathbf{eq}}$ /cm^2

- present results show that planar sensors are good enough
  - → readout on n-type electrode is essential!
  - → n-in-p (or n-in-n becoming n-in-p after inversion) detectors
    - need high bias voltage , but may be less demanding with thin sensors
- 3D detectors promising
  - → lower bias voltage
    - may be more difficult to produce but IBL results are encouraging

Outer layers: fluences up to 10^{15} n/cm^{-2}

- n-in-p type FZ microstrip detectors are ATLAS baseline:
  - → Collected charge over 10^4 electrons at 500 V (over $1.5 \cdot 10^4$ el. at 900 V)
- p-in-n MCz detectors possible option
  - → exploit damage compensation in mixed radiation field
  - → lower cost

Research with all types of material: FZ, MCz and Epi still going on

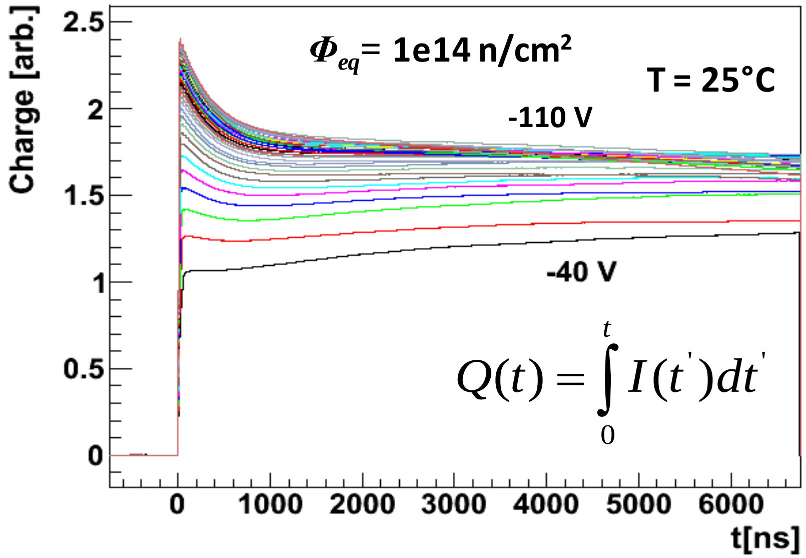
Thank you!

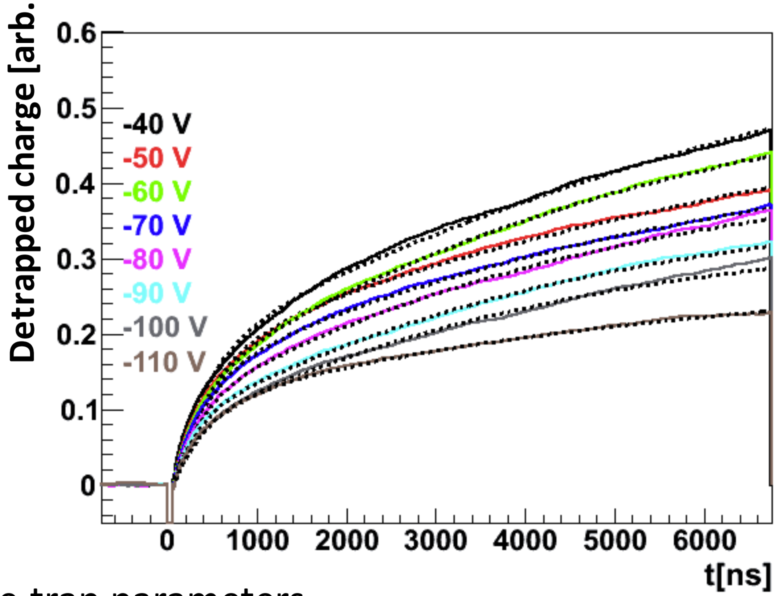
RD50 is a large and active collaboration!

→ only very limited selection of results included in this presentation
→ please visit www.cern.ch/rd50 for more information

Defect Characterization: carrier de-trapping

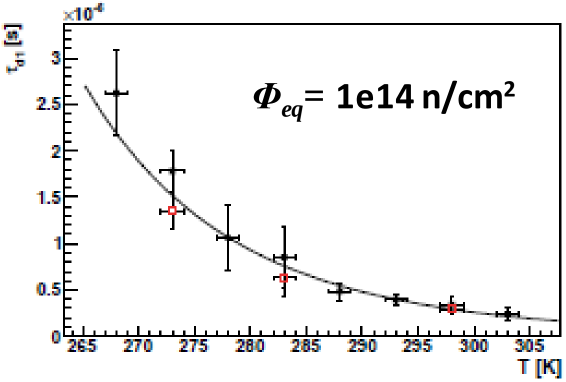
Standard TCT setup: illuminate with short red laser pulse → record time resolved pulse → integrate the pulse → subtract (measured) response curve → fit with 2 exponentials

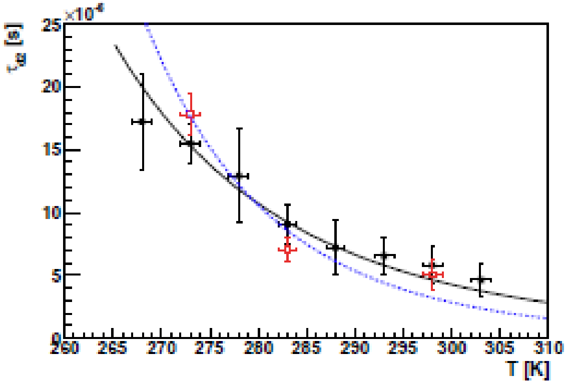




[G.Kramberger et al., 2012 JINST 7 P04006]
[G.Kramberger et al., 18th RD50 Workshop Liverpool]
See also [M. Gabrysh, 20th RD50 Workshop, Bari]

→ measure at different temperatures → estimate trap parameters





Trap	σ_h (cm^{-2})	E_t (eV)
H1(short τ)	$(3\pm2)\cdot10^{-13}$	0.44±0.04
H2(long τ)	$(5\pm5)\cdot10^{-16}$	0.355±0.04

H152K

H140K,H116K

→ de-trapping times for holes are in the range from 1-10 µs, the long term dominates

→ de-trapping times of electrons are larger than ~10 µs → not investigated in this measurement