RD50: Radiation-Hard Silicon for HL-LHC Trackers

Monica Scaringella, University of Florence

On behalf of the RD50 collaboration

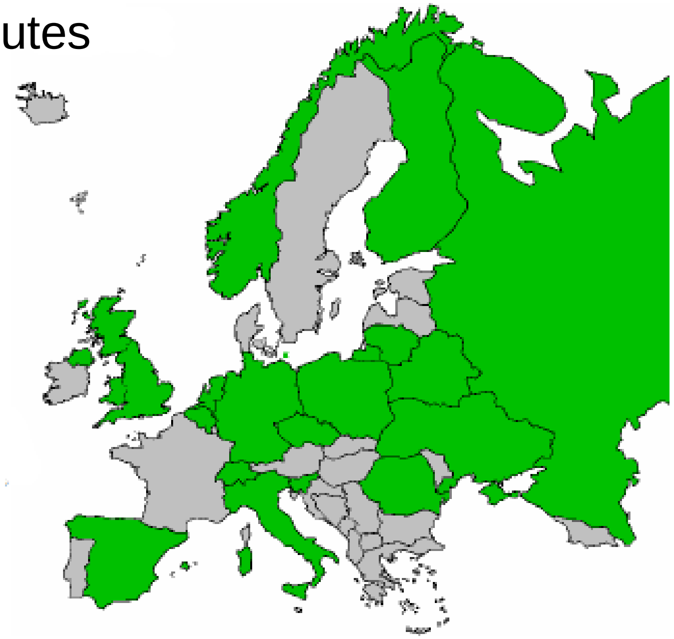
OUTLINE

- Introduction: the rd50 collaboration
- Charge collection in n-on-p detectors
    - Enhanced collected charge
    - Multiplication effects
    - simulations
- Estimation of the electric field distribution in heavily irradiated planar detectors: the Edge TCT technique
- 3D detectors:
    - Present Designs
    - Charge collection measurements on irradiated devices
    - Development of new structures

The RD50 collaboration

RD50: Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

258 Members from 47 Institutes



38 European institutes

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

8 North-American institutes

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

1 Middle East institute

Israel (Tel Aviv)

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

Scientific Organization of RD50

Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

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)

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

Richard Bates

(Glasgow University)

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

- 3D (R.Bates)
- Semi 3D (Z.Li)
- Thinned detectors (M.Boscardin)

Full Detector Systems

Gregor Kramberger

(Ljubljana University)

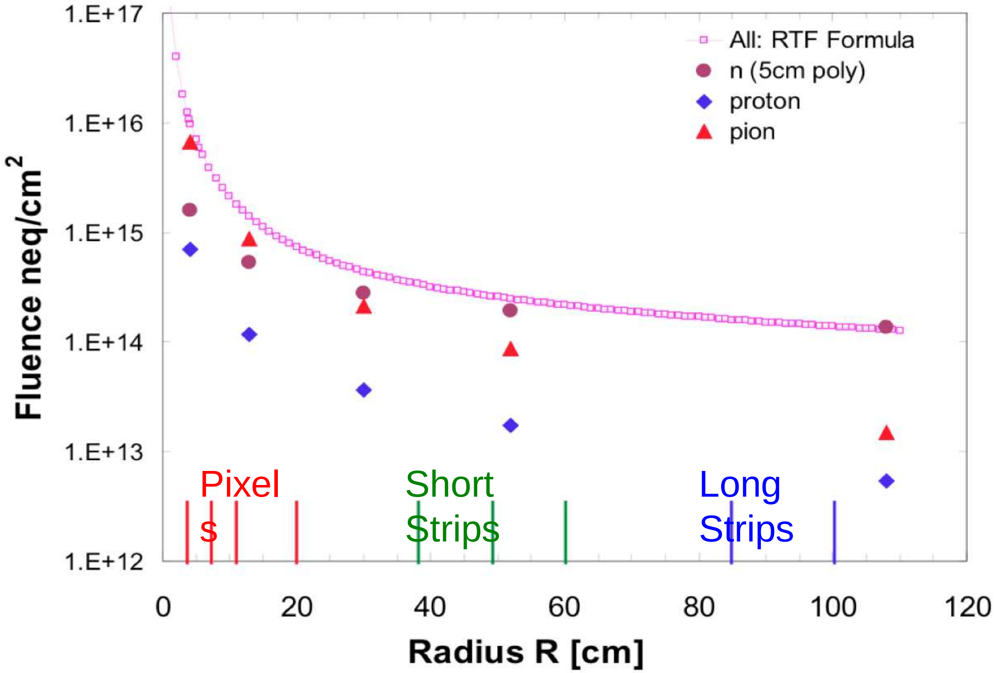
- LHC-like tests
- Test beams
- Links to HEP
- Links electronics R&D
- Comparison:
  - pad-mini-full detectors
  - different producers

- Pixel Europe (T.Rohe)
- Pixel US (D.Bortoletto)

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

Motivations

Expected fluence after 5 years of operation of HL-LHC



ATLAS Radiation Taskforce [ATL-GEN-2005-01] & H. Sadrozinski [IEEE NSS 2007]

Detectors will have to withstand to fluences up to:

- $2\cdot10^{16}$ n_{eq}/cm^2 for pixels
- 10^{15} n_{eq}/cm^2 for short strips

(2x safety factor included)

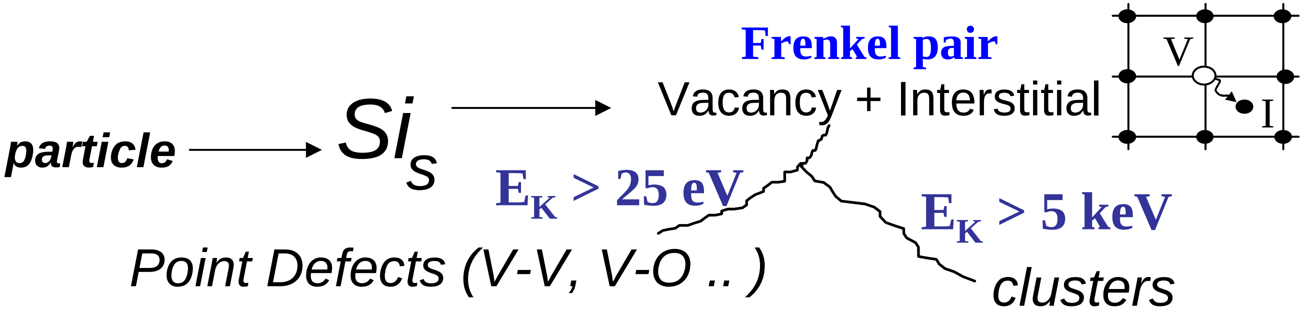
Scientific strategies

- Materials engineering:
  - Defect and material characterization
  - Correlation between microscopic properties and macroscopic effects
- Device engineering (new structures)
  - p-type silicon detectors
  - Thin detectors
  - 3d detectors

Investigated materials

Standard Float-zone (n and p type)	FZ
Diffusion Oxygenated Float-zone (n and p type)	DOFZ
Czochralski (n-type)	Cz
Magnetic Czochralski (n and p type)	MCz
Epitaxial (n and p type)	EPI

Radiation induced damage



particle → Si_s →

Frenkel pair

Vacancy + Interstitial

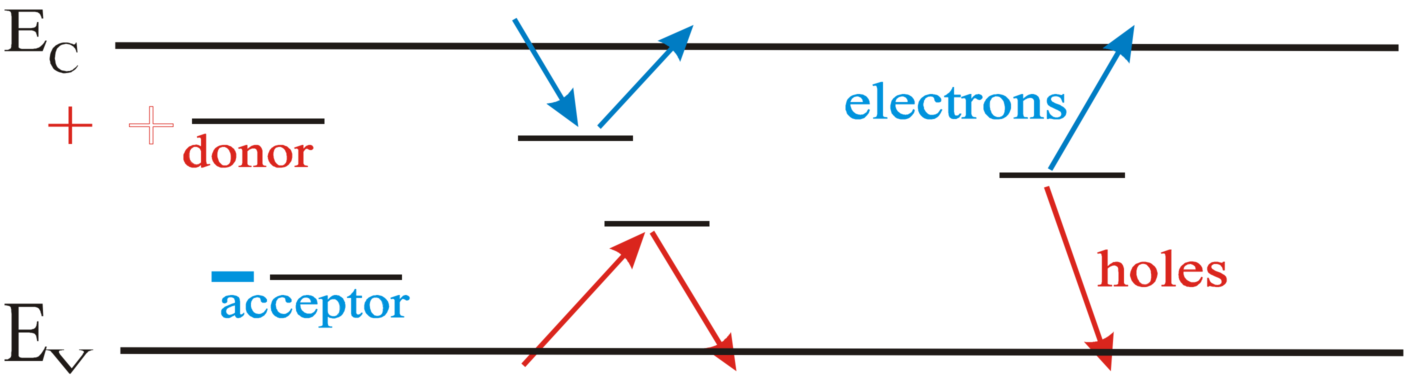
$E_K > 25$ eV

Point Defects (V-V, V-O ..)

$E_K > 5$ keV

clusters

Influence of defects on the material and device properties



charged defects

⇒ N_{eff} , V_{dep}

e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h)

⇒ CCE

shallow defects do not contribute at room temperature due to fast detrapping

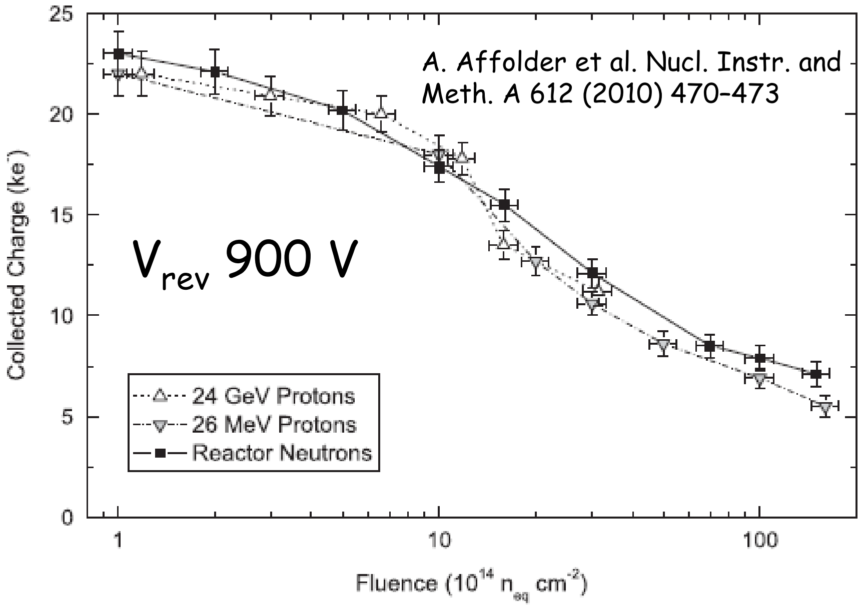
generation

⇒ leakage current

Levels close to midgap most effective

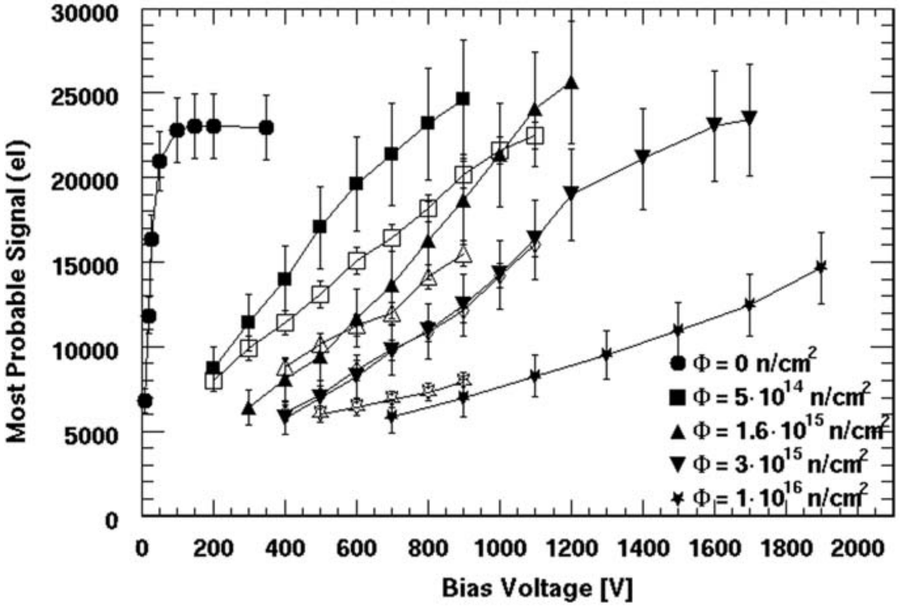
Charge collection in n on p FZ

Advantage of n-side read-out: higher mobility of electrons with respect to holes. Better performances compared to standard p-side read-out already proved by n on n technology



A. Affolder et al. Nucl. Instr. and Meth. A 612 (2010) 470–473

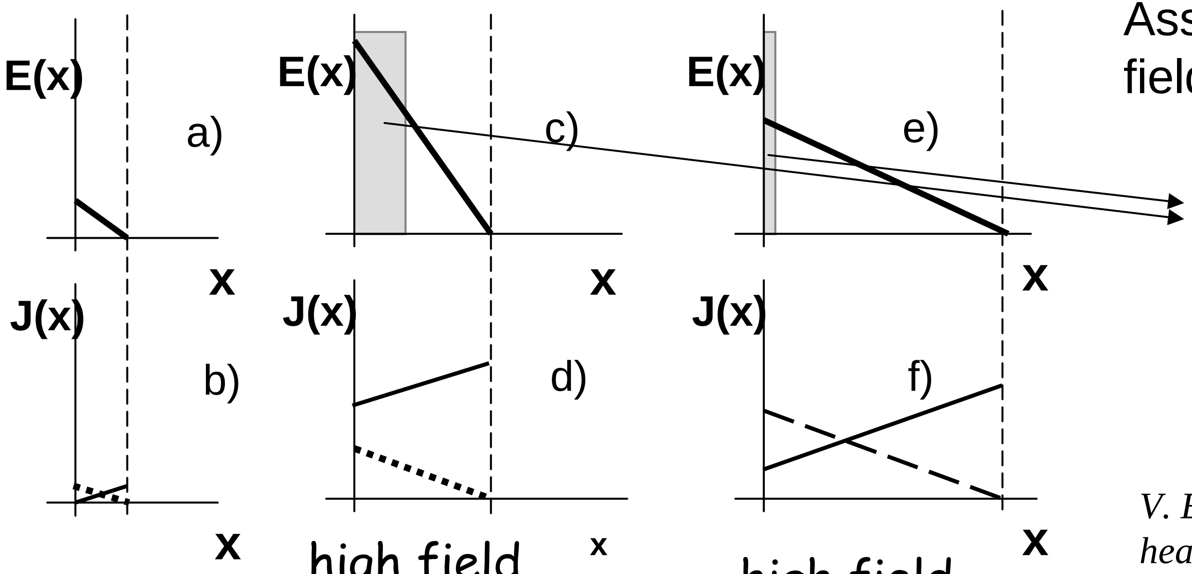
V_{rev} 900 V



I. Mandic et al. Nucl. Inst. And Meth. A 612 (2010) 474–477

- Charge still measurable after $2x10^{16}$ n_{eq}/cm^2
- Collected charge higher than expected from V_{dep} and carriers trapping times at high fluences.
- at high voltages collected charge in irradiated detectors can be higher than unirradiated. Possible explanation: charge multiplication in high field region

Modeling of charge multiplication effect on heavily irradiated n on p Si detectors



Low field

high field, non-steady state

high field, steady state

Assumption: linear electric field distribution

Regions where charge multiplication occurs

V. Eremin, et al. Avalanche effect in Si heavily irradiated detectors: physical model and perspectives for application. Nucl. Instr. and Meth. A (2011) doi:10.1016/j.nima.2011.05.002.

- at low field the current density is given by the bulk generated e^- and h^+
- at high fields the electron multiplication occurs in a region close to the n^+ contact which results in an avalanche injection of holes inside the bulk. The hole current density will be the sum of the bulk generated current and the avalanche hole injection.
- A fraction of this injected holes will be trapped inside the bulk contributing to a positive N_{eff} and thus a higher depletion depth

Space Charge Limited Avalanche (SCLA)

Combination of three processes:

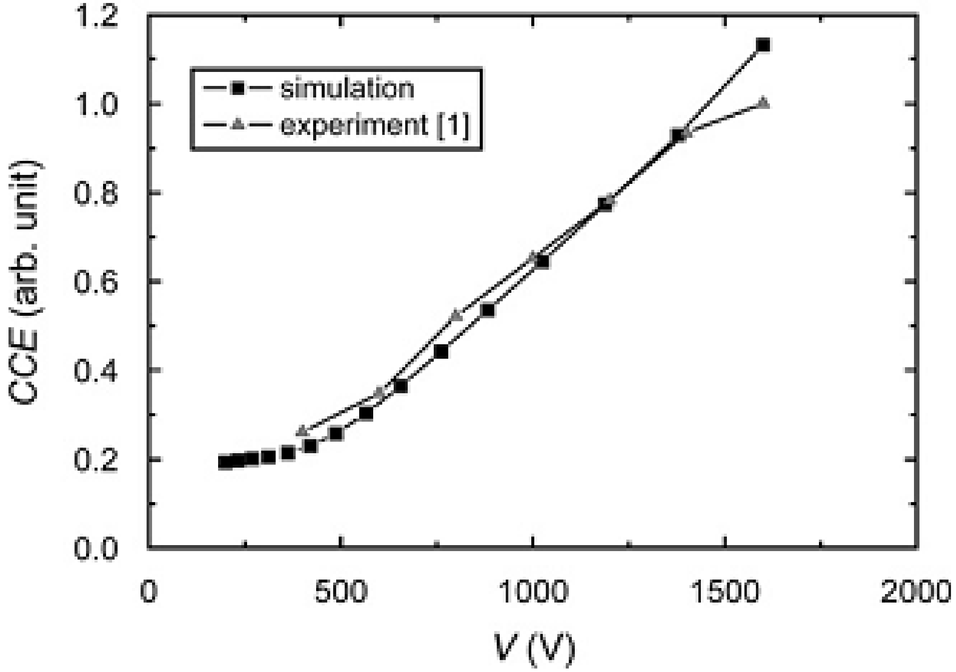
- avalanche hole generation,
- hole injection into the detector bulk,
- hole trapping from the deep levels of radiation induced defects in the bulk

gives rise to the negative feedback that:

- stabilizes the avalanche multiplication,
- prevents the detector breakdown,
- smoothes out the CCE-V and I-V characteristics.

Correlation between experimental data and calculated CCE

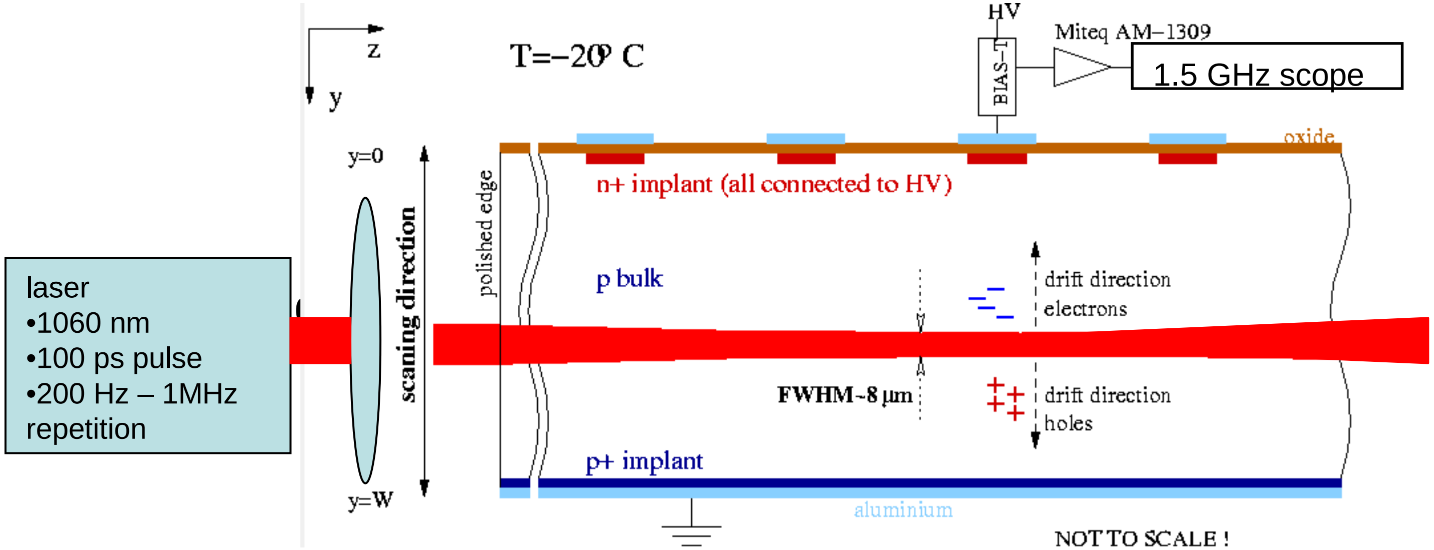
$F_n = 3\text{x}10^{15}\ \text{cm}^{-2}$



V. Eremin, et al. Avalanche effect in Si heavily irradiated detectors: physical model and perspectives for application. Nucl. Instr. and Meth. A (2011) doi:10.1016/j.nima.2011.05.002.

In plot: 1. I. Mandić, et al. *NIM A* 612 (2010) 474

Edge-Transient Current Technique (TCT): a tool to estimate the electric field distribution within the thickness of the detector



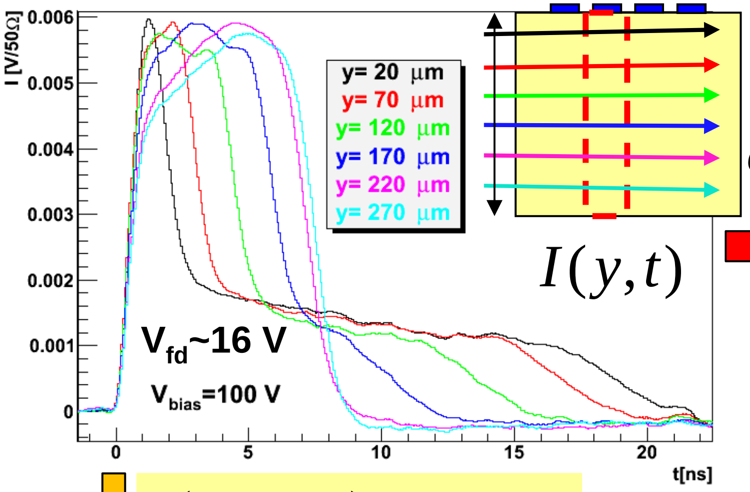
laser
- 1060 nm
- 100 ps pulse
- 200 Hz – 1MHz repetition

- The detector is illuminated by a collimated pulsed infrared laser beam
- The beam is focused below the readout strip and is scanned along the thickness
- At each depth the current transient is sampled by a wide bandwidth oscilloscope

From the analysis of the current transients the carrier drift velocity and efficiency can be extracted

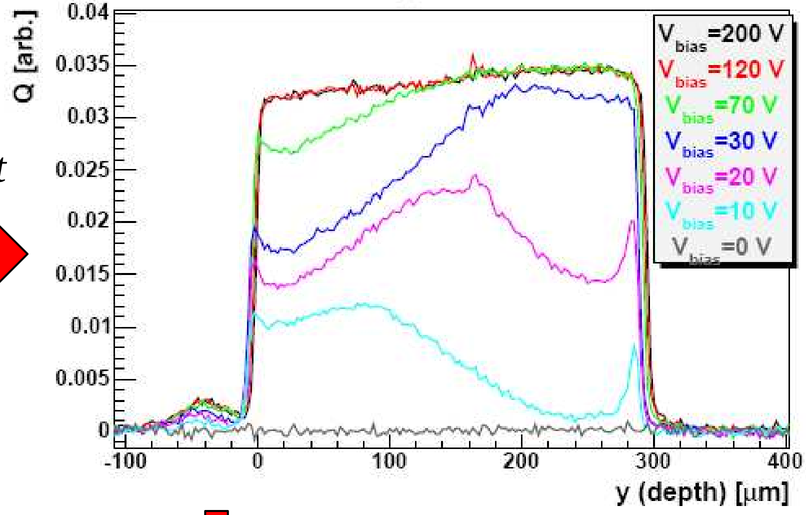
Charge collection and velocity profiles

Unirradiated device



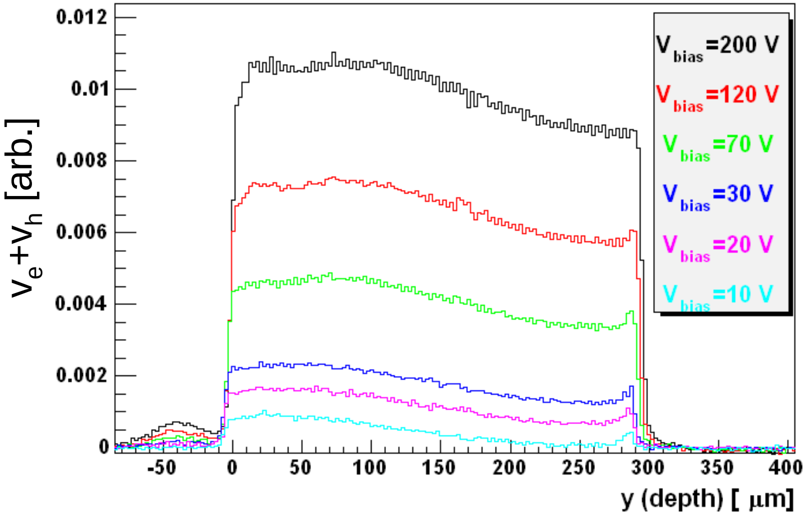
$$Q(y) = \int_0^{25ns} I(y,t)\,dt$$

CHARGE COLLECTION PROFILE



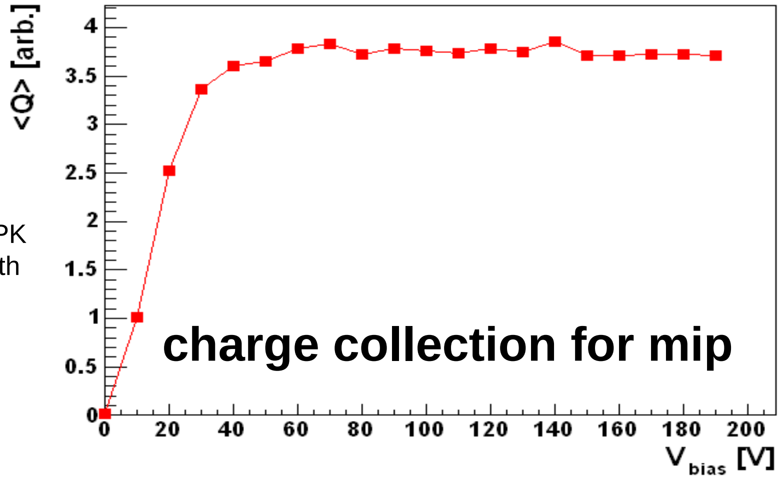
$$I(y,t\sim 0) \propto v_e + v_h$$

VELOCITY PROFILE

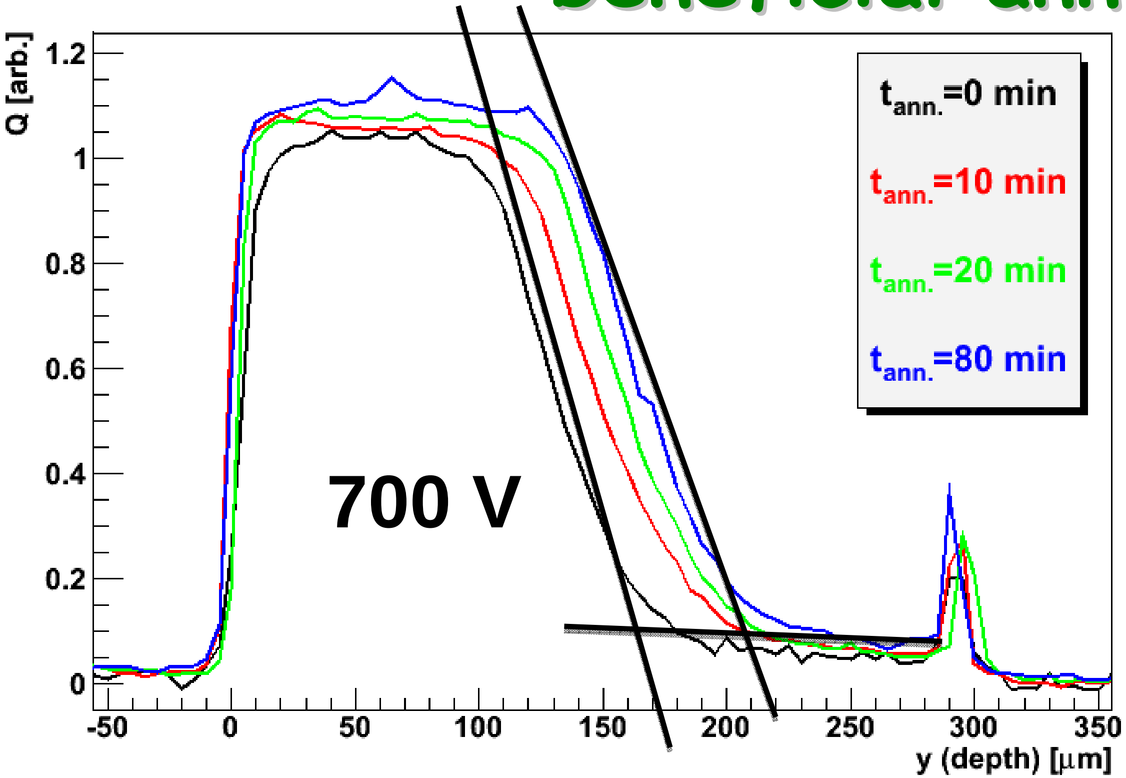


$$Q_{mip} \propto \langle Q \rangle = \int_0^W Q(y)\,dy$$

G. Kramberger, "Edge-TCT measurements of heavily irradiated HPK p-type sensors", 17th RD50 Workshop, CERN, 11/2010



neutron irradiated n on p (Φ_{eq}=10^{15} cm^{-2}) beneficial annealing



$$N_{eff} \approx g_c \cdot \Phi_{eq} + N_{eff\,0} \quad , \quad g_c = 2 \cdot 10^{-2}\ \mathrm{cm}^{-2}$$

$$V_{fd}(80\,\mathrm{min\ at\ }60^{o}C) \approx 1600\mathrm{V}$$

$$\Downarrow$$

$$\text{predicted}: \mathrm{y}_{\mathrm{act}}(700\ \mathrm{V}) \approx 200\ \mu\mathrm{m}$$

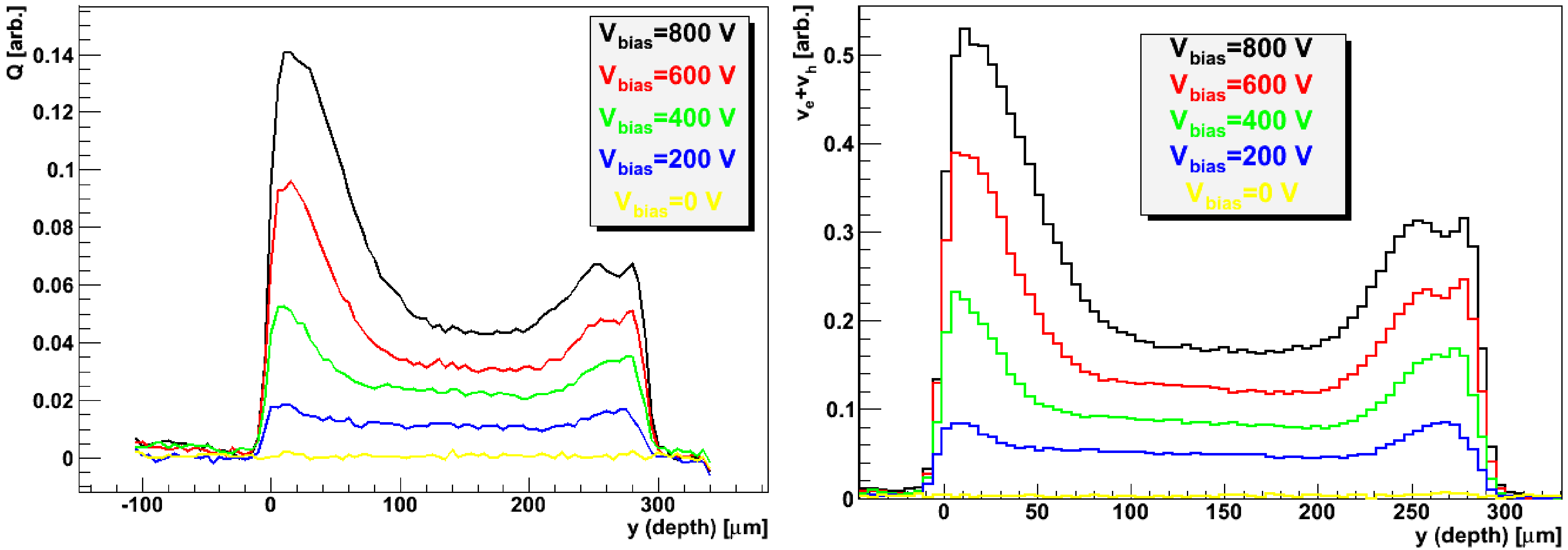
$$\text{measured}: \mathrm{y}_{\mathrm{act}}(700\ \mathrm{V}) = 205\ \mu\mathrm{m}$$

- the predicted active region (N_{eff}=const.) is very close to the measured
- A small peak at the back junction appears (double jounction)

In agreement with expectations based on RD48 and RD50 data – up to 10^{15} cm^{-2} the device behaves in accordance with expectations derived at lower fluences.

G. Kramberger, "Edge-TCT measurements of heavily irradiated HPK p-type sensors", 17th RD50 Workshop, CERN, 11/2010

$\Phi_{eq}=10^{16}$ cm^{-2}

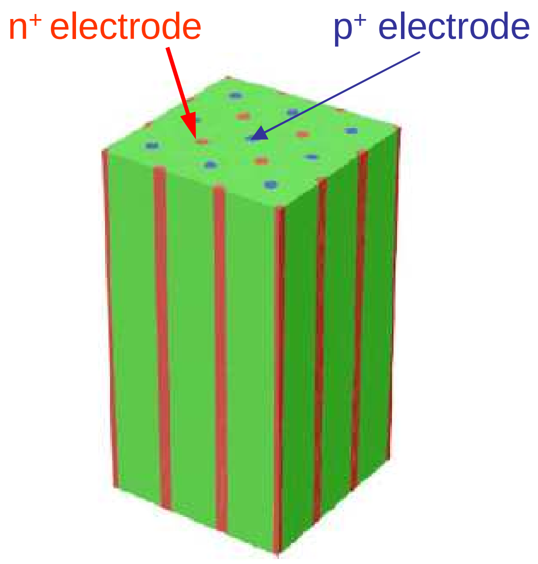


- Electric field is established in the whole detector – more pronounced double junction profile
- An important contribution to the collected charge from the base regions which brings extra signal with respect of the predicted values from Vdep. This contribution adds up to the one due to charge multiplication

G. Kramberger, "Edge-TCT measurements of heavily irradiated HPK p-type sensors", 17th RD50 Workshop, CERN, 11/2010

3D detectors

Conceptual design*

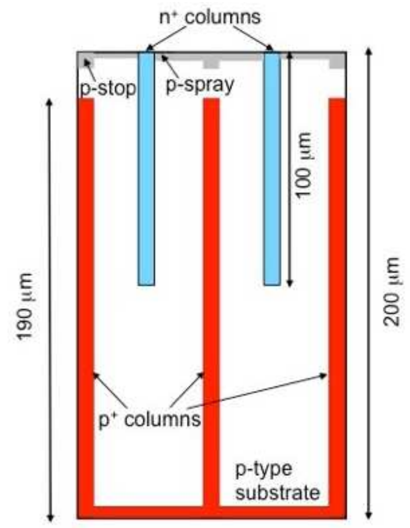


- The charge is collected in the narrow region in between the columns (50 – 100 μm) → radiation hard
- the depletion occurs laterally in between the coulumns → low V_{dep}

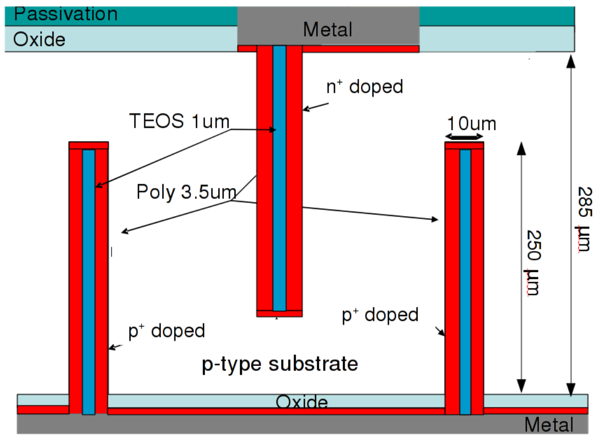
Simplified version of the original design: double sided 3D

*S.I. Parker et 395 (1997) 328

FKB – Trento design



CNM – Barcelona design

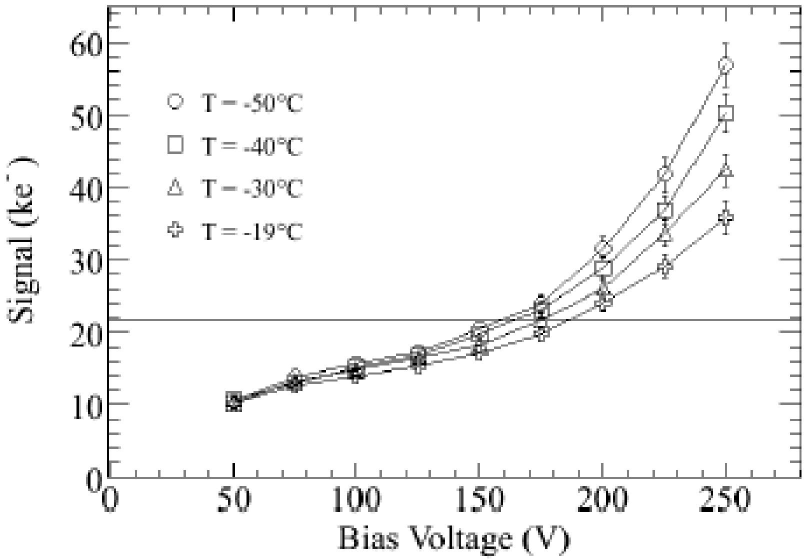


Charge collection measurements

- CNM samples irradiated at the proton cyclotron Karlsruhe with 25 MeV protons
- cce measurements performed with ^{90}Sr beta source and LCHb “beetle” readout chip (ALIBAVA) at varying temperatures

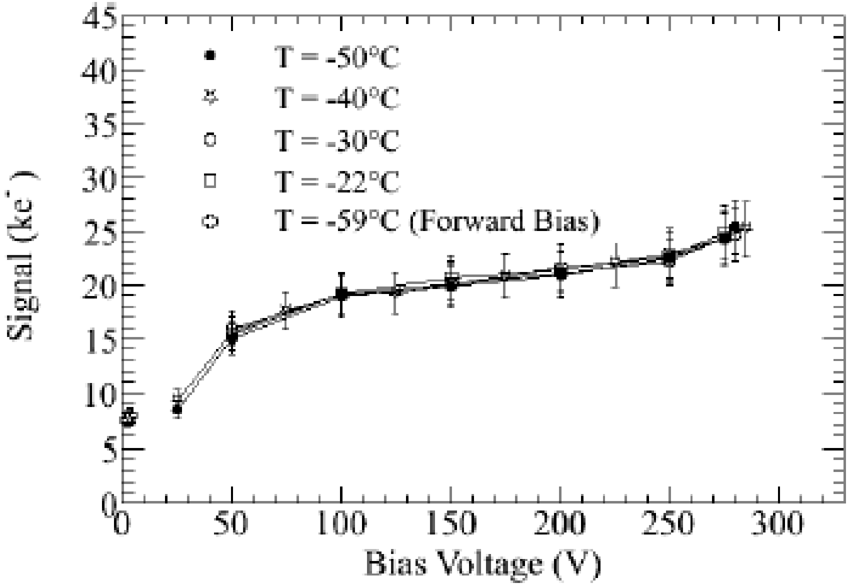
Samples irradiated at $2\times10^{15}\ n_{eq}/cm^2$

n-in-p



- Charge multiplication above 150 V
- Lower temperatures: higher charge multiplication

p-in-n

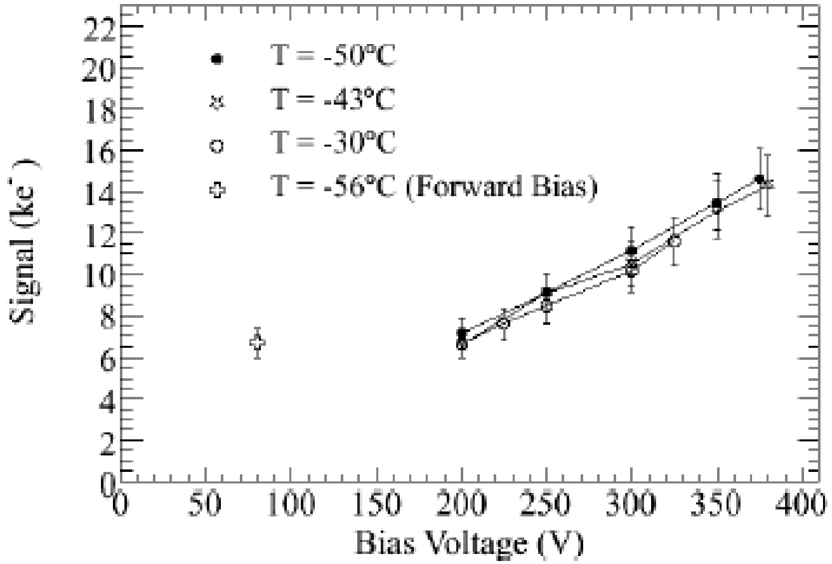


- Charge multiplication above 260 V?
- No temperature dependence

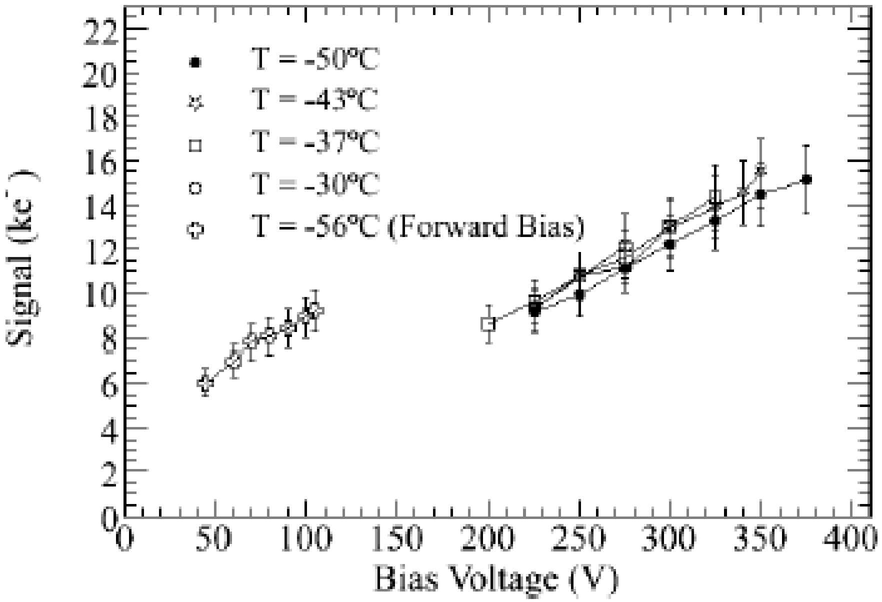
M. Köhler, presented at 6th Trento Workshop on Advanced Radiation Detectors, Trento (Italy) - March 2011

Samples irradiated at $2x10^{16}$ n_{eq}/cm^2

n-in-p



p-in-n



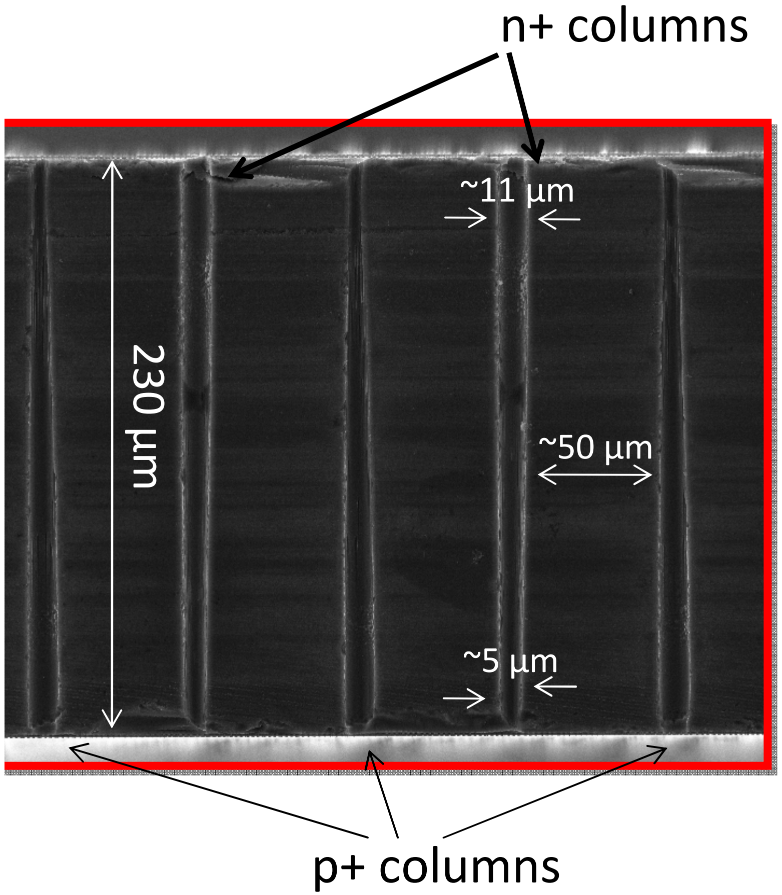
15 ke^- at 380 V reverse bias

15 ke^- at 350 V reverse bias

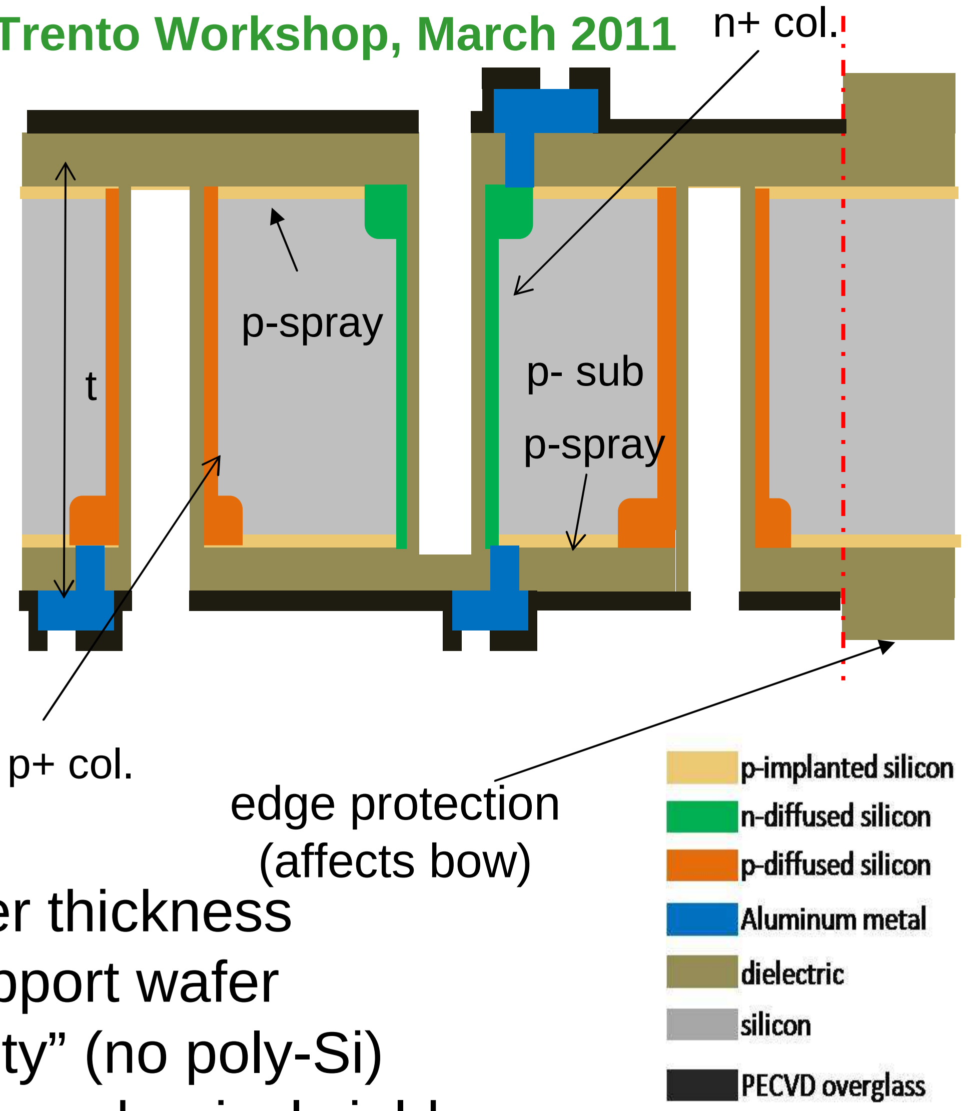
- **The maximum signal for n-type and p-type substrate is the same**
- **No significant temperature dependence**

M. Köhler, presented at 6th Trento Workshop on Advanced Radiation Detectors, Trento (Italy) - March 2011

3D-DTC with passing through columns at FBK



E. Vianello, et al.,
6th Trento Workshop, March 2011



- column depth equal to the wafer thickness
- full double side process, no support wafer
- holes (~11 µm diam.) are “empty” (no poly-Si)
- edge protection to improve the mechanical yield

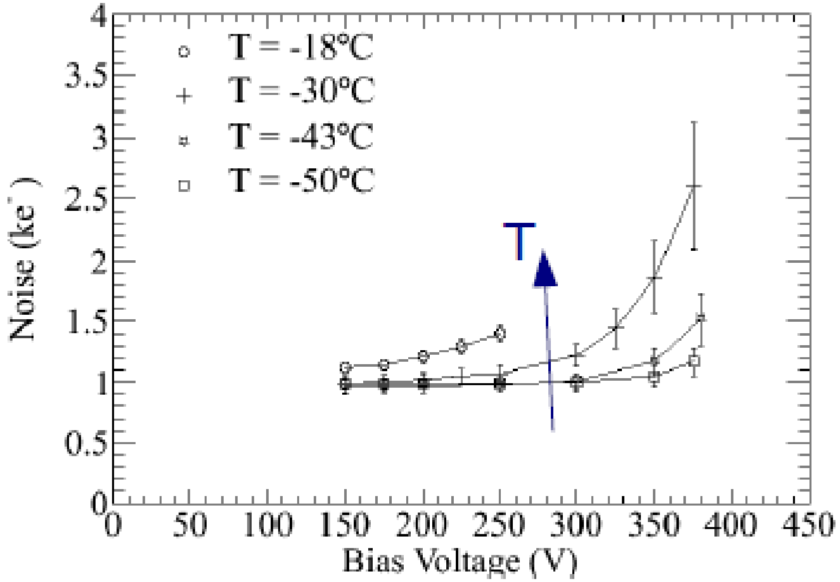
Conclusions

- The RD50 collaboration is working on the development of radiation hard detectors for high luminosity collider (e.g. HC-LHC)
- Charge collection efficiency measurements on n-on p FZ on highly irradiated silicon detectors show very good performances, better than expected by simulations:
  - extension of the electric field over the whole thickness of the detectors
  - Charge multiplication effects
- Double sided 3D detectors were produced in the framework of the collaboration (CNM, FBK)
- Charge collection measurements on irradiated devices show:
  - Charge multiplication effects (at lower voltages for p-type substrate)
  - High charge (15 ke-) measured after HL-LHC fluence
- Full 3D detectors (passing columns) are under development within the collaboration

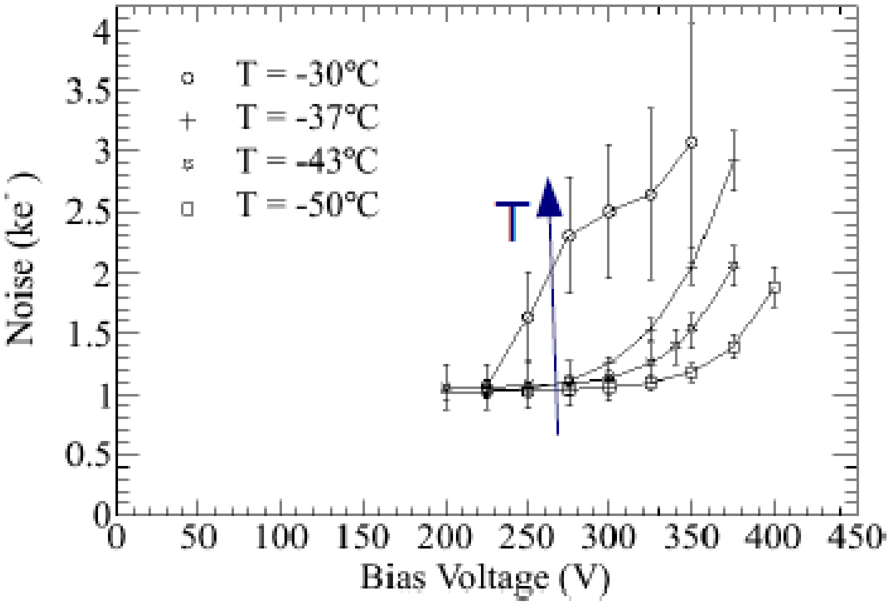
spares

Noise for 2x10^{16} n$_{eq}$/cm^2

n-in-p



p-in-n

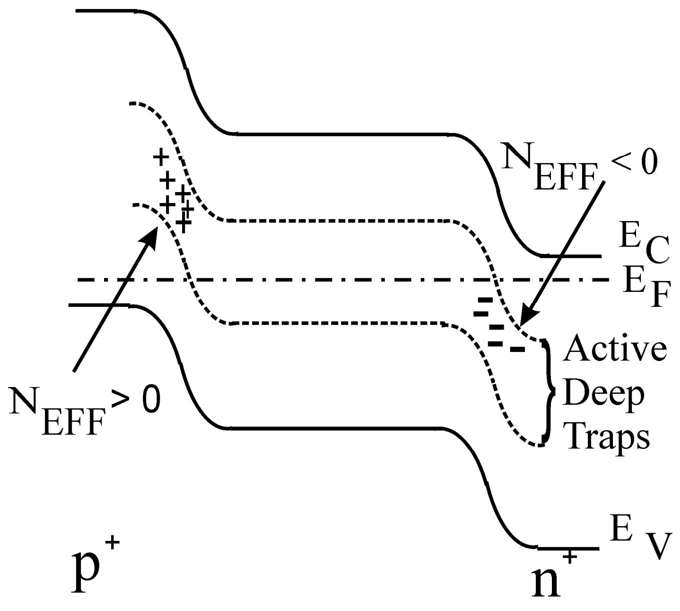


- **Strong noise increase with temperature – stronger than expected by standard shot noise parameterisation**
- **Lower temperature improves signal-to-noise ratio strongly!**

M. Köhler, presented at 6th Trento Workshop on Advanced Radiation Detectors, Trento (Italy) - March 2011

DOUBLE JUNCTION (DJ) EFFECT

For very high fluences (of the order of 10^{14} n/cm^2) a depletion region can be observed on both sides of the device for STFZ p$^+$/n diodes



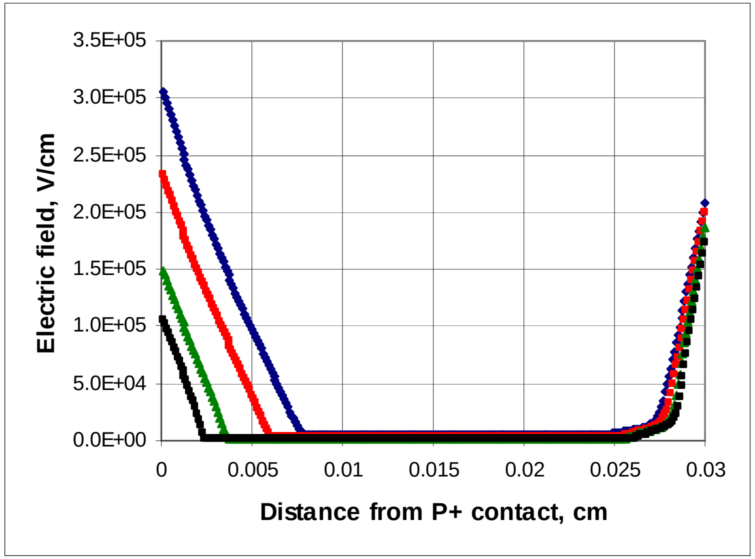
Electric Field simulation with consideration of current focusing in strip detectors

- The electric field was simulated with the PTI model* which takes into account two effective energy levels: a midgap donor and a migap acceptor
- A correction for electric field focusing has been introduced

NO electric field focusing

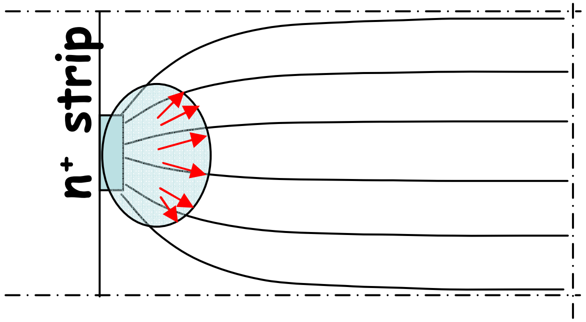
(PAD configuration)

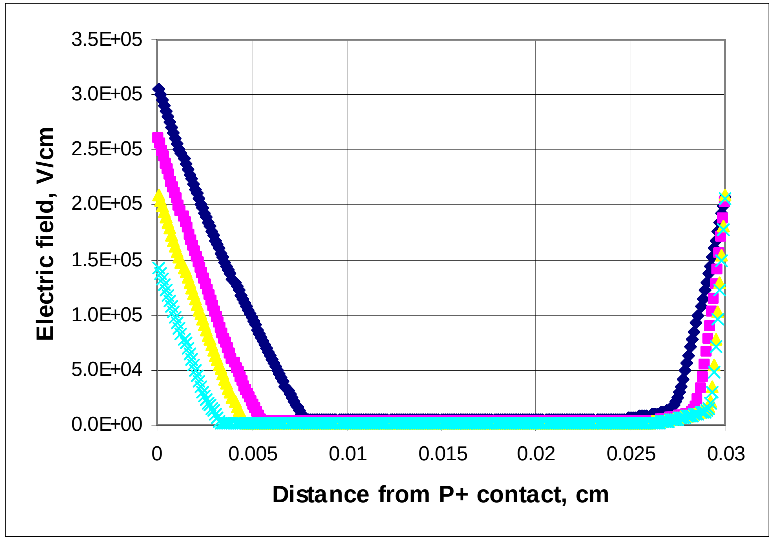
F_n = 1x10^{16} cm^{-2}, V = 1500, 1000, 700, 500V



*V. Eremin, E. Verbitskaya, Z. Li, Nucl. Instr. and Meth. A 426 (2002) 537.

electric field focusing

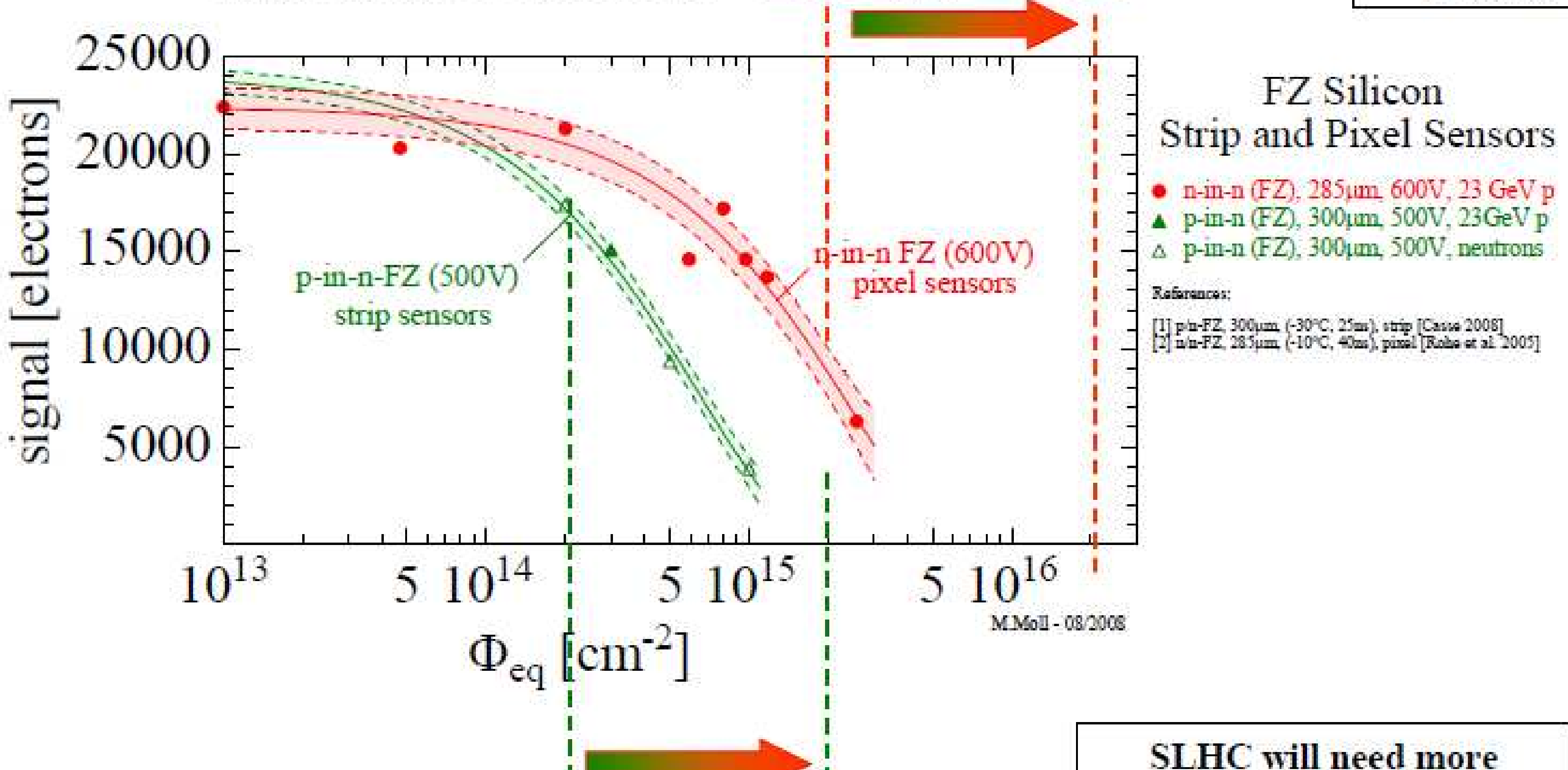




RD50 Signal degradation for LHC Silicon Sensors

Note: Measured partly
under different conditions!
Lines to guide the eye
(no modeling)!

Pixel sensors:
max. cumulated fluence for LHC and SLHC



Strip sensors:
max. cumulated fluence for LHC and SLHC

SLHC will need more radiation tolerant tracking detector concepts!