A guide to radiation damage in silicon detectors by RD50

Michael Moll (CERN), Jaakko Härkönen
(Helsinki Institute of Physics)

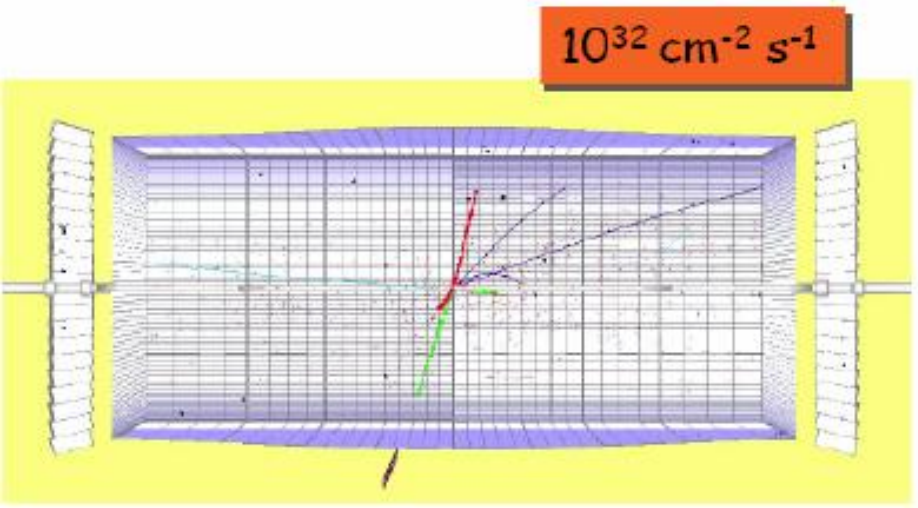
Outline

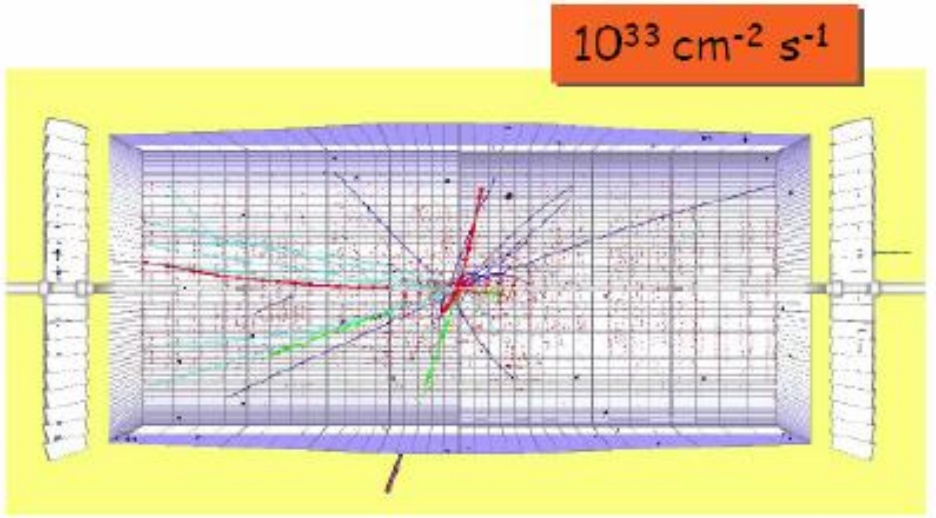
- **Motivation to develop radiation harder detectors**
  - **expected radiation levels at the upgraded LHC (sLHC)**
  - **Radiation induced degradation of detector performance**

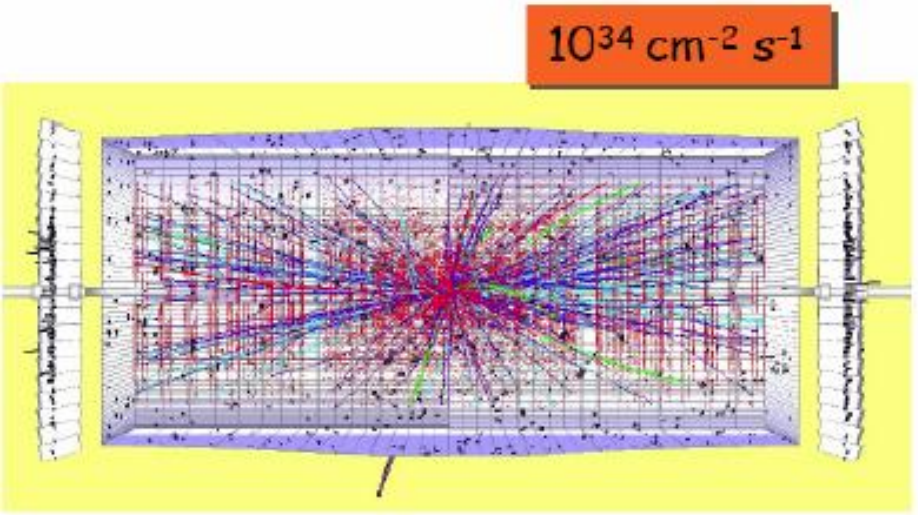
- **Radiation Damage in Silicon Detectors**
  - **Microscopic damage (crystal damage), NIEL**
  - **Macroscopic damage (changes in detector properties: N_{eff}, I_R, CC(V)**
- **Changes with time after irradiation**
  - **Annealing of the detector electrical properties: N_{eff}, I_R, CCE(V)**
- **Radiation hardening of Silicon sensors**
  - **Material Engineering**
    - **New silicon materials – FZ, MCZ, DOFZ, EPI**

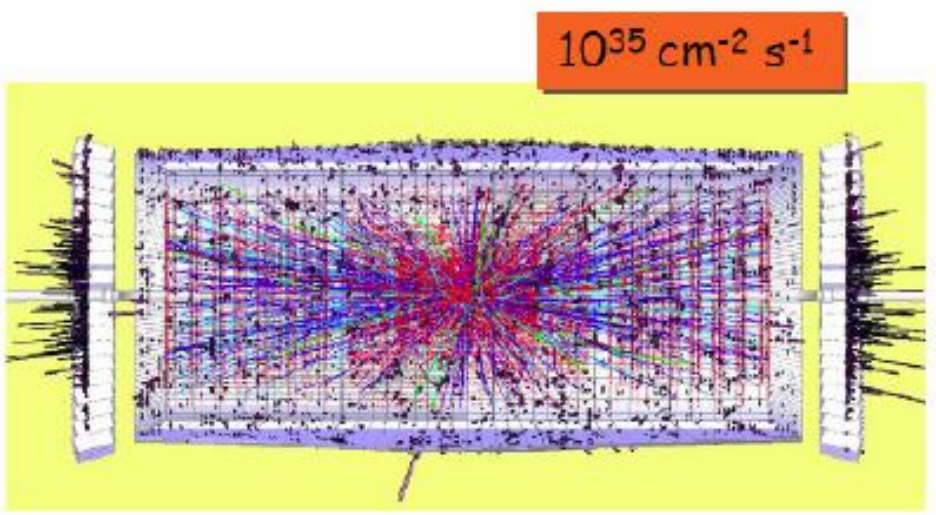
    - Device Engineering
    - **p-in-n, n-in-n and n-in-p sensors, 3D sensors**
- **Conclusions**

The challenge: Super LHC - visually









LHC luminosity

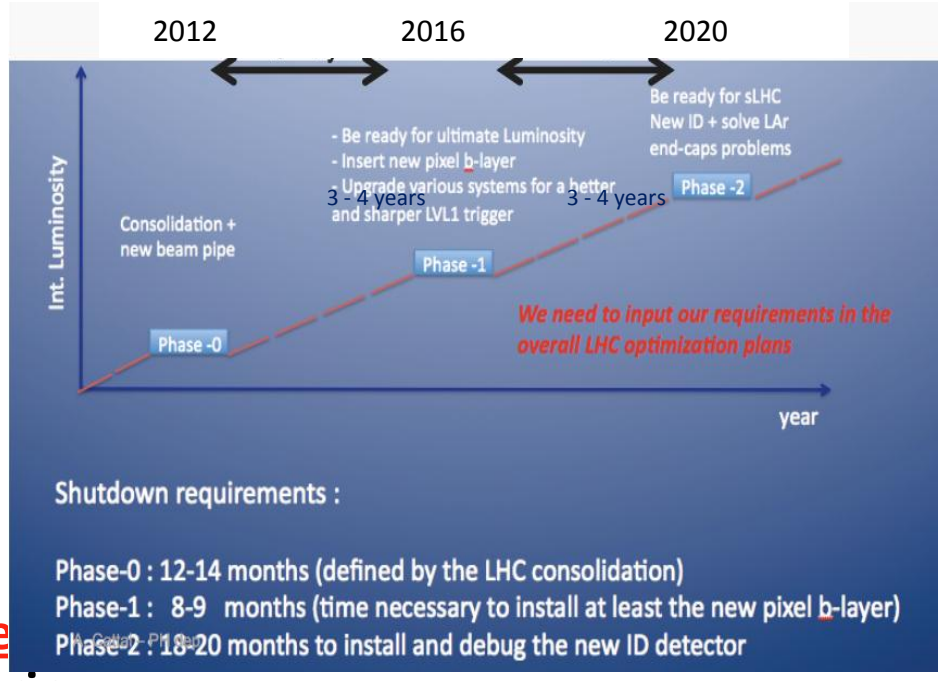
SLHC luminosity ~300-400 interactions/bx

Upgrading the LHC for High Luminosity

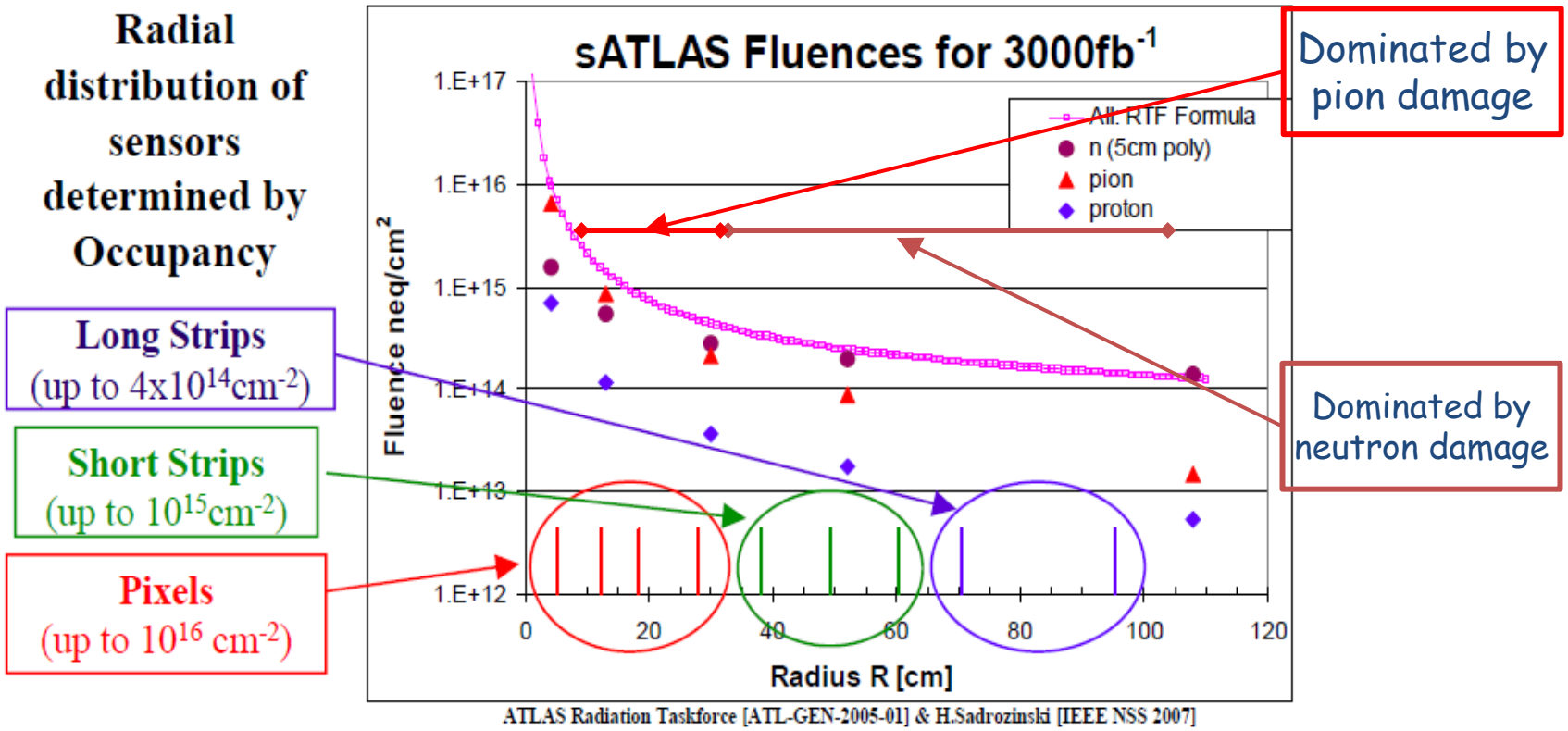
With modest investment, the LHC can run at much higher collision rates, greatly increasing the scope to search for new particles and study rare processes

Expected Development in Luminosity

- **Phase-I (after 5 years)**
  - **Up to ~ 60fb^{-1}/year**
  - **Experiments need:**
    - **New vertex detectors**
    - **New off-line electronics**
    - **…**
- **Phase-II (after 10 years)**
  - **Up to ~ 300fb^{-1}/year**
  - **Experiments need:**
    - **Complete tracker replaceme**
    - **Much improved on-line filtering**
    - **New read-out for many subsystems**
    - **…**



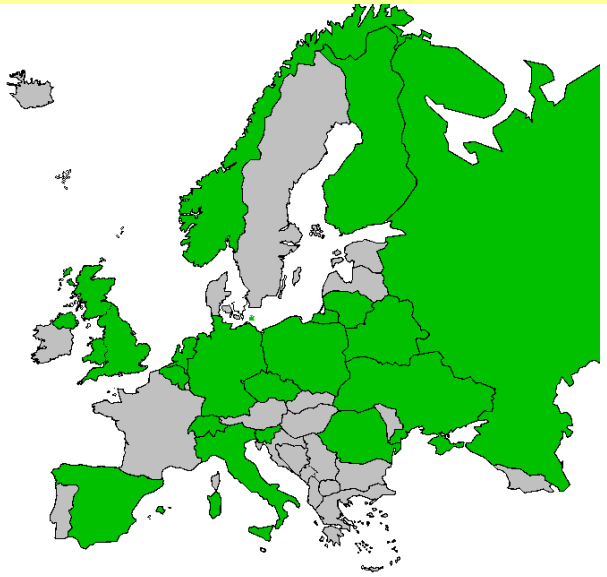
Radiation levels expected with sLHC



- **Radiation hardness requirements (including safety factor of 2)**
  - **2×10^{16} n_{eq}/cm^2 for the innermost pixel layers**
  - **1×10^{15} n_{eq}/cm^2 for the innermost strip layers**

[M.Moll]

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



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

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

1 Middle East institute

Israel (Tel Aviv)

257 Members from 47 Institutes

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

ODEAN: Workshop 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

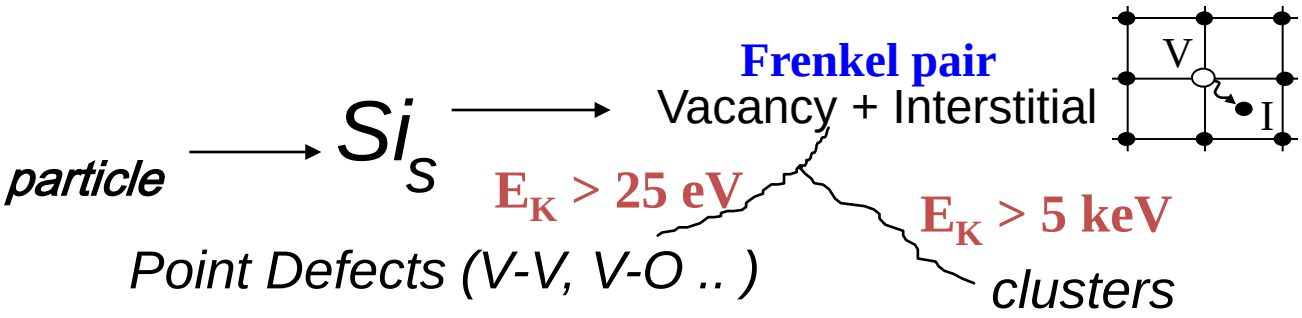
Gregor Kramberger
(Ljubljana University)

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

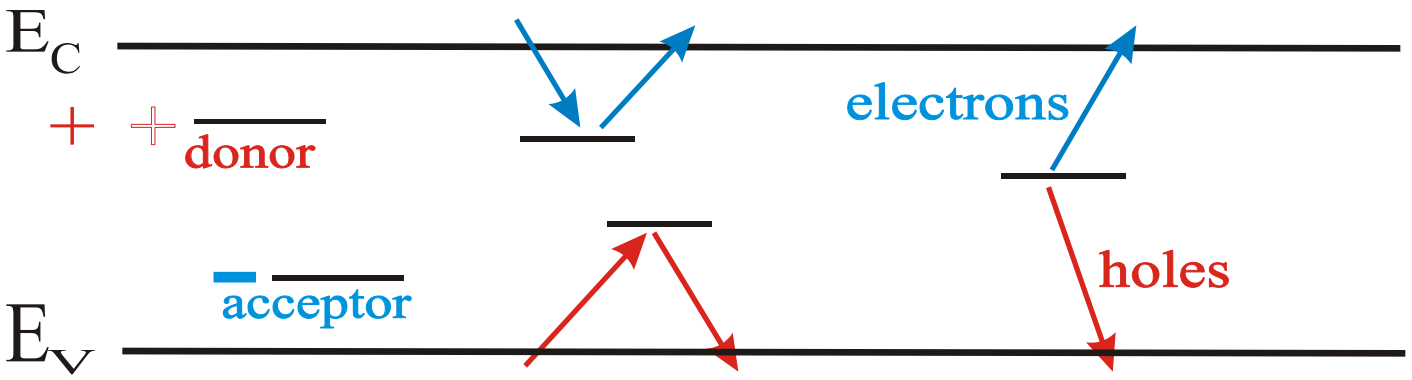
- Pixel Europe (T.Rohe)
- Pixel US (D.Bortoletto)

Collaboration Board Chair & Deputy: E.Fretwurst (Hamburg) & J.Vaitkus (Vilnius), Conference committee: U.Parzefall (Freiburg

Radiation induced damage



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

Vacancy amount and distribution depends on particle kind and energy

^{60}Co-gammas

– Compton Electrons with max. $E_\gamma \approx 1$ MeV (no cluster production)

Electrons

– $E_e > 255$ keV for displacement

– $E_e > 8$ MeV for cluster

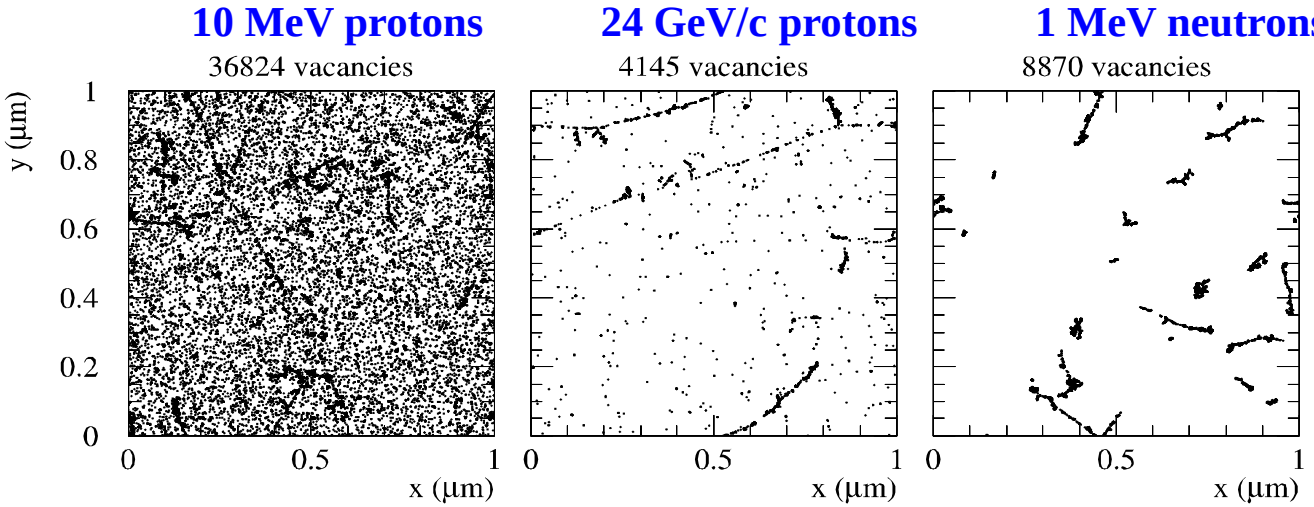
Neutrons (elastic scattering)

– $E_n > 185$ eV for displacement

– $E_n > 35$ keV for cluster

Only point defects ⟷ point defects & clusters ⟷ Mainly clusters

Initial distribution of vacancies in $(1\mu m)^3$ after 10^{14} particles/cm^2



[Mika Huhtinen NIMA 491(2002) 194]

How to normalize radiation damage from different particles?

- **NIEL - Non Ionizing Energy Loss scaling using hardness factors**

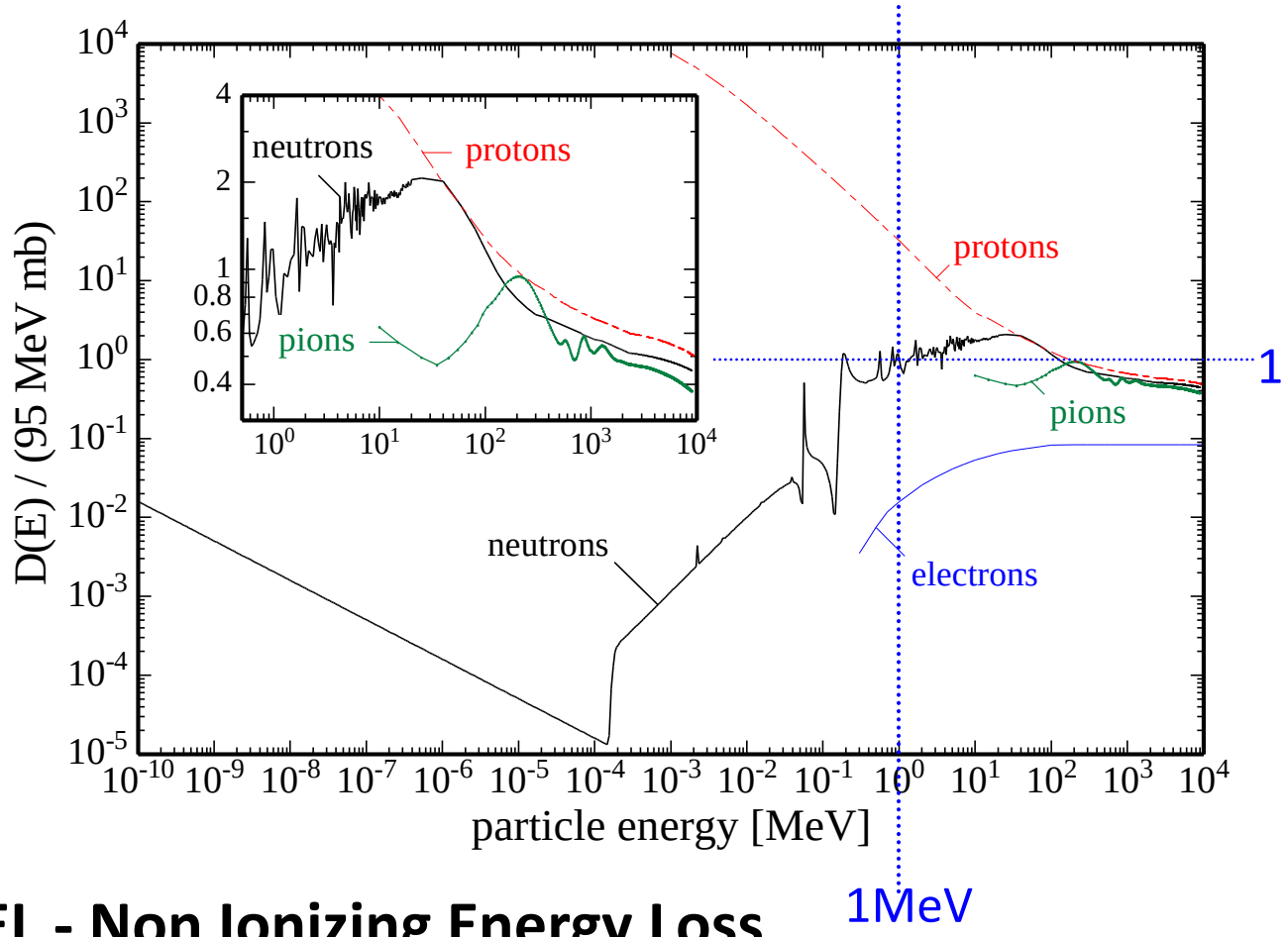
$$\kappa = \frac{1}{D(1MeV\ neutrons)} \bullet \frac{\int D(E)\,\phi(E)\,dE}{\int \phi(E)\,dE}$$

Hardness factor κ of a radiation field (or monoenergetic particle) with respect to 1 MeV neutrons.

- **E** energy of particle
- **D(E)** displacement damage cross section for a certain particle at energy E
  D(1MeV neutrons)=95 MeV·mb
- **ϕ(E)** energy spectrum of radiation field

The integrals are evaluated for the interval [E_{MIN},E_{MAX}], being E_{MIN} and E_{MAX} the minimum and maximum cut-off energy values, respectively, and covering all particle types present in the radiation field

NIEL - Displacement damage functions

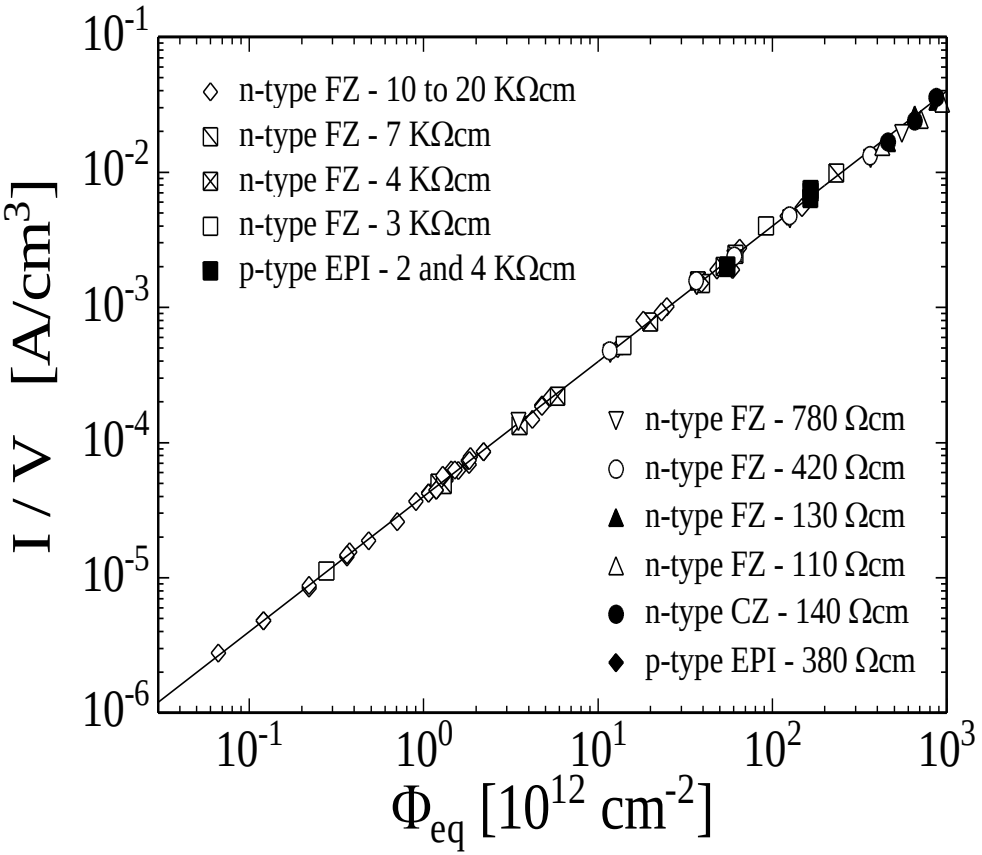


1 MeV neutron equivalent damage

- **NIEL - Non Ionizing Energy Loss**
- **NIEL - Hypothesis: Damage parameters scale with the NIEL**
  - ***Be careful, does not hold for all particles & damage parameters (see later)***

Radiation Damage: macroscopic parameters

I. Increase of leakage current with the fluence



- **Damage parameter α (slope in figure):**
  Leakage current per unit volume and particle fluence

$$\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}$$

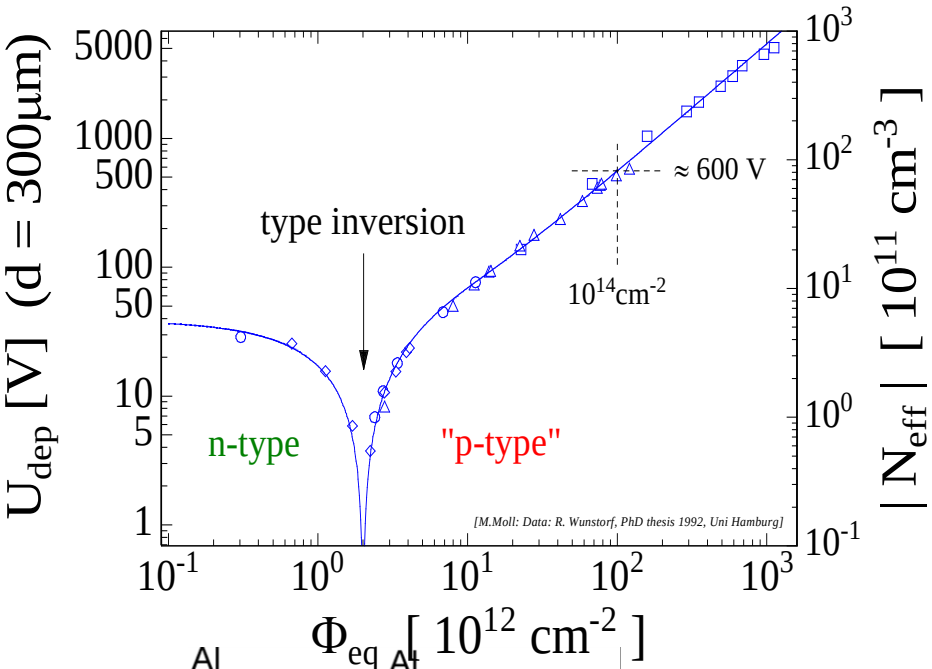
α independent of Φ_{eq} and impurities ⇨ used for fluence calibration (NIEL-Hypothesis)

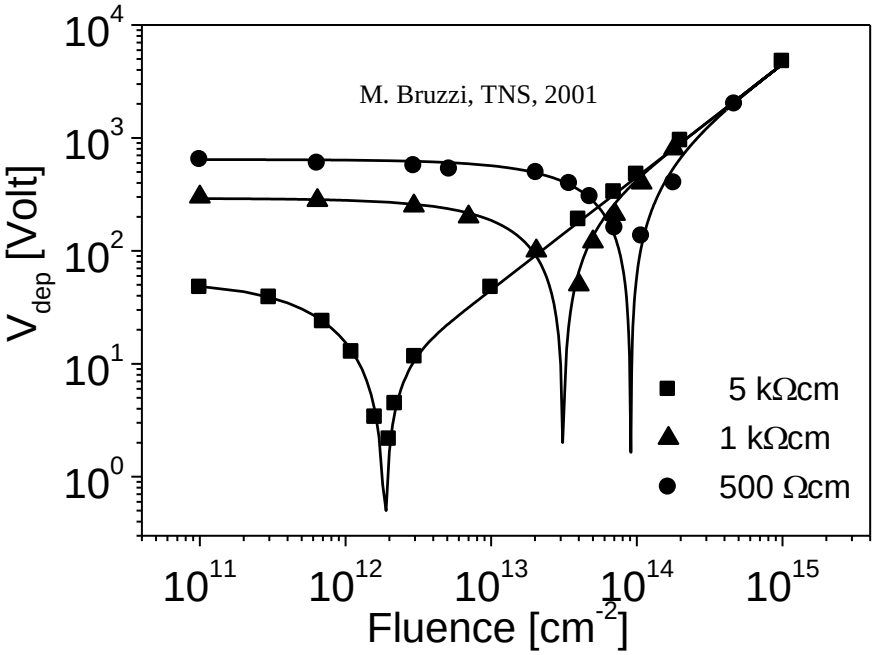
II. Change of V_{fd} and N_{eff} with fluence

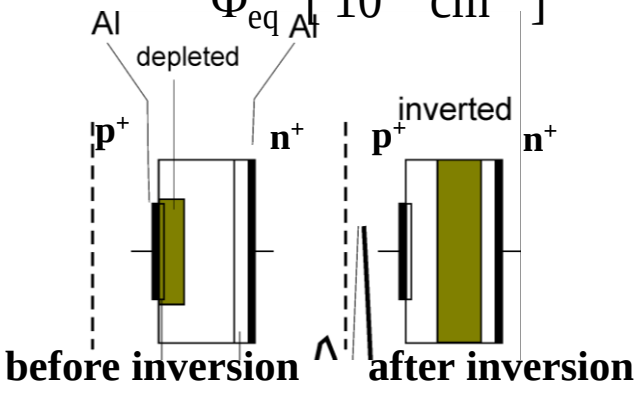
$$\Delta N_{eff}(\Phi) = | N_{C0}(1-e^{-c\Phi}) - \beta \cdot \Phi |$$

Production of acceptor like defect

Removal of the shallow dopant level

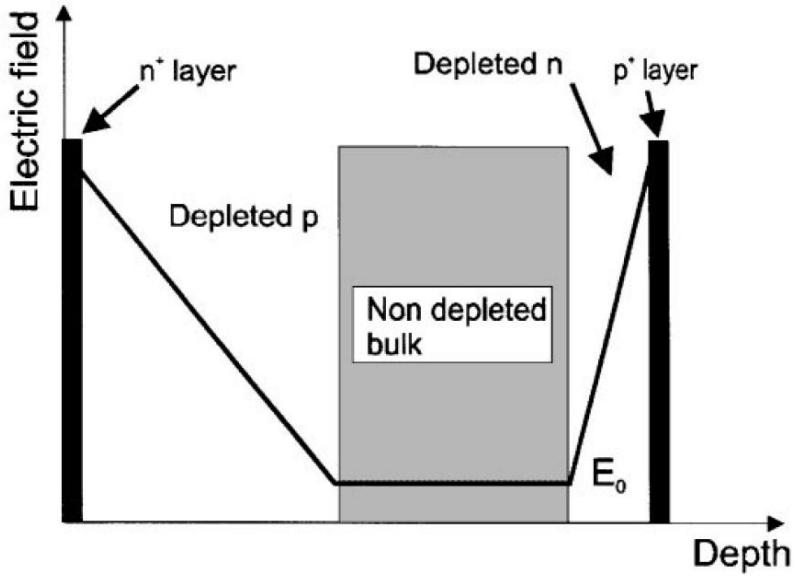






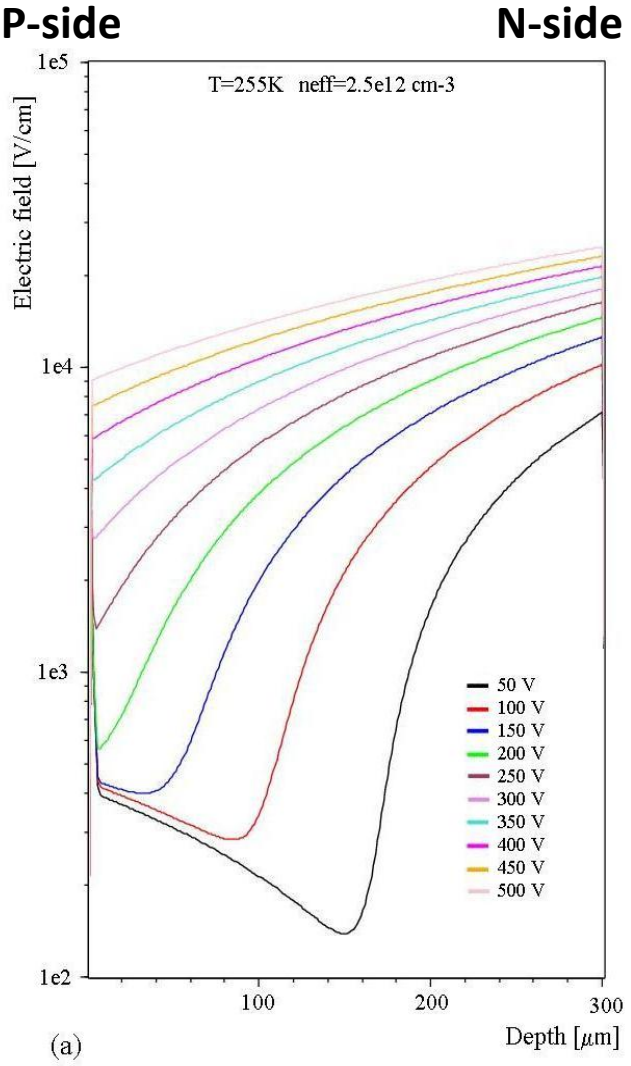
V_{dep} vs. fluence plot indicates an inversion of the Space Change Sign at high fluences

Double Junction



In reality, after irradiation electric fields show a double junction structure with a non-depleted bulk in the middle of the sensor below the full depletion voltage

See G. Casse, et. al., NIMA 426 (1999) 140-146 and G. Kramberger, et. al., NIMA 579 (2007) 762-765 for details



ISE-TCAD simulation after 6. 10^{14} p cm^{-2}

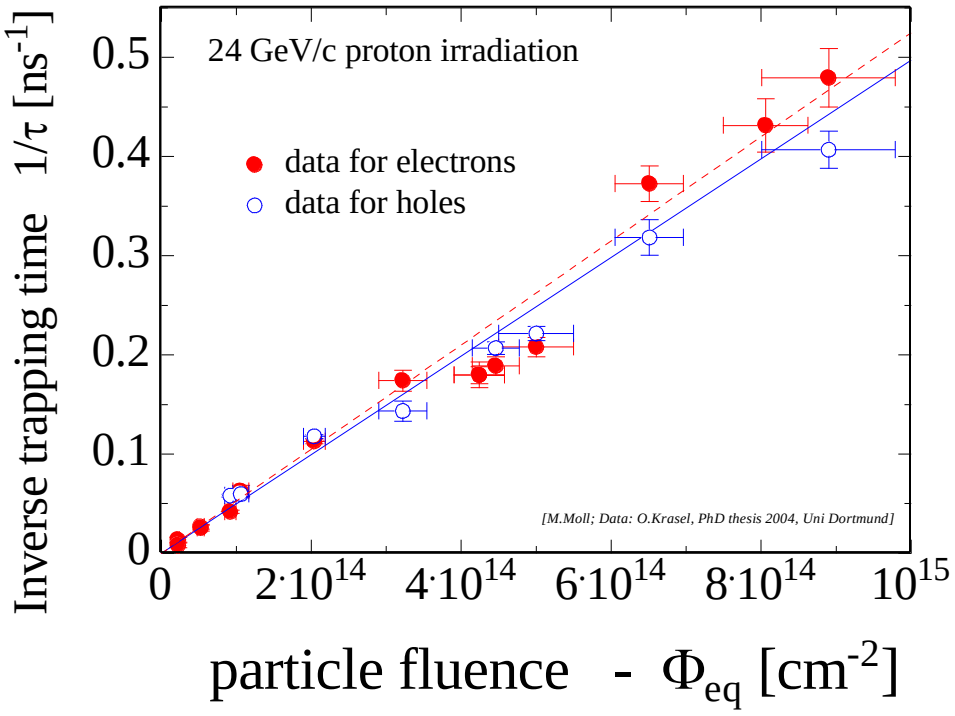
III. Charge Collection Efficiency (CCE) degradation due to trapping

CCE degradation is mainly due to partial depletion and trapping.

Effective trapping time τ_{eff} for electrons and holes:

$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t\right) \qquad \textbf{where} \qquad \frac{1}{\tau_{eff\ e,h}} \propto N_{defects}$$

Increase of inverse trapping time ($1/\tau$) with fluence →



Expected signal from charge trapping

Effect of trapping on the Charge Collection Distance:

$$Q_{tc} \cong Q_0 \exp(-t_c/\tau_{tr}),\ 1/\tau_{tr} = \beta\Phi.$$

$$v_{sat,e} \times \tau_{tr} = \lambda_{av}$$

$$\beta_e = 4.2E{-}16\ cm^{-2}/ns$$

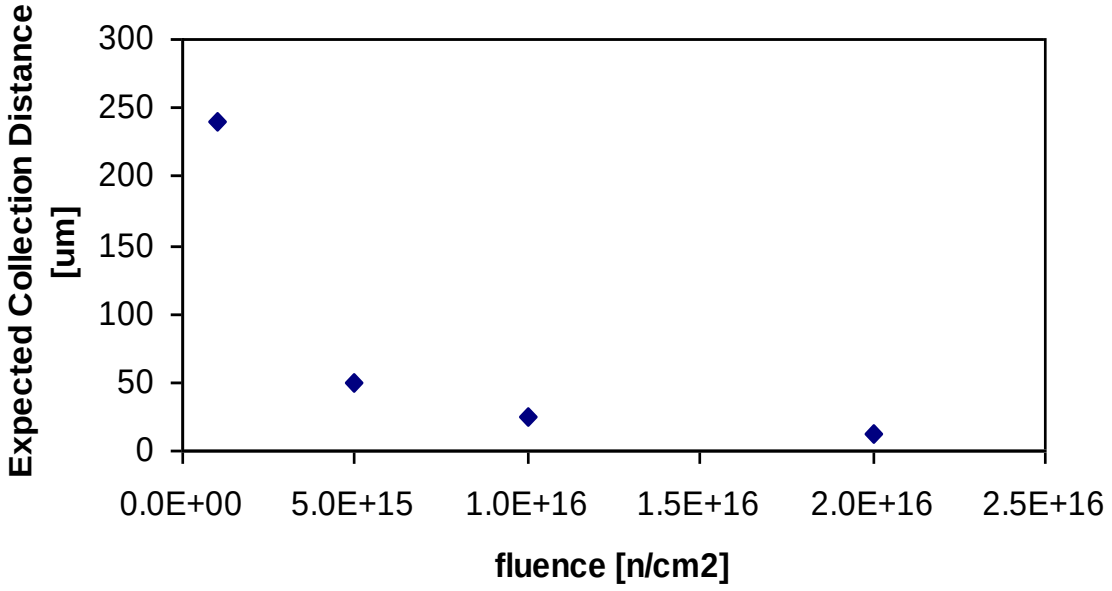
$$\beta_h = 6.1E{-}16\ cm^{-2}/ns$$

G. Kramberger et al., NIMA 476(2002), 645-651.

Expected collection distance at saturation velocity λ_{av} :

after $1x10^{15}$ n_{eq} cm^{-2}: 240µm expected charge ~19ke.

λ_{av} after $1x10^{16}$ n_{eq} cm^{-2}: 25µm expected charge <1.3ke : quite inefficient detector!



Signal to Noise ratio Example with diodes

- **Landau distribution has a low energy tail**
  - **becomes even lower by noise broadening**

- **Noise sources: (ENC = Equivalent Noise Charge)**

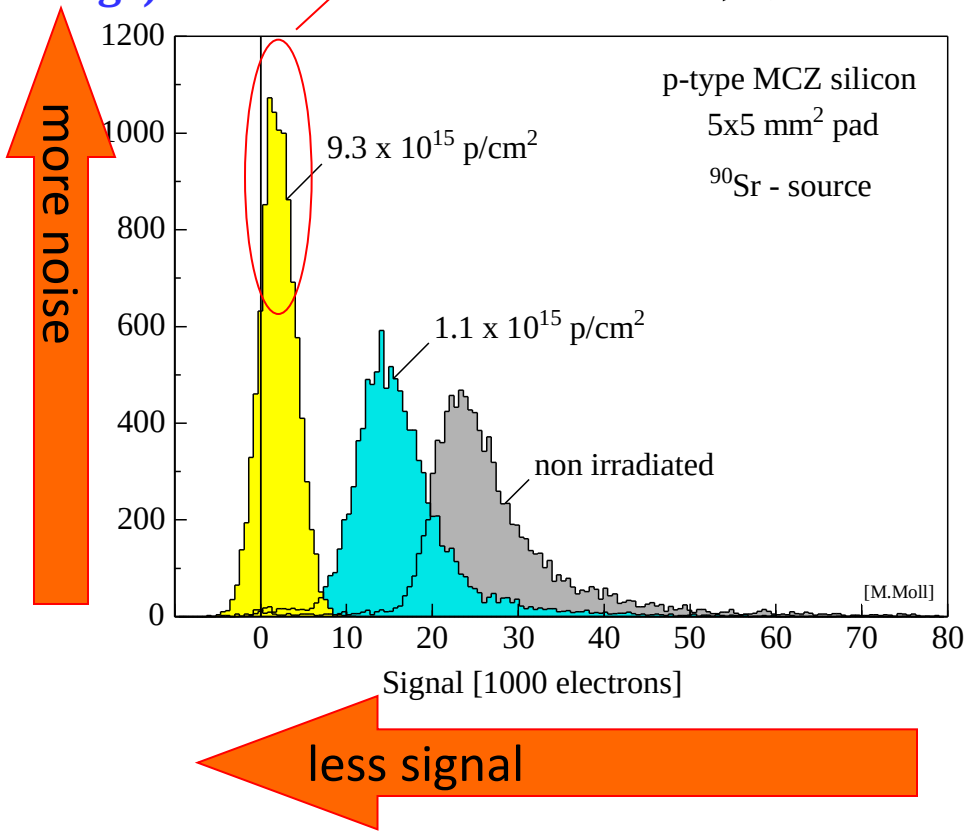
  - **Capacitance** $ENC \propto C_d$

  - **Leakage Current** $ENC \propto \sqrt{I}$

  - **Thermal Noise (bias resistor)** $ENC \propto \sqrt{k_B T / R}$

- **Figure of Merit: Signal-to-Noise Ratio S/N. Radiation damage severely degrades the S/N, people get nervous below 10.**

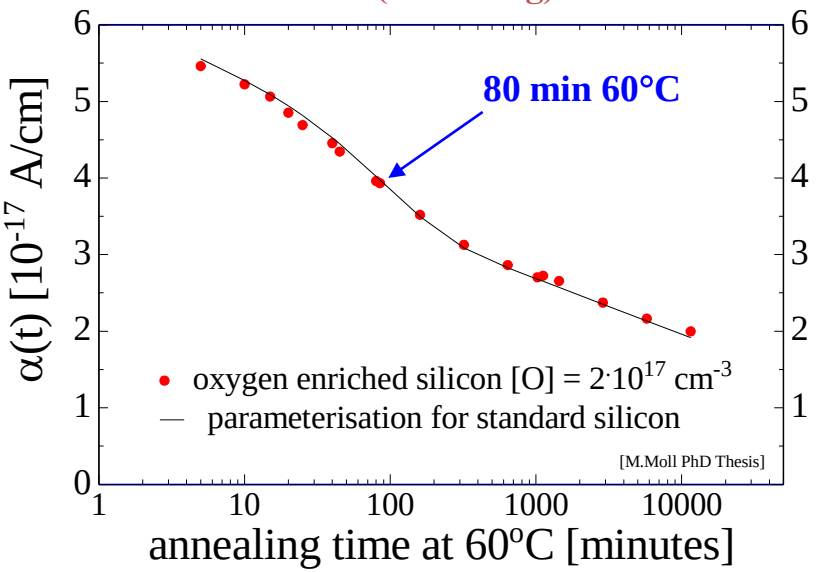
What is signal and what is noise?



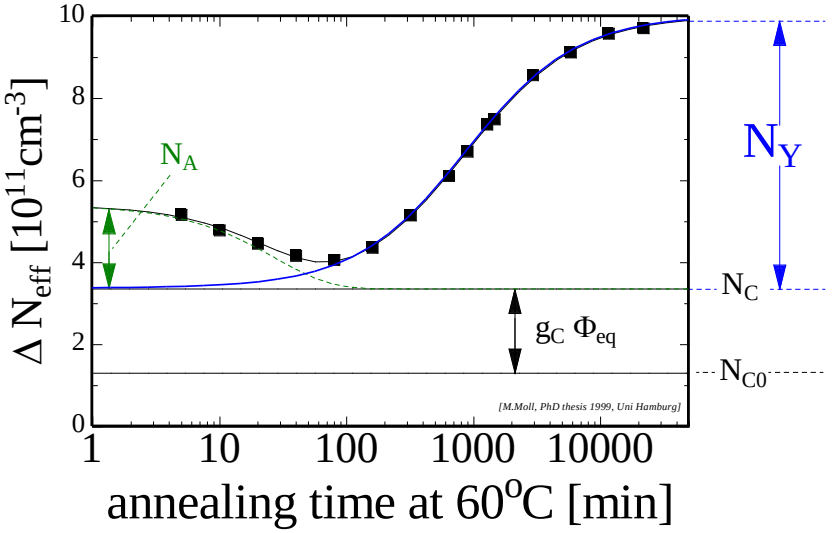
Changes with time and temperature after irradiation (annealing)

- **Leakage Current and N_{eff} (after hadron irradiation)**

…. with time (annealing):



…. with time (annealing):



- **Leakage current decreasing in time (depending on temperature)**
- **Strong temperature dependence**

$$I \propto \exp\left(-\frac{E_g}{2k_BT}\right)$$

Consequence:

Cool detectors during operation!

Example: *I*(-10°C) ~1/16 *I*(20°C)

- Short term: **"Beneficial annealing"**
- Long term: **"Reverse annealing"**

- time constant depends on temperature:

~ 500 years (-10°C)

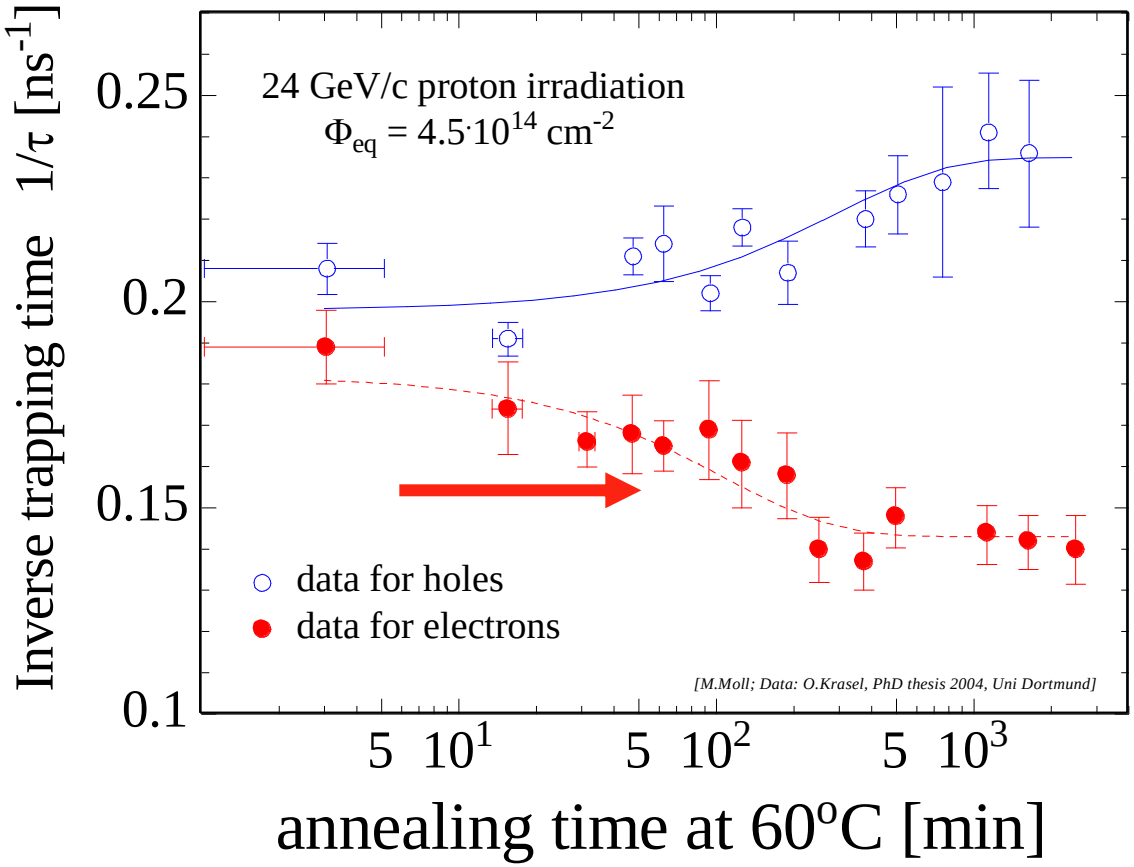
~ 500 days (20°C)

~ 21 hours (60°C)

- Consequence: **Detectors must be cooled even when the experiment is not running!**

Change of inverse trapping time

Decrease of inverse trapping time (1/τ) with annealing for electrons



Approaches to develop radiation harder solid state tracking detectors

Scientific strategies:

I. Material engineering

II. Device engineering

III. Change of detector operational conditions

CERN-RD39
"Cryogenic Tracking Detectors"
operation at 100-200K
to reduce charge loss

- **Defect Engineering of Silicon**

Deliberate incorporation of impurities or defects into the silicon bulk to improve radiation tolerance of detectors

  - **Needs: Profound understanding of radiation damage**
    - **microscopic defects, macroscopic parameters**
    - **dependence on particle type and energy**
    - **defect formation kinetics and annealing**
  - **Examples:**
    - **Oxygen rich Silicon (DOFZ, Cz, MCZ, EPI)**
    - **Oxygen dimer & hydrogen enriched Si**
    - **Pre-irradiated Si**
    - **Influence of processing technology**

- **New Materials**
  - **Silicon Carbide (SiC), Gallium Nitride (GaN)**
  - **Diamond (CERN RD42 Collaboration)**
  - **Amorphous silicon**

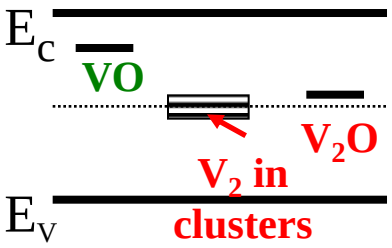
- **Device Engineering (New Detector Designs)**
  - **p-type silicon detectors (n-in-p)**
  - **thin detectors, epitaxial detectors**
  - **3D detectors and Semi 3D detectors, Stripixels**
  - **Cost effective detectors**
  - **Monolithic devices**

Oxygen Enrichment for Radiation Hardening

RD48 (ROSE) and RD50 CERN Collaborations

Main Hypothesis: Oxygen beneficial as sink of vacancies

$V\text{-}O_i$ complex concentration increase → reduction of deeper levels mainly divacancy related



Typical oxygen concentration in Si:

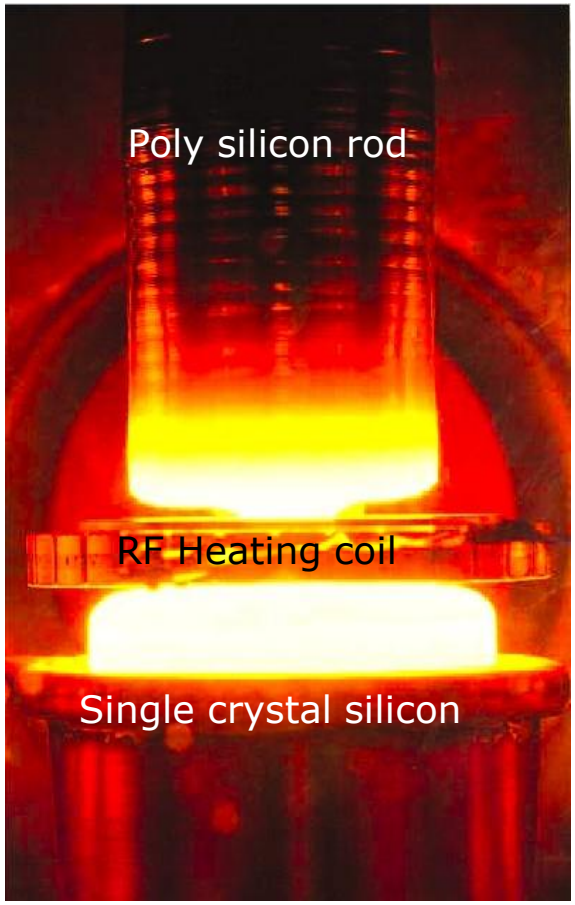
- **FZ [Oi] $10^{15}cm^{-3}$**
- **Diffusion oxygenated FZ : DOFZ [O_i] 10^{16}-$10^{17}cm^{-3}$**
- **Czochralski Si: [O_i] up to $10^{18}cm^{-3}$**

Note: as VO is a point defect the beneficial effect of oxygen is expected especially when cluster formation by irradiation is less important than point defect formation.

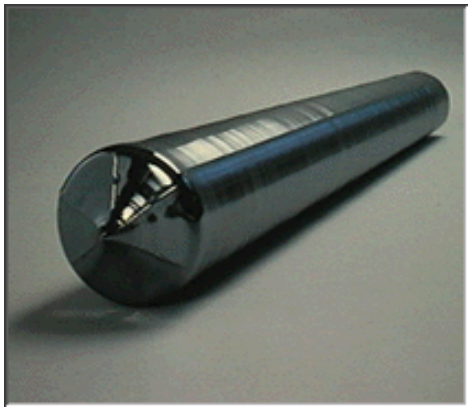
Material: Float Zone Silicon (FZ)

Float Zone process

- Using a single Si crystal seed, melt the vertically oriented rod onto the seed using RF power and “pull” the monocrystalline ingot



Mono-crystalline Ingot



Wafer production

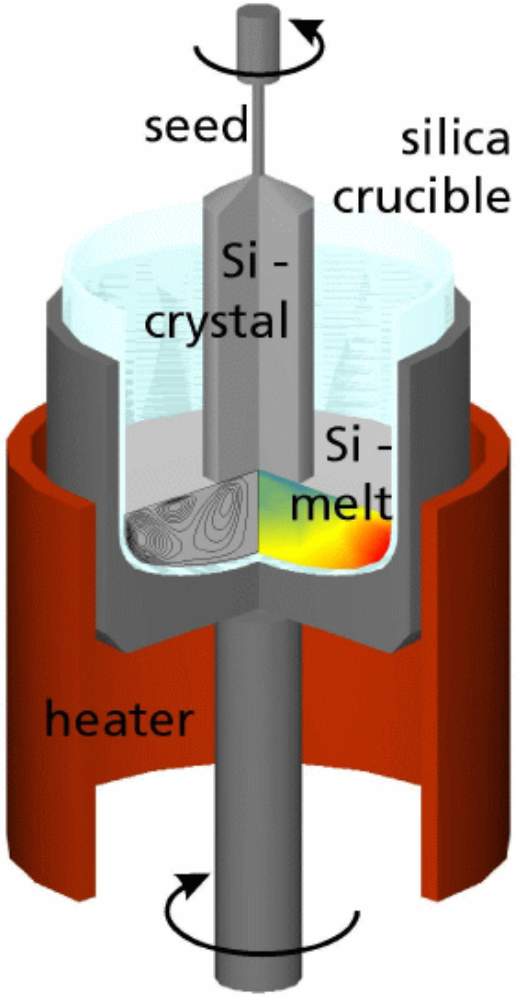
- Slicing, lapping, etching, polishing

Highly pure crystal

- Low concentration of [O] and [C] $10^{15}cm^{-3}$

Czochralski silicon (Cz) & Epitaxial silicon (EPI)

Czochralski silicon



- Pull Si-crystal from a Si-melt contained in a silica crucible while rotating.
- Silica crucible is dissolving oxygen into the melt ⇨ high concentration of O in CZ
- Material used by IC industry (cheap)
- Recent developments (~5 years) made CZ available in sufficiently high purity (resistivity) to allow for use as particle detector.

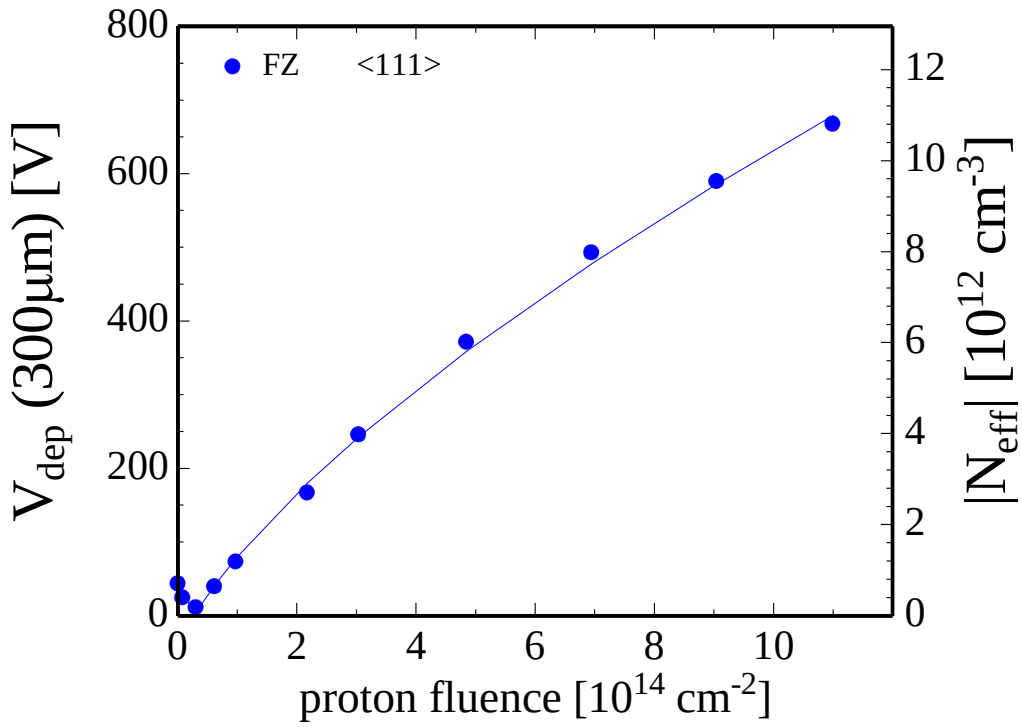
Epitaxial silicon

- Chemical-Vapor Deposition (CVD) of Silicon
- CZ silicon substrate used ⇨ **in-diffusion of oxygen**
- growth rate about 1μm/min
- excellent homogeneity of resistivity
- up to 150 μm thick layers produced (thicker is possible)
- price depending on thickness of epi-layer but not extending ~ 3 x price of FZ wafer

Standard FZ, DOFZ, MCz and Cz silicon

24 GeV/c proton irradiation

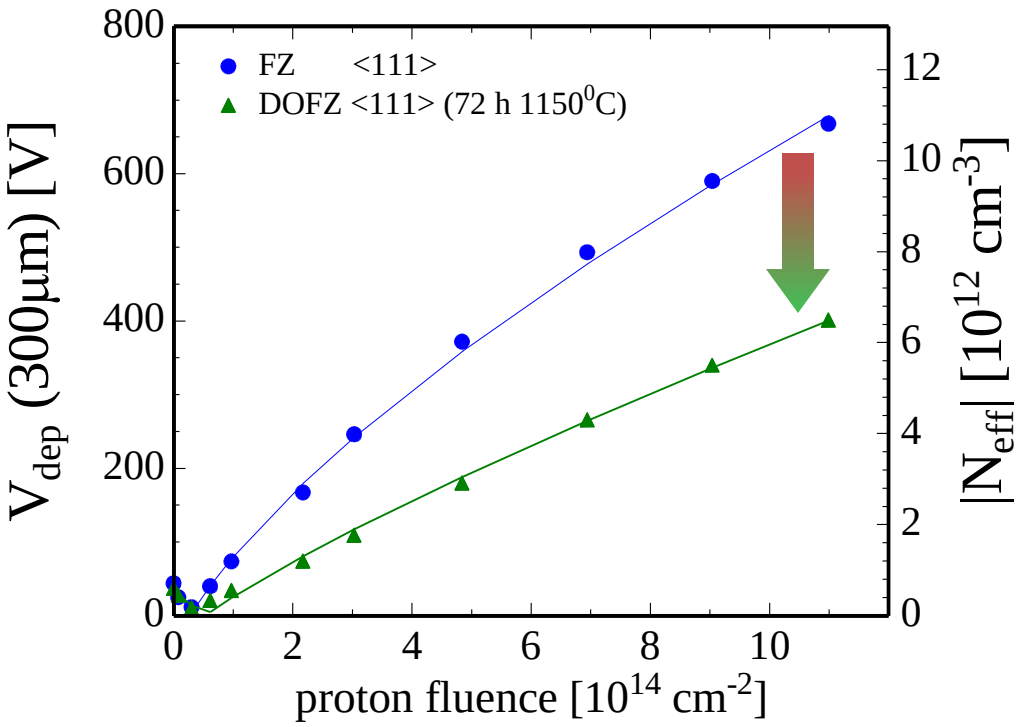
- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong N_{eff} increase at high fluence



Standard FZ, DOFZ, MCz and Cz silicon

24 GeV/c proton irradiation

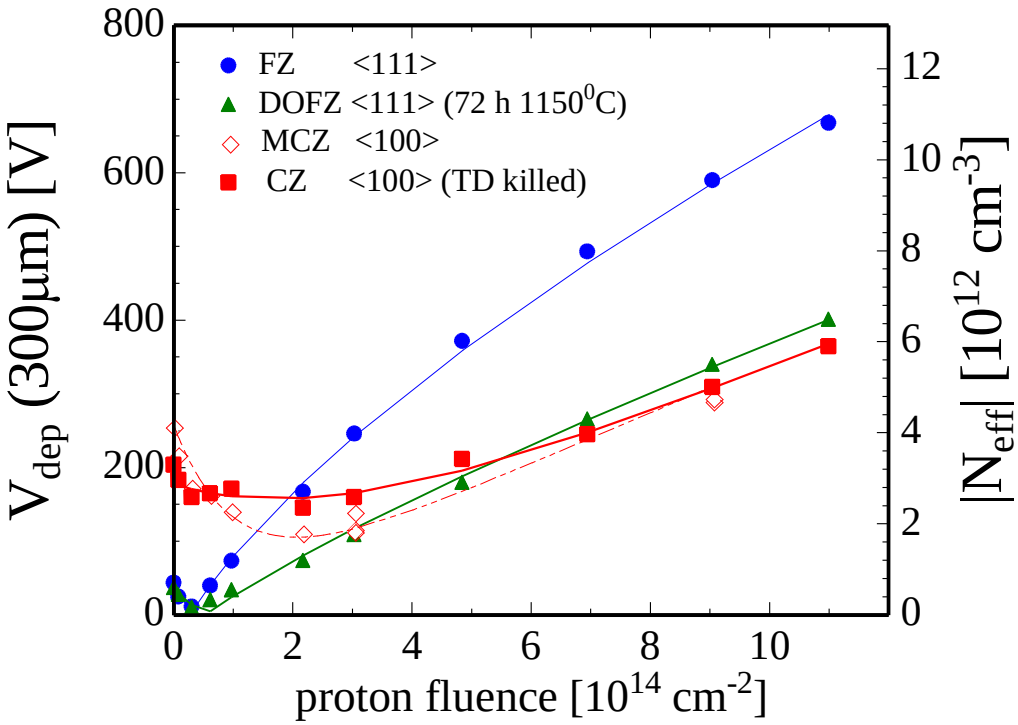
- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong N_{eff} increase at high fluence
- **Oxygenated FZ (DOFZ)**
  - type inversion at ~ 2×10^{13} p/cm^2
  - reduced N_{eff} increase at high fluence



Standard FZ, DOFZ, MCz and Cz silicon

24 GeV/c proton irradiation

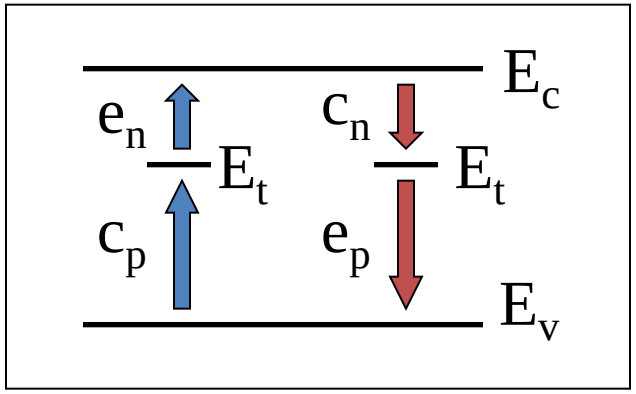
- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong N_{eff} increase at high fluence
- **Oxygenated FZ (DOFZ)**
  - type inversion at ~ 2×10^{13} p/cm^2
  - reduced N_{eff} increase at high fluence
- **CZ silicon and MCZ silicon**
  - "no type inversion" in the overall fluence range



(for experts: there is no "real" type inversion, a more clear understanding of the observed effects is obtained by investigating directly the internal electric field; look for: TCT, MCZ, double junction)

- **Common to all materials** *(after hadron irradiation, not after γ irradiation)*:
  - **reverse current increase**
  - **increase of trapping (electrons and holes) within ~ 20%**

The Microscopic View: Defects in irradiated silicon



E_t, σ, N_t Trap parameters

Concentration

Cross section

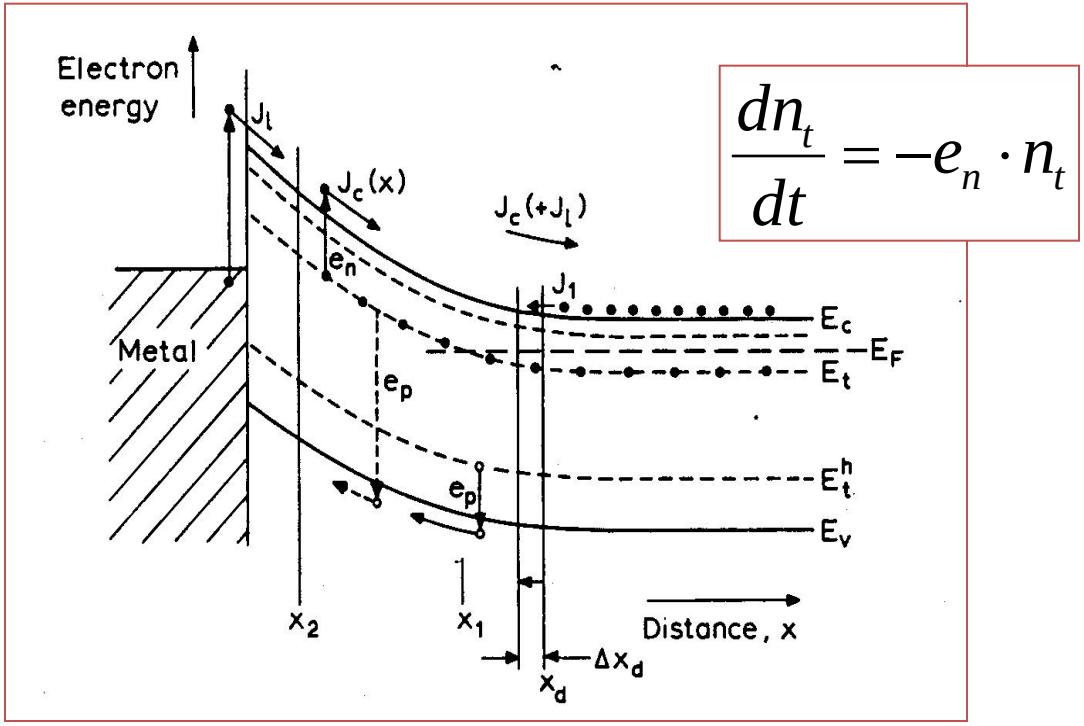
Activation energy

Emission coefficient:

$$e_n = N_c \sigma_n v_{th} \cdot e^{-\frac{E_c - E_t}{KT}}$$

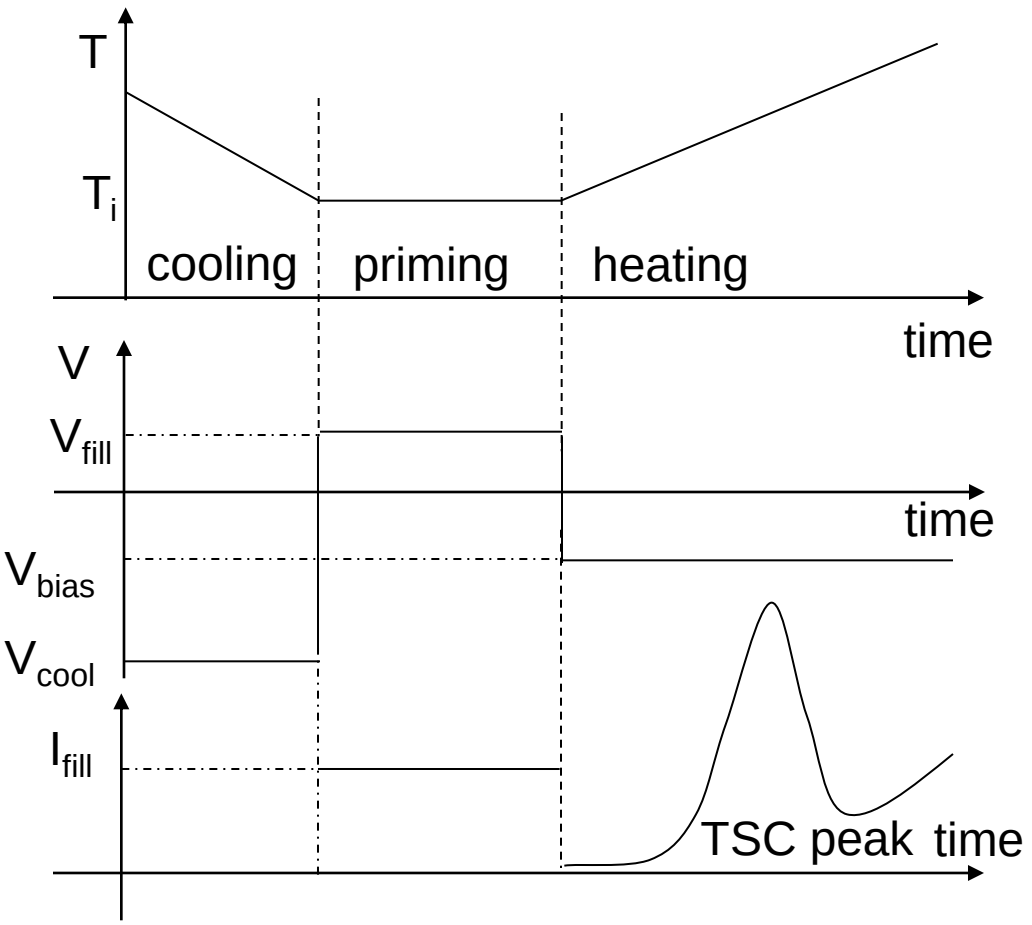
Capture coefficient :

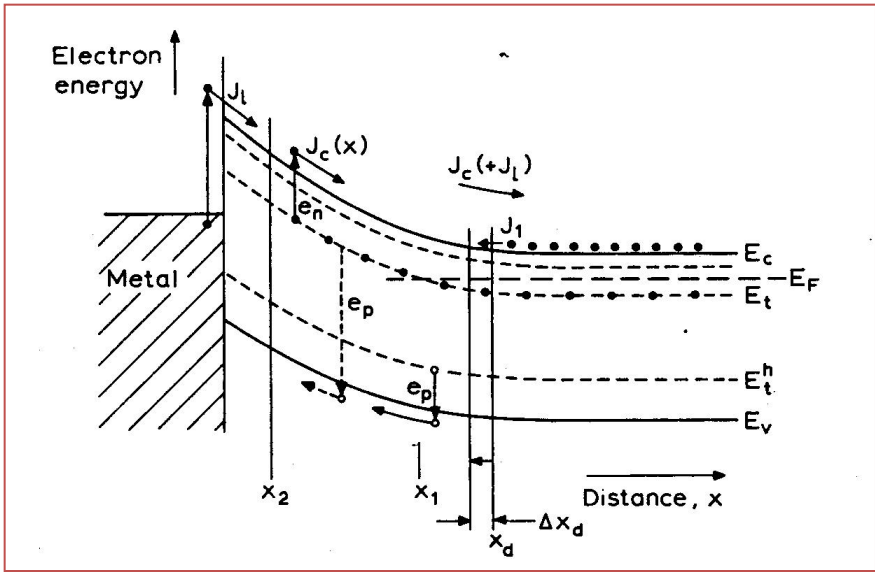
$$c_n = n \sigma_n v_{th}$$



$$\frac{dn_t}{dt} = -e_n \cdot n_t$$

Thermally Stimulated Current: TSC





-Cooling with applied reverse V_{cool} or null bias

-Forward voltage applied V_{fill} at T_i or illumination with optical source

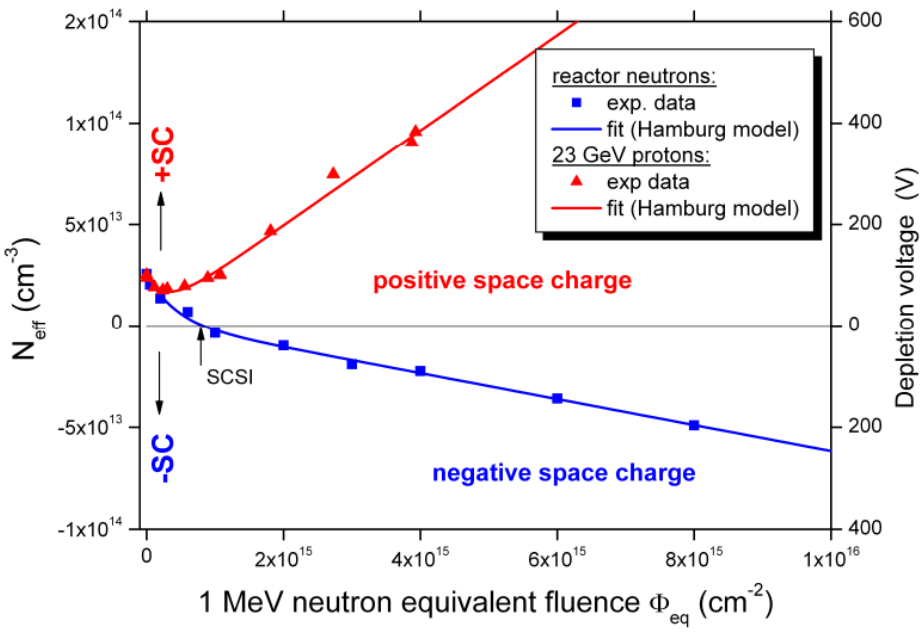
- V_{bias} applied

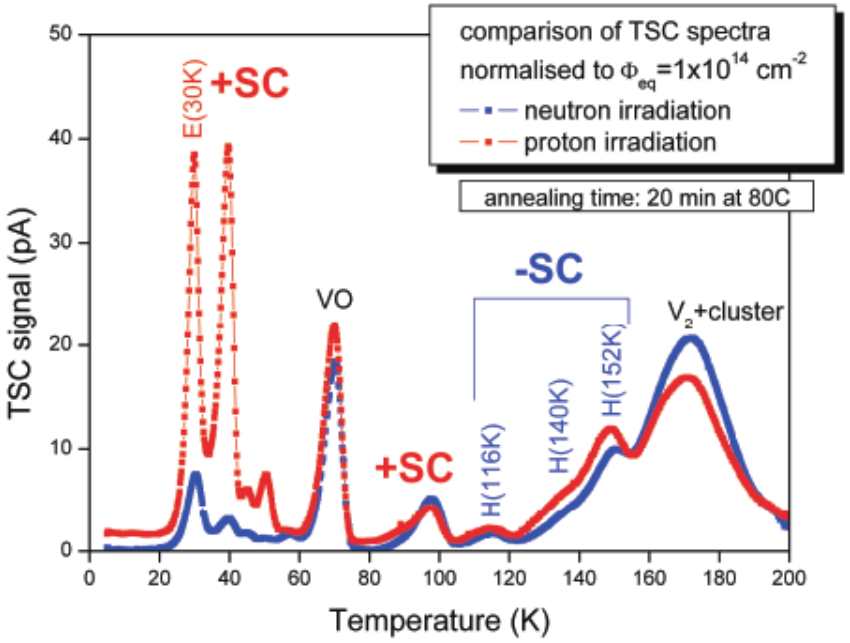
-Thermally stimulated current read-out

$$I_{TSC}(T) = -\frac{1}{2} q \cdot A \cdot N_t \cdot W \cdot e_n(T) \exp\left(-\frac{1}{b} \int_{Ti}^{T} e_n(T) dT \right)$$

From microscopic to macroscopic: N_{eff} changes explained with TSC

Epi-Si irradiated with 23 GeV protons and reactor neutrons





[Pintilie, Lindstroem, Junkes, Fretwurst, NIM A 611 (2009) 52–68]

- SCSI "Type Inversion" after neutrons but not after protons
- donor generation enhanced after proton irradiation

Main Defects Affecting the Device Properties

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

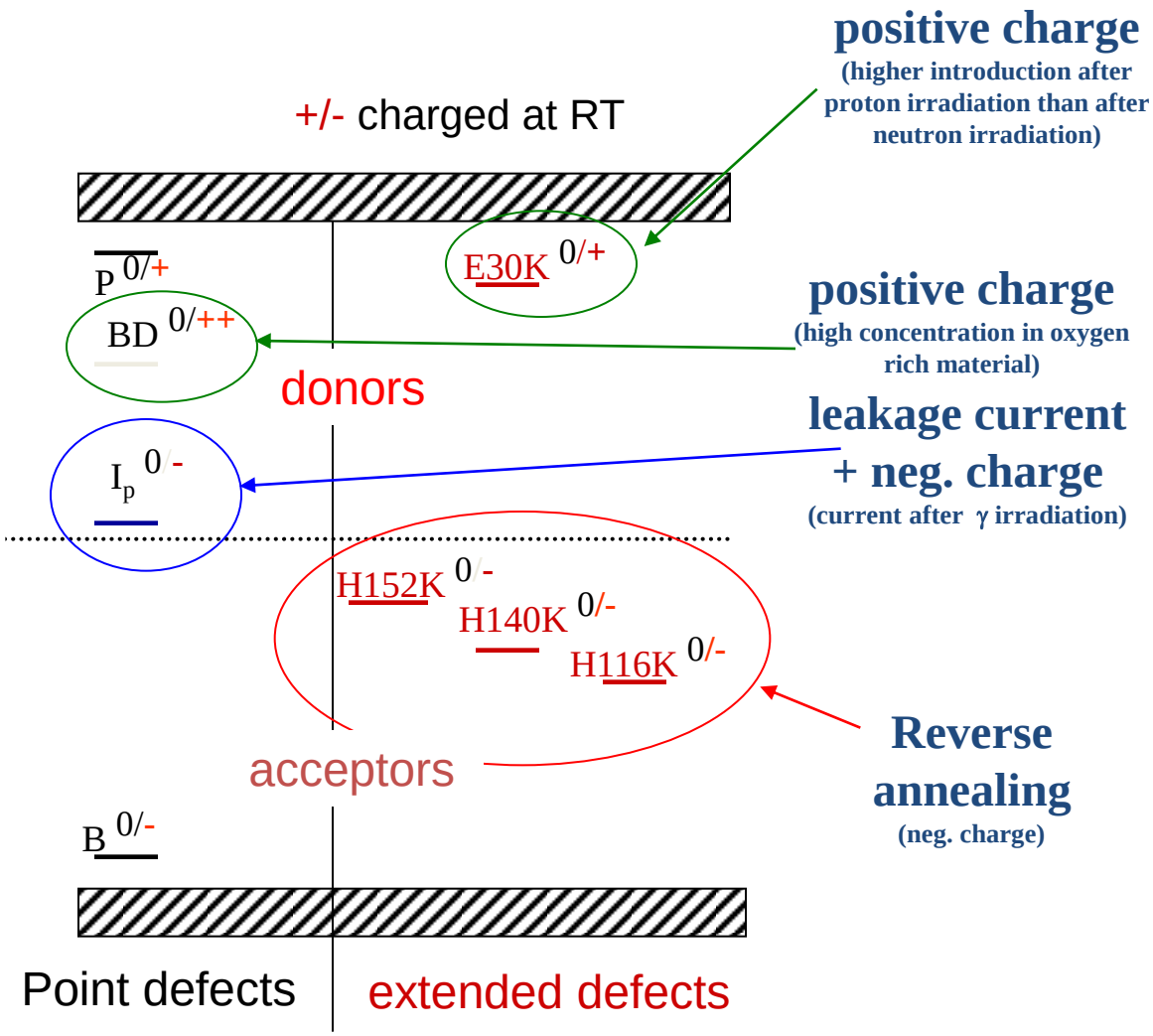
Cluster related centers

- $E_i^{116K} = E_v + 0.33$eV
- $\sigma_p^{116K} = 4 \cdot 10^{-14}$ cm^2

- $E_i^{140K} = E_v + 0.36$eV
- $\sigma_p^{140K} = 2.5 \cdot 10^{-15}$ cm^2

- $E_i^{152K} = E_v + 0.42$eV
- $\sigma_p^{152K} = 2.3 \cdot 10^{-14}$ cm^2

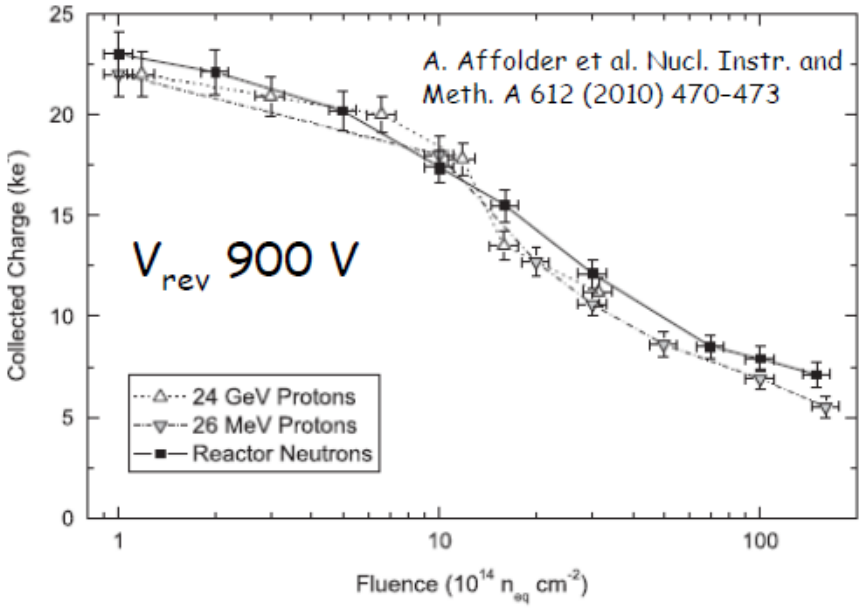
- $E_i^{30K} = E_c - 0.1$eV
- $\sigma_n^{30K} = 2.3 \cdot 10^{-14}$ cm^2

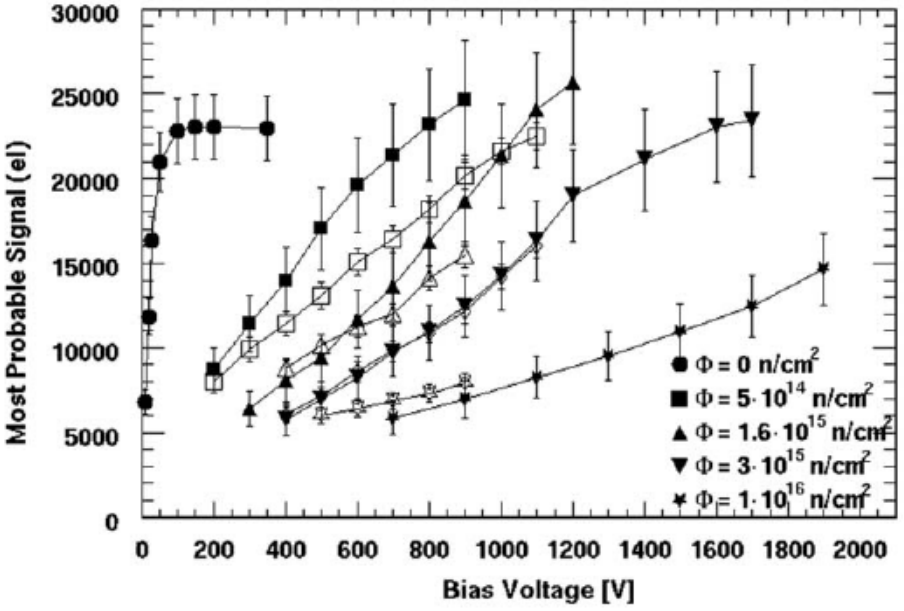


[I.Pintilie et al., Appl. Phys. Lett.92 024101,2008]

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

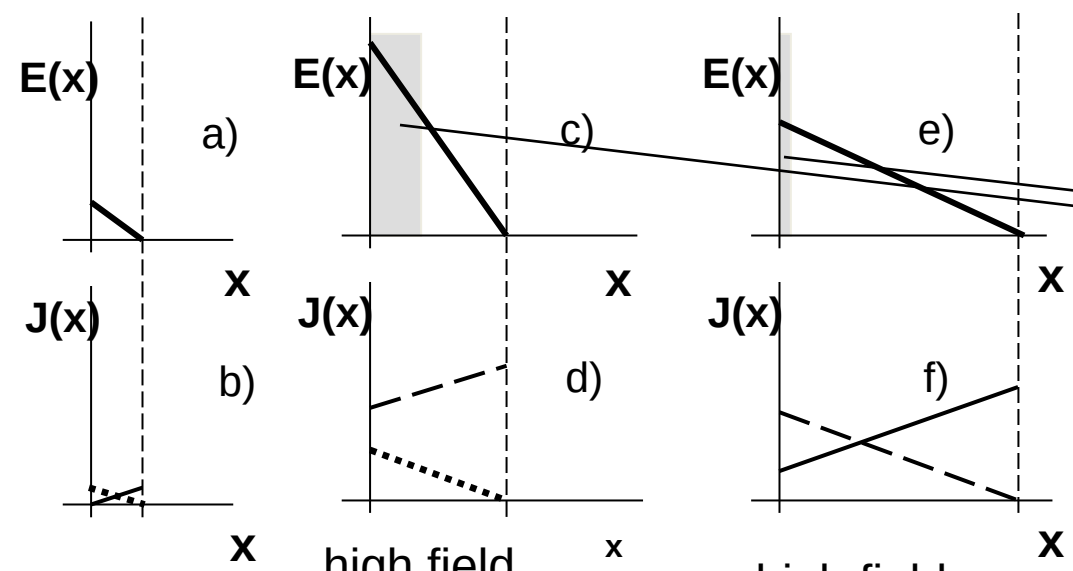




I. Mandic et al. Nucl. Inst. And Meth. A 612 (2010) 474-477

- 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^+
- when a sufficiently enough high voltage is applied 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 Neff 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 to the deep levels of radiation induced defects in the bulk

gives rise to the negative feedback that:

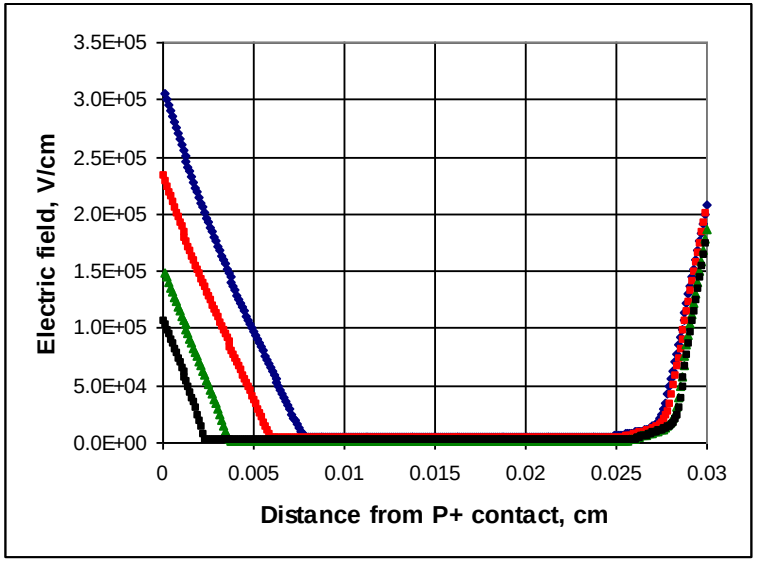
-reduces and stabilizes maximum electric field at n+ contact,
-this stabilization takes place in both designs – pad and strip,
in strips for any strip width to pitch ratio;
- stabilizes the avalanche multiplication,
- prevents the detector breakdown,
- smoothes out the signal on voltage and current on voltage characteristics.

Electric Field simulation with consideration of current focusing in strip detectors

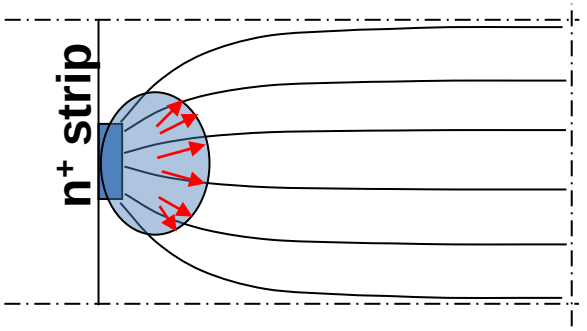
- The electric field was simulated with the PTI model* which takes into account two effective energy levels: a midgap donor and a migap acceptor
- A correction for electric field focusing has been introduced

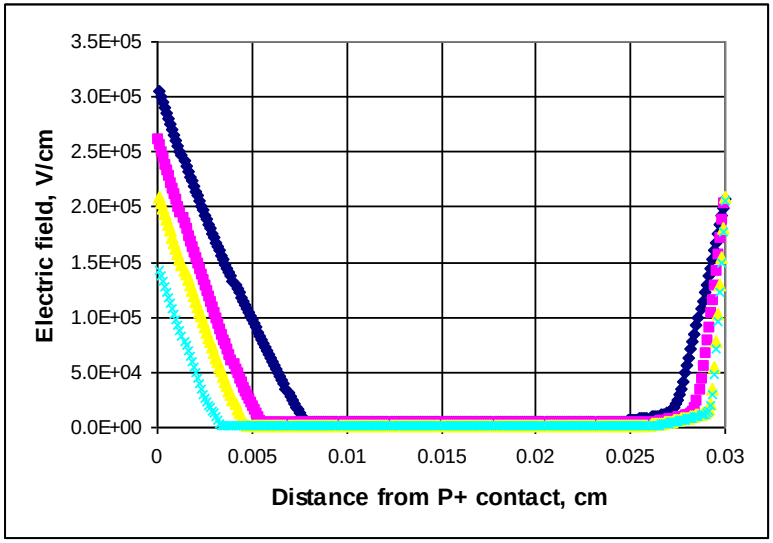
NO electric field focusing
(PAD configuration)

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



electric field focusing

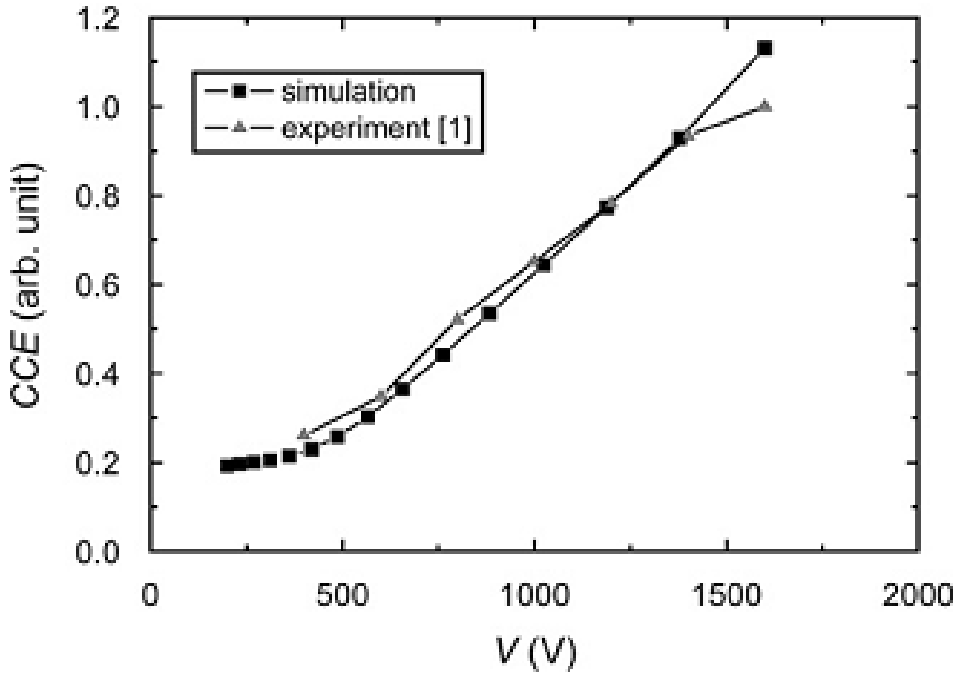




*V. Eremin, E. Verbitskaya, Z. Li, Nucl. Instr. and Meth. A 426 (2002) 537.

Correlation between experimental data and calculated CCE

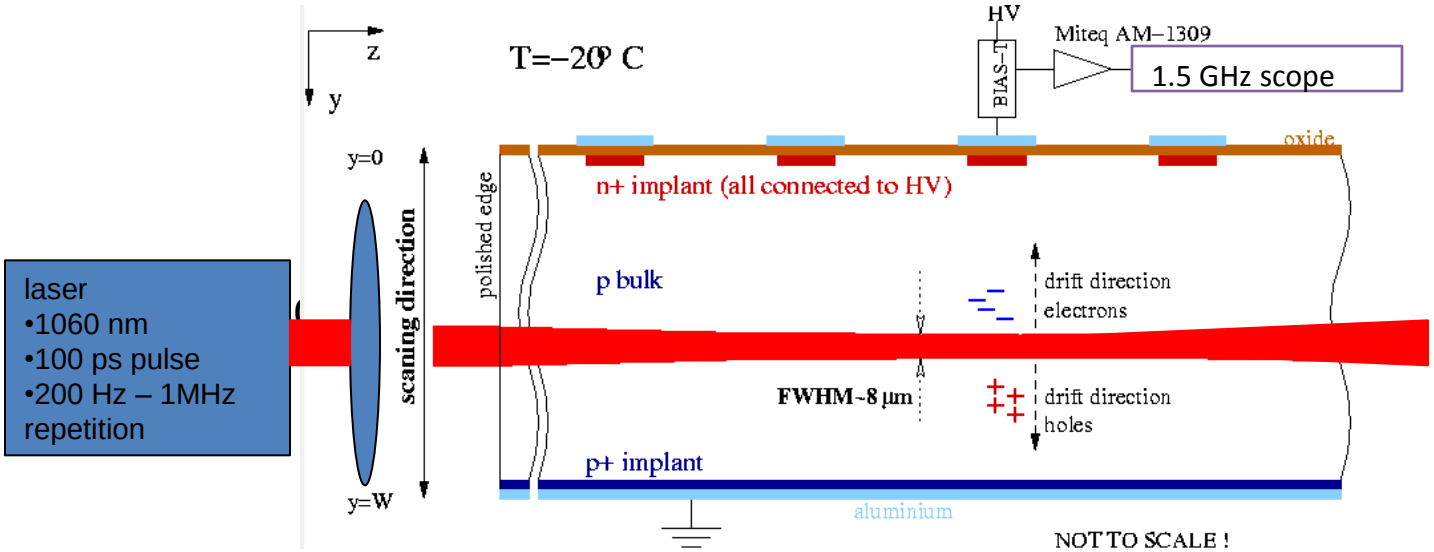
$F_n = 3x10^{15}$ cm^{-2}



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

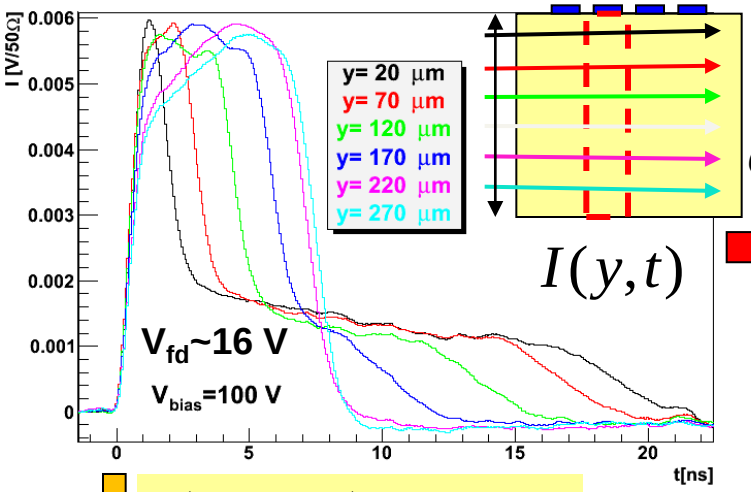
Edge-Tranient Current Technique (TCT): a tool to estimate the electric field distribution within the thickness of the detector



- 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

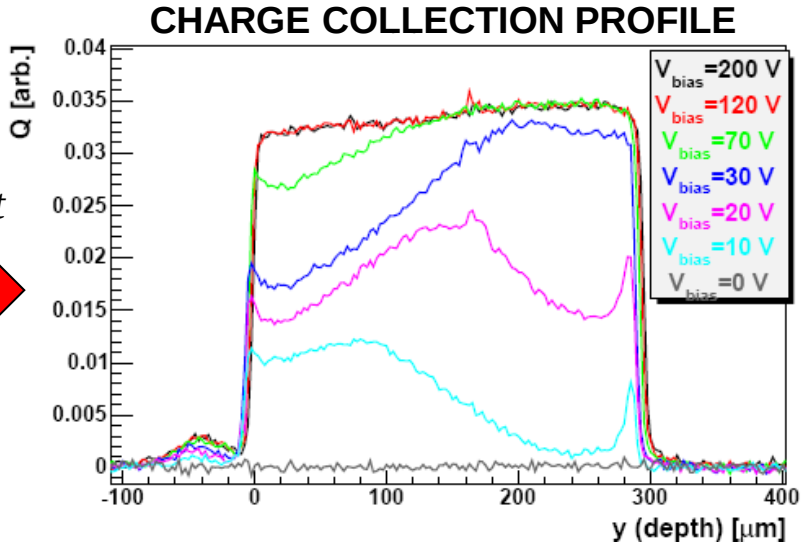
From the analysis of the current transients the carrier drift velocity and efficiency can be extracted

Charge collection and velocity profiles



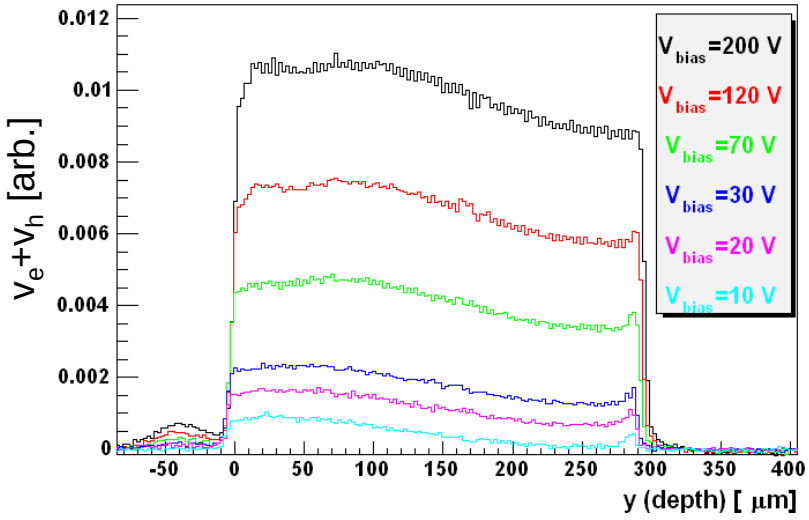
$I(y,t)$

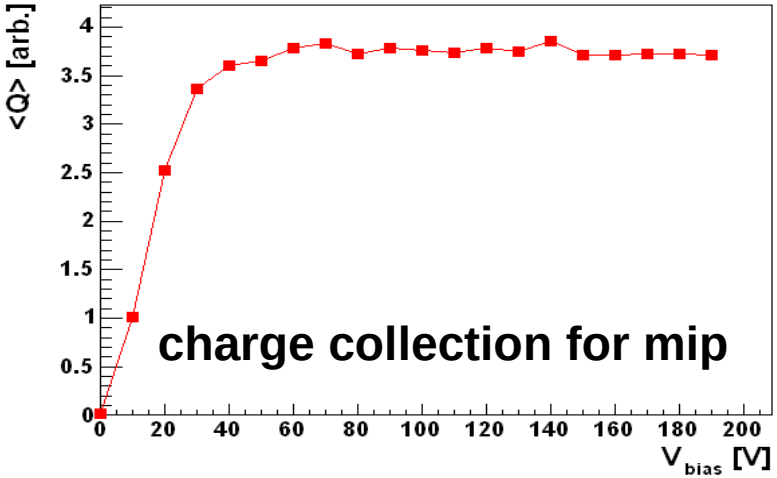
$$Q(y) = \int_0^{25ns} I(y,t)\,dt$$



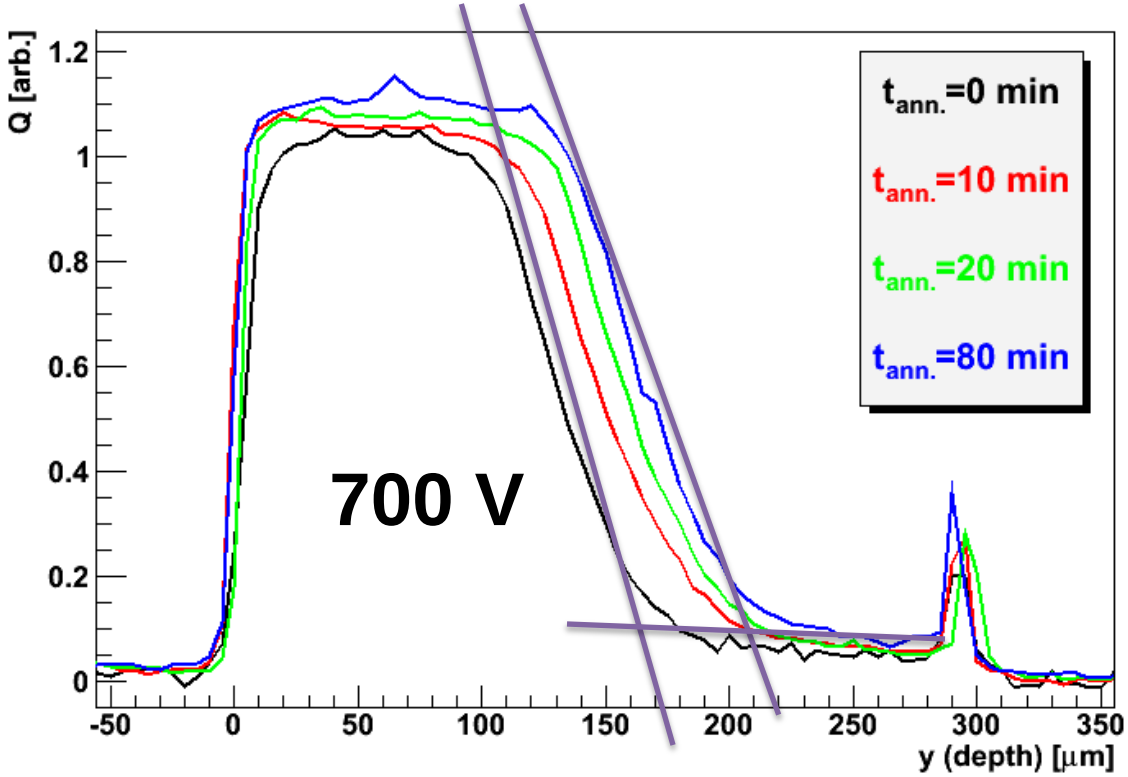
$$I(y,t\sim 0) \propto v_e + v_h$$

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





HPK (Φ_{eq}=10^{15} cm^{-2}) – beneficial annealing



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

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

$$\Downarrow$$

$$\mathrm{predicted:}\ y_{act}(700\,\mathrm{V}) \approx 200\,\mu\mathrm{m}$$

$$\mathrm{measured:}\ y_{act}(700\,\mathrm{V}) = 205\,\mu\mathrm{m}$$

$$\Delta N_{eff} \approx N_{eff} \cdot \left[\frac{y_{act}(0\mathrm{min})}{y_{act}(80\mathrm{min})}\right]^2$$

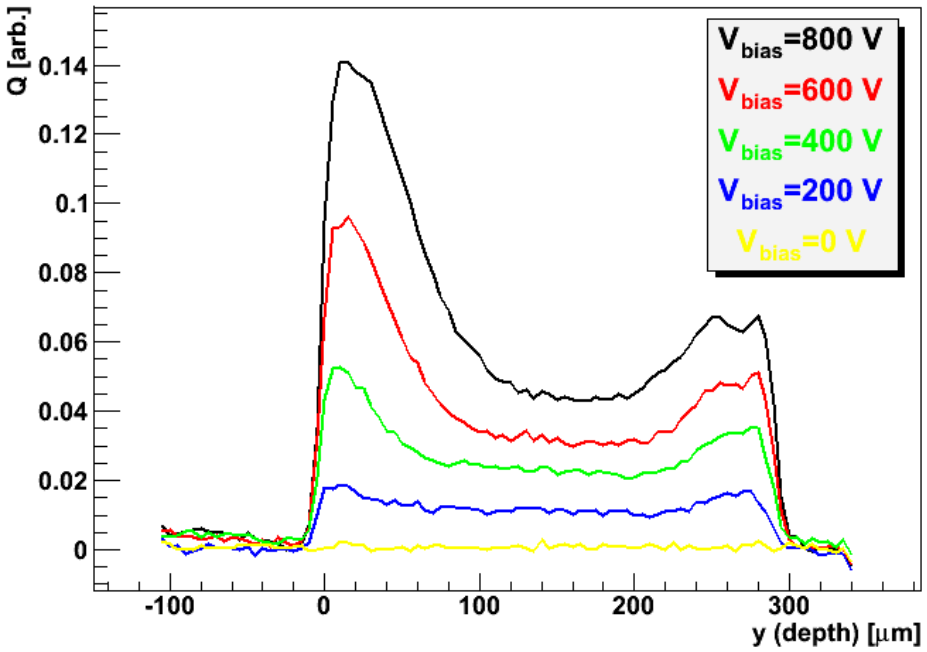
$$g_a \approx \frac{\Delta N_{eff}}{\Phi_{eq}} \approx 0.008\,\mathrm{cm}^{-1}$$

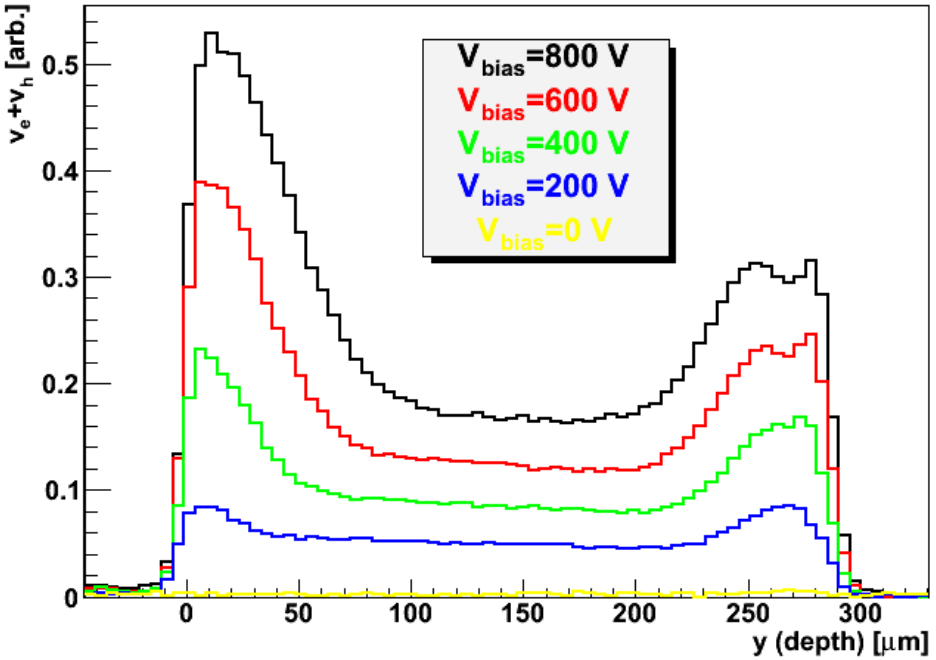
- the predicted active region (N_{eff}=const.) is very close to the measured
- A small peak at the back junction appears (double jounction)

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

HPK (Φ_{eq}=10^{16} cm^{-2})

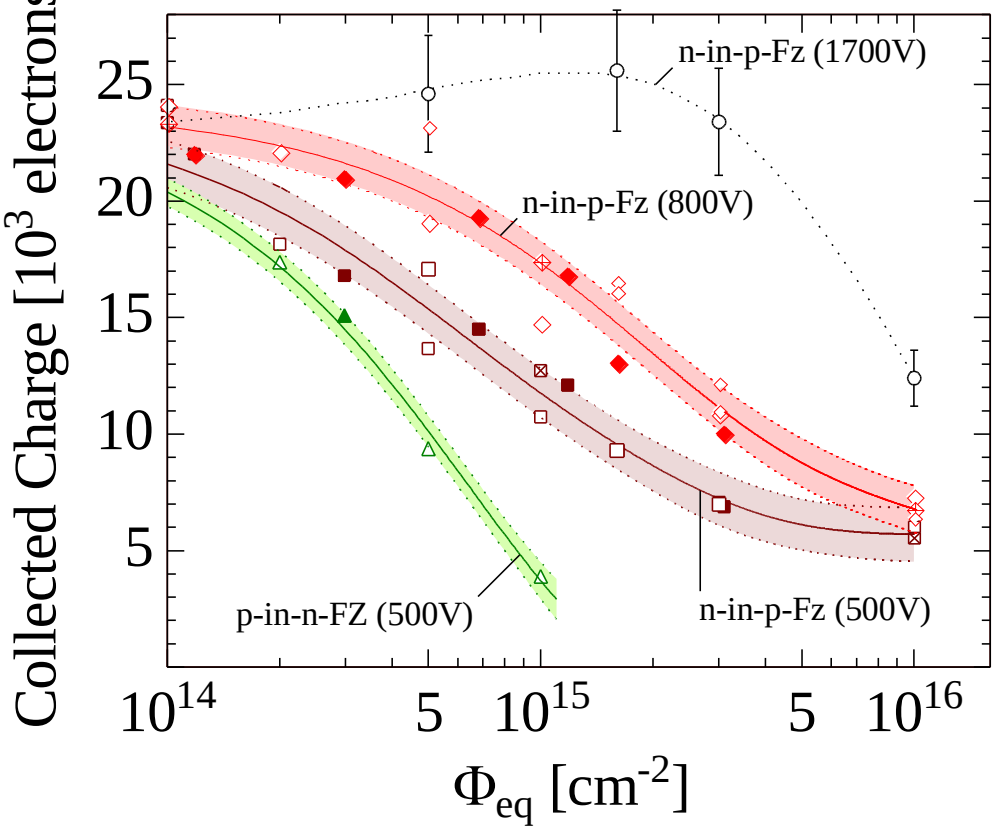




Electric field is established in the whole detector – more pronounced double junction profile

An important contribution to the collected charge from “non active” regions which brings extra signal with respect of the predicted values from Vdep. This contribution adds up to the one due to charge multiplication

RD50 Planar Detector Compilation



FZ Silicon Strip Sensors

- n-in-p (FZ), 300µm, 500V, 23GeV p
- n-in-p (FZ), 300µm, 500V, neutrons
- n-in-p (FZ), 300µm, 500V, 26MeV p
- n-in-p (FZ), 300µm, 800V, 23GeV p
- n-in-p (FZ), 300µm, 800V, neutrons
- n-in-p (FZ), 300µm, 800V, 26MeV p
- n-in-p (FZ), 300µm, 1700V, neutrons
- p-in-n (FZ), 300µm, 500V, 23GeV p
- p-in-n (FZ), 300µm, 500V, neutrons

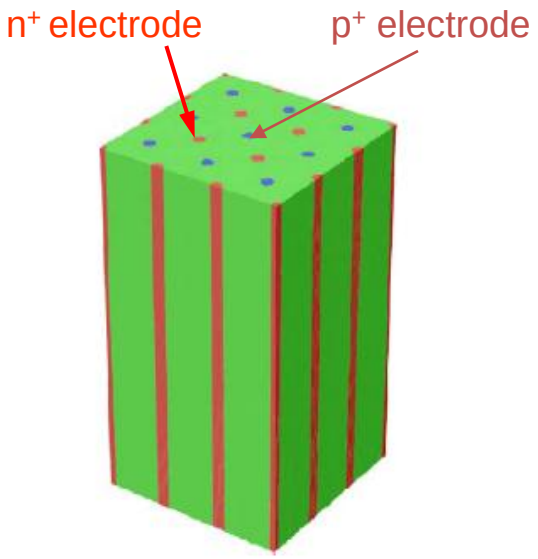
RD50 - M. Moll

- p-in-n fades away well before $10^{15}N_{eq}$
- n-in-p still gets 50% charge at $10^{16}N_{eq}$ at high bias voltages
- n-in-p benefits from charge multiplication (at high bias voltages)
- CM effect also seen for p-in-n (but less strong in partial depletion mode)
- n-in-p (n-in-n) superior material for high radiation environments

3D detectors

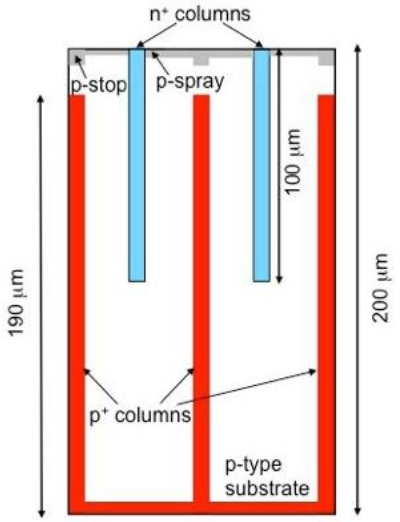
Conceptual design*

- 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}

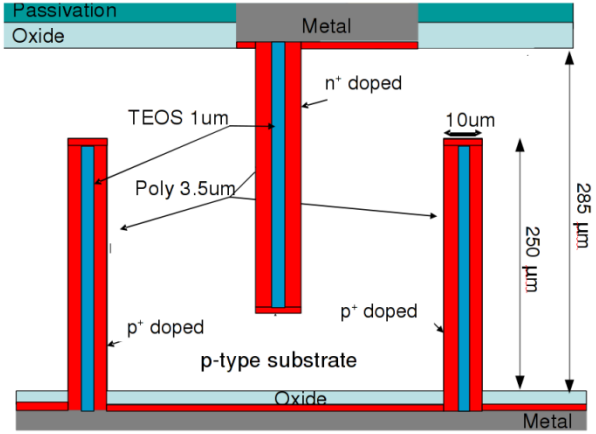


Simplified version of the original design: double sided 3D

FKB – Trento design



CNM – Barcelona design



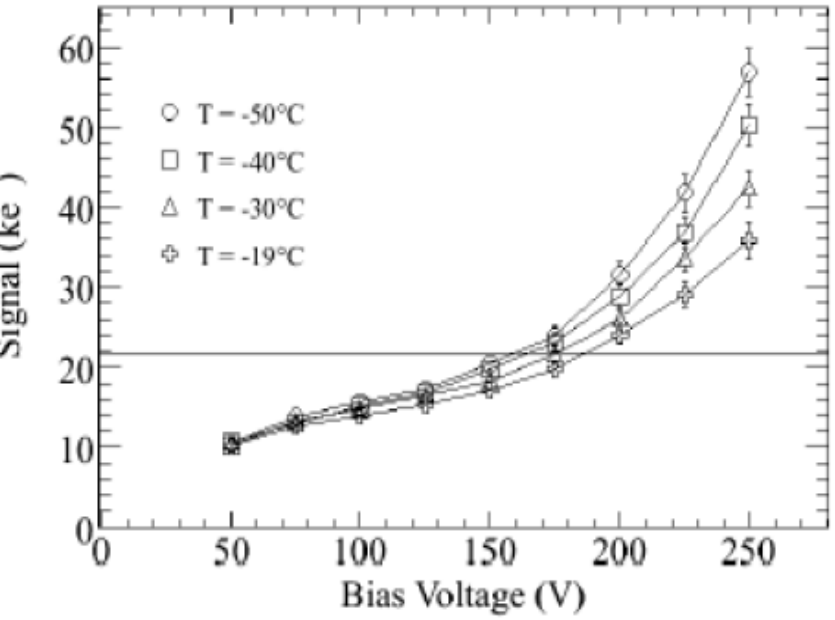
*S.I. Parker et al., NIMA 395 (1997) 328

Charge collection measurements

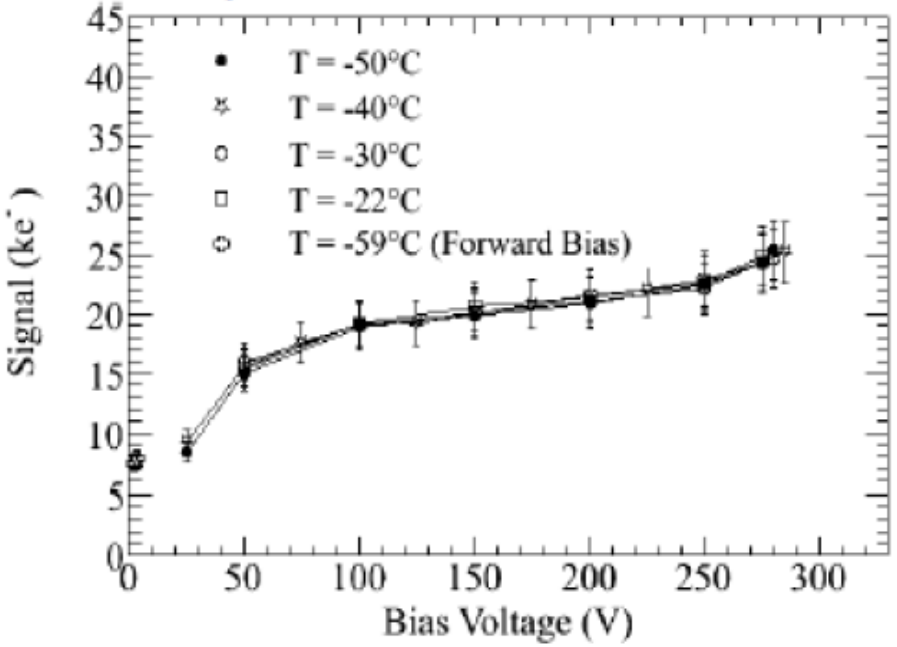
- CNM samples irradiated at the proton cyclotron Karlsruhe with 25 MeV protons
- cce measurements performed with ^{90}Sr beta source and LCHb "beetle" readout chip (ALIBAVA) at varying temperatures

Samples irradiated at 2×10^{15} n_{eq}/cm^2

n-in-p



p-in-n

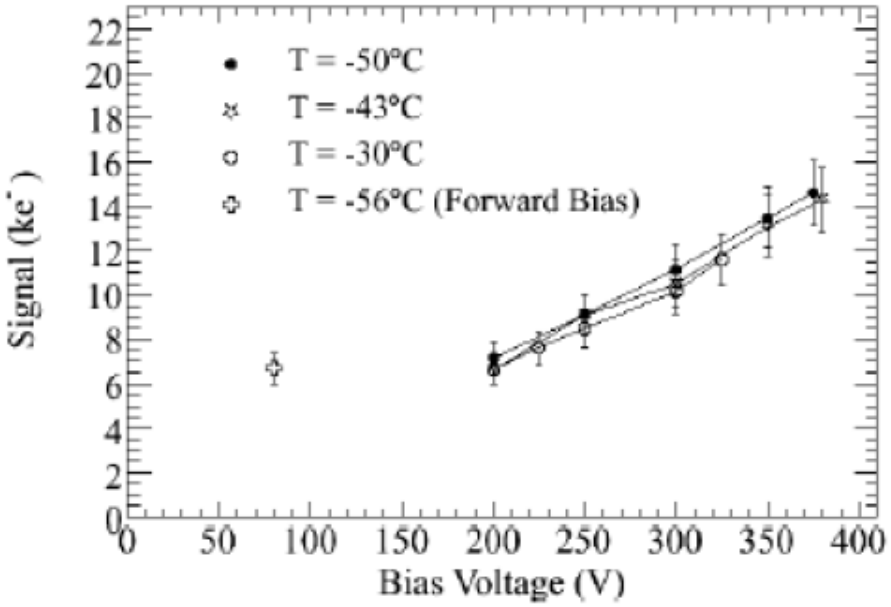


- Charge multiplication above 150 V
- Lower temperatures: higher charge multiplication

- Charge multiplication above 260 V?
- No temperature dependence

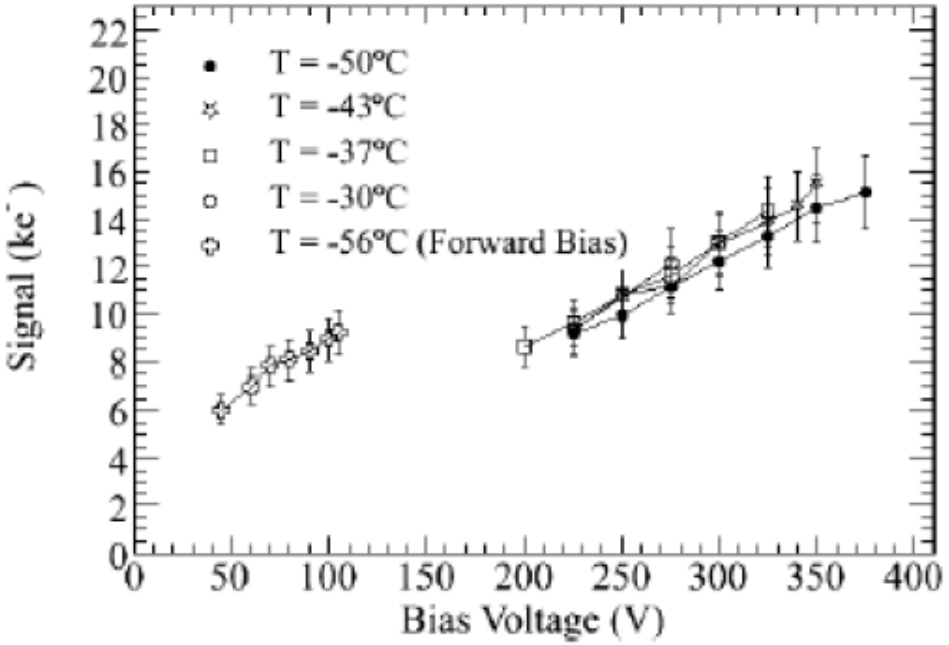
Samples irradiated at 2×10^{16} n_{eq}/cm^2

n-in-p



15 ke⁻ at 380 V reverse bias

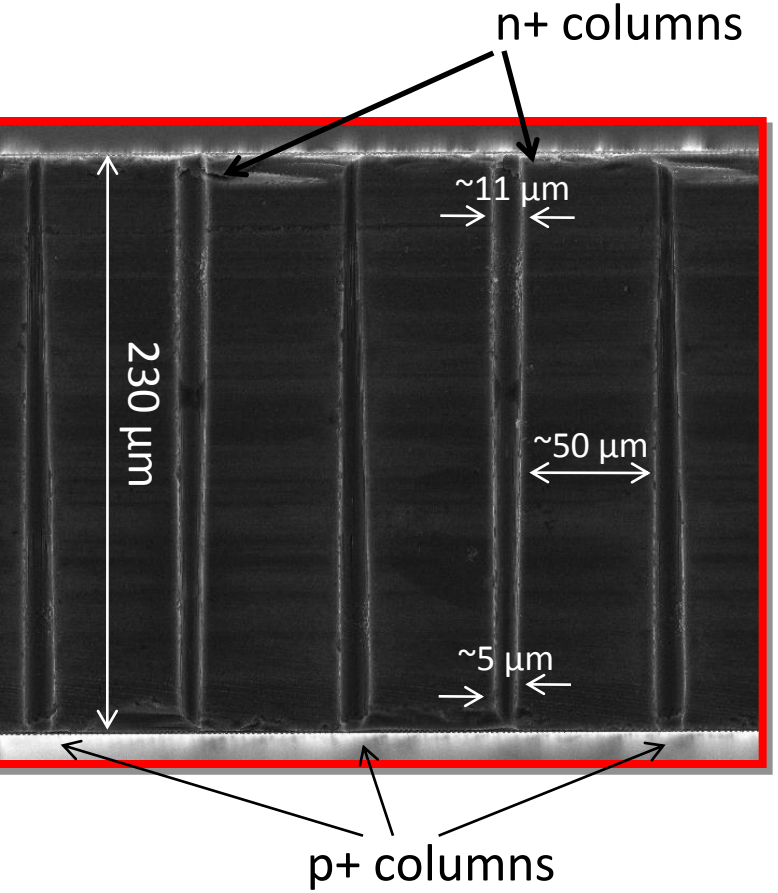
p-in-n



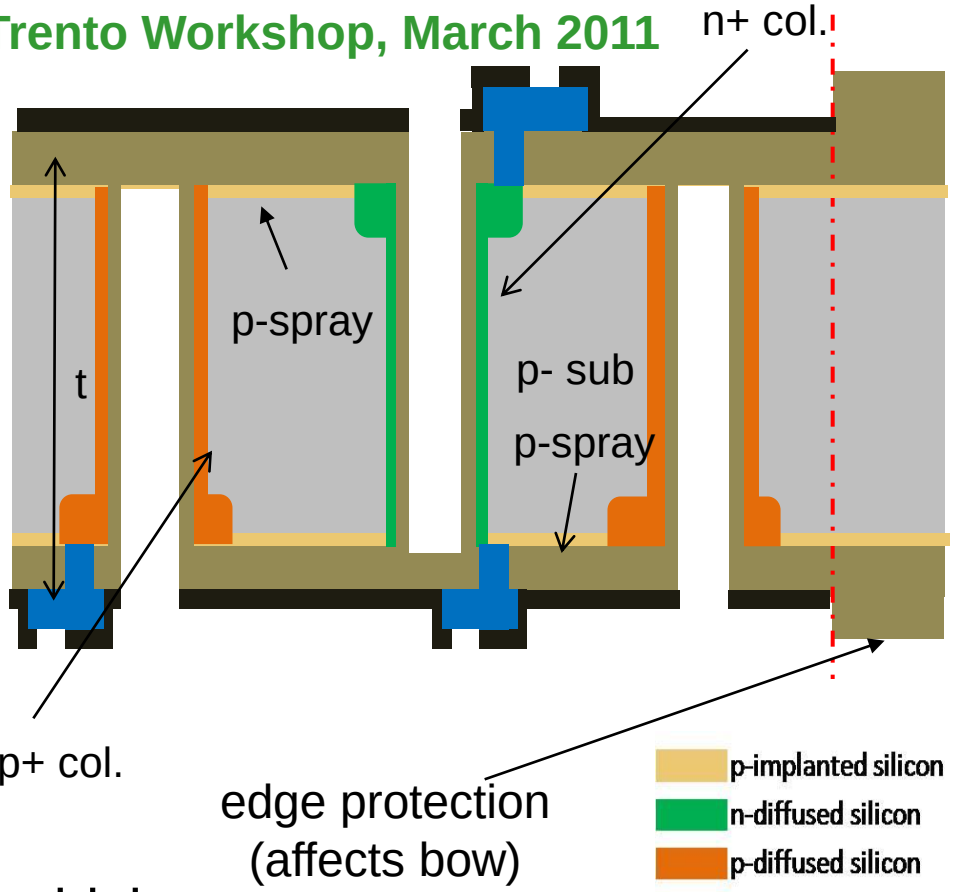
15 ke⁻ at 350 V reverse bias

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

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 silicon detectors show very good performances, better than expected by simulations
- At high voltages the collected charge can be higher than in unirradiated devices → charge multiplication
- A model was proposed to explain the self-stabilizing effect for charge multiplication in highly irradiated detectors
- Edge-TCT measurements were performed in order to estimate the electric field distribution along the thickness of the sample. A significant amount of charge is collected outside of the active volume
- Double sided 3D detectors were produced in the framework of the collaboration (CNM, FBK)
- Charge collection measurements on irradiated 3D detector 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