Radiation Tolerant Detectors for Future HEP Experiments

Results from the CERN-RD50 Collaboration

Gunnar Lindstroem
University of Hamburg

See also:

Michael Moll

Radiation Tolerant Sensors for Pixel Detectors

- CERN-RD50 project -

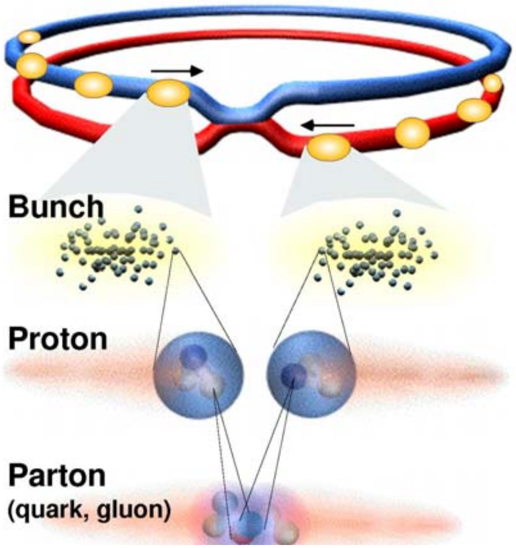
Pixel2005 Bonn September 05

http://www.cern.ch/rd50

Outline

- Silicon Detectors for Particle Tracking
- Motivation for R&D, the Challenge for Radiation Tolerance
- The RD50 Collaboration
- Radiation Damage, Deterioration of Detector Properties
- Approaches for Solutions, Material and Device Engineering
- Summary and Outlook

Silicon Detectors: Favorite Choice for Particle Tracking



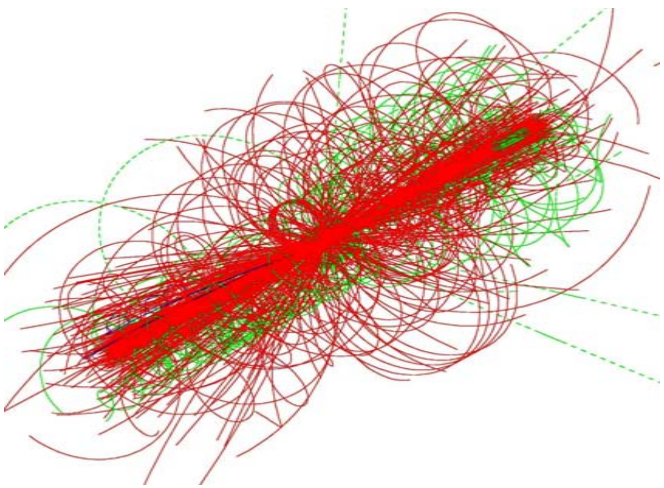
LHC properties →

Proton-proton collider, 2 x 7 TeV
Luminosity: 10^{34}

Bunch crossing: every 25 nsec, Rate: 40 MHz
event rate: 10^{9}/sec (23 interactions per bunch crossing)

Annual operational period: 10^{7} sec

Expected total op. period: 10 years

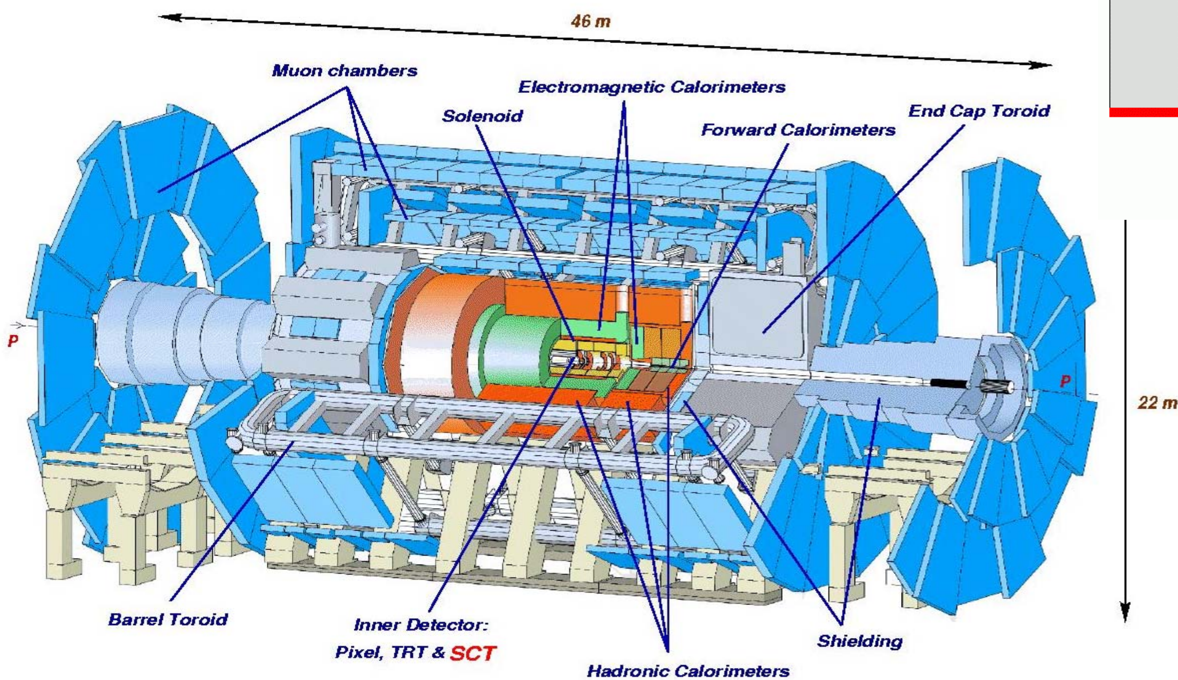


Experimental requests	Detector properties
Reliable detection of mips →	S/N ≈ 10
High event rate →	time + position resolution:
high track accuracy →	~10 ns and ~10 µm
Complex detector design →	low voltage operation in normal ambients
Intense radiation field during 10 years →	Radiation tolerance up to 10^{15} hadrons/cm²
Feasibility, e.g. 200 m² for CMS →	large scale availability known technology, low cost

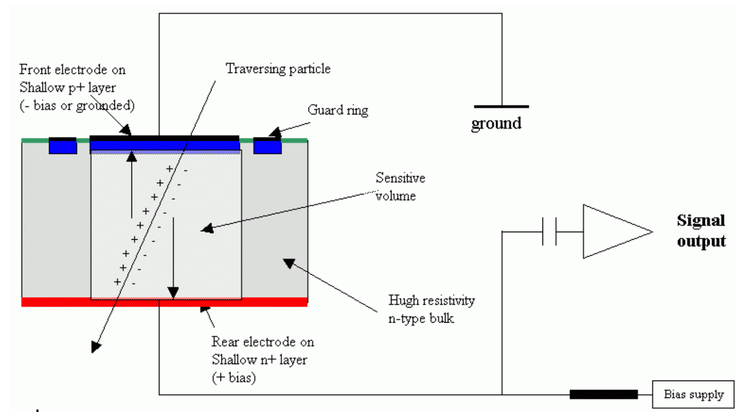
! Silicon Detectors meet all Requirements !

LHC ATLAS Detector – a Future HEP Experiment

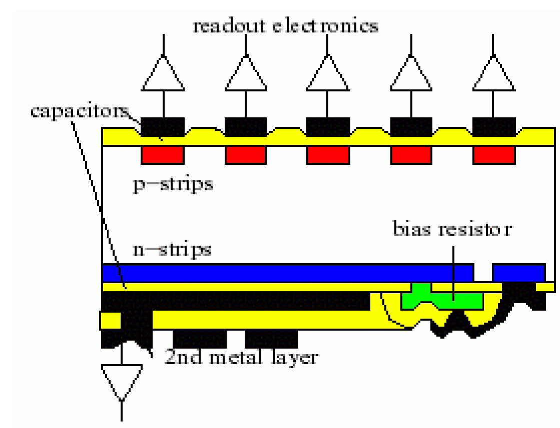
Overall length: 46m, diameter: 22m,
total weight: 7000t, magnetic field: 2T
ATLAS collaboration: 1500 members



principle of a silicon detector:
solid state ionization chamber

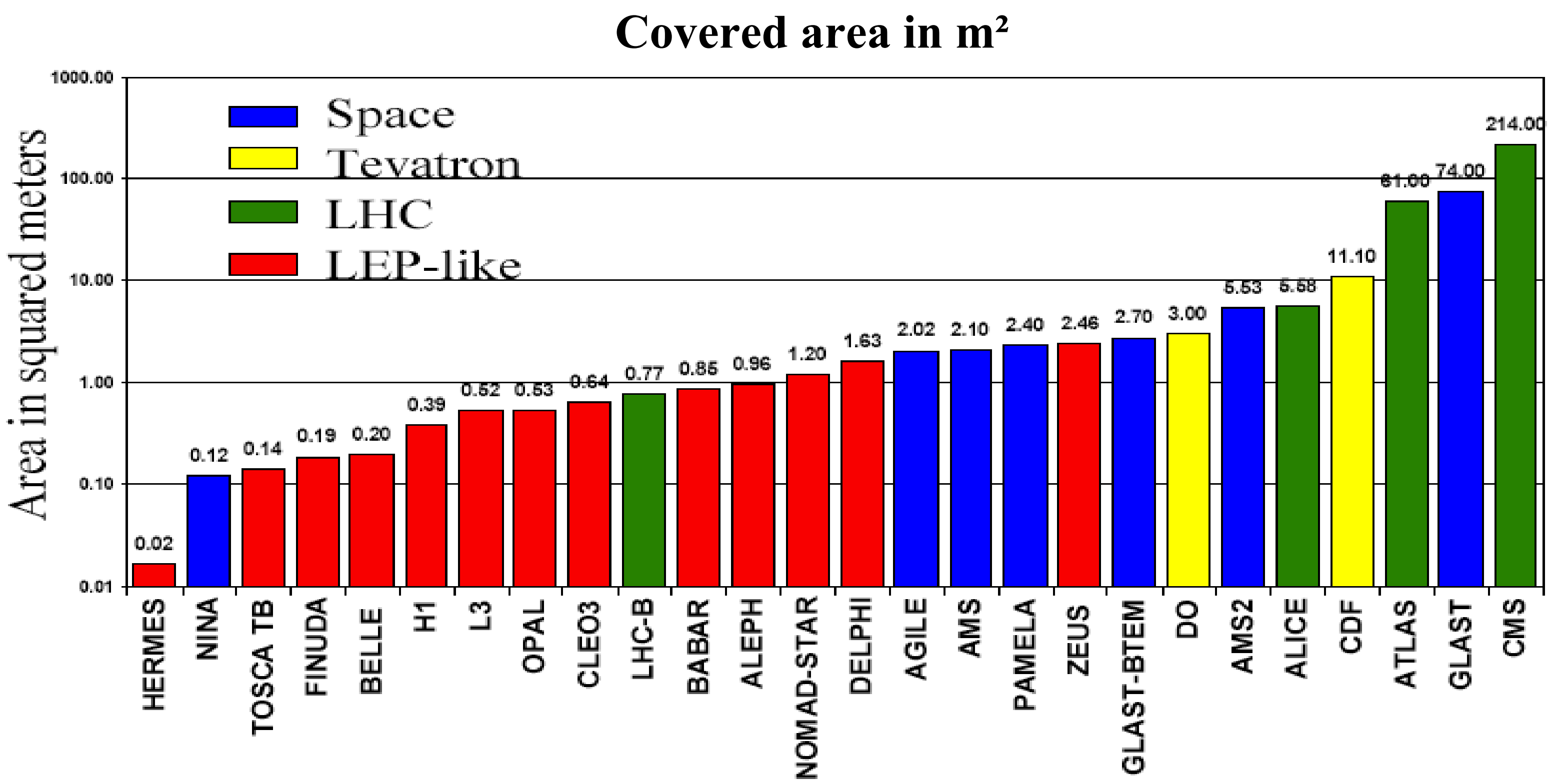


micro-strip detector
for particle tracking



Growing demand for Si-detectors in tracking applications

Experiments using silicon strip detectors



E. do Couto e Silva – SLAC/Stanford University Vertex 2000, Sept 10-15, National Lakeshore, MI, USA

Main motivations for R&D on Radiation Tolerant Detectors: Super - LHC

- **LHC upgrade**

  ⇨ **LHC (2007), L = 10^{34}cm^{-2}s^{-1}**

  10 years → **500 fb^{-1}** ϕ(r=4cm) ~ $3\cdot10^{15}$cm^{-2}

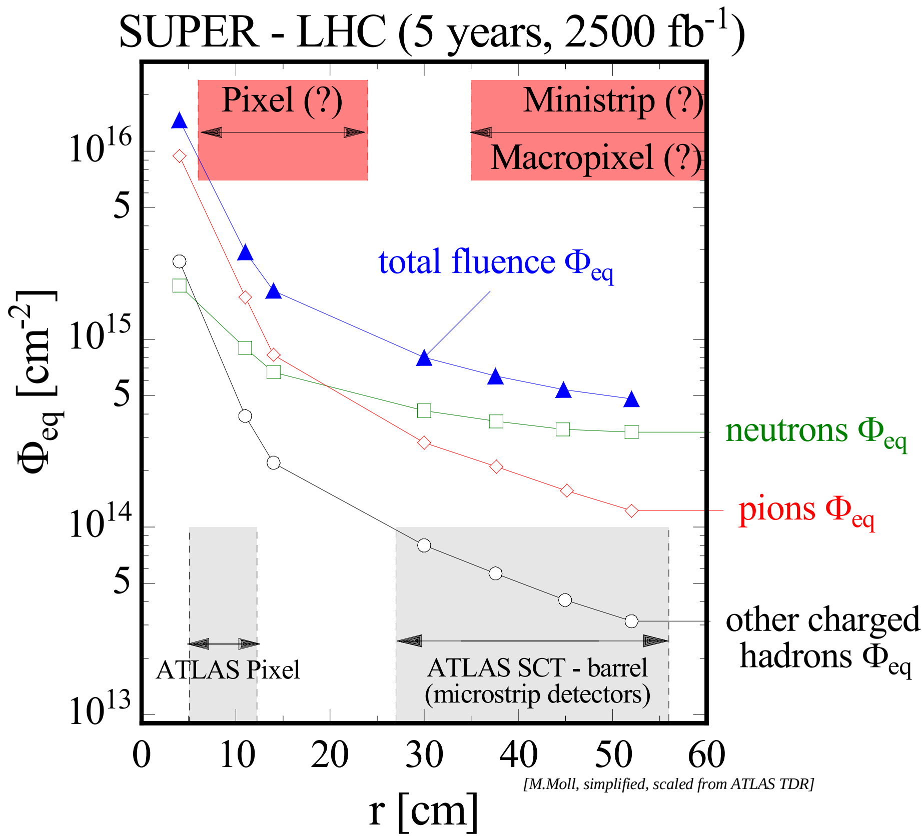
  CERN-RD48

  × 5

  ⇨ **Super-LHC (2015 ?), L = 10^{35}cm^{-2}s^{-1}**

  5 years → **2500 fb^{-1}** ϕ(r=4cm) ~ $1.6\cdot10^{16}$cm^{-2}

  CERN-RD50



- **LHC (Replacement of components)**

  e.g. - LHCb Velo detectors (~2010)

  - ATLAS Pixel B-layer (~2012)

- Linear collider experiments (generic R&D)

  Deep understanding of radiation damage will be fruitful for linear collider experiments where high doses of e, γ will play a significant role.

Adopted from M. Moll,CERN, Bonn, Sep-05

RD50 The CERN RD50 Collaboration http://www.cern.ch/rd50

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

- Collaboration formed in November 2001
- Experiment approved as RD50 by CERN in June 2002
- Main objective:

Development of ultra-radiation hard semiconductor detectors for the luminosity upgrade of the LHC to 10^{35} cm^{-2}s^{-1} ("Super-LHC").

Challenges:
- **Radiation hardness up to 10^{16} cm^{-2} required**
- **Fast signal collection** (Going from 25 ns to 10 ns bunch crossing ?)
- **Low mass** (reducing multiple scattering close to interaction point)
- **Cost effectiveness** (big surfaces have to be covered with detectors!)

Presently 251 members from 51 institutes

Belarus (Minsk), Belgium (Louvain), Canada (Montreal), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), Germany (Berlin, Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe), Israel (Tel Aviv), Italy (Bari, Bologna, Florence, Padova, Perugia, Pisa, Trento, Turin), Lithuania (Vilnius), 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 (Exeter, Glasgow, Lancaster, Liverpool, Sheffield, University of Surrey), USA (Fermilab, Purdue University, Rochester University, SCIPP Santa Cruz, Syracuse University, BNL, University of New Mexico)

Adopted from M. Moll,CERN, Bonn, Sep-05

Scientific Organization of RD50

Spokesperson
Mara Bruzzi
INFN and University of Florence

↔

Deputy-Spokesperson
Michael Moll
CERN

Defect / Material Characterization
Bengt Svensson
(Oslo University)

- Characterization: (pre/post irradiation) SIMS, IR, PL, Hall, TSC, DLTS, EPR,…
  - V_2O, O-dimers,…
  - high res. CZ, …
  - clusters, ..
- Theory: Defect formation, defect annealing, energy states,…..

Defect Engineering
Eckhart Fretwurst
(Hamburg University)

- DOFZ/Oxygenation
- High resistivity CZ
- Epitaxial Silicon
- Dimerization
- Other impurities H, N, Ge, …
- Thermal donors
- Pre-irradiation treatments

New Materials
Juozas V.Vaitkus
(Vilnius University)

- SiC
- CdTe
- other materials

Macroscopic Effects
Jaakko Härkönen
(Helsinki HIP)

- Test structure characterization IV, CV, CCE
- NIEL
- Device modeling
- Operational conditions

New Structures
Mahfuzur Rahman
(Glasgow University)

- 3D detectors
- Thin detectors
- Cost effective solutions

Full Detector Systems
Gianluigi Casse
(Liverpool University)

- LHC-like tests
- Links to HEP
- Links to R&D of electronics
- Comparison: pad-mini-full detectors

CERN contact: Michael Moll

Radiation Damage in Silicon Sensors

- **Two general types of radiation damage in detector materials:**

  - **Bulk (Crystal) damage** due to **Non Ionizing Energy Loss (NIEL)**
    - displacement damage, built up of crystal defects –

    I. Change of **effective doping concentration** (higher depletion voltage, under- depletion)
    II. Increase of **leakage current** (increase of shot noise, thermal runaway)
    III. Increase of **charge carrier trapping** (loss of charge)

  - **Surface damage** due to **Ionizing Energy Loss (IEL)**
    - accumulation of positive in the oxide (SiO_2) and the Si/SiO_2 interface –
    affects: interstrip capacitance (noise factor), breakdown behavior, …

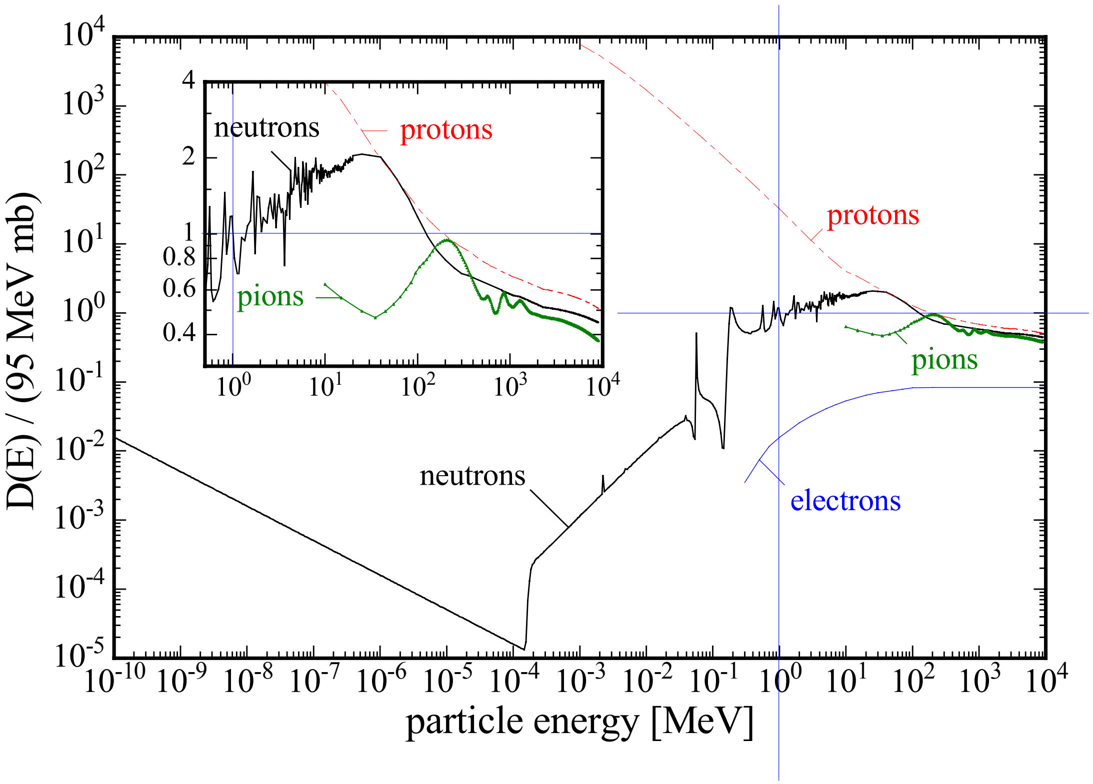
- **Impact on detector performance and Charge Collection**
  (depending on detector type and geometry and readout electronics!)

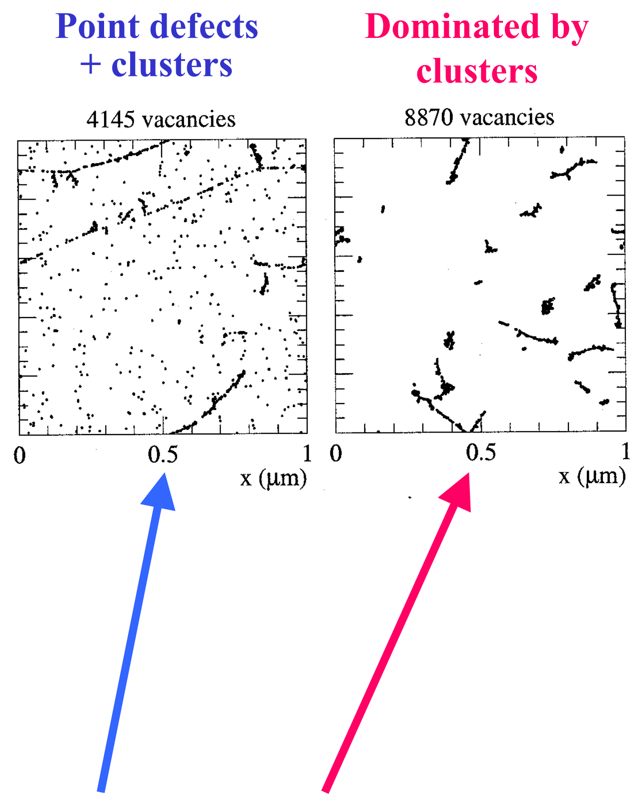
Signal/noise ratio is the quantity to watch

⇒ Sensors can fail from radiation damage !

Adopted from M. Moll,CERN, Bonn, Sep-05

Non Ionizing Energy Loss NIEL: displacement damage



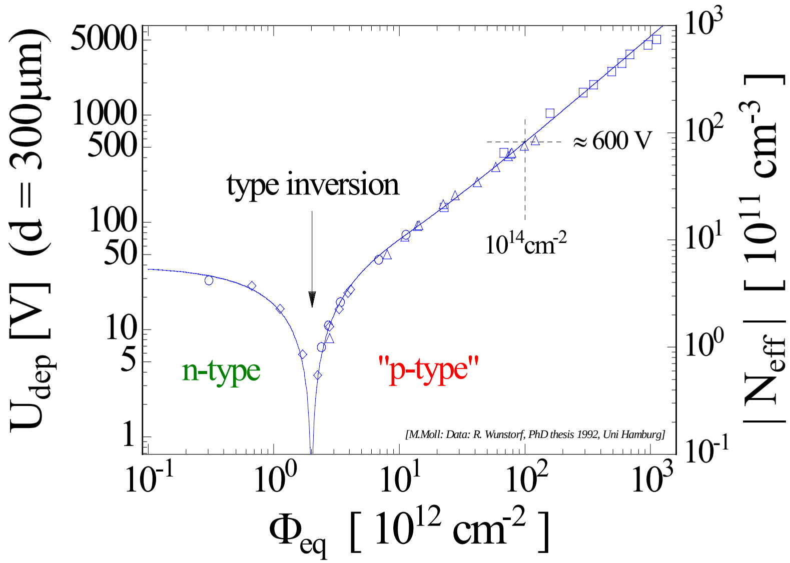


Damage effects generally ~ NIEL, however differences between proton & neutron damage

Radiation Damage I. – Effective doping concentration

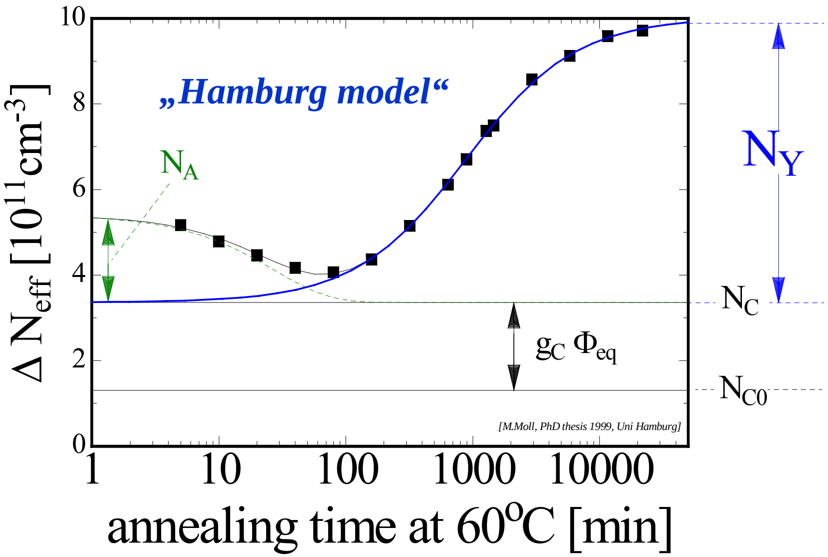
Change of Depletion Voltage V_{dep} (N_{eff})

…. with particle fluence:



"**Type inversion**": N_{eff} changes from positive to negative (Space Charge Sign Inversion)

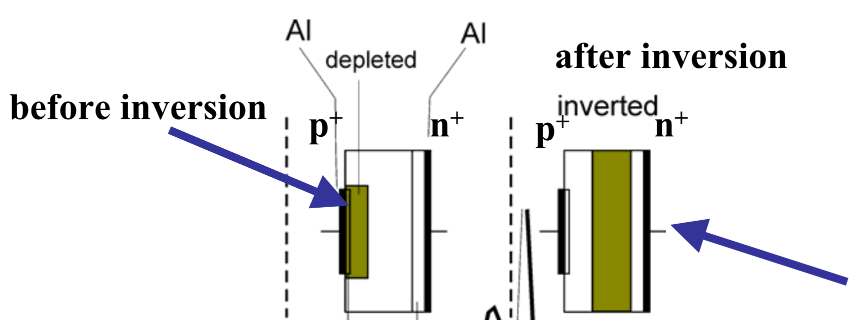
…. with time (annealing):



Short term: "**Beneficial annealing**"

Long term: "**Reverse annealing**"

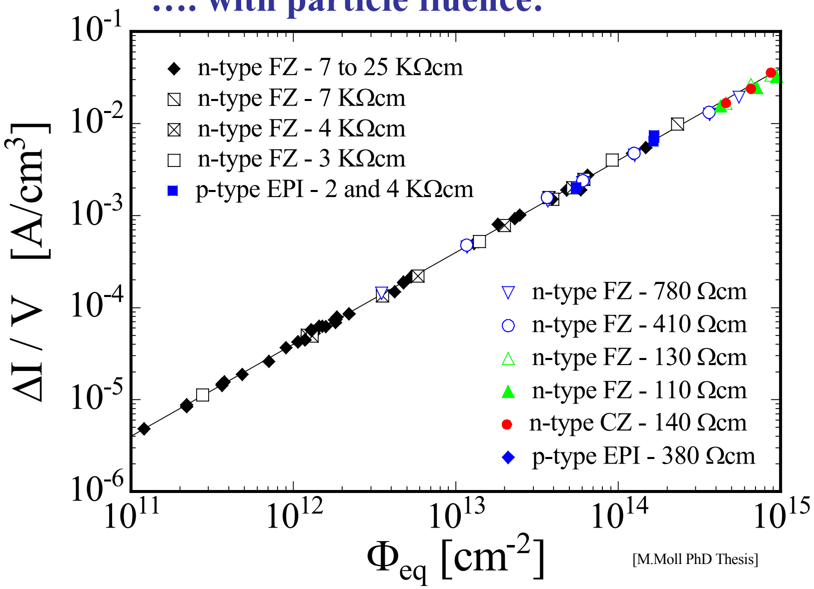
- time constant depends on temperature:
  - ~ 500 years (-10°C)
  - ~ 500 days (20°C)
  - ~ 21 hours (60°C)
- **Consequence:** Detectors must be cooled even when the experiment is not running!



Radiation Damage II. – Leakage current

- Change of Leakage Current (after hadron irradiation)

…. with particle fluence:



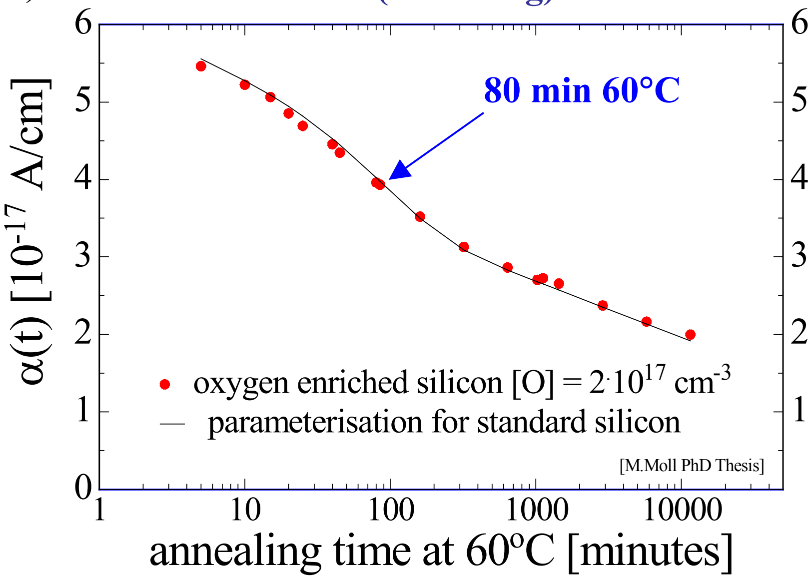
- Damage parameter α (slope in figure)

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

Leakage current per unit volume and particle fluence

- α is constant over several orders of fluence and independent of impurity concentration in Si
  ⇨ can be used for fluence measurement

…. with time (annealing):



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

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

Consequence:

Cool detectors during operation!

Example: $I(-10°C) \sim 1/16\ I(20°C)$

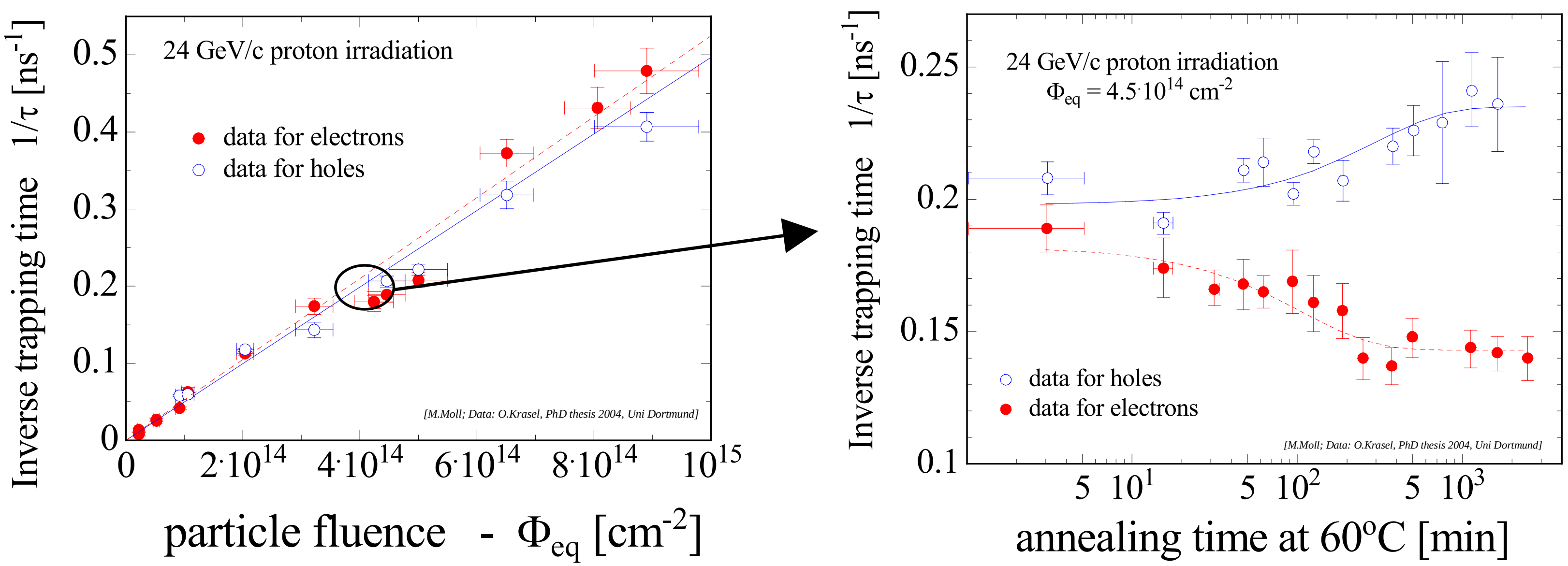
Radiation Damage III. – Charge carrier trapping

- **Deterioration of Charge Collection Efficiency (CCE) by trapping**

Trapping is characterized by an effective trapping time τ_{eff} for electrons and holes:

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

Increase of inverse trapping time (1/τ) with fluence **….. and change with time (annealing):**



Adopted from M. Moll,CERN, Bonn, Sep-05

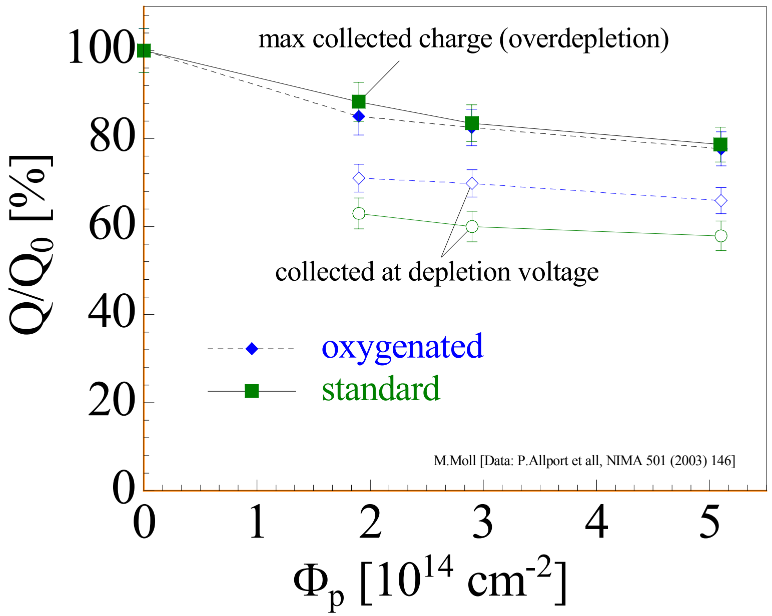
Impact on Detector: Decrease of CCE

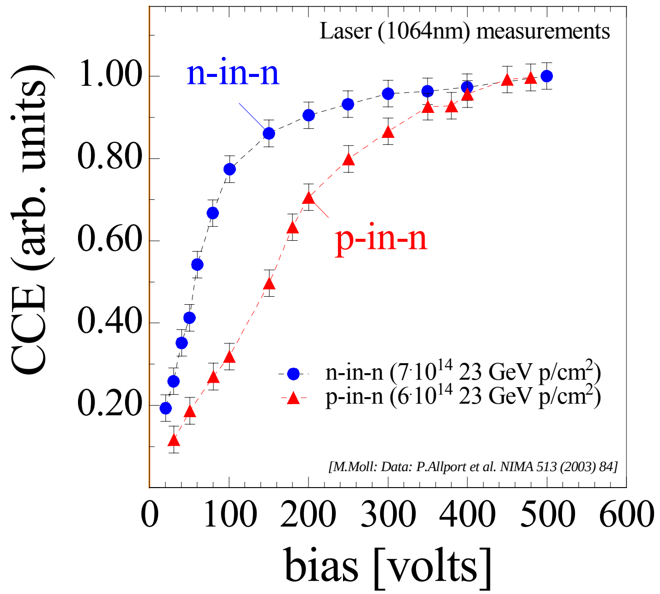
- **Two basic mechanisms reduce collectable charge:**
  - trapping of electrons and holes ⇨ (depending on drift and shaping time !)
  - under-depletion ⇨ (depending on detector design and geometry !)

Example: ATLAS microstrip detectors + fast electronics (25ns)

p-in-n : oxygenated versus standard FZ
- beta source
- 20% charge loss after $5x10^{14}$ p/cm^2 (23 GeV)

n-in-n versus p-in-n
- same material, ~ same fluence
- over-depletion needed





Adopted from M. Moll,CERN, Bonn, Sep-05

Approaches for Radiation Hardening

Scientific strategies:

I. Material engineering

II. Device engineering

III. Change of detector operational conditions

CERN-RD39
"Cryogenic Tracking Detectors"
„Lazarus Effect"

Defect Engineering of Silicon

- Understanding radiation damage
  - **Macroscopic effects and Microscopic defects**
  - **Simulation of defect properties & kinetics**
  - **Irradiation with different particles & energies**
- 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
- 3D and Semi 3D detectors
- Stripixels
- Cost effective detectors
- Simulation of highly irradiated detectors
- Monolithic devices

Adopted from M. Moll,CERN, Bonn, Sep-05

Different Sensor mMaterials

Example: is SiC an option?

Property	Diamond	GaN	4H SiC	Si
E_g [eV]	**5.5**	**3.39**	**3.26**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4 \cdot 10^6$	$2.2 \cdot 10^6$	$3 \cdot 10^5$
μ_e [cm²/Vs]	1800	1000	800	1450
μ_h [cm²/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2 \cdot 10^7$	-	$2 \cdot 10^7$	$0.8 \cdot 10^7$
Z	6	31/7	14/6	14
ε_r	5.7	9.6	9.7	11.9
e-h energy [eV]	**13**	**8.9**	**7.6-8.4**	**3.6**
Density [g/cm3]	3.515	6.15	3.22	2.33
Displacem. [eV]	**43**	**≥15**	**25**	**13-20**

Wide bandgap (3.3eV)
lower leakage current than silicon

Signal:
Diamond 36 e/μm
SiC 51 e/μm
Si 89 e/μm
more charge than diamond

Higher displacement threshold than silicon
radiation harder than silicon (?)

R&D on diamond detectors:
RD42 – Collaboration
http://cern.ch/rd42/

Result for SiC: very low CCE even for very thin devices

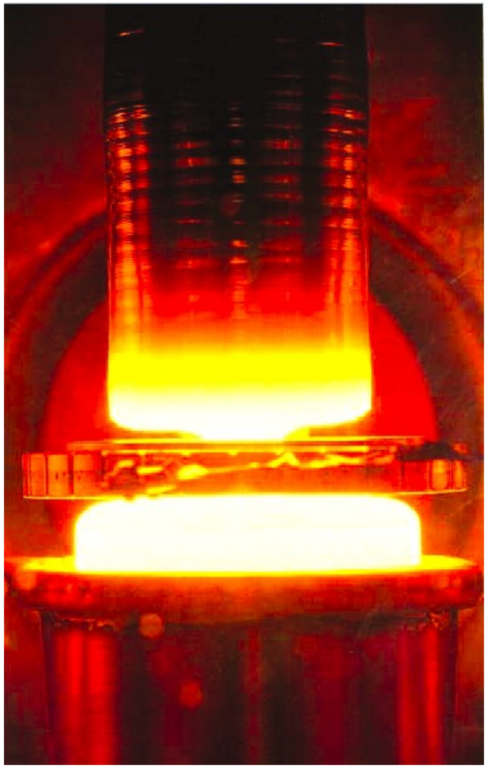
Recent review: P.J.Sellin and J.Vaitkus on behalf of RD50
"New materials for radiation hard semiconductor detectors", submitted to NIMA

Adopted from M. Moll,CERN, Bonn, Sep-05

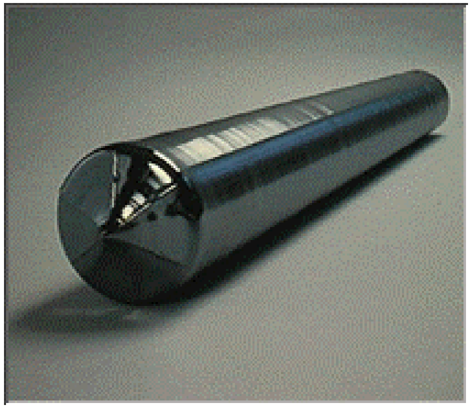
Monocrystalline Material: Float Zone Silicon (FZ)

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

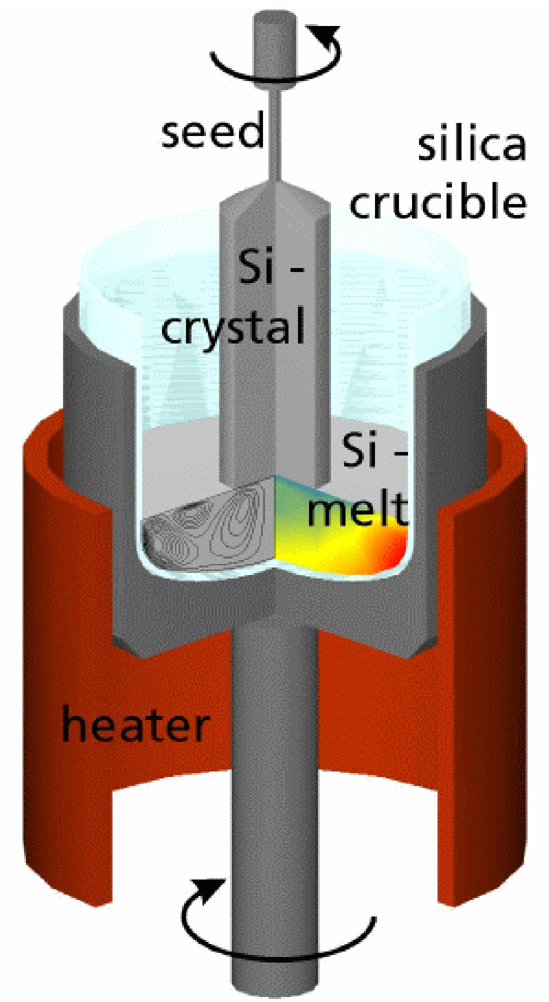
Oxygen enrichment (DOFZ)

- Oxidation of wafer at high temperatures

Adopted from M. Moll,CERN, Bonn, Sep-05

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 (~2 years) made CZ available in sufficiently high purity (resistivity) to allow for use as particle detector.

❑ Epitaxial silicon

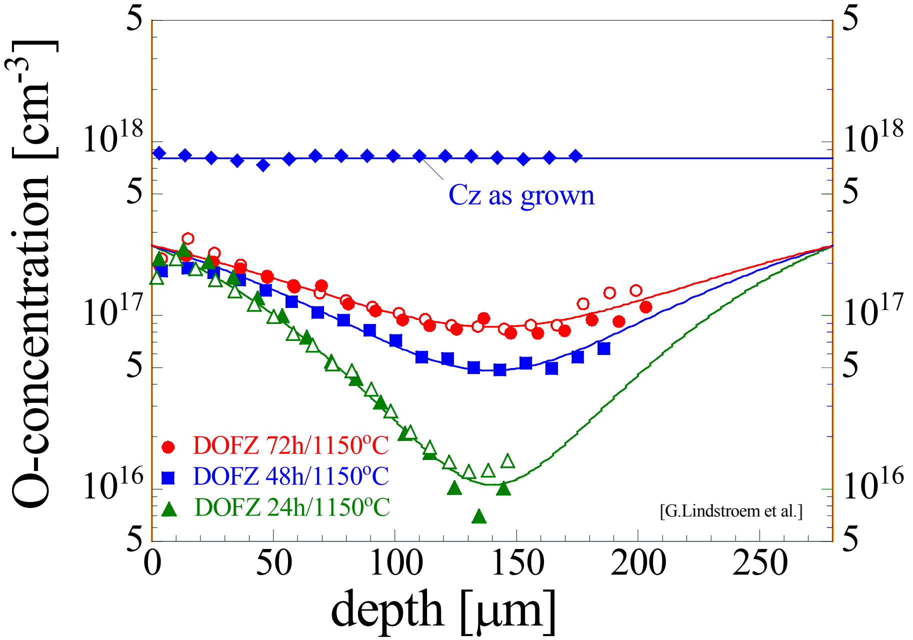
- Chemical-Vapor Deposition (CVD) of Silicon
- CZ silicon substrate used ⇨ in-diffusion of oxygen
- growth rate about 1μm/min
- excellent homogeneity of resistivity
- up to 150 μ m thick layers produced (thicker is possible)
- price depending on thickness of epi-layer but not extending ~ 3 x price of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

Adopted from M. Moll,CERN, Bonn, Sep-05

Oxygen in FZ, Cz and EPI

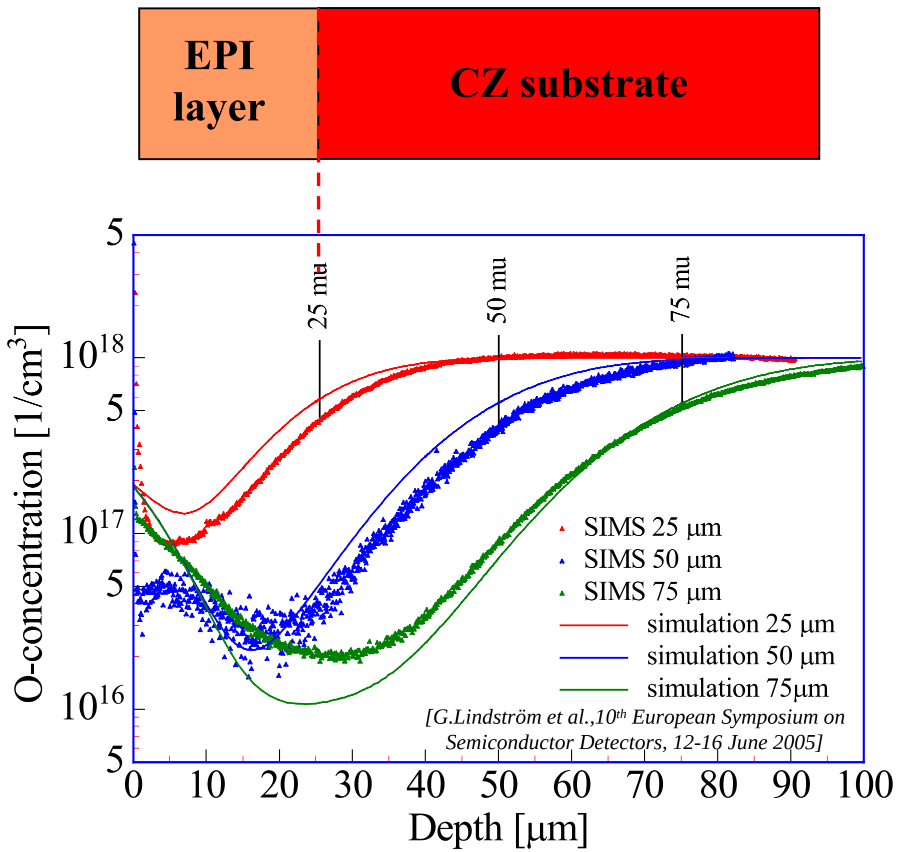
❑ Cz and DOFZ silicon

- **CZ: high O_i (oxygen) and O_{2i} (oxygen dimer) concentration (homogeneous)**
- **CZ: formation of Thermal Donors possible !**



- **DOFZ: inhomogeneous oxygen distribution**
- **DOFZ: oxygen content increasing with time at high temperature**

❑ Epitaxial silicon

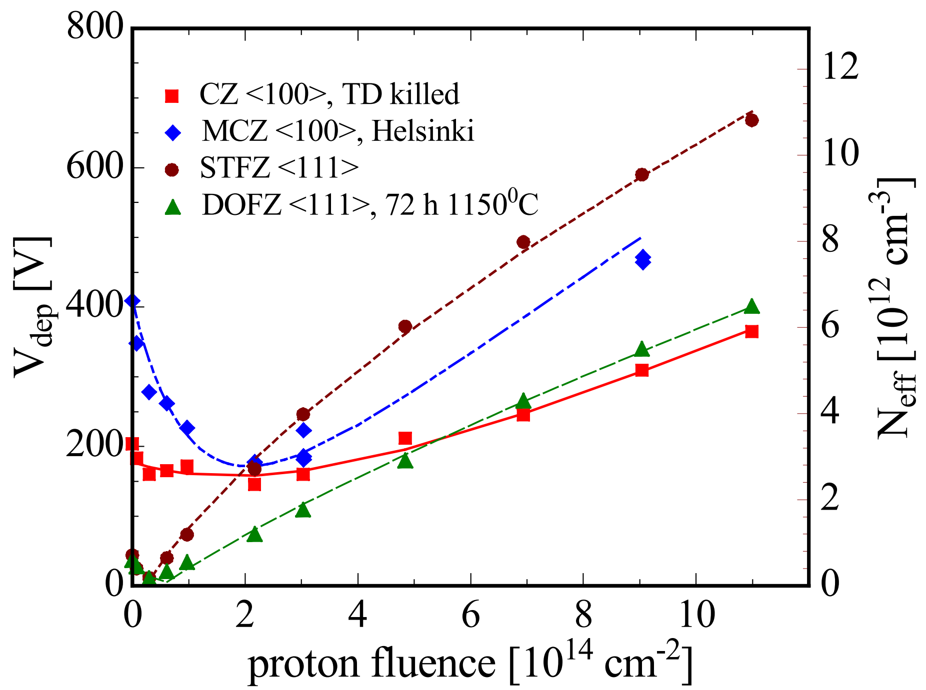


- **EPI: O_i and O_{2i} (?) diffusion from substrate into epi-layer during production**
- **EPI: in-homogeneous oxygen distribution**

Change of Neff: FZ, DOFZ, Cz and MCz 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**
  - **<u>no type inversion</u> in the overall fluence range (verified by TCT measurements)**
    (verified for CZ silicon by TCT measurements, preliminary result for MCZ silicon)
    ⇒ **donor generation overcompensates acceptor generation in high fluence range**

- **Common to all materials (after hadron irradiation):**
  - **reverse current increase**
  - **increase of trapping (electrons and holes) within ~ 20%**

Adopted from M. Moll,CERN, Bonn, Sep-05

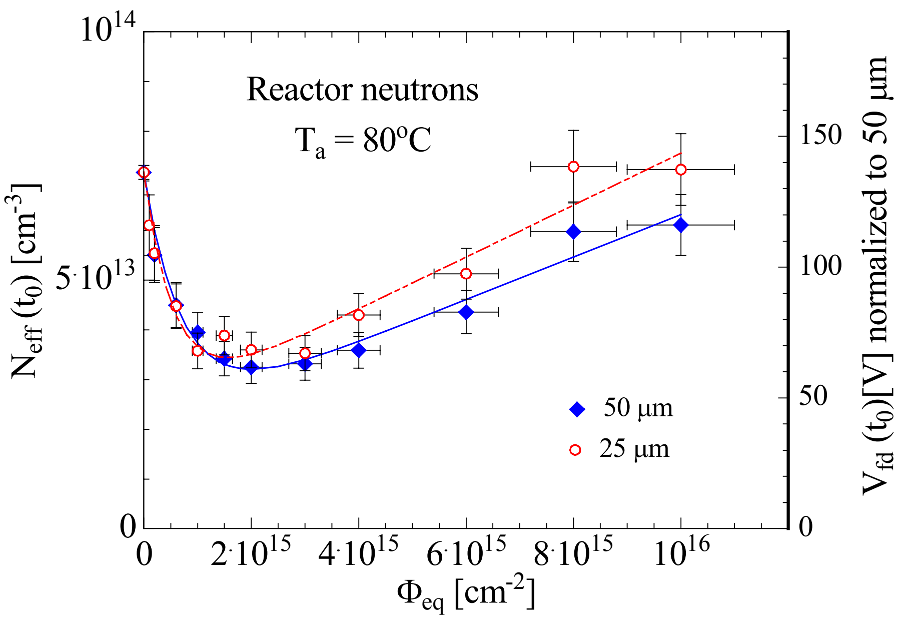
Change of Neff: EPI Silicon

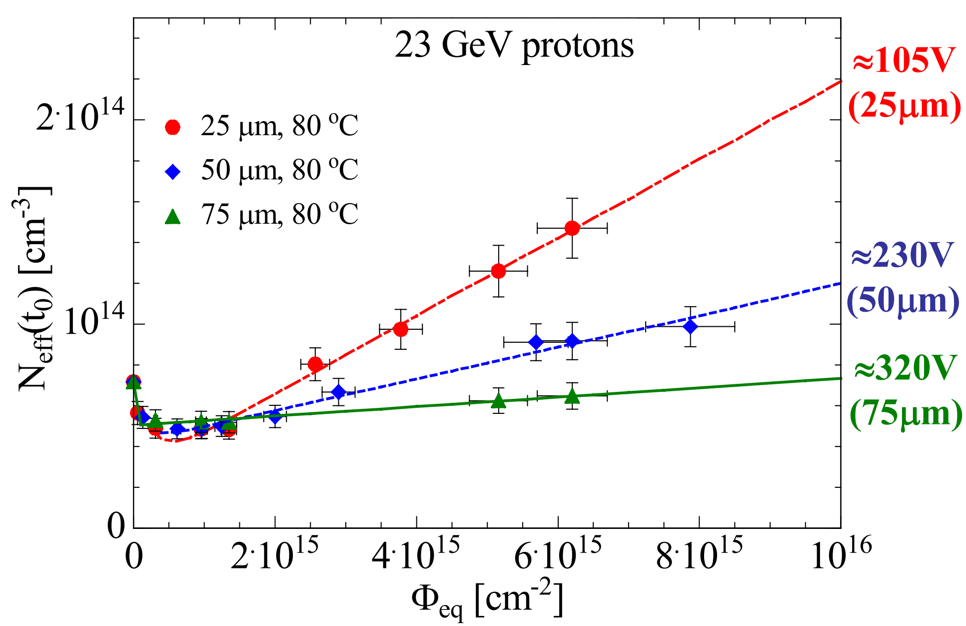
- **Epitaxial silicon grown by ITME**

G.Lindström et al.,10th European Symposium on Semiconductor Detectors, 12-16 June 2005

Layer thickness: 25, 50, 75 µm; resistivity: ~ 50 Ωcm

Oxygen: [O] ≈ $9\times10^{16}cm^{-3}$; Oxygen dimers (detected via IO_2-defect formation)





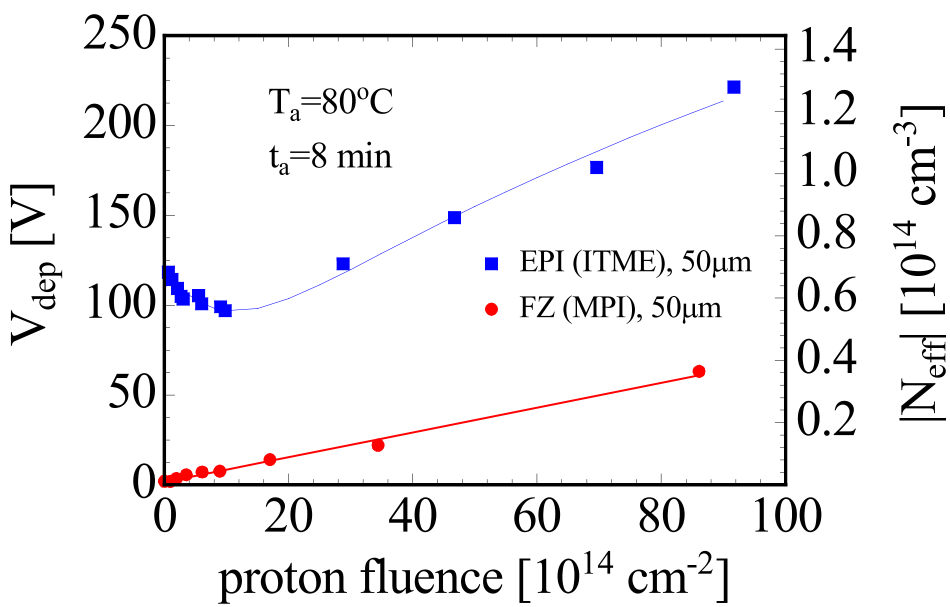
- **No type inversion in the full range up to ~ 10^{16} p/cm² and ~ 10^{16} n/cm²**
  (type inversion only observed during long term annealing)

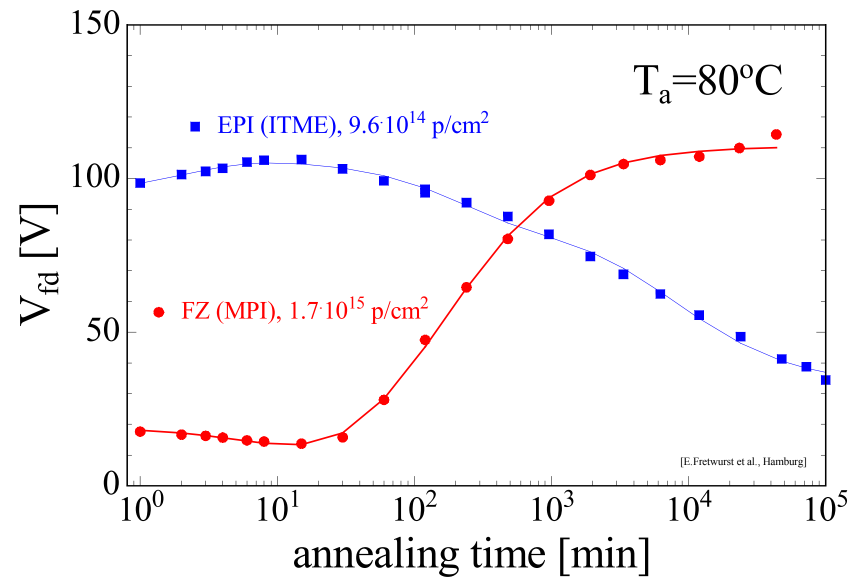
  Proposed explanation:

  introduction of shallow donors bigger than generation of deep acceptors

Epitaxial Silicon - Annealing

- **50 µm thick silicon detectors:**
  - Epitaxial silicon (50 Ωcm on CZ substrate, ITME & CiS)
  - Thin FZ silicon (4KΩcm, MPI Munich, wafer bonding technique)





- **Thin FZ silicon: Type inverted, increase of depletion voltage with time**
- **Epitaxial silicon: No type inversion, decrease of depletion voltage with time**
  ⇒ No need for low temperature during maintenance of SLHC detectors!

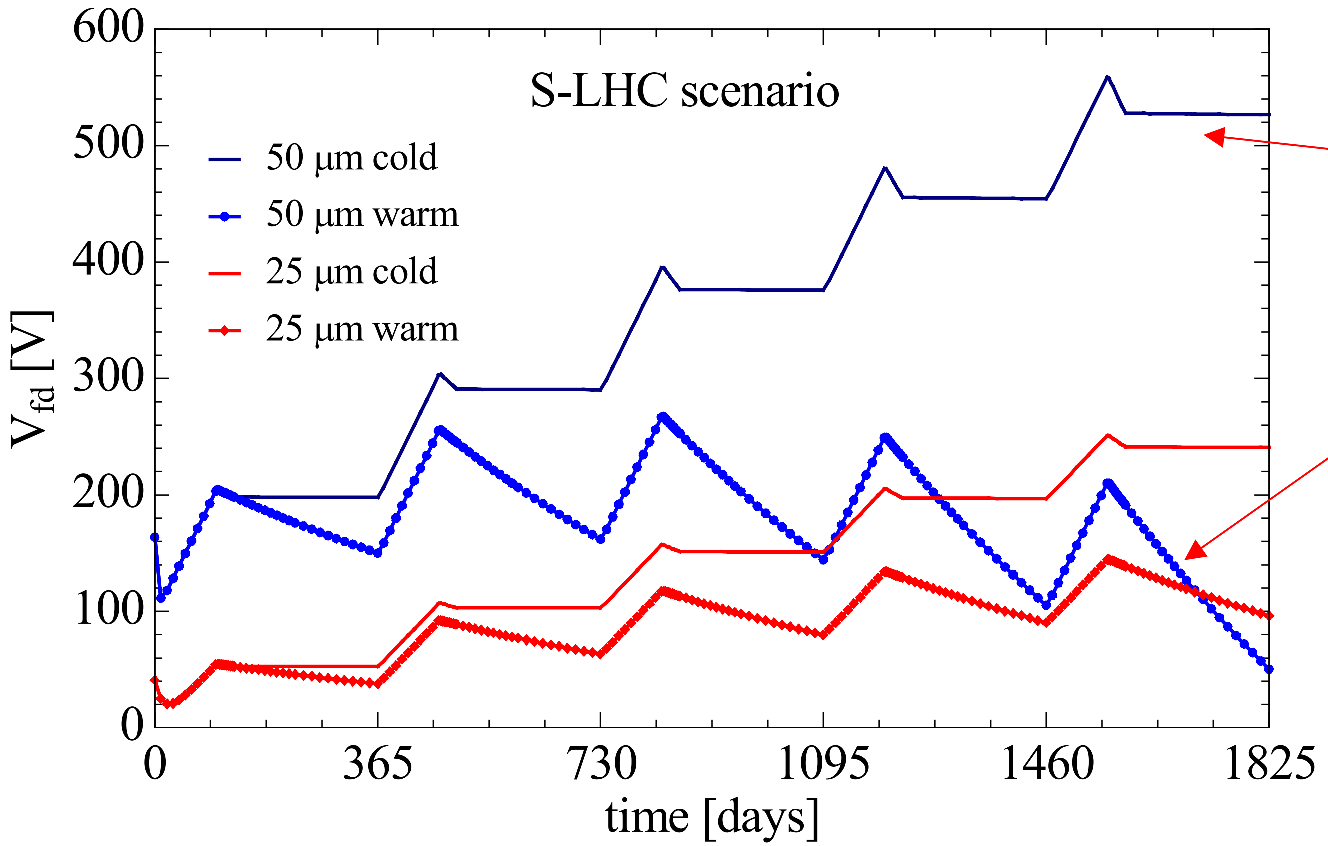
Adopted from M. Moll,CERN, Bonn, Sep-05

Damage Projection – SLHC

- 50 μm EPI silicon: a solution for pixels ?-

G.Lindström et al.,10th European Symposium on Semiconductor Detectors, 12-16 June 2005 (Damage projection: M.Moll)

- **Radiation level (4cm):** $\Phi_{eq}(\text{year}) = 3.5 \times 10^{15}\ \text{cm}^{-2}$
- **SLHC-scenario:** 1 year = 100 days beam (-7°C)
  30 days maintenance (20°C)
  235 days no beam (-7°C or 20°C)



Detector with cooling when not operated

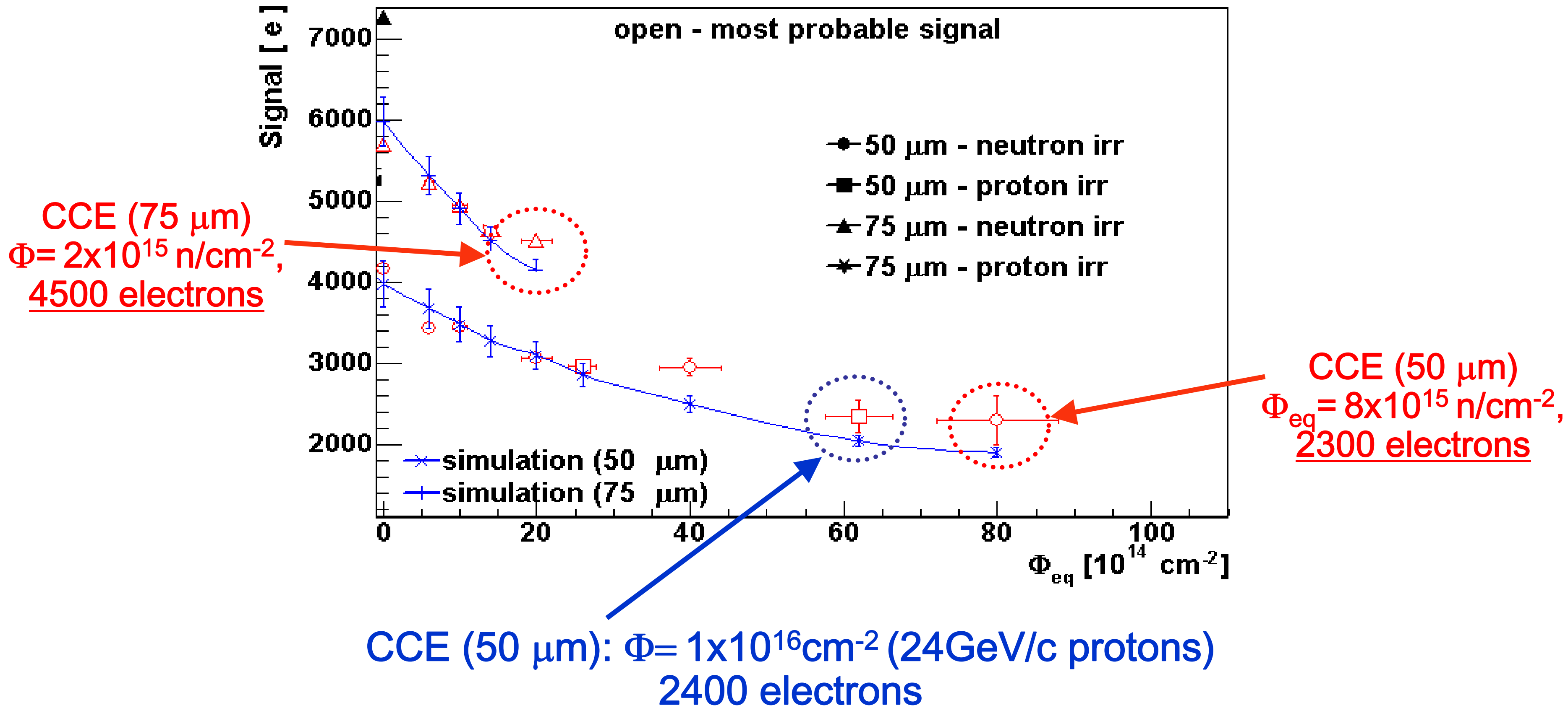
Detector without cooling when not operated

Signal from irradiated EPI

- **Epitaxial silicon: CCE measured with beta particles (^{90}Sr)**

  25ns shaping time

  proton and neutron irradiations of 50 μm and 75 μm epi layers



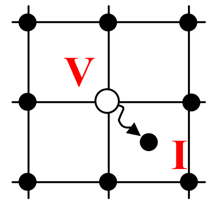
[G.Kramberger et al.,RESMDD - October 2004]

Adopted from M. Moll,CERN, Bonn, Sep-05

Microscopic defects

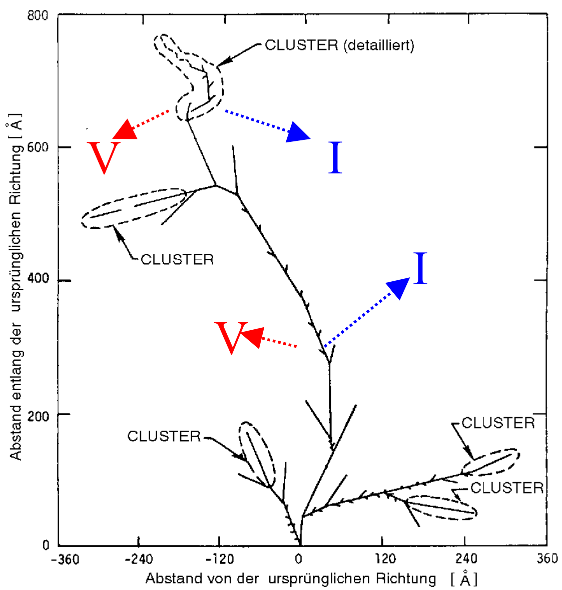
- **Damage to the silicon crystal:** Displacement of lattice atoms

particle → Si_S — $E_K > 25$ eV →



Vacancy + Interstitial ⇔ "point defects", mobile in silicon, can react with impurities (O,C,..)

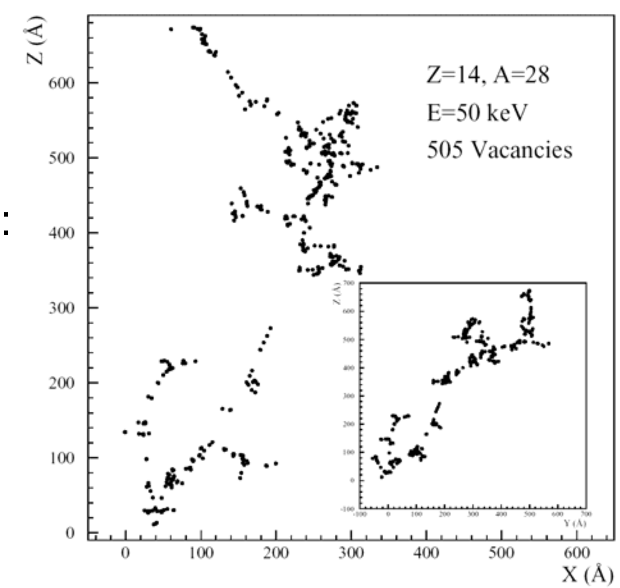
$E_K > 5$ keV → **point defects and defect clusters**



Distribution of vacancies created by a 50 keV Si-ion in silicon (typical recoil energy for 1 MeV neutrons):

Schematic [Van Lint 1980]

Simulation [M.Huhtinen 2001]



- **Defects can be electrically active (levels in the band gap)**
  - capture and release electrons and holes from conduction and valence band

  ⇒ can be charged - can be generation/recombination centers - can be trapping centers

Adopted from M. Moll,CERN, Bonn, Sep-05

Characterization of microscopic defects

- gamma and proton irradiated silicon detectors -

- **2003: Major breakthrough on g-irradiated samples**
  For the first time macroscopic changes of the depletion voltage and leakage current can be explained by electrical properties of measured defects ! [APL, 82, 2169, March 2003]
- **2004: Big step in understanding the improved radiation tolerance of oxygen enriched and epitaxial silicon after proton irradiation**

[I.Pintilie, RESMDD, Oct.2004]

Levels responsible for depletion voltage changes after proton irradiation:

Almost independent of oxygen content:

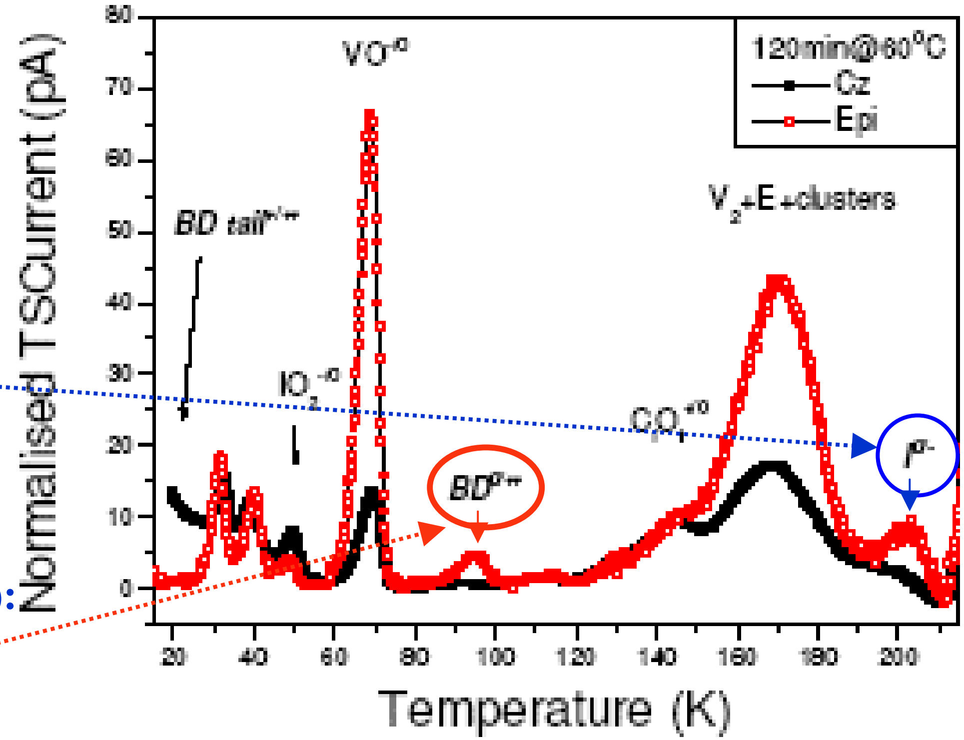
- **Donor removal**
- **"Cluster damage"** ⇒ **negative charge**

Influenced by initial oxygen content:

- **I–defect:** deep acceptor level at E_C-0.54eV (good candidate for the V_2O defect) ⇒ negative charge

Influenced by initial oxygen dimer content (?):

- **BD-defect:** bistable shallow thermal donor (formed via oxygen dimers O_{2i}) ⇒ positive charge

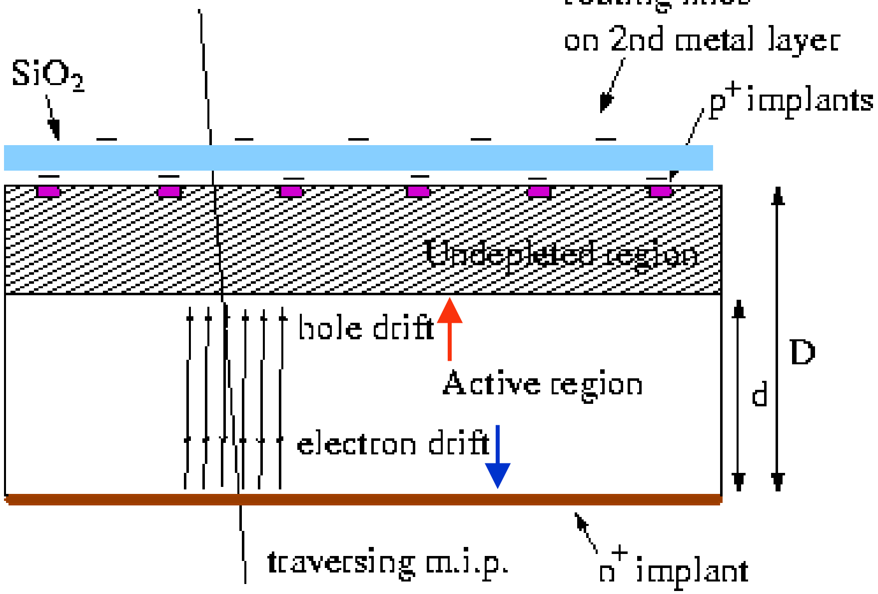


See further: I. Pintilie et al, NIM A 556 (2005) 56 + NIM A, in press

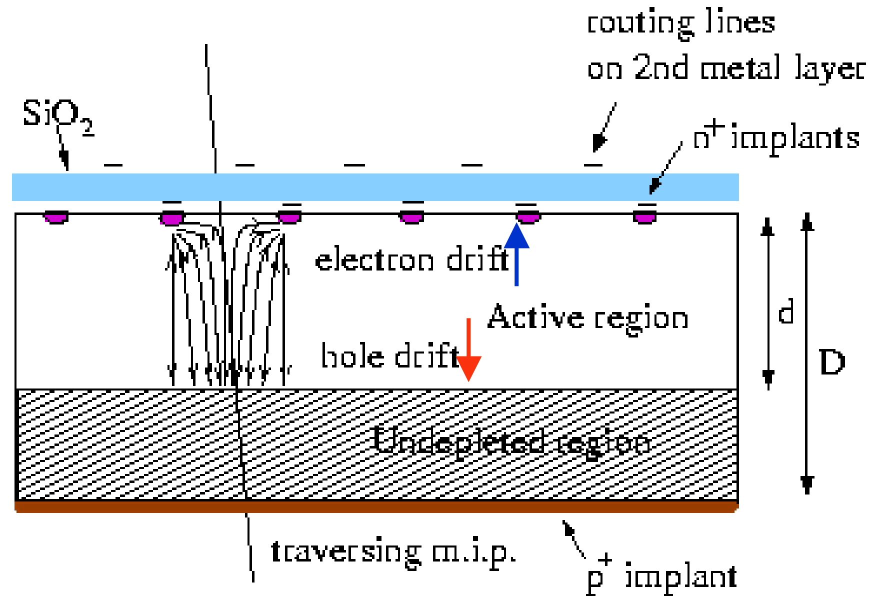
Device Engineering: p-in-n versus n-in-n

n-type silicon after type inversion:

p^{+}on-n



n^{+}on-n



p-on-n silicon, under-depleted:

- Charge spread – degraded resolution
- Charge loss – reduced CCE

n-on-n silicon, under-depleted:

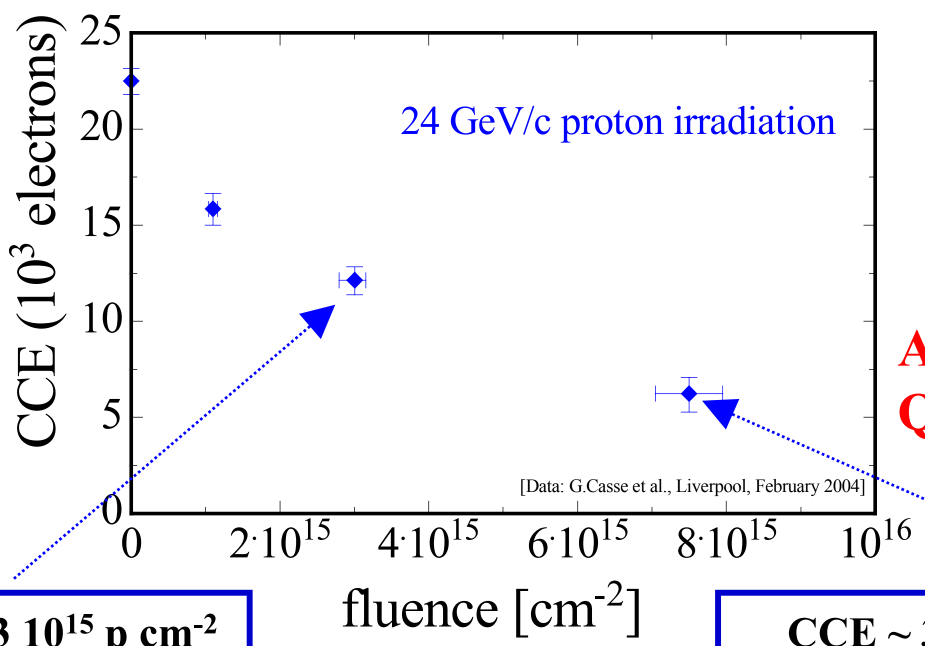
- Limited loss in CCE
- Less degradation with under-depletion
- Collect electrons (fast)

Adopted from M. Moll,CERN, Bonn, Sep-05

n-in-p microstrip detectors

n-in-p: **- no type inversion, high electric field stays on segmented side**
- collection of electrons

- Miniature n-in-p microstrip detectors (280mm)
- Detectors read-out with LHC speed (40MHz) chip (SCT128A)
- Material: standard p-type and oxygenated (DOFZ) p-type
- Irradiation:



G. Casse et al., NIMA 535 (2004) 362

At the highest fluence Q~6500e at V_{bias}=900V

$\Phi_{eq} = 4.6\ 10^{15}\ cm^{-2}$

CCE ~ 60% after 3 10^{15} p cm^{-2} at 900V(standard p-type)

CCE ~ 30% after 7.5 10^{15} p cm^{-2} 900V (oxygenated p-type)

Adopted from M. Moll,CERN, Bonn, Sep-05

Does thickness pay?

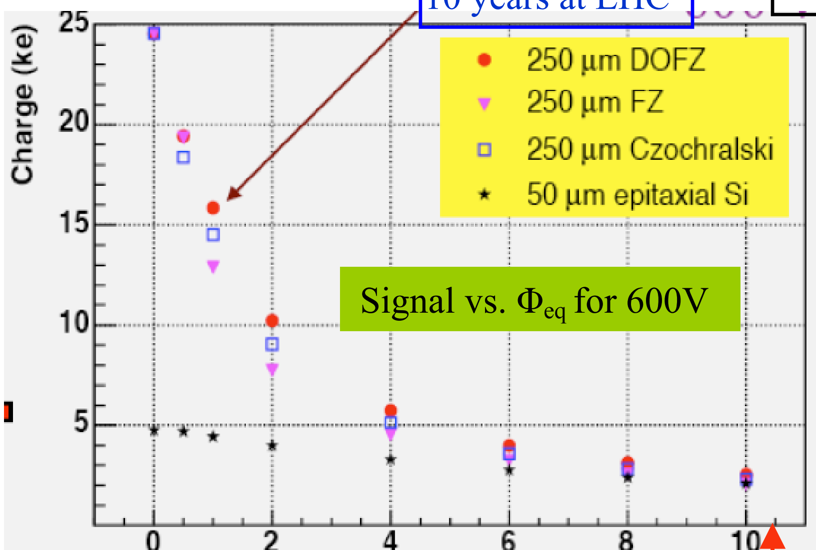
- **Low fluence $\Phi_{eq} \leq 10^{14}$ cm^{-2}:**
negligible trapping of charge carriers, signal for mip
(minimum ionizing particle) proportinal to detector thickness: **$S \sim d$**

- **Trapping material independent, strong increase with fluence (see above)**

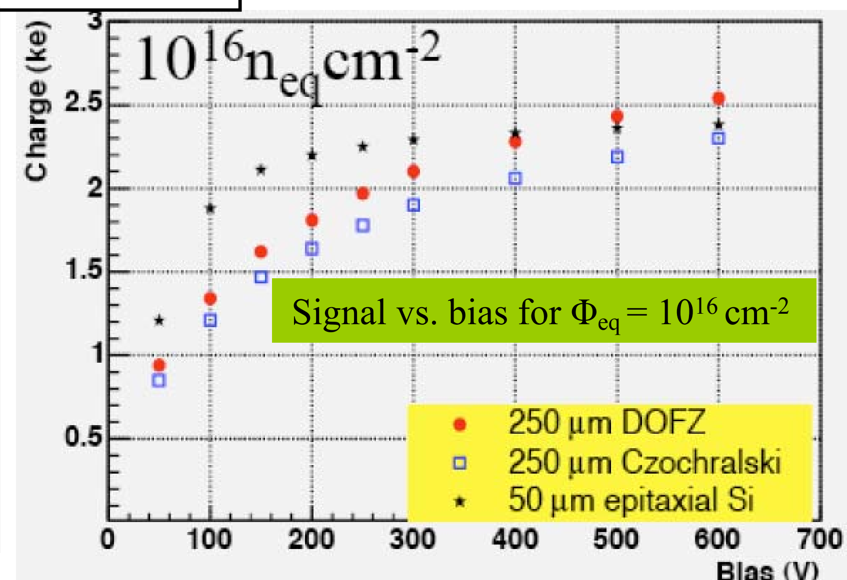
- **Large fluence $\Phi_{eq} \geq 5{\cdot}10^{15}$ cm^{-2}:**
signal height dominated by charge trapping, collection distance $d_{eff} \leq 100$ µm
signal for mip: **$S \sim d_{eff}$**

10 years at LHC

T. Lari, Milano



Equiv. Fluence in 10^{15} cm^{-2}



5 y S-LHC

! After Φeq = 1016 cm-2 S(mip) = about 2000-2500 e regardless of material and thickness !

Summary

- **At fluences up to 10^{15}cm^{-2} (Outer layers of a SLHC detector) the change of depletion voltage and the large area to be covered by detectors is the major problem.**
  - **CZ silicon detectors could be a cost-effective radiation hard solution**
    (no type inversion, use p-in-n technology)
  - **p-type silicon microstrip detectors show very encouraging results:**
    CCE ≈ 6500 e; $\Phi_{eq} = 4\times10^{15}$ cm^{-2}, 300µm, collection of electrons,
    no reverse annealing observed in CCE measurement!

- **At the fluence of 10^{16}cm^{-2} (Innermost layer of a SLHC detector) the active thickness of any silicon material is significantly reduced due to trapping.**
  The promising new options are:
  -Thin/EPI detectors : drawback: radiation hard electronics for low signals needed
  e.g. 2300e at Φ_{eq} 8x10^{15}cm^{-2}, 50µm EPI,
  …. thicker layers will be tested in 2005/2006
  - 3D detectors : drawback: technology has to be optimized
  ….. steady progress within RD50

- **New Materials like SiC and GaN** (not shown) have been characterized .
  - CCE tests show that these materials are not radiation harder than silicon

Further information: http://cern.ch/rd50/

Adopted from M. Moll,CERN, Bonn, Sep-05