3rd MC-PAD Network Training Event,
Jožef Stefan Institute, Ljubljana, Slovenia
- 29 September 2010 -

Radiation Hardness of Semiconductor Detectors

- Radiation Effects and Detector Operation -

… including an introduction to ongoing radiation tolerant sensors developments

Michael Moll (CERN/PH)

Outline

- **Motivation to develop radiation harder detectors**
  - **LHC upgrade and expected radiation levels**
  - **Radiation induced degradation of detector performance**
- **Radiation Damage in Silicon Detectors**
  - **Microscopic damage (crystal damage), NIEL**
  - **Macroscopic damage (changes in detector properties)**
- **Approaches to obtain radiation tolerant sensors**
  - **Material Engineering**
    - New silicon materials – FZ, MCZ, DOFZ, EPI
    - Other semiconductors: Diamond, SiC, GaN, ….
  - **Device Engineering**
    - p-in-n, n-in-n and n-in-p sensors, 3D sensors and thin devices
- **Silicon Sensors for the LHC upgrade**

  ….. open questions and ongoing developments
- **Summary**

For details on LHC detectors see lecture of *Phil Allport*

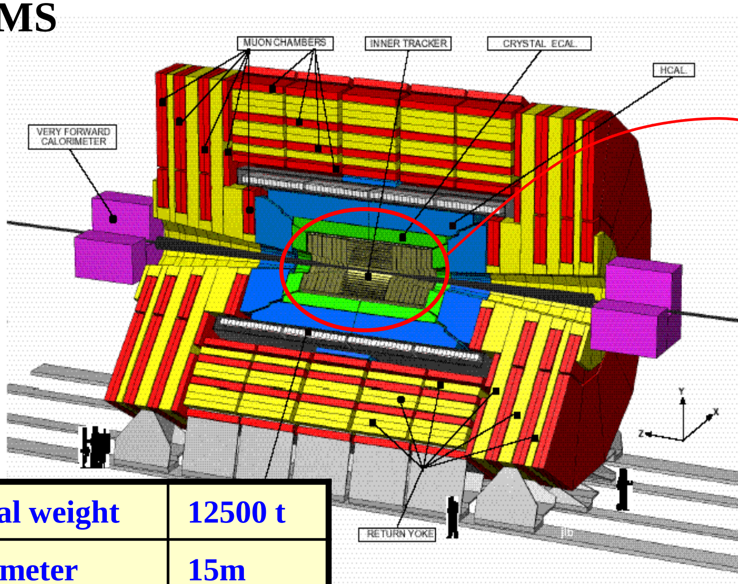
For details on radiation induced defects see lecture of *Ioana Pintilie*

For surface effects see lecture of *G.-F. Dalla Betta*

For details on sensor production see lecture of *Manolo Lozano*

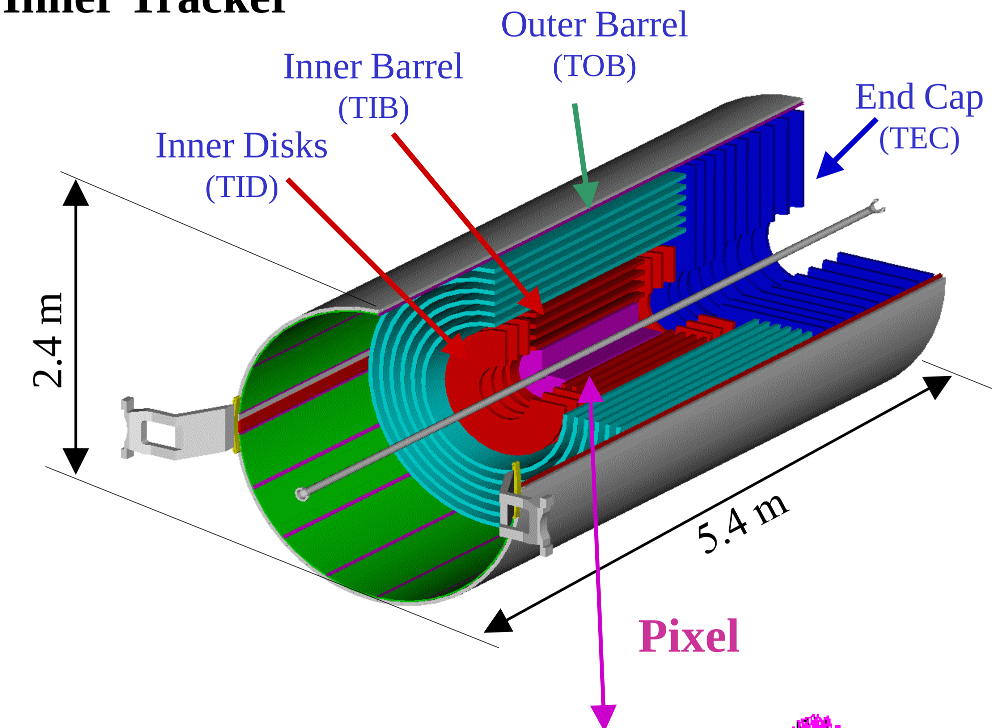
LHC example: CMS inner tracker

CMS



Total weight	**12500 t**
Diameter	**15m**
Length	**21.6m**
Magnetic field	**4 T**

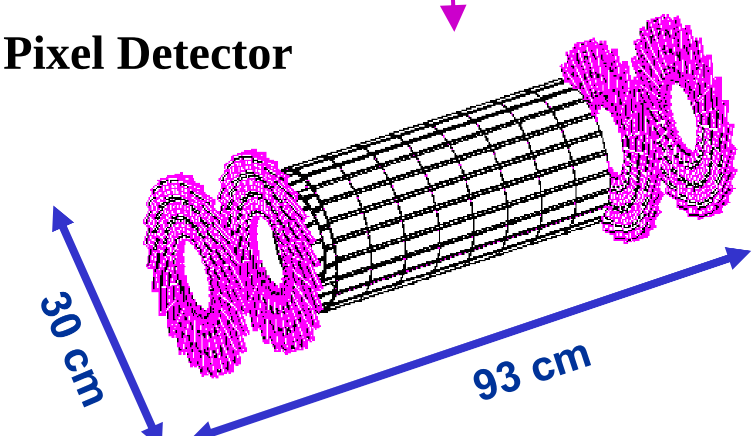
Inner Tracker



CMS – "Currently the Most Silicon"

- **Micro Strip:**
- **~ 214 m^2 of silicon strip sensors, 11.4 million strips**
- **Pixel:**
- **Inner 3 layers: silicon pixels (~ 1m^2)**
- **66 million pixels (100x150μm)**
- **Precision: σ(rφ) ~ σ(z) ~ 15μm**
- **Most challenging operating environments (LHC)**

Pixel Detector



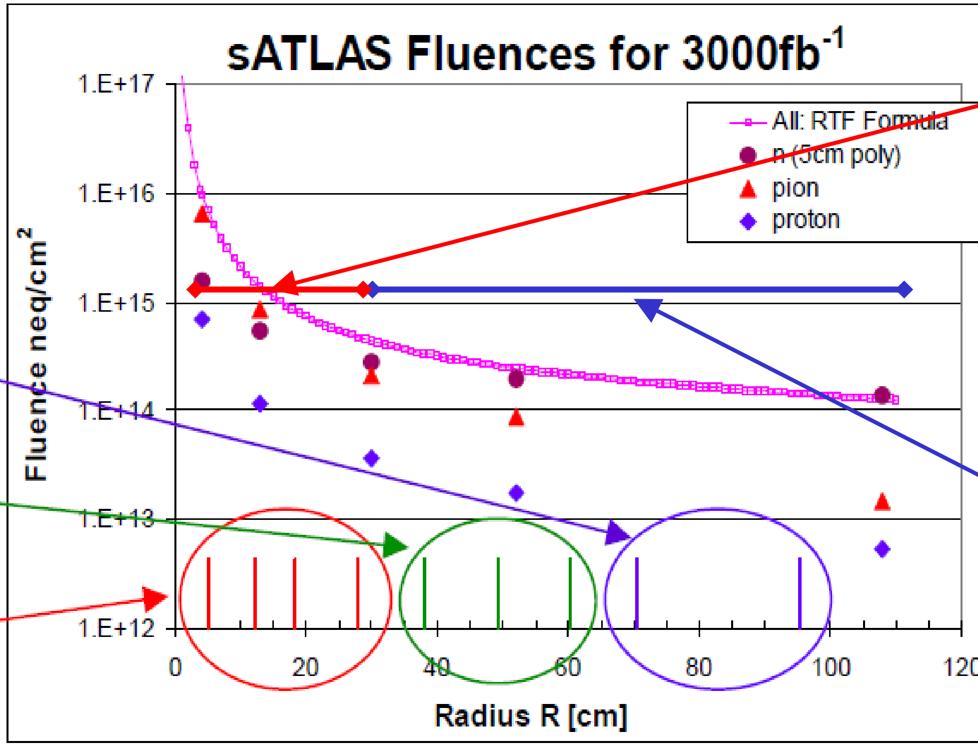
Radiation levels after 3000 fb^{-1}

Radial distribution of sensors determined by Occupancy

Long Strips (up to 4×10^{14} cm^{-2})

Short Strips (up to 10^{15} cm^{-2})

Pixels (up to 10^{16} cm^{-2})



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

Dominated by pion damage

Dominated by neutron damage

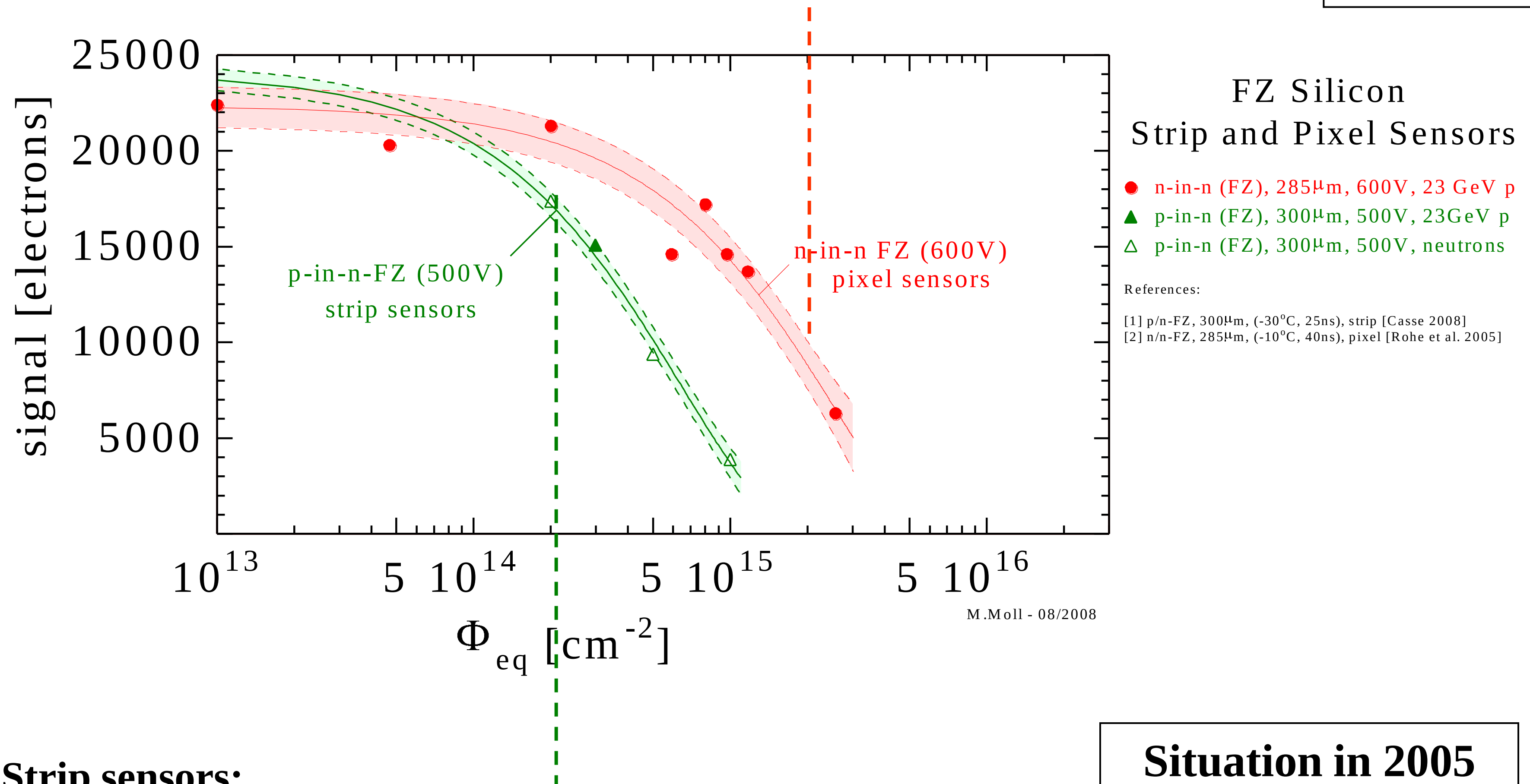
- **Radiation hardness requirements (including safety factor of 2)**
  - 2×10^{16} n_{eq}/cm^2 for the innermost pixel layers
  - 7×10^{14} n_{eq}/cm^2 for the innermost strip layers

B-layer (R=3.7 cm):	2.5×10^{16} n_{eq}/cm^2 = 1140 Mrad
2nd Inner Pixel Layer (R=7 cm):	7.8×10^{15} n_{eq}/cm^2 = 420 Mrad
1st Outer Pixel Layer (R=11 cm):	3.6×10^{15} n_{eq}/cm^2 = 207 Mrad
Short strips (R=38 cm):	6.8×10^{14} n_{eq}/cm^2 = 30 Mrad
Long strips (R=85 cm):	3.2×10^{14} n_{eq}/cm^2 = 8.4 Mrad

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



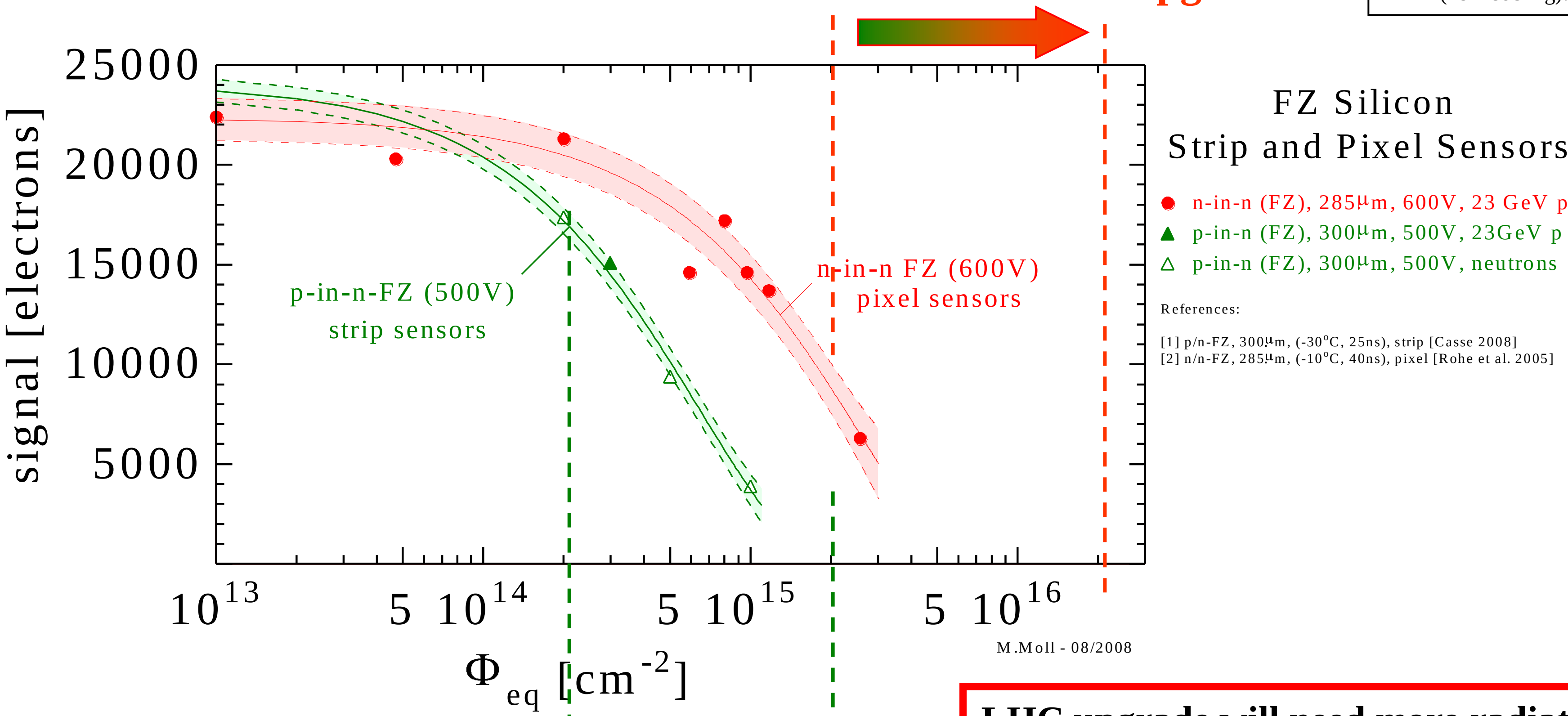
Strip sensors:
max. cumulated fluence for LHC

Situation in 2005

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 LHC upgrade



Strip sensors:
max. cumulated fluence for LHC and LHC upgrade

LHC upgrade will need more radiation tolerant tracking detector concepts!

Boundary conditions & other challenges: Granularity, Powering, Cooling, Connectivity, Triggering, Low mass, Low cost!

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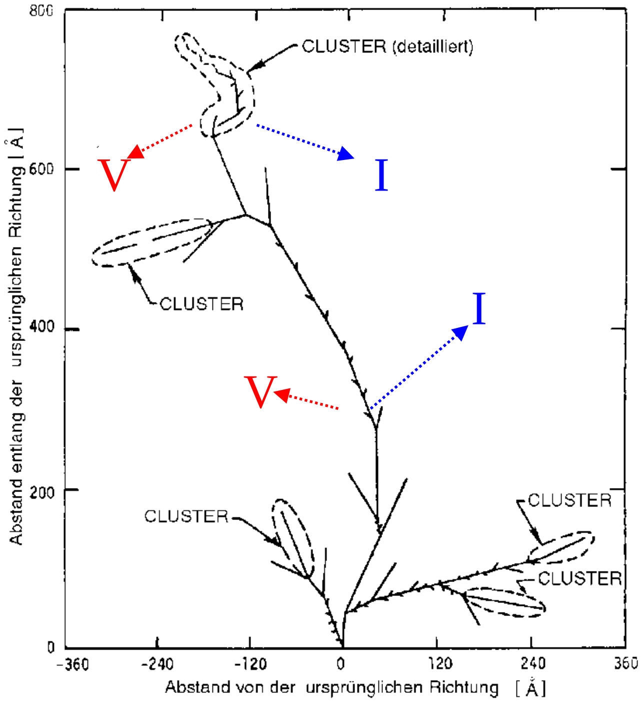
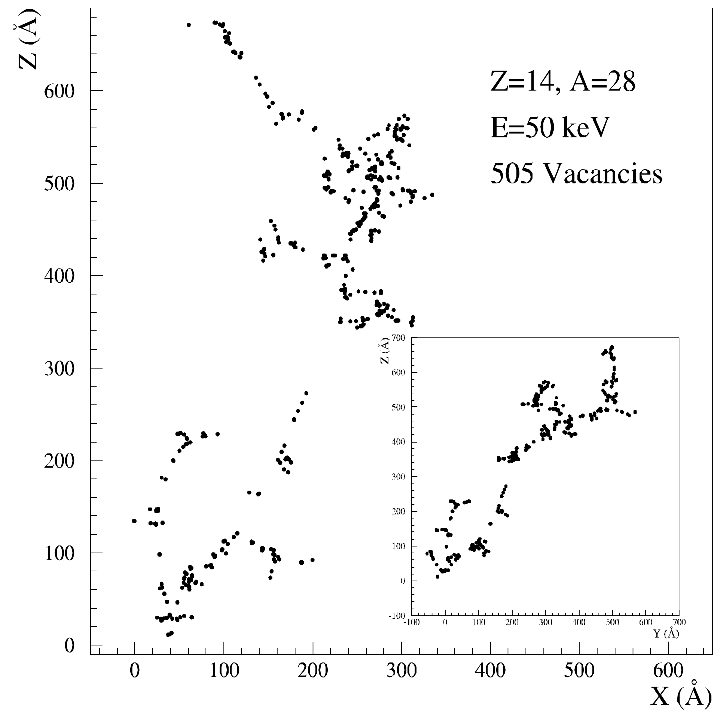
- **Spatial distribution of vacancies created by a 50 keV Si-ion in silicon.**
  (typical recoil energy for 1 MeV neutrons)

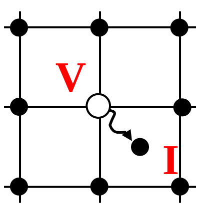
van Lint 1980

M.Huhtinen 2001





particle → Si_s → E_K>25 eV

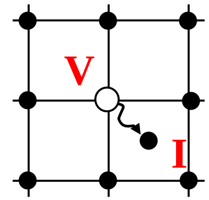


Vacancy + Interstitial → *point defects* ***(V-O, C-O, ..)***

→ E_K > 5 keV *point defects and clusters of defects*

Radiation Damage – Microscopic Effects

particle → Si_S → $E_K > 25$ eV



Vacancy + **I**nterstitial → *point defects (V-O, C-O, ..)*

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

- **^{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

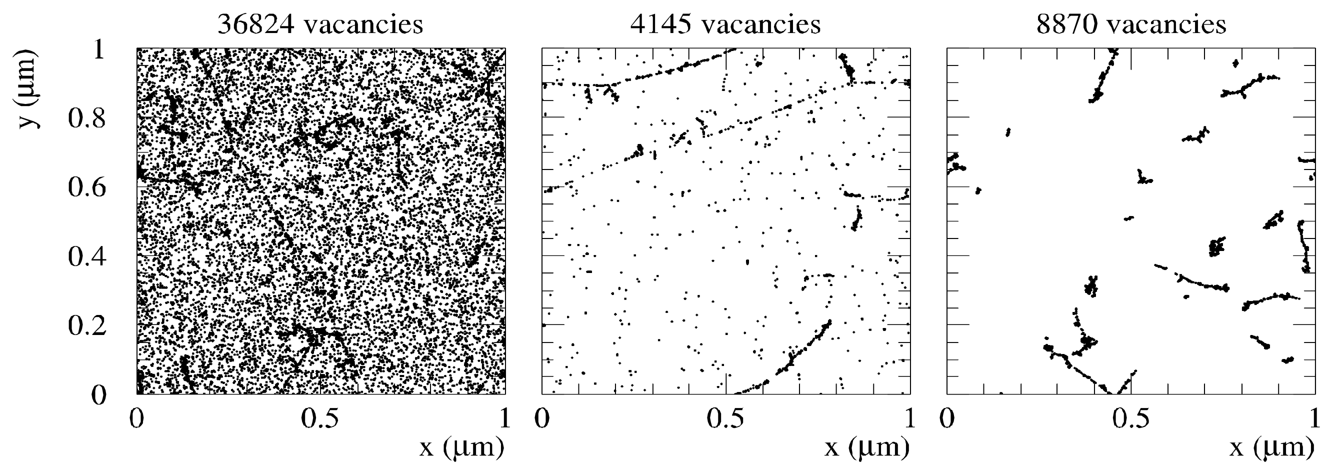
Only point defects ⟷ **point defects & clusters** ⟷ **Mainly clusters**

Simulation:

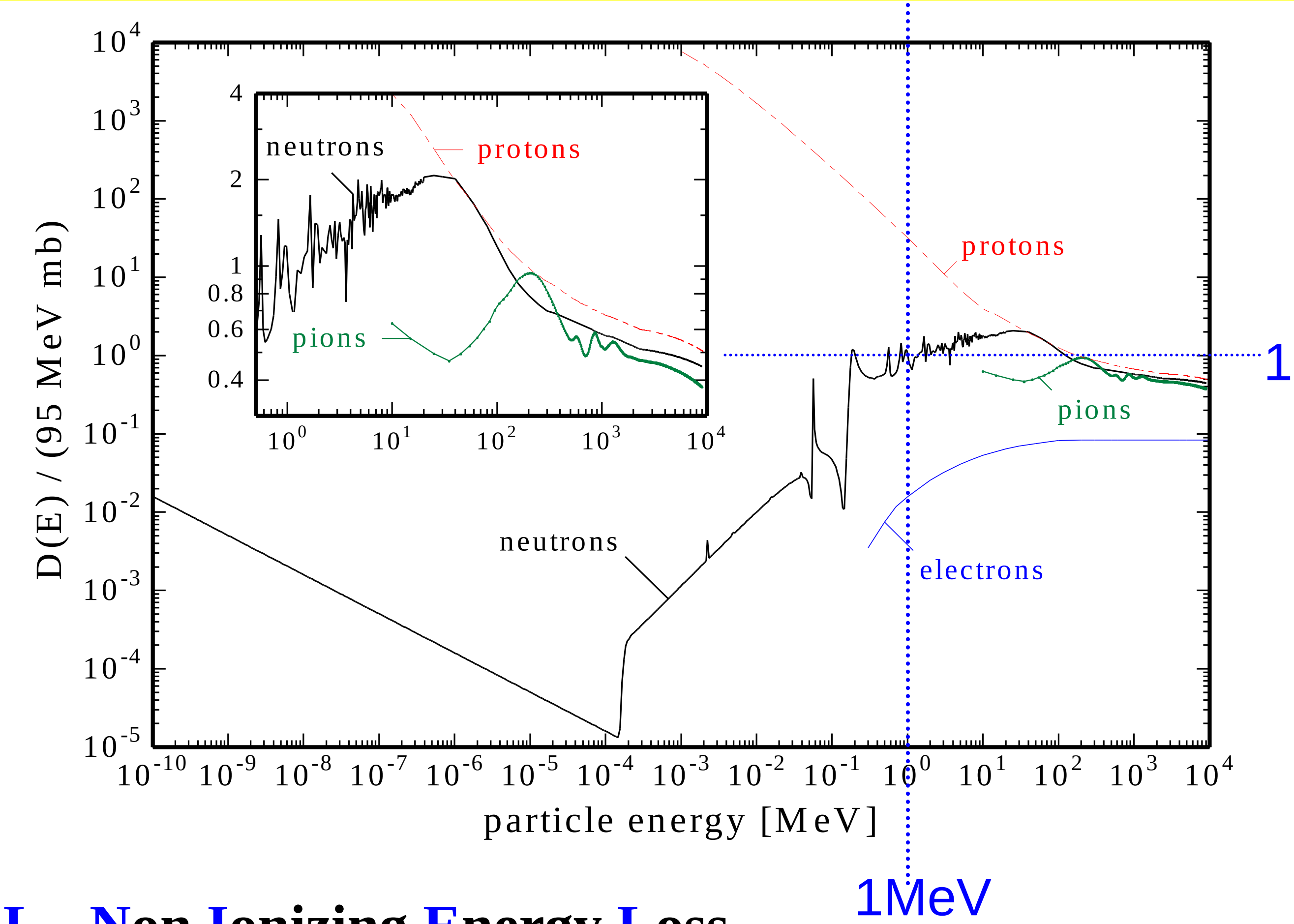
Initial distribution of vacancies in $(1\mu m)^3$ after 10^{14} particles/cm^2

[Mika Huhtinen NIMA 491(2002) 194]

10 MeV protons **24 GeV/c protons** **1 MeV neutrons**



NIEL - Displacement damage functions



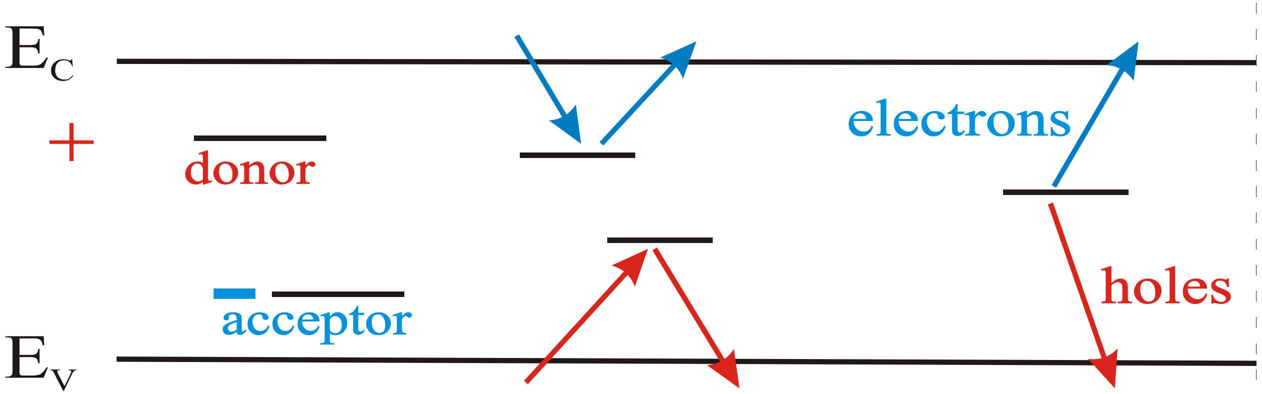
1 MeV neutron equivalent damage

- **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)*

Impact of Defects on Detector Properties

Details in next lecture by *Ioana Pintilie* on defects.

Shockley-Read-Hall statistics



charged defects	Trapping (e and h)	generation
⇒ N_{eff} , V_{dep}	⇒ CCE	⇒ leakage current
e.g. donors in upper and acceptors in lower half of band gap	shallow defects do not contribute at room temperature due to fast detrapping	Levels close to midgap most effective

Impact on detector properties can be calculated if all defect parameters are known:

$\sigma_{n,p}$: cross sections **ΔE : ionization energy** **N_t : concentration**

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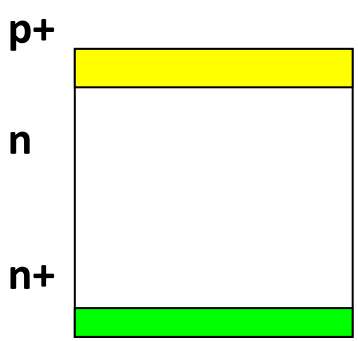
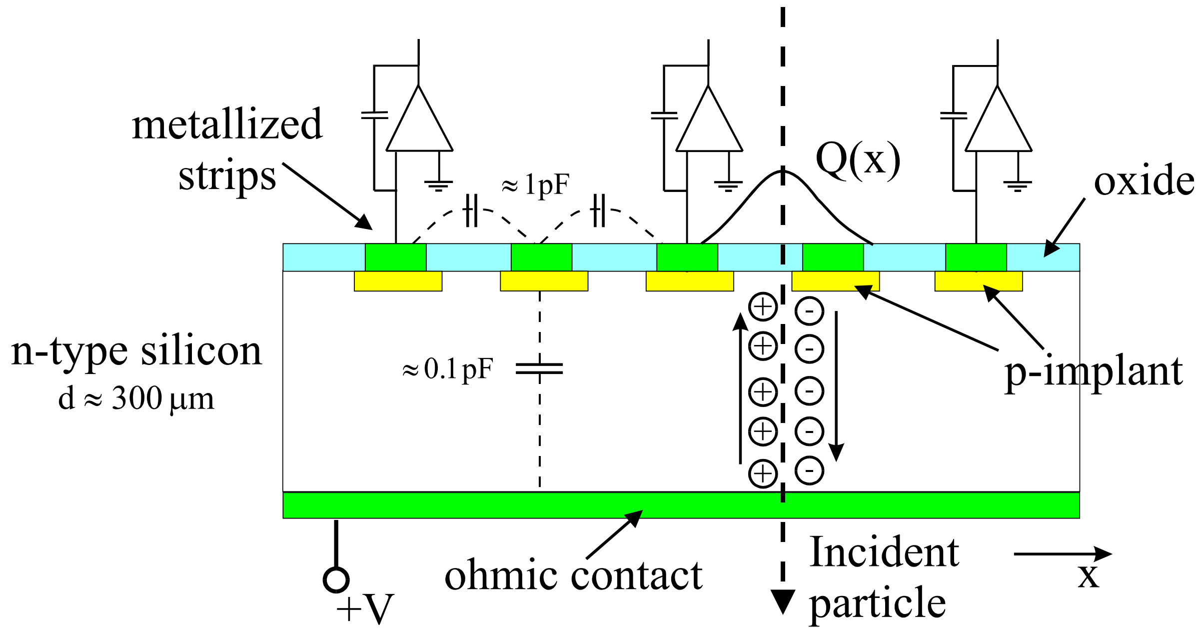
Impact of Defects on Detector Properties

- Detectors are basically p^+- n diodes made on high resistivity silicon

- **Standard detector grade silicon:**
  - **Float Zone silicon (FZ)**
  - **n-type: 2…20 KΩcm**
  - **[P] = 20…2×10^{11} cm^{-3} (very low concentration !! below 1ppba = 5×10^{13}cm^{-3})**
  - **[O] ≈ several 10^{15}cm^{-3}**
  - **[C] ≈ some 10^{15}cm^{-3}, usually [C] < [O]**
  - **crystal orientation: <111> or <100>**



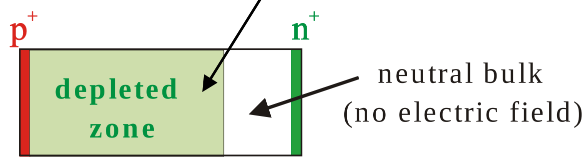


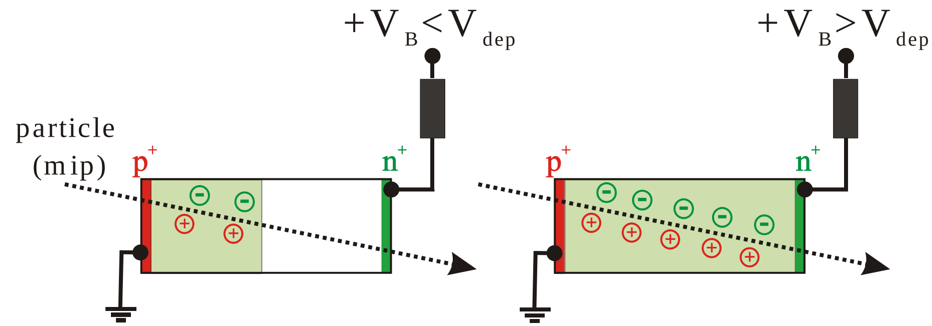
Reminder: Reverse biased abrupt p⁺-n junction

Poisson's equation

$$-\frac{d^2}{dx^2}\phi(x) = \frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}$$

Positive space charge, N_{eff} =[P] (ionized Phosphorus atoms)

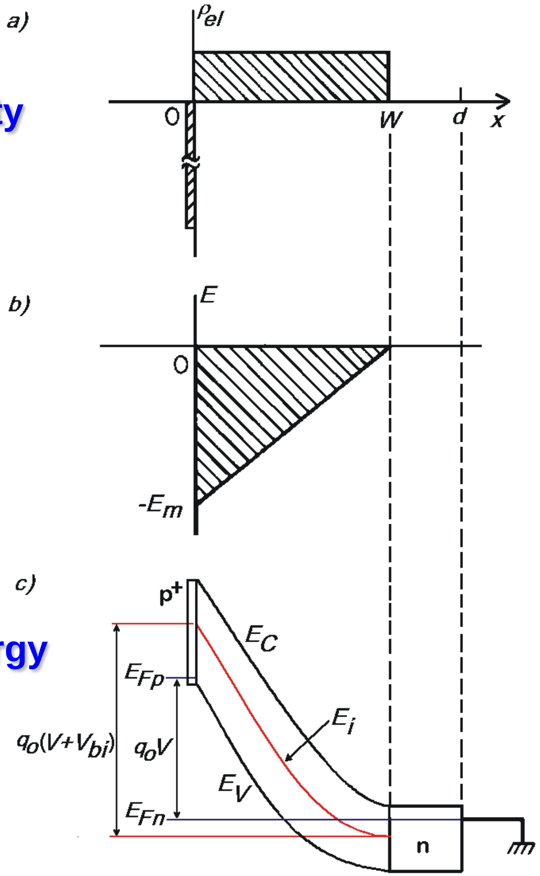




Electrical charge density

Electrical field strength

Electron potential energy



Full charge collection only for $V_B>V_{dep}$!

depletion voltage

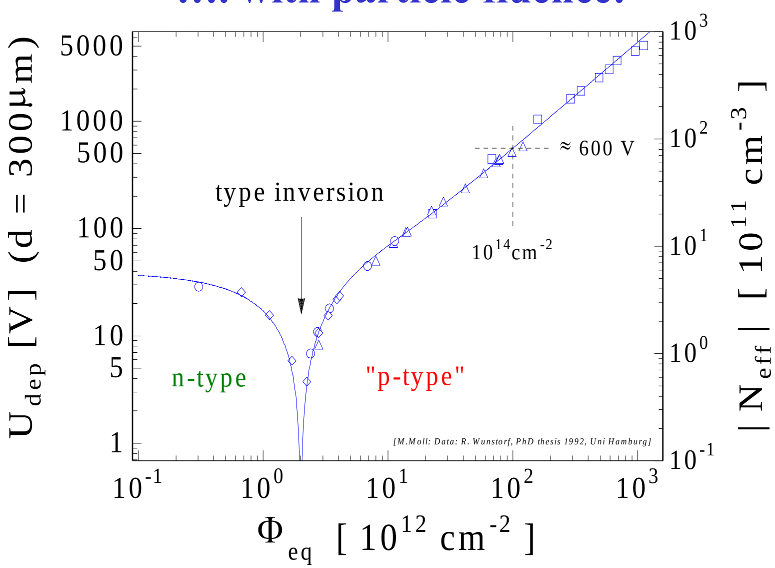
$$V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0}\cdot |N_{eff}|\cdot d^2$$

effective space charge density

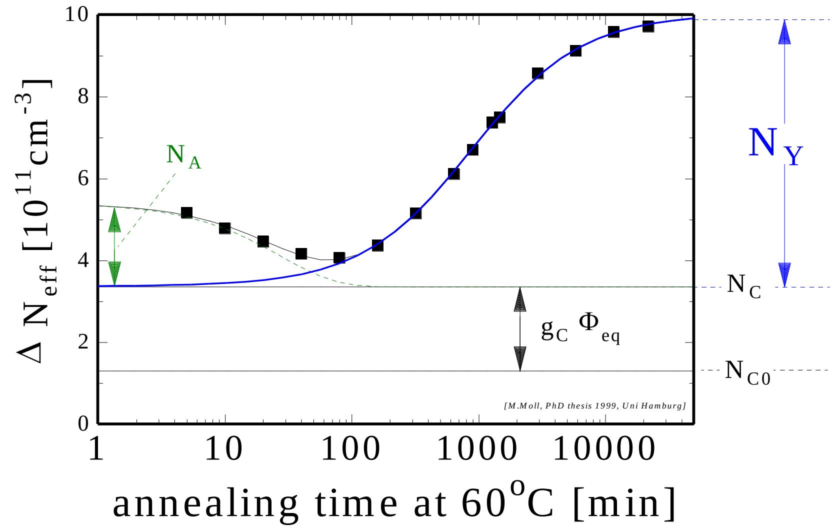
Macroscopic Effects – I. Depletion Voltage

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

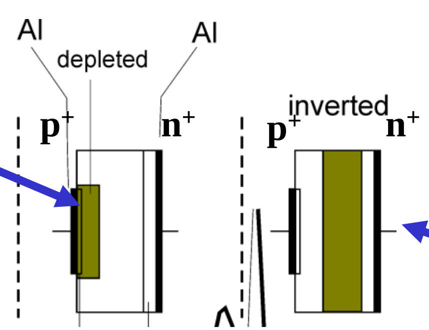
…. with particle fluence:



…. with time (annealing):



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

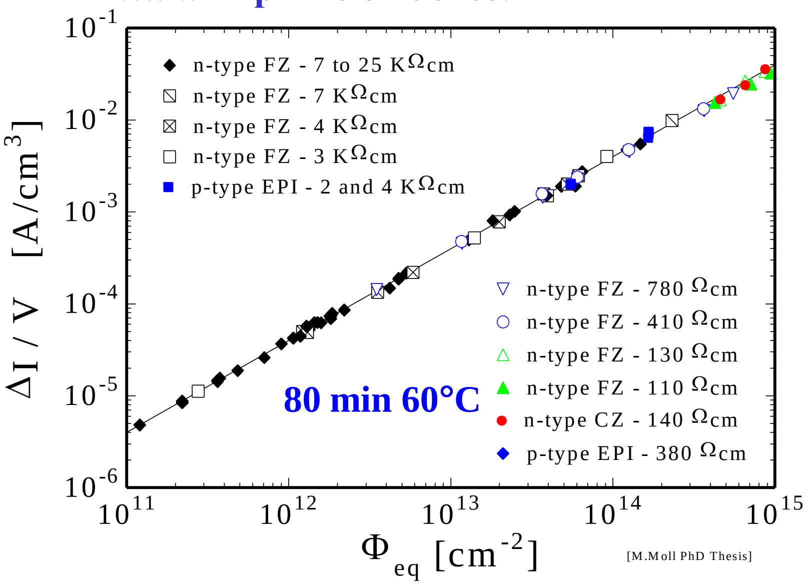


- Short term: "**Beneficial annealing**"
- Long term: "**Reverse annealing**"
  - **- time constant depends on temperature:**
    - **~ 500 years (-10 C)**
    - **~ 500 days (20 C)**
    - **~ 21 hours (60 C)**
  - - Consequence: **Detectors must be cooled even when the experiment is not running!**

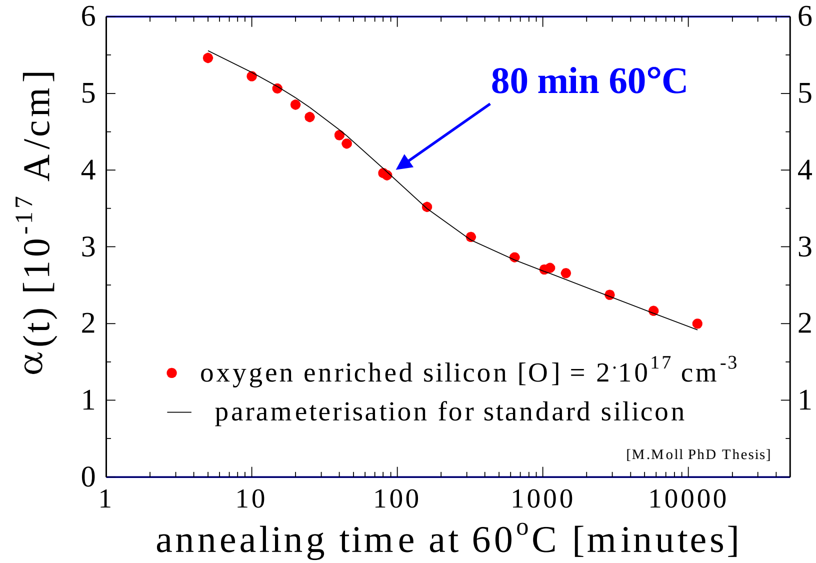
Radiation Damage – II. Leakage Current

Change of Leakage Current (after hadron irradiation)

…. with particle fluence:



…. with time (annealing):



- **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**

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

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

Consequence:

Cool detectors during operation!

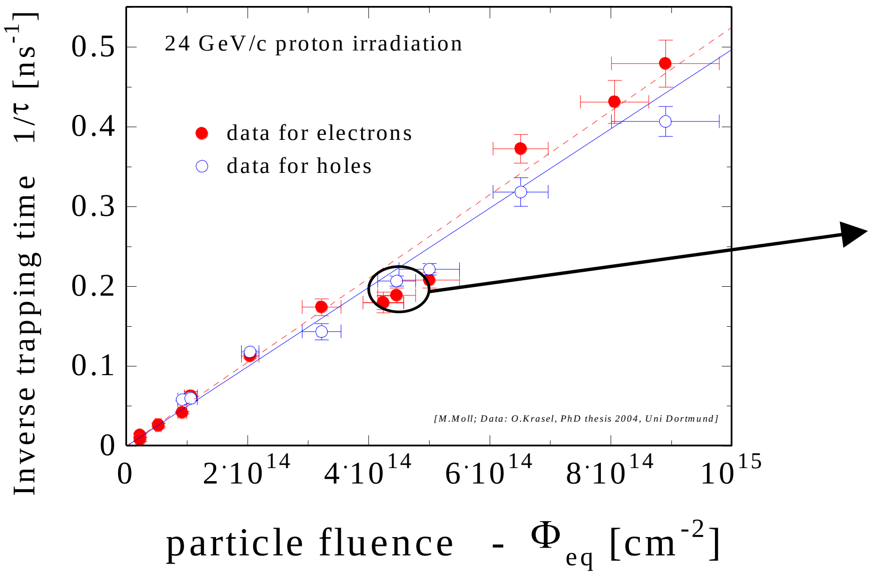
Example: I(-10 C) ~1/16 I(20 C)

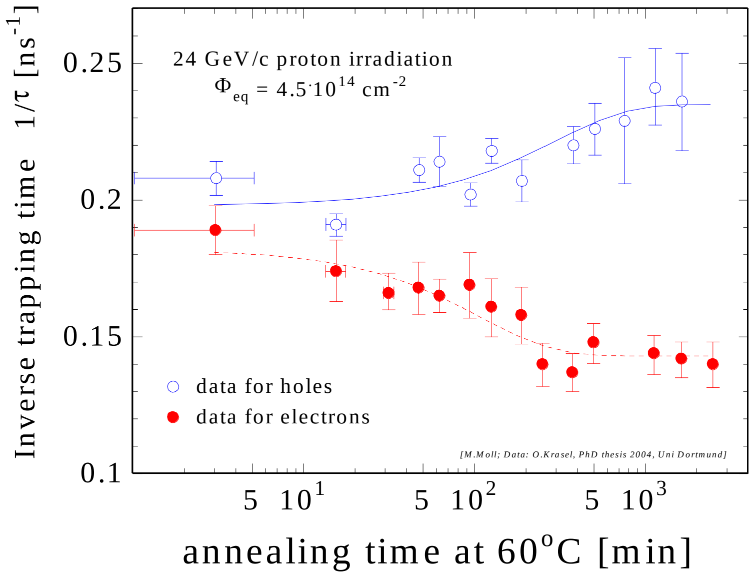
- **Deterioration of Charge Collection Efficiency (CCE) by trapping**

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

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

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





Summary: Radiation Damage in Silicon Sensors

- **Two general types of radiation damage to the detector materials:**

Influenced by impurities in Si – Defect Engineering is possible!

- **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)**

Same for all tested Silicon materials!

- **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 Efficiency**
  (depending on detector type and geometry and readout electronics!)

Signal/noise ratio is the quantity to watch

⇒ Sensors can fail from radiation damage !

Can be optimized!

The charge signal

Collected Charge for a Minimum Ionizing Particle (MIP)

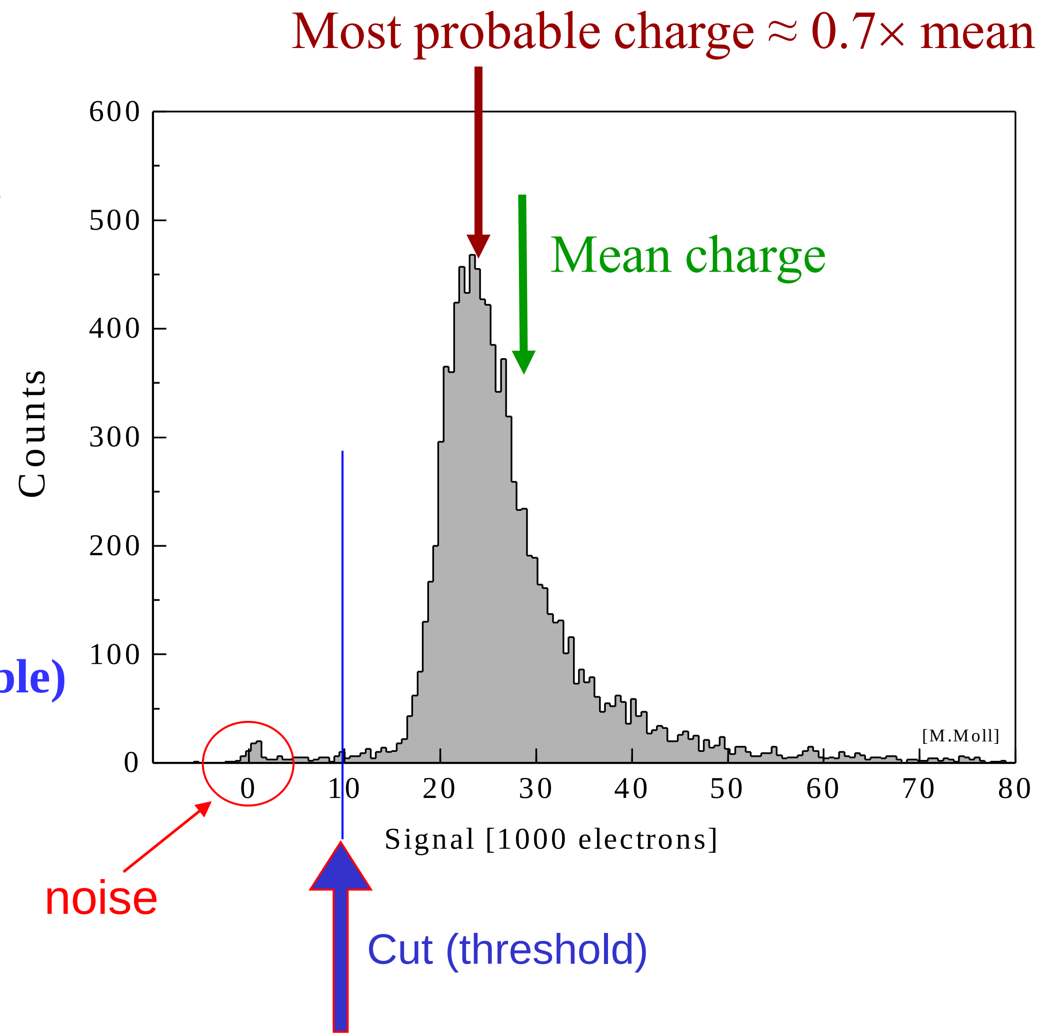
- **Mean energy loss**
  dE/dx (Si) = 3.88 MeV/cm
  ⇒ 116 keV for 300µm thickness

- **Most probable energy loss**
  ≈ 0.7 ×mean
  ⇒ 81 keV

- **3.6 eV to create an e-h pair**
  ⇒ 72 e-h / µm (mean)
  ⇒ 108 e-h / µm (most probable)

- **Most probable charge (300 µm)**

  ≈ 22500 e   ≈ 3.6 fC



Signal to Noise ratio

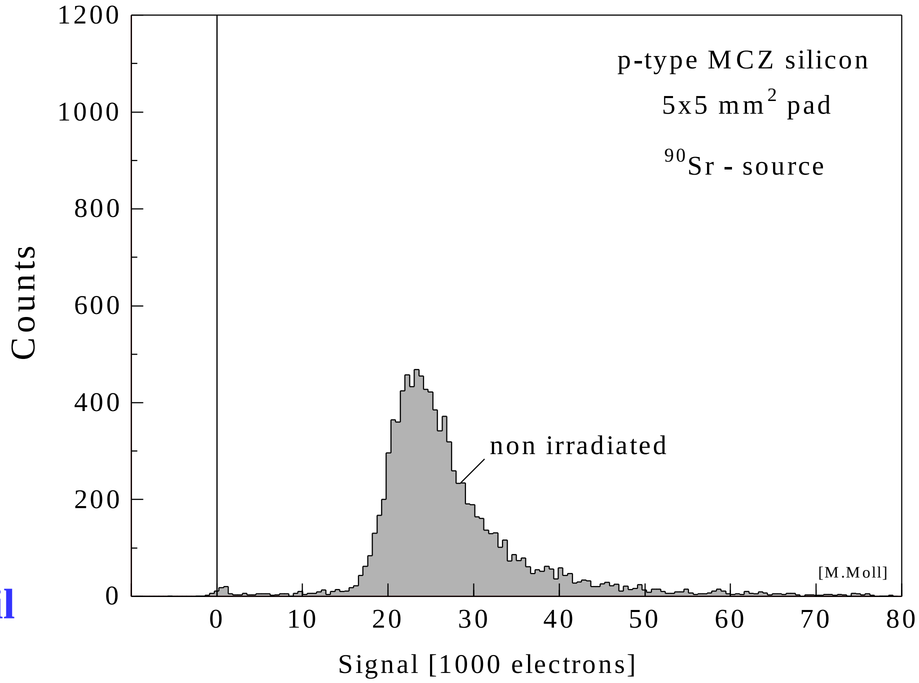
- **Landau distribution has a low energy tail**
  - becomes even lower by noise broadening

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

  - Capacitance $ENC \propto C_d$

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

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



- **Good hits selected by requiring NADC > noise tail**
  If cut too high ⇒ efficiency loss
  If cut too low ⇒ noise occupancy

- **Figure of Merit: Signal-to-Noise Ratio S/N**

- **Typical values >10-15, people get nervous below 10.**
  Radiation damage severely degrades the S/N.

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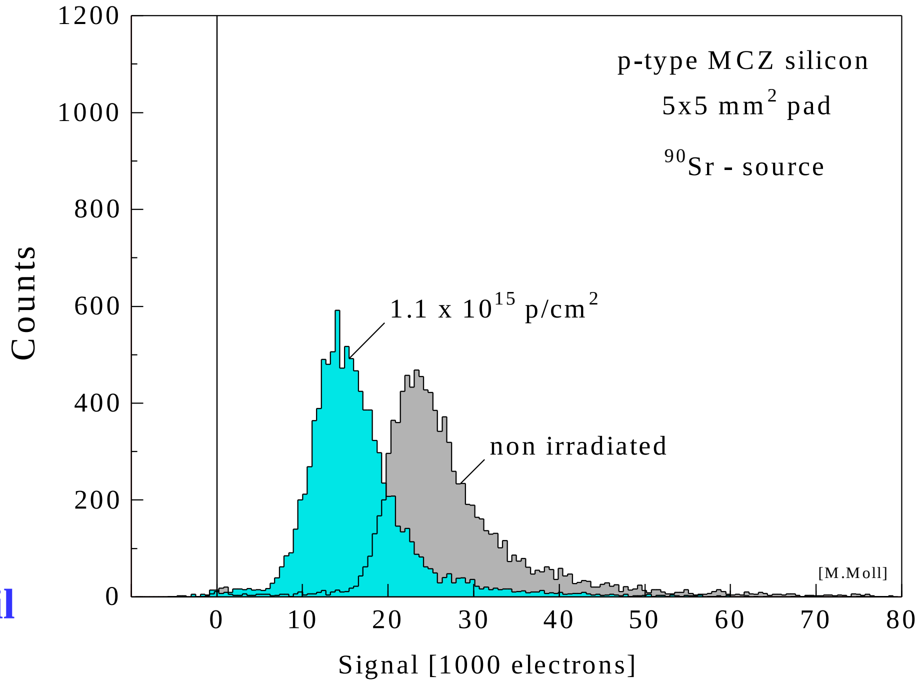

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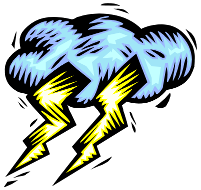
What is signal and what is noise?



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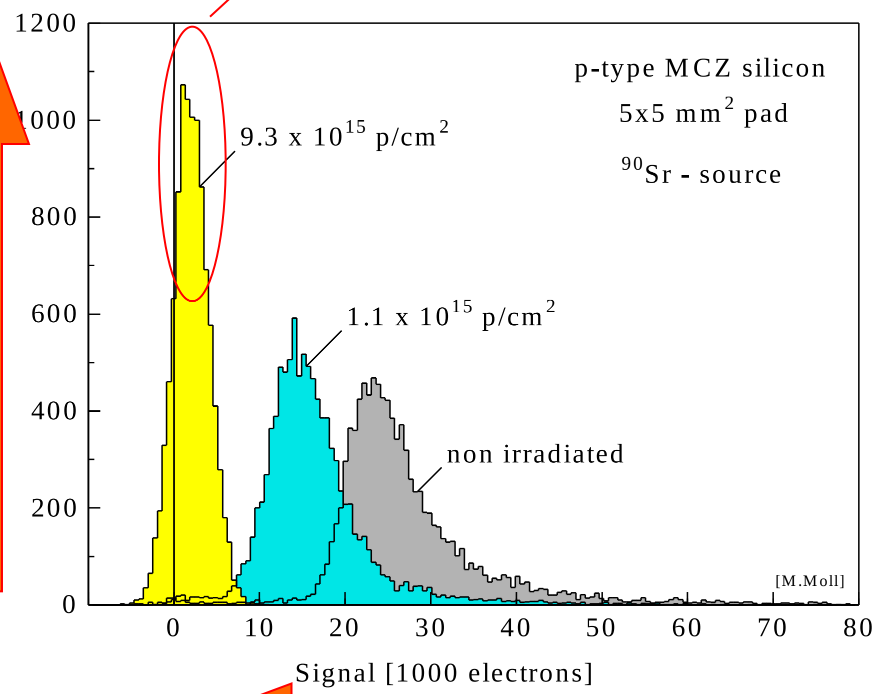
more noise



less signal

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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

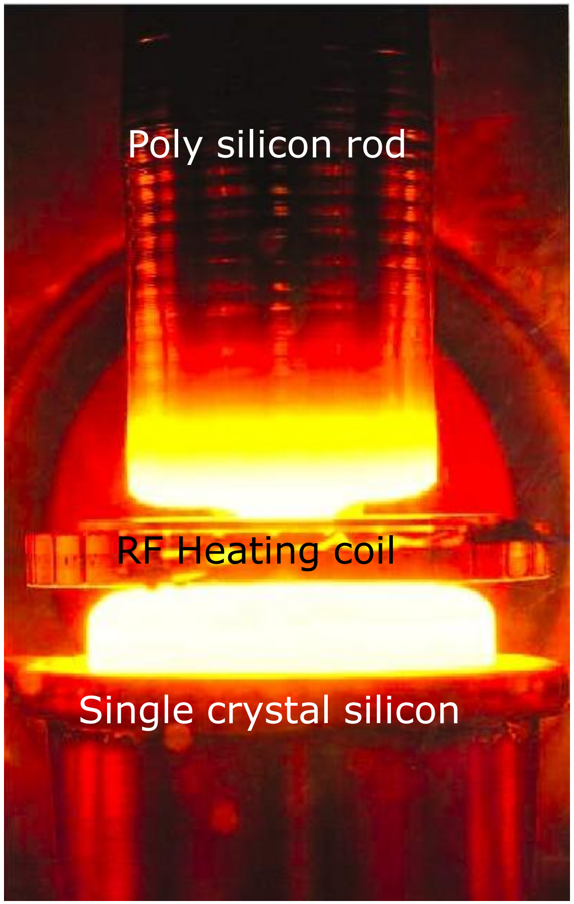
- **New Materials**
  - Silicon Carbide (SiC), Gallium Nitride (GaN)
  - Diamond (CERN RD42 Collaboration)
  - Amorphous silicon

- **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

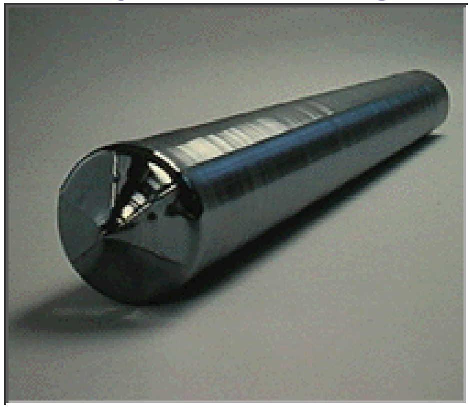
Material: Float Zone Silicon (FZ)

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

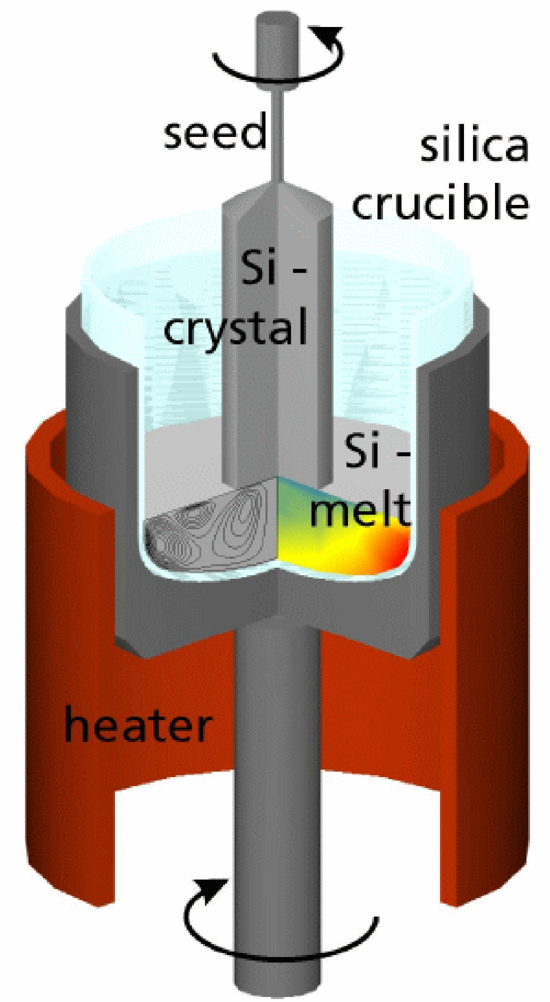
- Slicing, lapping, etching, polishing

Oxygen enrichment (DOFZ)

- Oxidation of wafer at high temperatures

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.

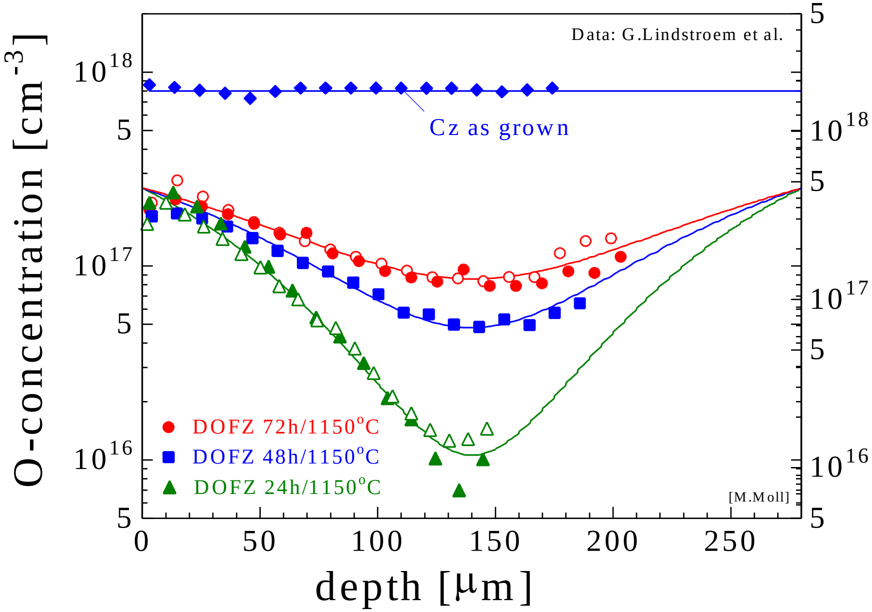
Epitaxial silicon

- 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

Oxygen concentration in FZ, CZ and EPI

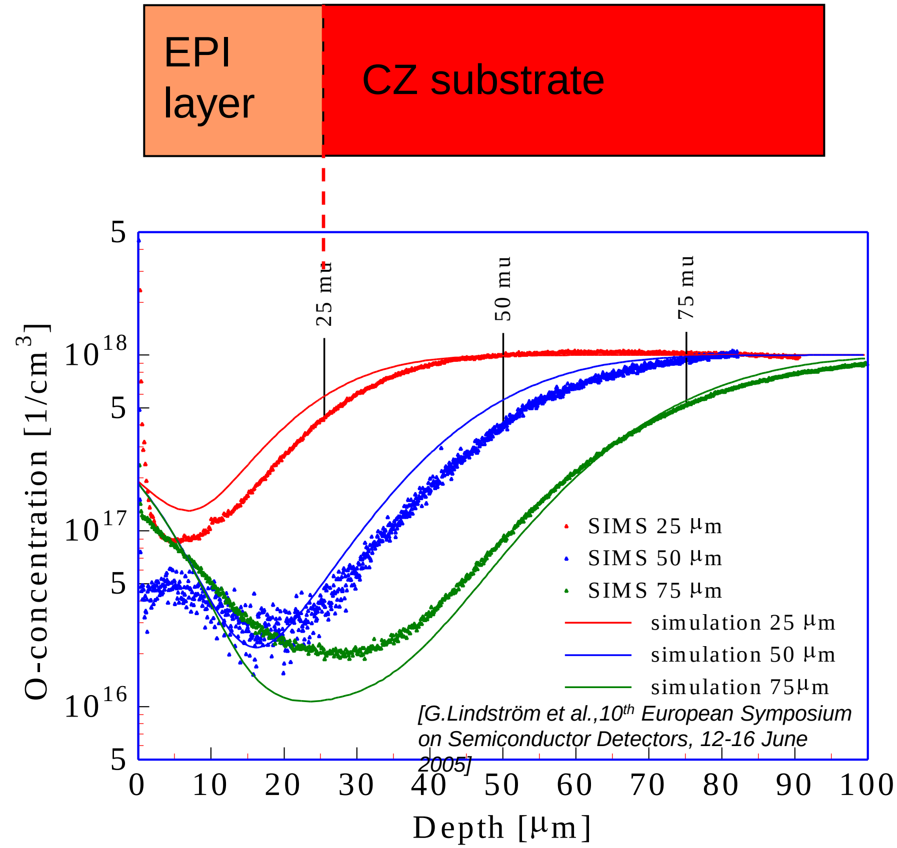
DOFZ and CZ silicon

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



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

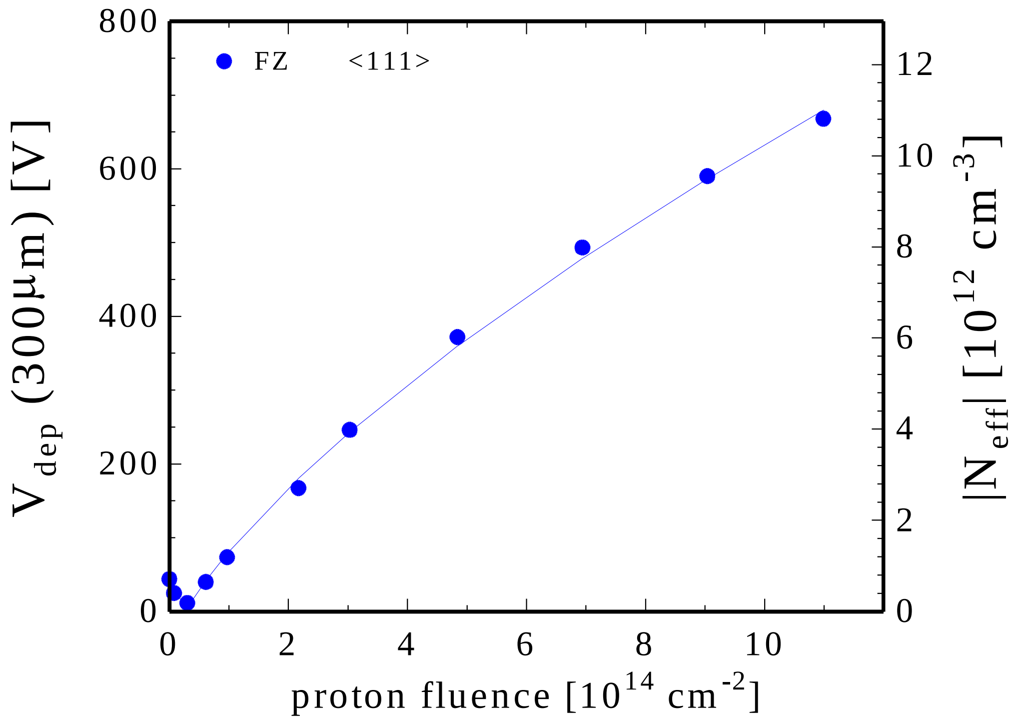
Epitaxial silicon



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

24 GeV/c proton irradiation

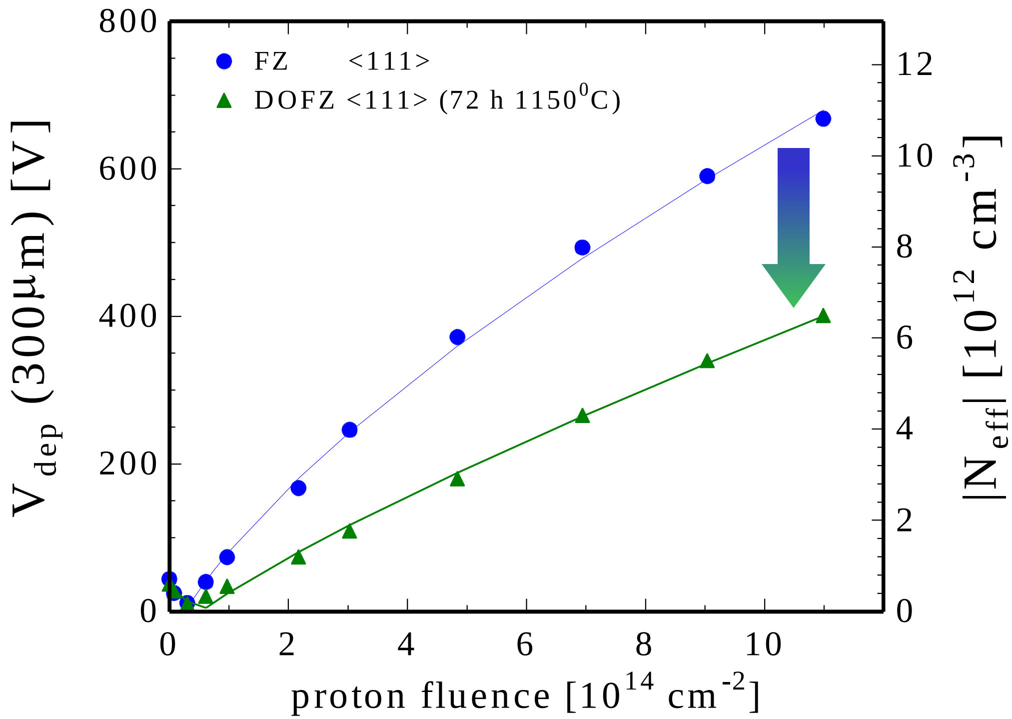
- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong N_{eff} increase at high fluence



Standard FZ, DOFZ, MCz and Cz silicon

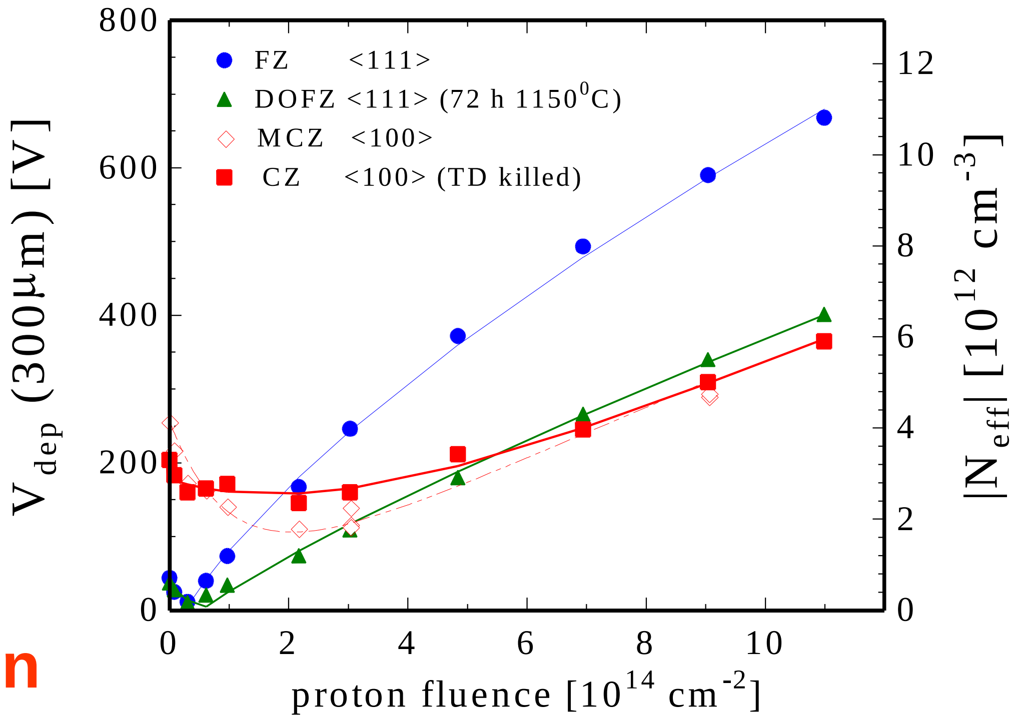
24 GeV/c proton irradiation

- **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



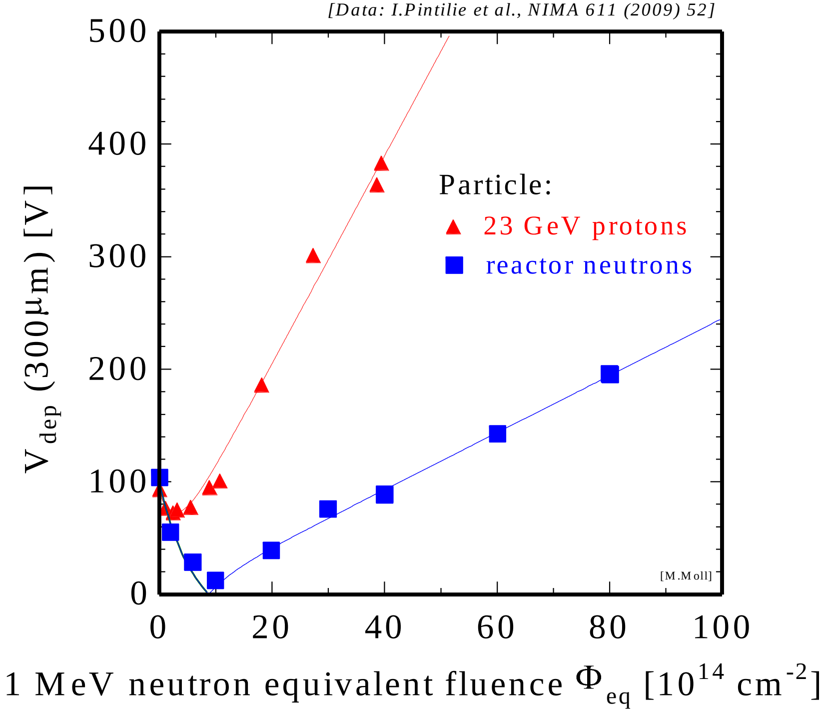
- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong N_{eff} increase at high fluence
- **Oxygenated FZ (DOFZ)**
  - type inversion at ~ 2×10^{13} p/cm^2
  - reduced N_{eff} increase at high fluence
- **CZ silicon and MCZ silicon**
  - "no type inversion" in the overall fluence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

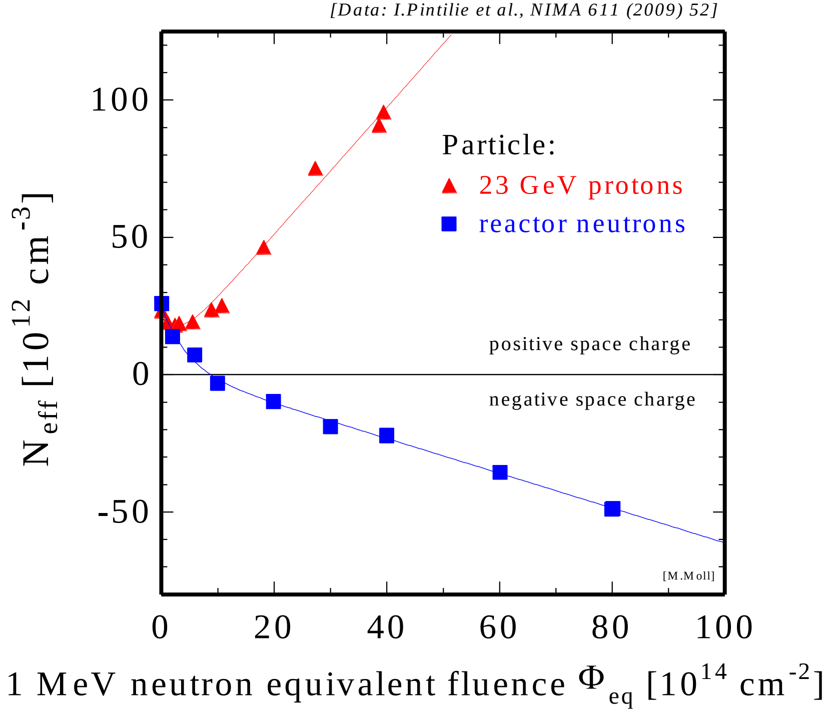
(for experts: there is no "real" type inversion, a more clear understanding of the observed effects is obtained by investigating directly the internal electric field; look for: TCT, MCZ, double junction)

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

Proton vs. Neutron irradiation of oxygen rich silicon

- **Epitaxial silicon** *(EPI-DO, 72μm, 170Ωcm, diodes)*
  irradiated with 23 GeV protons or reactor neutrons





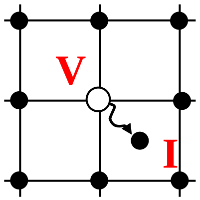
depletion voltage →

$$V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0} \cdot |N_{eff}| \cdot d^2$$

← ***absolute effective space charge density***

Why is proton and neutron damage different?

particle → Si_s → E_K>25 eV



Vacancy + Interstitial → *point defects (V-O, C-O, ..)*

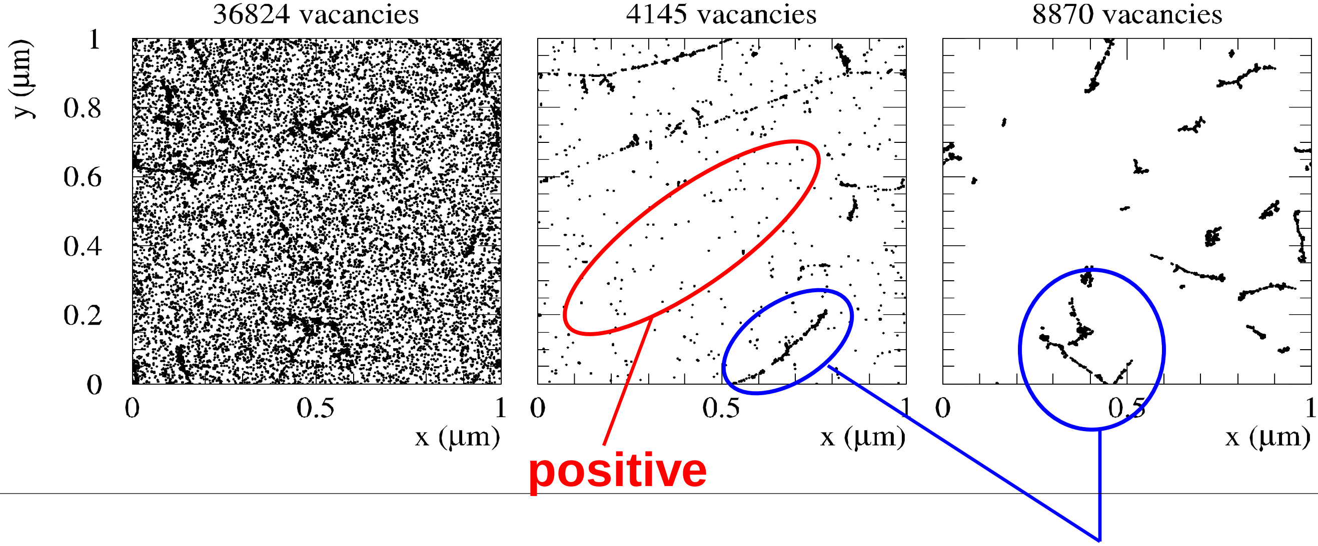
→ E_K > 5 keV *point defects and clusters of defects*

Simulation:

Initial distribution of vacancies in (1μm)³ after 10^{14} particles/cm²

[Mika Huhtinen NIMA 491(2002) 194]

10 MeV protons **24 GeV/c protons** **1 MeV neutrons**



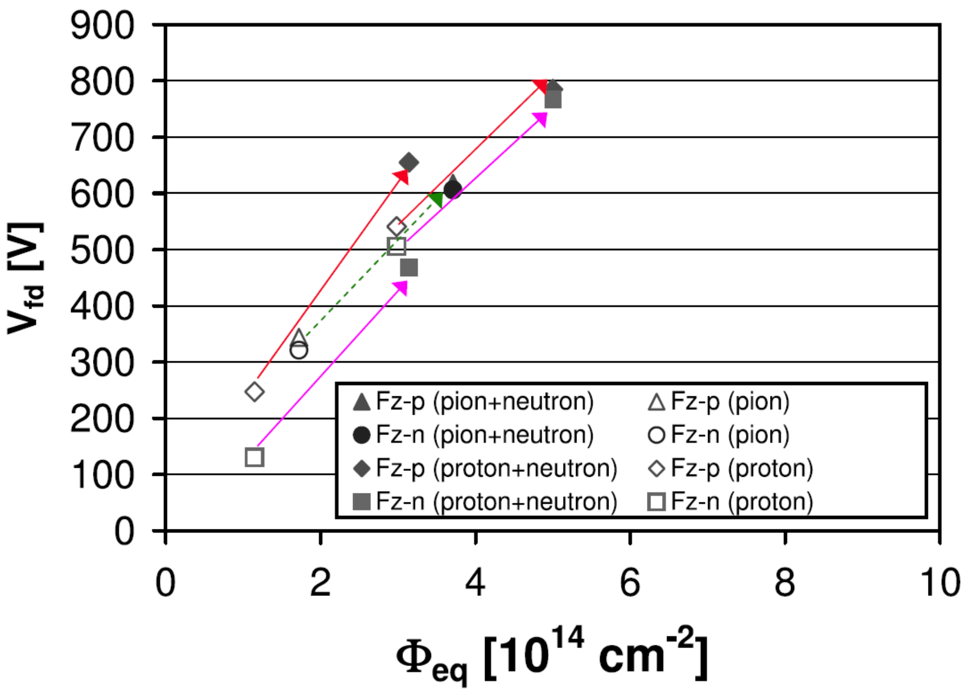
- **A 'simplified' explanation for the 'compensation effects'**
  - Defect clusters produce predominantly **negative space charge**
  - Point defects produce predominantly **positive space charge** (in '<u>oxygen rich</u>' silicon)

For the experts: Note the NIEL violation

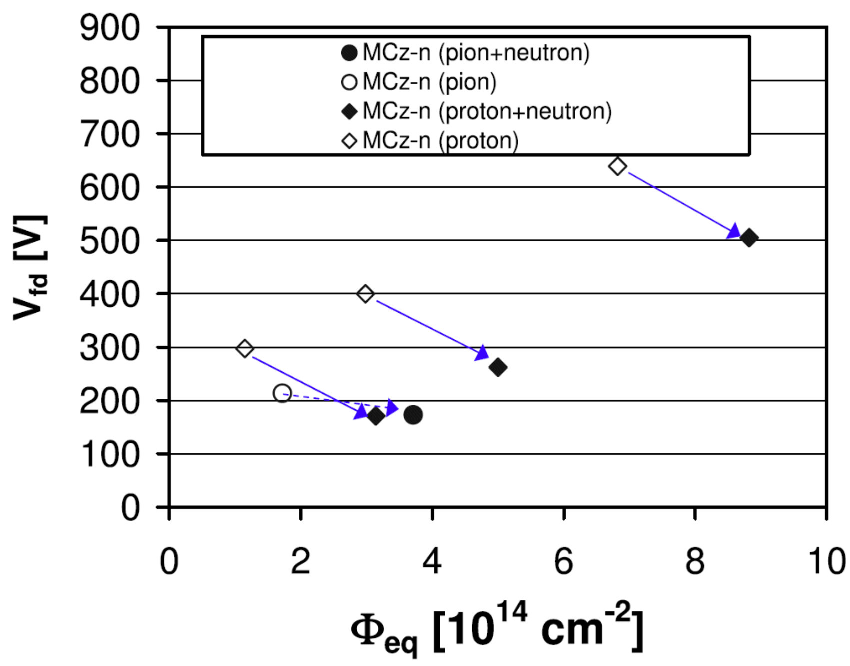
Mixed irradiations – Change of N_{eff}

- **Exposure of FZ & MCZ silicon sensors to 'mixed' irradiations**
  - **First step: Irradiation with protons or pions**
  - **Second step: Irradiation with neutrons**

FZ: Accumulation of damage



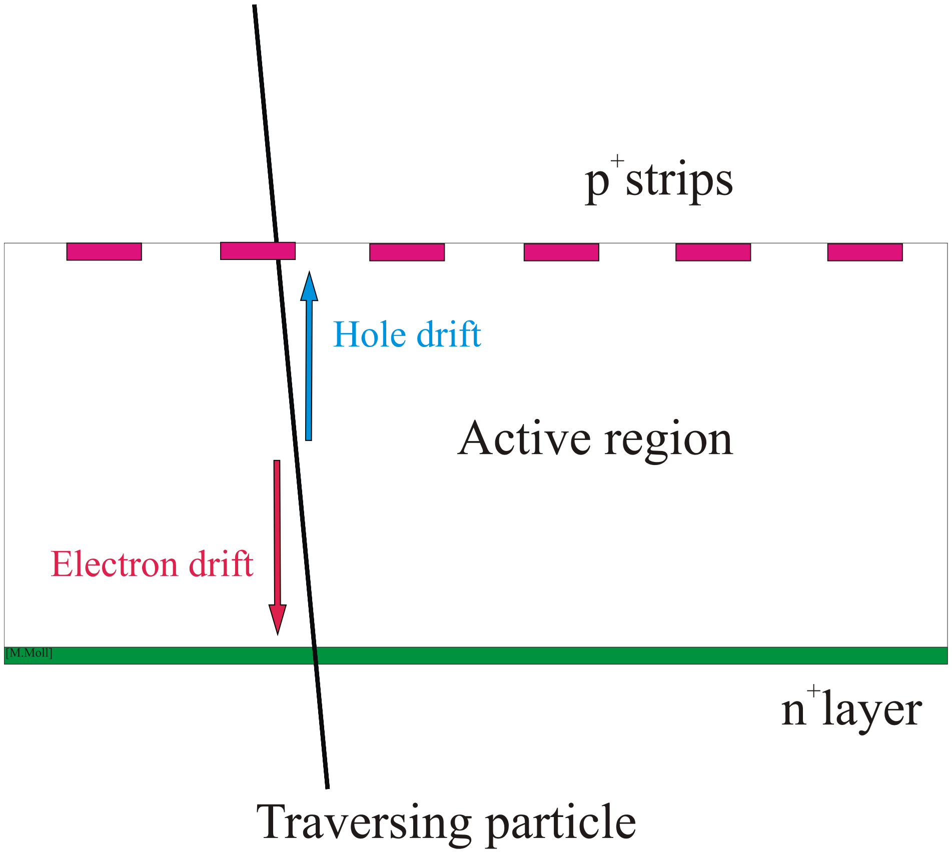
MCZ: Compensation of damage



[G.Kramberger et al., "Performance of silicon pad detectors after mixed irradiations with neutrons and fast charged hadrons", NIMA 609 (2009) 142-148]

Advantage of non-inverting material
p-in-n detectors (schematic figures!)

Fully depleted detector
(non – irradiated):

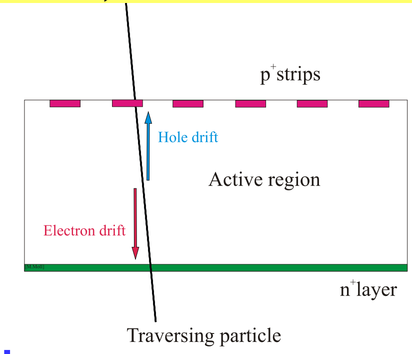


Advantage of non-inverting material

p-in-n detectors (schematic figures!)

Be careful, this is a very schematic explanation, reality is more complex !

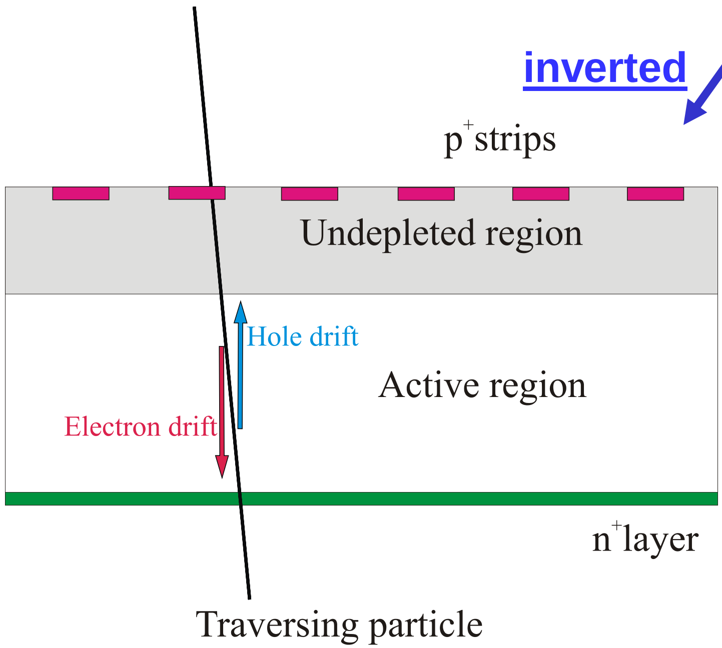
Fully depleted detector (non – irradiated):

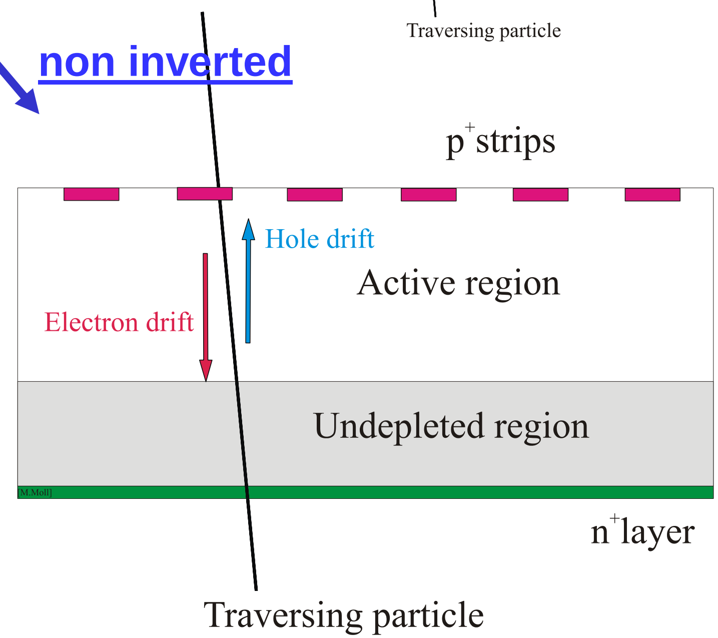


heavy irradiation

inverted

non inverted





inverted to "p-type", under-depleted:

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

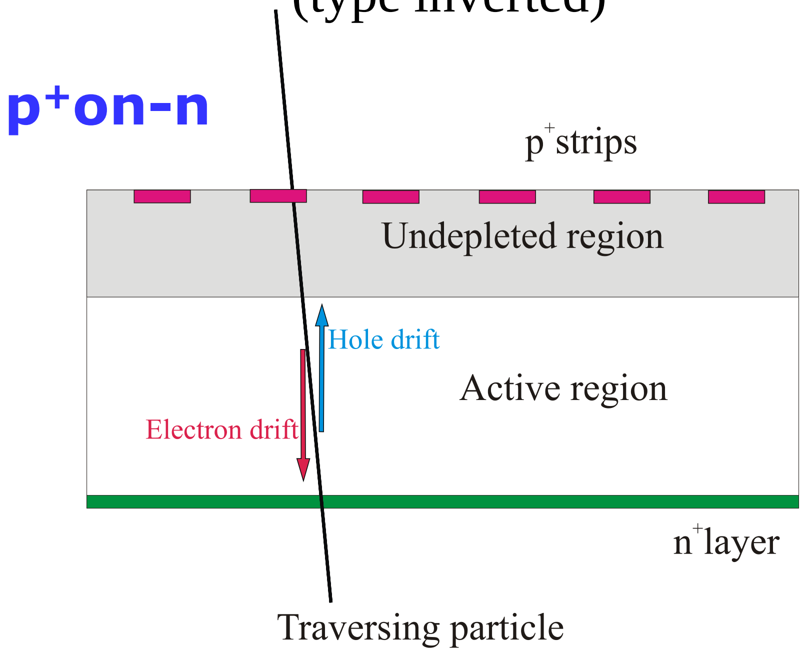
non-inverted, under-depleted:

- Limited loss in CCE
- Less degradation with under-depletion

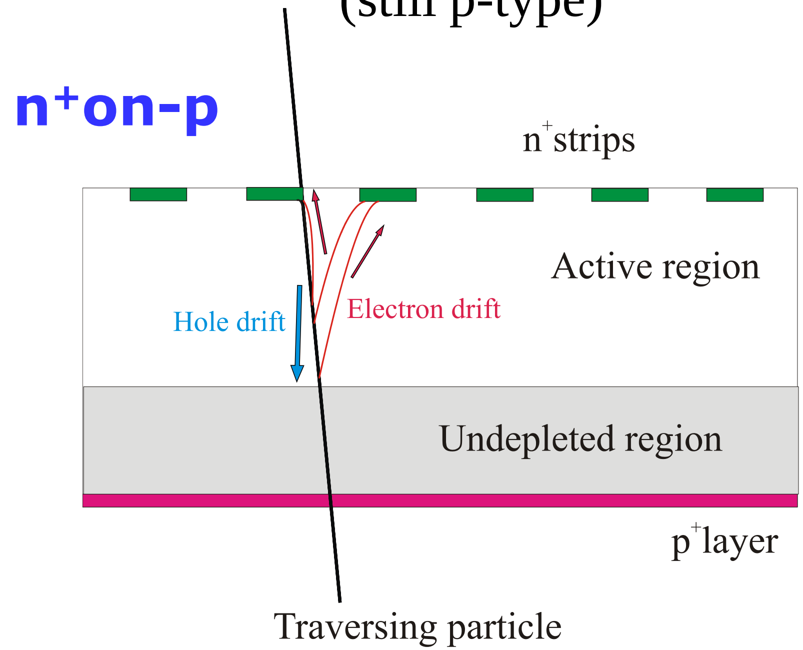
Device engineering

p-in-n versus n-in-p (or n-in-n) detectors

n-type silicon after high fluences:
(type inverted)



p-type silicon after high fluences:
(still p-type)



p-on-n silicon, under-depleted:

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

n-on-p silicon, under-depleted:

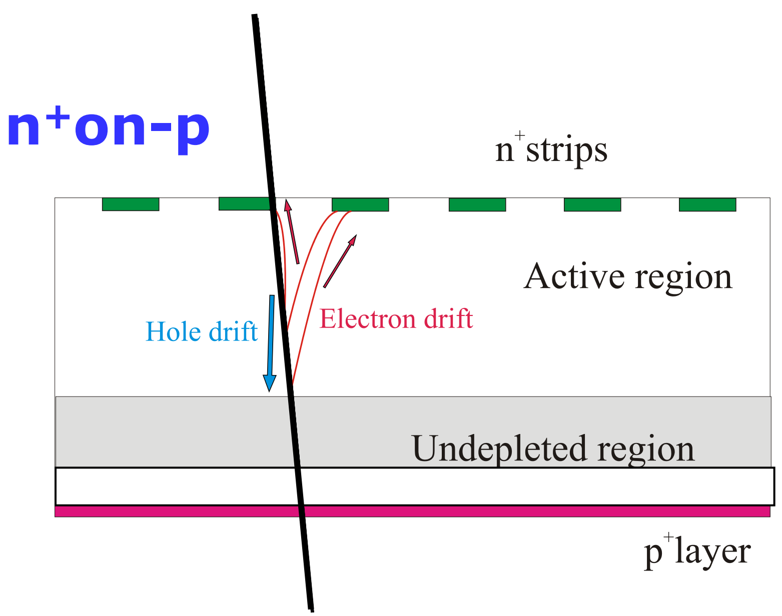
- **Limited loss in CCE**
- **Less degradation with under-depletion**
- **Collect electrons (3 x faster than holes)**

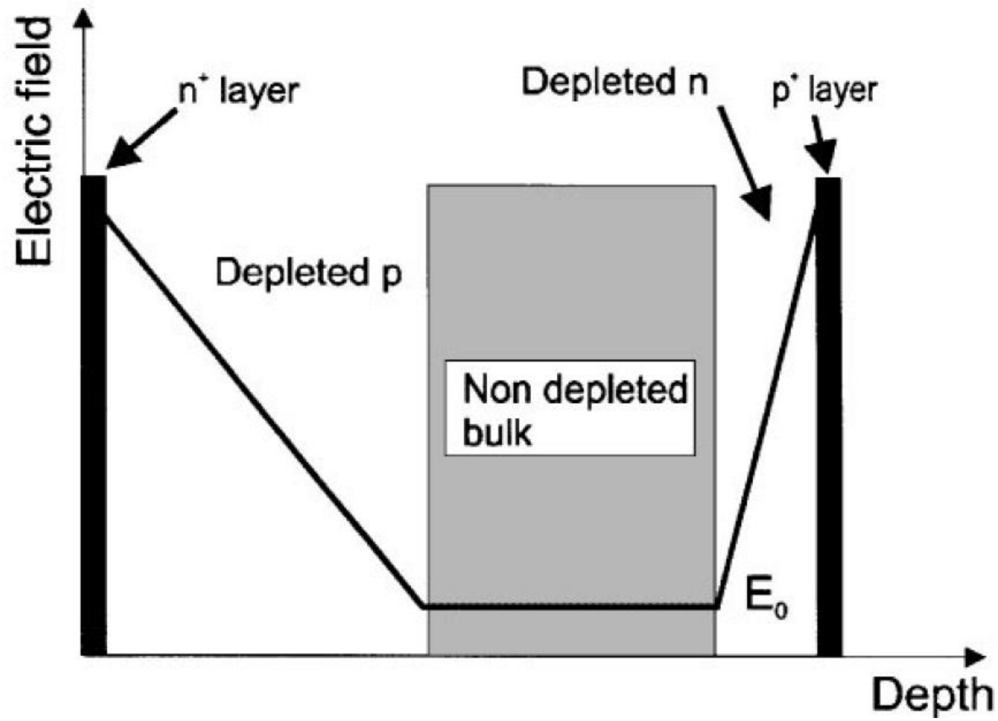
Comments:
- Instead of n-on-p also n-on-n devices could be used

Reality is more complex: *Double junctions*

p-type silicon after high fluences:

(still "p-type")



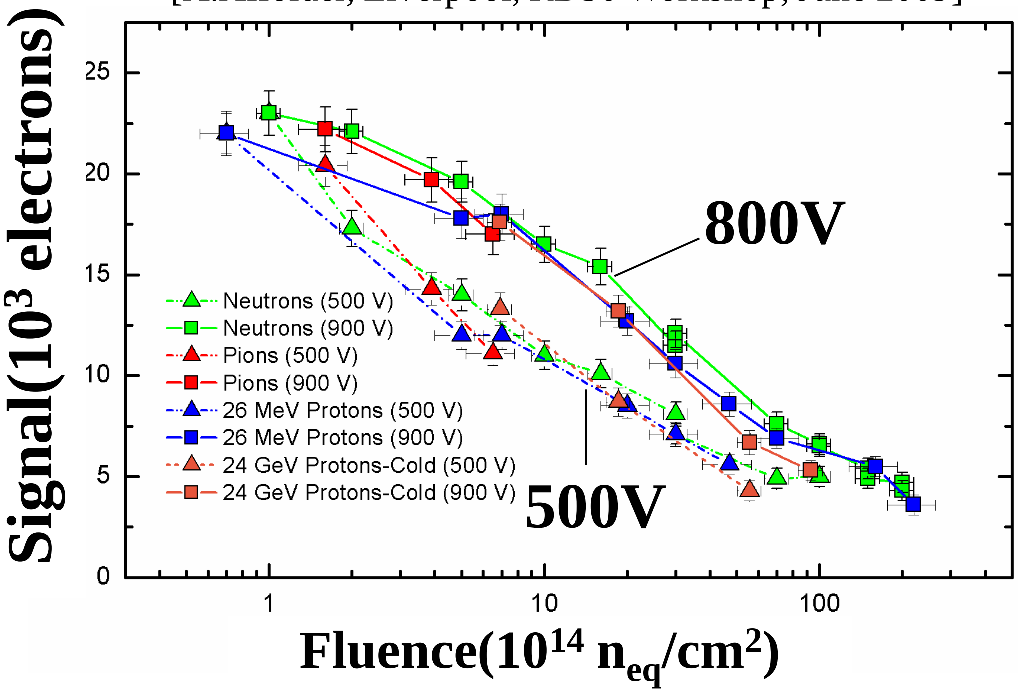


- **Dominant junction close to n+ readout strip for FZ n-in-p**
- **For MCZ p-in-n even more complex fields have been reported:**
  - **no "type inversion"(SCSI) = dominant field remains at p implant**
  - **"equal double junctions" with almost symmetrical fields on both sides**

FZ n-in-p microstrip detectors (n, p, p - irrad)

- **n-in-p microstrip p-type FZ detectors** (Micron, 280 or 300µm thick, 80µm pitch, 18µm implant)
- **Detectors read-out with 40MHz** (SCT 128A)

[A.Affolder, Liverpool, RD50 Workshop, June 2009]



- **CCE: ~7300e (~30%)**
  after ~ 1×10^{16}cm^{-2} 800V
- **n-in-p sensors are strongly considered for ATLAS upgrade** (previously p-in-n used)

FZ n-in-p microstrip detectors (n, p, π – irrad)

- **n-in-p microstrip p-type FZ detectors** (Micron, 280 or 300μm thick, 80μm pitch, 18μm implant)
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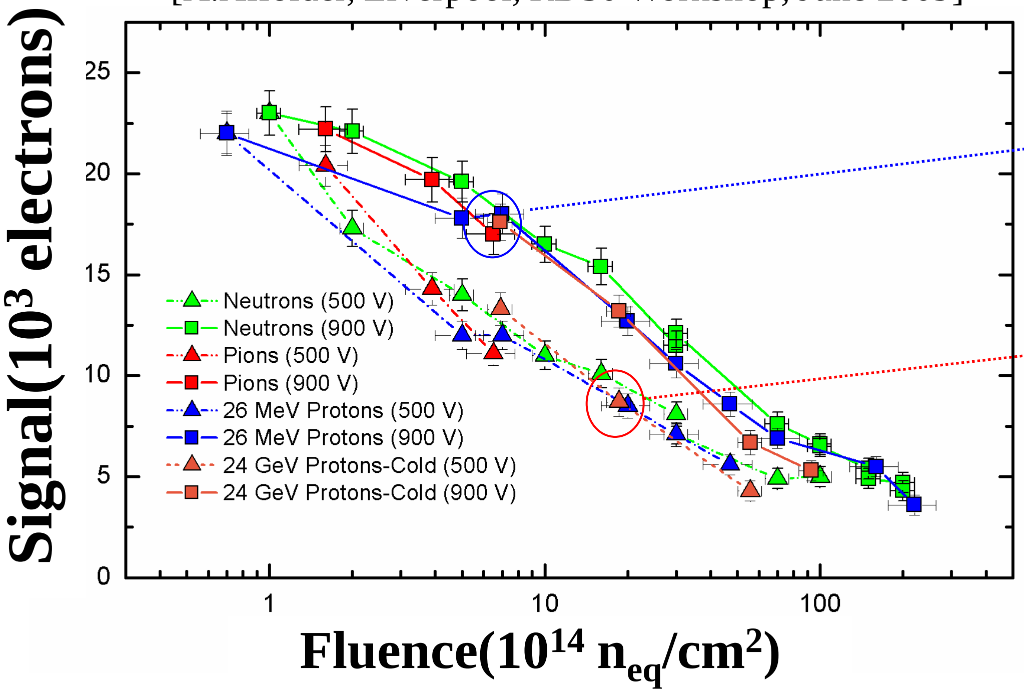
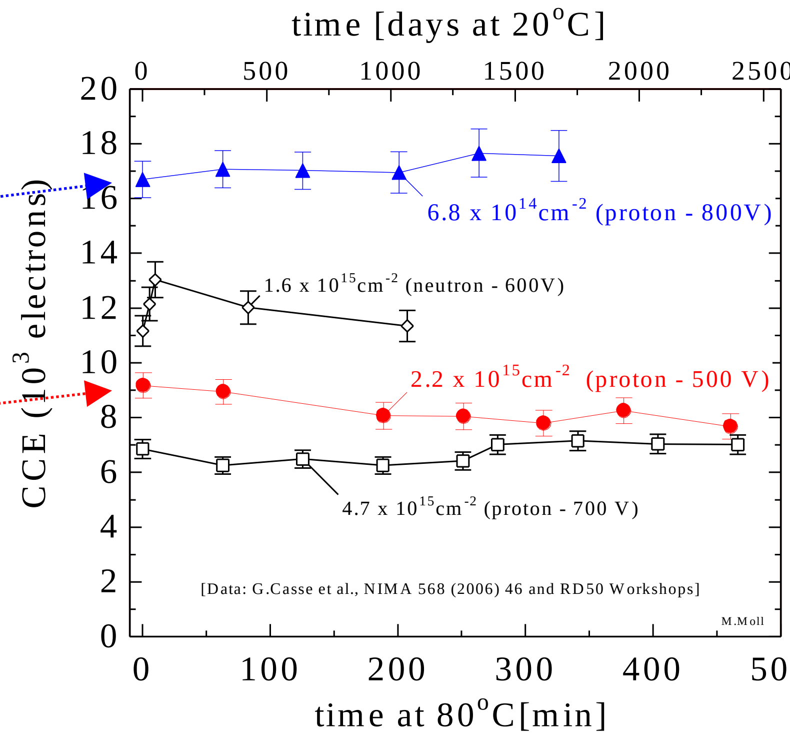


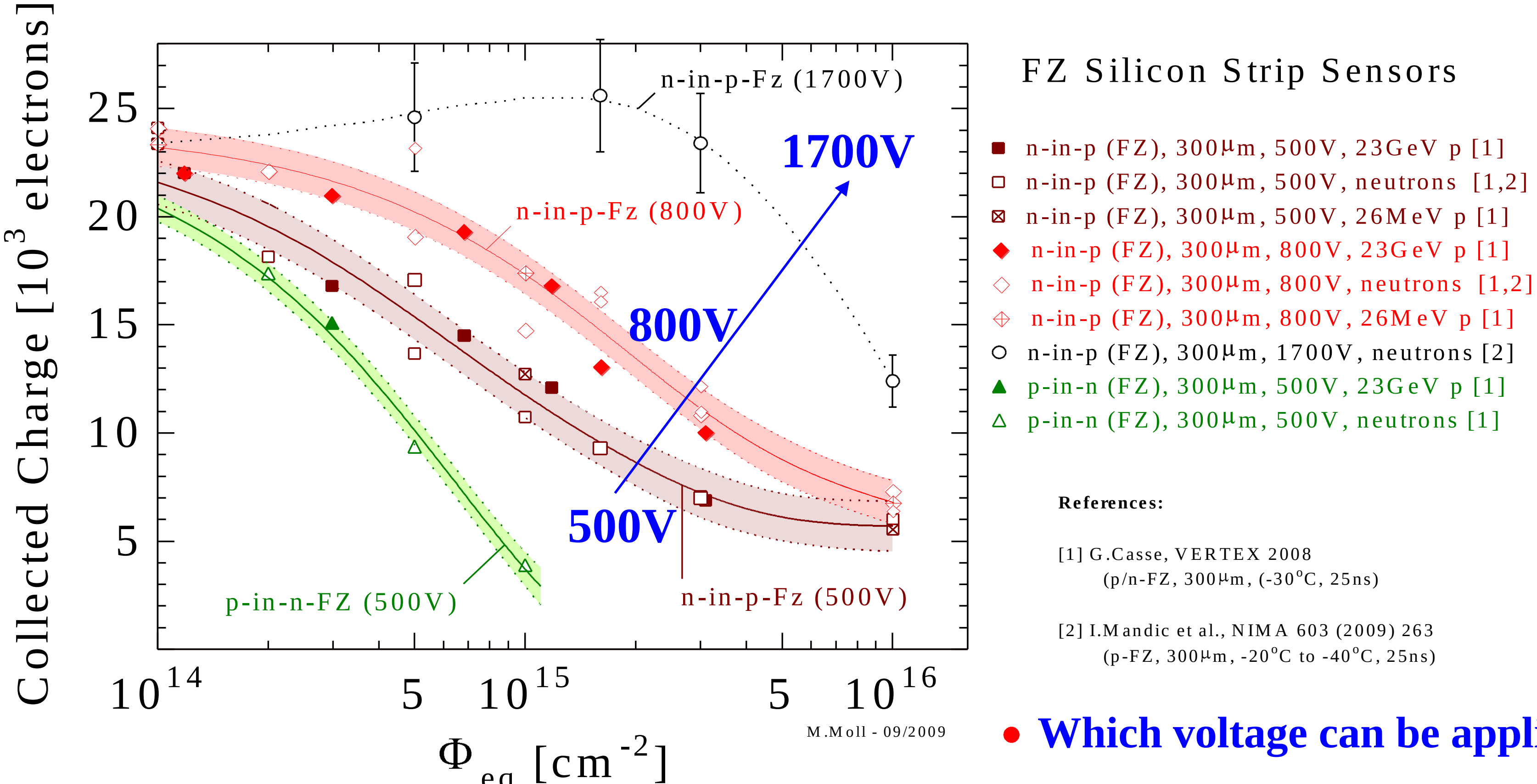


- **CCE: ~7300e (~30%)**
  after ~ $1\times10^{16}cm^{-2}$ 800V
- **n-in-p sensors are strongly considered for ATLAS upgrade** (previously p-in-n used)

- **<u>no reverse annealing</u> in CCE measurements for neutron and proton irradiated detectors**

Good performance of planar sensors at high fluence

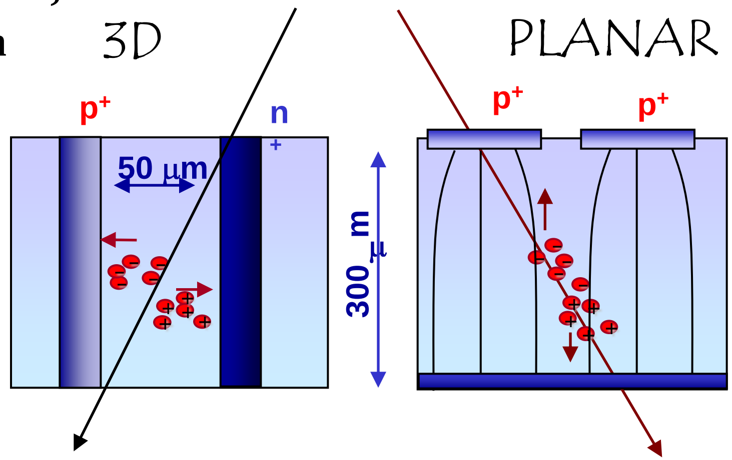
- **Why do planar silicon sensors with n-strip readout give such high signals after high levels (>10^{15} cm^{-2} p/cm^2) of irradiation?**
  - **Extrapolation of charge trapping parameters obtained at lower fluences would predict much lower signal!**
  - **Assumption: 'Charge multiplication effects' as even CCE > 1 was observed**

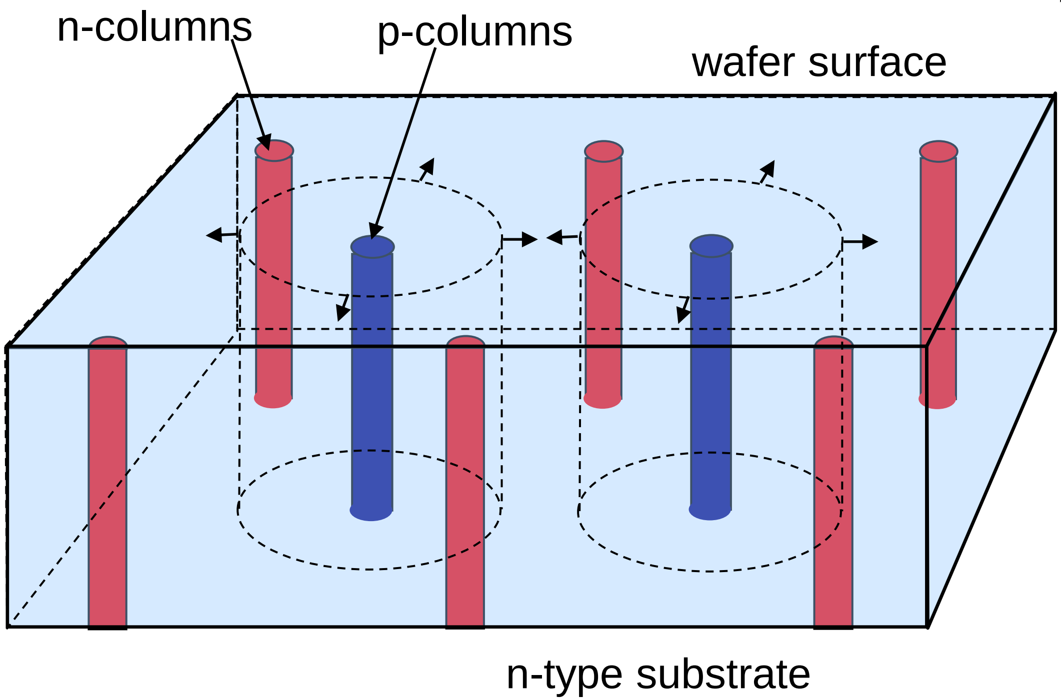


- **Which voltage can be applied?**

3D detector - concept

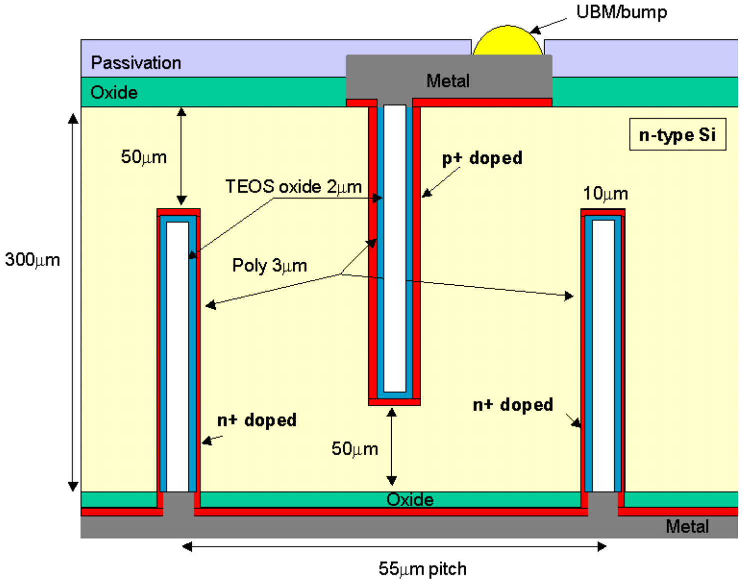
- **"3D" electrodes:** - narrow columns along detector thickness,
  - diameter: 10µm, distance: 50 - 100µm
- **Lateral depletion:** - lower depletion voltage needed
  - thicker detectors possible
  - fast signal
  - radiation hard



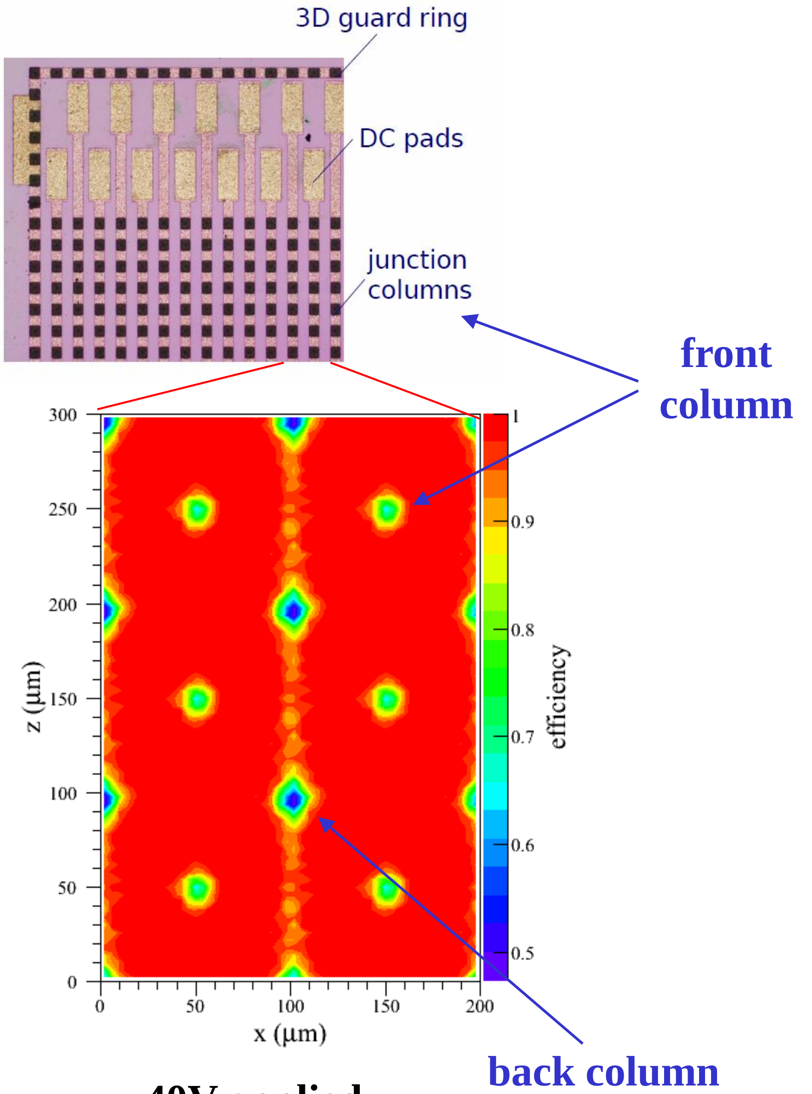


Example: Testbeam of 3D-DDTC

- **DDTC – Double sided double type column**



[G.Fleta, RD50 Workshop, June 2007]



- **Testbeam data – Example: efficiency map**
  [M.Koehler, Freiburg Uni, RD50 Workshop June 09]

- **Processing of 3D sensors is challenging, but many good devices with reasonable production yield produced.**

see lecture by *Manuel Lozano*

- **Competing e.g. for ATLAS IBL pixel sensors**

40V applied
~98% efficiency

Use of other semiconductor materials?

Property	Diamond	GaN	4H SiC	Si
E_g [eV]	**5.5**	**3.39**	**3.3**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4 \cdot 10^6$	$2.2 \cdot 10^6$	$3 \cdot 10^5$
μ_e [cm^2/Vs]	1800	1000	800	1450
μ_h [cm^2/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2 \cdot 10^7$	-	$2 \cdot 10^7$	$0.8 \cdot 10^7$
e-h energy [eV]	**13**	**8.9**	**7.6-8.4**	**3.6**
e-h pairs/X_0	4.4	~2-3	4.5	10.1

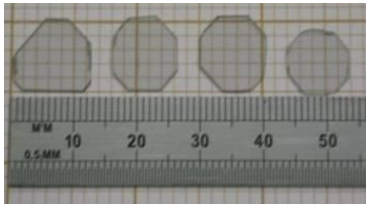
- **Diamond: wider bandgap**
  - ⇒ **lower leakage current**
  - ⇒ **less cooling needed**
  - ⇒ **less noise**
- **Signal produced by m.i.p:**
  Diamond 36 e/μm
  Si 89 e/μm
  ⇒ **Si gives more charge than diamond**

- **GaAs, SiC and GaN** ⇒ **strong radiation damage observed**
  ⇒ **no potential material for LHC upgrade detectors**
  (judging on the investigated material)

- **Diamond (RD42)** ⇒ **good radiation tolerance** ***(see later)***
  ⇒ **already used in LHC beam condition monitoring systems**
  ⇒ **considered as potential detector material for sLHC pixel sensors**

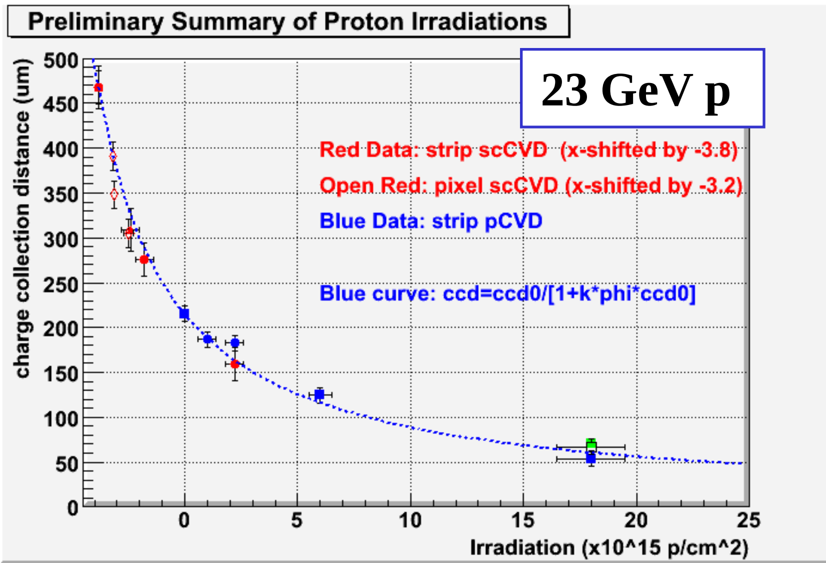
poly-CVD Diamond –16 chip ATLAS pixel module

single crystal CVD Diamond of few cm^2

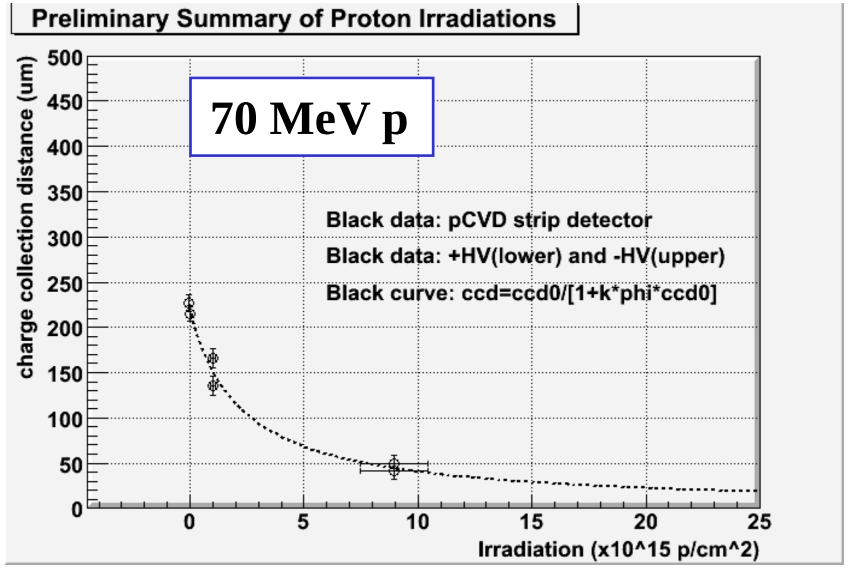


Diamond sensors are heavily used in LHC Experiments for Beam Monitoring

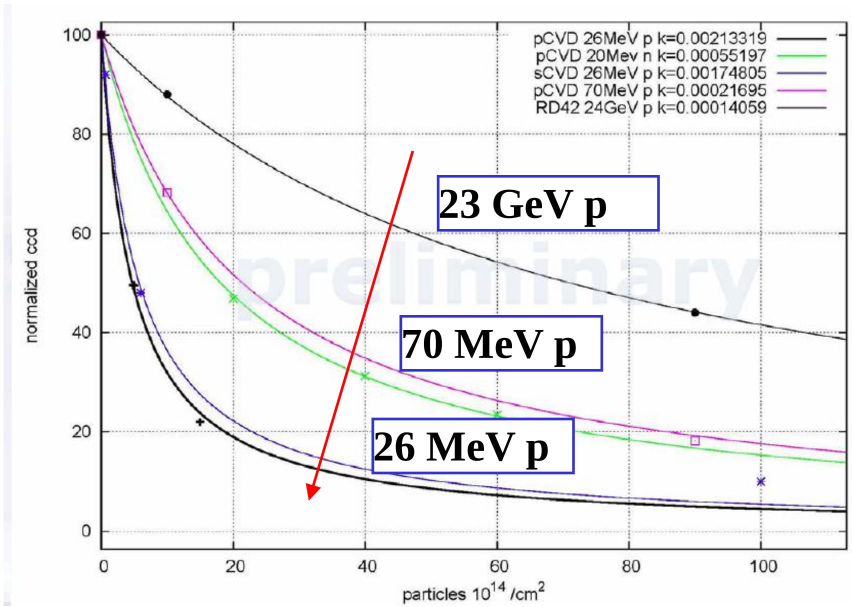
Are diamond sensors radiation hard?



[RD42, LHCC Status Report, Feb. 2010]



[RD42, LHCC Status Report, Feb. 2010]



[V.Ryjov, CERN ESE Seminar 9.11.2009]

- **Most published results on 23 GeV protons**
- **70 MeV protons 3 times more damaging than 23 GeV protons**
- **25 MeV protons seem to be even more damaging** ***(Preliminary: RD42 about to cross check the data shown to the left)***
- **In line with NIEL calc. for Diamond**
  [W. de Boer et al. Phys.Status Solidi 204:3009,2007]

Summary – Radiation Damage

- **Radiation Damage in Silicon Detectors**
  - Change of **Depletion Voltage** (internal electric field modifications, “type inversion”, reverse annealing, loss of active volume, …) (can be influenced by defect engineering!)
  - Increase of **Leakage Current** (same for all silicon materials)
  - Increase of **Charge Trapping** (same for all silicon materials)

Signal to Noise ratio is quantity to watch (material + geometry + electronics)

- **Microscopic defects & Damage scaling factors**
  - Microscopic crystal defects are the origin to detector degradation.
  - **NIEL** – Hypothesis used to scale damage of different particles with different energy
  - Different particles produce different types of defects! (NIEL – violation!)
  - There has been an enormous progress in the last 5 years in understanding defects.

Details in next lecture by *Ioana Pintilie* on defects.

- **Approaches to obtain radiation tolerant devices:**
  - **Material Engineering:** - explore and develop new silicon materials (oxygenated Si)
    - use of other semiconductors (Diamond)
  - **Device Engineering:** - look for other sensor geometries
    - 3D, thin sensors, n-in-p, n-in-n, …

Detectors for the LHC upgrade

- **At fluences up to $10^{15}cm^{-2}$ (outer layers – ministrip sensors):**
  The change of the depletion voltage and the large area to be covered by detectors are major problems.
  - **n-MCZ silicon detectors** show good performance in mixed fields due to compensation of charged hadron damage and neutron damage (N_{eff} compensation) (more work needed)
  - **p-type silicon microstrip detectors show very encouraging results**
    CCE ≈ 6500 e; $\Phi_{eq} = 4\times10^{15}$ cm^{-2}, 300µm, immunity against reverse annealing!
    This is presently the "most considered option" for the ATLAS SCT upgrade

- **At fluences > $10^{15}cm^{-2}$ (Innermost tracking layers – pixel sensors)**
  The active thickness of any silicon material is significantly reduced due to trapping.
  Collection of electrons at electrodes essential: Use n-in-p or n-in-n detectors!
  - **Recent results show that planar silicon sensors might still give sufficient signal,**
    (still some interest in epitaxial silicon and thin sensor options)
  - **3D detectors : looks promising, drawback: technology has to be optimized!**
    Many collaborations and sensor producers working on this.
  - **Diamond has become an interesting option *(Higher damage due to low energy protons?)***

Details in lecture by *Phil Allport*

- **Questions to be answered:**
  - **a) Can we profit from avalanche effects and control them?**
  - **b) Can we profit from compensation effects in mixed fields?**
  - **c) Can we understand detector performance on the basis of simulations using defect parameters as input?**

? ? ?

Acknowledgements & References

- **Many thanks to the MC-PAD Network for the invitation to give this lecture**

- **Most references to particular works given on the slides**

- **Some additional material taken from the following presentations:**
  - ***RD50 presentations: http://www.cern.ch/rd50/***
  - ***Anthony Affolder: Presentations on the RD50 Workshop in June 2009 (sATLAS fluence levels)***
  - ***Frank Hartmann: Presentation at the VCI conference in February 2010 (Diamond results)***

- **Books containing chapters about radiation damage in silicon sensors**
  - ***Helmuth Spieler, "Semiconductor Detector Systems", Oxford University Press 2005***
  - ***Frank Hartmann, "Evolution of silicon sensor technology in particle physics", Springer 2009***
  - ***L.Rossi, P.Fischer, T.Rohe, N.Wermes "Pixel Detectors", Springer, 2006***
  - ***Gerhard Lutz, "Semiconductor radiation detectors", Springer 1999***

- **Research collaborations and web sites**
  - ***The RD50 collaboration (http://www.cern.ch/rd50) - Radiation Tolerant Silicon Sensors***
  - ***The RD39 collaboration – Cryogenic operation of Silicon Sensors***
  - ***The RD42 collaboration – Diamond detectors***
  - ***ATLAS IBL, ATLAS and CMS upgrade groups***