Scuola Nazionale "Rivelatori ed Elettronica per Fisica delle Alte Energie, Astrofisica, Applicazioni Spaziali e Fisica Medica“

INFN Laboratori Nazionali di Legnaro, 20-24 Aprile 2009

Recent Developments to improve the radiation tolerance of semiconductor sensors

Michael Moll

CERN - Geneva - Switzerland

… with a main focus on RD50 activities

Outline

- **Motivation to develop radiation harder detectors**
  - **Radiation levels at the Super LHC**
  - **Radiation induced degradation of detector performance**
- **Radiation Damage in Silicon Detectors**
  - **Macroscopic damage (changes in detector properties)**
- **Approaches to obtain radiation hard sensors**
  - **Material Engineering**
    - Silicon materials – FZ, MCZ, DOFZ, EPI
    - Other semiconductors
  - **Device Engineering**
    - p-in-n, n-in-n and n-in-p sensors
    - 3D sensors and thin devices
- **Some recent results and a comparison**
  - **Collected Charge – Signal to Noise**
  - **Mixed irradiations**
- **Summary**

Some overlap with other lectures

Basics on Silicon Sensors and Detector Systems D.Creanza

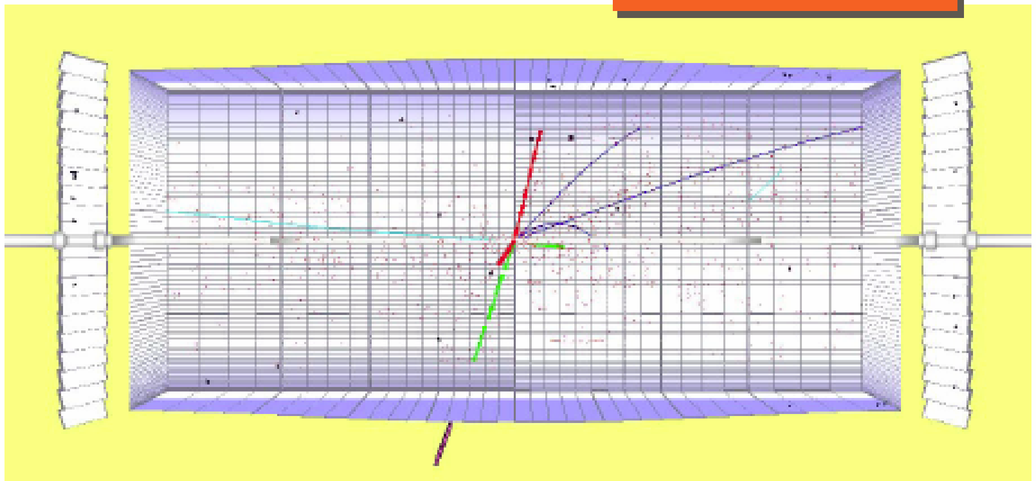
Defects and radiation damage in silicon M.Bruzzi

Diamond Detectors Cristina Tuvè

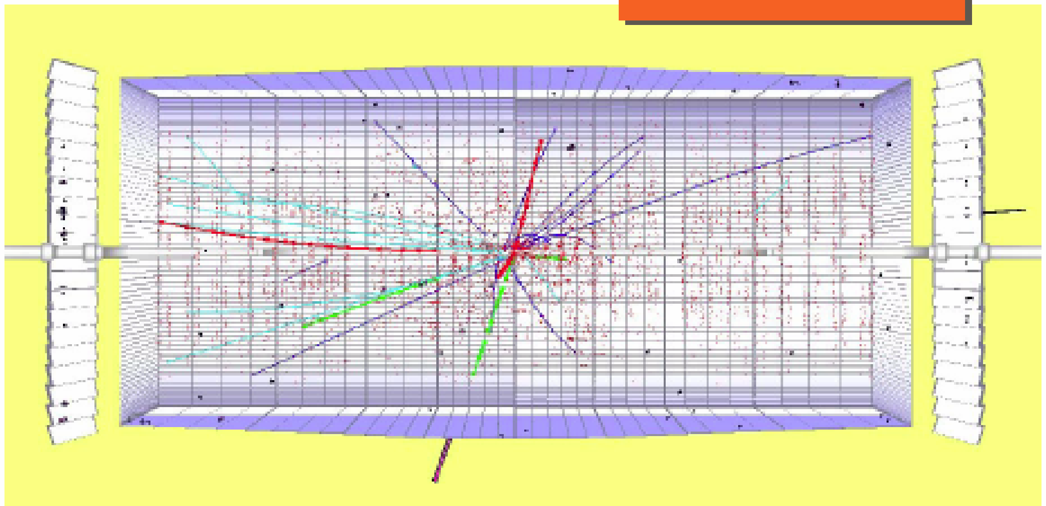
3D Detectors Maurizio Boscardin Claudio Piemonte

The challenge: Super LHC - visually

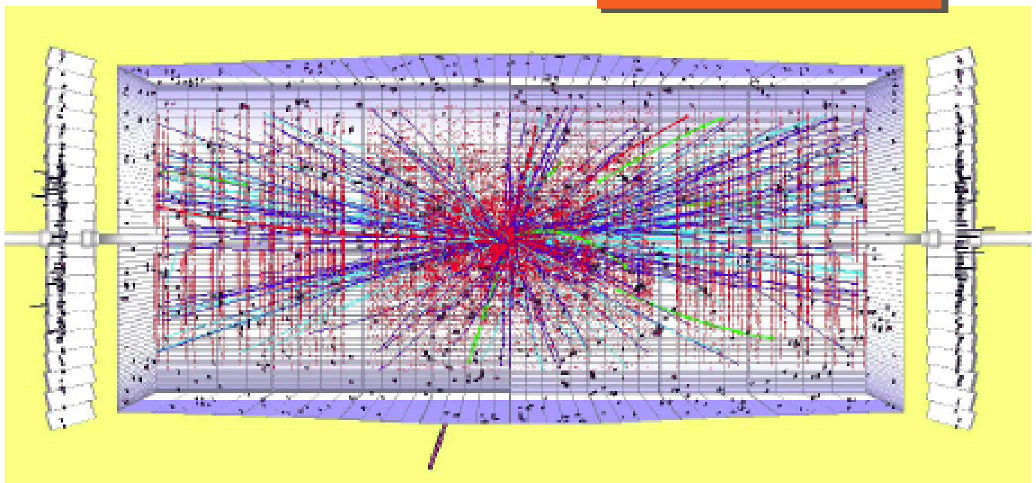
$10^{32}\ cm^{-2}\ s^{-1}$



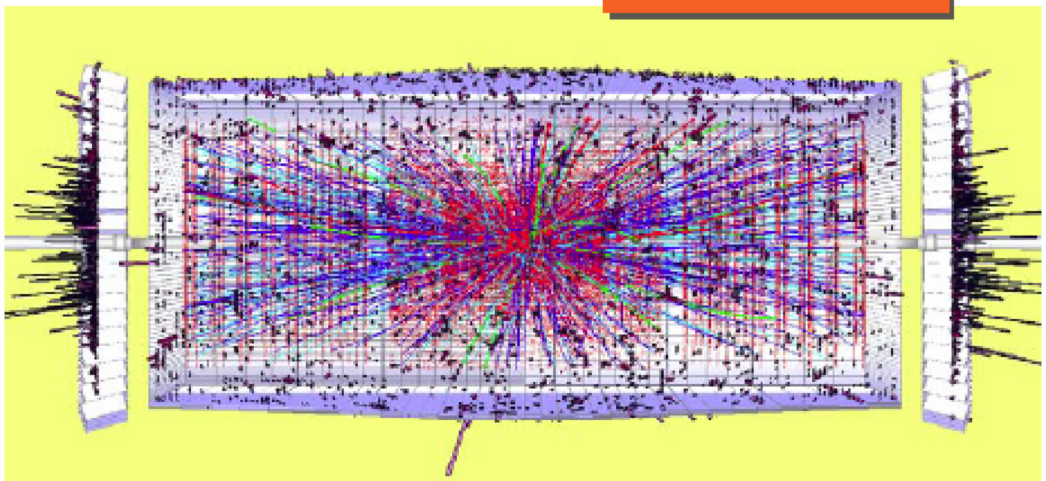
$10^{33}\ cm^{-2}\ s^{-1}$



$10^{34}\ cm^{-2}\ s^{-1}$



$10^{35}\ cm^{-2}\ s^{-1}$



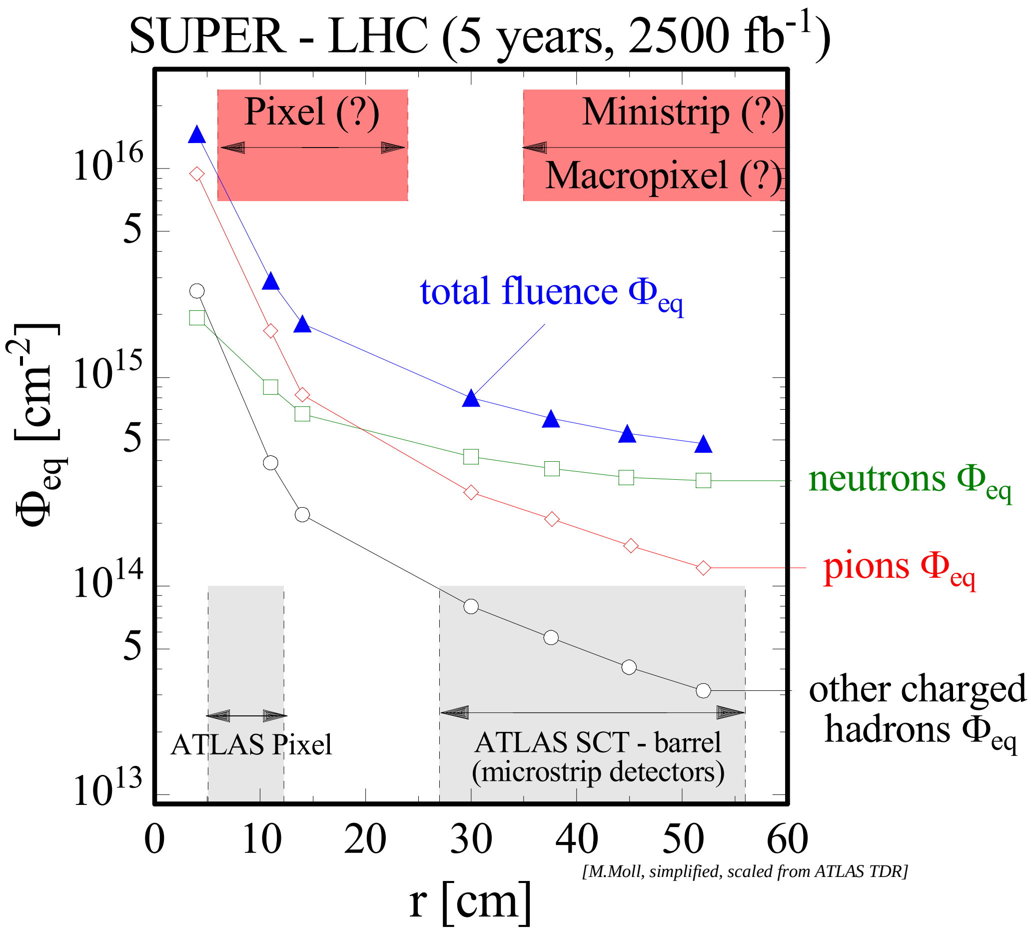
LHC luminosity

SLHC luminosity ~300-400 interactions/bx

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

- **LHC upgrade**
  - ⇨ **LHC (2009)** **L = $10^{34}cm^{-2}s^{-1}$**
    - **10 years**, **500 fb^{-1}** → ϕ(r=4cm) ~ $3\cdot10^{15}cm^{-2}$
  - ⇨ **Super-LHC (2018 ?)** **L = $10^{35}cm^{-2}s^{-1}$**
    - **5 years**, **2500 fb^{-1}** → ϕ(r=4cm) ~ $1.6\cdot10^{16}cm^{-2}$

× 5



- **LHC (Replacement of components)**
  e.g. - LHCb Velo detectors
  - ATLAS Pixel B-layer

SLHC compared to LHC:

- **Higher radiation levels ⇨ Higher radiation tolerance needed!**
- **Higher multiplicity ⇨ Higher granularity needed!**

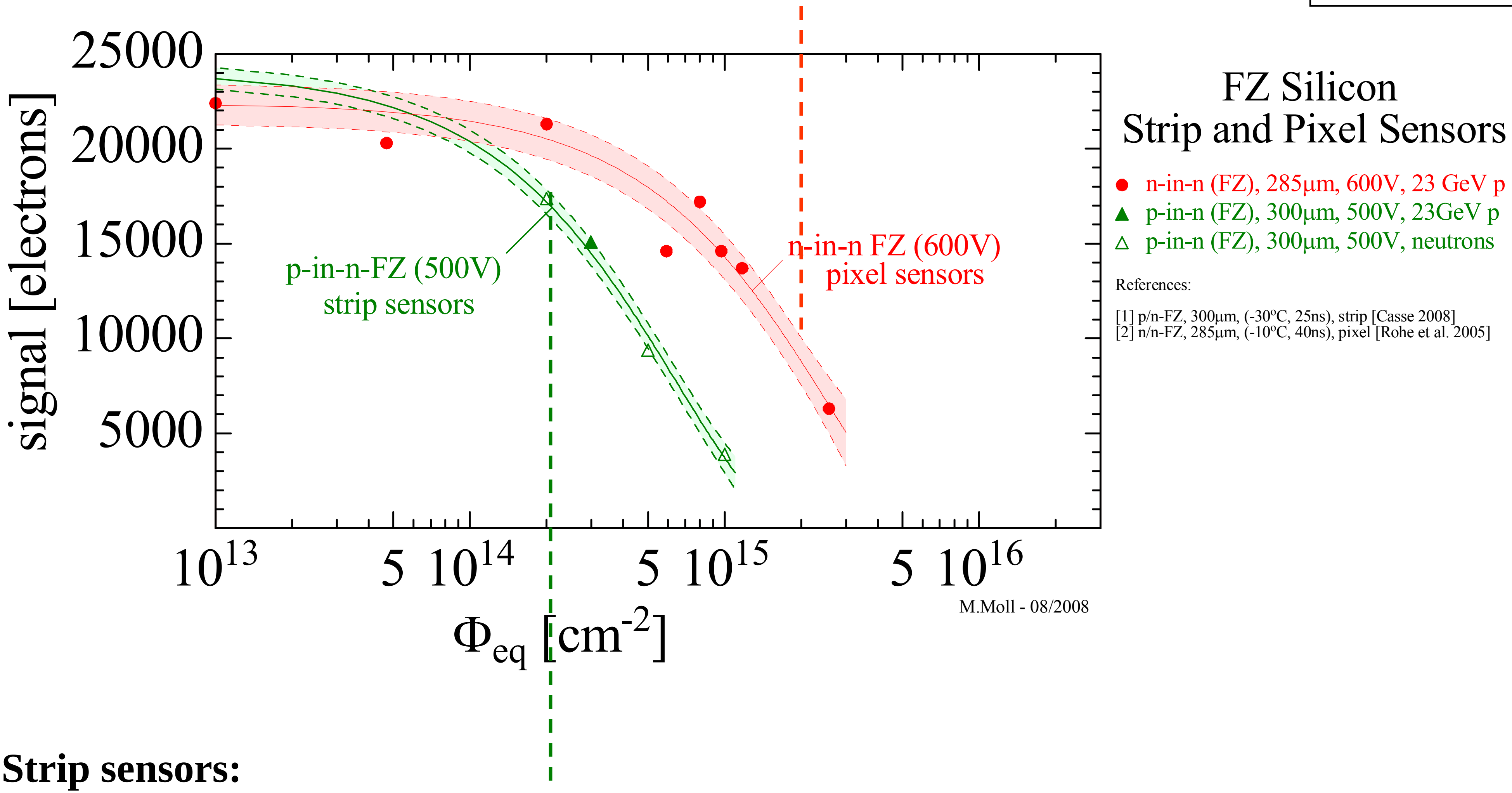
⇨ Need for new detectors & detector technologies

⇔ **Power Consumption ?**
Cooling ?
Connectivity
Low mass ?
Costs ?

Signal degradation for LHC Silicon Sensors

Pixel sensors:
max. cumulated fluence for LHC

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

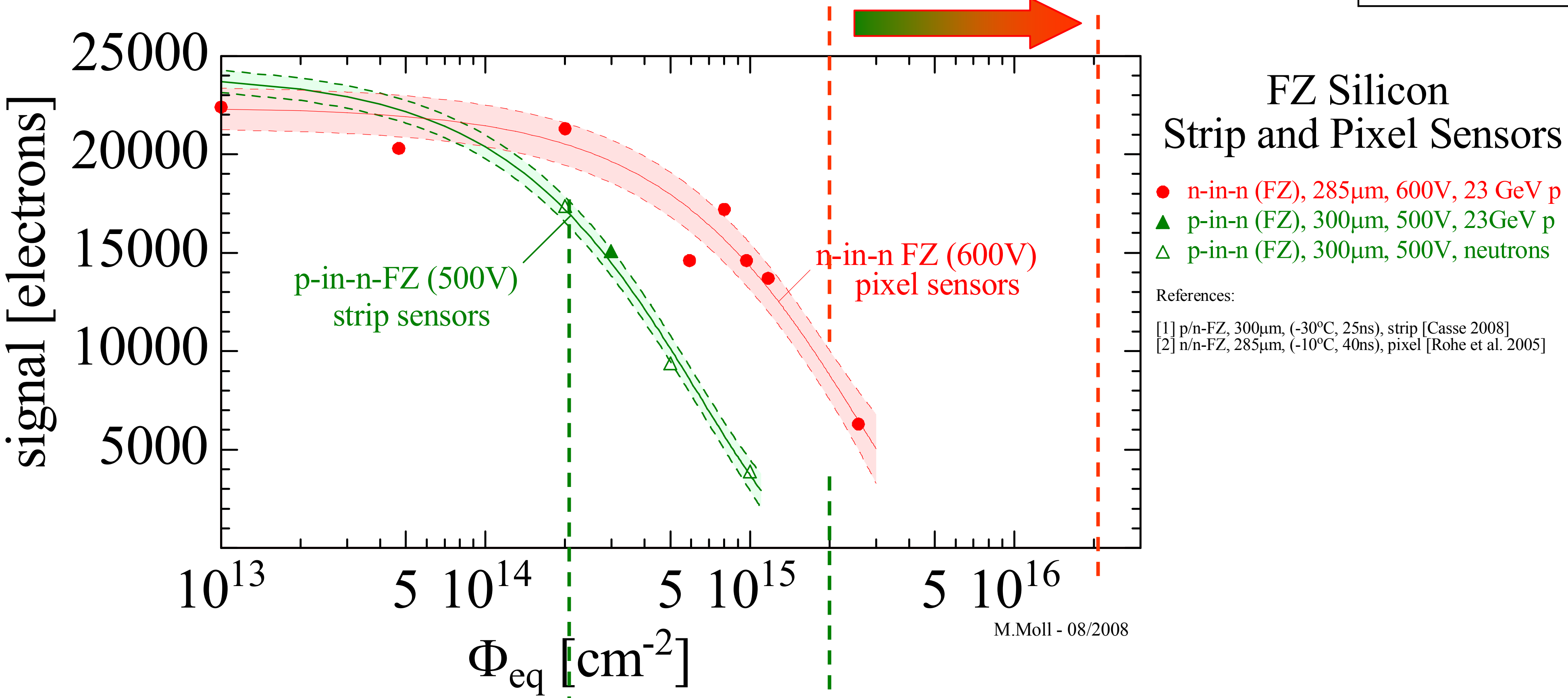


Strip sensors:
max. cumulated fluence for LHC

Signal degradation for LHC Silicon Sensors

Pixel sensors:
max. cumulated fluence for LHC and SLHC

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



Strip sensors:
max. cumulated fluence for LHC and SLHC

SLHC will need more radiation tolerant tracking detector concepts!

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  - **Macroscopic damage (changes in detector properties)**

Defects and radiation damage in silicon see M.Bruzzi

- **Approaches to obtain radiation hard sensors**
  - **Material Engineering**
    - Silicon materials – FZ, MCZ, DOFZ, EPI
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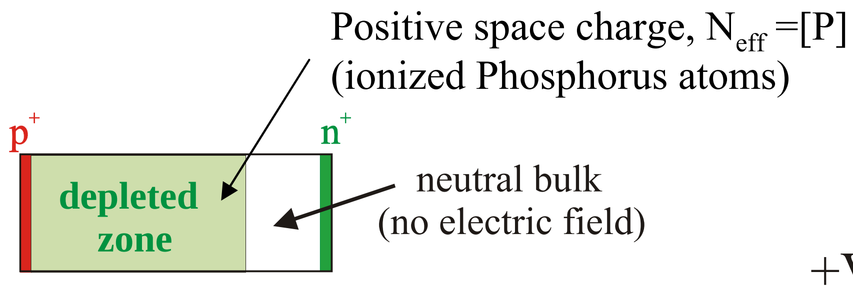
Reverse biased abrupt p^+-n junction

Poisson's equation

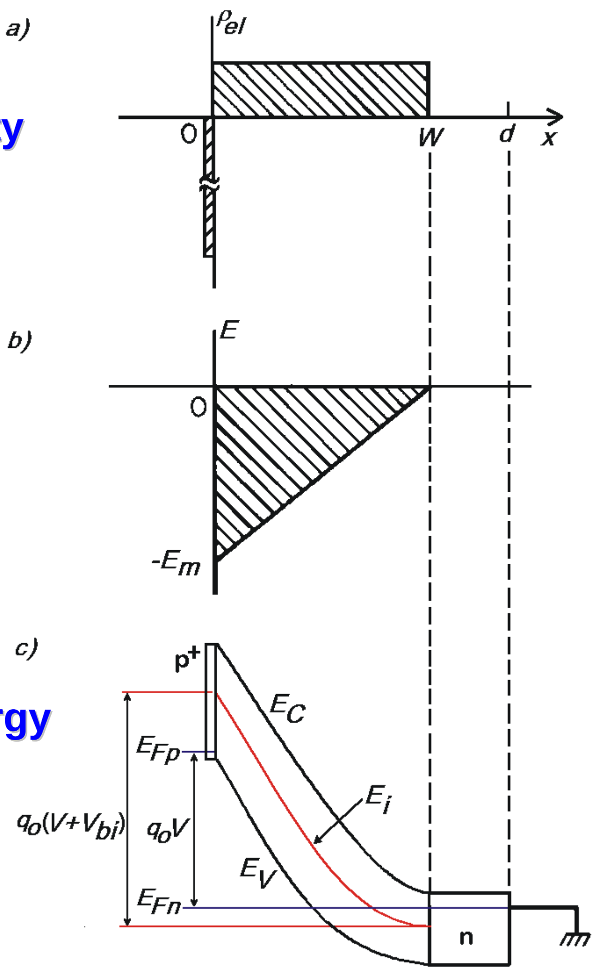
$$-\frac{d^2}{dx^2}\phi(x) = \frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}$$

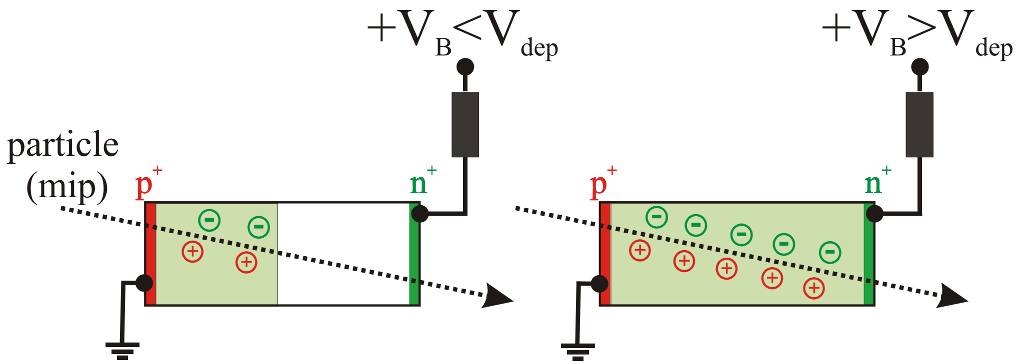


Electrical charge density

Electrical field strength

Electron potential energy





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

depletion voltage

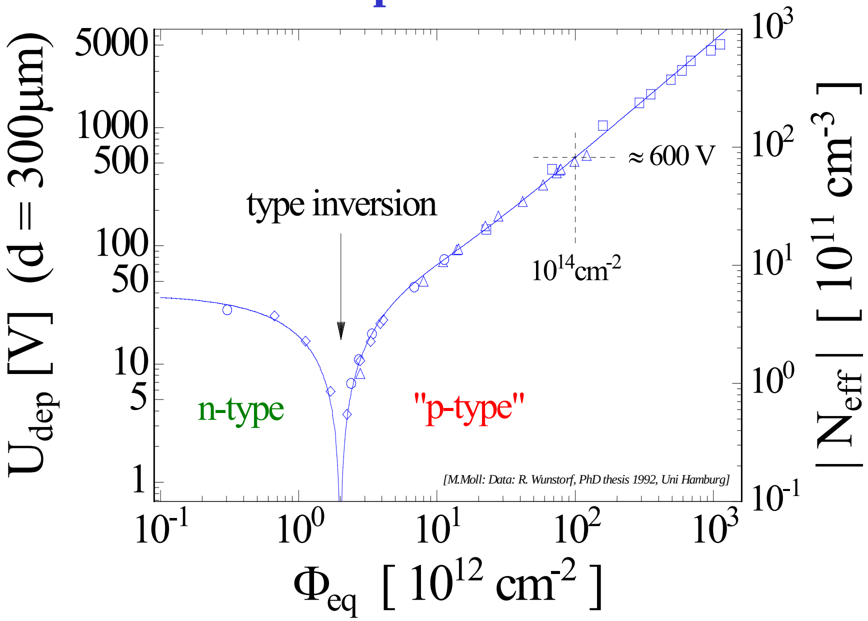
$$V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0}\cdot\left|N_{eff}\right|\cdot d^2$$

effective space charge density

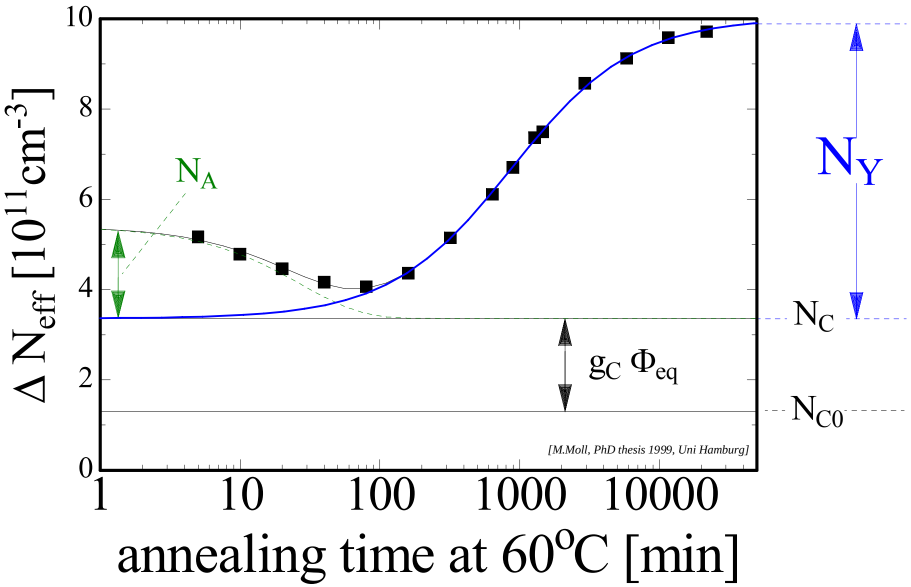
Macroscopic Effects – I. Depletion Voltage

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

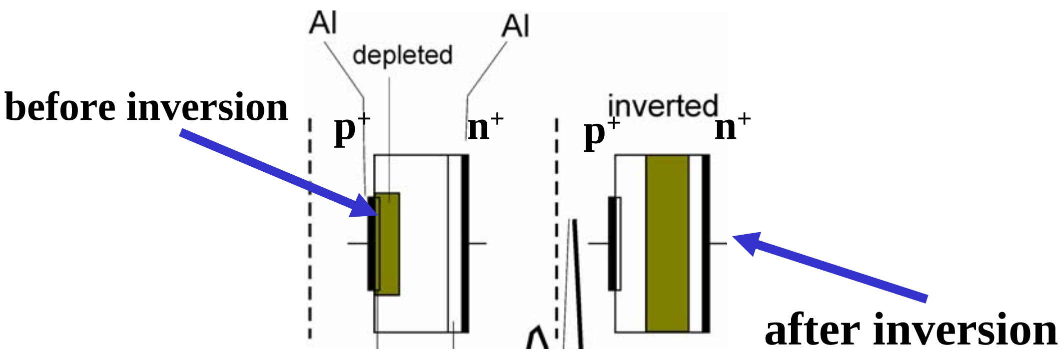
…. with particle fluence:



…. with time (annealing):



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

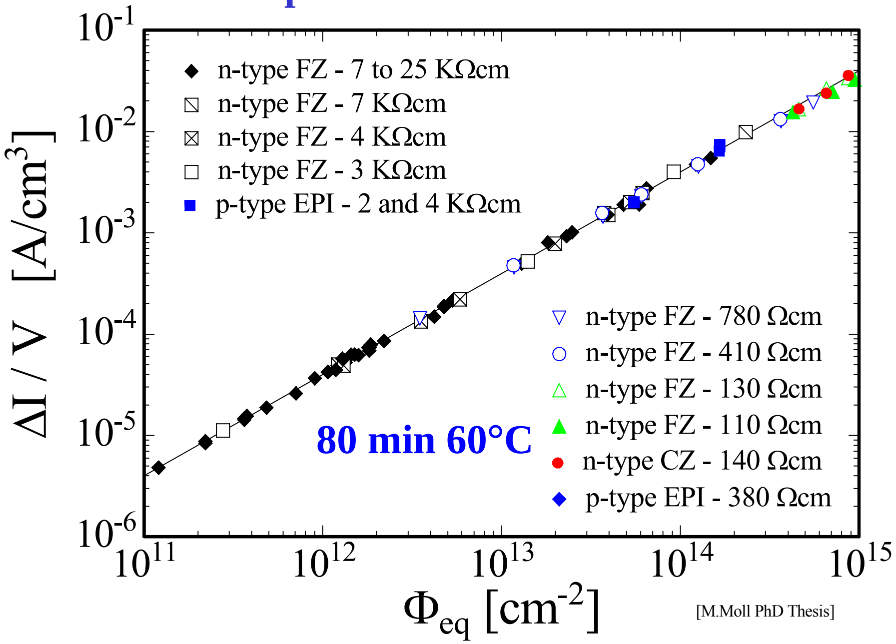


- Short term: "**Beneficial annealing**"
- Long term: "**Reverse annealing**"
  - **time constant depends on temperature:**
    - **~ 500 years (-10°C)**
    - **~ 500 days (20°C)**
    - **~ 21 hours (60°C)**
  - Consequence: **Detectors must be cooled even when the experiment is not running!**

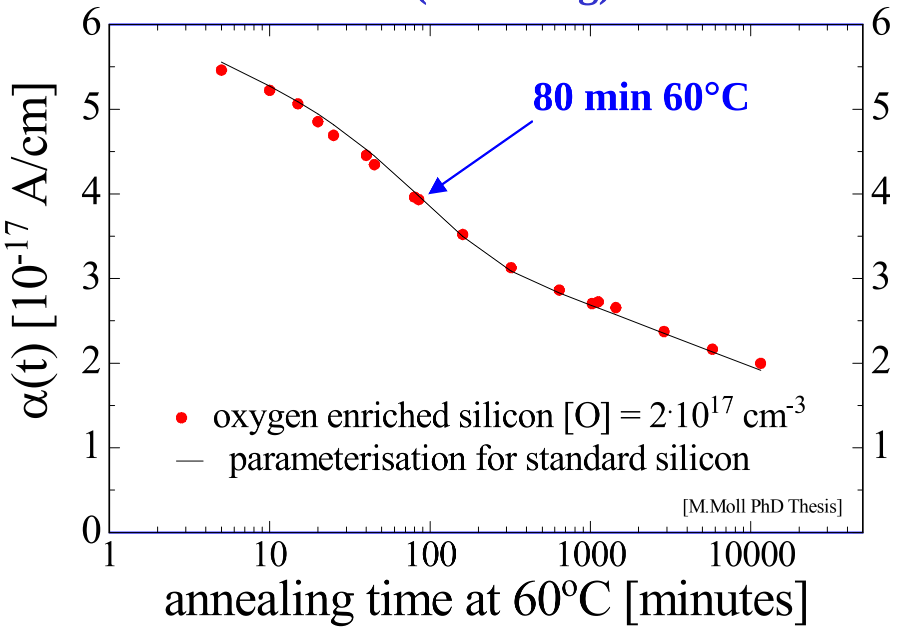
Radiation Damage – II. Leakage Current

- 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**

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

Consequence:

Cool detectors during operation!
Example: I(-10°C) ~1/16 I(20°C)

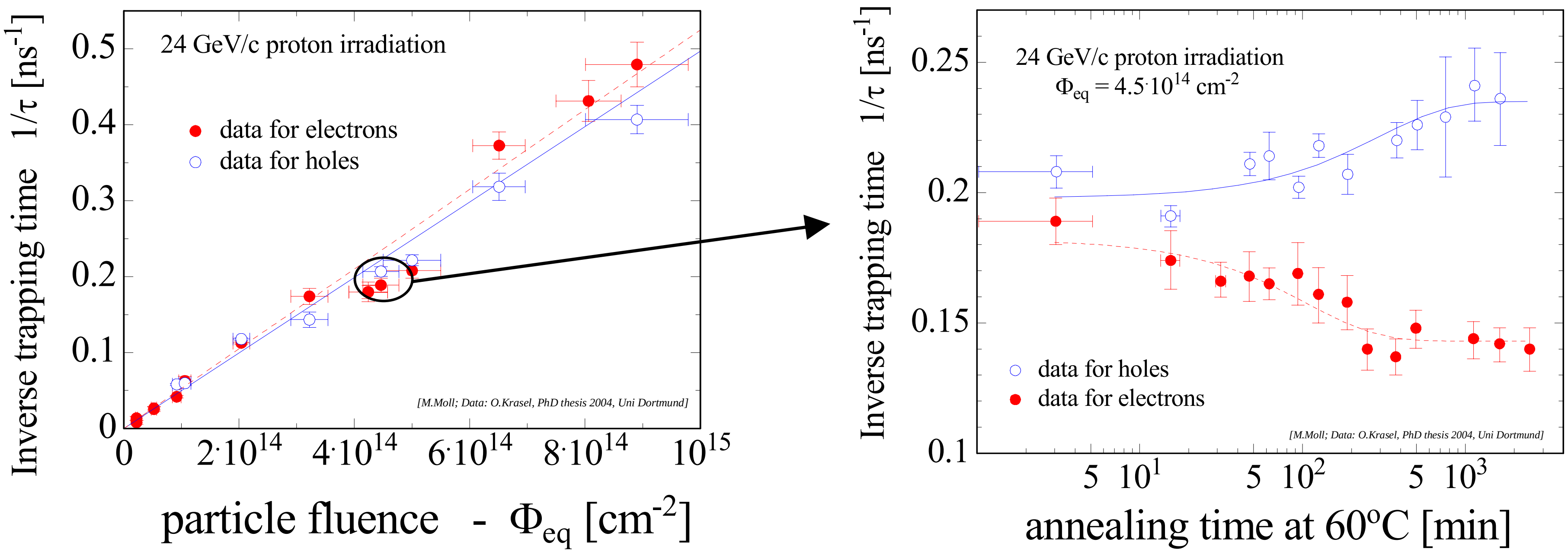
Radiation Damage – III. CCE (Trapping)

- **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):



Summary: Radiation Damage in Silicon Sensors

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

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

Influenced by impurities in Si – Defect Engineering is possible!

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!)

Can be optimized!

Signal/noise ratio is the quantity to watch

⇒ Sensors can fail from radiation damage !

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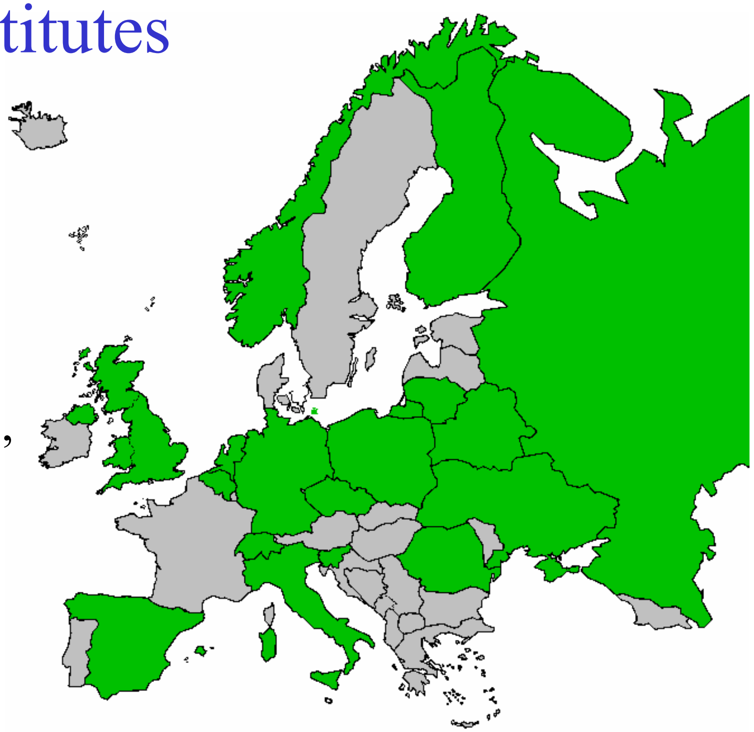
Diamond Detectors
Cristina Tuvè

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

250 Members from 49 Institutes



40 European and Asian institutes

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

8 North-American institutes

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

1 Middle East institute

Israel (Tel Aviv)

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

RD50: Nov.2001 collaboration formed ; June 2002 approved by CERN

Approaches to develop radiation harder tracking detectors

Scientific strategies:

I. Material engineering

II. Device engineering

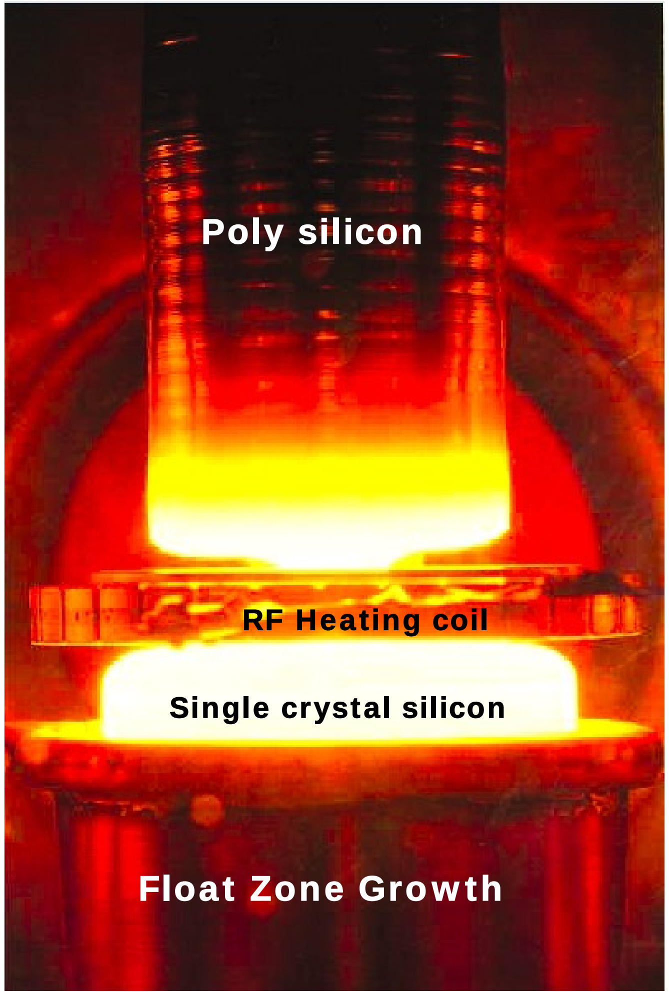
III. Variation of detector operational conditions

CERN-RD39
"Cryogenic Tracking Detectors"

- **Defect Engineering of Silicon**
  - Understanding radiation damage
    - Macroscopic effects and Microscopic defects
    - Simulation of defect properties and defect kinetics
    - Irradiation with different particles at different energies
  - Oxygen rich silicon
    - DOFZ, Cz, MCZ, EPI
  - Oxygen dimer enriched silicon
  - Hydrogen enriched silicon
  - Pre-irradiated silicon
  - Influence of processing technology
- **New Materials**
  - Silicon Carbide (SiC), Gallium Nitride (GaN)
  - Diamond: CERN RD42 Collaboration
- **Device Engineering (New Detector Designs)**
  - p-type silicon detectors (n-in-p)
  - Thin detectors
  - 3D and Semi 3D detectors
  - Cost effective detectors
  - Simulation of highly irradiated detectors
  - Monolithic silicon sensors (??)

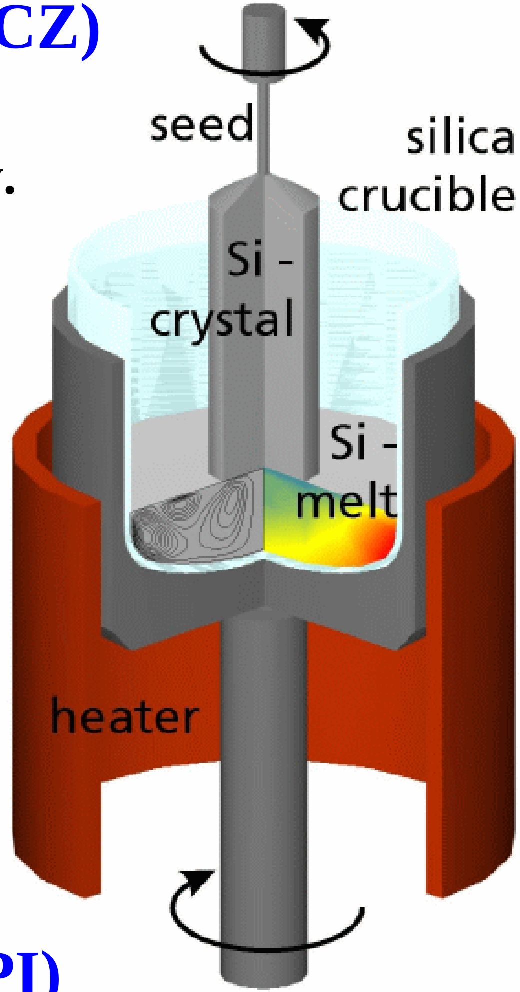
Silicon Growth Processes

- **Floating Zone Silicon (FZ)**



- **Basically all silicon detectors made out of high resistivity FZ silicon**

- **Czochralski Silicon (CZ)**
  - **The growth method used by the IC industry.**
  - **Difficult to produce very high resistivity**



- **Epitaxial Silicon (EPI)**
  - **Chemical-Vapor Deposition (CVD) of Si**
  - **up to 150 μm thick layers produced**
  - **growth rate about 1μm/min**

Silicon Materials under Investigation by RD50

standard for particle detectors

used for LHC Pixel detectors

"new" silicon material

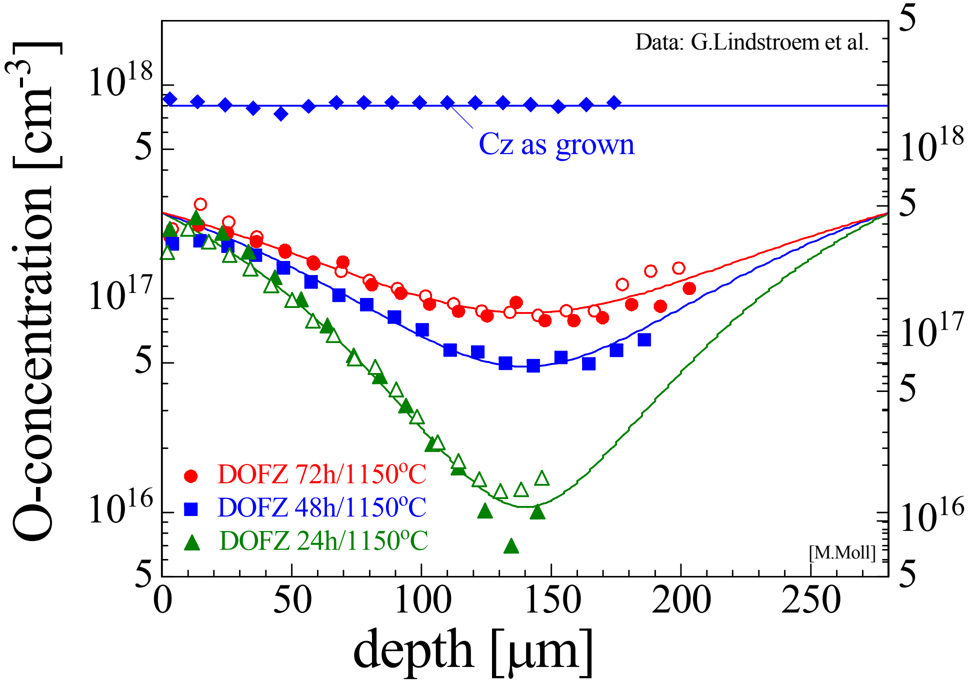
Material	Thickness [μm]	Symbol	ρ (Ωcm)	$[O_i]$ (cm^{-3})
Standard FZ (n- and p-type)	50,100,150, 300	FZ	$1–30\times10^3$	$< 5\times10^{16}$
Diffusion oxygenated FZ (n- and p-type)	300	DOFZ	$1–7\times10^3$	$\sim 1–2\times10^{17}$
Magnetic Czochralski Si, Okmetic, Finland (n- and p-type)	100, 300	MCz	$\sim 1\times10^3$	$\sim 5\times10^{17}$
Czochralski Si, Sumitomo, Japan (n-type)	300	Cz	$\sim 1\times10^3$	$\sim 8-9\times10^{17}$
Epitaxial layers on Cz-substrates, ITME, Poland (n- and p-type)	25, 50, 75, 100, 150	EPI	50 – 100	$< 1\times10^{17}$
Diffusion oxyg. Epitaxial layers on CZ	75	EPI–DO	50 – 100	$\sim 7\times10^{17}$

- **DOFZ silicon** - Enriched with oxygen on wafer level, inhomogeneous distribution of oxygen
- **CZ/MCZ silicon** - high Oi (oxygen) and O_{2i} (oxygen dimer) concentration (homogeneous)
  - formation of shallow Thermal Donors possible
- **Epi silicon** - high O_i, O_{2i} content due to out-diffusion from the CZ substrate (inhomogeneous)
  - thin layers: high doping possible (low starting resistivity)
- **Epi-Do silicon** - as EPI, however additional O_i diffused reaching homogeneous O_i content

Oxygen concentration in FZ, CZ and EPI

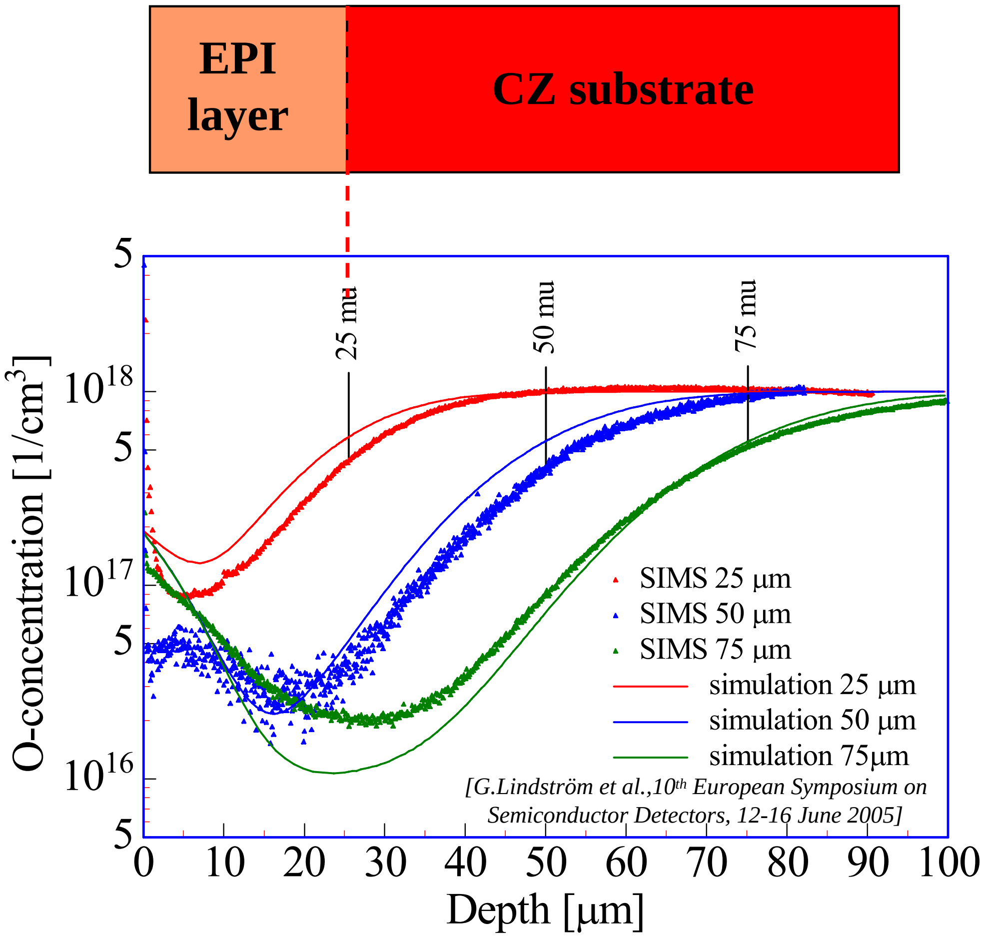
DOFZ and CZ silicon

- **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

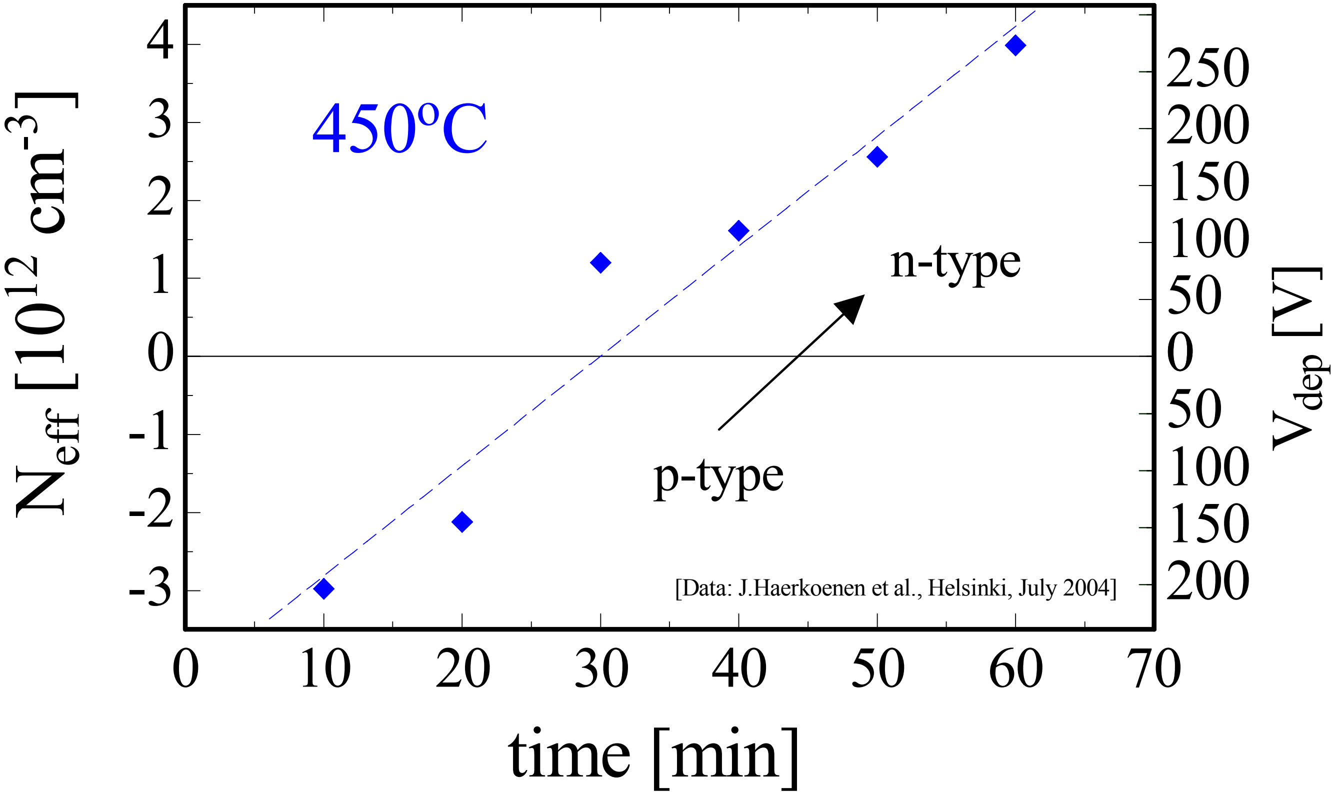


- **EPI: O_i and O_{2i} (?) diffusion from substrate into epi-layer during production**
- **EPI: in-homogeneous oxygen distribution**

p-type (Magnetic CZ)

- **Thermal Donor generation due to <u>heat treatment at 450°C</u>**
- **Effective doping concentration (depletion voltage) can be tailored**

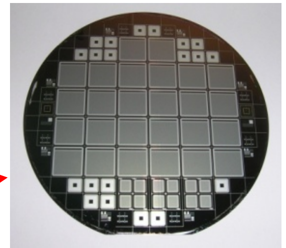
  (here: starting with p-type material and converting it to n-type)

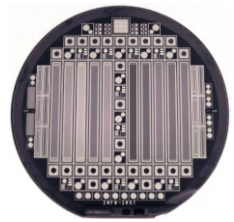


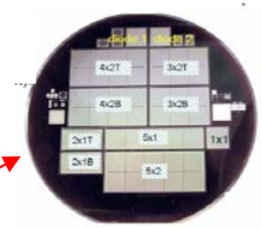
- **Radiation hardness of thermal donor doped MCZ under test**

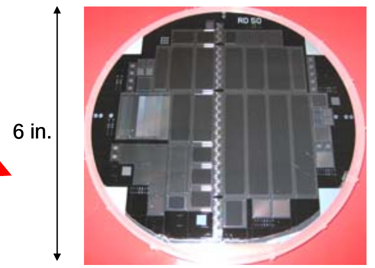
RD50 Test Sensor Production Runs (2005-2008)

- **Recent production of Silicon Strip, Pixel and Pad detectors (non exclusive list):**
  - **CIS Erfurt, Germany**
    - **2005/2006/2007 (RD50): Several runs with various epi 4” wafers only pad detectors**
  - **CNM Barcelona, Spain**
    - **2006 (RD50): 22 wafers (4”), (20 pad, 26 strip, 12 pixel),(p- and n-type),(MCZ, EPI, FZ)**
    - **2006 (RD50/RADMON): several wafers (4”), (100 pad), (p- and n-type),(MCZ, EPI, FZ)**
  - **HIP, Helsinki, Finland**
    - **2006 (RD50/RADMON): several wafers (4”), only pad devices, (n-type),(MCZ, EPI, FZ)**
    - **2006 (RD50) : pad devices, p-type MCz-Si wafers, 5 p-spray doses, Thermal Donor compensation**
    - **2006 (RD50) : full size strip detectors with 768 channels, n-type MCz-Si wafers**
  - **IRST, Trento, Italy**
    - **2004 (RD50/SMART): 20 wafers 4” (n-type), (MCZ, FZ, EPI), mini-strip, pad 200-500µm**
    - **2004 (RD50/SMART): 23 wafers 4” (p-type), (MCZ, FZ), two p-spray doses 3E12 amd 5E12 cm^{-2}**
    - **2005 (RD50/SMART): 4” p-type EPI**
    - **2008 (RD50/SMART): new 4” run**
  - **Micron Semiconductor L.t.d (UK)**
    - **2006 (RD50): 4”, microstrip detectors on 140 and 300µm thick p-type FZ and DOFZ Si.**
    - **2006/2007 (RD50): 93 wafers, 6 inch wafers, (p- and n-type), (MCZ and FZ), (strip, pixel, pad)**
  - **Sintef, Oslo, Norway**
    - **2005 (RD50/US CMS Pixel) n-type MCZ and FZ Si Wafers**
  - **Hamamatsu, Japan [ATLAS ID project – not RD50]**
    - **In 2005 Hamamatsu started to work on p-type silicon in collaboration with ATLAS upgrade groups (surely influenced by RD50 results on this material)**









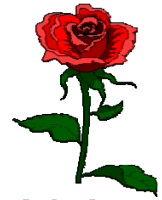
Hundreds of samples (pad/strip/pixel) recently produced on various materials (n- and p-type).

- M.Lozano, 8th RD50 Workshop, Prague, June 2006
- A.Pozza, 2nd Trento Meeting, February 2006
- G.Casse, 2nd Trento Meeting, February 2006
- D. Bortoletto, 6th RD50 Workshop, Helsinki, June 2005
- N.Zorzi, Trento Workshop, February 2005
- H. Sadrozinski, rd50 Workshop, Nov. 2007

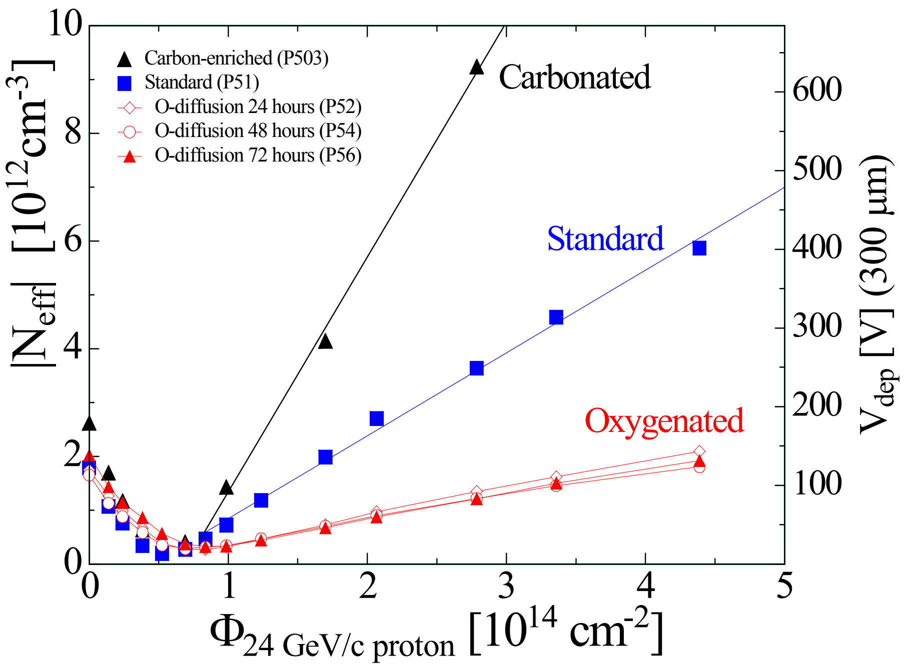
Oxygen enriched silicon – DOFZ
- proton irradiation -

- **DOFZ (Diffusion Oxygenated Float Zone Silicon)**
  - 1982 First oxygen diffusion tests on FZ [Brotherton et al. J.Appl.Phys.,Vol.53, No.8.,5720]
  - 1995 First tests on detector grade silicon [Z.Li et al. IEEE TNS Vol.42,No.4,219]
  - **1999 Introduced to the HEP community by RD48 (ROSE)**

ROSE
RD48
http://cern.ch/rd48

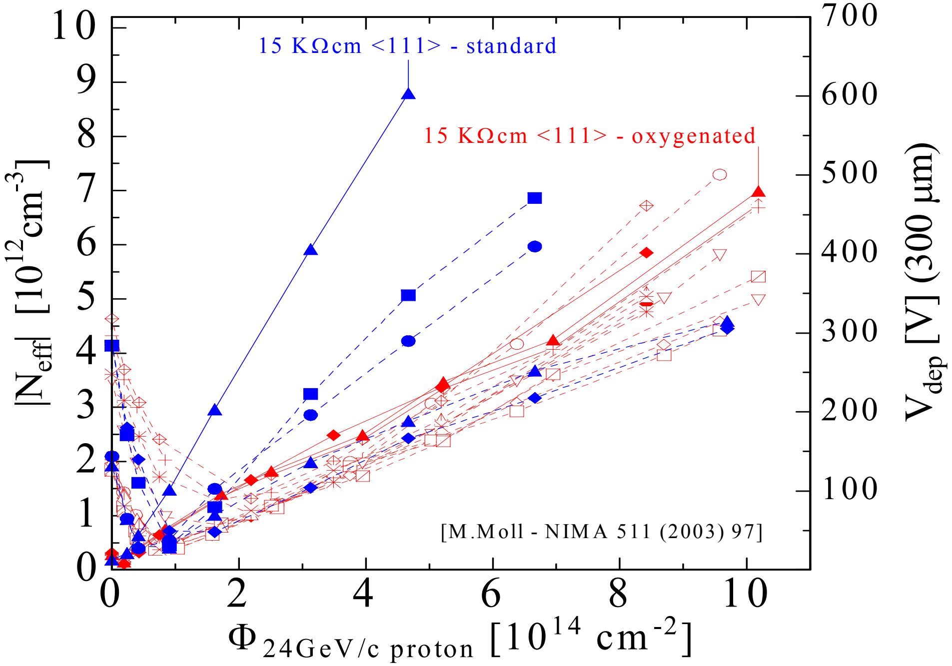


First tests in 1999 show clear advantage of oxygenation



[RD48-NIMA 465(2001) 60]

Later systematic tests reveal strong variations with no clear dependence on oxygen content

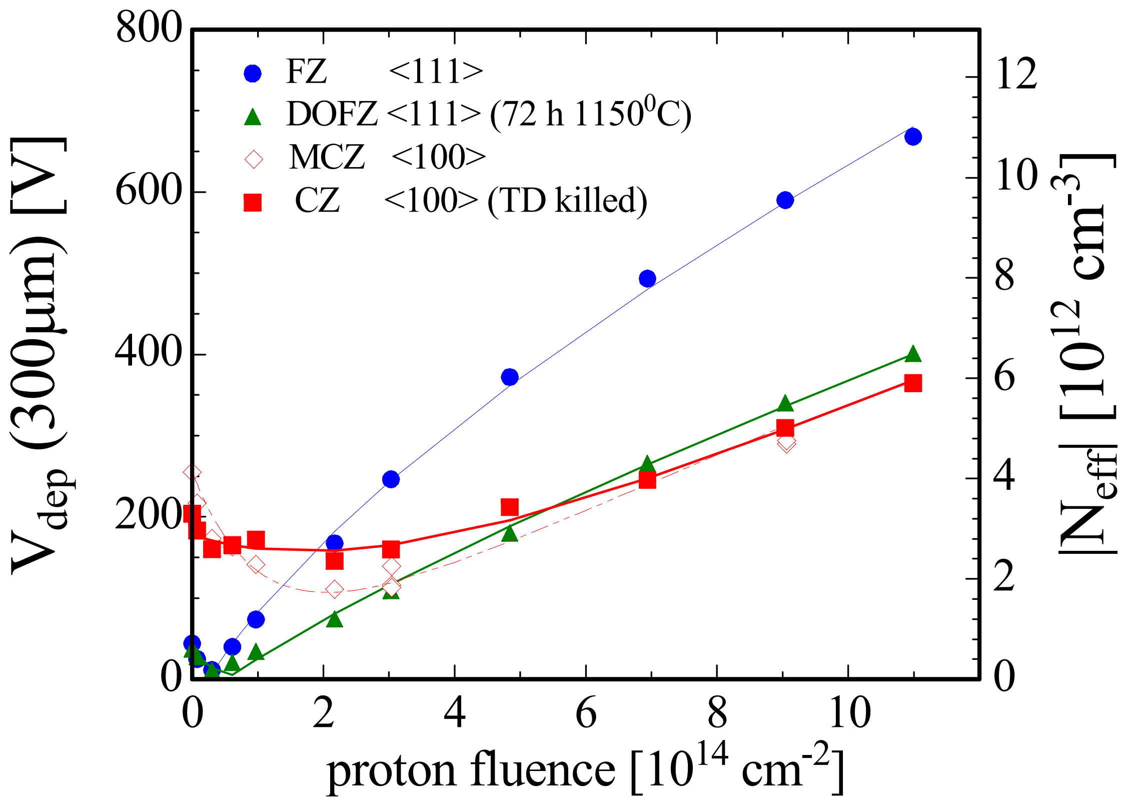


However, only non-oxygenated diodes show a "bad" behavior.

Standard 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**

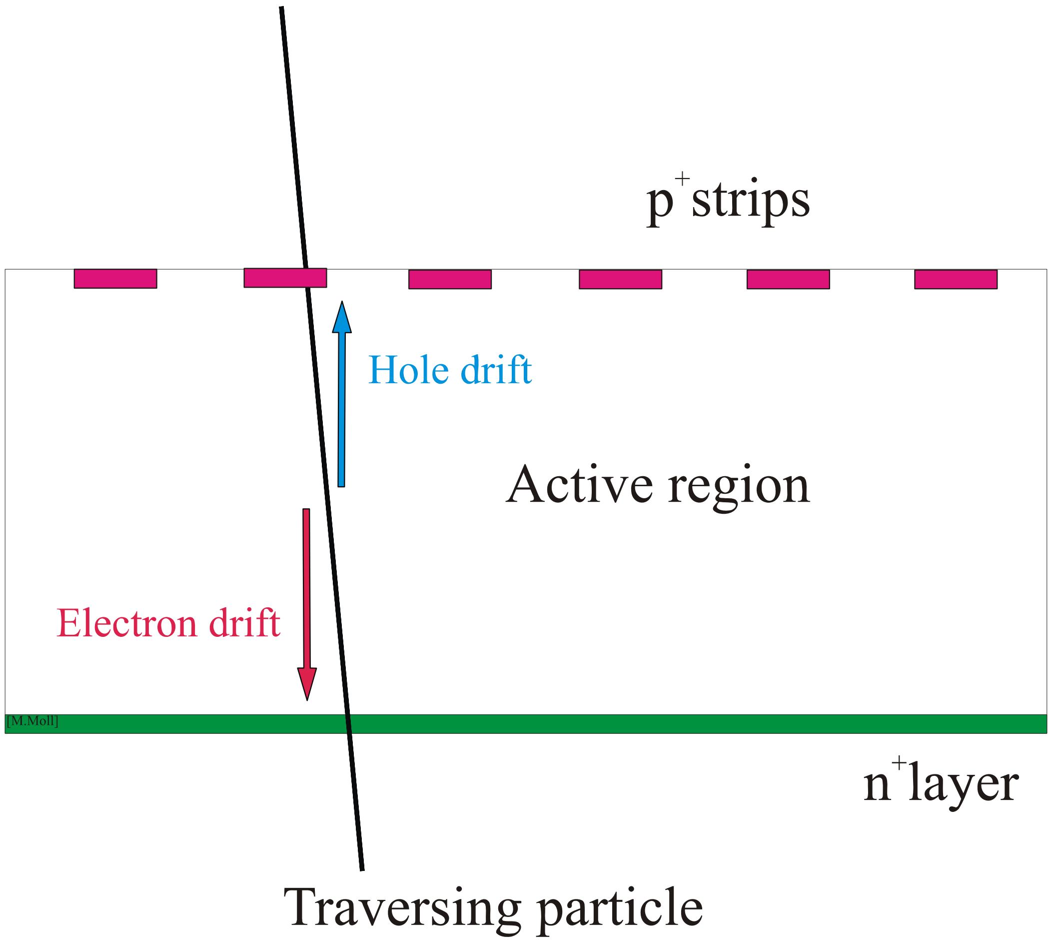
- **Common to all materials (after hadron irradiation):**
  - **reverse current increase**
  - **increase of trapping (electrons and holes) within ~ 20%**

** beware: reality is more complex, see later*

Advantage of non-inverting material

p-in-n detectors (schematic figures!)

Fully depleted detector
(non – irradiated):

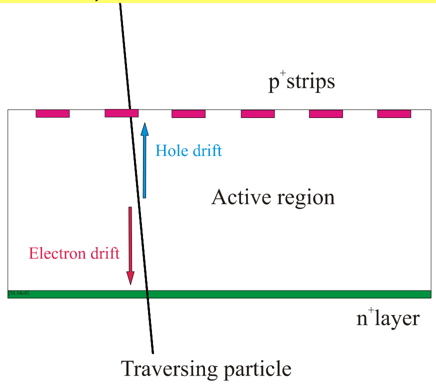


Advantage of non-inverting material

p-in-n detectors (schematic figures!)

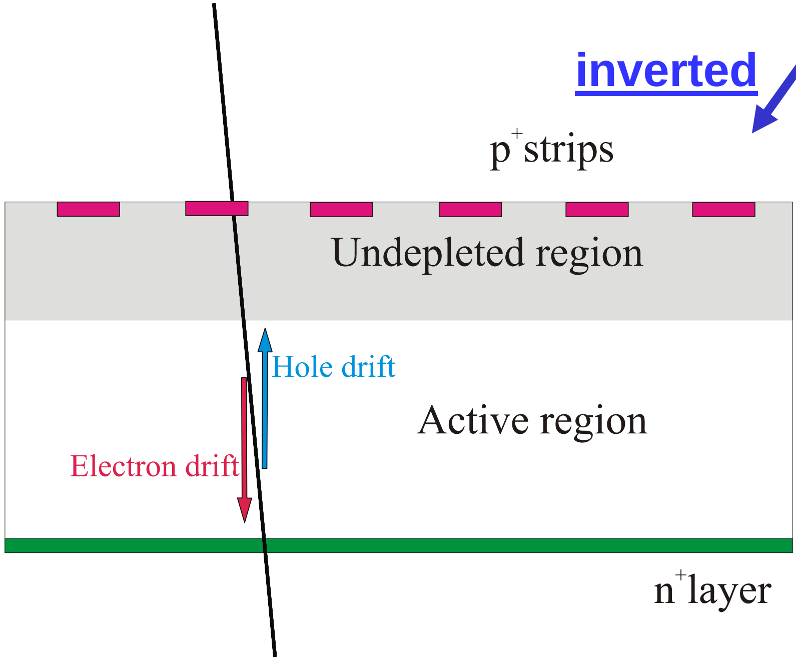
Be careful, this is a very schematic explanation, reality is more complex !

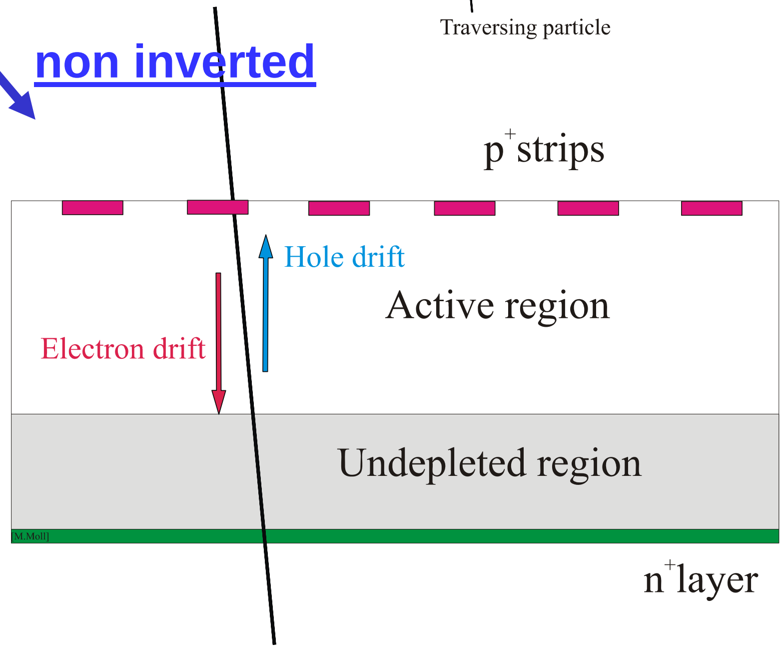
Fully depleted detector (non – irradiated):



heavy irradiation

inverted | **non inverted**





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

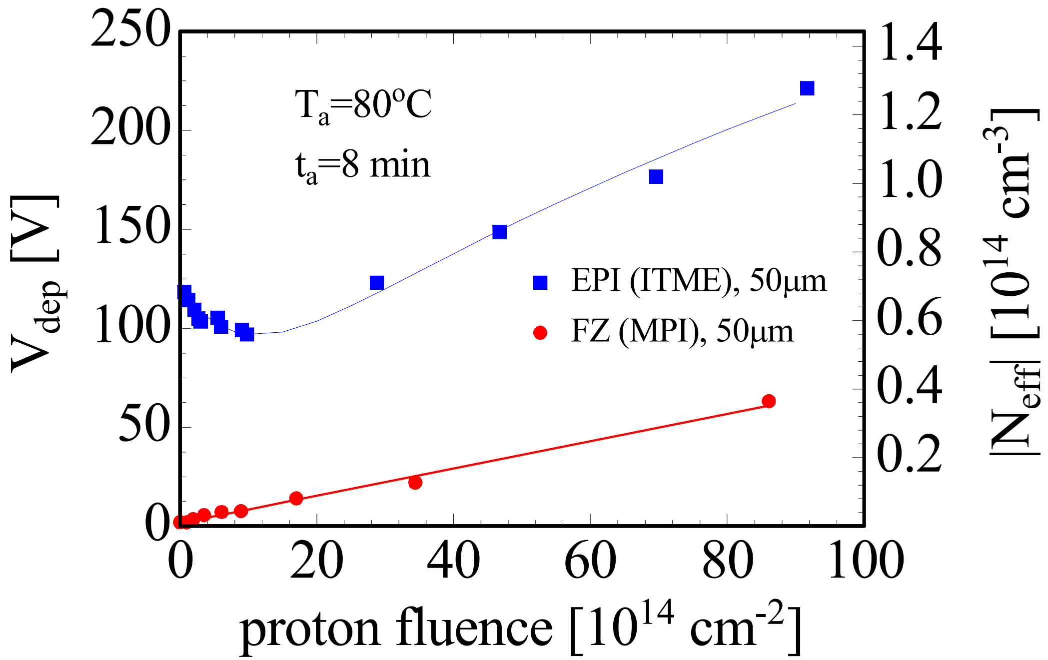
- **Charge spread – degraded resolution**
- **Charge loss – reduced CCE**

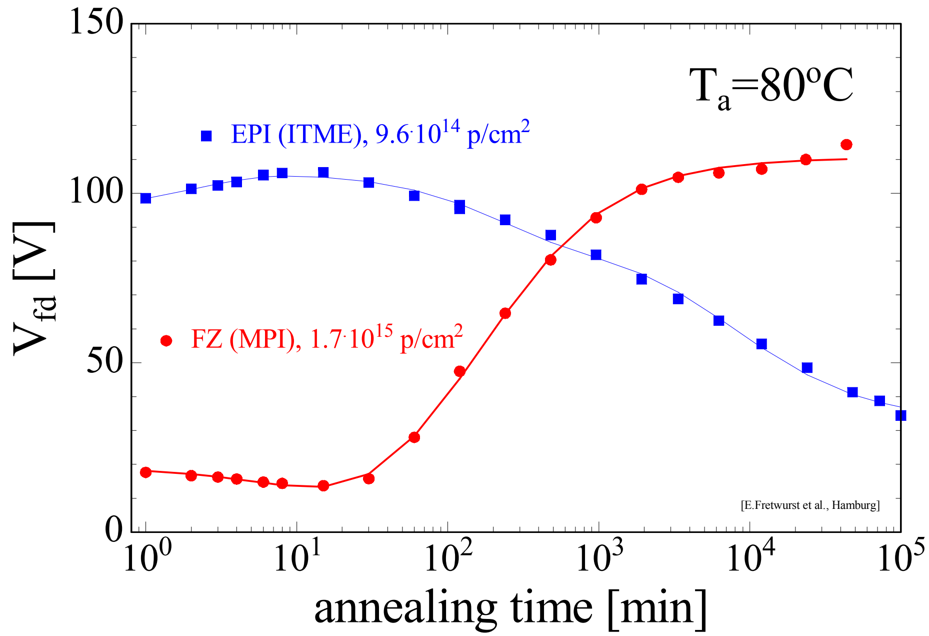
non-inverted, under-depleted:

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

Epitaxial silicon - Annealing

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





[E.Fretwurst et al.,RESMDD - October 2004]

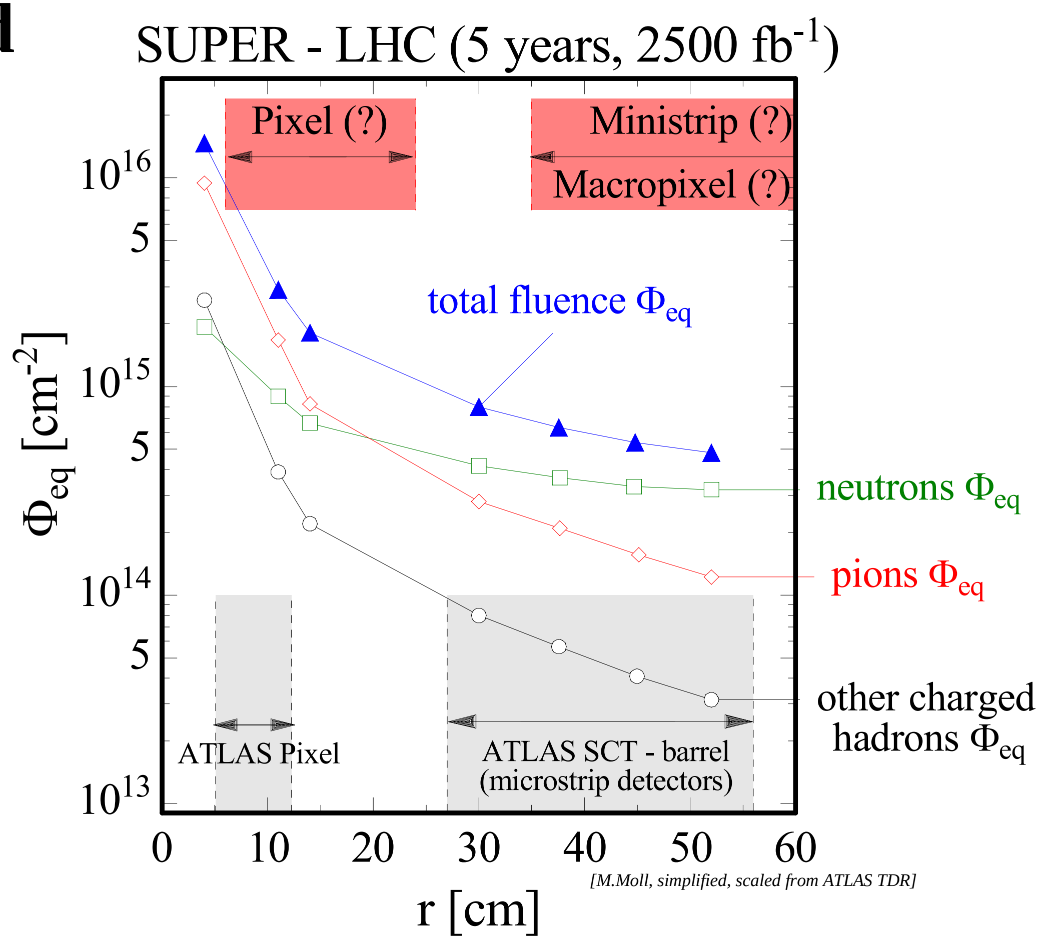
- **Thin FZ silicon: Type inverted, increase of depletion voltage with time**
- **Epitaxial silicon: No type inversion, decrease of depletion voltage with time**
  ⇒ No need for low temperature during maintenance of SLHC detectors!

"Mixed Irradiations"

- **LHC Experiments radiation field is a mix of different particles**

  (in particular: charged hadrons ⇔ neutrons)

- **MCZ silicon has shown an interesting behavior:**
  - **build up of net negative space charge after neutron irradiation**
  - **build up of net positive space charge after proton irradiation**

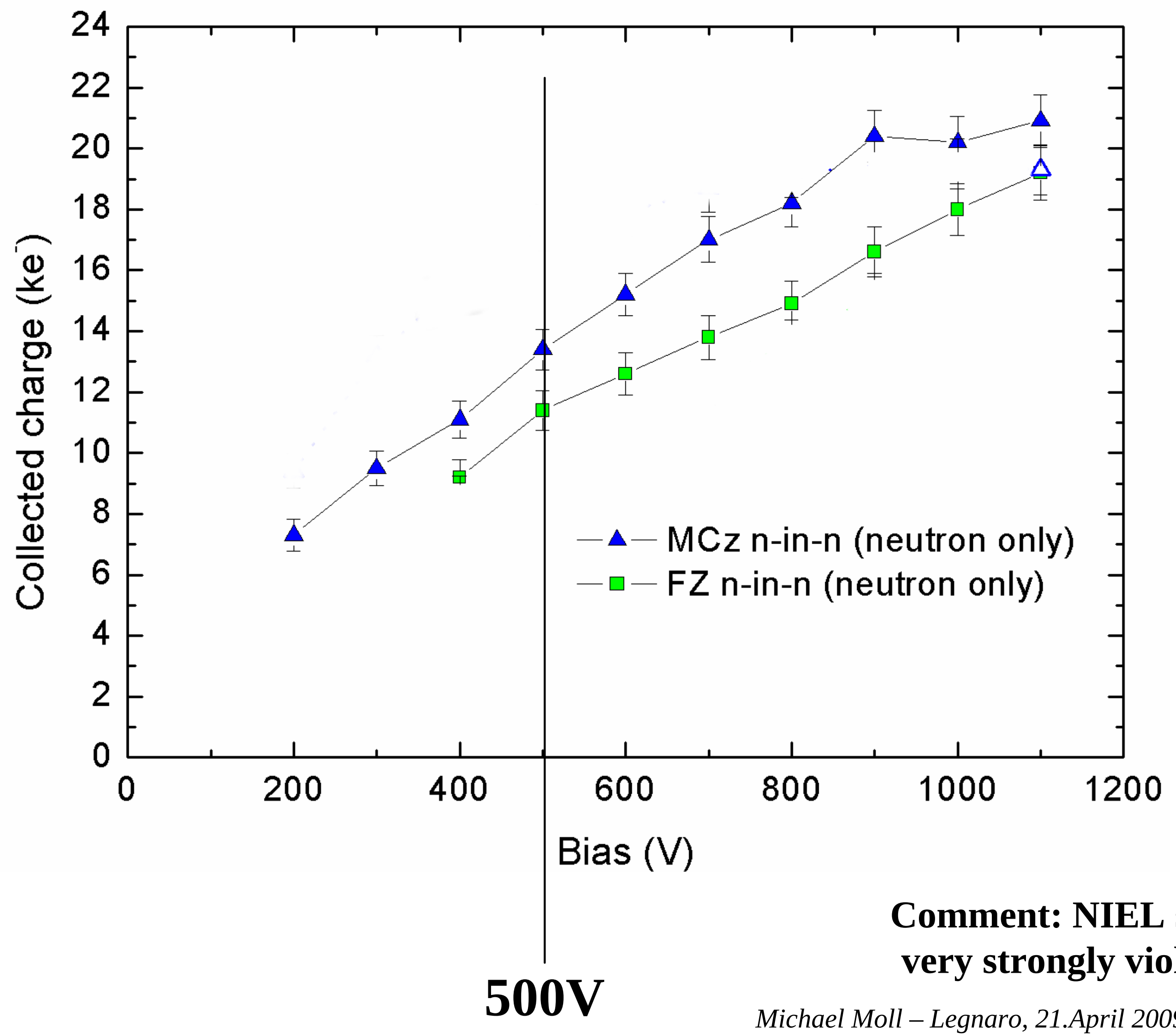


- **Question:**
  - **What happens when (MCZ) detectors are exposed to a 'mixed' radiation field?**

“Mixed Irradiations” n-type MCZ

[T.Affolder et al. 13th RD50 Workshop, Nov.2008]

- **Mixed irradiations performed with:**
  - **(a) $5x10^{14}$ neutrons (1 MeV equivalent fluence)**



Comment: NIEL scaling very strongly violated !

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[T.Affolder et al. 13th RD50 Workshop, Nov.2008]

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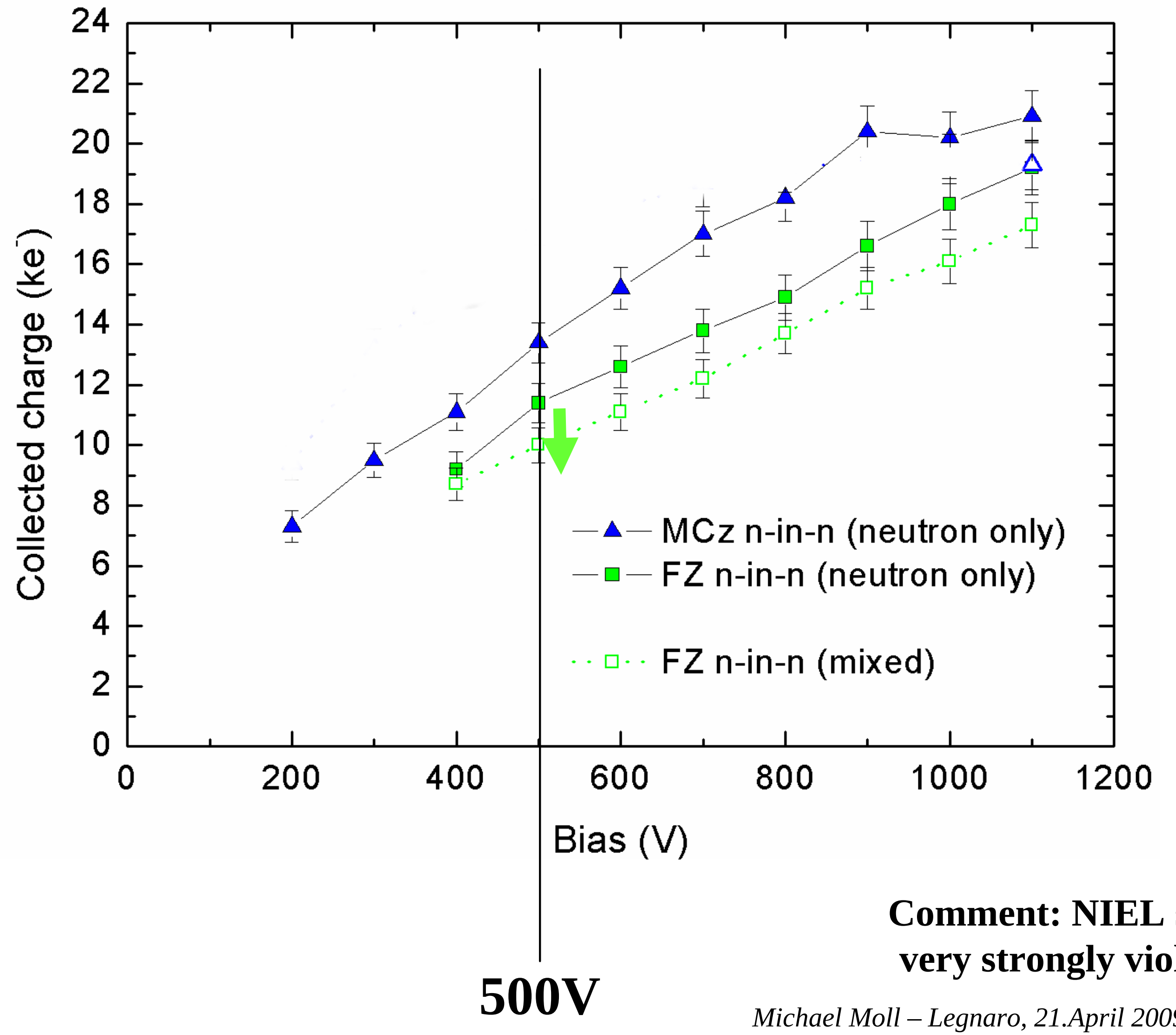
  - **(b) $5x10^{14}$ protons (1 MeV equivalent fluence)**

- **FZ (n-in-n)**

Mixed Irradiation:

Damage additive!



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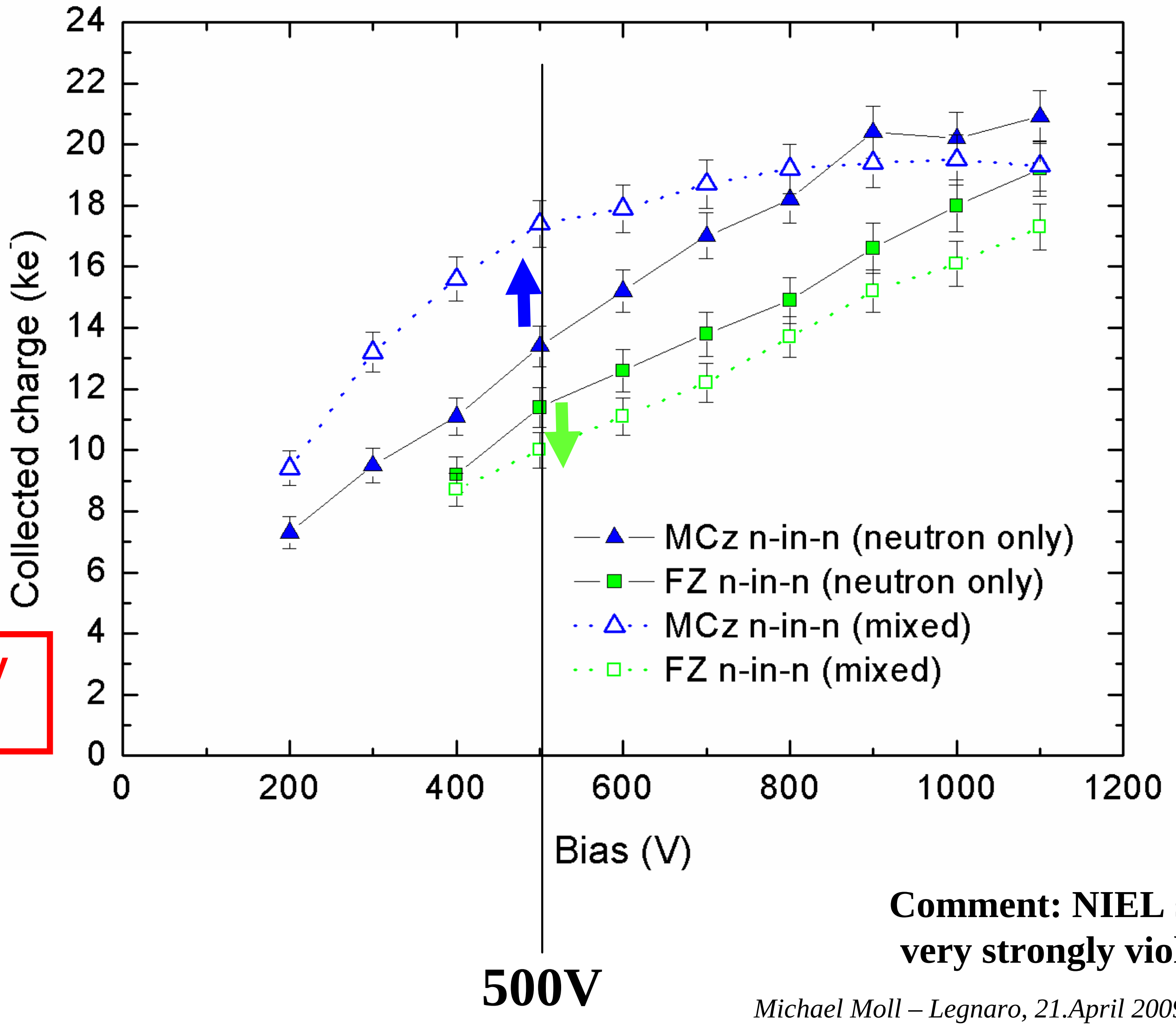
Mixed Irradiation:
Proton damage "compensates" part of neutron damage (N_{eff})

More charge collected at 500V after additional irradiation!!!



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"Mixed Irradiations" n-type MCZ

[T.Affolder et al. 13th RD50 Workshop, Nov.2008]

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  - **(b) $5x10^{14}$ protons (1 MeV equivalent fluence)**

•FZ (n-in-n)

Mixed Irradiation:

Damage additive!

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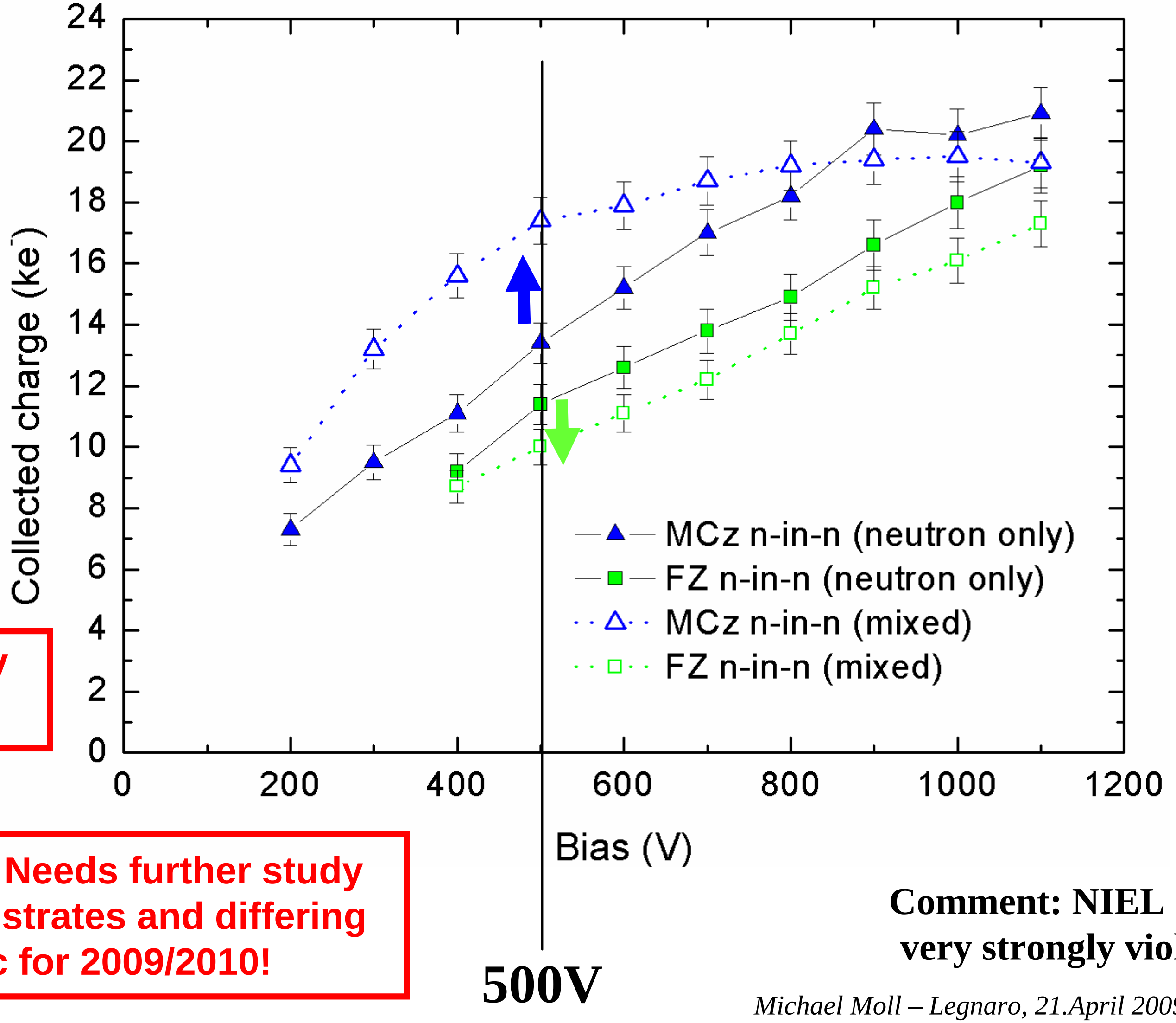


Results from November 2008: Needs further study with both nMCz and pMCz substrates and differing mixed doses … hot topic for 2009/2010!

Comment: NIEL scaling very strongly violated !

Other semiconductors: Epitaxial SiC, GaN and Diamond

Property	Diamond	GaN	4H SiC	Si
E_g [eV]	**5.5**	**3.39**	**3.3**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4\cdot10^6$	$2.2\cdot10^6$	$3\cdot10^5$
μ_e [cm²/Vs]	1800	1000	800	1450
μ_h [cm²/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2\cdot10^7$	-	$2\cdot10^7$	$0.8\cdot10^7$
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/

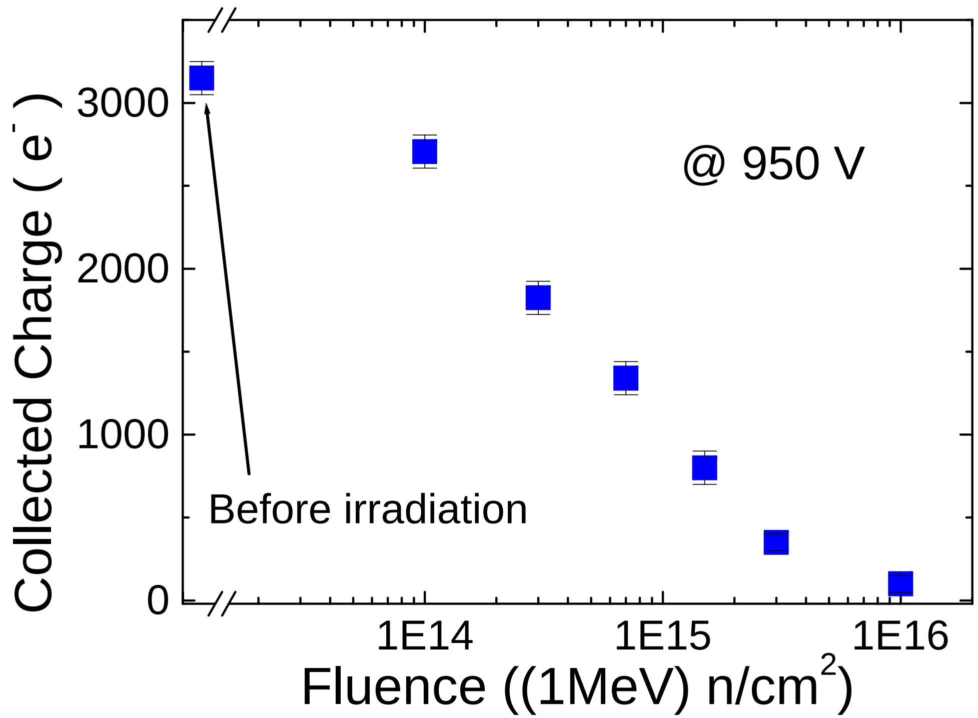
SiC: CCE after neutron irradiation

- **CCE before irradiation**
  - **100 % with α particles and MIPS**

- **CCE after irradiation (example)**
  - **material produced by CREE**
  - **55 μm thick layer**
  - **neutron irradiated samples**
  - **tested with β particles**

- **Conclusion:**
  - **SiC is less radiation tolerant than expected**

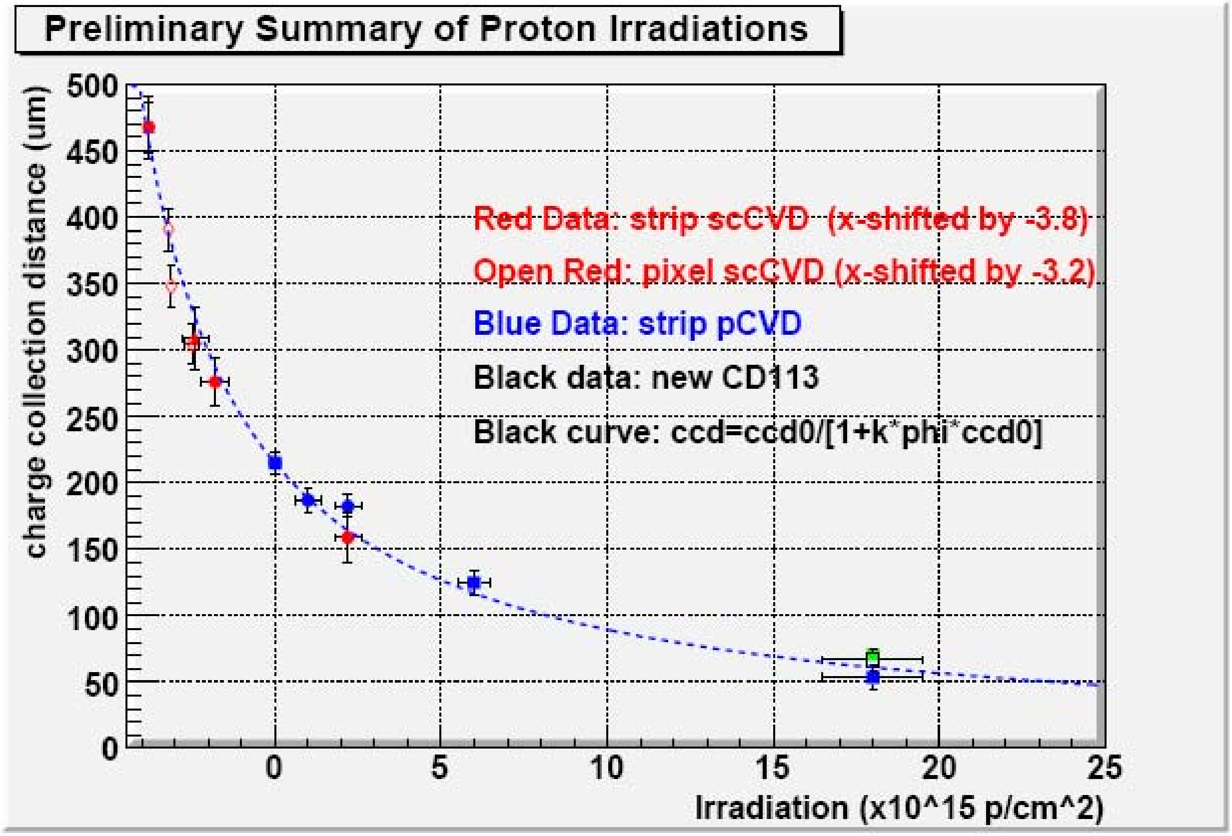
- **Consequence:**
  - **RD50 stopped working on this topic**



[F.Moscatelli, Bologna, December 2006]

Proton Irradiation Summary - This Year:

New results from pixel modules - diamond and electronics irradiated!



Irradiation results up to 1.8×10^{16} p/cm^2 (~500Mrad).
pCVD and scCVD diamond follow the same damage curve:
$1/\text{ccd} = 1/\text{ccd}_0 + k\,\phi$.

Outline

- **Motivation to develop radiation harder detectors**
  - **Radiation levels at the Super LHC**
  - **Radiation induced degradation of detector performance**

- **Radiation Damage in Silicon Detectors**
  - **Macroscopic damage (changes in detector properties)**

- **Approaches to obtain radiation hard sensors**
  - **Material Engineering**
    - Silicon materials – FZ, MCZ, DOFZ, EPI
    - Other semiconductors
  - **Device Engineering**
    - **p-in-n, n-in-n and n-in-p sensors**
    - **3D sensors and thin devices**

3D Detectors
Maurizio Boscardin
Claudio Piemonte

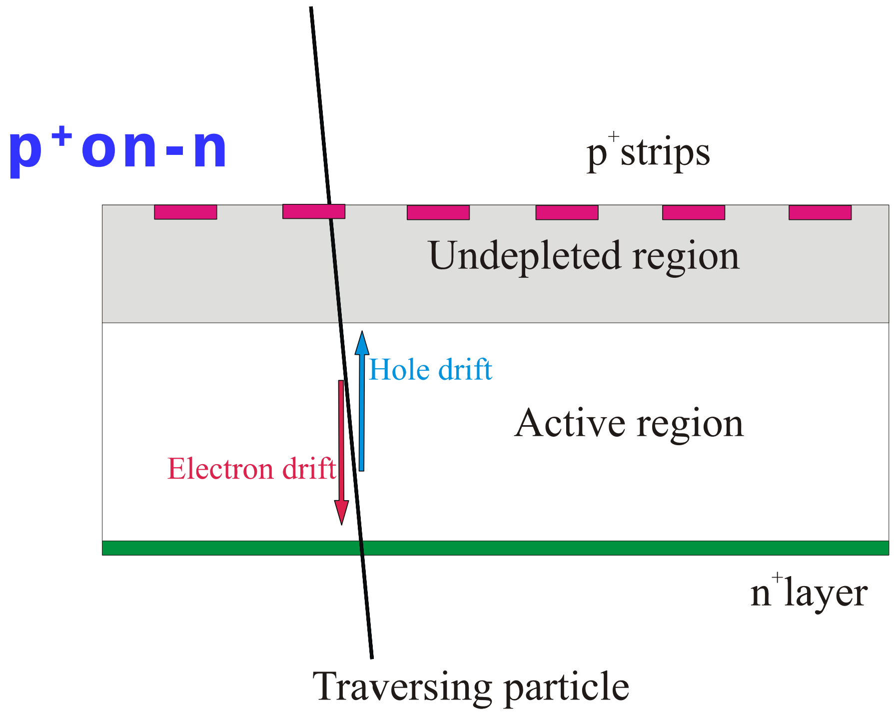
- **Some recent results and a comparison**
  - **Collected Charge – Signal to Noise**
  - **Mixed irradiations**

- **Summary**

Device engineering (p-type silicon)

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

p+ strip readout (p-in-n) after high fluences:

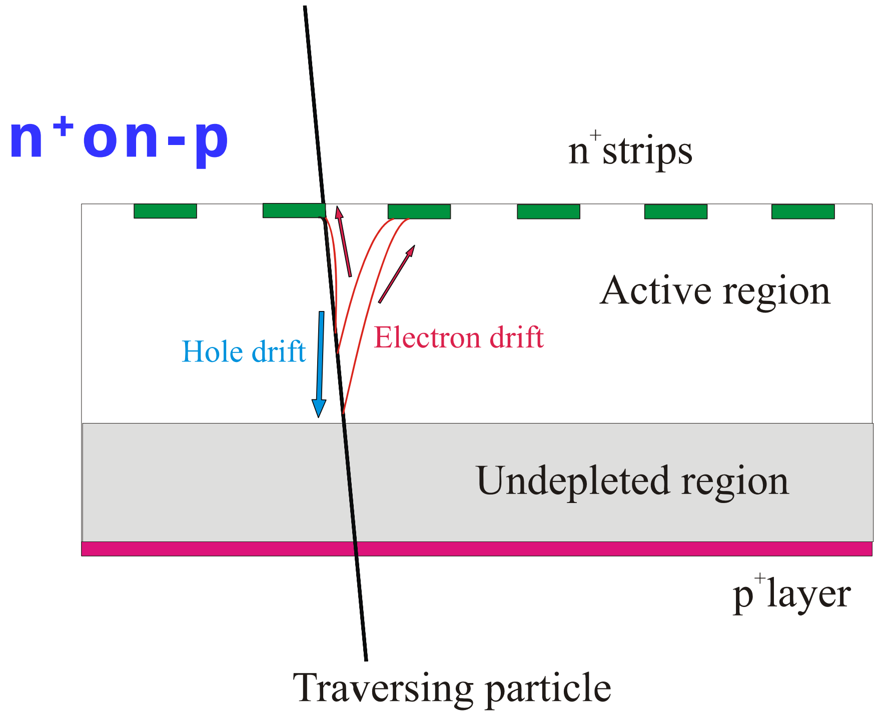


p-on-n silicon, under-depleted:

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

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

n+ strip readout (n-in-p or n-in-n) after high fluences:

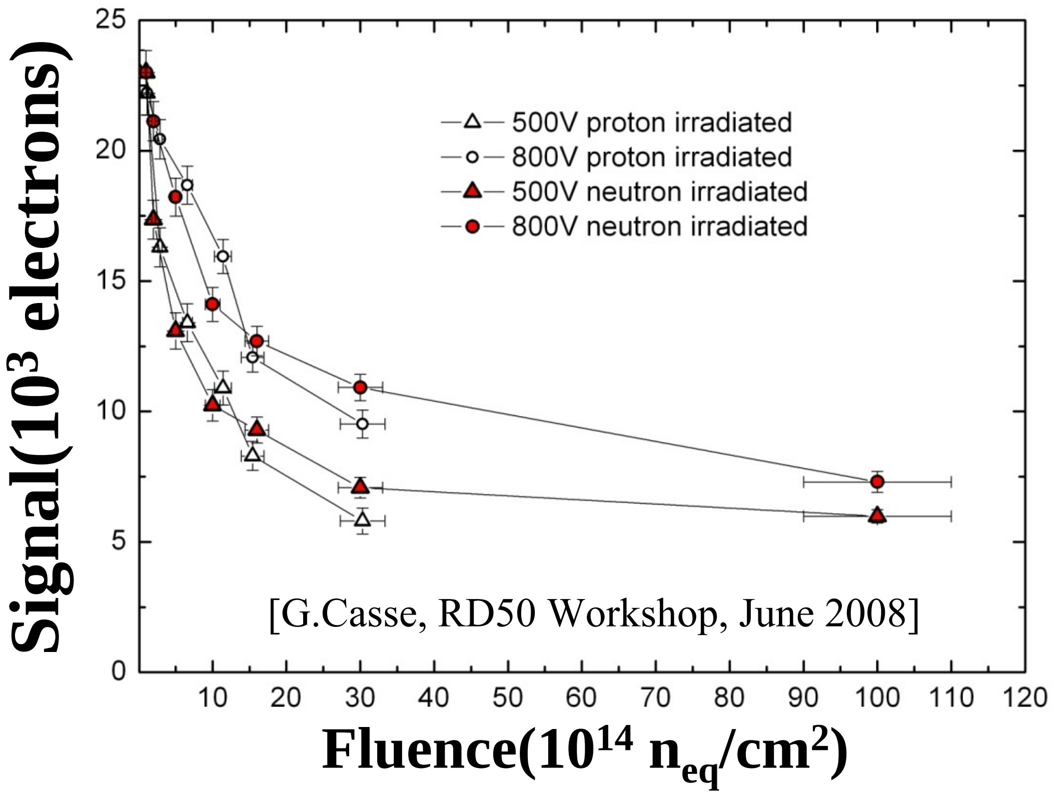


n-on-p silicon, under-depleted:

- Limited loss in CCE
- Less degradation with under-depletion
- <u>Collect electrons</u> (fast)

n-in-p microstrip detectors

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



- **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)

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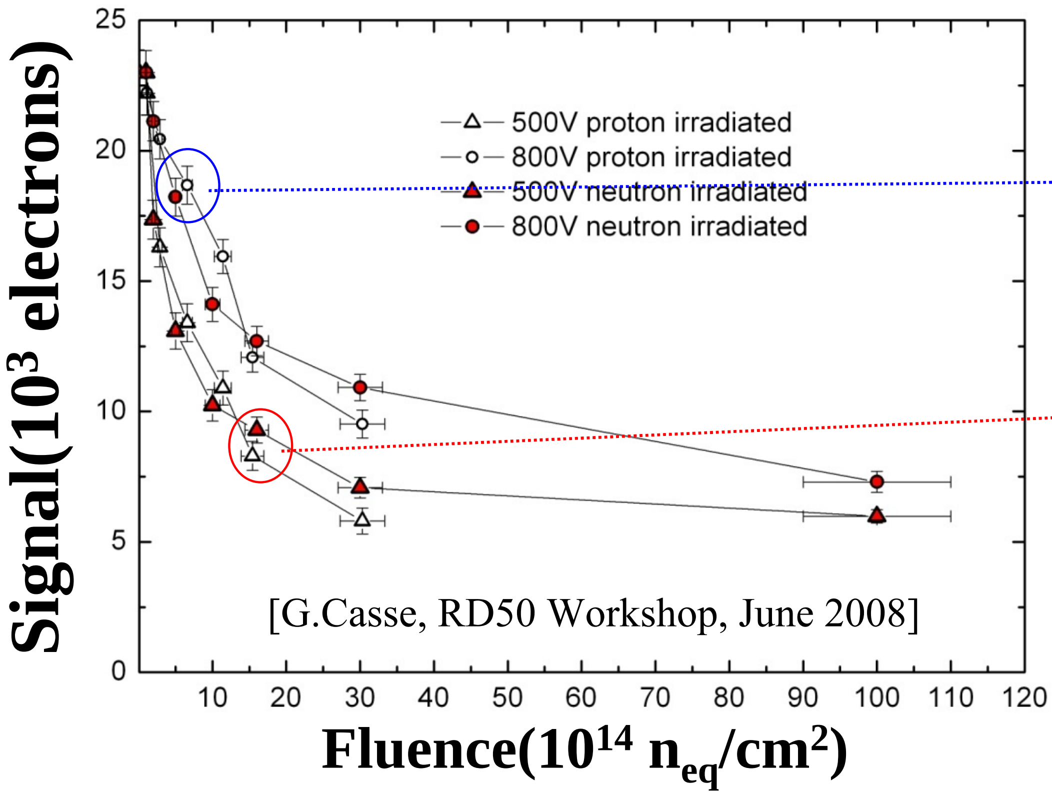
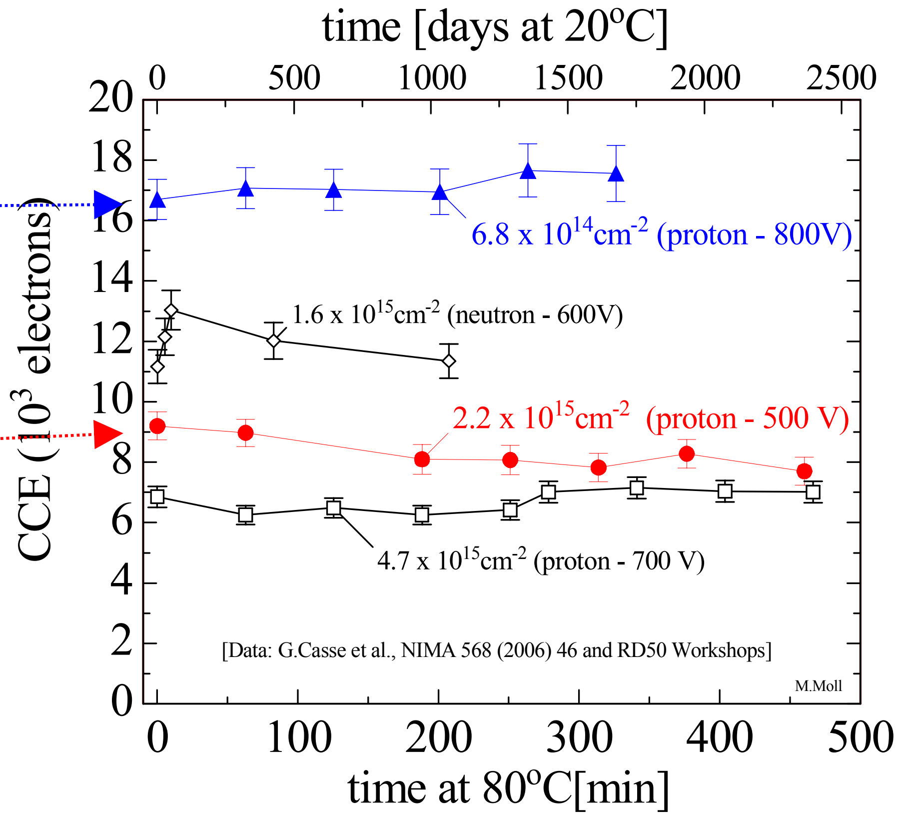




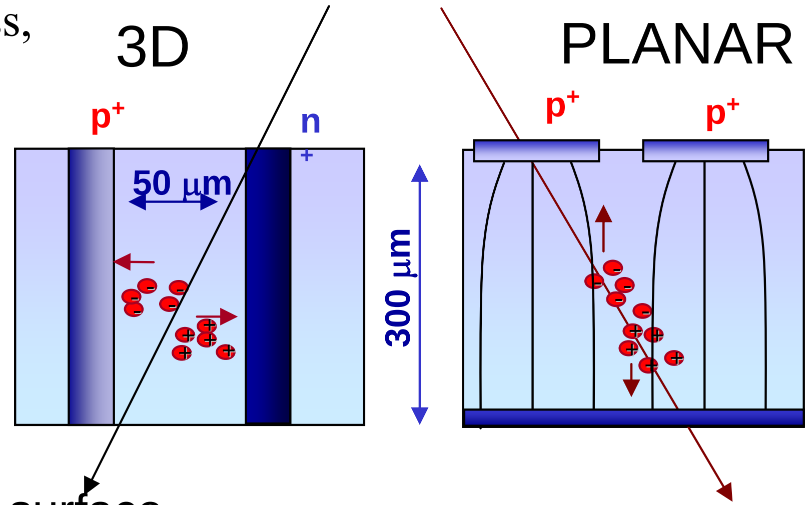
- **CCE: ~7300e (~30%)**
  after ~ 1×10^{16}cm^{-2} 800V
- **n-in-p sensors are strongly considered for ATLAS upgrade** (previously p-in-n used)

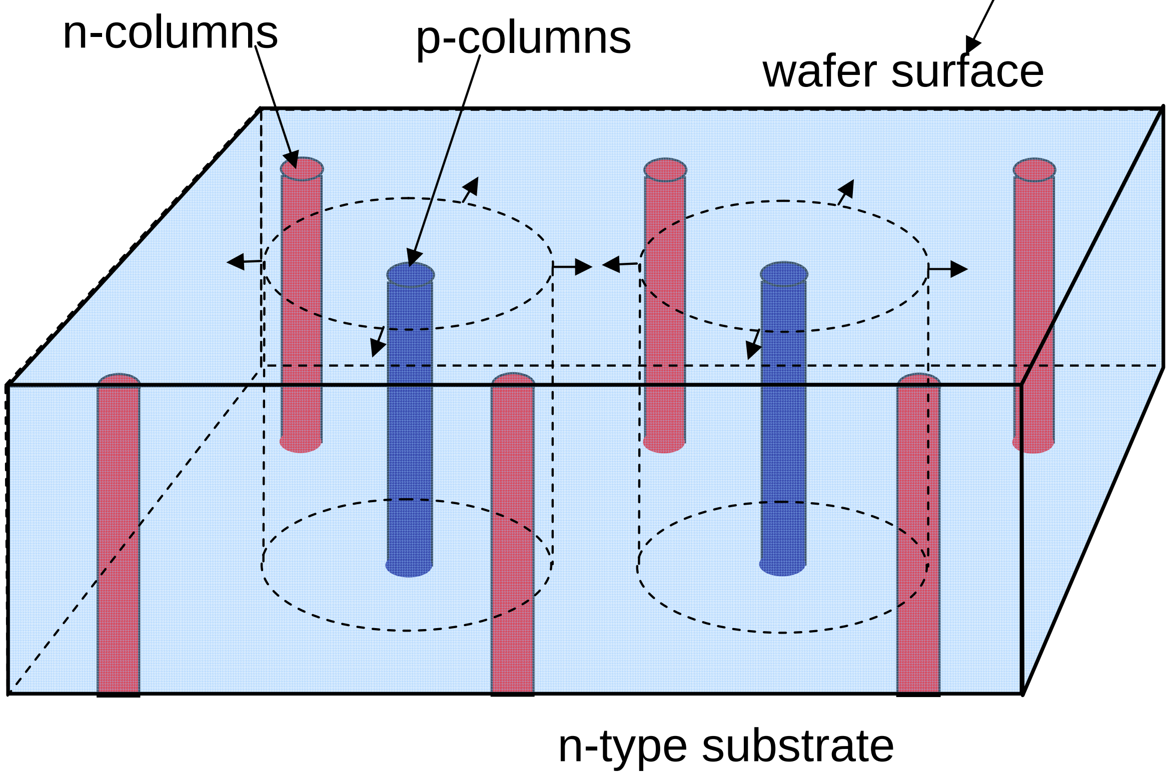
- **no reverse annealing in CCE measurements for neutron and proton irradiated detectors**

3D detector - concepts

Introduced by: S.I. Parker et al., NIMA 395 (1997) 328

- **"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





See lecture on
3D Detectors
Maurizio Boscardin
Claudio Piemonte

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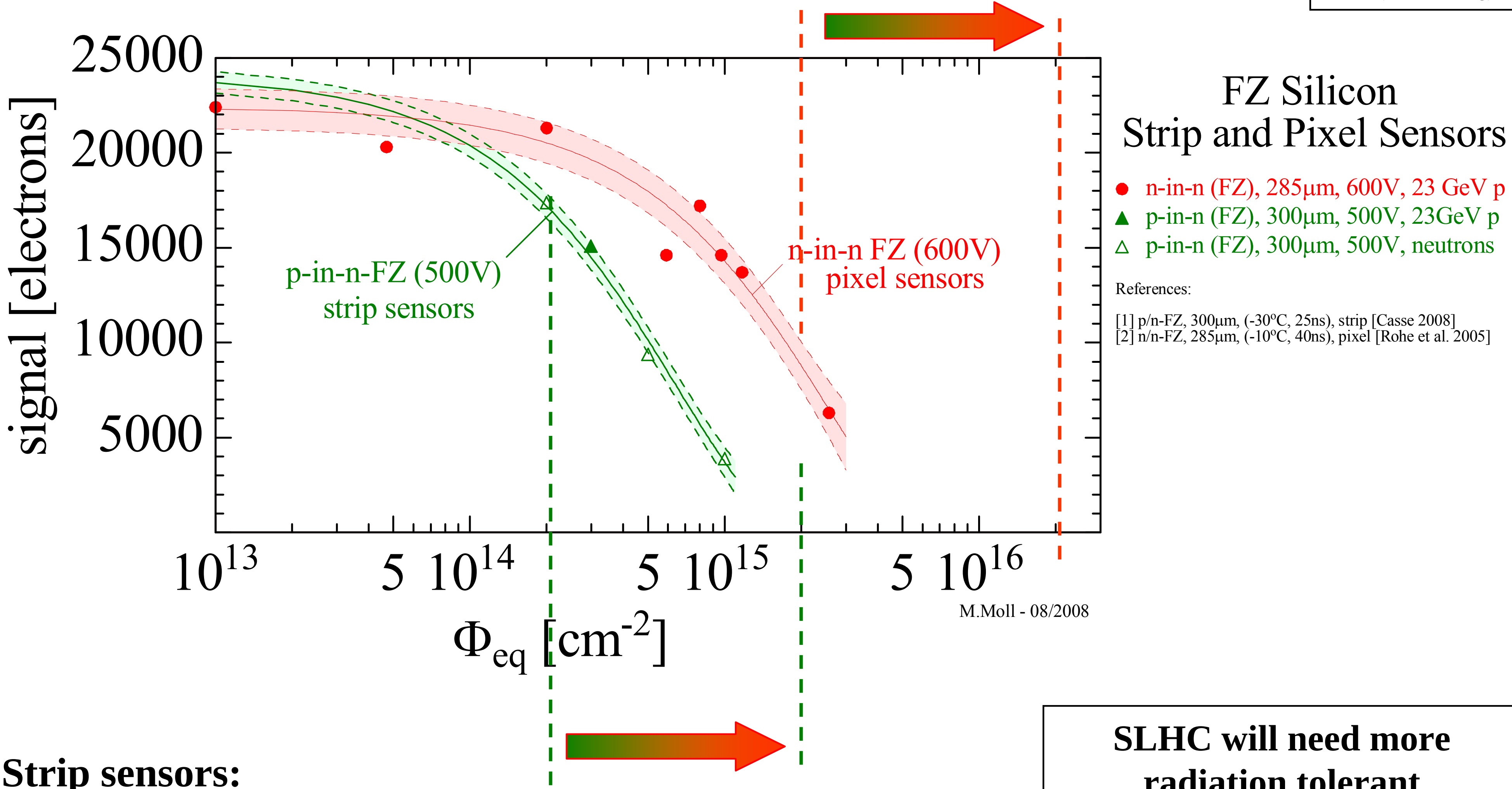
    - 3D sensors and thin devices
- **Some recent results and a comparison**
  - **Collected Charge – Signal to Noise**
- **Summary**

Signal degradation for LHC Silicon Sensors

Pixel sensors:
max. cumulated fluence for LHC and SLHC

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



Strip sensors:
max. cumulated fluence for LHC and SLHC

SLHC will need more radiation tolerant tracking detector concepts!

Comparison of measured collected charge on different radiation-hard materials and devices

- **In the following:**

  Comparison of collected charge as published in literature

- **Be careful:**

  Values obtained partly under different conditions !!

  - **irradiation**
  - **temperature of measurement**
  - **electronics used (shaping time, noise)**
  - **voltage applied to sensor**
  - **type of device – strip detectors or pad detectors**

  ⇒ This comparison gives only an indication of which material/technology could be used, to be more specific, the exact application should be looked at!

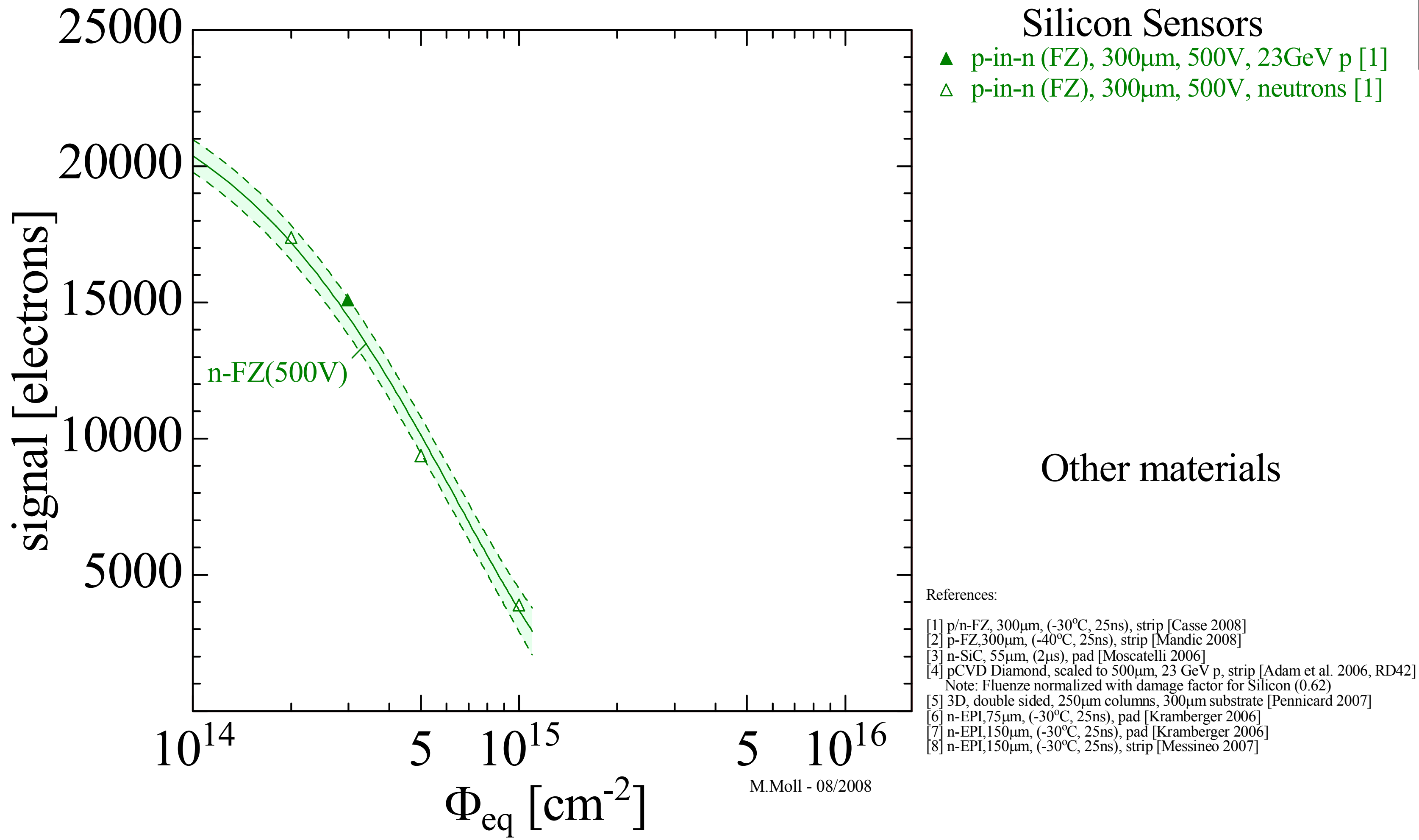
- **Remember:**

  The obtained signal has still to be compared to the noise !!

Silicon materials for Tracking Sensors

- **Signal comparison for various Silicon sensors**

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



Silicon materials for Tracking Sensors

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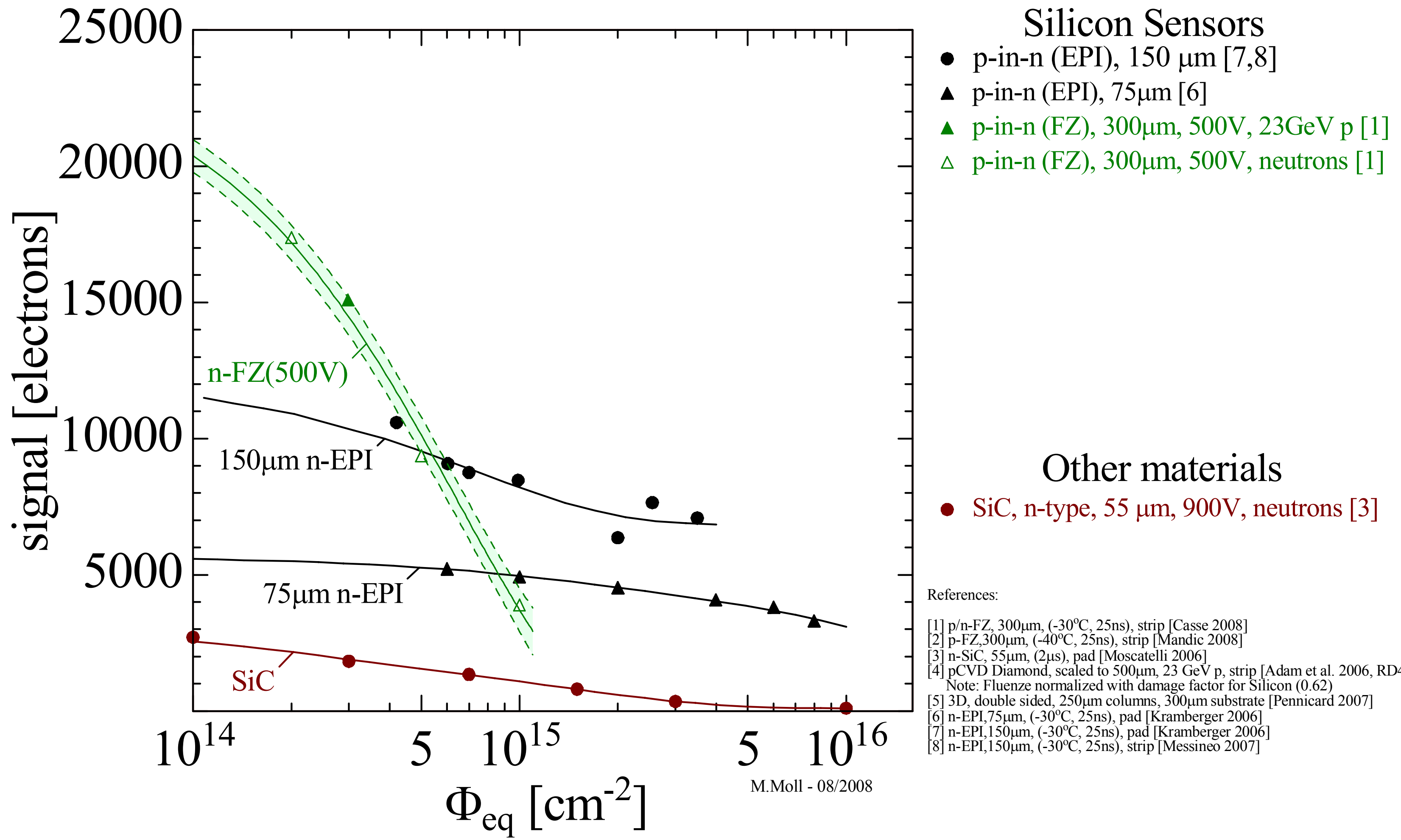

References:

[1] p/n-FZ, 300µm, (-30°C, 25ns), strip [Casse 2008]
[2] p-FZ,300µm, (-40°C, 25ns), strip [Mandic 2008]
[3] n-SiC, 55µm, (2µs), pad [Moscatelli 2006]
[4] pCVD Diamond, scaled to 500µm, 23 GeV p, strip [Adam et al. 2006, RD42]
Note: Fluenze normalized with damage factor for Silicon (0.62)
[5] 3D, double sided, 250µm columns, 300µm substrate [Pennicard 2007]
[6] n-EPI,75µm, (-30°C, 25ns), pad [Kramberger 2006]
[7] n-EPI,150µm, (-30°C, 25ns), pad [Kramberger 2006]
[8] n-EPI,150µm, (-30°C, 25ns), strip [Messineo 2007]

Silicon materials for Tracking Sensors

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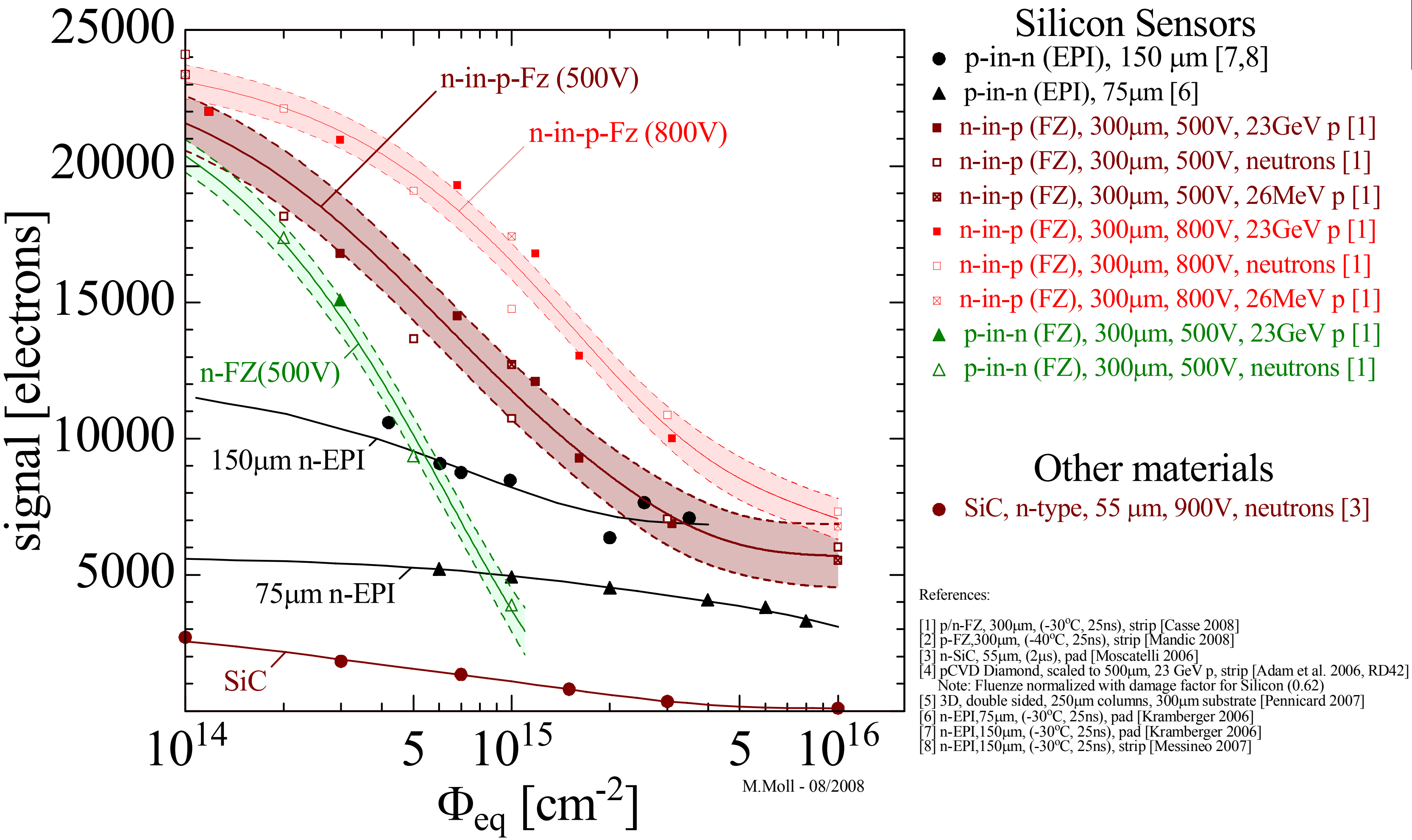

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Silicon materials for Tracking Sensors

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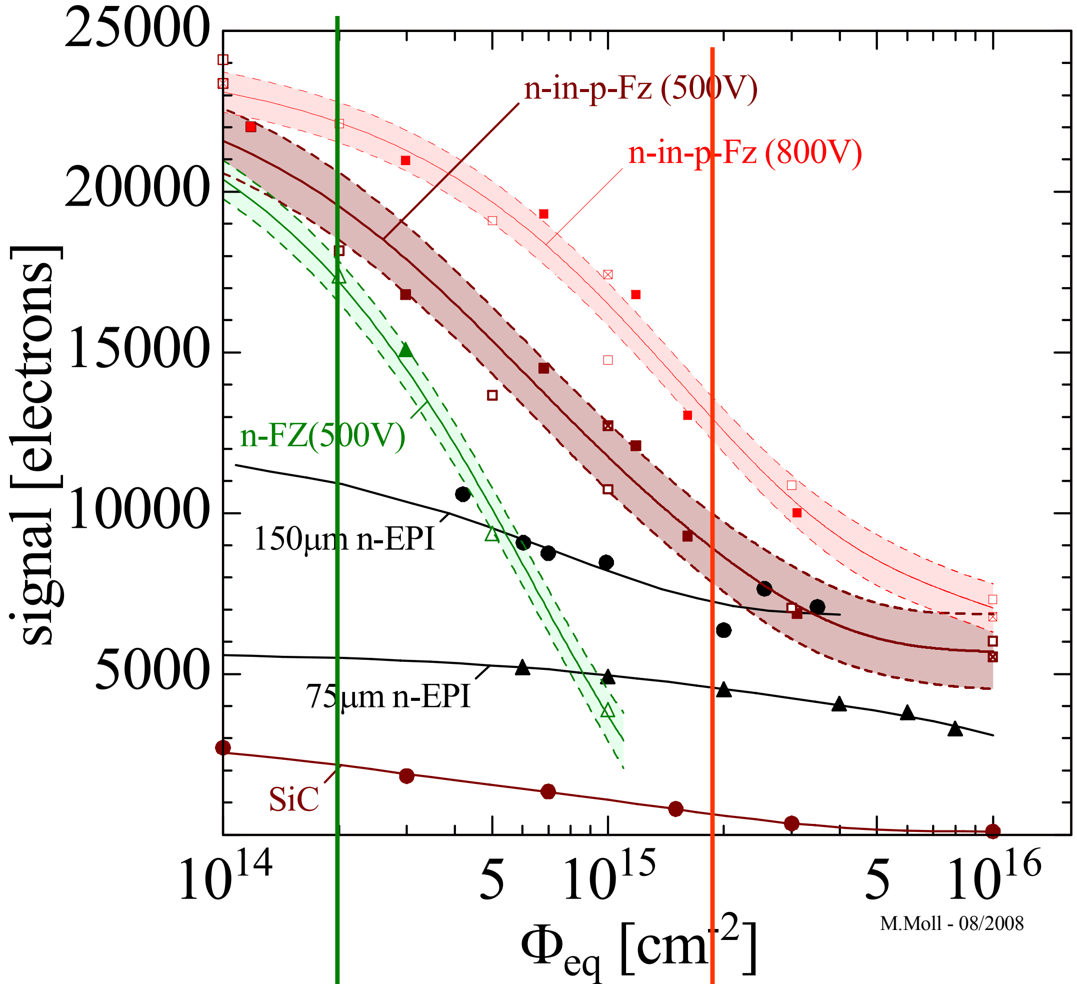

Silicon Sensors
- ● p-in-n (EPI), 150 µm [7,8]
- ▲ p-in-n (EPI), 75µm [6]
- ■ n-in-p (FZ), 300µm, 500V, 23GeV p [1]
- □ n-in-p (FZ), 300µm, 500V, neutrons [1]
- ⊠ n-in-p (FZ), 300µm, 500V, 26MeV p [1]
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- △ p-in-n (FZ), 300µm, 500V, neutrons [1]

Other materials
- ● SiC, n-type, 55 µm, 900V, neutrons [3]

References:

[1] p/n-FZ, 300µm, (-30°C, 25ns), strip [Casse 2008]
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LHC → **SLHC**

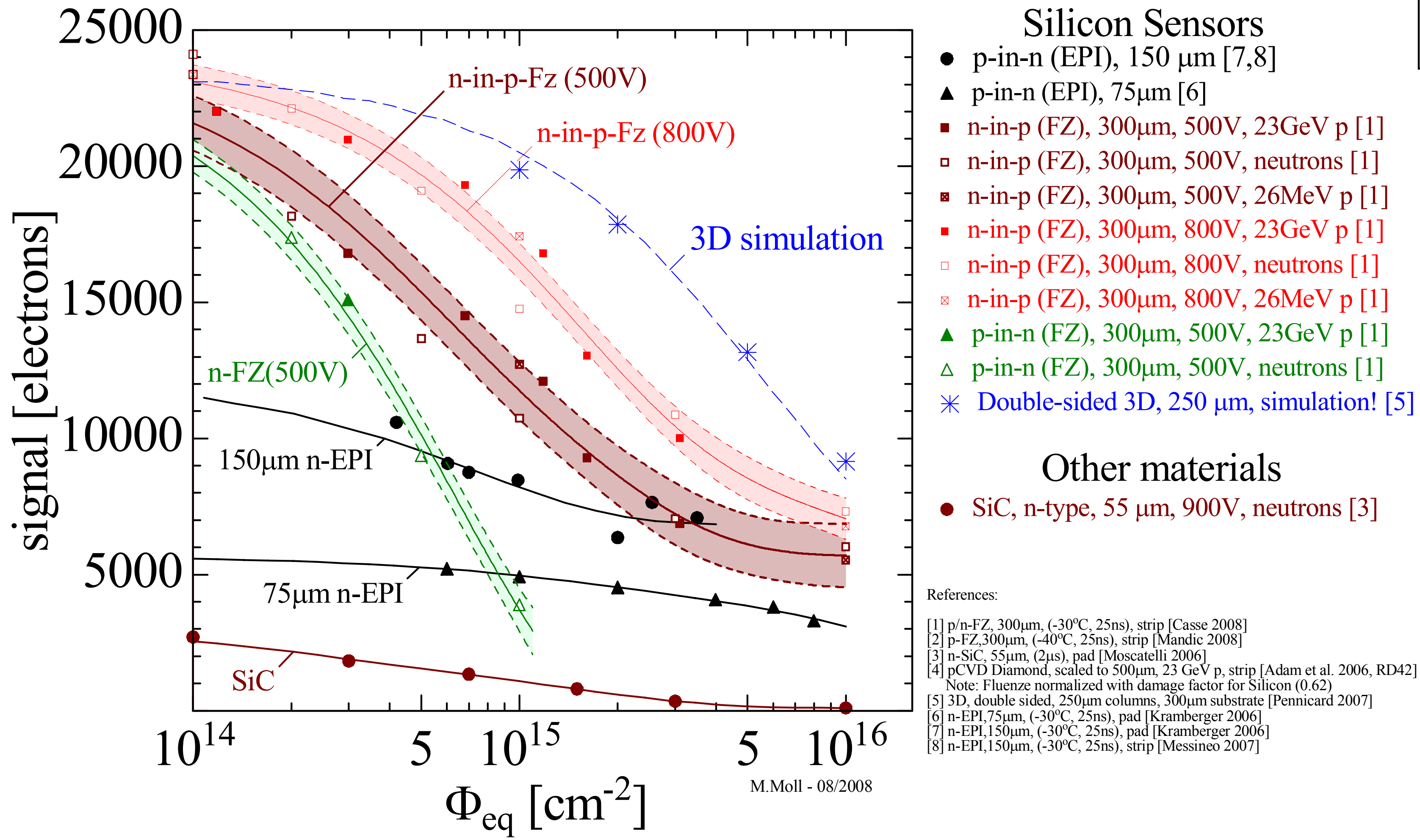
highest fluence for strip detectors in LHC: The used p-in-n technology is sufficient

n-in-p technology should be sufficient for Super-LHC at radii presently (LHC) occupied by strip sensors

Silicon materials for Tracking Sensors

- **Signal comparison for various Silicon sensors**

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

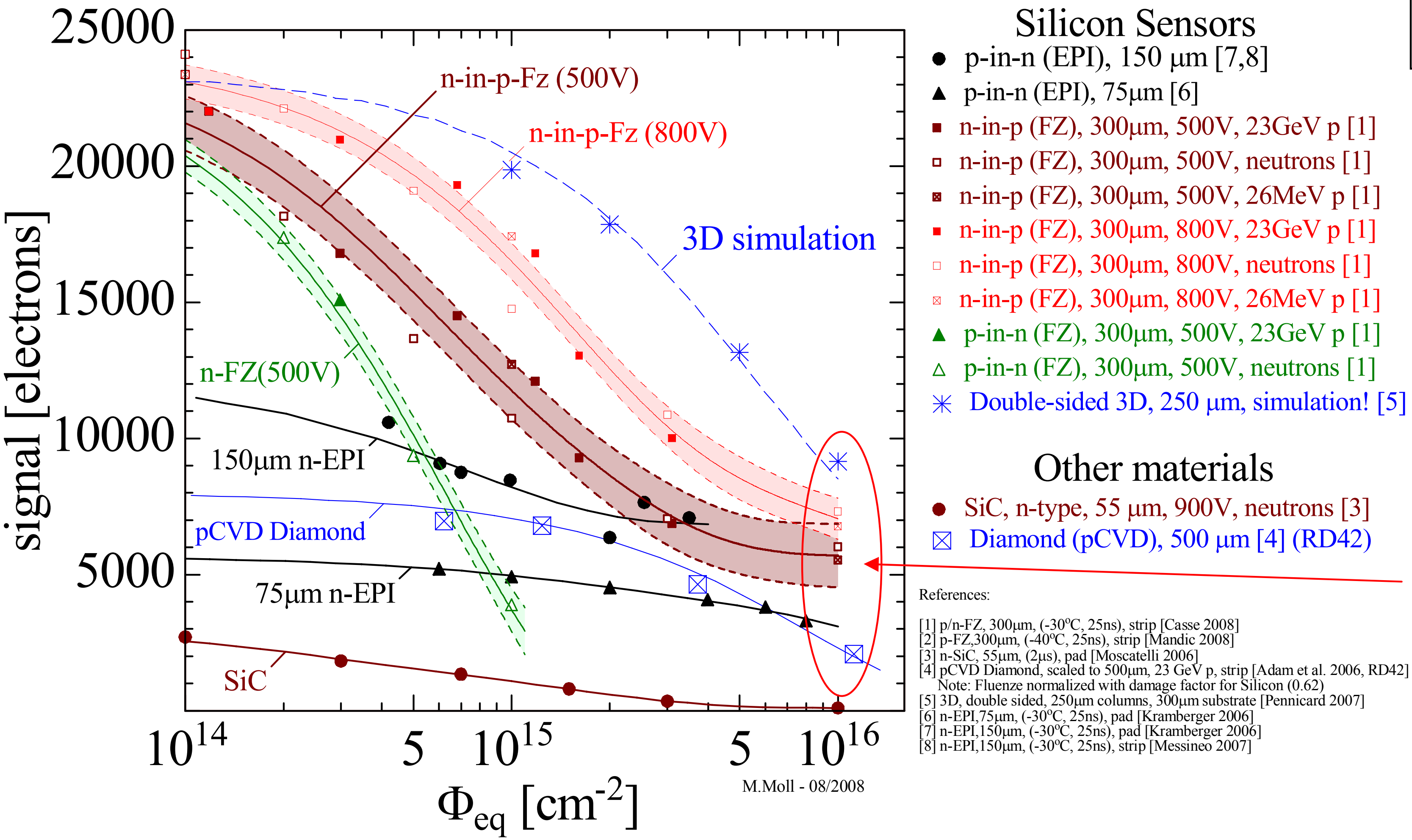


- **At a fluence of ~ 10^{15} n_{eq}/cm^2 all planar sensors loose sensitivity: on-set of trapping !**
- **No obvious material for innermost pixel layers:**
  - **Are 3-D sensors an option ??** (decoupling drift distance from active depth)
  - **Develop detectors that can live with very small signals ?? or regularly replace inner layers ??**

Silicon materials for Tracking Sensors

- **Signal comparison for various Silicon sensors**

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



Beware: Signal shown and not S/N !

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Summary – Radiation Damage

- **Radiation Damage in Silicon Detectors**
  - Change of **Depletion Voltage** (type inversion, reverse annealing, …)
    (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** (→ see lecture of M.Bruzzi)
  - Good understanding of damage after γ-irradiation (point defects)
  - Damage after hadron damage still to be better understood (cluster defects), however enormous progress in last 2 years

- **CERN-RD50 collaboration working on:**
  - **Material Engineering** (Silicon: DOFZ, MCZ, EPI, …) (**RD42: Diamond**)
  - **Device Engineering (**3D, thin sensors, n-in-p, n-in-n,..) (**RD39: Cryogenic, CI**)

⇒ **To obtain ultra radiation hard sensors a combination of material and device engineering approaches depending on radiation environment, application and available readout electronics will be best solution**

Summary – Detectors for SLHC

- **At fluences up to 10^{15}cm^{-2} (outer layers of SLHC detector):**
  The change of the depletion voltage and the large area to be covered by detectors are major problems.
  - **MCZ silicon detectors could be a solution (some more work needed!)**
    n-MCZ no type inversion under proton irradiation, excellent performance in mixed fields due to compensation of charged hadron damage and neutron damage (N_{eff} compensation)
  - **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 baseline option for the ATLAS SCT upgrade

- **At the fluence of 10^{16}cm^{-2} (Innermost layers of SLHC detector)**
  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.

- **SiC and GaN have been characterized and abandoned by RD50.**
- **Diamond has become an interesting option for the innermost pixel layers**

Further information: RD50 (http://cern.ch/rd50/), RD42, RD39