4th NoRHDia Workshop, GSI, Darmstadt, June 8-10, 2008

Recent RD50 Developments on Radiation Tolerant Silicon Sensors

Michael Moll (CERN-PH-DT)

OUTLINE

- Motivation, RD50, RD50 work program
- Radiation Damage in Silicon Sensors (1 slide)
- Silicon Materials (MCZ, EPI, FZ) (2 slides)
- Recent results and future plans on
  - Pad detectors (diode structures)
  - Strip detectors (segmented structures)
  - 3D detectors
- Summary

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

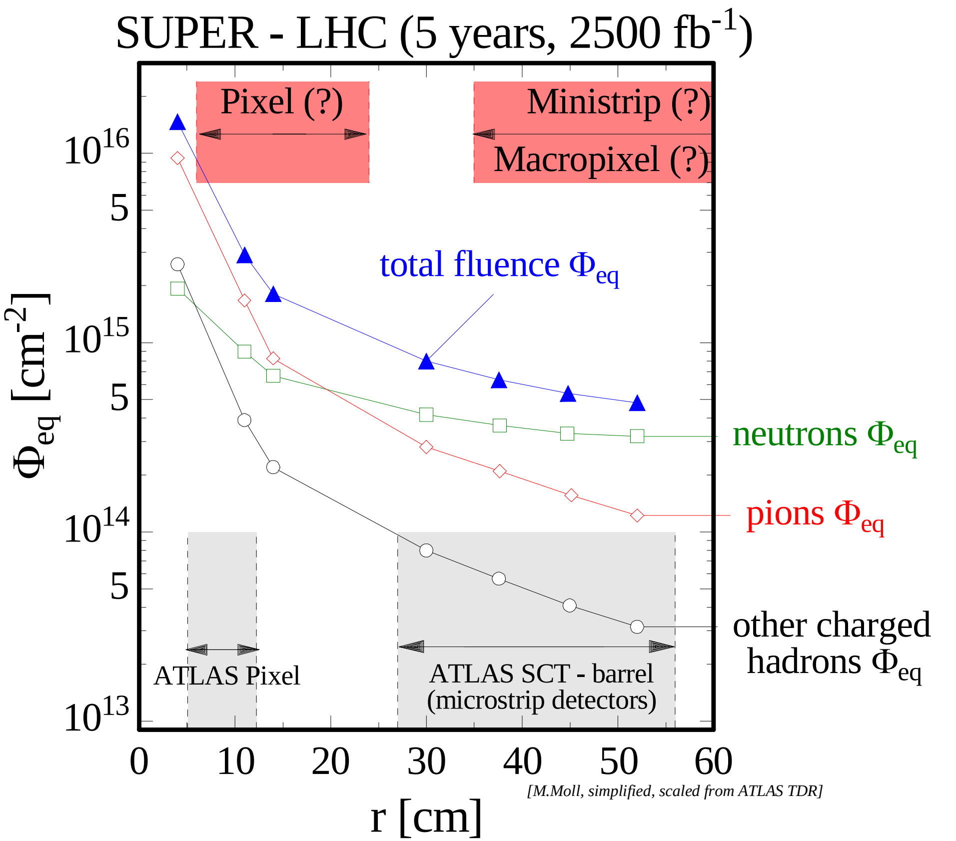
- **LHC upgrade**
  - ⇨ LHC (2008) **L = 10^{34}cm^{-2}s^{-1}**

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

  - ⇨ Super-LHC (2018 ?) **L = 10^{35}cm^{-2}s^{-1}**

    5 years / 2500 fb^{-1} → ϕ(r=4cm) ~ $1.6 \cdot 10^{16}$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!**

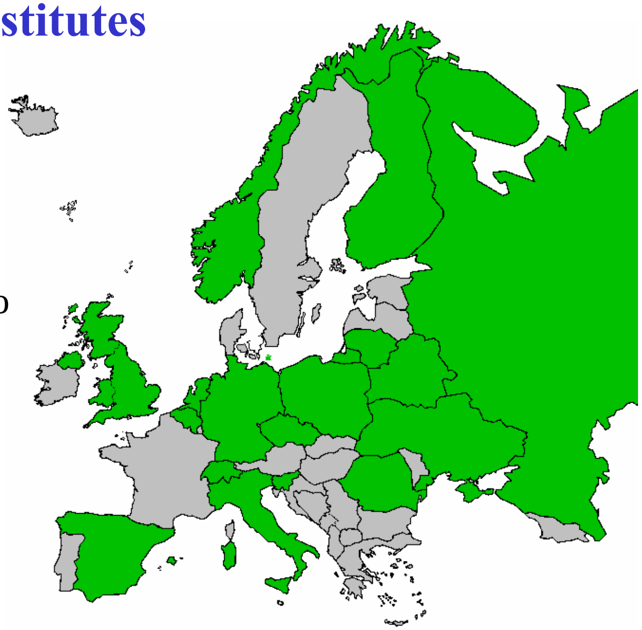
⇨ Need for new detectors & detector technologies

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

RD50 Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

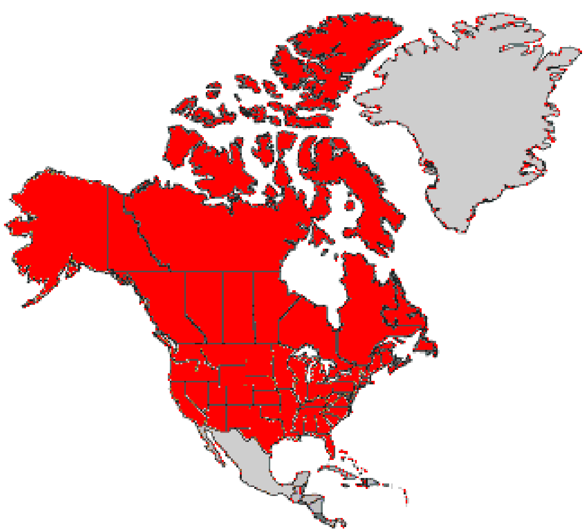
Approved as CERN R&D project "RD50" in June 2002

Presently :257 Members from 49 Institutes



40 European and Asian institutes

Belarus (Minsk), **Belgium** (Louvain), **Czech Republic** (Prague (3x)), **Finland** (Helsinki), **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** (Exeter, 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

Two general types of radiation damage:

- **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.

I. Change of <u>effective doping concentration</u>
⇒ type inversion, higher depletion voltage, under-depletion
⇒ loss of active volume ⇒ decrease of signal, increase of noise

II. Increase of <u>leakage current</u>
⇒ increase of shot noise, thermal runaway, power consumption…

III. Increase of <u>charge carrier trapping</u>
⇒ loss of charge

Same for all tested Silicon materials! → II., III.

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

Impact on detector performance and Charge Collection Efficiency
(depending on detector type and <u>geometry</u> and <u>readout electronics</u>!)

Can be optimized!

⇒ **Signal/noise ratio is the quantity to watch**

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RD50 approaches to develop radiation harder tracking detectors

- **Material Engineering -- 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 Silicon**
  - **Influence of processing technology**

- **Material Engineering-New Materials** (work concluded)
  - **Silicon Carbide (SiC), Gallium Nitride (GaN)**

- **Device Engineering (New Detector Designs)**
  - **p-type silicon detectors (n-in-p)**
  - **thin detectors**
  - **3D detectors**
  - **Simulation of highly irradiated detectors**
  - **Semi 3D detectors and Stripixels**
  - **Cost effective detectors**

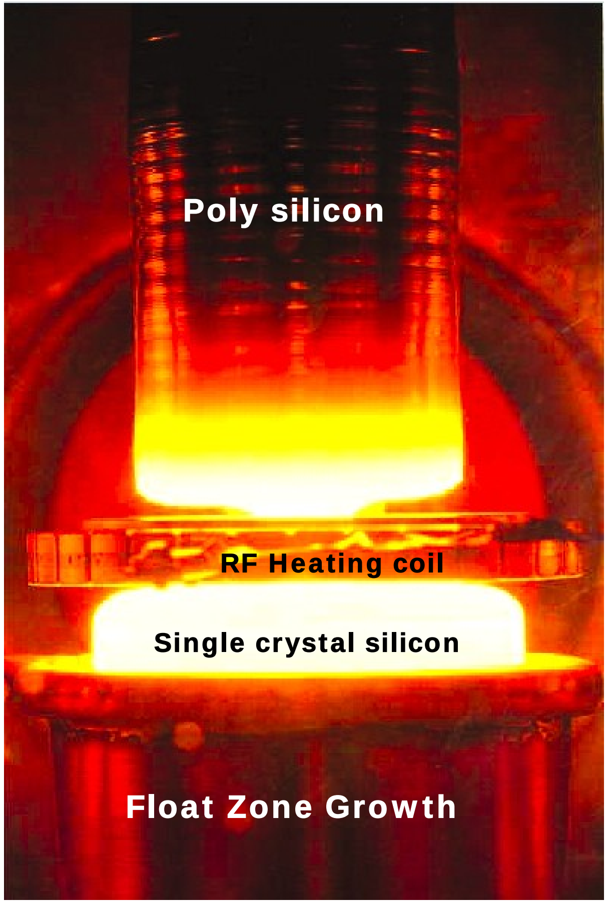
- **Development of test equipment and measurement recommendations**

Related Works – Not conducted by RD50

- **"Cryogenic Tracking Detectors"** (CERN RD39)
- **"Diamond detectors"** (CERN RD42)
- **Monolithic silicon detectors**
- **Detector electronics**

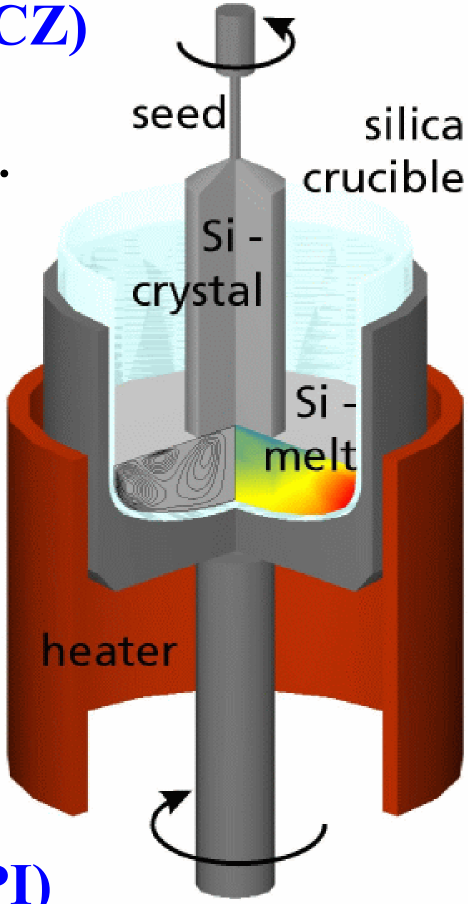
Silicon Growth Processes

- **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**

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Silicon Materials under Investigation

standard for particle detectors

used for LHC Pixel detectors

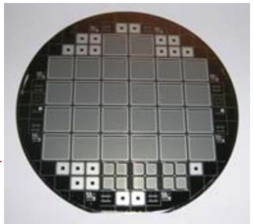
"new" silicon material

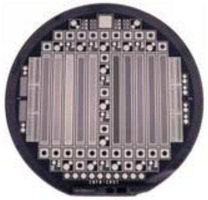
Material	Thickness [μm]	Symbol	ρ (Ωcm)	$[O_i]$ (cm^{-3})
Standard FZ (n- and p-type)	**50,100,150, 300**	**FZ**	**$1–30\times10^3$**	**$< 5\times10^{16}$**
Diffusion oxygenated FZ (n- and p-type)	**300**	**DOFZ**	**$1–7\times10^3$**	**$\sim 1–2\times10^{17}$**
Magnetic Czochralski Si, Okmetic, Finland (n- and p-type)	**100, 300**	**MCz**	**$\sim 1\times10^3$**	**$\sim 5\times10^{17}$**
Czochralski Si, Sumitomo, Japan (n-type)	**300**	**Cz**	**$\sim 1\times10^3$**	**$\sim 8\text{-}9\times10^{17}$**
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**	**$\sim 7\times10^{17}$**

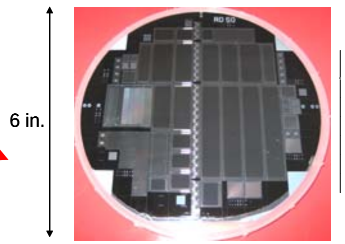
- **DOFZ silicon** - **Enriched with oxygen on wafer level, <u>inhomogeneous</u> distribution of oxygen**
- **CZ/MCZ silicon** - **high Oi (oxygen) and O_{2i} (oxygen dimer) concentration (homogeneous)**
  - **formation of shallow Thermal Donors possible**
- **Epi silicon** - **high O_i, O_{2i} content 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**

RD50 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).

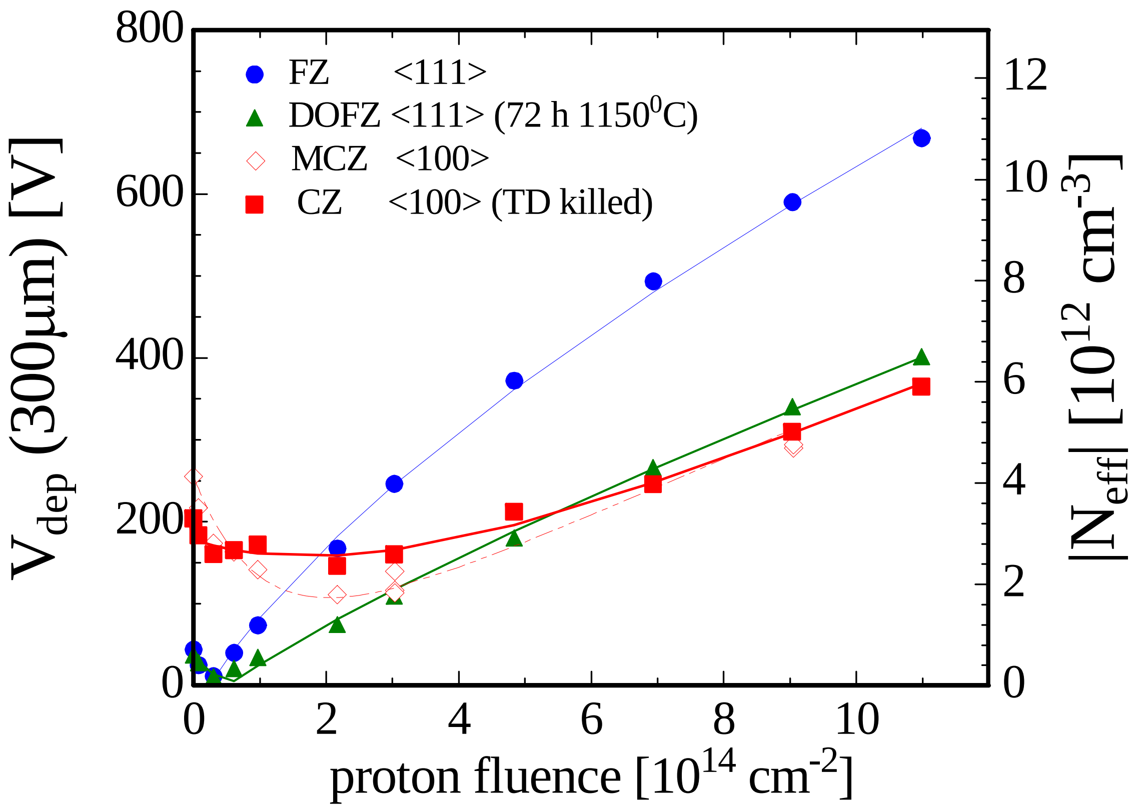
- M.Lozano, 8th RD50 Workshop, Prague, June 2006
- A.Pozza, 2nd Trento Meeting, February 2006
- G.Casse, 2nd Trento Meeting, February 2006
- D. Bortoletto, 6th RD50 Workshop, Helsinki, June 2005
- N.Zorzi, Trento Workshop, February 2005
- H. Sadrozinski, rd50 Workshop, Nov. 2007

FZ, DOFZ, Cz and MCz Silicon

- **Strong differences in V_{dep}**
  - **Standard FZ silicon**
  - **Oxygenated FZ (DOFZ)**
  - **CZ silicon and MCZ silicon**
- **Strong differences in internal electric field shape**

  (type inversion in FZ, no type inversion in MCZ silicon, double junction effects,…)
- **Different impact on pad and strip detector operation!**
  - **e.g.: a lower V_{dep} or $|N_{eff}|$ does not necessarily correspond to a higher CCE for strip detectors (see later)!**

24 GeV/c proton irradiation (n-type silicon)



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

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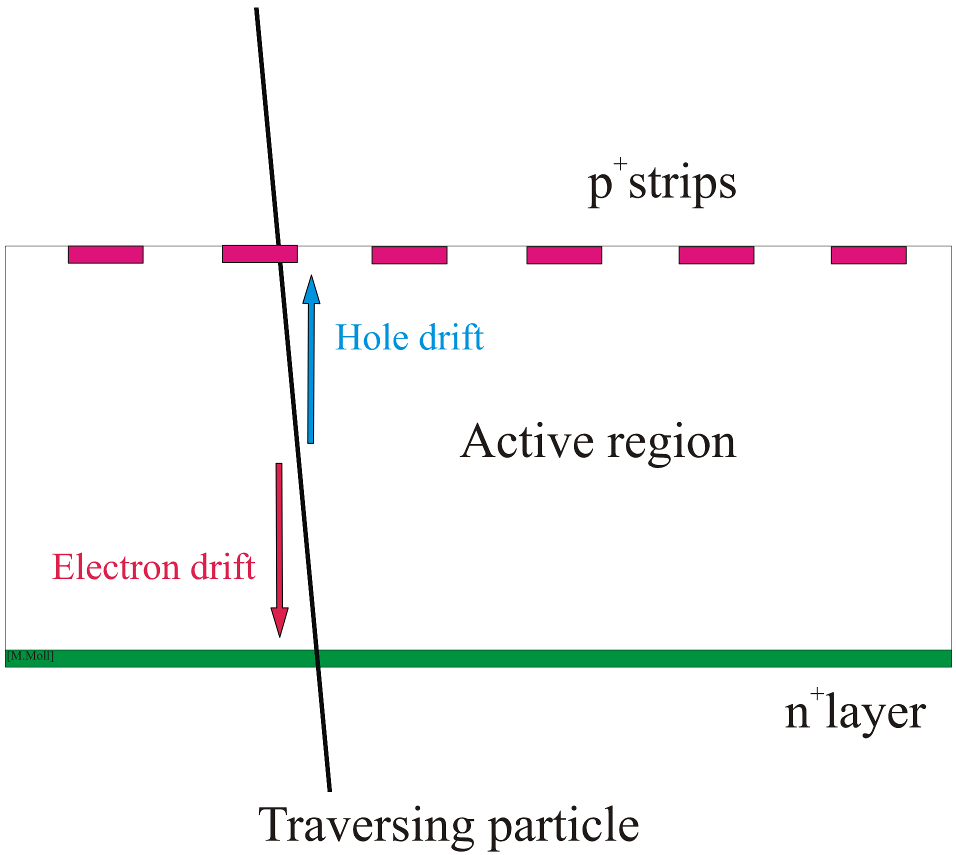
Advantage of non-inverting material

p-in-n detectors (schematic figures!)

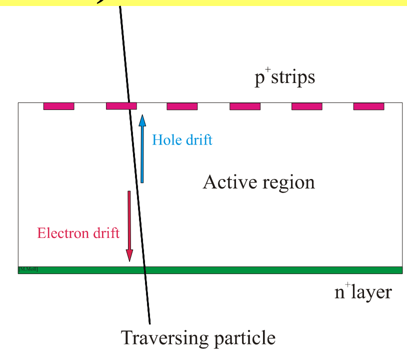
Fully depleted detector
(non – irradiated):



RD50 Advantage of non-inverting material
p-in-n detectors (schematic figures!)

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

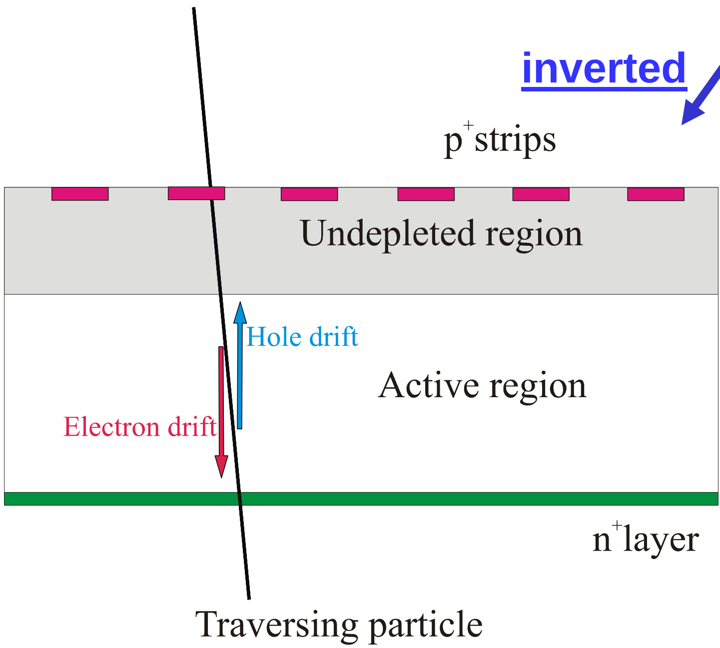
Fully depleted detector (non – irradiated):

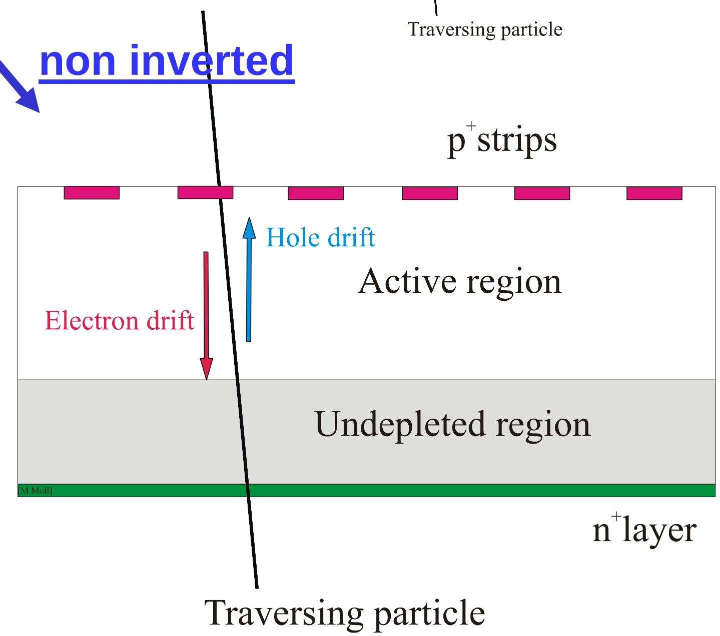


heavy irradiation

inverted

non inverted





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

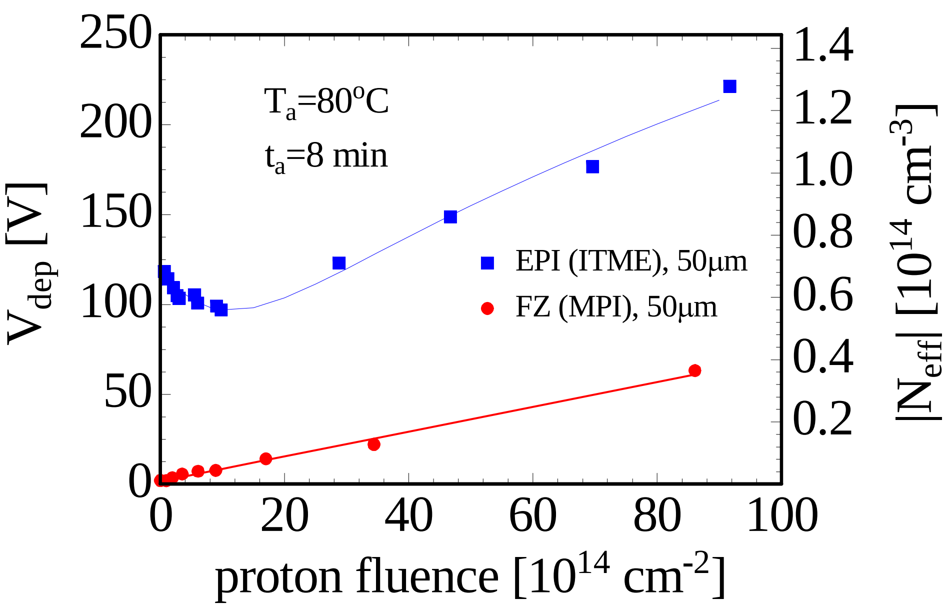
- **Charge spread – degraded resolution**
- **Charge loss – reduced CCE**

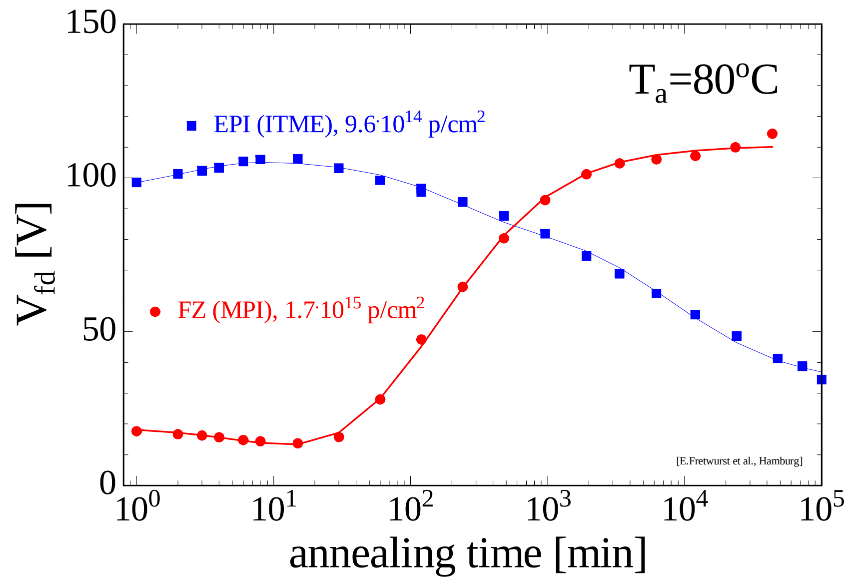
non-inverted, under-depleted:

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

RD50 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)





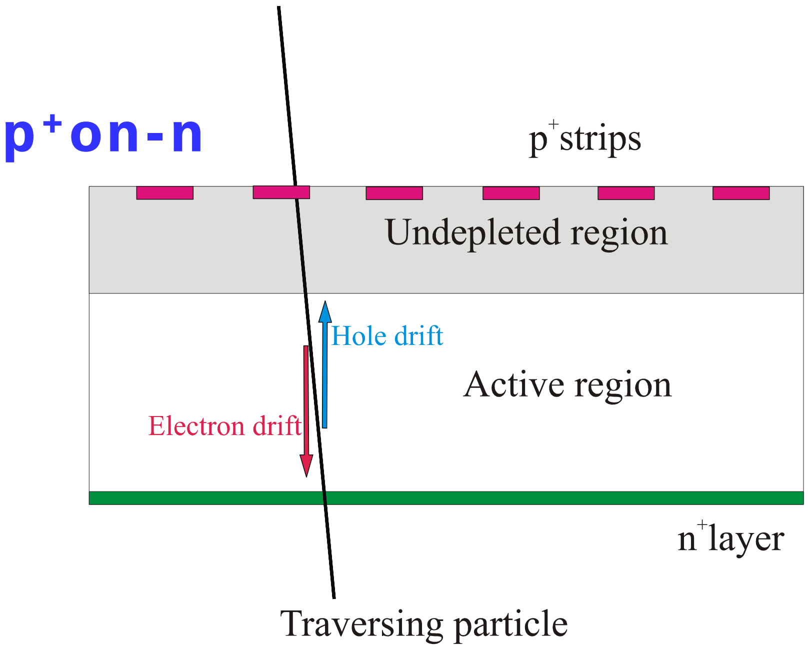
[E.Fretwurst et al.,RESMDD - October 2004]

- **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!

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:

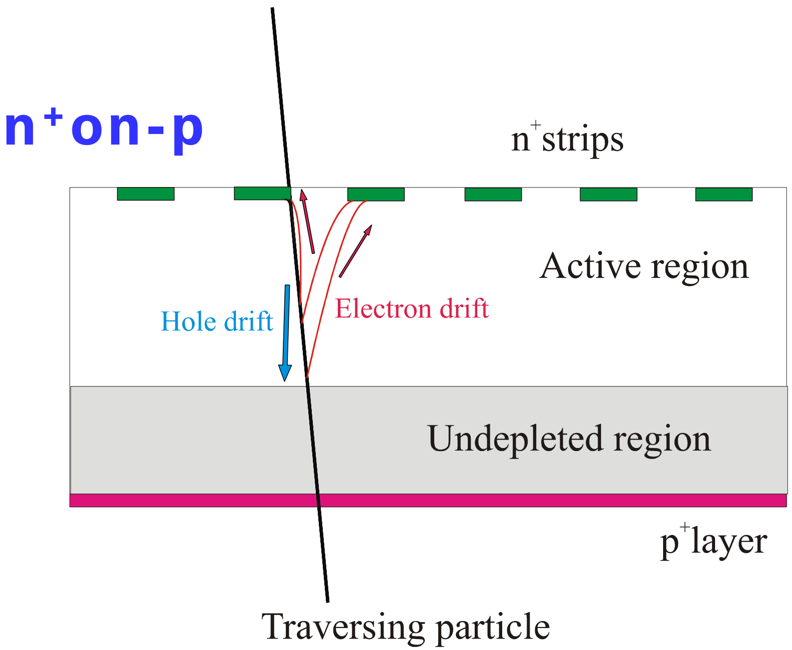


p-on-n silicon, under-depleted:

- **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:



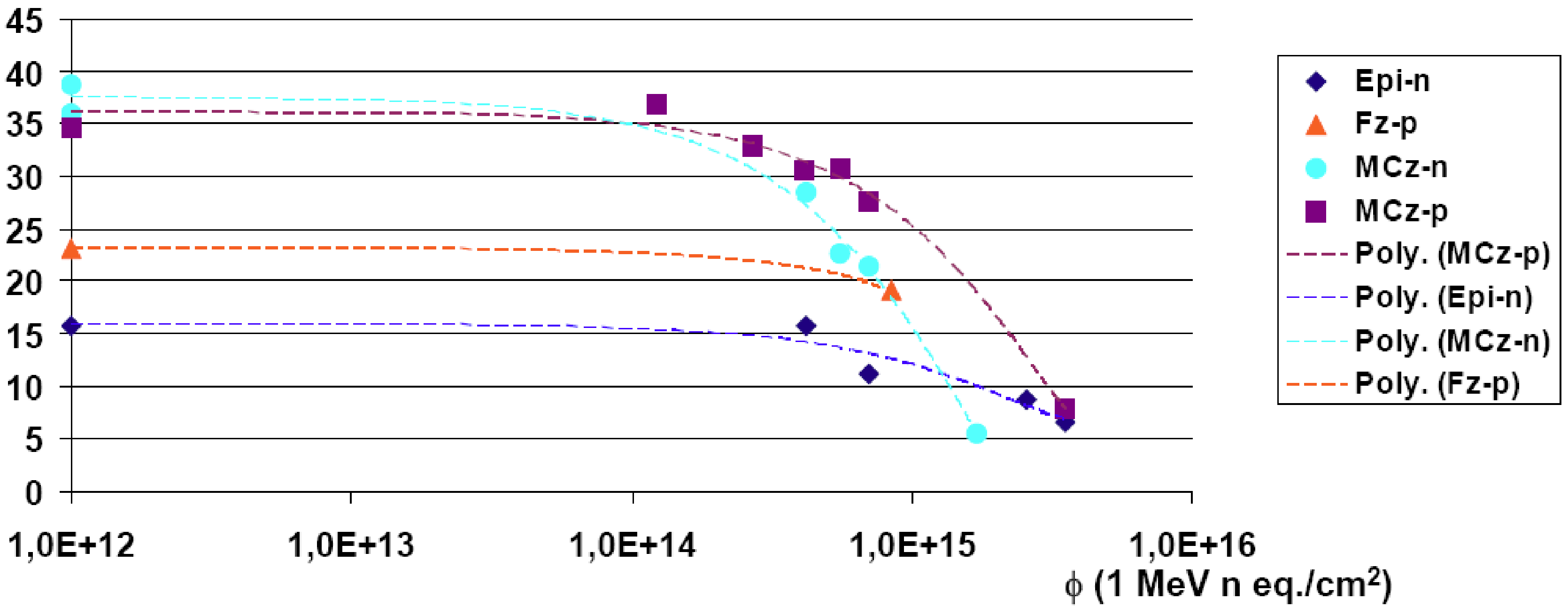
n-on-p silicon, under-depleted:

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

RD50 Strip detector tests: SMART/RD50

- **Experiment performed in framework of RD50 / SMART / CMS**
- **Irradiation:** 26 MeV protons, reactor neutrons
- **Measurement:** CMS DAQ (APV25, 25ns), -30°C
- **Signal/Noise representation:**

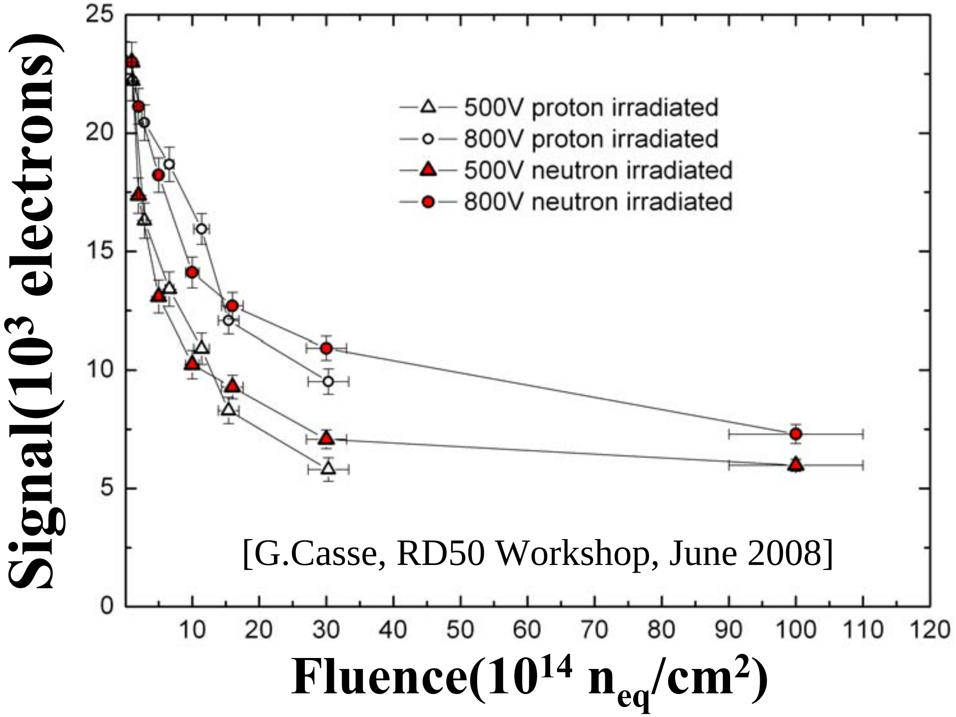
[A.Messineo, 11th RD50 Workshop, November 2007]



- **Material:** 150 µm Epitaxial silicon (n-type)
  300 µm MCZ silicon (n-type and p-type)
  200 µm FZ silicon (p-type)

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

n-in-p microstrip detectors

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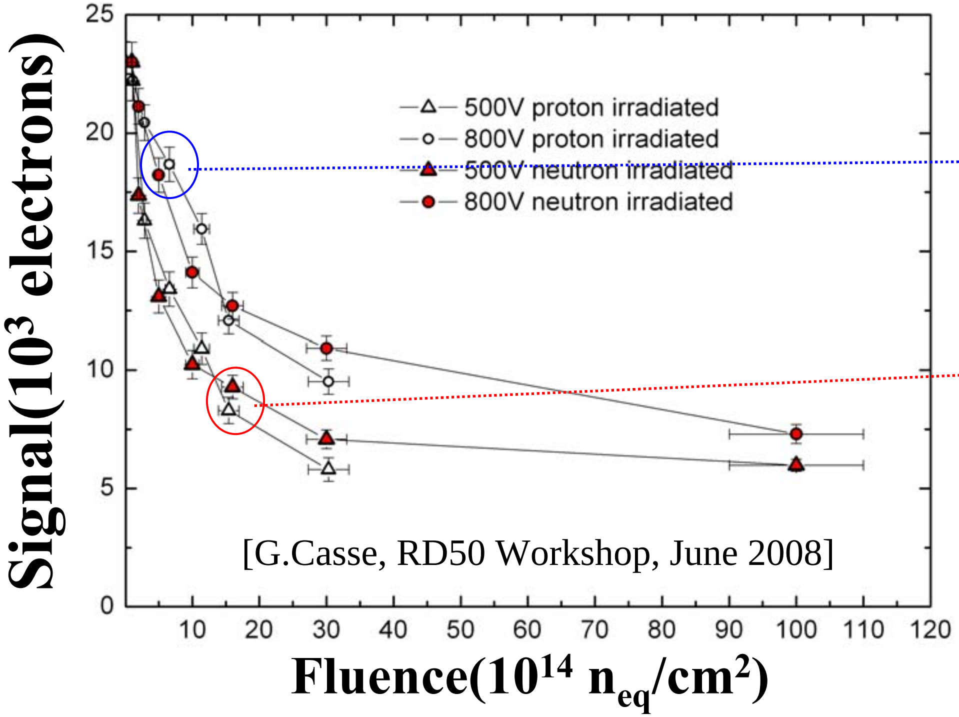
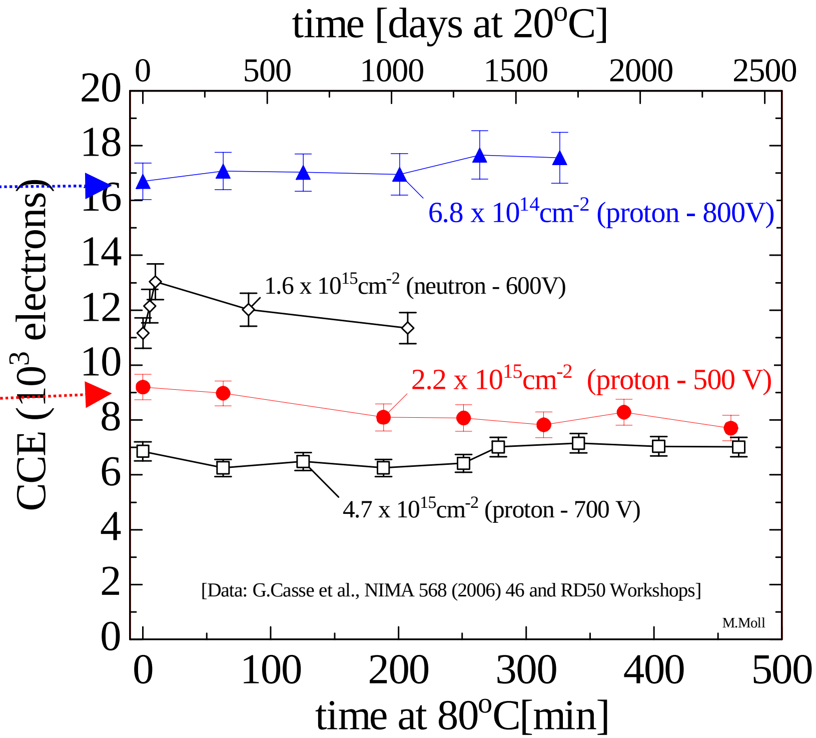




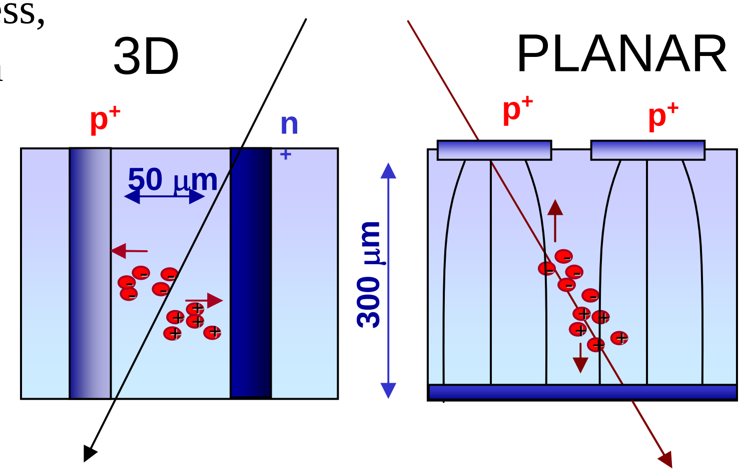
- **CCE: ~7300e (~30%)**
  after ~ 1×10^{16}cm^{-2} 800V
- **n-in-p sensors are strongly considered for ATLAS upgrade** (previously p-in-n used)

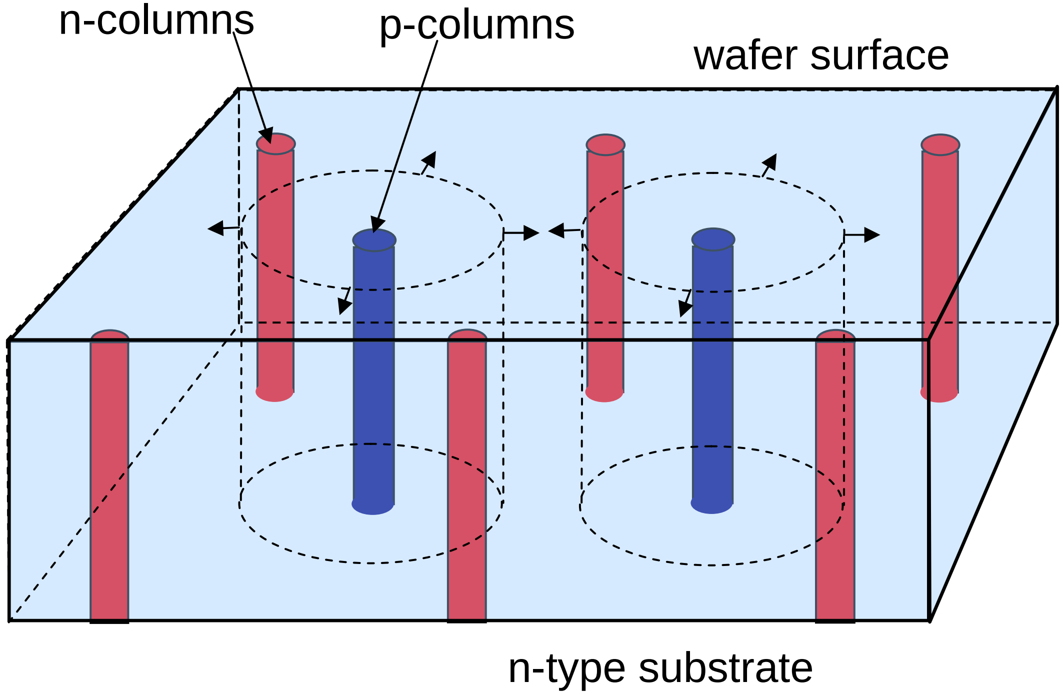
- **no reverse annealing in CCE measurements for neutron and proton irradiated detectors**

3D detector - concept

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

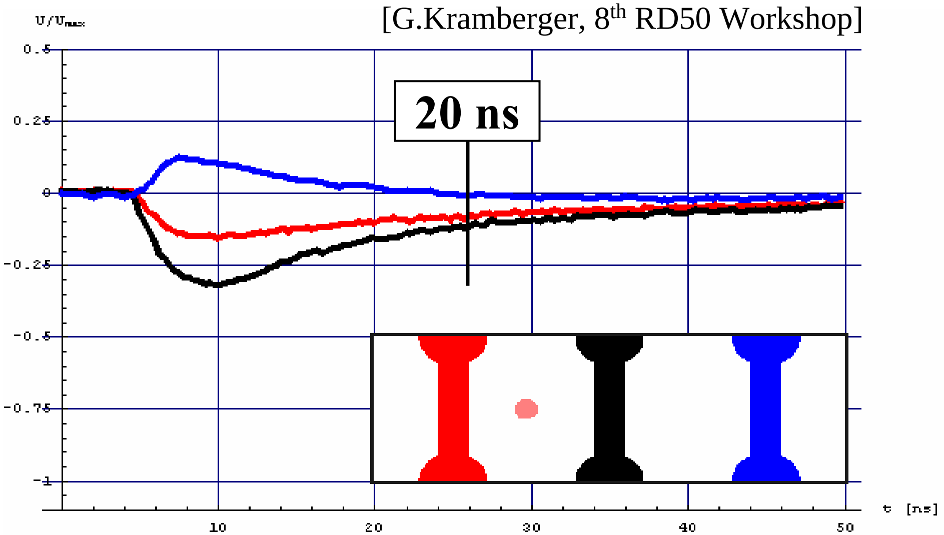




3D - SCT: Single Column Type

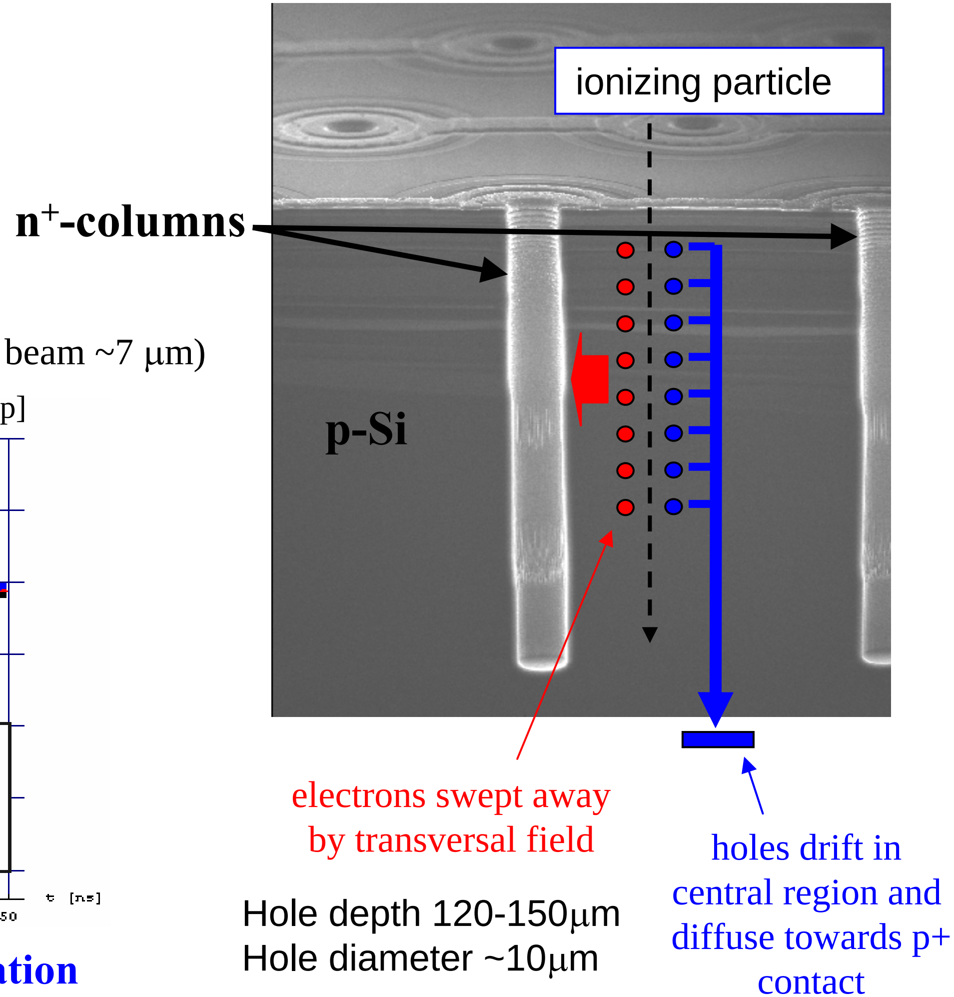
- **Simplified 3D architecture (proposed in 2005)**
  - n^+ columns in p-type substrate, p^+ backplane
- **Simplified process**
  - hole etching and doping only done once
  - no wafer bonding technology needed
  - single side process (uniform p^+ implant)
- **Position sensitive TCT on strip detector** (laser beam ~7 μm)

[G.Kramberger, 8th RD50 Workshop]



- **CCE measurements (^{90}Sr source) after irradiation**
  - As expected the devices are not radiation tolerant

- **Fabricated in 2006 (strips, pads, ..)**
  - IRST(Italy), CNM Barcelona



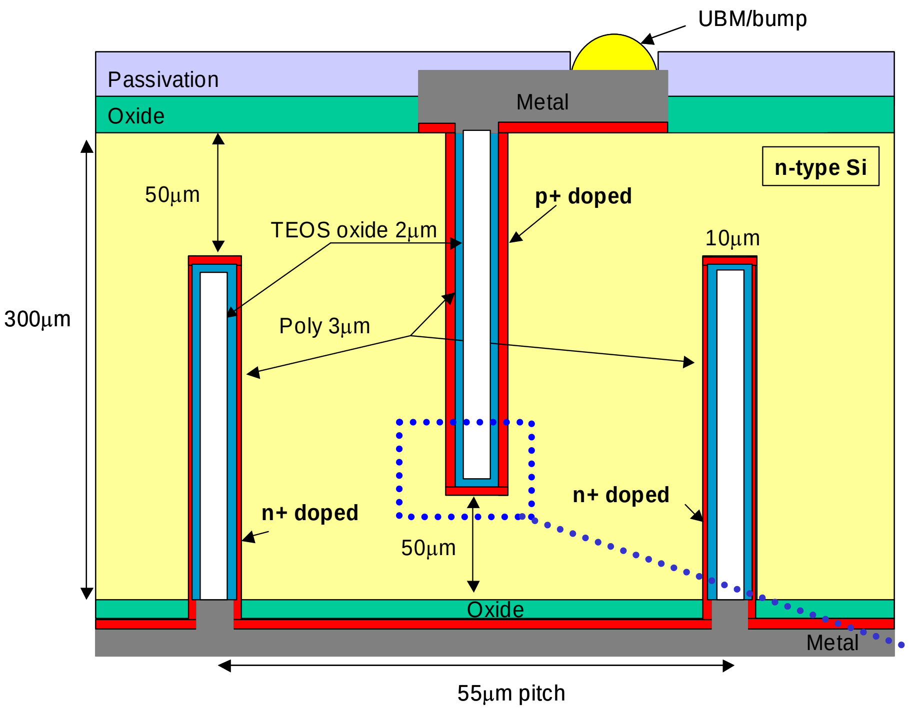
Hole depth 120-150μm
Hole diameter ~10μm

RD50 Next step: Double-Sided 3D detectors

- **Under processing at CNM, Barcelona**

  RD50 collaborative work (CNM, Glasgow, Valencia, …)

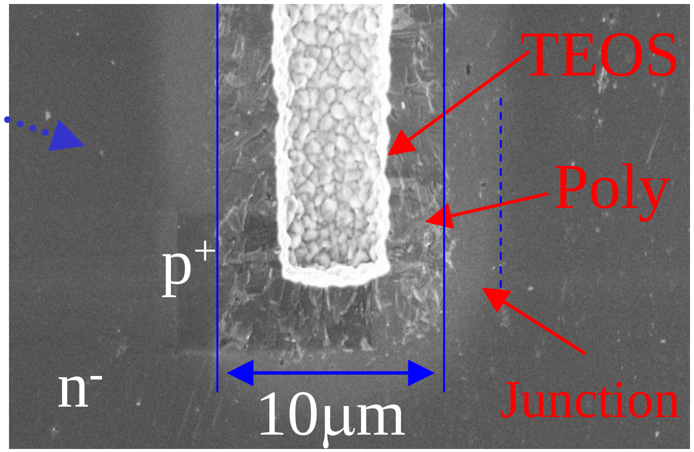
[G.Fleta, RD50 Workshop, June 2007]



- **4" wafer with Pad, Strip** (short and long, 80µm pitch) **and Pixel** (ATLAS, Medipix2, Pilatus) **structures under processing at CNM, Barcelona**
  - **-** p-in-n wafers finished, under test now
  - - n-in-p wafers expected until end of 2007

- **Processing at FBK, Trento and IceMOS, Belfast ongoing**

- **Advantages against standard 3D:**
  - Less complicated (expensive) process (??)
    - No wafer bonding
    - p^+ and n^+ columns accessed from opposite surfaces
- **Disadvantages (?) :**
  - lower field region below/above columns
- **Successful process evaluation runs:**
  - etching of holes with aspect ratio 25:1 (10 µm diameter, 250 µm depth)
  - polysilicon deposit, doping, TEOS, ..



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**

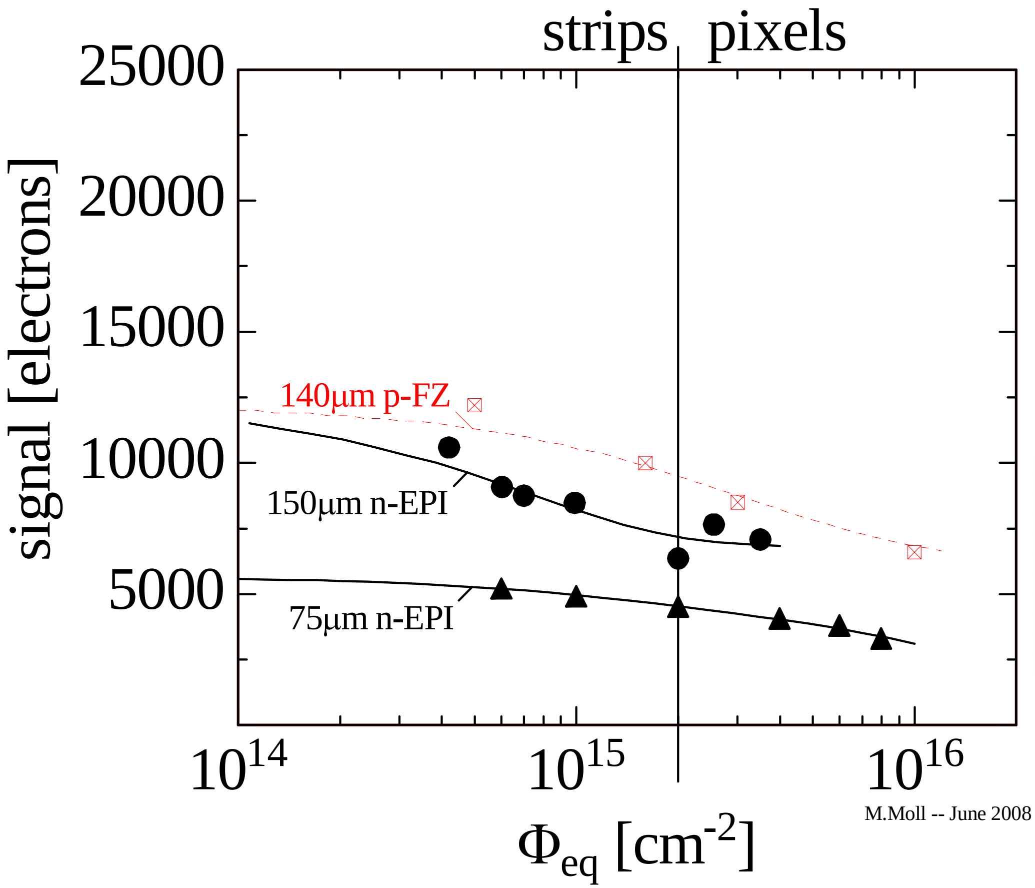
  ⇒ This comparison gives only an indication of which material/technology could be used, to be more specific, the exact application should be looked at!

- **Remember:**
  The obtained signal has still to be compared to the noise !!

RD50 Silicon materials for Tracking Sensors

- **Signal comparison for various Silicon sensors**

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



- n-in-p (FZ), 140 µm, 500V [7]
- p-in-n (EPI), 150 µm [8,9]
- p-in-n (EPI), 75µm [10]

[1] 3D, double sided, 250µm columns, 300µm substrate [Pennicard 2007]
[2] p-FZ, 280µm, (-30°C, 25ns), strip [Casse 2007]
[3] p-FZ, 280µm, (-30°C, 25ns), strip [Casse 2004]
[4] p-MCZ, 300µm, (-30°C, µs), pad [Bruzzi 2006]
[5] p-MCZ, 300µm, (<0°C, µs), strip [Bernadini 2007]
[6] n-MCZ, 300µm, (-30°C, 25ns), strip [Messineo 2007]
[7] p-FZ, 140µm, (-30°C, 25ns), strip [Casse 2007]
[8] n-EPI, 150µm, (-30°C, 25ns), strip [Messineo 2007]
[9] n-epi Si, 150µm, (-30°C, 25ns), pad [Kramberger 2006]
[10] n-epi Si, 75µm, (-30°C, 25ns), pad [Kramberger 2006]
[11] n-MCZ Si, 300µm, (-25°C, 25ns), n-strip [Casse 2008]

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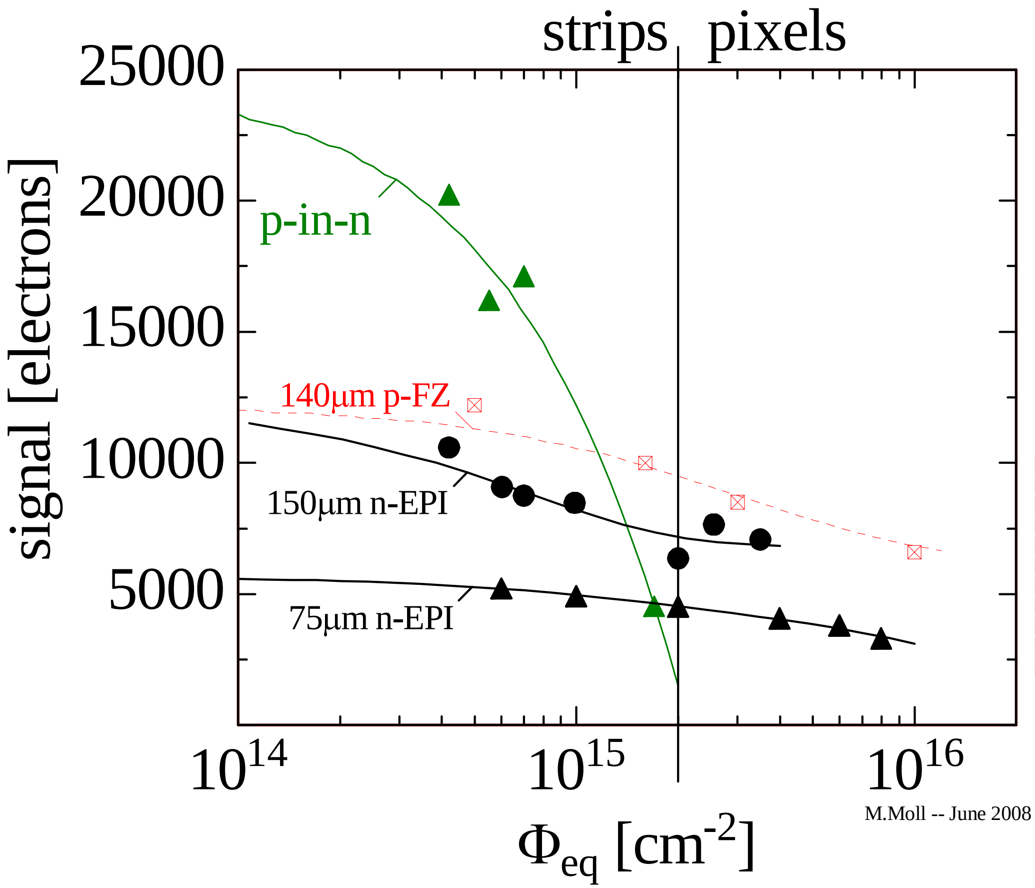


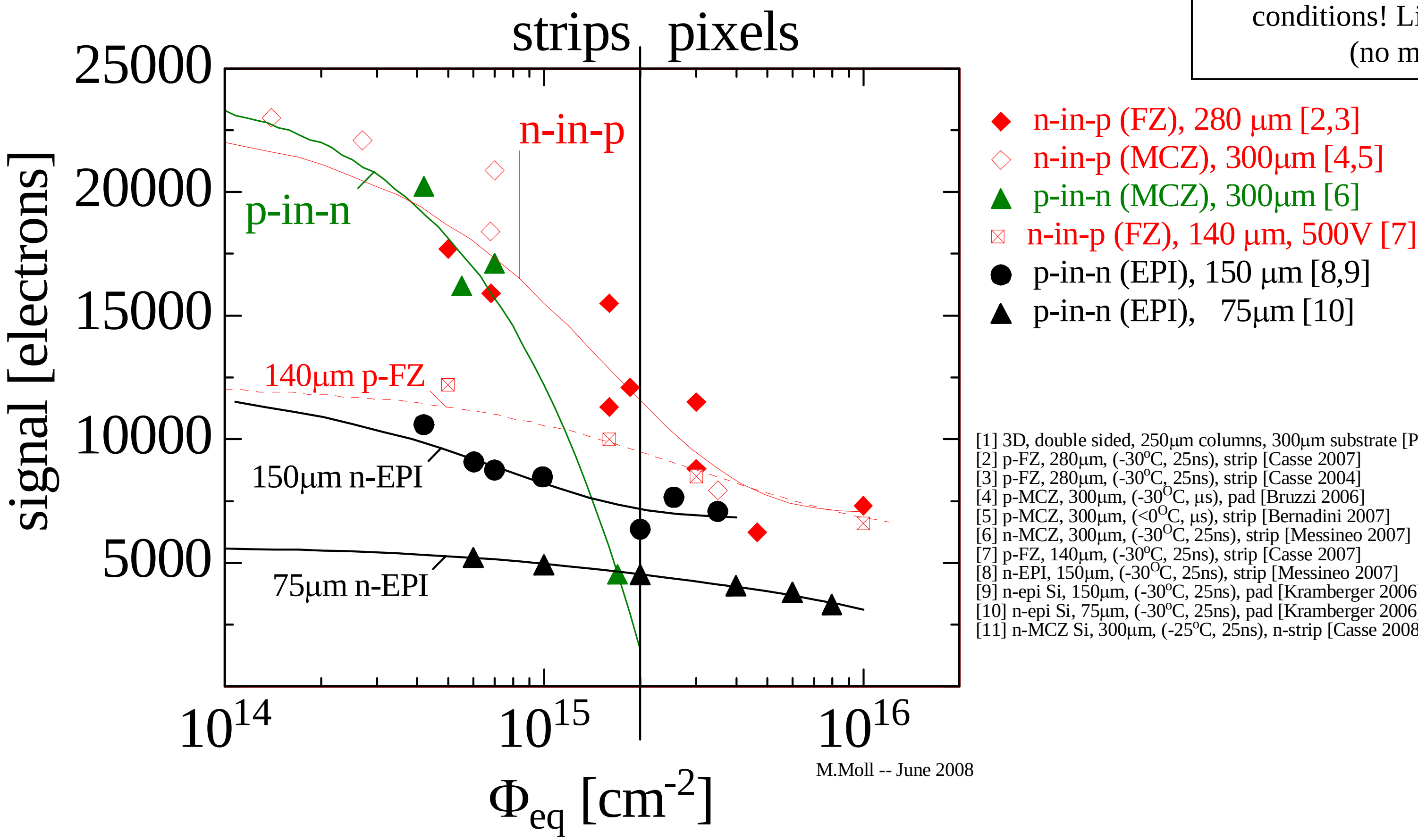
▲ p-in-n (MCZ), 300µm [6]
⊠ n-in-p (FZ), 140 µm, 500V [7]
● p-in-n (EPI), 150 µm [8,9]
▲ p-in-n (EPI), 75µm [10]

[1] 3D, double sided, 250µm columns, 300µm substrate [Pennicard 2007]
[2] p-FZ, 280µm, (-30^{o}C, 25ns), strip [Casse 2007]
[3] p-FZ, 280µm, (-30^{o}C, 25ns), strip [Casse 2004]
[4] p-MCZ, 300µm, (-30^{O}C, µs), pad [Bruzzi 2006]
[5] p-MCZ, 300µm, (<0^{O}C, µs), strip [Bernadini 2007]
[6] n-MCZ, 300µm, (-30^{O}C, 25ns), strip [Messineo 2007]
[7] p-FZ, 140µm, (-30^{o}C, 25ns), strip [Casse 2007]
[8] n-EPI, 150µm, (-30^{O}C, 25ns), strip [Messineo 2007]
[9] n-epi Si, 150µm, (-30^{o}C, 25ns), pad [Kramberger 2006]
[10] n-epi Si, 75µm, (-30^{o}C, 25ns), pad [Kramberger 2006]
[11] n-MCZ Si, 300µm, (-25^{o}C, 25ns), n-strip [Casse 2008]

RD50 Silicon materials for Tracking Sensors

- **Signal comparison for various Silicon sensors**

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



[1] 3D, double sided, 250µm columns, 300µm substrate [Pennicard 2007]
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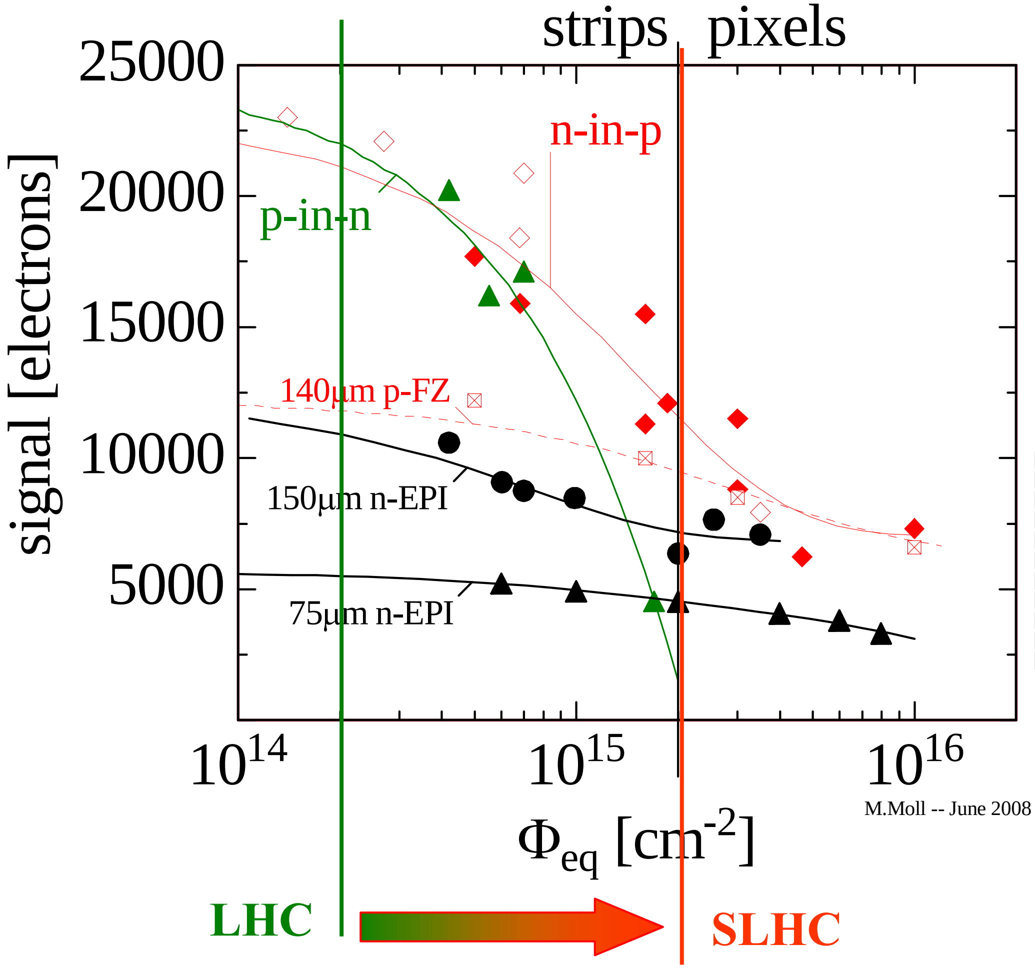

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highest fluence for strip detectors in LHC: The used p-in-n technology is sufficient

p-in-n technology not sufficient for Super-LHC detectors any more

RD50 Silicon materials for Tracking Sensors

- **Signal comparison for various Silicon sensors**

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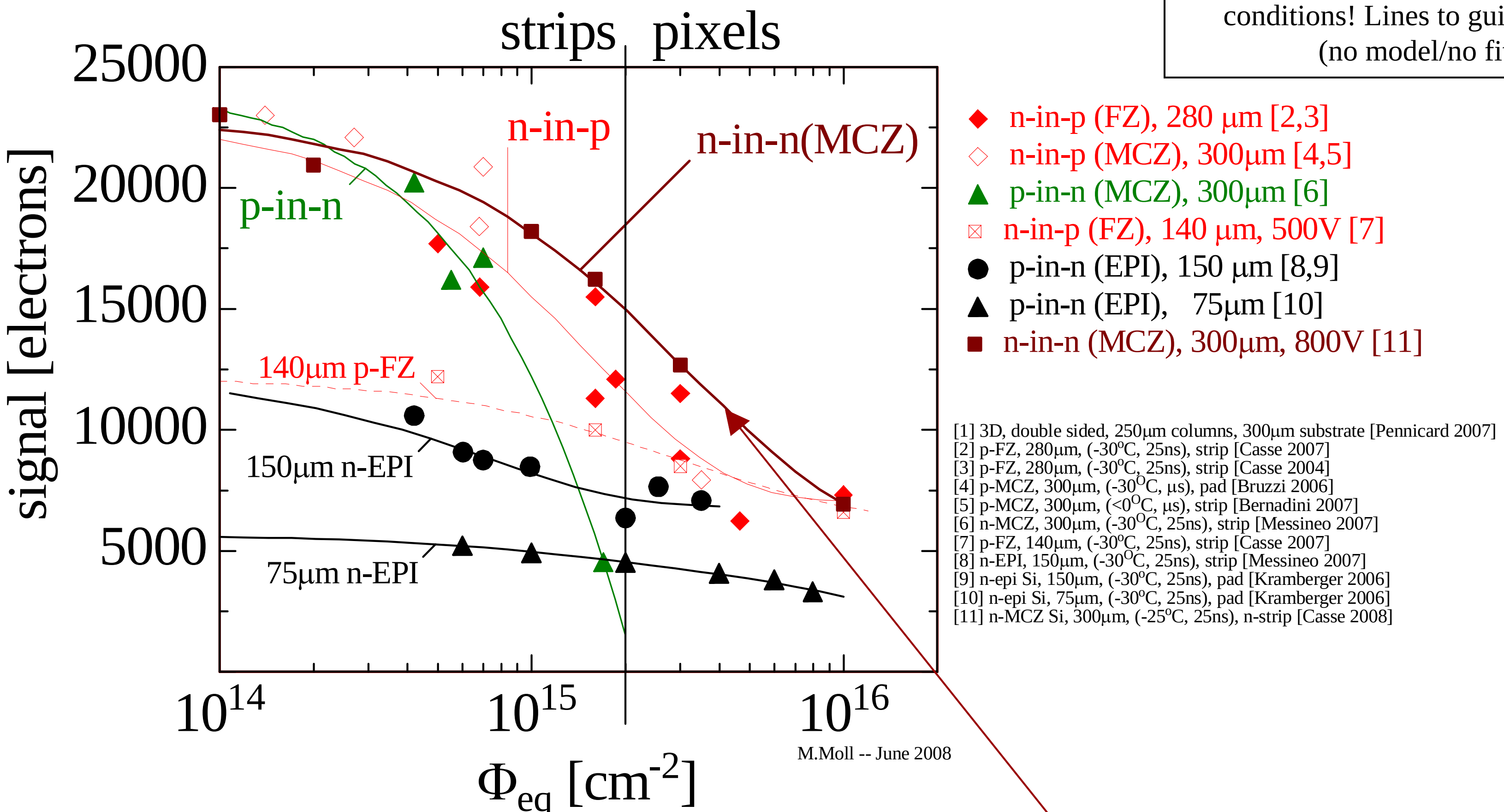
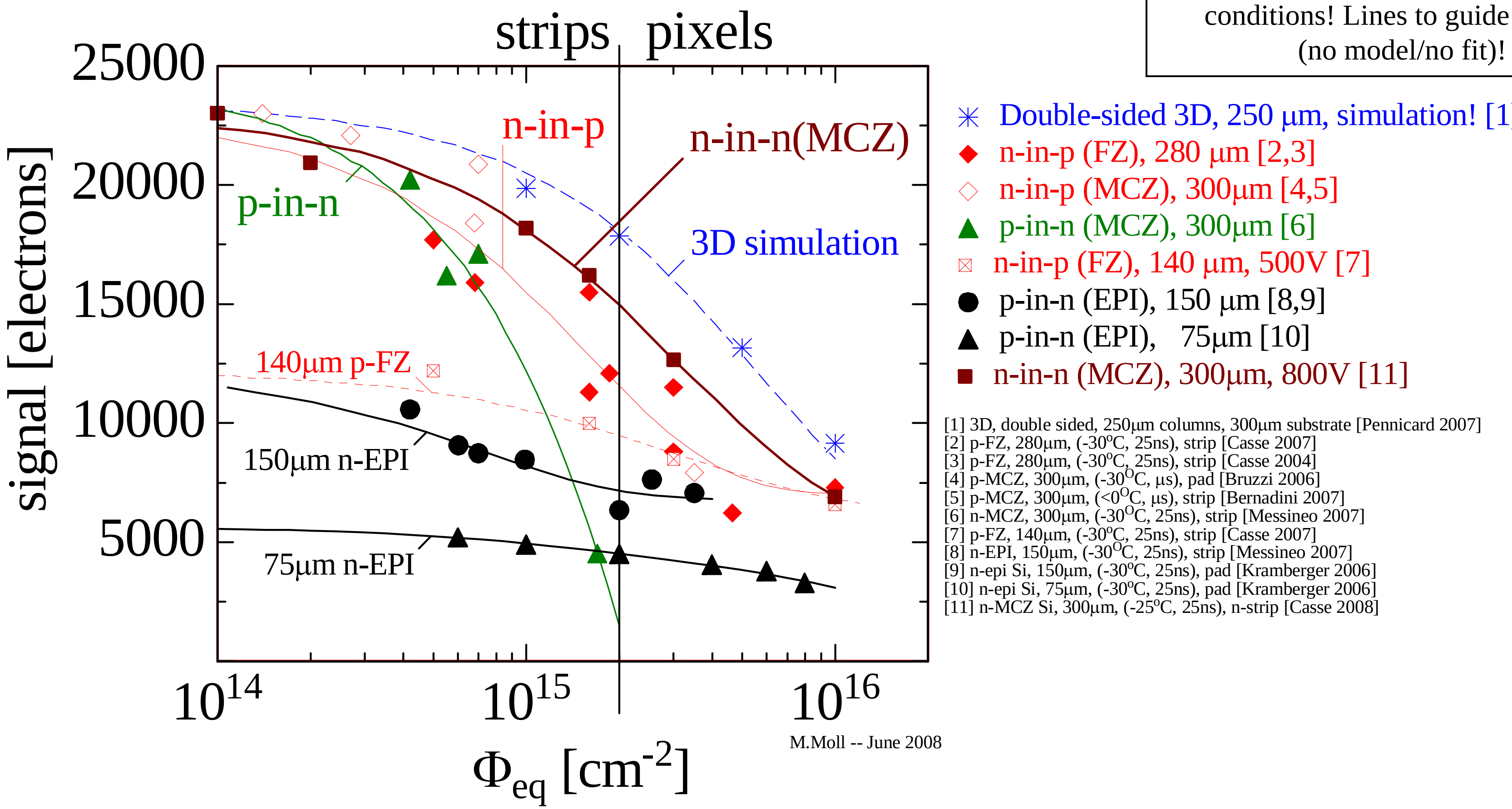


Surprise: Data shown on RD50 Workshop last week by Casse et al. (Liverpool)!

- **Signal comparison for various Silicon sensors**

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



- **At a fluence of ~ 10^{15} n_{eq}/cm² 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 ??**

Summary

- **Wide range of silicon materials under investigation within RD50**
  - **Floating Zone (FZ), Magnetic Czochralski (MCZ), Epitaxial (EPI) silicon**
  - **n- and p-type silicon with different thickness ranging from 25 to 300 μm**
  - **Some materials do not 'type-invert' under proton irradiation (n-type MCZ, EPI)**
    Very complex internal electric field structure (double junction effects)
- **Segmented detectors at high fluences ($\Phi > 10^{15}cm^{-2}$):**
  - **Collection of electrons at electrodes essential: Use n-in-p or n-in-n detectors!**
  - **Good radiation tolerance of n-in-p detectors and 'CCE immunity' against reverse annealing**
  - **MCZ and FZ p-type show similar results**
  - **MCZ n-type (n-in-n) shows excellent results (would need double sided processing)**
- **3D detectors**
  - **Single type column 3D – processed, irradiated, analyzed : Not radiation tolerant (as expected) – However, 'paved the way' for double column 3D detectors**
  - **Production of Double Sided and Full 3D detectors under way in several facilities (IRST, CNM, Sintef, IceMOS,…). First unirradiated devices characterized.**
- **Not reported on:**
  - **Defect studies: "WODEAN"** - Massive work program under way using C-DLTS, I-DLTS, TSC, PITS, TCT, FTIR, EPR, PL, PC, CV, IV, .. methods – (~10 RD50 Institutes) – about 250 detectors irradiated with neutrons for a first experiment.

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