TIPP09 - The 1st international conference on Technology and Instrumentation in Particle Physics

Recent advances in the development of semiconductor detectors for SLHC

Esa Tuovinen
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on behalf of RD50

Outline:

Motivation

Silicon materials

Defect characterization

Irradiation studies

3D detectors

Conclusions

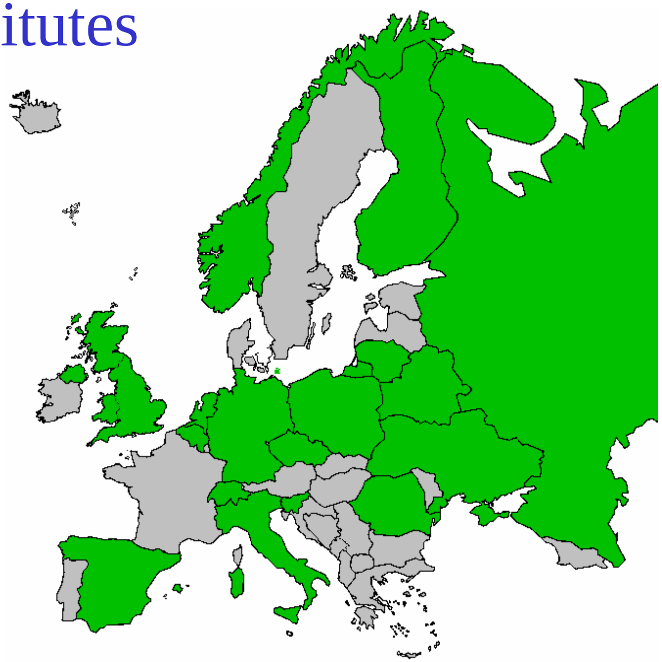
http://www.cern.ch/rd50

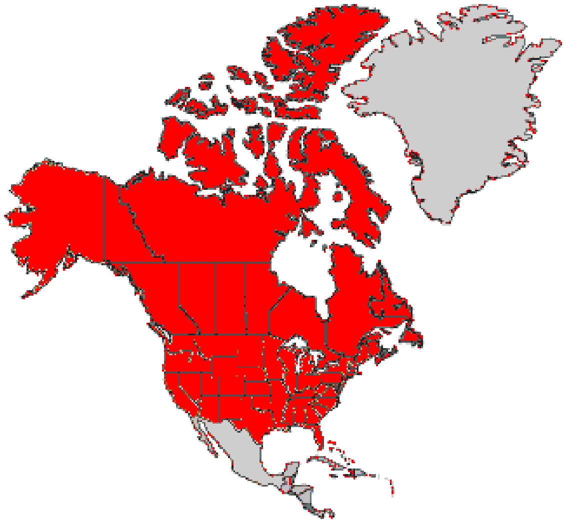
RD50 Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

250 Members from 48 Institutes

41 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** (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

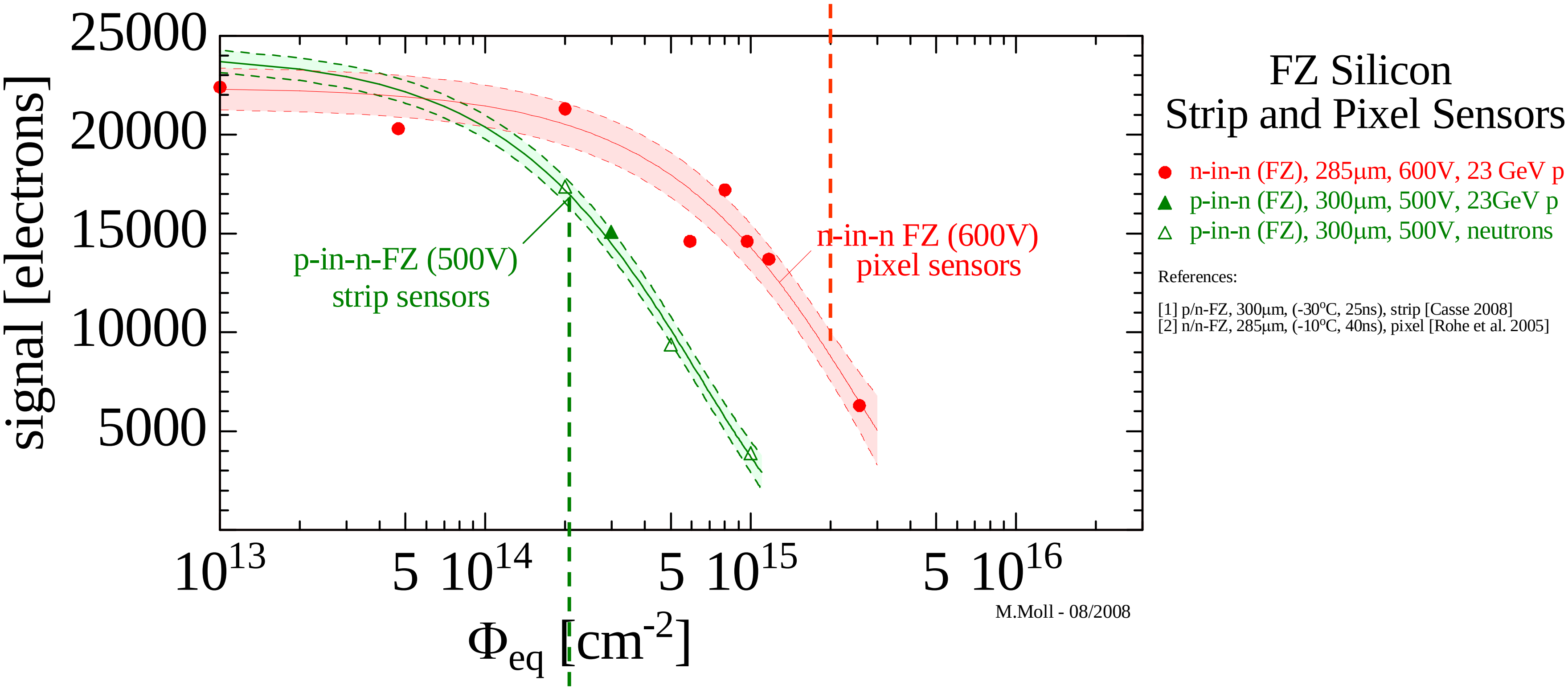
RD50

Motivation:

Signal degradation for LHC Silicon Sensors

Pixel sensors:

max. cumulated fluence for LHC



Strip sensors:

max. cumulated fluence for LHC

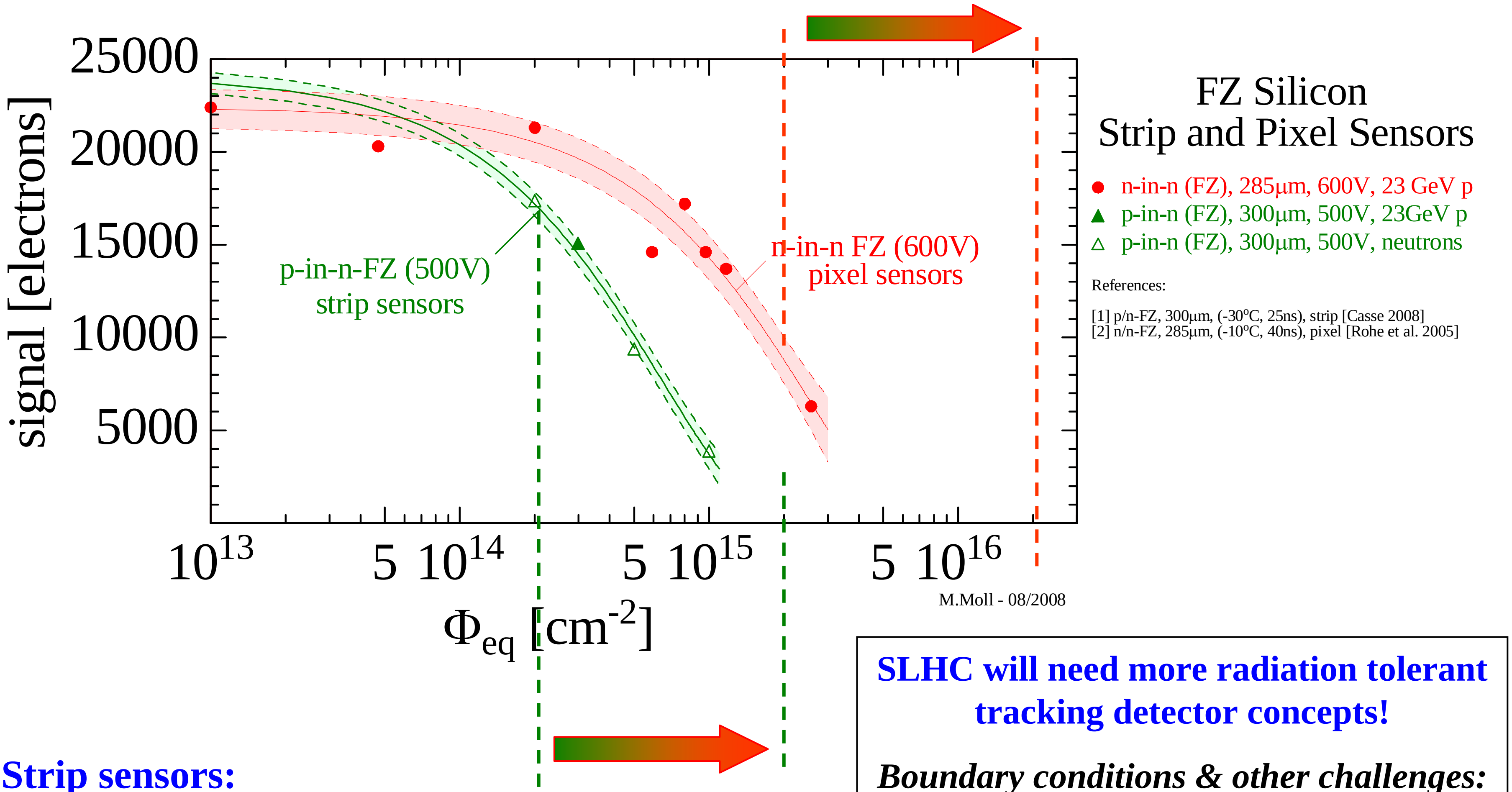
RD50

Motivation:

Signal degradation for LHC Silicon Sensors

Pixel sensors:

max. cumulated fluence for LHC and SLHC



Strip sensors:

max. cumulated fluence for LHC and SLHC

SLHC will need more radiation tolerant tracking detector concepts!

Boundary conditions & other challenges:

Granularity, Powering, Cooling, Connectivity, Triggering, Low mass, Low cost !

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

Radiation Damage to Sensors:

- **Bulk damage due to NIEL**
  - Change of effective doping concentration
  - Increase of leakage current
  - Increase of charge carrier trapping
- **Surface damage due to IEL**

  (accumulation of positive charge in oxide & interface charges)

- **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

Available Irradiation Sources in RD50

- ☐ 24 GeV/c protons, PS-CERN
- ☐ 10-50 MeV protons, Jyvaskyla +Helsinki
- ☐ Fast neutrons, Louvain
- ☐ 26 MeV protons, Karlsruhe
- ☐ TRIGA reactor neutrons, Ljubljana

- Development of test equipment and measurement recommendations

Silicon Materials under Investigation

standard for particle detectors

used for LHC Pixel detectors

“new” silicon material

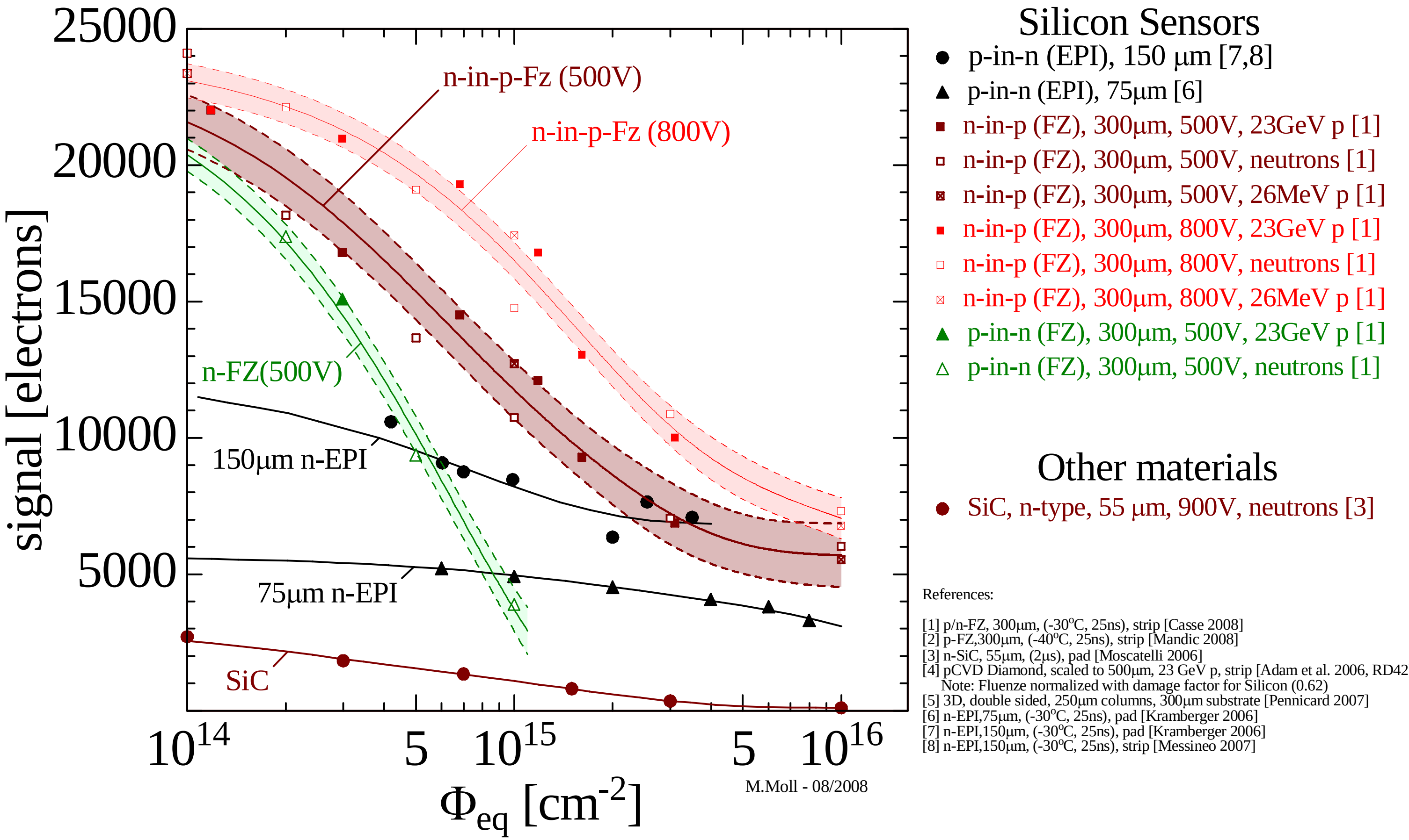
Material	Thickness [µm]	Symbol	ρ (Ωcm)	[O_i] (cm^{-3})
Standard FZ (n- and p-type)	**50,100,150, 300**	**FZ**	**$1–30\times10^{3}$**	**$< 5\times10^{16}$**
Diffusion oxygenated FZ (n- and p-type)	**300**	**DOFZ**	**$1–7\times10^{3}$**	**$\sim 1–2\times10^{17}$**
Magnetic Czochralski Si, Okmetic, Finland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

RD50 Silicon materials for Tracking Sensors

- Signal comparison for various Silicon sensors

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



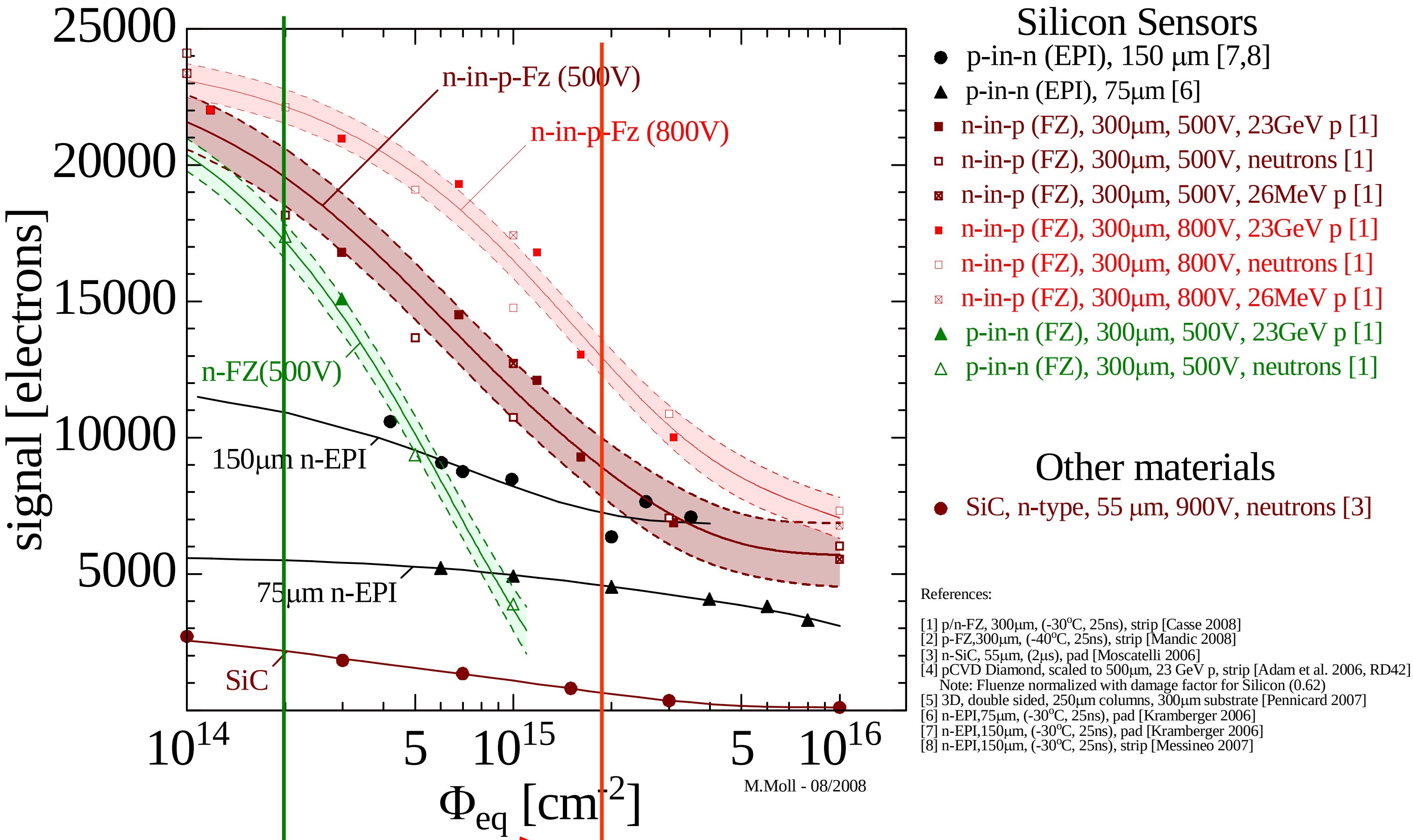
References:

[1] p/n-FZ, 300µm, (-30^{o}C, 25ns), strip [Casse 2008]
[2] p-FZ,300µm, (-40^{o}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^{o}C, 25ns), pad [Kramberger 2006]
[7] n-EPI,150µm, (-30^{o}C, 25ns), pad [Kramberger 2006]
[8] n-EPI,150µm, (-30^{o}C, 25ns), strip [Messineo 2007]

RD50 Silicon materials for Tracking Sensors

- **Signal comparison for various Silicon sensors**

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



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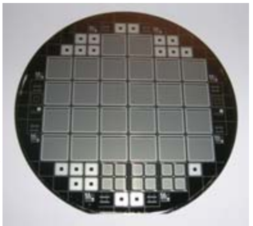
LHC → **SLHC**

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

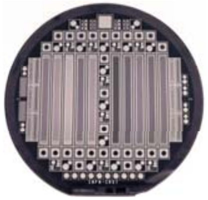
n-in-p technology should be sufficient for Super-LHC at radii presently (LHC) occupied by strip sensors

RD50 RD50 Test Sensor Production Runs (2005-2008)

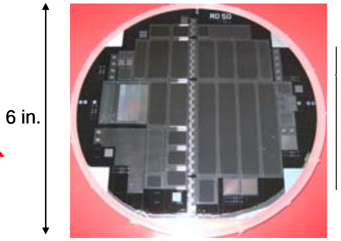
- **Recent production of Silicon Strip, Pixel and Pad detectors (non exclusive list):**
  - **CIS Erfurt, Germany**
    - **2005/2006/2007 (RD50): Several runs with various epi 4” wafers only pad detectors**
  - **CNM Barcelona, Spain**
    - **2006 (RD50): 22 wafers (4”), (20 pad, 26 strip, 12 pixel),(p- 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 3 and 5 × 10^{12} 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)**

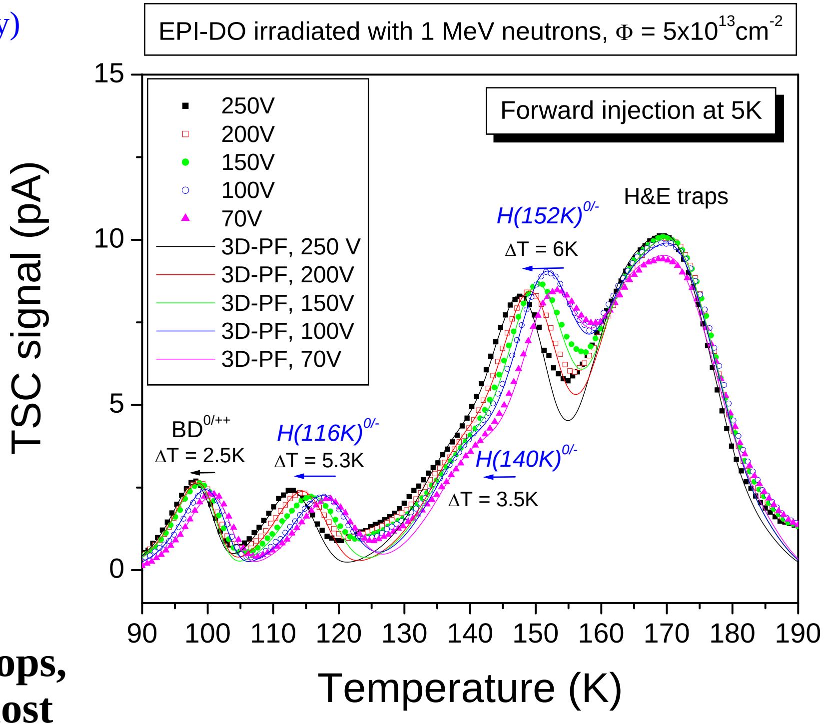
Hundreds of samples (pad/strip/pixel) recently produced on various materials (n- and p-type).

- **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**

RD50 Defect Characterization - WODEAN

- **WODEAN project** (initiated in 2006, 10 RD50 institutes, guided by G.Lindstroem, Hamburg)
  - **Aim:** **Identify defects responsible for Trapping, Leakage Current, Change of N_{eff}**
  - **Method:** **Defect Analysis on identical samples performed with the various tools available inside the RD50 network:**
    - **C-DLTS** (Capacitance Deep Level Transient Spectroscopy)
    - **I-DLTS** (Current Deep Level Transient Spectroscopy)
    - **TSC** (Thermally Stimulated Currents)
    - **PITS** (Photo Induced Transient Spectroscopy)
    - **FTIR** (Fourier Transform Infrared Spectroscopy)
    - **RL** (Recombination Lifetime Measurements)
    - **PC** (Photo Conductivity Measurements)
    - **EPR** (Electron Paramagnetic Resonance)
    - **TCT** (Transient Charge Technique)
    - **CV/IV**
  - **~ 240 samples irradiated with protons and neutrons**
  - **first results presented on 2007 RD50 Workshops, further analyses in 2008 and publication of most important results in Applied Physics Letters**

… significant impact of RD50 results on silicon solid state physics – defect identification



Example: TSC measurement on defects (acceptors) responsible for the reverse annealing

Summary – defects with strong impact on the device properties at operating temperature

Point defects

- $E_i^{BD} = E_c - 0.225$ eV
- $\sigma_n^{BD} = 2.3\times10^{-14}$ cm^2

- $E_i^{I} = E_c - 0.545$ eV
  - $\sigma_n^{I} = 2.3\times10^{-14}$ cm^2
  - $\sigma_p^{I} = 2.3\times10^{-14}$ cm^2

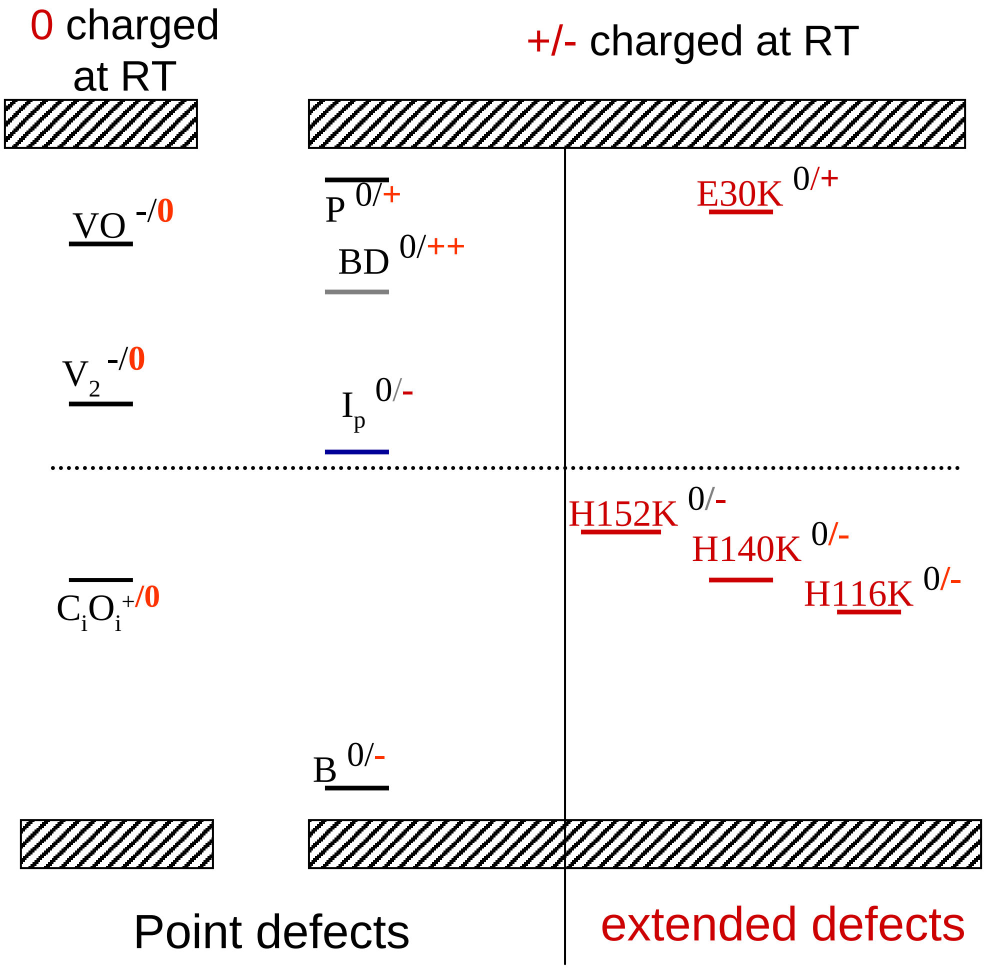
Cluster related centers

- $E_i^{116K} = E_v + 0.33$eV
- $\sigma_p^{116K} = 4\times10^{-14}$ cm^2

- $E_i^{140K} = E_v + 0.36$eV
- $\sigma_p^{140K} = 2.5\times10^{-15}$ cm^2

- $E_i^{152K} = E_v + 0.42$eV
- $\sigma_p^{152K} = 2.3\times10^{-14}$ cm^2

- $E_i^{30K} = E_c - 0.1$eV
- $\sigma_n^{30K} = 2.3\times10^{-14}$ cm^2



I.Pintilie, NSS, 21 October 2008, Dresden

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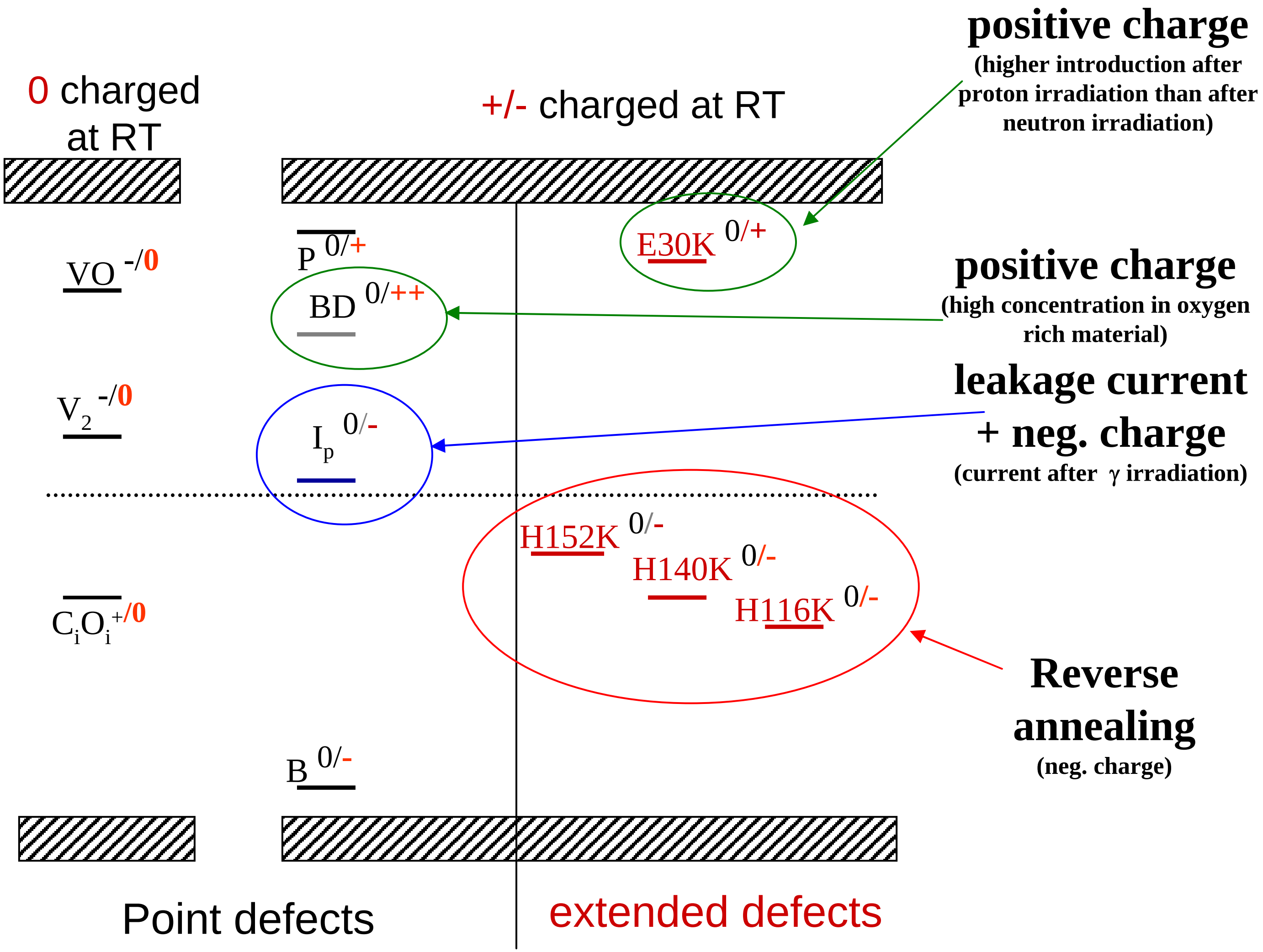


positive charge
(higher introduction after proton irradiation than after neutron irradiation)

positive charge
(high concentration in oxygen rich material)

leakage current + neg. charge
(current after γ irradiation)

Reverse annealing
(neg. charge)

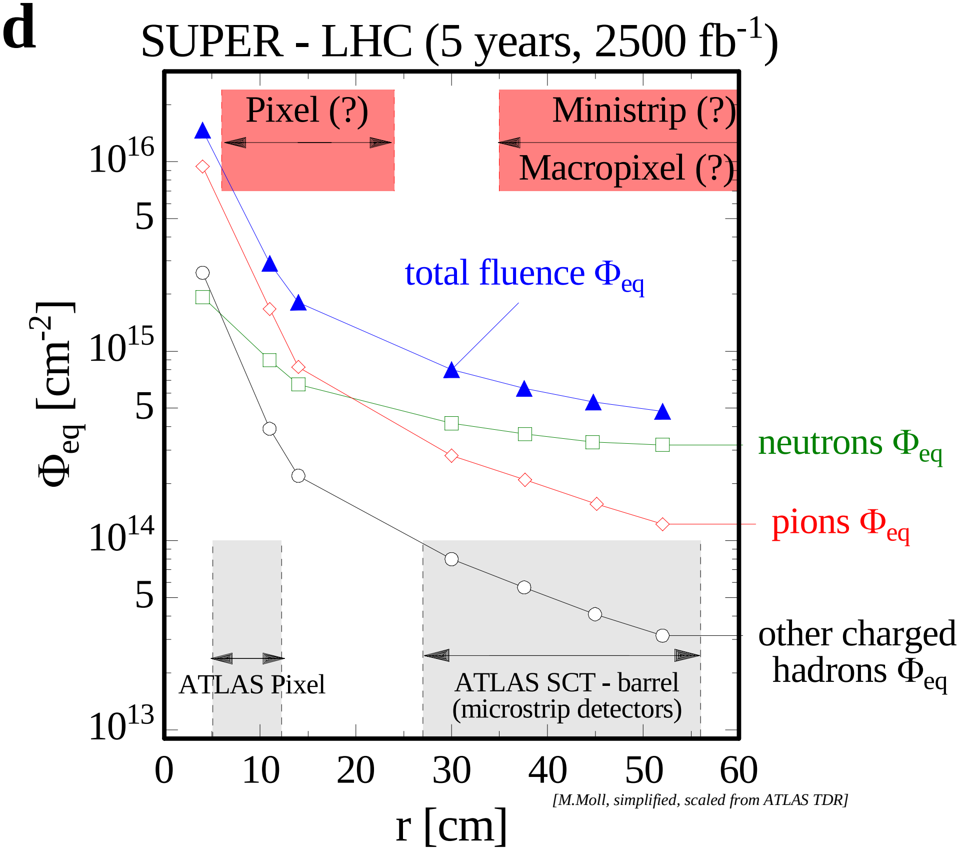
I.Pintilie, NSS, 21 October 2008, Dresden

“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**

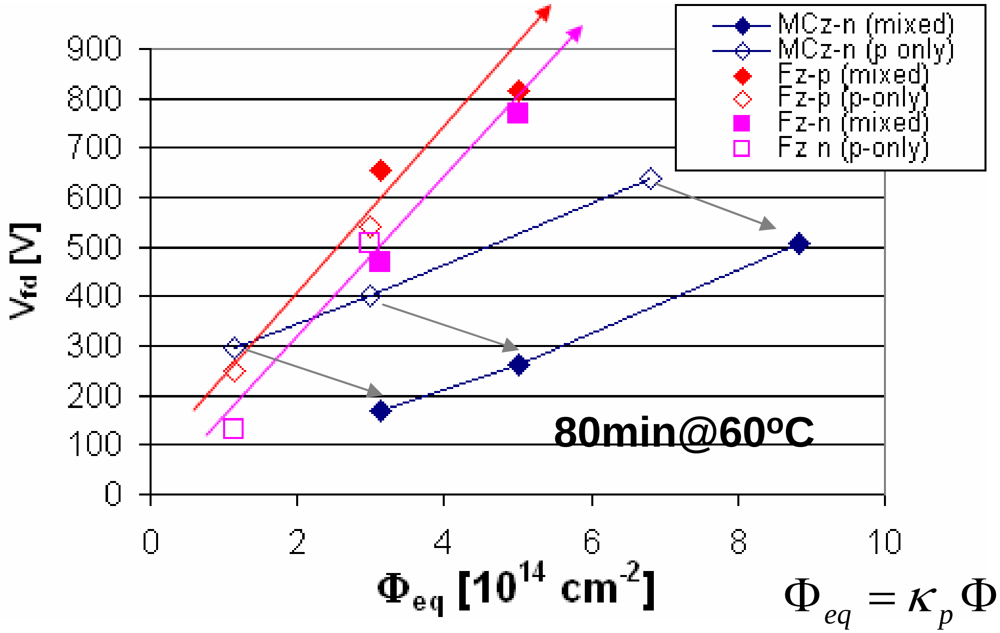


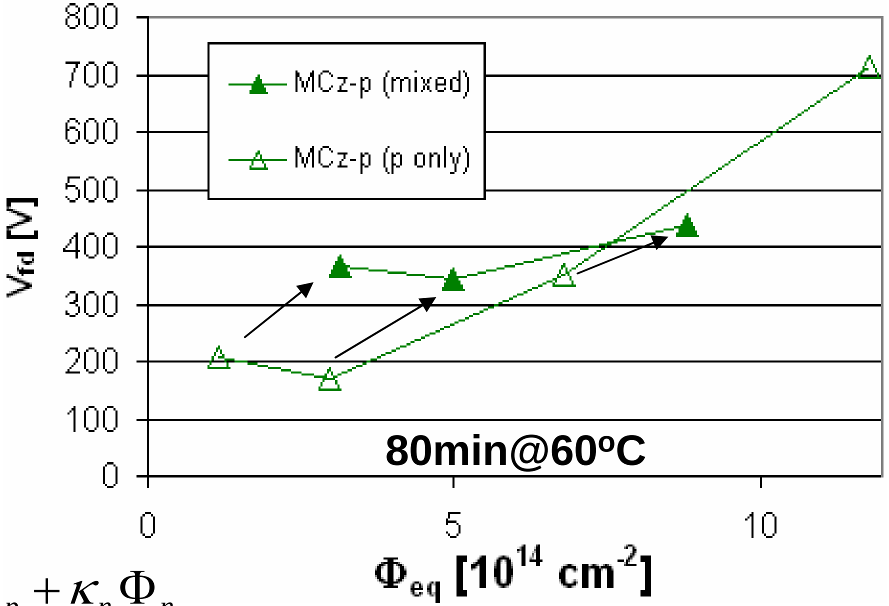
[M.Moll, simplified, scaled from ATLAS TDR]

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

RD50 Mixed irradiations: 23 GeV protons+neutrons

Micron diodes irradiated with protons first and then with 2×10^{14} n cm^{-2} (control samples p-only, open marker)





$$\Phi_{eq} = \kappa_p \Phi_p + \kappa_n \Phi_n$$

$$N_C = g_{c,p} \Phi_{eq,p} + g_{c,n} \Phi_{eq,n}$$

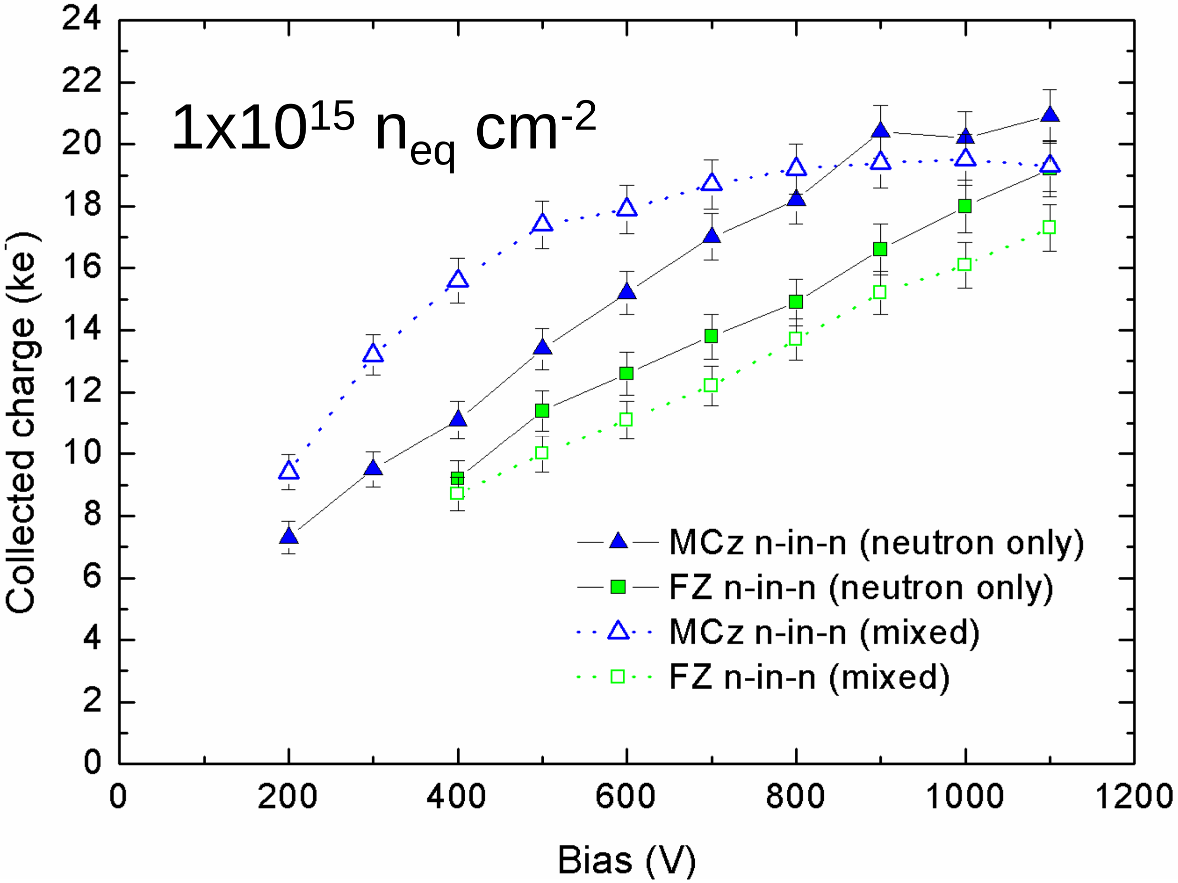
g_c can be + or -

always +

- FZ-p,n: increase of V_{fd} proportional to Φ_{eq}
- MCz-n: decrease of V_{fd} , due to different signs of $g_{c,n}$ and $g_{c,p}$
- **MCz-p at larger fluences the increase of V_{fd} is not proportional to the added fluence –as if material becomes more “n-like” with fluence – same as observed in annealing plots**

Mixed Irradiations (Neutrons+Protons)

- Both FZ and MCz show “predicted” behaviour with mixed irradiation
  - FZ doses add
    - $|N_{eff}|$ increases
  - MCz doses compensate
    - $|N_{eff}|$ decreases

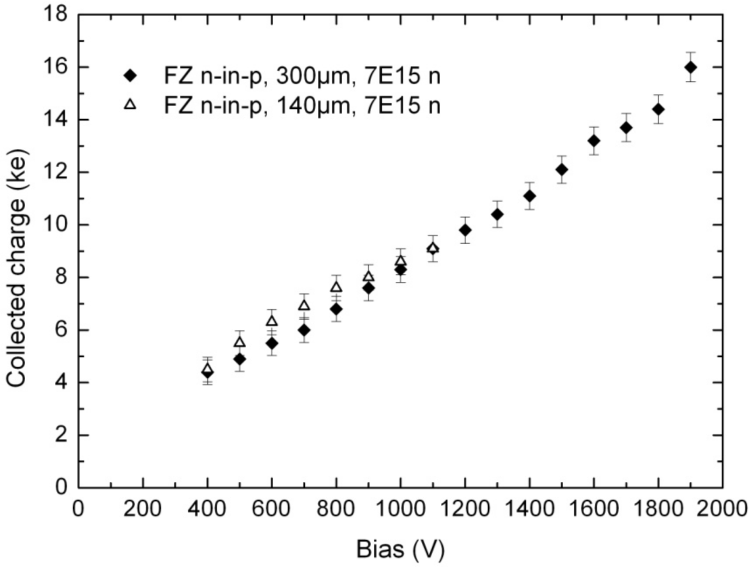


Needs further study with both nMCz and pMCz substrates and differing mixed doses

[A.Affolder 13th RD50 Workshop, Nov.2008]

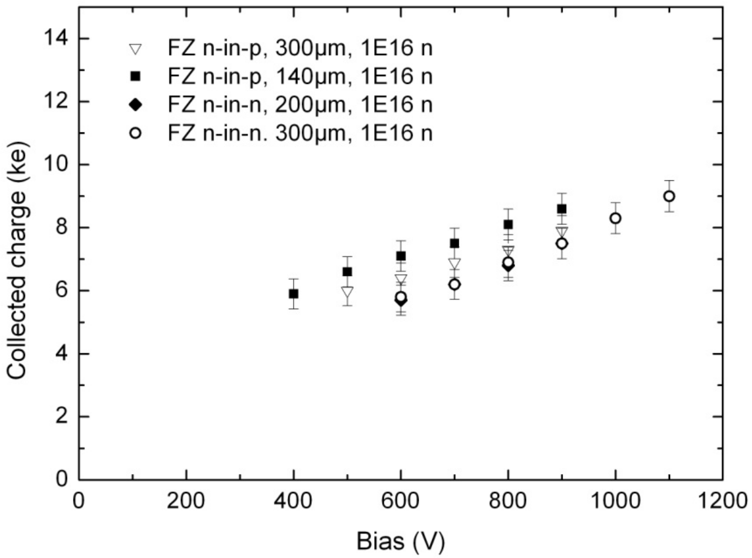
RD50

Response of 140µm and 300µm thick strip detectors after 0.7 and 1 × 10^{16} n cm-2



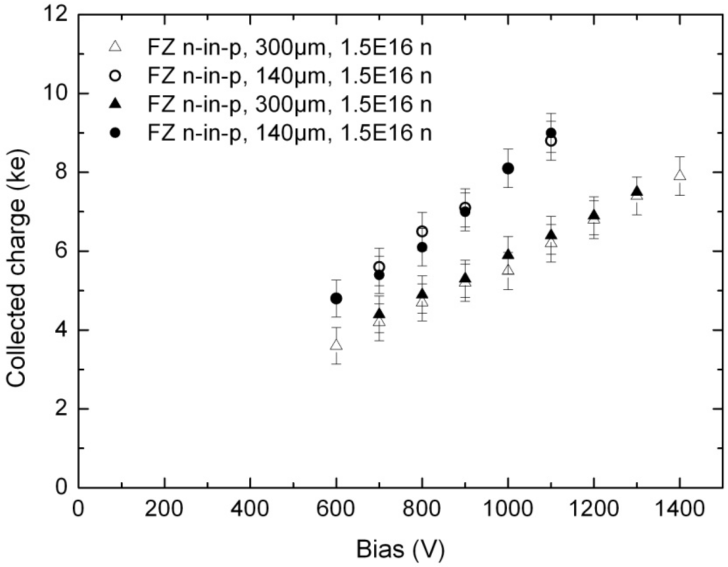
G. Casse, A. Affolder,
A. Allport, M. Wormald

Both n-in-n and n-in-p behave the same.

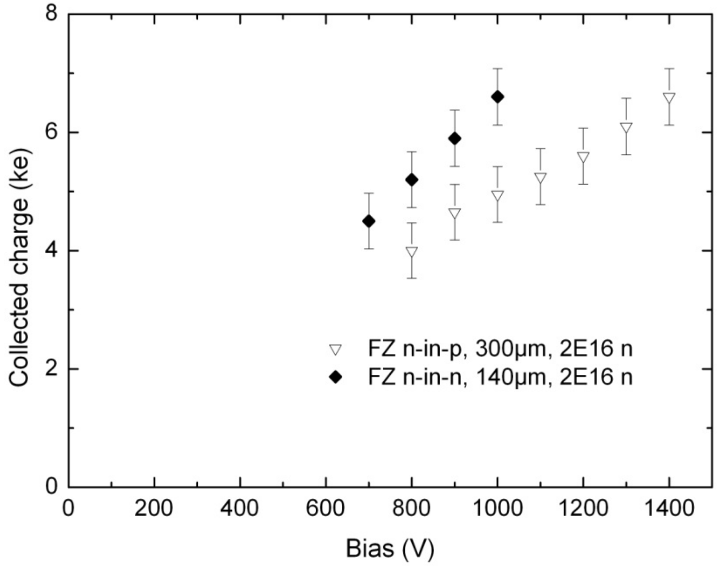


RD50

Response of 140µm and 300µm thick strip detectors after 1.5 and 2 × 10^{16} n cm-2



The benefit of higher electric field in thinner detectors is only apparent after heavy irradiations.

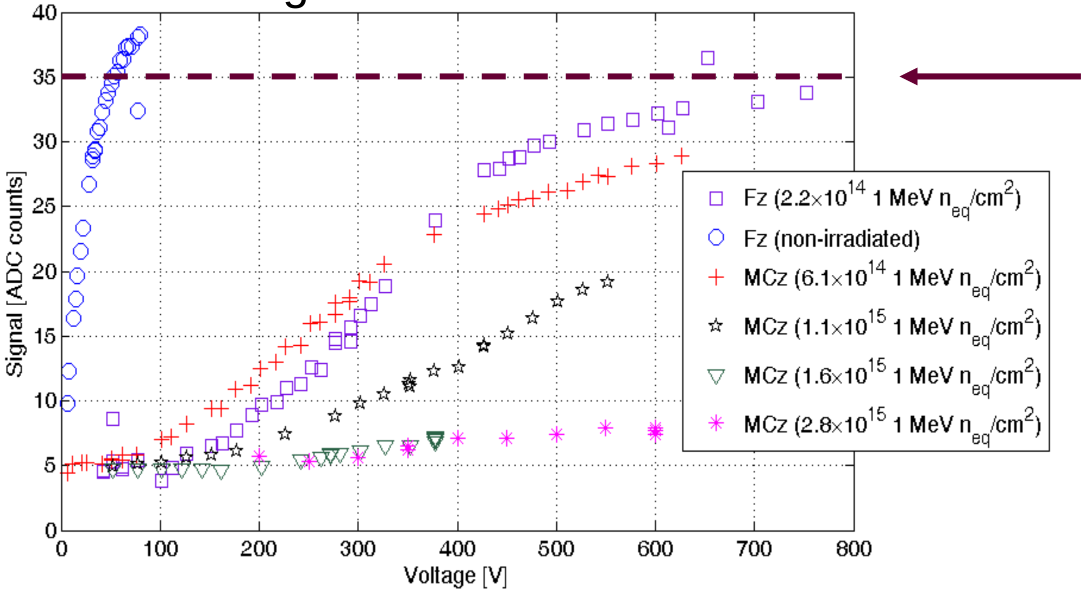


G. Casse, A. Affolder,
A. Allport, M. Wormald

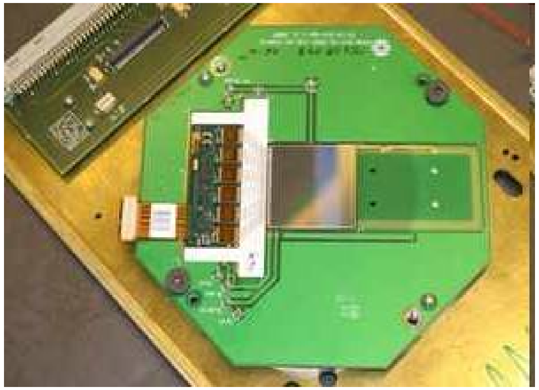
RD50

Test beam results from full-size n-type MCz-Si and FZ-Si detectors

Signal:

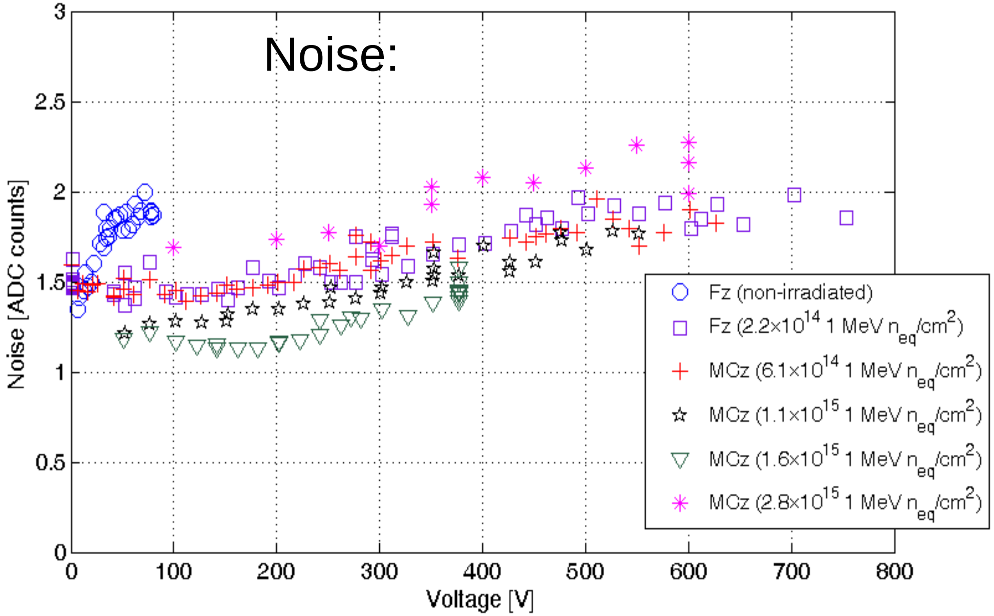


← Reference plane signal



N-type MCz-Si strip detectors have an **acceptable S/N at least up to the fluence of 1×10^{15} 1 MeV n_{eq}/cm^2.**

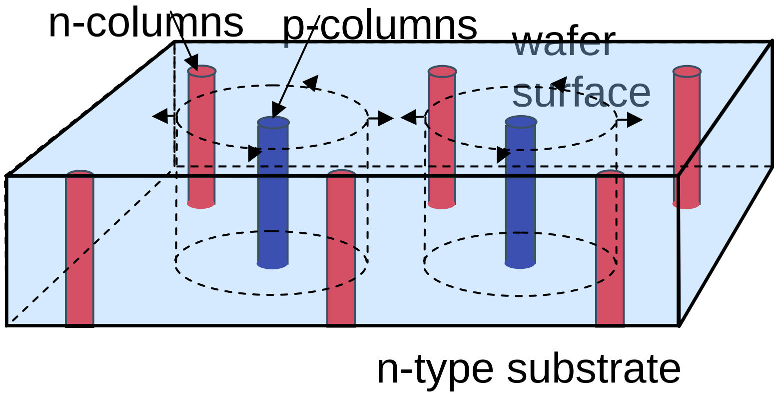
I.e. MCz-Si detectors **are a feasible option for the outer strips layers** of the SLHC CMS tracker.



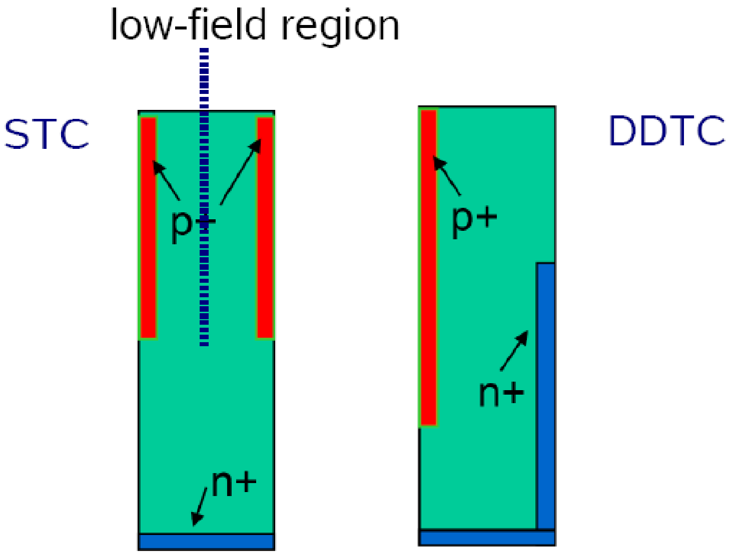
P. Luukka, J. Härkönen, L. Spiegel et al.

Development of 3D detectors

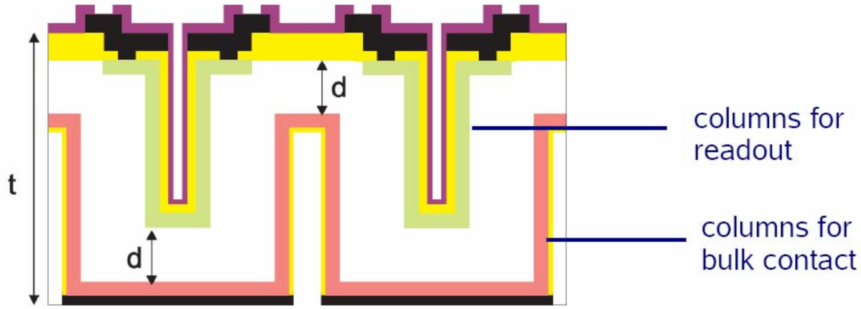
- **“3D” electrodes:** - narrow columns along detector thickness,
  - diameter: 10µm,
  distance: 50 - 100µm
- **Lateral depletion:** - lower depletion voltage needed
  - thicker detectors possible
  - fast signal
  - radiation hard



From STC to DTC

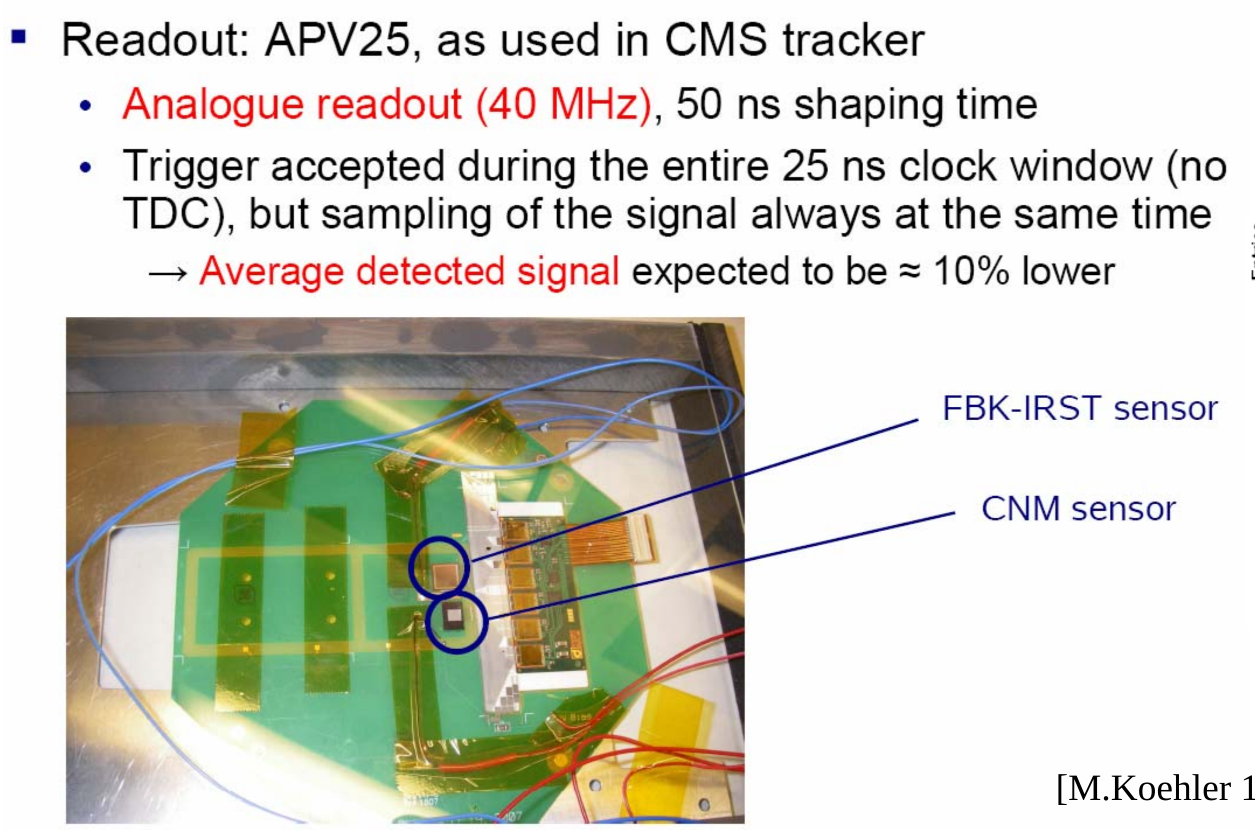


- DDTC: “double-sided double type columns”
- Columnar electrodes of both doping types are etched into the detector from both wafer sides
- Columns are not etched through the entire detector
  - Charge collection expected to be similar to “full 3D” detectors, but the fabrication process is much simpler



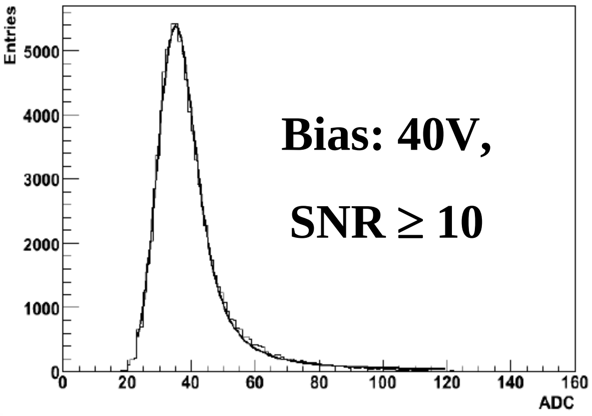
2008 test beam with 3D sensors

- Two microstrip 3D DDTC detectors tested in beam (setup CMS SiBT)
  - One produced by CNM (Barcelona), studied by Glasgow
  - One produced by FBK-IRST (Trento), studied by Freiburg



- Readout: APV25, as used in CMS tracker
  - Analogue readout (40 MHz), 50 ns shaping time
  - Trigger accepted during the entire 25 ns clock window (no TDC), but sampling of the signal always at the same time

    → Average detected signal expected to be ≈ 10% lower



Bias: 40V,

SNR ≥ 10

Result: Landau MP = 33.32 ± 0.02 ADC counts

[M.Koehler 13th RD50 Workshop, Nov.2008]

Conclusions

- n-in-p technology should be sufficient for the SLHC in the radii currently occupied by strip detectors
- For inner layers, advances in technology are still needed (3D etc.)

- Magnetic Czochralski silicon shows promising performance after mixed irradiations. Needs further studies
- CCE of planar detectors could yield ~4ke after the final fluence at the innermost pixel layer radius, with a bias voltage of 900V.
- Thin and thick devices do not appear to have a significant difference in CCE. The choice of thickness can be left to other considerations, like material budget…