MPGD Conference, June 14 2009

RD50 Recent Developments

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on behalf of the RD50 Collaboration

http://www.cern.ch/rd50

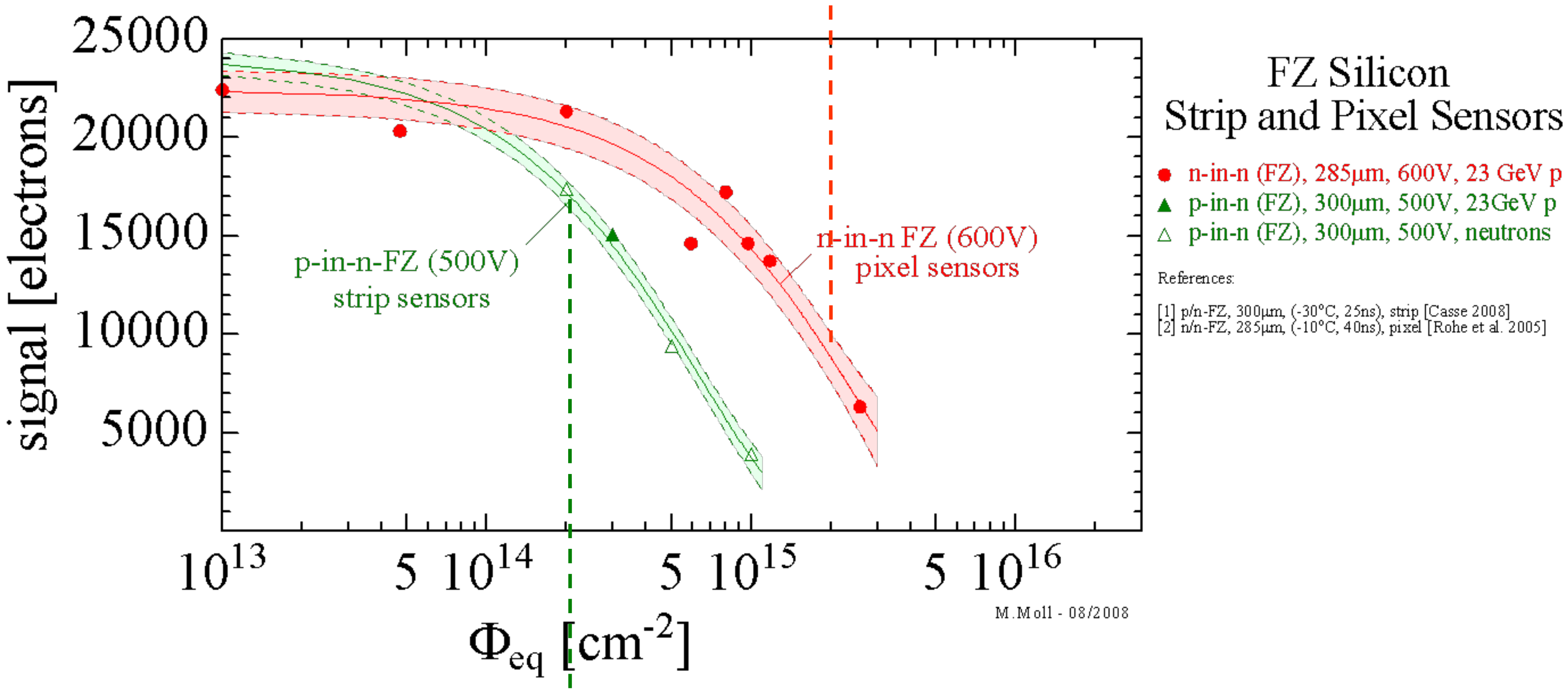
RD50

Motivation:

Signal degradation for LHC Silicon Sensors

Pixel sensors:

max. cumulated fluence for LHC



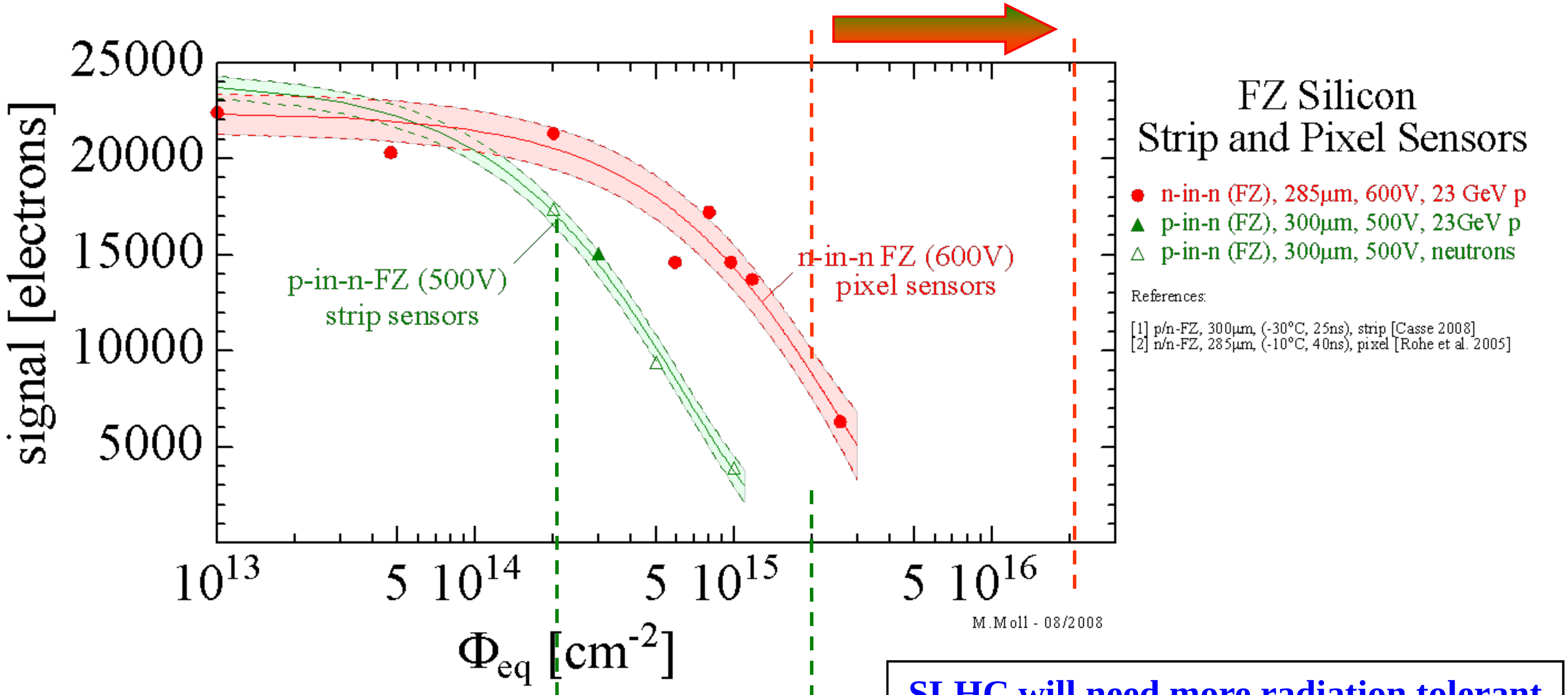
Strip sensors:

max. cumulated fluence for LHC

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 !

The CERN RD50 Collaboration

http://www.cern.ch/rd50

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

• Main objective:

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

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

• Further objectives:

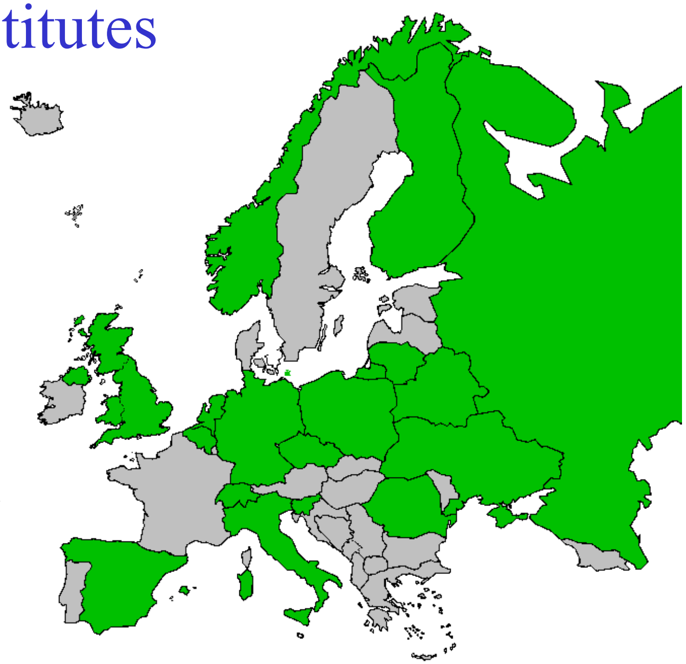
- Replacement of LHC detectors
- Generic research on radiation damage in detectors : Link to ILC community

The CERN RD50 Collaboration
- History -

- **10/2000: Last RD48 (ROSE) Workshop – End of RD48 collaboration**
  - Leaving behind a list of open questions regarding radiation damage in silicon and a community that is willing to form a new collaboration
- **2000-2001 Difficult time to form collaboration (CERN financial crises)**
  - Keep low profile in R&D at CERN (e.g. No CERN member in collaboration management allowed)
- **11/2001: 3 days workshop with discussions on how to set up collaboration**
  - Formation of **editing team for proposal** *(3 persons: C.DaVia, C.Joram, M.Moll)*
  - Appointment of **Spokesperson Search Committee** *(3 wise men: W.de Boer, E.Heijne, P.Weilhammer)*
  - Collection of interested institutes (Every institute to submit a letter of interest stating: motivation, present work, man-power, resources, infrastructure, ….)
- **2/2002: Submission of proposal to LHCC (signed by 45 Institutes)**
- **2/2002: Formation of the collaboration**
  - Formation of Collaboration Board, decision on election procedures, election of CB chair and deputy, decision on organizational structure of collaboration, common fund, role of industrial partners, publication guidelines, …
  - Election of spokesperson and deputy, nomination of budget holder, CERN contact person, …
  - second CB meeting in 10/2002: establishment of **MOU** based on discussions in first meeting
- **5/2002: LHCC recommends approval**
- **6/2002: Experiment approved as RD50 by Research Board**

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

Scientific Organization of RD50

Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

Spokespersons
Mara Bruzzi, Michael Moll
INFN Florence, CERN ECP

Defect / Material Characterization
Bengt Svensson
(Oslo University)

Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation

WODEAN project (G. Lindstroem)

Defect Engineering
Eckhart Fretwurst
(Hamburg University)

Development and testing of defect engineered silicon:
- Epitaxial Silicon
- High res. CZ, MCZ
- Other impurities H, N, Ge, …
- Thermal donors
- Pre-irradiation

Pad Detector Characterization
G. Kramberger
(Ljubljana)

- Test structure characterization IV, CV, CCE
- NIEL
- Device modeling
- Operational conditions
- Common irrad.
- Standardisation of macroscopic measurements (A.Chilingarov)

New Structures
R. Bates
(Glasgow University)

- 3D detectors
- Thin detectors
- Cost effective solutions
- 3D (M. Boscardin)
- Semi 3D (Z.Li)

Full Detector Systems
Gianluigi Casse
(Liverpool University)

- LHC-like tests
- Links to HEP
- Links to R&D of electronics
- Comparison: pad-mini-full detectors
- Comparison of detectors different producers (Eremin)
- pixel group (D. Bortoletto,T. Rohe)

RD50

Reminder: 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 –
  - Change of effective doping concentration (higher depletion voltage, under- depletion)
  - Increase of leakage current (increase of shot noise, thermal runaway)
  - Increase of charge carrier trapping (loss of charge)

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

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

Signal/noise ratio is the quantity to watch

⇒ Sensors can fail from radiation damage !

RD50

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**

Available Irradiation Sources in RD50

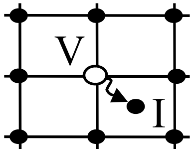
- **24 GeV/c protons, PS-CERN**
- **10-50 MeV protons, Jyvaskyla +Helsinki**
- **Fast neutrons, Louvain**
- **26 MeV protons, Karlsruhe**
- **TRIGA reactor neutrons, Ljubljana**

UNDERSTANDING RADIATION DAMAGE

particle → Si_s →

Frenkel pair

Vacancy + Interstitial



E_K > 25 eV **E_K > 5 keV**

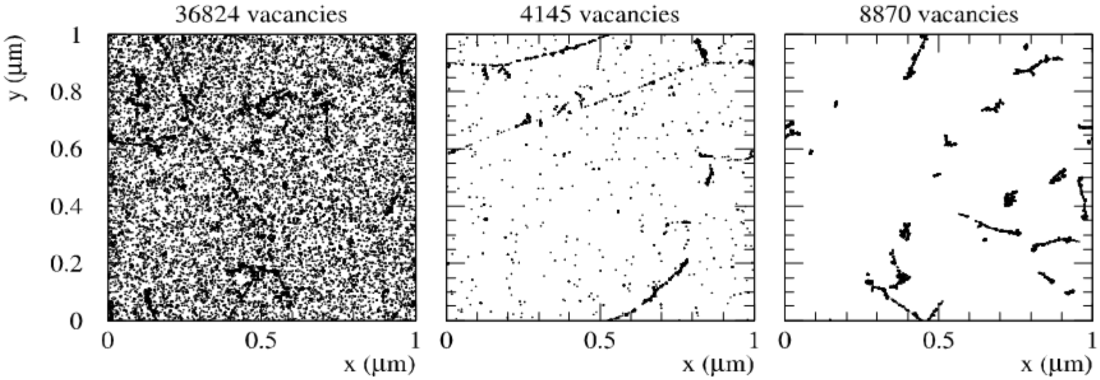
Point Defects (V-V, V-O ..)

clusters

Earlier simulation works: [Mika Huhtinen NIMA 491(2002) 194]

10 MeV protons 24 GeV/c protons 1 MeV neutrons

Initial distribution of vacancies after 10^{14} particles/cm^2

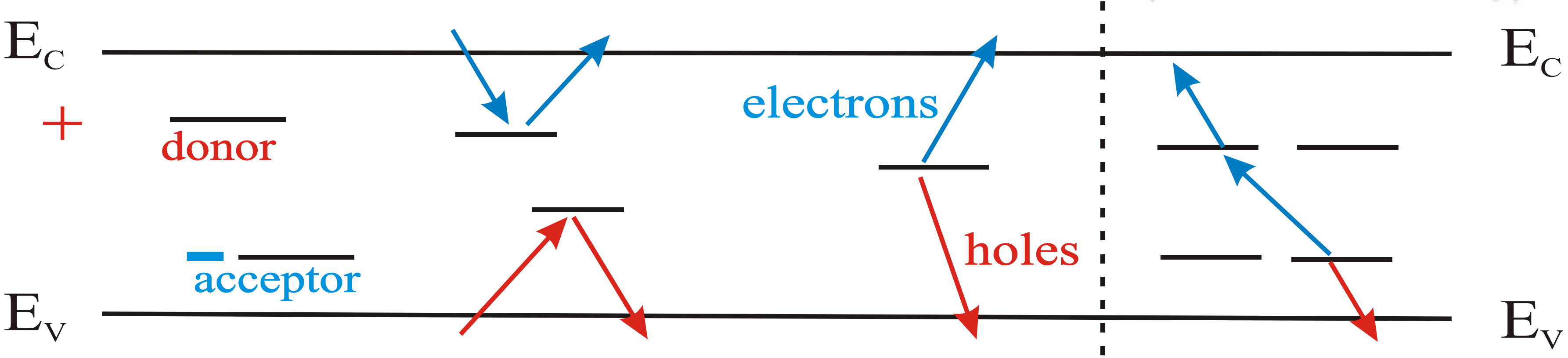


More point defects **Mainly clusters**

RD50 Impact of Defects on Detector properties

Shockley-Read-Hall statistics
(standard theory)

Inter-center charge
transfer model
(inside clusters only)



charged defects
⇒ N_{eff} , V_{dep}
e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h)
⇒ CCE
shallow defects do not contribute at room temperature due to fast detrapping

generation
⇒ leakage current
Levels close to midgap most effective

enhanced generation
⇒ leakage current
⇒ space charge

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

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

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

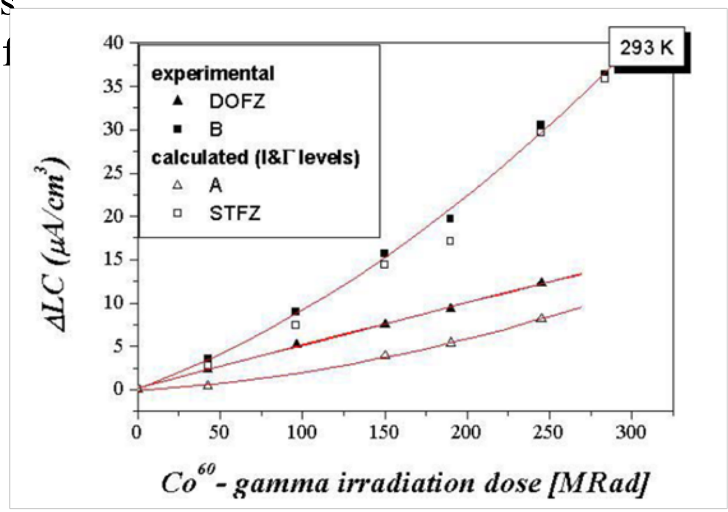
Earlier Works: γ Co^{60} irradiation

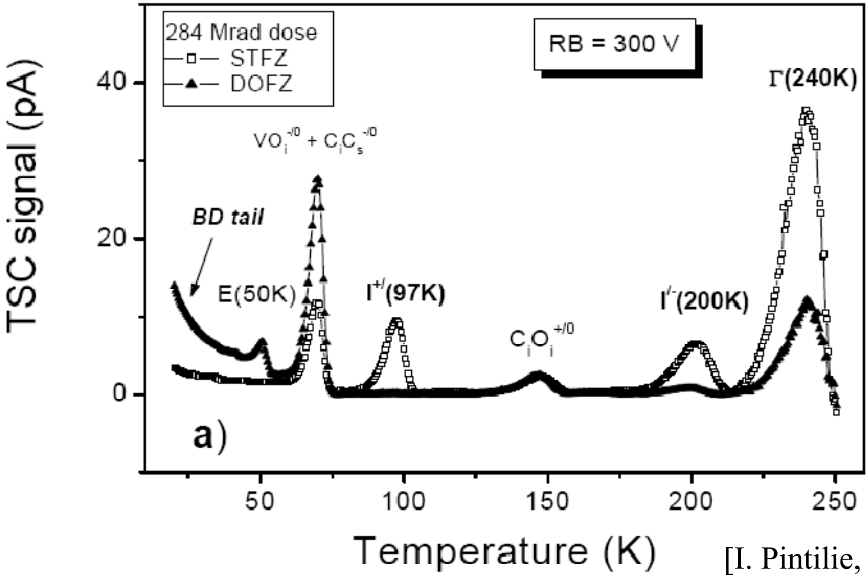
2003: To investigate only point defects; Main focus on differences between standard and oxygen enriched material and impact of the observed defect generation on pad detector properties.

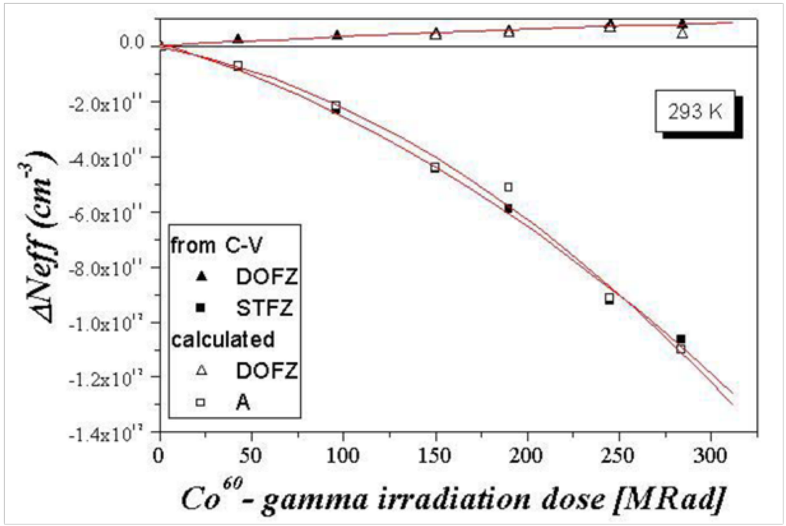
Beneficial oxygen effect consists in:

(a) suppressing deep acceptors responsible for the type inversion effect in oxygen lean material. So called I and Γ close to midgap acceptor like levels and are generated in higher concentrations in STFZ silicon than in DOFZ;

- shallow donors (BD) creation as well;





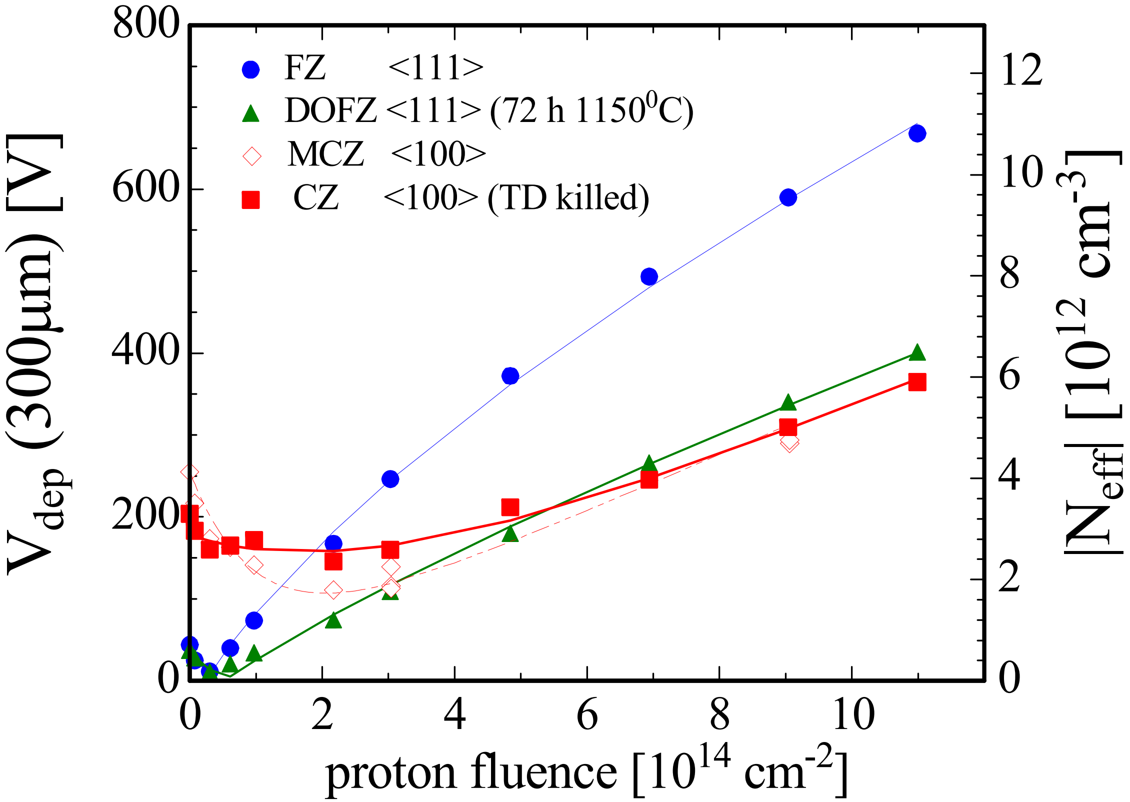


[I. Pintilie, APL, 82, 2169, March 2003]

RD50 Proton irradiation: 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, double junction,…)
- Different impact on pad and strip detector operation!

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%

Earlier Studies - proton irradiated silicon detectors I

2004: Levels responsible for depletion voltage after 23 GeV proton irradiation:

Almost independent of oxygen content:

- Donor removal
- “Cluster damage” ⇒ negative charge

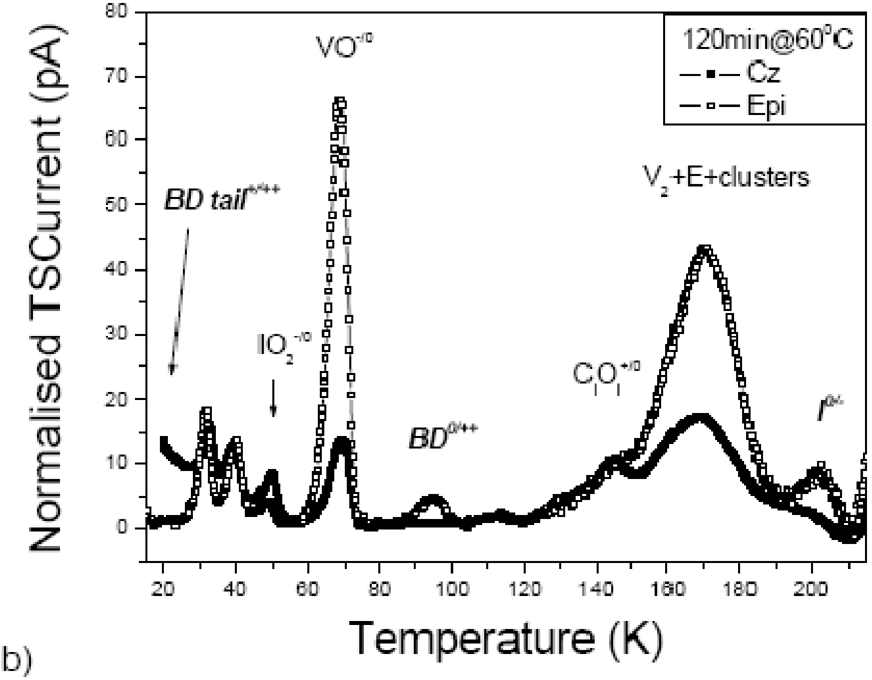
Influenced by initial oxygen content:

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

Influenced by initial oxygen dimer content (?):

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

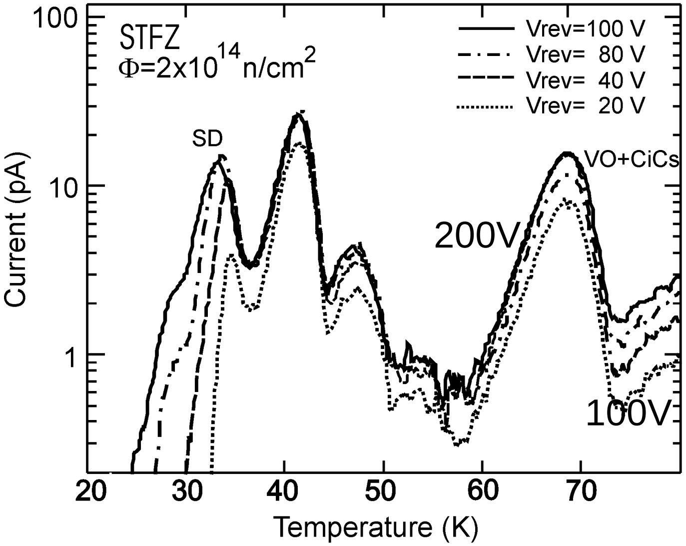
[I.Pintilie, RESMDD, Oct.2004]

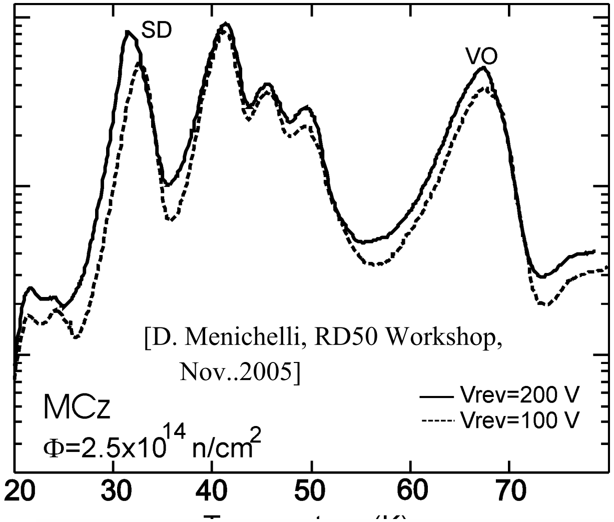


TSC after irradiation with 23 GeV protons with an equivalent fluence of 1.84×10^{14} cm^{-2} recorded on Cz and Epi material after an annealing treatment at 600C for 120 min.

RD50 Earlier Studies - proton irradiated silicon detectors III

- 2005: Shallow donor generated by proton irradiation in MCz and Epitaxial silicon



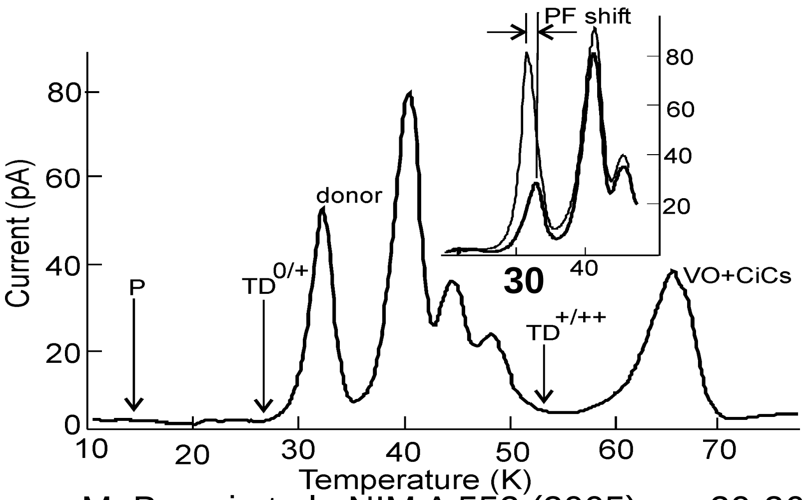


[D. Menichelli, RD50 Workshop, Nov..2005]

MCz n-type 26 MeV p irradiated, $\Phi=4\times10^{14}$ cm^{-2}

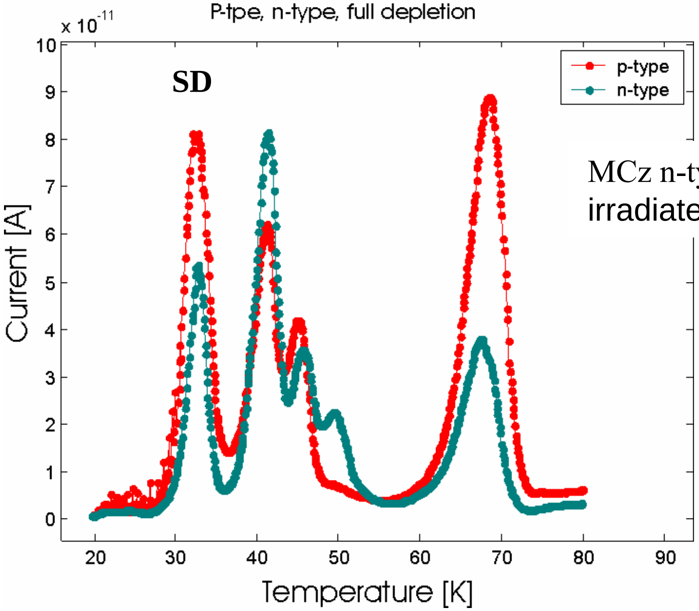
$[SD]_{MCz}/[SD]_{FZ} > 5$

M. Scaringella et al.
NIM A 570 (2007) 322–329



M. Bruzzi et al., NIM A 552 (2005) pp. 20-26.

[G. Lindstroem, RD50 Workshop, Nov..2005]



MCz n-type and p-type 24 GeV p irradiated, $\Phi=4\times10^{14}$ cm^{-2}

[M. Bruzzi, Trento Workshop, Feb. 2005]

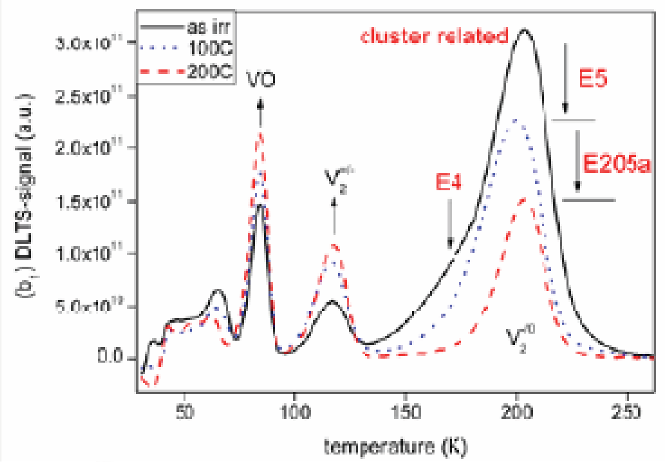
The WODEAN Project

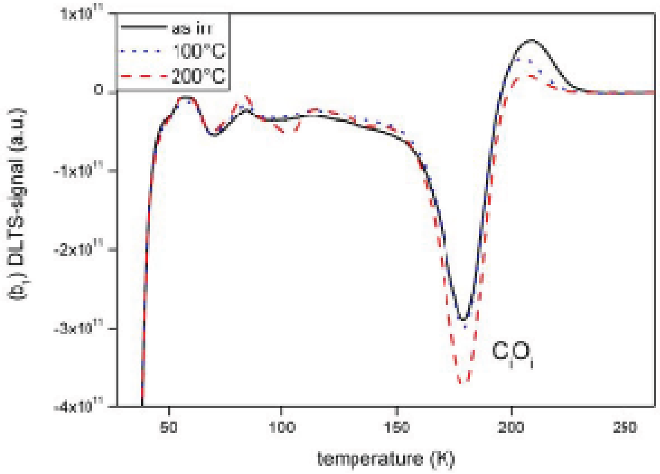
- **WODEAN project** (initiated in 2006, 10 RD50 institutes, guided by G.Lindstroem, Hamburg)
  - **Aim: Identify defects responsible for Trapping, Leakage Current, Change of N_{eff}**
  - **Method: Defect Analysis on identical samples performed with the various tools available inside the RD50 network:**
    - •**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 in Applied Physics Letters**

11 Institutes/Institutions Involved

CERN
Bucharest NIMP
Florence University
Hamburg University
Ljubljana JSI
London King's College
Minsk University
Minsk NAS
Oslo University
Warsaw ITME
Vilnius University

C-DLTS studies – fluence $3\cdot10^{11}$ cm^{-2}



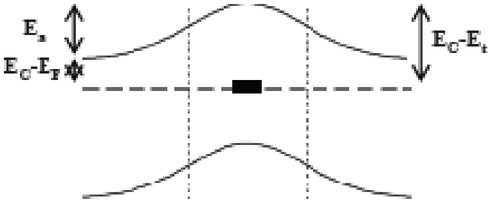


C-DLTS requires $N_t \ll N_d$ → low fluence only

Electron traps:

- VO at T=80 K
- V_2(=/-) at T=120 K → strongly suppressed due to potential barrier surrounding cluster
- V related defects in cluster at T~170-220 K, V_2(-/0), E4/E5, E205a

Band structure in a disordered region



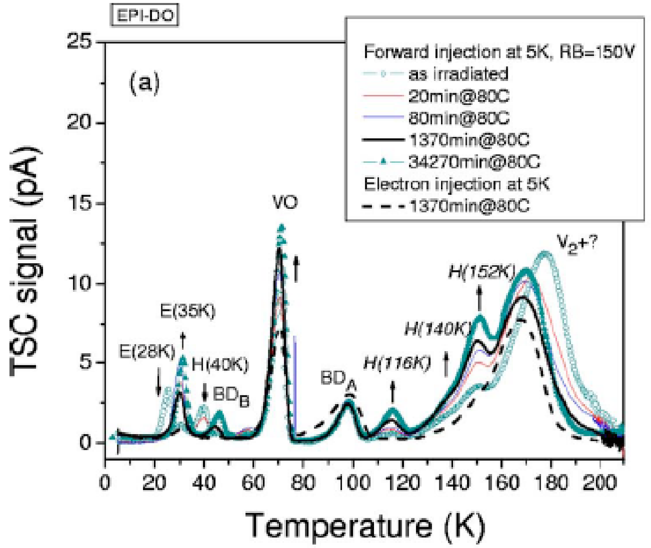
Hole trap:

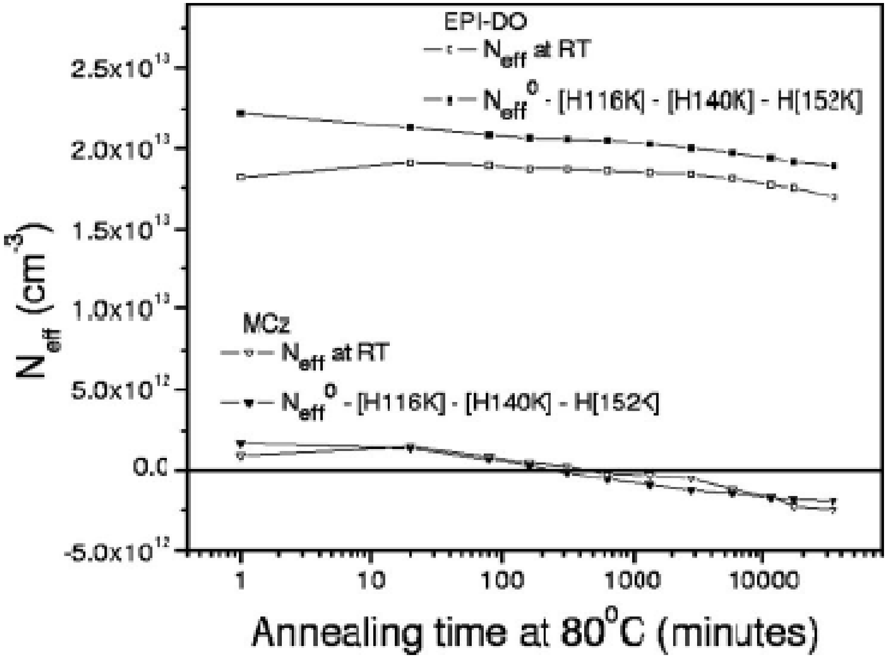
- C_iO_i at T=180 K

Increasing temperature: Cluster dissolution
→ "Cluster-peak" at 200 K decreases
→ potential barrier drops
→ V_2(=/-) and VO increase

Cluster related hole traps as source for long term annealing

Hole traps *H*116 K, *H*140 K, and *H*152K, cluster related defects (not present after γ-irradiation) observed in neutron irradiated *n*-type Si diodes during 80 °C annealing.





Hole traps *H*116 K, *H*140 K, and *H*152K concentration in agreement with Neff changes during 80 °C annealing, they are believed to be causing the long term annealing effects.

I. Pintilie, E. Fretwurst, and G. Lindström, APL **92**, 024101 2008

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

Point defects

- $E_i^{BD} = E_c - 0.225$ eV
- $\sigma_n^{BD} = 2.3\cdot10^{-14}$ cm^2

- $E_i^{I} = E_c - 0.545$ eV
  - $\sigma_n^{I} = 2.3\cdot10^{-14}$ cm^2
  - $\sigma p^{I} = 2.3\cdot10^{-14}$ cm^2

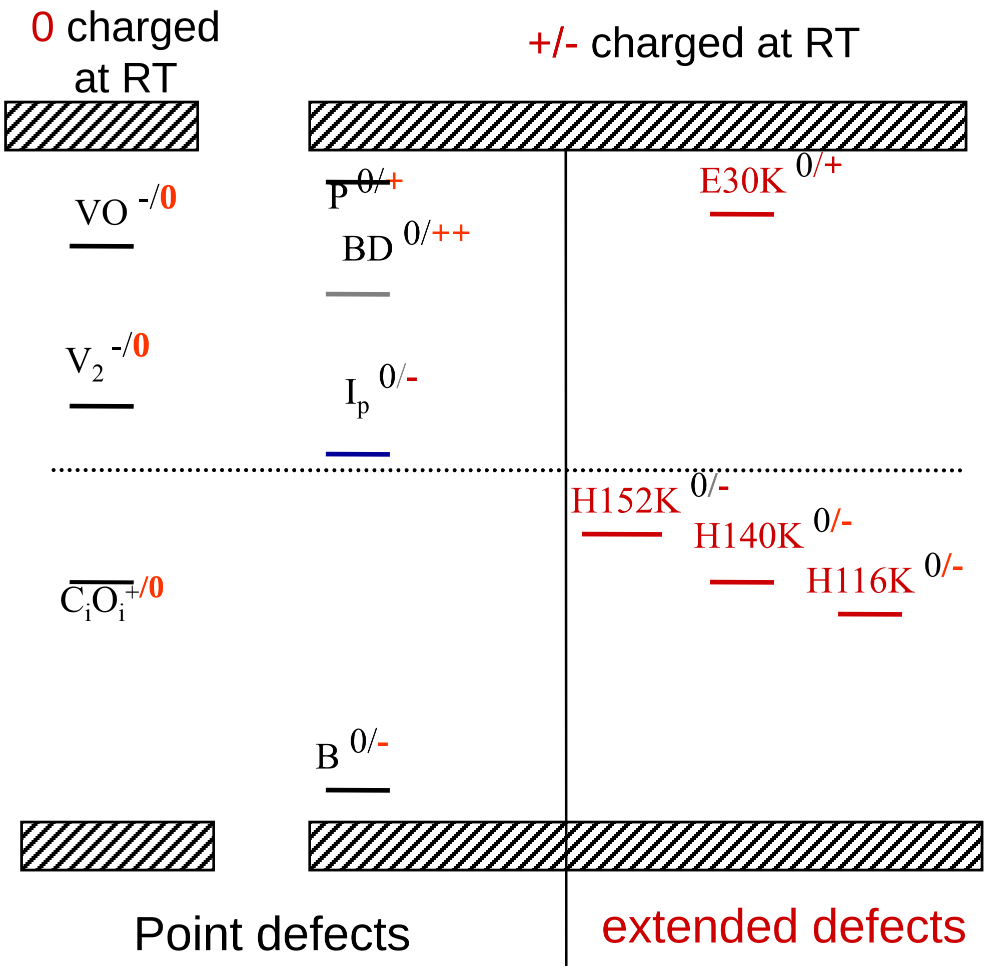
Cluster related centers

- $E_i^{116K} = E_v + 0.33$eV
- $\sigma_p^{116K} = 4\cdot10^{-14}$ cm^2

- $E_i^{140K} = E_v + 0.36$eV
- $\sigma_p^{140K} = 2.5\cdot10^{-15}$ cm^2

- $E_i^{152K} = E_v + 0.42$eV
- $\sigma_p^{152K} = 2.3\cdot10^{-14}$ cm^2

- $E_i^{30K} = E_c - 0.1$eV
- $\sigma_n^{30K} = 2.3\cdot10^{-14}$ cm^2



I.Pintilie, NSS, 21 October 2008, Dresden

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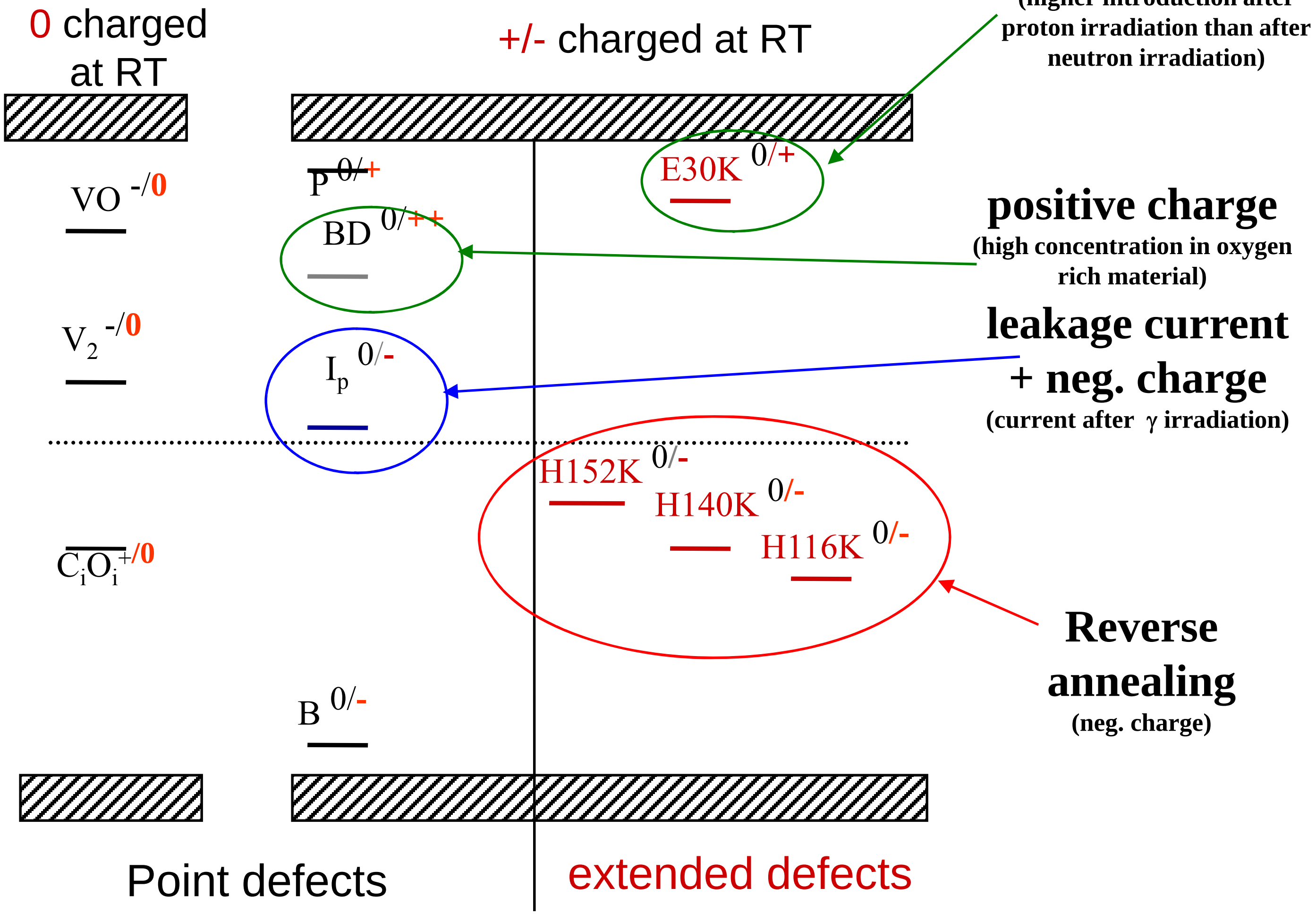


positive charge
(higher introduction after proton irradiation than after neutron irradiation)

positive charge
(high concentration in oxygen rich material)

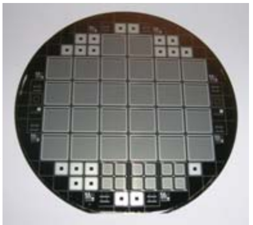
leakage current + neg. charge
(current after γ irradiation)

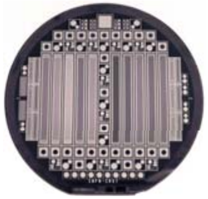
Reverse annealing
(neg. charge)

I.Pintilie, NSS, 21 October 2008, Dresden

RD50 RD50 Test Sensor Production Runs (2005-2008)

- Recent production of Silicon Strip, Pixel and Pad detectors (<u>non exclusive list</u>):
  - **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, <u>6 inch wafers</u>, (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)**





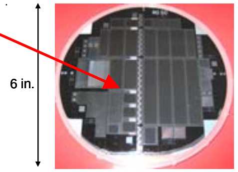


Table of Micron Devices

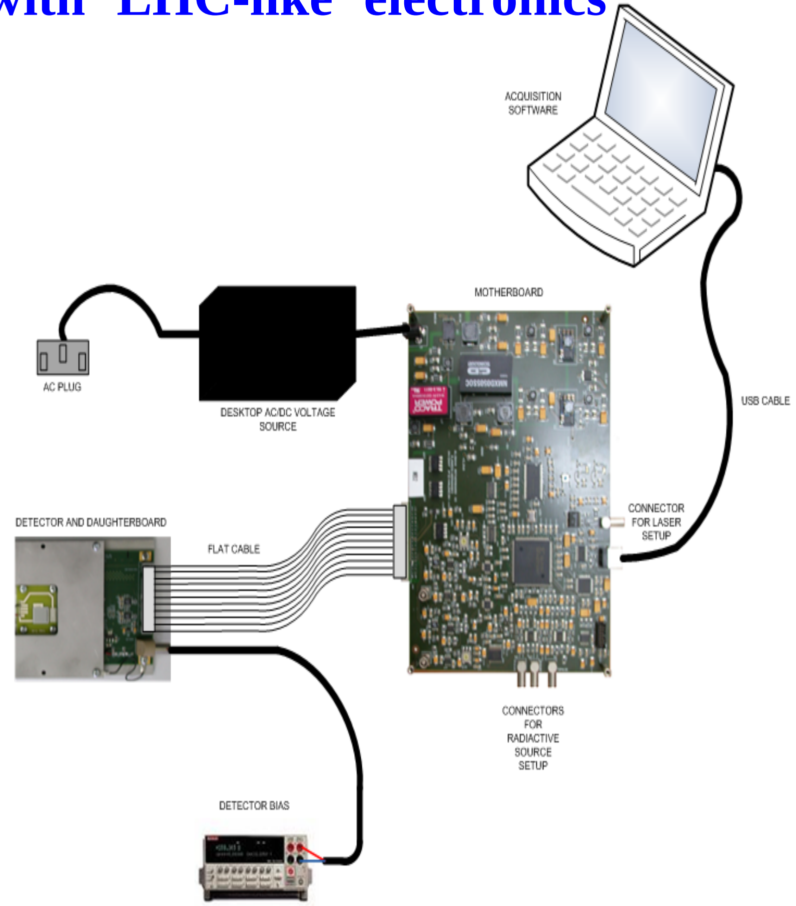
Type	Substrate	Resistivity (ohm-cm)	Thickness (um)	# Delivered	ID # Wafers
N-on-P	FZ	11000	300	6	255
N-on-P	MCz	1000	300	5	255
P-on-N	FZ	3000	300	4	
P-on-N	MCz	500	300	12	
N-on-N	FZ	3000	300	1	
N-on-N	MCz	500	300	2	2553

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**

Test equipment: ALIBAVA

- **ALIBAVA – A LIverpool BArcelona VAlencia collaboration**
- **System supported by RD50: Will enable more RD50 groups to investigate strip sensors with ‘LHC-like’ electronics**

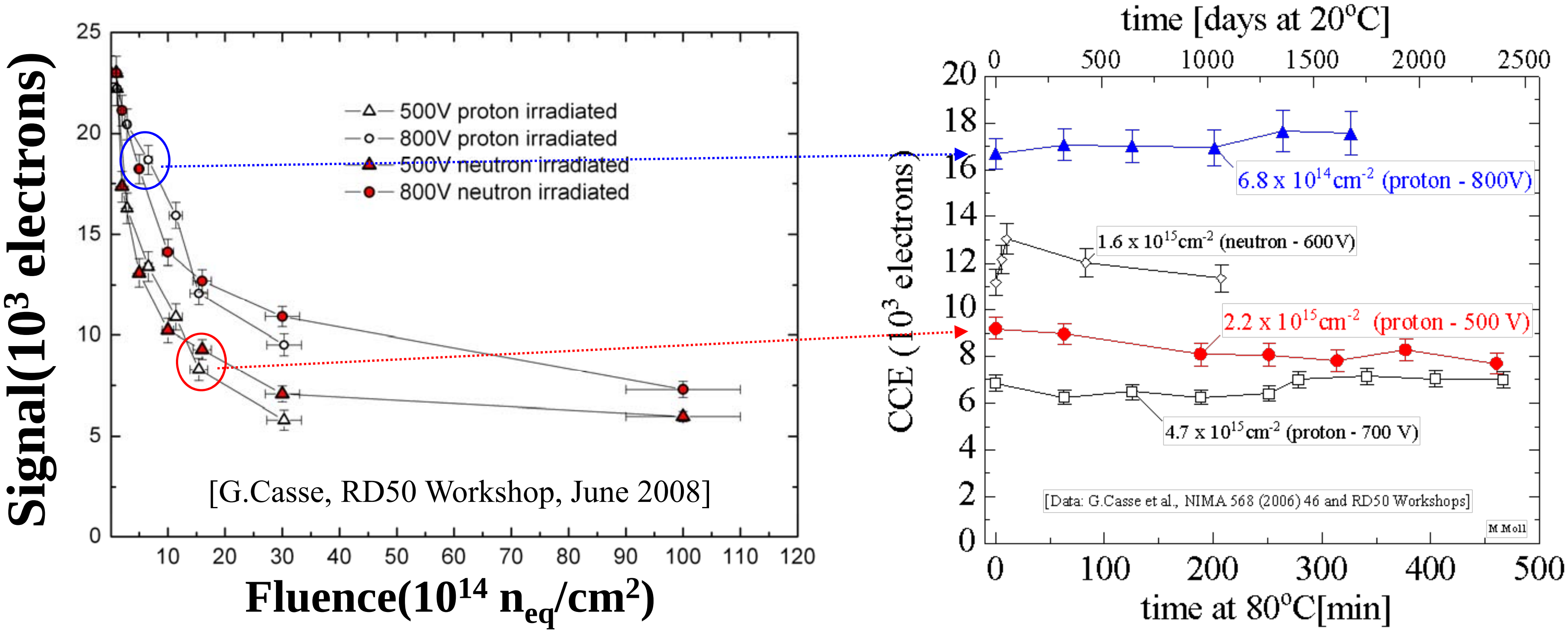


- System:
  Software part (PC) and hardware part connected by USB.
- Hardware part: a dual board based system connected by flat cable.
  - Mother board intended:
    - **To process the analogue data that comes from the readout chips.**
    - **To process the trigger input signal in case of radioactive source setup or to generate a trigger signal if a laser setup is used.**
    - **To control the hardware part.**
    - **To communicate with a PC via USB.**
  - Daughter board :
    - **It is a small board.**
    - **It contains two Beetle readout chips**
    - **It has fan-ins and detector support to interface the sensors.**
- Software part:
  - It controls the whole system (configuration, calibration and acquisition).
  - It generates an output file for further data processing.

[R.Marco-Hernández, 13th RD50 Workshop, Nov.2008]

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)



[G.Casse, RD50 Workshop, June 2008]

[Data: G.Casse et al., NIMA 568 (2006) 46 and RD50 Workshops]

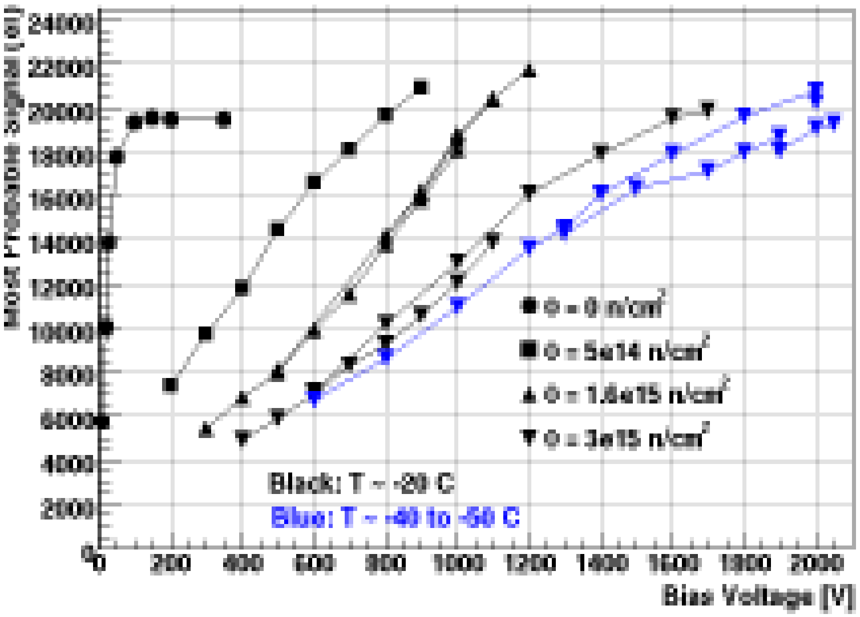
- CCE: ~7300e (~30%)
  after ~ 1×10^{16}cm^{-2} 800V
- n-in-p sensors are strongly considered for ATLAS upgrade (previously p-in-n used)

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

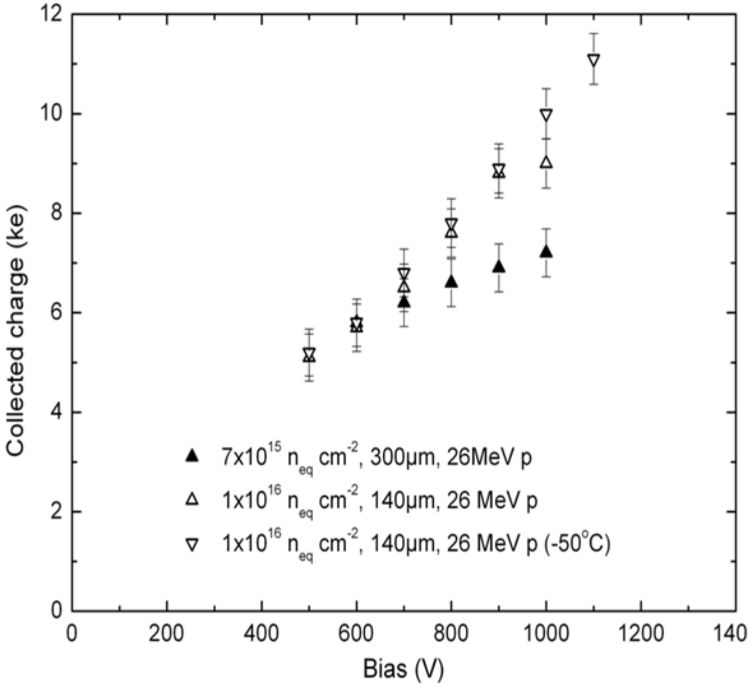
CCE: Recent Results

- CCE increases over expectation for very high fluence
- CCE > 100% for high bias voltage
- There is charge multiplication ! (Avalanche effect ?)

Or other effect, like field dependent de-trapping?
Even after heavy irradiation it is possible to recover the entire ionised charge.



[I. Mandic, 12th RD50 workshop, 2008]

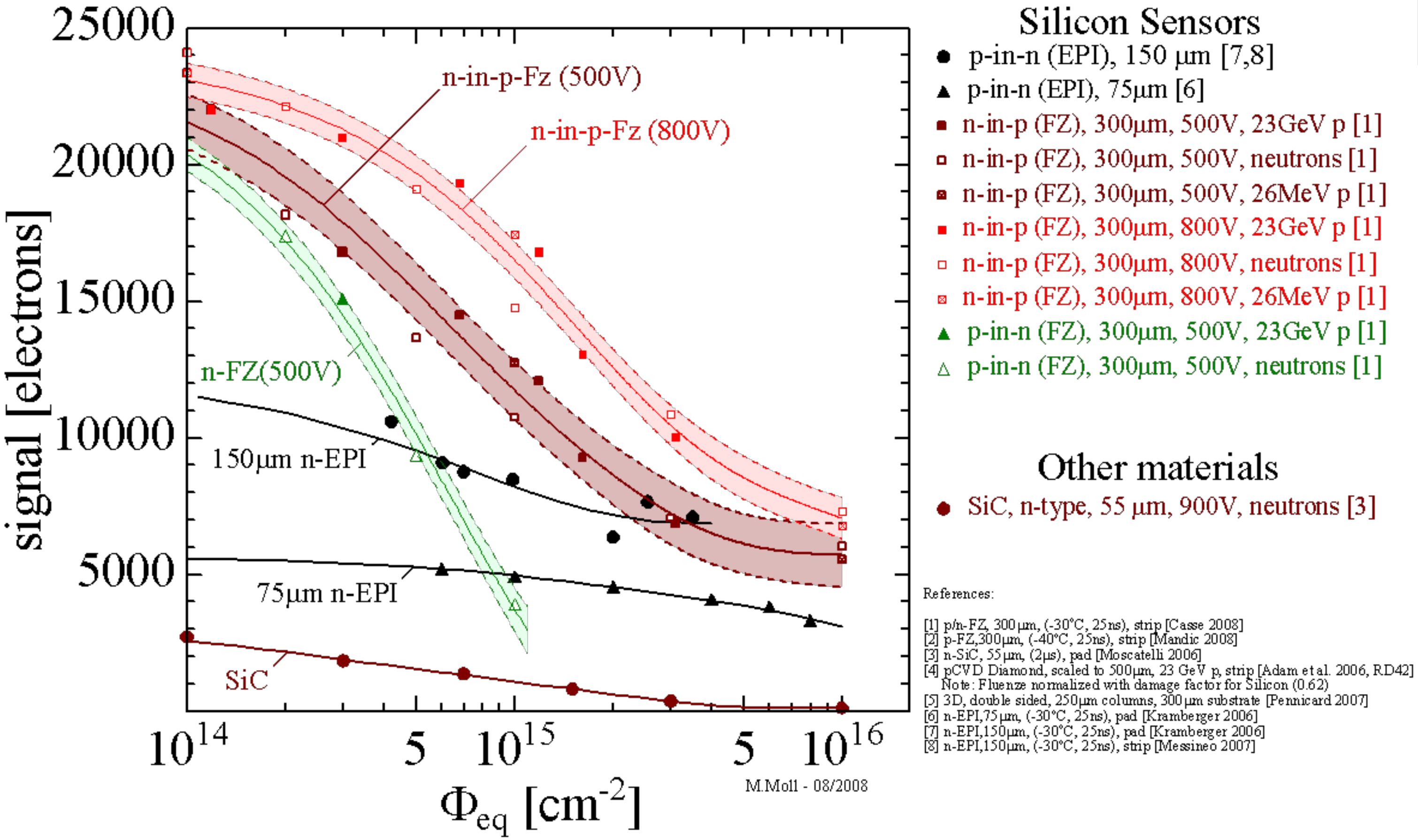


G. Casse, 14th RD50, Freiburg 5-7 June 2009.

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, 300 µm, (-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]
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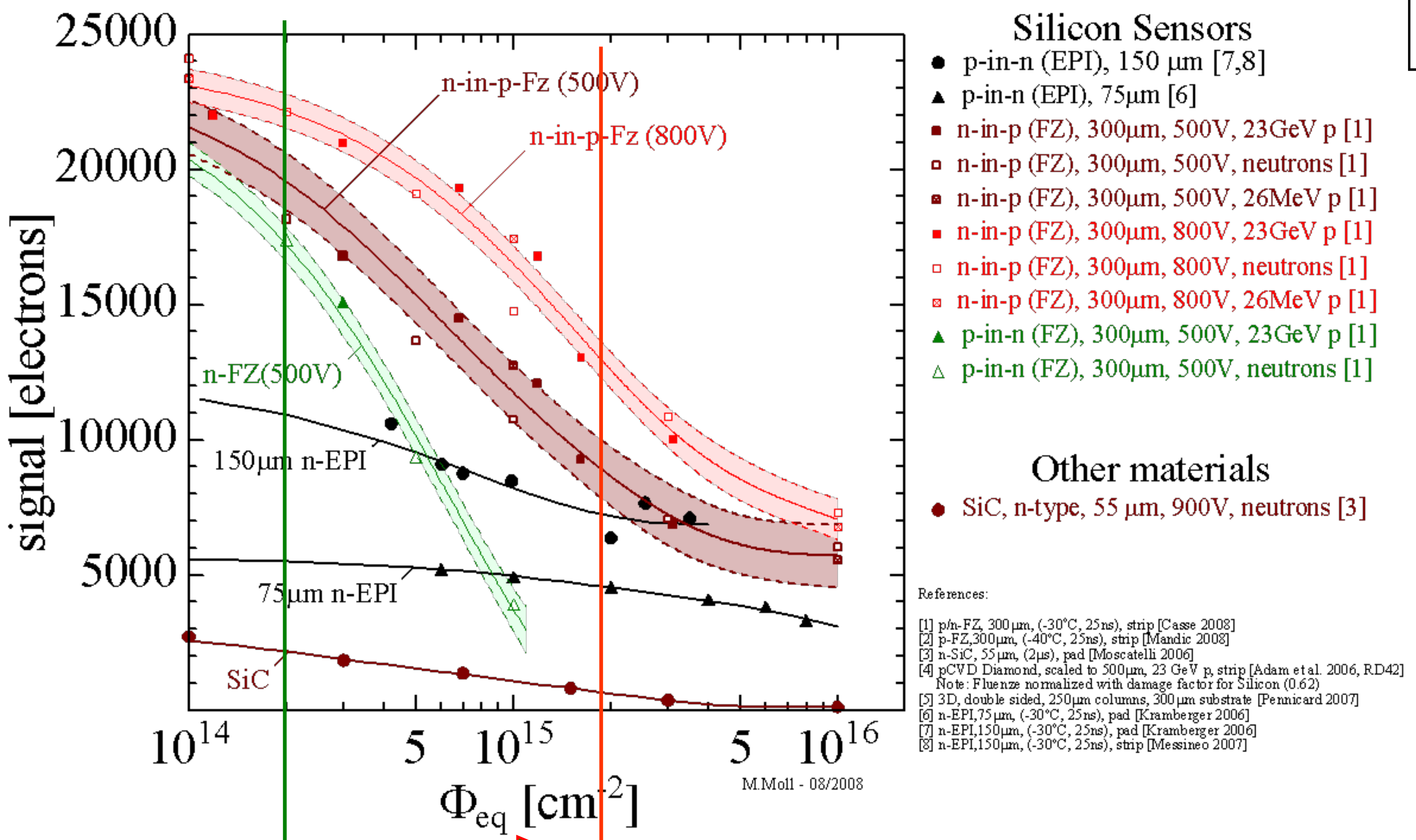

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LHC

SLHC

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

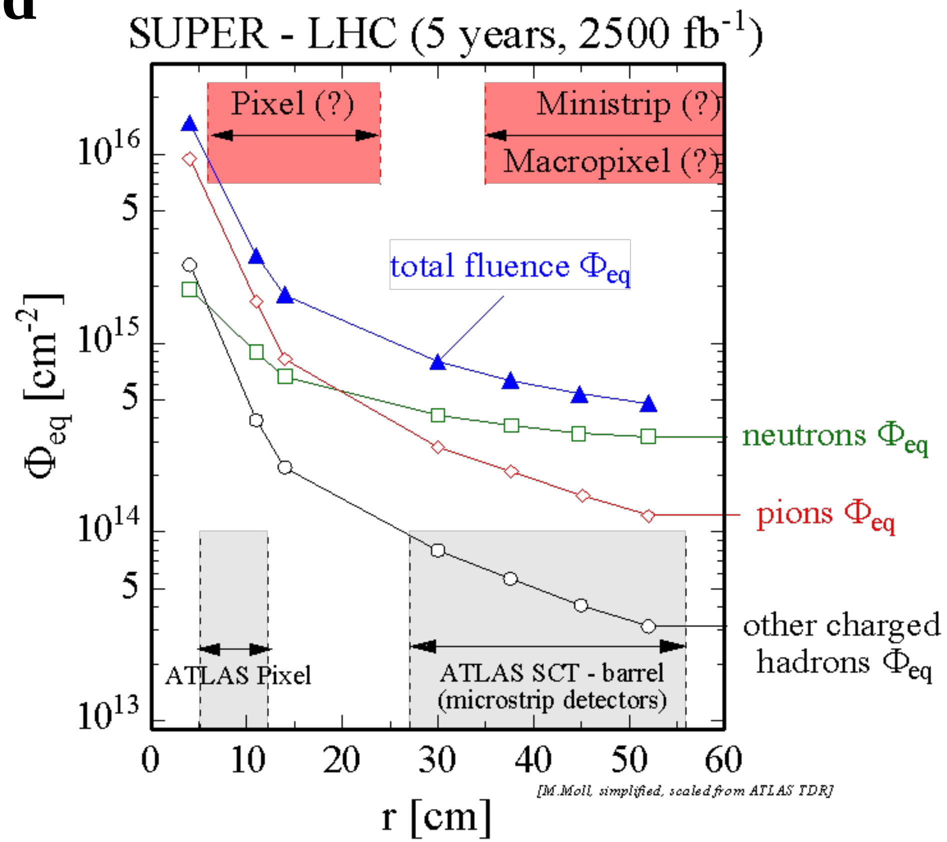
n-in-p technology should be sufficient for Super-LHC at radii presently (LHC) occupied by strip sensors

RD50 “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**



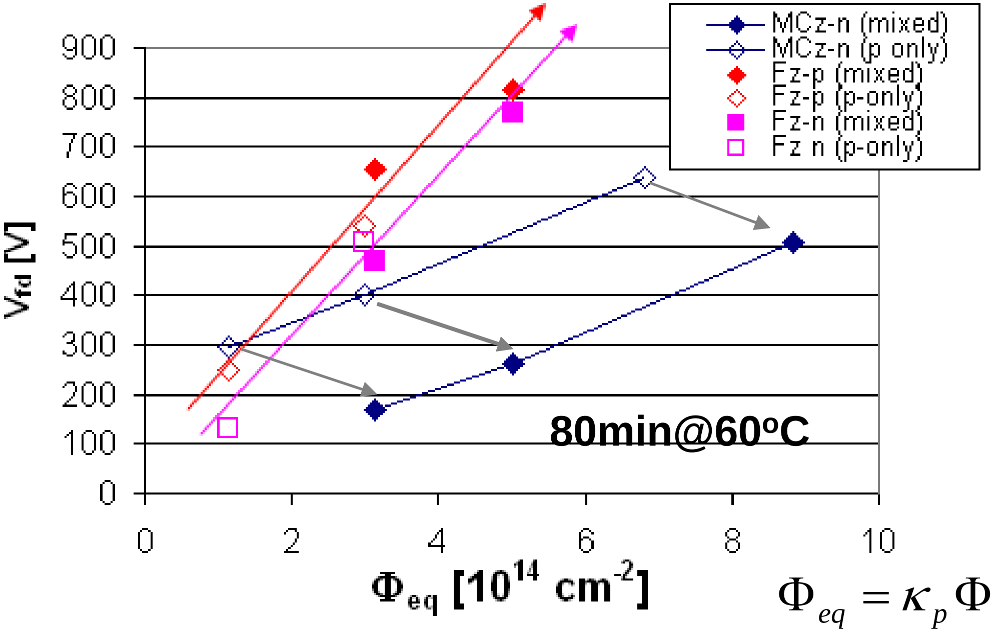
[M.Moll, simplified, scaled from ATLAS TDR]

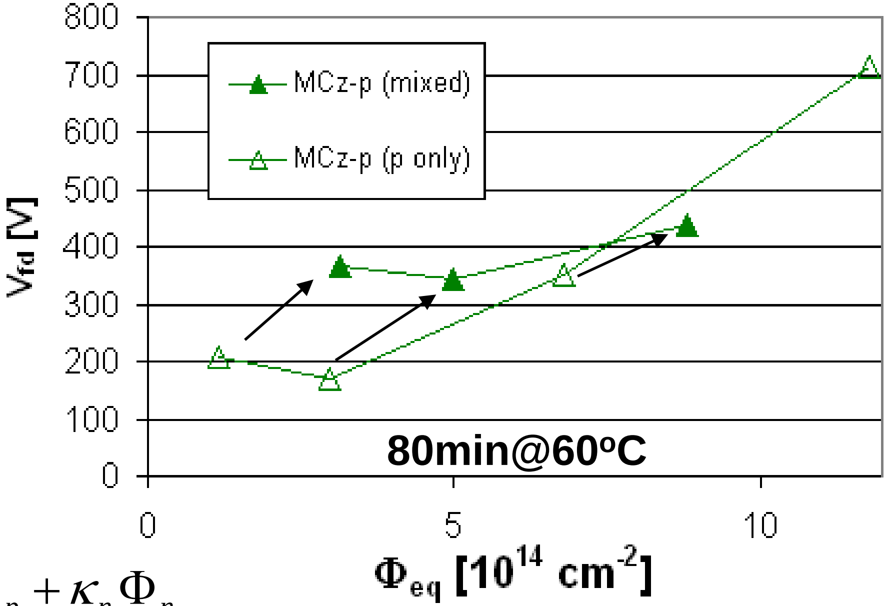
- **Question:**

  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 2e14 n cm^{-2} (control samples p-only, open marker)





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

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

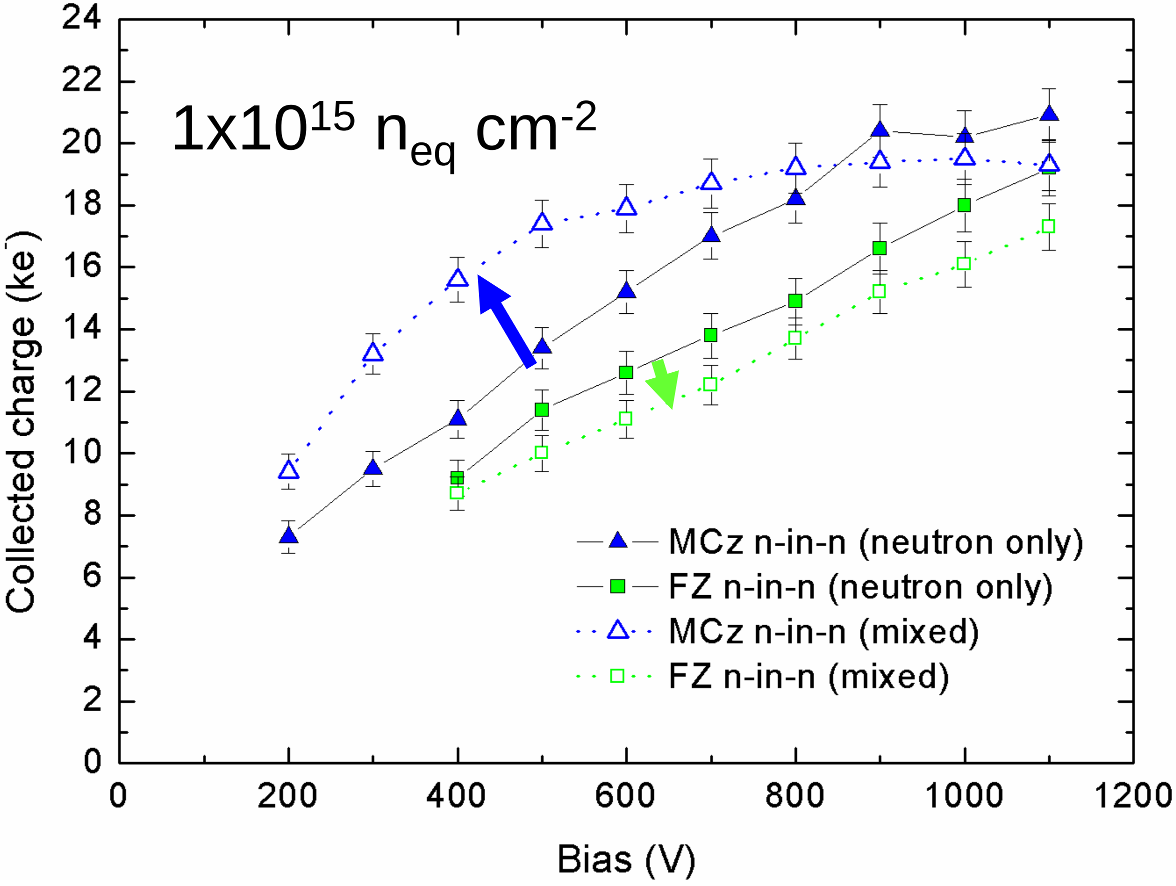
g$_c$ can be + or -

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



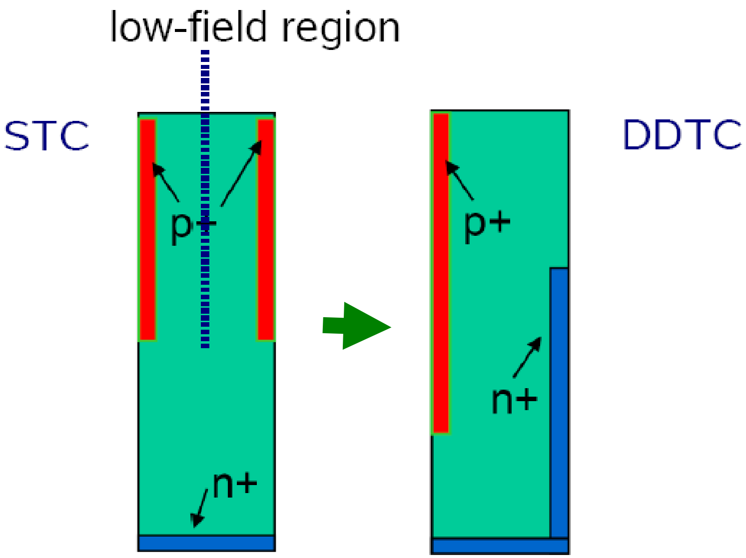
Needs further study with both nMCz and pMCz substrates and differing mixed doses

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

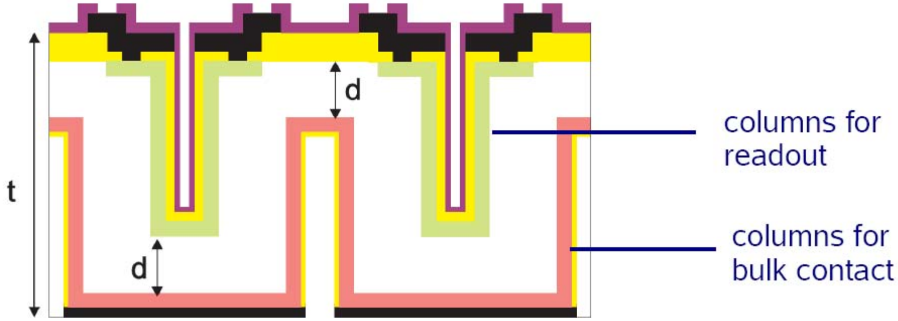
Development of 3D detectors

- “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



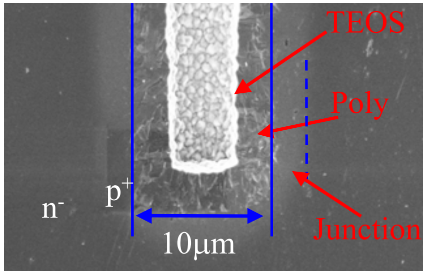
- DDTC: “double-sided double type columns”
- Columnar electrodes of both doping types are etched into the detector from both wafer sides
- Columns are not etched through the entire detector
  - Charge collection expected to be similar to “full 3D” detectors, but the fabrication process is much simpler

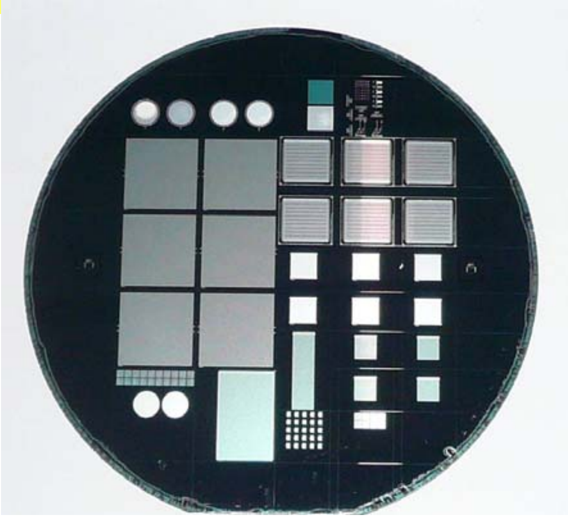


Processing of Double-Column 3D detectors

1. CNM Barcelona (2 wafers fabricated in Nov. 2007)

- Double side processing with holes not all the way through
- n-type bulk
- bump bond 1 wafer to Medipix2 chips
- Further production (n and p-type)



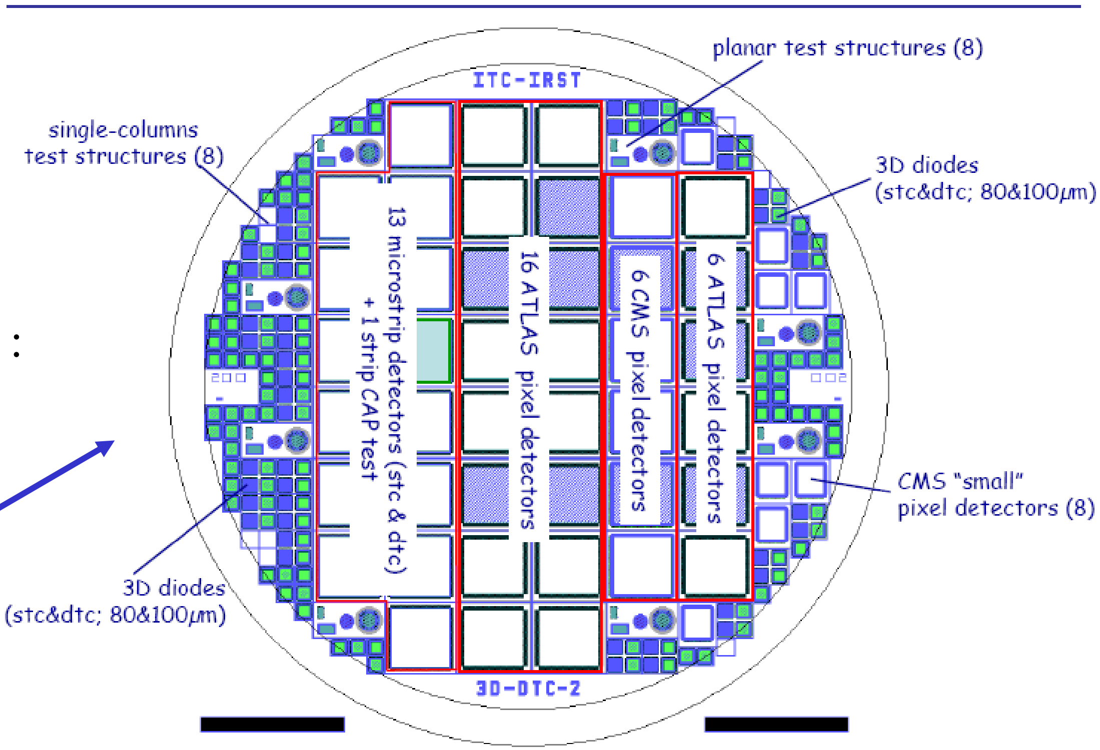


- First tests on irradiated devices performed (CNM devices, strip sensors, ^{90}Sr , Beetle chip, $5\text{x}10^{15} n_{eq}/cm^2$ with reactor neutrons) : 12800 electrons

2. FBK (IRST-Trento)

- very similar design to CNM
- 2 batches produced (n-type and p-type)

DDTC on p-type, wafer layout

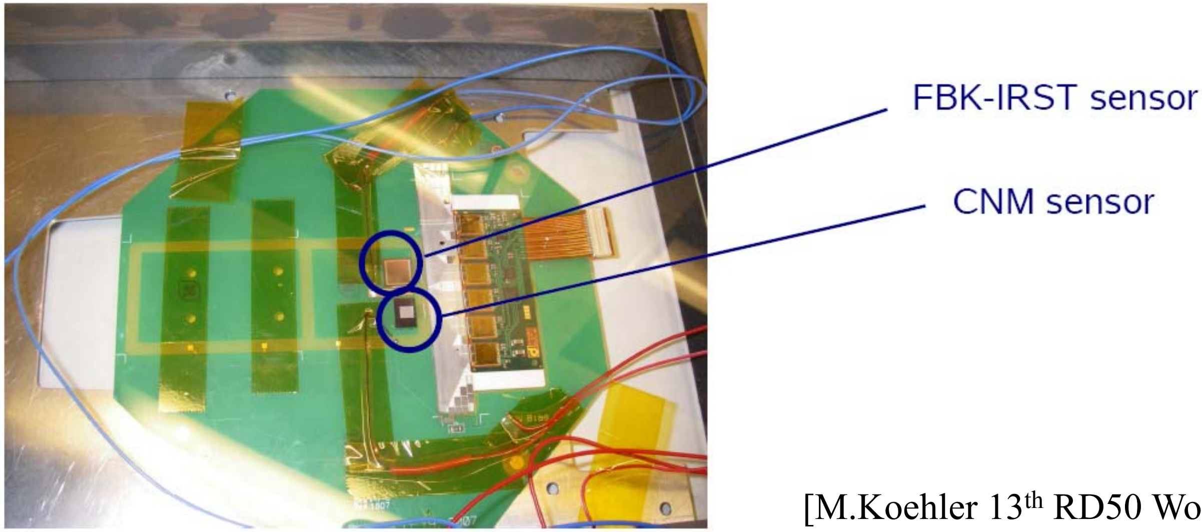


Andrea Zoboli RESMDD'08 Florence, 15-17 October 2008

2008 test beam with 3D sensors

- Two microstrip 3D DDTC detectors tested in testbeam (CMS/RD50)
  - One produced by CNM (Barcelona), studied by Glasgow
  - One produced by FBK-IRST (Trento), studied by Freiburg

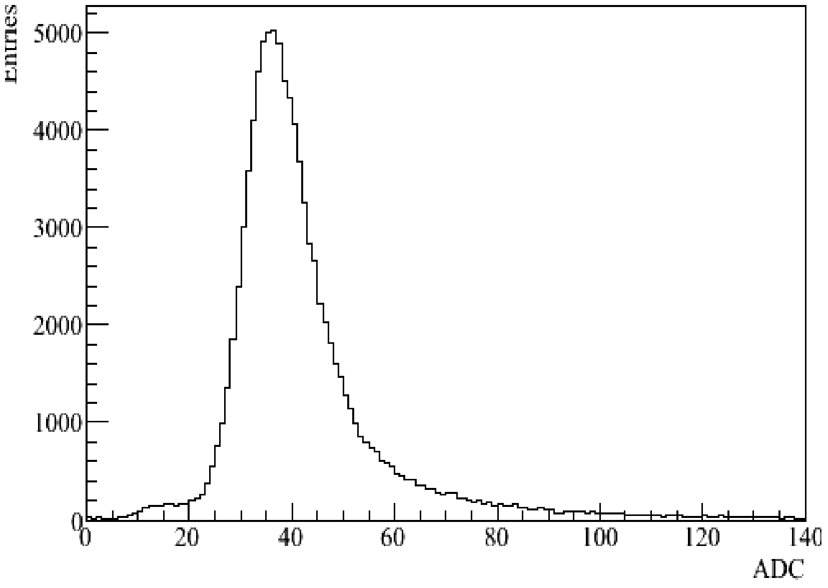
- Readout: APV25, as used in CMS tracker
  - Analogue readout (40 MHz), 50 ns shaping time
  - Trigger accepted during the entire 25 ns clock window (no TDC), but sampling of the signal always at the same time
    → Average detected signal expected to be ≈ 10% lower

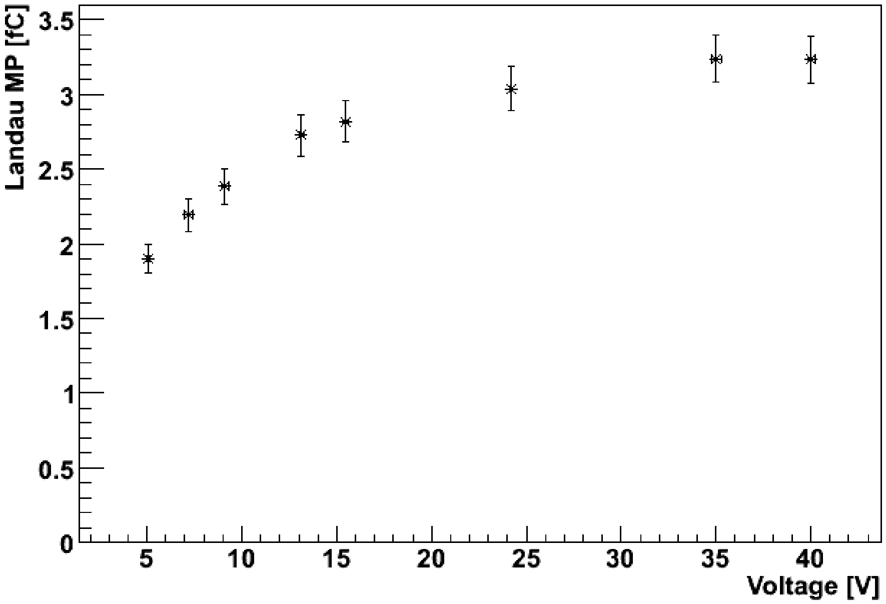


[M.Koehler 13th RD50 Workshop, Nov.2008]

3DDTC sensors (test beam)

- Maximum charge ≈ 20±1 ke$^-$ (3.2±0.2 fC)
    - expected for 300 μm silicon: 22000 e$^-$ (3.5 fC)
- Charge collection time according to simulations ≈ 45 ns (for n-type, depends also on column depth)
    - No significant ballistic deficit (shaping time 50ns)

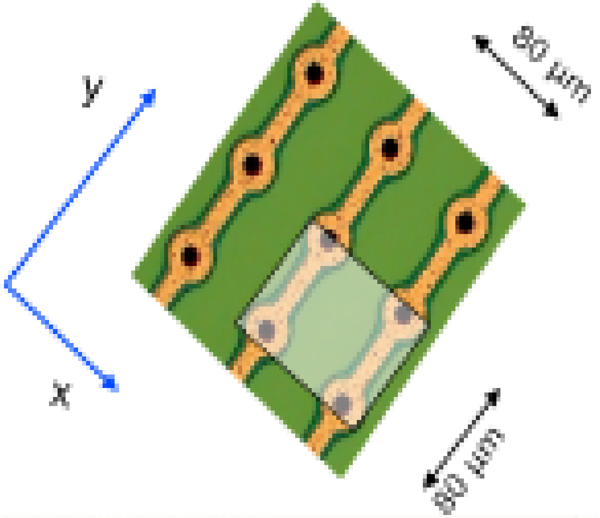


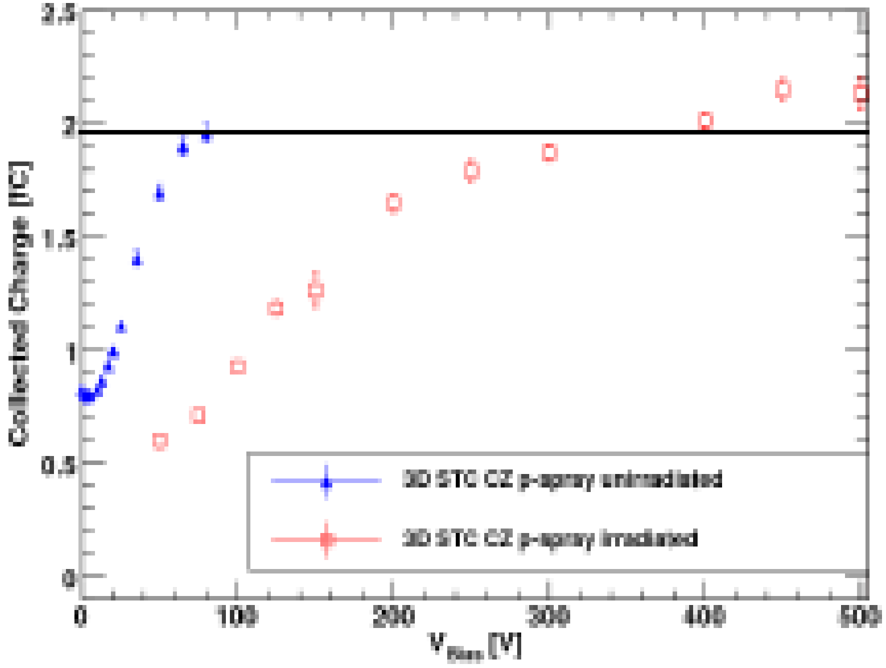


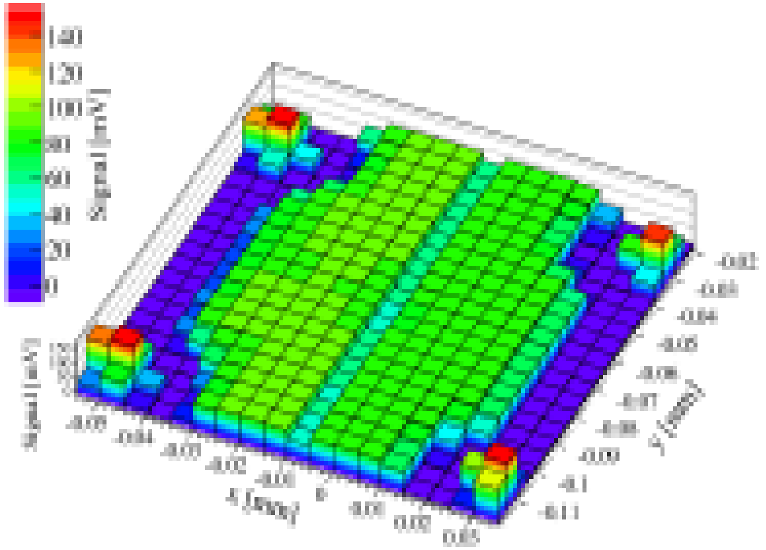
[M.Koehler 14th RD50 Workshop, June 2009]

3DDTC sensors (rad. damage)

- Laser scan with small spot ~5μm
- Lower signal in-between the columns as expected from electric field
- CCE after irradiation with 25MeV protons to $9 \cdot 10^{14}$ neq/cm² close to 100%







U. Parzefall et al.,"Silicon microstrip detectors in 3D technology for the sLHC", doi:10.1016/j.nima.2009.03.122]

RD50 achievements & links to LHC Experiments

Some important contributions of RD50 towards the SLHC detectors:

- **p-type silicon (brought forward by RD50 community) is now considered to be the base line option for the ATLAS Tracker upgrade**
- **RD50 results on reverse annealing of p-type silicon (no cooling during maintenance periods needed) are already taken into account by Experiments**
- **n- and p- type MCZ (introduced by RD50 community) are under investigation in ATLAS, CMS and LHCb**
- **RD50 results on very highly irradiated silicon strip sensors have shown that planar pixel sensors are a promising option also for the upgrade of the Experiments**

Close links to and knowledge exchange with Experiments

- **Many RD50 groups are directly involved in ATLAS, CMS and LHCb upgrade activities (<u>natural close contact</u>).**
- **Many common activities: Irradiation campaigns, test beams, wafer procurement, sensor production, …**

- **LHC speed front-end electronics (ATLAS, CMS and LHCb) used by RD50 members**