96th meeting of the LHCC, 19 November 2008

RD50 STATUS REPORT 2008

Development of radiation hard sensors for very high luminosity colliders

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[2]CERN- PH-DT - Geneva - Switzerland

on behalf of RD50

OUTLINE

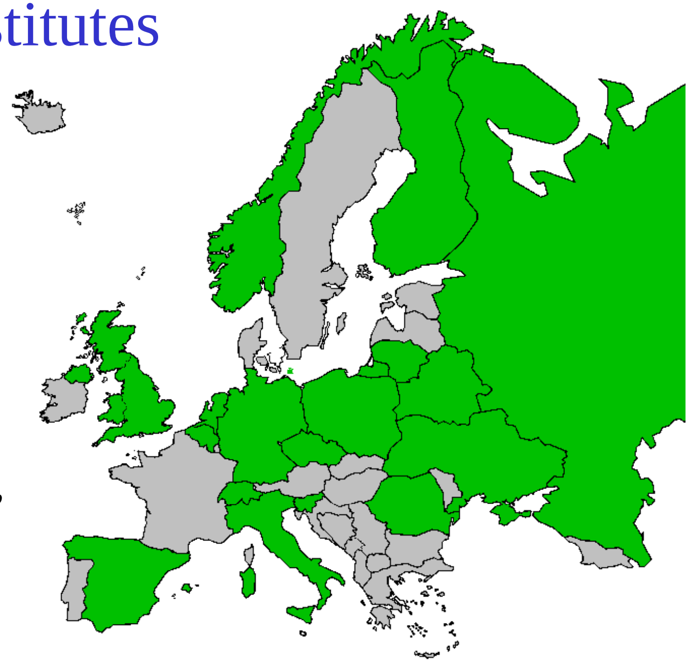
- **The RD50 collaboration**
- **Results obtained in 2008**
- **Work plan for 2009**
- **Resources request for 2009**

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

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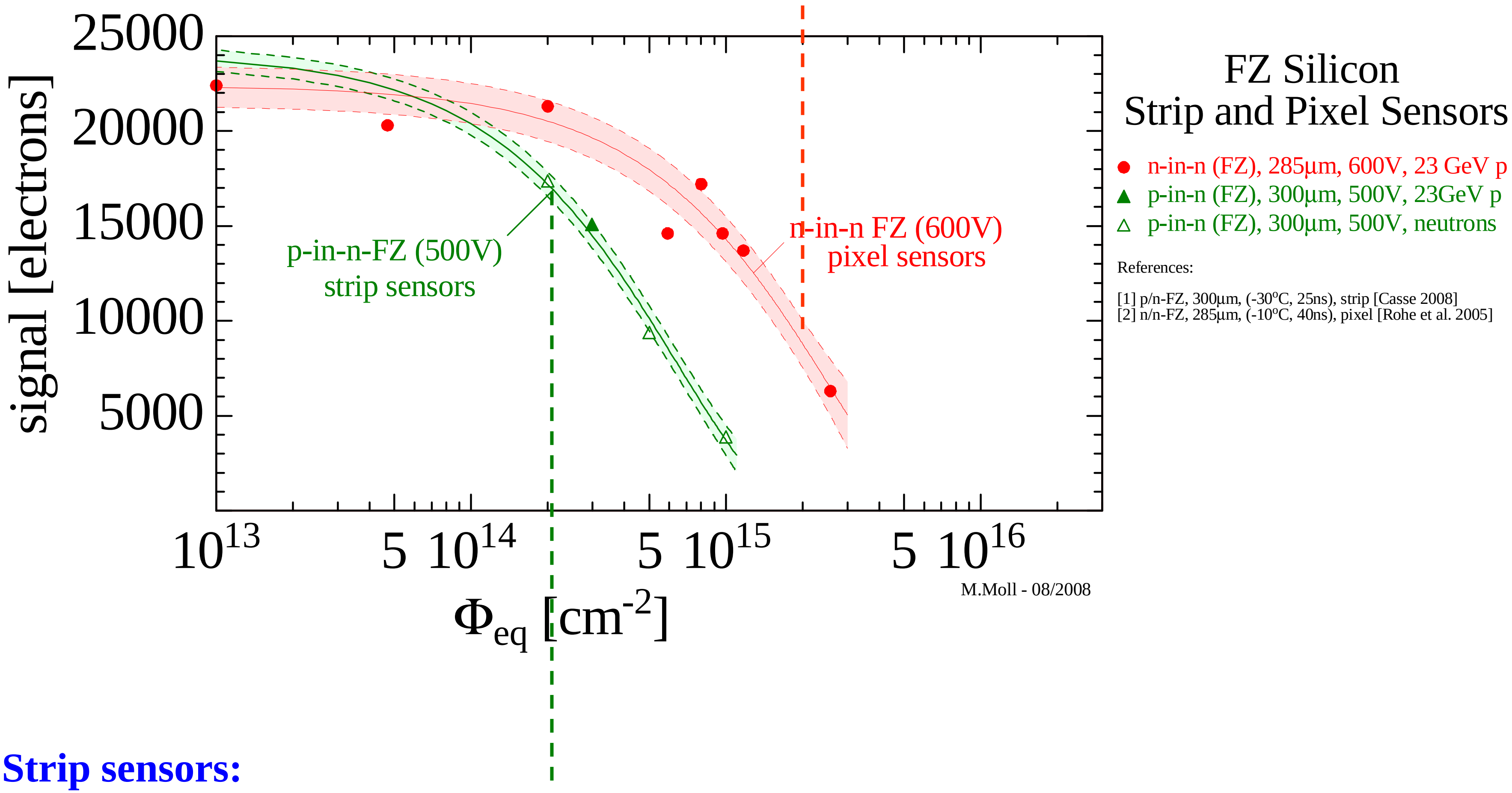
Motivation:

Signal degradation for LHC Silicon Sensors

Pixel sensors:

max. cumulated fluence for LHC



Strip sensors:

max. cumulated fluence for LHC

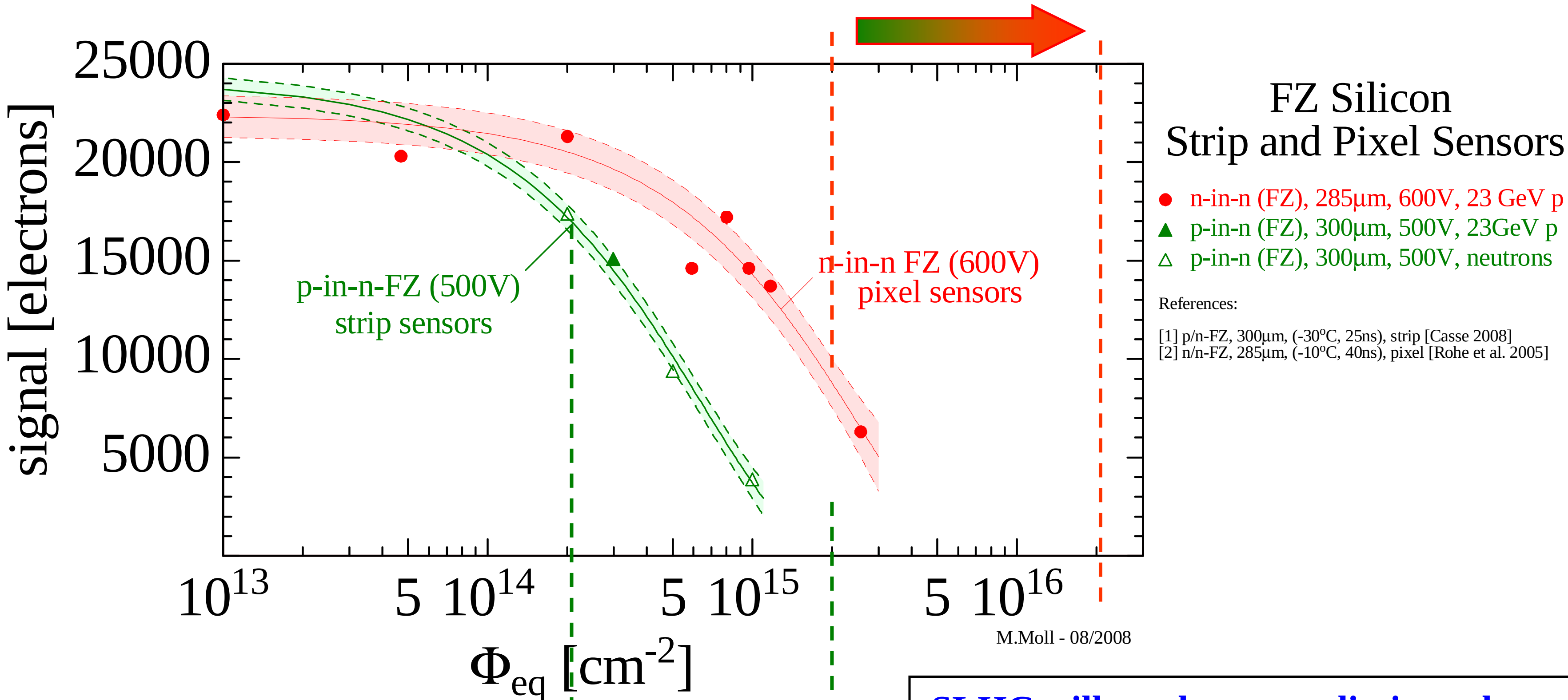
RD50

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

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

- 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**

RD50 Reminder: Silicon Materials under Investigation

standard for particle detectors

used for LHC Pixel detectors

"new" silicon material

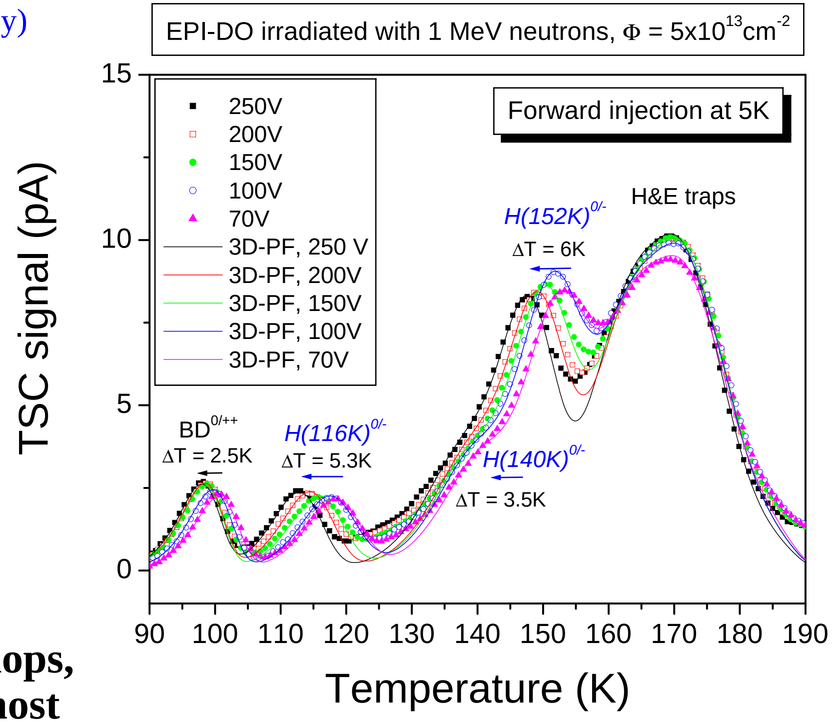
Material	Thickness [μm]	Symbol	ρ (Ωcm)	$[O_i]$ (cm^{-3})
Standard FZ (n- and p-type)	50,100,150, 300	FZ	$1\text{–}30\times10^{3}$	$< 5\times10^{16}$
Diffusion oxygenated FZ (n- and p-type)	300	DOFZ	$1\text{–}7\times10^{3}$	$\sim 1\text{–}2\times10^{17}$
Magnetic Czochralski Si, Okmetic, Finland (n- and 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 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 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
- $\sigma_n^{BD} = 2.3 \cdot 10^{-14}$ cm^2

- $E_i^{I} = E_c - 0.545$ eV
  - $\sigma_n^{I} = 2.3 \cdot 10^{-14}$ cm^2
  - $\sigma p^{I} = 2.3 \cdot 10^{-14}$ cm^2

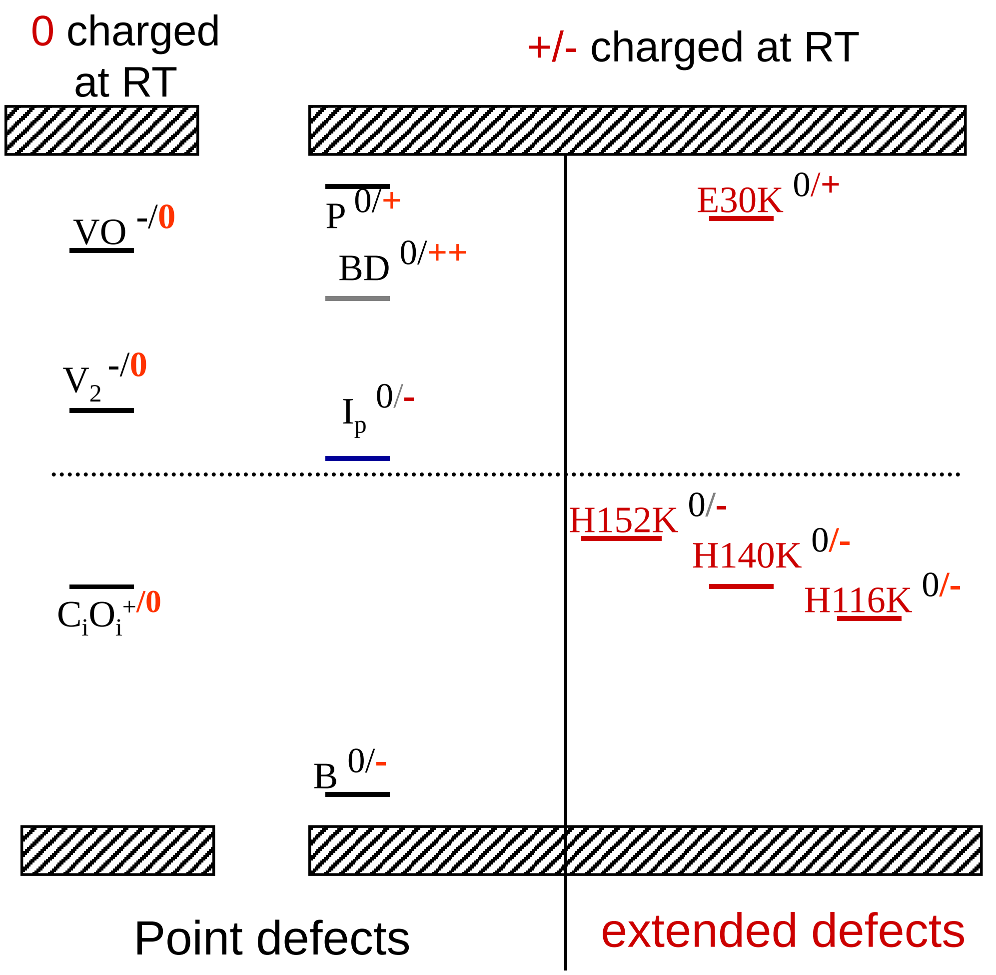
Cluster related centers

- $E_i^{116K} = E_v + 0.33$eV
- $\sigma_p^{116K} = 4 \cdot 10^{-14}$ cm^2

- $E_i^{140K} = E_v + 0.36$eV
- $\sigma_p^{140K} = 2.5 \cdot 10^{-15}$ cm^2

- $E_i^{152K} = E_v + 0.42$eV
- $\sigma_p^{152K} = 2.3 \cdot 10^{-14}$ cm^2

- $E_i^{30K} = E_c - 0.1$eV
- $\sigma_n^{30K} = 2.3 \cdot 10^{-14}$ cm^2



I.Pintilie, NSS, 21 October 2008, Dresden

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

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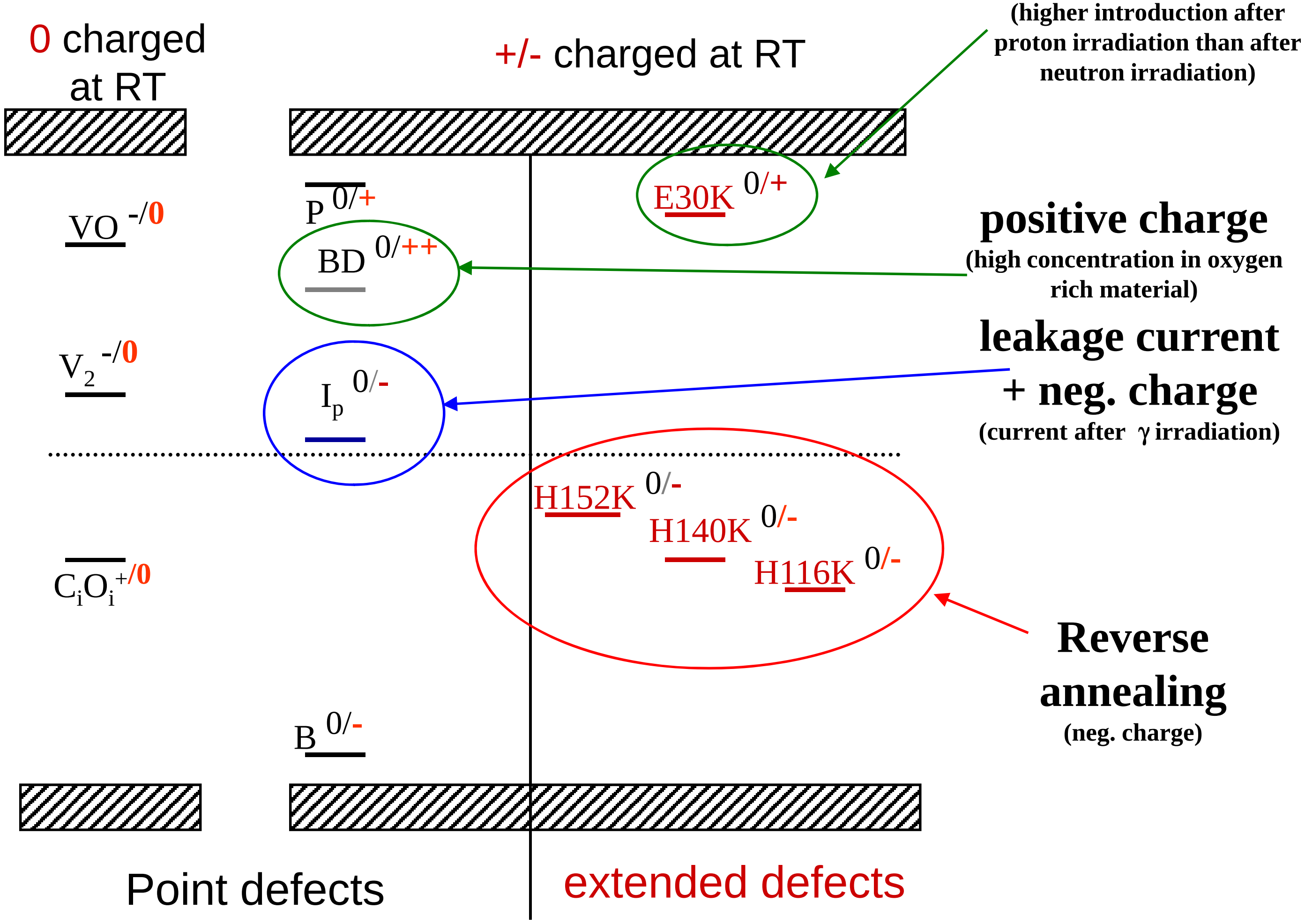
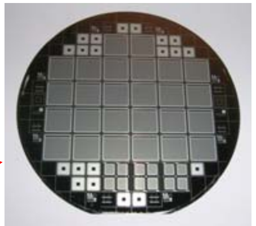
- $\sigma_n^{30K} = 2.3\cdot10^{-14}$ cm^2

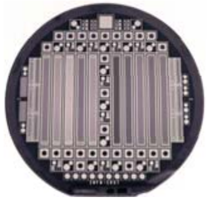


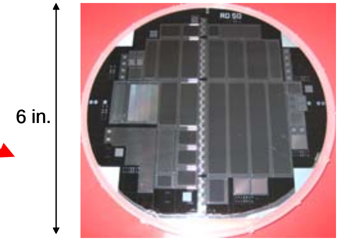
I.Pintilie, NSS, 21 October 2008, Dresden

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)**





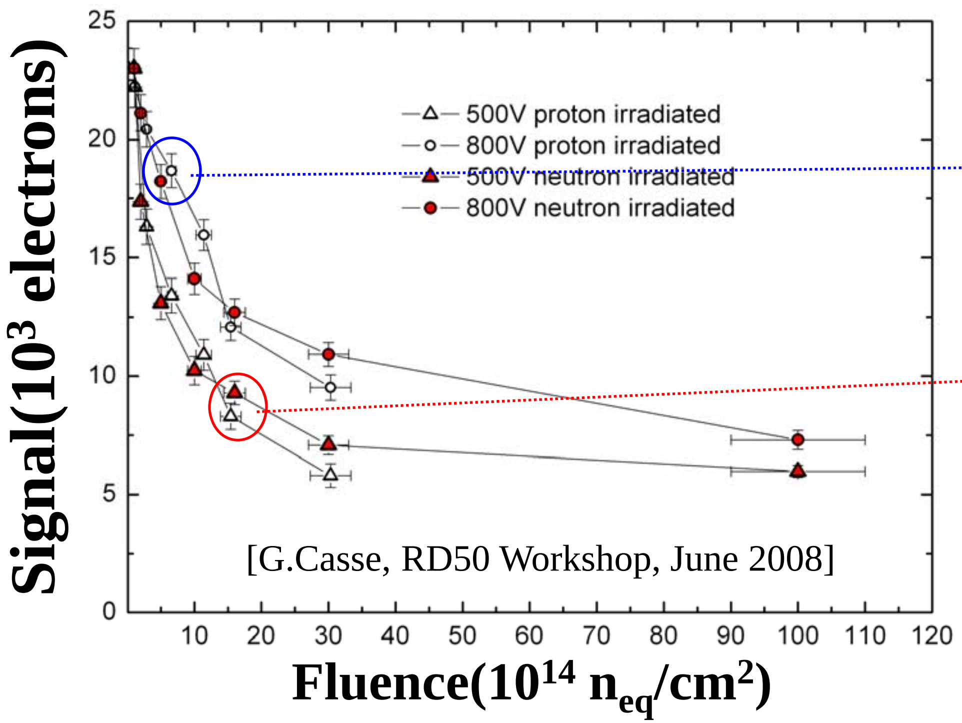


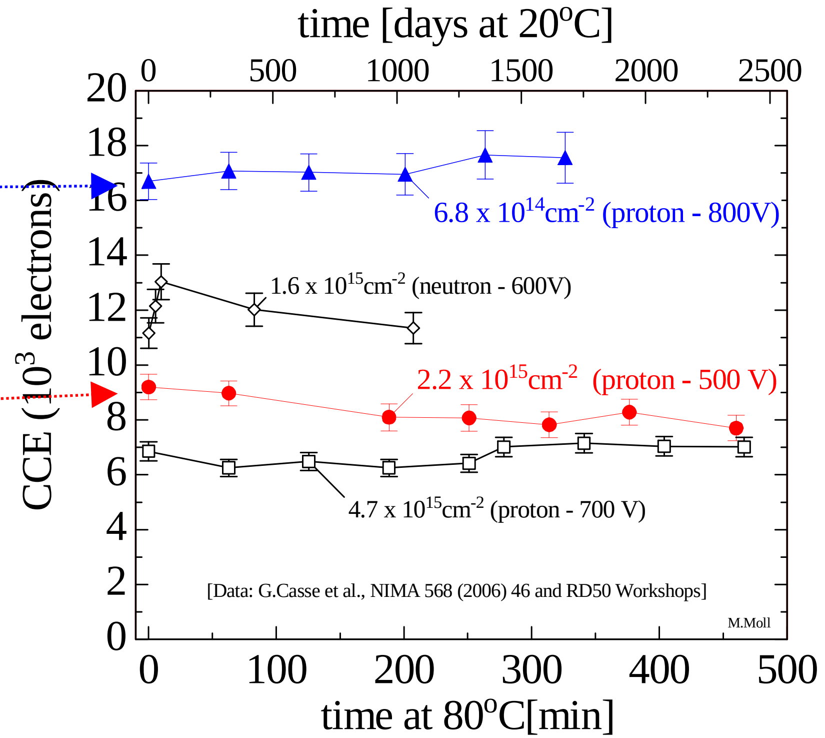
Hundreds of samples (pad/strip/pixel) recently produced on various materials (n- and p-type).

- 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 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)





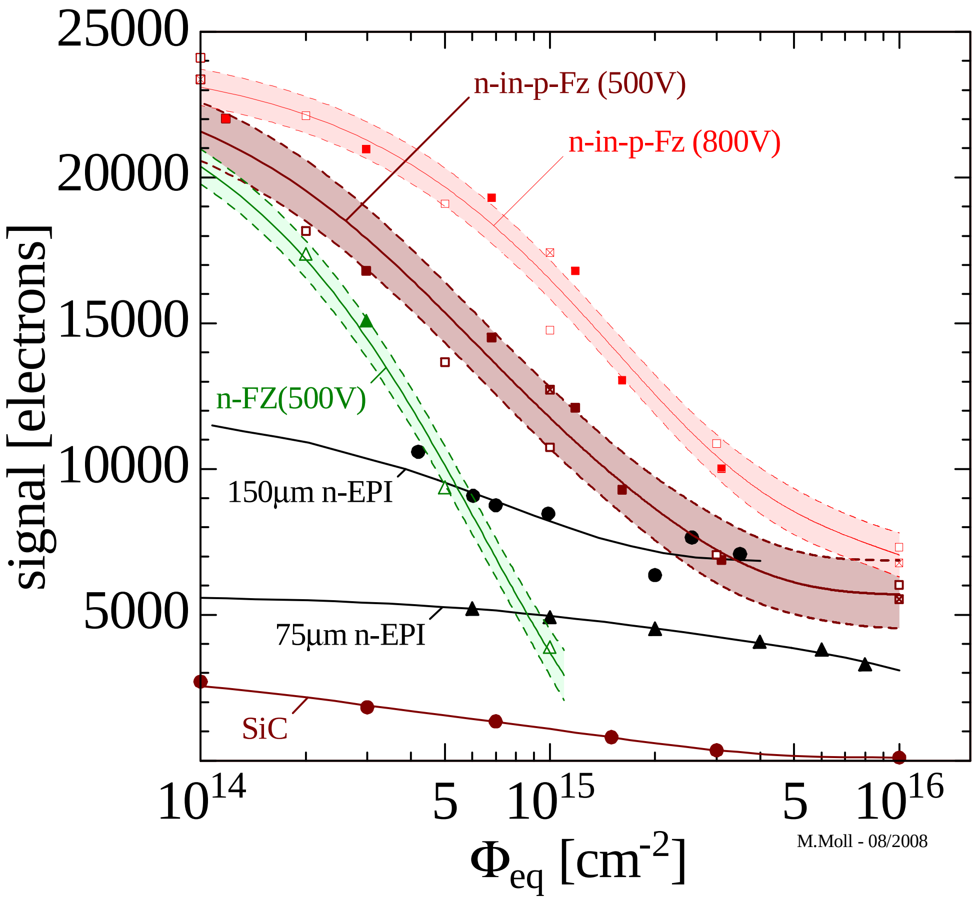
- **CCE: ~7300e (~30%)**
  after ~ 1×10^{16}cm^{-2} 800V
- **n-in-p sensors are strongly considered for ATLAS upgrade** (previously p-in-n used)

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

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)!



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]
- ■ n-in-p (FZ), 300µm, 800V, 23GeV p [1]
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- △ p-in-n (FZ), 300µm, 500V, neutrons [1]

Other materials

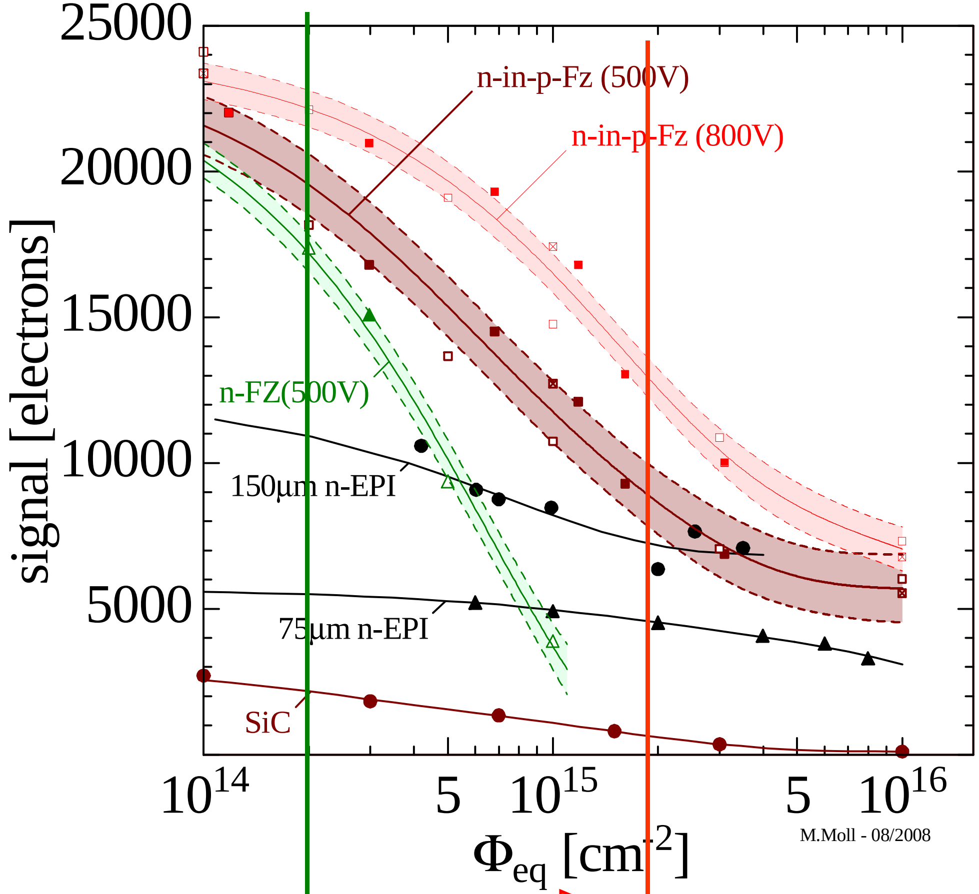
- ● SiC, n-type, 55 µm, 900V, neutrons [3]

References:

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

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)!

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]
- ■ n-in-p (FZ), 300µm, 800V, 23GeV p [1]
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[8] n-EPI,150µm, (-30°C, 25ns), strip [Messineo 2007]

LHC → **SLHC**

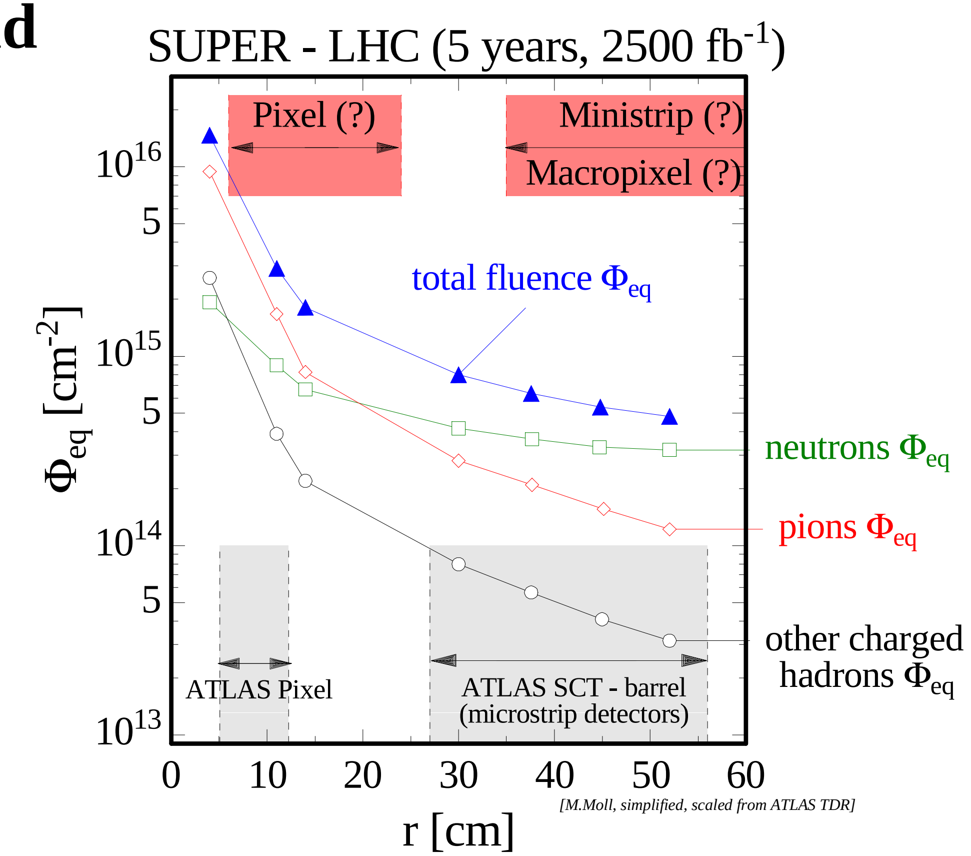
highest fluence for strip detectors in LHC: The used p-in-n technology is sufficient

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)

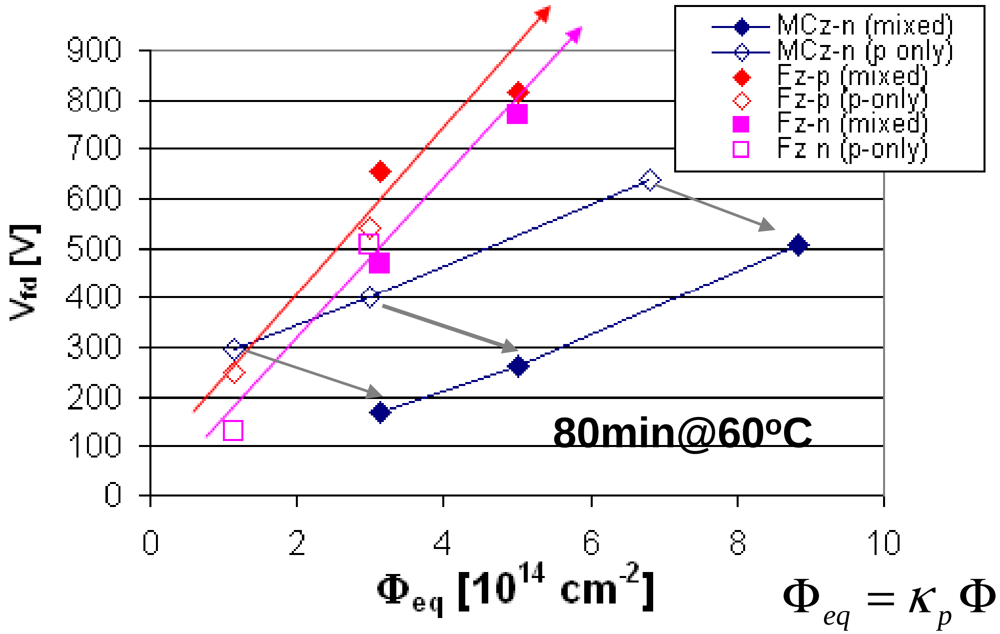


- **MCZ silicon has shown an interesting behavior:**
  - **build up of net negative space charge after neutron irradiation**
  - **build up of net positive space charge after proton irradiation**

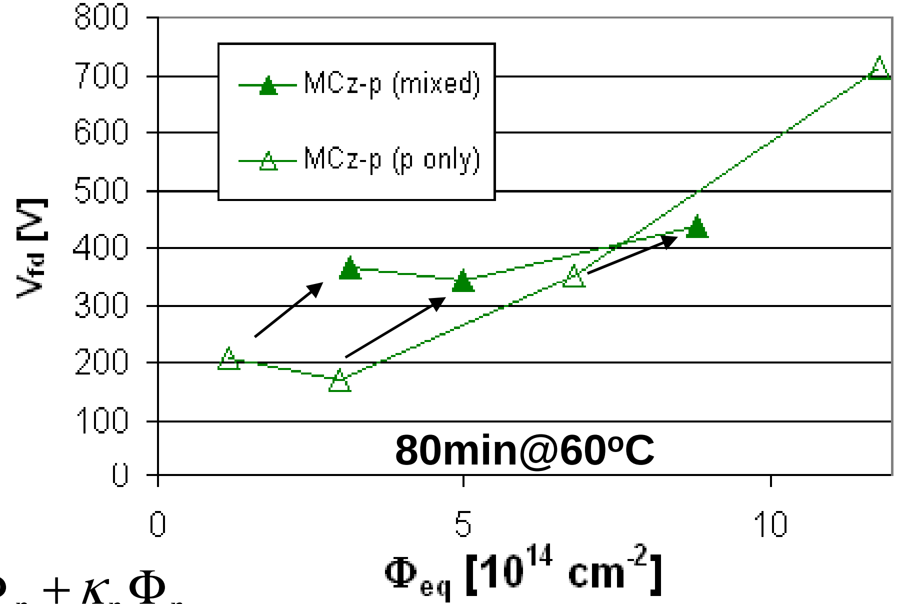
- **Question:**
  - **What happens when (MCZ) detectors are exposed to a ‘mixed’ radiation field?**

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 -

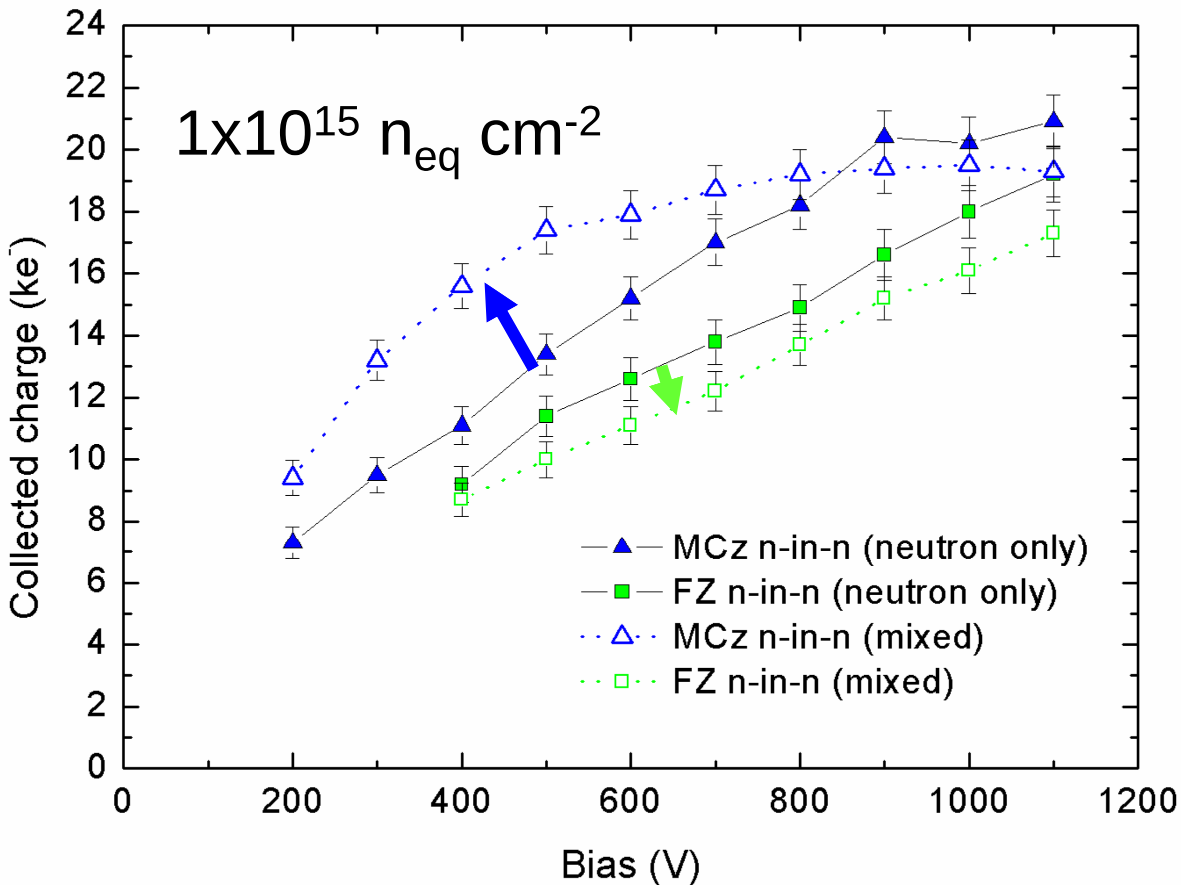
always +

- **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

RD50 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



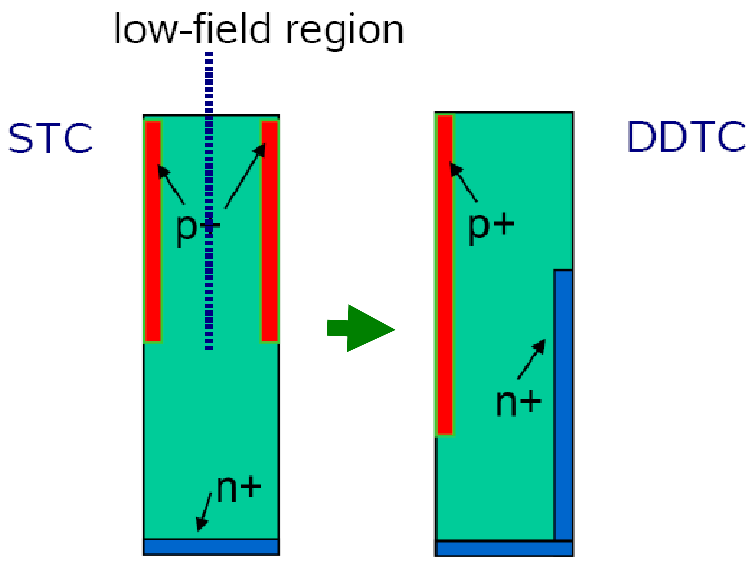
Needs further study with both nMCz and pMCz substrates and differing mixed doses

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

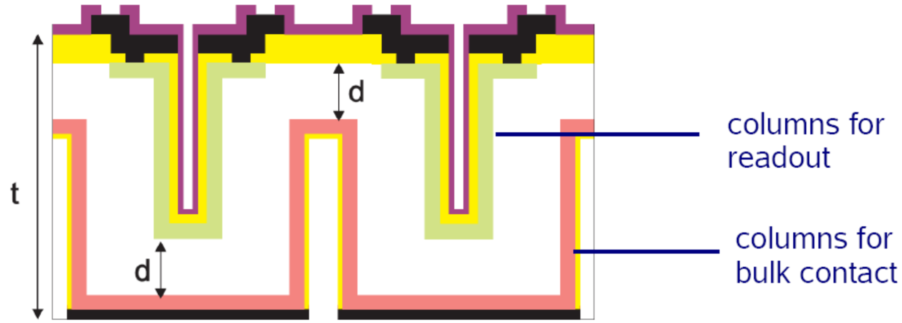
RD50 Development of 3D detectors

- **"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

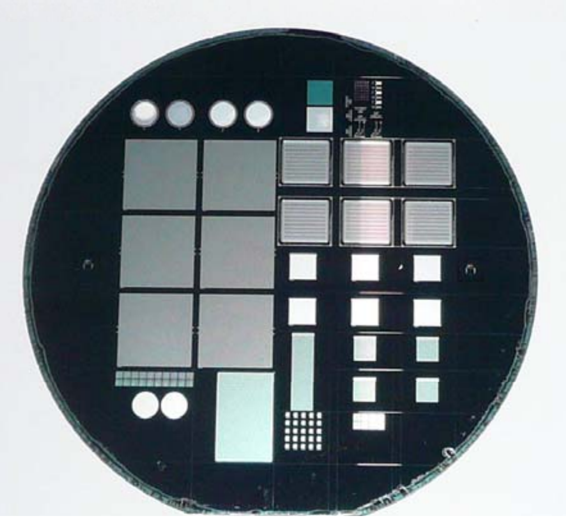
From STC to DTC



- 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

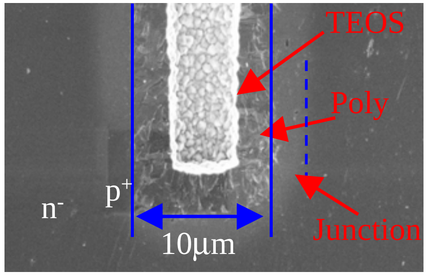


Processing of Double-Column 3D detectors



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

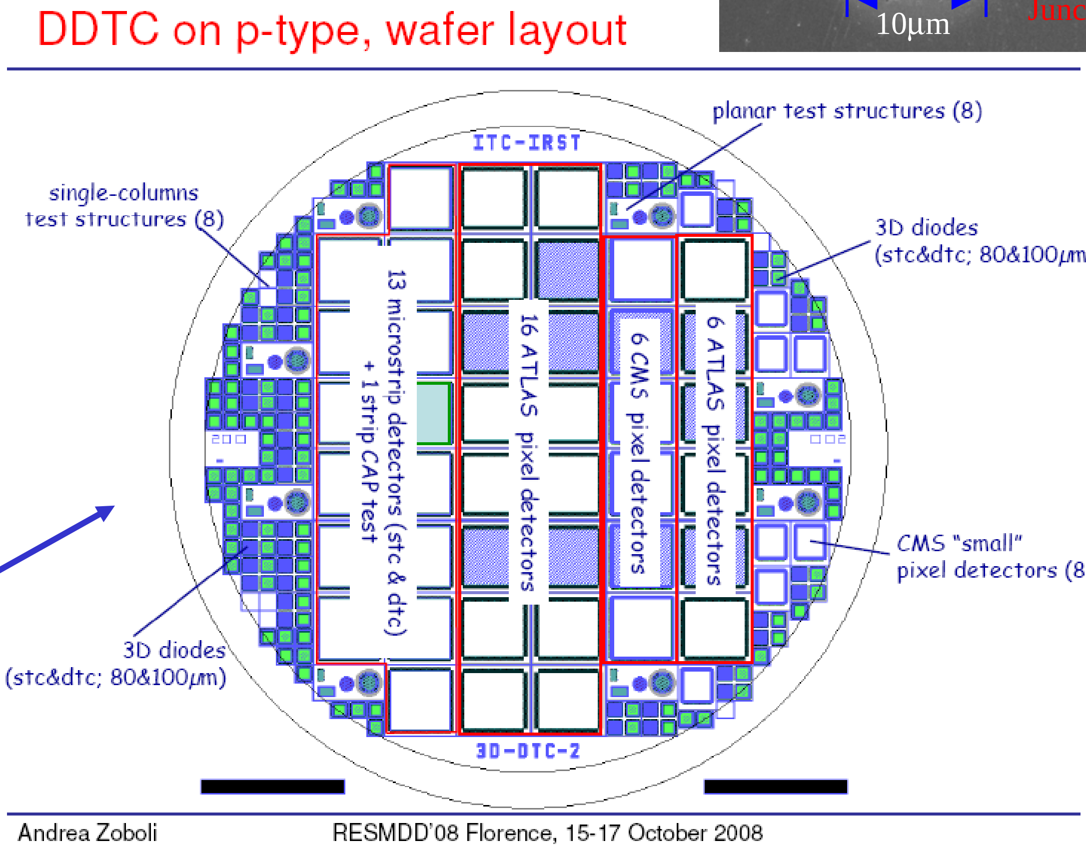
- Double side processing with holes not all the way through
- n-type bulk
- bump bond 1 wafer to Medipix2 chips
- Further production (n and p-type)



- First tests on irradiated devices performed (CNM devices, strip sensors, ^{90}Sr , Beetle chip, $5x10^{15} n_{eq}/cm^2$ with reactor neutrons) : 12800 electrons

2. FBK (IRST-Trento)

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



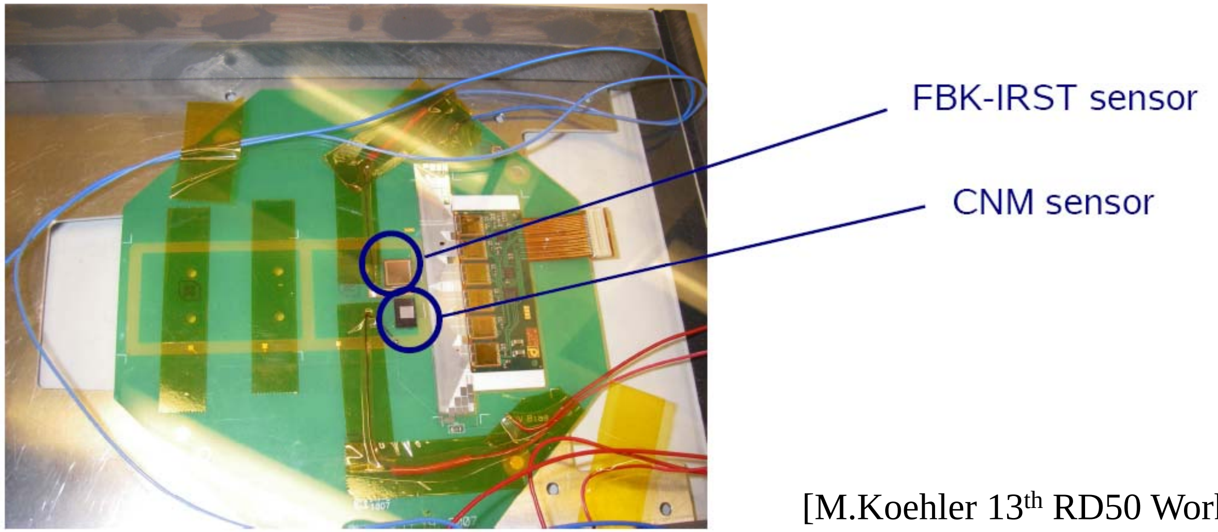
RD50

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 – first data)

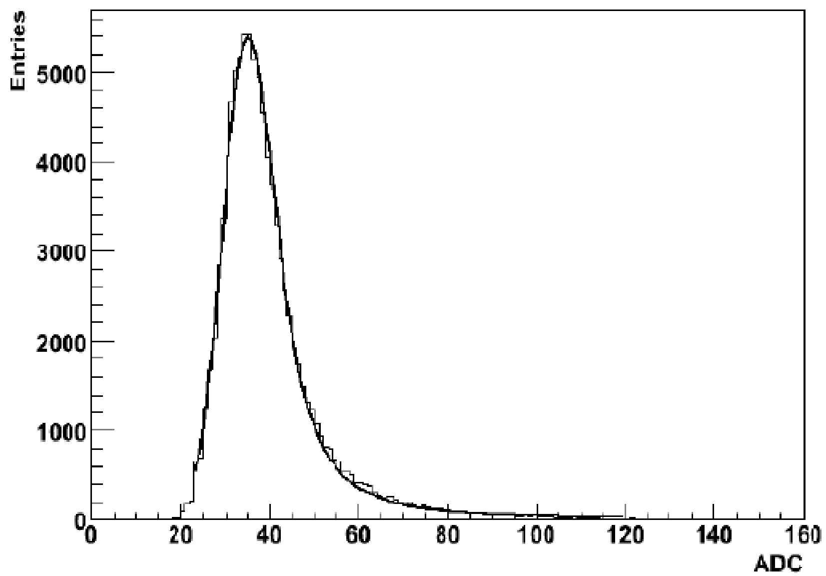
Landau distribution

- ADC distribution with fit of a convoluted Landau and Gaussian

- Bias voltage: 40 V, SNR ≥ 10
- Result:

Landau MP= (33.32±0.02) ADC counts

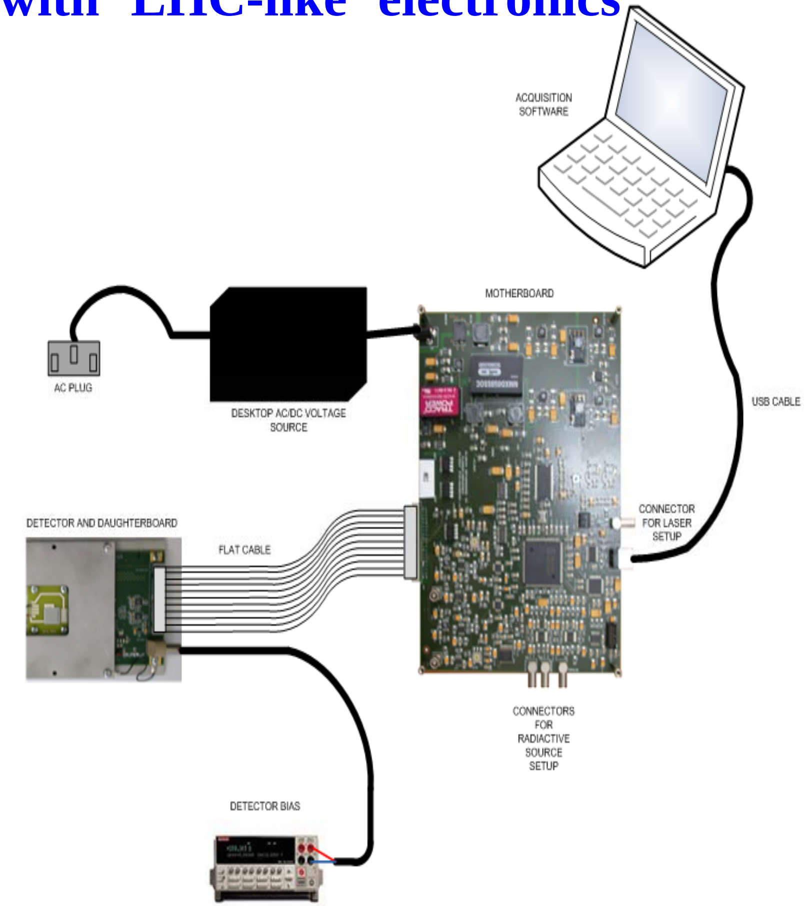
- Calibration ADC counts → charge so far not available
- Histogram contains data from all bonded strips (not position resolved)



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

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]

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 (natural close contact).**
- **Many common activities: Irradiation campaigns, test beams, wafer procurement, sensor production, …**
- **LHC speed front-end electronics (ATLAS, CMS and LHCb) used by RD50 members**

RD50 Workplan for 2009 (1/2)

Defect and Material Characterization	• **Characterization of irradiated silicon:** ▪ **Continue WODEAN program** ▪ **Common publication in Phys. Rev. B on new results** ▪ **Modelling and understanding role of clusters** ▪ **Extend studies to p-type silicon detectors** ▪ **Extend search on defects responsible for trapping**
Defect Engineering & Pad Detector Characterization	• **Secure supply of 150μm thick epitaxial silicon** • **Production of epitaxial silicon on FZ substrate** • **Extend common irrad. programs with fluences up to $10^{16}cm^{-2}$ (get clear understanding on trapping and avalanche processes)** • **Extend investigations on 'mixed' irradiations** • **Cold irradiations (down to -40°C)** • **Irradiations with and without applied bias** • **Develop techniques to measure the electric field strength inside the detectors**

Workplan for 2009 (2/2)

New Structures	• **Working, high quality double column 3D devices (pad, strip, pixel) are now available within RD50:** **Perform irradiation & test program for 3D sensors as previously performed for strip sensors!**
Full Detector Systems	• **Further explore fluence range between 10^{15} and 10^{16} cm^{-2}** • **'Mixed irradiations' & cold irradiations** (see also pad detector characterization) • **Long term annealing of segmented sensors** Consolidate finding that no reverse annealing is visible in CCE, which will have major impact on detector maintenance and performance • **Extend activity on pixel sensor fabrication & characterization** (intensify collab. with ATLAS/CMS pixel) • **Support and distribute Alibava system among RD50 members** • **Investigation on electric field profile in irradiated segmented sensors and impact on CCE**

Resources requested for 2009

- **Common Fund:**

RD50 does not request a direct financial contribution to the RD50 common fund.

- **<u>Acknowledgement</u>:** Council Whitepaper – Theme 3 R&D – PH Workpackages

The CERN-RD50 group activities are included in and supported by the Work Package 4 "*Radiation Hard Semiconductor Detectors*"

- **Lab space and technical support at CERN:**

As a member of the collaboration, the PH-DT should provide (as in 2008) access to **lab space in building 14** (characterization of irradiated detectors), **in building 28** (lab space for general work) and in the **Silicon Facility** (hall 186, clean space).

- **CERN Infrastructure:**

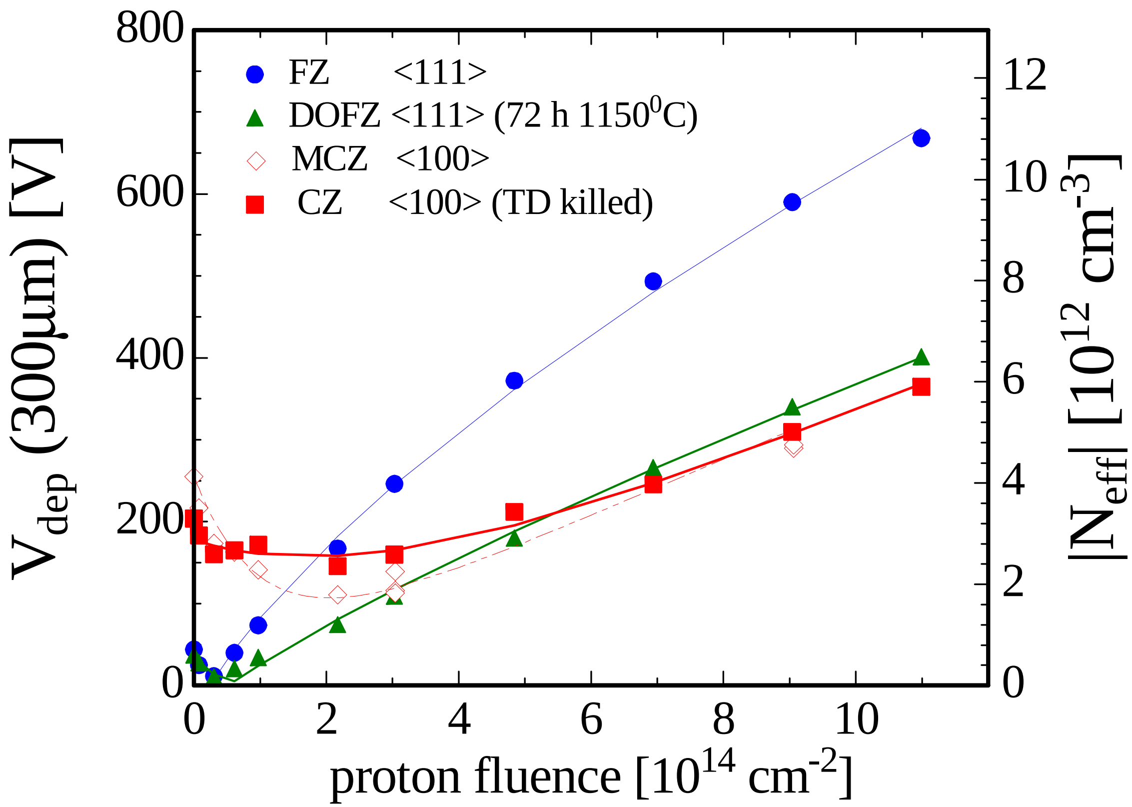
- One collaboration workshop in November 2008 and working group meetings
- Administrative support at CERN through PH-DT secretariat

Spares

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!**
  - 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%