100th meeting of the LHCC, 18 February 2010

RD50 STATUS REPORT 2009

Development of radiation hard sensors for very high luminosity colliders

Mara Bruzzi[1] and Michael Moll[2]

[1]INFN Florence, Italy
[2]CERN- PH-DT - Geneva - Switzerland

on behalf of RD50

OUTLINE

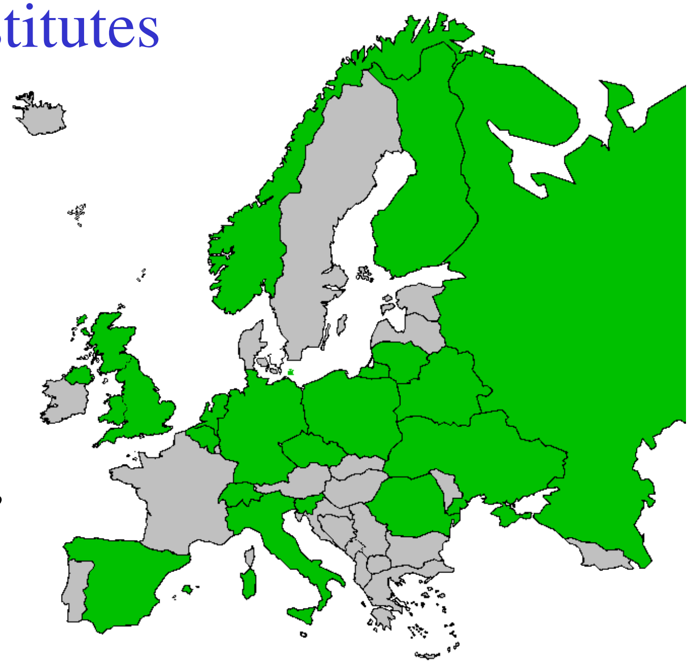
- **The RD50 collaboration**
- **Results obtained in 2009**
- **Work plan for 2010**
- **Resources request for 2010**

http://www.cern.ch/rd50

250 Members from 47 Institutes

41 European and Asian institutes

Belarus (Minsk), **Belgium** (Louvain), **Czech Republic** (Prague (3x)), **Finland** (Helsinki, Lappeenranta), **Germany** (Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe, Munich), **Italy** (Bari, Florence, Padova, Perugia, Pisa, 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)

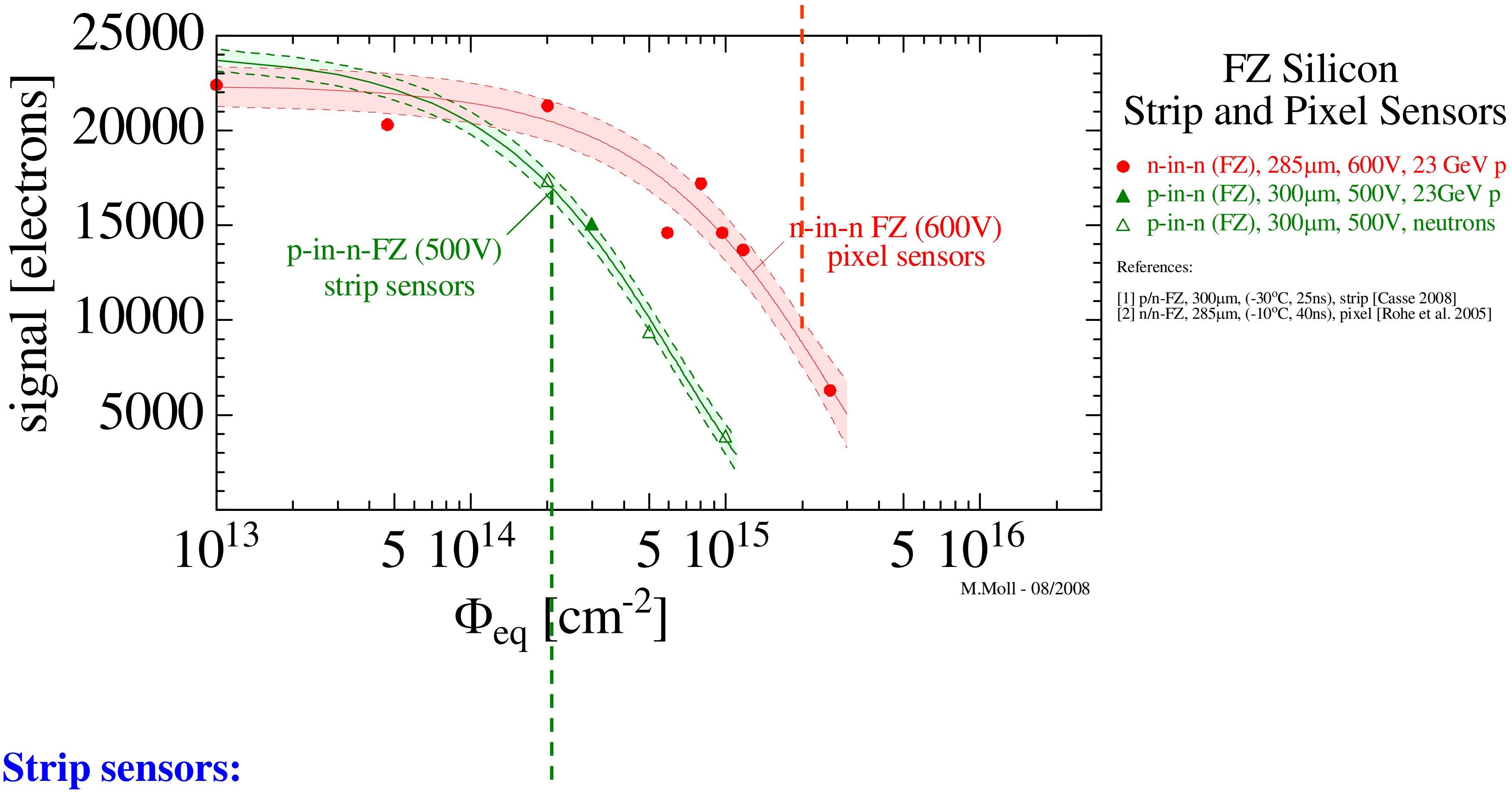
Detailed member list: http://cern.ch/rd50

Motivation:

Signal degradation for LHC Silicon Sensors

Pixel sensors:

max. cumulated fluence for LHC



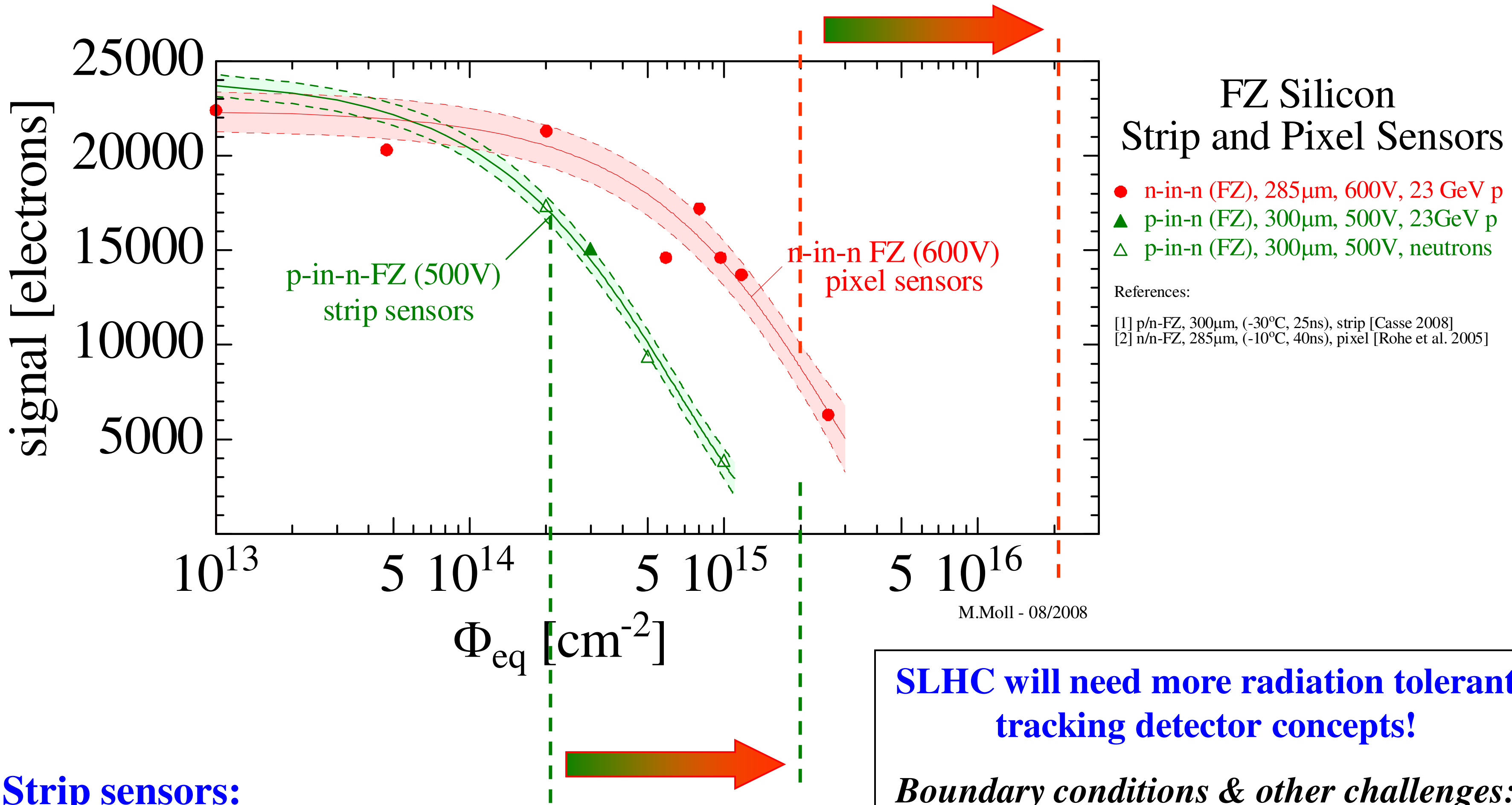
Strip sensors:

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 !

Scientific Organization of RD50

Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

Co-Spokespersons

Mara Bruzzi and ***Michael Moll***

INFN and University of Florence — CERN PH-DT

Defect / Material Characterization
Bengt Svensson
(Oslo University)

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

- **WODEAN:** Workshop on Defect Analysis in Silicon Detectors (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

- Wafer procurement (M.Moll)

Pad Detector Characterization
Gregor Kramberger
(Ljubljana University)

- Characterization of test structures: IV, CV, CCE, TCT, ….
- NIEL
- Device modeling
- Operational conditions
- Common irradiations

- Standardisation of measurements (A.Chilingarov)
- New Materials (E. Verbitskaya)

New Structures
Richard Bates
(Glasgow University)

- 3D detectors
- Thin detectors
- Cost effective solutions
- Other new structures

- 3D (R.Bates)
- Semi 3D (Z.Li)
- Thinned detectors (M.Boscardin)

Full Detector Systems
Gianluigi Casse
(Liverpool University)

- LHC-like tests
- Test beams
- Links to HEP
- Links electronics R&D
- Comparison:
  - pad-mini-full detectors
  - different producers

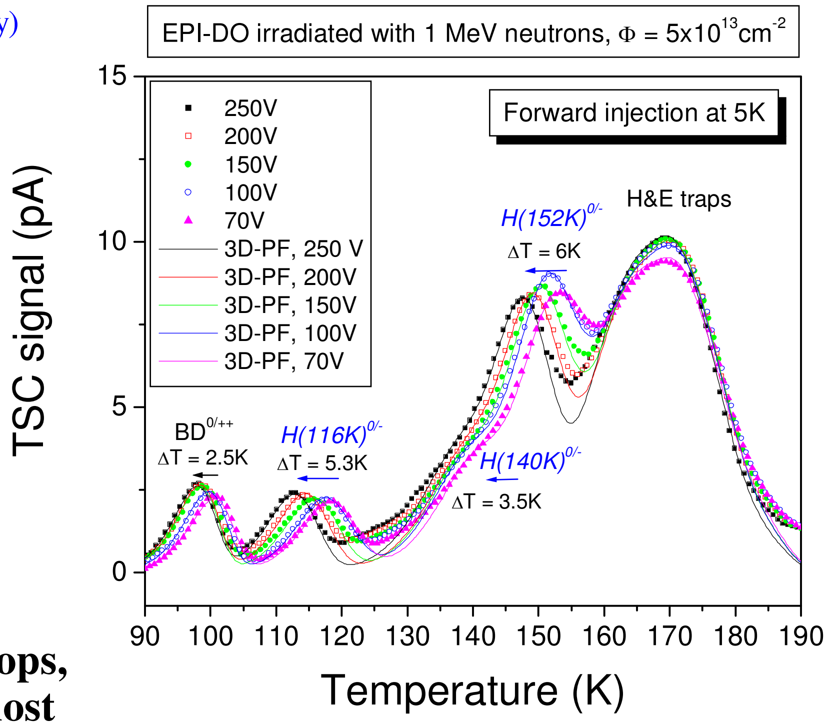
- Pixel Europe: T.Rohe
- Pixel US: D.Bortoletto

Collaboration Board Chair & Deputy: E.Fretwurst (Hamburg) & J.Vaitkus (Vilnius), Conference committee: U.Parzefall (Freiburg)
CERN contact: M.Moll (PH-DT), Secretary: V.Wedlake (PH-DT), Budget holder: M.Glaser (PH-DT)

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

RD50 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

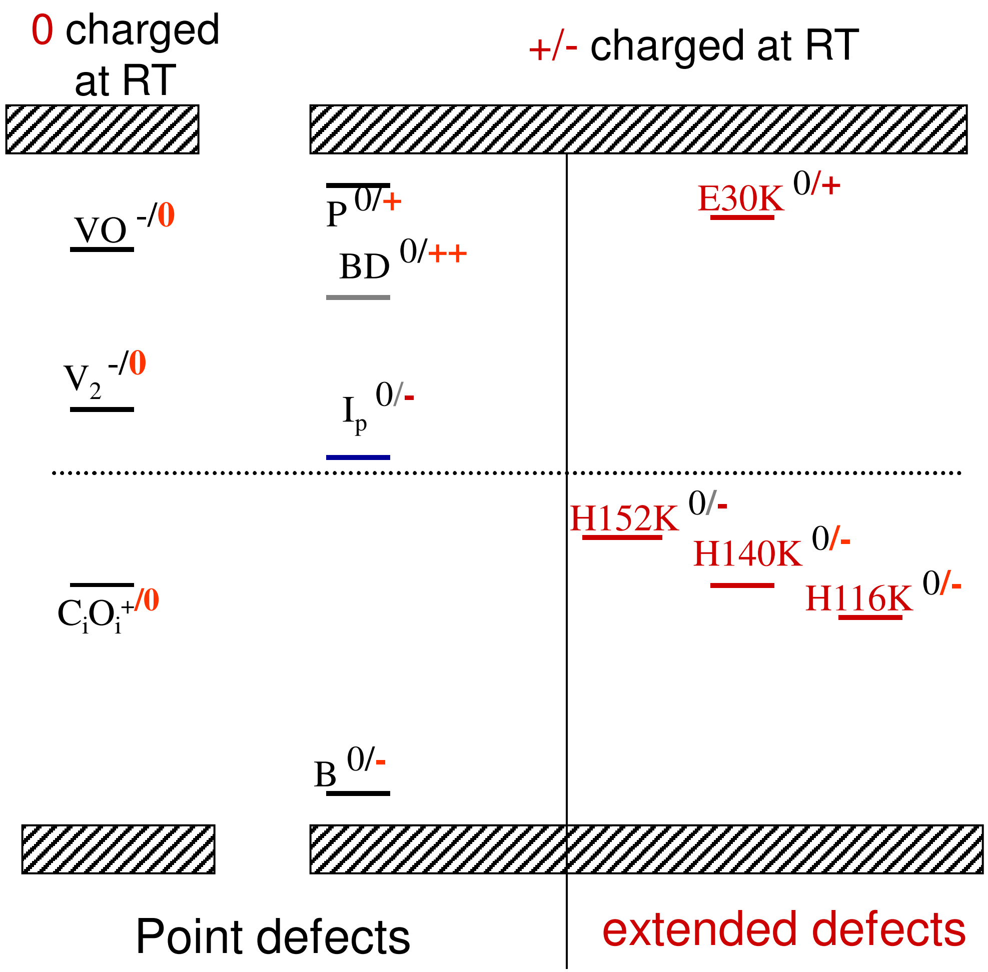
Cluster related centers

- $E_i^{116K} = E_v + 0.33$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



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

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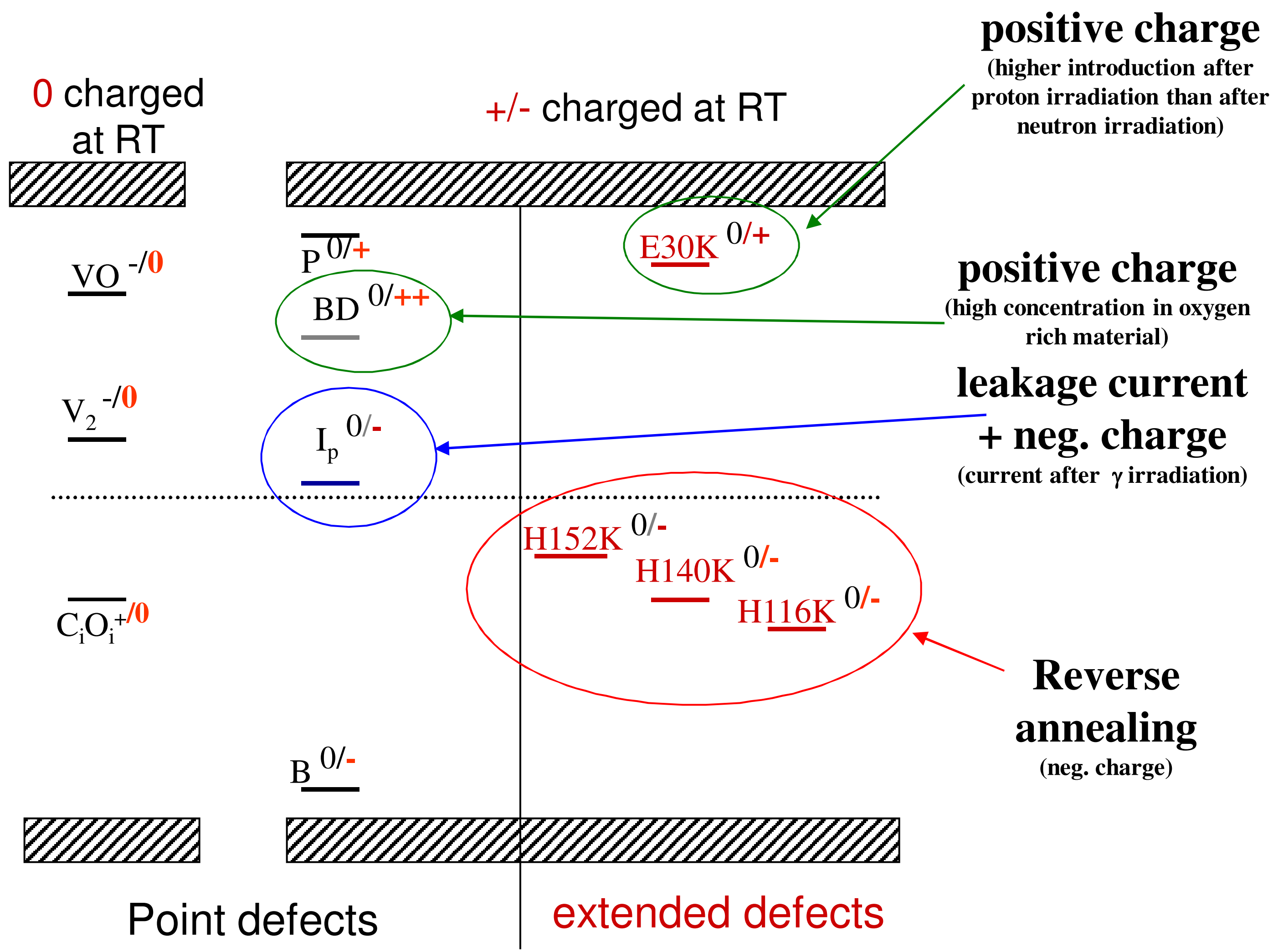
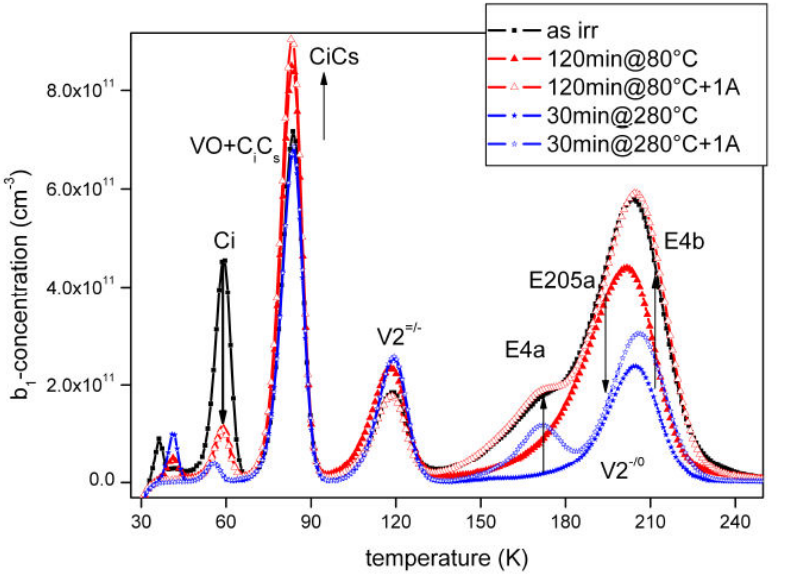


RD50 Correlation: Microscopic and Macroscopic data

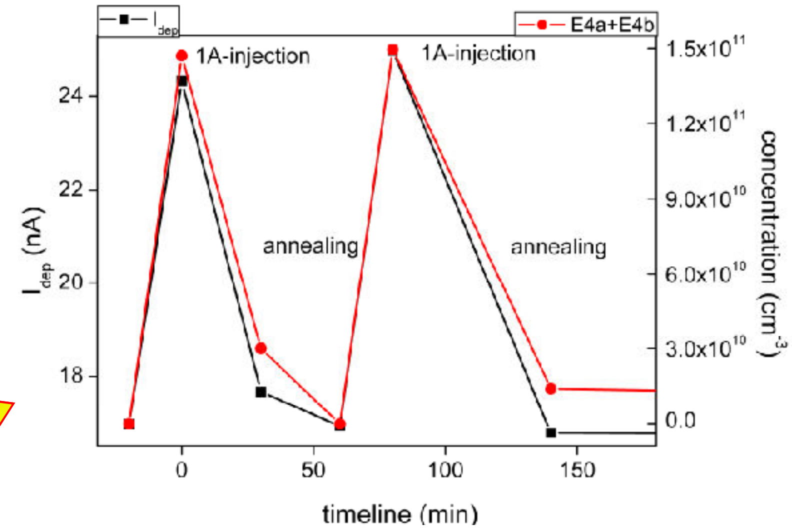
- **Bistable cluster related defect responsible for fraction of leakage current**

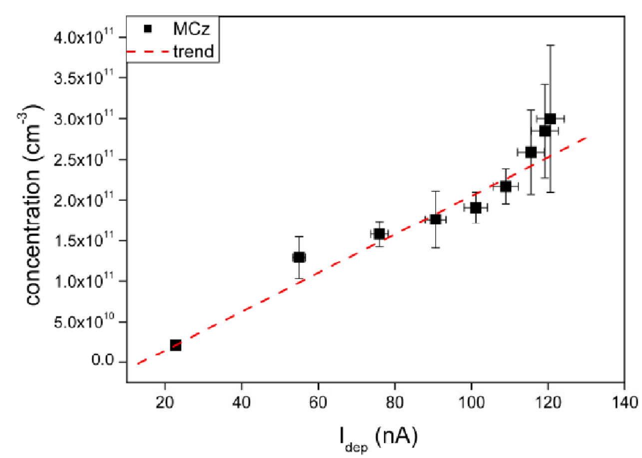
FZ - proton irradiated (DLTS)



[A.Junkes et al.,"Annealing of a bistable cluster defect', NIMA 612 (2010) 525]]

Injection of 1A and annealing at 80C switches leakage current 'on' and 'off'



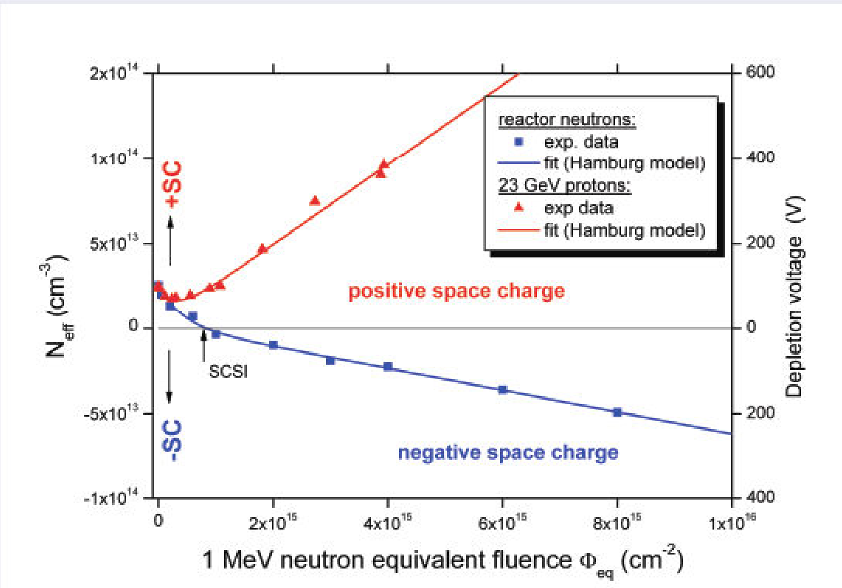


Total current correlates with sum of E4a+E4b+E205a

RD50 Correlation: Microscopic and Macroscopic data

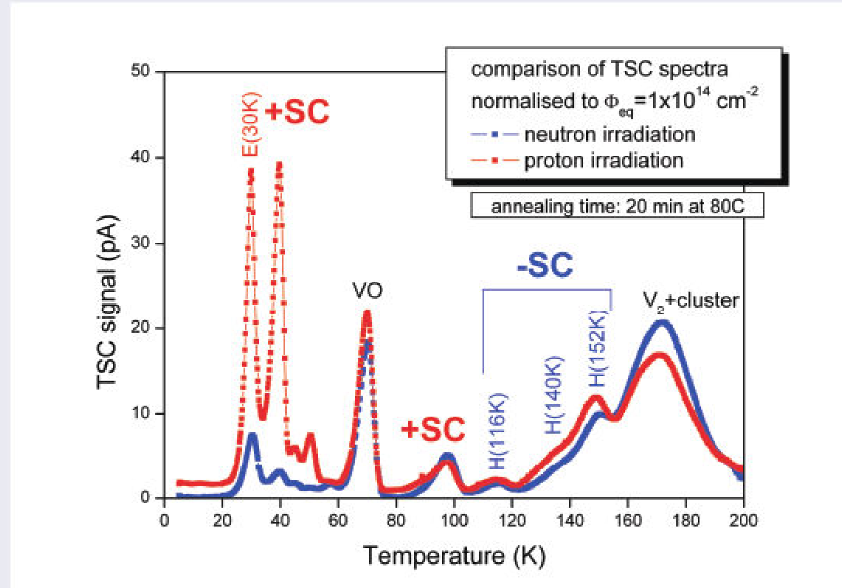
- **Epitaxial silicon irradiated with 23 GeV protons vs reactor neutrons**

delopment of N_{eff} for EPI-DO after neutron and proton irradiation



I. Pintilie, et al., to be published.

TSC results after neutron and proton irradiation



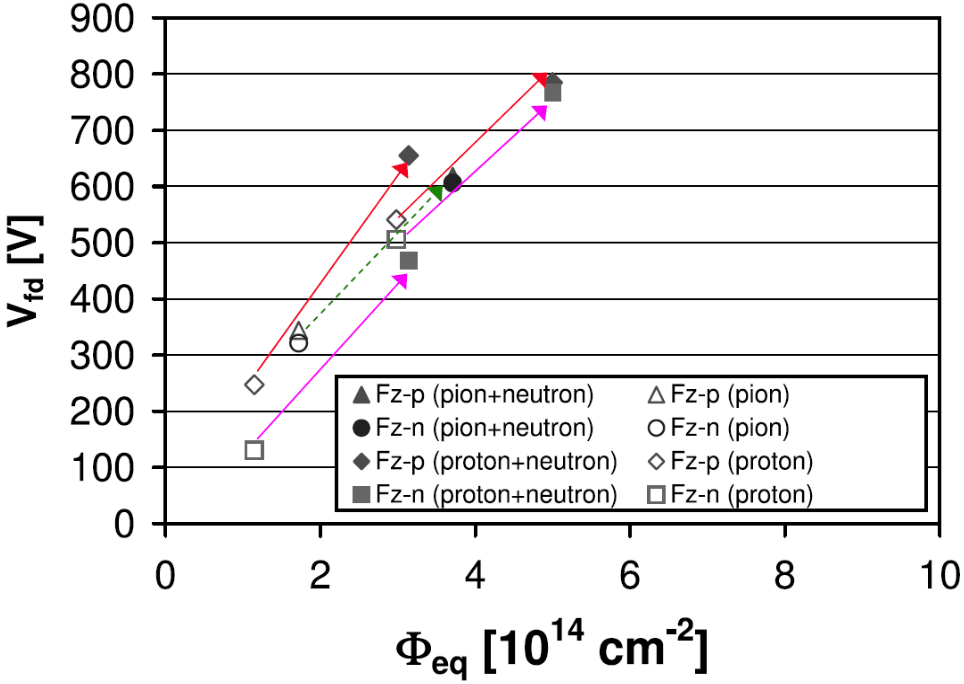
- SCSI after neutrons but not after protons
- donor generation enhanced after proton irradiation
- microscopic defects explain macroscopic effect at low Φ_{eq}

[A.Junkes, Hamburg University, RD50 Workshop June 2009]

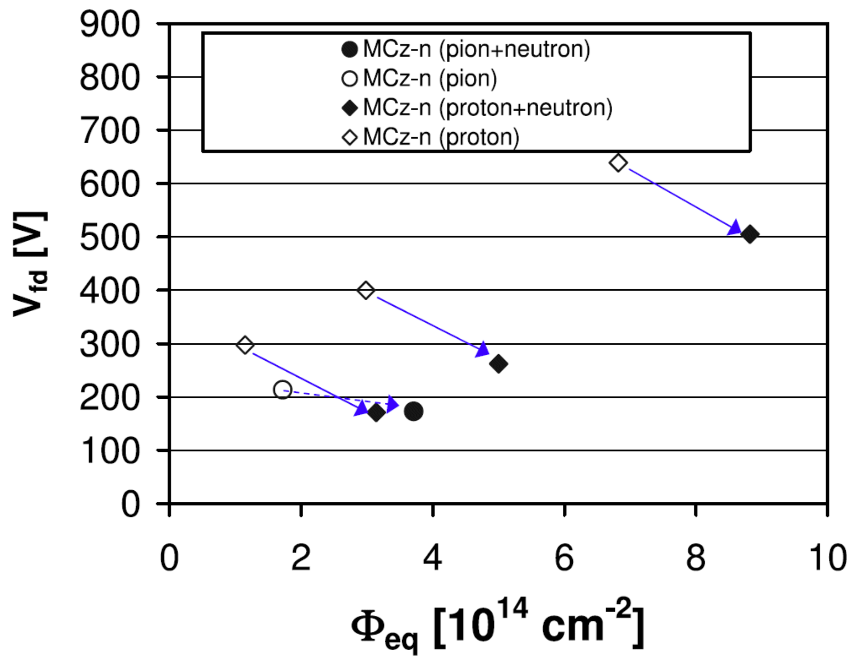
RD50 Mixed irradiations – Change of N_{eff}

- **Exposure of FZ & MCZ silicon sensors to 'mixed' irradiations**
  - **First step: Irradiation with protons or pions**
  - **Second step: Irradiation with neutrons**

FZ: Accumulation of damage



MCZ: Compensation of damage

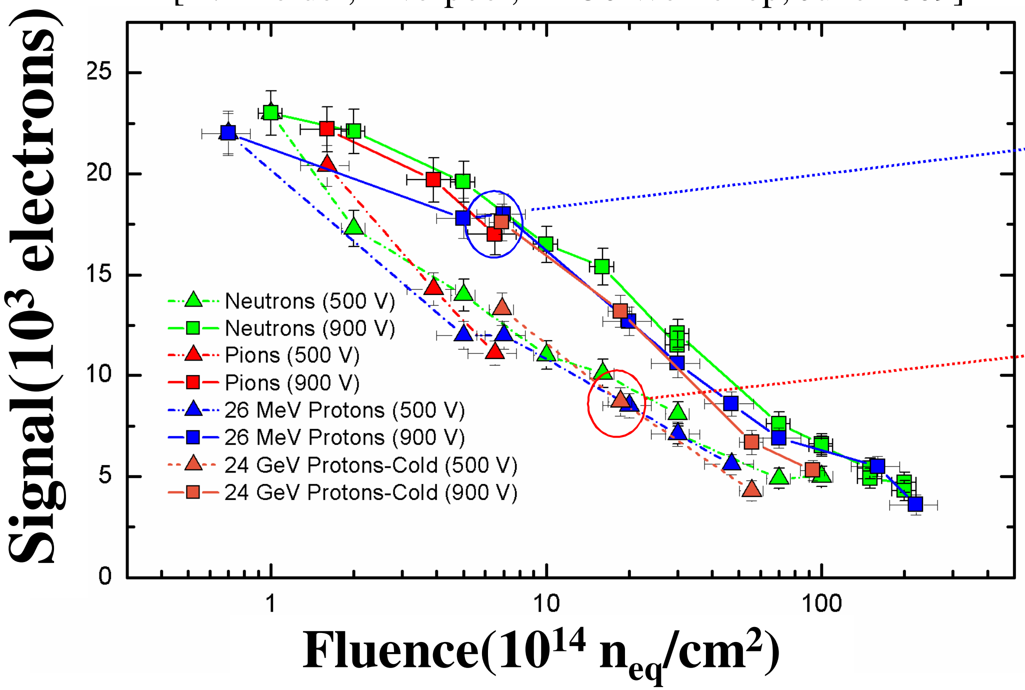


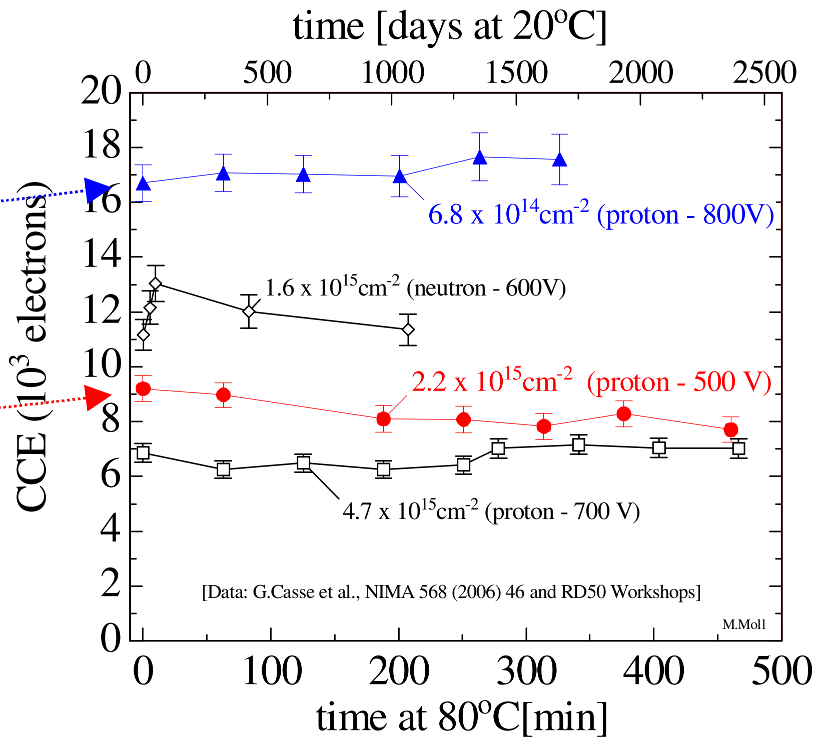
[G.Kramberger et al., "Performance of silicon pad detectors after mixed irradiations with neutrons and fast charged hadrons", NIMA 609 (**2009**) 142-148]

FZ n-in-p microstrip sensors (n, p, π – irrad)

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

[A.Affolder, Liverpool, RD50 Workshop, June 2009]



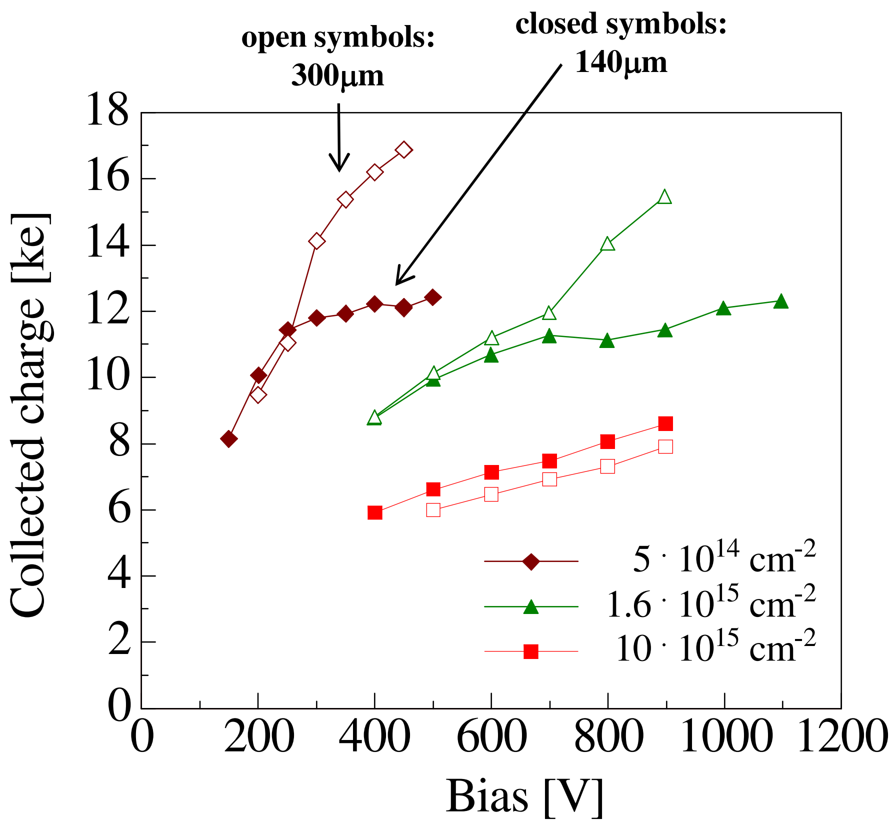


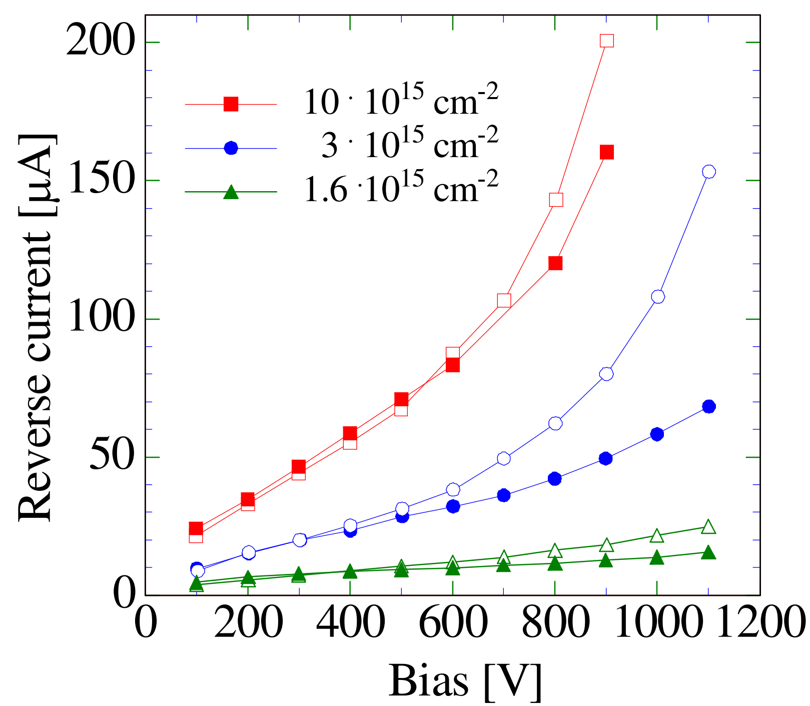
- **CCE: ~7300e (~30%)**
  after ~ 1×10^{16}cm^{-2} 800V
- **n-in-p sensors are strongly considered for ATLAS upgrade** (previously p-in-n used)

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

Do thin sensors offer advantages ?

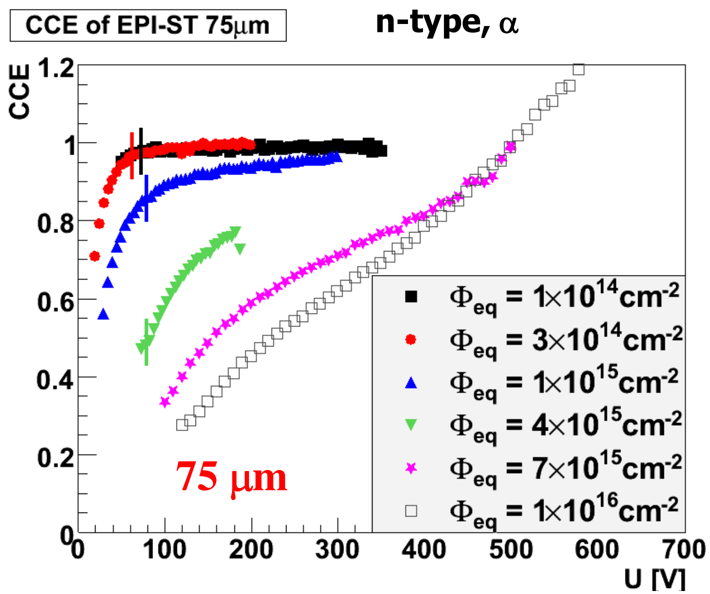
- Comparison of n-in-p sensors of 140 and 300 μm thickness





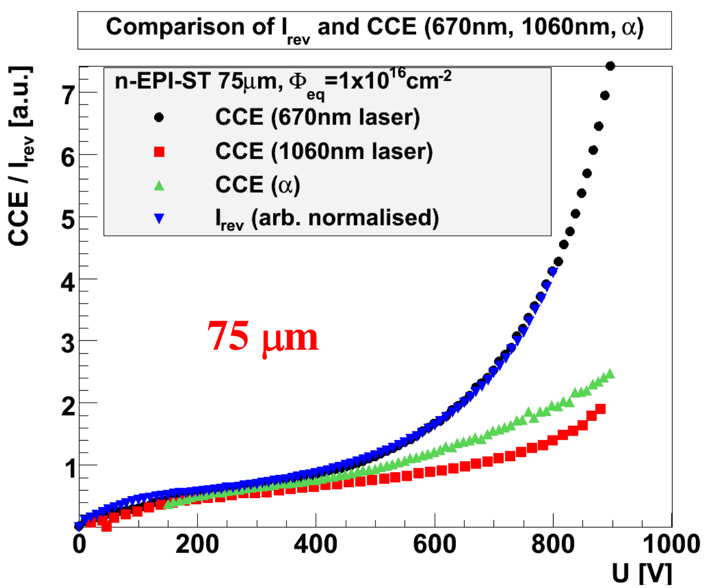
[G.Casse et al., IEEE TNS 55 (2008) 1695 & 14th RD50 Workshop, June 2009]

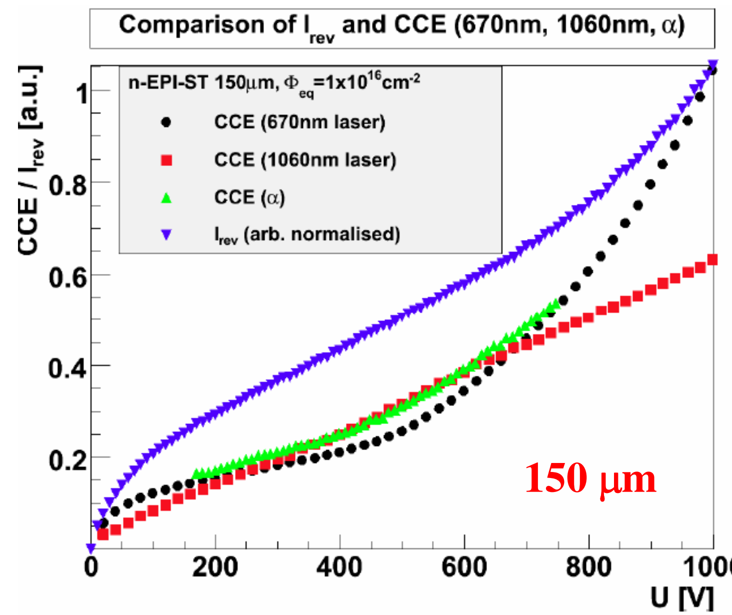
RD50 Charge Multiplication –Epi Diodes



[J.Lange et al., 14th RD50 Workshop, June 2009]

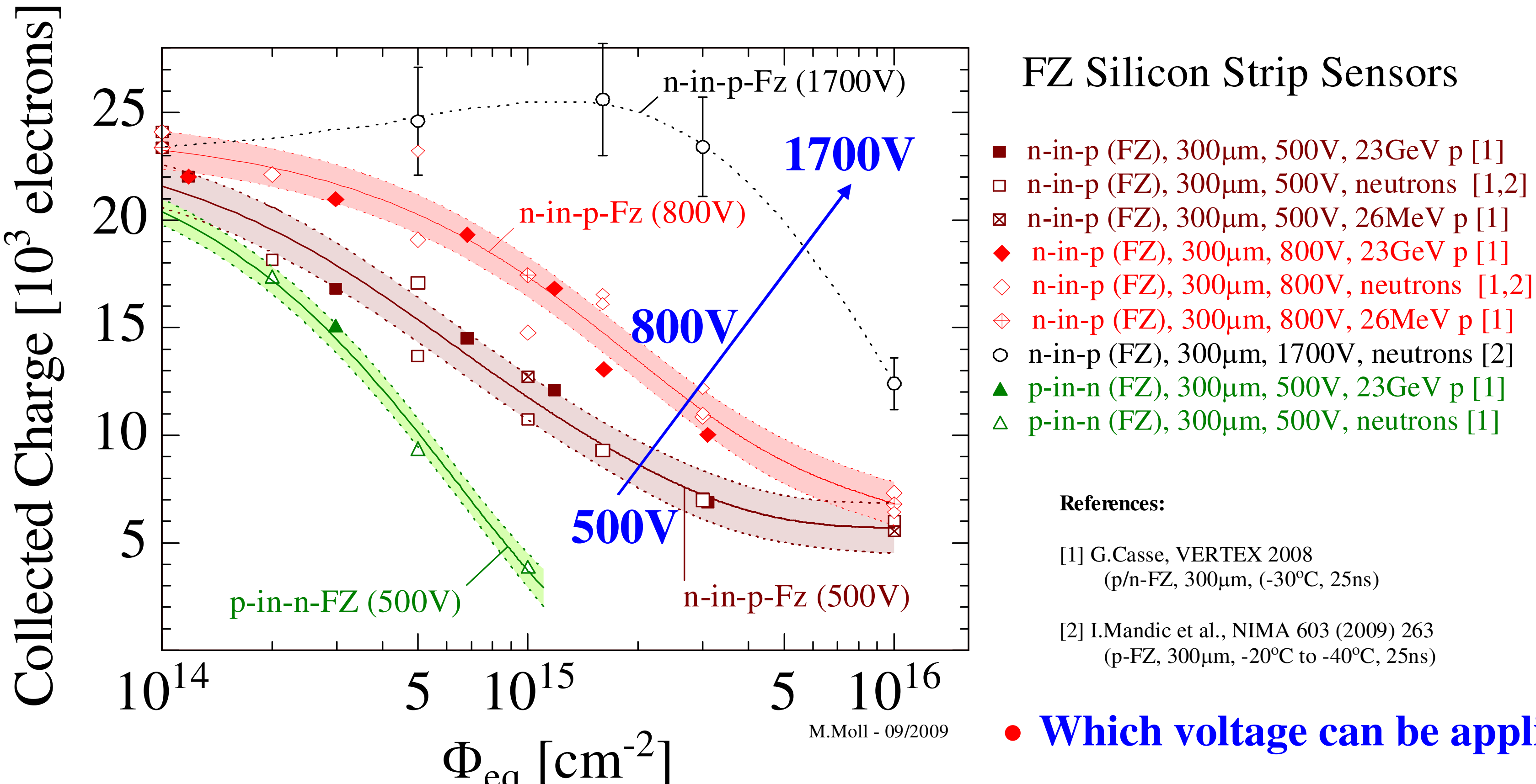
- Epi diodes, 75 and 150 µm thick
- Measured trapping probability found to be proportional to fluence and consistent with values extracted in FZ
- Multiplication effect stronger for 75 µm diodes
- Smaller penetration depth (670 nm laser) → stronger charge multiplication





RD50 Good performance of planar sensors at high fluence

- **Why do planar silicon sensors with n-strip readout give such high signals after high levels (>10^{15} cm^{-2} p/cm^2) of irradiation?**
  - **Extrapolation of charge trapping parameters obtained at lower fluences would predict much lower signal!**
  - **Assumption: 'Charge multiplication effects' as even CCE > 1 was observed**



References:

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

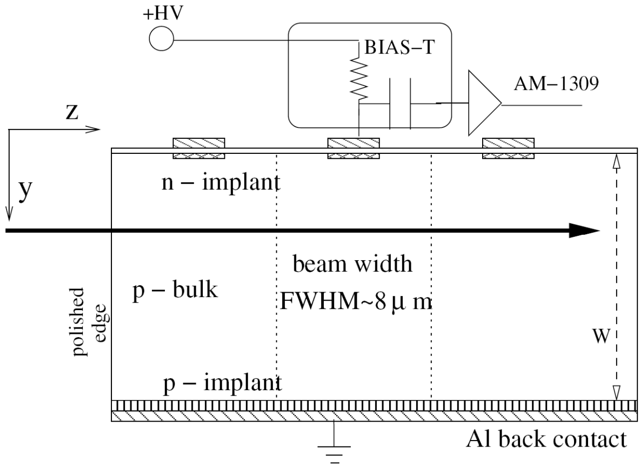
[2] I.Mandic et al., NIMA 603 (2009) 263
(p-FZ, 300µm, -20°C to -40°C, 25ns)

- **Which voltage can be applied?**

A new tool: Edge - TCT

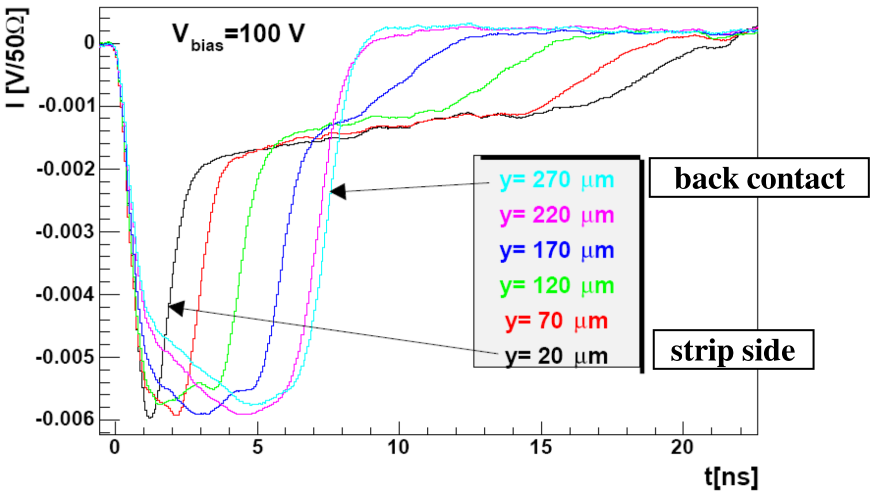
- **A new tool to study**
  - **electric field, charge trapping and 'charge collection profile'**
- **Principle of operation**
  - **IR laser focused on sensor edge**
    - small beam width (e.g. 8 μm) and pulse length (e.g. 200 ps)
    - precise beam positioning (e.g. some μm)
  - **requires pixel or strip sensor**
    - structured sensor with polished edge

[G.Kramberger, 15th RD50 Workshop, CERN, Nov. 09]

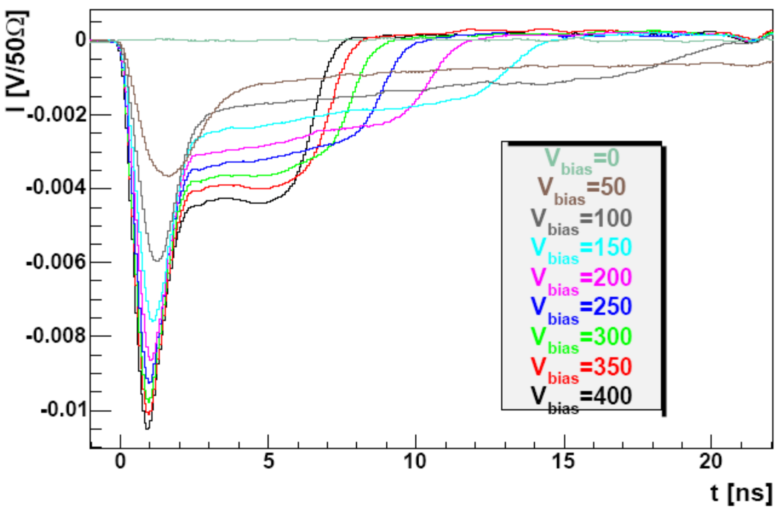


- **Example: Non irradiated n-in-p minstrip sensor**

Position scan at fixed voltage

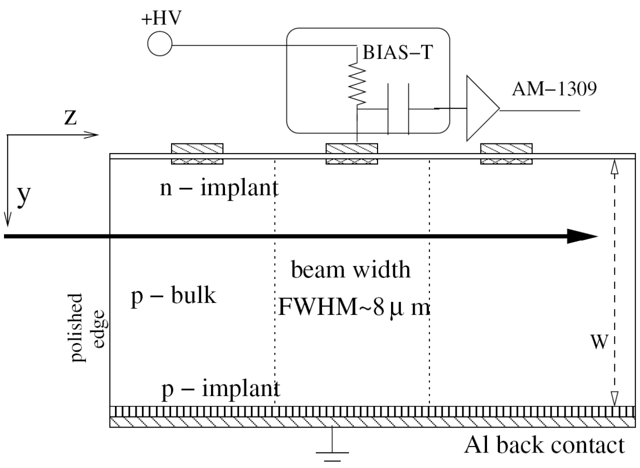


Voltage scan at fixed position (20 μm)



Edge–TCT: indications for avalanche

- **Neutron irradiated p-type sensor**
  - **n+-p strip sensor** (Micron, 300 µm thick, 80 µm pitch)
  - **Φ_{eq} = 5×10^{15} cm^{-2}** (annealed: 80 min at 60C; measured: -20ºC)

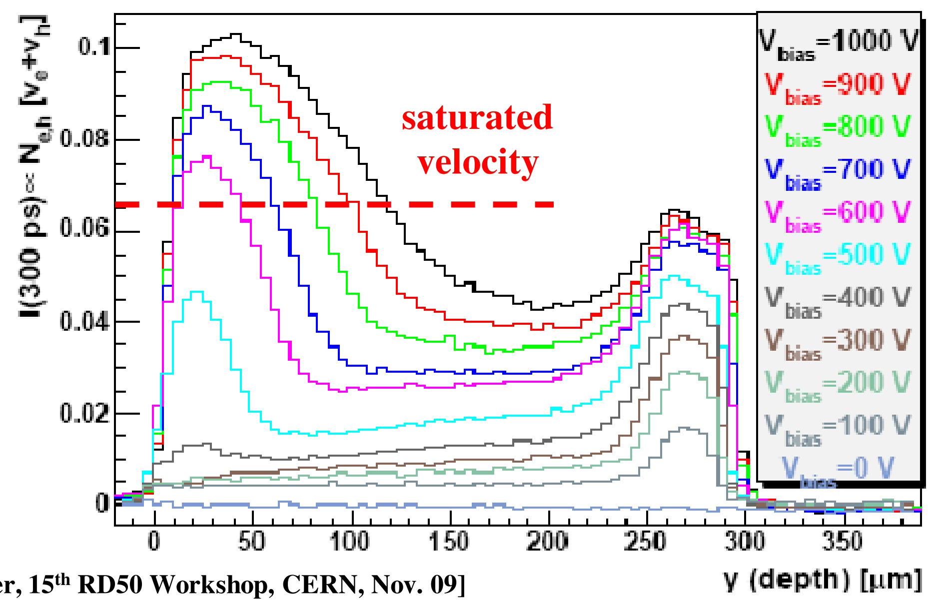


- Velocity profile ('Prompt Current Method')
  - measure current at ½ of rise time of system (i.e. at 300 ps)

$$I(y,t\sim 0)\approx \frac{Ae_0 N_{e,h}}{W}\left[\bar{v}_e(y)+\bar{v}_h(y)\right] \quad , \quad t << \tau_{eff,e,h}$$

constant
(if no charge multiplication)

- **measured after very short times: trapping does not yet influence the signal**

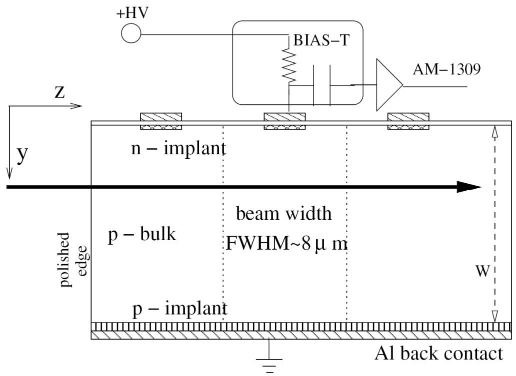


[G.Kramberger, 15th RD50 Workshop, CERN, Nov. 09]

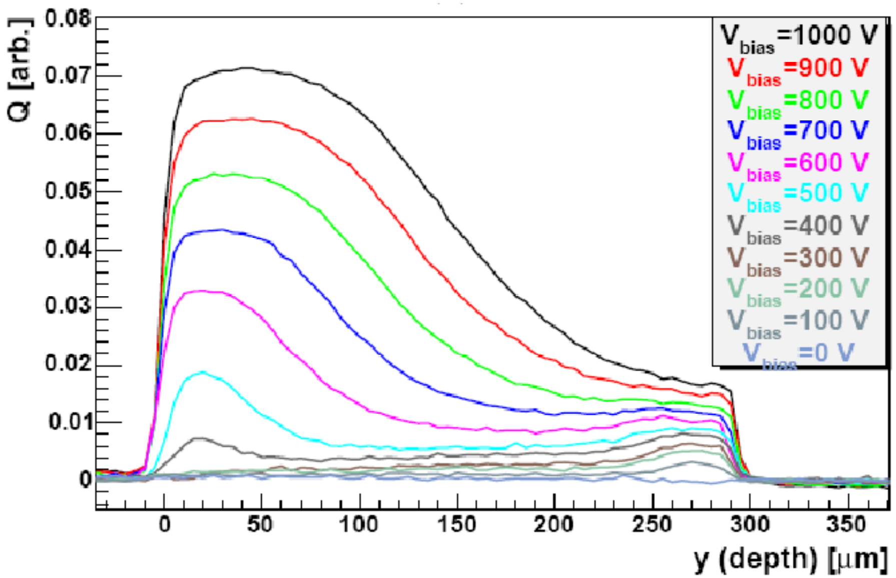
- **For non-irradiated sensors: Velocity profile can directly be transferred into Electric Field profile.**
- **For this heavily irradiated sensor current is higher than allowed by 'saturation velocity'**
  Proposed solution:
  Carrier Multiplication!

RD50 Edge–TCT: indications for avalanche

- Neutron irradiated p-type sensor
  - **n+-p strip sensor** (Micron, 300 μm thick, 80 μm pitch)
  - **Φ_{eq} = 5×10^{15} cm^{-2}** (annealed: 80 min at 60C; measured: -20ºC)

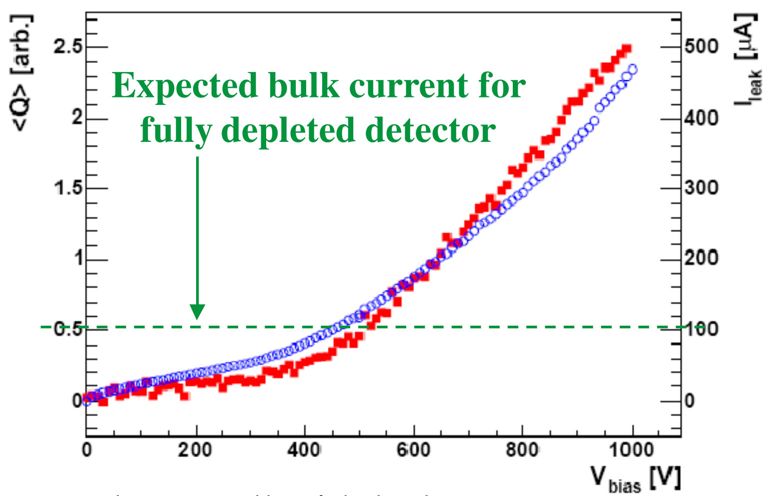


- Charge collection profile
  - estimate how much charge e-h pair delivers that is created in certain depth of the sensor



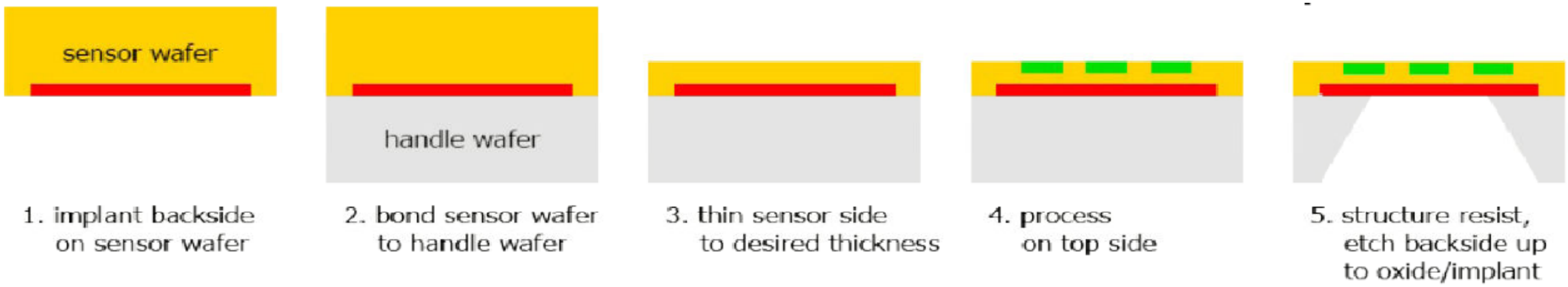
[G.Kramberger, 15th RD50 Workshop, CERN, Nov. 09]

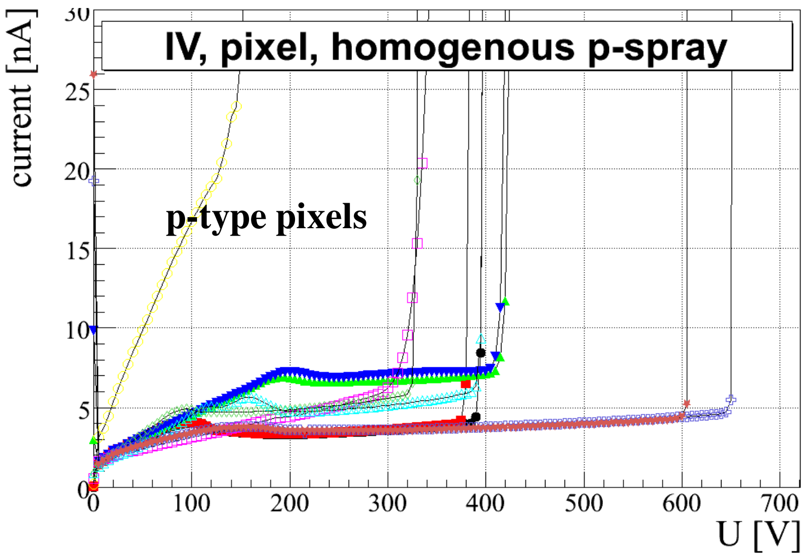
- Total charge produced by a m.i.p.
  - integration over charge collection profile gives total charge <Q> for a m.i.p.



- correlates well with leakage current I_{leak}

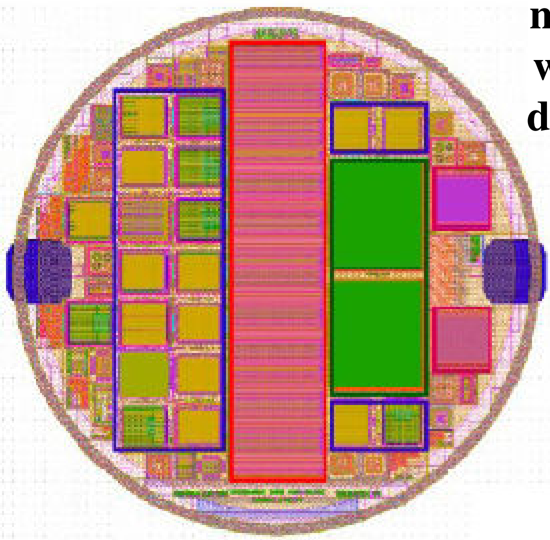
RD50 Planar pixel productions





- MPP-HLL thin pixel production (75 and 150 µm) on n- and p-type FZ silicon using a wafer bonding technique that allows variable thicknesses down to 50 µm
- Pre-irradiation characterization of the p-type wafers shows high yield and good breakdown performances

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



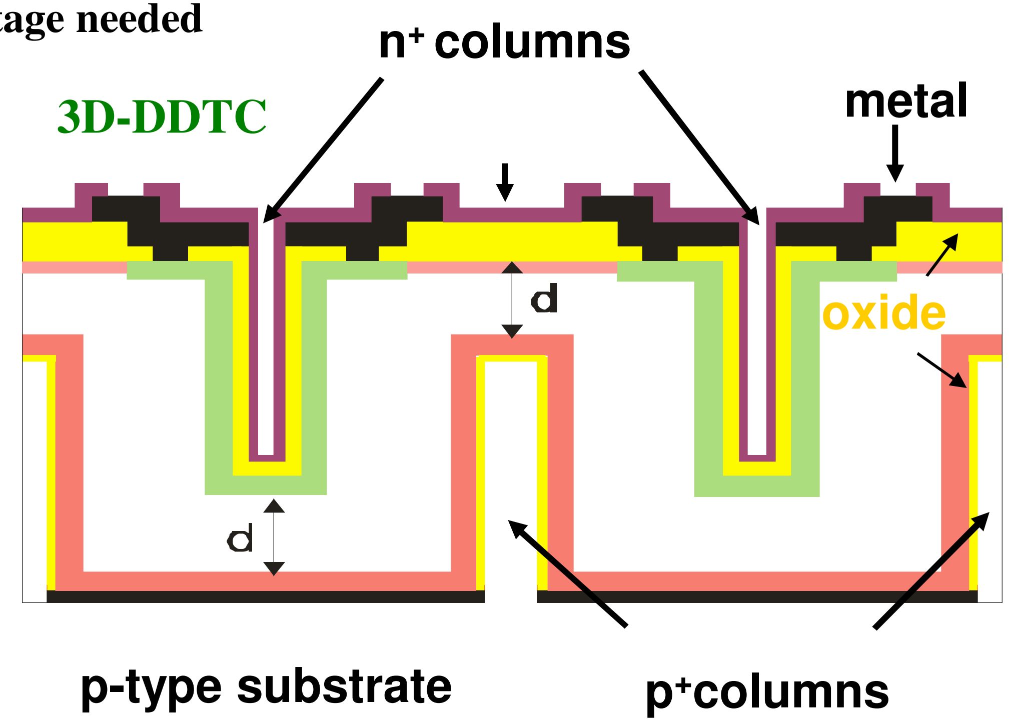
n-in-n wafer design

- RD50 Planar Pixel project : production of pixels at CiS (CMS and ATLAS geometries) on FZ and MCz silicon with R&D focus on:
  - direct comparison of n-in-n and n-in-p performances
  - slim edges (needed for inner pixel layers in ATLAS)
  - Pixel isolation methods (moderated, uniform p-spray)

Development of 3D detectors

- **"3D" electrodes:** - narrow columns along detector thickness,
  - diameter: 10μm, distance: 50 - 100μm
- **Lateral depletion:** - decoupling of detector thickness and charge collection distance
  - lower depletion voltage needed
  - fast signal
  - radiation hard

- **Fabrication of 3D detectors challenging: modified design under investigation within RD50**
  - Columnar electrodes of both doping types are etched into the detector from both wafer sides
  - Columns are not etched through the entire detector: no need for wafer bonding technology but column overlap defines the performance.



- **Two manufacturers:** CNM (Barcelona): 14 wafers (p- and n-type)
  FBK (Trento): 3 3D-DDTC batches fabricated with different overlaps

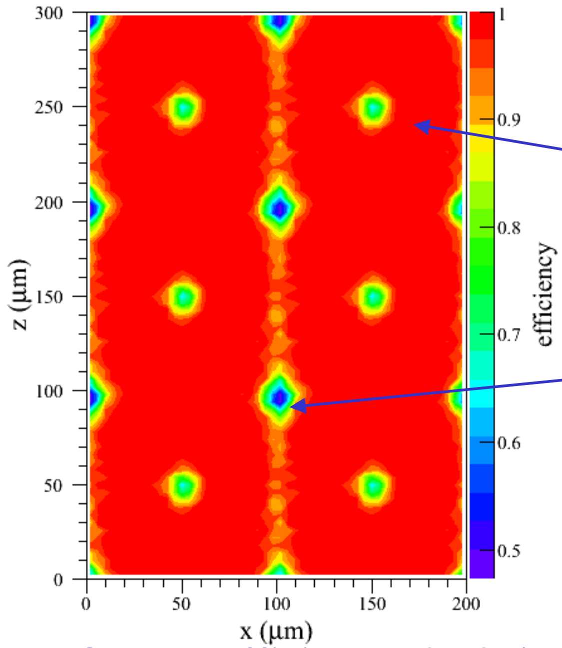
RD50 3D-DTC sensors –Test-beam data

- **Device from FBK:** **p-type strip sensor, 50 µm column overlap**
- **Test-beam at CERN:** **225 GeV/c muons and APV25 analogue readout (40 MHz)**

No clustering

strips with highest and 2nd highest signal joined into clusters

2D efficiency at 40 V for Q>2fC

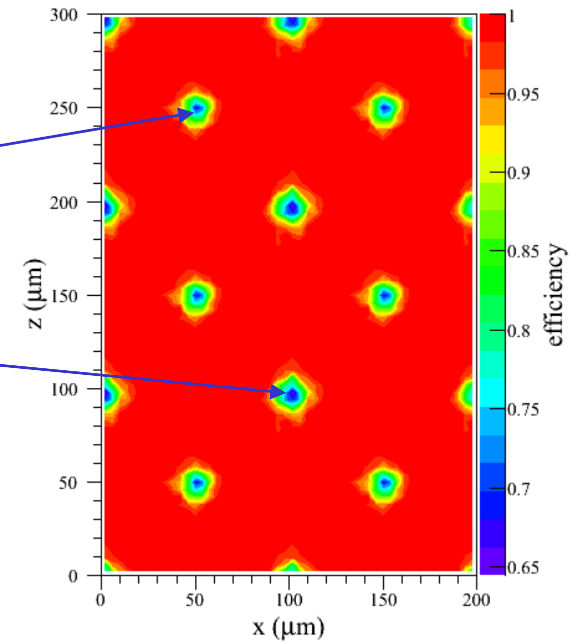


Overall efficiency: 97.3%

front column

back column

Strip structure is clearly visible only when clustering is not applied.



Overall efficiency: 98.6%

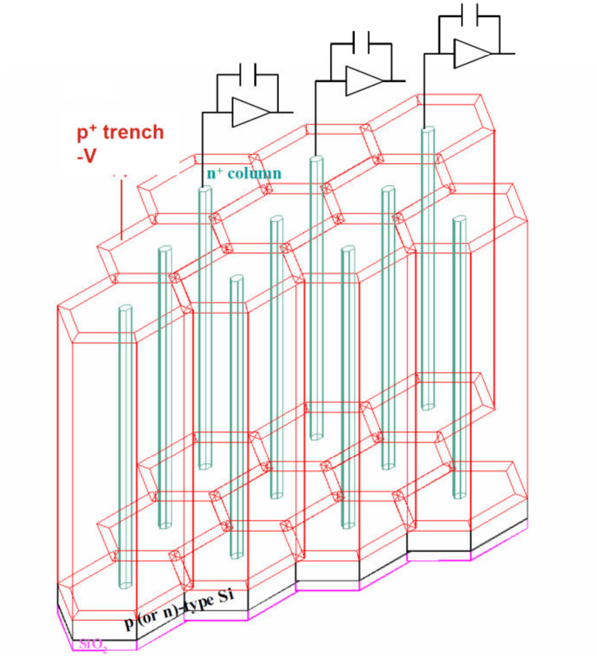
[M.Koehler 14th RD50 Workshop, June.2009]

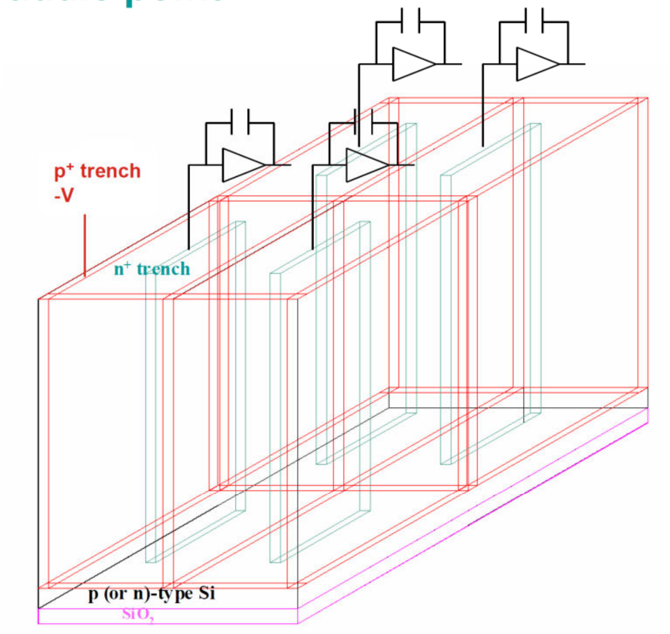
New structures …. new ideas

- **Concept of the new Independent Coaxial Detector Array (ICDA)** ------ US patent pending (3D-Trench Electrode Detectors), any projects related to this subject must sign official agreements with BNL Office of Technology Commercialization and Partnership (*Kimberley Elcess,* Principal Licensing Specialist, elcess@bnl.gov, 001-631-344-4151)

At least one electrode is a trench, each cell can be an independent detector

Homogeneous electric field, no saddle point





Concentric type

Electric field with nearly no θ dependence

Parallel plate type

Near-linear electric field

Zheng Li, 15th CERN RD50 Workshop, CERN, 11-18-2009

RD50 Workplan for 2010 (1/2)

Defect and Material Characterization	• **Characterization of irradiated silicon:** ▪ **Continue WODEAN program (Extend EPR activities)** ▪ **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** • **Study of hydrogenated silicon sensors**

Workplan for 2010 (2/2)

New Structures	• **Working, high quality double column 3D devices (pad, strip, pixel) are now available within RD50: Further tests in 2010** • **Comment: Strong R&D performed now within ATLAS-3D group (not part of RD50)**
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** • **In depth study on S/N behaviour in 'charge multiplication mode'** • **Support and distribute Alibava system among RD50 members** • **Investigate on electric field profile in irradiated segmented sensors and impact on CCE: *Exploit new Edge-TCT technique*** • **Study impact of implant shape on charge multiplication** • **Perform another RD50 test beam** • **Pion irradiation (Beam request to PSI posed)**

RD50 Resources requested for 2010

- **Common Fund:**

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

- **Acknowledgement:** 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 2009) 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 2010 and working group meetings
- Administrative support at CERN through PH-DT secretariat
- **Request for one additional office in blg. 28 next to Silicon Facility**

RD50

Main results in 2009

- **Progress in understanding microscopic defects**
  - **Defects responsible for reverse annealing identified**
  - **Defects responsible for positive charge build up in MCZ and EPI identified**
- **Consolidation of data obtained on p-type silicon strip sensors**
  - **Further results on radiation tolerance**
  - **Further results on long term annealing**
- **New tool developed: Edge-TCT**
  - **Charge carrier velocity profile; Electric field profile; Charge collection profile, …**
- **Installation of the ALIBAVA readout system in many RD50 institutions**
- **Good progress in understanding the 'good performance' of highly irradiated structured sensors with n-implant readout: Charge multiplication processes**
- **ATLAS planar pixel group & RD50: Common project on pixel sensors**