Silicon Detectors for the sLHC
an Overview of Recent RD50 Results

A. Dierlamm

Institut für Experimentelle Kernphysik

on behalf of the RD50 Collaboration

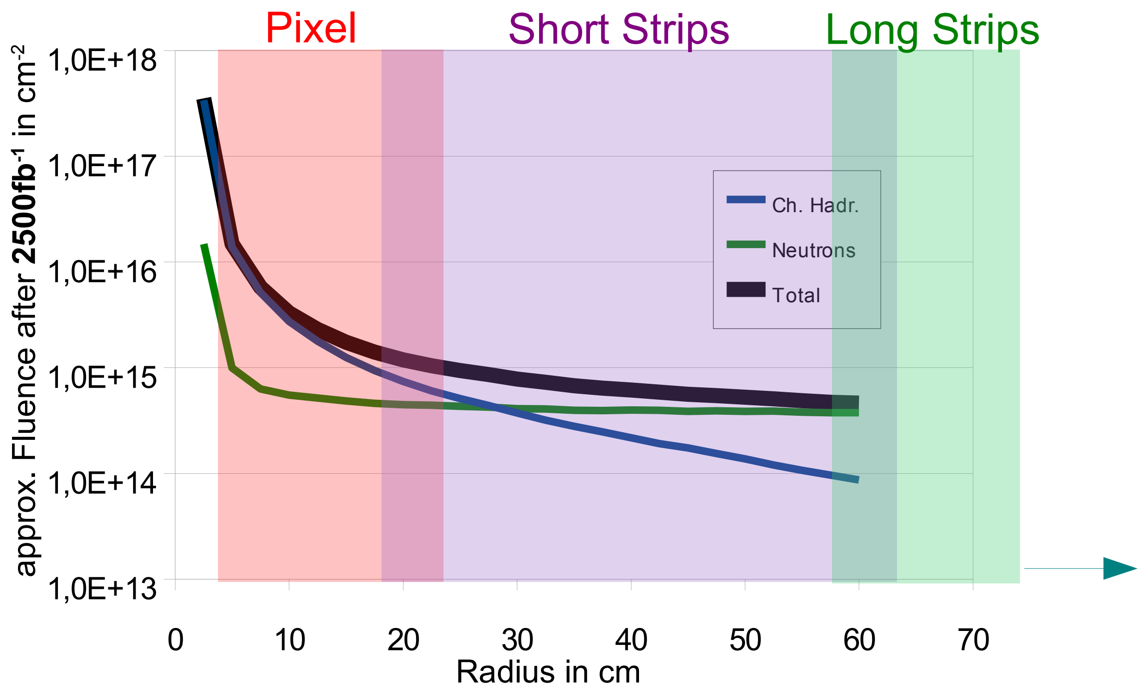
Overview

- Radiation environment and requirements for silicon sensors at SLHC
- Introduction of the RD50 Collaboration
- Some examples from the five research lines within RD50
  - This report cannot be complete!
  - See coming Status Report for more details
- Recommendations for SLHC

http://cern.ch/rd50/

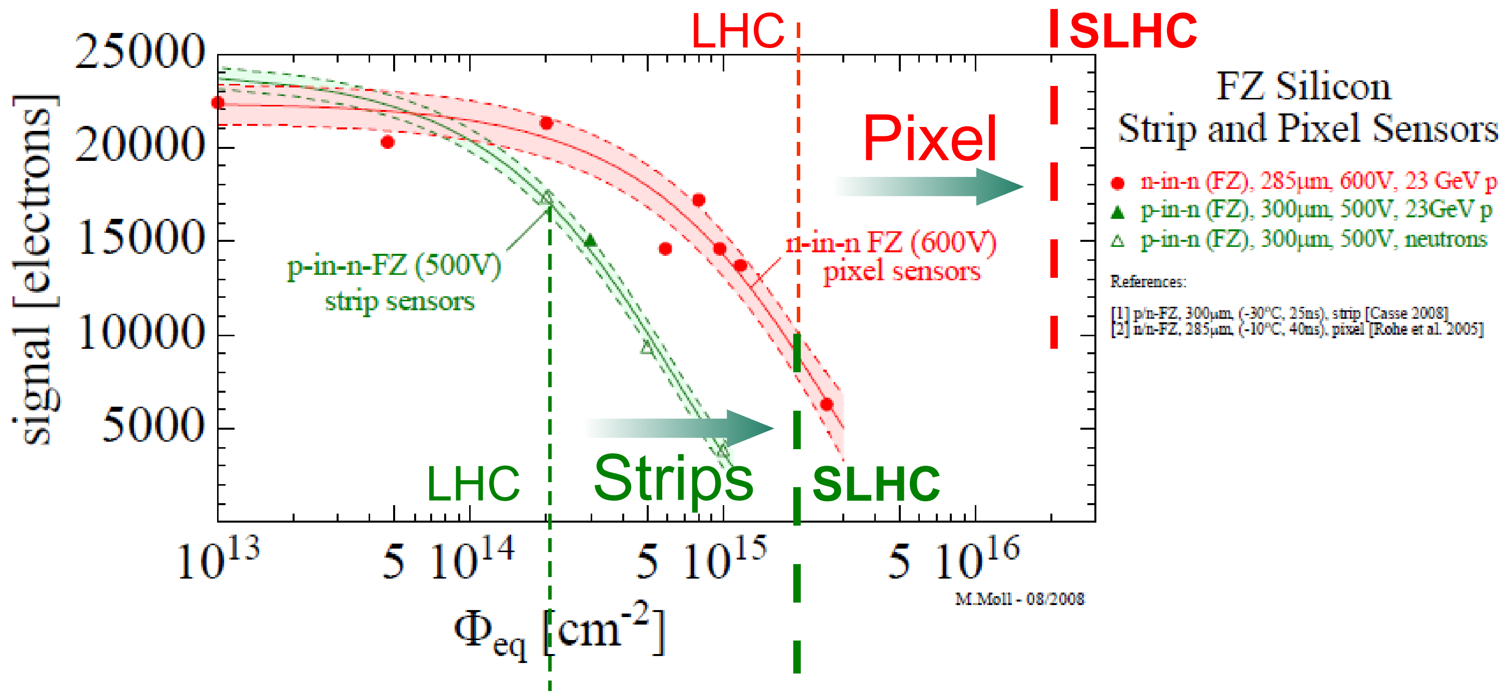
Radiation Environment

Extrapolated values from simulations for the CMS detector done by M. Huhtinen



- Pixel dominated by charged hadron radiation (up to $2.5\cdot10^{16}$ cm^{-2}).
- From about 40cm on neutron radiation is dominating ($\sim4\cdot10^{14}$ cm^{-2}).
- Ratio of neutron fraction vs. charged hadron fraction is changing with radius.
- Have to investigate damage due to neutral and charged particles and combinations.

Requirements at SLHC

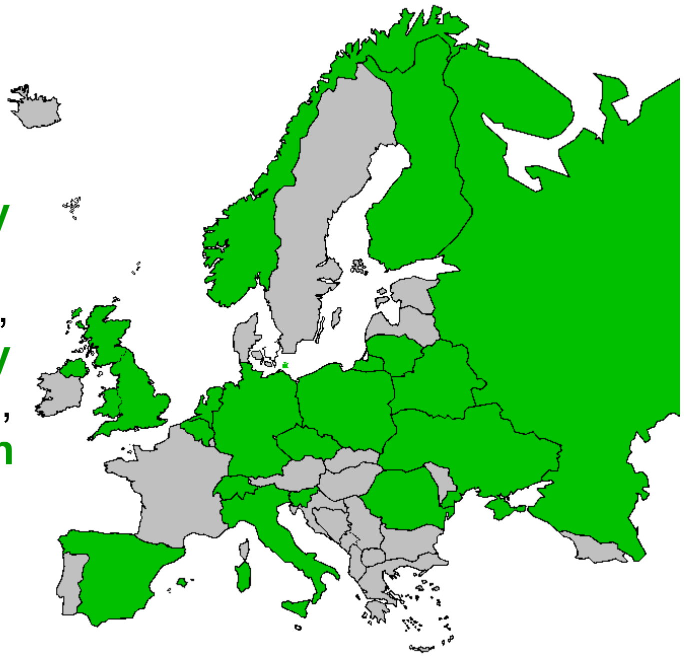


- Much higher radiation tolerance required at SLHC
- Standard FZ material and operation not sufficient any more
- Need new sensor materials and/or technologies
- To find a suitable sensor technology for SLHC is the aim of RD50

Karlsruhe Institute of Technology

The RD50 Collaboration

RD50



41 European and Asian institutes

Belarus (Minsk), **Belgium** (Louvain), **Czech Republic** (Prague (3x)), **Finland** (Helsinki) , Laappeenranta), **Germany** (Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe, Munich), **Italy** (Bari, Bologna, Florence, Padova, Perugia, Pisa, Torino, Trento), **Lithuania** (Vilnius), **Netherlands** (NIKHEF), **Norway** (Oslo (2x)), **Poland** (Warsaw(2x)), **Romania** (Bucharest (2x)), **Russia** (Moscow, St.Petersburg), **Slovenia** (Ljubljana), **Spain** (Barcelona, Valencia), **Switzerland** (CERN, PSI), **Ukraine** (Kiev), **United Kingdom** (Exeter, Glasgow, Lancaster, Liverpool)

8 North-American institutes

Canada (Montreal), **USA** (BNL, Fermilab, New Mexico, Purdue, Rochester, Santa Cruz, Syracuse)

1 Middle East institute

Israel (Tel Aviv)

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

Spokespersons
Mara Bruzzi, Michael Moll
INFN Florence, CERN PH

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)

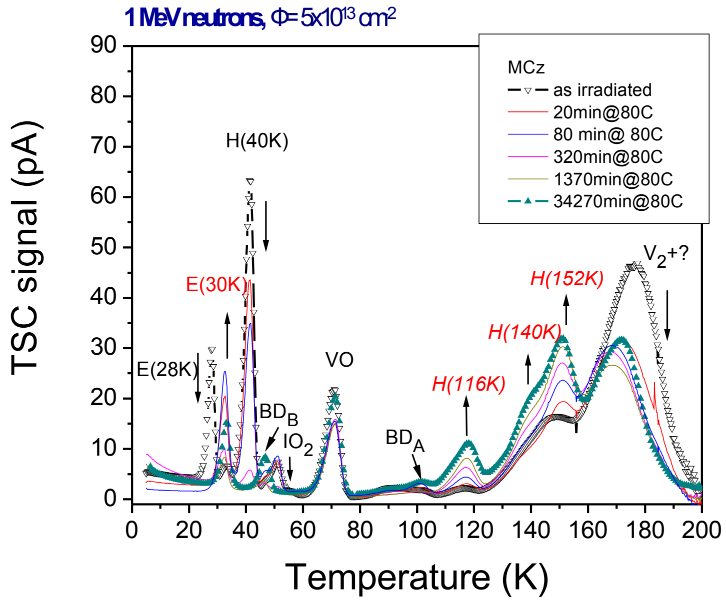
- 3D detectors
- Thin detectors
- Cost effective solutions
- 3D (M. Boscardin)
- Semi 3D (Z.Li)

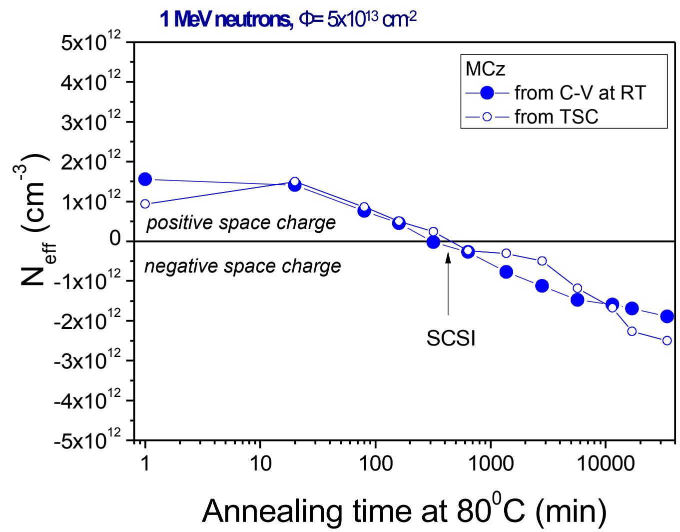
Full Detector Systems
Gianluigi Casse
(Liverpool University)

- 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)

Long Term Annealing

- The defect centres H(116K), H(140K), H(152K) are hole traps with acceptor like levels in the lower band gap (neg. space charge)
- They are not generated by gamma irradiation, thus cluster related
- Concentrations are increasing with annealing time
  → contribute to long term/reverse annealing
- N_{eff} can be calculated from measured defect concentrations with TSC including BD and E(30K) defects
- Comparison with N_{eff} from CV-measurements strikingly good





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

Defect Overview

Point defects

- $E_i^{BD} = E_c - 0.225$ eV
- $\sigma_n^{BD} = 2.3\times10^{-14}$ cm²

- $E_i^{I} = E_c - 0.545$ eV
  - $\sigma_n^{I} = 2.3\times10^{-14}$ cm²
  - $\sigma_p^{I} = 2.3\times10^{-14}$ cm²

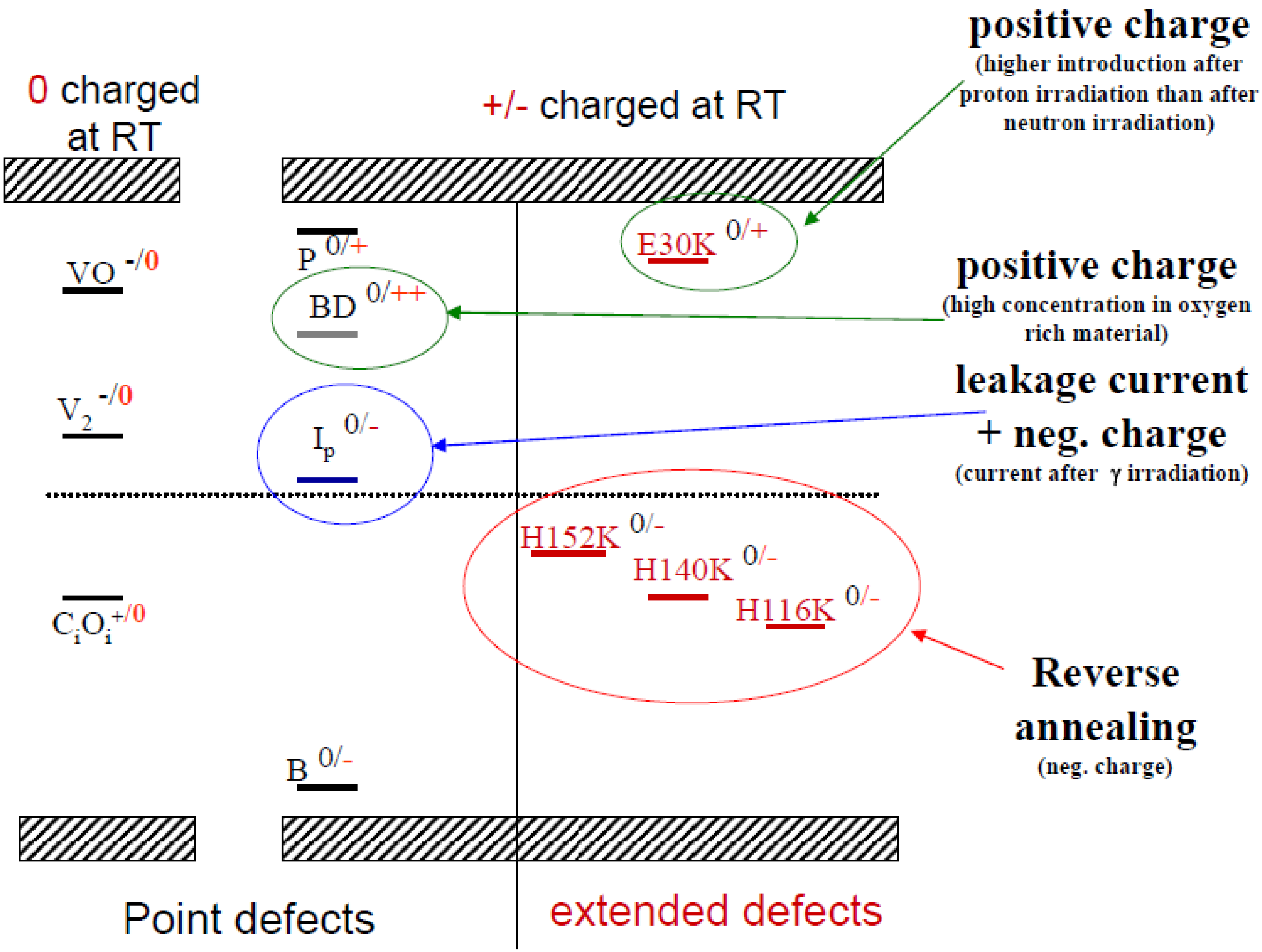
Cluster related centers

- $E_i^{116K} = E_v + 0.33$eV
- $\sigma_p^{116K} = 4\times10^{-14}$ cm²

- $E_i^{140K} = E_v + 0.36$eV
- $\sigma_p^{140K} = 2.5\times10^{-15}$ cm²

- $E_i^{152K} = E_v + 0.42$eV
- $\sigma_p^{152K} = 2.3\times10^{-14}$ cm²

- $E_i^{30K} = E_c - 0.1$eV
- $\sigma_n^{30K} = 2.3\times10^{-14}$ cm²

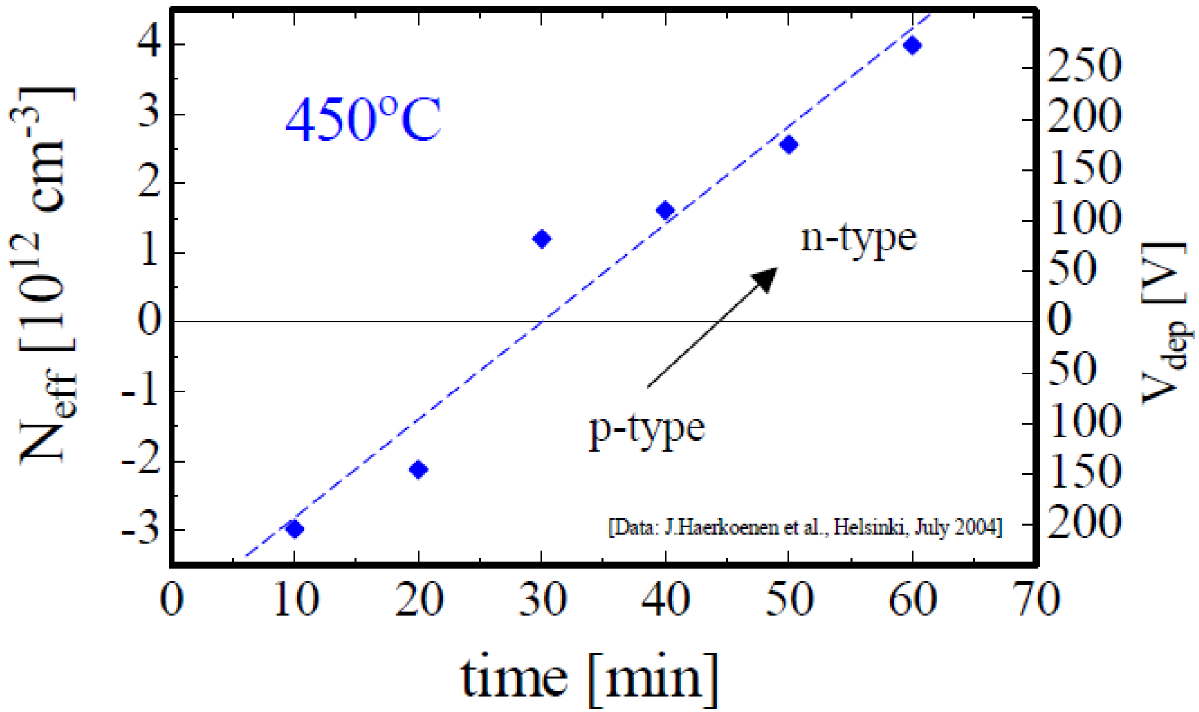


I.Pintilie, NSS, 21 October 2008, Dresden

Spokespersons
Mara Bruzzi, Michael Moll
INFN Florence, CERN PH

Defect / Material Characterization *Bengt Svensson* (Oslo University)	Defect Engineering *Eckhart Fretwurst* (Hamburg University)	Pad Detector Characterization *G. Kramberger* (Ljubljana)	New Structures *R. Bates* (Glasgow University)	Full Detector Systems *Gianluigi Casse* (Liverpool University)
Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation WODEAN project (G. Lindstroem)	Development and testing of defect engineered silicon: - Epitaxial Silicon - High res. CZ, MCZ - Other impurities H, N, Ge, … - Thermal donors - Pre-irradiation	•Test structure characterization IV, CV, CCE •NIEL •Device modeling •Operational conditions •Common irrad. •Standardisation of macroscopic measurements (A.Chilingarov)	•3D detectors •Thin detectors •Cost effective solutions •3D (M. Boscardin) •Semi 3D (Z.Li)	•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)

Thermal Donors



Tailoring of N_{eff} in **p-type MCz** silicon by creation of thermal donors after heat treatment at 450°C

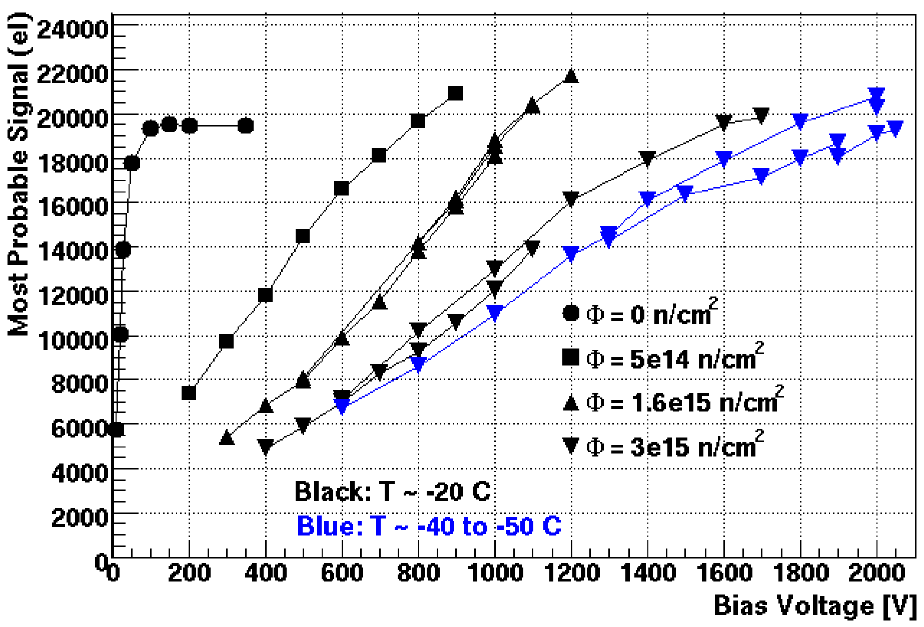
Radiation hardness is being tested...

Spokespersons
Mara Bruzzi, Michael Moll
INFN Florence, CERN PH

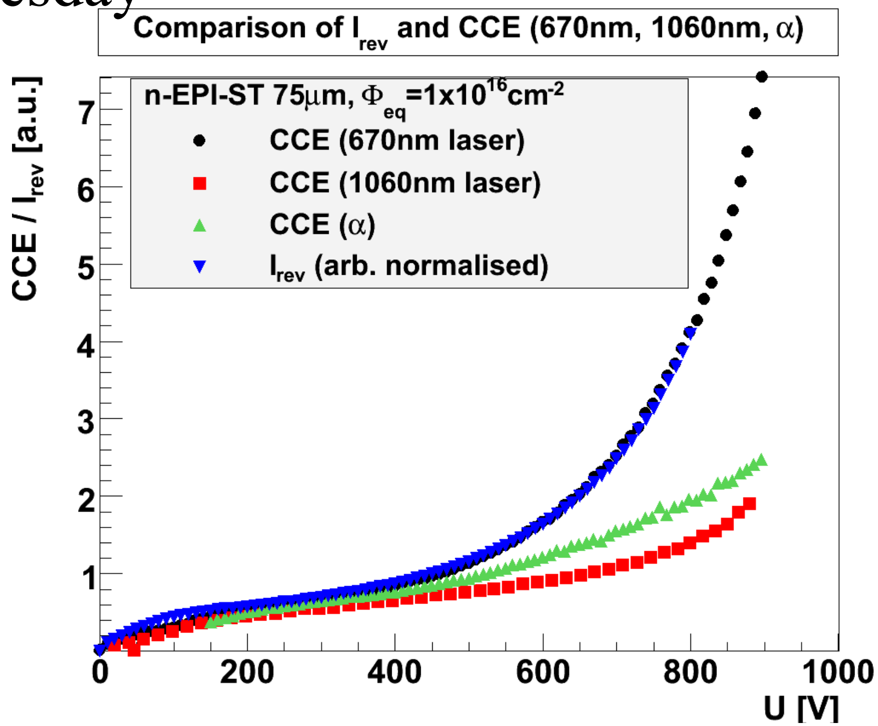
Defect / Material Characterization	Defect Engineering	Pad Detector Characterization	New Structures	Full Detector Systems
Bengt Svensson (Oslo University)	*Eckhart Fretwurst* (Hamburg University)	*G. Kramberger* (Ljubljana)	*R. Bates* (Glasgow University)	*Gianluigi Casse* (Liverpool University)
Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation WODEAN project (G. Lindstroem)	Development and testing of defect engineered silicon: - Epitaxial Silicon - High res. CZ, MCZ - Other impurities H, N, Ge, … - Thermal donors - Pre-irradiation	•Test structure characterization IV, CV, CCE •NIEL •Device modeling •Operational conditions •Common irrad. •Standardisation of macroscopic measurements (A.Chilingarov)	•3D detectors •Thin detectors •Cost effective solutions •3D (M. Boscardin) •Semi 3D (Z.Li)	•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)

Charge Multiplication

- CCE increases over expectation for very high fluence
- CCE > 100% for high bias voltage
- There is charge multiplication ! (Avalanche effect ?)
- See also talk of J. Lange on Wednesday



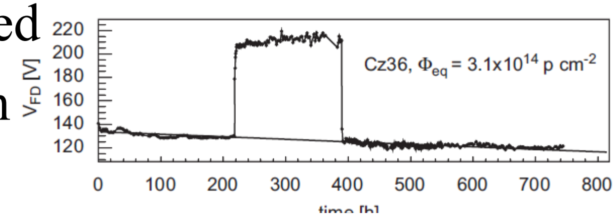
[I. Mandic, 12th RD50 workshop, 2008]

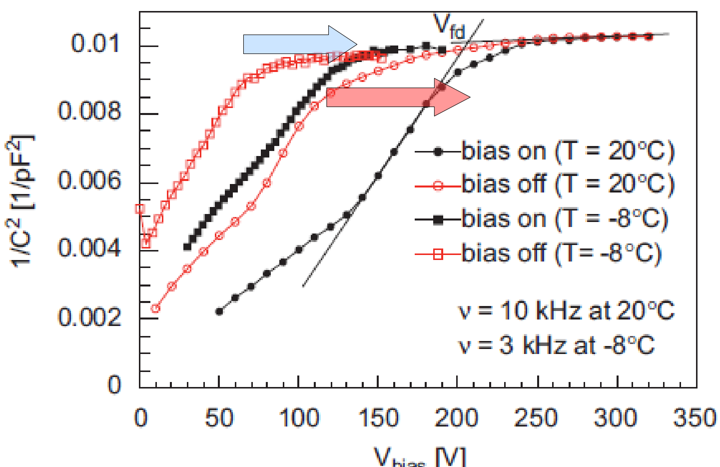


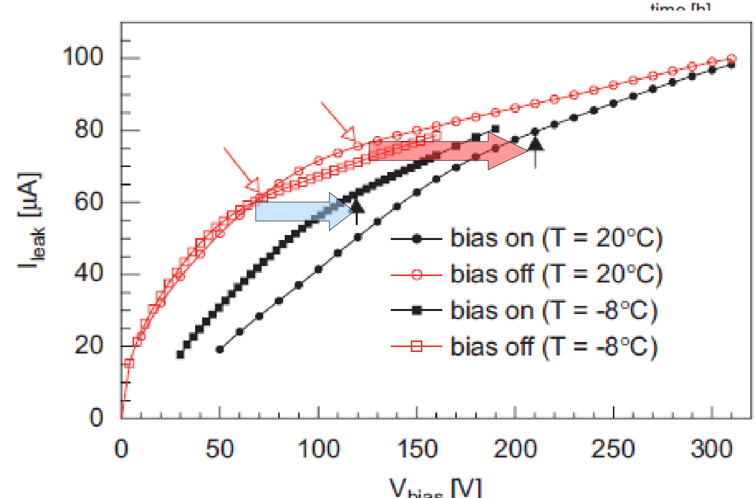
[J. Lange et al., 14th RD50 workshop, 2009]

Bias depending V_{fd}

- It was observed that full depletion voltage of irradiated FZ devices increases with time when bias is applied and goes back to previous value without bias
- This effect is seen in MCz and EPI material as well
- Introduction rate $g_b \sim 0.004\ cm^{-1}$ ($g_s(FZ)=0.02 cm^{-1}$)
- Effect can reach level of stable damage in MCz and EPI for fast charged hadrons
- No significant increase in leakage current at V_{fd} observed
- Has to be taken into account during long term operation







Cz samples irradiated with 24 GeV/c protons to $3\cdot10^{14} n_{eq}/cm^2$ before and after applying bias for 140h

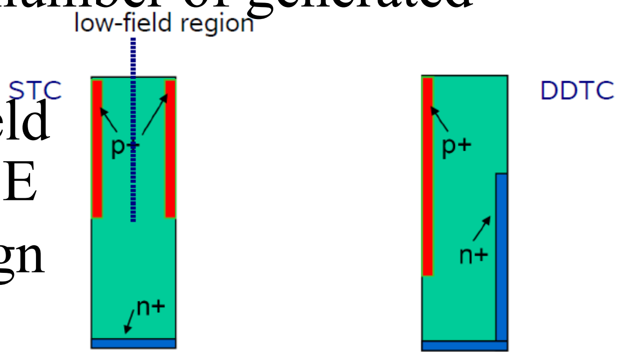
[G. Kramberger et al, "Effect of bias voltage on the space charge in irradiated silicon detectors", NIM A 600 p.555-559]

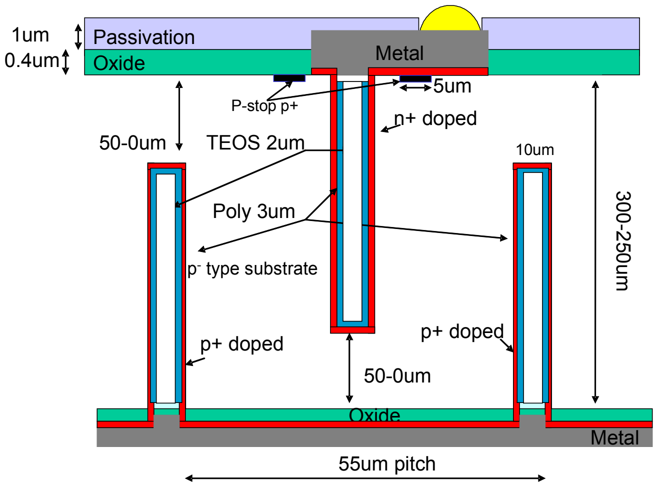
Spokespersons
Mara Bruzzi, Michael Moll
INFN Florence, CERN PH

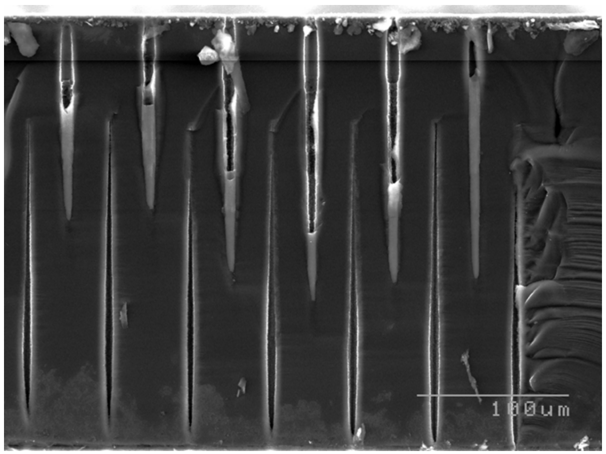
Defect / Material Characterization	Defect Engineering	Pad Detector Characterization	New Structures	Full Detector Systems
Bengt Svensson (Oslo University)	*Eckhart Fretwurst* (Hamburg University)	*G. Kramberger* (Ljubljana)	*R. Bates* (Glasgow University)	*Gianluigi Casse* (Liverpool University)
Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation WODEAN project (G. Lindstroem)	Development and testing of defect engineered silicon: - Epitaxial Silicon - High res. CZ, MCZ - Other impurities H, N, Ge, … - Thermal donors - Pre-irradiation	•Test structure characterization IV, CV, CCE •NIEL •Device modeling •Operational conditions •Common irrad. •Standardisation of macroscopic measurements (A.Chilingarov)	•3D detectors •Thin detectors •Cost effective solutions •3D (M. Boscardin) •Semi 3D (Z.Li)	•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)

From STC to DDTC

- In 3D sensors the charge collecting electrodes reach as columns into the silicon bulk allowing a sidewards charge collection → short drift time (drift distance = pitch) by keeping a high number of generated charge carriers (silicon thickness ~300µm)
- Single Type Column (STC) sensors have a low field region between columns, which causes low CCE
- Double-sided Double Type Column (DDTC) design developed at CNM can cure this drawback





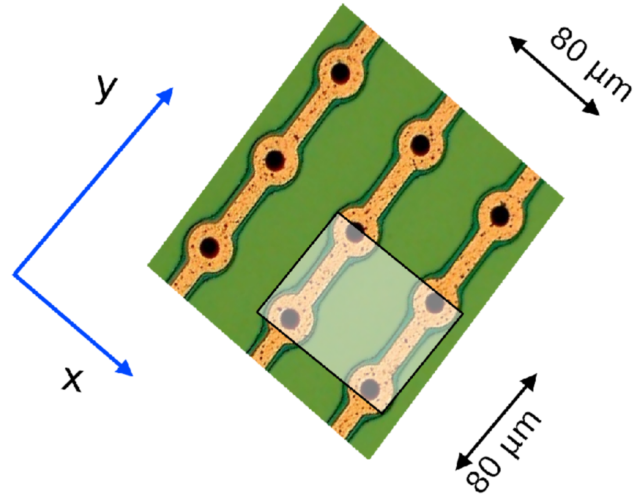


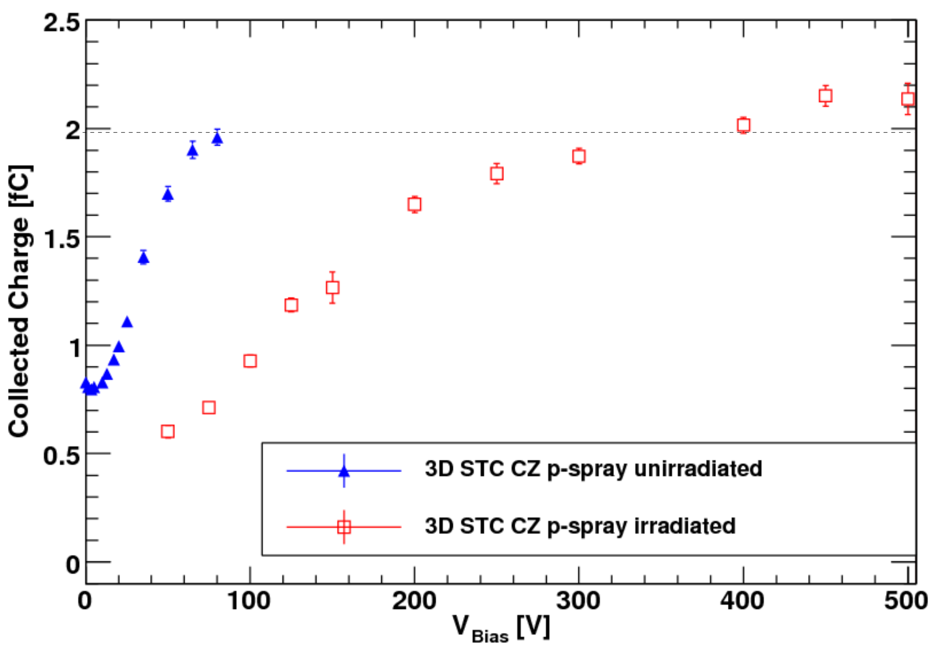
Real photo of diagonal cut

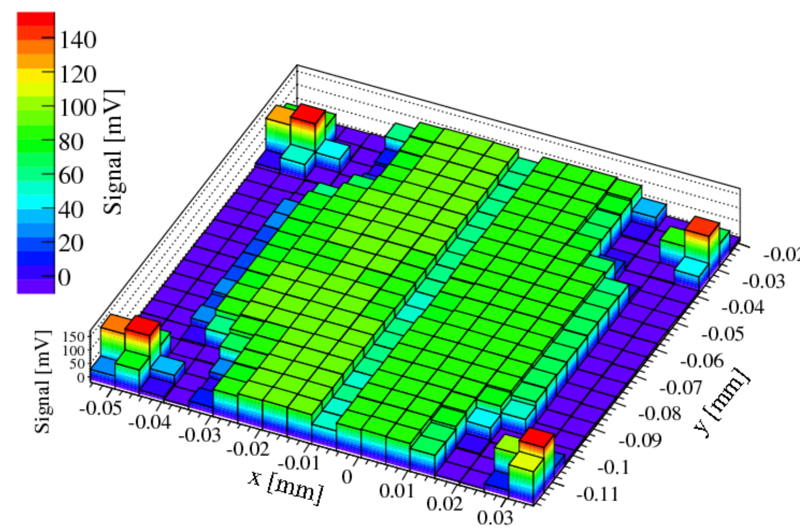
[G. Pellegrini, 2nd Trento Workshop on Advanced Silicon Radiation Detectors, Trento, 2006]

CCE in STC

- 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%



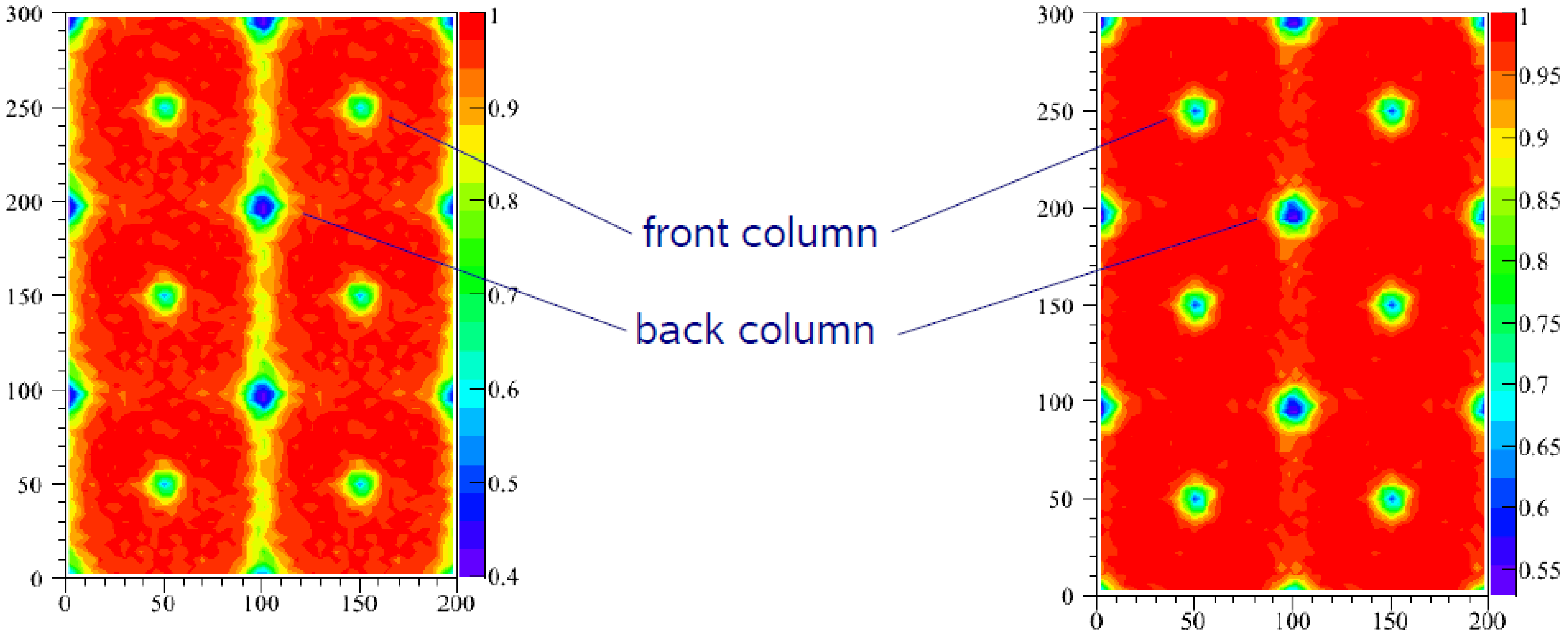




[U. Parzefall et al.,"Silicon microstrip detectors in 3D technology for the sLHC", doi:10.1016/j.nima.2009.03.122]

CCE in DDTC

- Device from FBK-IRST (Trento)
- Test-beam 2008 with 225GeV/c muons and APV25 read-out
- 2D-efficiency at S/N>10 (Q>2fC)
- Bias: 40V
- Overall efficiency: 97% with clustering and 93% with no clustering
- See also poster of G.-F. Dalla Betta after this session



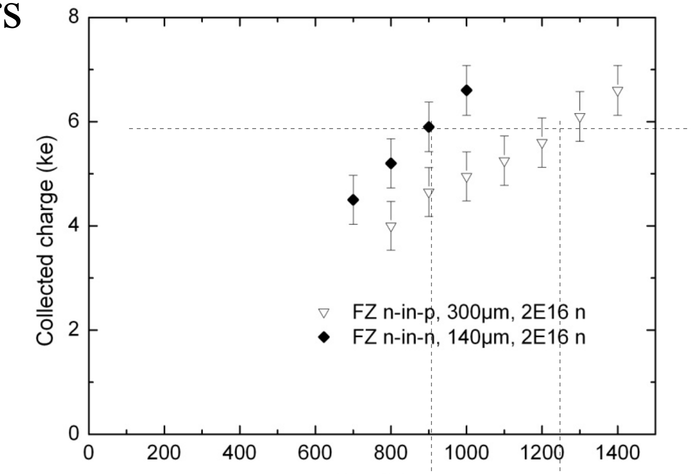
[M. Köhler, Freiburg, 4th Trento Workshop Feb 2009]

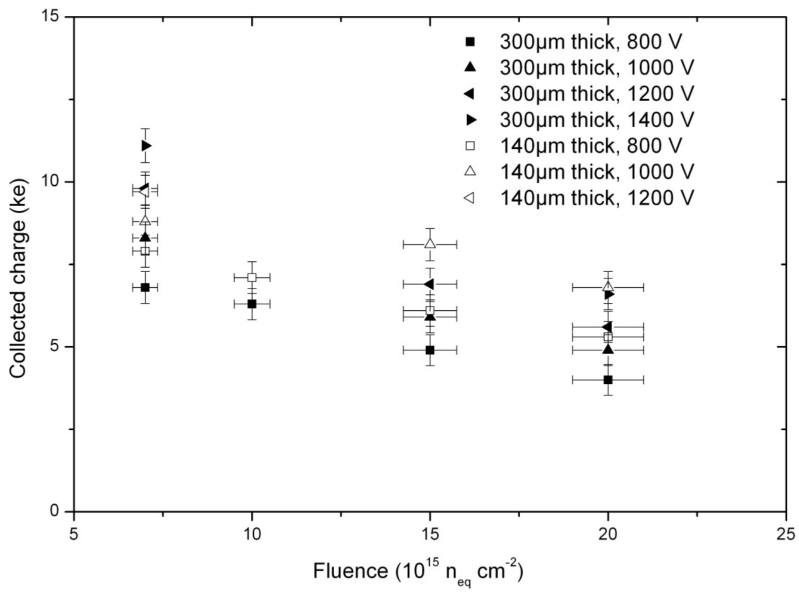
Spokespersons
Mara Bruzzi, Michael Moll
INFN Florence, CERN PH

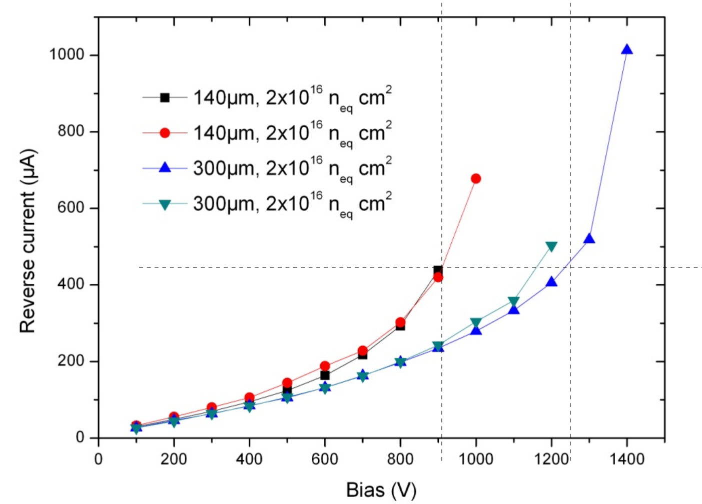
Defect / Material Characterization *Bengt Svensson* (Oslo University)	**Defect Engineering** *Eckhart Fretwurst* (Hamburg University)	**Pad Detector Characterization** *G. Kramberger* (Ljubljana)	**New Structures** *R. Bates* (Glasgow University)	**Full Detector Systems** *Gianluigi Casse* (Liverpool University)
Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation WODEAN project (G. Lindstroem)	Development and testing of defect engineered silicon: - Epitaxial Silicon - High res. CZ, MCZ - Other impurities H, N, Ge, … - Thermal donors - Pre-irradiation	•Test structure characterization IV, CV, CCE •NIEL •Device modeling •Operational conditions •Common irrad. •Standardisation of macroscopic measurements (A.Chilingarov)	•3D detectors •Thin detectors •Cost effective solutions •3D (M. Boscardin) •Semi 3D (Z.Li)	•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)

Thin Sensors

- Collected charge in heavily irradiated thin sensors is higher than in thick sensors at same bias voltage
- Reverse current is similar for the same charge !
- No beneficial effect of thin sensors on leakage current ?
- Further investigations ongoing...
- See also talk from G. Casse on Wednesday



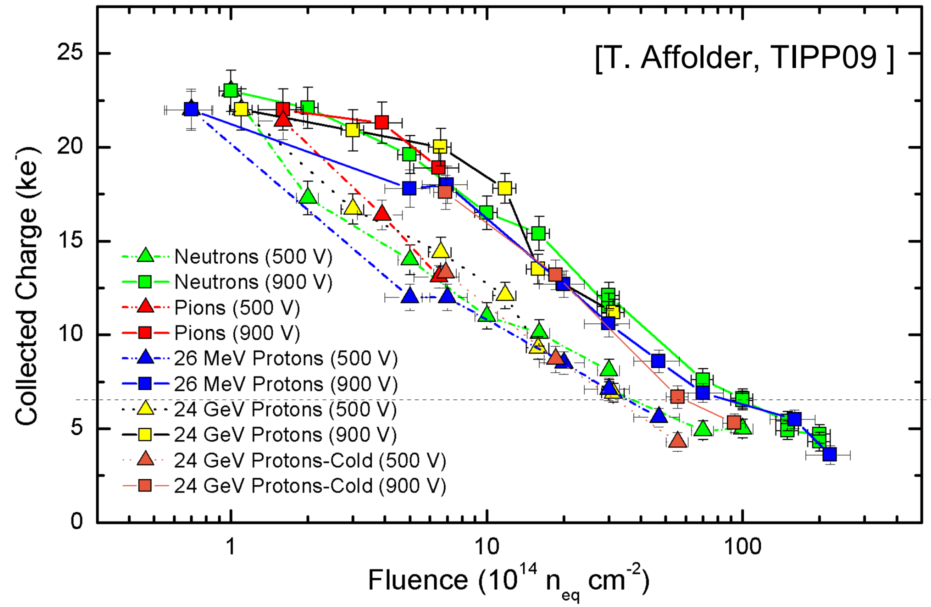


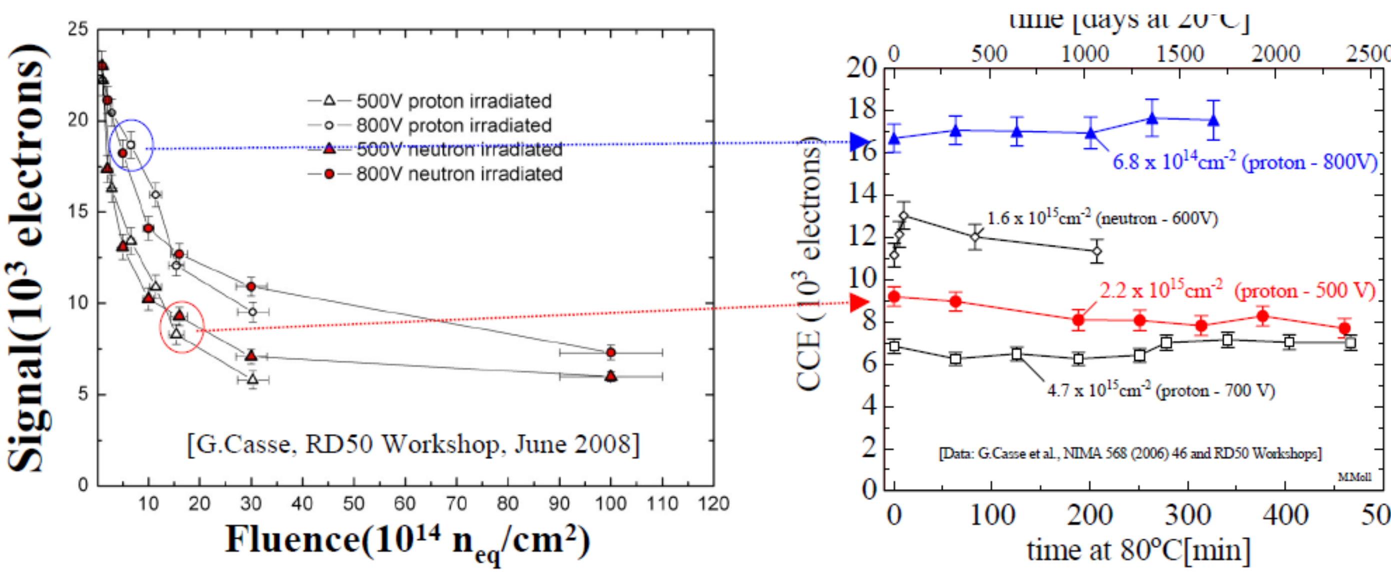


[G. Casse, Liverpool, 4th Trento Workshop Feb. 2009]

p-type FZ Silicon

- Still sufficient signal (7000e-) in p-type FZ strip sensors after $10^{16} n_{eq}/cm^2$ for 900V
- Almost no annealing effect on CCE





Mixed Irradiations

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

- **Mixed irradiations performed with:**
  - (a) 5×10^{14} neutrons (1 MeV equivalent fluence)
  - (b) 5×10^{14} protons (1 MeV equivalent fluence)

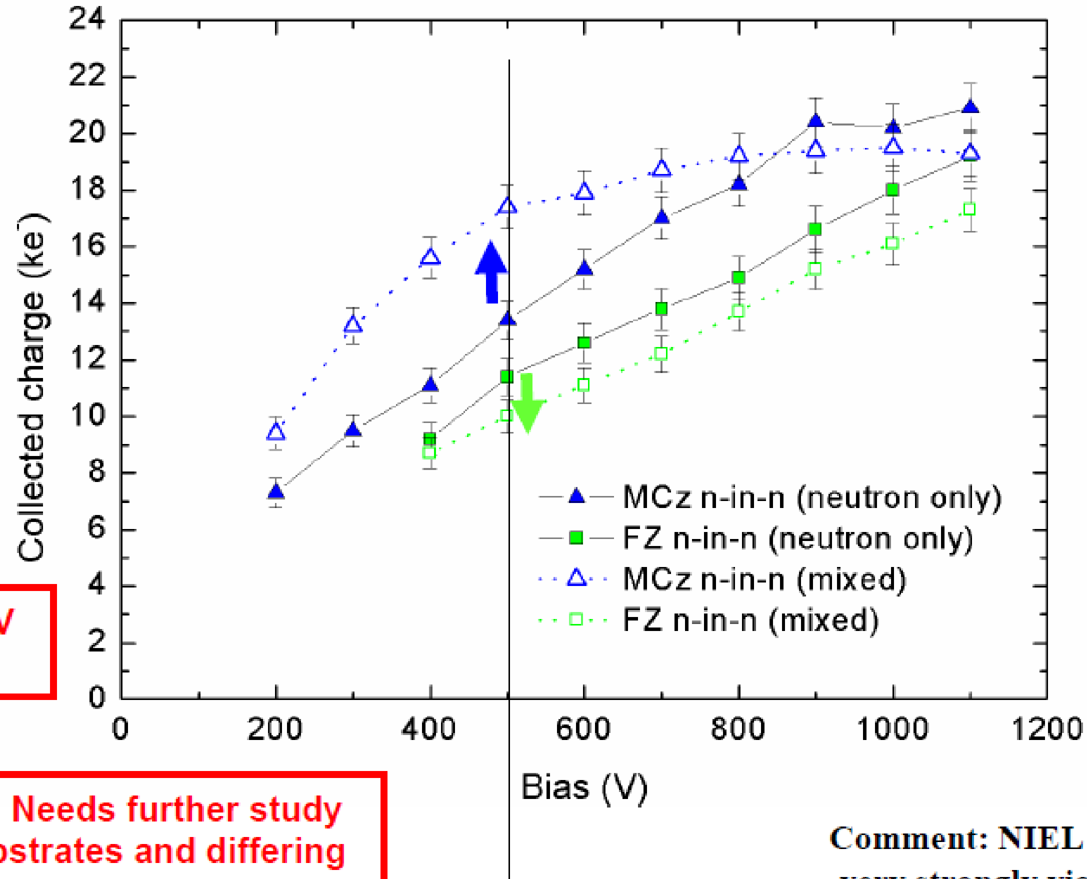
- **FZ (n-in-n)**

  Mixed Irradiation:

  Damage additive!

- **MCZ (n-in-n)**

  Mixed Irradiation:
  Proton damage "compensates" part of neutron damage (N_{eff})



More charge collected at 500V after additional irradiation!!!

Results from November 2008: Needs further study with both nMCz and pMCz substrates and differing mixed doses … hot topic for 2009/2010!

Comment: NIEL scaling very strongly violated !

Michael Moll – Legnaro, 21 April 2009 -30-

Recommendations for SLHC RD50

- Outer Layers (R>20cm, F<$10^{15} n_{eq}/cm^2$)
  - p-type silicon microstrip detectors show encouraging results
    - collected charge >10000e- (300µm) at 500V after F=10^{15} n_{eq}/cm^2
    - no reverse annealing in CCE
  - MCz could be a solution
    - n-MCz has improved performance in mixed fields due to compensation of n and p damage
- Innermost Layers (R<20cm, F~$10^{16} n_{eq}/cm^2$)
  - active thickness reduced due to trapping
  - collect electrons (use n^+-n or n^+-p sensors)
  - thin planar silicon still an option
  - 3D detectors promising, but technology has to be optimized → intensive work going on