Université de Genève, Ecole de physique, December 13, 2006

Radiation Tolerant Sensors for Solid State Tracking Detectors

- CERN-RD50 project –

http://www.cern.ch/rd50

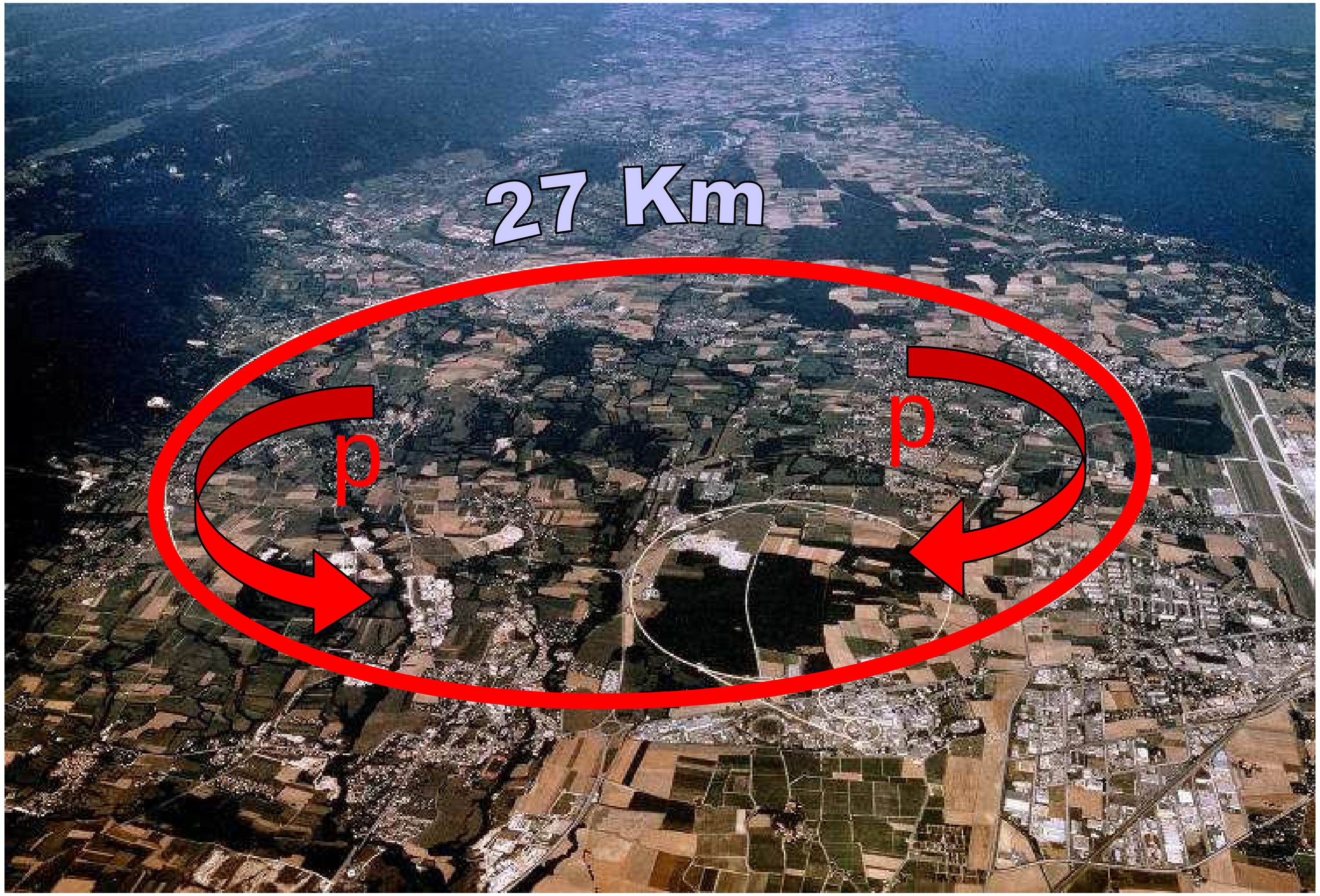
Michael Moll

CERN - Geneva - Switzerland

Outline

- Introduction: LHC and LHC experiment
- Motivation to develop radiation harder detectors
- Introduction to the RD50 collaboration
- **Part I:** Radiation Damage in Silicon Detectors (A very brief review)
  - Microscopic defects (changes in bulk material)
  - Macroscopic damage (changes in detector properties)
- **Part II:** RD50 - Approaches to obtain radiation hard sensors
  - Material Engineering
  - Device Engineering
- Summary and preliminary conclusion

RD50 LHC - Large Hadron Collider

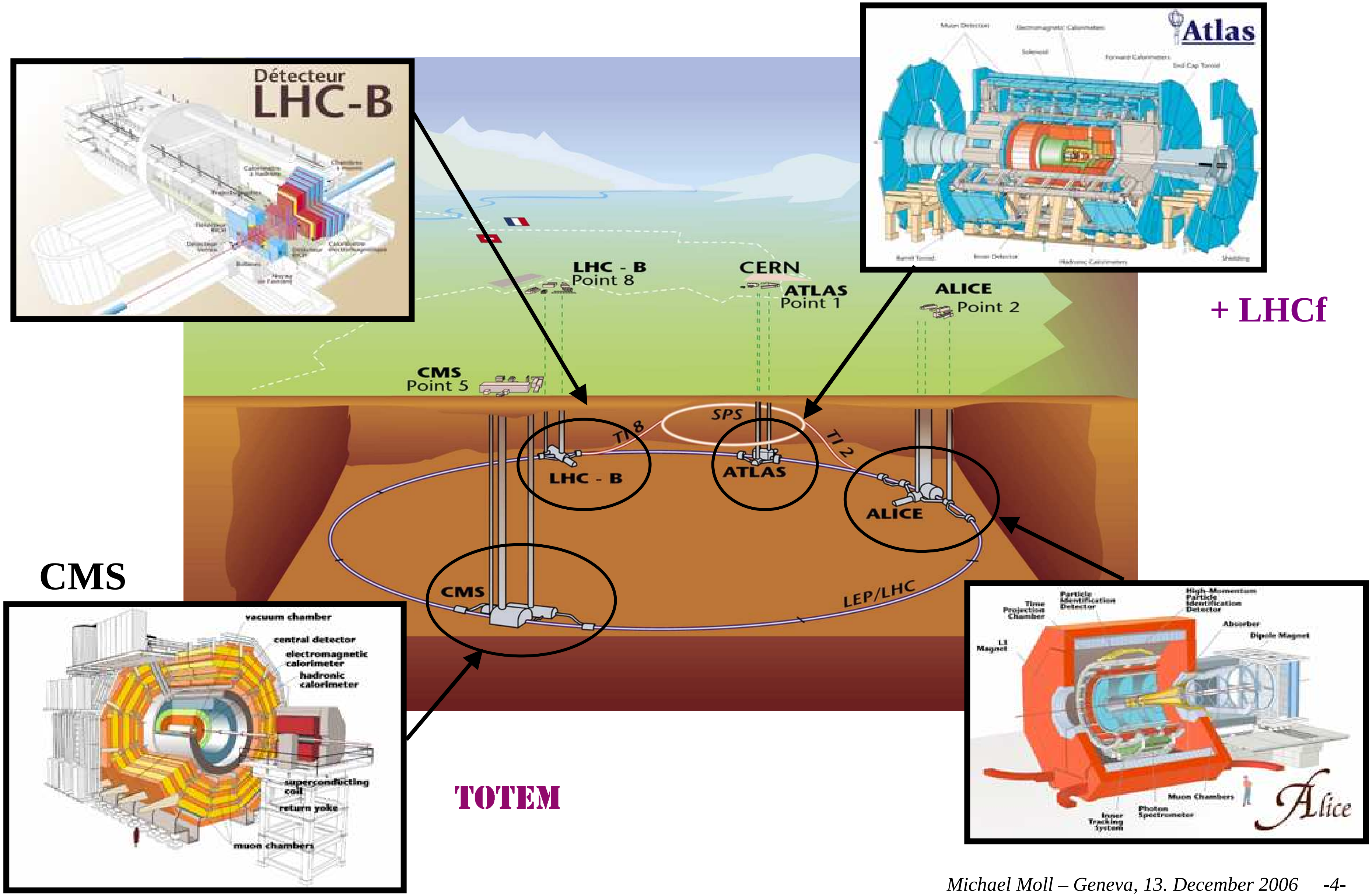


Start : 2007

- Installation in existing LEP tunnel
- 27 Km ring
- 1232 dipoles B=8.3T
- ≈ 4000 MCHF (machine+experiments)
- pp $\sqrt{s}$ = 14 TeV
  $L_{design} = 10^{34}\ cm^{-2}\ s^{-1}$
- Heavy ions
  (e.g. Pb-Pb at $\sqrt{s}$ ~ 1000 TeV)

LHC experiments located at 4 interaction points

LHC Experiments

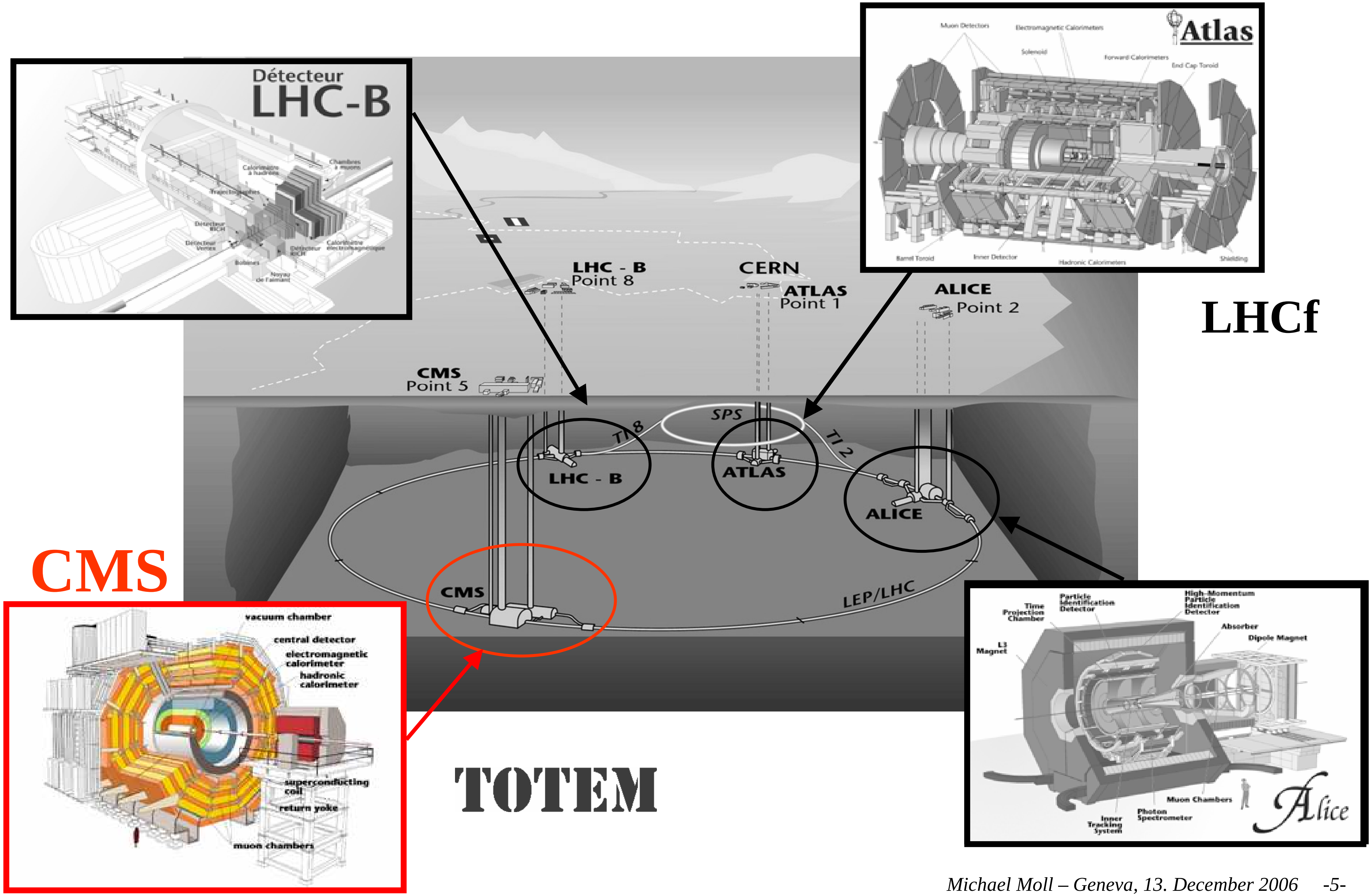


CMS

+ LHCf

TOTEM

LHC Experiments



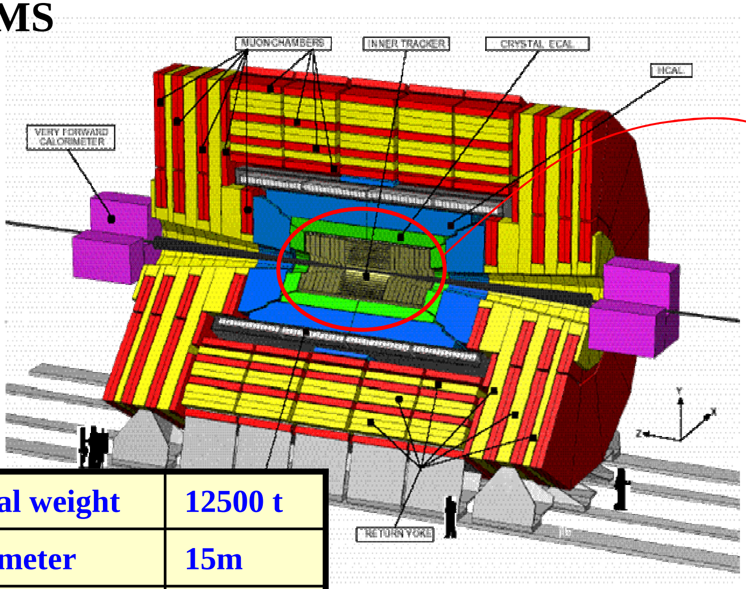
LHCf

CMS

TOTEM

RD50 LHC example: CMS inner tracker

CMS

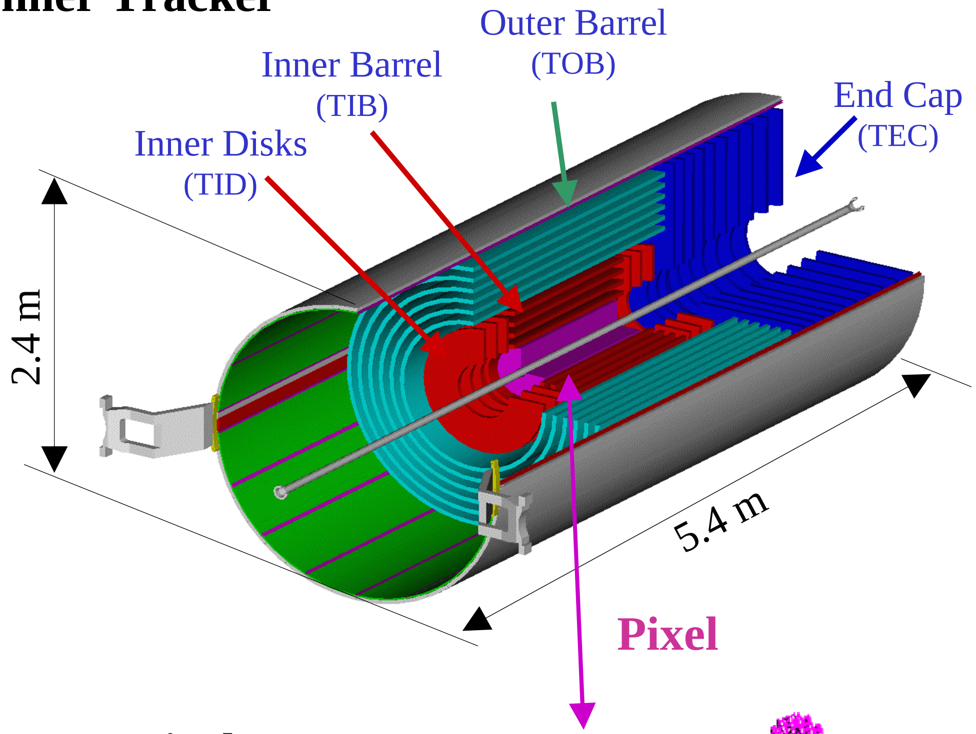


Total weight	**12500 t**
Diameter	**15m**
Length	**21.6m**
Magnetic field	**4 T**

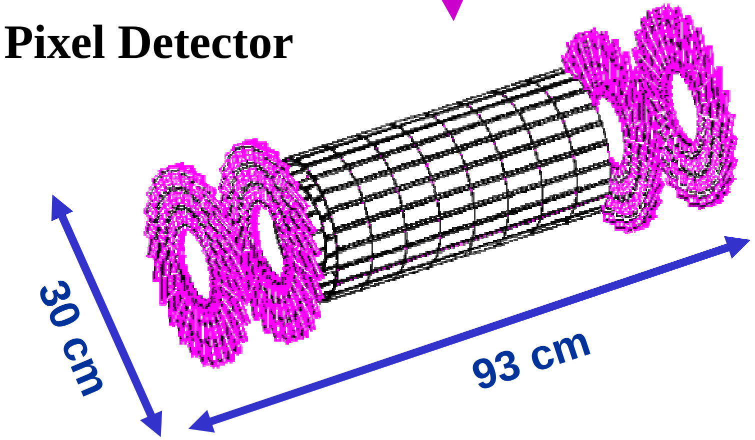
CMS – “Currently the Most Silicon”

- **Micro Strip:**
- **~ 214 m^2 of silicon strip sensors, 11.4 million strips**
- **Pixel:**
- **Inner 3 layers: silicon pixels (~ 1m^2)**
- **66 million pixels (100x150μm)**
- **Precision: $\sigma(r\varphi) \sim \sigma(z) \sim 15\mu m$**
- **Most challenging operating environments (LHC)**

Inner Tracker



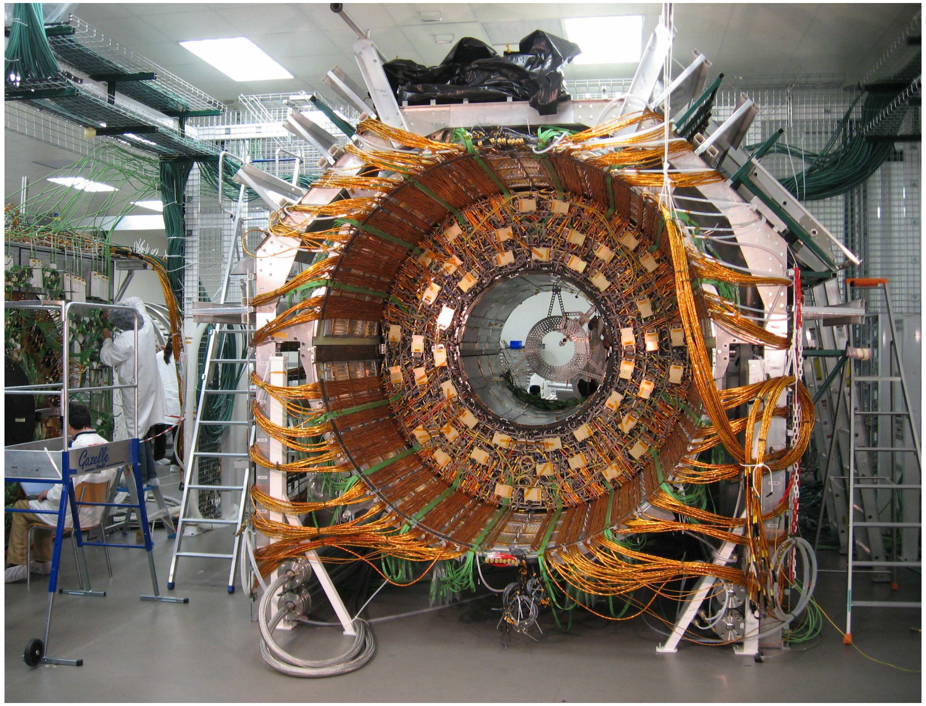
Pixel Detector



Status December 2006

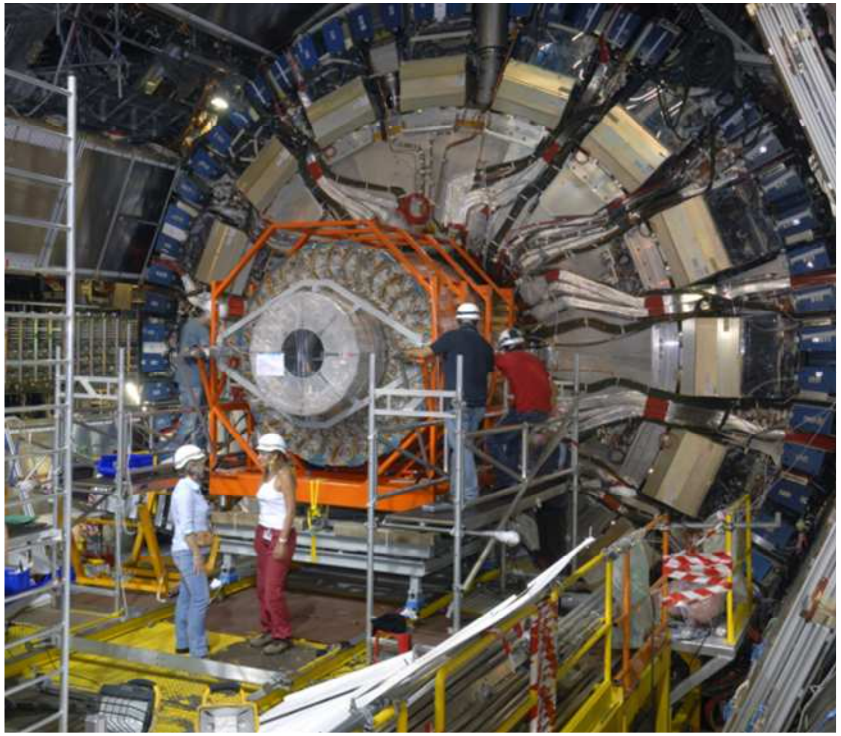
- LHC Silicon Trackers close to or under commissioning

- **CMS Tracker (12/2006)**
  (foreseen: June 2007 into the pit)



CMS Tracker Outer Barrel

- **ATLAS Silicon Tracker (08/2006)**
  August 2006 – installed in ATLAS



RD50

Motivation for R&D on Radiation Tolerant Detectors: Super - LHC

- **LHC upgrade**

⇨ **LHC (2007), L = 10^{34}cm^{-2}s^{-1}**

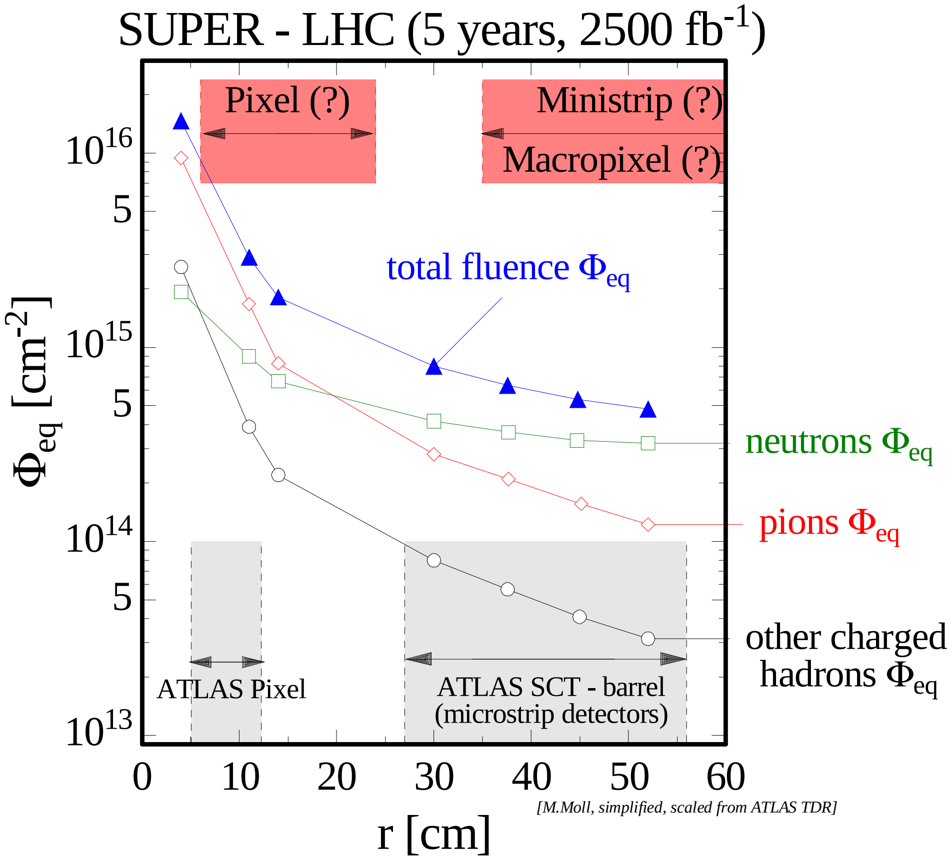
10 years → **500 fb^{-1}** ϕ(r=4cm) ~ $3\cdot10^{15}$cm^{-2}

× 5

⇨ **Super-LHC (2015 ?), L = 10^{35}cm^{-2}s^{-1}**

5 years → **2500 fb^{-1}** ϕ(r=4cm) ~ $1.6\cdot10^{16}$cm^{-2}

SUPER - LHC (5 years, 2500 fb^{-1})



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

- **LHC (Replacement of components)**

  e.g. - LHCb Velo detectors (~2010)
  - ATLAS Pixel B-layer (~2012)

- **Linear collider experiments (generic R&D)**

  Deep understanding of radiation damage will be fruitful for linear collider experiments where high doses of e, γ will play a significant role.

RD50

The CERN RD50 Collaboration

http://www.cern.ch/rd50

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

- Collaboration formed in November 2001
- Experiment approved as RD50 by CERN in June 2002
- 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** (Going from 25ns to 10 ns bunch crossing ?)
- **Low mass** (reducing multiple scattering close to interaction point)
- **Cost effectiveness** (big surfaces have to be covered with detectors!)

- Presently 264 members from 52 institutes

Belarus (Minsk), Belgium (Louvain), Canada (Montreal), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), Germany (Berlin, Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe), Israel (Tel Aviv), Italy (Bari, Bologna, Florence, Padova, Perugia, Pisa, Trento, Turin), Lithuania (Vilnius), The Netherlands (Amsterdam), 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 (Diamond, Exeter, Glasgow, Lancaster, Liverpool, Sheffield), USA (Fermilab, Purdue University, Rochester University, SCIPP Santa Cruz, Syracuse University, BNL, University of New Mexico)

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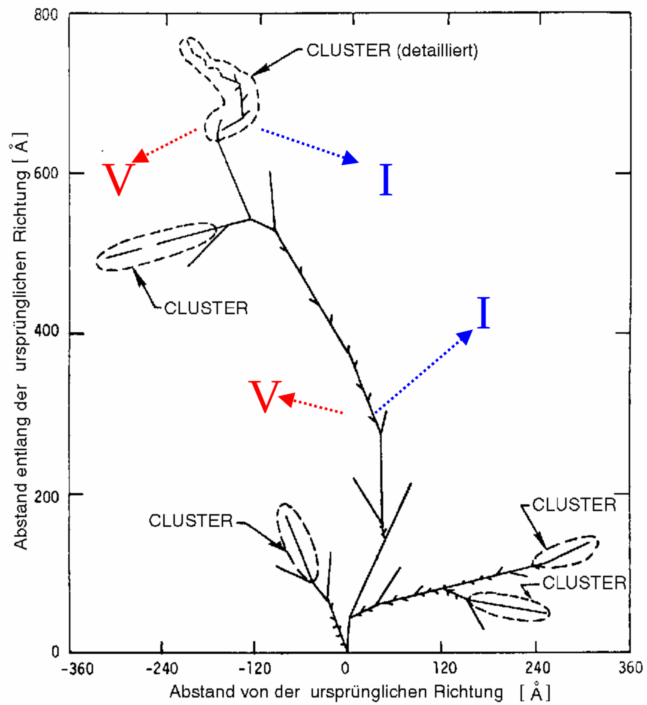
RD50

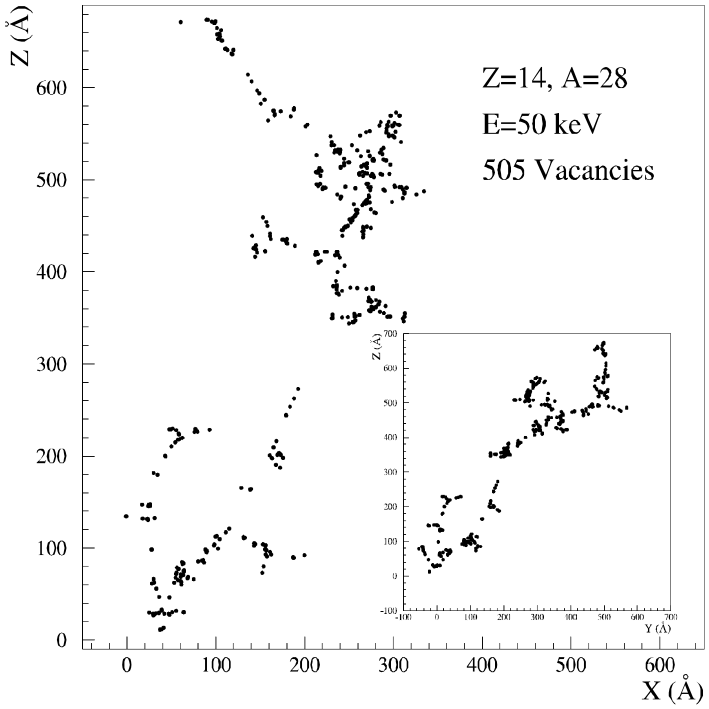
Radiation Damage – Microscopic Effects

- **Spatial distribution of vacancies created by a 50 keV Si-ion in silicon.**
  (typical recoil energy for 1 MeV neutrons)

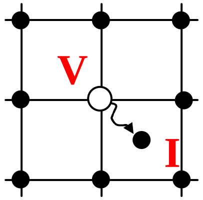
van Lint 1980



M.Huhtinen 2001



particle → Si_s → **E_K>25 eV**

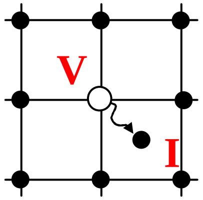


Vacancy
+
Interstitial → *point defects*
(V-O, C-O, ..)

→ **E_K > 5 keV** *point defects and clusters of defects*

RD50 Radiation Damage – Microscopic Effects

particle → Si_s → E_K>25 eV



Vacancy
+
Interstitial → *point defects*
(V-O, C-O, ..)

→ E_K > 5 keV *point defects and clusters of defects*

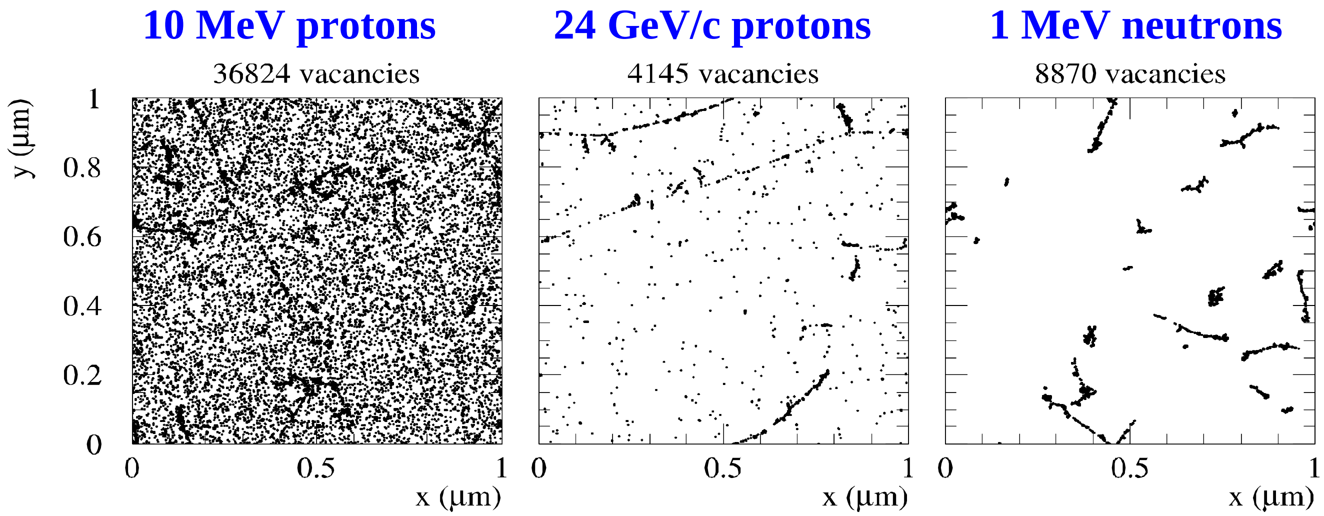
- **^{60}Co-gammas**
  - Compton Electrons with max. $E_\gamma \approx 1$ MeV (<u>no cluster production</u>)
- **Electrons**
  - E_e > 255 keV for displacement
  - E_e > 8 MeV for cluster
- **Neutrons (elastic scattering)**
  - E_n > 185 eV for displacement
  - E_n > 35 keV for cluster

Only point defects ⟷ **point defects & clusters** ⟷ **Mainly clusters**

Simulation:

Initial distribution of vacancies in (1µm)^3 after 10^{14} particles/cm^2

[Mika Huhtinen NIMA 491(2002) 194]



RD50 Primary Damage and secondary defect formation

- **Two basic defects**

  I - Silicon Interstitial   V - Vacancy

- **Primary defect generation**

  I, I_2 higher order I (?)

  ⇒ **I** -CLUSTER **(?)** ⇐

  V, V_2, higher order V (?)   **Damage?!**

  ⇒ **V** -CLUSTER **(?)** ⇐

- **Secondary defect generation**

  Main impurities in silicon: Carbon (C_s)

  Oxygen (O_i)

$I+C_s \rightarrow C_i \Rightarrow C_i+C_s \rightarrow C_iC_S$

$C_i+O_i \rightarrow C_iO_i$

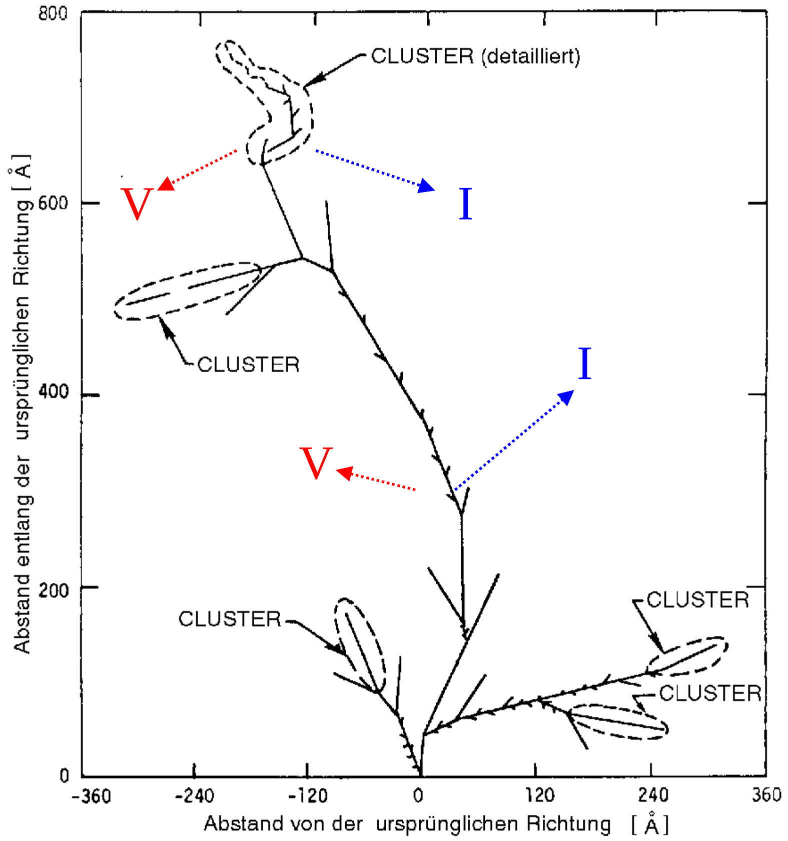
$C_i+P_s \rightarrow C_iP_S$

$V+V \rightarrow V_2$ $V+V_2 \rightarrow V_3$

$V+O_i \rightarrow VO_i \Rightarrow V+VO_i \rightarrow \underline{V_2O_i}$ ⇐ **Damage?! (“V_2O-model”)**

$V+P_s \rightarrow VP_s$

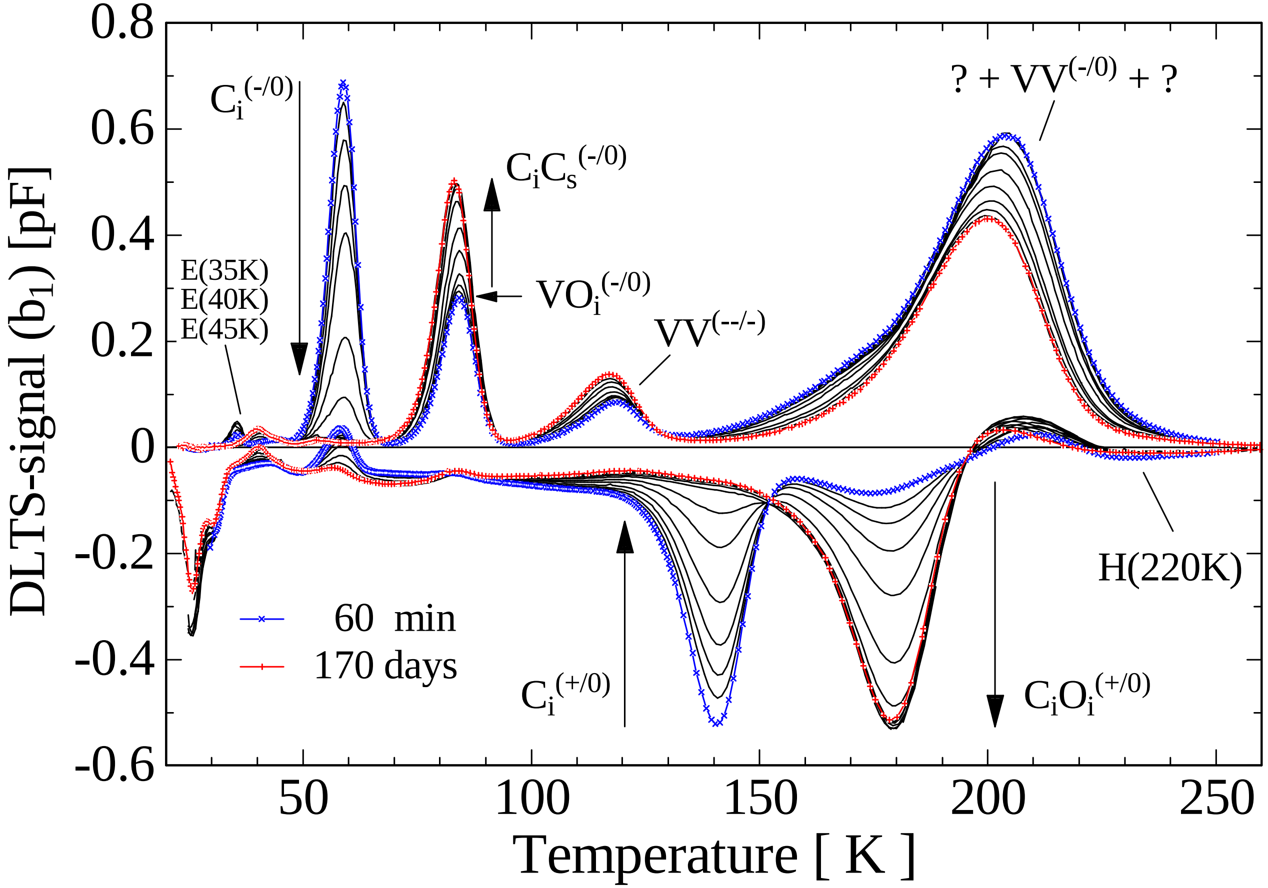
$I+V_2 \rightarrow V$ $I+VO_i \rightarrow O_i$ ……………………



Example of defect spectroscopy

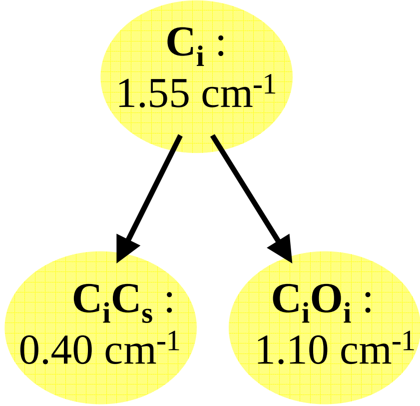
- neutron irradiated -

Deep Level Transient Spectroscopy



Introduction Rates

N_t/Φ_{eq}:



C_i :
$1.55\ cm^{-1}$

C_iC_s :
$0.40\ cm^{-1}$

C_iO_i :
$1.10\ cm^{-1}$

- **Introduction rates of main defects** **$\approx 1\ cm^{-1}$**
- **Introduction rate of negative space charge** **$\approx 0.05\ cm^{-1}$**

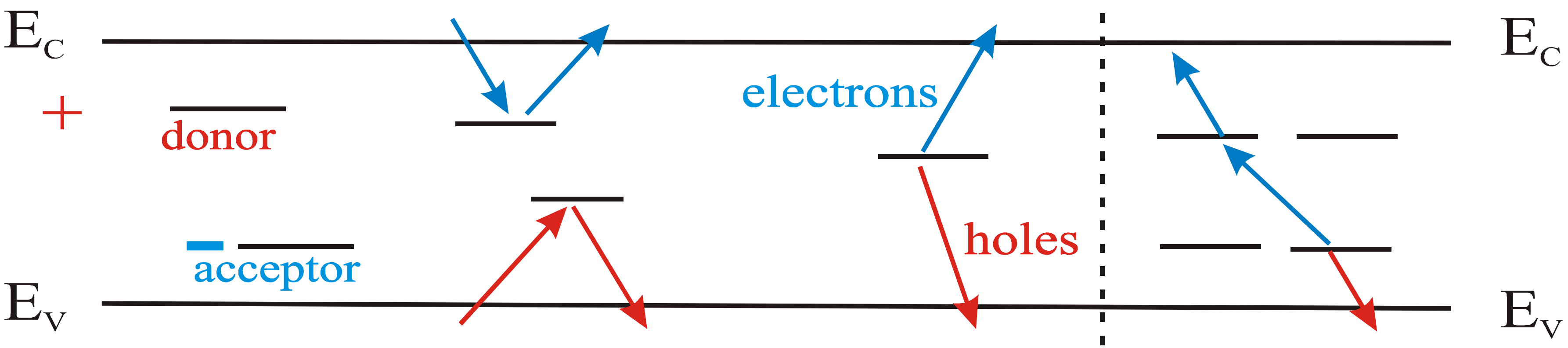
example : $\Phi_{eq} = 1\times10^{14}\ cm^{-2}$

defects $\approx 1\times10^{14}\ cm^{-3}$
space charge $\approx 5\times10^{12} cm^{-3}$

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**

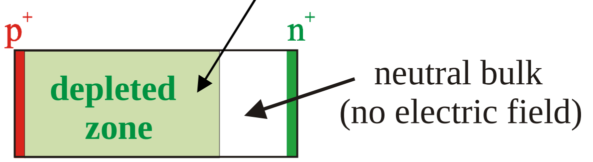
ΔE : **ionization energy**

N_t : **concentration**

RD50 Reverse biased abrupt p⁺-n junction

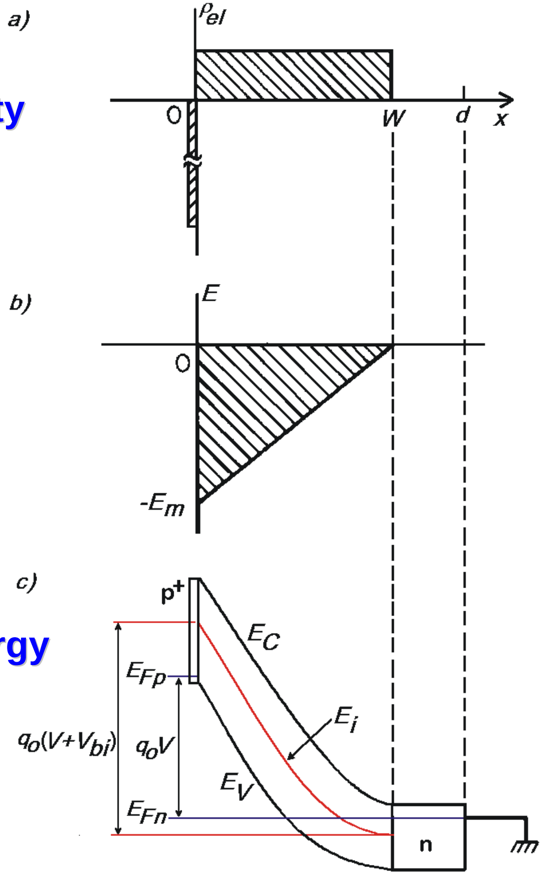
Poisson's equation

$$-\frac{d^2}{dx^2}\phi(x)=\frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}$$



Positive space charge, N_{eff} =[P]
(ionized Phosphorus atoms)

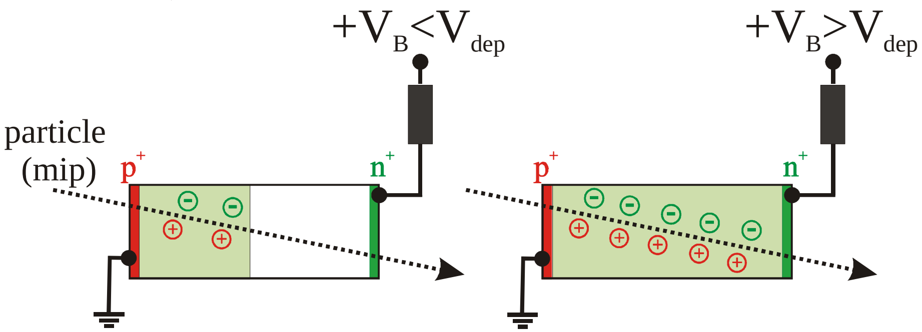
neutral bulk
(no electric field)



Electrical charge density

Electrical field strength

Electron potential energy



Full charge collection only for $V_B>V_{dep}$!

depletion voltage

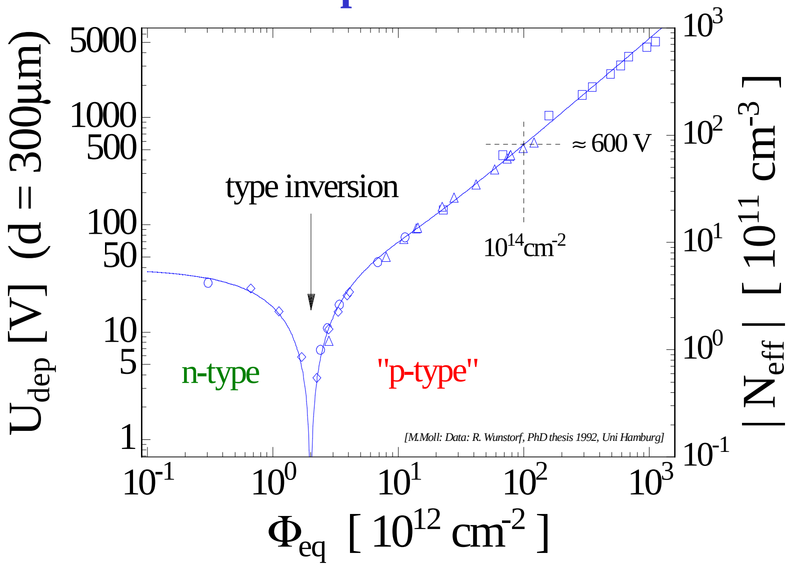
$$\boxed{V_{dep}=\frac{q_0}{\varepsilon\varepsilon_0}\cdot\left|N_{eff}\right|\cdot d^2}$$

effective space charge density

RD50 Macroscopic Effects – I. Depletion Voltage

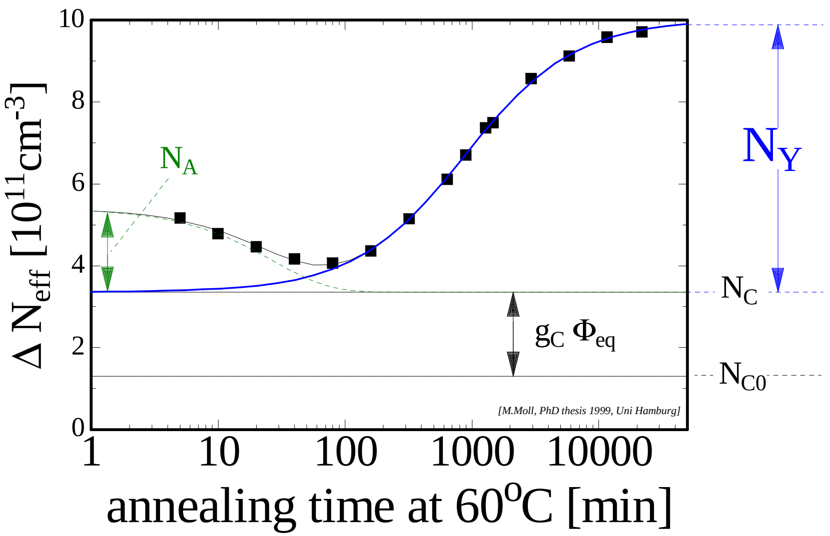
- **Change of Depletion Voltage V_{dep} (N_{eff})**

…. with particle fluence:



[M.Moll: Data: R. Wunstorf, PhD thesis 1992, Uni Hamburg]

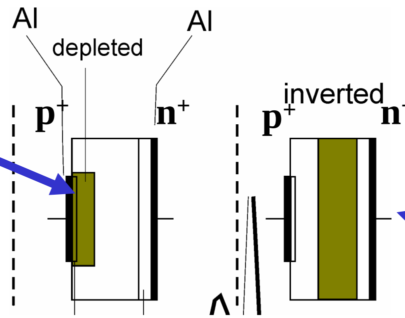
…. with time (annealing):



[M.Moll, PhD thesis 1999, Uni Hamburg]

- "**Type inversion**": N_{eff} changes from positive to negative (Space Charge Sign Inversion)

before inversion



after inversion

- Short term: "**Beneficial annealing**"
- Long term: "**Reverse annealing**"

- time constant depends on temperature:

~ 500 years (-10°C)

~ 500 days (20°C)

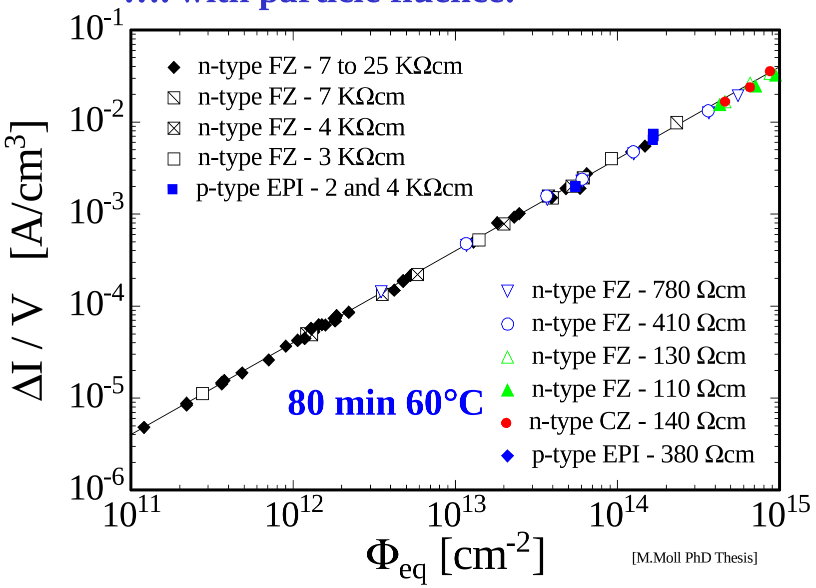
~ 21 hours (60°C)

- Consequence: **Detectors must be cooled even when the experiment is not running!**

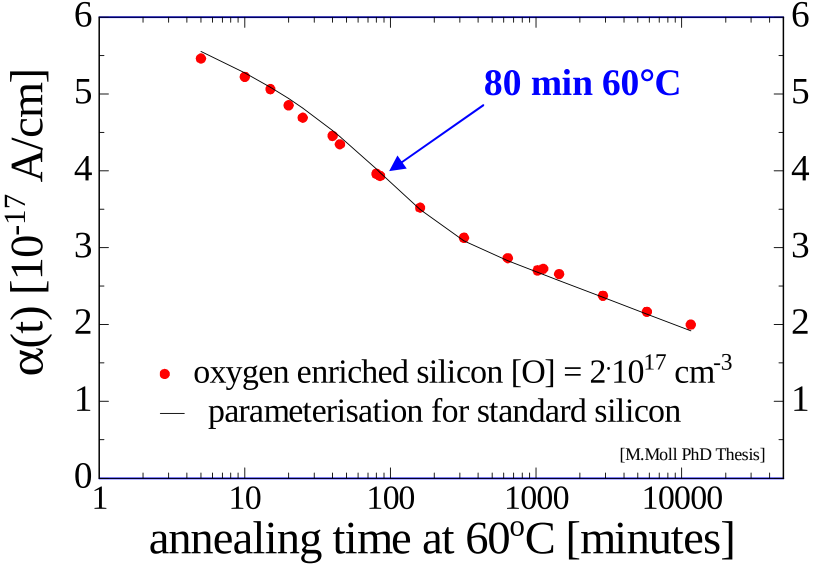
RD50 Radiation Damage – II. Leakage Current

Change of Leakage Current (after hadron irradiation)

…. with particle fluence:



…. with time (annealing):



- **Damage parameter α (slope in figure)**

$$\boxed{\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}}$$

Leakage current per unit volume and particle fluence

- **α is constant over several orders of fluence and independent of impurity concentration in Si**
  - ⇨ **can be used for fluence measurement**

- **Leakage current decreasing in time (depending on temperature)**
- **Strong temperature dependence**

$$I \propto \exp\left(-\frac{E_g}{2k_B T}\right)$$

Consequence:

Cool detectors during operation!
Example: *I*(-10°C) ~1/16 *I*(20°C)

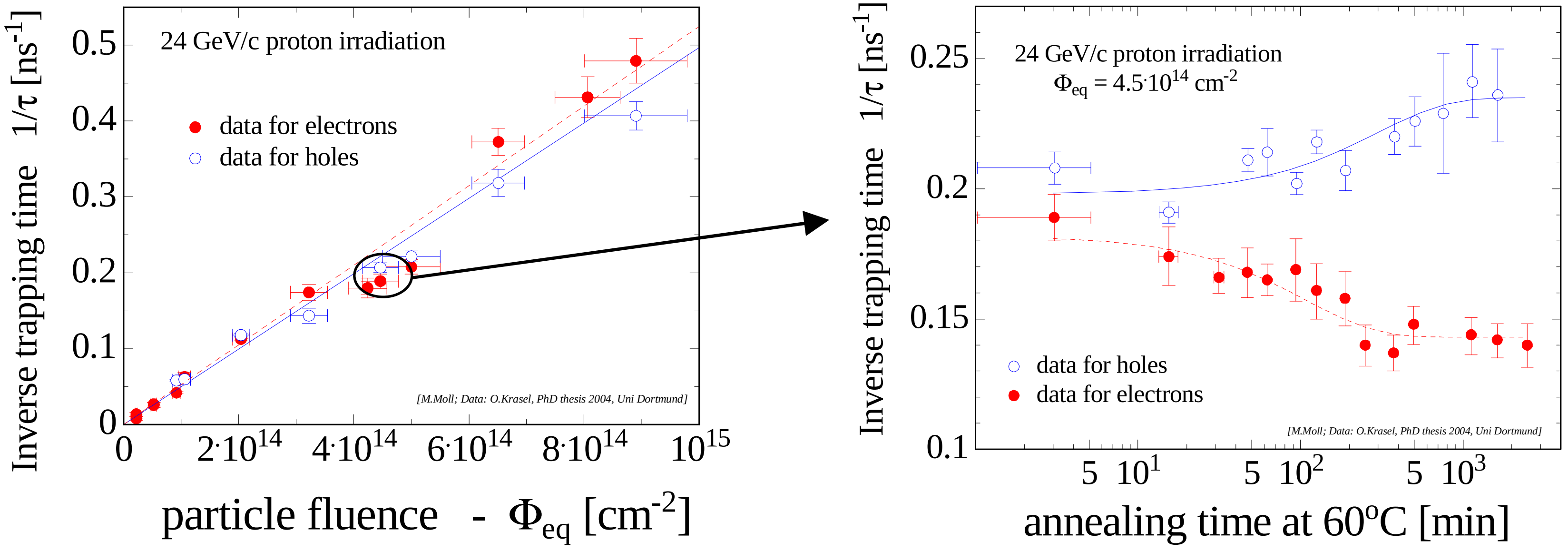
RD50 Radiation Damage – III. CCE (Trapping)

- **Deterioration of Charge Collection Efficiency (CCE) by trapping**

Trapping is characterized by an effective trapping time τ_{eff} for electrons and holes:

$$Q_{e,h}(t) = Q_{0\,e,h} \exp\left(-\frac{1}{\tau_{eff\;e,h}} \cdot t \right) \qquad \text{where} \qquad \frac{1}{\tau_{eff\;e,h}} \propto N_{defects}$$

Increase of inverse trapping time ($1/\tau$) with fluence …… and change with time (annealing):



RD50 Summary: 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 –

    I. Change of effective doping concentration (higher depletion voltage, under- depletion)

    II. Increase of leakage current (increase of shot noise, thermal runaway)

    III. Increase of charge carrier trapping (loss of charge)

Influenced by impurities in Si – Defect Engineering is possible!

Same for all tested Silicon materials!

  - **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!)

Can be optimized!

Signal/noise ratio is the quantity to watch

⇒ Sensors can fail from radiation damage !

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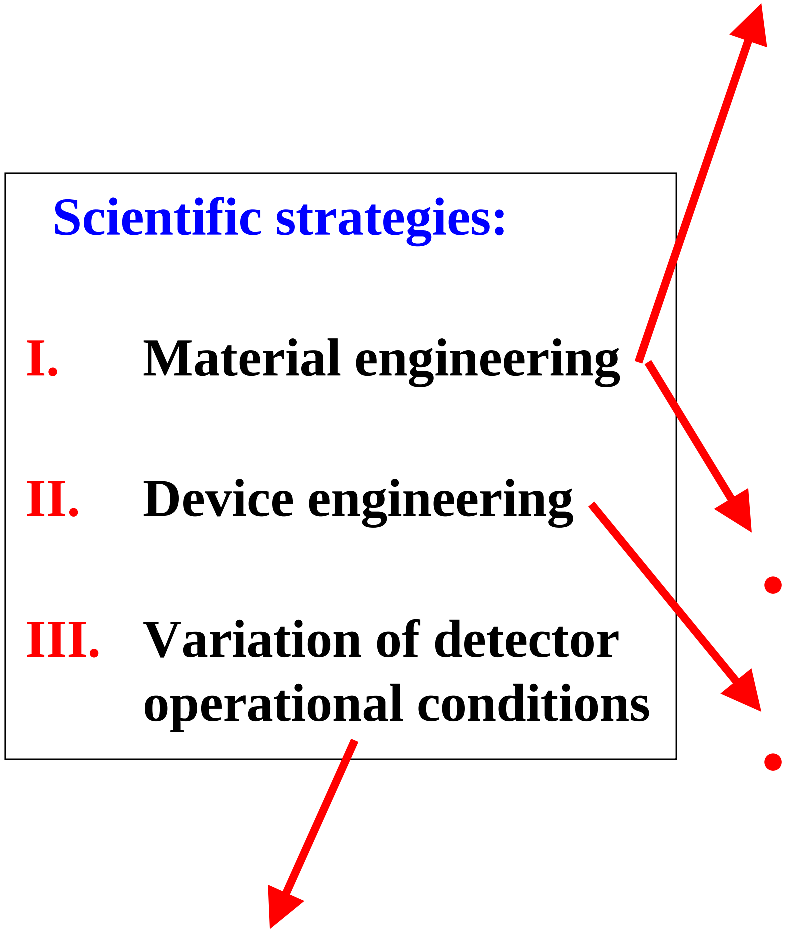
Approaches of RD50 to develop radiation harder tracking detectors



Scientific strategies:

I. **Material engineering**

II. **Device engineering**

III. **Variation of detector operational conditions**

CERN-RD39
“Cryogenic Tracking Detectors”

- **Defect Engineering of Silicon**
  - **Understanding radiation damage**
    - **Macroscopic effects and Microscopic defects**
    - *Simulation of defect properties and defect kinetics*
    - *Irradiation with different particles at different energies*
  - **Oxygen rich silicon**
    - **DOFZ, Cz, MCZ, EPI**
  - *Oxygen dimer enriched silicon*
  - *Hydrogen enriched silicon*
  - *Pre-irradiated silicon*
  - *Influence of processing technology*
- **New Materials**
  - **Silicon Carbide (SiC),** *Gallium Nitride (GaN)*
  - *Diamond: CERN RD42 Collaboration*
- **Device Engineering (New Detector Designs)**
  - **p-type silicon detectors (n-in-p)**
  - **Thin detectors**
  - **3D** *and Semi 3D* **detectors**
  - *Cost effective detectors*
  - *Simulation of highly irradiated detectors*

Defect Engineering of Silicon

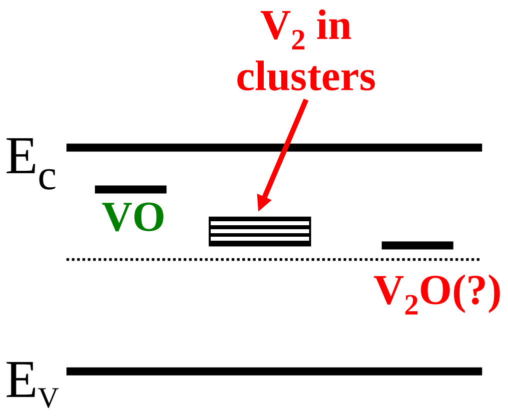
- **Influence the defect kinetics by incorporation of impurities or defects**
- **Best example: Oxygen**

Initial idea: Incorporate Oxygen to getter radiation-induced vacancies
⇒ prevent formation of Di-vacancy (V_2) related deep acceptor levels

Observation: **Higher oxygen content ⇒ less negative space charge**
(less charged acceptors)

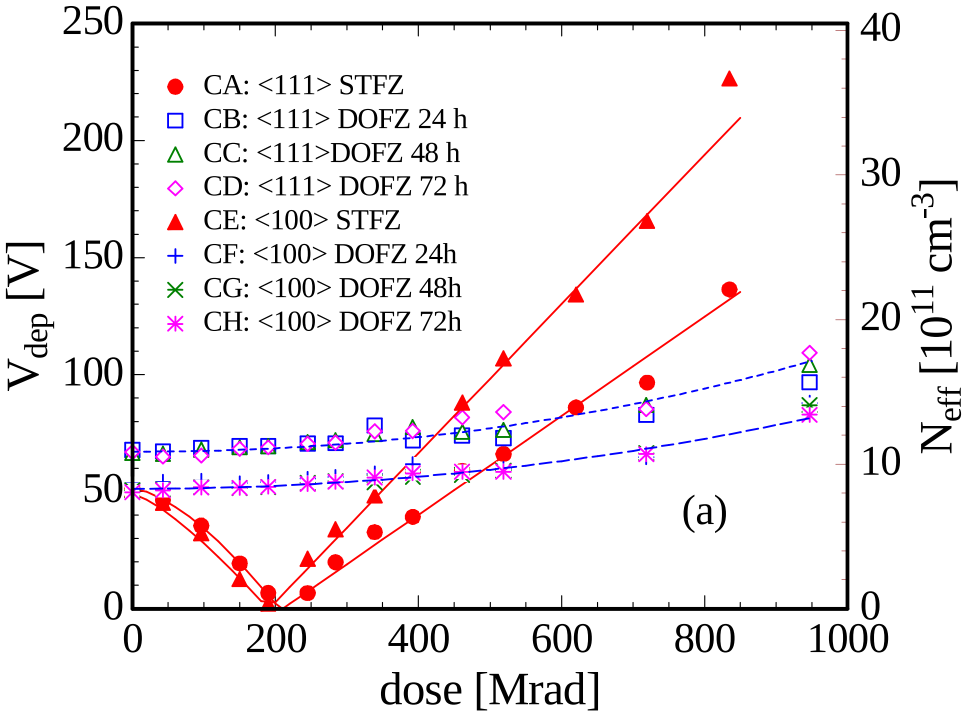
- **One possible mechanism: V_2O is a deep acceptor**

V → **O** ⟶ **VO** **(not harmful at room temperature)**
V → **VO** ⟶ **V_2O** **(negative space charge)**

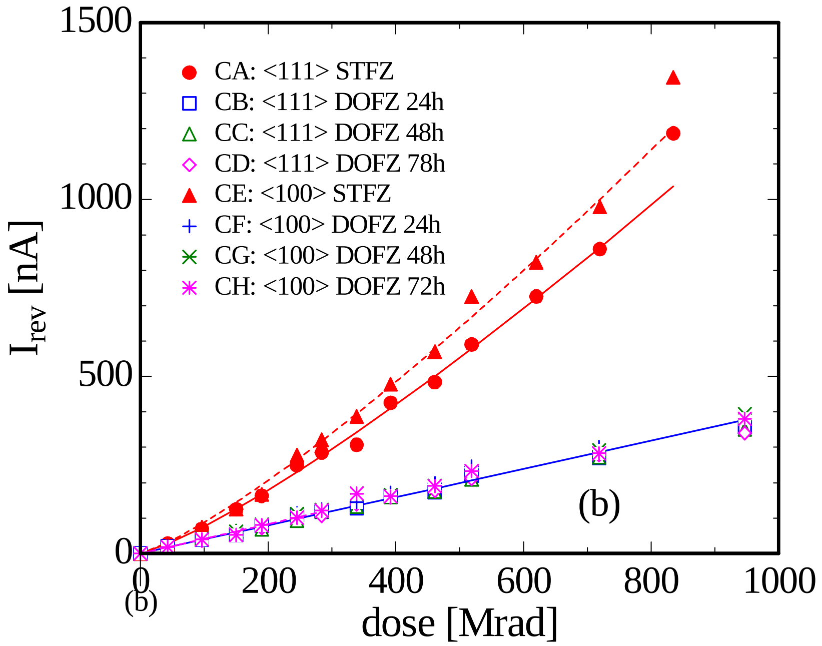


Spectacular Improvement of γ-irradiation tolerance

Depletion Voltage



Leakage Current



- **No type inversion for oxygen enriched silicon!**
- **Slight increase of positive space charge**
  (due to Thermal Donor generation?)
- **Leakage increase not linear and depending on oxygen concentration**

[E.Fretwurst et al. 1st RD50 Workshop]
See also:
- Z.Li et al. [NIMA461(2001)126]
- Z.Li et al. [1st RD50 Workshop]

RD50 Characterization of microscopic defects

- γ and proton irradiated silicon detectors -

- **2003: Major breakthrough on γ-irradiated samples**
  - For the first time macroscopic changes of the depletion voltage and leakage current can be explained by electrical properties of measured defects ! [APL, 82, 2169, March 2003]
- **since 2004: Big steps in understanding the improved radiation tolerance of oxygen enriched and epitaxial silicon after proton irradiation**

[I.Pintilie, RESMDD, Oct.2004]

Levels responsible for depletion voltage changes after proton irradiation:

Almost independent of oxygen content:

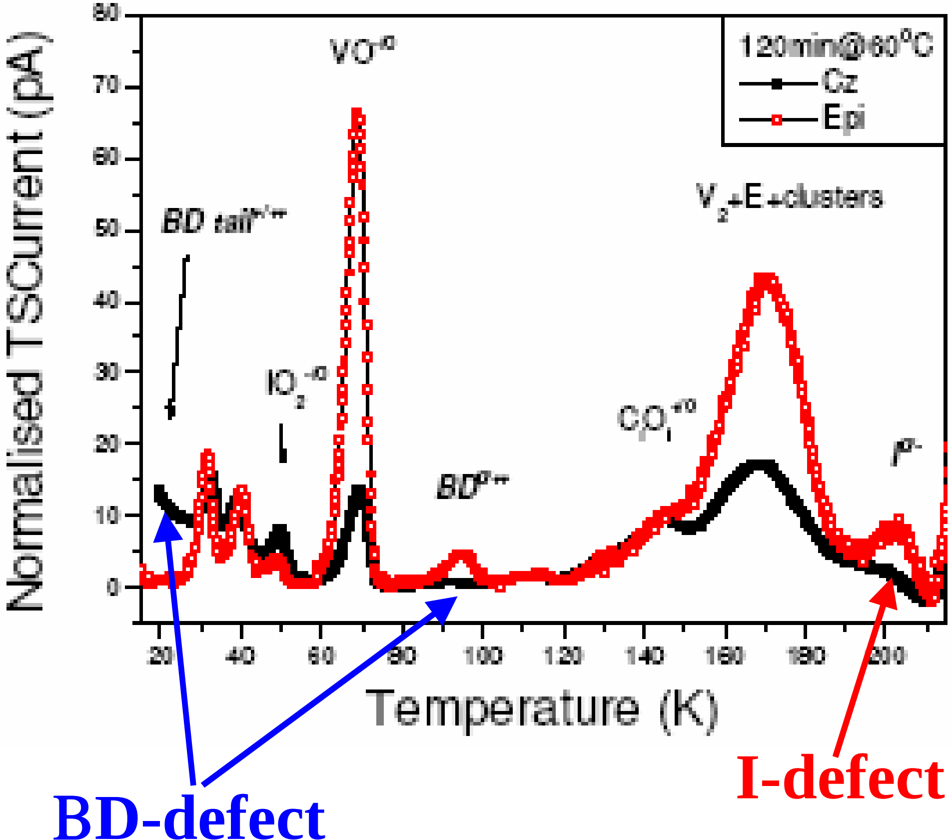
- **Donor removal**
- **"Cluster damage"** ⇒ **negative charge**

Influenced by initial oxygen content:

- **I–defect:** 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**



BD-defect

I-defect

RD50

Oxygen enriched silicon – DOFZ

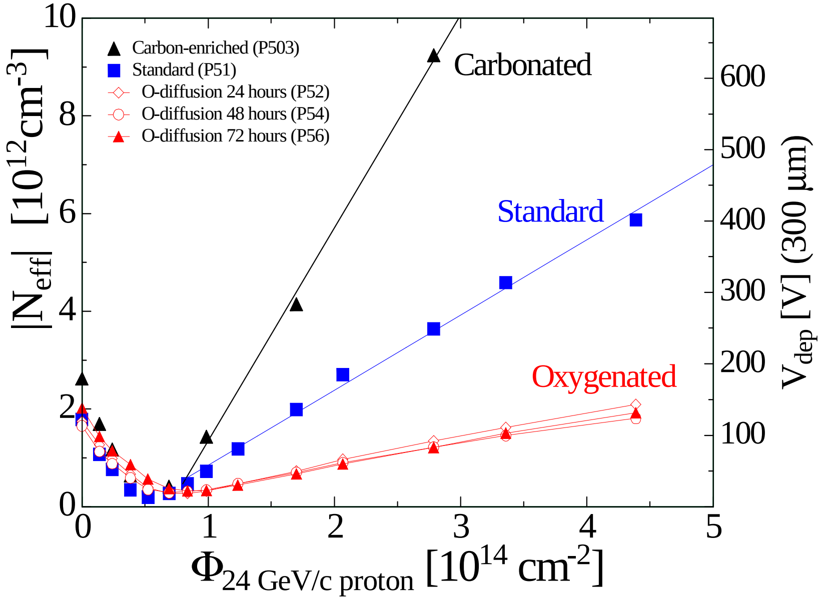
- proton irradiation -

- **DOFZ (Diffusion Oxygenated Float Zone Silicon)**
  - 1982 First oxygen diffusion tests on FZ [Brotherton et al. J.Appl.Phys.,Vol.53, No.8.,5720]
  - 1995 First tests on detector grade silicon [Z.Li et al. IEEE TNS Vol.42,No.4,219]
  - **1999 Introduced to the HEP community by RD48 (ROSE)**

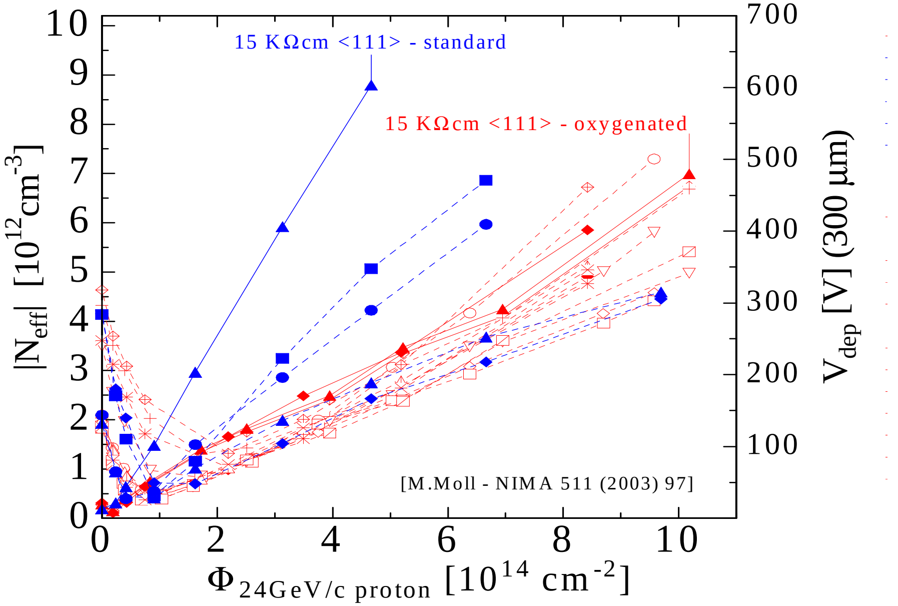
ROSE
RD48
http://cern.ch/rd48

First tests in 1999 show clear advantage of oxygenation

Later systematic tests reveal strong variations with no clear dependence on oxygen content



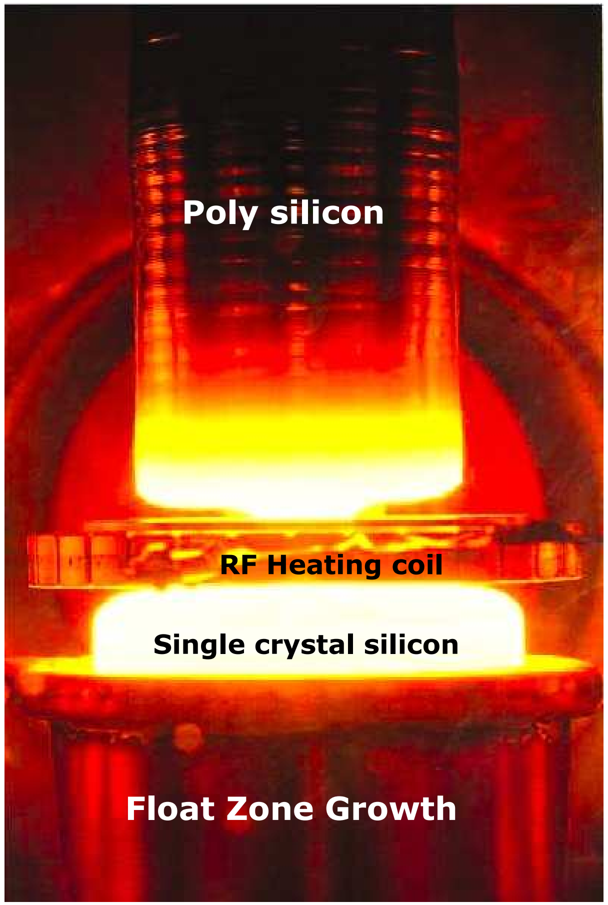
[RD48-NIMA 465(2001) 60]



However, only non-oxygenated diodes show a “bad” behavior.

Silicon Growth Processes

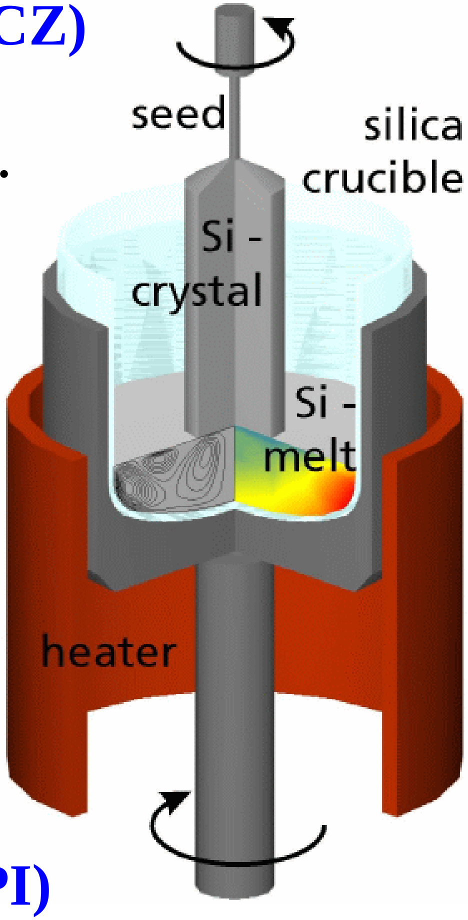
Floating Zone Silicon (FZ)



- Basically all silicon detectors made out of high resistivety FZ silicon

Czochralski Silicon (CZ)

- The growth method used by the IC industry.
- Difficult to produce very high resistivity



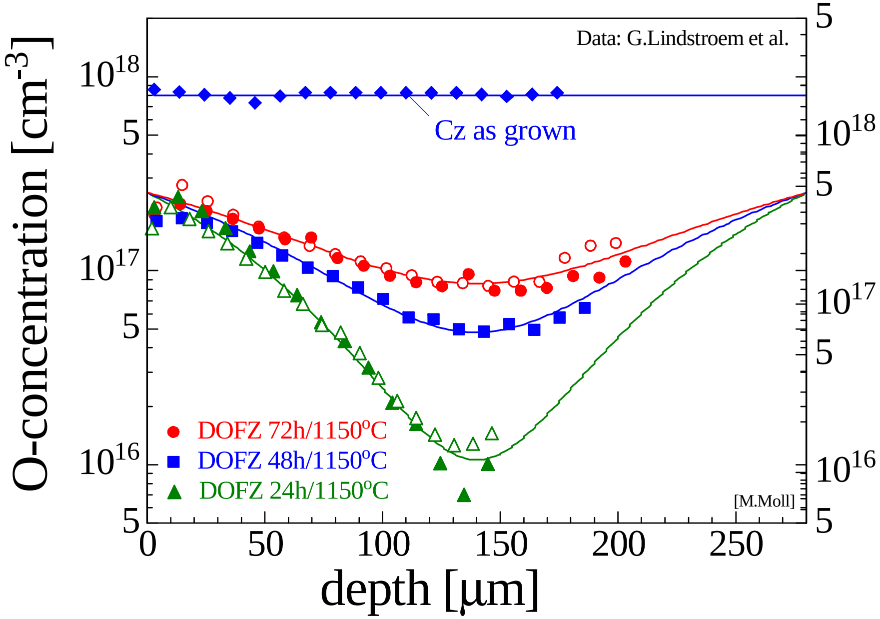
Epitaxial Silicon (EPI)

- Chemical-Vapor Deposition (CVD) of Si
- up to 150 µm thick layers produced
- growth rate about 1µm/min

Oxygen concentration in FZ, CZ and EPI

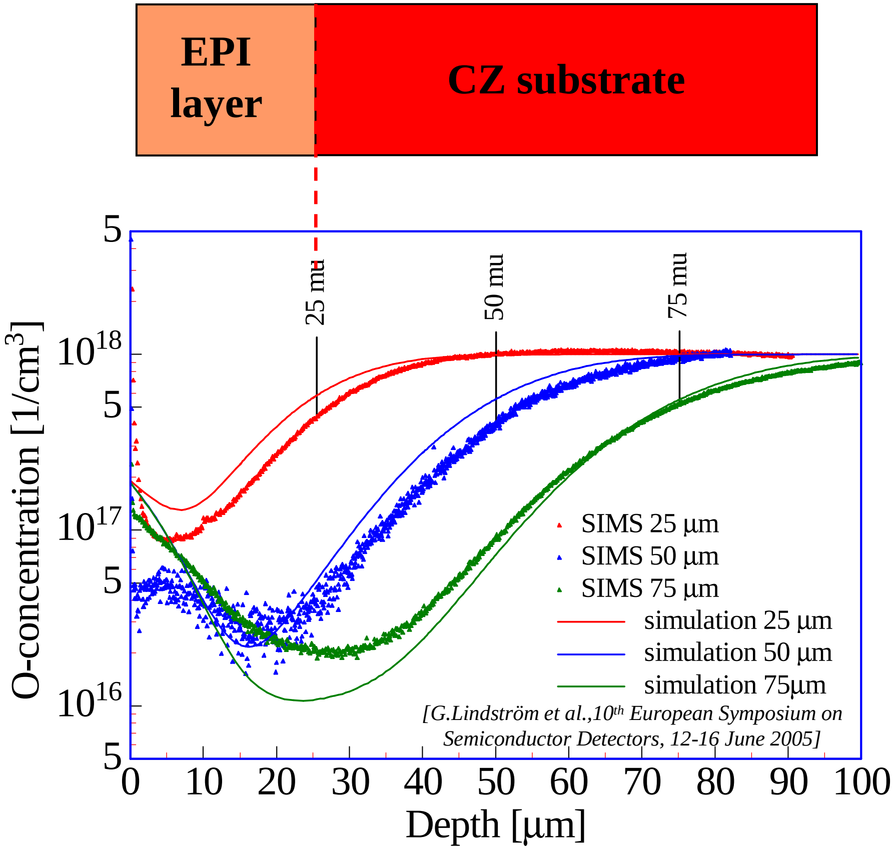
DOFZ and CZ silicon

- **DOFZ: inhomogeneous oxygen distribution**
- **DOFZ: oxygen content increasing with time at high temperature**



- **CZ: high O_i (oxygen) and O_{2i} (oxygen dimer) concentration (homogeneous)**
- **CZ: formation of Thermal Donors possible !**

Epitaxial silicon



[G.Lindström et al.,10th European Symposium on Semiconductor Detectors, 12-16 June 2005]

- **EPI: O_i and O_{2i} (?) diffusion from substrate into epi-layer during production**
- **EPI: in-homogeneous oxygen distribution**

RD50 Silicon Materials under Investigation by RD50

standard for particle detectors

used for LHC Pixel detectors

“new” material

Material	Symbol	ρ (Ωcm)	$[O_i]$ (cm^{-3})
Standard FZ (n- and p-type)	**FZ**	$1–7\times10^{3}$	$< 5\times10^{16}$
Diffusion oxygenated FZ (n- and p-type)	**DOFZ**	$1–7\times10^{3}$	$\sim 1–2\times10^{17}$
Magnetic Czochralski Si, Okmetic, Finland (n- and p-type)	**MCz**	$\sim 1\times10^{3}$	$\sim 5\times10^{17}$
Czochralski Si, Sumitomo, Japan (n-type)	**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, 150 μm thick)	**EPI**	50 – 400	$< 1\times10^{17}$
Diffusion oxygenated Epitaxial layers on CZ	**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

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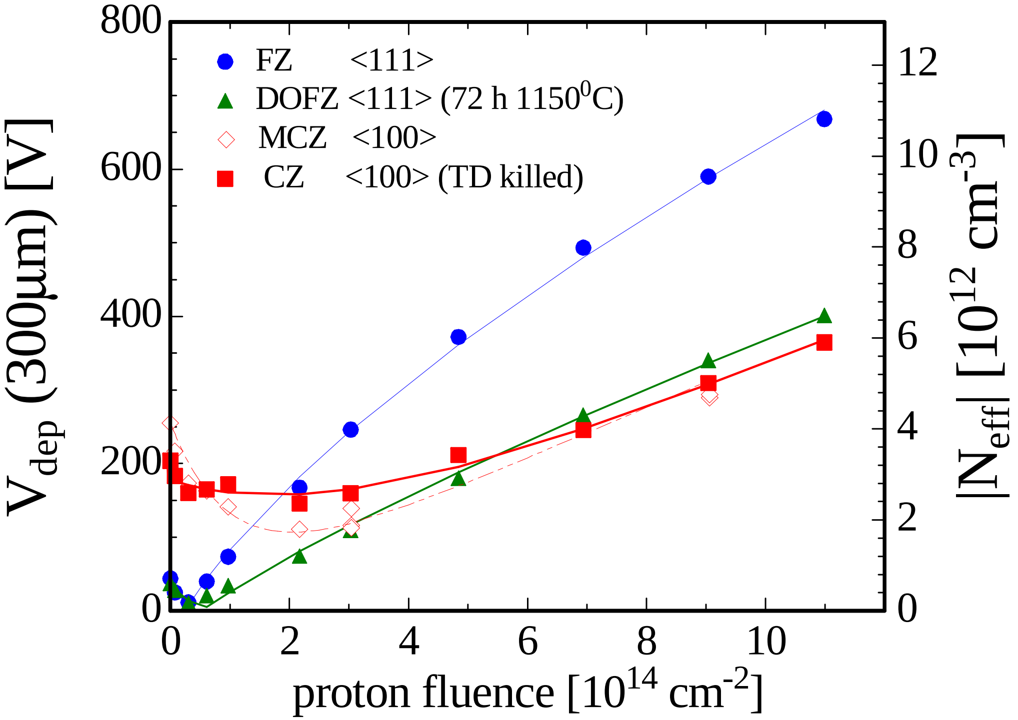
Standard FZ, DOFZ, Cz and MCz Silicon

24 GeV/c proton irradiation

- **Standard FZ silicon**
  - **type inversion at ~ 2×10^{13} p/cm^2**
  - **strong N_{eff} increase at high fluence**
- **Oxygenated FZ (DOFZ)**
  - **type inversion at ~ 2×10^{13} p/cm^2**
  - **reduced N_{eff} increase at high fluence**



- **CZ silicon and MCZ silicon**
  - **<u>no type inversion</u> in the overall fluence range (verified by TCT measurements)**
    (verified for CZ silicon by TCT measurements, preliminary result for MCZ silicon)
    ⇒ **donor generation overcompensates acceptor generation in high fluence range**

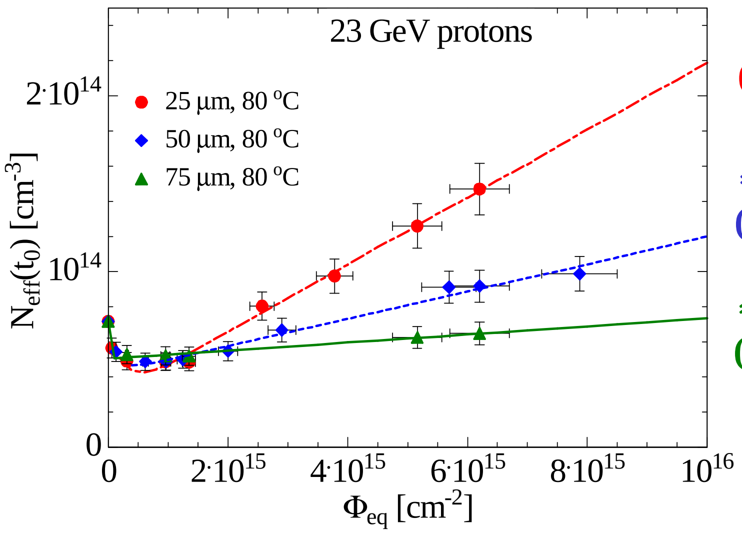
- **Common to all materials (after hadron irradiation):**
  - **reverse current increase**
  - **increase of trapping (electrons and holes) within ~ 20%**

EPI Devices – Irradiation experiments

- **Epitaxial silicon**

G.Lindström et al.,10th European Symposium on Semiconductor Detectors, 12-16 June 2005
G.Kramberger et al., Hamburg RD50 Workshop, August 2006

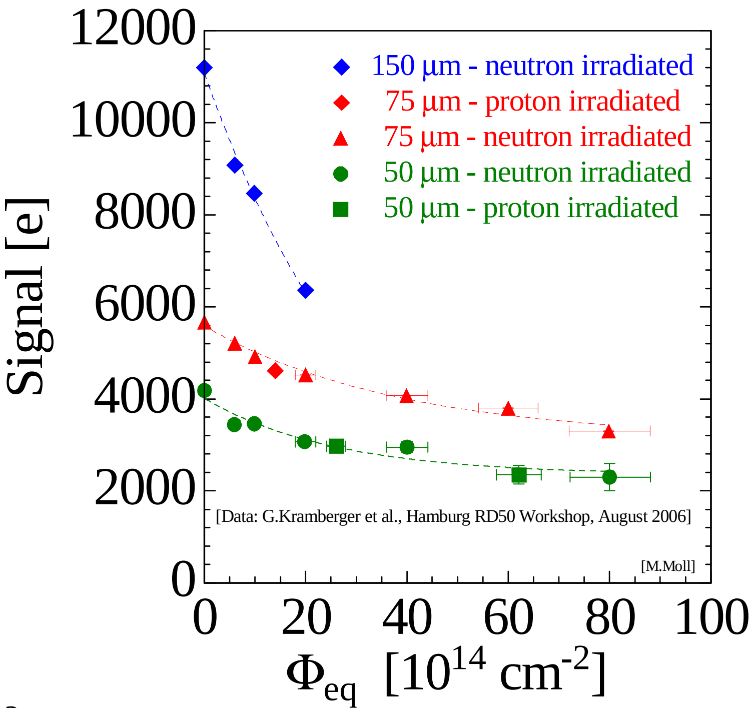
  - **Layer thickness: 25, 50, 75 µm** (resistivity: ~ 50 Ωcm); **150 µm** (resistivity: ~ 400 Ωcm)
  - **Oxygen: [O] ≈ 9×10^{16}cm^{-3}; Oxygen dimers** (detected via IO$_2$-defect formation)



≈105V (25µm)

≈230V (50µm)

≈320V (75µm)



[Data: G.Kramberger et al., Hamburg RD50 Workshop, August 2006]

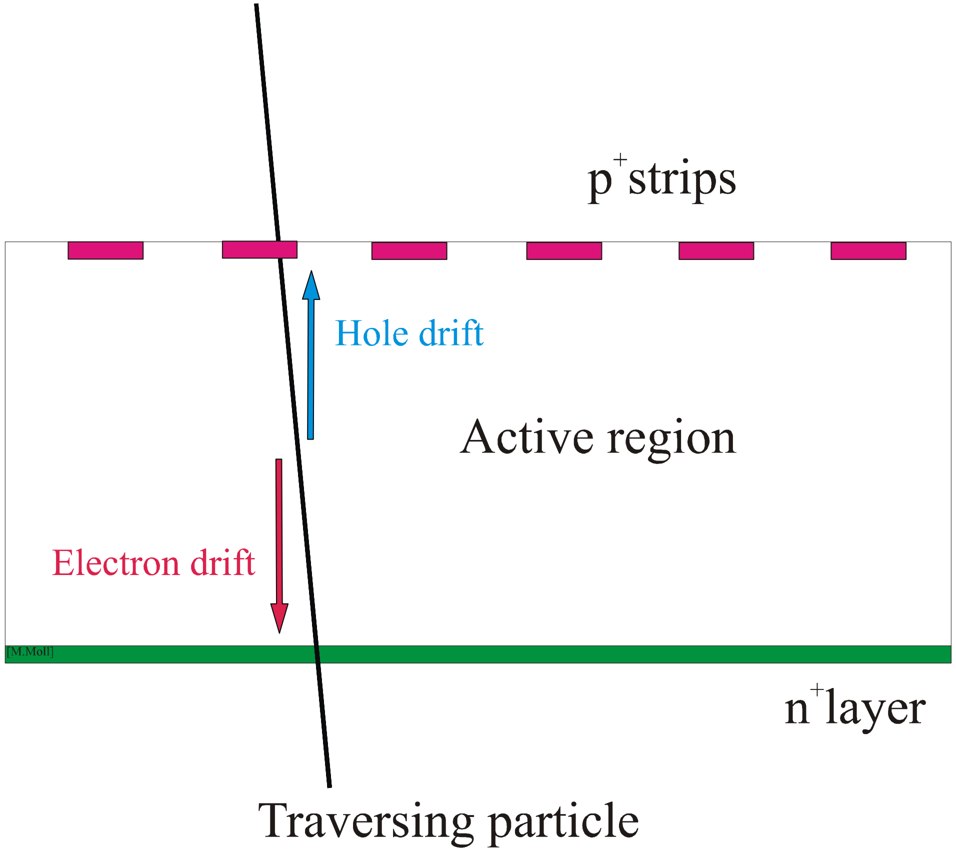
- **Only little change in depletion voltage**
- **No type inversion up to ~ 10^{16} p/cm^2 and ~ 10^{16} n/cm^2**
  ⇨**high electric field will stay at front electrode!**
  ⇨**reverse annealing will decreases depletion voltage!**
- **Explanation: introduction of shallow donors is bigger than generation of deep acceptors**

- **CCE (Sr^{90} source, 25ns shaping):**
  ⇨ **6400 e (150 µm; 2x10^{15} n/cm^{-2})**
  ⇨ **3300 e (75µm; 8x10^{15} n/cm^{-2})**
  ⇨ **2300 e (50µm; 8x10^{15} n/cm^{-2})**

Advantage of non-inverting material

p-in-n detectors (schematic figures!)

Fully depleted detector (non – irradiated):



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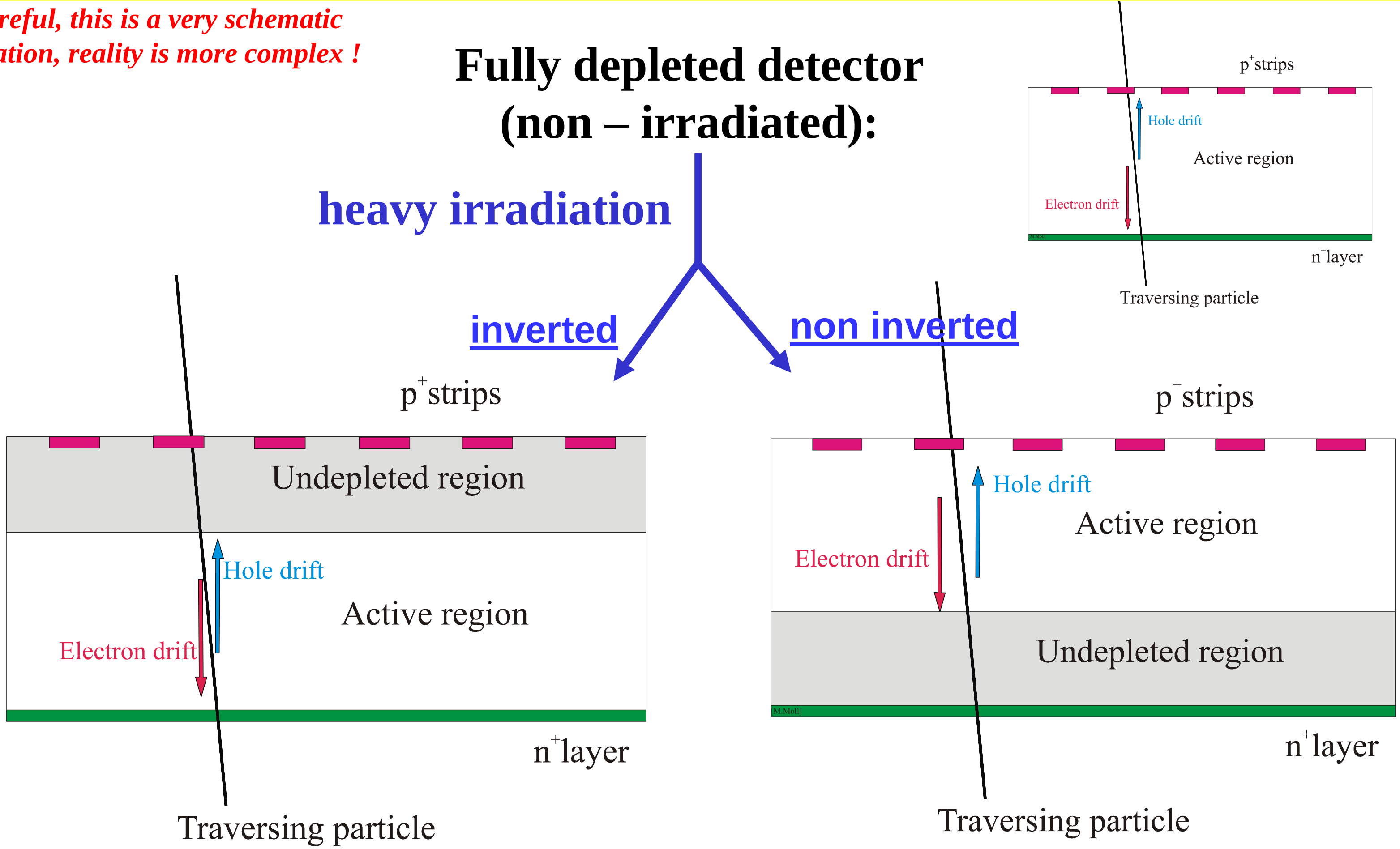
Advantage of non-inverting material

p-in-n detectors (schematic figures!)

Be careful, this is a very schematic explanation, reality is more complex !



Fully depleted detector (non – irradiated):

heavy irradiation

inverted

non inverted

inverted to "p-type", under-depleted:

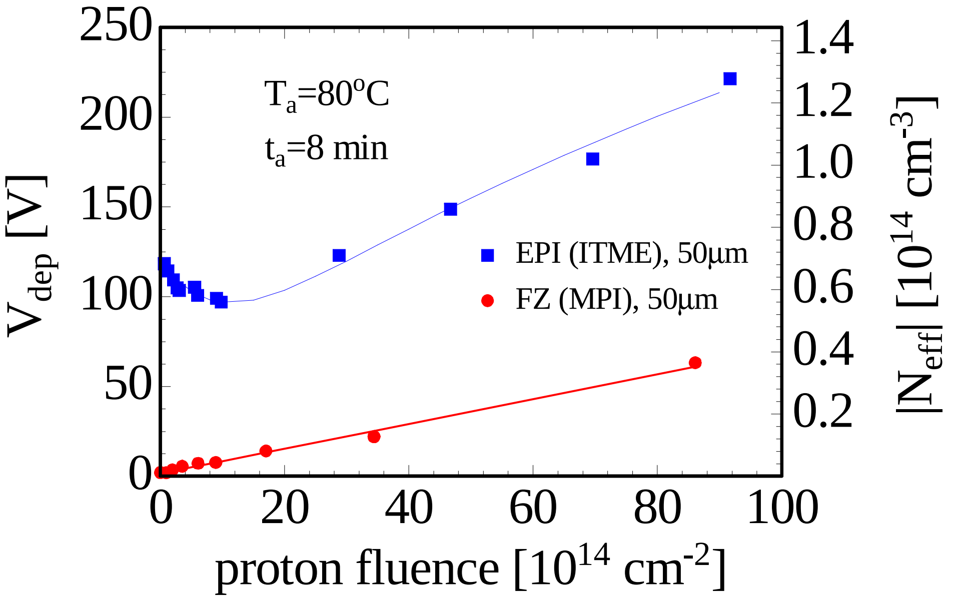
- **Charge spread – degraded resolution**
- **Charge loss – reduced CCE**

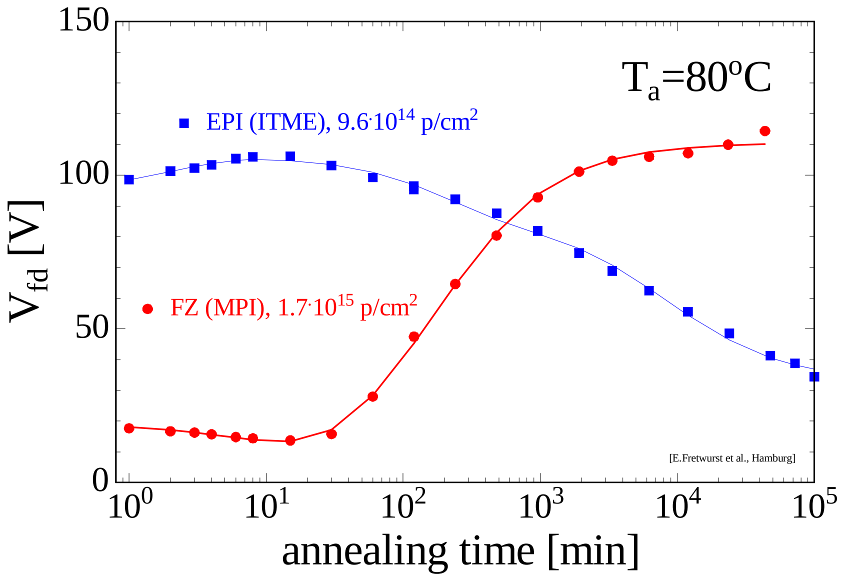
non-inverted, under-depleted:

- **Limited loss in CCE**
- **Less degradation with under-depletion**

Epitaxial silicon - Annealing

- **50 μm thick silicon detectors:**
  - Epitaxial silicon (50Ωcm on CZ substrate, ITME & CiS)
  - Thin FZ silicon (4KΩcm, MPI Munich, wafer bonding technique)





[E.Fretwurst et al.,RESMDD - October 2004]

- **Thin FZ silicon: Type inverted, increase of depletion voltage with time**
- **Epitaxial silicon: No type inversion, decrease of depletion voltage with time**

⇒ No need for low temperature during maintenance of SLHC detectors!

New Materials: Epitaxial SiC

“A material between Silicon and Diamond”

Property	Diamond	GaN	4H SiC	Si
E_g [eV]	**5.5**	**3.39**	**3.3**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4 \cdot 10^6$	$2.2 \cdot 10^6$	$3 \cdot 10^5$
μ_e [cm^2/Vs]	1800	1000	800	1450
μ_h [cm^2/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2 \cdot 10^7$	-	$2 \cdot 10^7$	$0.8 \cdot 10^7$
Z	6	31/7	14/6	14
ε_r	5.7	9.6	9.7	11.9
e-h energy [eV]	**13**	**8.9**	**7.6-8.4**	**3.6**
Density [g/cm3]	3.515	6.15	3.22	2.33
Displacem. [eV]	**43**	**≥15**	**25**	**13-20**

- **Wide bandgap (3.3eV)**

⇒ lower leakage current than silicon

- **Signal:**

Diamond	**36 e/μm**
SiC	**51 e/μm**
Si	**89 e/μm**

⇒ more charge than diamond

- **Higher displacement threshold than silicon**

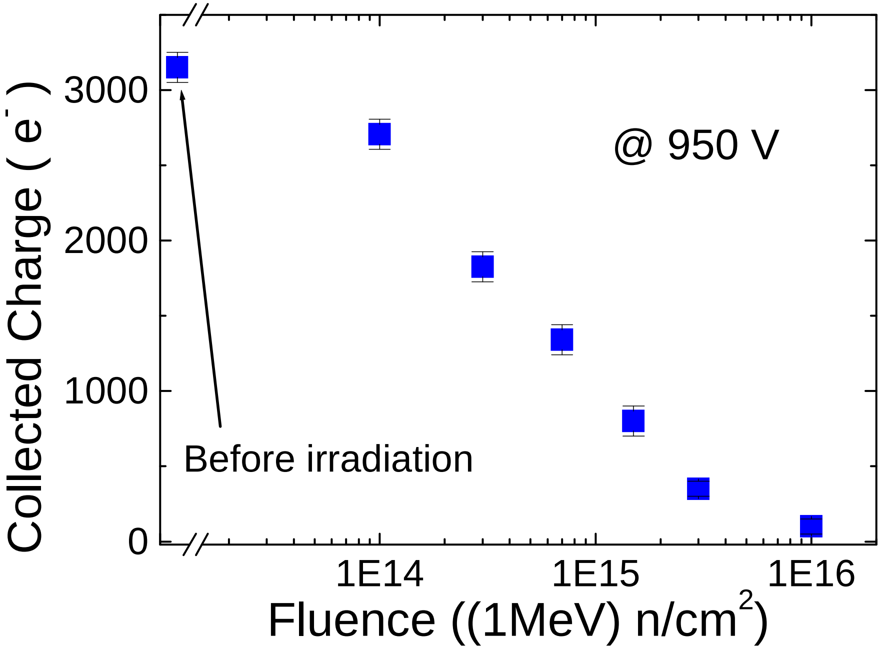
⇒ radiation harder than silicon (?)

R&D on diamond detectors:
RD42 – Collaboration
http://cern.ch/rd42/

RD50 SiC: CCE after neutron irradiation

- **CCE before irradiation**
  - **100 % with α particles and MIPS**

- **CCE after irradiation (example)**
  - **material produced by CREE**
  - **55 µm thick layer**
  - **neutron irradiated samples**
  - **tested with β particles**



[F.Moscatelli, Bologna, December 2006]

- **Conclusion:**
  - **SiC is less radiation tolerant than expected**

- **Consequence:**
  - **RD50 will stop working on this topic**

Outline

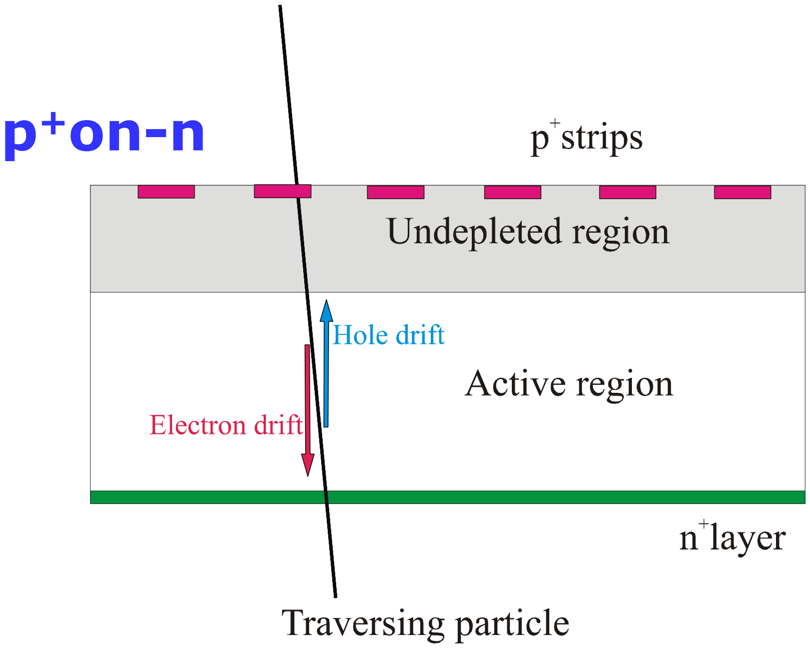
- Motivation to develop radiation harder detectors
- Introduction to the RD50 collaboration
- Part I: Radiation Damage in Silicon Detectors (A very brief review)
  - Microscopic defects (changes in bulk material)
  - Macroscopic damage (changes in detector properties)
- **Part II: RD50 - Approaches to obtain radiation hard sensors**
  - Material Engineering
  - Device Engineering
- Summary and preliminary conclusion

RD50

Device engineering

p-in-n versus n-in-p detectors

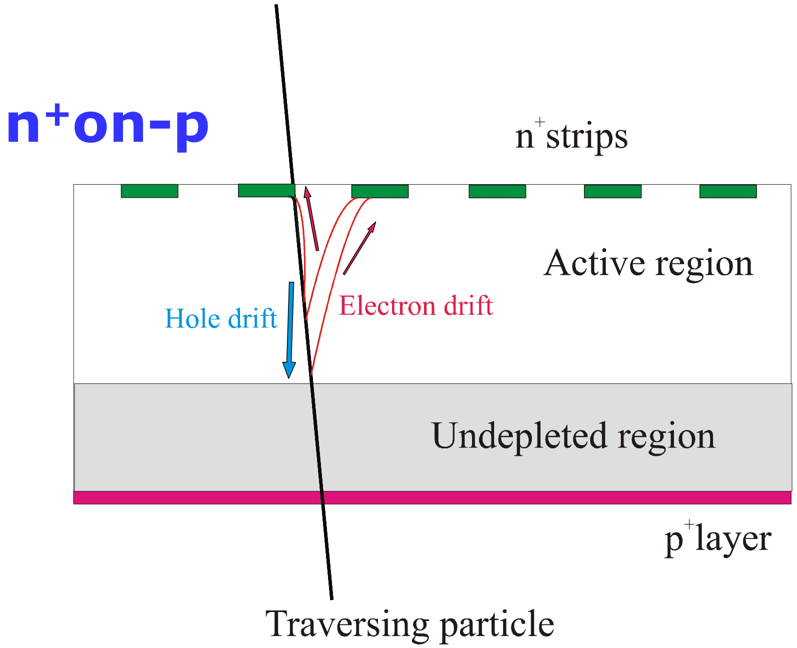
n-type silicon after high fluences:



p-on-n silicon, under-depleted:

- Charge spread – degraded resolution
- Charge loss – reduced CCE

p-type silicon after high fluences:



n-on-p silicon, under-depleted:

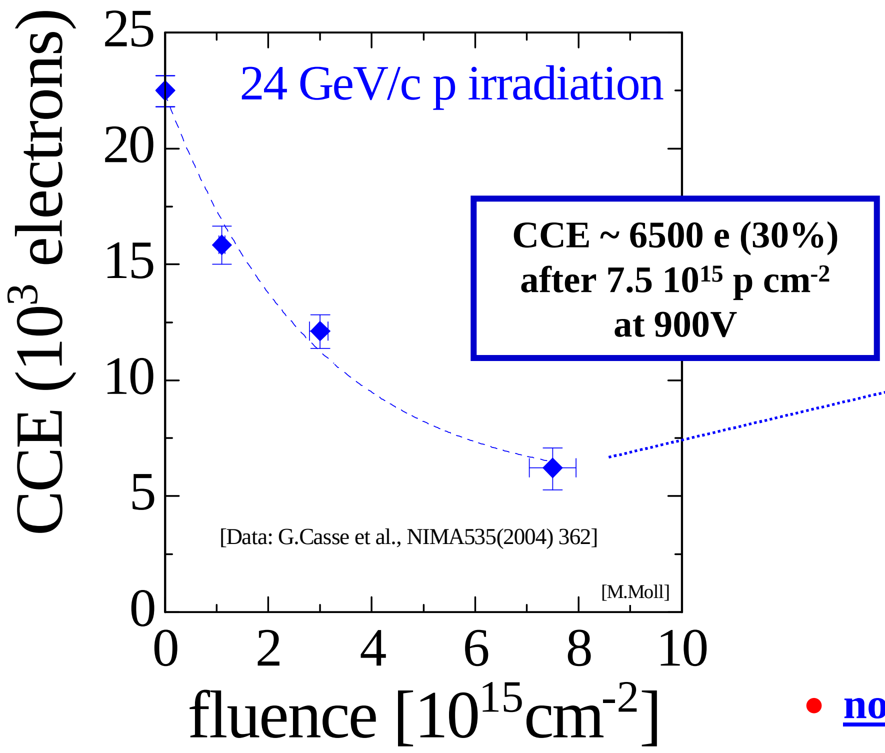
- Limited loss in CCE
- Less degradation with under-depletion
- Collect electrons (fast)

Be careful, this is a very schematic explanation, reality is more complex !

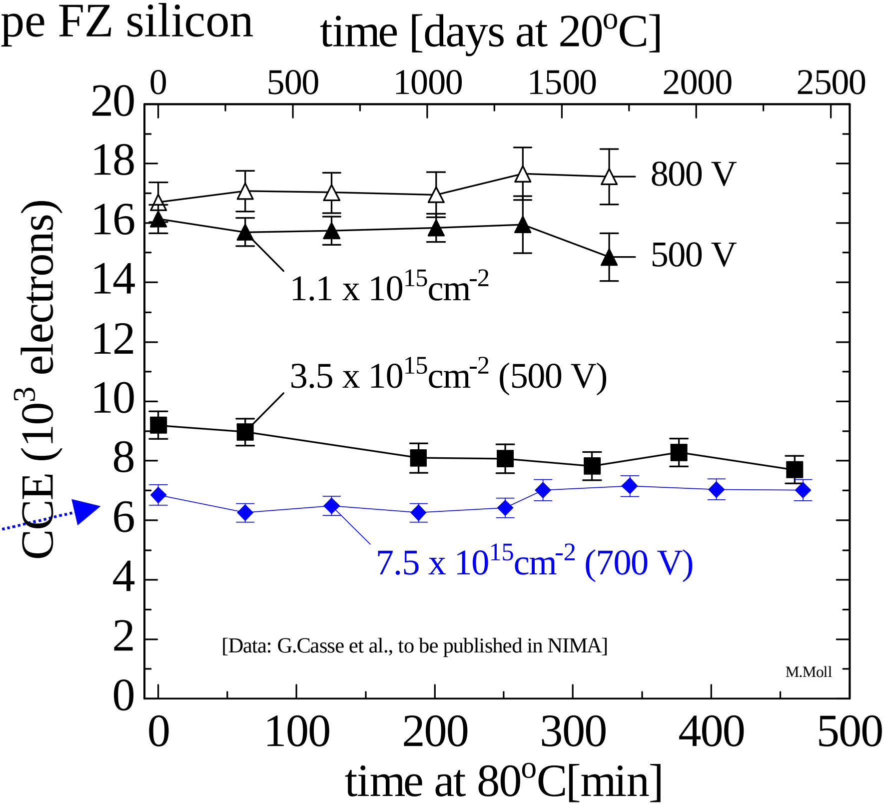
RD50 n-in-p microstrip detectors

n-in-p: - no type inversion, high electric field stays on structured side
- collection of electrons

- n-in-p microstrip detectors (280μm) on p-type FZ silicon
- Detectors read-out with 40MHz



CCE ~ 6500 e (30%)
after 7.5 10^{15} p cm^{-2}
at 900V



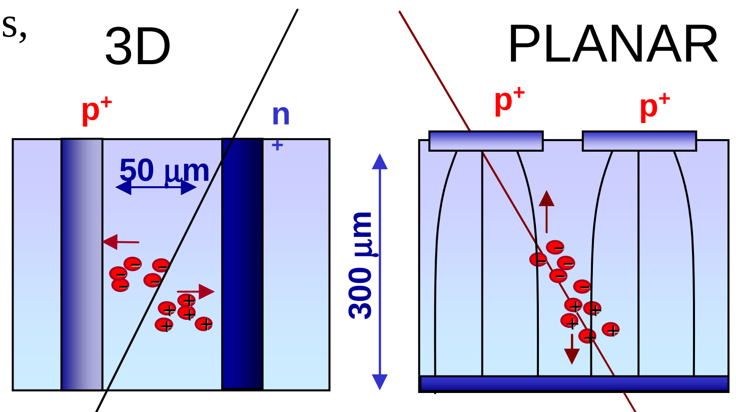
- **no reverse annealing visible in the CCE measurement !**

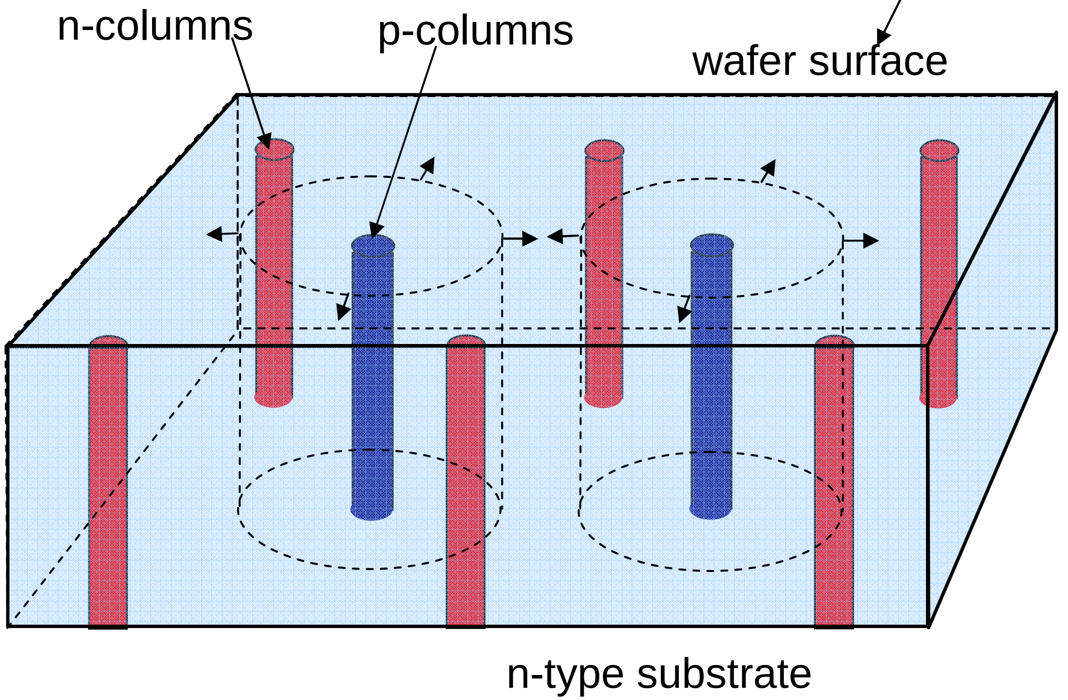
e.g. for 7.5 × 10^{15} p/cm^2 increase of V_{dep} from
V_{dep}~ 2800V to V_{dep} > 12000V is expected !

3D detector - concepts

Introduced by: S.I. Parker et al., NIMA 395 (1997) 328

- **“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





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3D detector - concepts

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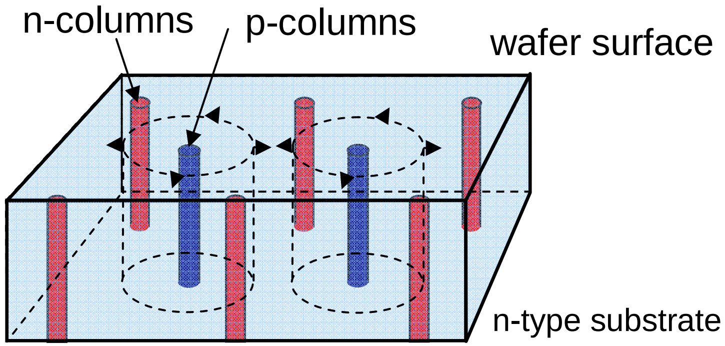
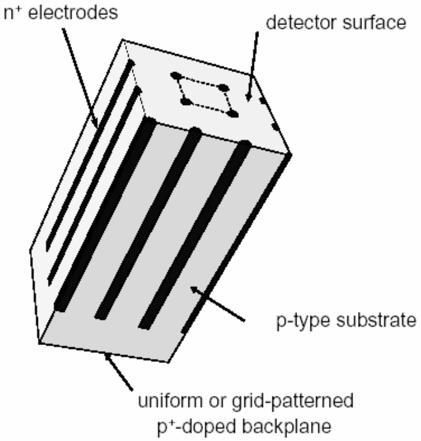


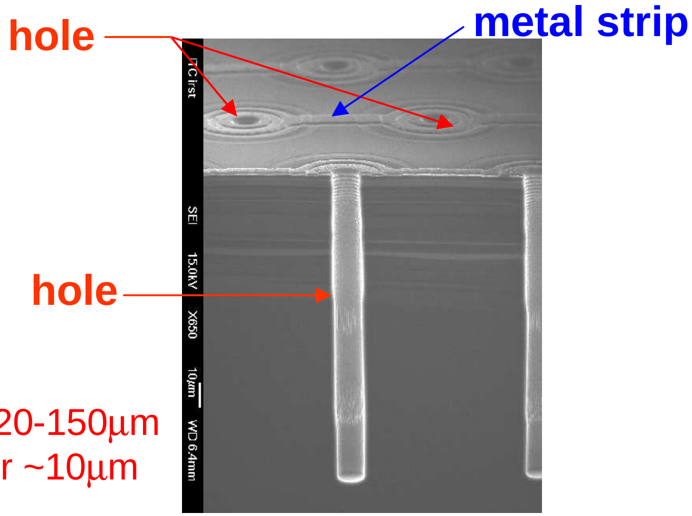
- **Simplified 3D architecture**
  - n^+ columns in p-type substrate, p^+ backplane
  - operation similar to standard 3D detector



[C. Piemonte et al.,
NIM A541 (2005) 441]

- **Simplified process**
  - hole etching and doping only done once
  - no wafer bonding technology needed

- **Simulations performed**
- **Fabrication:**
  - IRST(Italy), CNM Barcelona



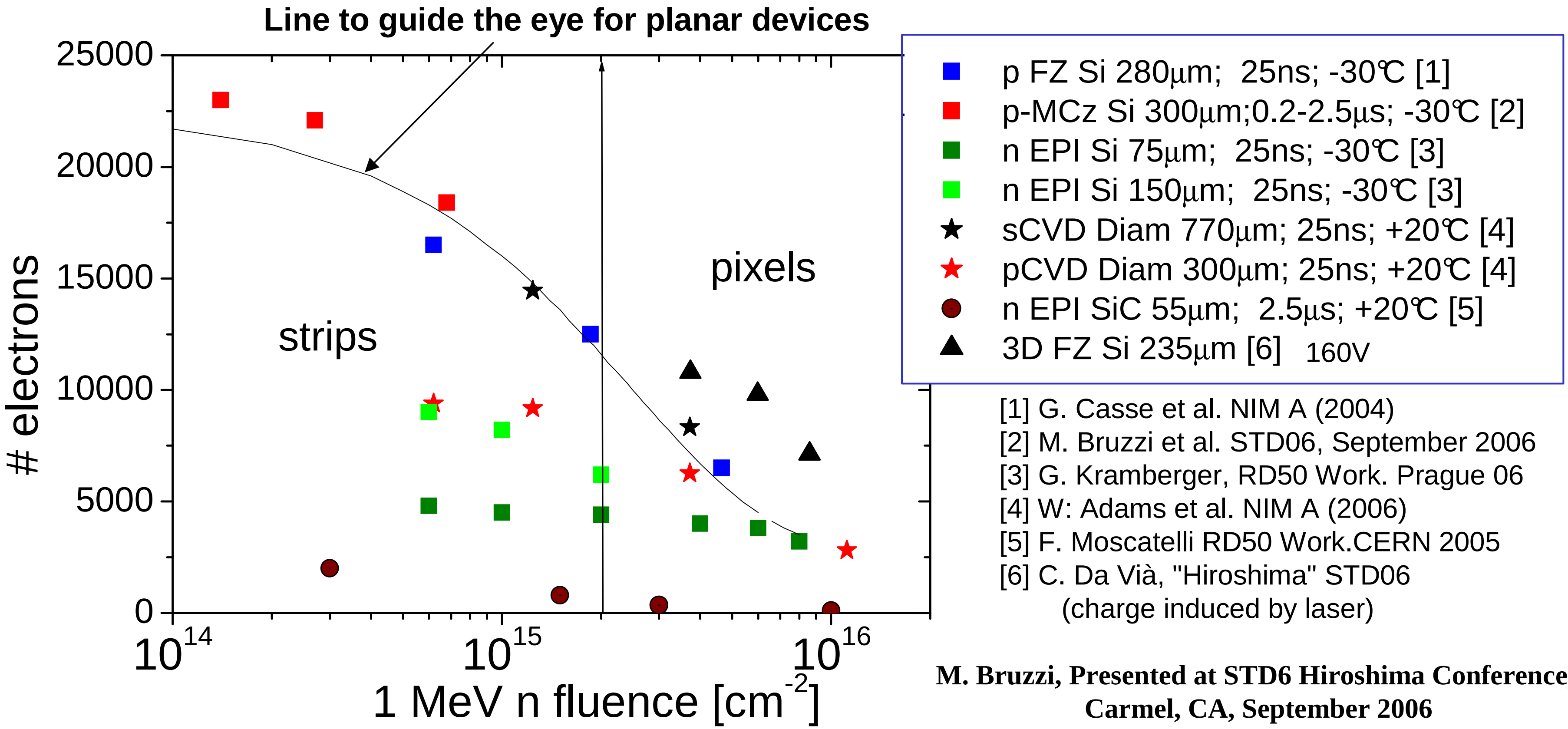
Hole depth 120-150µm
Hole diameter ~10µm

C.Piemonte et al., STD06, September 2006

- **First CCE tests under way**

RD50

Comparison of measured collected charge on different radiation-hard materials and devices



[1] G. Casse et al. NIM A (2004)
[2] M. Bruzzi et al. STD06, September 2006
[3] G. Kramberger, RD50 Work. Prague 06
[4] W: Adams et al. NIM A (2006)
[5] F. Moscatelli RD50 Work.CERN 2005
[6] C. Da Vià, "Hiroshima" STD06
(charge induced by laser)

M. Bruzzi, Presented at STD6 Hiroshima Conference, Carmel, CA, September 2006

- **Thick (300µm) p-type planar detectors can operate in partial depletion, collected charge higher than 12000e up to 2x10^{15}cm^{-2}.**
- **Most charge at highest fluences collected with 3D detectors**
- **Silicon comparable or even better than diamond in terms of collected charge (BUT: higher leakage current – cooling needed!)**

RD50 Summary – Radiation Damage

- **Radiation Damage in Silicon Detectors**
  - Change of **Depletion Voltage** (type inversion, reverse annealing, …)
    (can be influenced by defect engineering!)
  - Increase of **Leakage Current** (same for all silicon materials)
  - Increase of **Charge Trapping** (same for all silicon materials)

Signal to Noise ratio is quantity to watch (material + geometry + electronics)

- **Microscopic defects**
  - Good understanding of damage after γ-irradiation (point defects)
  - Damage after hadron damage still to be better understood (cluster defects)

- **CERN-RD50 collaboration working on:**
  - **Material Engineering** (Silicon: DOFZ, CZ, EPI, other impurities,.) (Diamond)
  - **Device Engineering (**3D and thin detectors, n-in-p, n-in-n, …)

⇒ **To obtain ultra radiation hard sensors a combination of material and device engineering approaches depending on radiation environment, application and available readout electronics will be best solution**

RD50 Summary – Detectors for SLHC

- **At fluences up to 10^{15}cm^{-2} (Outer layers of SLHC detector) the change of the depletion voltage and the large area to be covered by detectors are major problems.**

  - **CZ silicon detectors could be a cost-effective radiation hard solution**
    no type inversion (to be confirmed), use cost effective p-in-n technology
  - **oxygenated p-type silicon microstrip detectors show very encouraging results:**
    CCE ≈ 6500 e; $\Phi_{eq} = 4\times10^{15}$ cm^{-2}, 300μm

- **At the fluence of 10^{16}cm^{-2} (Innermost layers of SLHC detector) the active thickness of any silicon material is significantly reduced due to trapping.**

  The two most promising options besides regular replacement of sensors are:
  Thin/EPI detectors : drawback: radiation hard electronics for low signals needed
  (e.g. 2300e at Φ_{eq} $8\text{x}10^{15}$cm^{-2}, 50μm EPI)

  3D detectors : drawback: technology has to be optimized

- **SiC and GaN have been characterized and abandoned by RD50.**

Further information: http://cern.ch/rd50/