Joint Instrumentation Seminar
of the Particle Physics and Photon Science communities
at DESY, Hamburg University and XFEL
- 26 March 2010 -

Development of radiation tolerant silicon detectors for the Super - LHC

… with strong focus on the results of the RD50 collaboration

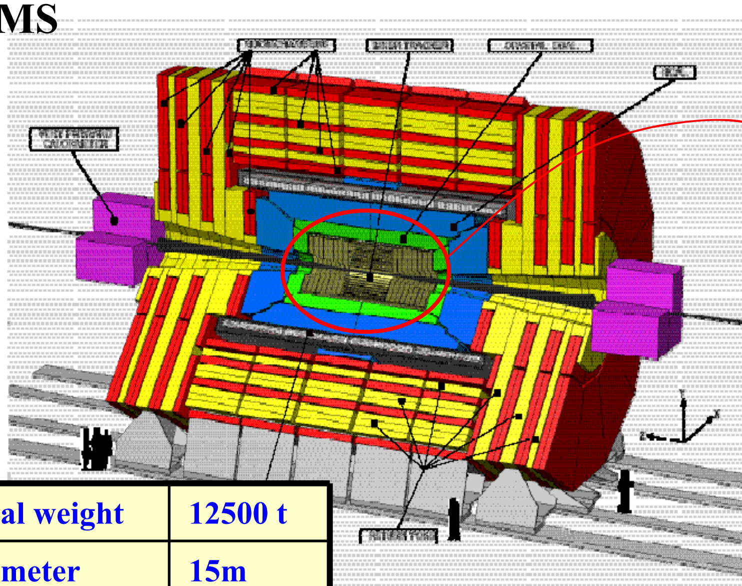
Michael Moll (CERN/PH)

Outline

- **Motivation to develop radiation harder detectors**
  - **Super-LHC and expected radiation levels at the Super-LHC**
  - **Radiation induced degradation of detector performance**
- **Radiation Damage in Silicon Detectors**
  - **Macroscopic damage (changes in detector properties)**
  - **Microscopic damage (crystal damage)**
- **Approaches to obtain radiation hard sensors**
  - **Material Engineering**
    - Silicon materials – FZ, MCZ, DOFZ, EPI
    - Other semiconductors
  - **Device Engineering**
    - p-in-n, n-in-n and n-in-p sensors
    - 3D sensors and thin devices
- **Silicon Sensors for the LHC upgrade and open questions**
  - **Collected Charge – Signal to Noise – Avalanche effects**
  - **Mixed irradiations**
- **Summary**

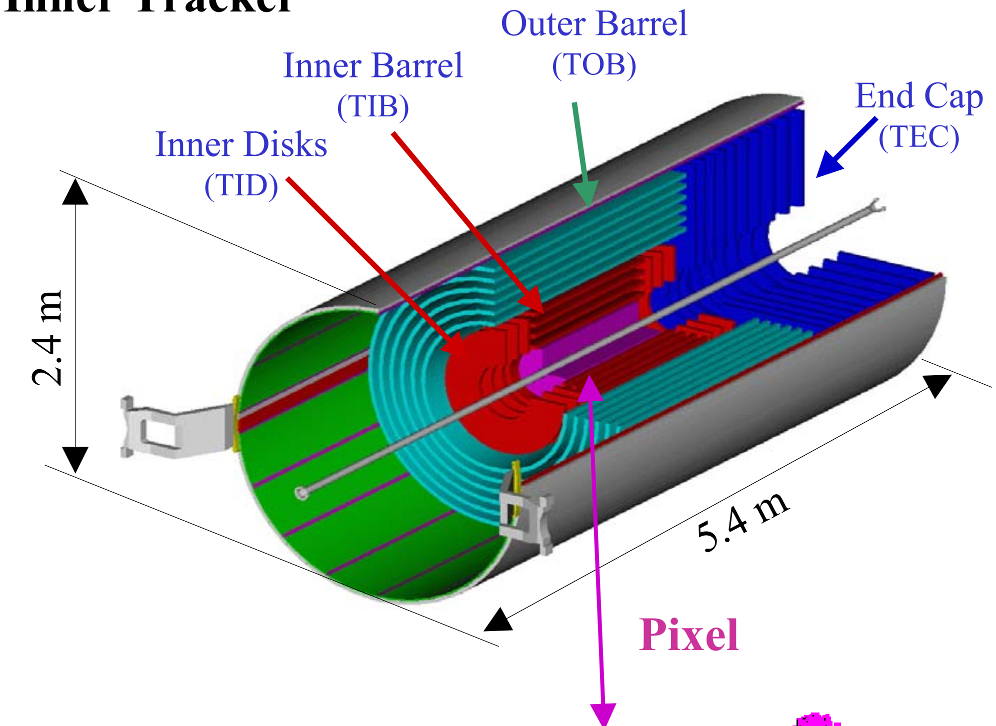
LHC example: CMS inner tracker

- **CMS**



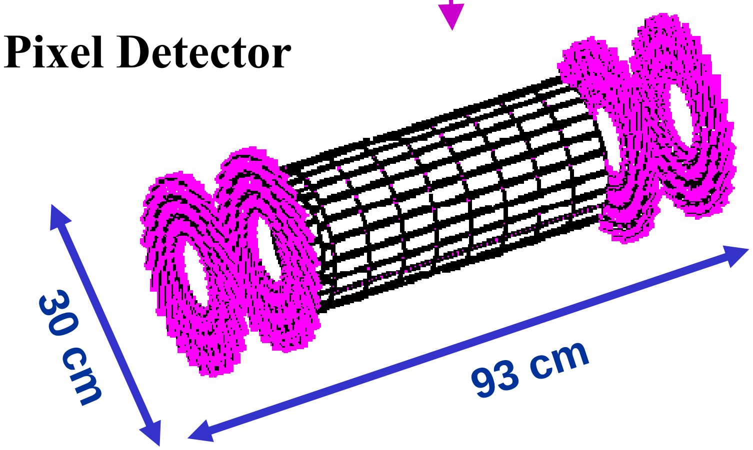
Total weight	**12500 t**
Diameter	**15m**
Length	**21.6m**
Magnetic field	**4 T**

- **Inner Tracker**



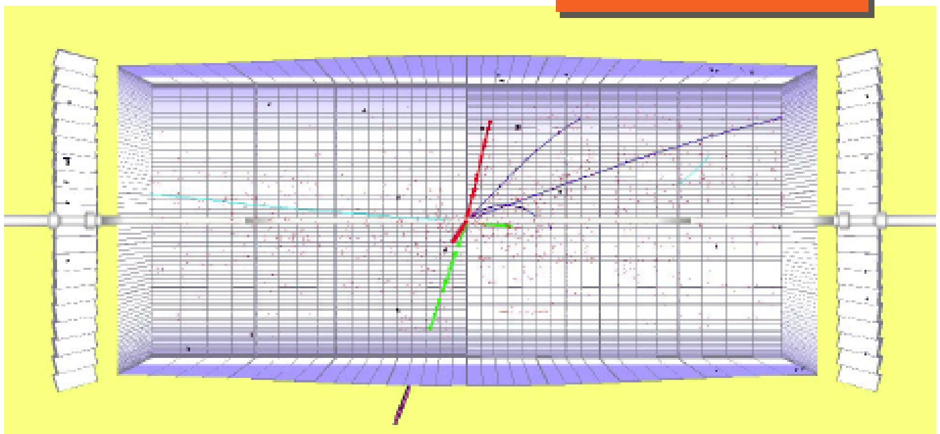
- **CMS – "Currently the Most Silicon"**
  - **Micro Strip:**
  - **~ 214 m² of silicon strip sensors, 11.4 million strips**
  - **Pixel:**
  - **Inner 3 layers: silicon pixels (~ 1m²)**
  - **66 million pixels (100x150µm)**
  - **Precision: σ(rφ) ~ σ(z) ~ 15µm**
  - **Most challenging operating environments (LHC)**

- **Pixel Detector**

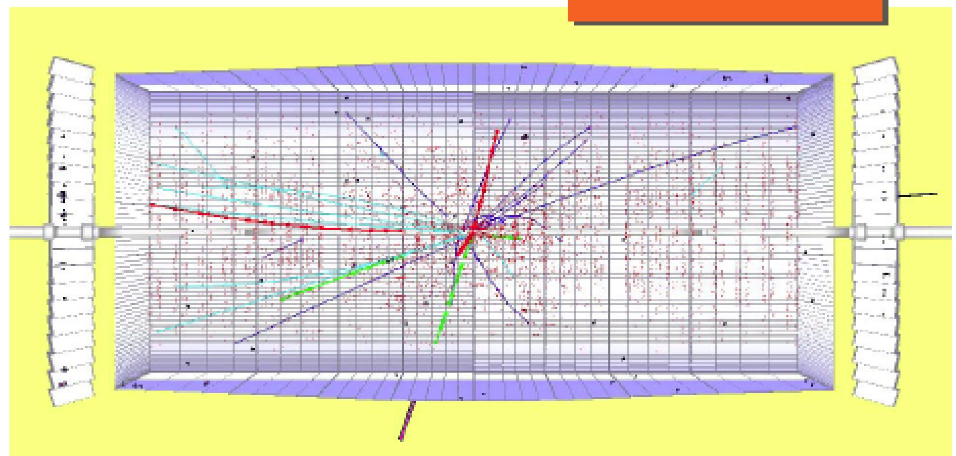


The challenge: Super LHC - visually

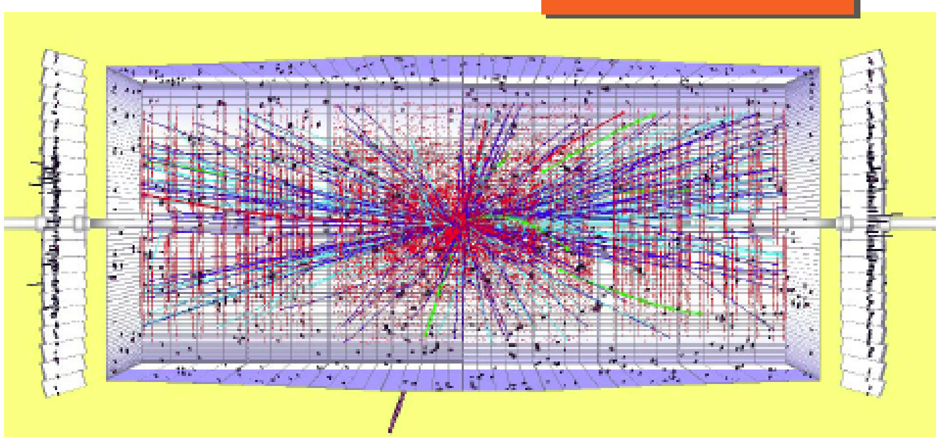
$10^{32}\ cm^{-2}\ s^{-1}$



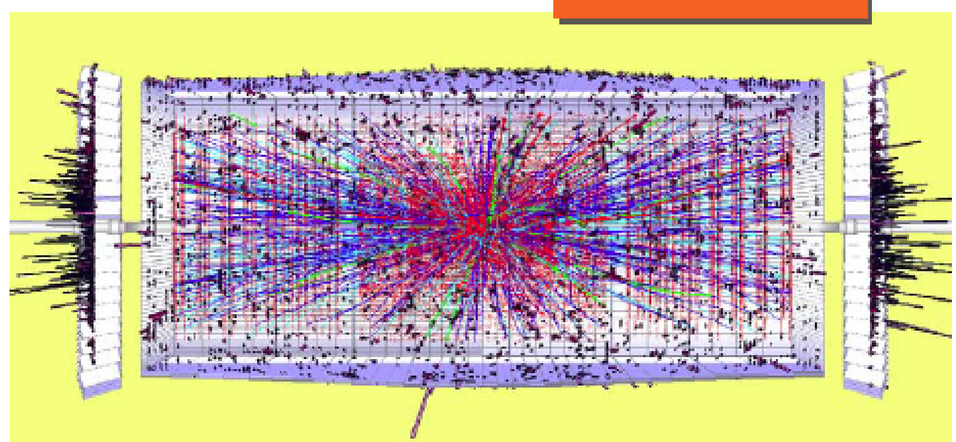
$10^{33}\ cm^{-2}\ s^{-1}$



$10^{34}\ cm^{-2}\ s^{-1}$



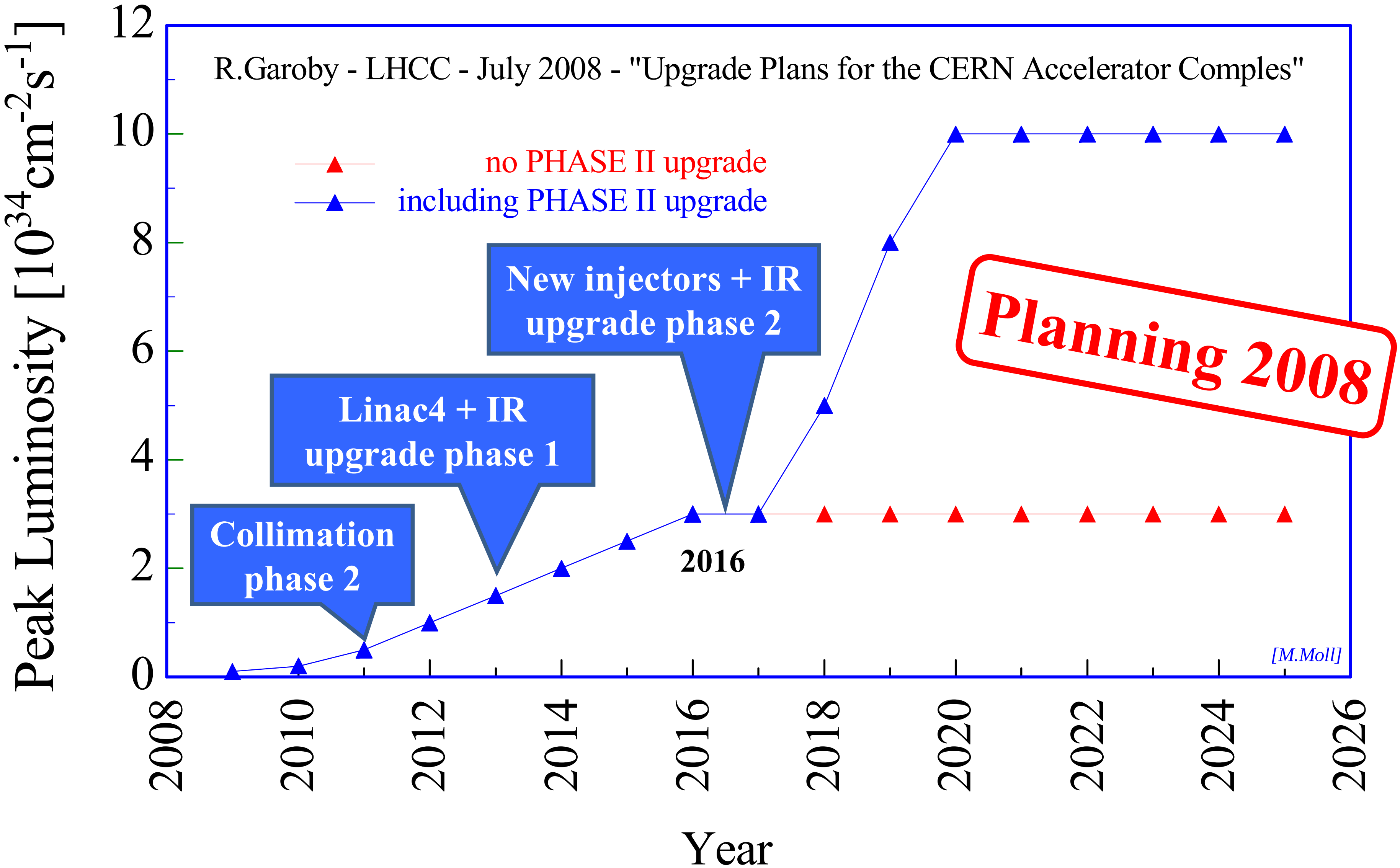
? $10^{35}\ cm^{-2}\ s^{-1}$



LHC nominal luminosity

SLHC luminosity ~300-400 interactions/bx

Future Plans: Towards sLHC



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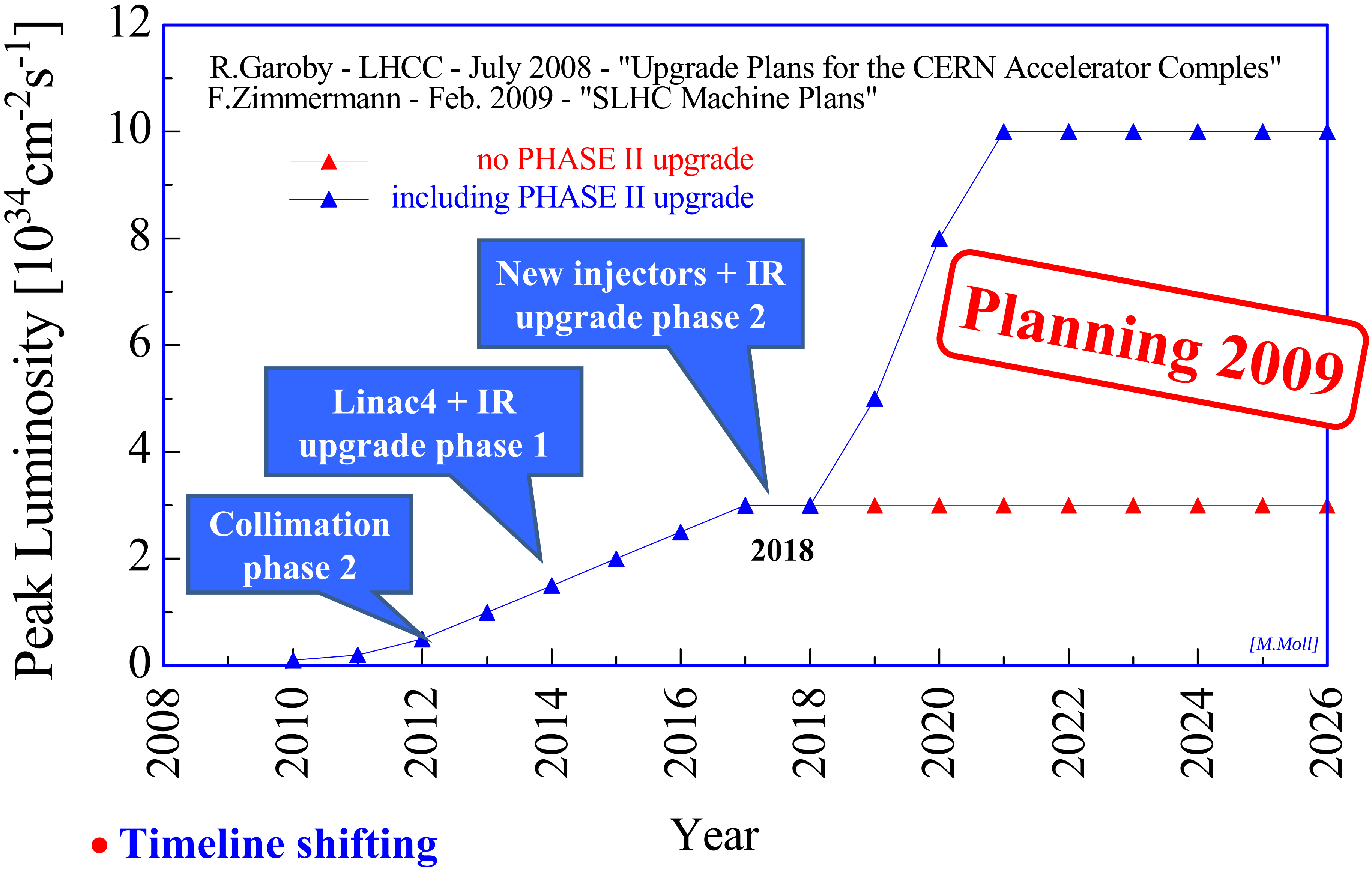
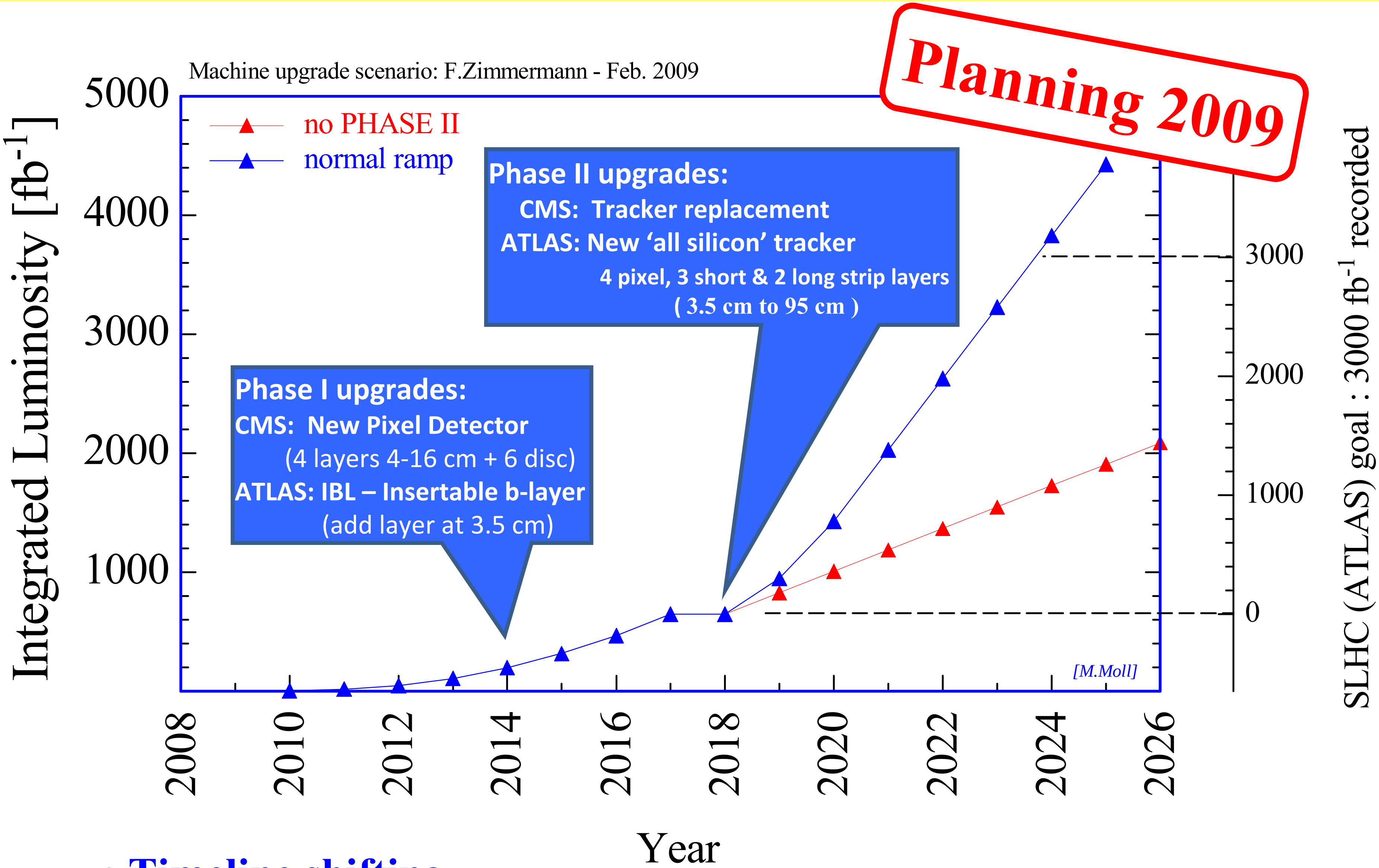


- **Timeline shifting**

Future Plans: Towards sLHC



- **Timeline shifting**

Future Plans: Towards sLHC

2009 — **Start of LHC**

Ramp up luminosity to few 10^{32} $cm^{-2}s^{-1}$
Energy of 3.5 TeV per beam (50%)
•19. March 2010 – Beams accelerated to 3.5 TeV
•30. March 2010 – First collisions at 2 x 3.5 TeV … run for 2 years

Planning 2010
(very uncertain at the moment)

new timeline in June 2010 ?

2012 — **Modify splices … go to 7 TeV**

Run at 7 TeV per beam and ramp up luminosity to ~30% nominal

2016 — **New Linac 4 injector and full collimation scheme**
Small upgrades to ATLAS and CMS

New Pixel

Ramp up luminosity even slightly beyond nominal

~2020 — **sLHC: New LHC focusing magnets, CRAB cavities, …**
Major Upgrades of ATLAS and CMS

New Tracker

Collect data until > 3000 fb^{-1}

Use this value for further discussions

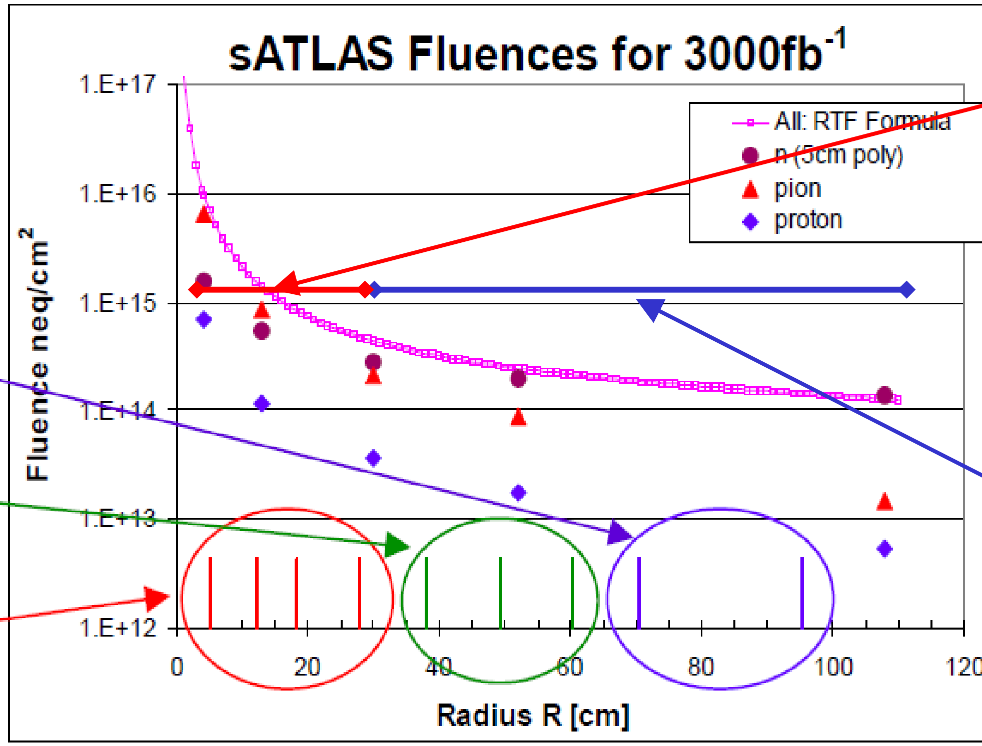
Radiation levels after 3000 fb^{-1}

Radial distribution of sensors determined by Occupancy

Long Strips (up to $4x10^{14}cm^{-2}$)

Short Strips (up to $10^{15}cm^{-2}$)

Pixels (up to 10^{16} cm^{-2})



ATLAS Radiation Taskforce [ATL-GEN-2005-01] & H.Sadrozinski [IEEE NSS 2007]

Dominated by pion damage

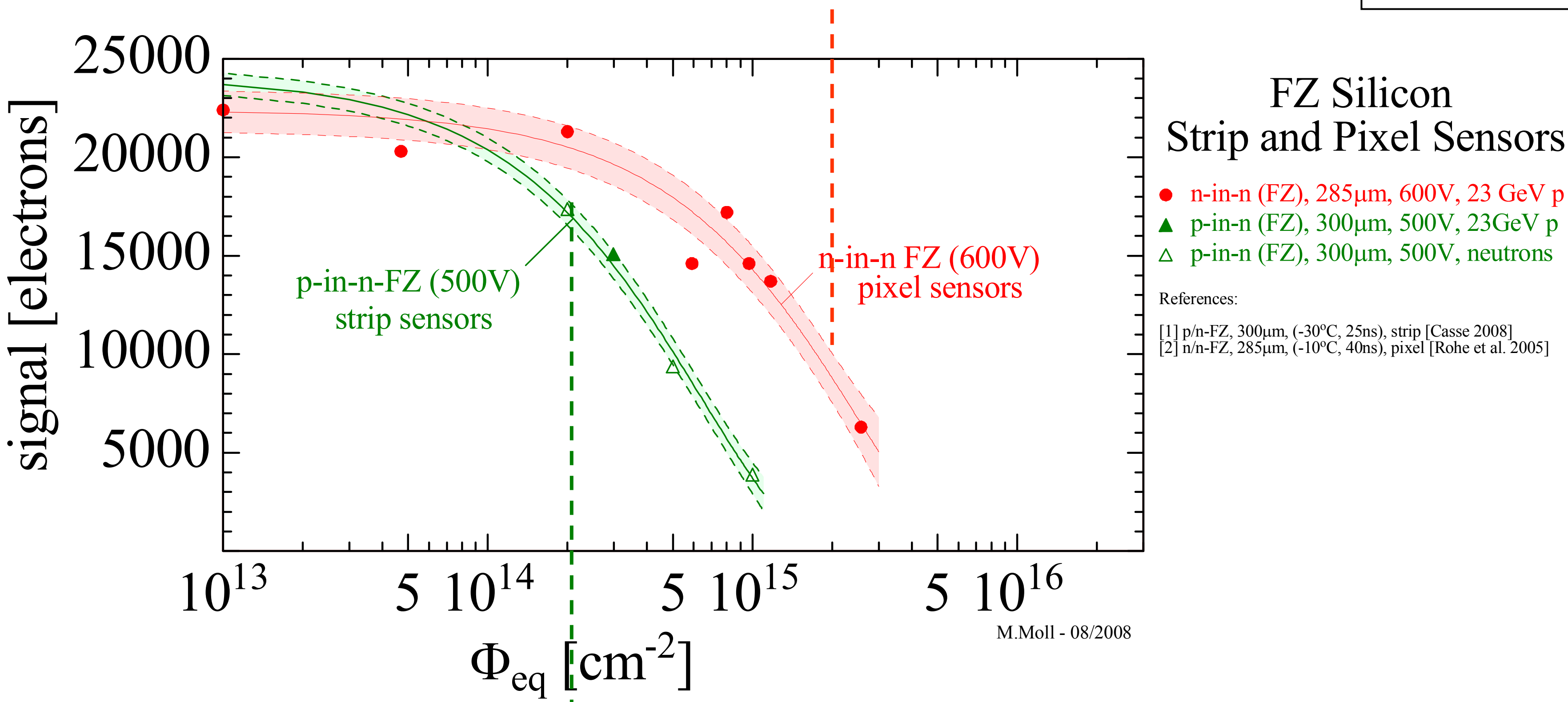
Dominated by neutron damage

- **Radiation hardness requirements (including safety factor of 2)**
  - 2×10^{16} n_{eq}/cm^2 for the innermost pixel layers
  - 7×10^{14} n_{eq}/cm^2 for the innermost strip layers

B-layer (R=3.7 cm):	2.5×10^{16} n_{eq}/cm^2 = 1140 Mrad
2nd Inner Pixel Layer (R=7 cm):	7.8×10^{15} n_{eq}/cm^2 = 420 Mrad
1st Outer Pixel Layer (R=11 cm):	3.6×10^{15} n_{eq}/cm^2 = 207 Mrad
Short strips (R=38 cm):	6.8×10^{14} n_{eq}/cm^2 = 30 Mrad
Long strips (R=85 cm):	3.2×10^{14} n_{eq}/cm^2 = 8.4 Mrad

Signal degradation for LHC Silicon Sensors

Pixel sensors:
max. cumulated fluence for LHC



Note: Measured partly under different conditions! Lines to guide the eye (no modeling)!

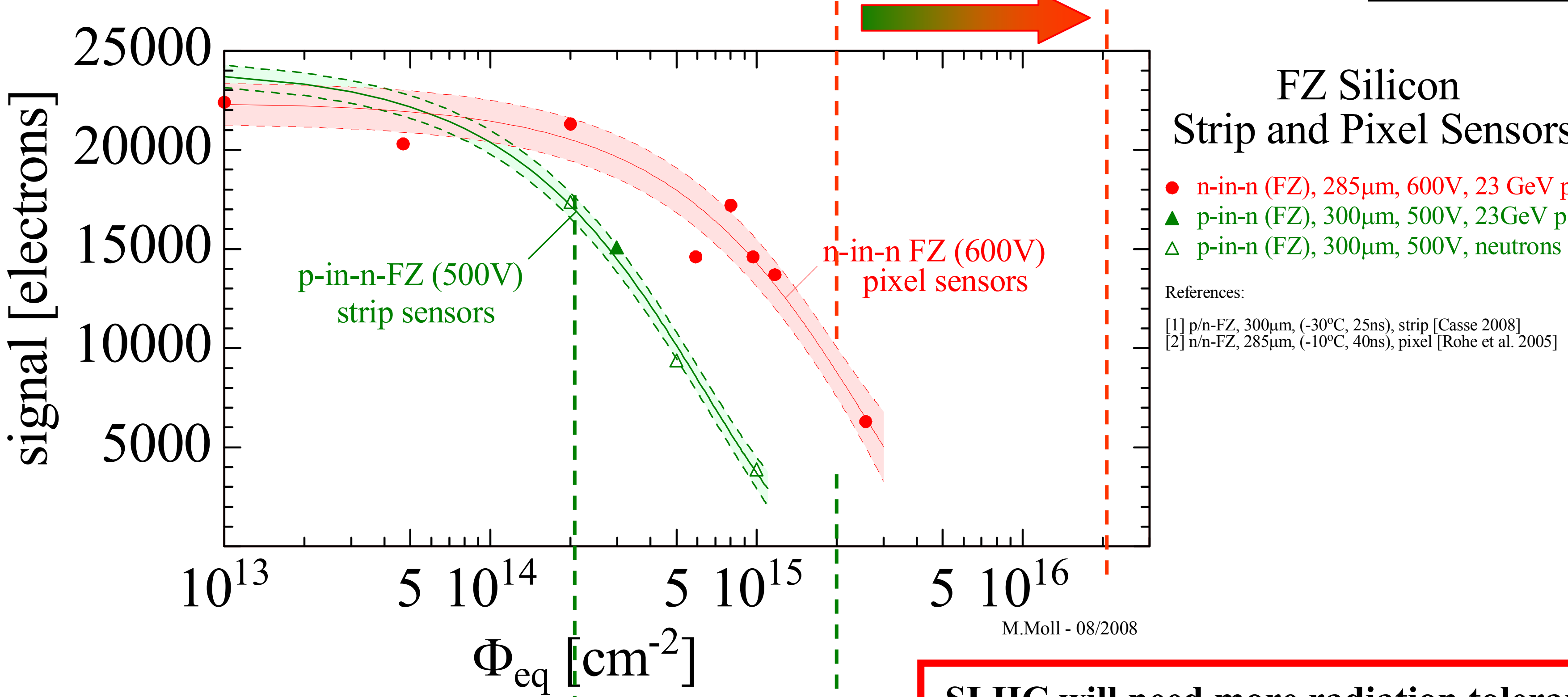
Situation in 2005

Strip sensors:
max. cumulated fluence for LHC

Signal degradation for LHC Silicon Sensors

Note: Measured partly under different conditions! Lines to guide the eye (no modeling)!

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!

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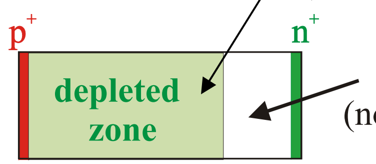
Reminder: Reverse biased abrupt p⁺-n junction

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)

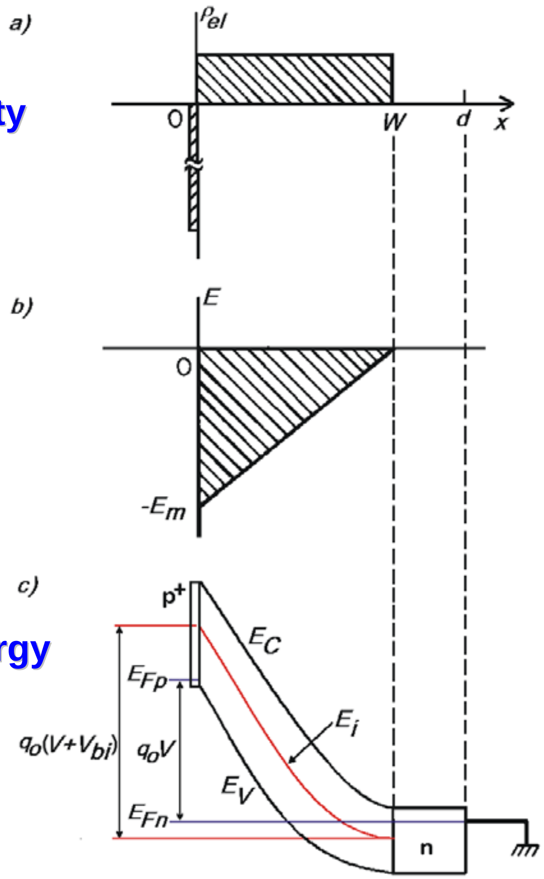


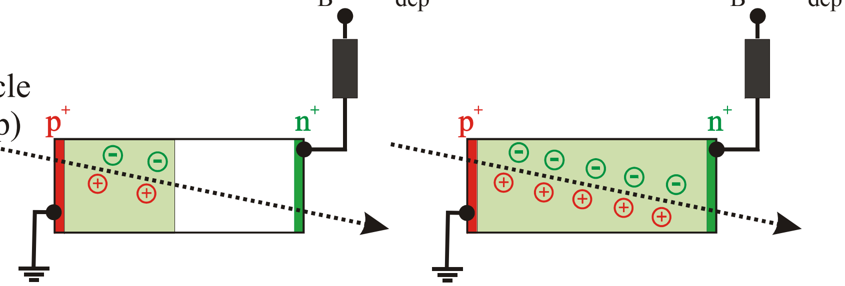
neutral bulk
(no electric field)

Electrical charge density

Electrical field strength

Electron potential energy





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

depletion voltage

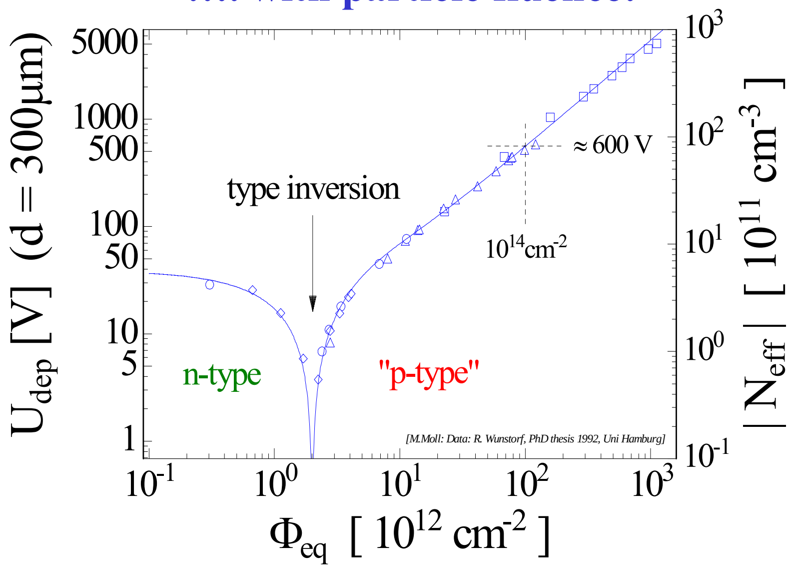
$$V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0}\cdot\left|N_{eff}\right|\cdot d^2$$

effective space charge density

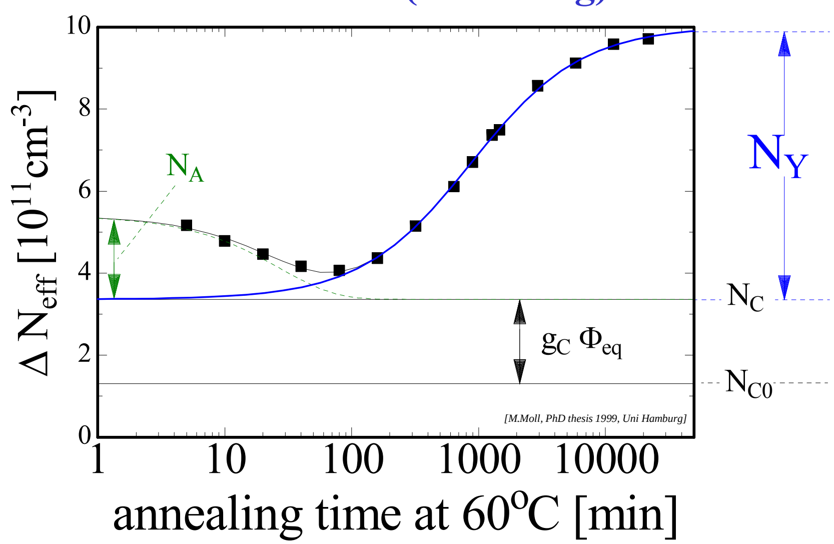
Macroscopic Effects – I. Depletion Voltage

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

…. with particle fluence:

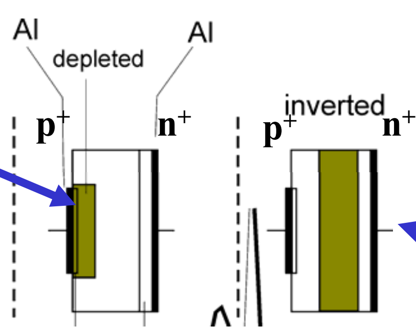


…. with time (annealing):



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

before inversion



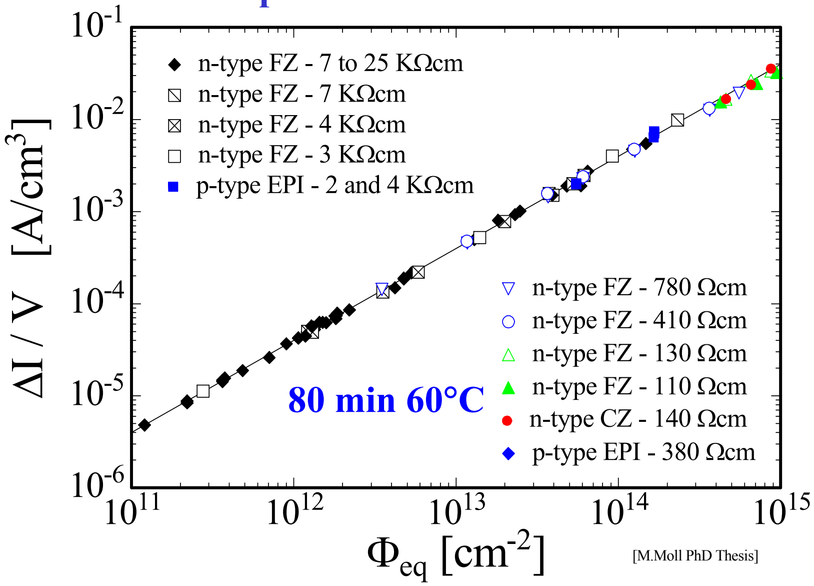
after inversion

- 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!**

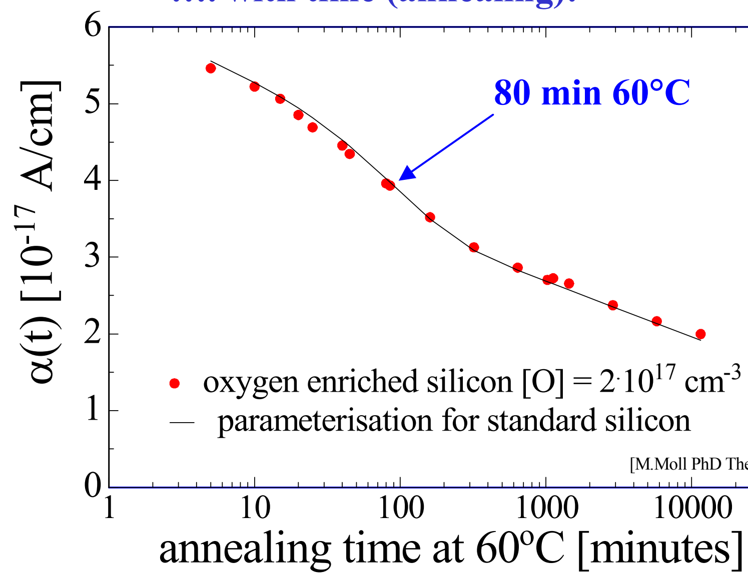
Radiation Damage – II. Leakage Current

- **Change of Leakage Current (after hadron irradiation)**

…. with particle fluence:



…. with time (annealing):



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

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

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)

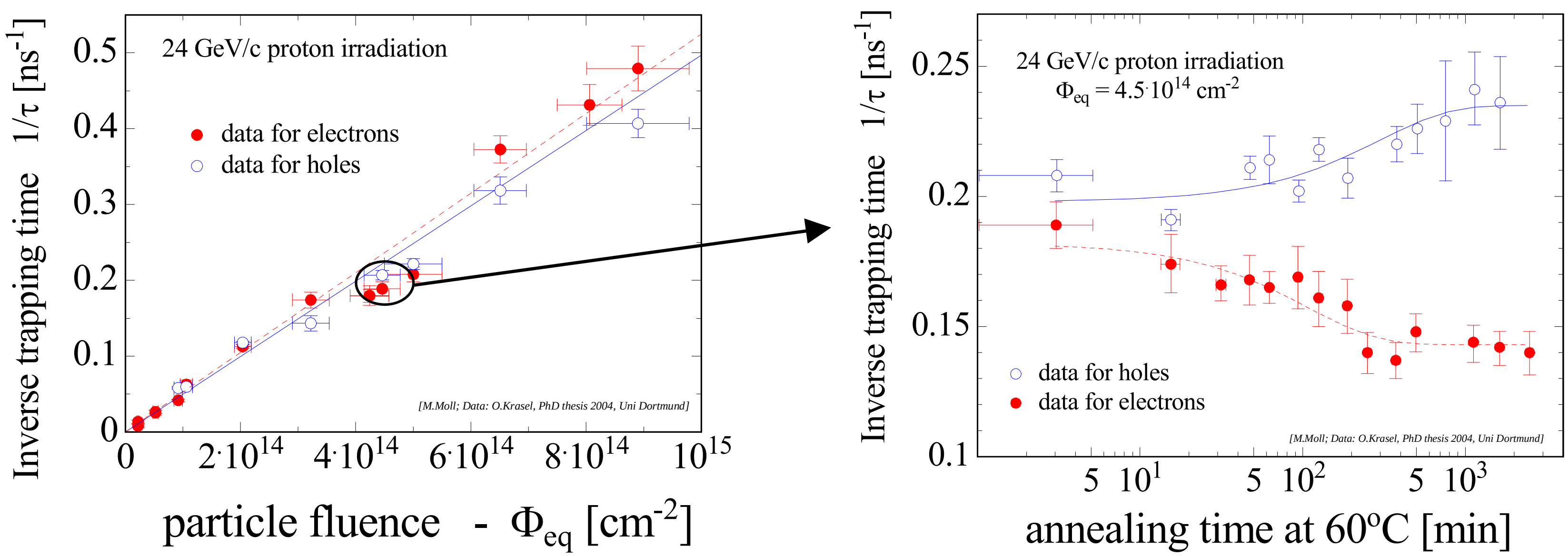
Radiation Damage – III. CCE (Trapping)

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

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

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

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



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! (I.)

  Same for all tested Silicon materials! (II., III.)

  - **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! (geometry, readout electronics)

Signal/noise ratio is the quantity to watch

⇒ Sensors can fail from radiation damage !

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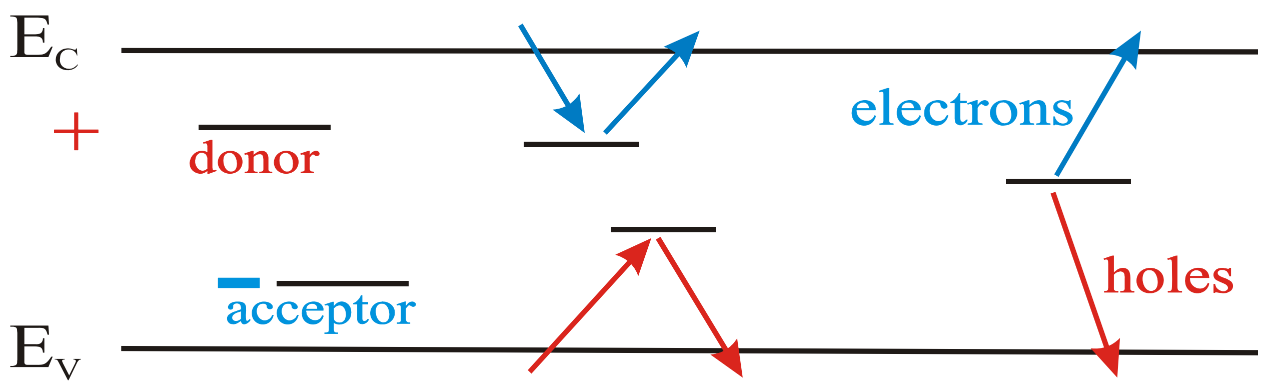
Impact of Defects on Detector Properties

Shockley-Read-Hall statistics



charged defects	Trapping (e and h)	generation
⇒ N_{eff} , V_{dep}	**⇒ CCE**	**⇒ leakage current**
e.g. donors in upper and acceptors in lower half of band gap	shallow defects do not contribute at room temperature due to fast detrapping	Levels close to midgap most effective

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

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

Defect Characterization - Methods

Methods used by RD50 Collaboration

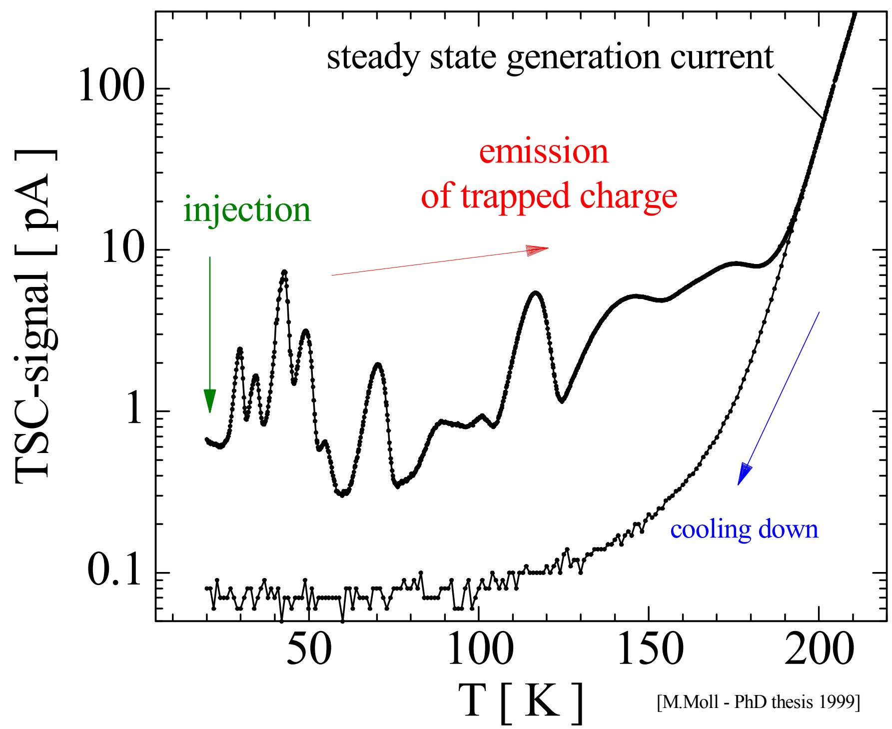
RD50-WODEAN project
guided by G.Lindstroem (HH):

- **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)**
- **PL (Photo Luminescence)**
- **EPR (Electron Paramagnetic Resonance)**
- **TCT (Transient Charge Technique)**
- **CV/IV (Capacitance Voltage and Current Voltage Characteristics)**

Further interesting methods:

- **Positron Annihilation, TEM, TSCAP, ...**

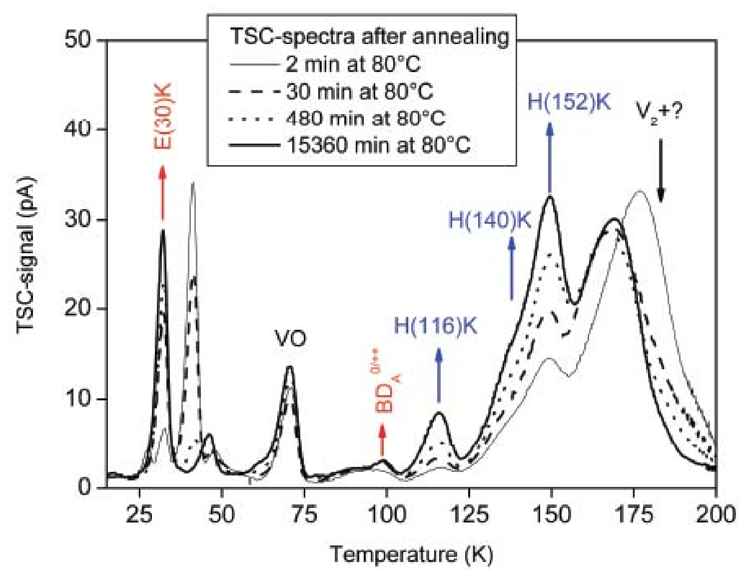
TSC (Thermally Stimulated Currents)



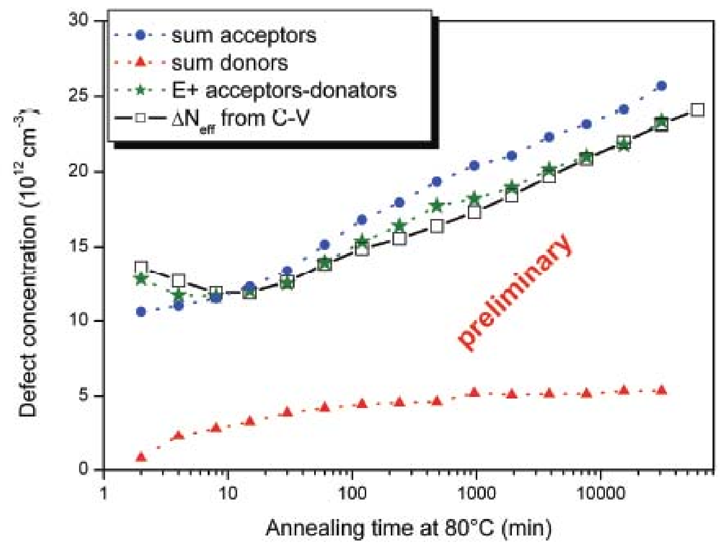
Correlation: Microscopic and Macroscopic data

- **TSC and CV measurements (Isothermal annealing after 2x10^{14} n/cm^2)**

TSC-results (EPI-ST)



comparison to ΔN_{eff}



- short term annealing well described
- microscopic results predict macroscopic findings!

[Alexandra Junkes, Hamburg University, RD50 Workshop June 2009]

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

Point defects

- $E_i^{BD} = E_c - 0.225$ eV
- $\sigma_n^{BD} = 2.3 \cdot 10^{-14}$ cm²

- $E_i^{I} = E_c - 0.545$ eV
  - $\sigma_n^{I} = 2.3 \cdot 10^{-14}$ cm²
  - $\sigma p^{I} = 2.3 \cdot 10^{-14}$ cm²

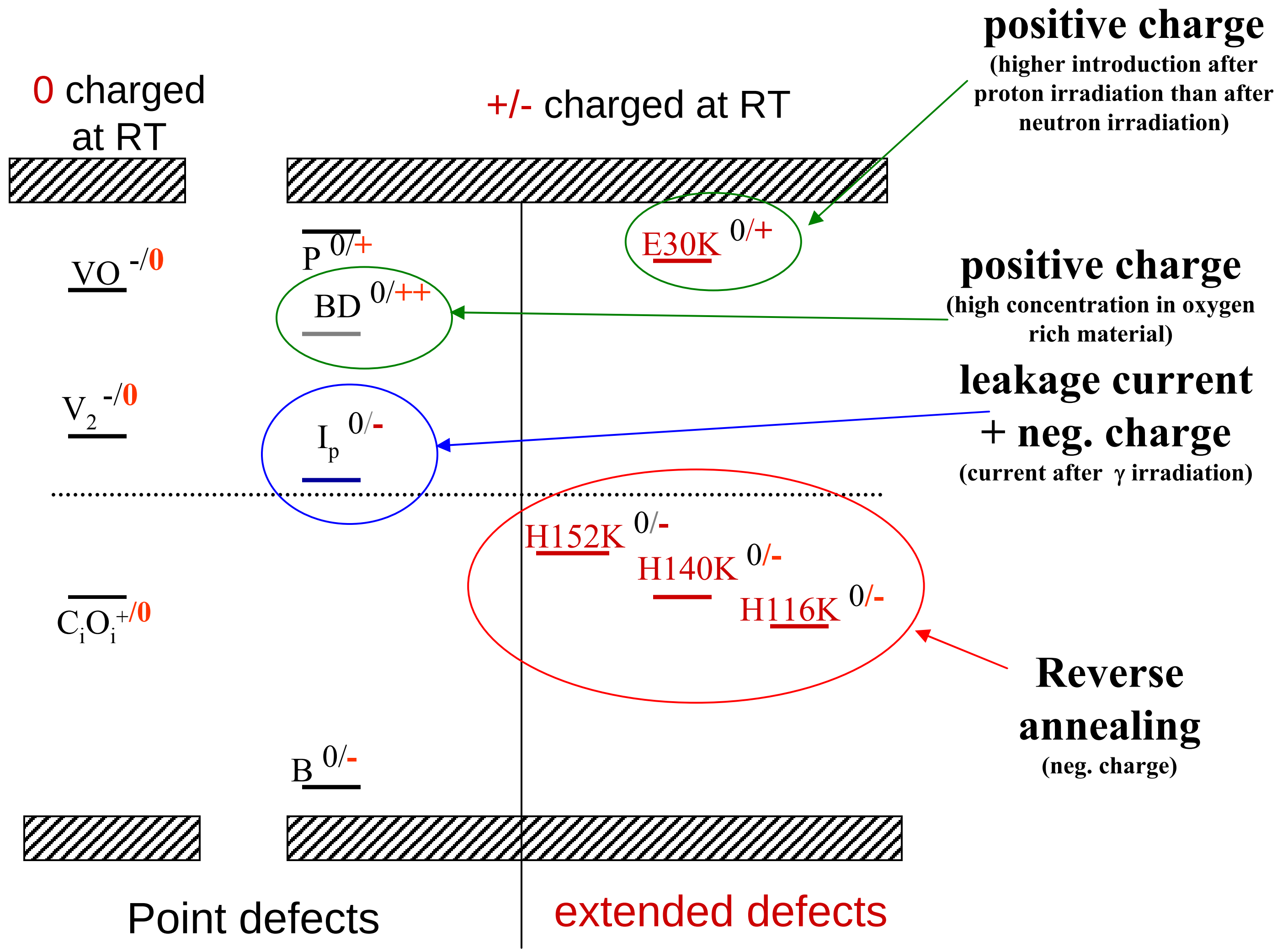
Cluster related centers

- $E_i^{116K} = E_v + 0.33$eV
- $\sigma_p^{116K} = 4 \cdot 10^{-14}$ cm²

- $E_i^{140K} = E_v + 0.36$eV
- $\sigma_p^{140K} = 2.5 \cdot 10^{-15}$ cm²

- $E_i^{152K} = E_v + 0.42$eV
- $\sigma_p^{152K} = 2.3 \cdot 10^{-14}$ cm²

- $E_i^{30K} = E_c - 0.1$eV
- $\sigma_n^{30K} = 2.3 \cdot 10^{-14}$ cm²



[I.Pintilie et al., Appl. Phys. Lett.92 024101,2008]

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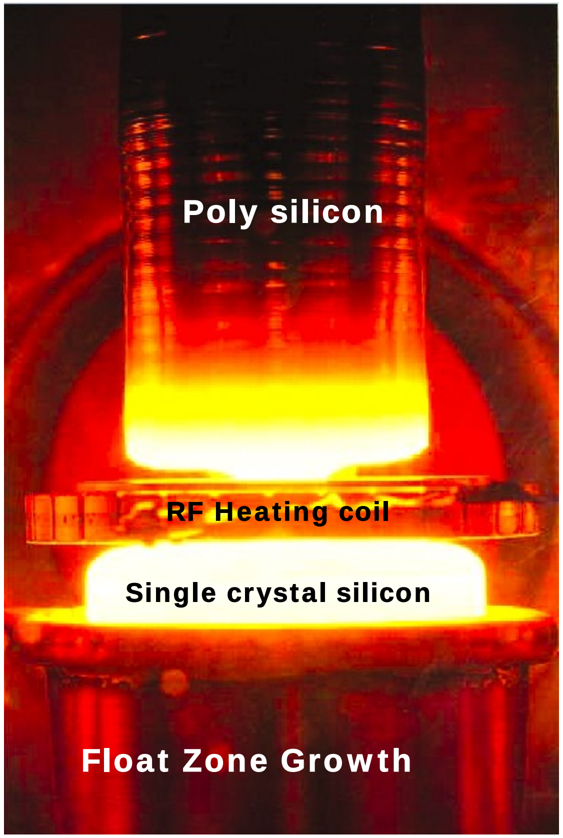
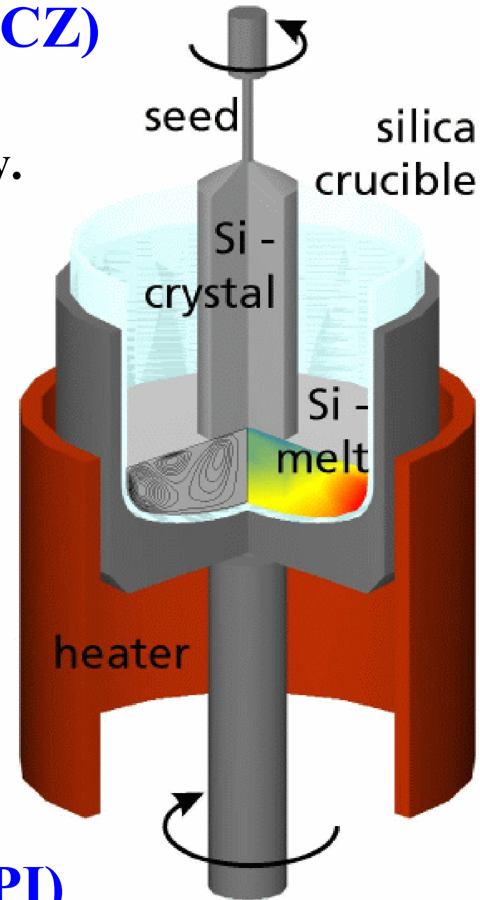
Silicon Growth Processes

- **Floating Zone Silicon (FZ)**



- Basically all silicon tracking detectors made out of FZ silicon
- Some pixel sensors out of DOFZ Diffusion Oxygenated 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

Silicon Materials under Investigation by RD50

standard for particle detectors

used for LHC Pixel detectors

"new" silicon material

Material	Thickness [µm]	Symbol	ρ (Ωcm)	$[O_i]$ (cm^{-3})
Standard FZ (n- and p-type)	50,100,150, 300	FZ	$1–30\times10^3$	$< 5\times10^{16}$
Diffusion oxygenated FZ (n- and p-type)	300	DOFZ	$1–7\times10^3$	$\sim 1–2\times10^{17}$
Magnetic Czochralski Si, Okmetic, Finland (n- and p-type)	100, 300	MCz	$\sim 1\times10^3$	$\sim 5\times10^{17}$
Czochralski Si, Sumitomo, Japan (n-type)	300	Cz	$\sim 1\times10^3$	$\sim 8\text{-}9\times10^{17}$
Epitaxial layers on Cz-substrates, ITME, Poland (n- and p-type)	25, 50, 75, 100, 150	EPI	50 – 100	$< 1\times10^{17}$
Diffusion oxyg. Epitaxial layers on CZ	75	EPI–DO	50 – 100	$\sim 7\times10^{17}$

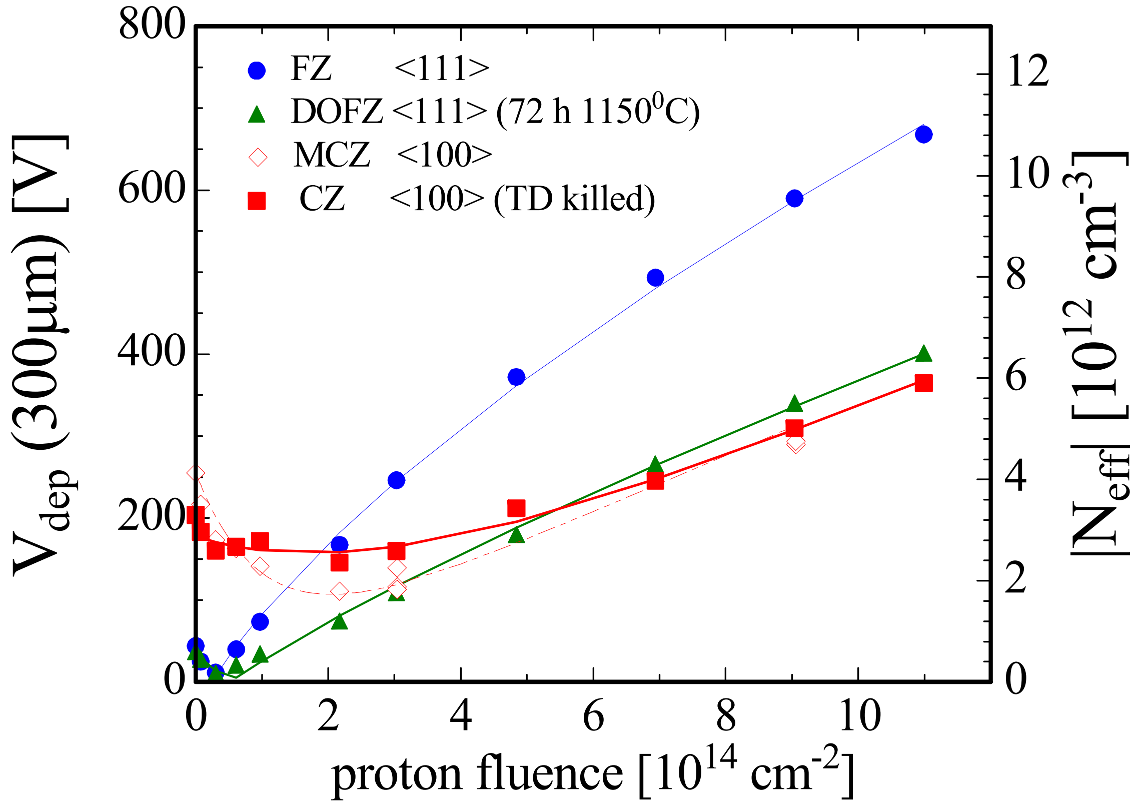
- **DOFZ silicon** - Enriched with oxygen on wafer level, <u>inhomogeneous</u> distribution of oxygen
- **CZ/MCZ silicon** - high Oi (oxygen) and O_{2i} (oxygen dimer) concentration (<u>homogeneous</u>)
  - formation of shallow Thermal Donors possible
- **Epi silicon** - high O_i , O_{2i} content due 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 <u>homogeneous</u> O_i content

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**

  (space charge sign inversion, no inversion, double junction effects,…)
- **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)

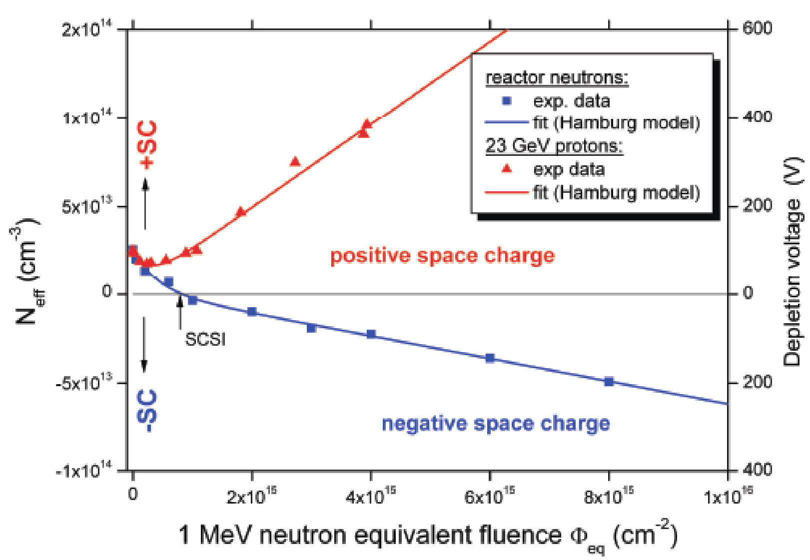


- **Common to all materials** *(after hadron irradiation, not after γ irradiation)*:
  - **reverse current increase**
  - **increase of trapping (electrons and holes) within ~ 20%**

Correlation: Microscopic and Macroscopic data

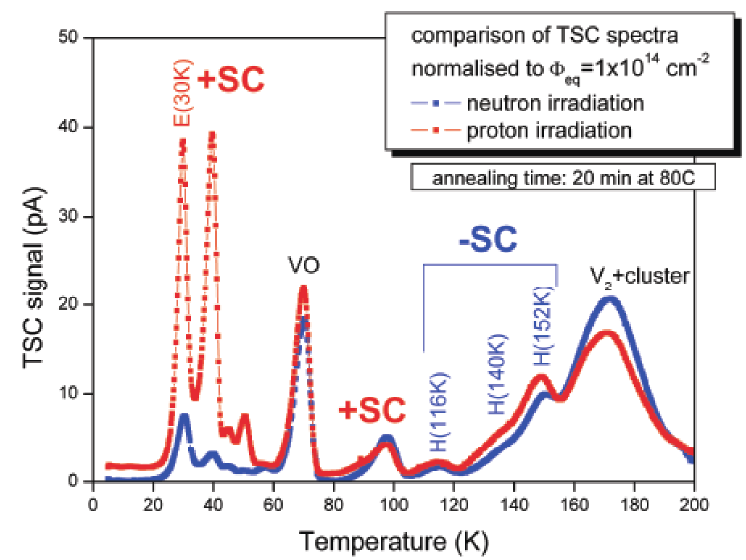
- **Epitaxial silicon irradiated with 23 GeV protons vs reactor neutrons**

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



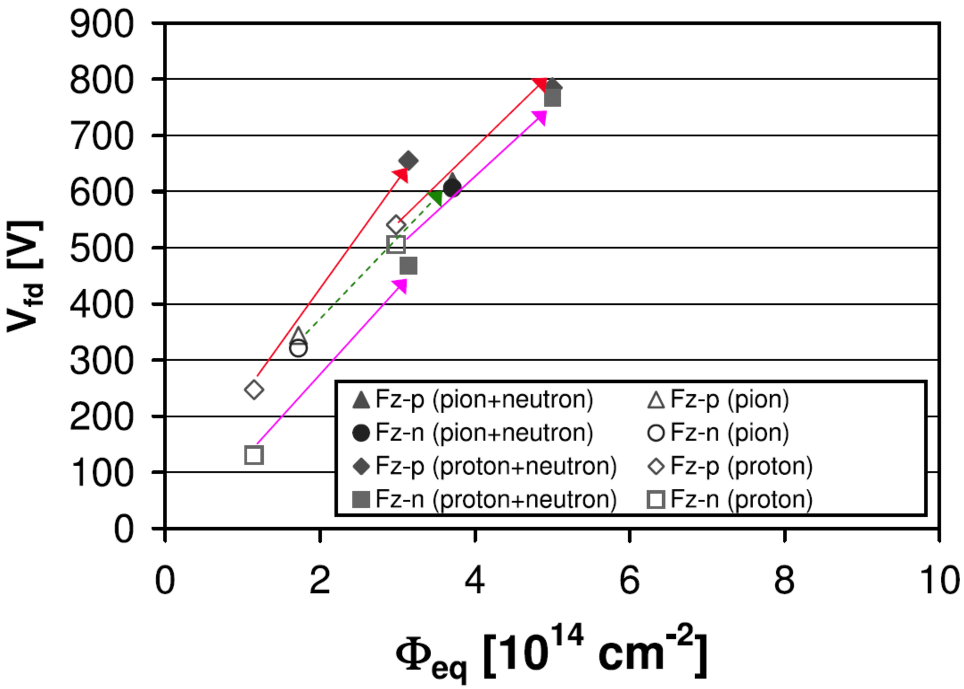
- SCSI after neutrons but not after protons
- donor generation enhanced after proton irradiation
- microscopic defects explain macroscopic effect at low Φ_{eq}

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

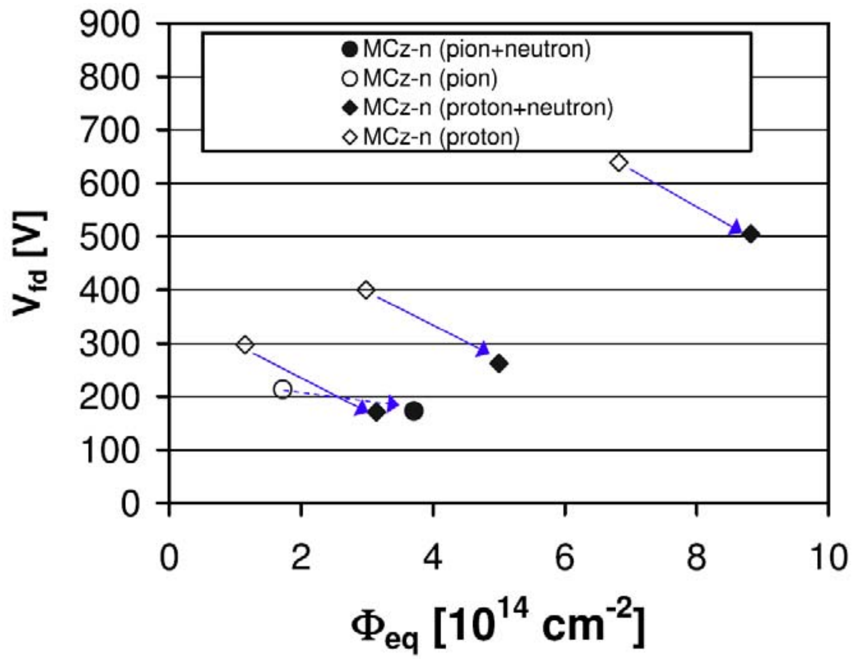
Mixed irradiations – Change of N_{eff}

- **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



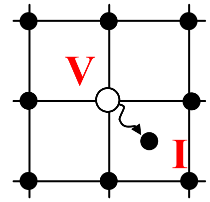
MCZ: Compensation of damage



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

Why is proton and neutron damage different?

particle → Si_S → $E_K > 25$ eV



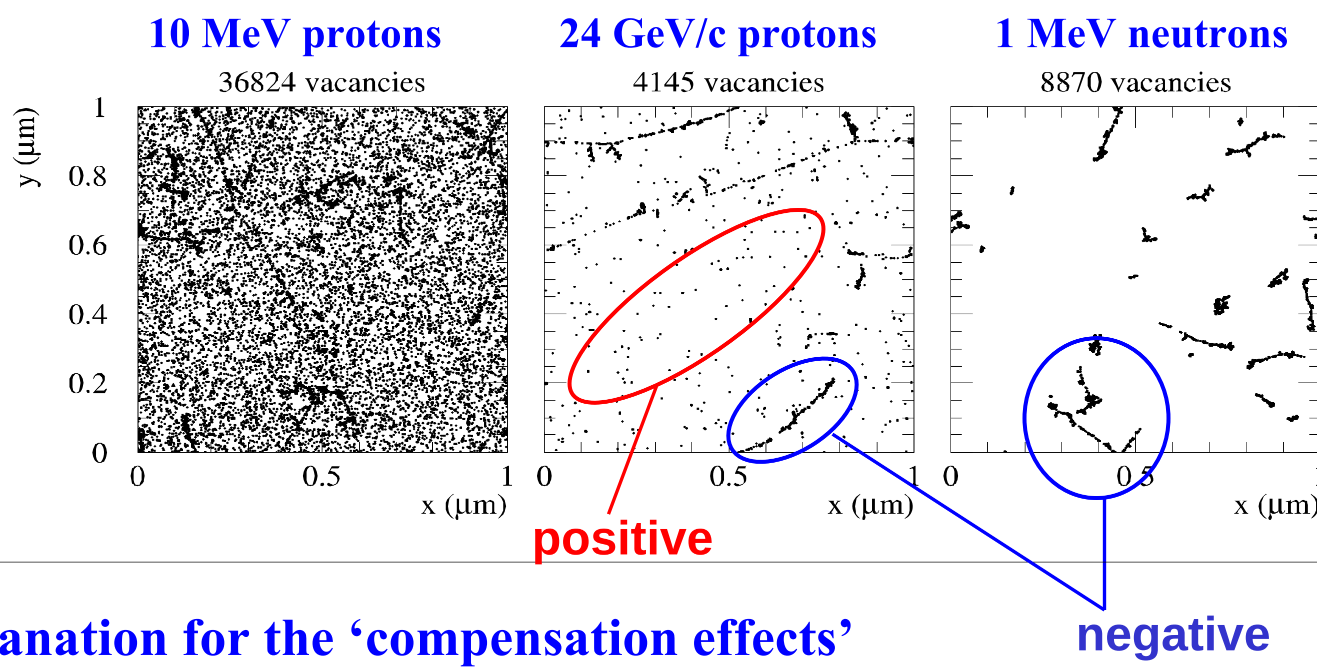
Vacancy + Interstitial → *point defects (V-O, C-O, ..)*

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

Simulation:

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

[Mika Huhtinen NIMA 491(2002) 194]

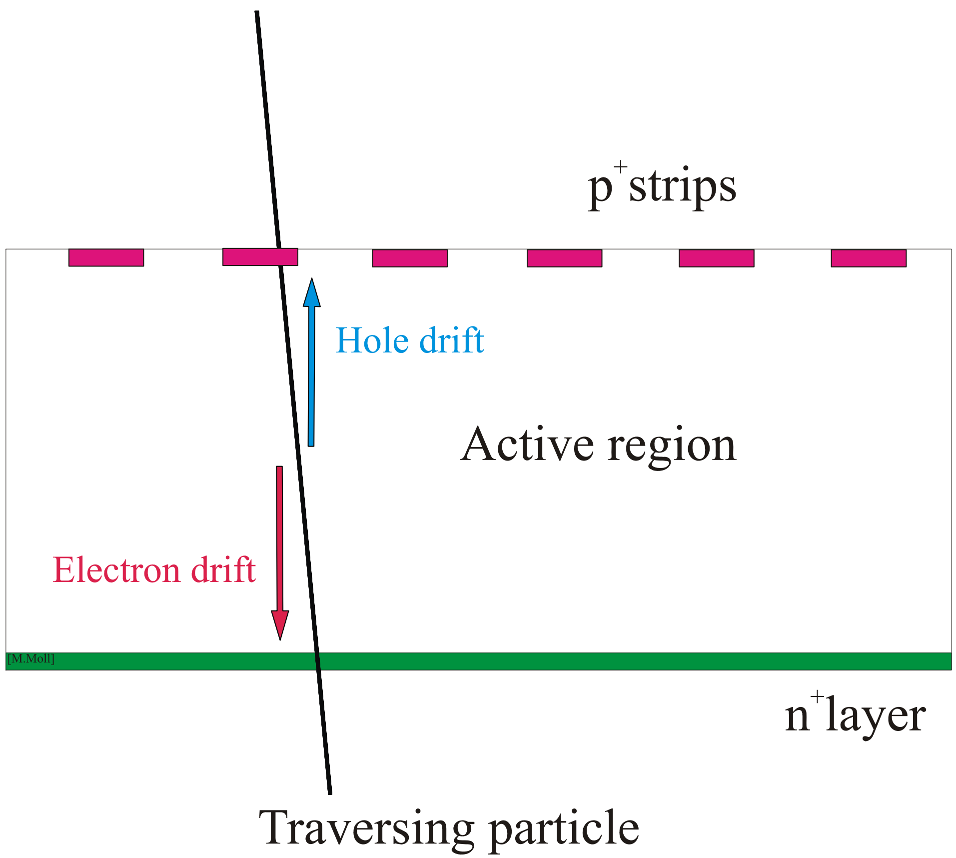


- **A 'simplified' explanation for the 'compensation effects'**
  - Defect clusters produce predominantly **negative space charge**
  - Point defects produce predominantly **positive space charge** (in 'oxygen rich' silicon)

For the experts: Note the NIEL violation

Advantage of non-inverting material
p-in-n detectors (schematic figures!)

Fully depleted detector (non – irradiated):

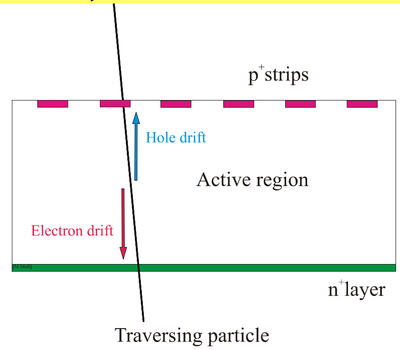


Advantage of non-inverting material

p-in-n detectors (schematic figures!)

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

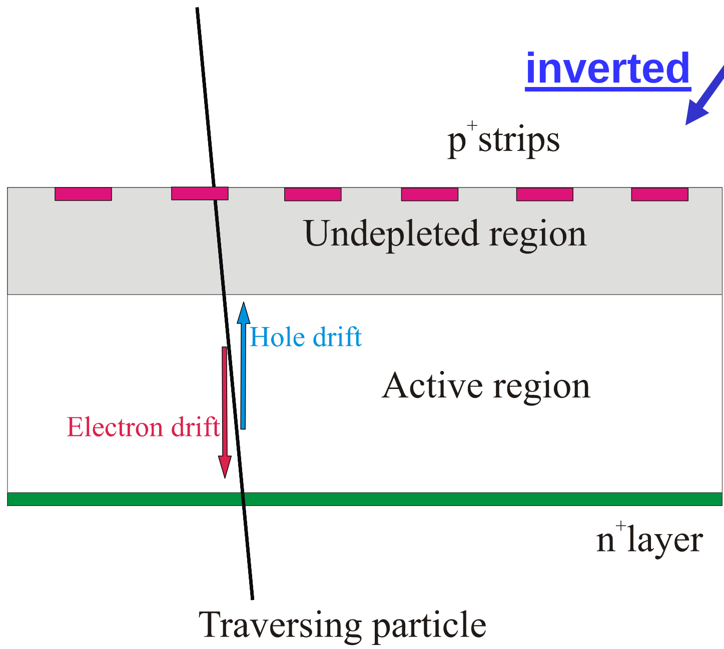
Fully depleted detector (non – irradiated):

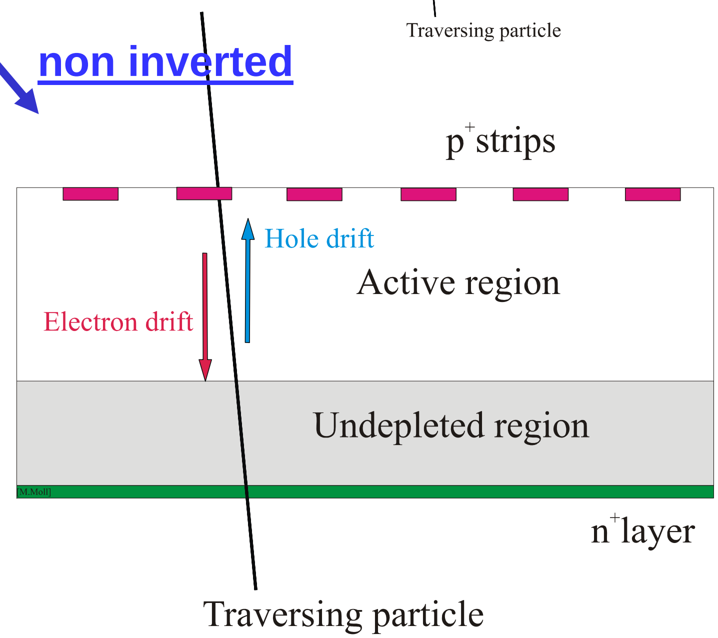


heavy irradiation

inverted

non inverted





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

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

non-inverted, under-depleted:

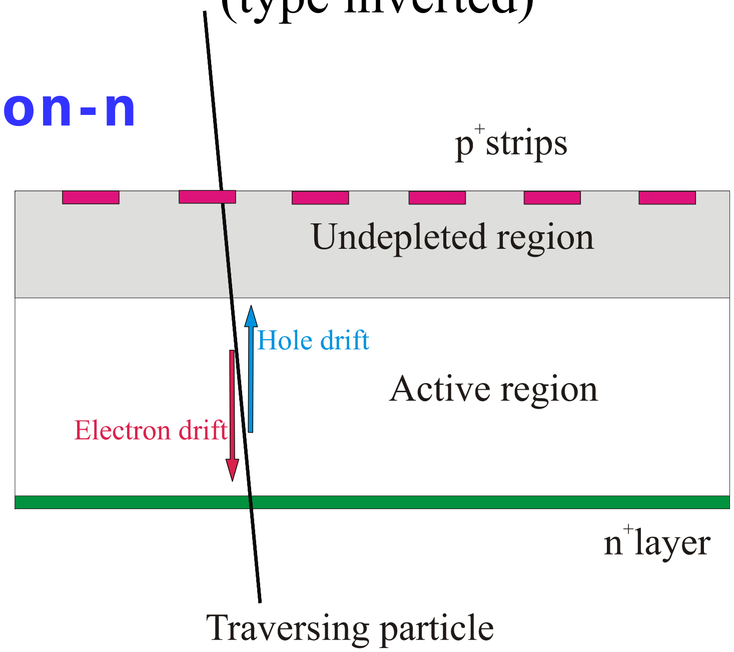
- Limited loss in CCE
- Less degradation with under-depletion

Device engineering

p-in-n versus n-in-p (or n-in-n) detectors

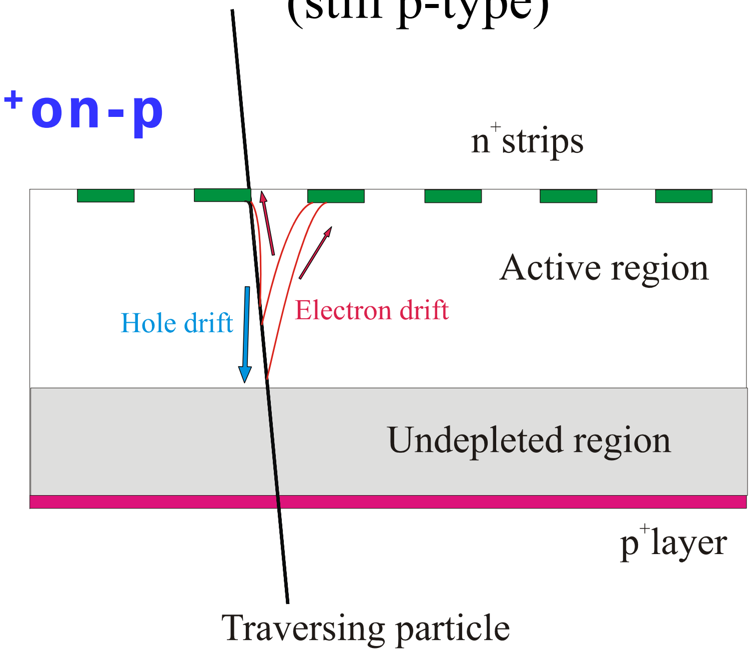
n-type silicon after high fluences:
(type inverted)

p^+on-n



p-type silicon after high fluences:
(still p-type)

n^+on-p



p-on-n silicon, under-depleted:

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

n-on-p silicon, under-depleted:

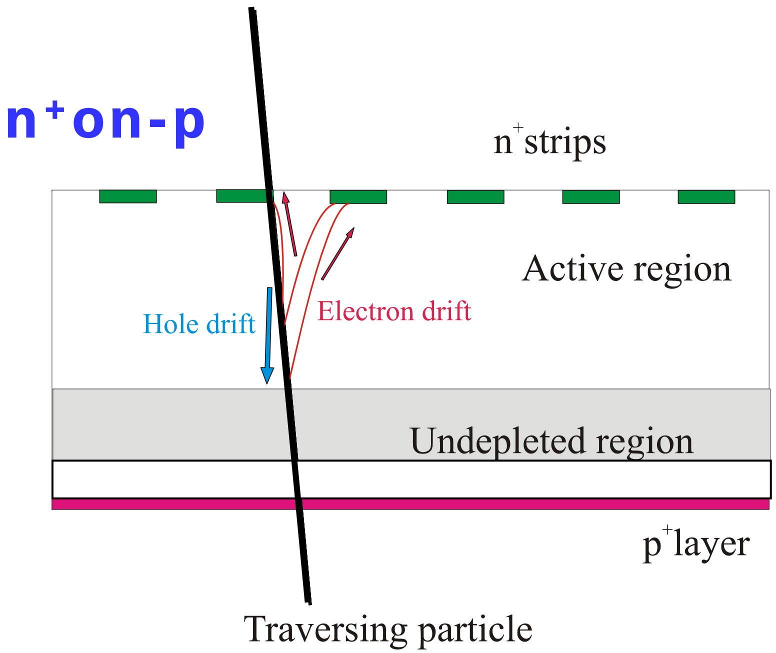
- **Limited loss in CCE**
- **Less degradation with under-depletion**
- **Collect electrons (3 x faster than holes)**

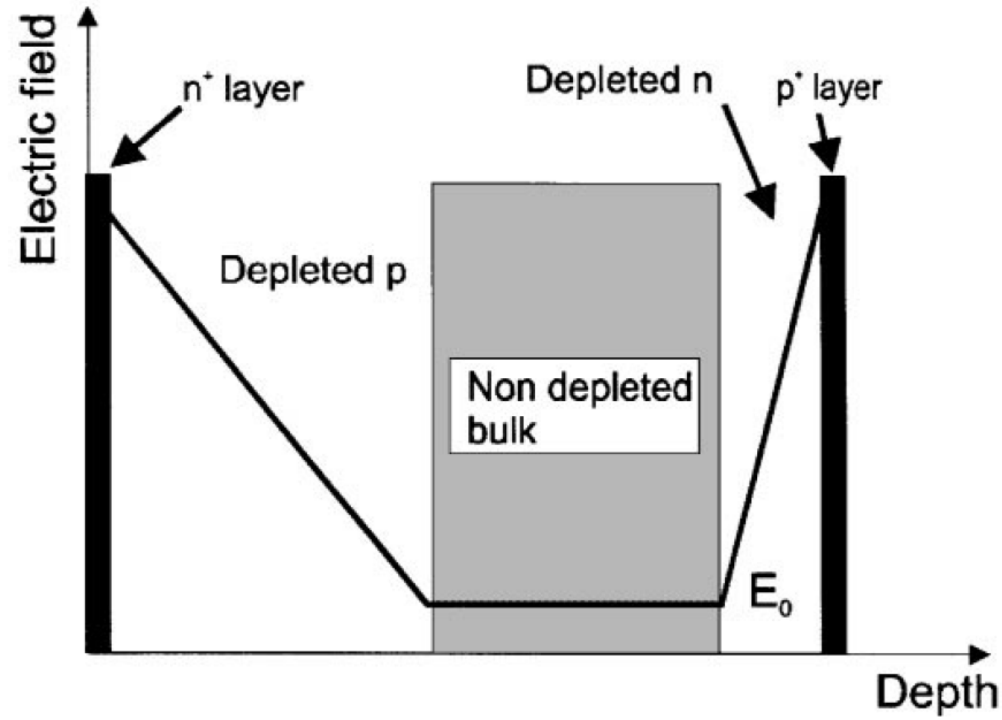
Comments:
- Instead of n-on-p also n-on-n devices could be used

Reality is more complex: *Double junctions*

p-type silicon after high fluences:

(still "p-type")



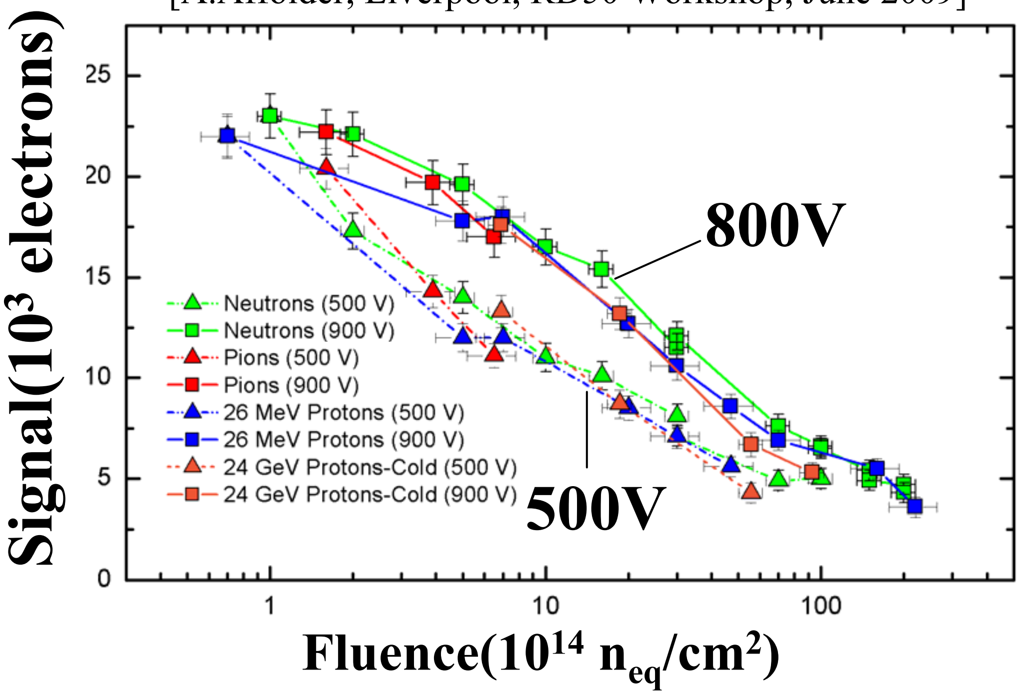


- **Dominant junction close to n+ readout strip for FZ n-in-p**
- **For MCZ p-in-n even more complex fields have been reported:**
  - **no "type inversion"(SCSI) = dominant field remains at p implant**
  - **"equal double junctions" with almost symmetrical fields on both sides**

FZ n-in-p microstrip detectors (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)

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

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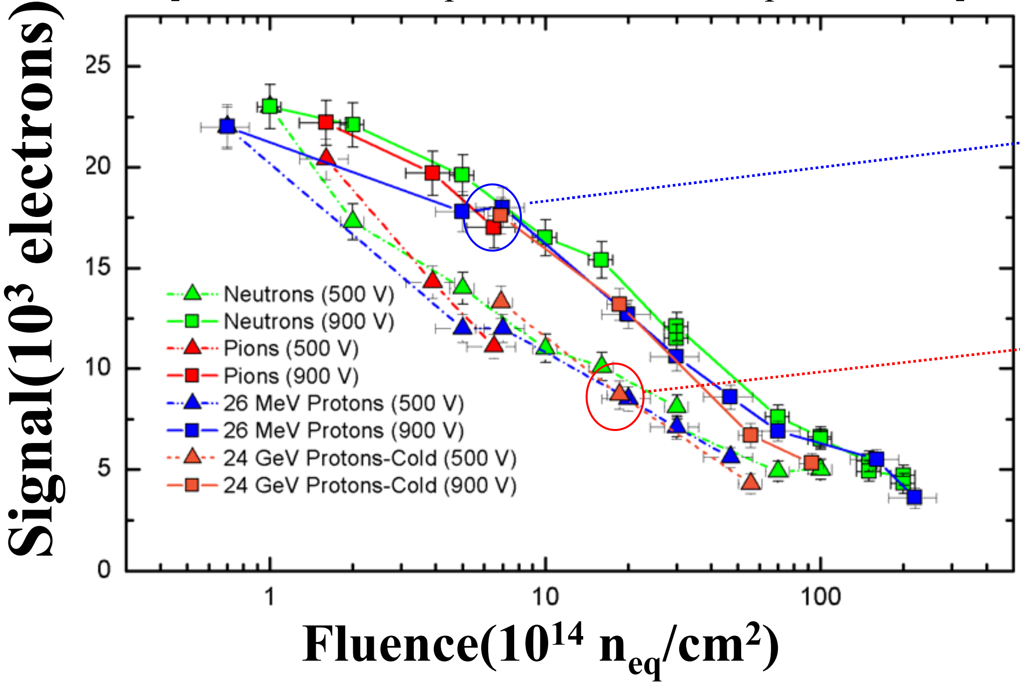
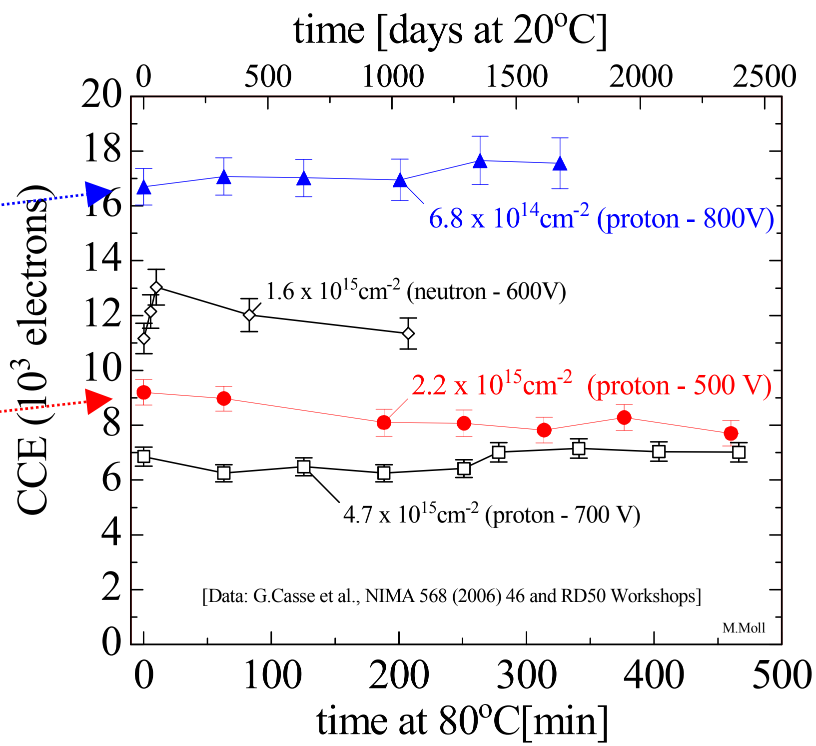


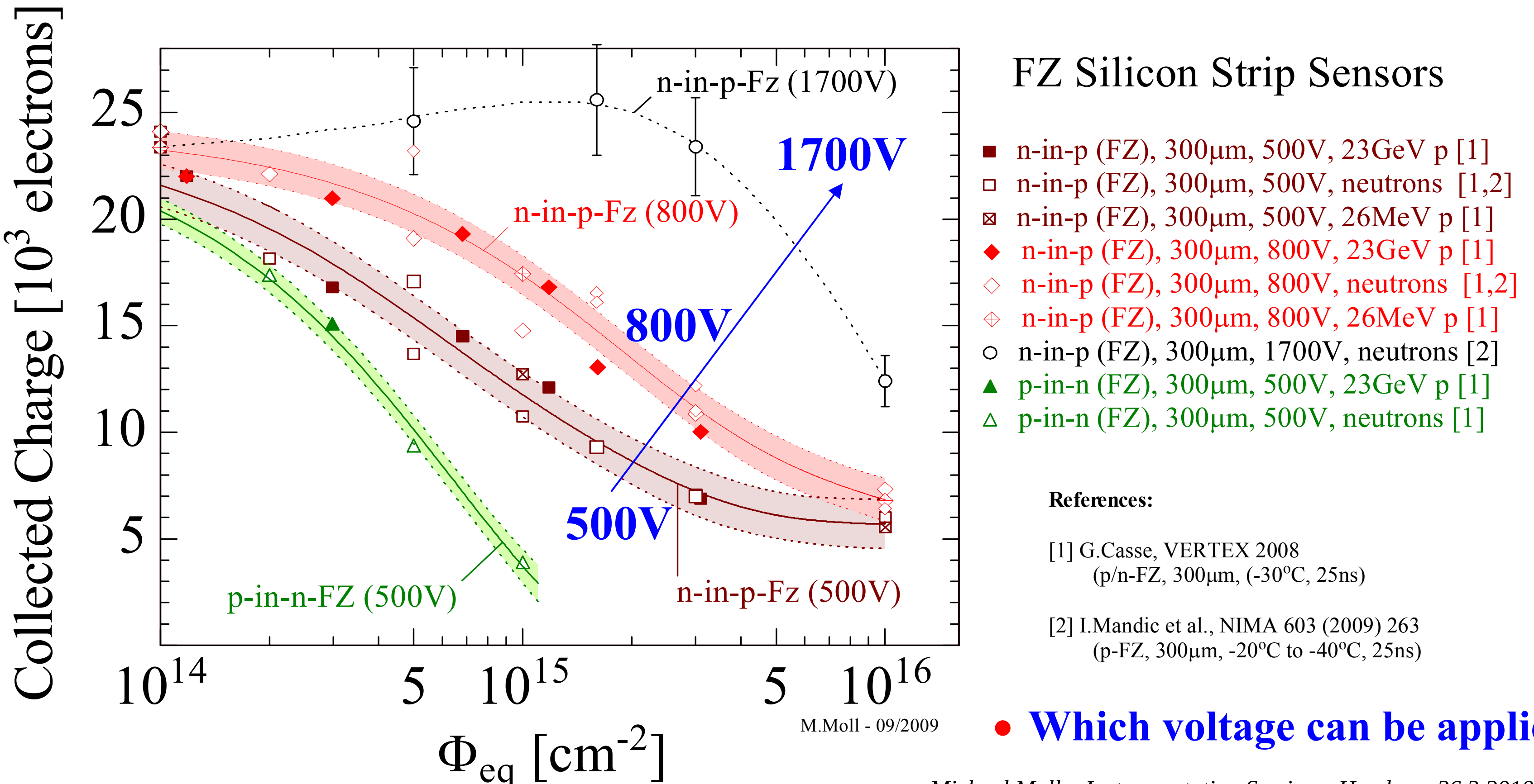


- **CCE: ~7300e (~30%)**
  after ~ 1×10^{16}cm^{-2} 800V
- **n-in-p sensors are strongly considered for ATLAS upgrade** (previously p-in-n used)

- **<u>no reverse annealing</u> in CCE measurements for neutron and proton irradiated detectors**

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**



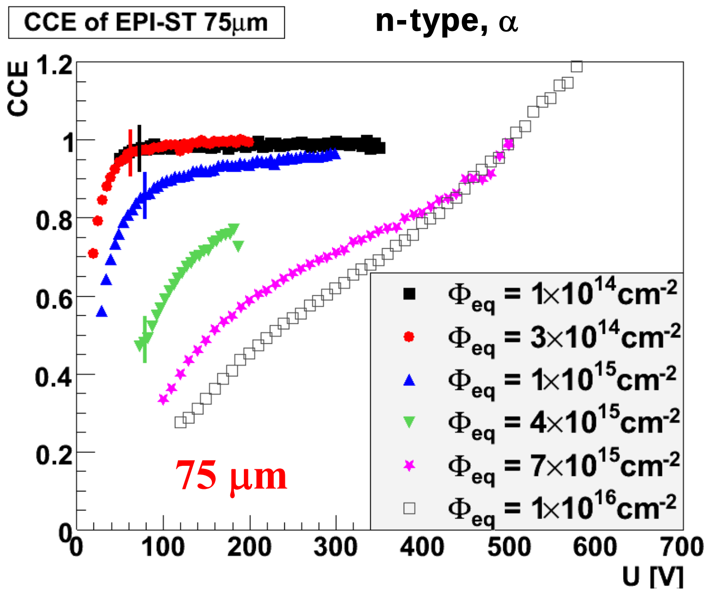
References:

[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)

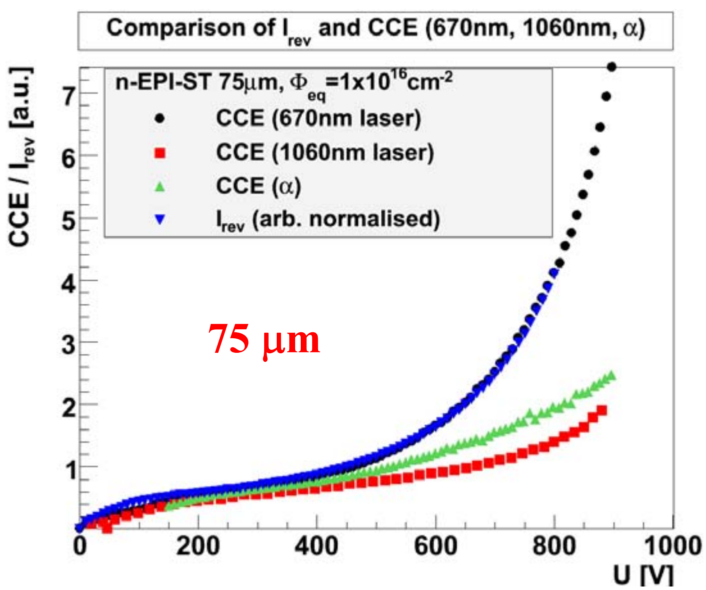
- **Which voltage can be applied?**

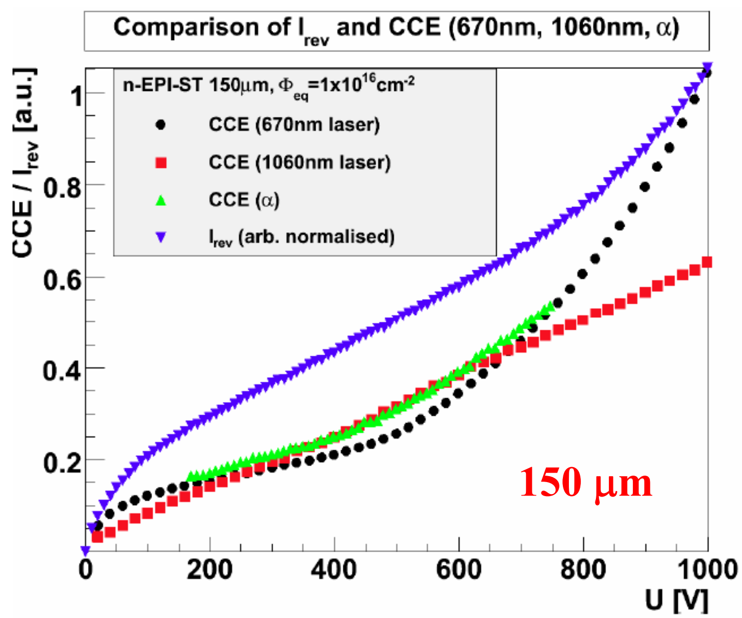
Charge Multiplication –Epi Diodes



[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

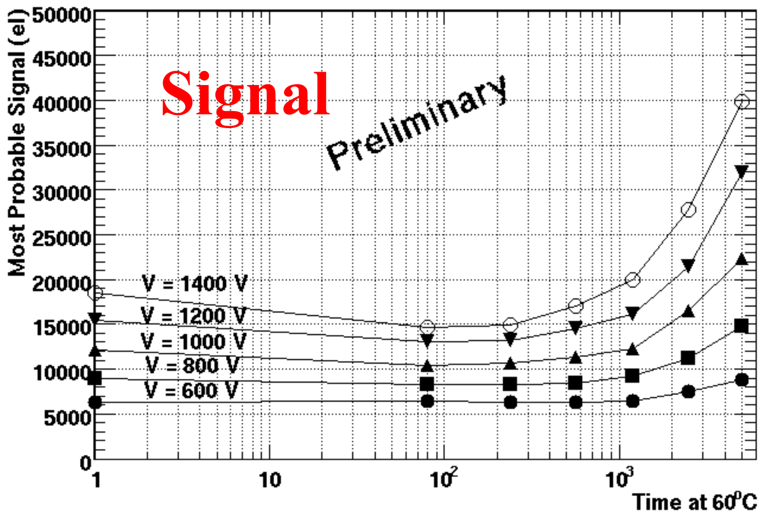


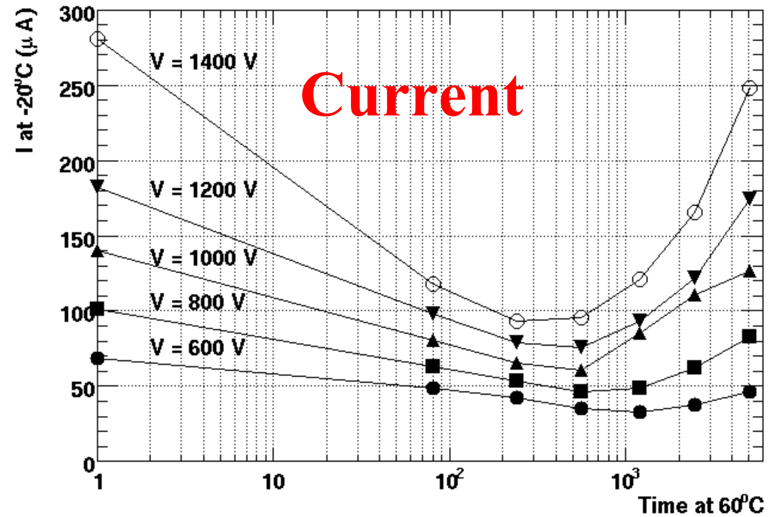


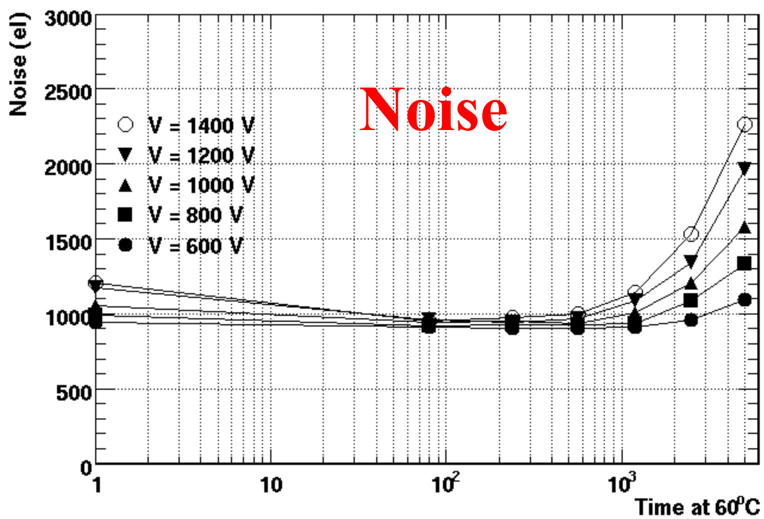
Annealing studies on strip sensors

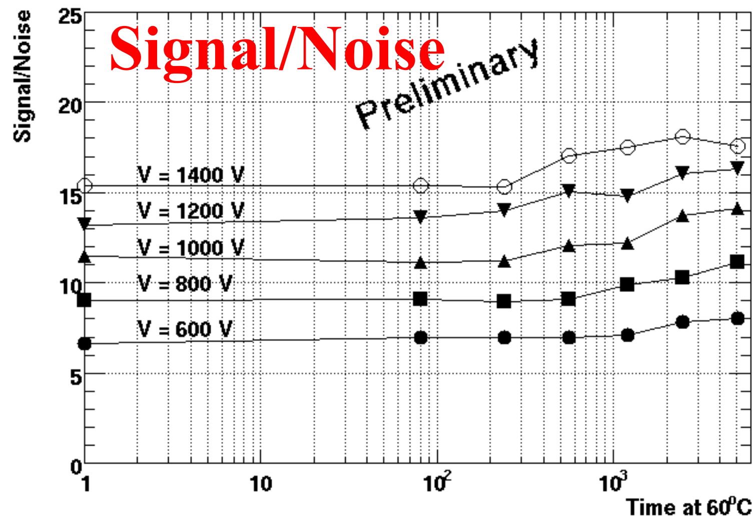
[I.Mandic, 15th RD50 Workshop, Nov.09 – Measured on HPK ATLAS sensors]

- p-type strip sensor; $\Phi_{eq} = 5\times10^{15}$ cm^{-2} (neutrons) [ATLAS – HPK – sensors]





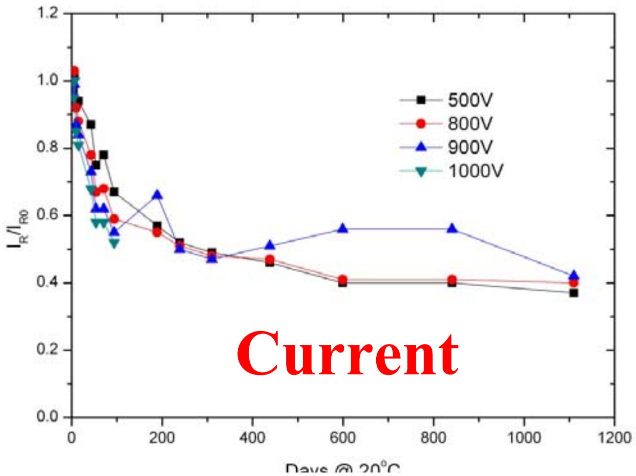




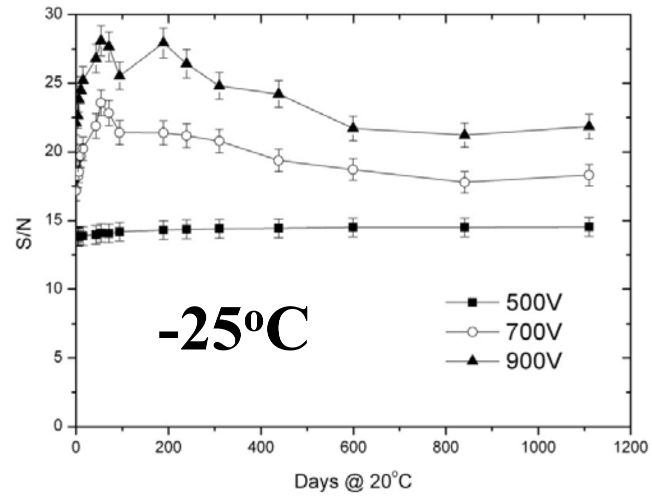
Further annealing studies

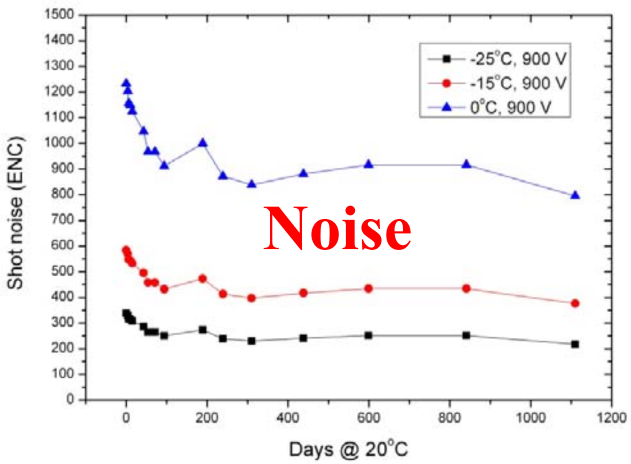
[G.Casse, Trento Workshop, Feb.2010 – Measured on HPK ATLAS sensors]

- p-type strip sensor; [ATLAS – HPK]
- $\Phi_{eq} = 1\text{x}10^{15}\ n_{eq}\ cm^{-2}$ (26MeV protons)



Signal to Noise

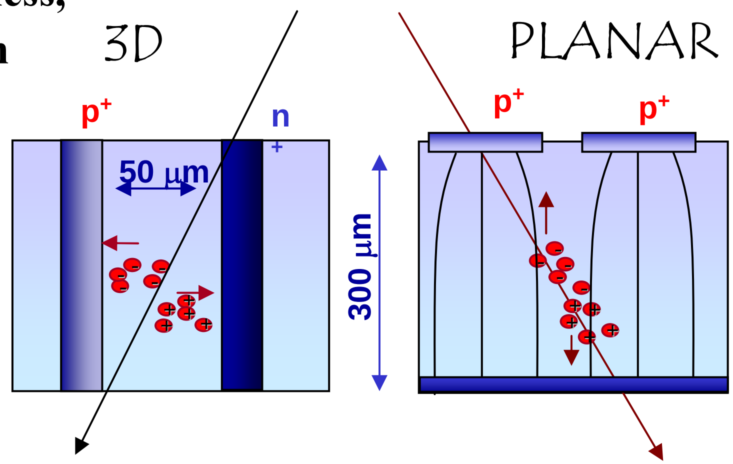


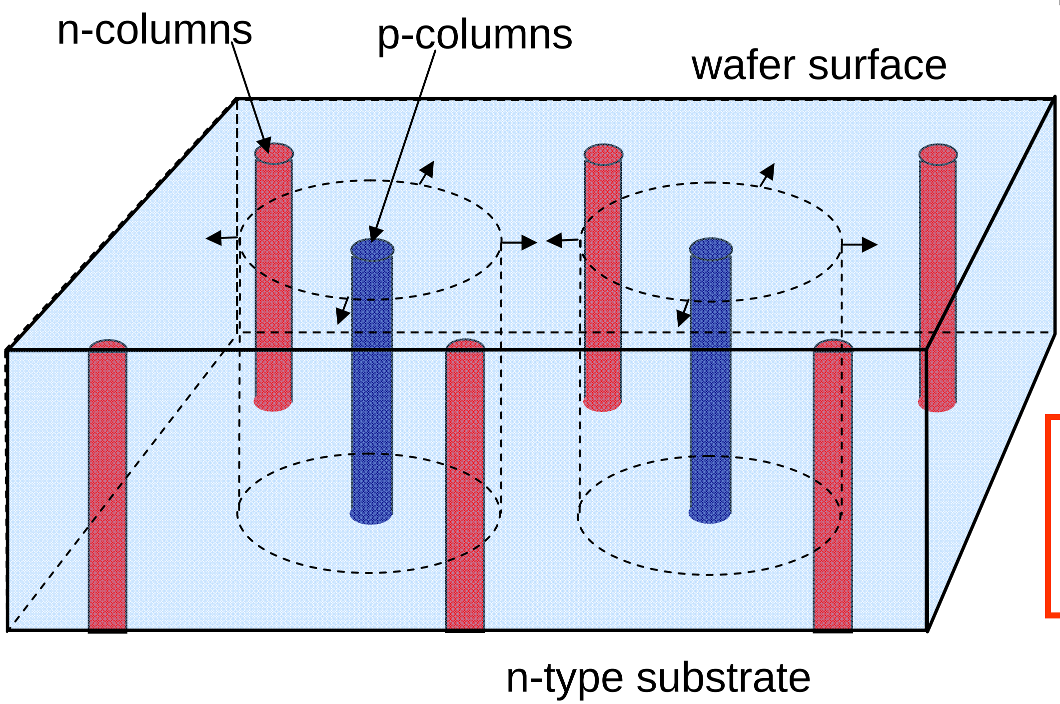


- Stable operation of n-in-p sensors without cooling during maintenance periods seems feasible
- Still long way to fully understand high voltage operation of highly irradiated sensors

3D detector - concept

- **"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



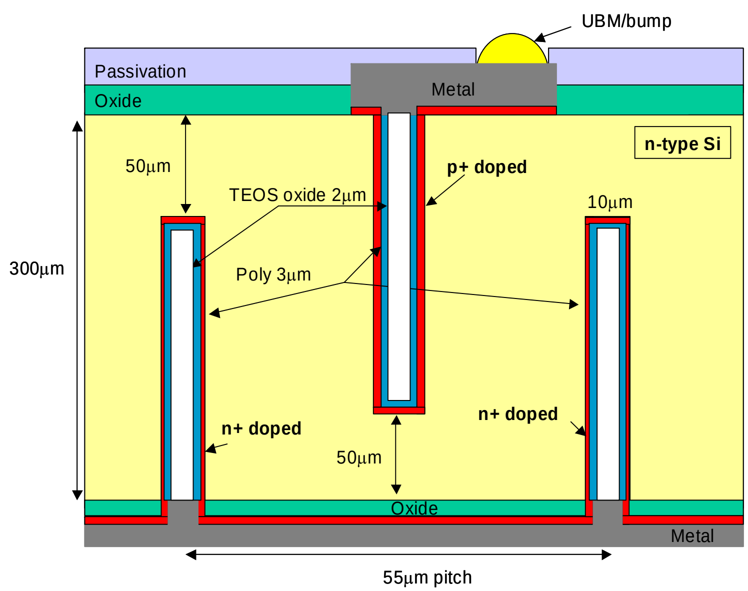


Not discussed here in detail: Seminar on 9. April dedicated entirely to 3D sensors

Example: Testbeam of 3D-DDTC

- **DDTC – Double sided double type column**

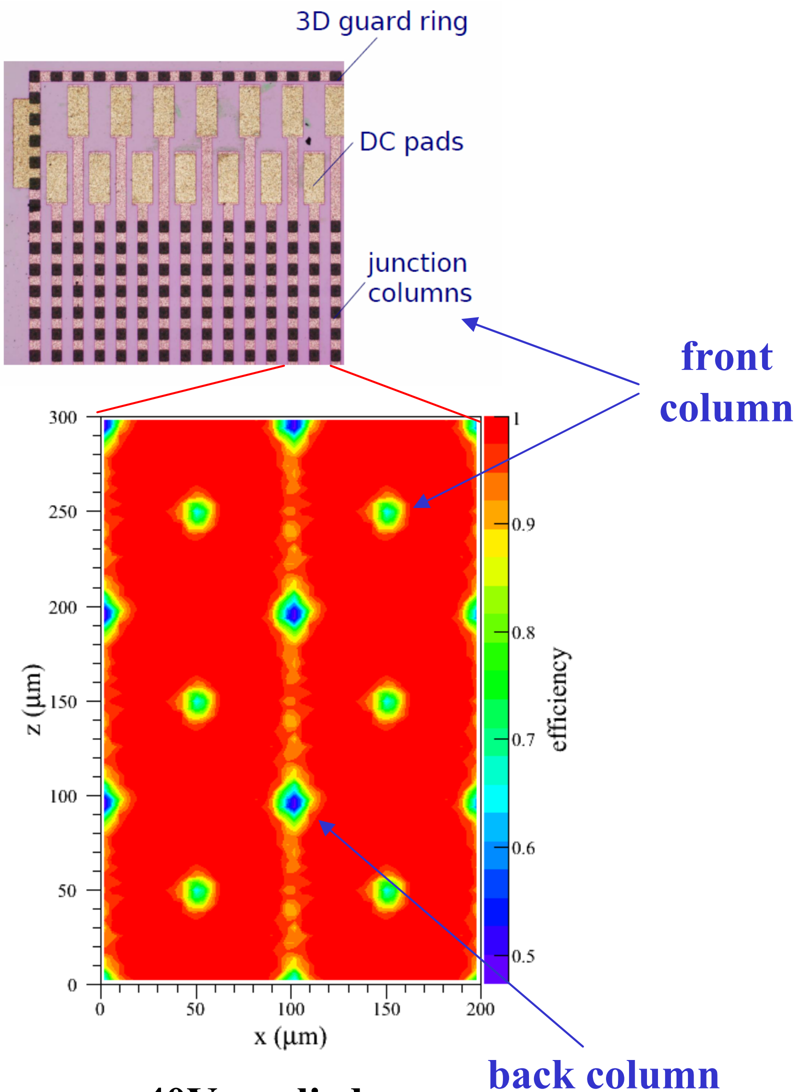
[G.Fleta, RD50 Workshop, June 2007]



- **Testbeam data – Example: efficiency map**
  [M.Koehler, Freiburg Uni, RD50 Workshop June 09]

- **Processing of 3D sensors is challenging, but many good devices with reasonable production yield produced.**

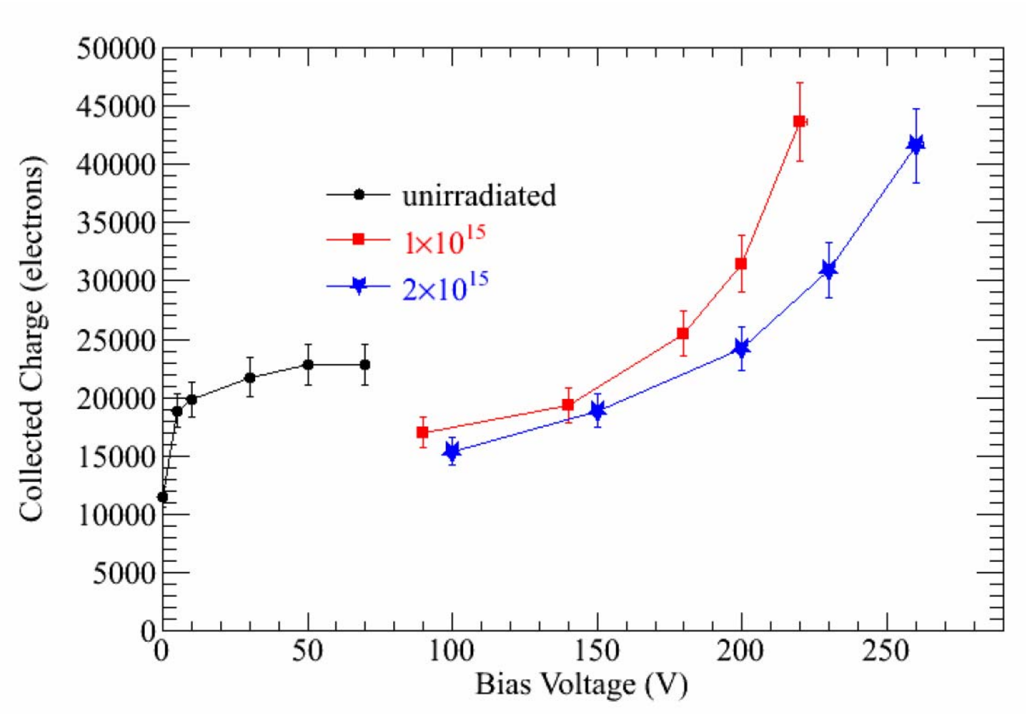
- **Competing e.g. for ATLAS IBL pixel sensors**



3D-DDTC – Study after irradiation

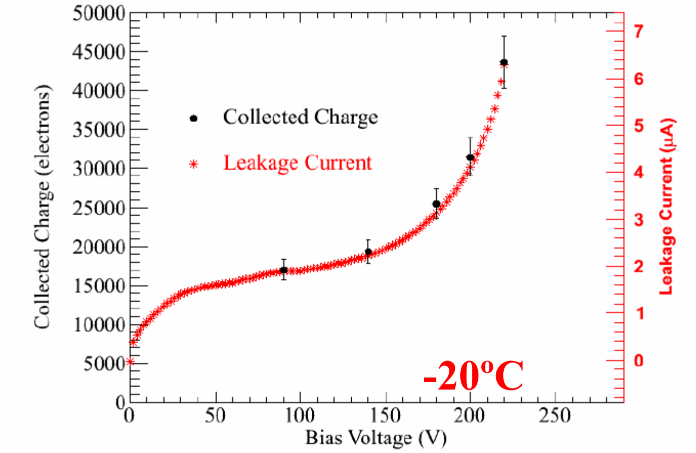
[M.Koehler, Trento Workshop, Feb. 2009]

- DDTC sensors irradiated with 26 MeV protons

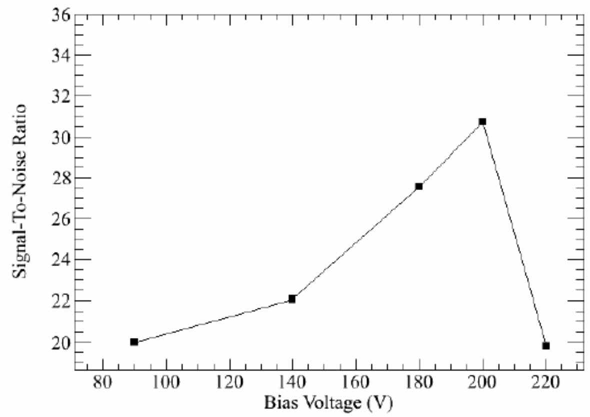


- Avalanche effects in 3D sensors

1X10^15 n_eq/cm²



- Signal scales with leakage current



- Signal to Noise

Use of other semiconductor materials?

Property	Diamond	GaN	4H SiC	Si
E_g [eV]	**5.5**	**3.39**	**3.3**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4\cdot10^6$	$2.2\cdot10^6$	$3\cdot10^5$
μ_e [cm^2/Vs]	1800	1000	800	1450
μ_h [cm^2/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2\cdot10^7$	-	$2\cdot10^7$	$0.8\cdot10^7$
e-h energy [eV]	**13**	**8.9**	**7.6-8.4**	**3.6**
e-h pairs/X_0	4.4	~2-3	4.5	10.1

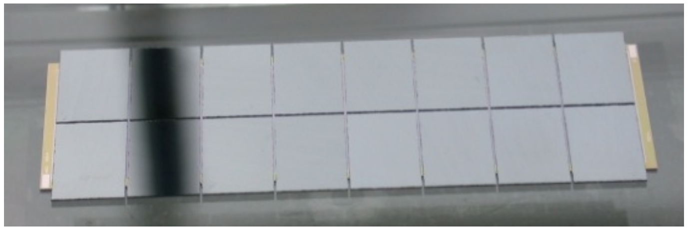
- **Diamond: wider bandgap**
  ⇒ lower leakage current
  ⇒ less cooling needed

- **Signal produced by m.i.p:**
  Diamond 36 e/µm
  Si 89 e/µm
  ⇒ Si gives more charge than diamond

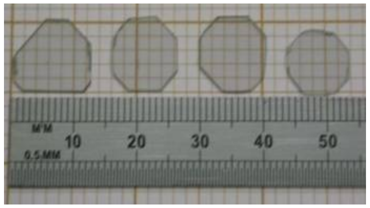
- **GaAs, SiC and GaN ⇒ strong radiation damage observed**
  ⇒ no potential material for sLHC detectors
  (judging on the investigated material)

- **Diamond (RD42) ⇒ good radiation tolerance *(see later)***
  ⇒ already used in LHC beam condition monitoring systems
  ⇒ considered as potential detector material for sLHC pixel sensors

poly-CVD Diamond –16 chip ATLAS pixel module

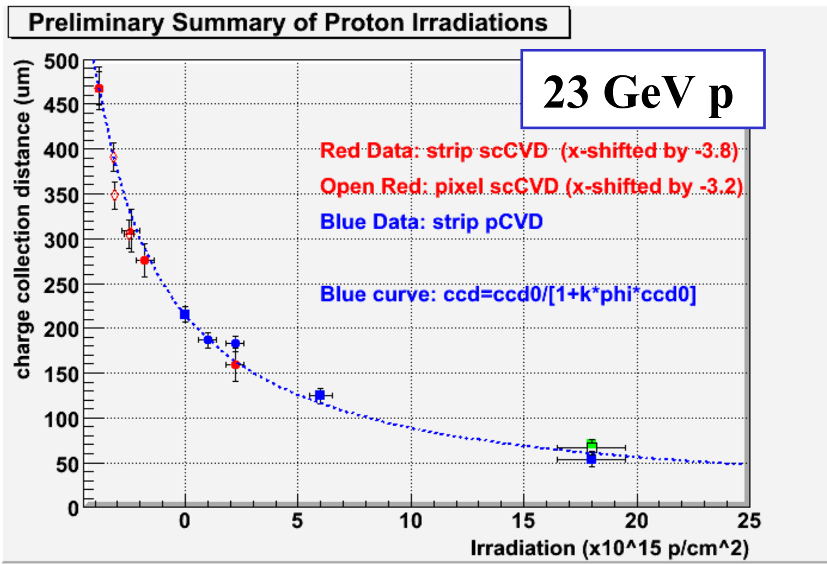


single crystal CVD Diamond of few cm^2

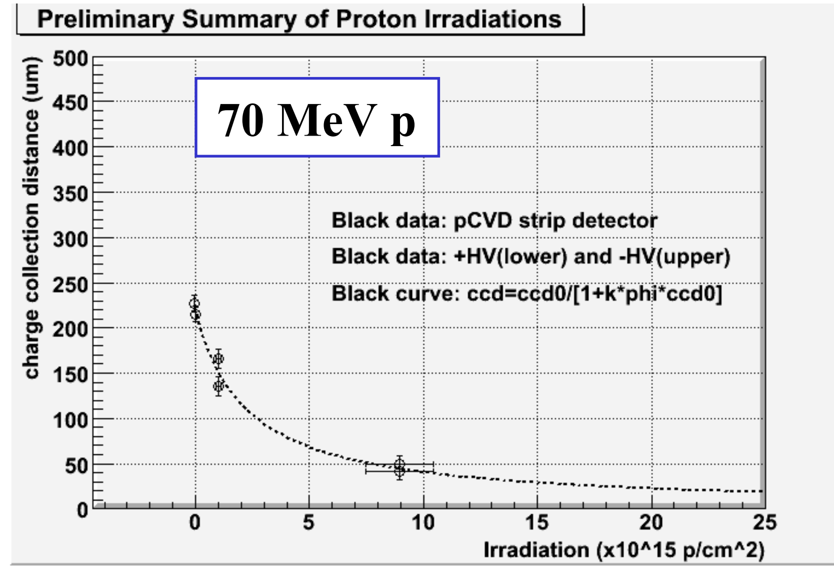


Diamnond sensors are heavily used in LHC Experiments for Beam Monitoring

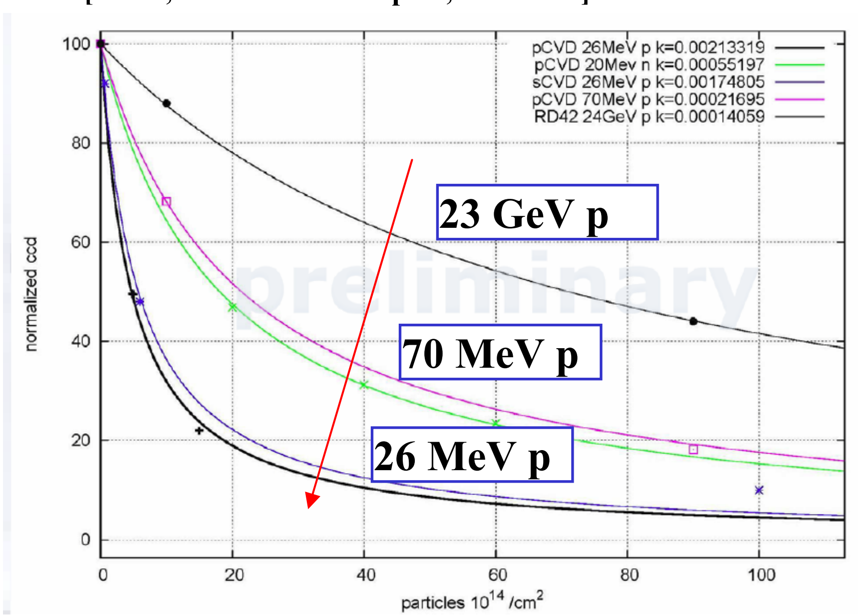
Are diamond sensor radiation hard?



[RD42, LHCC Status Report, Feb. 2010]



[RD42, LHCC Status Report, Feb. 2010]



[V.Ryjov, CERN ESE Seminar 9.11.2009]

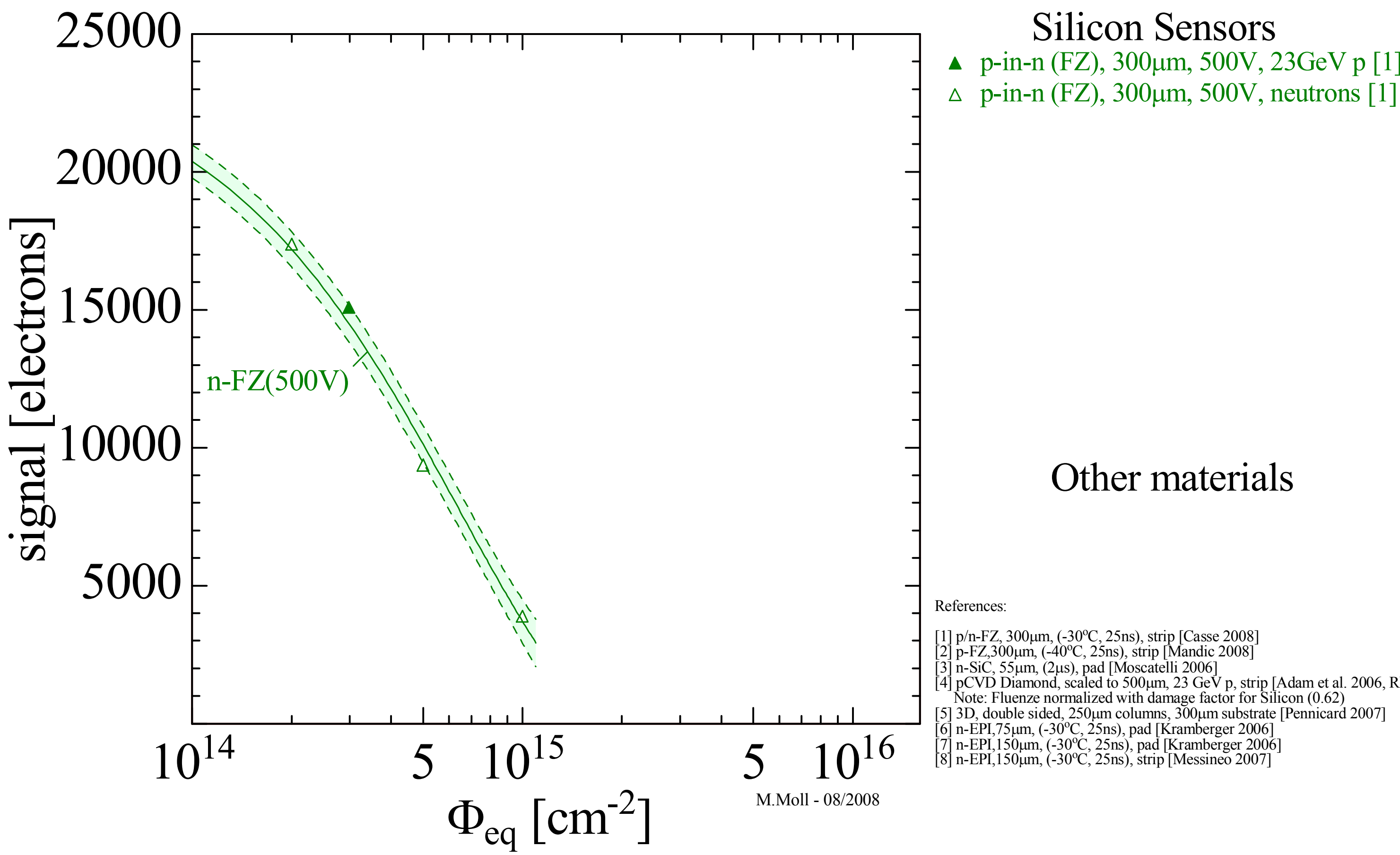
- **Most published results on 23 GeV protons**
- **70 MeV protons 3 times more damaging than 23 GeV protons**
- **25 MeV protons seem to be even more damaging** ***(Preliminary: RD42 about to cross check the data shown to the left)***
- **In line with NIEL calc. for Diamond**
  [W. de Boer et al. Phys.Status Solidi 204:3009,2007]

Outline

- **Motivation to develop radiation harder detectors**
  - **Super-LHC and expected radiation levels at the Super-LHC**
  - **Radiation induced degradation of detector performance**
- **Radiation Damage in Silicon Detectors**
  - **Macroscopic damage (changes in detector properties)**
  - **Microscopic damage (crystal damage)**
- **Approaches to obtain radiation hard sensors**
  - **Material Engineering**
    - Silicon materials – FZ, MCZ, DOFZ, EPI
    - Other semiconductors
  - **Device Engineering**
    - p-in-n, n-in-n and n-in-p sensors
    - 3D sensors and thin devices
- **Silicon Sensors for the LHC upgrade**
  - **Collected Charge – Signal to Noise – Avalanche effects**
  - **Mixed irradiations**
- **Summary**

Silicon materials for Tracking Sensors

- **Signal comparison for various Silicon sensors**



Note: Measured partly under different conditions! Lines to guide the eye (no modeling)!

References:

[1] p/n-FZ, 300µm, (-30ºC, 25ns), strip [Casse 2008]
[2] p-FZ,300µm, (-40ºC, 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, (-30ºC, 25ns), pad [Kramberger 2006]
[7] n-EPI,150µm, (-30ºC, 25ns), pad [Kramberger 2006]
[8] n-EPI,150µm, (-30ºC, 25ns), strip [Messineo 2007]

Silicon materials for Tracking Sensors

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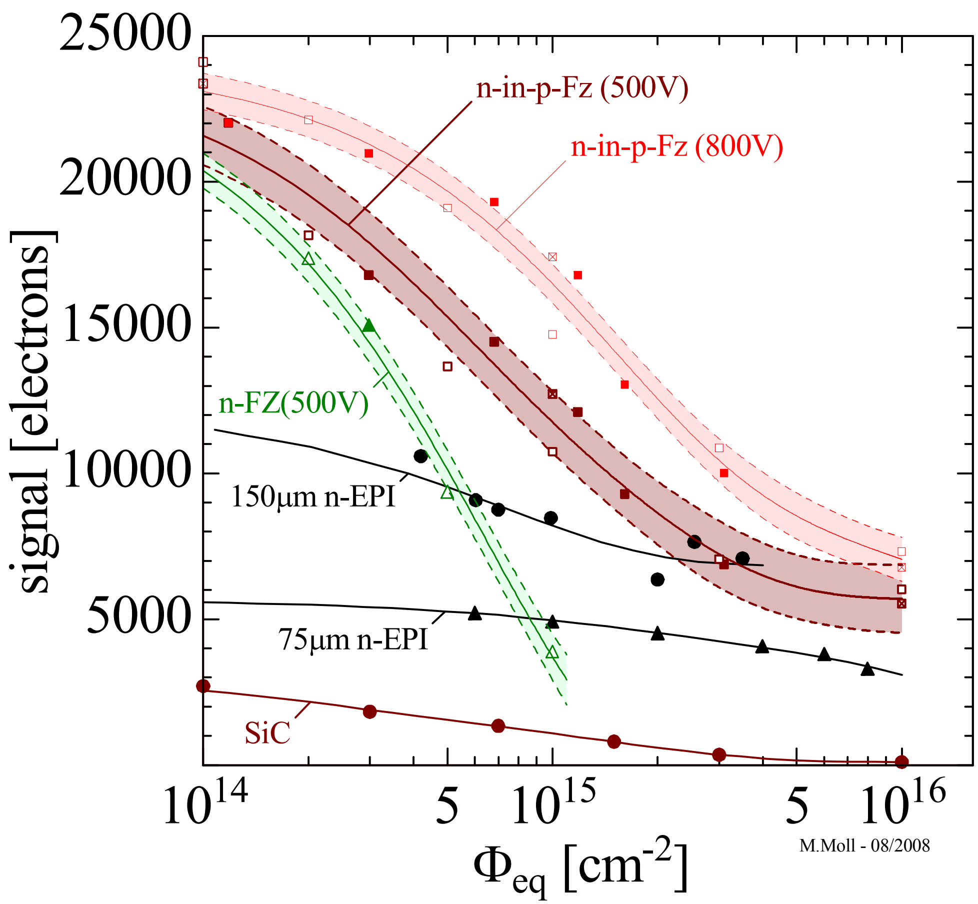

Silicon Sensors

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

Other materials

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

References:

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[2] p-FZ,300µm, (-40°C, 25ns), strip [Mandic 2008]
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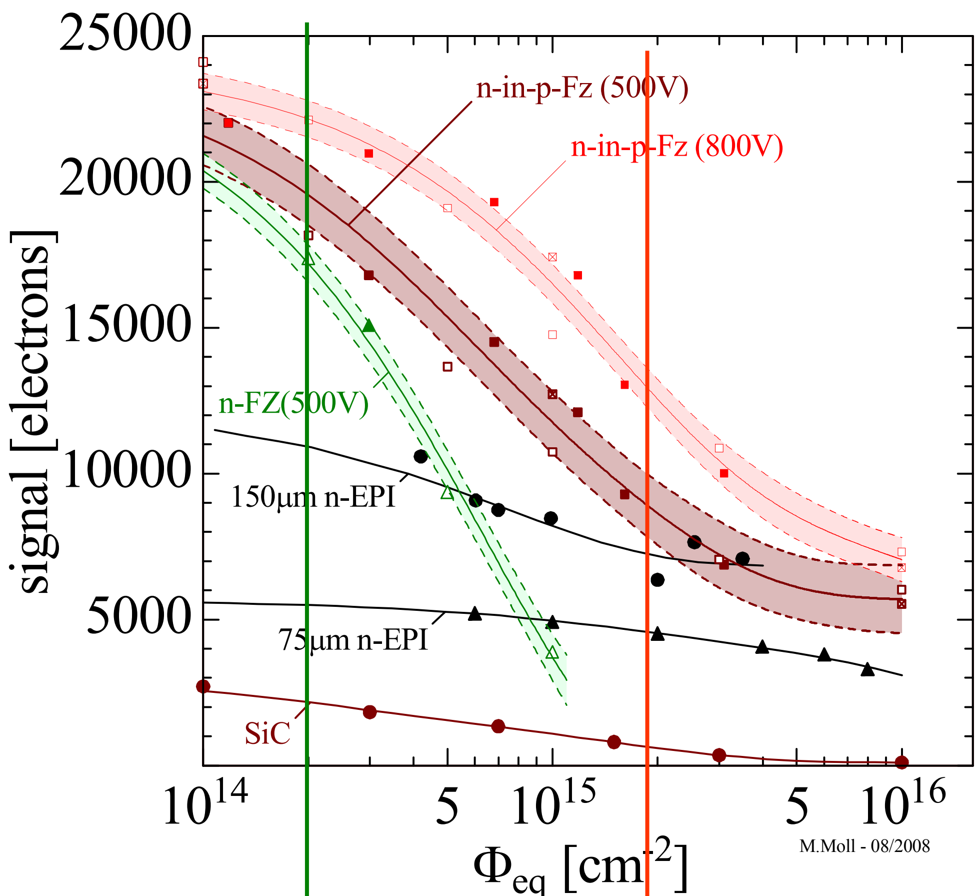

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References:

[1] p/n-FZ, 300µm, (-30ºC, 25ns), strip [Casse 2008]
[2] p-FZ,300µm, (-40ºC, 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, (-30ºC, 25ns), pad [Kramberger 2006]
[7] n-EPI,150µm, (-30ºC, 25ns), pad [Kramberger 2006]
[8] n-EPI,150µm, (-30ºC, 25ns), strip [Messineo 2007]

LHC → **SLHC**

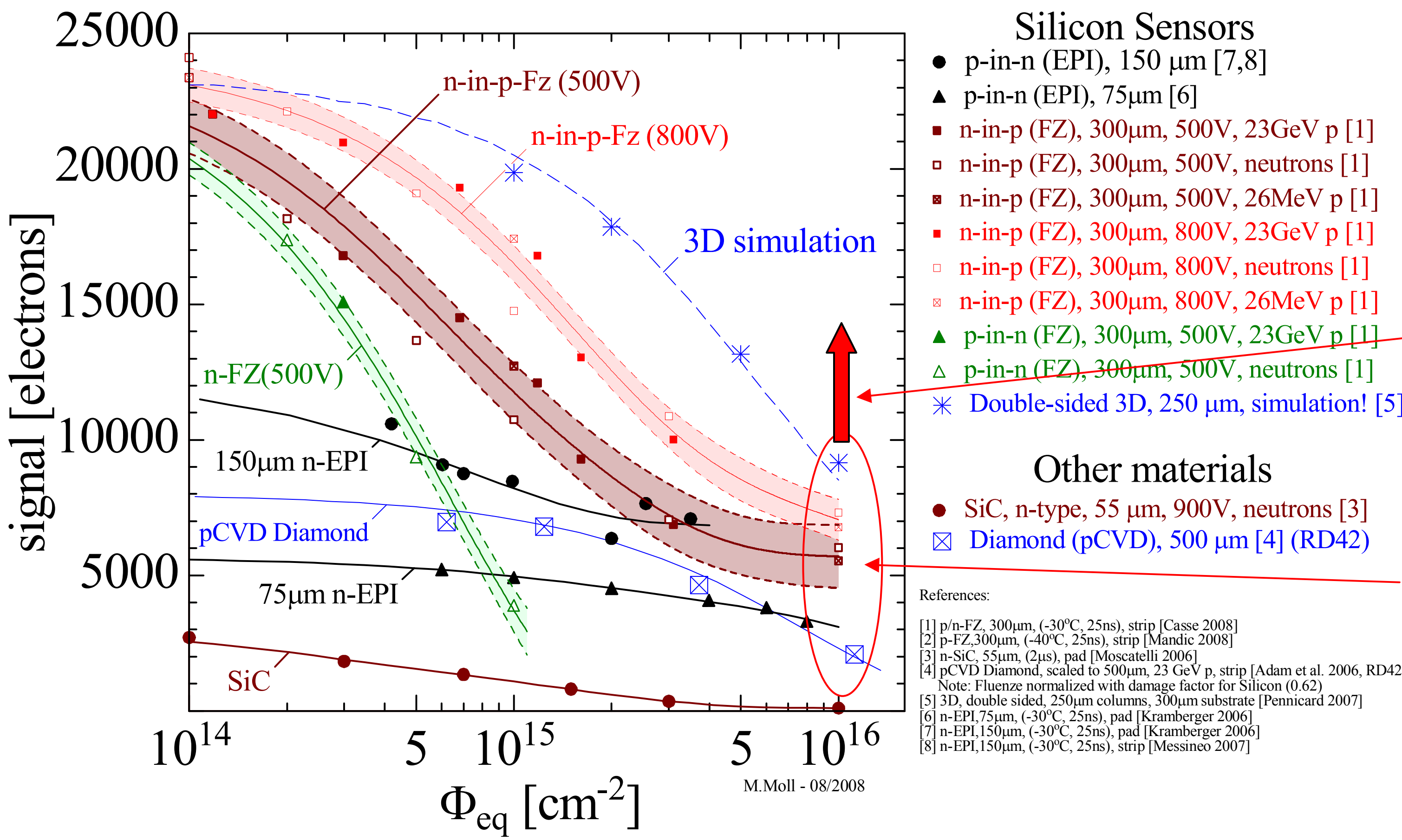
highest fluence for strip detectors in LHC: The used p-in-n technology is sufficient

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

Silicon materials for Tracking Sensors

- **Signal comparison for various Silicon sensors**

Note: Measured partly under different conditions! Lines to guide the eye (no modeling)!



Higher Voltage leads to charge multiplication

Beware: Signal shown and not S/N !

- **All sensors suffer from radiation damage**
- **Presently three options for innermost pixel layers under investigation:**
  - **3-D silicon sensors** (decoupling drift distance from active depth)
  - **Diamond sensors**
  - **Silicon planar sensors**

Ongoing Work / Open Questions

- Performance of MCZ silicon in mixed fields -

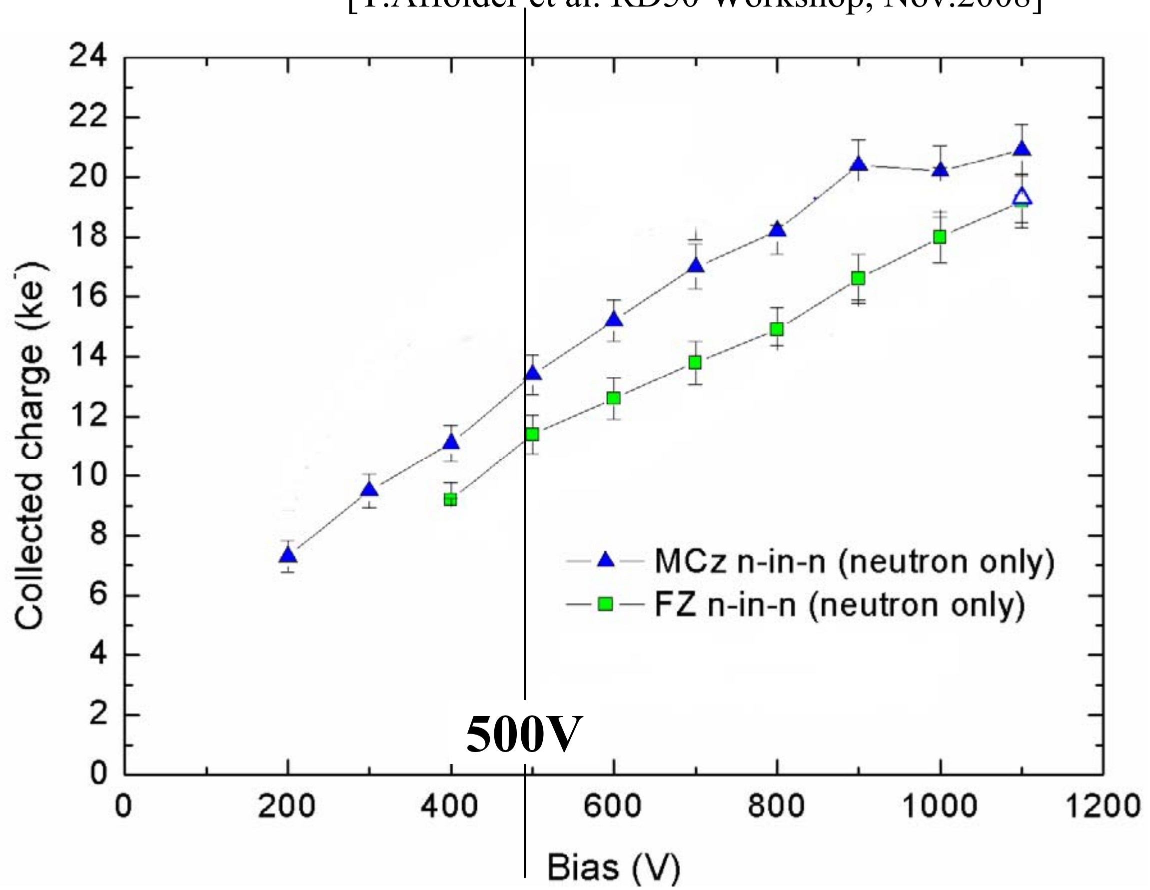
- **Is MCZ silicon (n- and p-type) an option for SLHC detectors?**
  - **Protons induce predominantly defects that are positively charged**
  - **Neutrons induce predominantly defects that are negatively charged**
  - **Mixed Fields: Compensation?**

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

- **Mixed irradiations:**
  - **(a) Φ_{eq}= 5x10^{14} neutrons**
  - **(b) Φ_{eq}= 5x10^{14} protons**

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

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



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  Damage additive!

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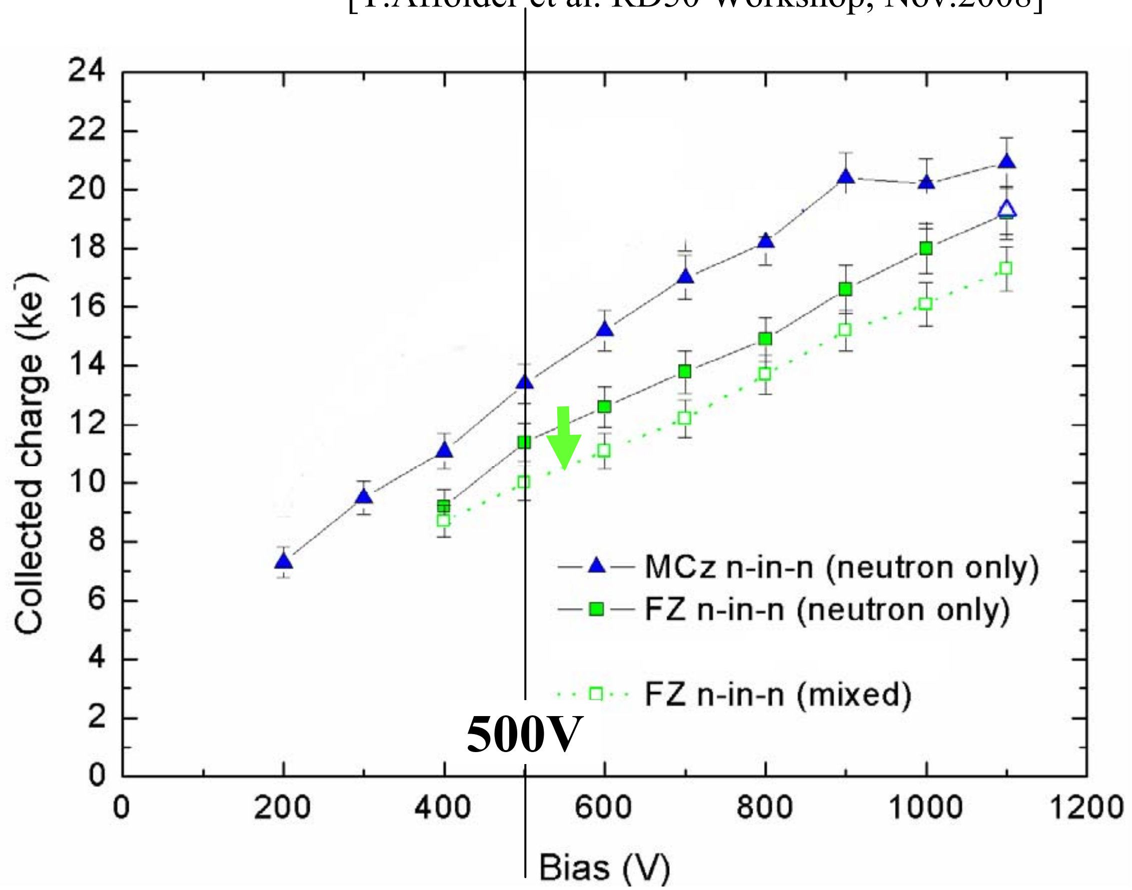

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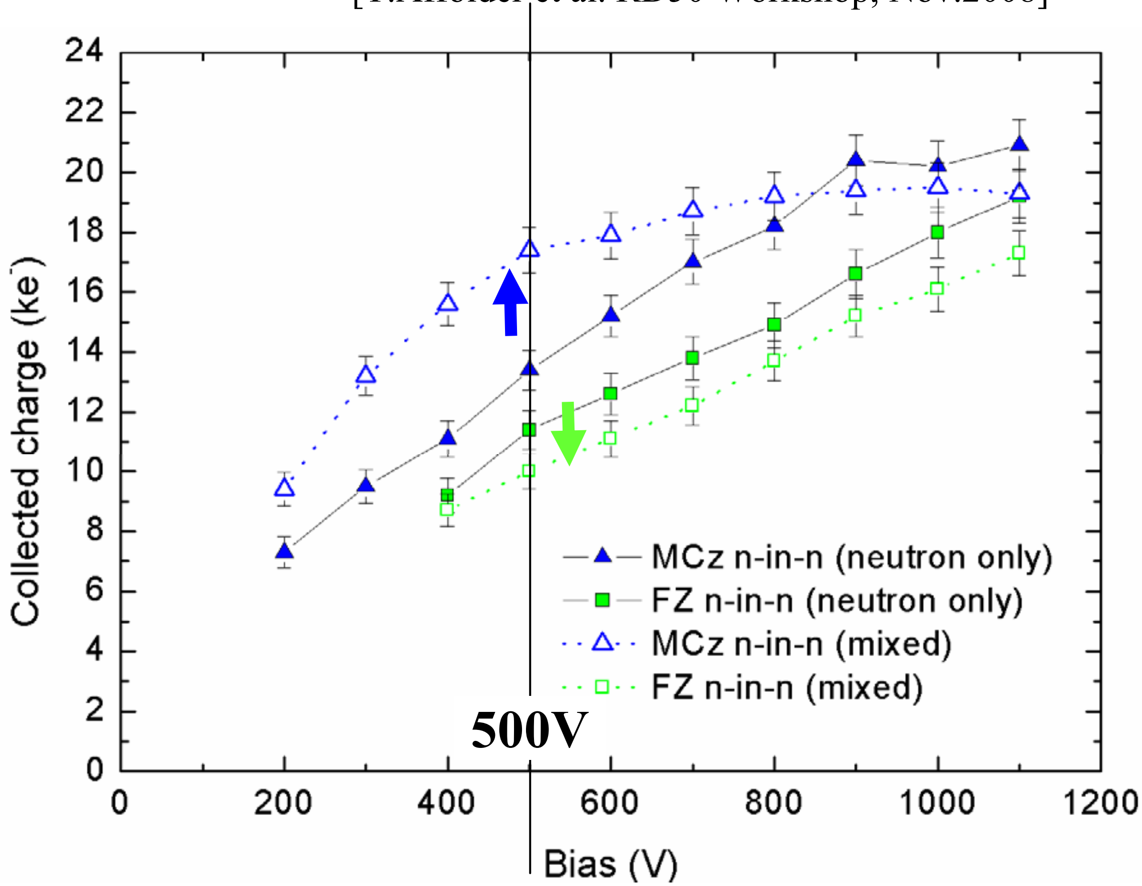
- **MCZ (n-in-n)**

  Mixed Irradiation:

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



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

Summary – Radiation Damage

- **Radiation Damage in Silicon Detectors**
  - Change of **Depletion Voltage** (internal electric field, "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 & Defect Engineering**
  - Good understanding of damage after γ-irradiation (point defects)
  - Defects after hadron damage still to be better understood (cluster defects) although enormous progress in last 5 years a big question remains:
    Which are the defects responsible for the charge trapping?

- **Approaches to obtain radiation tolerant devices:**
  - **Material Engineering:** explore and develop new silicon materials
  - **Device Engineering:** 3D, thin sensors, n-in-p, n-in-n, …

$\Rightarrow$ **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**

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.
  - **MCZ silicon detectors: n-MCZ** show good performance in mixed fields due to compensation of charged hadron damage and neutron damage (N_{eff} compensation) (more work needed)
  - **p-type silicon microstrip detectors show very encouraging results:**
    CCE ≈ 6500 e; $\Phi_{eq} = 4\times10^{15}$ cm^{-2}, 300µm, immunity against reverse annealing!
    This is presently the "most considered option" for the ATLAS SCT upgrade

- **At fluences > 10^{15}cm^{-2} (Inner SLHC layers or innermost upgraded LHC pixel)**
  The active thickness of any silicon material is significantly reduced due to trapping.
  Collection of electrons at electrodes essential: Use n-in-p or n-in-n detectors!
  - **Recent results show that planar silicon sensors might still give sufficient signal,**
    (still some interest in epitaxial silicon and thin sensor options)
  - **3D detectors : looks promising, drawback: technology has to be optimized!**
    Many collaborations and sensor producers working on this.
  - **Diamond has become an interesting option *(Higher damage due to low energy protons?)***

- **Questions to be answered:**
  - **a) Can we profit from the avalanche effects and control them ?**
  - **b) Can we profit from MCZ (mixed field operation?)**

? ? ?

Acknowledgements

- **Some material taken from the following summary talks:**
  - ***RD50 presentations on conferences: http://www.cern.ch/rd50/***
  - ***Nigel Hessey: Eiroforum RADHARD 2010 Workshop, Lisbon 16-18 March 2010 (Path to upgrade)***
  - ***Anthony Affolder: Presentations on the RD50 Workshop in June 2009 (sATLAS fluence levels)***
  - ***Frank Hartmann: Presentation at the VCI conference in February 2010 (Diamond results)***
  - ***… most references to particular works given on slides.***

Further information about RD50 activities: http://cern.ch/rd50/

Further R&D: RD42, RD39, ATLAS & CMS detector upgrade meetings, ATLAS IBL

… or go to DESY bldg. 67b …

…. where you will find the

Particle Physics & Detector Development Group

.. and more expertise

in this research field than I can offer.