Radiation Hardness Studies of Pixel Silicon Detectors

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Outline

- Motivation
- Description of the simulation.
- ATLAS Pixel test beam results and comparison with simulation
- Simulation of ultra rad-hard pixel detectors for use at the SLHC.

Motivation

At high-luminosity hadron colliders, **radiation damage** affects the performances of silicon vertex detectors:

- Increase of space charge density (full depletion voltage)
- Increase of leakage current
- Loss of drifting charge due to trapping

The expected hadron fluence at the LHC (**10^{15} $n_{eq}cm^{2}$**) is already very challenging for current silicon detector technology.

The luminosity upgrade of LHC **(SLHC)** will require vertex detectors to be radiation-hard up to **10^{16} n_{eq} cm^{2}** .

Role of Simulation

The simulation of detector response to ionizing radiation allows

- To optimize the detectors design for performance
- To extrapolate from test beam to collider operation and produce realistic Monte Carlo data samples

It also plays an important role in the R&D of new rad-hard detectors (see talk of A. Candelori), since it allows to understand the effects on detector performance of

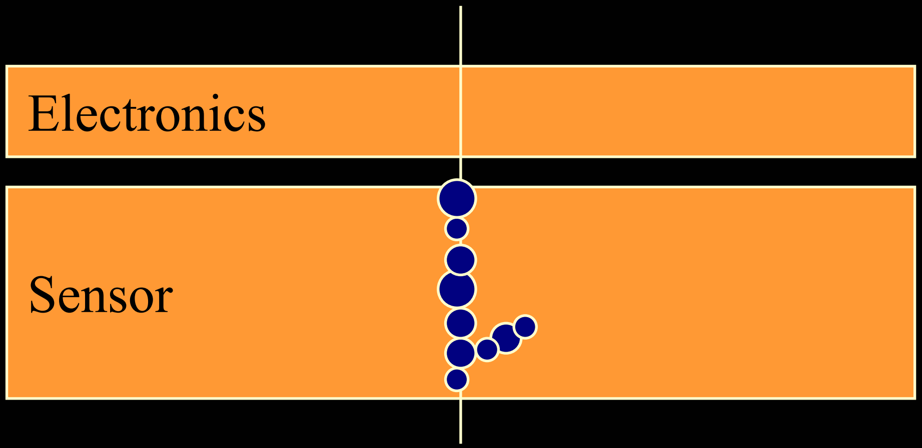
- Material radiation hardness properties (density of defects and charge carrier lifetime)
- Geometry (electrode size and thickness) and operating conditions (temperature, bias voltage)

Basics of simulation

- Ionizing particles interactions in the sensors simulated with **Geant4**
- **Charge drift** in silicon (drift, diffusion, trapping).
- Signal induced on pixel electrodes with **Ramo** potential
- **Front-end electronics** response (threshold, noise)

Charge generation

- GEANT4 simulation of particle interactions with sensor material – includes δ-rays, Landau fluctuations, etc.
- On electron-hole pair every 3.6 eV of energy deposit. Pairs generated inside each GEANT4 tracking segment (20 μm) are spread uniformly along the segment for subsequent drift simulation.



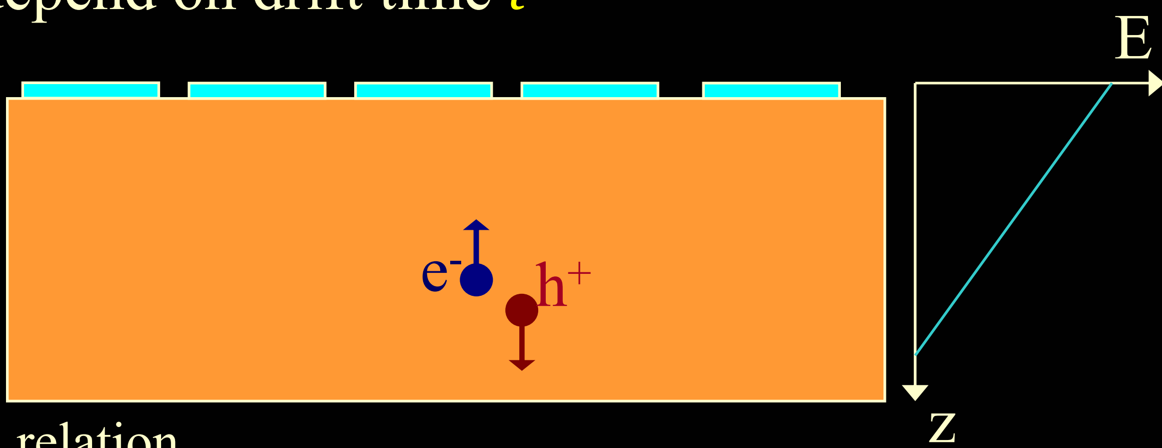
Charge drift

- Electrons and holes are followed inside the sensor in 1 μm steps
- Drift velocity and direction depend on local field $\vec{E}$ and temperature T
- Diffusion and trapping depend on drift time t

Drift $\vec{v} = \mu \vec{E}$

Diffusion $\sigma = 2Dt$

Trapping $P = 1-exp(-t/\tau)$



Diffusivity $D(E,T)$ from Einstein relation

Mobility $\mu(E,T)$ from literature [1]

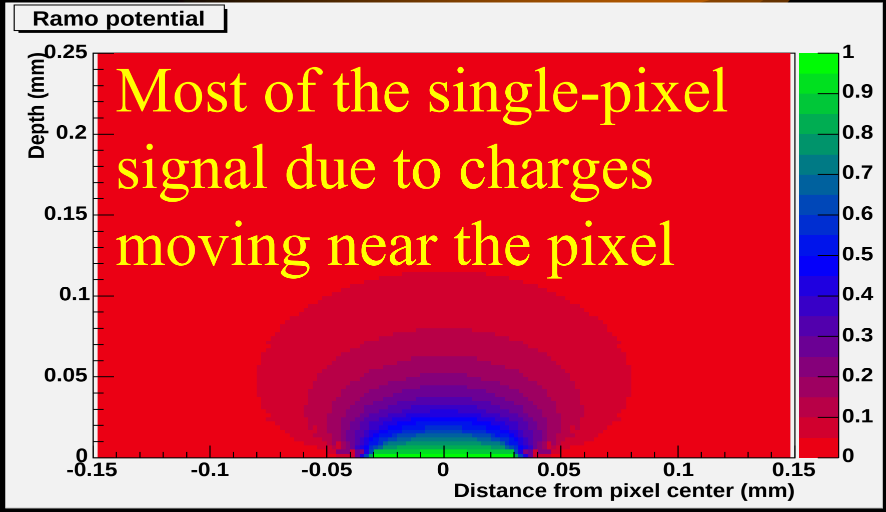
[1] C. Jacoponi et al., Solid State Electr. 20 (1977) 77.

Signal formation

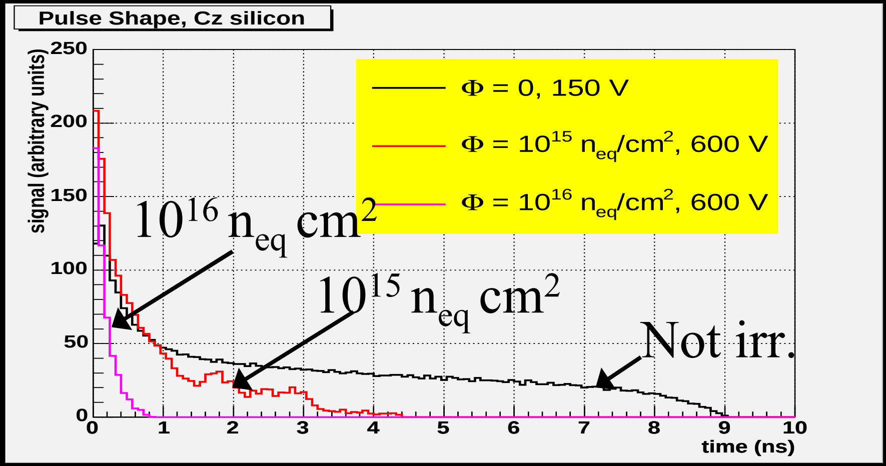
- Moving charges induce a signal on the electrodes
- Computed with weighting field technique

$$I(t) = q\,\vec{\nabla}\,\Phi_w(\vec{r}(t))\,\vec{v}(t)$$

Φ from Laplace equation with appropriate boundary conditions. It depends on electrodes geometry- not on the depleted depth, since resistive (intrinsic) undepleted bulk in irradiated sensors.



Time profile of induced signal.
As irradiation reduces depleted depth
And charge lifetime signal gets shorter
(well below 1 ns for 10^{16} n cm^{-2})

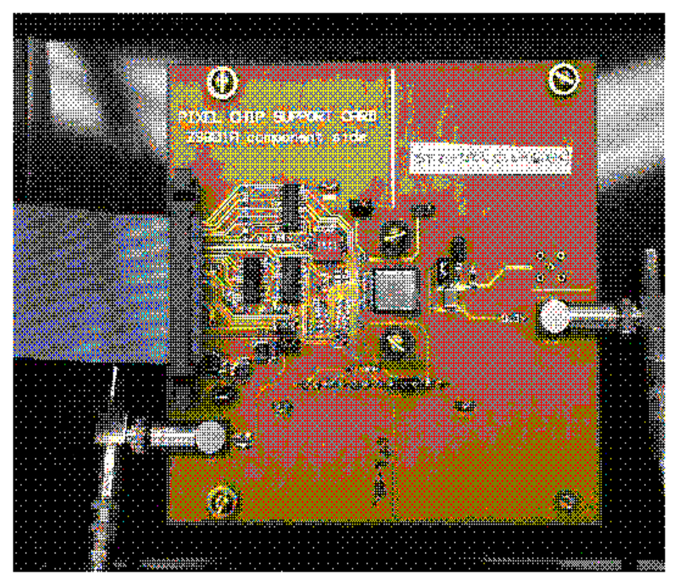


Electronics response

- Gaussian noise
- Cross-talk between neighboring pixels
- Discriminator threshold
- Threshold dispersion

ATLAS Pixel Test Beam

- Performed at CERN with 180 GeV pion beam
- Microstrip beam telescope with 6 μm resolution
- Asynchronous beam. A scintillator provides the time of particles relative to the 40 MHz clock edge.

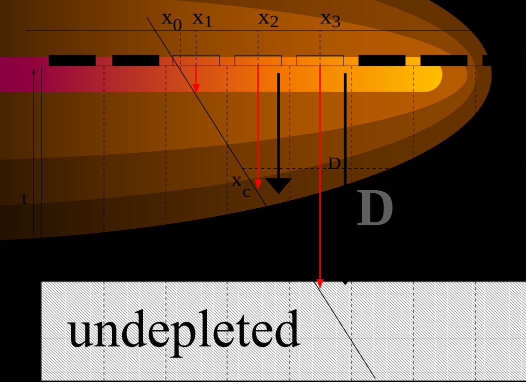


An ATLAS Pixel detector (at the center) on its test beam support board

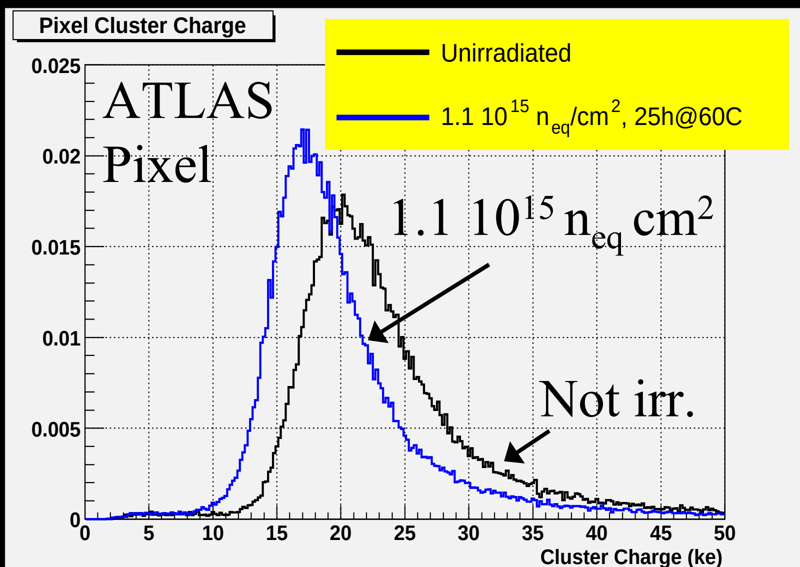
- Diffusion oxygenated silicon sensors [2] and rad-hard electronics [3,4] irradiated to **10^{15} n_{eq} cm^{-2}**

[2] I. Gorelov et al., Nucl. Instr. and Meth. A489, 202
[3] E. Mandelli et al., IEEE Trans. on Nucl. Sci. 49, 1774.
[4] L. Blanquart et al., IEEE Trans. on Nucl. Sci. 49, 1778.

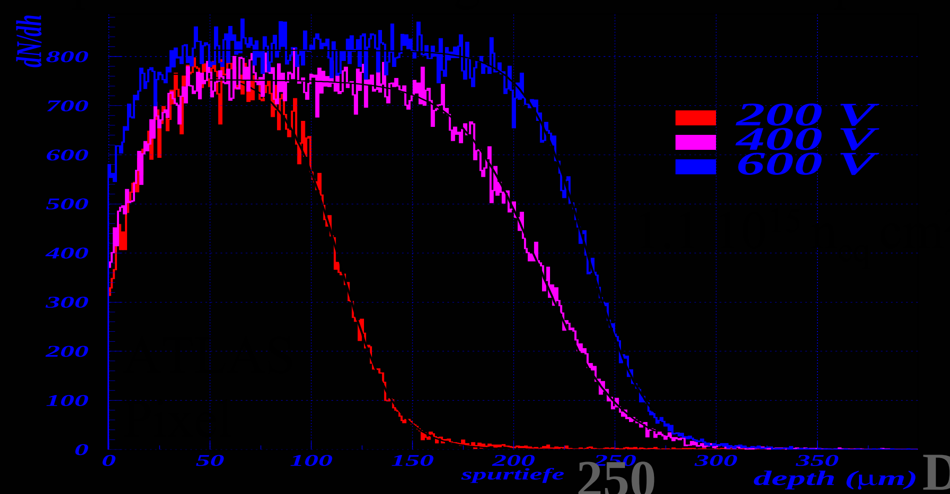
Experimental results (I)



Total charge of the pixels above threshold



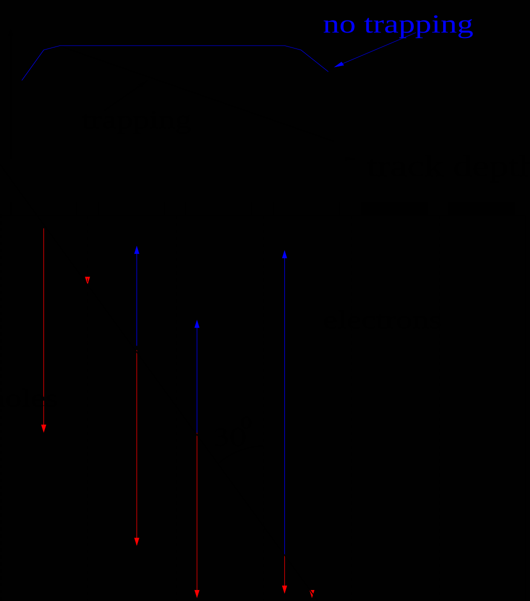
Before irradiation Q = 25ke$^-$±10%
After irradiation Q = 21ke$^-$±10%
80% charge collection efficiency

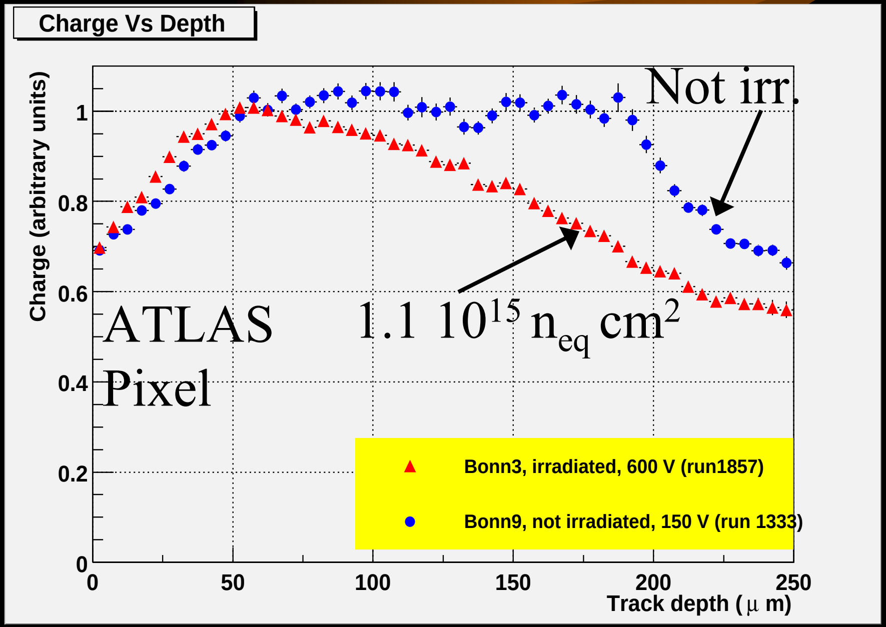


250 μm thick oxygenated sensors are **fully depleted** at 600V [5]

[5] C. Troncon, Nucl. Instr. and Meth. A530, 65.

Experimental results (II)

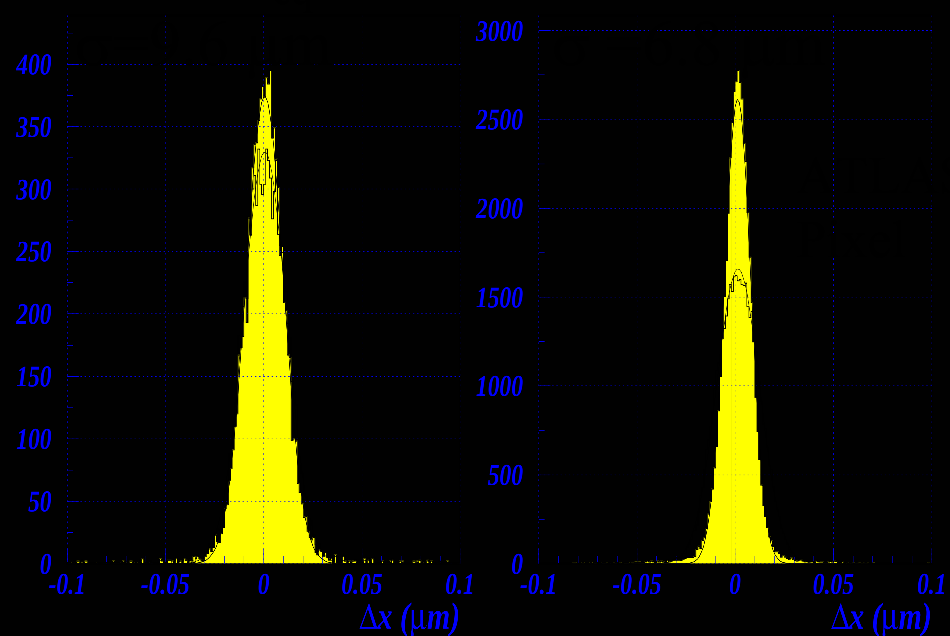


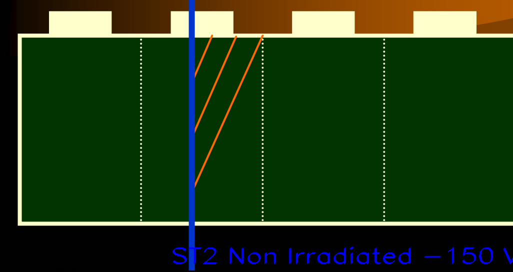


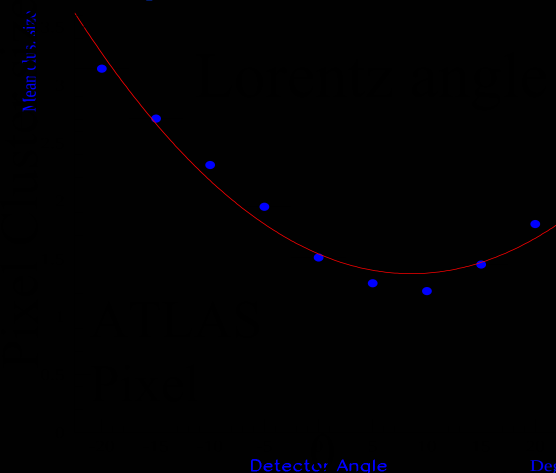
Trapping is seen as a decrease of pixel charge with track segment depth [6]. A comparison with simulation is used to extract charge lifetime (see later).

[6] T. Lari, Nucl. Instr. and Meth. A518, 349.

Experimental results (III)





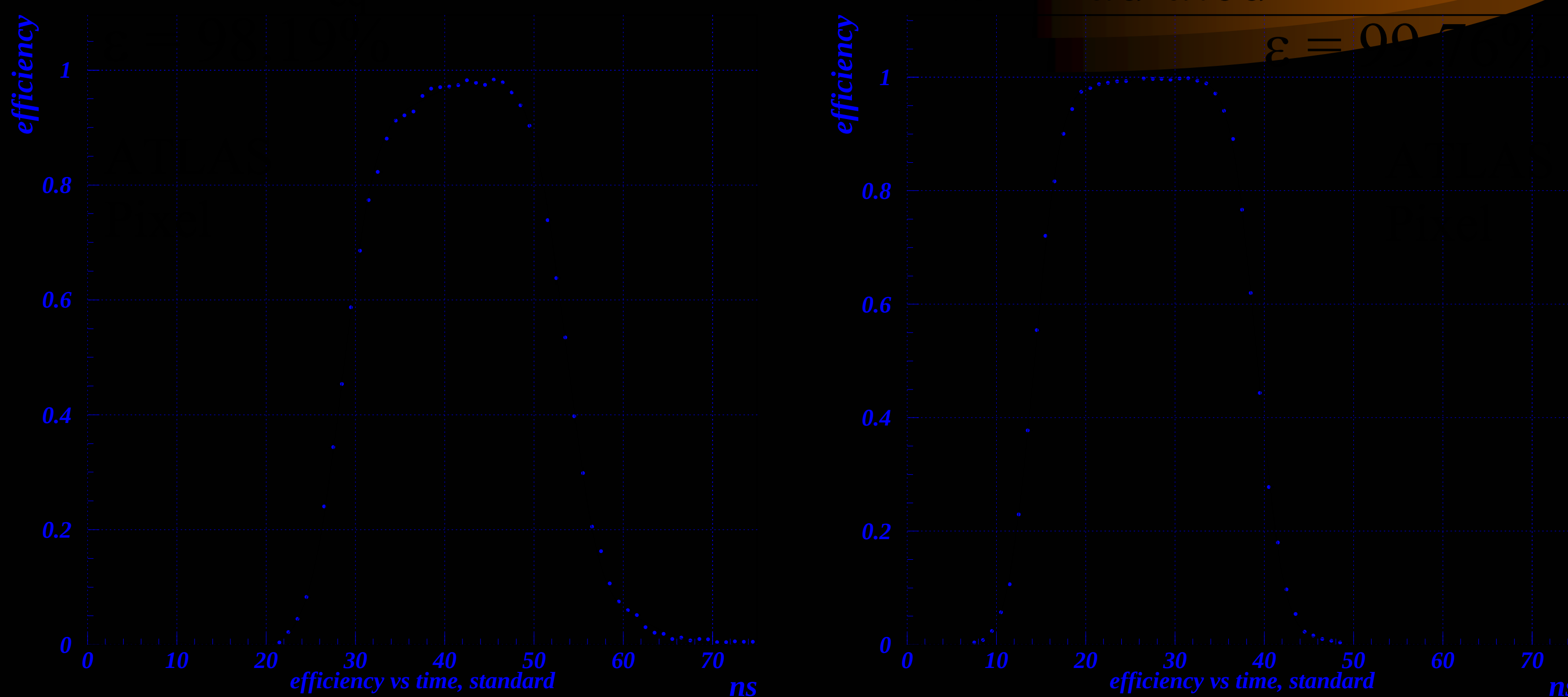


Spatial resolution at 10^0 incidence angle along the short pixel direction [7,8]

[7] I. Gorelov et al., Nucl. Instr. and Meth. A481, 204
[8] A. Andreazza, Nucl. Instr. and Meth. A513, 103.

Lorentz angle @2T,150V = -15^0
Lorentz angle @2T,600V = -5^0
Pixel modules tilt in ATLAS=20^0

Experimental results (IV)



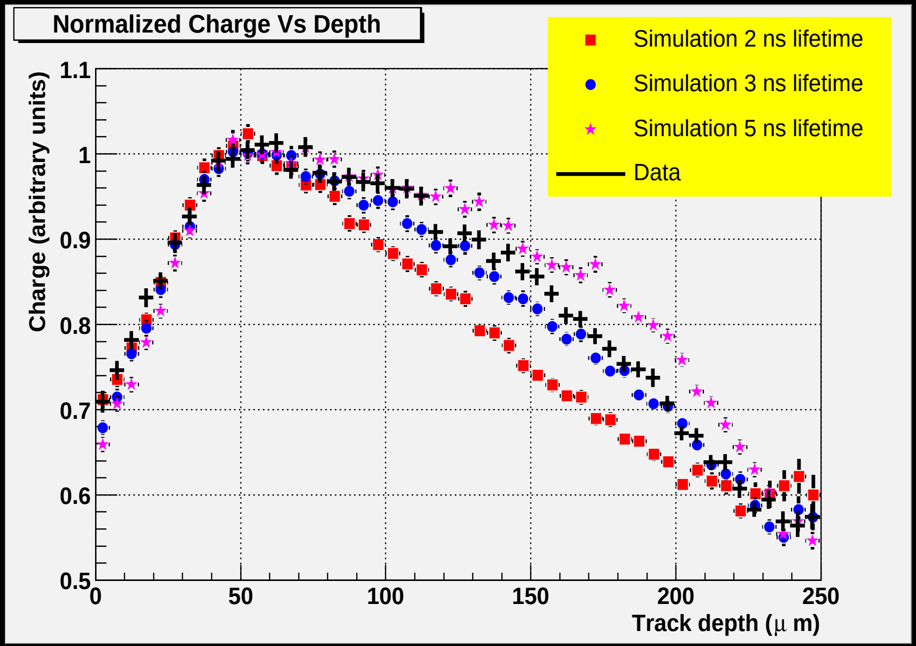
Efficiency vs phase between particle TDC and clock edge [8]

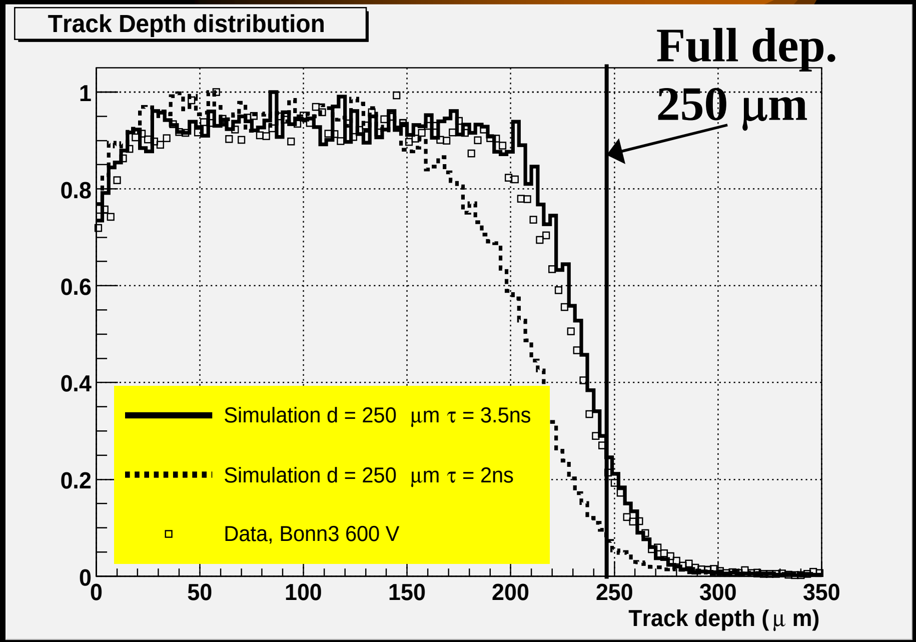
[8] A. Andreazza, Nucl. Instr. and Meth. A513, 103.

Test Beam Simulation

- Electronics parameters are taken from laboratory measurements
  - threshold = 3100 e
  - threshold dispersion = 180 e
  - noise = 410 e
  - xTalk = 3.7 %
- Beam telescope is not simulated; track extrapolation is true position smeared with 6 μm telescope resolution
- Charge lifetime and depleted depth from test beam measurements

Simulation Vs Data (I)



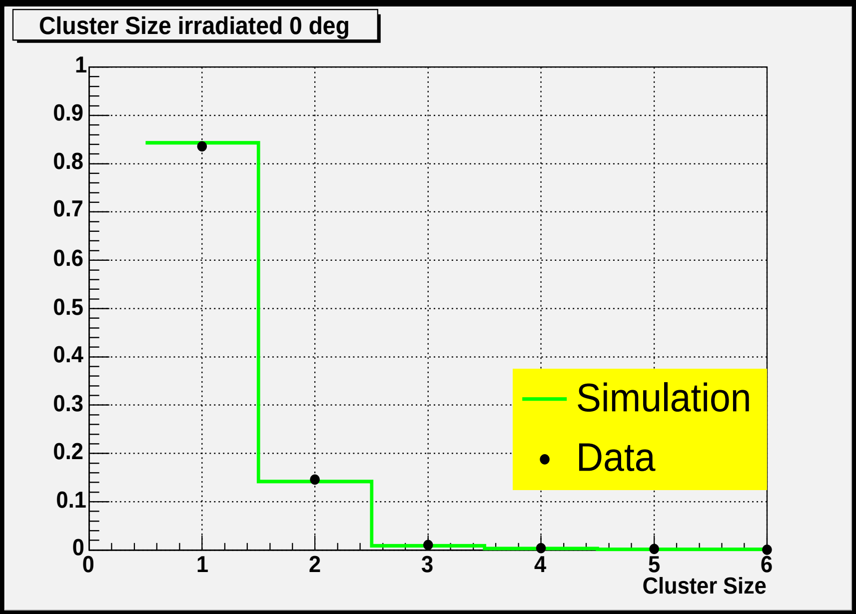


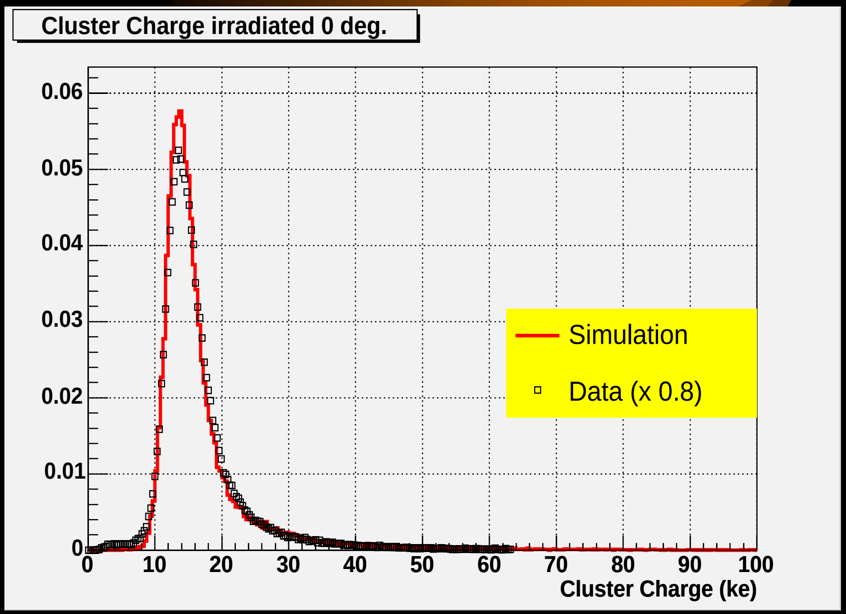
Charge lifetime is extracted comparing the experimental and simulated Charge Vs Depth distributions. Here, $\tau = 3.5$ ns

Equal hole and electron lifetime assumed.

Assuming full depletion gives a good agreement with data.

Simulation Vs Data (II)

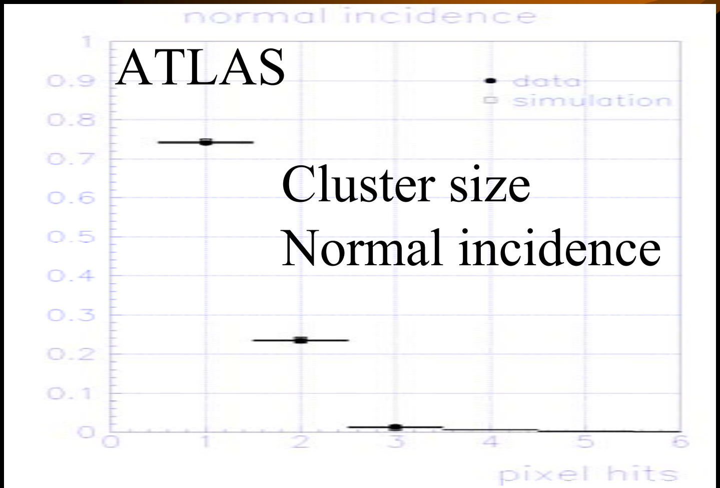


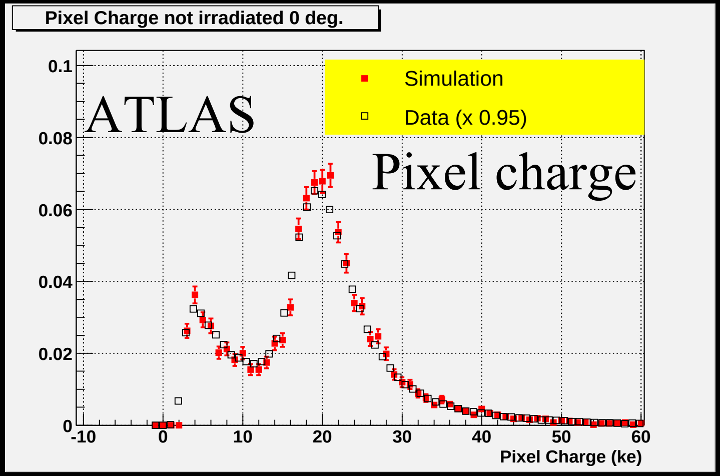


Basic experimental distributions (cluster size and charge distributions) are reproduced reasonably well by the simulation.
Good agreement is found also for larger incidence angles and not irradiated sensors.

ATLAS Simulation

- The simulation used to produce ATLAS Monte Carlo data needs to be faster. G4 hits are mapped directly to the surface – no description of drift and signal induction processes. Also no description of radiation damage yet.
- In good agreement with test beam data for not irradiated sensors (comparison made with ATLAS simulation code, only geometry description is test-beam specific)
- The detailed simulation will be used to develop (fast) parameterization of radiation damage effects to insert in ATLAS official simulation code.





The upgraded LHC

- With moderate hardware changes the LHC may be upgraded to a luminosity of 10^{35} cm^{-2} s^{-1} (Gianotti et al., hep-ph/0204087)
- The experiments trackers will require major changes to cope with the increased integrated fluence and track density.
- An increase of the bunch crossing rate to 80 MHz is also foreseen.
- The operation of silicon pixel detectors at the current radius of the inner ATLAS layer will require

- Tolerance to an hadron fluence of the order of **10^{16} n_{eq} cm^{-2}** and a dose of the order of 5 MGy
- Smaller pixel size to cope with increased track density
- Faster readout

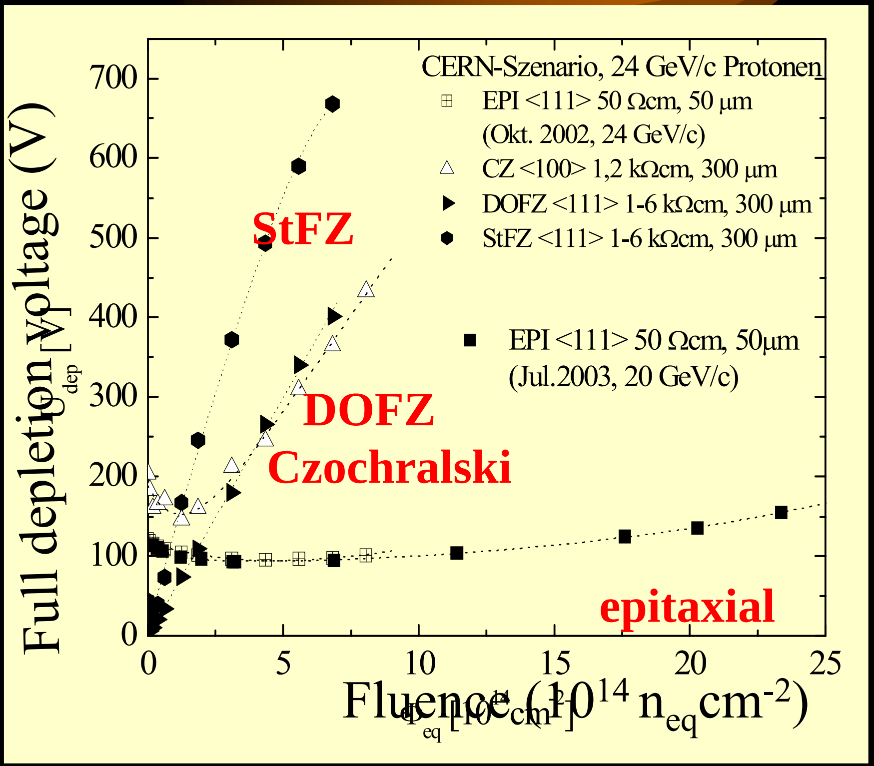
New Rad-Hard materials

See talk of A. Candelori

Developed by RD50 collaboration. Most promising [10]:

- **Diffusion oxygenated** [9,10] (used by ATLAS)
- **Czochralski**. [9,11] Excess of radiation-induced Donors, so material becomes more n-type with irradiation
- **Epitaxial [9,12]** Thin active layer (some 50 µm). Room temperature operation possible, and an almost zero net radiation induced space charge

Trapping lifetime is however similar for all materials



Picture from [9,12]

[9] RD50 Collaboration Status Report, CERN-LHCC-2003-058.
[10] G. Lindstrom et al., Nucl. Instr. and Meth. A466 (2001) 308.
[11] J. Harkonen et al., Nucl. Instr. and Meth. A518 (2004) 224.
[12] G. Kramberger et al., Nucl. Instr. and Meth. A515 (2003) 665.

Simulation for SLHC

- Introduction of charged defects :

$N_{eff} = g\Phi$

$g = 0.023\ cm^{-1}$ **Standard FZ**

$g = 0.009\ cm^{-1}$ **DOFZ**

$g = -0.009\ cm^{-1}$ **Czochralski**

(negative space charge)

$N_{eff} = -5.79\ 10^{13}\ cm^{-3}$ **epitaxial**

(constant space charge)

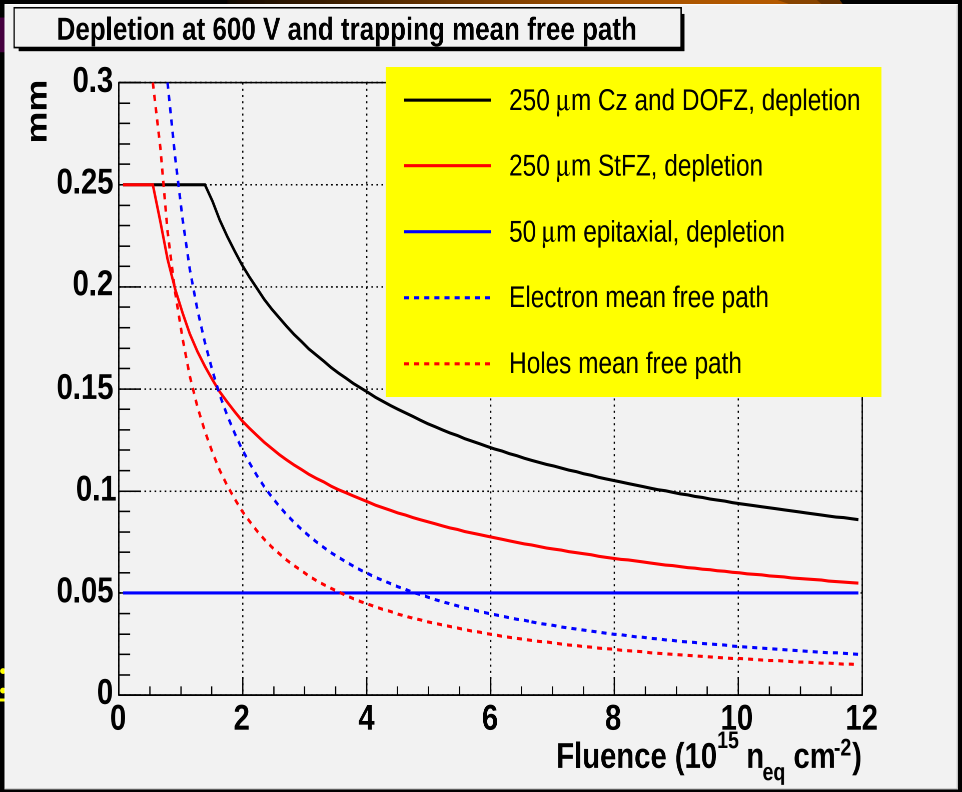
($V_{fd} = 100$ V for a 50 μm sensor)

- Trapping (same for all materials) [9,13]:

$1/\tau = \beta\Phi$

$\beta_e = 5\ 10^{-16}\ (T/263K)^{-0.86}\ cm^2/ns$

$\beta_h = 5\ 10^{-16}\ (T/263K)^{-1.52}\ cm^2/ns$



At high fluences charge collection is limited by trapping mean free path

[9] RD50 Collaboration Status Report, CERN-LHCC-2003-058.

[13] G. Kramberger et al., Nucl. Instr. and Meth. A481, 297.

Some parameters

- Unless otherwise specified…
- Pixel size was chosen to be 70 μm x 70 μm (smaller than in ATLAS to deal with a larger track density – possible with 0.13 μm electronics?)
- Thickness was 250 μm, except for epitaxial sensors (a typical thickness of 50 μm was used)
- Bias voltage: 600 V irradiated FZ and Cz, 150 V not irradiated and epitaxial.
- Temperature: -10 ^{0}C
- Zero incidence angle, no magnetic field

n-type or p-type?

The readout have been chosen to be on the side where the electric field is maximum after irradiation, since this choice results in a better CCE and allows operation in partial depletion mode:

- n-side readout for FZ and DOFZ
- p-side readout for Cz
- p-side readout for epitaxial (first RD50 samples had n-type bulk).

Charge Collection Vs Fluence

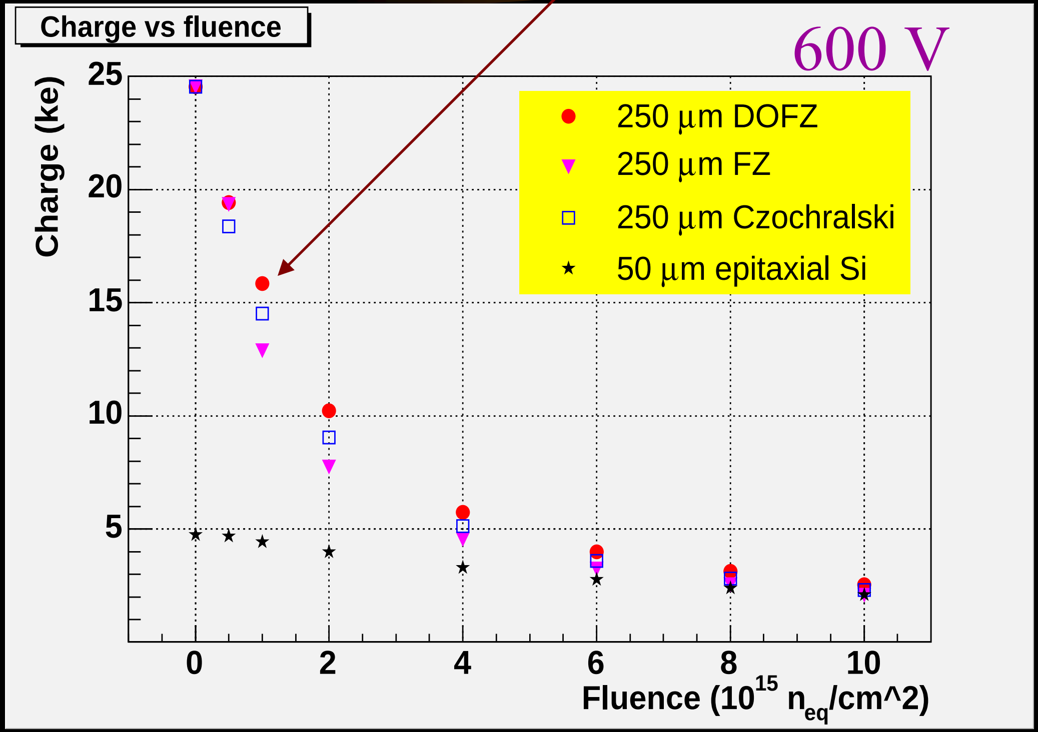
ATLAS end-of-lifetime irradiated

10^{15} fluence:

- DOFZ better than StFZ when the latter is no longer fully depleted at 600 V
- DOFZ slightly better than Cz (because of n-side signal)
- epitaxial signal very low (because of thin sensor)

10^{16} fluence:

- All detectors are similar (trapping dominant)

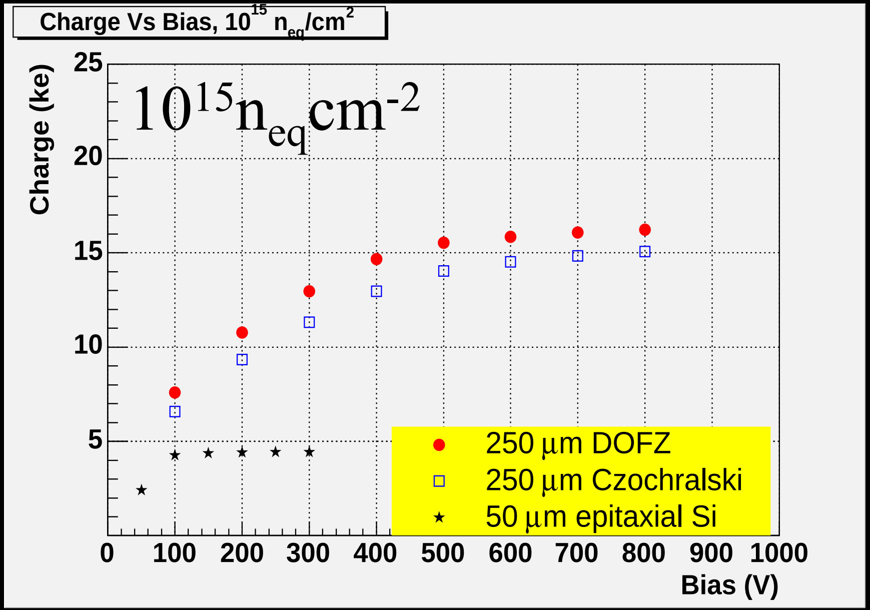


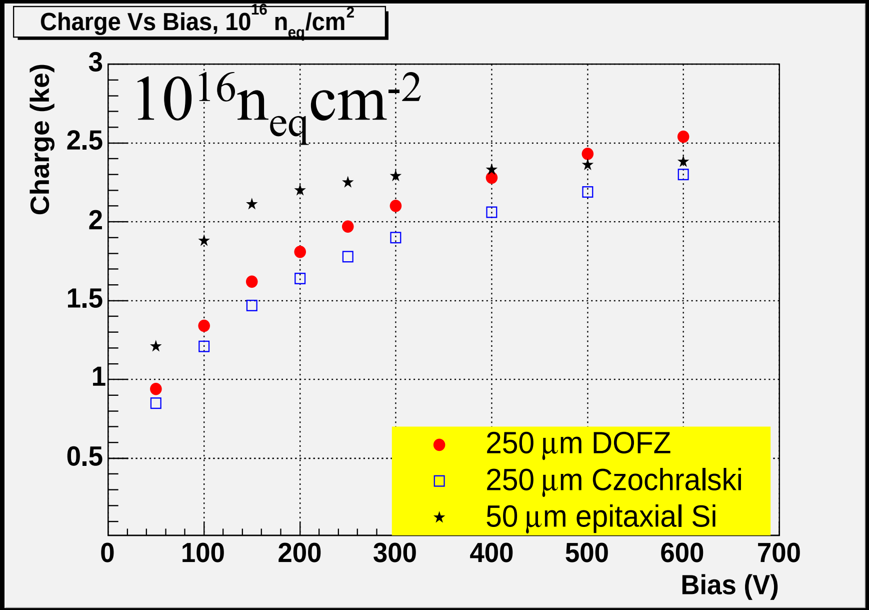
Results should be very similar for strip detectors

Charge collection vs bias voltage

$\Phi = 10^{15}$ n/cm^2 : Cz and DOFZ fully depleted at 440 V, epitaxial at 100 V. Signal increases up to full depletion voltage and is (almost) constant above it.

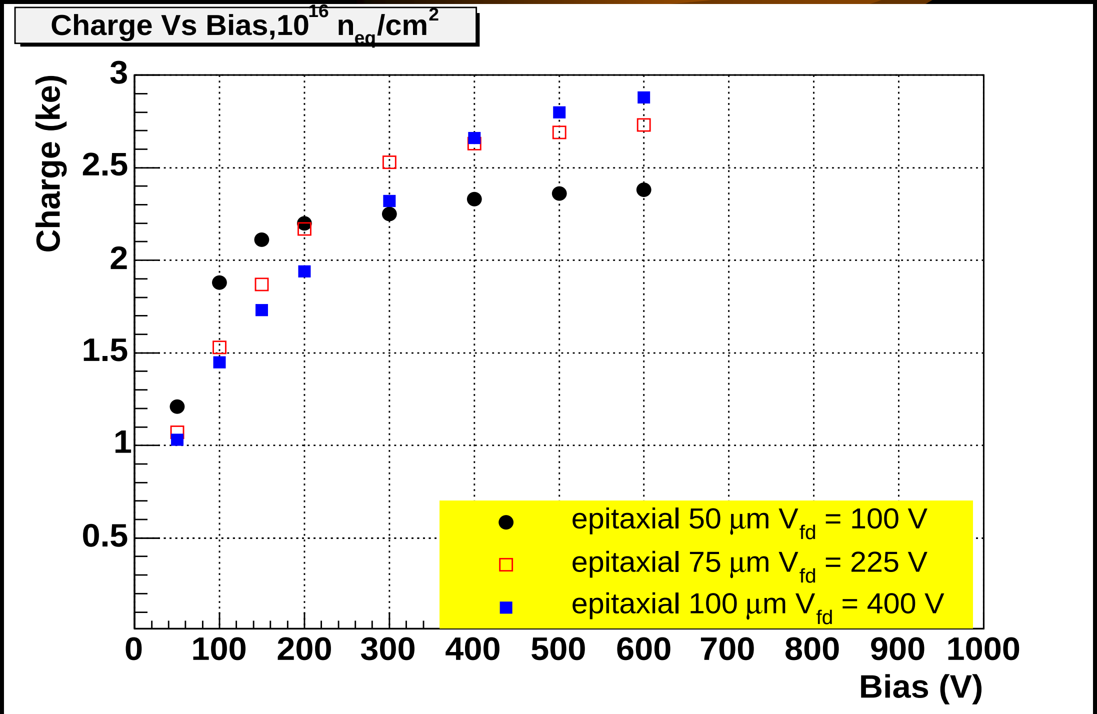
$\Phi = 10^{16}$ n/cm^2 : Cz and DOFZ fully depleted at 4400 V, epitaxial at 100 V. Signal limited by trapping gradually saturates as drift velocity approaches the high-field limit





Charge versus epi thickness

- At low bias (partial depletion) it is convenient to have thin sensors, to avoid the pixel weighting field extending in the undepleted region.
- At high bias (full depletion) it is convenient to have thick sensors to get all the charge.
- Maximum is about 3000 e^-.



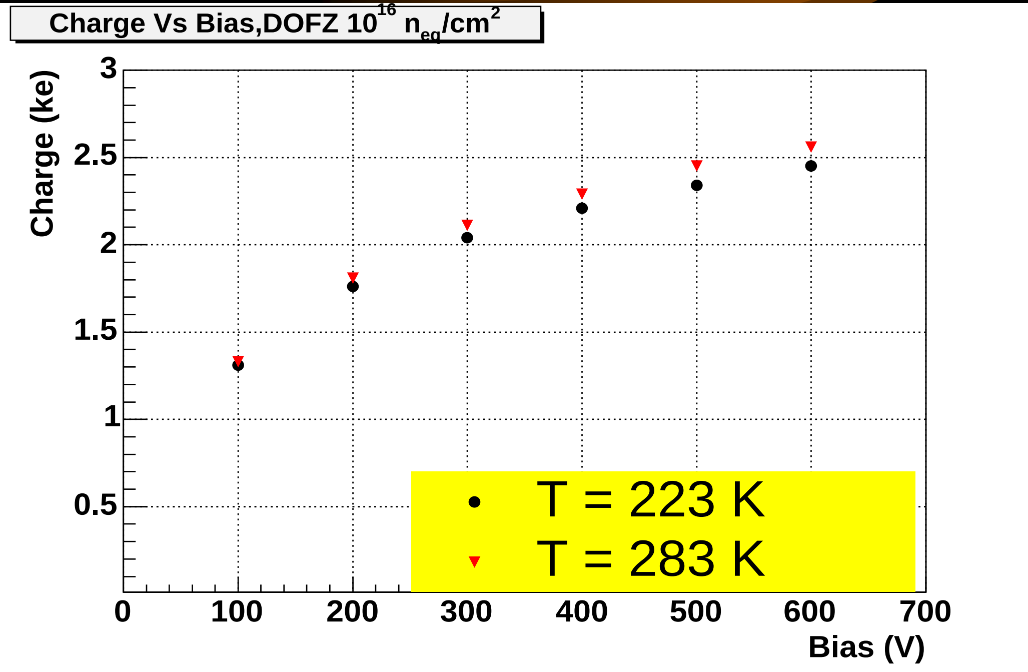
Charge collected after 10^{16} n/cm^2 as a function of bias, for 50 µm, 75 µm and 100 µm thick epitaxial sensors

Cold vs Hot

Two contrasting effects:

- Trapping lifetime increases with temperature
- Mobility decreases with temperature

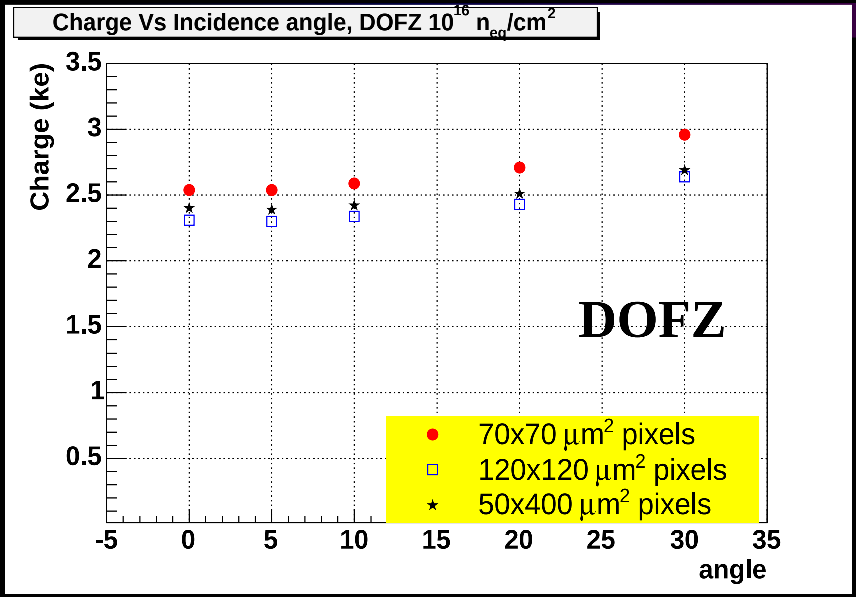
Net result is that collected charge depends very little on temperature

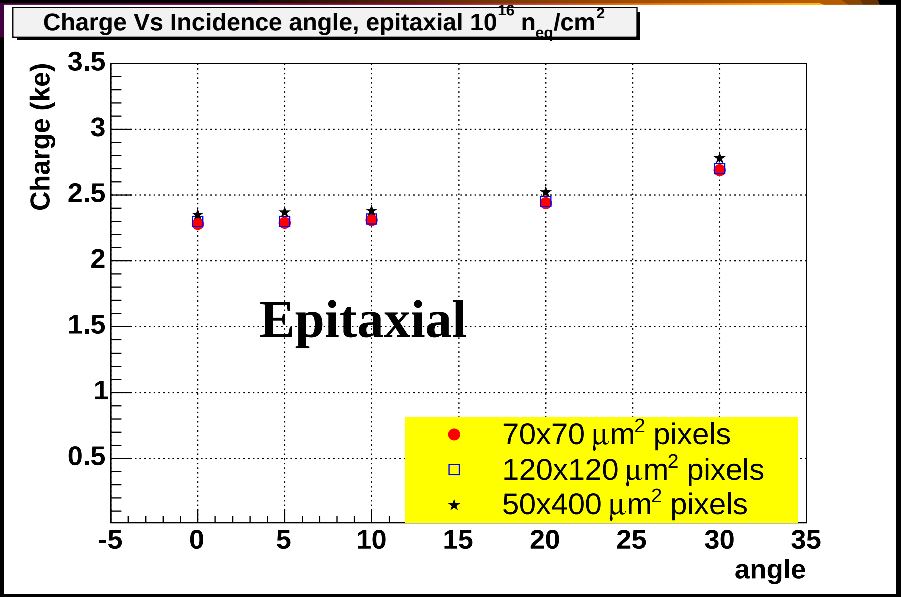


Below 200 K changes in the dynamics of radiation-induced defects (Lazarus effect), not considered here.

Charge collected after 10^{16} n/cm^2 as a function of bias, for two different temperatures and DOFZ sensor

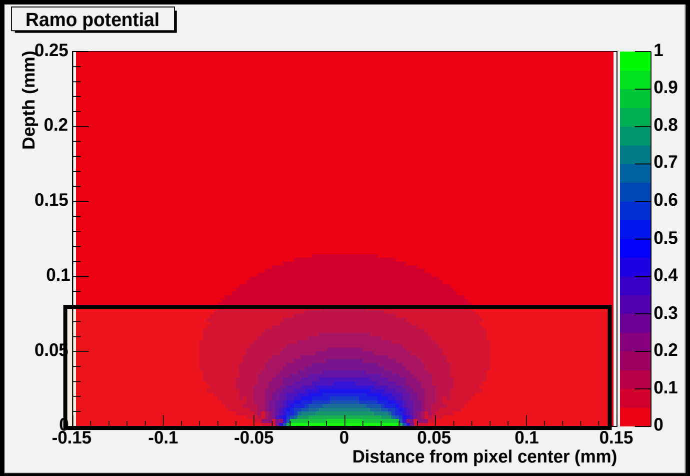
Angle and Pixel size





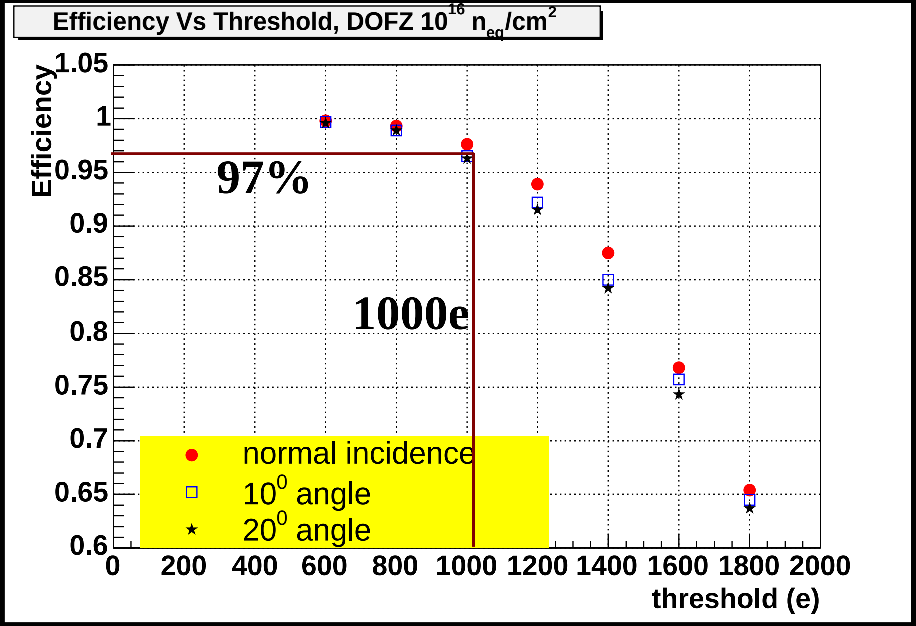
Thick, largely undepleted sensor: larger pixel size ⇒ more pixel weighting field in the undepleted region ⇒ less charge

Thin sensor: no dependence of total charge size.

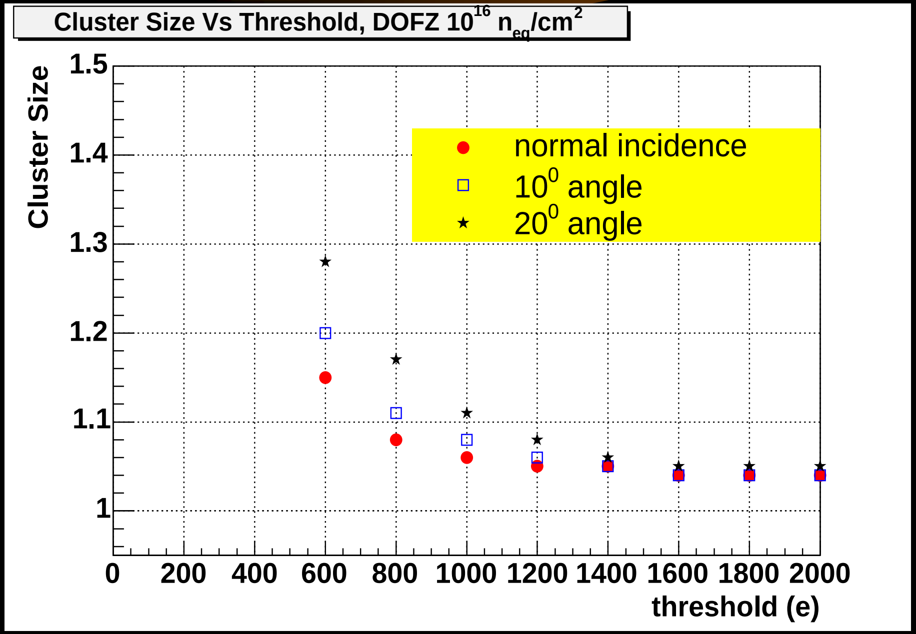


Efficiency and Cluster Size

DOFZ, 600V, 10^{16} n/cm^2

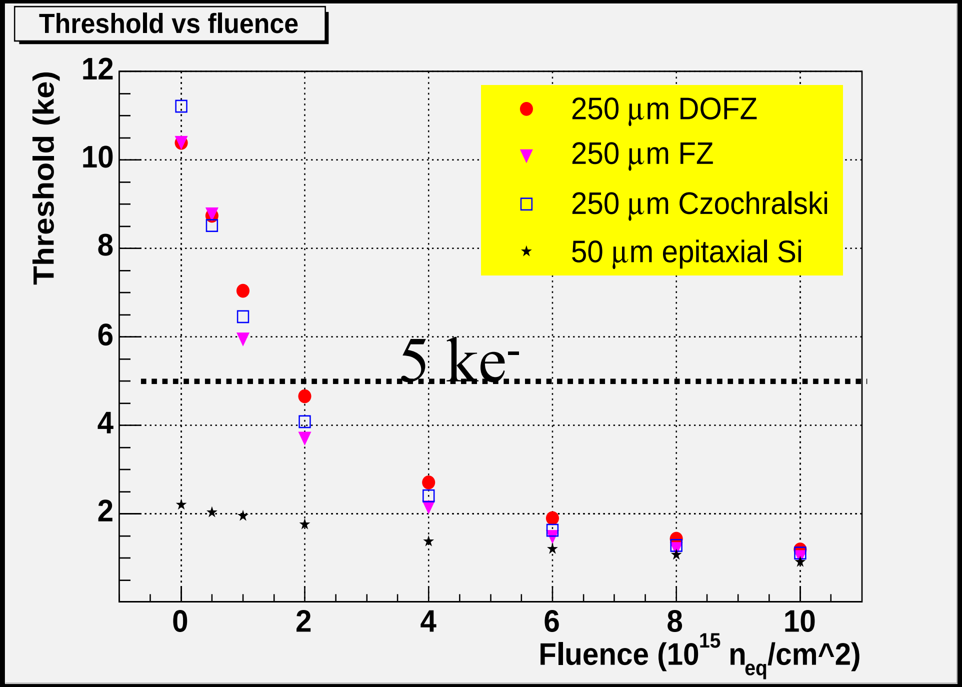


Detection efficiency vs electronics threshold.



Average cluster size vs electronics threshold. Mostly single pixel hits.

Threshold and detection efficiency



- The minimum charge which is detected within the trigger window is the in-time threshold.
- Present ATLAS Pixel detectors irradiated to **10^{15} n_{eq} cm^{-2}** do achieve a detection efficiency of **98.2%** with an in-time threshold (at 40 MHz) of about 5000 e^-.
- After **10^{16} n_{eq} cm^{-2}** an in-time threshold of 1000 e^- is needed (at 80 MHz) to have 97% detection efficiency.

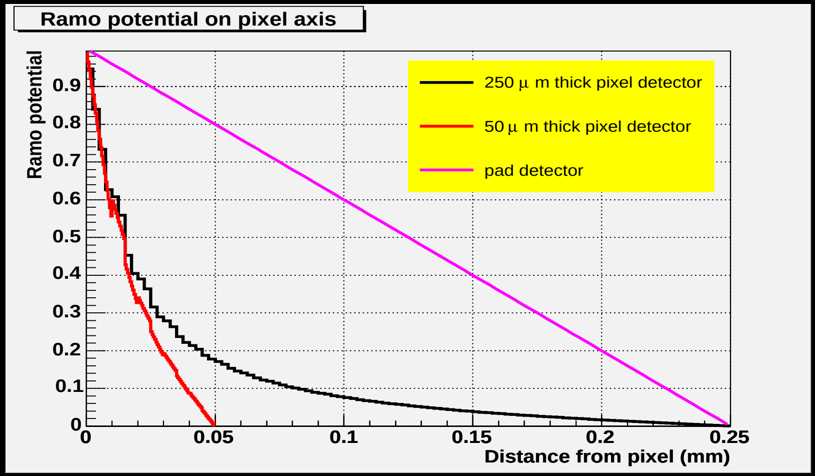
Big challenge for front-end electronics!

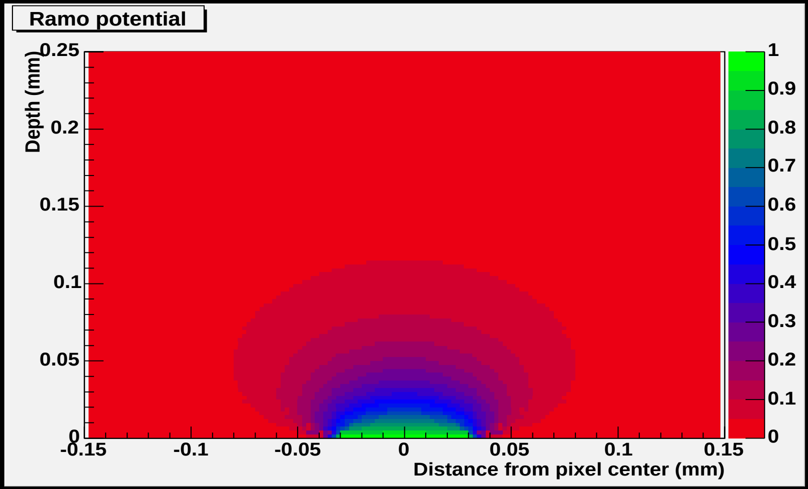
Conclusions

- **LHC**: At the test beam Present ATLAS Pixel detectors irradiated to **10^{15} $n_{eq}cm^2$** fluence still do achieve 98% detection efficiency, 10 μm resolution (see also the talk of C. Gemme)
- A detailed simulation of irradiated silicon detectors was used to get a deeper understanding of test beam data.
- **SLHC**: The performance of pixel detectors using different silicon materials was simulated after irradiation up to **10^{16} n_{eq} cm^{-2}**
- At the highest fluence, mean signal is **2000-3000 electrons** regardless of material, limited by charge trapping.
- Sensitivity to **1000 electrons** (fast and low noise rad-hard front-end electronics) is required to operate with high (97%) detection efficiency.

Backup slides

Small pixels vs pad diode



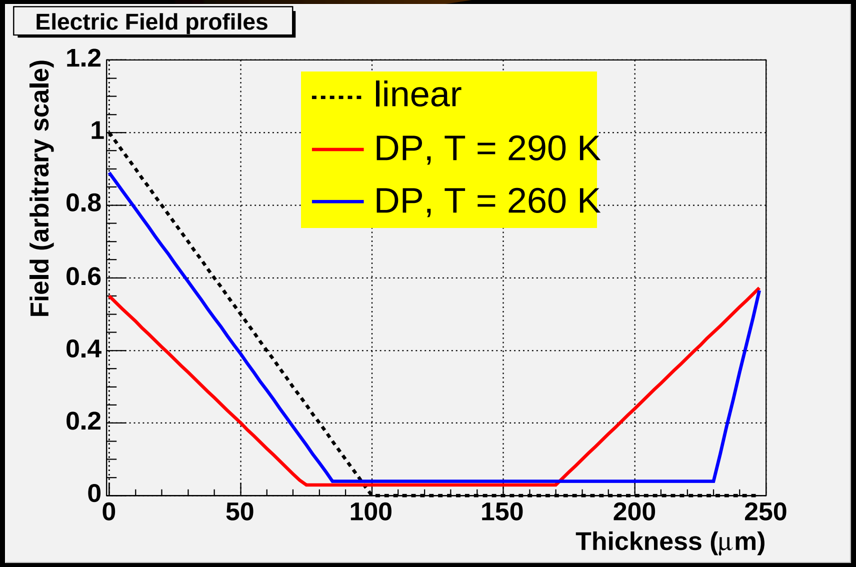


- In a detector with small electrodes most of the signal comes from charges moving near the electrodes.
- Example: in a 250 μm thick detector with 50 μm depletion a charge traversing the depleted region would give **80%** CCE on the nearest pixel. The response of a pad detector (= sum of **negative and positive** signals on all pixels) is only **20%** of the charge!

In this talk the charge collected is the sum of **positive** signals (because of electronics threshold, negative signals are useless) . Can be **very different** from pad diode CCE.

Electric field

- The field distribution in irradiated silicon has a double peak structure and is a function of dose and temperature. [14-16]
- Power consumption and noise issues require operation at low (about -10 ^{0}C) temperature to control leakage current.
- At these temperatures the linear field aproximation is good for small strips/pixels: charge drift far from the electrodes contributes very little to detector response.



Presently we use the linear field aproximation.

[14] G. Casse, NIM A426, 140
[15] V. Eremin et al., NIM A360, 458
[16] V. Eremin et al., NIM A476, 556

Other parameters

- At a temperature of -10 ^{0}C the leakage current for DOFZ detectors after 10^{16} n_{eq} cm^{-2} is
- 2x smaller (per pixel): less shot noise (35 e for 10 ns integration time)
- 2x larger (per unit area): more power consumption

than for ATLAS pixels after 10^{15} $n_{eq} cm^{-2}$ (larger fluence compensated by smaller active volume and temperature)