Simulation of irradiated silicon detectors: an update

T. Lari, C. Troncon
INFN Milano

Motivation

- SLHC vs LHC: larger fluences, higher track density, faster readout.
- Silicon detectors operation will require fast, rad-hard, sensitive front-end electronics, smaller pixel size, new (more rad-hard) sensors (DOFZ, Cz, epitaxial, thin silicon, ?)
- Simulation of irradiated silicon detectors allows
  - To connect material properties (N_{eff} and fluence) with detector performance
  - To understand the effect of geometry (electrode size and thickness) on performance
  - To understand if silicon detectors can be operated with high efficency at fluence around 10^{16} cm^{-1}

Our simulation

From parameterizations of N_{eff} and lifetime as a function of fluence/annealing it computes the performances of irradiated silicon pixel detectors for different

- materials
  - StFZ, DOFZ, epi Si, Cz
- doping
  - n+/p, p+/n
- geometries
  - pixel size, thickness
- operating conditions
  - bias, temperature
- front-end electronics parameters
  - threshold, noise

What is new?

In November, we have presented results for StFZ, DOFZ, thin DOFZ detectors with ATLAS pixel size (50 x 400 μm^2)

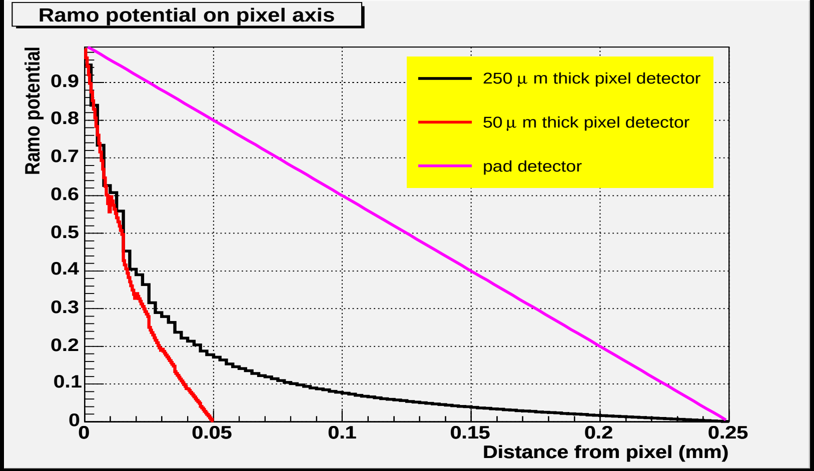
(Main) upgrades:

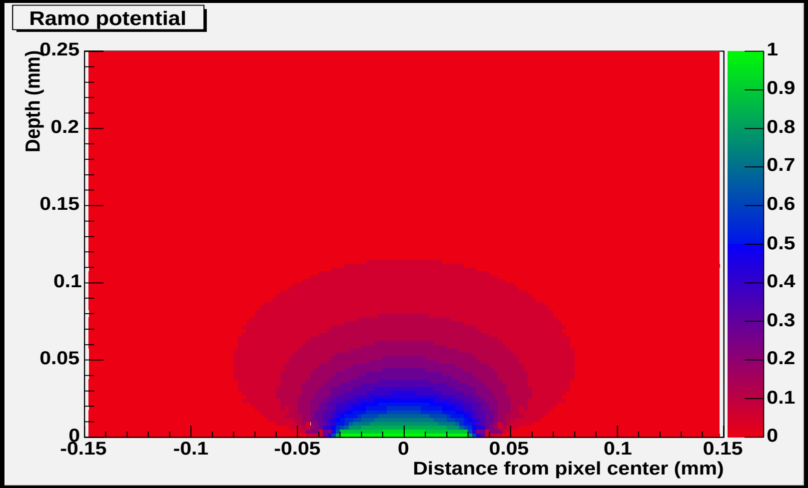
- added Cz and epitaxial Si.
- Pixel size is now a job parameter (strip simulation also possible). This talk: smaller pixel size (70 x 70 μm^2) to cope with increased track density at SLHC (use 0.13 μm electronics?).
- Pulse time profile and charge collection time.

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)
- See the presentation of November for more detailed info.

Small pixels vs pad diode



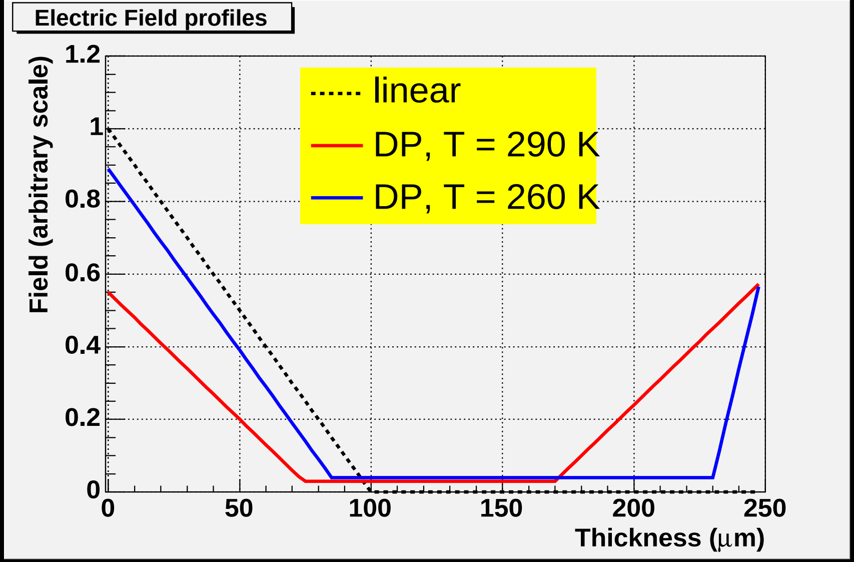


- In a detector with small electrodes most of the signal comes from charges moving near the electrodes.
- Example: in a 250 µm thick detector with 50 µm depletion a charge traversing the depleted region would give **80%** CCE on the nearest pixel. The response of a pad detector (= sum of **negative and 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. [1-3]
- 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.

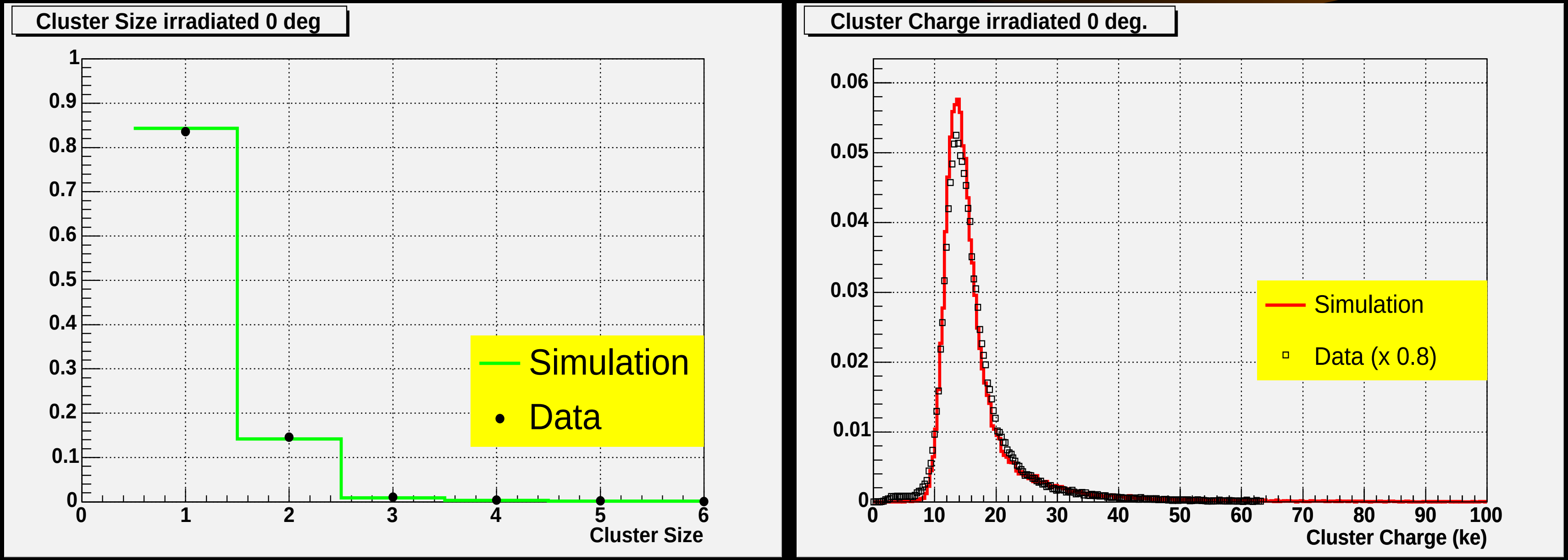


[1] G. Casse, NIM A426, 140
[2] V. Eremin et al., NIM A360, 458
[3] V. Eremin et al., NIM A476, 556

Presently we use the linear field aproximation.

Comparison with data

Simulation validated with experimental data



Comparison with ATLAS Pixel detectors irradiated to 1.1 10^{15} n_{eq} cm^{-2}

All parameters from measured values [4-5]

[4] T. Lari, ATL-INDET-2003-015

[5] T. Lari, NIM A518, 349

Radiation damage

- $N_{eff} = g\Phi$

$g = 0.023\ \mathrm{cm}^{-1}$ StFZ

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

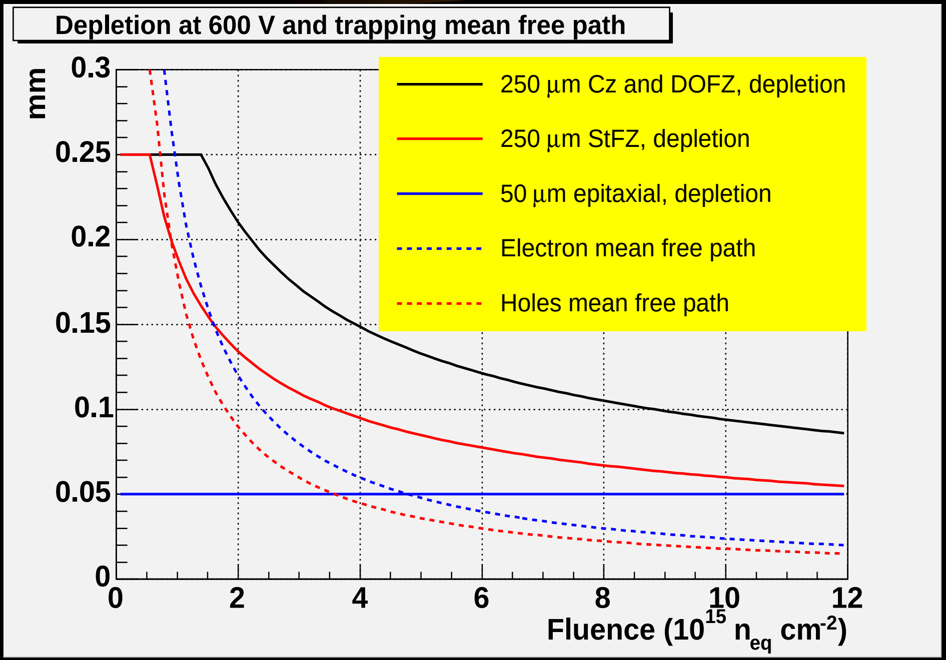
$g = -0.009\ \mathrm{cm}^{-1}$ Cz

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

($V_{fd} = 100$ V for 50 μm sensor)

- $1/\tau = \beta\Phi$

$\beta_e = \beta_h = 5\ 10^{-16}\ \mathrm{cm}^2/\mathrm{ns}$



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

n-type or p-type?

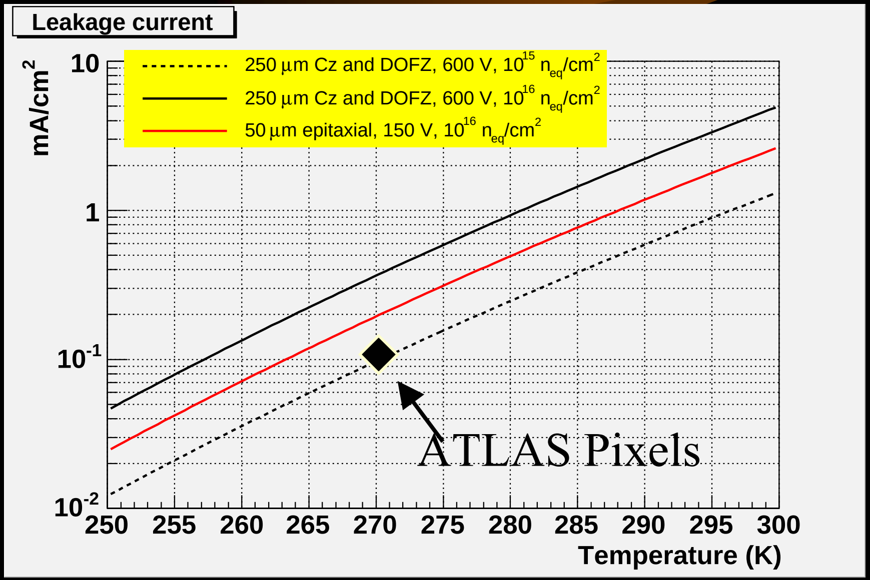
The readout have been chosen to be on the side where the electric field is maximum after irradiation, since this choice results in a better CCE and allows operation in partial depletion mode:

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

Other parameters

- Thickness 250 µm (as in ATLAS), 50 µm for epitaxial (as first RD50 samples). See November's talk for a DOFZ threshold scan.
- temperature = -10 ^{0}C
- Bias voltage: 600 V irradiated FZ and Cz (as in ATLAS),

  150 V not irradiated and epitaxial.
- Zero incidence angle, no magnetic field



With these parameters 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)

Charge Collection Vs Fluence

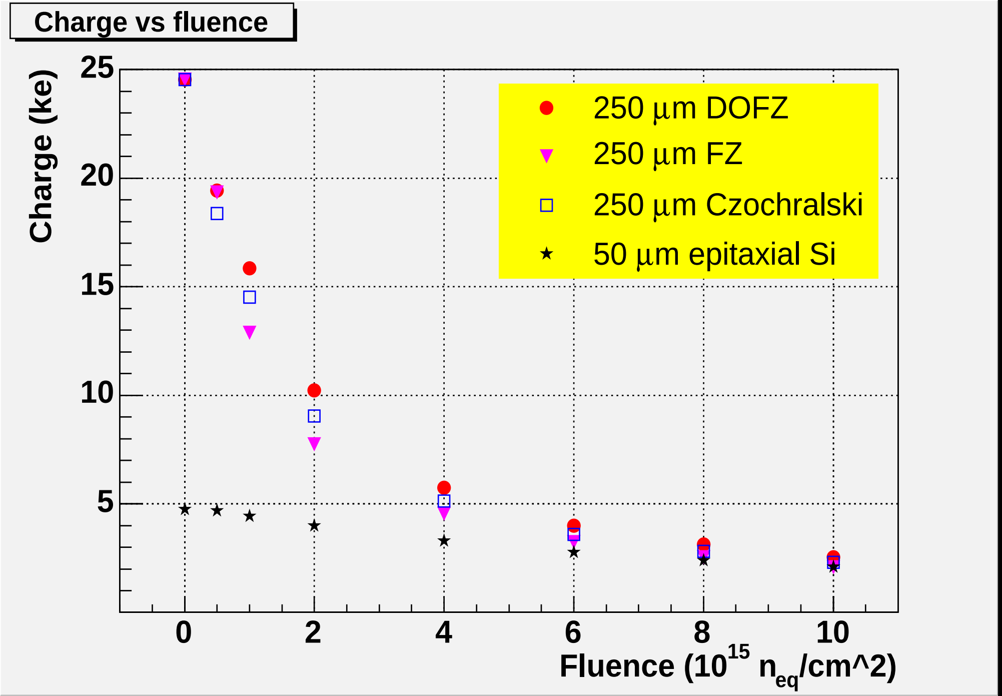
10^{15} fluence:

- 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)

600 V

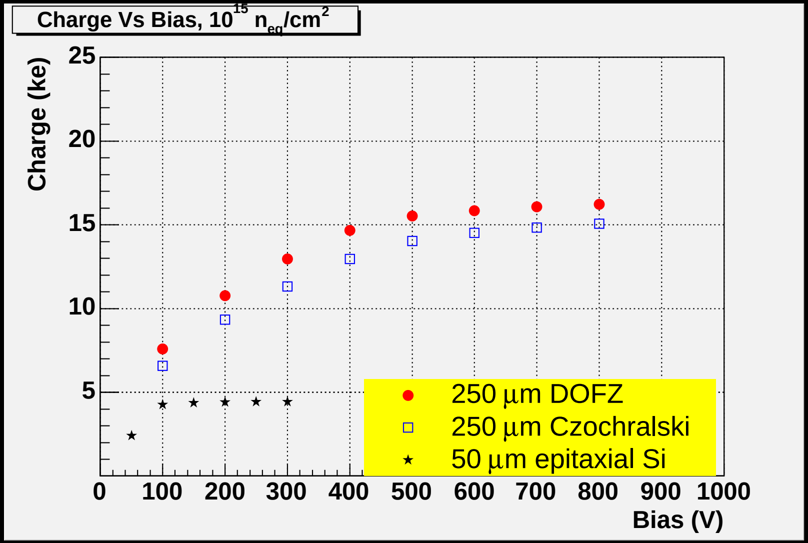


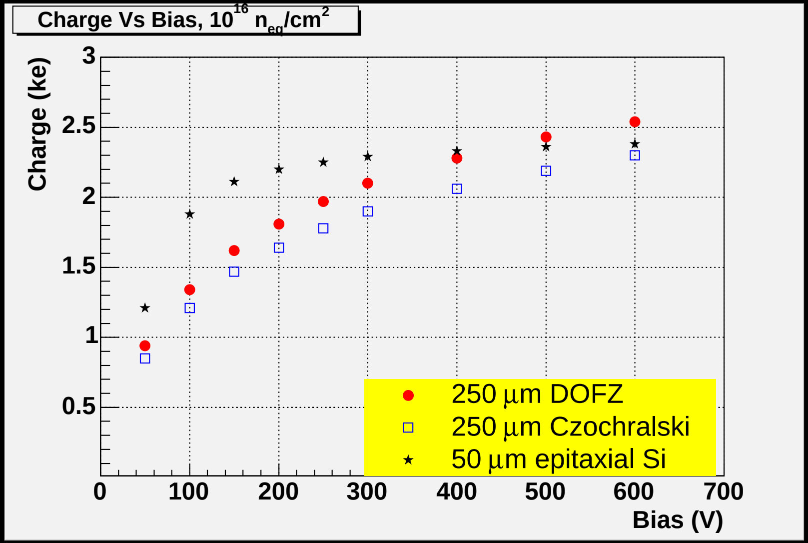
Results should be very similar for strip detectors

Charge collection vs bias voltage

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

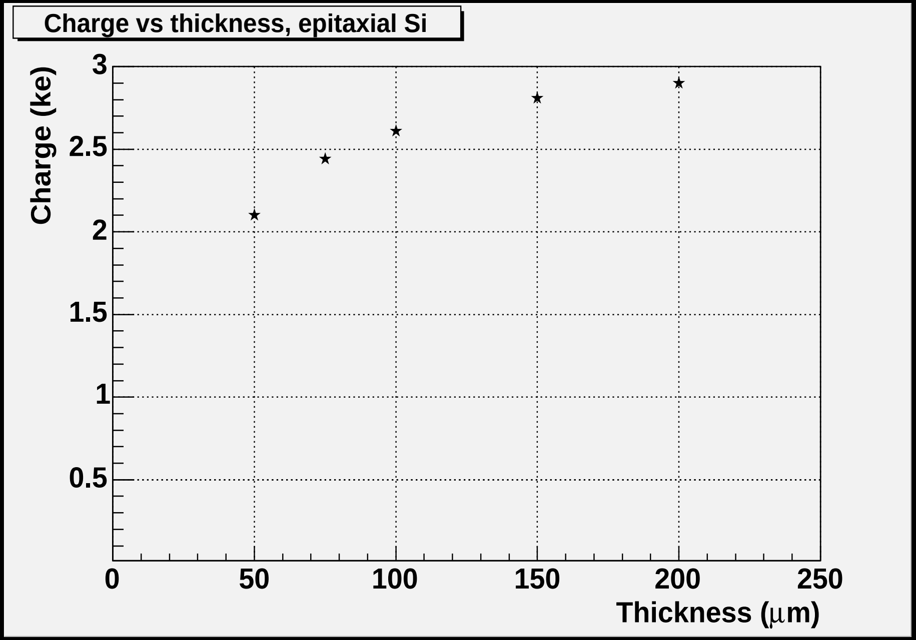
$\Phi = 10^{16}$ n/cm^2 : Cz and DOFZ fully depleted at 4400 V, epitaxial at 100 V. Signal limited by trapping gradually saturates as drift velocity approaches the high-field limit





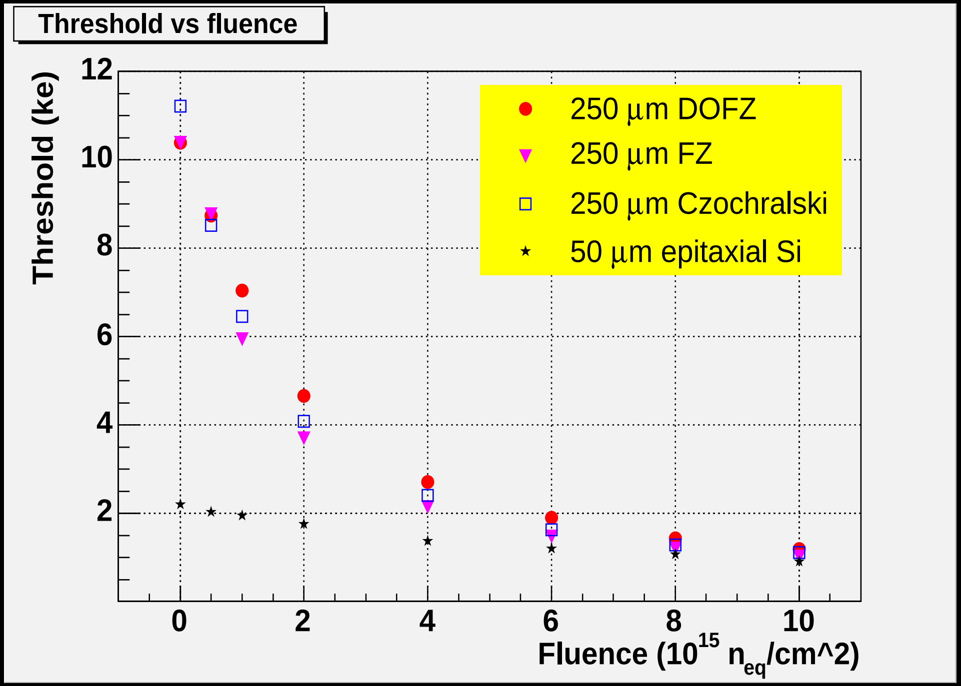
Charge versus epi thickness

- Charge collected after 10^{16} n/cm^2 as a function of sensor thickness (assuming full depletion)
- First RD50 samples were 50 µm thick (2100 electrons).
- Asymptotic value is 3000 e$^-$, when the thickness is much larger than the mean free path (20 µm) and the pixel dimensions: charges drifting far from pixels/strip does not contribute to signal.



- Thicker samples are thus predicted to have a significantly larger signal

Threshold and detection efficiency



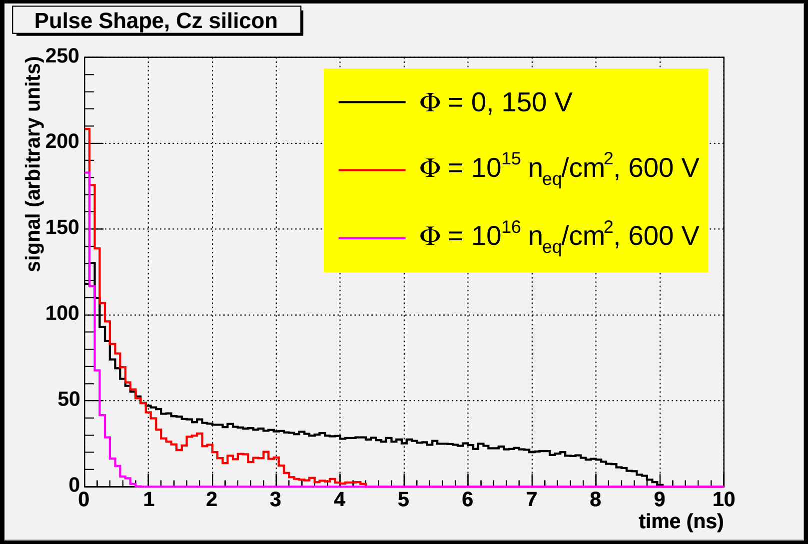
- The minimum charge which is detected within the trigger window is the in-time threshold.
- ATLAS Pixel detectors irradiated to 10^{15} n_{eq} cm^{-2} achieve a detection efficiency of 98.2% with an in-time threshold (at 40 MHz) of about 5000 e$^-$.
- After 10^{16} n_{eq} cm^{-2} an in-time threshold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

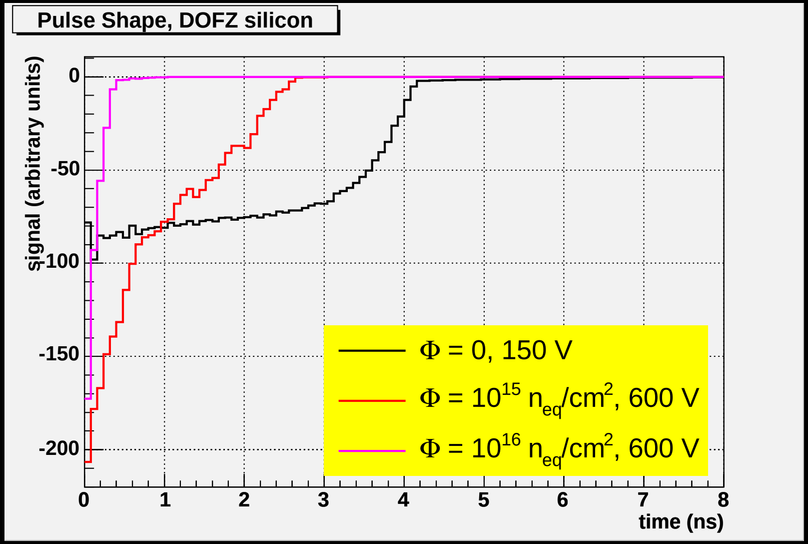
Big challenge for front-end electronics!

Collection time

With stronger irradiation the signal on electrodes is faster (lower depletion, stronger electric field, shorter lifetime).

For thin epitaxial sensors signal is always collected within 1 ns





Conclusions

- 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 **2000-2500 electrons** regardless of material, limited by charge trapping.
- Signal is lower if the thickness is below **100 μm**.
- Sensitivity to **1000 electrons** (fast and low noise rad-hard front-end electronics) is required to operate with high (97%) detection efficiency.