Characterisation of irradiated silicon sensors with the Transient Current Technique

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Future of the LHC

In collider experiments a large amount of data is needed for:

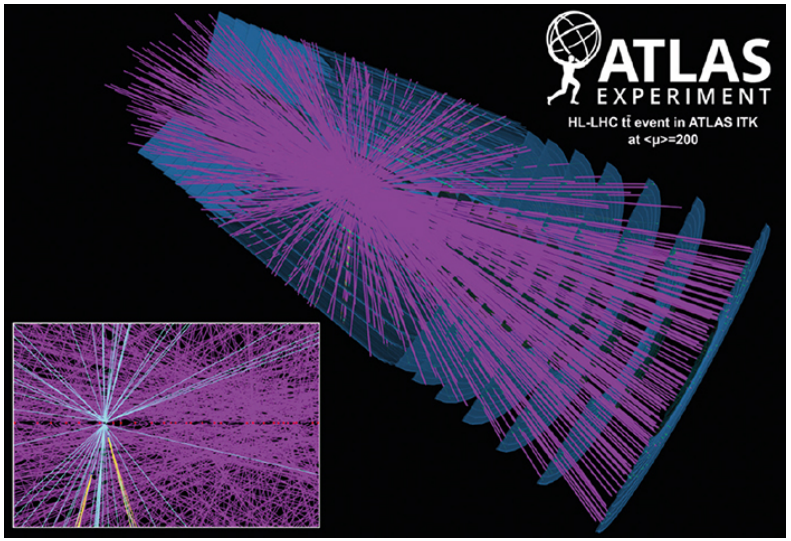
- precision measurements
- sensitivity to processes with low cross section

The second run of the LHC is exceeding any expectation:

- new record of peak luminosity: 1.74×10^{34} cm^{-2}s^{-1}
- integrated luminosity 52 fb^{-1}, for now ;)

The upgrade project already started: High Luminosity LHC

- up to 200 collisions per bunch crossing
- peak luminosity $> 7.5 \times 10^{34}$ cm^{-2}s^{-1}
- integrated luminosity > 3000 fb^{-1}



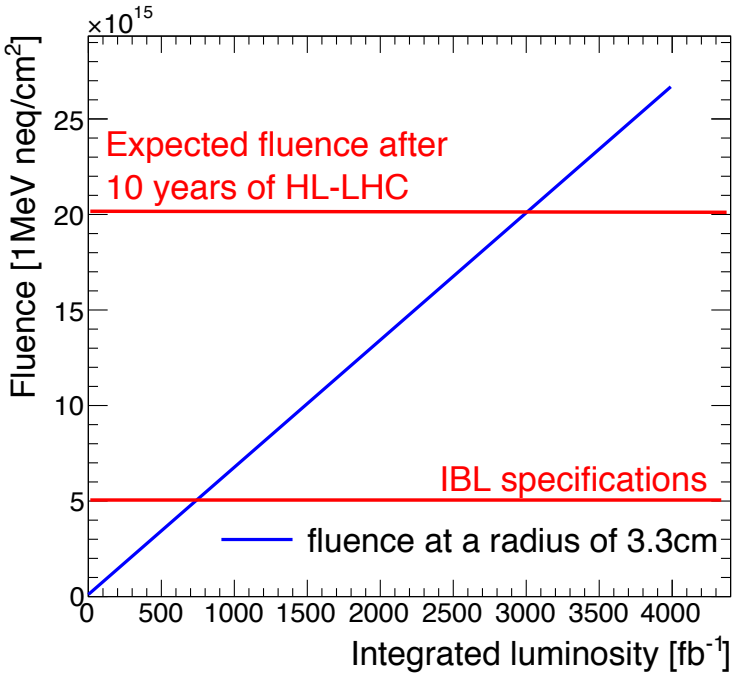
Consequences on the ATLAS tracking detectors

Tracking detectors will need major upgrades to cope with the new conditions whilst providing:

- separation of primary vertices in a busy environment
- efficient readout
- tolerance to high radiation doses

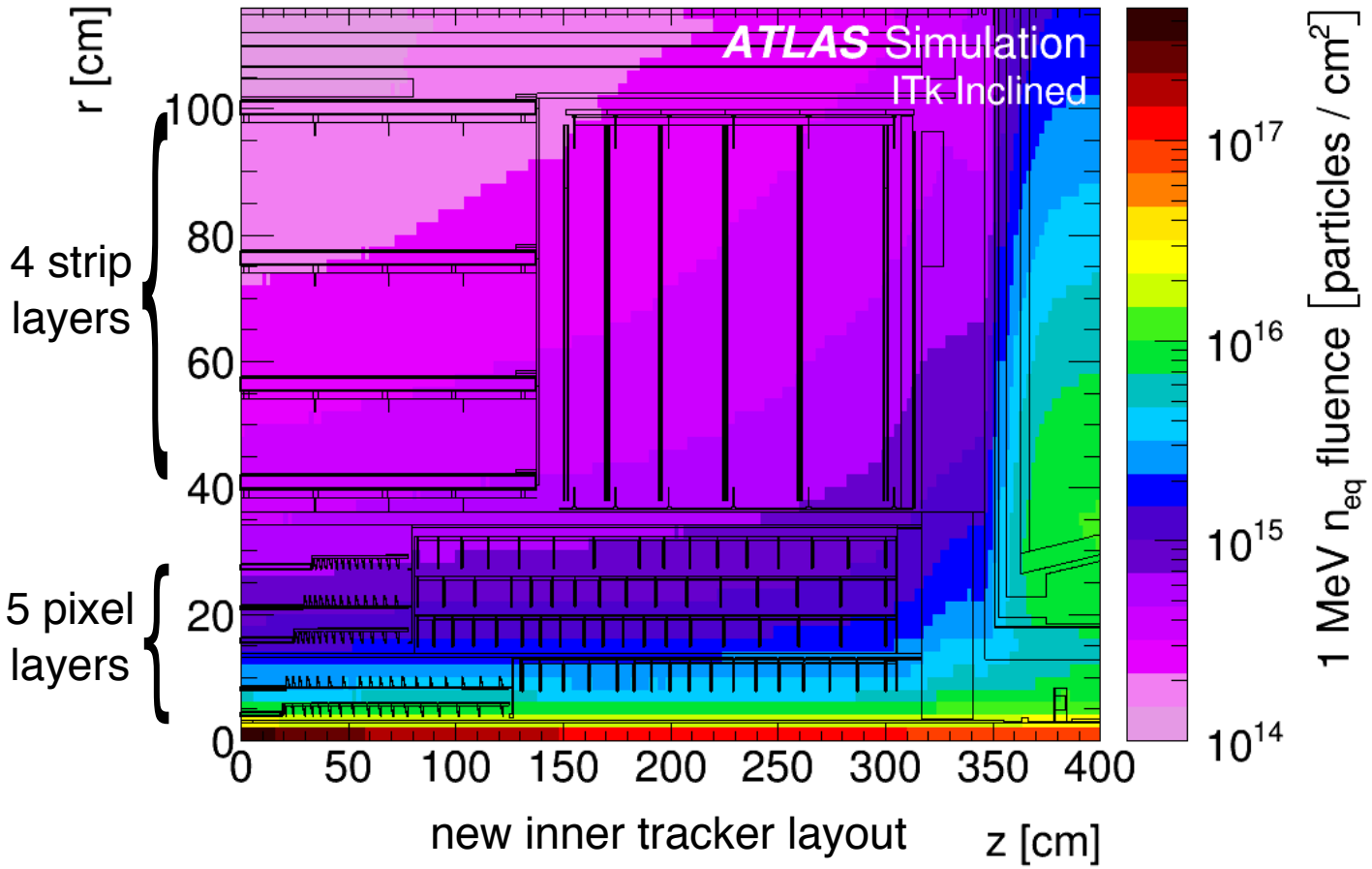
Focusing on the radiation problem:

- tracking detector mostly effected
  - close to the interaction point
- present ATLAS Inner Detector not designed for these conditions
  - all subsystems will be replaced
  - full silicon



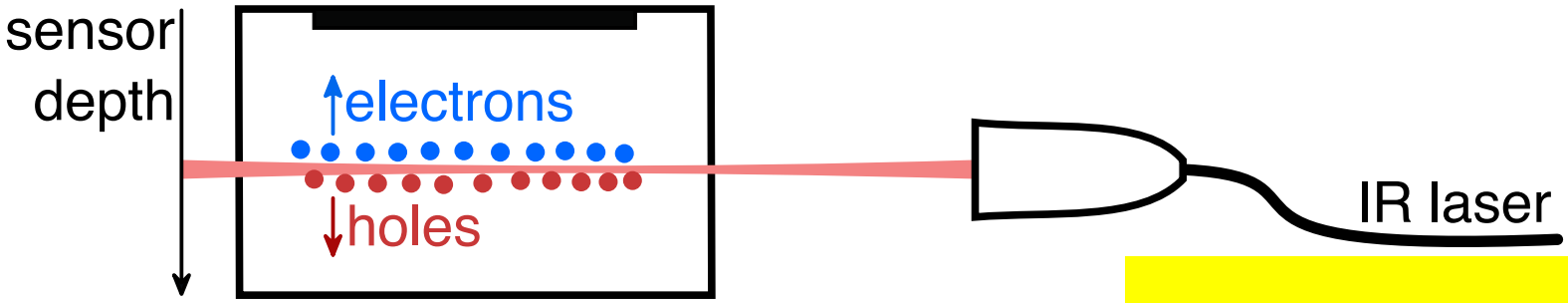
Expected dose for the ATLAS tracker upgrade

The total expected dose is studied with simulations
and all the technologies are being tested in those conditions
focus on HV-CMOS, sensors candidate for the 5th pixel layer



TDR for the ATLAS Inner Tracker Strip Detector
http://inspirehep.net/record/1614102

Transient Current Technique (TCT)



1054 nm wavelength

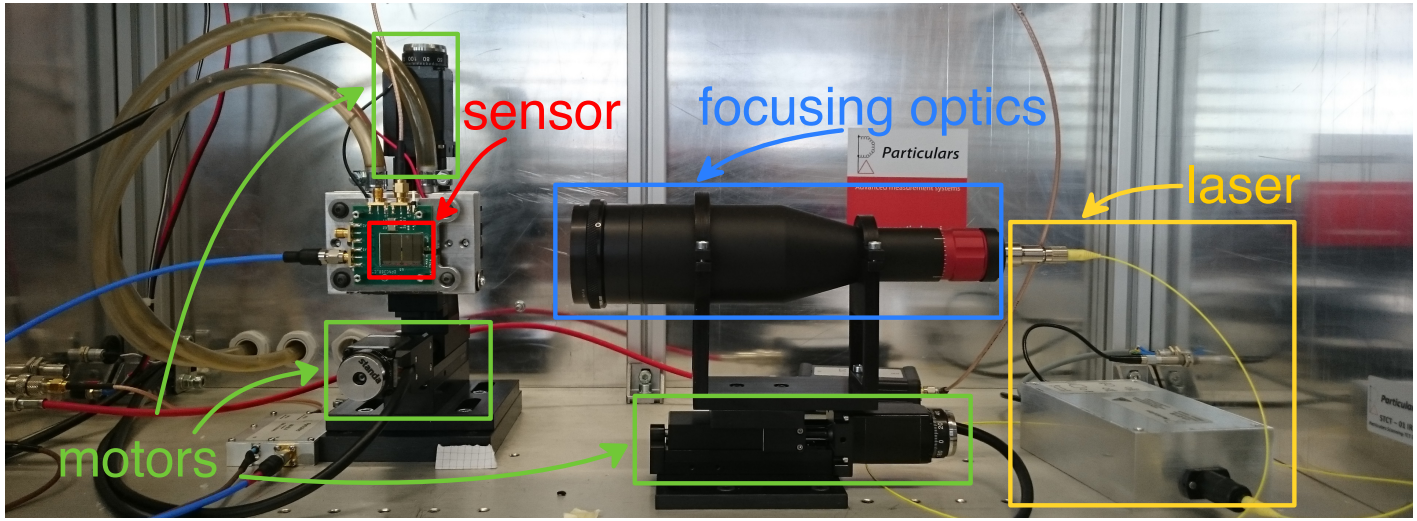
440 ns pulse width

10 kHz pulse frequency

10 µm beam spot

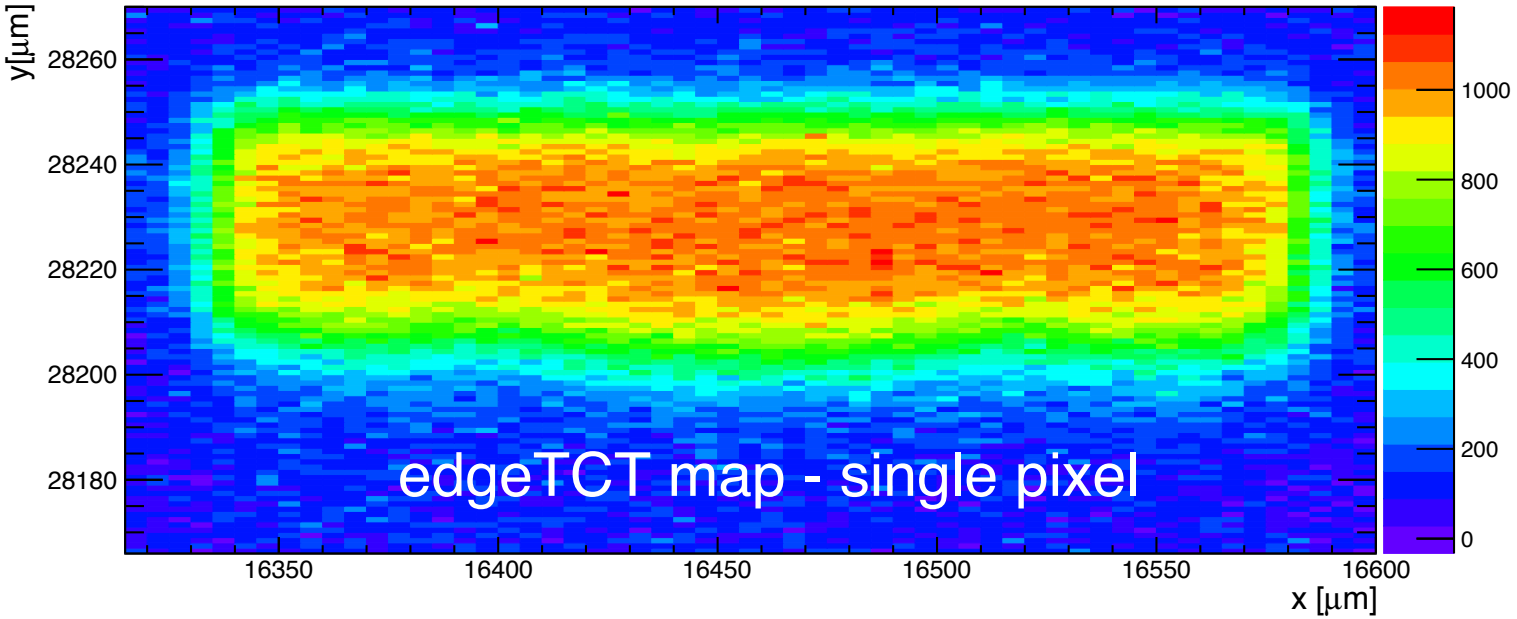
- injection with µm precision
- possibility of injection from the edge

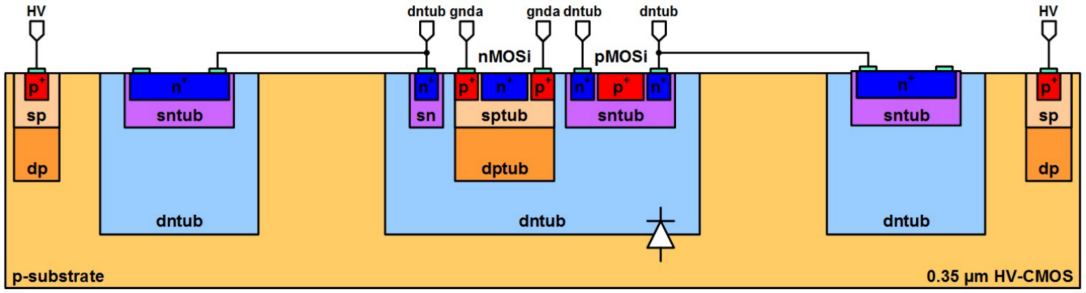
→ probe charge collection at different levels of the sensor depth



Charge collection maps

The measurements of the charge collected moving the laser along the sensor edge allow to create a 2D map of the active area



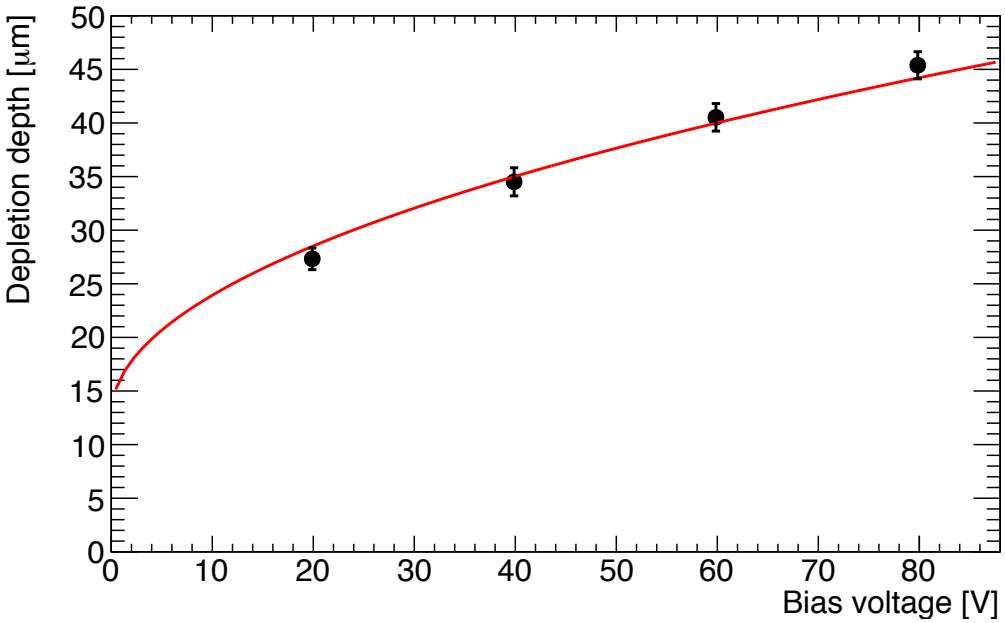


HV-CMOS pixel schematics

Depletion region

Signal of a particle that passes through the sensor $\propto$ to the depletion region
$\rightarrow$ important parameter to have under control to be fully efficient!

Evolution with the bias voltage



- 2D maps collected at different level of voltage
- good agreement with the expected evolution

$$d = \sqrt{\frac{2\varepsilon}{q}\left(\frac{1}{C_A} + \frac{1}{C_D}\right)\Delta V}$$

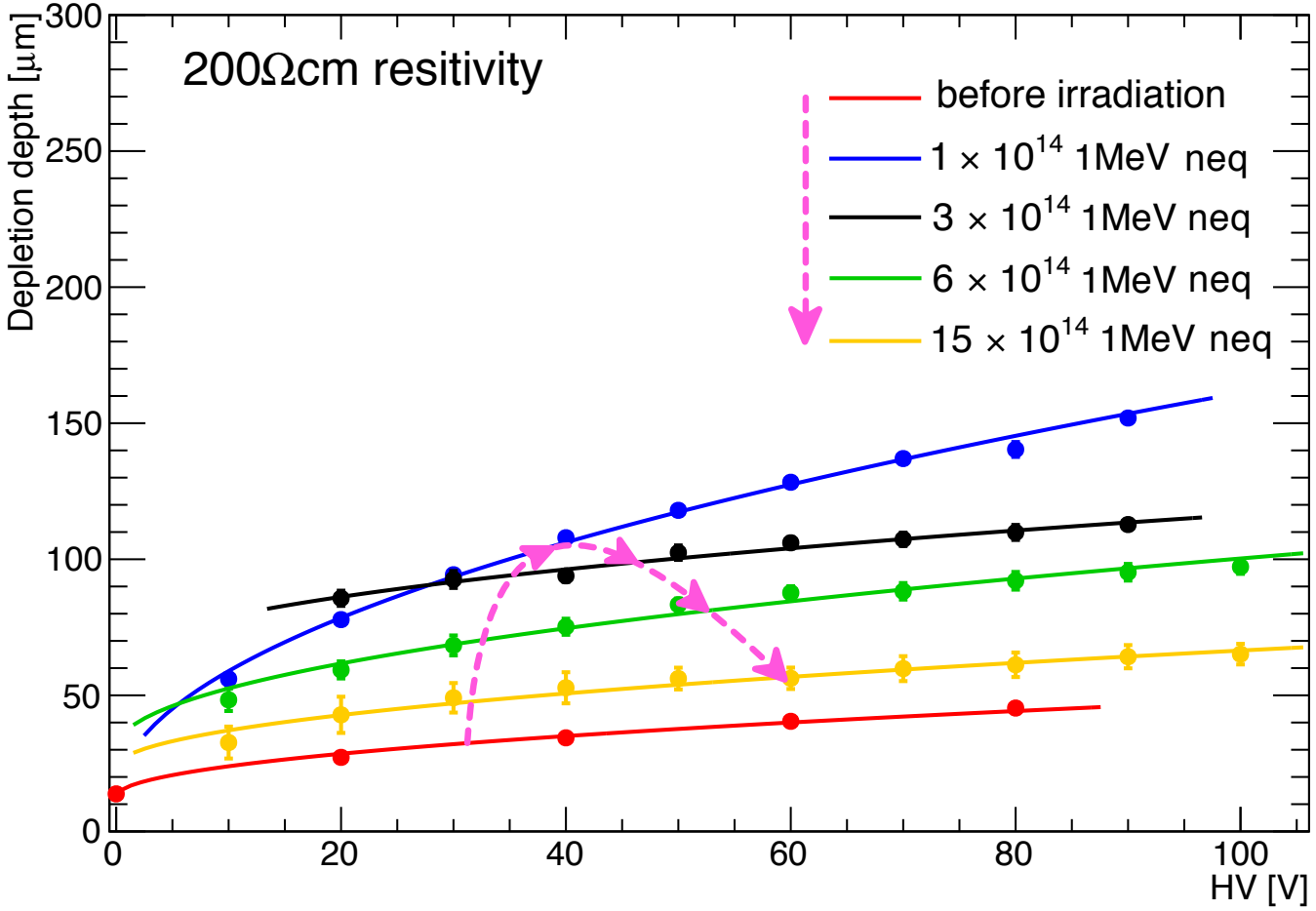
$C_{A/D}$ = concentration of acceptors/donors .

Evolution after irradiation with protons

The sensor is irradiated with 18 MeV protons at the Bern cyclotron

(see A. Fehr's presentation)

and characterised after each step of irradiation



Observations: strong increase of the depth at low dose, then slow decrease

Initial acceptor removal effect

The depletion region depends on the acceptor concentration:

$$d = \sqrt{\frac{2\varepsilon}{q}\left(\frac{1}{C_A} + \frac{1}{C_D}\right)\Delta V} = \sqrt{\frac{2\varepsilon}{q}\frac{1}{N_{eff}}\Delta V}$$

And the fluence Φ introduces two competitive effects:

$$N_{eff} = N_{eff0} - N_C \cdot (1 - \exp(-c \cdot \Phi)) + g_c \Phi$$

beneficial effect

negative effect

Our measurements quantitatively assess the two effects in proton irradiation

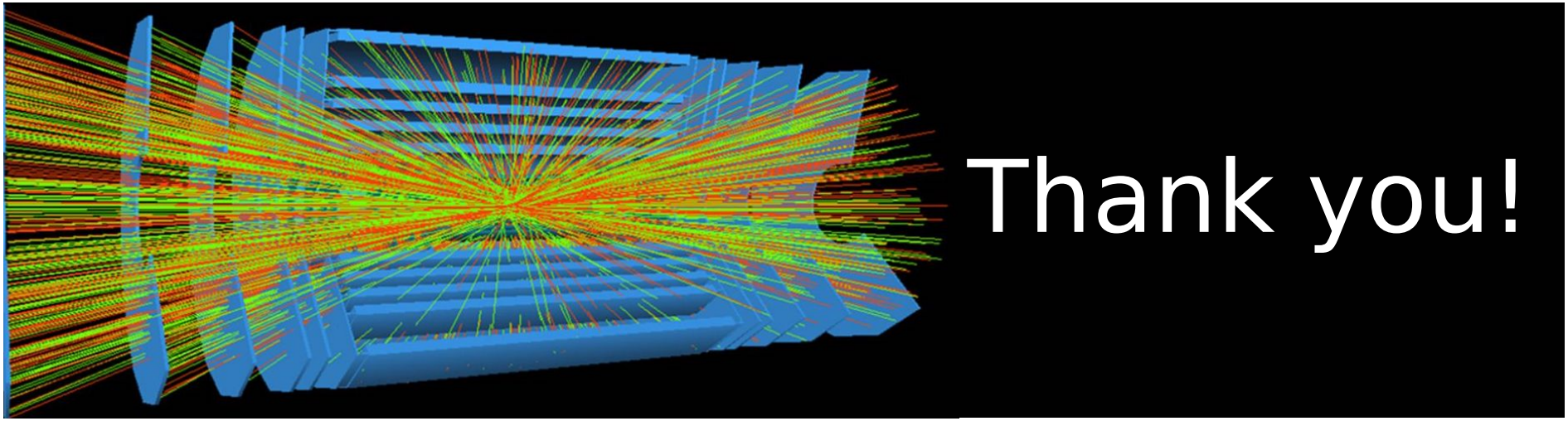
Conclusions

Upgrade of the ATLAS tracker detector for the High Luminosity LHC

- new frontier for radiation hard silicon detectors
- test on proton irradiated sensors prototypes
- edge-TCT studies for depletion depth evolution due to radiation dose
- parametrisation of the doping concentration VS fluence

Additional measurements:

- dependence on the initial doping concentration (sensor resistivity)
- dependence on radiation source



Backup slides

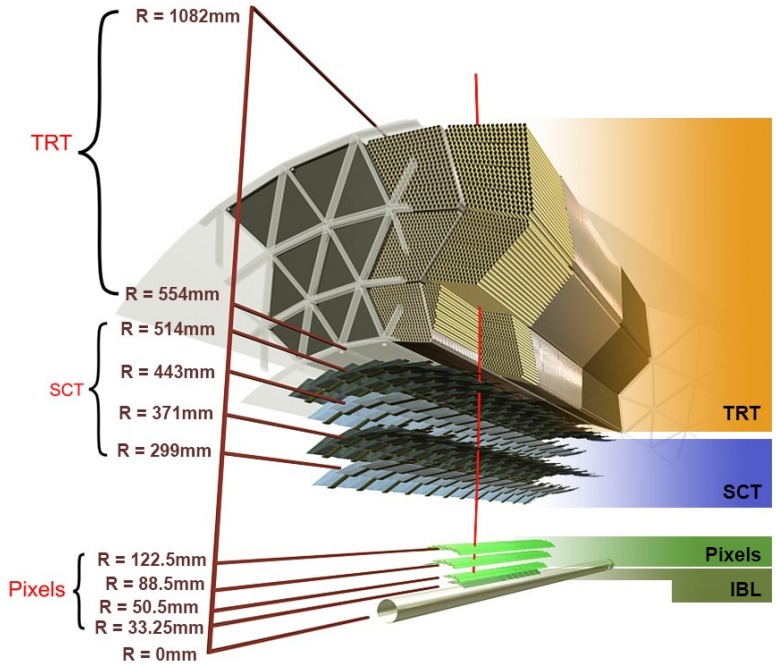
ATLAS Inner Detector now

The Inner Detector provides the reconstruction of charged particle tracks:

- transverse momentum measurement
- collision and decay vertex identification

$\rightarrow$

- high segmentation
- long lever arm
- as close as possible to the interaction point



Pixel Detector + IBL
Silicon sensors
highly segmentated, close to te beam pipe

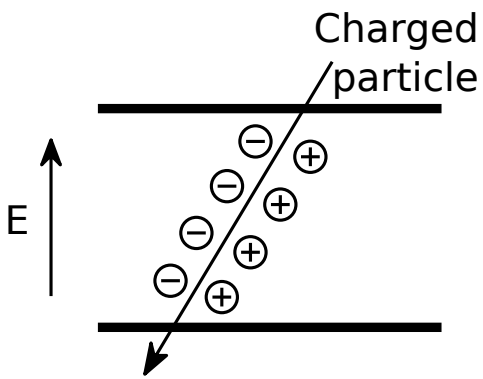
SCT
Larger silicon strips

TRT
Gaseous detector, covers a large area

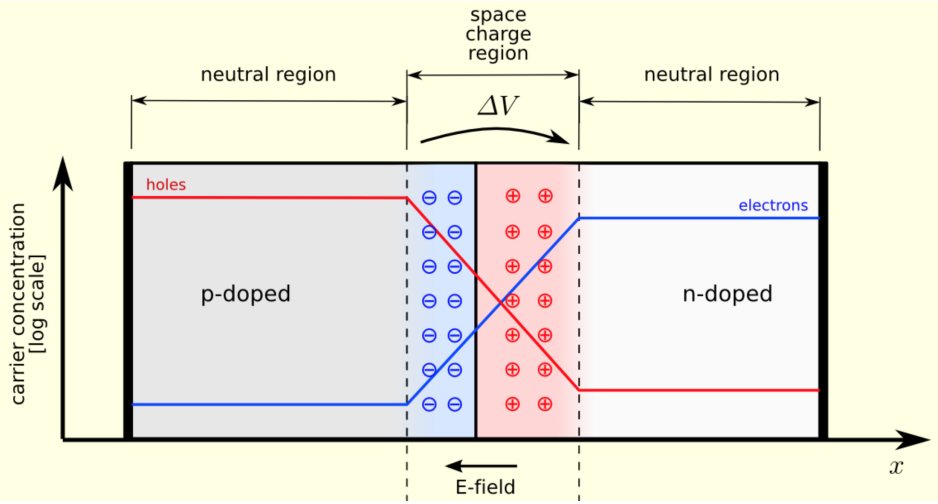
Detecting particles with silicon

Silicon is a semicontductor

- energy released by charged particle creates electron-hole pairs
- small band gap
  hard to discriminate from thermal excitation



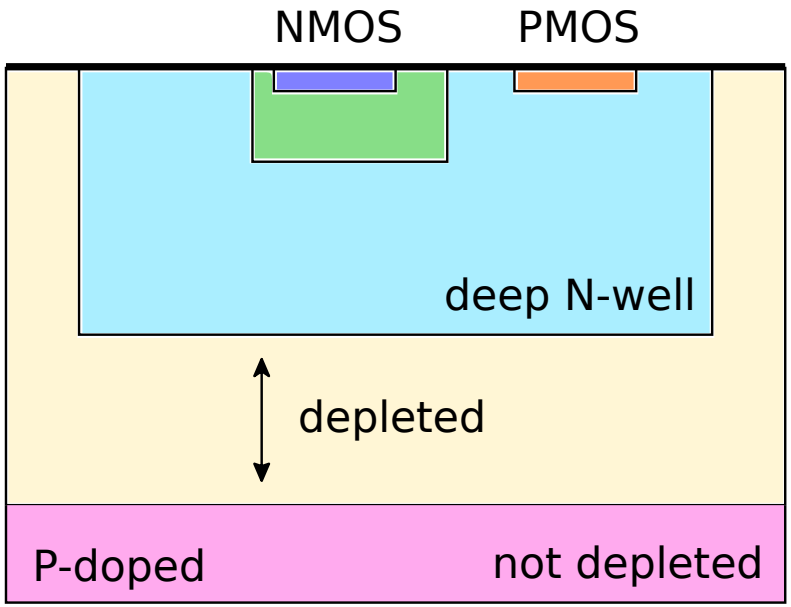
Solution: p-n junction



- created by joining n-type and p-type doped silicon
- charge migration creates a region without free charges (depletion zone)
- the depletion zone can be enlarged by applying a reverse bias voltage

HVCMOS - a radiation hard technology

New monolithic sensors proposed for the outer pixel layers



- CMOS technology embedded in each pixel
- shielded by a deep n-doped region

$\downarrow$

possibility to operate at high voltage (HV)

Pros:

- possibility of industrial production $\rightarrow$ lower cost
- small depletion zone $\rightarrow$ radiation hardness

Proton damage of silicon sensors

Protons give two different kind of radiation damage:

- total ionising dose (TID)
  fully recovered in the silicon bulk,
  important for the front-hand electronics
- nuclear collisions responsible for the non-ionising energy loss (NIEL)
  (expressed in 1 MeV $n_{\text{eq}}/\text{cm}^2$ to compare different particles)

Effects:

- change of effective doping concentration
  $\rightarrow$ higher operation voltage to obtain the same performances
- increase of the leakage current
- defects in the lattice $\rightarrow$ charge trapping

TID - NIEL conversion

$$\begin{cases} fluence = D(E) \times \dfrac{n_p}{\text{cm}^2} \\ TID = \dfrac{dE}{\rho dX} \times \dfrac{n_p}{\text{cm}^2} \end{cases}$$

Hardness factor ≈ 3 from database: `http://www.sr-niel.org`

(`http://rd50.web.cern.ch/RD50/NIEL/default.html` used for cross-cheks)