

Radiation Hardness of Silicon Detectors

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Advanced UK Instrumentation Training 2026

29 May 2026

Plan for the lectures

- Brief introduction
- Displacement damage
- Surface damage

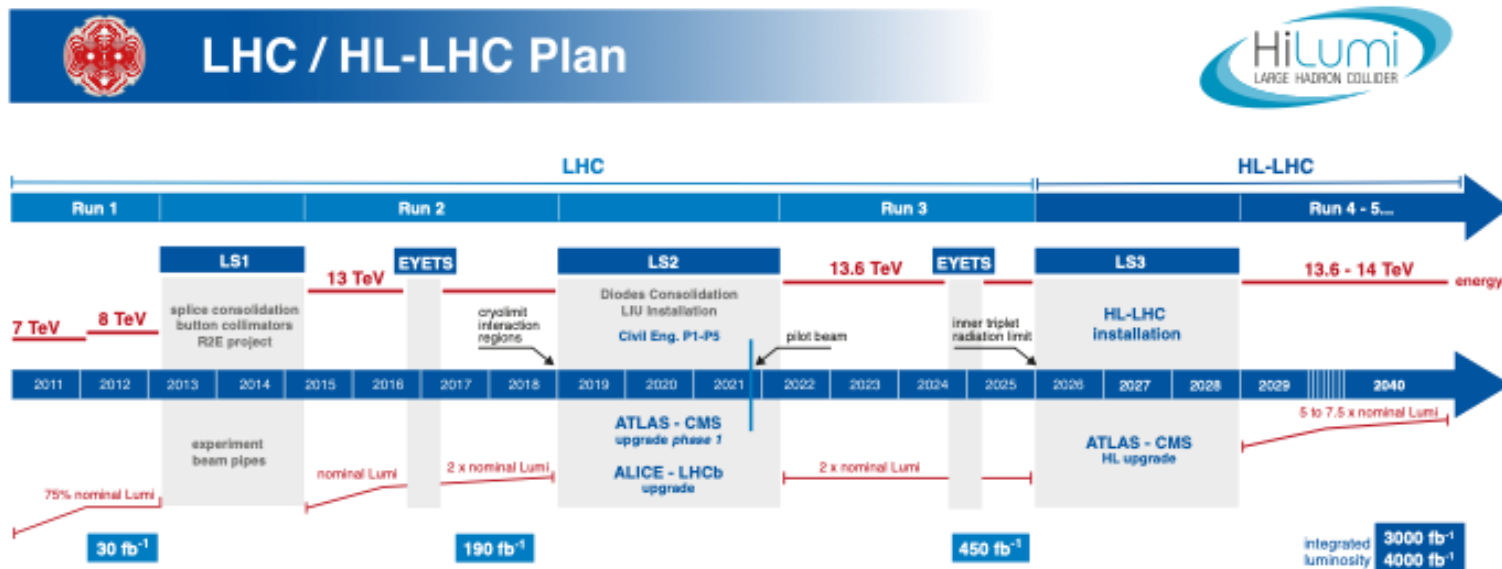
The material used to prepare the lectures is referenced to in the slides.

Plan for the lectures

- **Brief introduction**
- Displacement damage
- Surface damage

Why are we concerned about radiation?

- HEP detectors at collider experiments operate in a **high particle flux** environment.
- **High luminosity** is required to obtain large statistical samples to characterize rare processes.



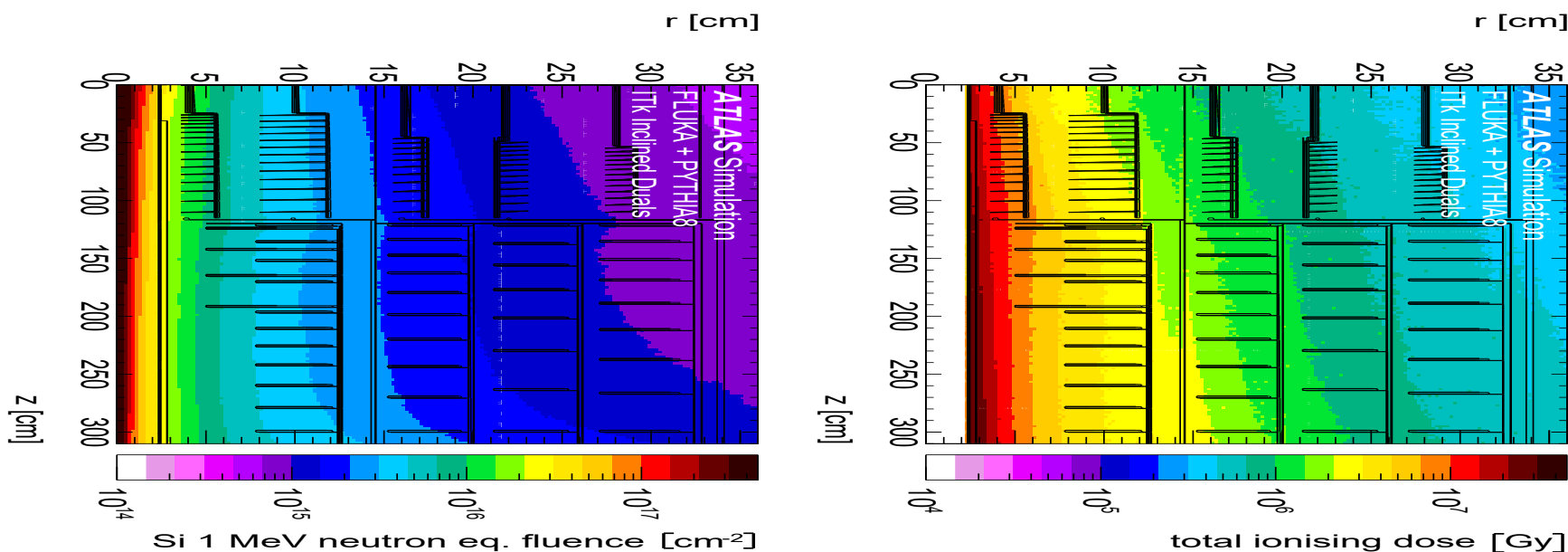
<https://hilumilhc.web.cern.ch/content/hl-lhc-project>

	Instantaneous peak luminosity	Integrated luminosity
LHC	$2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$	450 fb ⁻¹
HL-LHC	$5 - 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$	4000 fb ⁻¹

Radiation levels

- Silicon detectors are used for vertexing and tracking close to the interaction point and are exposed to **highest particle fluxes**.

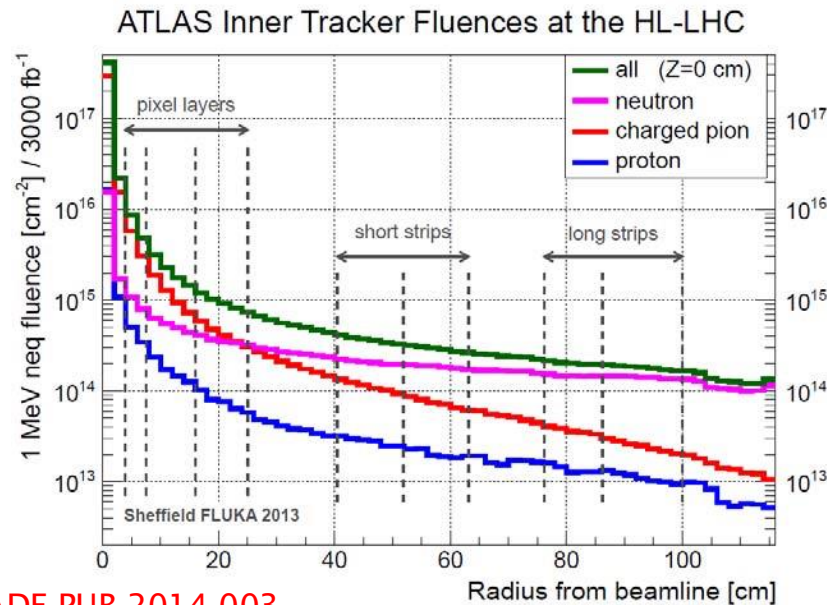
	Example: ATLAS innermost pixel layers	
	Fluence	Total Ionising Dose
@ LHC (300 fb ⁻¹)	$2 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$	300 kGy
@ HL-LHC (4000 fb ⁻¹)	$2 \times 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$	10 MGy



The fluence and dose distributions for the ATLAS Pixel Detector at the HL-LHC. Left: 1 MeV neutron equivalent fluence. Right: Total ionising dose. The two plots are normalised to 4000 fb⁻¹. No safety factors are taken into account for this Figure. <http://cdsweb.cern.ch/record/2285585>

Radiation fields

- The particle flux at (HL-)LHC is made of **charged and neutral particles, gamma and x-rays, neutrons**.
- Close to the interaction point the charged hadron component dominates.
 - At 5 cm distance from the LHC IP 90:10 pions to neutrons ratio.
- Further out, the neutron component dominates.
 - Neutrons occur from backscattering in dense materials in the calorimeter.
 - At 30 cm distance from the LHC IP 50:50 pions to neutrons ratio.



[ATL-UPGRADE-PUB-2014-003](#)

Radiation damage: Cumulative effects

- Cumulative effects leading to a gradual degradation taking place through the experiment lifetime: **displacement damage and surface damage**.
- Displacement damage.
 - Damage to the silicon crystal by particles impinging on the lattice.
 - Caused by collisions with the nuclei in the lattice atoms → **Non-Ionizing Energy Loss (NIEL)**.
 - Creates **dislocations of the lattice atoms** or more complex distortions of the crystal lattice.
- Surface damage.
 - Damage to silicon surfaces and interfaces, esp. **Si-SiO₂**.
 - **Ionisation energy loss** of impinging radiation.

A device sensitive to bulk or surface damage will exhibit failure in a radiation environment when the **accumulated fluence or Total Ionising Dose (TID)** has reached its tolerance limit.

Radiation damage: Single Event Effects

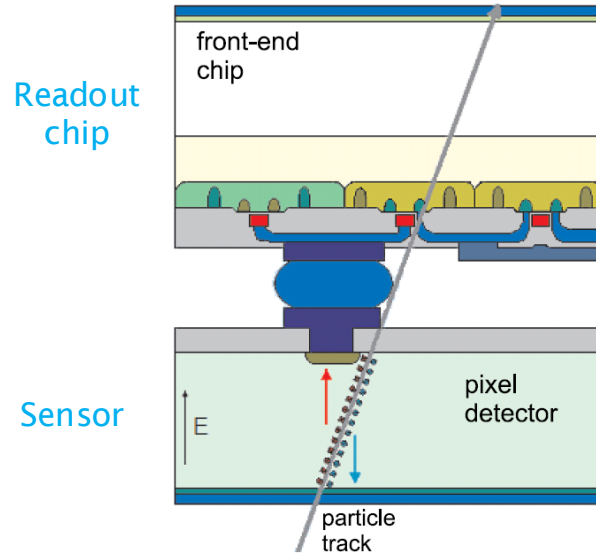
- Single Events Effects (SEE) are due to the energy deposited by one single particle in a circuit's sensitive node and they can happen in any moment.

A device sensitive to SEE can exhibit **failure at every moment** since the beginning of its operation in a radiation environment.

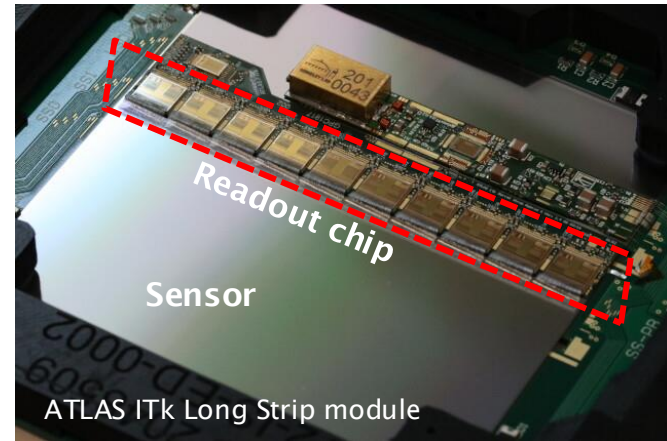
Not covered in these lectures.

Silicon detectors

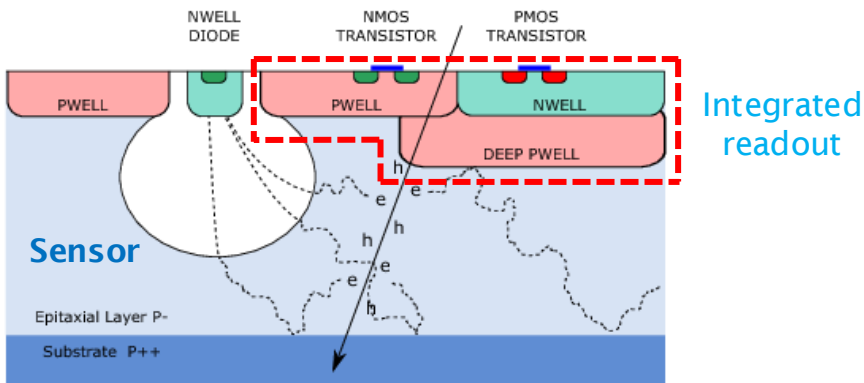
Pixels - Hybrid



Strips



Pixels - Monolithic



ALICE ITS2 ALPIDE detector, sketch of the cross-section of one pixel

Different flavours, basic elements:
sensor + readout electronics.

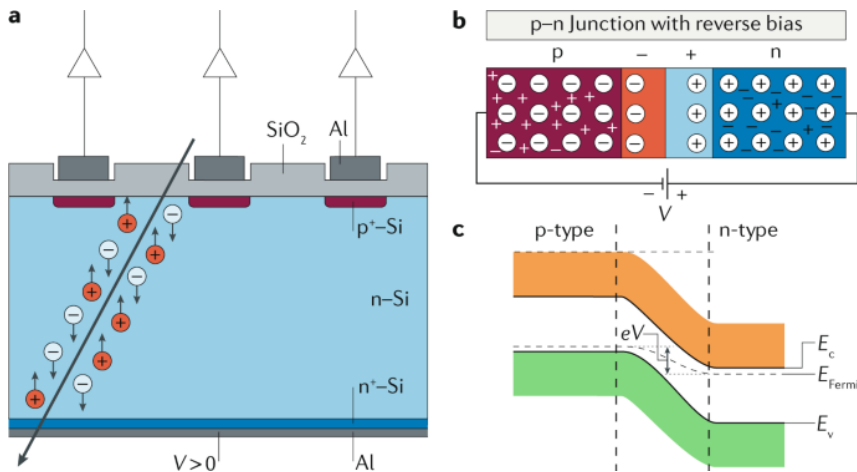
Both sensor and electronics are implemented in silicon.

Radiation damage to silicon detectors

- Sensor:

- Reverse biased pn-junction.
- Charge collection in the sensor volume.

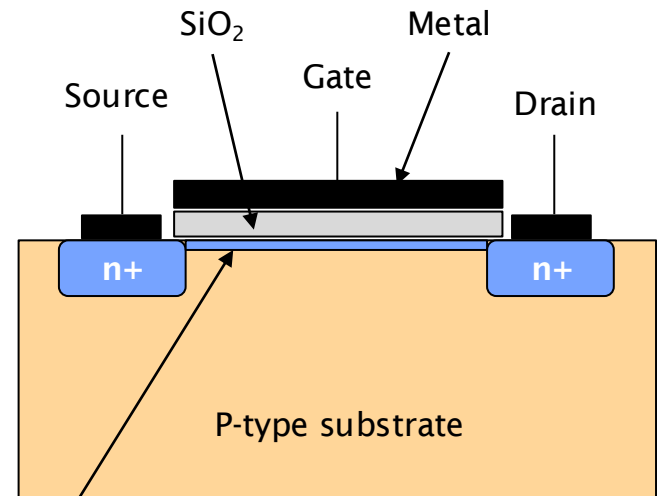
→ Mostly affected by **displacement damage**, but also surface effects.



- Electronics:

- Design and fabrication in deep-submicron CMOS technology.
- Basic building element MOSFET transistor.
- Current flowing in conduction channel a few nm below the Si-SiO₂ interface.

→ Affected by **surface effects and SEE**.



Channel for current flow

Units

- Displacement damage

- Fluence = number of particles per cm^2 traversing a material over a certain amount of time (typ. the lifetime of the experiment).
- For silicon sensors the NIEL displacement damage is normalised to the damage level caused by 1 MeV neutrons.
- Unit for fluence: 1 MeV neutron equivalents per cm^2 [$n_{\text{eq}}/\text{cm}^2$].

- Surface damage

- Total Ionising Dose = energy deposited per unit mass of material as a result of ionisation.
- Unit for TID:
 - Gy = J/Kg
 - 1 Gy = 100 rad

Plan for the lectures

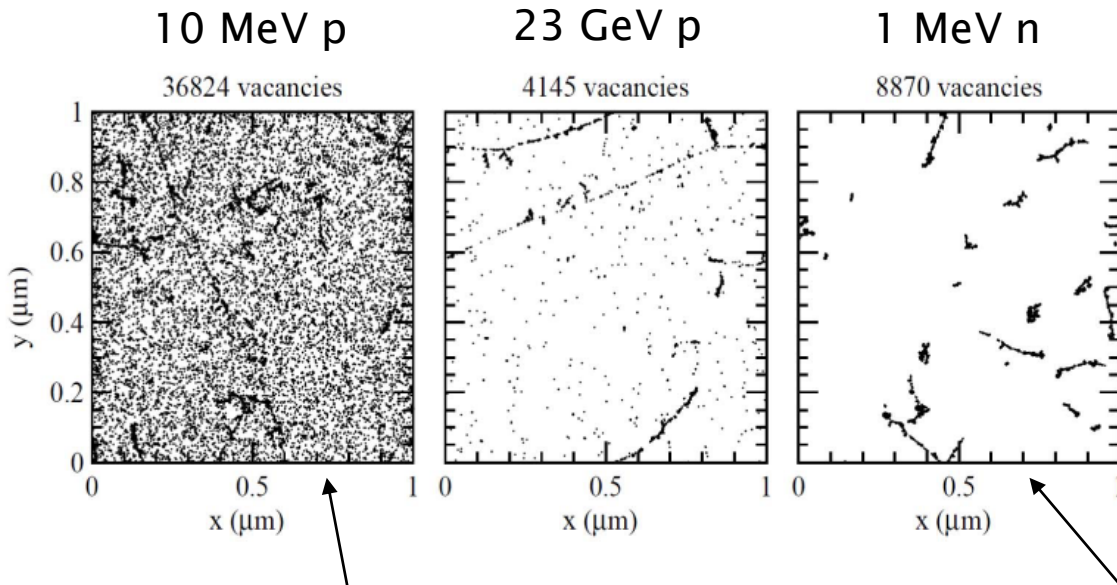
- Brief introduction
- **Displacement damage**
- Surface damage

Damage mechanism

- Non-ionising damage results from direct collisions with atomic nuclei of the crystal lattice.
 - Coulomb scattering off nuclei for electrons, protons, charged pions.
 - Elastic and inelastic scattering off nuclei for neutrons.
- Atoms can be knocked-off from their initial position with a certain recoil energy, E_R .
 - A **vacancy** is left behind, the recoil atom loses energy by ionisation and by creating further displacement damage, until it comes to rest as a lattice **interstitial**.
- Vacancies and interstitials in between lattice atoms → **primary point defects**.
 - Many point defects are unstable and will dissolve by recombination.
 - Since they are mobile in the lattice they can form stable **defect complexes** with existing impurities.

Primary displacements in Si

- Nucleons and nuclei produce more **cluster defects** consisting of many vacancies and interstitials.
 - Max energy transfer in a collision is much higher than the energy to kick-off a silicon atom from the lattice at 50% probability, i.e. $25eV$.
- Electrons, gamma rays, protons and charged pions create many more **point defects** than neutrons.
 - Smaller average energy transfer but larger cross-section.



Initial distribution of vacancies produced by 10 MeV protons (left), 23 GeV protons (middle), and 1 MeV neutrons (right). The plots are projected over 1 μm depth (z) and correspond to a fluence of 10^{14} particles/ cm^2 .

[DOI: 10.1016/S0168-9002\(02\)01227-5](https://doi.org/10.1016/S0168-9002(02)01227-5)

Primary defects **homogeneously scattered** over a large volume.

Primary defects **densely clustered** in small regions.

NIEL

- Non-ionizing energy loss, NIEL, is the portion of energy lost by a particle that does not go into ionisation and leads to displacement damage.
 - This portion depends on the energy of the impinging particle.
 - Ionisation in semiconductors is a reversible process and no damage remains in the crystal except in oxides and at interfaces (see “surface damage” later).
 - Only a fraction of the NIEL leads to displacement damage, part of it leads to phonon excitations (i.e. vibrational energy) that do not cause any damage.
- NIEL is defined in units of **MeV cm²/g** or as a NIEL cross section in units of **MeV mb**.
- NIEL can be calculated for electrons, protons, neutrons, pions as

$$\frac{dE}{dx}(E) = \frac{N_A}{A} D(E)$$

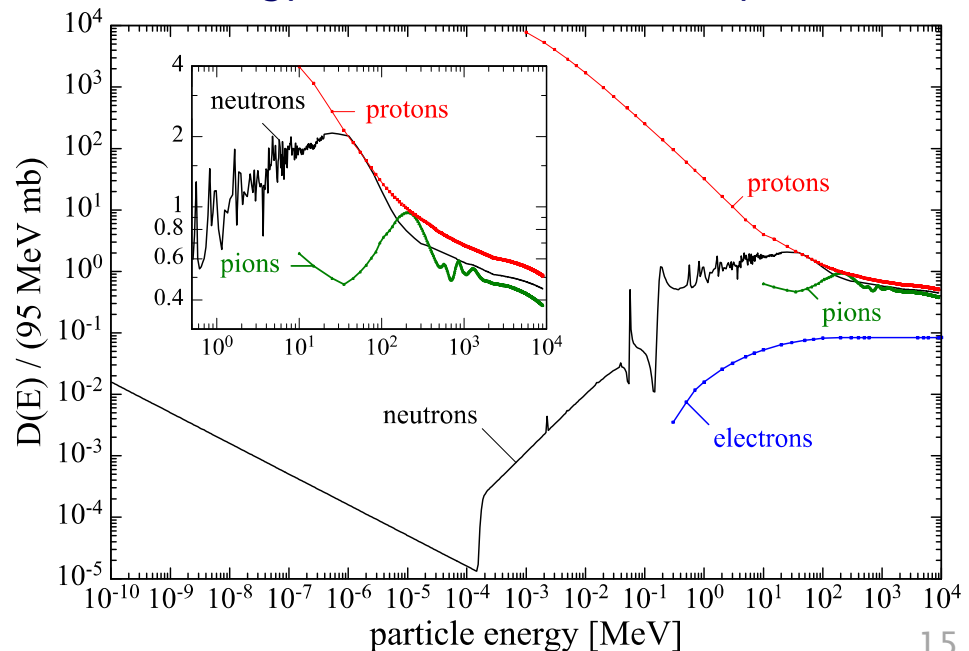
- N_A = Avogadro number.
- A = atomic mass [g/mol] of the target material.
- $D(E)$ = displacement damage function.

Displacement damage function

- $D(E)$ depends on the **type and energy** of the impinging particle.

$$D(E) = \sum_i \sigma_i(E) \int_{E_d}^{E_R^{max}} f_i(E, E_R) P(E_R) dE_R$$

- E, E_R : kinetic energies of the impinging particle and recoil atom resp.
 - E_d : minimum energy required for dislocation damage (in Si $E_d \approx 25\text{eV}$).
 - i : index running over all occurring reactions with cross section σ_i .
 - $f_i(E, E_R)$: probability that in reaction i a recoil atom of energy E_R is produced.
 - $P(E_R)$: partition function returning the fraction of energy available for further displacement damage.
- Damage curves/NIEL cross-section for silicon for different particles **normalised to 95 MeV mb.**



[DOI:10.1109/TNS.2018.2819506](https://doi.org/10.1109/TNS.2018.2819506)

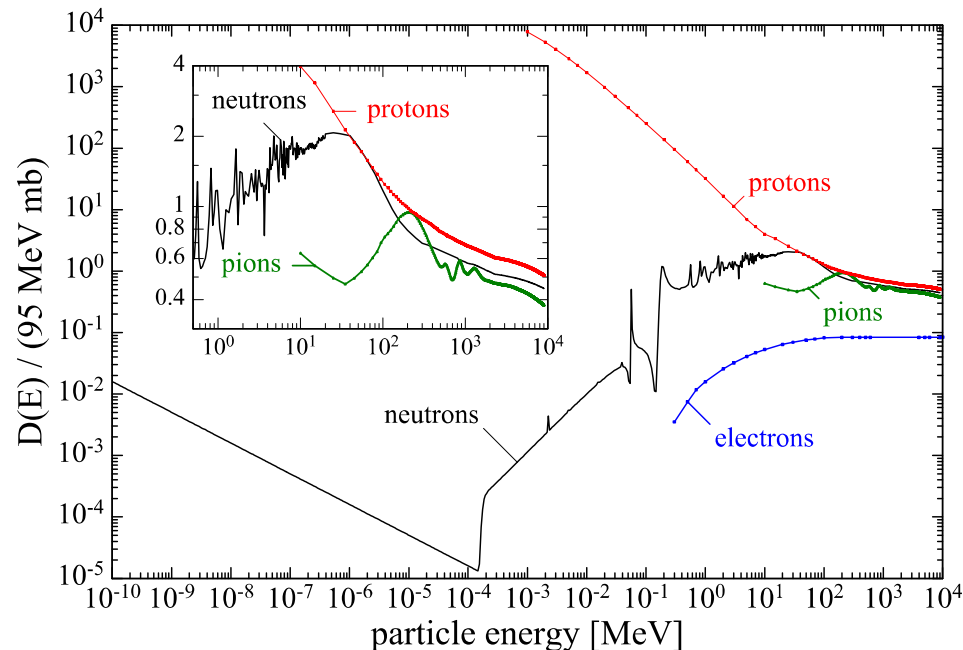
NIEL hypothesis for silicon

Radiation damage effects **scale linearly with NIEL** and can be traced back to the **initial number of primary defects**, irrespective of their distributions in space and energy.

- The NIEL hypothesis describes well the displacement damage effects observed in silicon detectors and allows to make **predictions of effects of such damage in radiation fields such as those at HEP collider experiments**.
 - It describes well the evolution of many device parameters with radiation, in particular the sensor leakage current.
- It has however shortcomings as **pointlike and cluster defects contribute differently** to the damage of certain device parameters.
 - Changes in effective space charge concentration (depends on impurity concentration), trap introduction rate (particle-type dependent), annealing effects (not included in NIEL scaling).

NIEL scaling

- Assuming this hypothesis, the observed differences in damage caused by different type of radiation with different energy can be scaled to each other using $D(E) \rightarrow$ **NIEL scaling**.
- Normalisation factor: **damage effect of 1 MeV neutrons $\rightarrow D(1\text{MeV}) = 95\text{ MeV mb}$** .



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Hardness factor

- Hardness factor k is the ratio of D_x for a particle species x with energy E to neutron damage D_n at 1 MeV:

$$k = \frac{\int_{E_{min}}^{E_{max}} D_x(E) \phi(E) dE}{D_n(1 \text{ MeV}) \int_{E_{min}}^{E_{max}} \phi(E) dE}$$

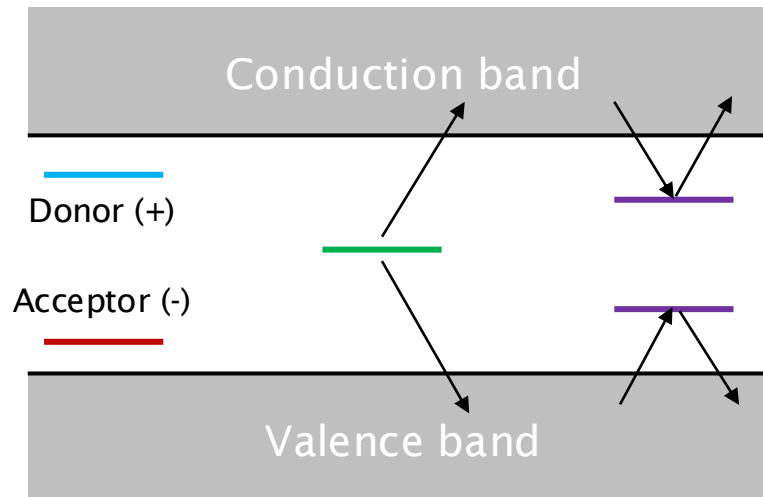
- It gives a measure of how damaging a certain particle of certain energy is.
- For 24 GeV protons, $k \approx 0.62$, for 25 MeV protons, $k \approx 2.0$.
- $\phi(E)$ is the fluence of a particle of a certain energy, E/cm^2 .
- The **equivalent fluence for 1 MeV neutrons** is the damage-weighted fluence received by the detector from a particle of a given species and energy.

$$\phi_{eq} = k \phi$$

Consequences of lattice defects in Si

- Lattice defects produced by displacement damage create **new energy levels** in the silicon bandgap.
- These can become electrically active, i.e. generate or absorb charge carriers by transitions to/from conduction and valence band.
- Depending on their location in the band gap they will act as donors or acceptors and have different effects on sensor performance.

Donors/acceptors centres
→ Change of effective
doping concentration.



Trapping centres
→ Charge trapping.

Generation-recombination centres
→ Increase of leakage current.

Shockley-Read-Hall framework

- The SRH statistics describes the impact of lattice defects on detector performance.
- The impact of each defect can be calculated by knowing:
 - The capture cross-section for electrons, σ_n , and holes, σ_p .
 - The position of the energy level in the bandgap.
 - The type of defect (donor, acceptor).
 - The concentration of defects, N_t .
- Three main effects on device performance can be described in the framework of SRH statistics:
 1. Change of effective doping concentration.
 2. Leakage current increase.
 3. Charge trapping.

1- Change of effective doping concentration

- In unirradiated silicon the bulk doping determines the effective space charge density, N_{eff} .

$$\rho = e(N_D - N_A) = eN_{eff}$$

- In irradiated sensors, the effective doping concentration changes depending on the fluence.
 - Defects can deactivate donor or acceptor atoms, or create new donor or acceptor levels.
- N_{eff} is given by the sum of the positively charged donors and negatively charged acceptors.

$$N_{eff} = \sum_{donors} (1 - f_t)N_t - \sum_{acceptors} f_t N_t$$

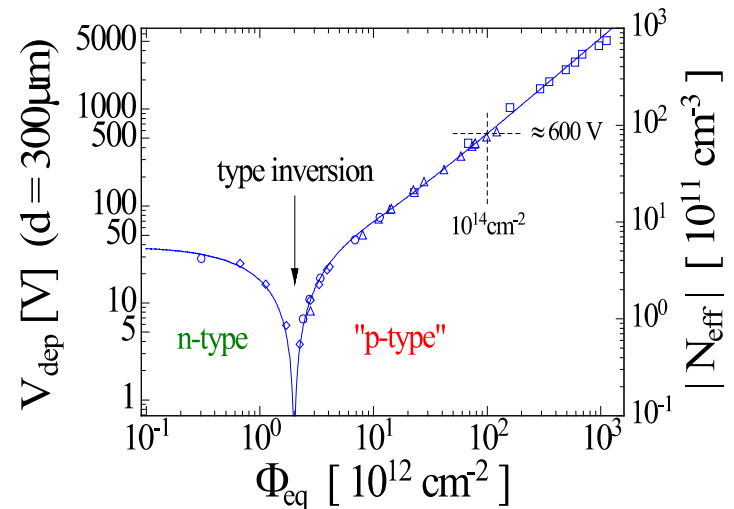
- $f_t = \frac{e_p}{(e_n + e_p)}$ defect occupation probability in the space charge region (neglecting free charge carriers).
 - e_p and e_n are the emission rates for holes and electrons.

Type inversion

- A consequence of the change is N_{eff} is type inversion in high resistivity n-doped substrates.
 - Irradiation of the sensor leads to the formation of negative space charge which compensates for the initial positive space charge.
 - High-resistivity p-type material does not undergo type inversion as the initial space charge is negative.
- Type inversion is the point at which the space charge sign changes from positive to negative.
- With fluence more negative space charge forms \rightarrow the sensor depletion voltage V_{dep} **increases** \rightarrow the sensor might be operating **underdepleted** and collect **less charge**.

$$V_{dep} \approx \frac{e|N_{eff}|d^2}{2\epsilon\epsilon_0}$$

- d is the sensor thickness.

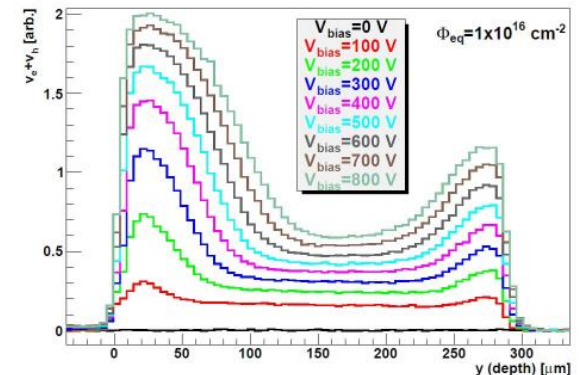
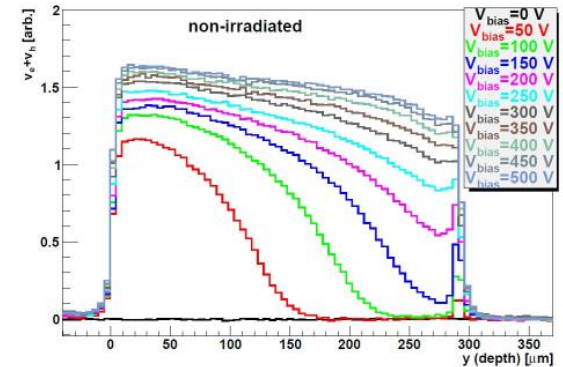


[DOI:10.1109/TNS.2018.2819506](https://doi.org/10.1109/TNS.2018.2819506)

Electric field in the bulk

- Changes in N_{eff} lead to changes in the **electric field distribution** in the sensor bulk.
 - After irradiation to high fluence, the space charge in the depletion region is not homogenous anymore.
- **Double peak** electric field structure observed.
 - Higher field at both ends than at the centre of the sensor volume.
- Polarisation effect.
 - Incoming radiation generates free e-/h+ pairs that drift to the n+/p+ electrode.
 - e-/h+ density higher at n+/p+ contact.
 - Free charge carriers can be trapped in the defect levels building negative/positive space charge close to the n+/p+ contact.
 - When N_{eff} is negative at the n+ contact and positive at the p+ contact, a double electric field exists.

Sum of drift velocities measured as a function of depth from the electrodes with TCT technique.



[DOI:10.1109/TNS.2018.2819506](https://doi.org/10.1109/TNS.2018.2819506)

Annealing

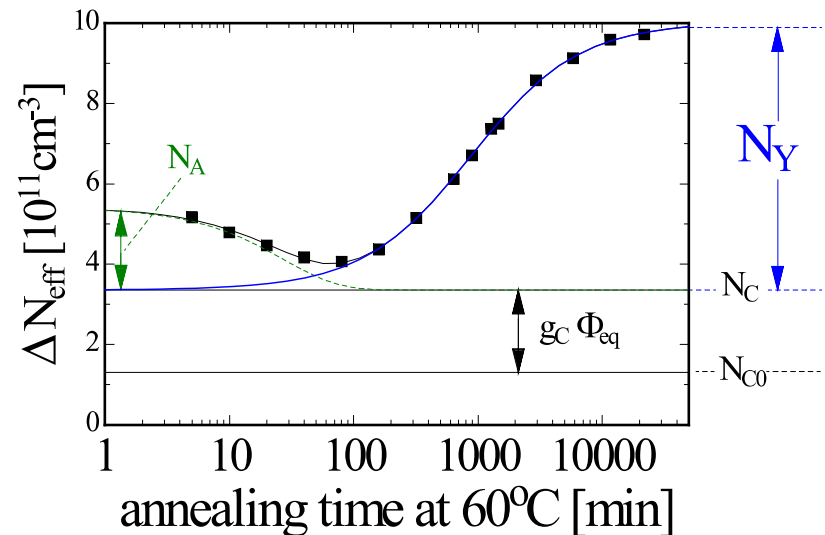
- The consequences of radiation damage and its development with time is temperature dependent.
- Annealing is the treatment of irradiated devices with temperature.
 - Typically higher temperatures “heal” the device.
- Change of effective doping concentration with irradiation

$$\Delta N_{eff} = N_{eff,0} - N_{eff}(t)$$

- $N_{eff,0}$ before irradiation.
- $N_{eff}(t)$ after irradiation.

$$\Delta N_{eff}(t) = N_A(t; \phi, T) + N_C(\phi) + N_Y(t; \phi, T)$$

- N_C stable damage.
- $N_A(t)$ short term/beneficial annealing.
- $N_Y(t)$ reverse annealing.

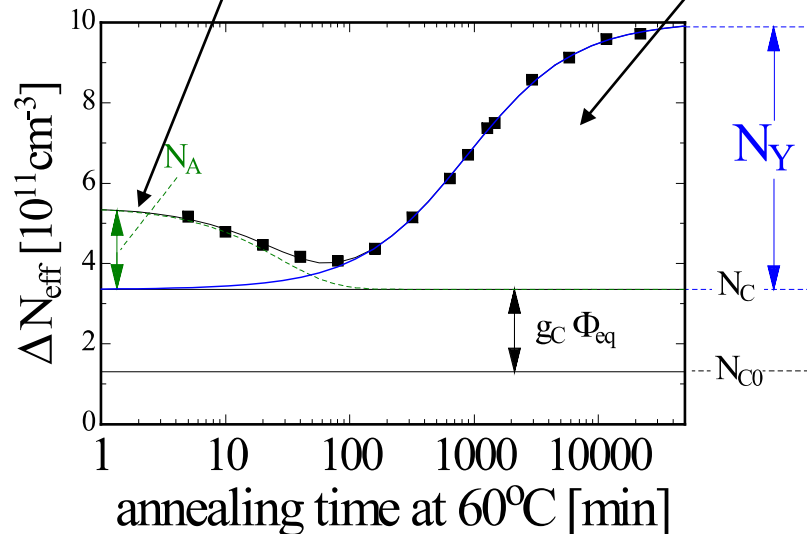


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Annealing

- Beneficial annealing

- Initial effective **decrease of acceptor-like states** when keeping the sensor for a few hours at 60C.
- Likely caused by increase of donor-like defects.



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- Reverse annealing

- Keeping the device at high temperature for longer, results in the **activation of acceptor-like defects** that counteract the beneficial annealing.
- To reduce reverse annealing silicon detectors at the LHC are kept at temperatures between -6C and -10C during operation and time without beam.

Annealing parametrisation

$$\Delta N_{eff}(t) = N_A(t; \phi, T) + N_C(\phi) + N_\gamma(t; \phi, T)$$

- The damage and annealing components are parametrised as

$$N_A(t; \phi, T) = g_a \phi_{eq} \exp(-t/\tau_a)$$

$$N_C(\phi) = g_c \phi_{eq} + N_{C,0}(1 - \exp(-c\phi_{eq}))$$

$$N_\gamma(t; \phi, T) = g_\gamma \phi_{eq}(1 - \exp(-t/\tau_\gamma))$$

- c is the removal coefficient.
- g_a, g_c, g_γ introduction rates for the space charge.
- $N_{C,0}$ accounts for incomplete doping removal.
- τ_a, τ_γ time constants for beneficial and reverse annealing resp., temperature dependence following Arrhenius law.
 - $E_a = 1.09\text{eV}$ for τ_a .
 - $E_a = 1.33\text{eV}$ for τ_γ
- Cooler temperatures = longer time constants.

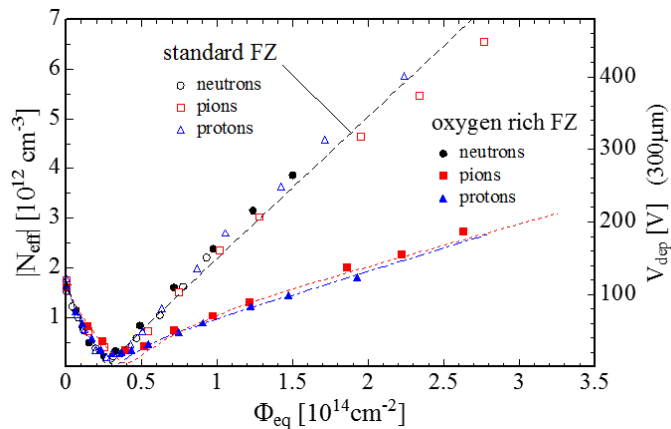
$$\tau_{a,\gamma} \propto \exp(E_a/T)$$

Material engineering

- The change in N_{eff} is strongly material dependent and depends on the particle type used for irradiation.
- This damage effect **does not scale directly with NIEL**.
- It can be **mitigated with defect engineering**.

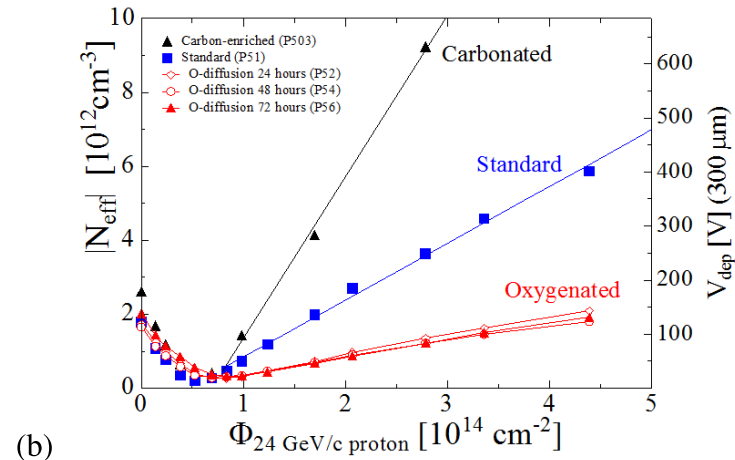
n-type silicon detectors.
Samples are irradiated, annealed, measured at each fluence point.

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Oxygenated material does not improve performance after neutron irradiation.

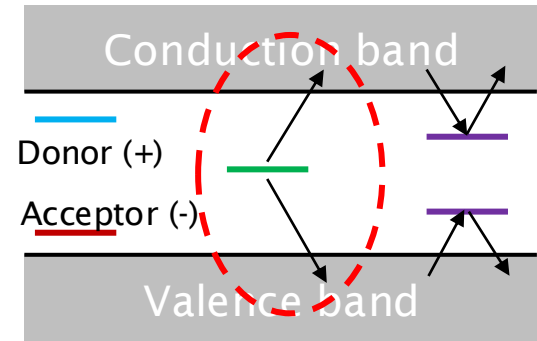
Significant **improvement for proton and pion** induced damage.



Adverse effect from carbonated substrates.

2- Leakage current increase

- Leakage current is produced by defect levels near the middle of the gap that act as **generation centres**.
 - Defect levels are generating leakage current by emission of electrons and holes.



- The generation rate for a single defect type t and neglecting free charge carriers in the depletion region is:

$$G_t = N_t f_t e_n = N_t (1 - f_t) e_p = N_t \frac{e_n e_p}{e_n + e_p}$$

- The **total leakage current** of the device is given by:
 - V is the active volume under the electrode

$$I_L = eV \sum_{\text{defects}} G_t$$

- Leakage current leads to increased **noise** in amplifiers and increased **power consumption**.

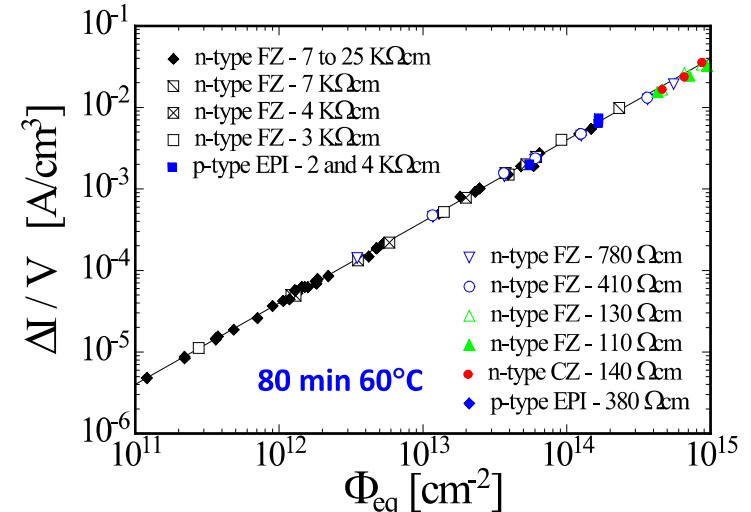
Fluence dependence of I_{leak}

- The leakage current follows the NIEL hypothesis scaling.
 - Defect engineering has no impact.
- After irradiation with highly energetic particles producing cluster defects, the leakage current increase depends only on the fluence.
 - Independent of type, resistivity, impurity content of material

Current increase by irradiation

$$\Delta I_L = \alpha \phi_{eq} V$$

- V volume contributing to current.
- ϕ_{eq} : 1 MeV neutron equivalent fluence.
- α : current-related damage factor.



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- For a fixed annealing time and temperature, α is a universal constant when normalised to a certain temperature.

$$\alpha(80 \text{ min}, 60\text{C}) = (3.99 \pm 0.03) \times 10^{-17} \frac{\text{A}}{\text{cm}}, \text{ at } 20\text{C}$$

Temperature dependence of I_{leak} & annealing

- The temperature dependence of the leakage current is dominated by deep-level defects residing in the middle of the bandgap.

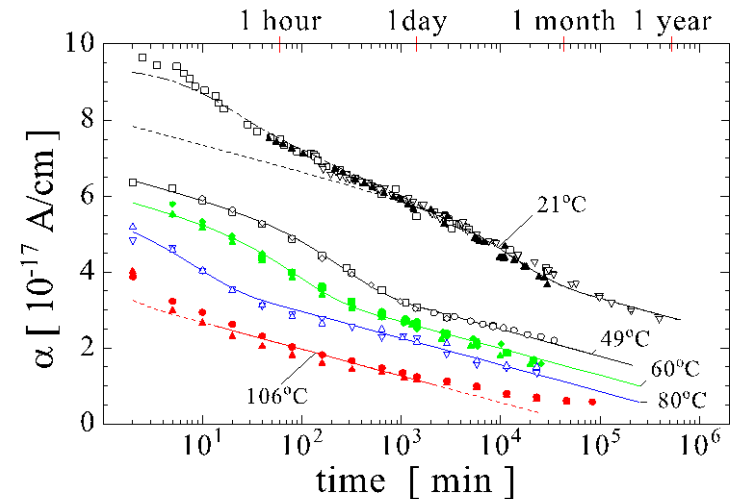
- Parametrisation $I_L(T) \propto T^2 \exp\left(-\frac{E_a}{2kT}\right)$

- $E_a = 1.19 - 1.21 \text{ eV}$.
- 8-10% reduction per degree C for $T = \text{RT to } -20\text{C}$.

- The exponential T dependence of the leakage current requires cooling of the sensors in the experiments to avoid thermal runaway.

- Annealing is beneficial to reduce leakage current.

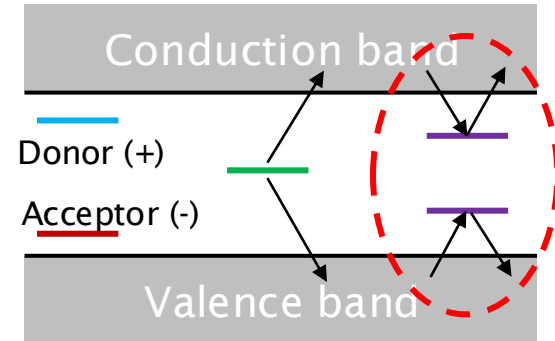
- α value continuously decreasing with time.



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3- Charge trapping

- Charge carriers generated by impinging radiation can be trapped by defect levels and released after some time.
- Long de-trapping time compared to the collection time of the sensor or high the density of trapping → **decreased signal**.
 - Decreased carriers lifetime and mean free path.
- Carrier trapping is described by an **effective trapping time** (inverse capture rate).



$$\frac{1}{\tau_{eff,e}} = \sum_{defects} c_{n,t}(1 - f_t)N_t$$

$$\frac{1}{\tau_{eff,h}} = \sum_{defects} c_{p,t}f_tN_t$$

- $c_{n,t}/c_{p,t}$ capture coefficient for e-/h+ for defect t .

Trapping dependence on fluence & temperature

- At high fluence charge trapping is dominating the deterioration of the detector response.
- Assuming that the charge trapping depends only on the time the carriers drift in the sensor, the evolution of trapping with time is described by:

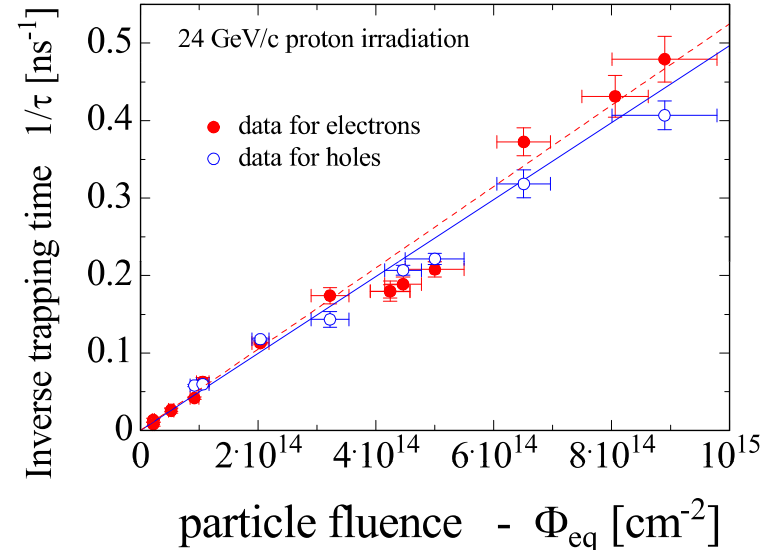
$$Q(t) = Q_0 \exp(-t/\tau_{eff})$$

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_0} + \beta \Phi_{eq}$$

- τ_0 : carrier lifetime before irradiation.
- β : effective trapping damage constant.
 - Depends on carrier capturing.
 - Large β = large damage.
 - Weak dependence on T.

$$\beta(T) = \beta(T_0) (T/T_0)^k$$

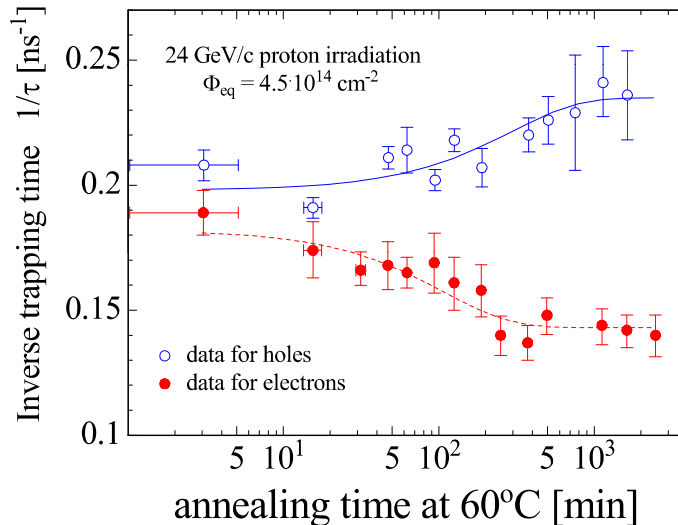
- k : -0.83 to -0.9 for e-, -1.52 to -1.69 for h+.



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Annealing of trapped charged

- The effective trapping damage constant depends on the annealing history of the sensor.



Decrease in β for electrons \rightarrow less trapping.
Increase in β for holes \rightarrow more trapping.

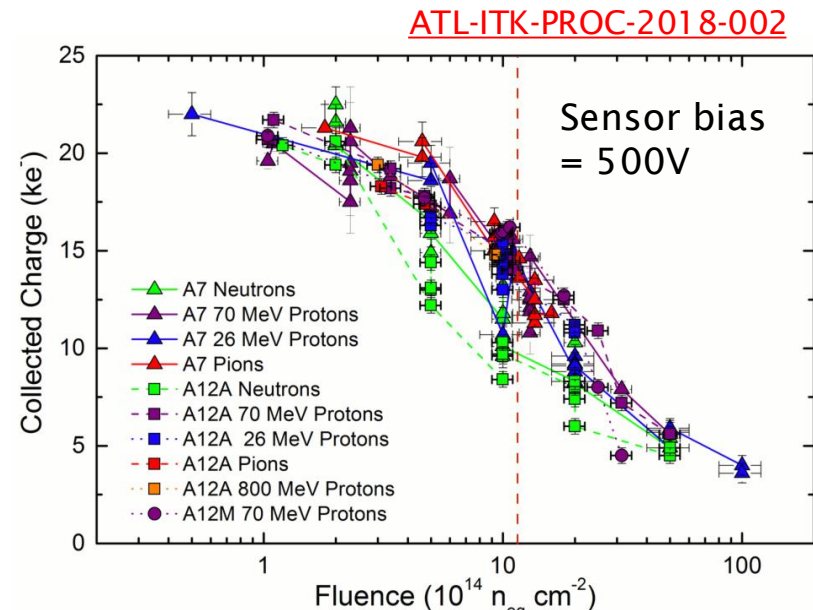
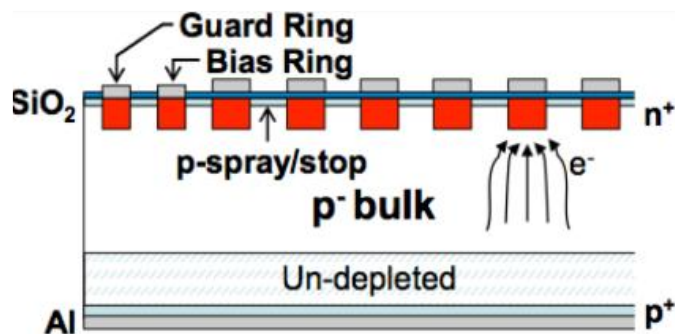
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$$\beta(t) = \beta_0 \exp(-t/\tau_a) + \beta_\infty (1 - \exp(-t/\tau_a))$$

- The trapping rate is governed by the time constants for beneficial annealing.
 - β_0/β_∞ trapping rate at the beginning/end of the annealing process.

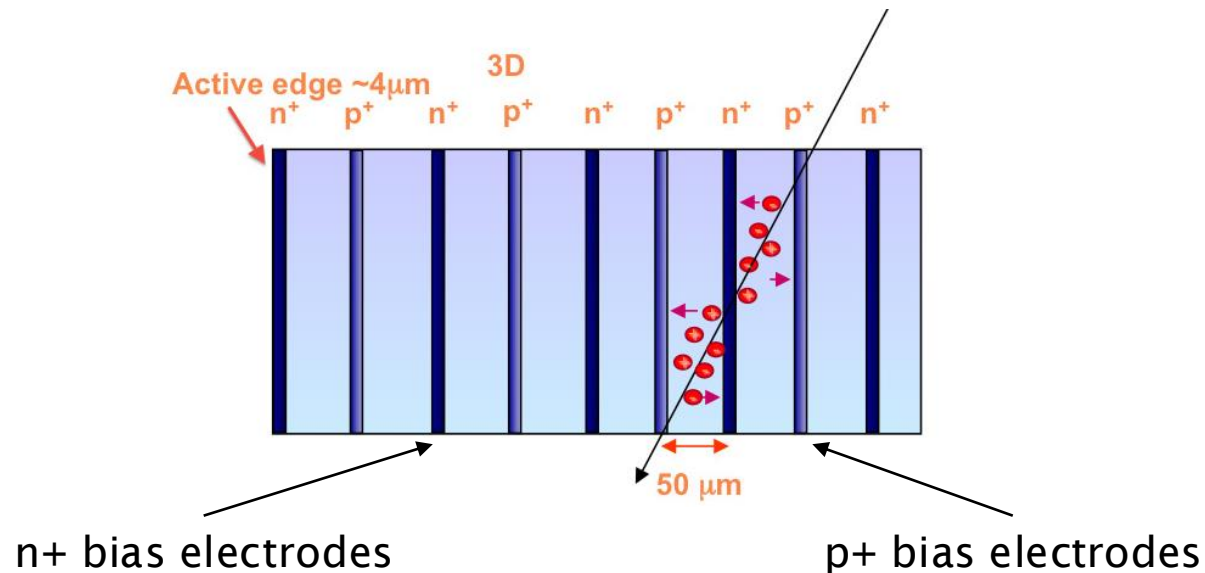
Radiation-hard sensors: planar n-in-p

- The ATLAS and CMS trackers at LHC deploy p-in-n strips sensors → For the HL-LHC they will use **n-in-p to improve radiation hardness**.
 - **Electrons** are collected at the n+ electrode → higher mobility, less trapping.
 - The depletion region grows from the collecting electrode side into the bulk → **Highest E-field at the collecting electrode**; sensor can be operated under-depleted.
 - **Guard ring** structure used to bring down the high sensor bias voltage needed after irradiation towards the edge of the sensor.
 - **P-spray/stop** are used to isolate collection electrodes in presence of oxide and interface charges (→ Surface damage).



Radiation-hard sensors: 3D sensors

- Alternative geometry for pixel sensors that provides higher radiation tolerance by design: **drift path decoupled from incoming particle path.**
- Electrodes penetrate vertically in the sensor bulk, drift distance $\sim 50 \mu\text{m}$.
 - Shorter charge collection distance \rightarrow **Less charge trapping.**
 - High field with low voltage \rightarrow **Lower power**, i.e. heat, after irradiation.

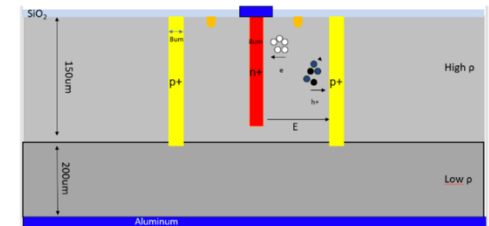
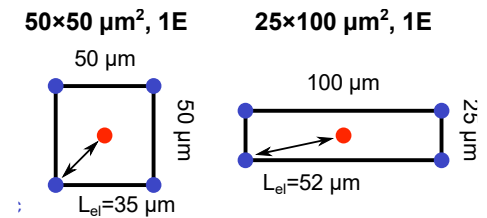


3D sensors for the ATLAS ITk pixel detector

- The ITk is the new ATLAS Inner Tracker system for the HL-LHC.
 - All-silicon detector made of pixels and strips layers.
 - The innermost pixel layers will use 3D sensor.

- 3D sensors with new single-side technology.

- Thin active substrates (150 μm) \rightarrow Reduced cluster size and data rates.
- Small pixels \rightarrow Low occupancy, improved impact parameter resolution.



- Efficiency $>96-97\%$ at $1.6 \times 10^{16} n_{\text{eq}}/\text{cm}^2$.

- $V_{\text{depl}} < 150\text{V}$, power $< 40 \text{ mW}/\text{cm}^2$ (at -25C).

