Radiation Hardness of Silicon Detectors

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Plan for the lectures

- Brief introduction
- Displacement damage
- Surface damage

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

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Plan for the lectures

- **Brief introduction**

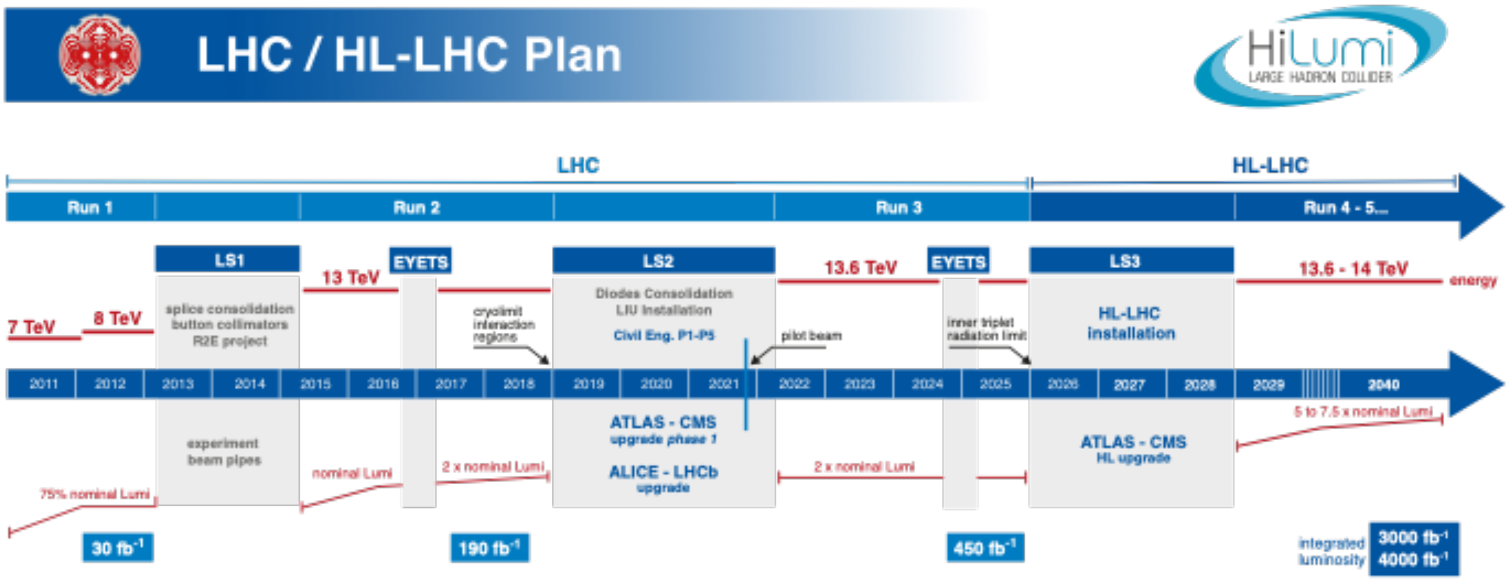
- Displacement damage

- 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.



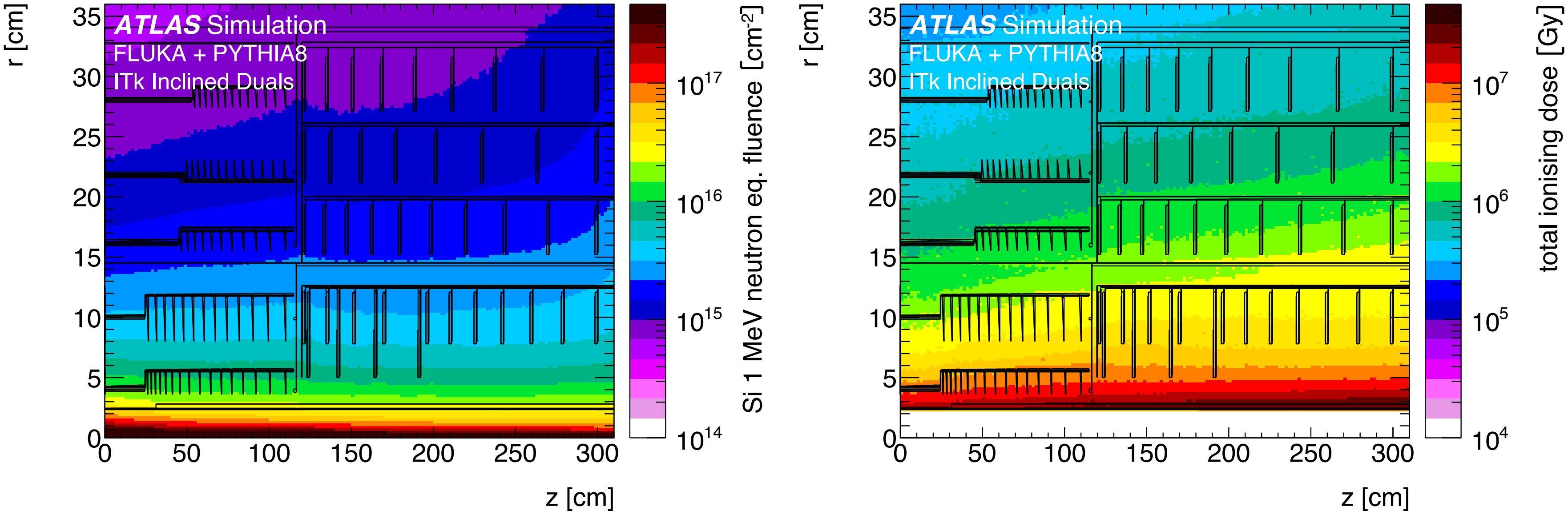
https://hilumilhc.web.cern.ch/content/hl-lhc-project

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

Radiation levels

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

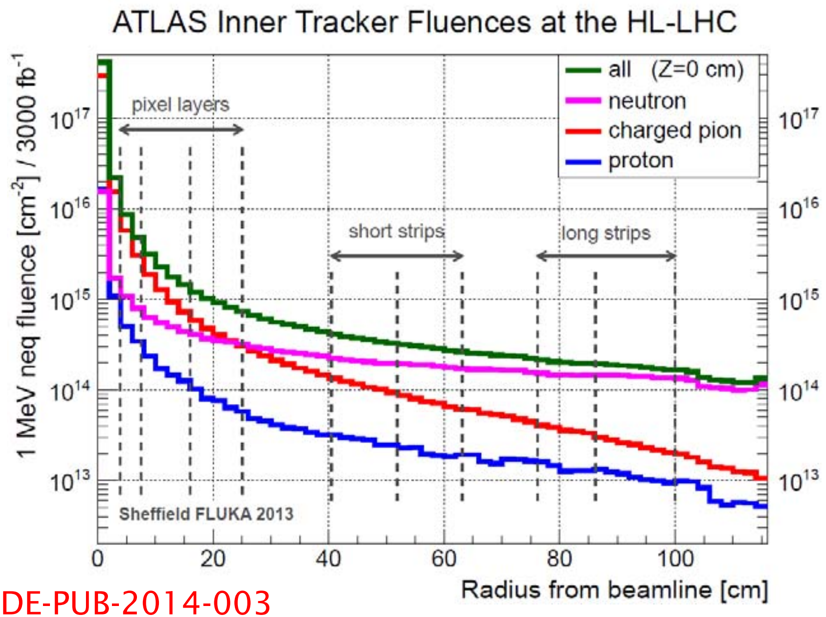
	Example: ATLAS innermost pixel layers	
	Fluence	**Total Ionising Dose**
@ **LHC (300 fb^{-1})**	2 x 10^{15} n_{eq}/cm^2	300 kGy
@ **HL-LHC (4000 fb^{-1})**	2 x 10^{16} n_{eq}/cm^2	10 MGy



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. $Si\text{-}SiO_2$.
  - 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

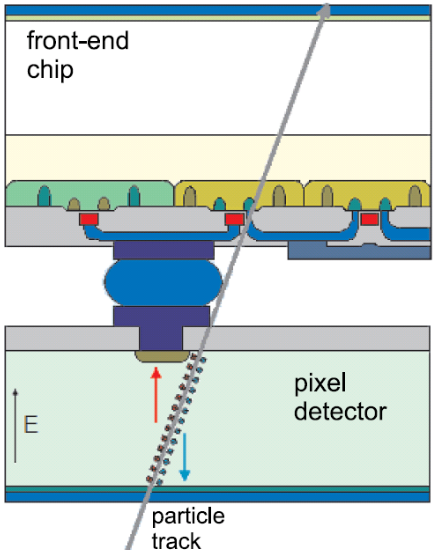
- Single Events Effects (SEE) are due to the energy deposited by one single particle in a circuit's sensitive node and they can happen in any moment.

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

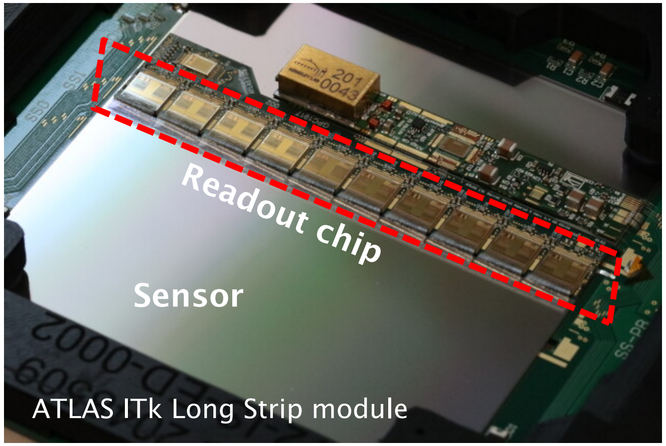
Not covered in these lectures.

Silicon detectors

Pixels - Hybrid

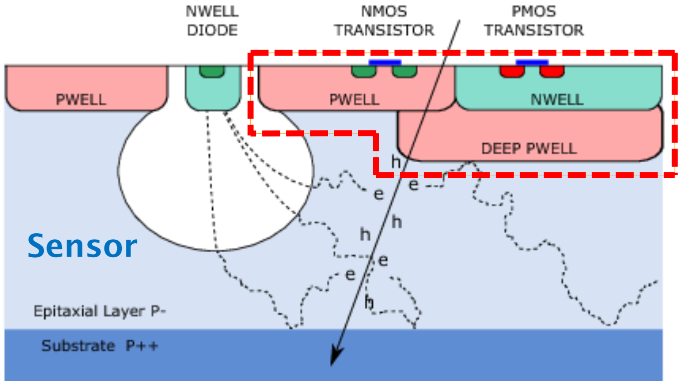


Strips



ATLAS ITk Long Strip module

Pixels - Monolithic



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

Different flavours, basic elements: sensor + readout electronics.

Both sensor are electronics are implemented in silicon.

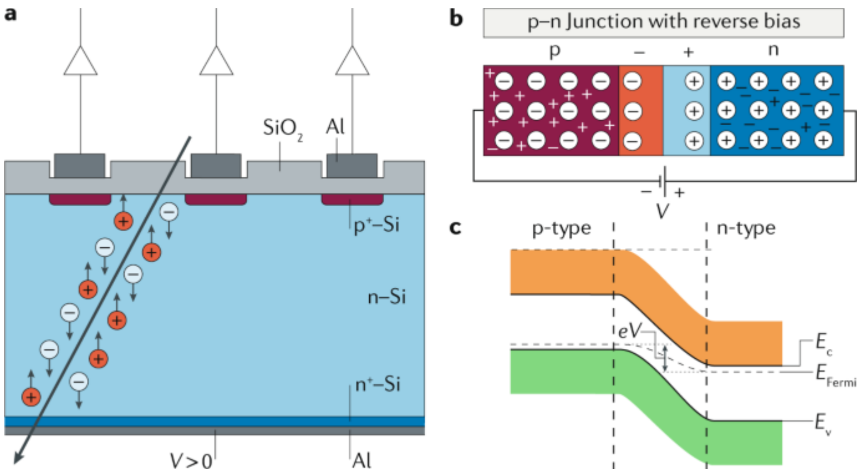
Radiation damage to silicon detectors

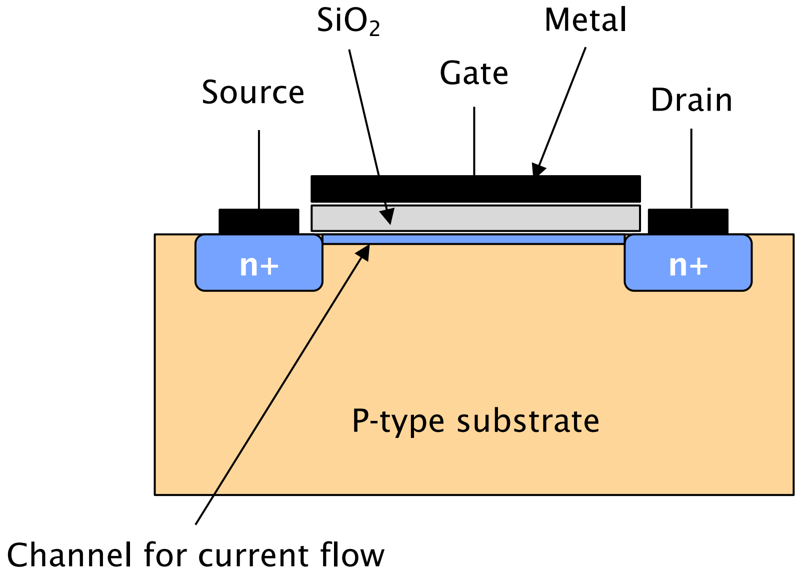
- Sensor:
  - Reverse biased pn-junction.
  - Charge collection in the sensor volume.

→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 $Si\text{-}SiO_2$ interface.

→ Affected by surface effects and SEE.





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_{eq}/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.

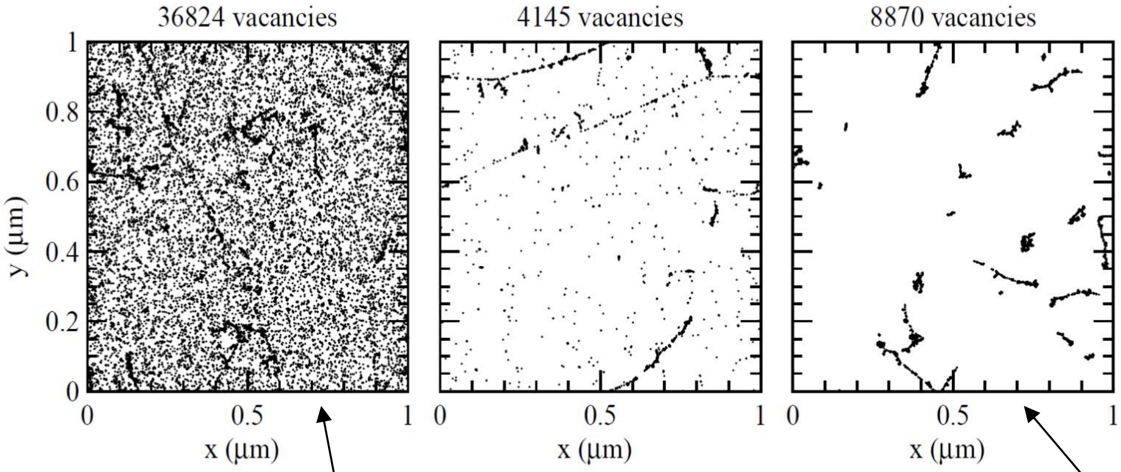
- Atoms can be knocked-off from their initial position with a certain recoil energy, E_R.
  - A vacancy is left behind, the recoil atom looses energy by ionisation and by creating further displacement damage, until it comes to rest as a lattice interstitial.

- 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 on 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.

10 MeV p 23 GeV p 1 MeV n



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

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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 if the impinging particle.
  - Ionisation in semiconductors is a reversible process and no damage remains in the crystal expect 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 cm^2/g or as a NIEL cross section in units of MeV mb.

- NIEL can be calculated for electrons, protons, neutron, 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.

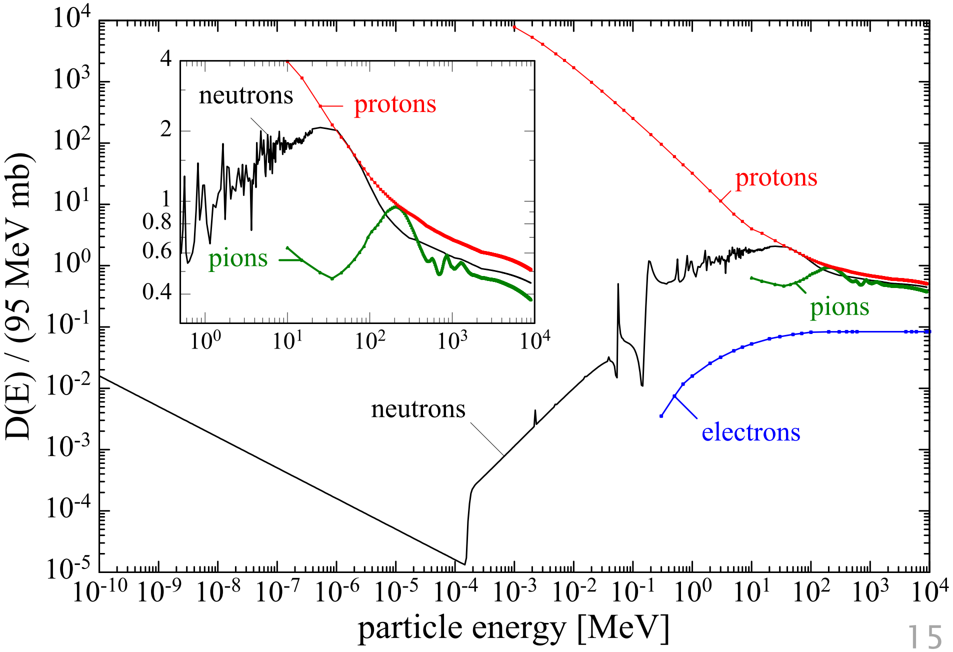
Displacement damage function

- $D(E)$ 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 $E_d \approx 25eV$).
  - 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.



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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.

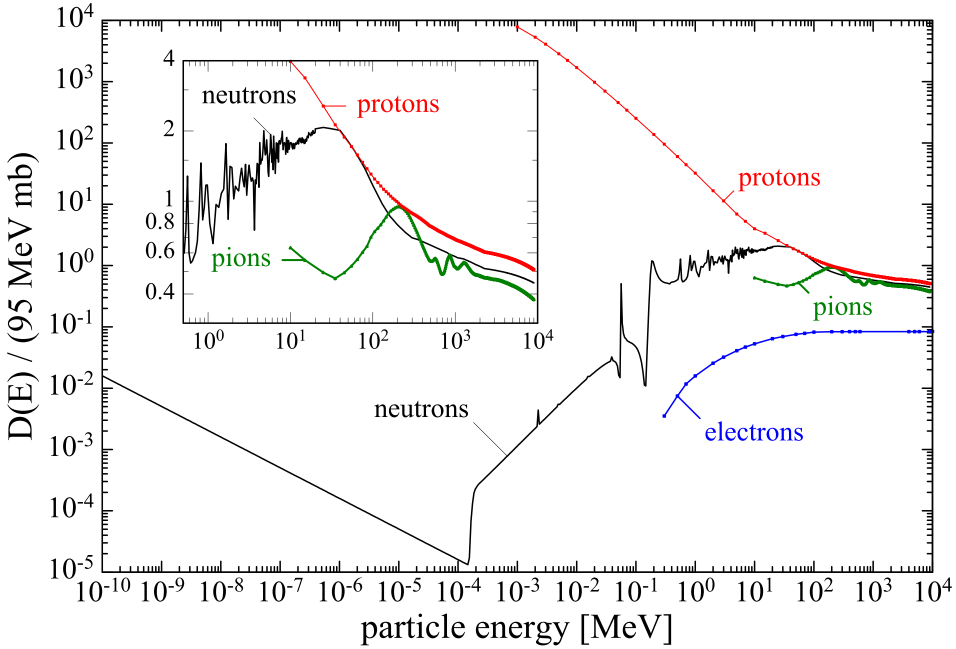
- The NIEL hypothesis describes well the displacement damage effects observed in silicon detectors and allows to make predictions of effects of such damage in radiation fields such as those at HEP collider experiments.
  - It describes well the evolution of many device parameters with radiation, in particular 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 $D(E)$ → NIEL scaling.

- Normalisation factor: damage effect of 1 MeV neutrons → $D_E(1 MeV) = 95\ MeV\ mb$.



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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:

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

  - 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, $k \approx 2.0$.

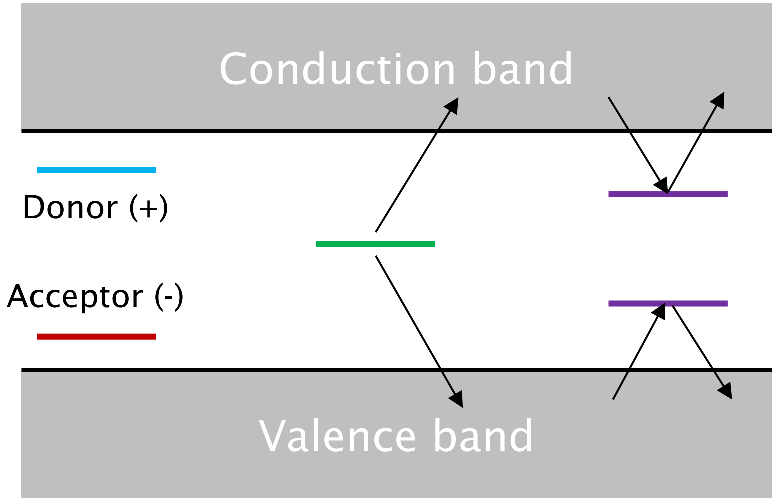
- $\phi(E)$ is the fluence, particle of a certain energy E/cm^2.

- 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 a 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.

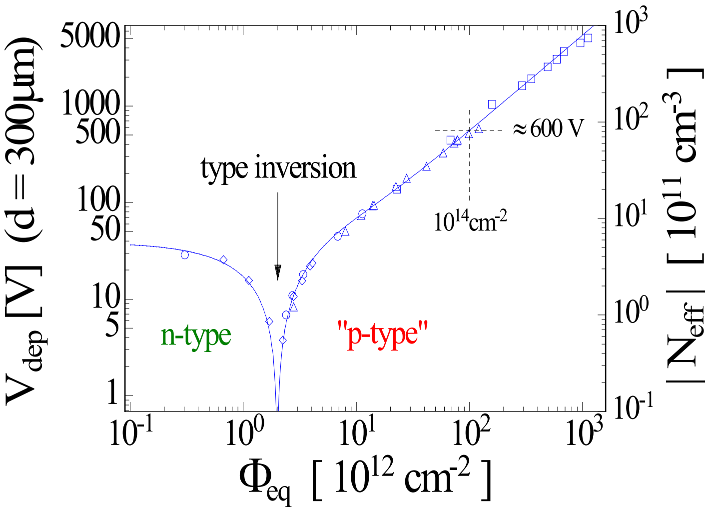
Type inversion

- 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 → the sensor depletion voltage V_{dep} increases → the sensor might be operating underdepleted and collect less charge.

$$V_{dep} \approx \frac{e|N_{eff}|d^2}{2\varepsilon\varepsilon_0}$$

  - d is the sensor thickness.



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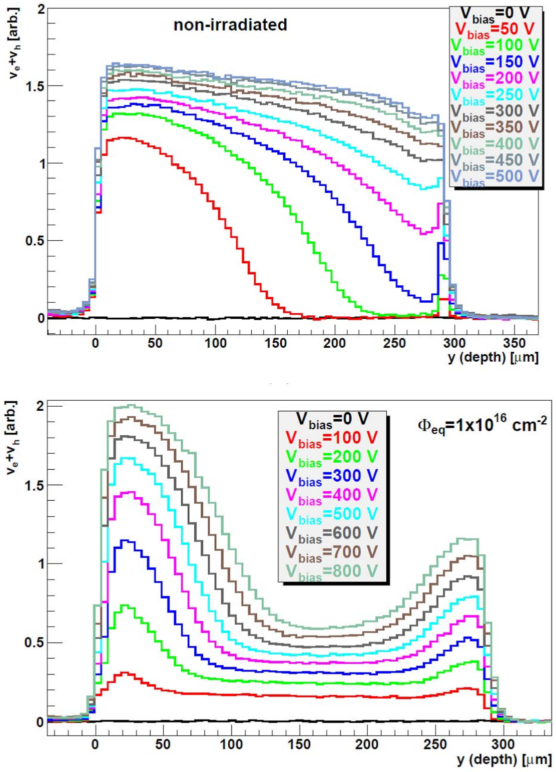
Electric field in the bulk

- 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.



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Annealing

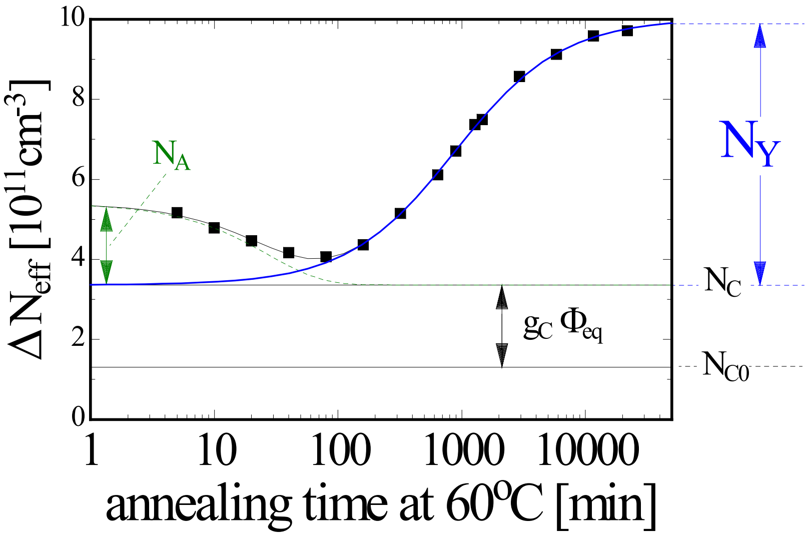
- The consequences of radiation damage and its development with time is temperature dependent.
- Annealing is the treatment of irradiated devices with temperature.
  - Typically higher temperatures “heal” the device.
- Change of effective doping concentration with irradiation

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

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

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

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



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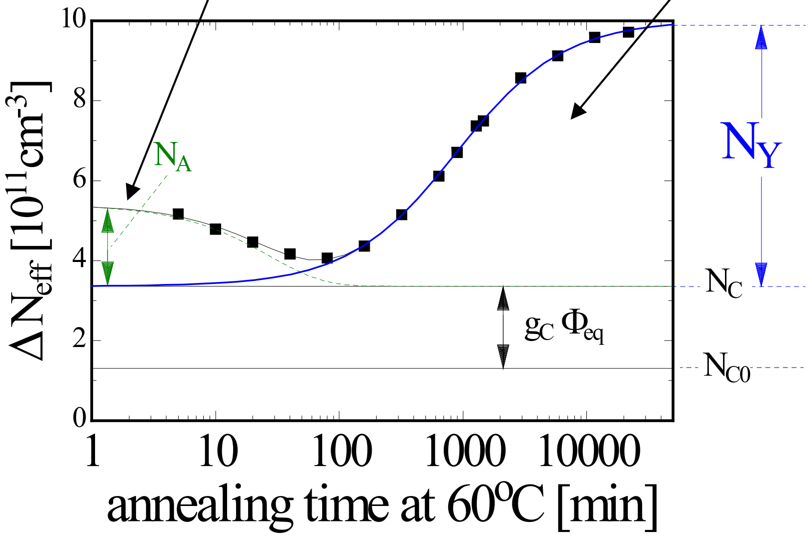
Annealing

- 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.

- 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.



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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

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

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

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

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

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

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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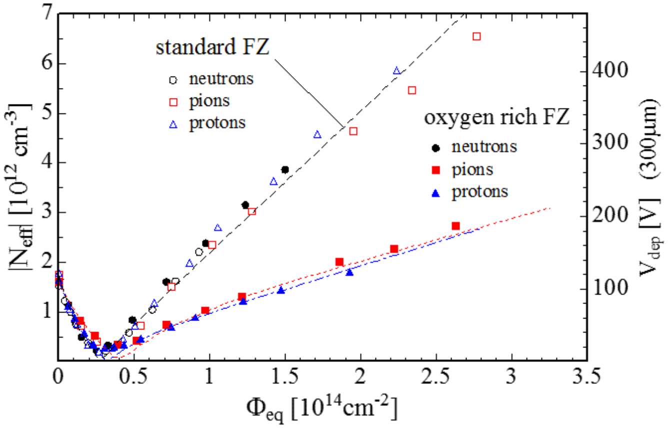

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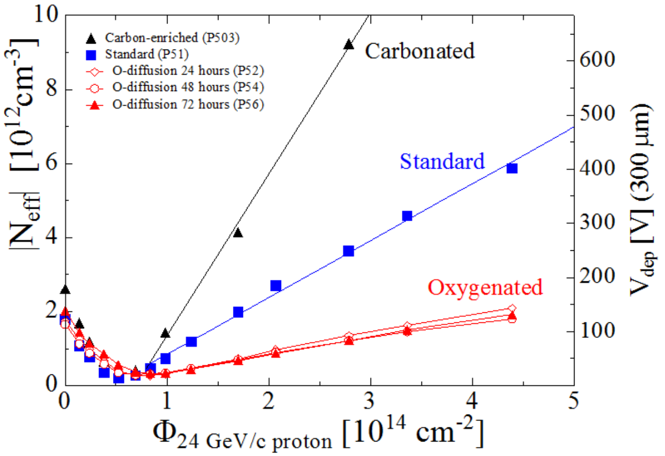
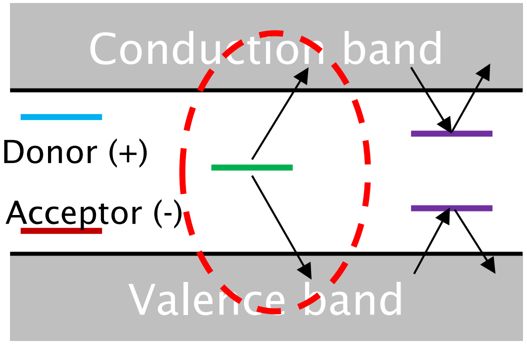


Oxygenated material does not improve performance after neutron irradiation.
Significant improvement for proton and pion induced damage.

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

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

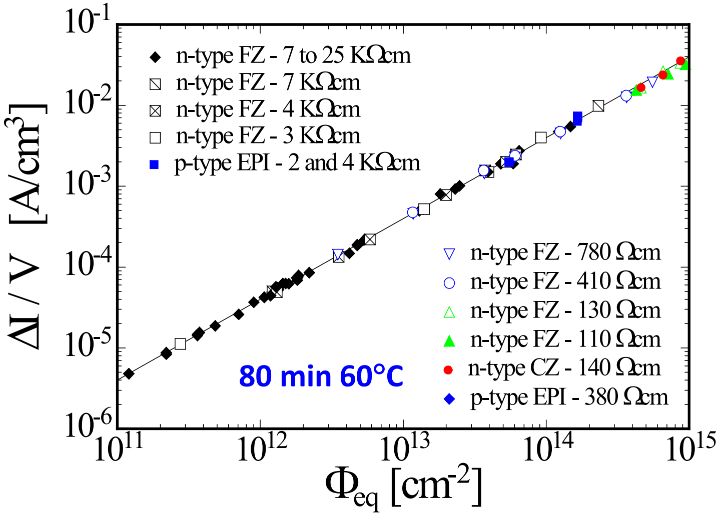
- Leakage current leads to increased noise in amplifiers and increased power consumption.

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.

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

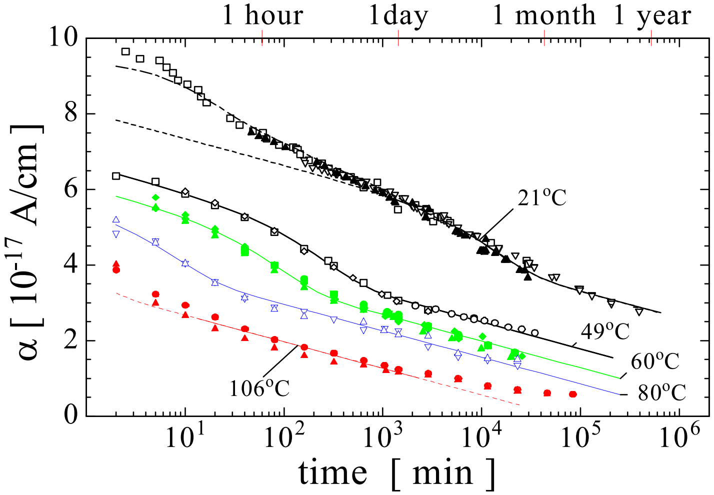
Temperature dependence of I_{leak} & annealing

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

- Parametrisation $I_L(T) \propto T^2 \exp\left(-\frac{E_a}{2kT}\right)$
  - $E_a = 1.19 - 1.21\, eV$.
  - 8-10% reduction per degree C for T = RT to -20C.

- 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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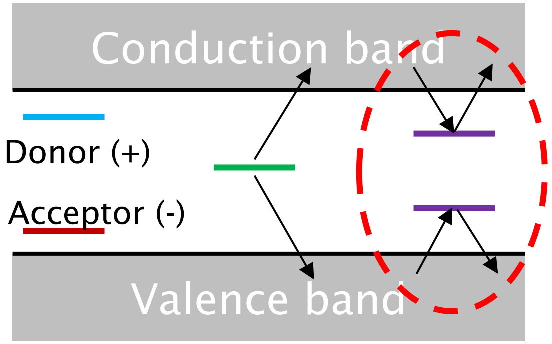
3- Charge trapping

- 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.

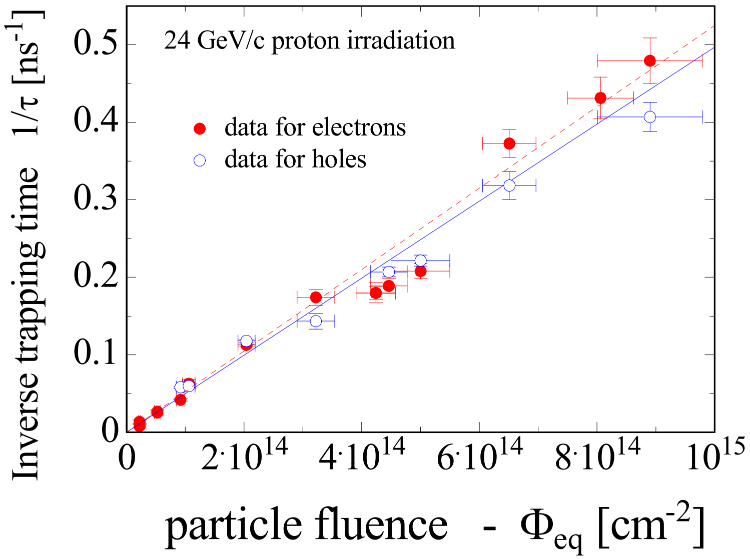
Trapping dependence on fluence & temperature

- At high fluence charge trapping is dominating the deterioration of the detector response.

- Assuming that the charge trapping depends only on the time the carrier drift in the sensor, the evolution of trapping with time is described by:

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

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



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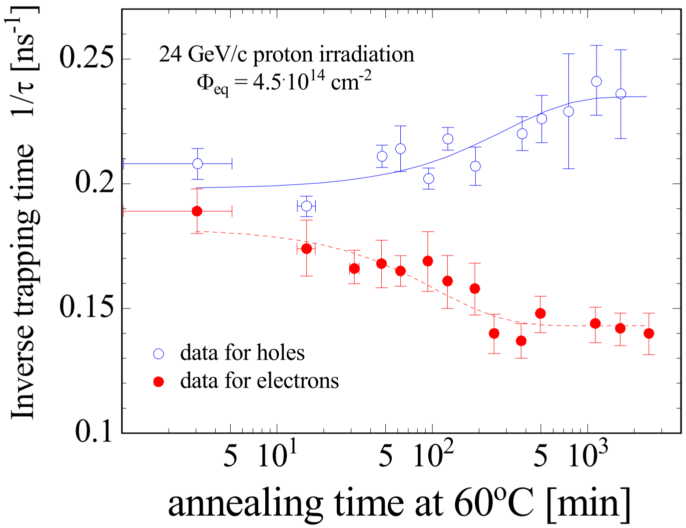
- τ_0: carrier lifetime before irradiation.
- β: effective trapping damage constant.
  - Depends on carrier capturing.
  - Large β = large damage.
  - Weak dependence on T.

$$\beta(T) = \beta(T_0)\left({}^{T}/_{T_0}\right)^k$$

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

Annealing of trapped charged

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



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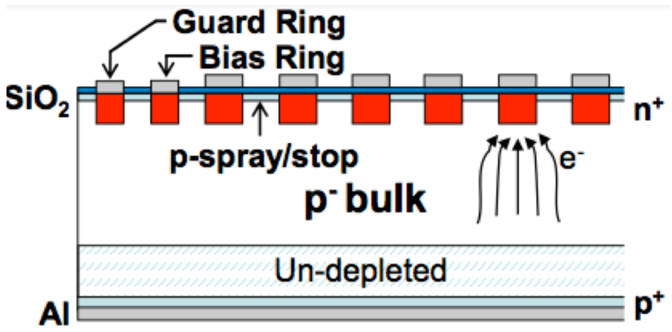
Decrease in β for electrons → less trapping.
Increase in β for holes → more trapping.

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

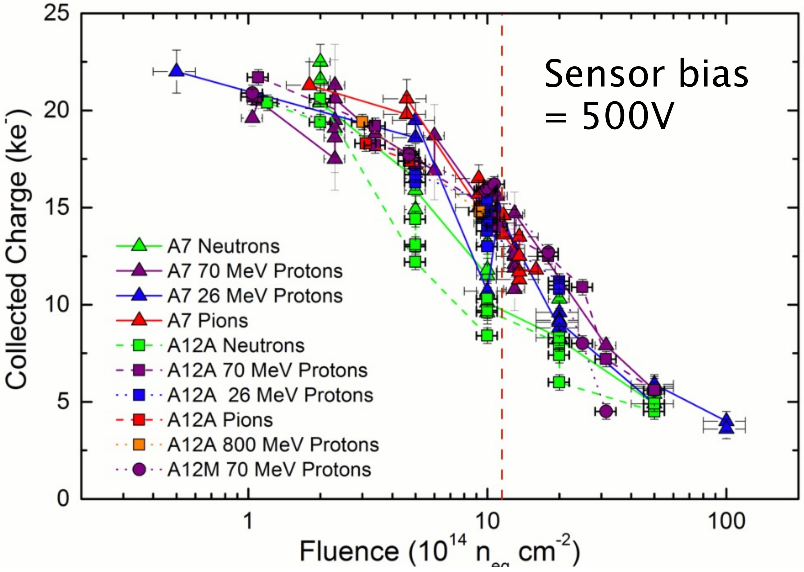
- The trapping rate is governed by the time constants for beneficial annealing.
  - β_0/β_∞ trapping rate at the beginning/end of the annealing process.

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 colleting 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).



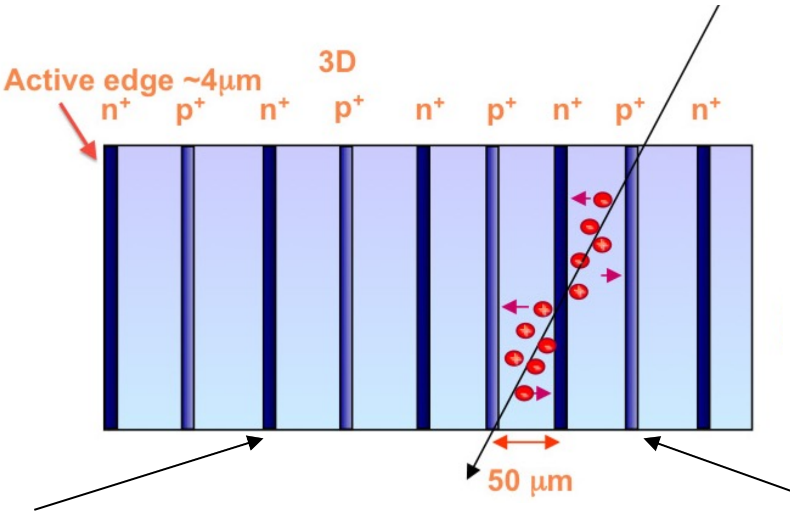
ATL-ITK-PROC-2018-002



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 $\sim 50\ \mu m$.
  - Shorter charge collection distance → Less charge trapping.
  - High field with low voltage → Lower power, i.e. heat, after irradiation.



n+ bias electrodes

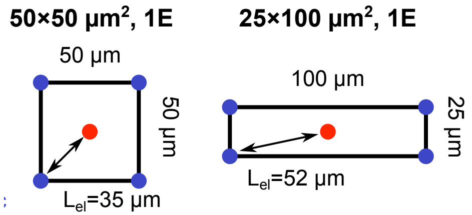
p+ bias electrodes

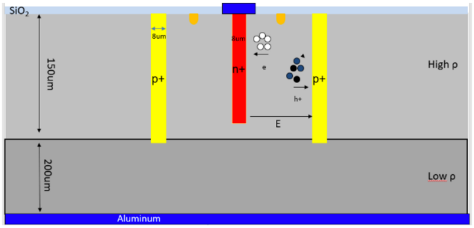
3D sensors for the ATLAS ITk pixel detector

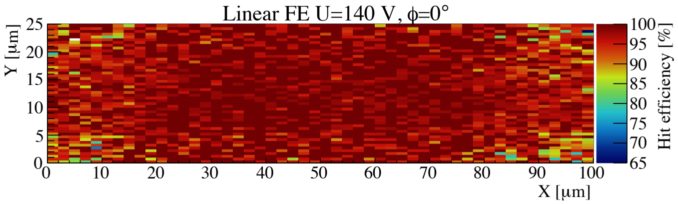
- The ITk is the new ATLAS Inner Tracker system for the HL-LHC.
  - All-silicon detector made of pixels and strips layers.
  - The innermost pixel layers will use 3D sensor.

- 3D sensors with new single-side technology.
  - Thin active substrates (150 μm) → Reduced cluster size and data rates.
  - Small pixels → Low occupancy, improved impact parameter resolution.

- Efficiency >96-97% at 1.6 x 10^{16} n_{eq}/cm2.
  - V_{depl} <150V, power < 40 mW/cm^2 (at -25C).







NIM A 182 (2020) 164587