# 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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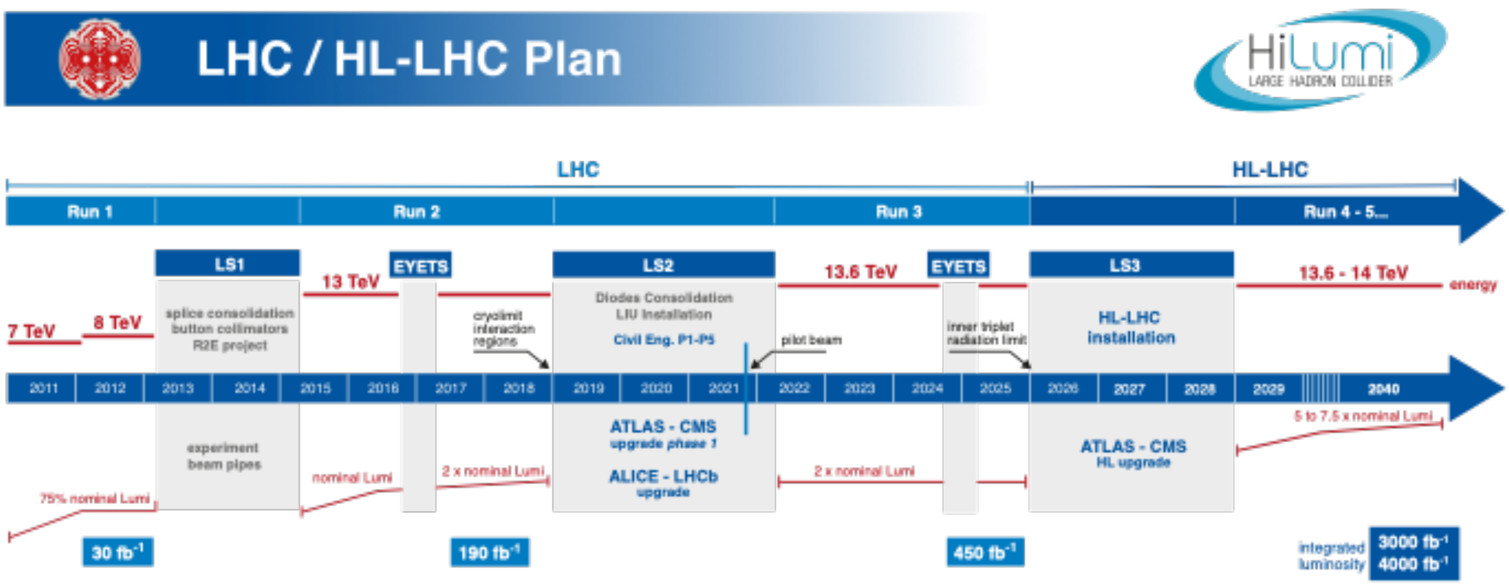
# Plan for the lectures

- **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.



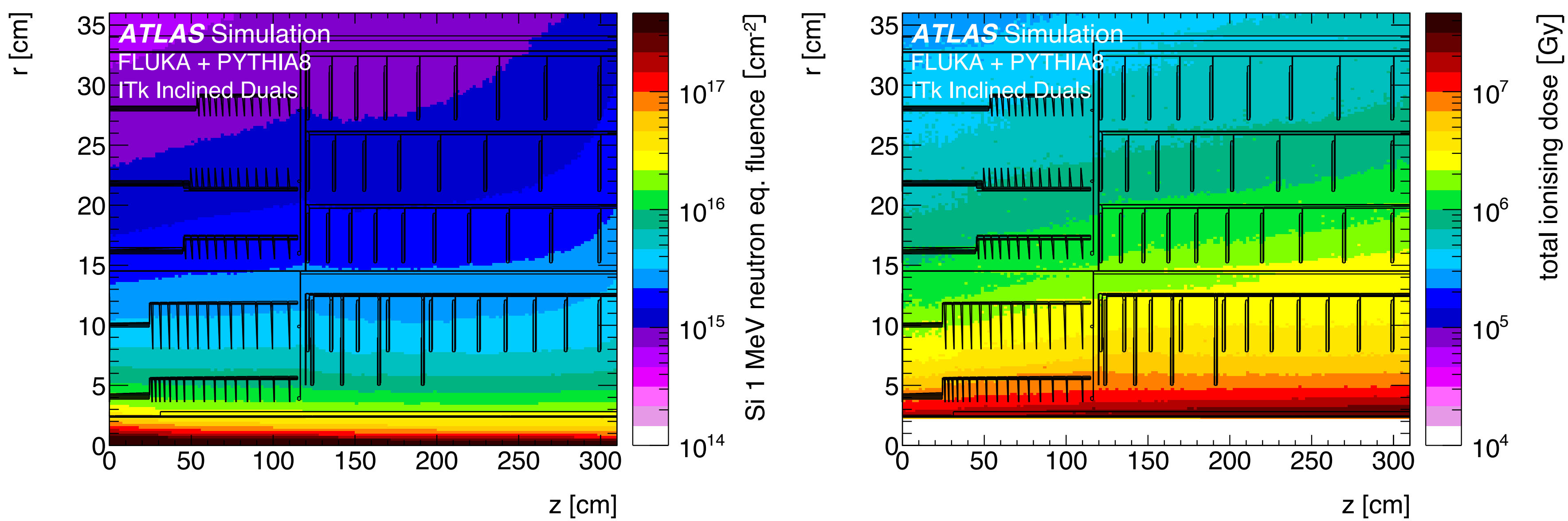

https://hilumilhc.web.cern.ch/content/hl-lhc-project

| | Instantaneous peak luminosity | Integrated luminosity |
|---|---|---|
| **LHC** | $2 \times 10^{34}$ $cm^{-2}s^{-1}$ | 450 $fb^{-1}$ |
| **HL-LHC** | $5 - 7.5 \times 10^{34}$ $cm^{-2}s^{-1}$ | 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.

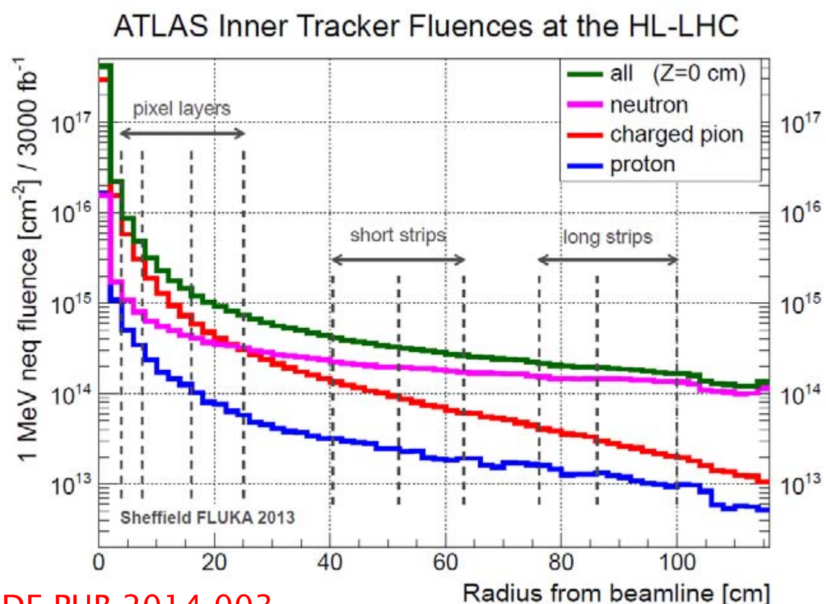
| | Example: ATLAS innermost pixel layers | |
|---|---|---|
| | **Fluence** | **Total Ionising Dose** |
| **@ LHC (300 fb$^{-1}$)** | 2 x $10^{15}$ $n_{eq}/cm^2$ | 300 kGy |
| **@ HL-LHC (4000 fb$^{-1}$)** | 2 x $10^{16}$ $n_{eq}/cm^2$ | 10 MGy |




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

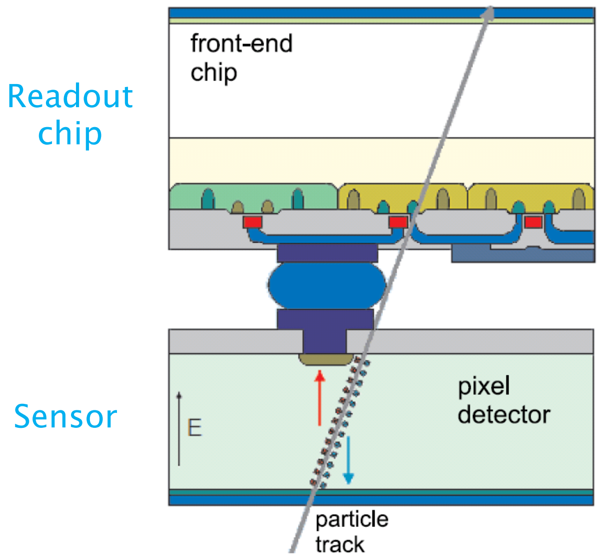
- Single Events Effects (SEE) are due to the energy deposited by one single particle in a circuit's sensitive node and they can happen in any moment.

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

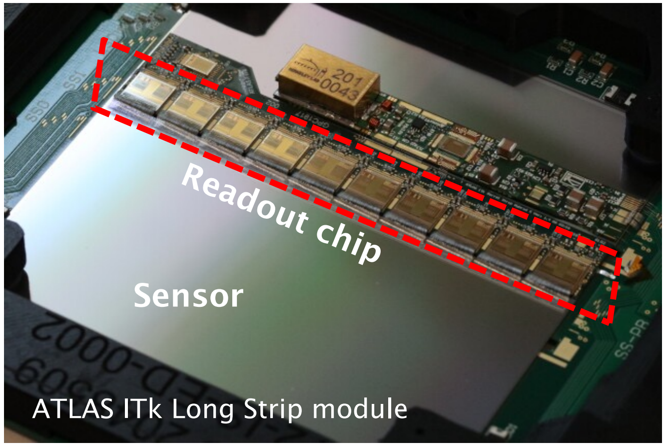
Not covered in these lectures.

# Silicon detectors

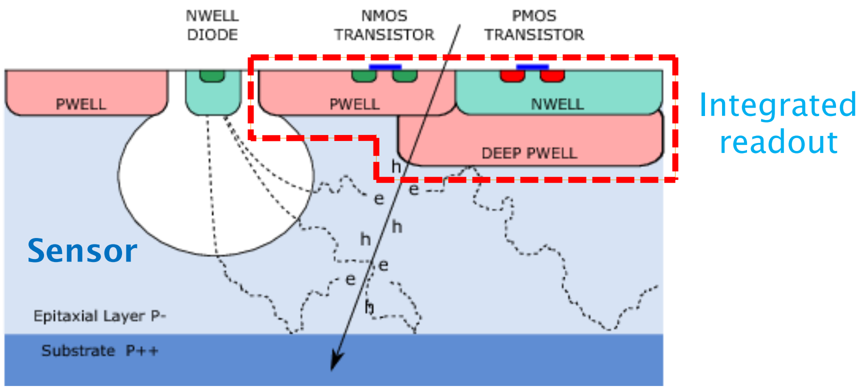
## Pixels - Hybrid




## Strips




## Pixels - Monolithic




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

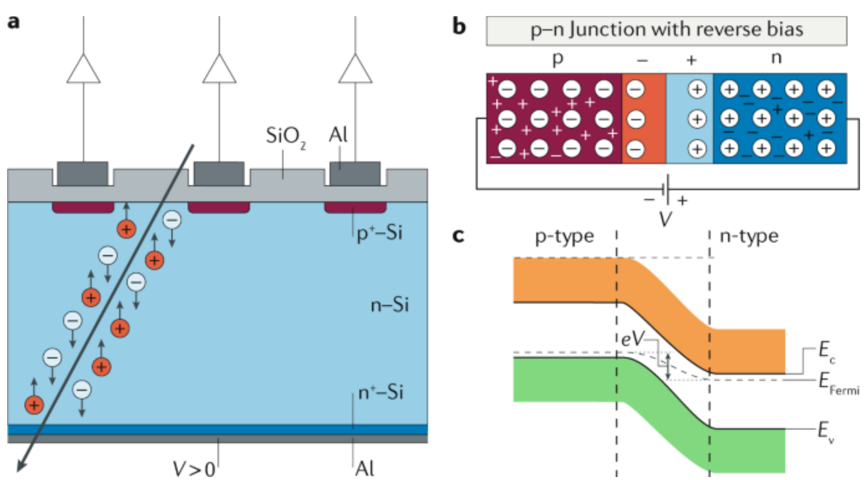
Different flavours, basic elements: **sensor + readout electronics**.

Both sensor are electronics are implemented in silicon.

# Radiation damage to silicon detectors

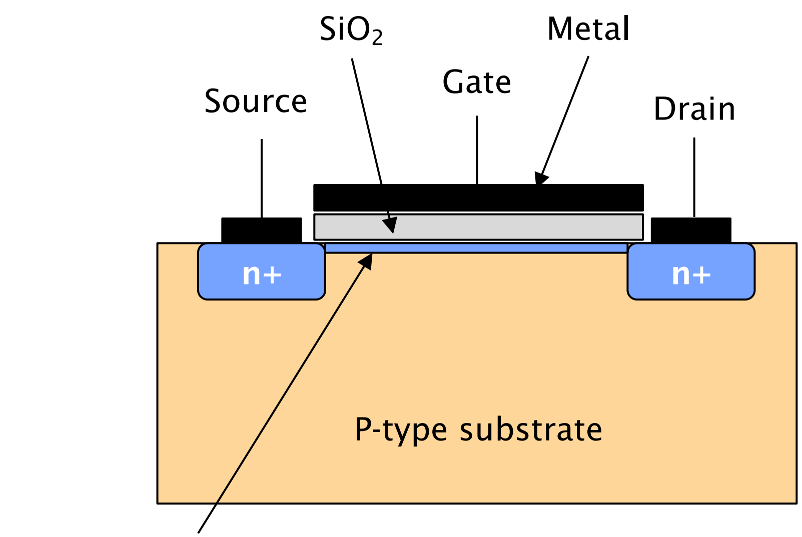
- Sensor:
  - Reverse biased pn-junction.
  - Charge collection in the sensor volume.

→ 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-$SiO_2$ 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.

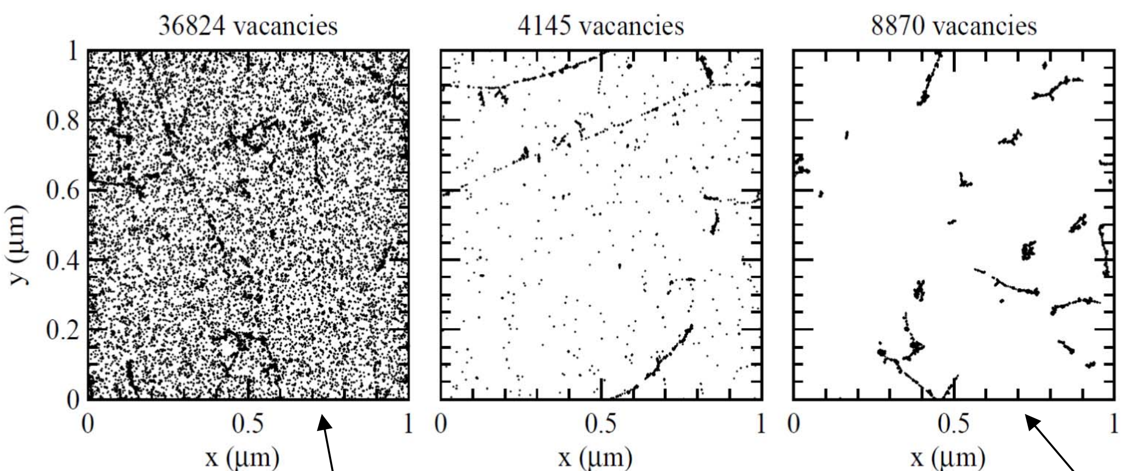
- Atoms can be knocked-off from their initial position with a certain recoil energy, $E_R$.
  - A vacancy is left behind, the recoil atom looses energy by ionisation and by creating further displacement damage, until it comes to rest as a lattice interstitial.

- 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 then 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$^2$.
DOI: 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 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.

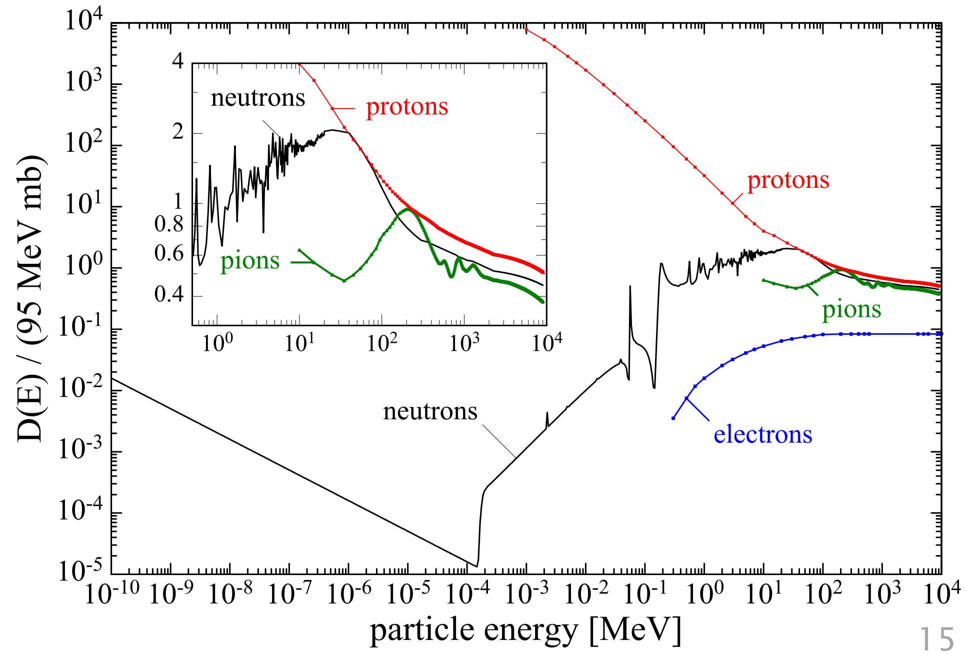
# Displacement damage function

- $D(E)$ 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 $\sigma_i$.
  - $f_i(E, E_R)$: 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.

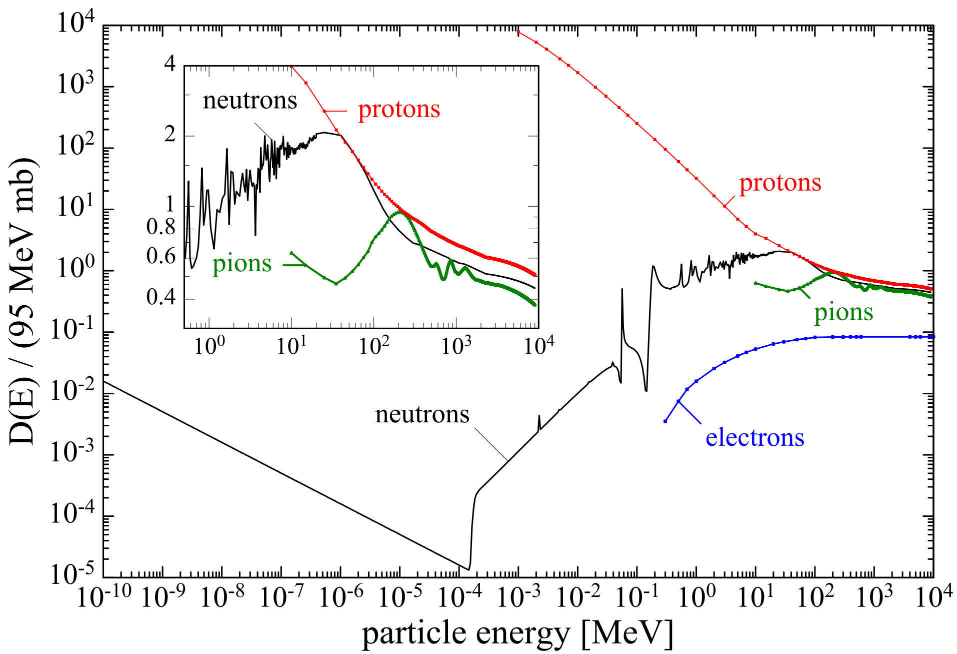
- The NIEL hypothesis describes well the displacement damage effects observed in silicon detectors and allows to make predictions of effects of such damage in radiation fields such as those at HEP collider experiments.
  - It describes well the evolution of many device parameters with radiation, in particular 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 → $D_E(1MeV) = 95\ MeV\ mb$.

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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$^2$.

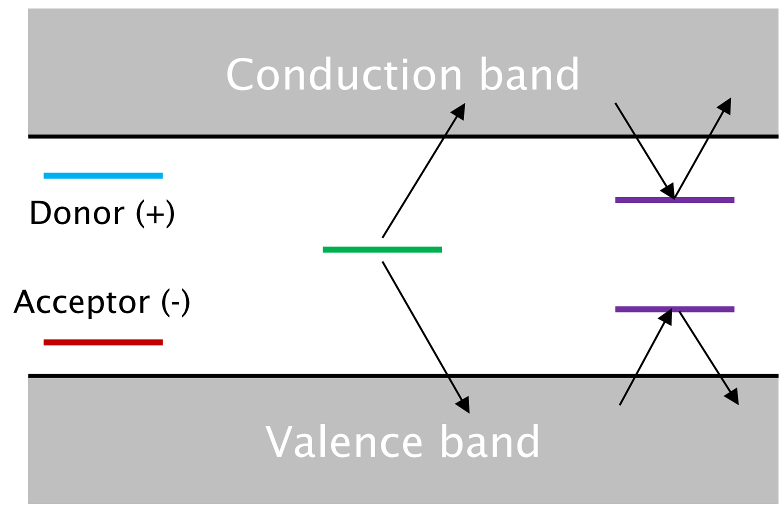
- The equivalent fluence for 1 MeV neutrons is the damage-weighted fluence received by the detector from a particle of a given species and energy.

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

# 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, $\sigma_n$, and holes, $\sigma_p$ .
  - 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.

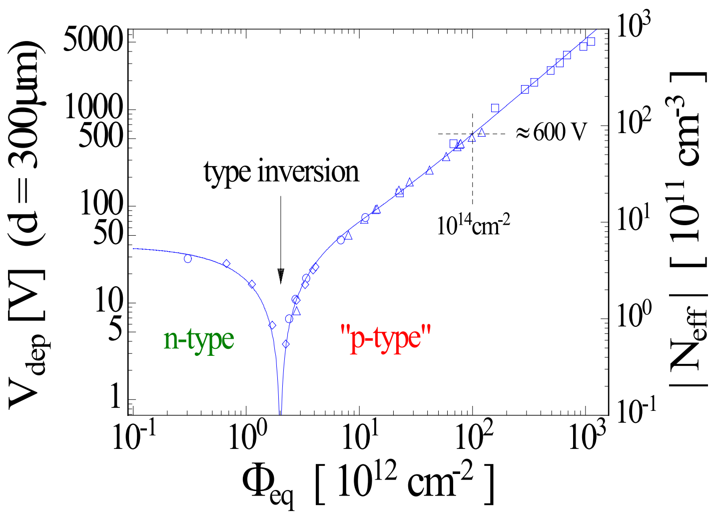
# Type inversion

- 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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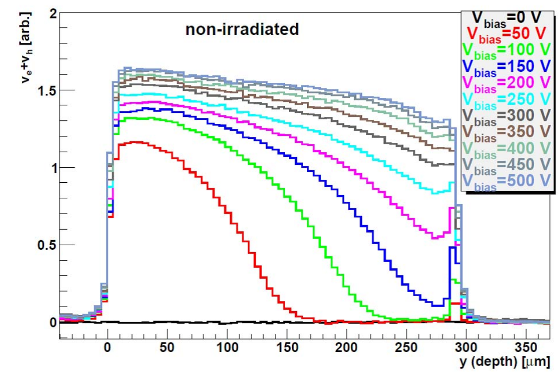
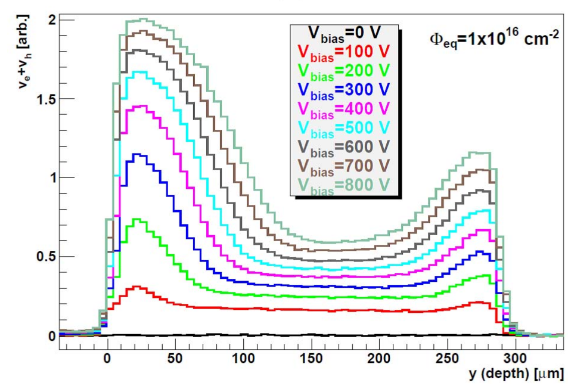
# Electric field in the bulk

- 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

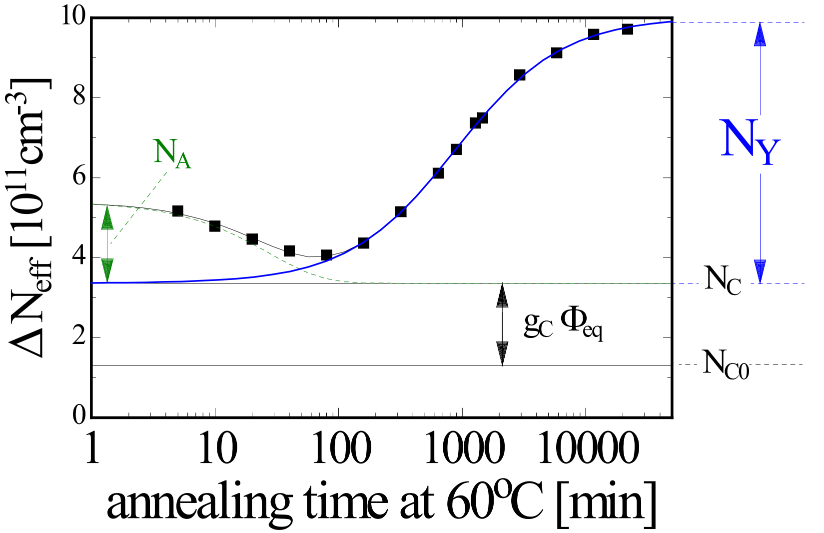
- The consequences of radiation damage and its development with time is temperature dependent.
- Annealing is the treatment of irradiated devices with temperature.
  - Typically higher temperatures “heal” the device.
- Change of effective doping concentration with irradiation

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

  - $N_{eff,0}$ 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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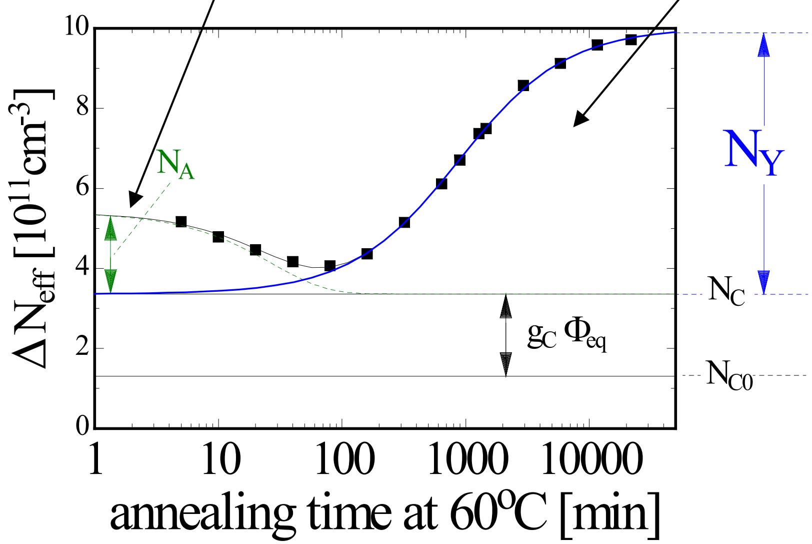
# Annealing

- 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.

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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

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

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

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

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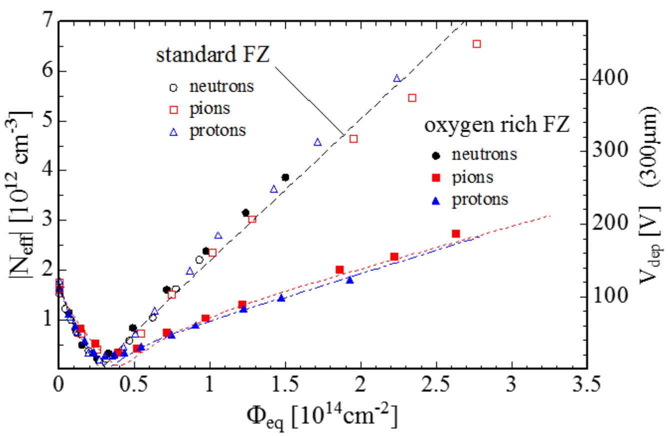


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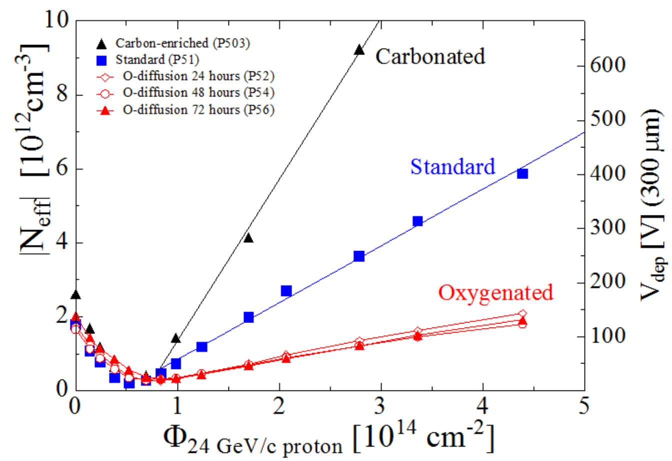
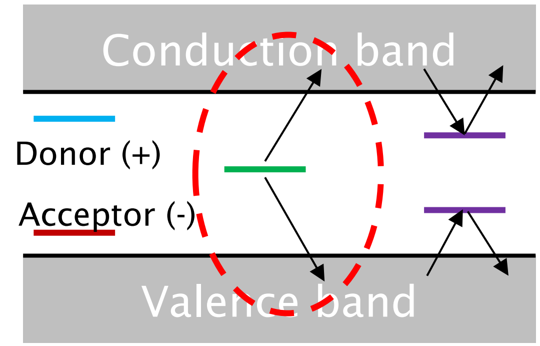



Oxygenated material does not improve performance after neutron irradiation.
Significant improvement for proton and pion induced damage.

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 neglected 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

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

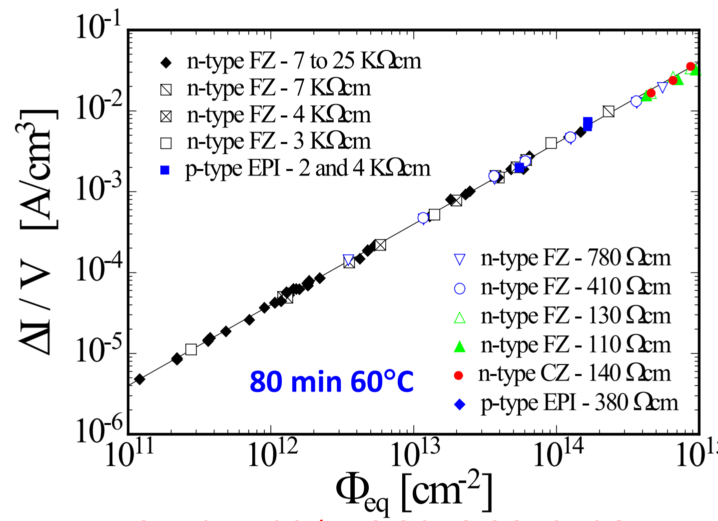
- Leakage current leads to increased noise in amplifiers and increased power consumption.

# 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.
  - $\phi_{eq}$: 1 MeV neutron equivalent fluence.
  - $\alpha$: current-related damage factor.

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

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

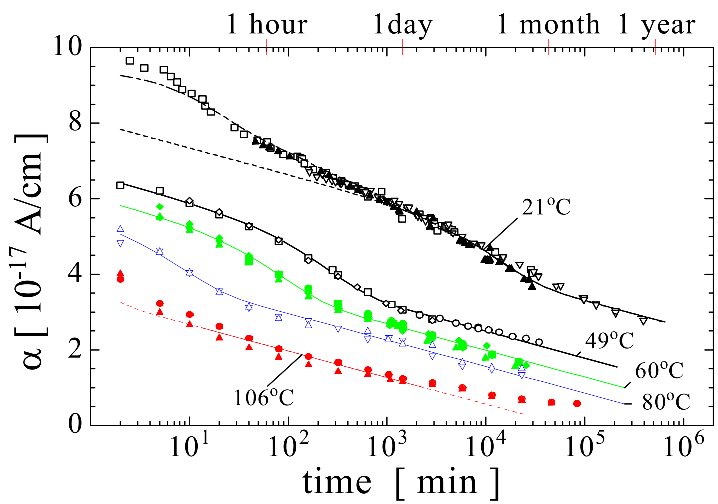
# Temperature dependence of $I_{leak}$ & annealing

- 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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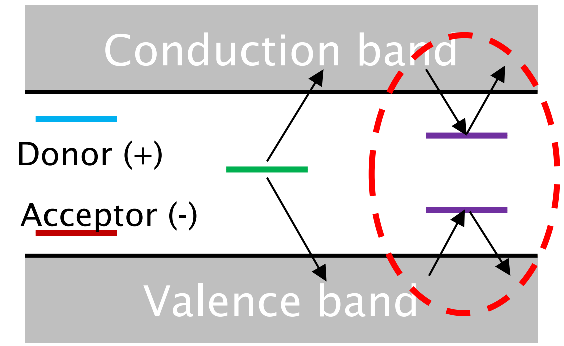
# 3- Charge trapping

- 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).

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

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

  - $c_{n,t}/c_{p,t}$ 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:

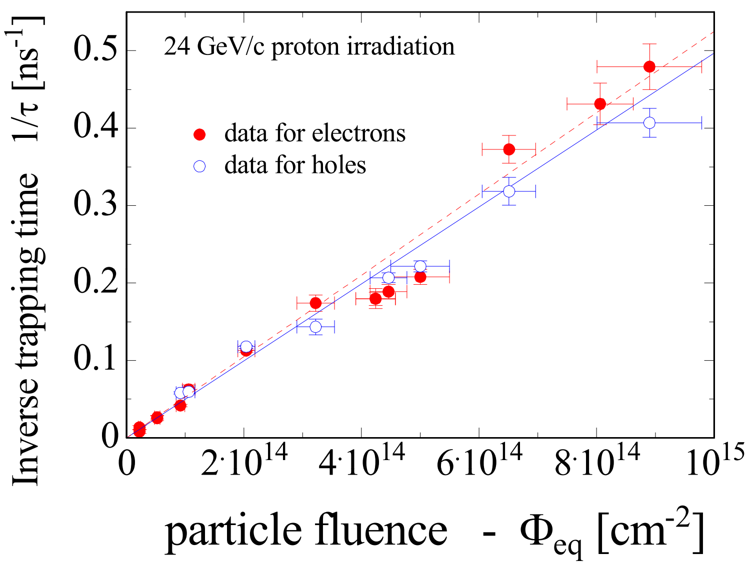
$$Q(t) = Q_0 \exp(-t/\tau_{eff})$$

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

- $\tau_0$: carrier lifetime before irradiation.
- $\beta$: effective trapping damage constant.
  - Depends on carrier capturing.
  - Large $\beta$ = 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+.

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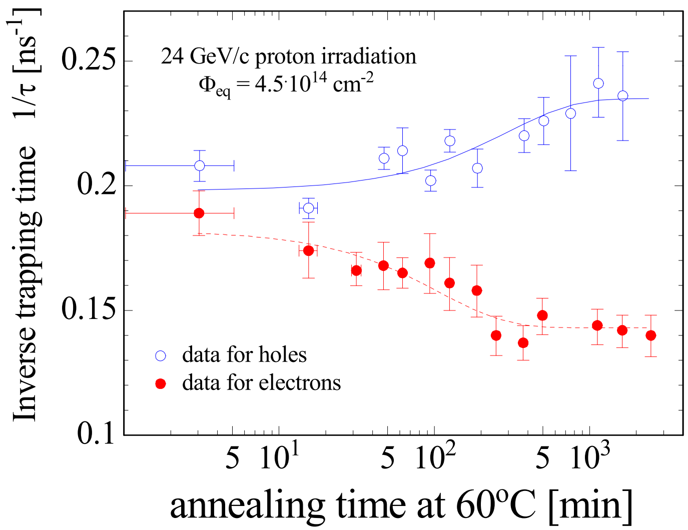
# Annealing of trapped charged

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

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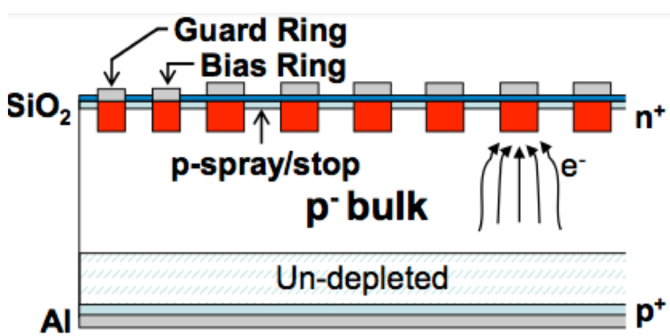
Decrease in $\beta$ for electrons → less trapping.
Increase in $\beta$ for holes → more trapping.

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

- The trapping rate is governed by the time constants for beneficial annealing.
  - $\beta_0/\beta_\infty$ 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).

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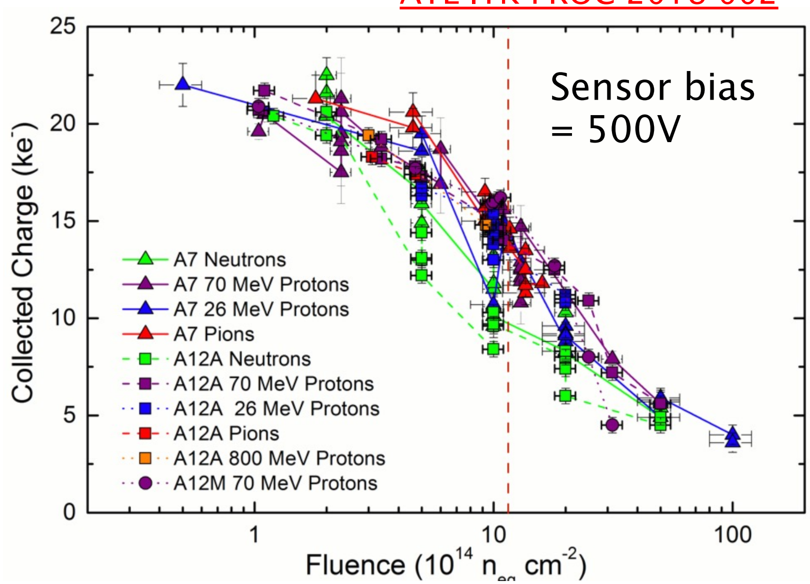
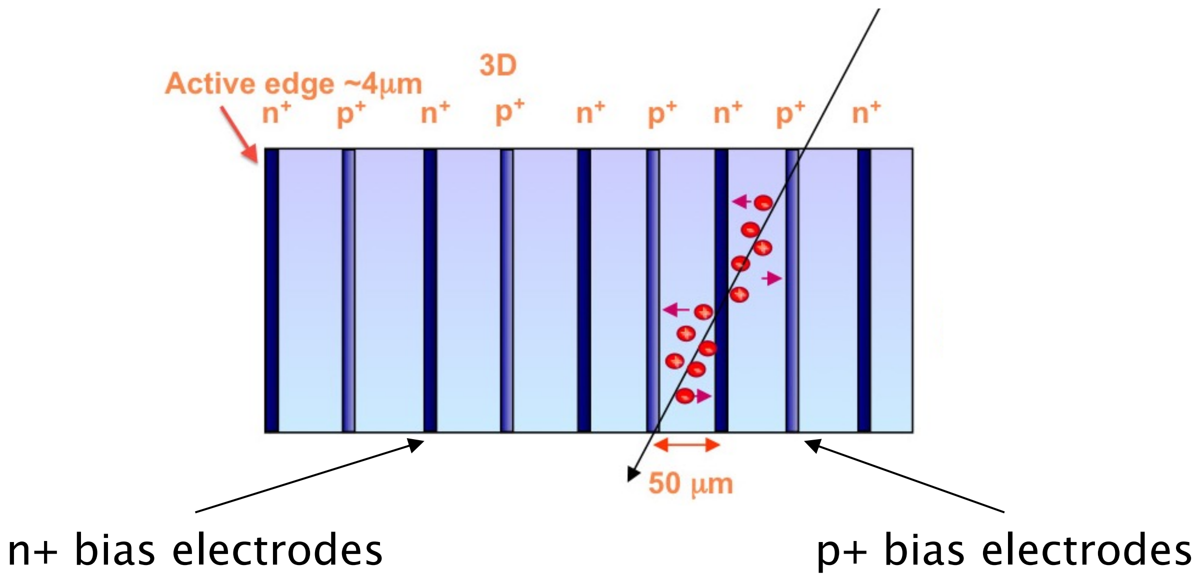


# Radiation-hard sensors: 3D sensors

- Alternative geometry for pixel sensors that provides higher radiation tolerance by design: drift path decoupled from incoming particle path.

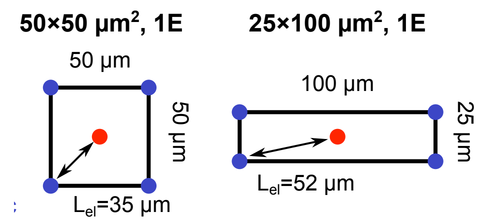
- Electrodes penetrate vertically in the sensor bulk, drift distance $\sim 50\ \mu m$.
  - Shorter charge collection distance → Less charge trapping.
  - High field with low voltage → Lower power, i.e. heat, after irradiation.

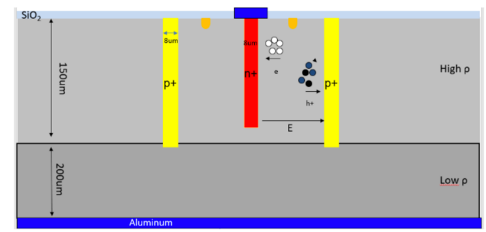


# 3D sensors for the ATLAS ITk pixel detector

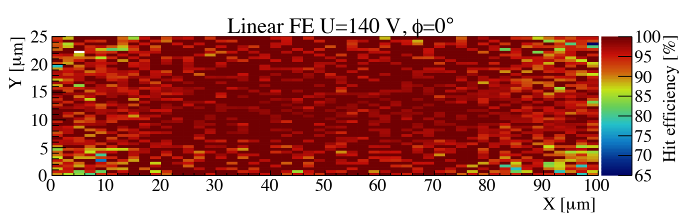
- The ITk is the new ATLAS Inner Tracker system for the HL-LHC.
  - All-silicon detector made of pixels and strips layers.
  - The innermost pixel layers will use 3D sensor.

- 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 $1.6 \times 10^{16}$ $n_{eq}$/cm2.
  - $V_{depl}$ <150V, power < 40 mW/cm² (at -25C).

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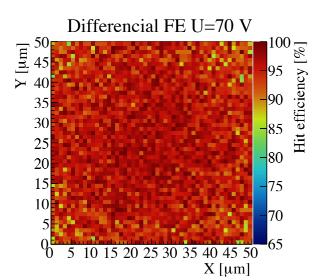
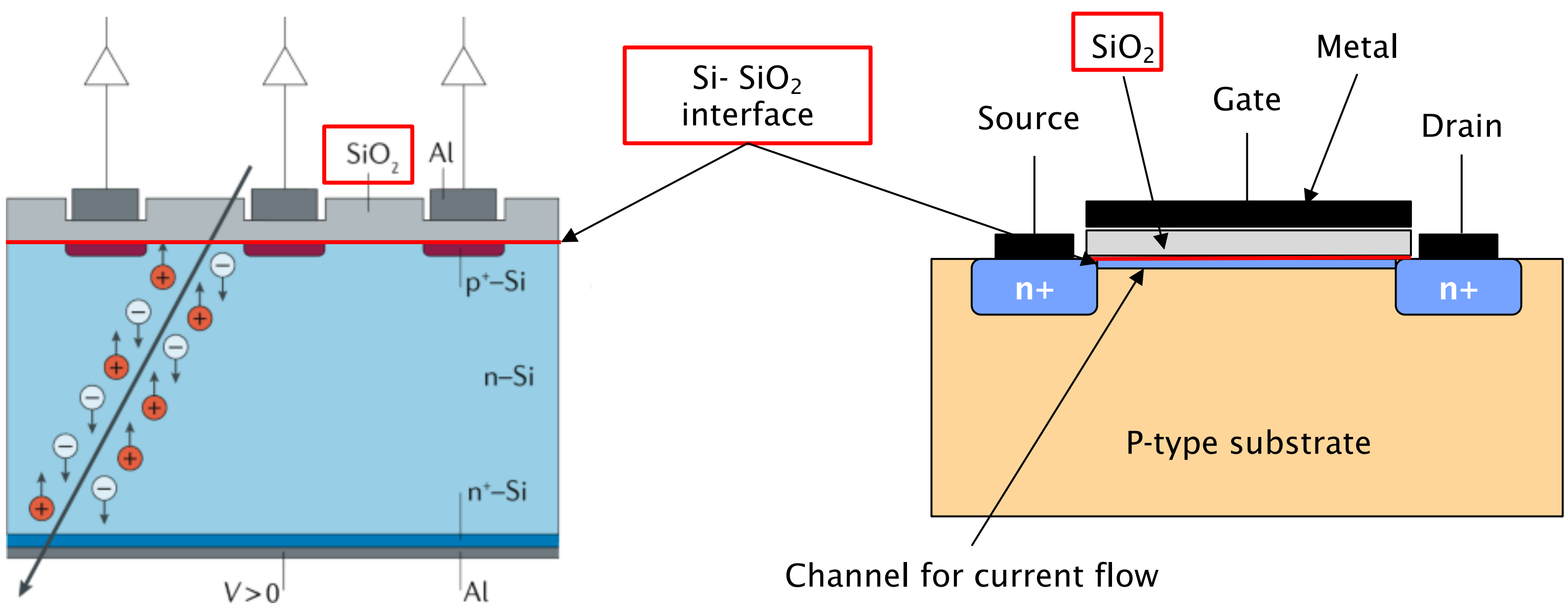


# Plan for the lectures

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

# Surface damage

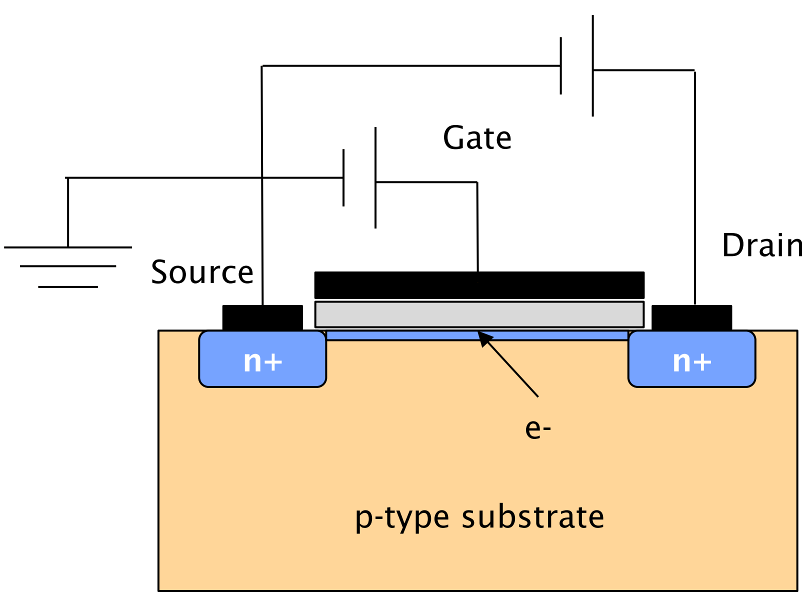
- Damage to the surface of silicon sensors and electronics, especially in the $SiO_2$ layer and at the $Si$-$SiO_2$ interface.
- $SiO_2$ is used as:
  - Passivation layer on silicon sensor.
  - Gate Oxide in MOSFET transistors.
  - Shallow Trench Isolation (STI) between transistors.
- Surface damage affects mostly electronics.



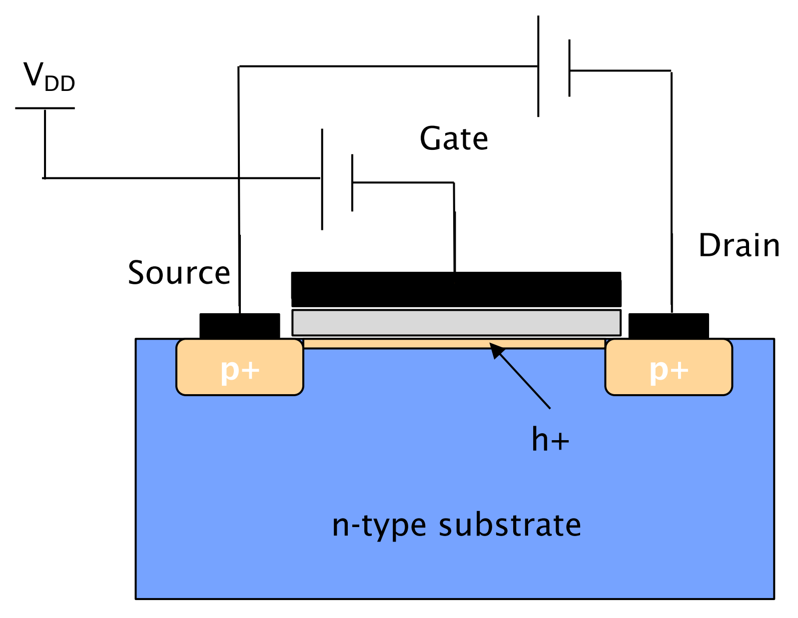
# MOSFET transistors basics

1. A voltage is applied to the gate to induce a channel of free charge carriers below the Si-SiO2 interface.
2. By applying a voltage on the drain, carriers can move → current.

- NMOS transistor:
  - $V_{GS} > 0$.
  - Electrons in the conduction channel.

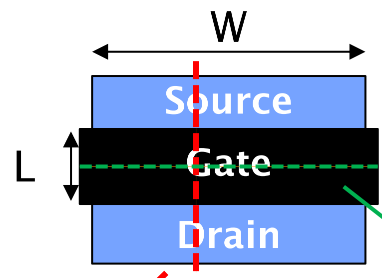



- PMOS transistor:
  - $V_{GS} < 0$.
  - Holes in the conduction channel.

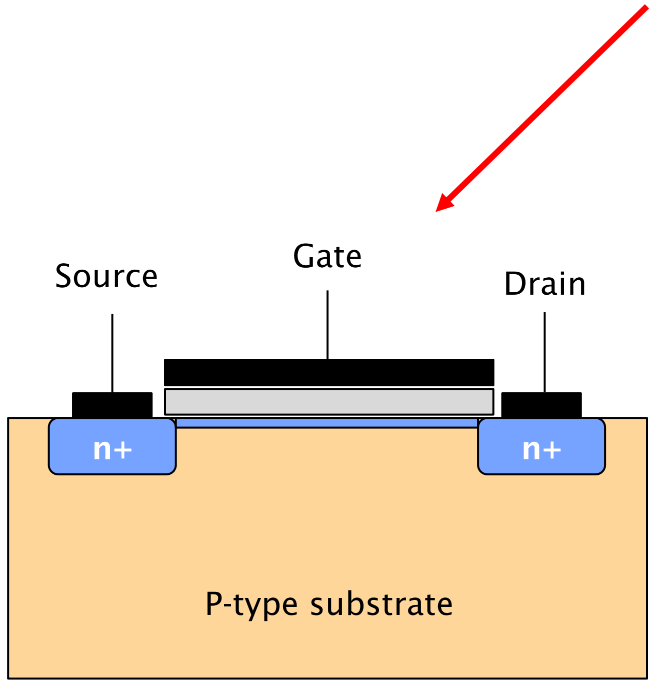


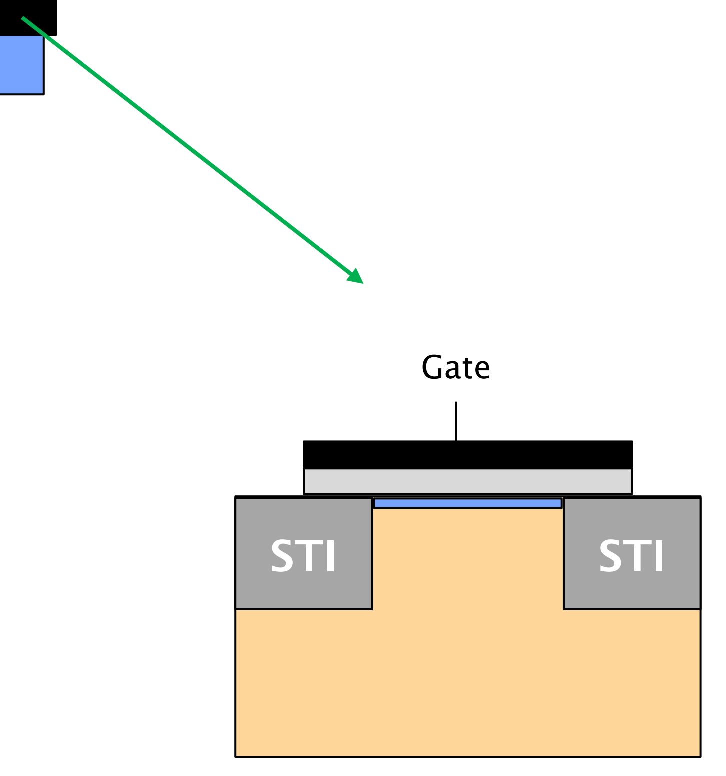
# Other transistor views

View from the top




L, W: length and width of the channel




Shallow Trench Isolation (STI)

# Damage to $SiO_2$

- Radiation causes ionisation and/or dislocation of lattice atoms in $SiO_2$.

- Damage impact from ionisation is more severe in $SiO_2$ → it creates charged defect states in the oxide and at the interface with the silicon that impact transistor's operational parameters.
  - High electric fields can exist in the oxide of MOS transistors.
  - Charge carriers generated by ionisation are separated.
  - Holes have a mobility $10^6$ times lower than electron mobility in $SiO_2$ (large hole capture cross section by shallow levels in the silicon oxide).

- NIEL damage does not get electrically active in the $SiO_2$.
  - Also, the substrate of integrated circuits is highly doped (i.e. low resistivity) which reduces the sensitivity to displacement damage.

# Defects in $SiO_2$ and Si-$SiO_2$ interface

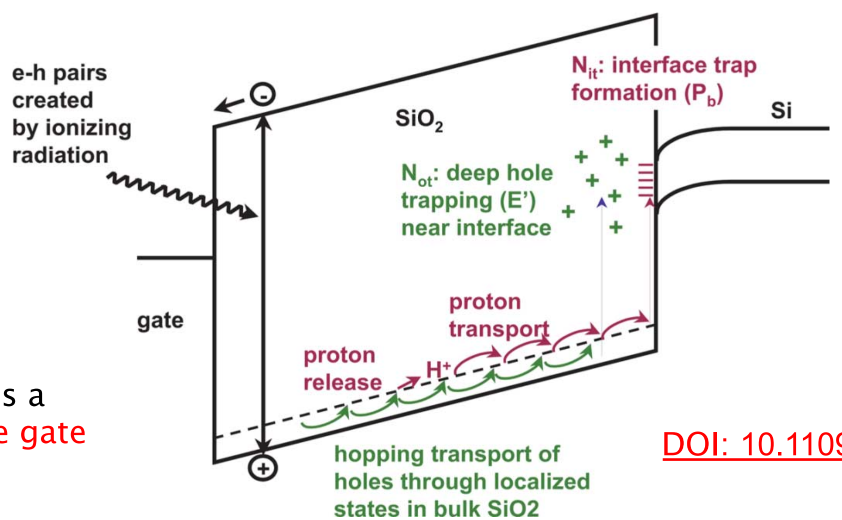
- Defects are present in the $SiO_2$ and at the Si-$SiO_2$ interface that introduced localised energy states in the bandgap of the material and act as traps for charge carriers.

- In the $SiO_2$ defects are due to a precursor that is not active in its normal condition but is active by radiation and becomes a trap for positive charges.
  - This precursor is the physical origin of oxide traps.
  - Oxide traps are donor like, i.e. positive.

- At the Si-$SiO_2$ interface defects are due to the abrupt transition between a crystalline material (Si) and an amorphous one ($SiO_2$) that interrupts the crystalline structure of silicon.
  - Interface states are located at the interface or a few angstrom from it.
  - Responsible for interface traps.
  - Interface traps can be both donor or acceptor like, i.e. their net charge will positive or negative according their position wrt. The Fermi level.

# Oxide charges

- The incoming radiation generates e-/h+ pairs.
- After a few ps a fraction of the e-/h+ pair has recombined, the other pairs are separated by the E-field and start to drift in opposite directions.
  - The fraction non-recombined pairs depends on the type of incident radiation, material, and applied electric field.
- Assuming a positive voltage on the gate.
  - The e- drift to the gate and exit the oxide in a few ps (higher mobility).
  - The h+ will drift (slowly) towards the Si-$SiO_2$ interface.

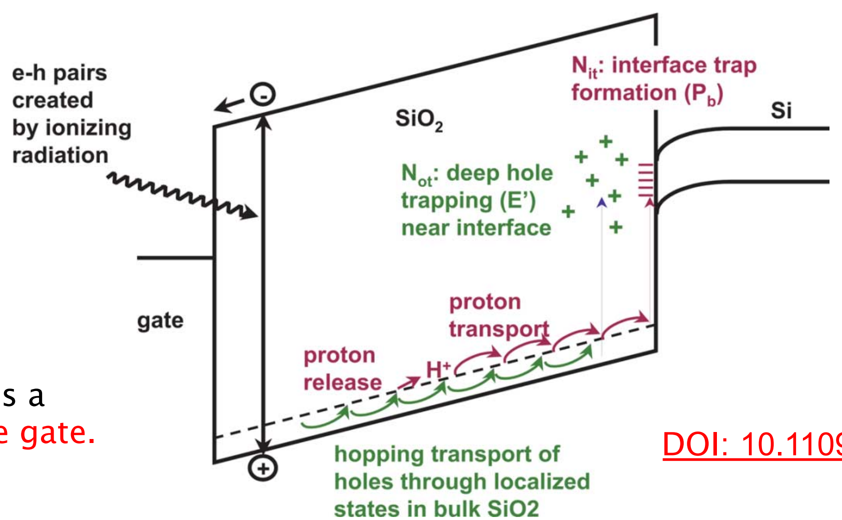



This figure assumes a positive bias on the gate (worse condition).

DOI: 10.1109/TNS.2008.2001040

# Oxide charges

- The h+ move with a dispersive transport phenomena called “polaron hopping”.
  - Being slow h+ are self-trapped, i.e. they are localised in the lattice distortion that they generate → polaron.
  - The polaron moves by hopping from one lattice location to the next → increased holes effective mass, lower mobility.
  - Higher T and E field = faster transport.
  - Dependent on oxide thickness.
  - Long time scales wrt. compared to the charge injection.

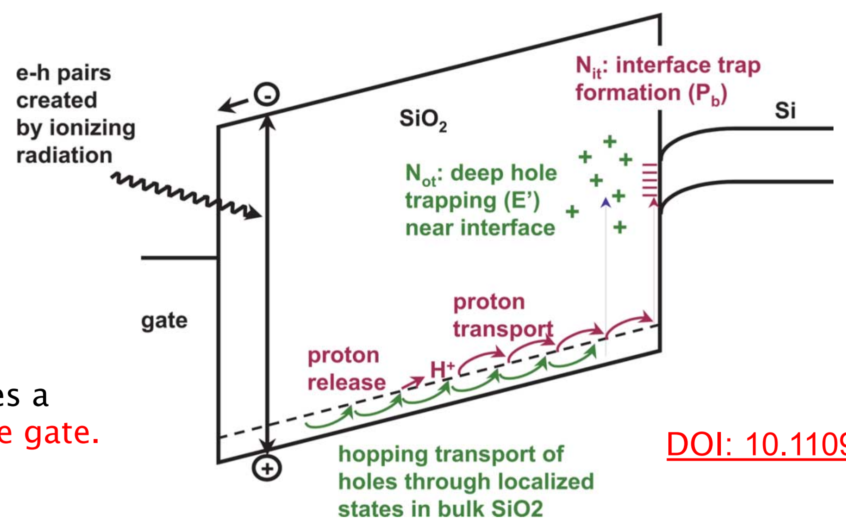



This figure assumes a positive bias on the gate.

DOI: 10.1109/TNS.2008.2001040

# Oxide charges

- The h+ can be trapped in defects presents in the $SiO_2$ and in oxygen vacancies close to the interface (deep hole trapping) giving origin to a fixed positive charge.
  - The fraction of trapped holes depends on the mean trap density, their hole capture cross-section, and the width of their distribution.




This figure assumes a positive bias on the gate.

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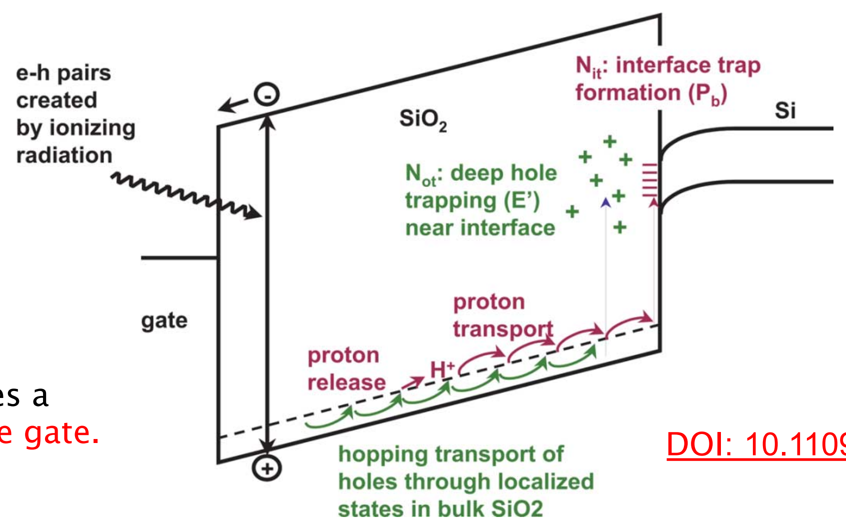
# Interface states

- Because of irradiation, the density of interface traps increases by orders of magnitude.
- Impurity hydrogen ions are released from the lattice by hole hopping.
- These ions move toward the Si-$SiO_2$ interface where they give origin to new interface states that serve as traps.
- Creation of interface states is a slower process than oxide charge formation due to the lower mobility of the hydrogen ions.



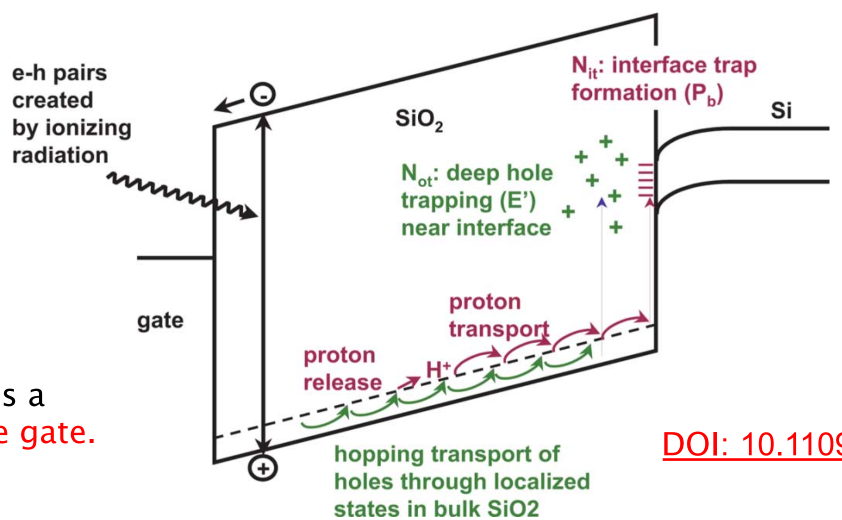

This figure assumes a positive bias on the gate.

DOI: 10.1109/TNS.2008.2001040

# Interface states

- The radiation-induced traps have energy levels in the bandgap.
  - Traps above midgap = acceptors.
  - Traps below midgap = donors.

- For NMOS under positive bias, interface traps are negatively charged.
- For PMOS under negative bias, interface traps are positively charged.




This figure assumes a positive bias on the gate.

DOI: 10.1109/TNS.2008.2001040

# Annealing

- Annealing happens through two mechanisms whereby electrons recombine with the trapped holes.

- Electron tunnelling from the silicon to the oxide traps.
  - Strongly dependent on the E-field in the oxide and on the spatial distribution of traps, which in turn depends on the fabrication process.

- Thermal emission of electrons from the oxide valence band into the trap levels.
  - Strong dependence on temperature.
  - Traps need to be close to the valence band.

- Annealing can start already during irradiation depending on dose rate, temperature during irradiation, and the electric field in the oxide, but it is a slow process.
  - Complete annealing can reach many months.

# TID technology dependence

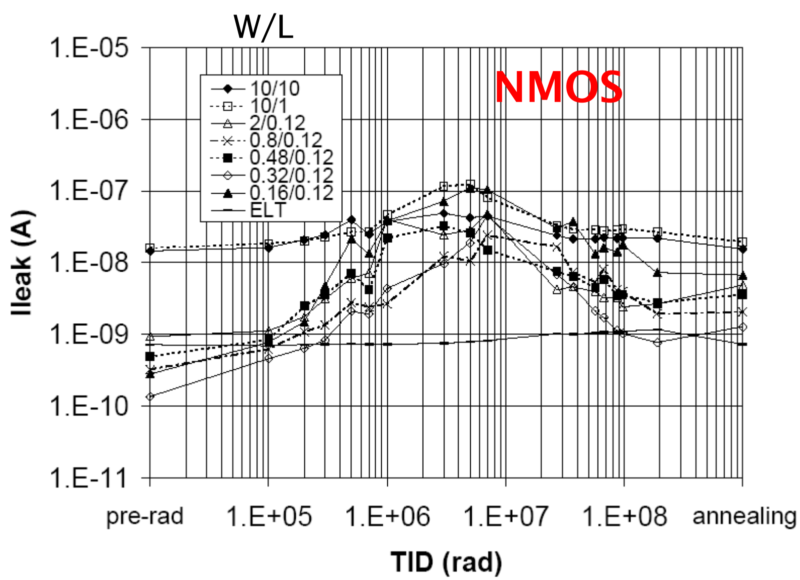
- The scaling of CMOS technologies and reduction of MOSFET gate oxide thickness has greatly improved the radiation hardness of integrated circuits for use at high luminosity experiments.
  - Thick oxides however still exists, e.g shallow trench isolation oxides, field oxides.

- TID damage is greatly influenced by the oxide growth process and the level of initial impurities.
  - Some technologies are more affected than others, even within the same node, i.e. same gate oxide thickness.
  - Even the technology from a specific foundry can have different radiation performance depending on the production sites.

- In the following slides I will discuss TID effects on the 130 nm CMOS technology used for various ATLAS and CMS upgrades.

# Leakage current

- Leakage current in MOSFET transistors is defined as the current that flows through the device for $V_{GS} = 0$.
- A change in leakage current is observed for NMOS transistors.
    - Increase in current up to a TID of a few Mrad, followed by a decrease towards the pre-irradiation value.
    - Peak at a few Mrad.
- No change is observed in PMOS transistors.

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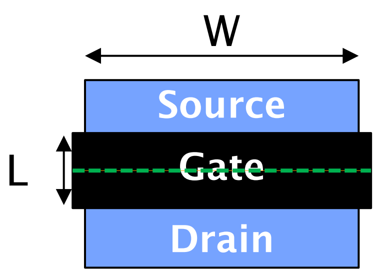
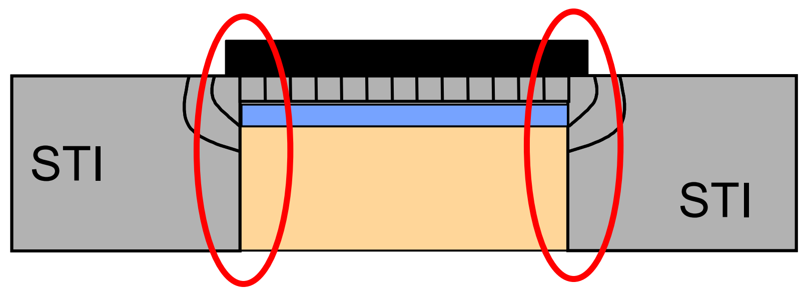
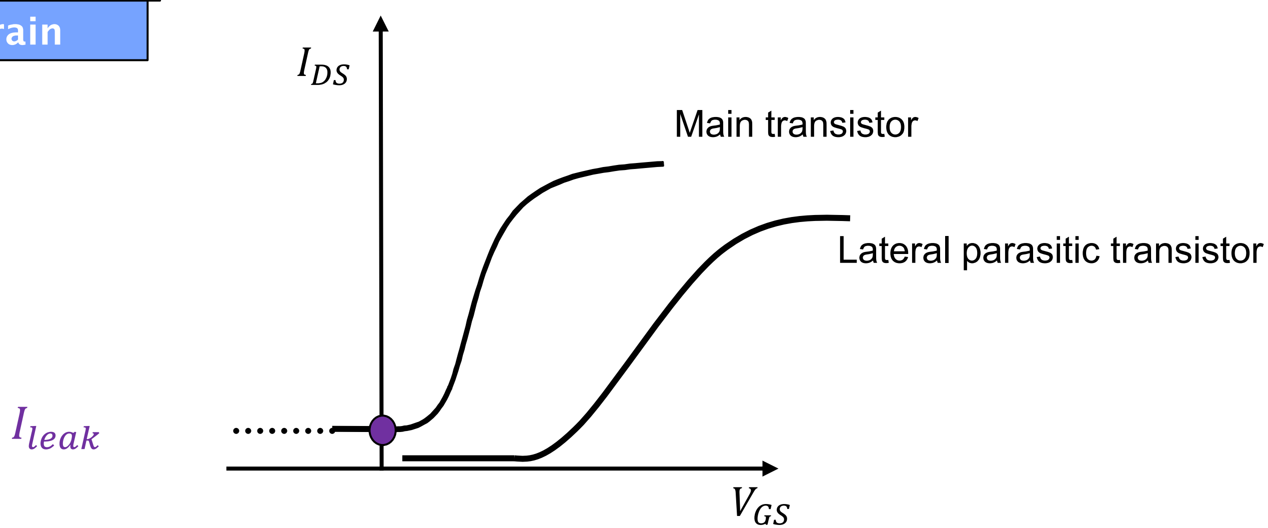
# Edge effects: NMOS

- Parasitic transistors exist at the edges of the transistor.
- Their gate oxide is the STI.

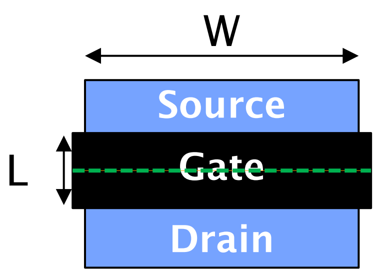


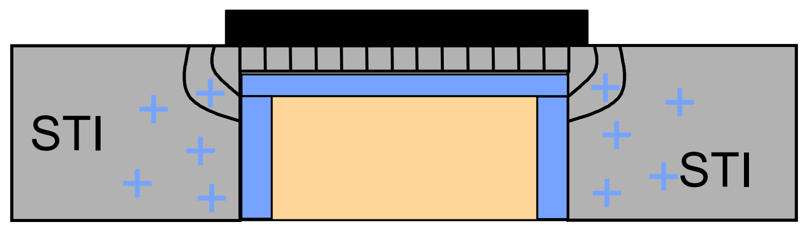



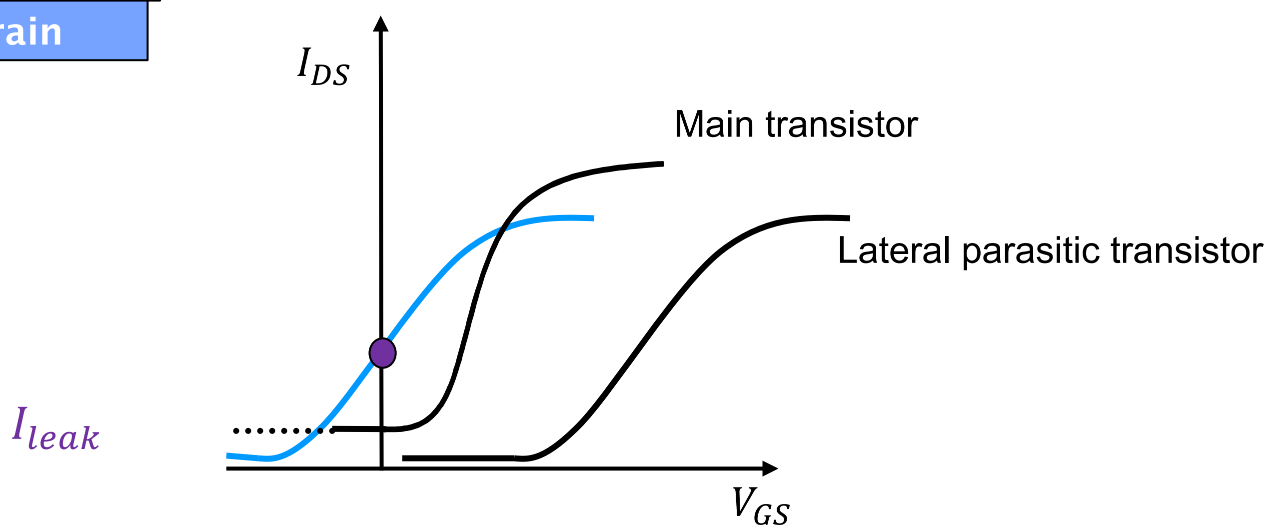



# Edge effects: NMOS

- Positive trapped charges quickly build up in the STI at the edge of the transistor.
- These open a conductive channel through which current can flow between drain and source → parasitic lateral transistor switches on.
- The leakage current increases.

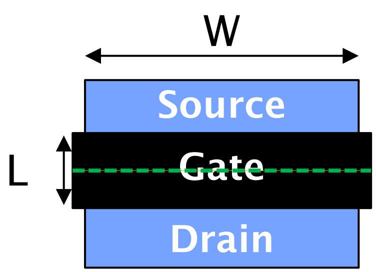


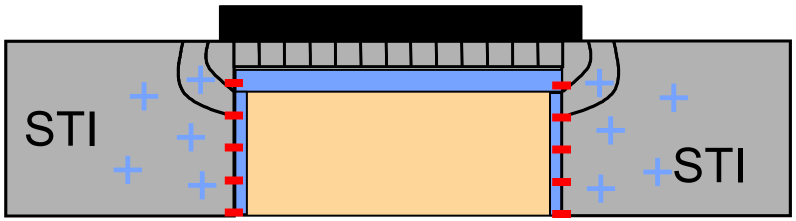



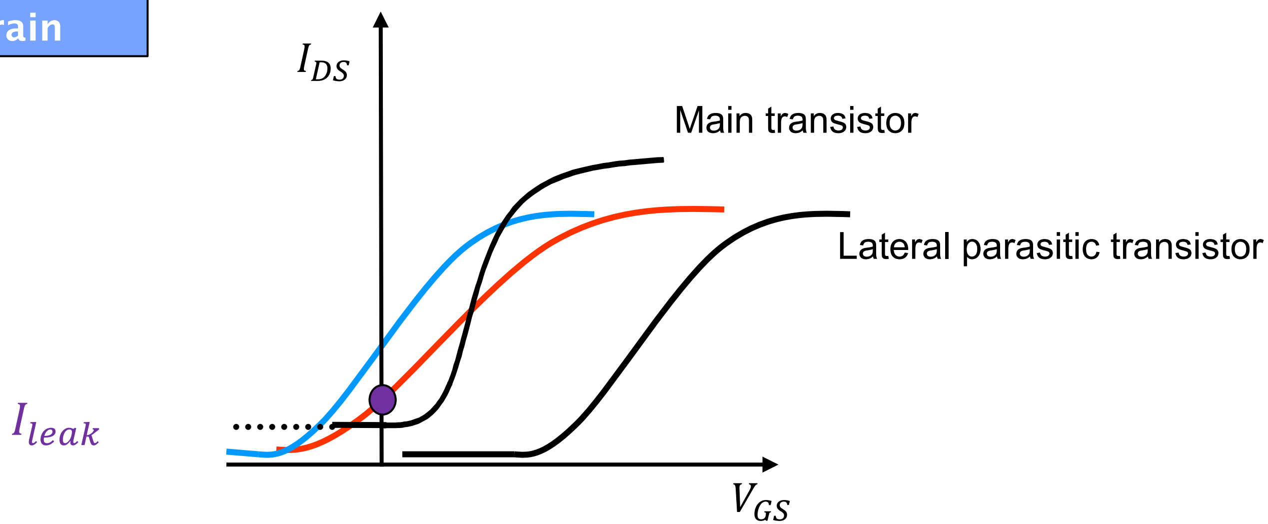



# Edge effects: NMOS

- At higher TID, due to the slower formation process, interface states start to build up.
- These are negatively charged for NMOS transistor and counteract the effect of positive charges trapped in the STI.
- The leakage current decreases.

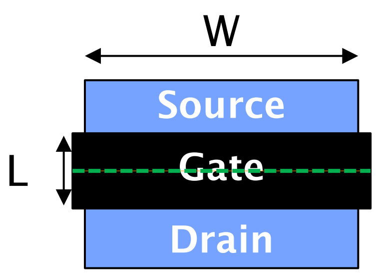


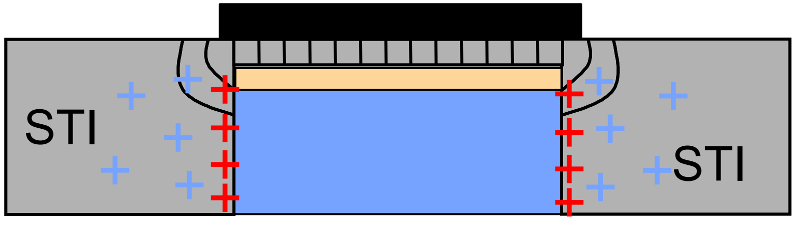



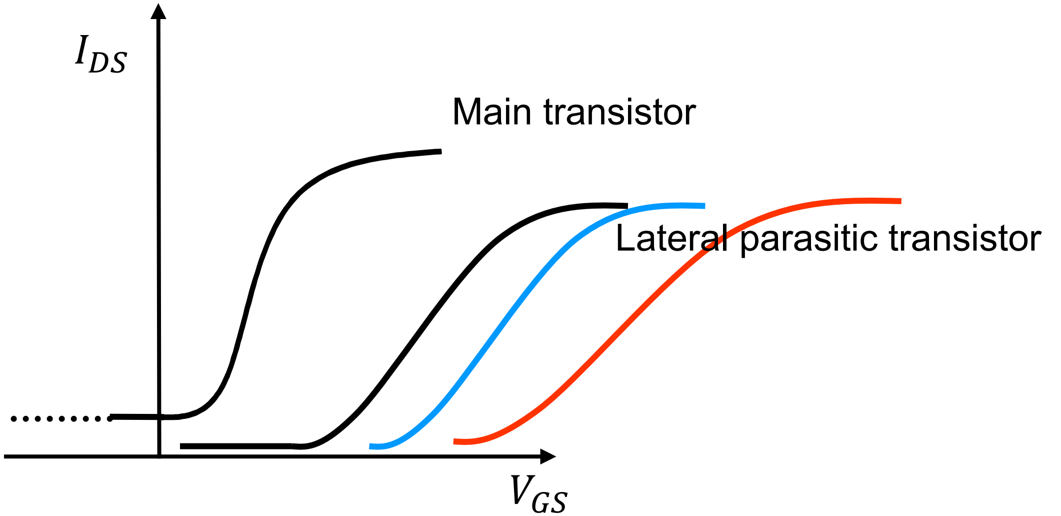



# Edge effects: PMOS

- In PMOS transistors, both oxide charges and interface states are positively charged.
- They repel further the holes from the side of the transistor → the parasitic transistors do not switch on.
- The leakage current does not change.



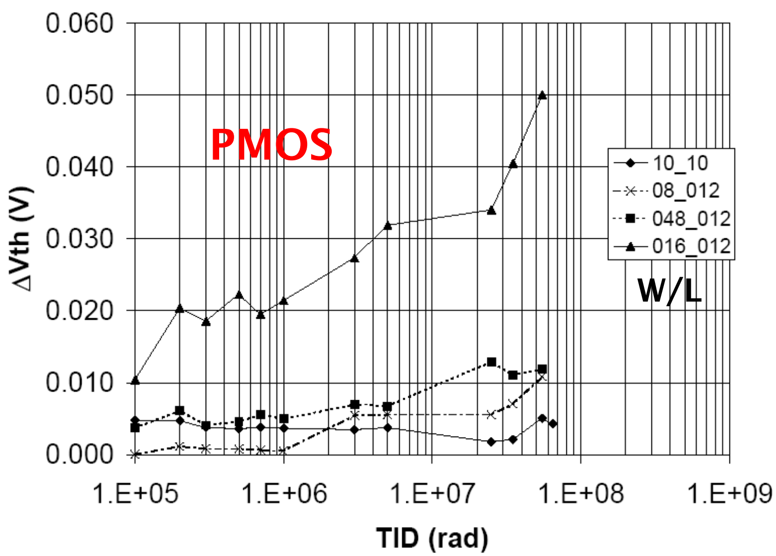



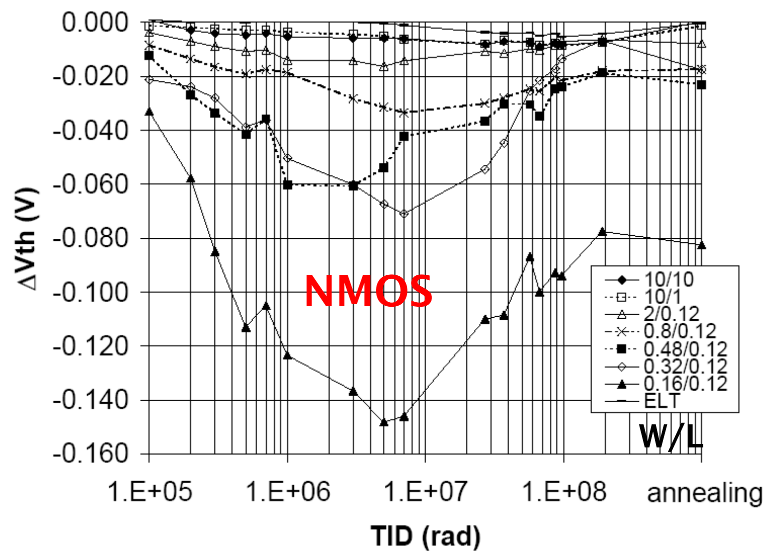



# Threshold voltage shift

- A threshold shift is observed for narrow transistors both NMOS and PMOS.

- For narrow transistors, i.e. small W, the net charge at the transistor edges influences the electric field in the main device → narrow channel effect.
    - Observed in deep-submicron CMOS technologies as a decrease of $V_{th}$ with transistor width.

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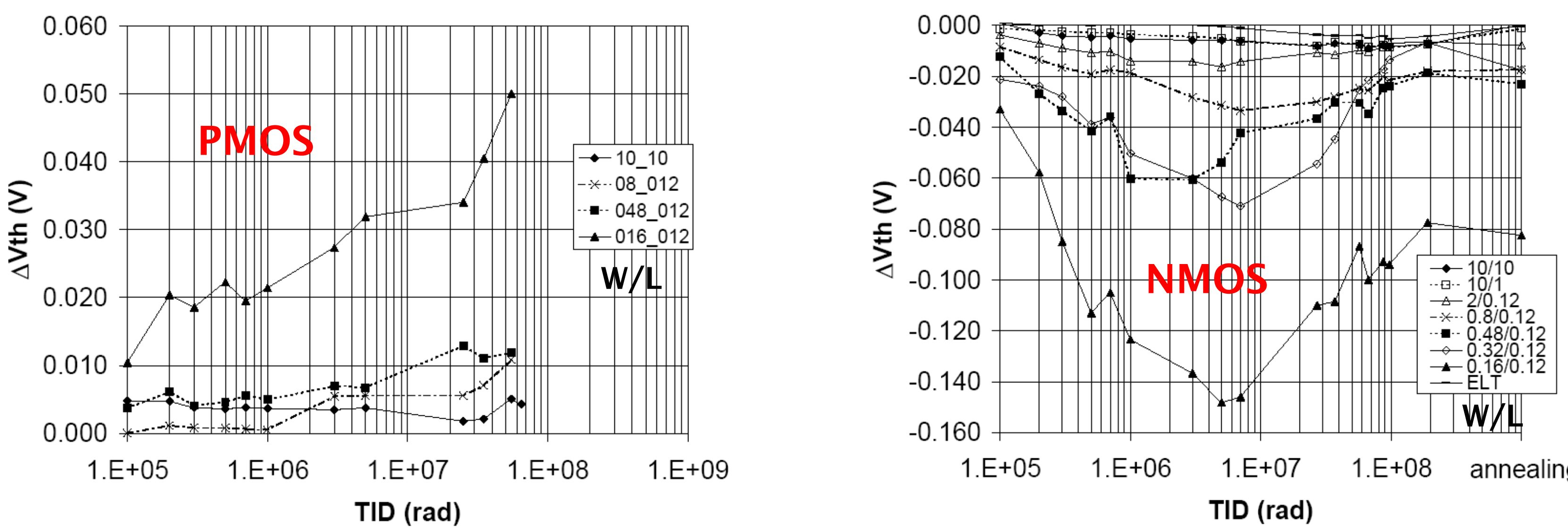
# RINCE

- Due to the positive oxide charge trapped in the STI oxide, the narrow channel effect decreases/increases the $V_{th}$ of NMOS/PMOS transistors.
- For NMOS, the negatively charged interface states counteract the effect of the positive oxide charge → rebound with peak at a few Mrad.
- For PMOS, the positively charged interface states add to the effect of the positive oxide charge → increase of the $V_{th}$ slope.

Radiation Induced Narrow Channel Effect (RINCE)

10.1109/TNS.2005.860698

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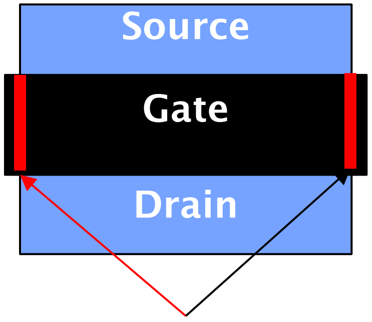
# Hardening by layout techniques

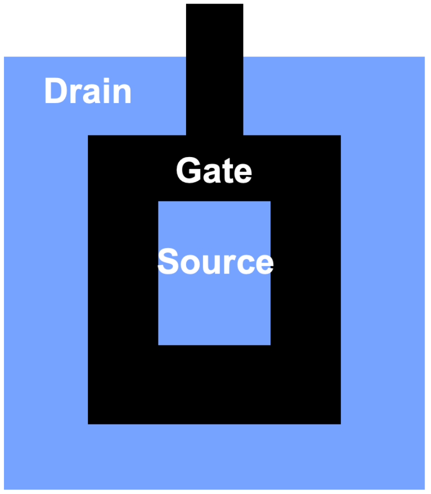
- Enclosed layout transistor can be used to cut leakage current paths at the edge of the transistors.
  - For the same W/L, ELT use more space → Loss of logic density.
  - Only really feasible for the analogue part of the circuit.
  - Lack of a commercial digital library for digital design

Linear transistor layout




Leakage current paths

Enclosed transistor layout (ELT)

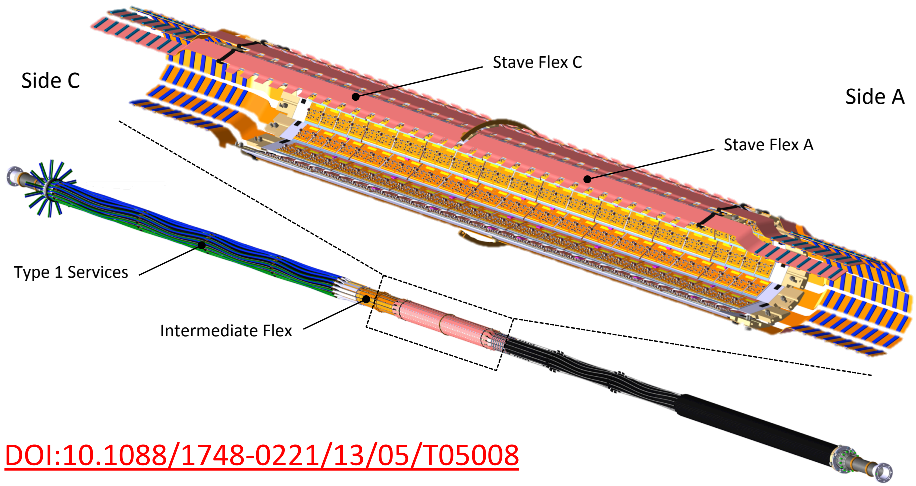


# TID effects on ATLAS IBL operation

- The ATLAS Insertable B-Layer is the innermost layer of the ATLAS tracking system at the LHC.
  - New layer inserted in the ATLAS Inner Detector during the LHS LS1 (2013-14).
  - Closest layer to IP, radius = 33.5 mm (beam pipe r = 23.5 mm).

- The IBL sensors and front-end electronics must cope with radiation doses of $5\times10^{15}$ $n_{eq}/cm^2$ NIEL and 250 MRad TID during the LHC Phase-I.

- New front-end chip in 130 nm CMOS technology → FE-I4.

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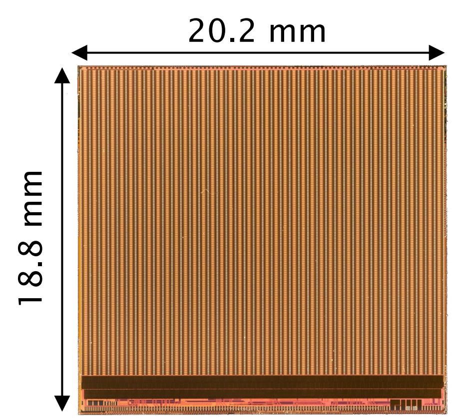
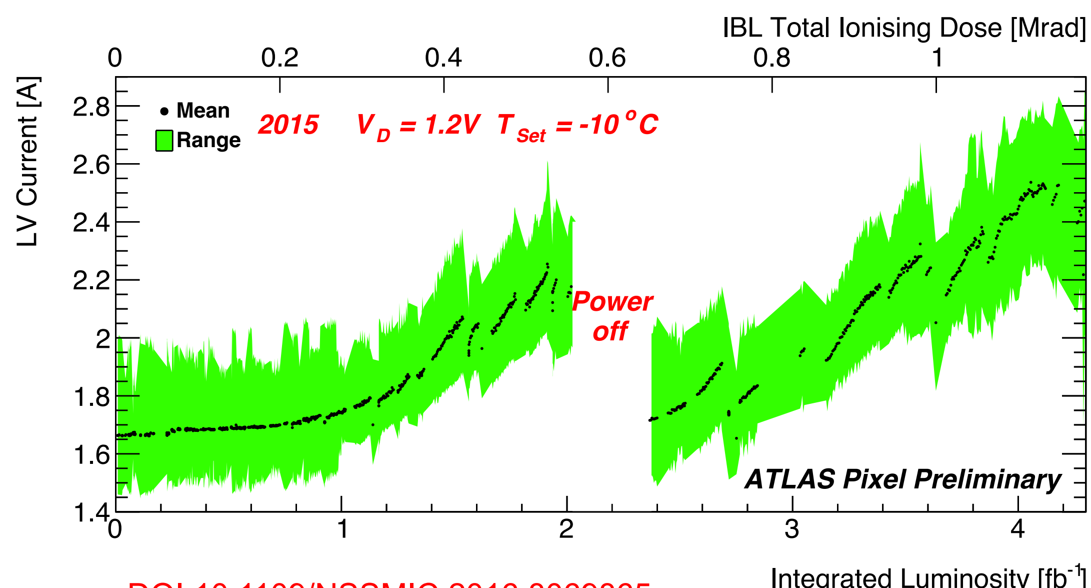


# TID effects on ATLAS IBL operation

- The current of the FE-I4 chip (LV current) was stable at a value of 1.6–1.7A (for a four-chip unit) until the middle of September 2015.
- The current then started to rise up significantly → consequence of $I_{leak}$ increase in transistors.
  - Between September to November 2015 the current increase was more than 0.2 A even within a single LHC fill, depending on the luminosity and the duration of the fill.
- This led to a temperature increase of the modules.
  - Increased IBL distortion.
  - Drifting module calibration.

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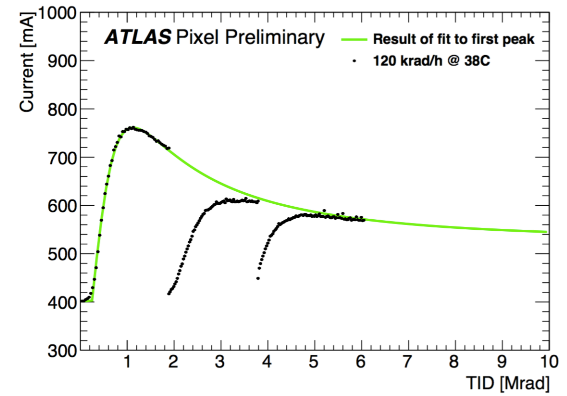
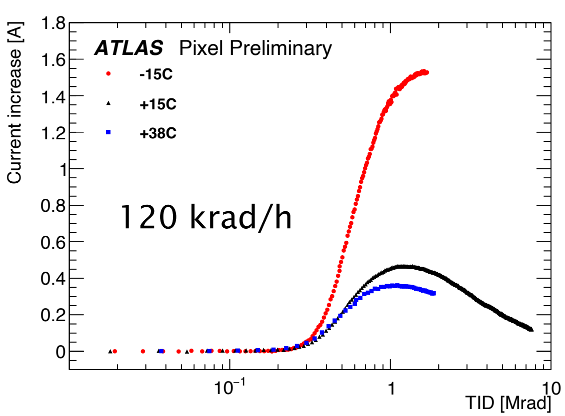
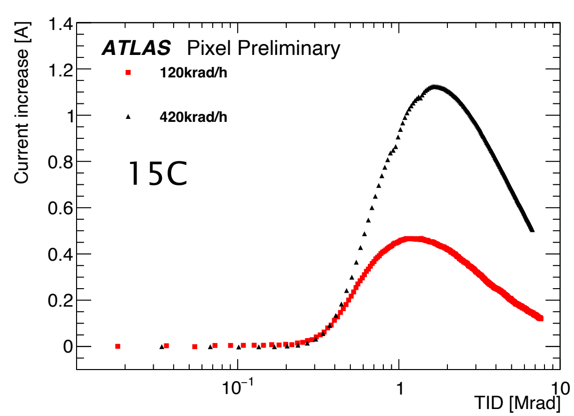
# Studies of IBL current increase

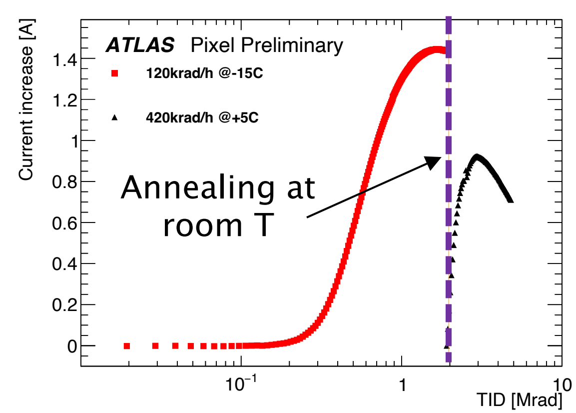
- X-rays irradiation were performed on IBL modules in the lab at different dose rates and temperatures.




- Important findings:
  - At a given temperature and dose rate, the current always approaches a boundary after annealing periods and re-irradiation.
  - At a given dose rate, the LV current increase is stronger at lower temperatures.
  - At a given temperature, the LV current increase is stronger at higher dose rates.
  - By increasing the operational temperature of the chip during irradiation the increase of the LV current can be kept below the boundary.

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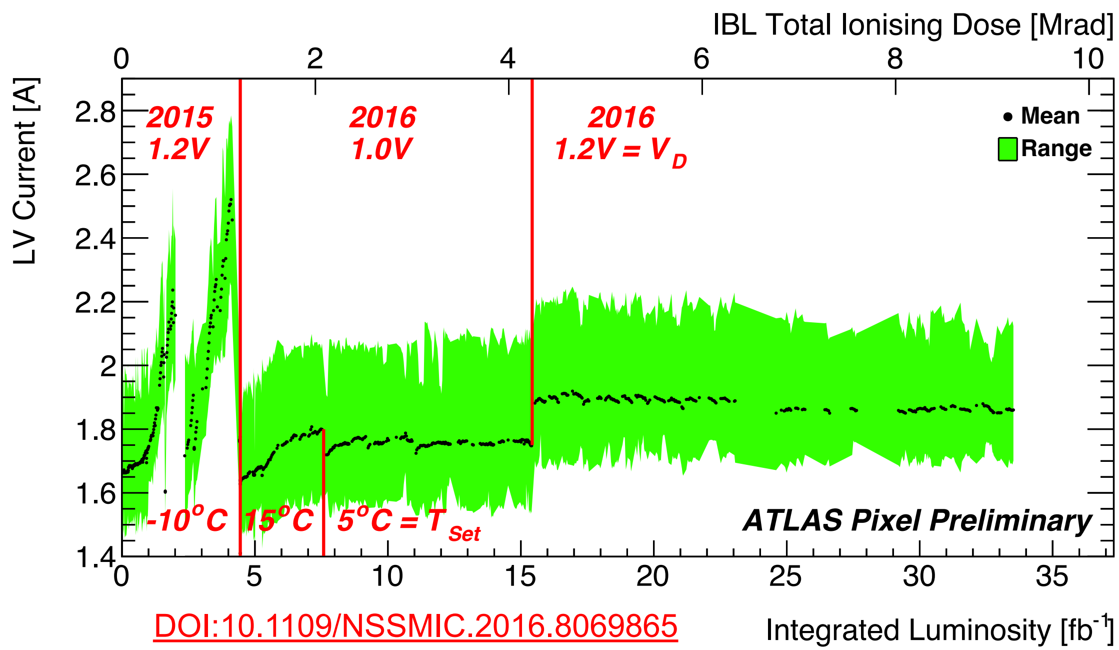
# IBL mitigation strategy

- Based on experience in 2015 and lab measurements, the IBL was run at higher temperatures and lower digital voltage for part of 2016.
- The digital voltage was increased back to 1.2V after 5 Mrad, well beyond the peak of current increase.

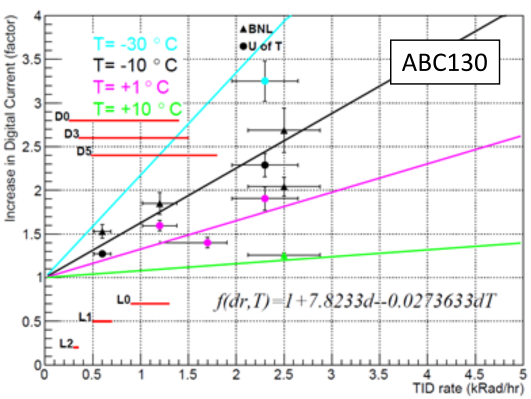


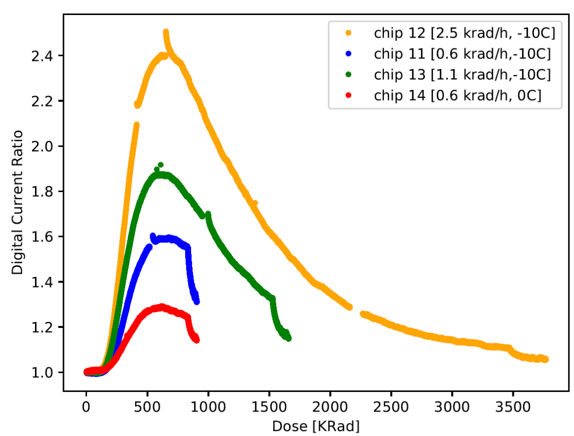

DOI:10.1109/NSSMIC.2016.8069865

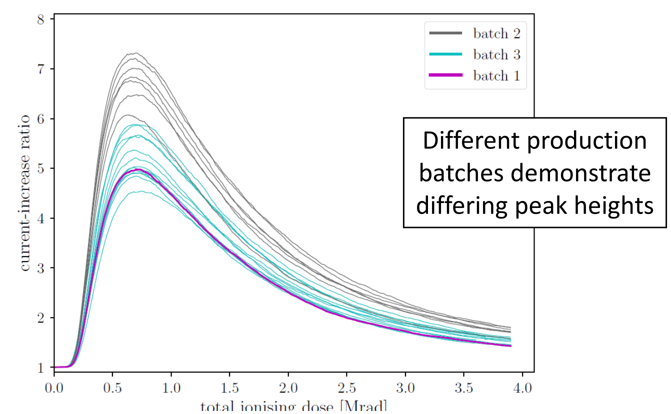
# TID mitigation measures for the ATLAS ITk

- The ITk is the new ATLAS Inner Tracker system for the HL-LHC.
  - All-silicon detector made of pixels and strips layers.

- The readout chip for the strips detector, the ABCStar, is designed in the same 130 nm CMOS process as the FE-I4.
  - Max TID at ITk for the ABCStar = 60-70 Mrad.
  - Enclosed layout transistors are used in the analogue part of the chip.
  - Extensive irradiation campaigns to study current increase versus temperature and dose rate.
    - Slow dose rate to estimate current increase during operation, high dose rate studies to gather information on larger samples of chips.

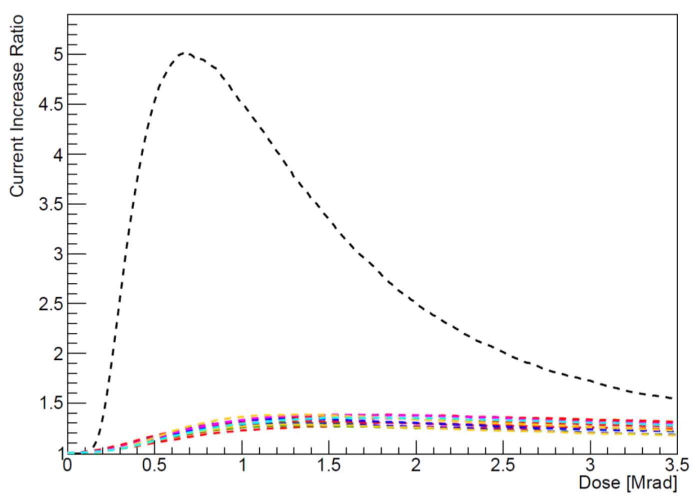


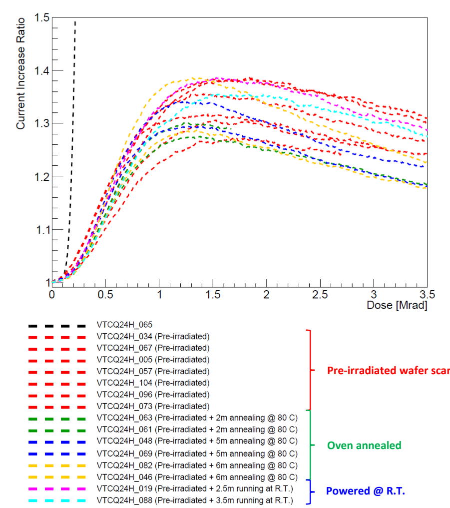



# ATLAS ITk TID consequences and mitigations

- Consequences of higher current for the operation:
  - Cable plant and cooling system requirements need to be adapted
  - Implications on system stability/alignment during runs.
  - Voltage regulators cannot support more Vdrop on cables.
  - Higher transients from module switch off.
  - Un-predictable Wafer-by-wafer and batch-by-batch variations un-predictable.
  - Thermo-electric models based on very low statistics.
- Mitigation: pre-irradiation of all ABCStar chips to be used in the experiment.
  - After pre-irradiation and annealing, current peak is lower.



# TID effects in CMOS 65 nm and 28 nm

- TID effects become more complex in smaller technology nodes.
- Thinner gate oxide is beneficial however…
  - Thick oxides still presents.
  - Effect from other structures, such as gate spacers (nitride).
  - Radiation Induced Short Channel Effect (RISCE).

- Suggestions for reading:
  - F. Faccio et at., Influence of LDD Spacers and H++ Transport on the Total-Ionizing-Dose Response of 65-nm MOSFETs Irradiated to Ultrahigh Doses, DOI: 10.1109/TNS.2017.2760629
  - G. Borghello, Ultra-high-dose effects on 28nm CMOS technology, https://indico.cern.ch/event/863071/contributions/3738765/attachments/2044482/3424763/ACES_2020.pdf

# Summary and final considerations

- Radiation hardness is one of the most important requirements for operation of silicon tracking systems at high luminosity collider experiments.

- Development of radiation hard sensors and electronics is carried out by large experimental collaborations and takes many years of development.

- Work on the silicon technologies is supported by modelling and simulations (see work by theRD50 collaboration).

- Silicon detectors exist that will be able to cope with the HL-LHC environment, i.e. up to $2 \times 10^{16}\ n_{eq}/cm^2$ and 1 Grad.

- For future hadron colliders (e.g. FCC hh), radiation levels will increase to $6 \times 10^{17}\ n_{eq}/cm^2$ and 40 Grad → Completely new challenge; Will silicon still work? Will we need new materials? Which ones? …