

Radiation damage in Alpix²

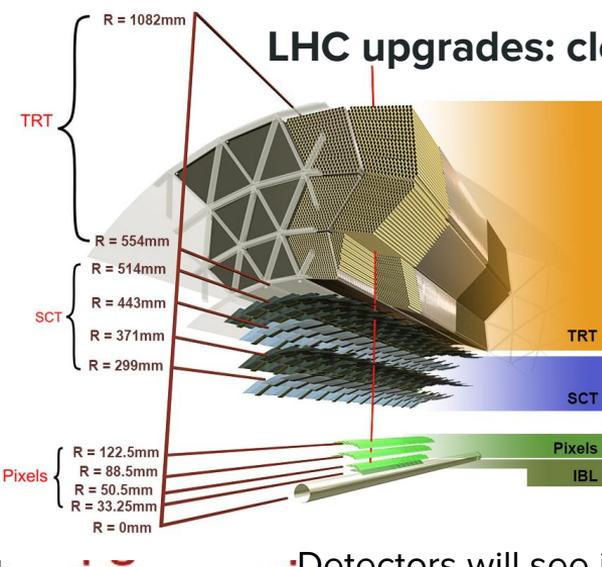
Jory Sonneveld and Sinuo Zhang



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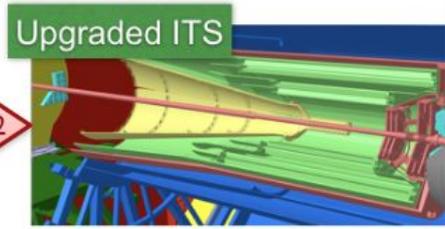
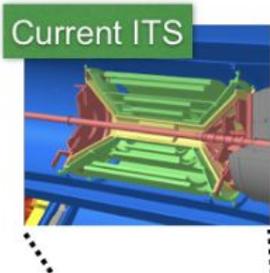
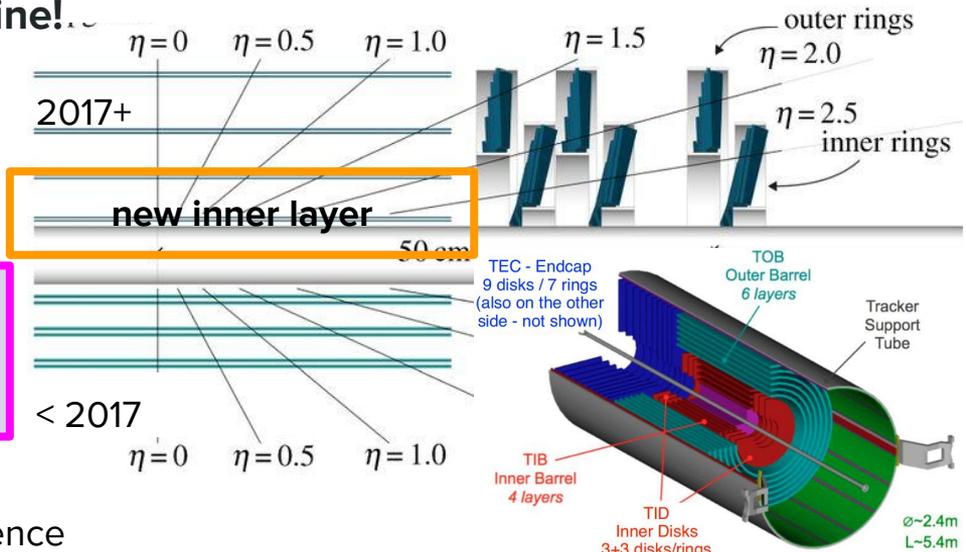


LHC upgrades: closer to the beam line!

ATLAS IBL:
3.325cm from beam line

LHC Run 3: inner detector systems now

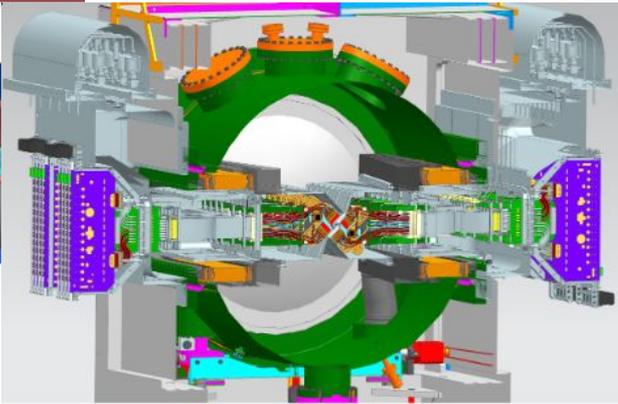
Detectors will see increasingly more fluence



LHC LS2

ALICE inner tracker: upgraded now

ALICE: 2.2 cm from beam line, monolithic active pixel sensors $33 \mu\text{m} \times 33 \mu\text{m}$

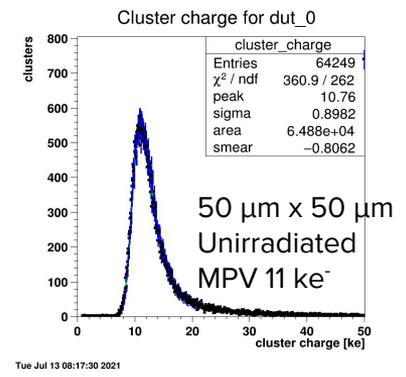
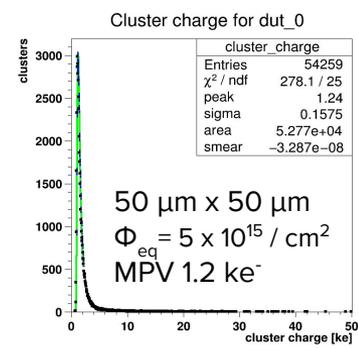
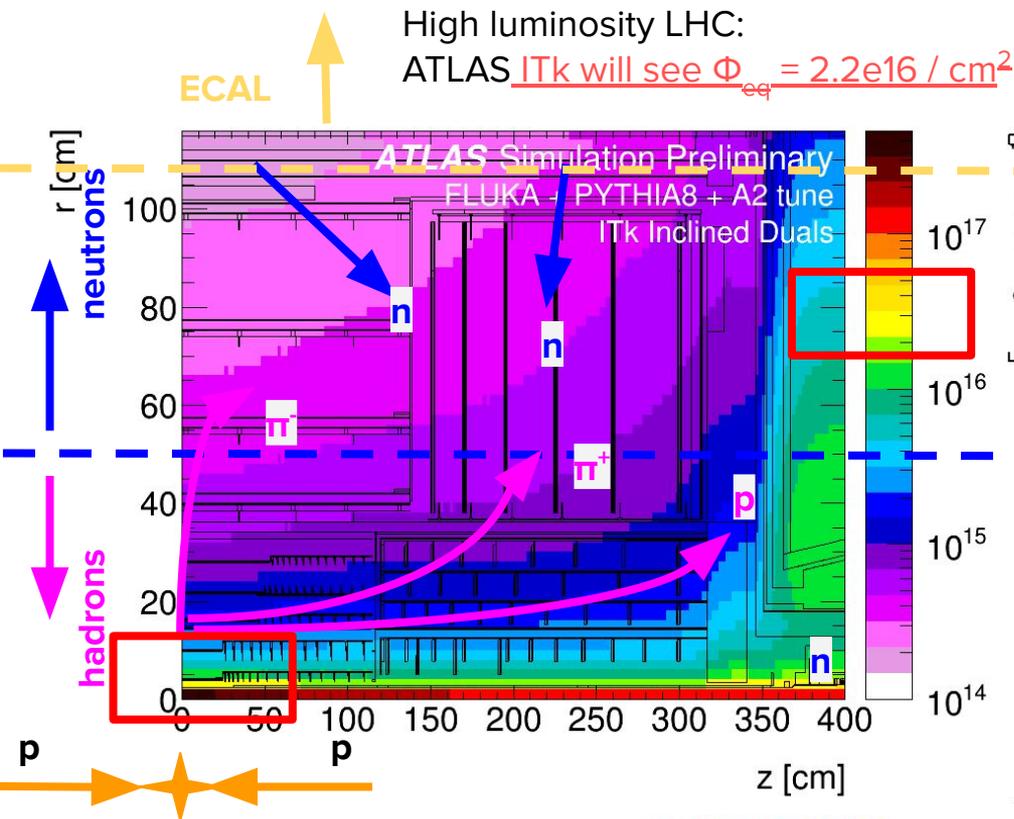


CMS: 2.9 cm from beam line

LHCb: 0.51 cm from beam line, pixel sensors $55 \mu\text{m} \times 55 \mu\text{m}$ in VELO

LHCb VELO and tracker upgrade: now

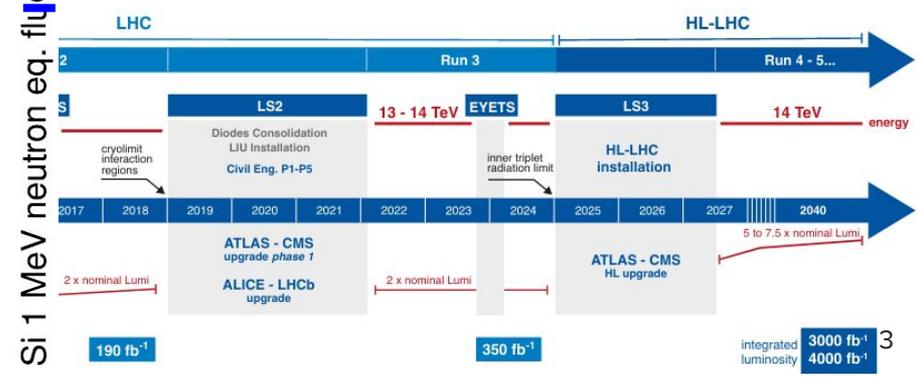
High particle rates at LHC



Tue Jul 13 08:17:32 2021

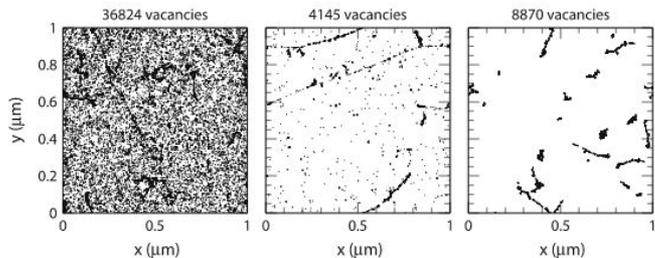
Tue Jul 13 08:17:30 2021

Strongly reduced **cluster charge** after HL-LHC fluences can be simulated with Allpix² by including trapping of charge carriers



Si 1 MeV neutron eq. fluence [cm⁻² / 4000fb⁻¹]

Radiation damage



10 MeV protons

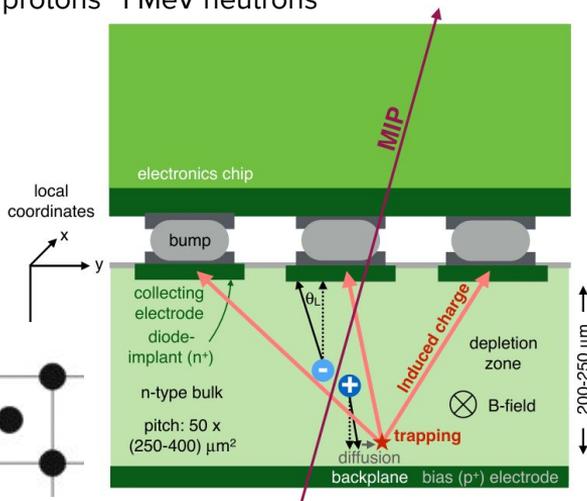
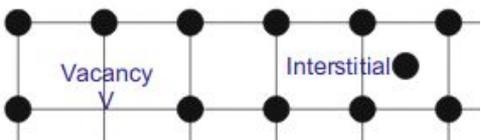
23 GeV protons

1 MeV neutrons

Simulation

$$\Phi_{eq} = 10^{14}/\text{cm}^2$$

Examples of bulk damage

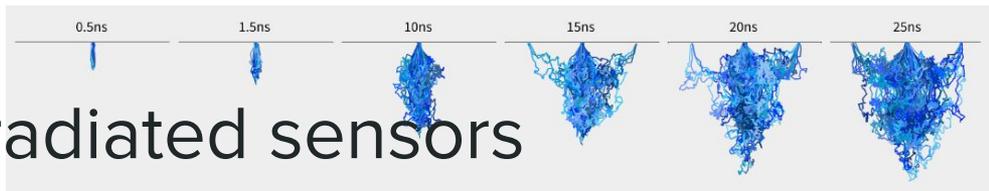


Effects from defects in silicon sensor bulk:

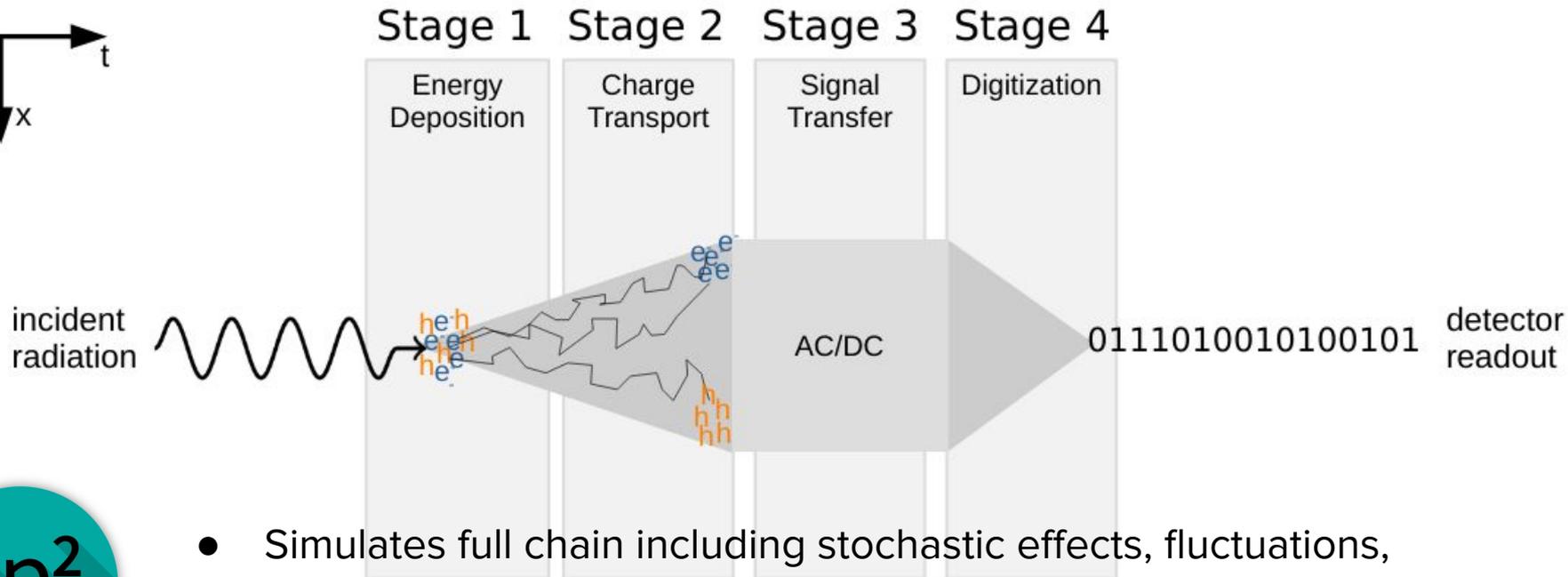
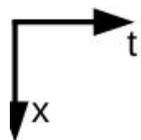
- Leakage current increase
 - more noise
 - more heat and power consumption
- Change in space charge distribution:
 - decreased active region
 - higher operational voltage
- Trapping of charge carriers:
 - decreased efficiency
 - decreased spatial resolution

Not considered here: ionizing energy loss resulting in surface damage

Allpix² simulation for unirradiated sensors

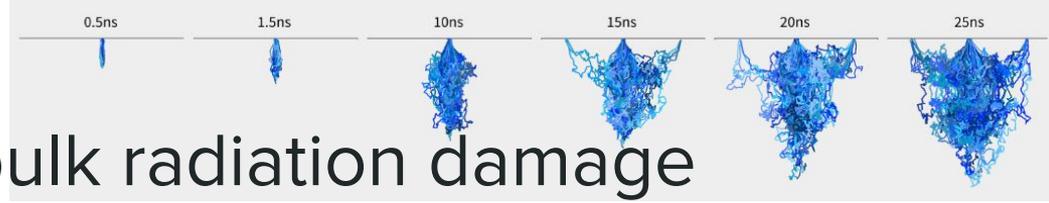


[Image from Paul Schütze](#)

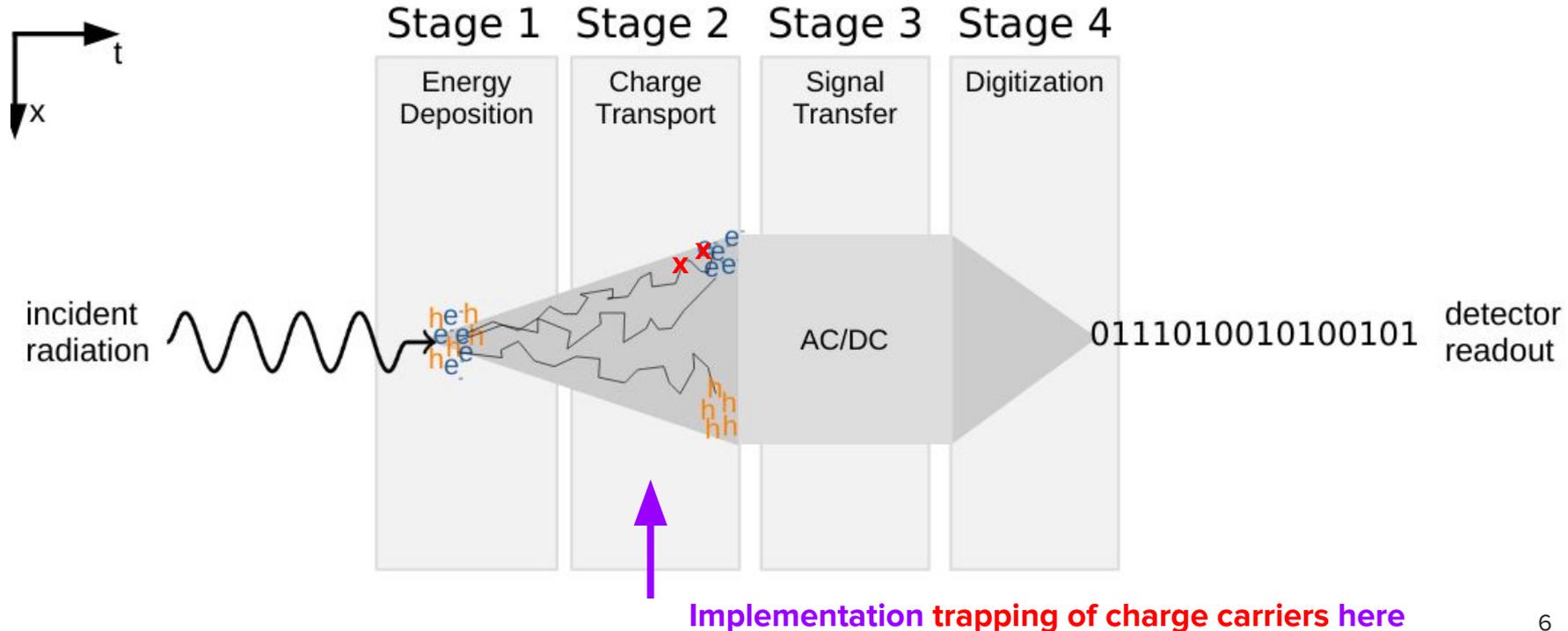


- Simulates full chain including stochastic effects, fluctuations, secondaries
- Simplifications: no self-interaction, static electric field

Allpix² simulation with bulk radiation damage



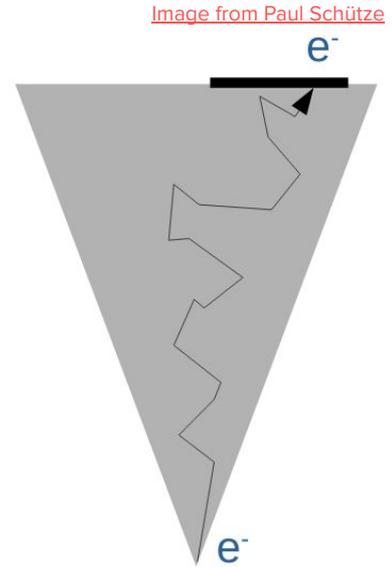
[Image from Paul Schütze](#)



Allpix² charge propagation

GenericPropagation module for charge transport:

- Mobility from electric (and magnetic if applicable) field with [Jacoboni, Canali et al.](#)
- Calculate the mobility, drift velocity using local electric field at each step
- Make a step and add diffusion offset from a Gaussian distribution
- Make N steps: O(N) computation time
- Steps for groups of charge carriers
- Default number of carriers per group: 10
- Default propagated charge: electrons



**Generic
propagation**

Implementation of trapping

Propagate only **part of the charges in a group** according to

$$Q(t) = Q(t = 0) \exp[-t/\tau]$$

t is the timestep

τ = [effective trapping time by Kramerberger et al.](#):

$$\frac{1}{\tau_{\text{eff}_{e,h}}} = \beta_{e,h} \Phi_{\text{eq}}$$

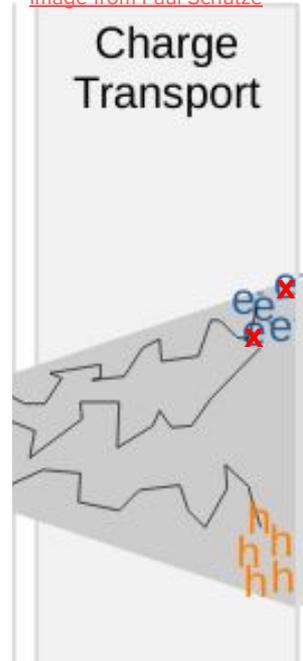
Effective trapping time is
a function of fluence

$$\beta_h = (6.1 \pm 0.3) \times 10^{-16} \text{ cm}^2/\text{ns}. \quad \beta_e = (4.2 \pm 0.3) \times 10^{-16} \text{ cm}^2/\text{ns}$$

Default trapping parameters from Kramerberger et. al. used in Allpix².

Note this linearity [does not necessarily hold](#) above fluences $\Phi_{\text{eq}} = 2 \times 10^{14} / \text{cm}^2$

[Image from Paul Schütze](#)



Code: <https://gitlab.cern.ch/jsonneve/allpix-squared>

Merge request:

https://gitlab.cern.ch/allpix-squared/allpix-squared/-/merge_requests/526

Trapping in Allpix²

- Implemented a trapping model into the `GenericPropagation` module
- Used an empirical trapping model by Kramberger $Q(t) = Q(t = 0) \exp[-t/\tau]$
- Q : propagated charge; t is the time step
- τ is the effective trapping time
- To activate the charge carrier trapping, the parameters can be specified in the `GenericPropagation` section in the configuration file:

```
[GenericPropagation]
name = "dut_0", "dut_1"
charge per step = 10
charge_carrier_trapping = true
constant_trapping_time = true
temperature_dependent_trapping = false
neutron_equivalent_fluence = 5e15
beta_e = 4.2e-16
beta_h = 6.1e-16
```

[Code merged with latest allpix-squared commits](#)

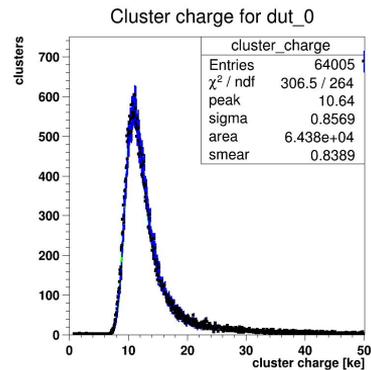
Trapping parameters

Code: <https://gitlab.cern.ch/jsonneve/allpix-squared>

Merge request:

https://gitlab.cern.ch/allpix-squared/allpix-squared/-/merge_requests/526

Example of trapping



Wed Jul 28 13:10:59 2021

GitLab Merge Request interface showing a commit titled "renamed file" by Jory Sonneveld. The commit history table is as follows:

Name	Last commit	Last update
...		
README.md	renamed file	17 hours ago
dut.conf	files and symlinks for running the example	2 months ago
eudet_rd53a_trapping_5e15.co...	updated example: fewer events, unused p...	17 hours ago

The README section contains the following text:

⚡ Radiation damage in RD53A modules with the EUDET RD53a example

Work in progress This example is similar to the EUDET-RD53a example, with trapping applied to the RD53a devices under test. After radiation damage to the bulk of a silicon sensor, charge carriers can get trapped and no longer propagate in a sensor, so that they no longer contribute to charge integration. In this example, a neutron equivalent fluence of $\Phi_{\text{eq}} = 1 \cdot 10^{15} / \text{cm}^2$ and constant trapping parameters are assumed.

The goal of this setup is to simulate the performance of sensors after radiation damage with a simple model of charge carrier trapping. The user can alter the trapping parameters, fluence, and choose to use trapping dependent on temperature and/or the electric field using the configuration parameters of the `GenericPreparation` module. See the documentation for this module for more details.

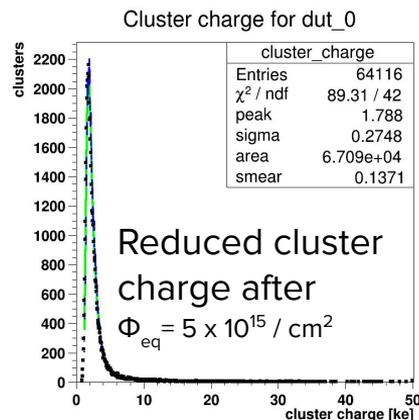
In this example, a linear electric field is applied; however, external electric fields can also be applied by changing the configuration of the `ElectricFieldReader` module.

Example of trapping in Allpix Squared:
<https://gitlab.cern.ch/jsonneve/allpix-squared/-/tree/master/examples/trapping>

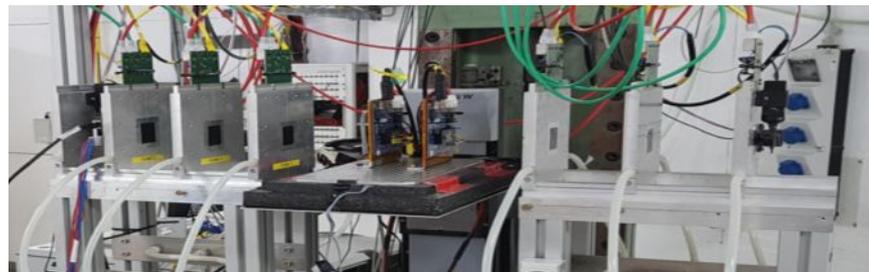
Test of trapping: simulation of RD53 modules for ITk

Simulated: RD53A

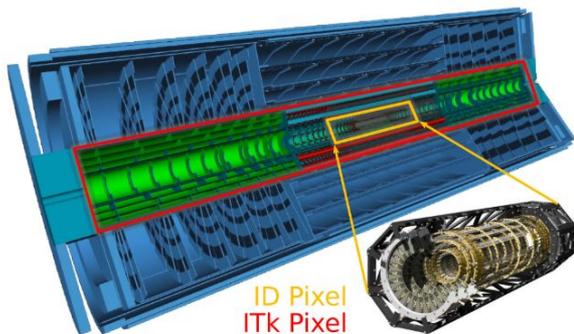
- 50 μm x 50 μm
- 25 μm x 100 μm
- 400 x 192 pixels
- 150 μm thick



Wed Jul 28 13:11:02 2021



EUDET telescope with 2 RD53A DUTs by R. Taibah:
[Telescope in Allpix²](#)
[RD53A 25x100](#) and [RD53A 50x50](#) models



ATLAS Inner Tracker (ITk)

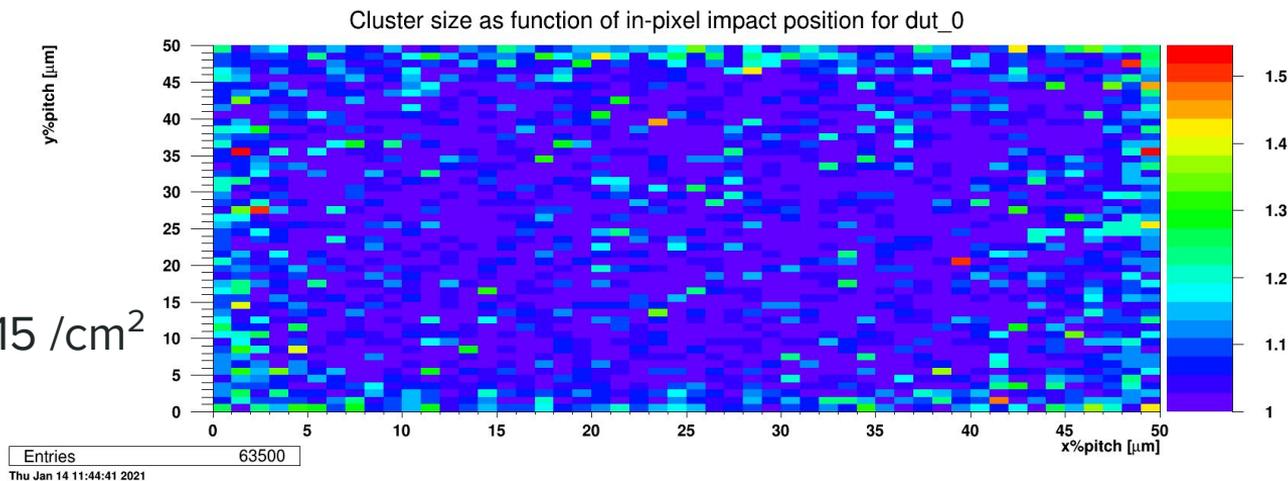
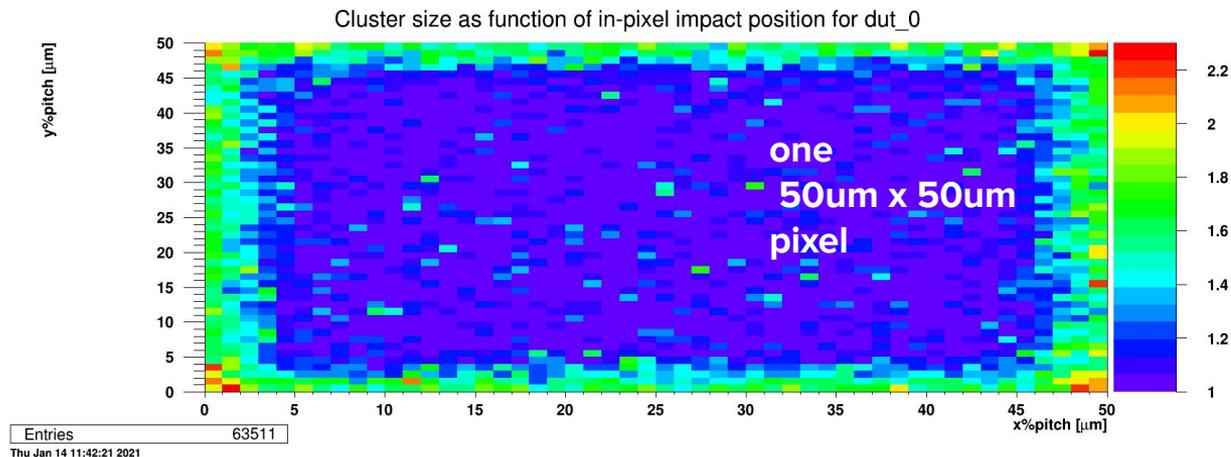
[From Tobias Fitschen](#)

layer	radius	$\Phi_{\text{eq}} / [\text{cm}^2]$	$\int L dt$	thickness
L0 3D	3.4 cm	1.23e16	2000 fb ⁻¹	150 μm
L1	9.9 cm	4.1e15	2000 fb ⁻¹	100 μm
L2-4	from 16 cm	up to 4.7e15	4000 fb ⁻¹	150 μm

Cluster size

- Unirradiated
- 100k events
- DUT RD53A
- Threshold $1000e^-$
- Trapping $\Phi_{eq} = 5e15 / cm^2$

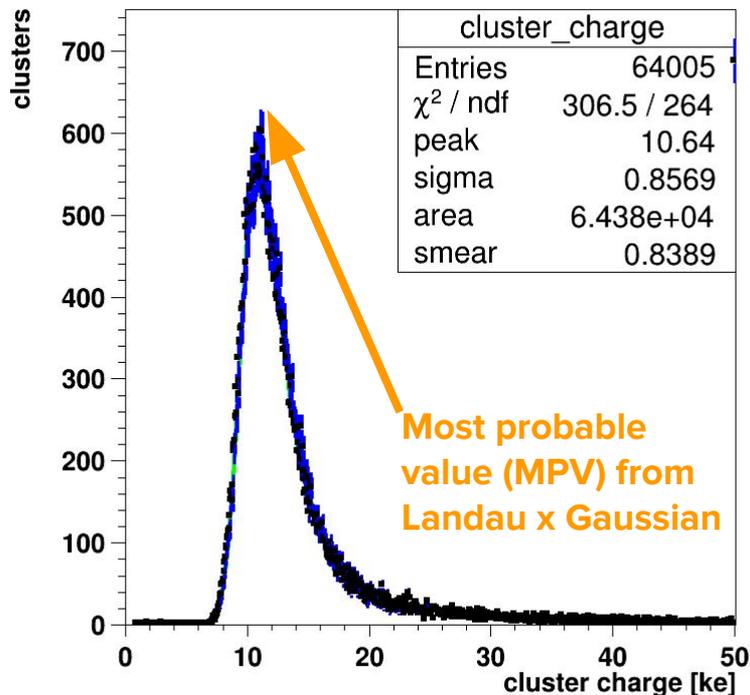
RD53A 50umx50um
100 um thick



Charge sharing at borders of a pixel reduces after bulk radiation damage

Landau fit on DUT cluster charge

Cluster charge for dut_0



Most probable value (MPV) from Landau x Gaussian

Includes trapping in Allpix² in GenericPropagation module

Simulated RD53A

50 μm x 50 μm

150 μm thick

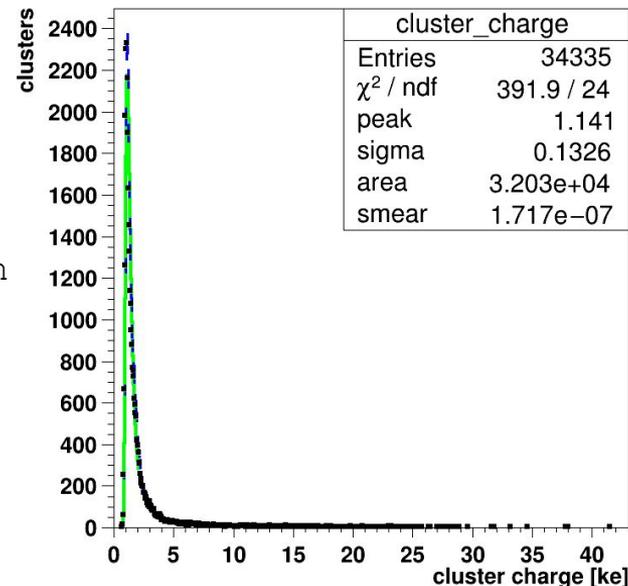
$V_{\text{bias}} = 600 \text{ V}$

$V_{\text{dep}} = 400 \text{ V}$

Linear electric field

Fluence: 1e15

Cluster charge for dut_0



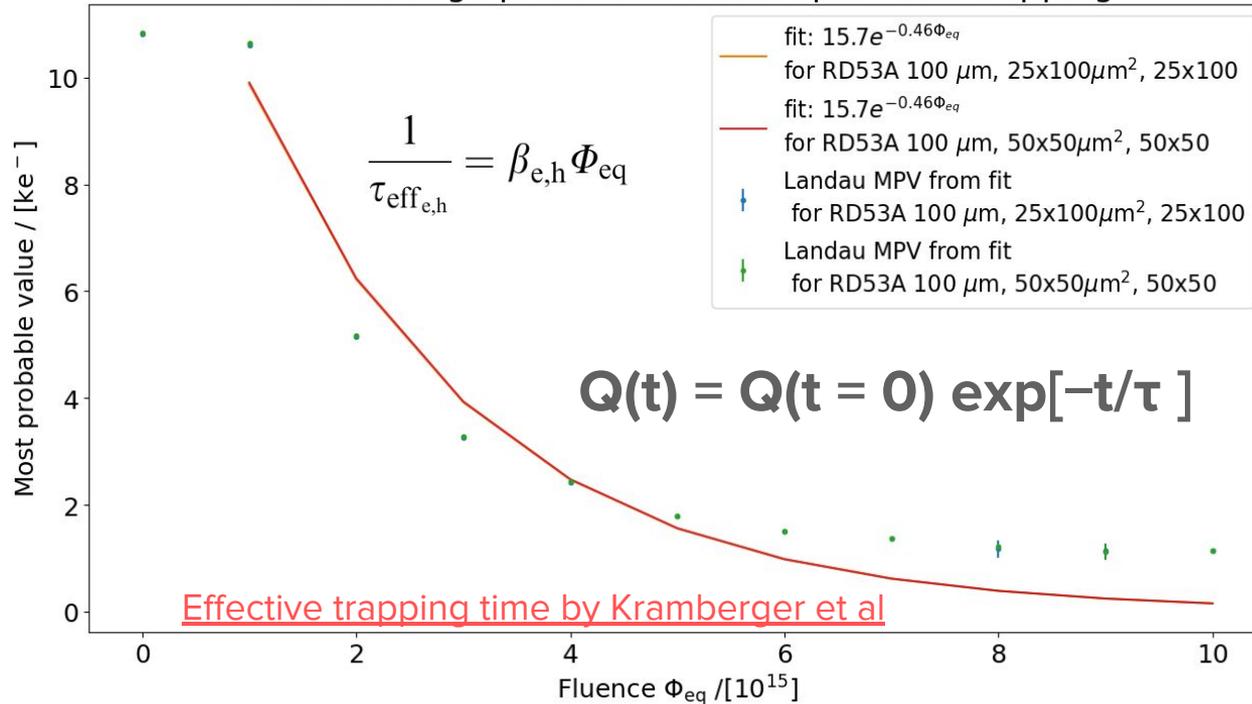
Wed Jul 28 13:11:06 2021

Fluence: 1e16

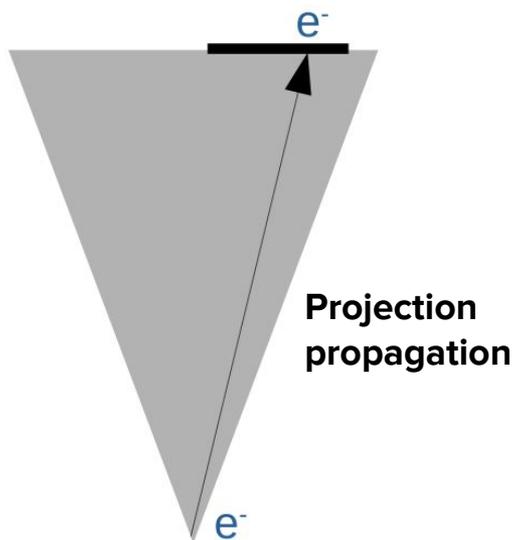
Cluster charge MPV vs fluence with trapping in Allpix²

Cluster charge prediction from Allpix² with trapping

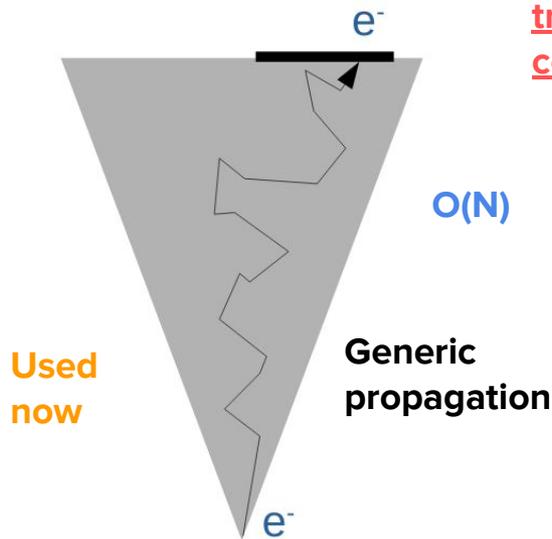
Each point
from
100000
events
simulated
in Allpix
Squared



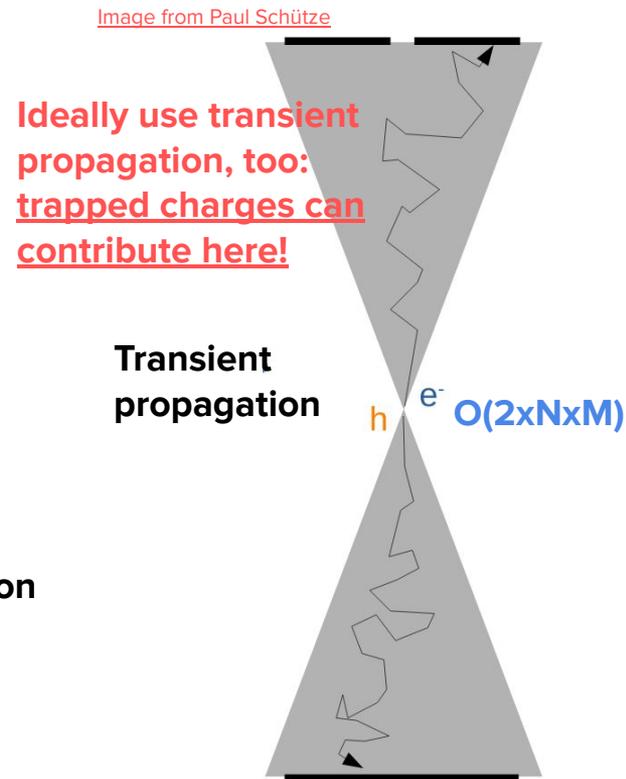
Allpix² charge propagation



- Compute drift and diffusion time
- Put charge on sensor surface with offset from Gaussian.



- Mobility from E and B fields with [Jacobi/Canali](#)
- Make N steps with each the drift velocity and diffusion offset.



Ideally use transient propagation, too: trapped charges can contribute here!

- In addition, get induced charge from **weighting potential** from M neighbors

Image from Paul Schütze

Methods of trapping charges: with a **factor** or **time**

Now used an empirical trapping model by [Kramberger](#) $Q(t) = Q(t = 0) \exp[-t/\tau]$

Now:

In generic propagation

Trapping ideally in module that can be used in all propagation types

Work in progress:

Trapping with a factor:

- **Multiply charges by a trapping factor $\exp(-\text{timestep}/\tau)$**
- **Trapping time $\tau = 1/(\beta\Phi_{eq})$**
- **Multiply at each timestep: final factor is multiple of all factors or one factor of sum of timesteps**

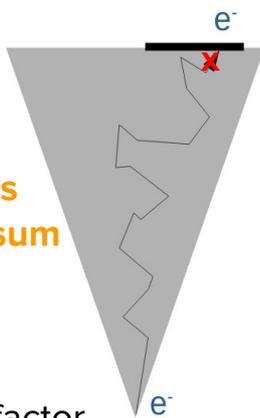


Image from [Paul Schütze](#)

- **Draw trapping time t_{trap} randomly from $\exp(-t_{trap} \cdot \beta\Phi_{eq})$ and add to propagation time**
- **Once propagation time is larger than integration time, do not continue propagation**
- **Detrapping with certain probability at each time step**

A charge group is either propagated or trapped depending on the trapping time.

A charge group can also be detrapped.

A number of charges reduced by a trapping factor that is a multiple of those computed at each timestep is left over in the end.

Possible trapping model extensions

The following are not yet tested or implemented:

- Temperature dependent trapping

[From Kramberger et al](#)

$$\kappa_e = -0.86 \pm 0.06$$

$$\kappa_h = -1.52 \pm 0.07$$

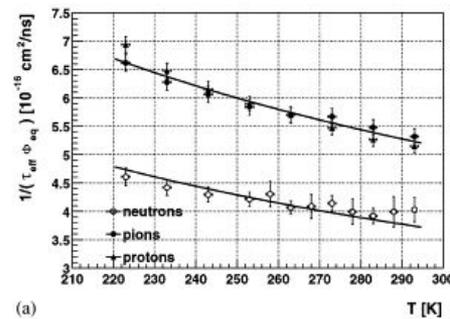
$$\beta_{e,h}(T) = \beta_{e,h}(T_0) \left(\frac{T}{T_0} \right)^{\kappa_{e,h}}$$

- Electric field dependent trapping

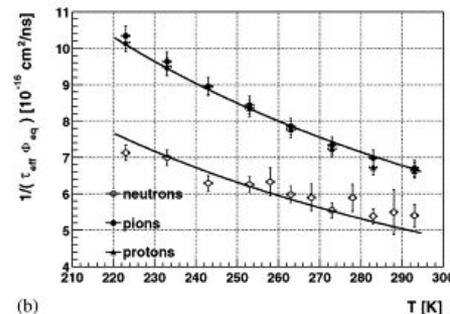
$$\tau(E) = \tau_0 + \tau_1 \cdot E$$

[Thesis by Thomas Pöhlsen](#)

- Error bars from errors on parameters: errors are not implemented / accounted for in Allpix Squared
- Variable or parametrized [trapping constants](#)



(a)



(b)

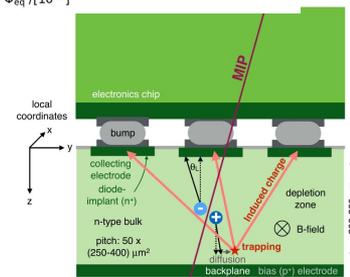
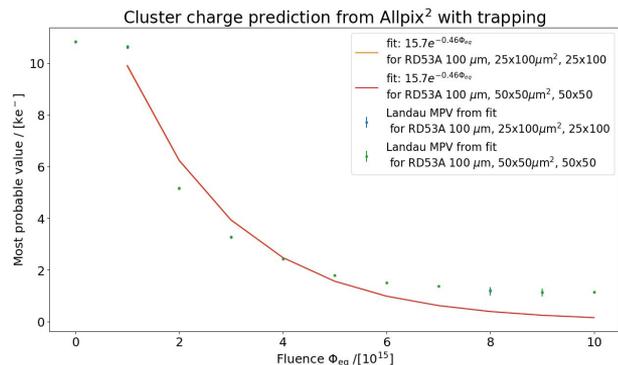
Summary

Trapping of charges after radiation damage:

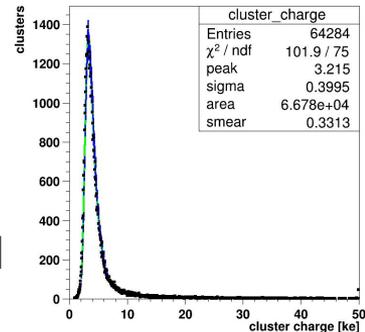
- Now implemented in Allpix Squared: still work in progress!
- Cluster charge reproduces exponential behavior
- Documentation in README for GenericPropagation
- Unit test: 09-trapping
- → will be moved to a separate module

Next:

- → investigate influence of electric field and weighting field
- → investigate time-dependent trapping



Cluster charge for dut_1



Additional material

LHC experiments



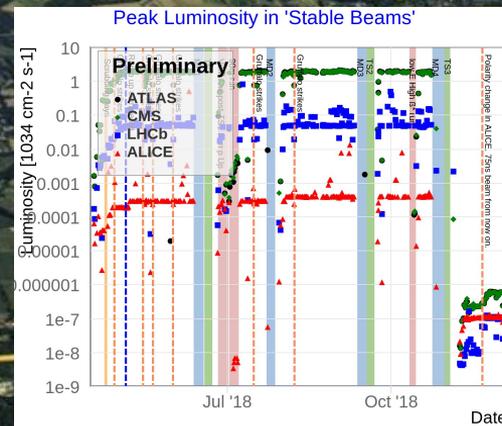
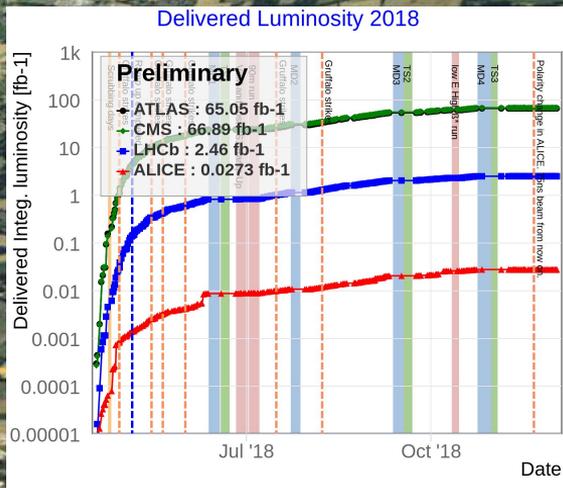
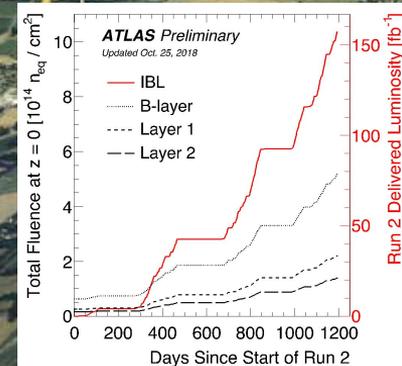
LHC Peak luminosity: $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Inner detector systems:

CMS fluences up to $7.9 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$

ATLAS: IBL now has $> 1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$!

LHCb: 10 years with a delivered 10 fb^{-1} and innermost region (VELO) $6.5 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$



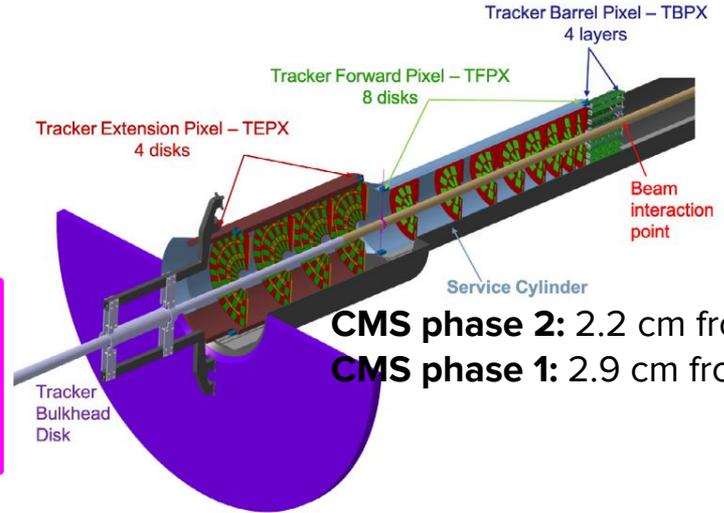
<https://cds.cern.ch/record/2700000/files/ATLAS-CONF-2018-027.pdf>
<https://cds.cern.ch/record/2700000/files/ATLAS-CONF-2018-027.pdf>
<https://cds.cern.ch/record/2700000/files/ATLAS-CONF-2018-027.pdf>

ATLAS TDR

LHC Run 4: inner detector systems late 2027

ATLAS ITk: 3.6 cm from beam line
ATLAS IBL: 3.325cm from beam line

CMS TDR



CMS phase 2: 2.2 cm from beam line
CMS phase 1: 2.9 cm from beam line

Fig. 2. A quarter of the IT system.

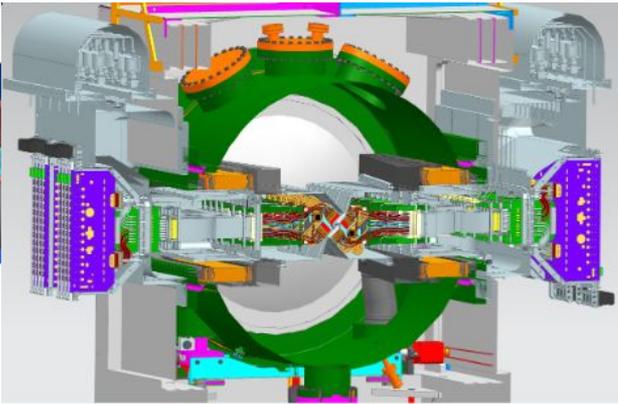
Current ITS

Upgraded ITS



ALICE inner tracker: upgraded now for Run 3 in 2022

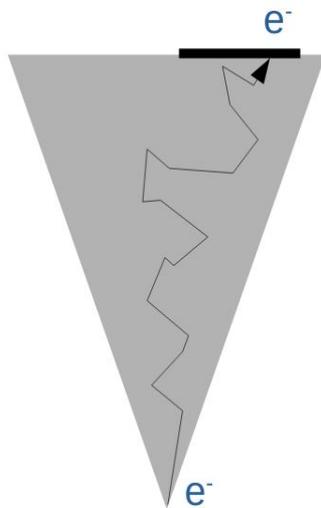
ALICE: 2.2 cm from beam line, monolithic active pixel sensors $33 \mu\text{m} \times 33 \mu\text{m}$



LHCb: 0.51 cm from beam line, pixel sensors $55 \mu\text{m} \times 55 \mu\text{m}$ in VELO

LHCb VELO and tracker upgrade: now for run 3 in 2022

Method of **propagation: generic propagation**



**Generic
propagation**

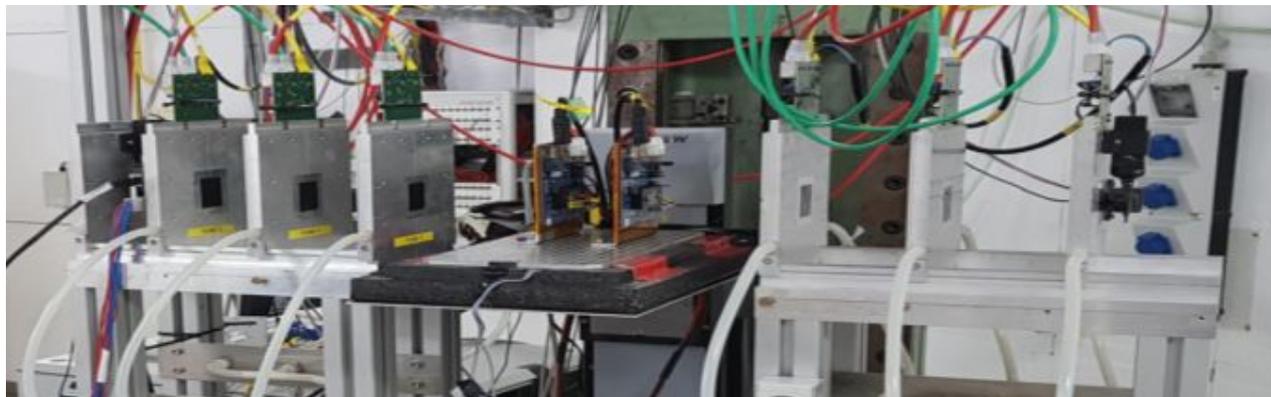
Propagation:

- Groups of 10 (default) charges propagated 1 step in one timestep: this case, electrons
 - Take into account mobility and drift velocity from local electric field and diffusion
 - Stop when drift time > integration time: by default LHC bunch crossing 25 ns
-
- Mobility from E and B fields with [Jacobi/Canali](#)
 - Make N steps with each the drift velocity and diffusion offset.

[From Paul Schütze](#)

Setup of testbeam environment in Allpix²

Reem Taibah -
JRJC 2019



5 GeV e^- at DESY test beam with EUDET telescope:

- 6 Mimosas26 planes
- 2 RD53A DUTs
- 1 IBL planar reference

Implemented in Allpix² by Reem Taibah:

[Telescope in Allpix²](#)

[RD53A 25x100](#) and [RD53A 50x50](#)

RD53A sensor

```
% cat model/rd53a_50_100.conf
type = "hybrid"

number_of_pixels = 400 192
pixel_size = 50um 50um

sensor_thickness = 100um
sensor_excess_direction = 0.0mm 0.0mm 0.6um 0.6um
bump_sphere_radius = 9.0um
bump_cylinder_radius = 7.0um
bump_height = 20.0um
bump_offset = 0.0um 0.0um

chip_thickness = 100um

[support]
thickness = 100um
size = 53mm 94mm
offset = 0 -28.2mm
location = "sensor"
material = "kapton"
```

Electric field and propagation

```
[ElectricFieldReader]
name = "dut_0", "dut_1", "Reference"
model = "linear"
bias_voltage = -600V
depletion_voltage = -400V
```

```
[ElectricFieldReader]
type = "mimosa26"
model = "linear"
bias_voltage = -4V
depletion_depth = 15um
```

```
[GenericPropagation]
name = "Reference"
temperature = 293K
charge_per_step = 10
```

```
[GenericPropagation]
name = "dut_0", "dut_1"
charge_per_step = 10
charge_carrier_trapping = true
constant_trapping_time = true
temperature_dependent_trapping = false
neutron_equivalent_fluence = 5e15
```