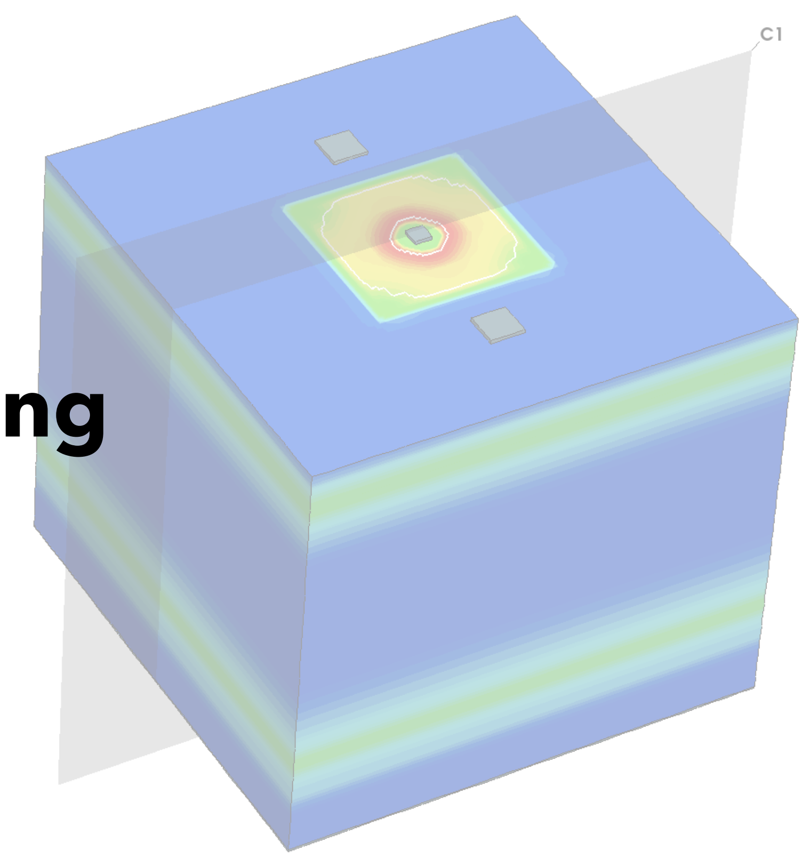
UPDATE ON TRANSIENT ALLPIX-SQUARED + TCAD SIMULATIONS FOR CLICTD

Katharina Dort

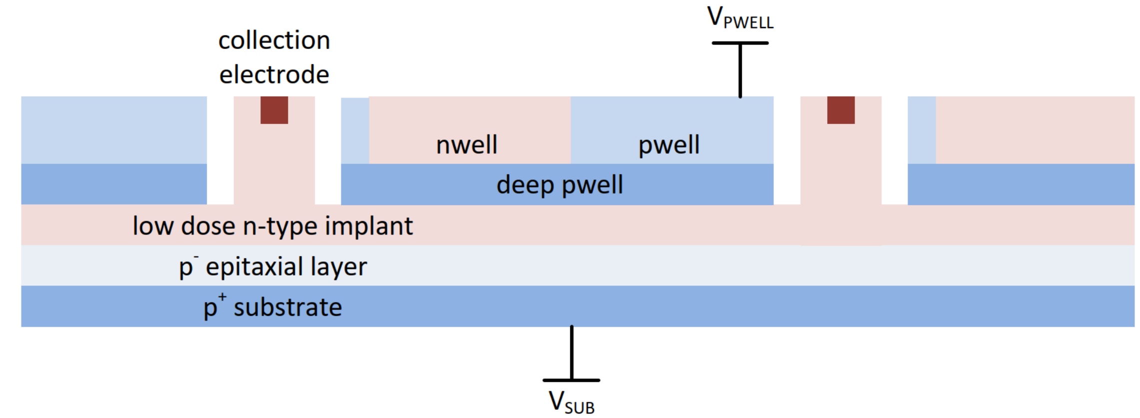
Vertex & Tracker Meeting

29/05/2020

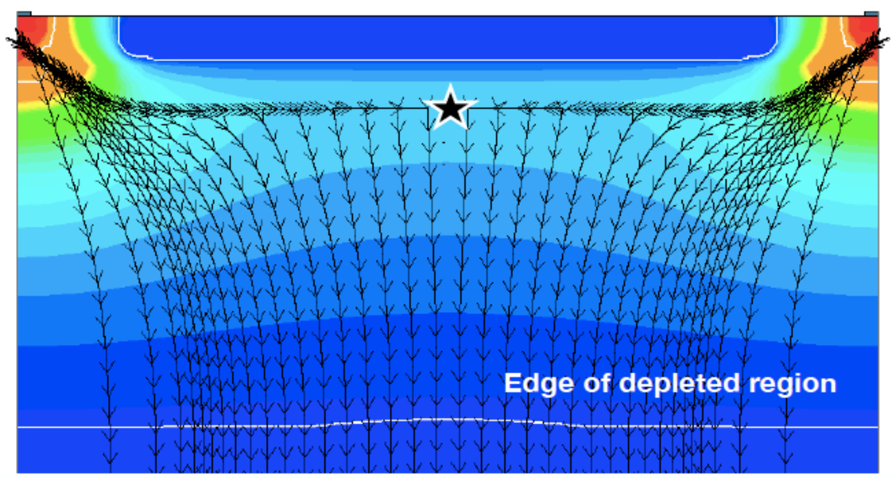


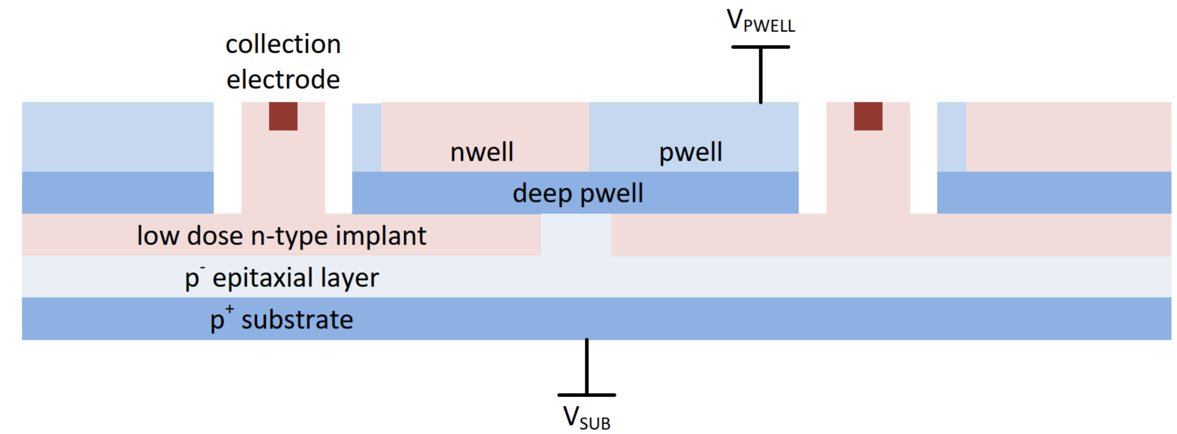
CLICTD - SENSOR PROCESS

- CLICTD (180 nm CMOS imaging process) was designed in two process variants
- Gap in the n-type implant was introduced to speed up charge collection



Electrostatic potential: Continuous N-type implant





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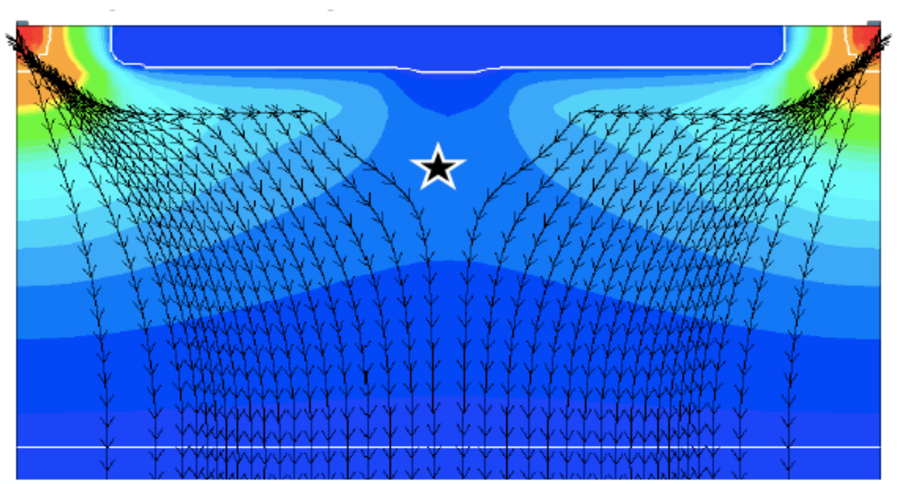

From Magdalena's electrostatic TCAD simulations

- Bias voltage applied to substrate and p-wells
- Best sensor performance expected at -6V / -6V
- Simulation shown here were only made at this bias voltage

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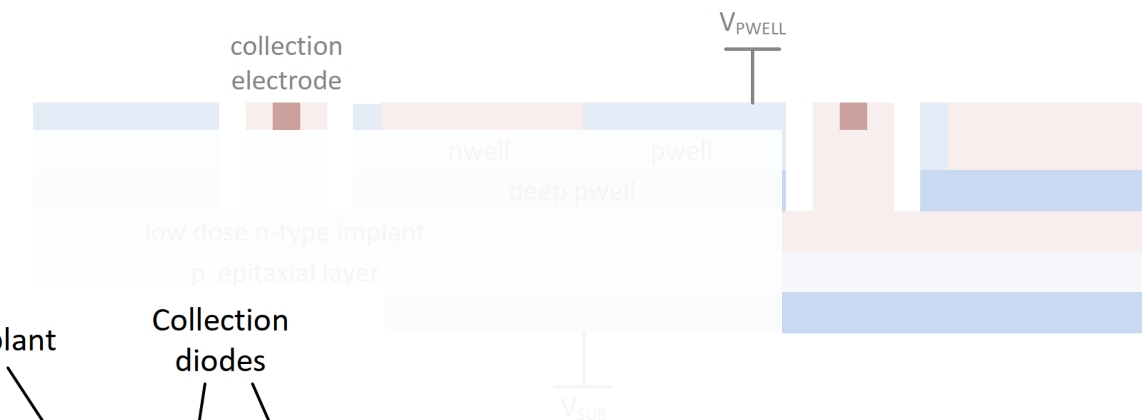
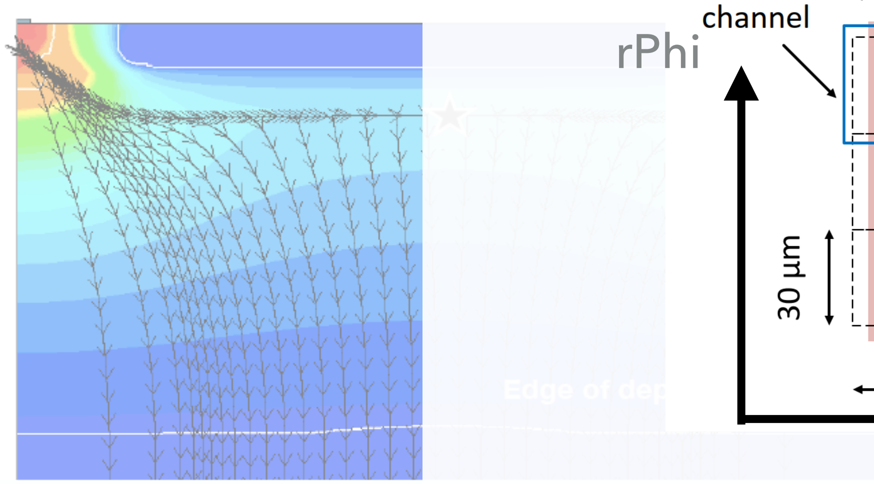
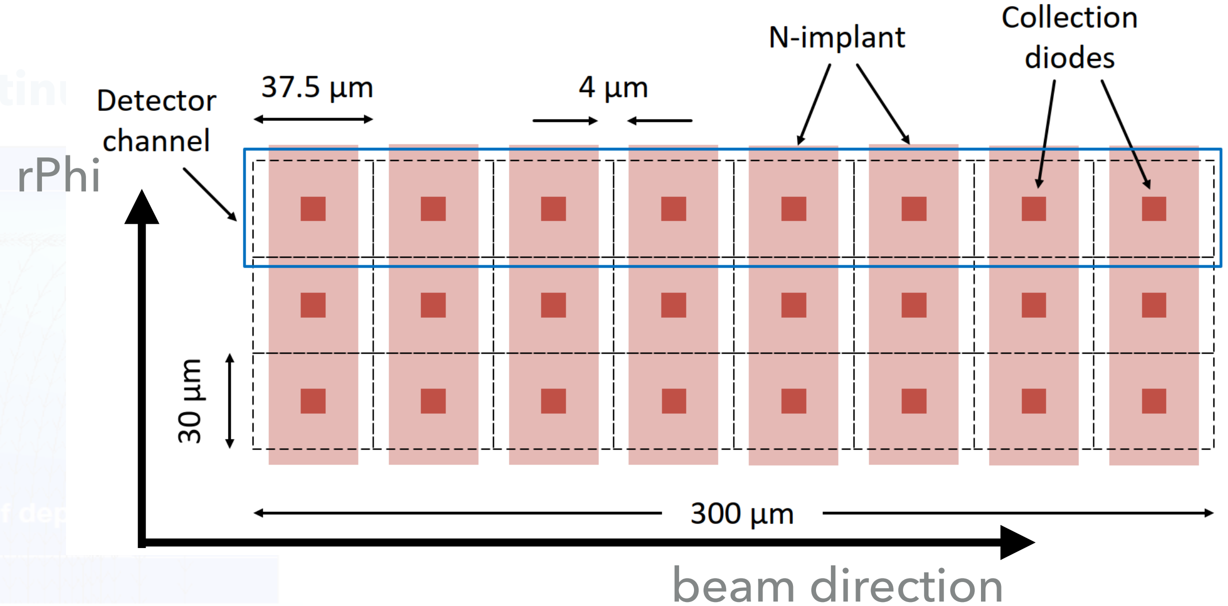
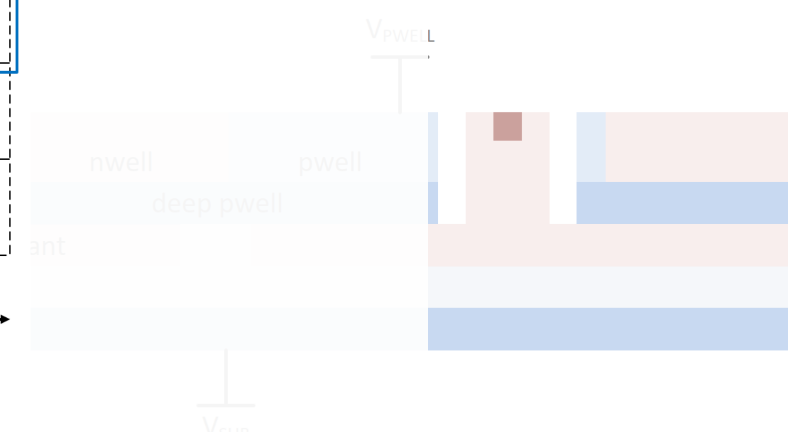


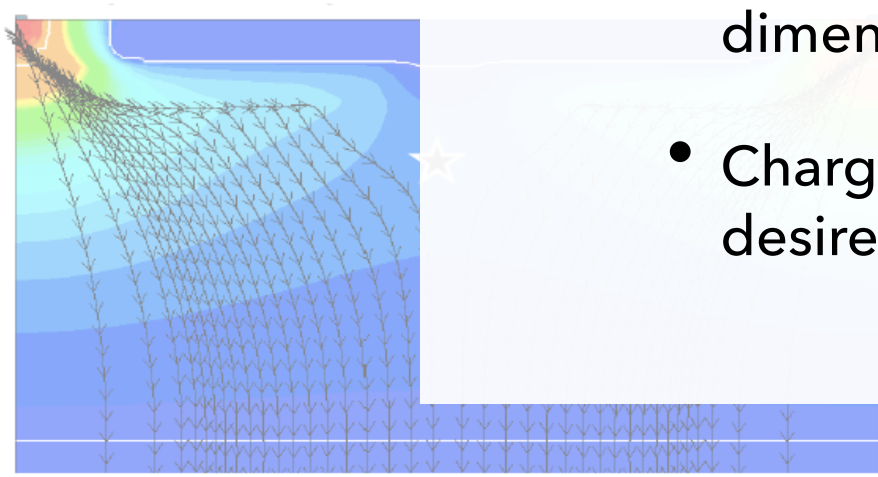
Electrostatic potential: Contin







Electrostatic potential: Gap in N



- Gap in n-layer only introduced along one dimension to speed up charge collection
- Charge sharing in other spatial dimension is desired for improved spatial resolution

- Bias voltage applied to substrate and p-wells
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From Magdalena's electrostatic TCAD simulations

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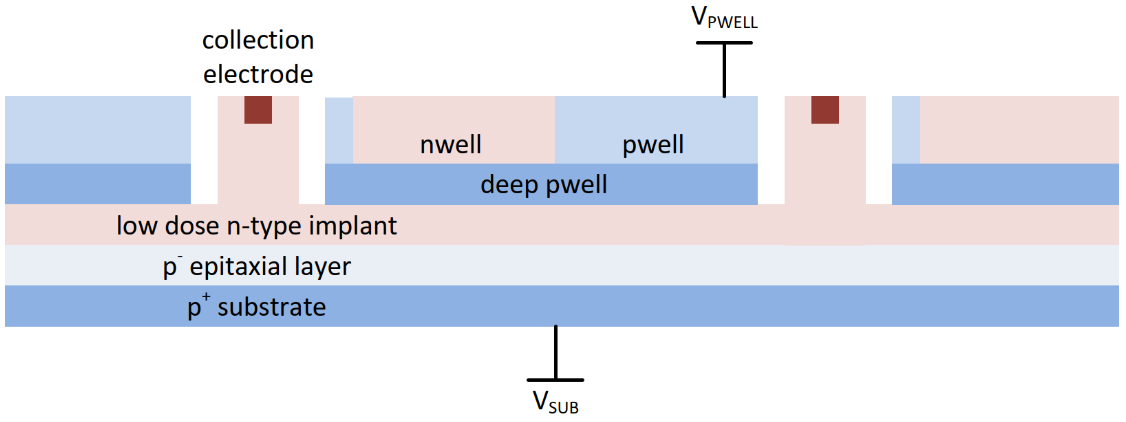
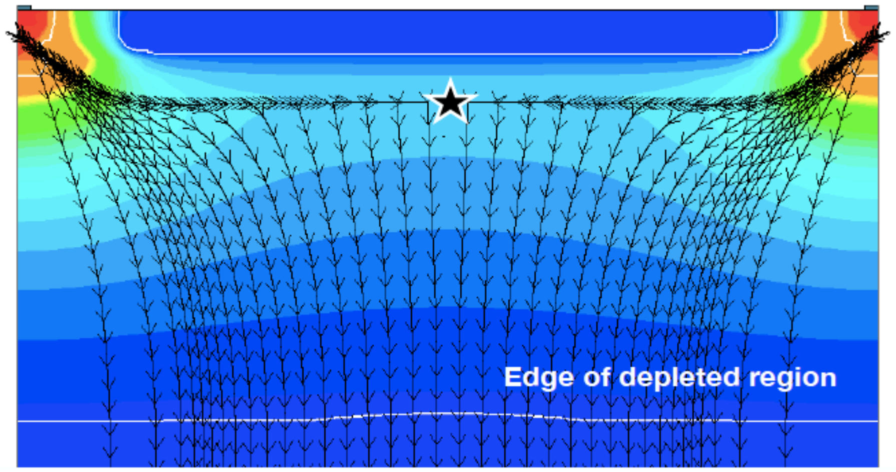
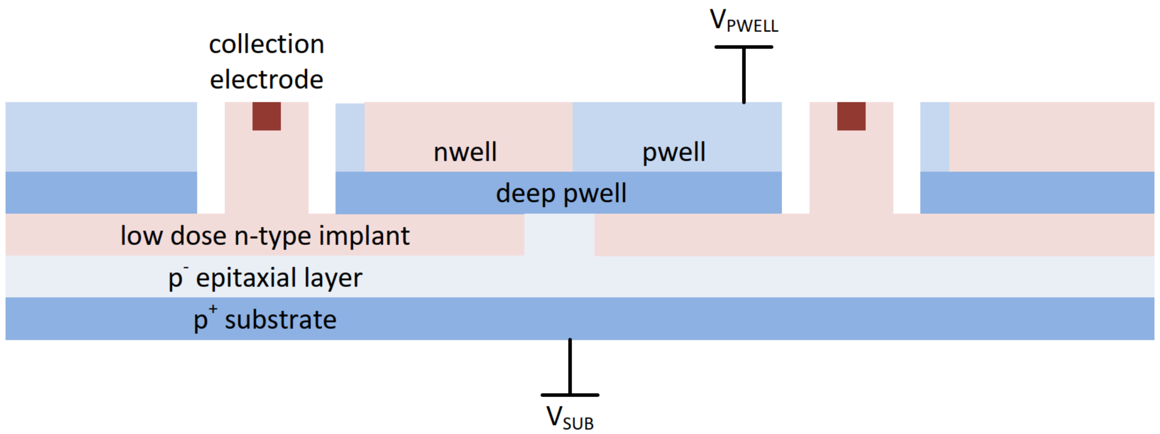
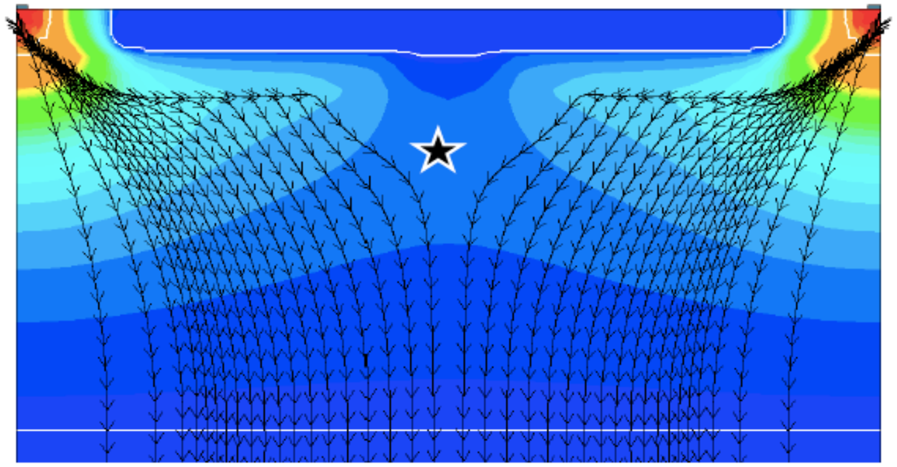


Electrostatic potential: Continuous N-type implant





Electrostatic potential: Gap in N-type implant



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ALLPIX SQUARED + TCAD SIMULATIONS

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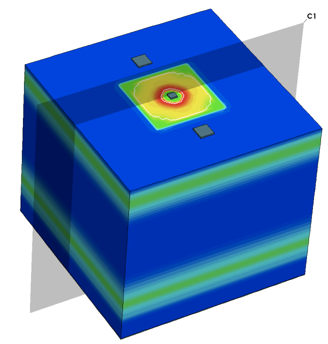
Simulation of **full detector response**

- Allpix Squared (APSQ) is a Monte Carlo simulation framework for silicon vertex and tracker detectors

- 3D **electrostatic** TCAD simulations are needed to model electric field which is imported into Allpix Squared simulations

➡ High statistics and accurate field modeling

- Validation of simulation with Investigator test-chip (developed within ALICE ITS upgrade)



Transient simulation

- Previous simulations of CLICTD with APSQ+TCAD were performed with a simplified charge collection model

- Now: induced current on collection electrode is simulated (*transient APSQ+TCAD simulations*)

- Limited lifetime of charge carriers in APSQ not simulated (yet)

- Simulation time / event (not optimized!):
  - APSQ + electrostatic TCAD: seconds
  - Transient TCAD: hours

Many thanks to Simon + APSQ developer team

WEIGHTING POTENTIAL IN APSQ

- Induced charge: $Q_{id} = q(\phi_w(\vec{r}_1) - \phi_w(\vec{r}_2))$
- With weighting potential: $\phi_w = \Delta\phi_0/\Delta U$

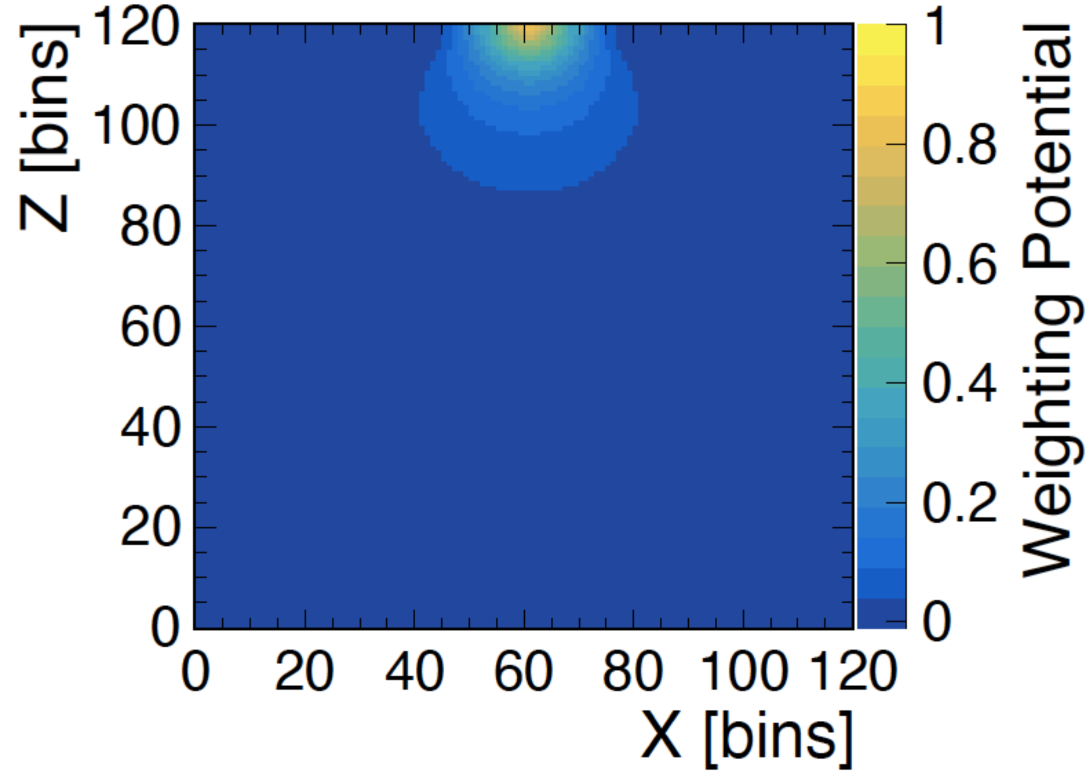
  See back-up slide

- Obtaining the weighting potential from TCAD:
  - Simulate electrostatic potential with TCAD for 0.8V and 0.81V at the collection diode
  - Subtract the two electrostatic potentials $\Delta\phi_0$ at every APSQ mesh point
  - Divide by the collection diode voltage difference $\Delta U = 0.01\ V$

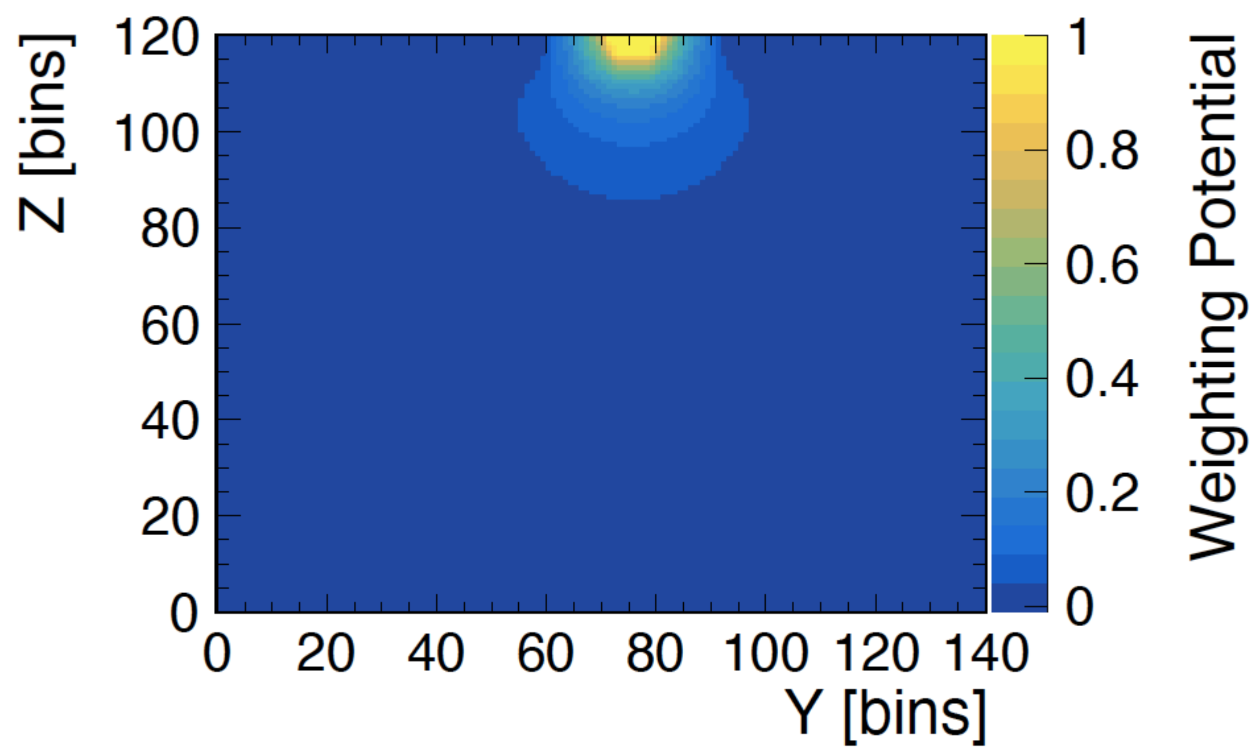
  Many thanks to Magdalena for all TCAD simulations shown in this talk

- High weighting potential values are concentrated around collection electrode
- Influence of neighboring pixel cells assumed to be small (1x1 weighting potential is used) but still has to be confirmed in simulations

Weighting potential - continuous n-layer

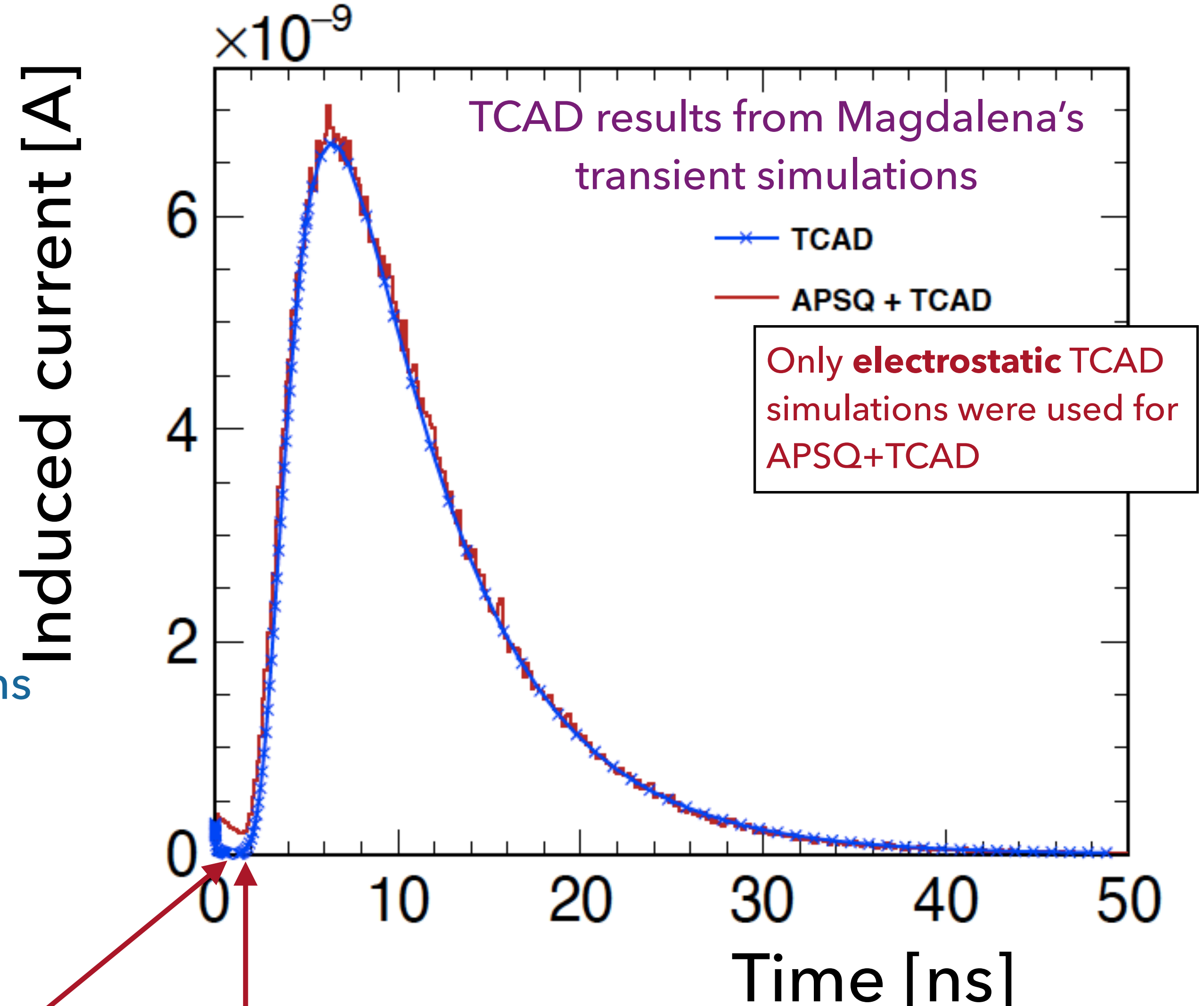


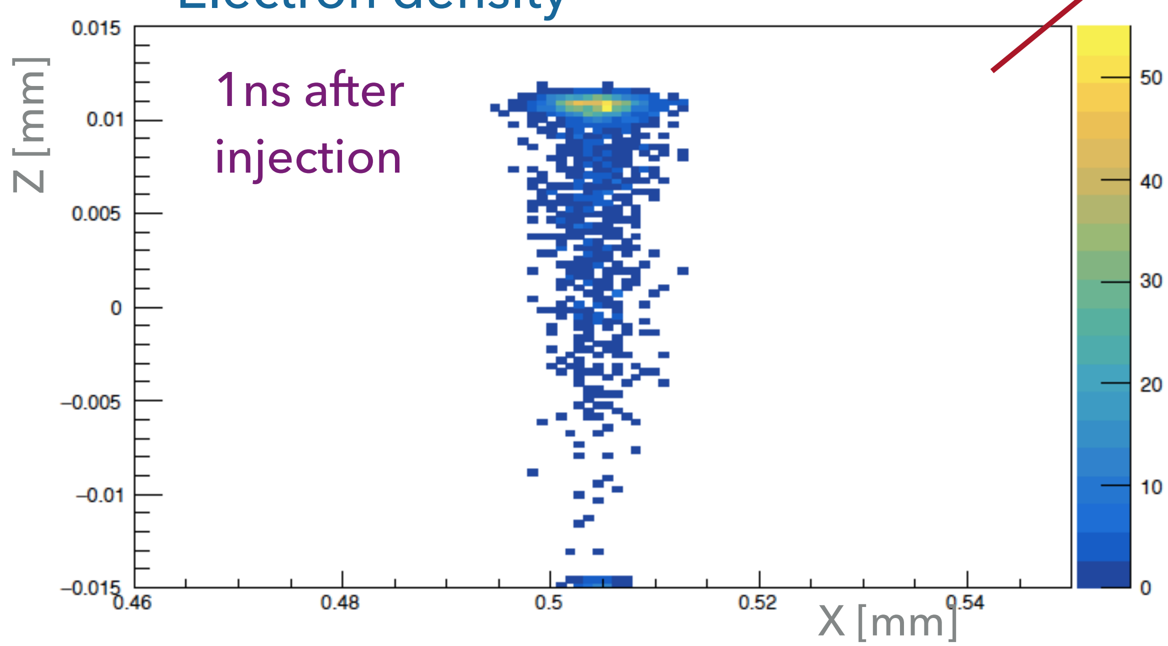
Weighting potential - continuous n-layer

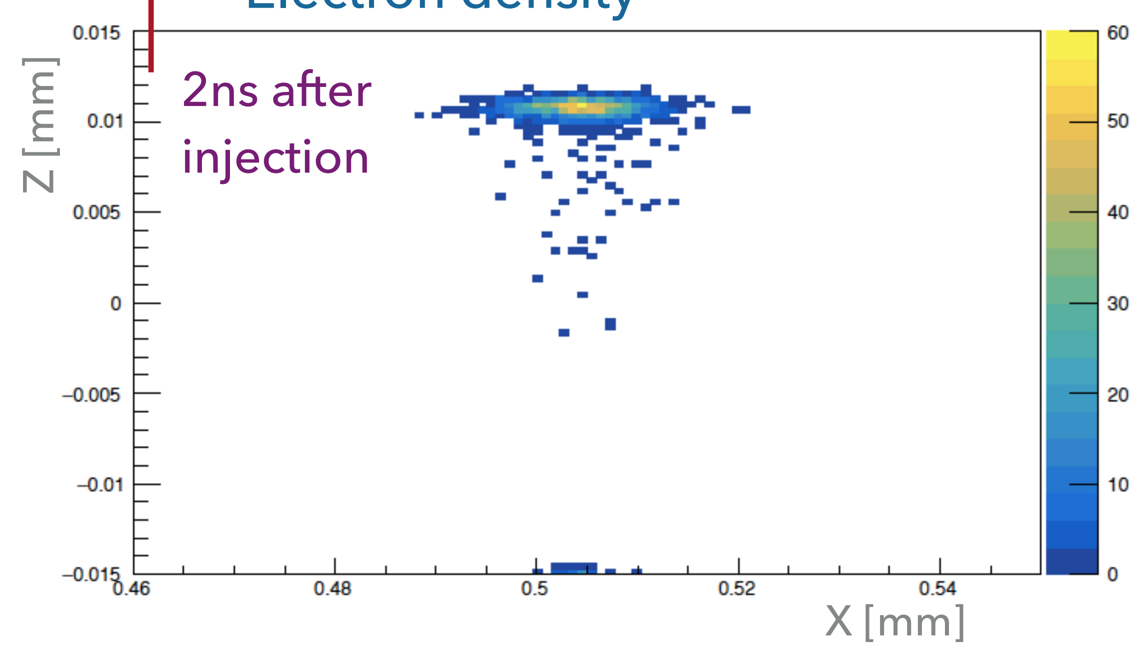


VALIDATION - CONTINUOUS N-LAYER

- To validate APSQ+TCAD simulations, same simulation conditions as in transient TCAD are replicated:
  - Charge carriers are injected along a straight line at the pixel corner (DepositionPointCharge instead of deposition with Geant4)
  - Only the epitaxial layer (30 um) is simulated
  - Fixed amount of charge carriers (no Landau fluctuations and no secondaries) : 63 charge carrier / um
  - Simulation repeated 100x and mean current pulse is computed

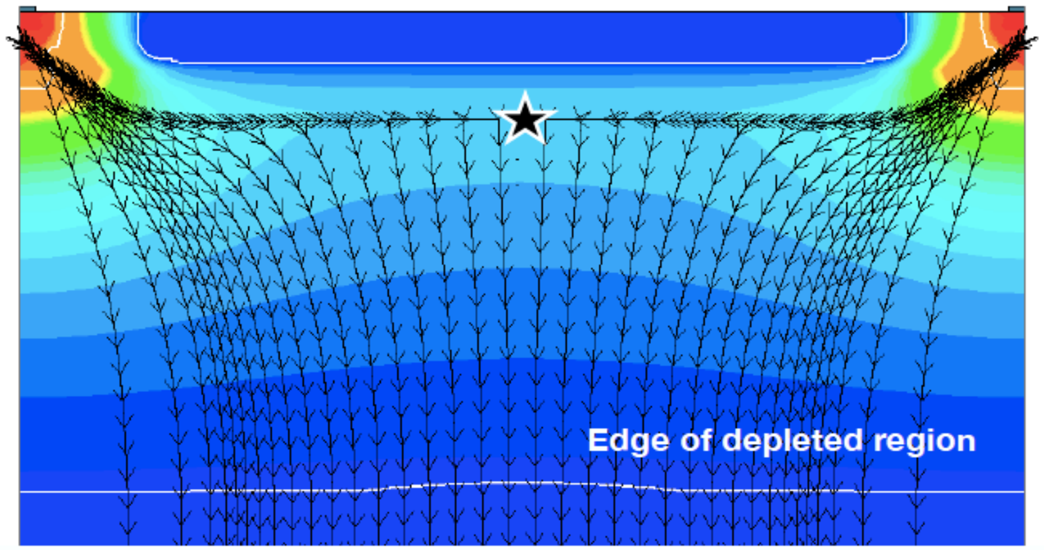




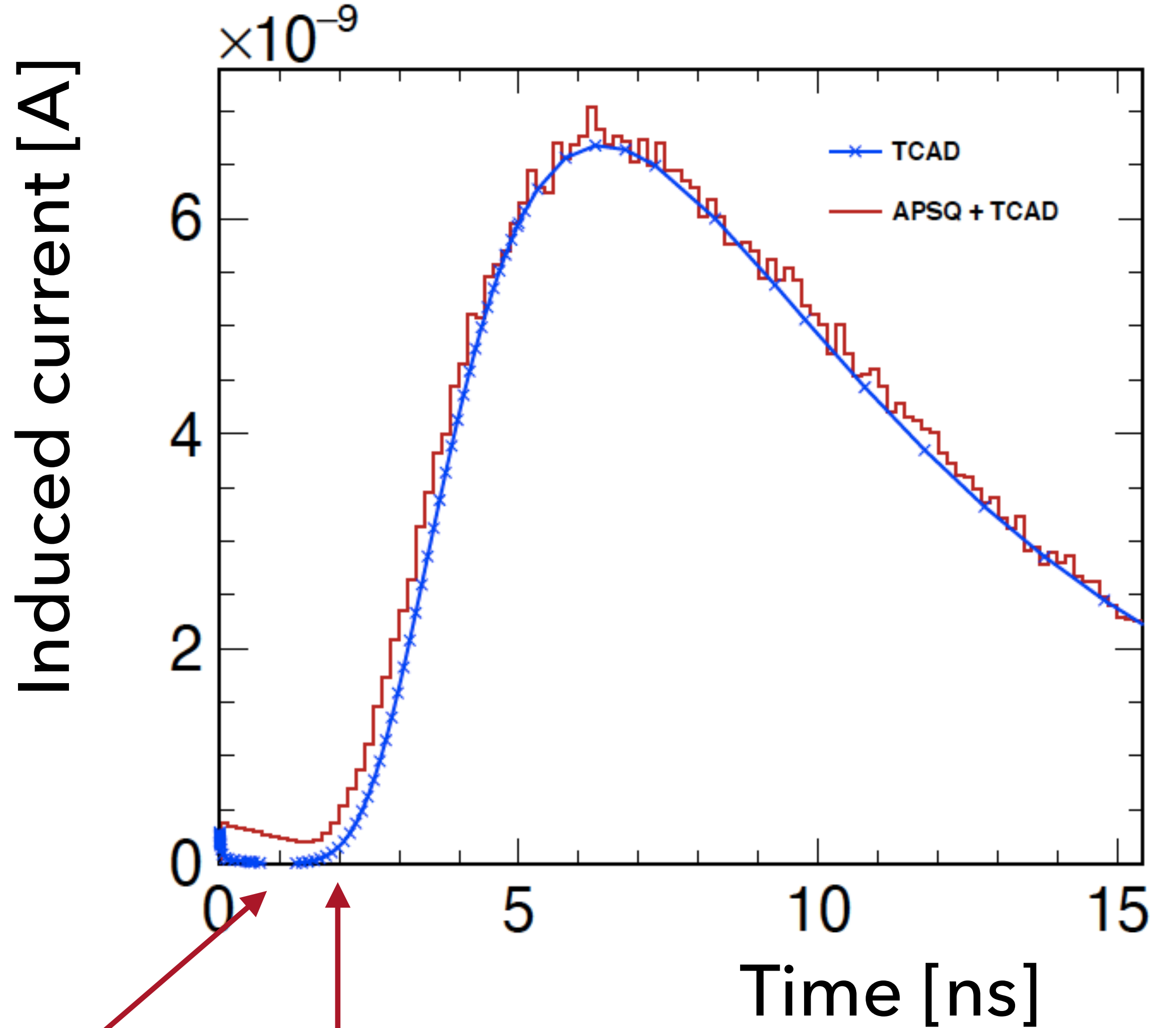


VALIDATION - CONTINUOUS N-LAYER

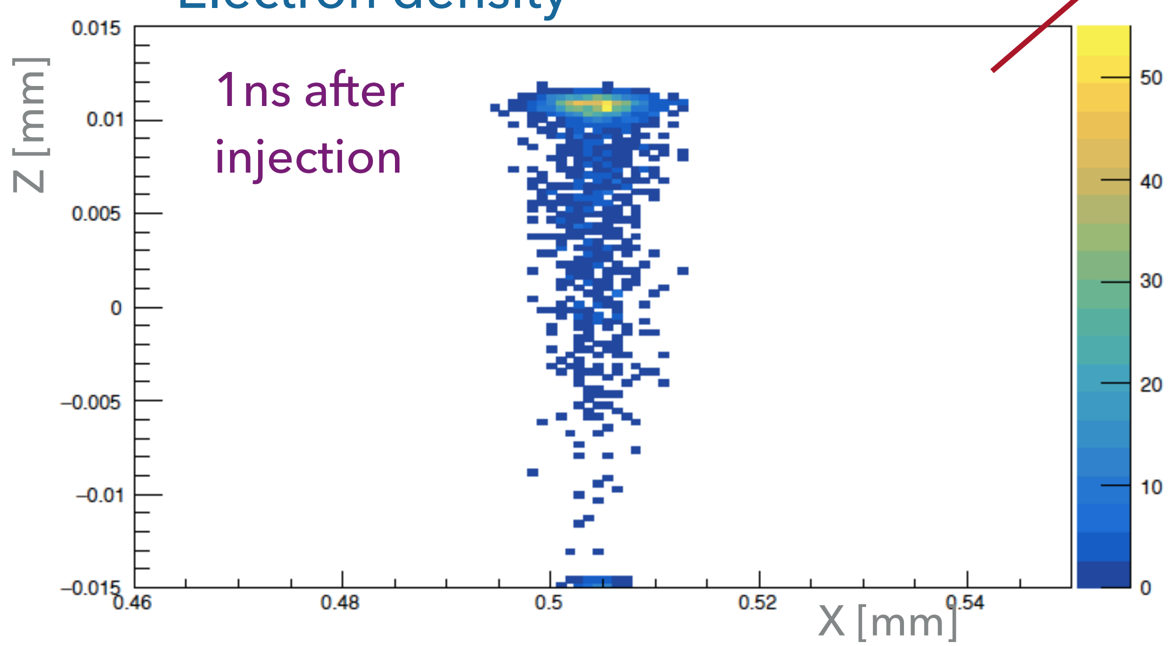
Electrostatic potential:
Continuous N-type implant



- Collection of charge carriers in the field minimum visible



Electron density



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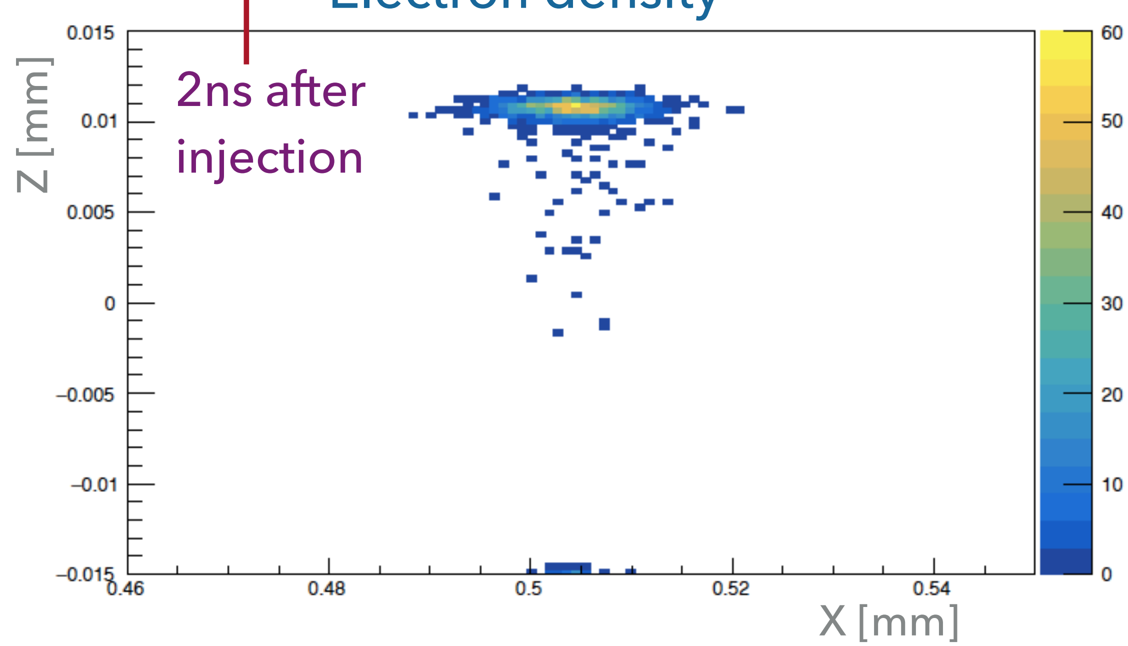
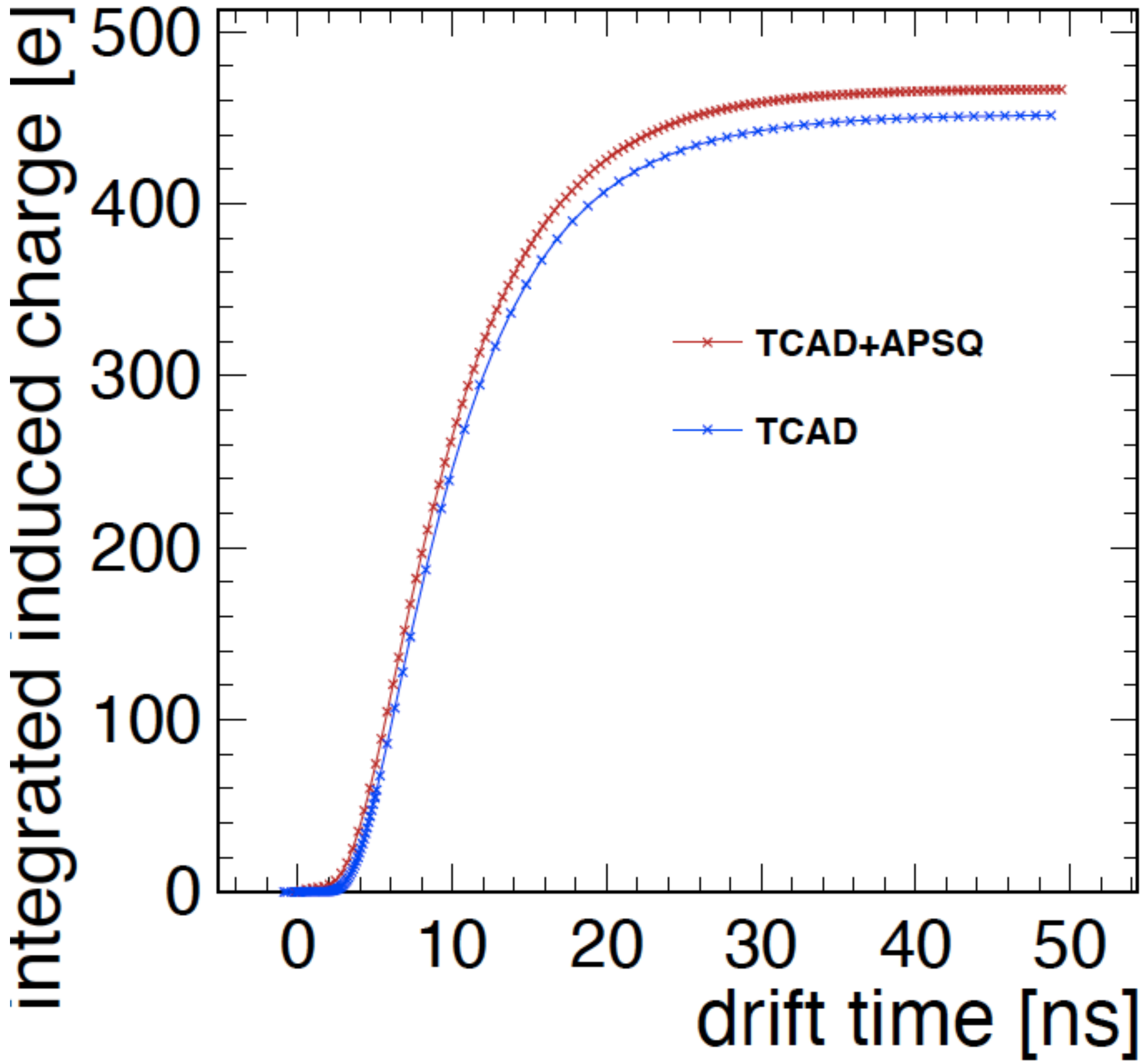


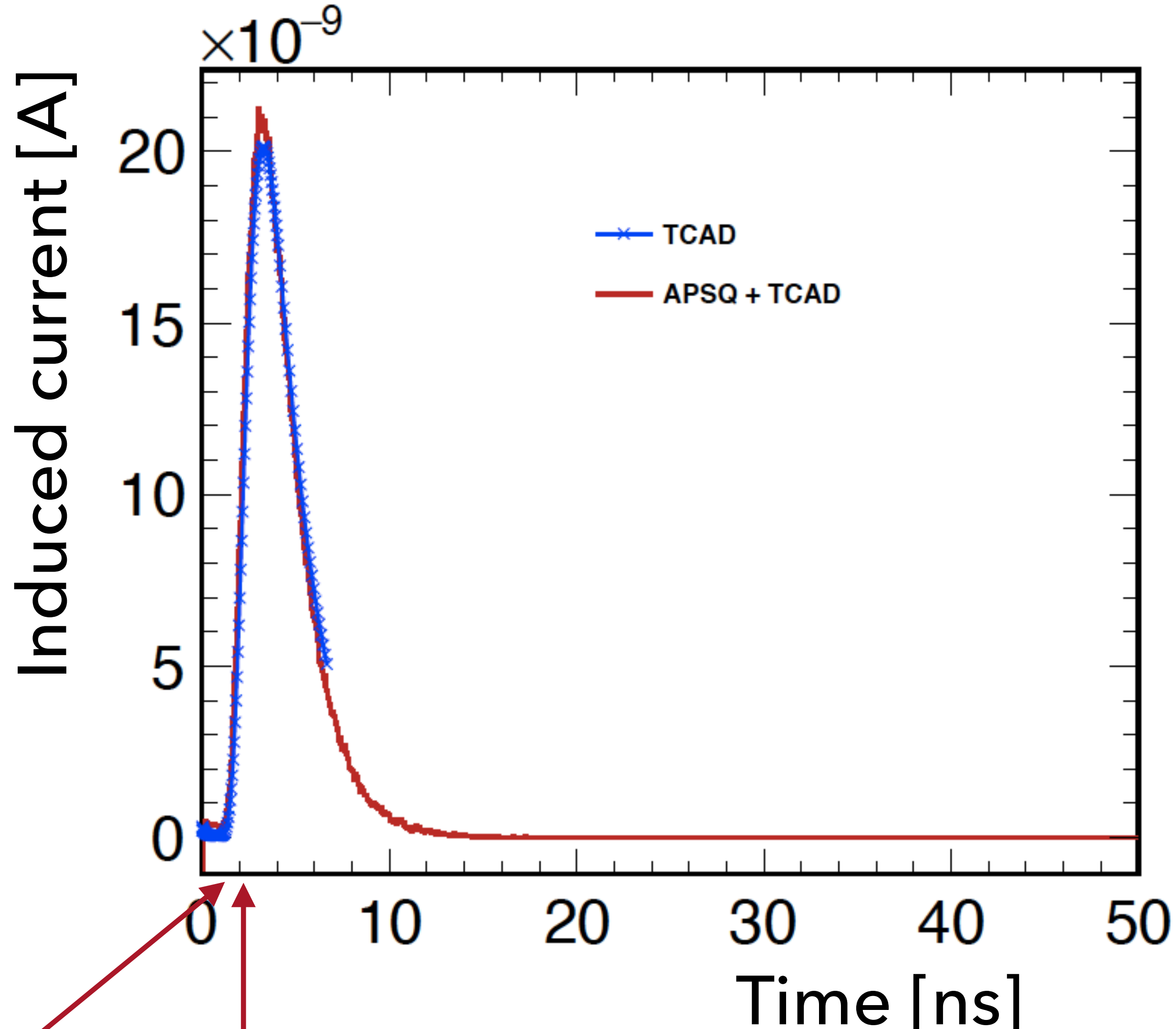
INTEGRATED CHARGE - CONTINUOUS N-LAYER

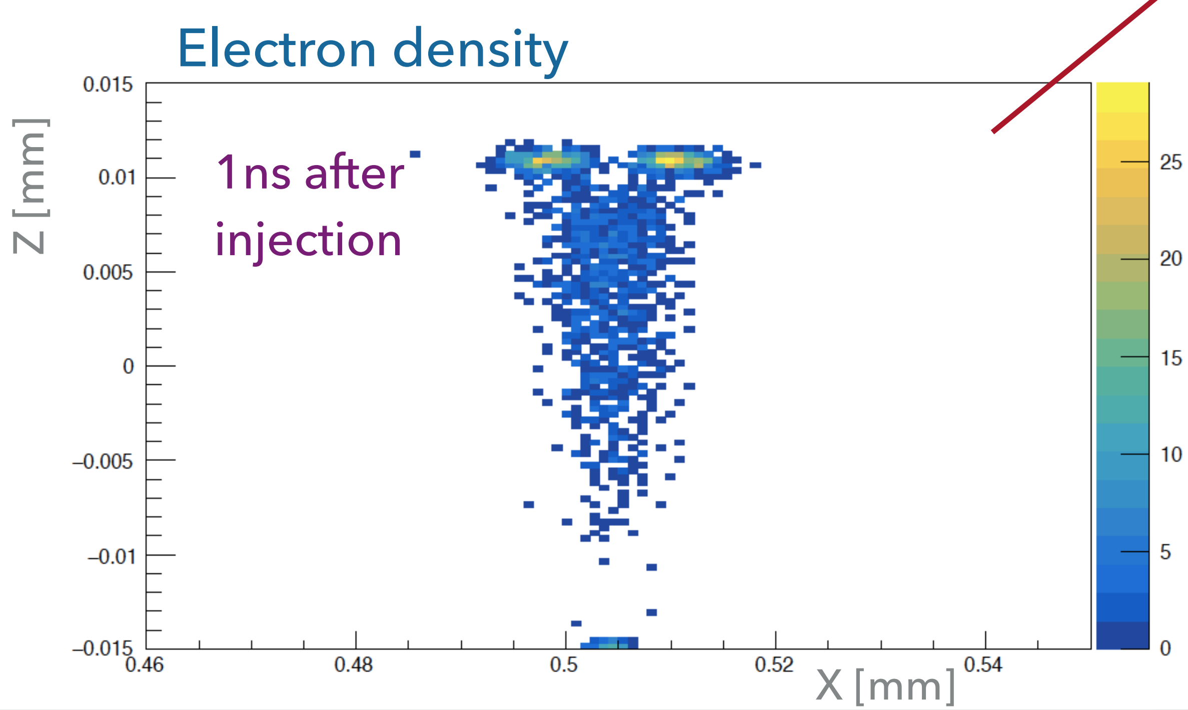


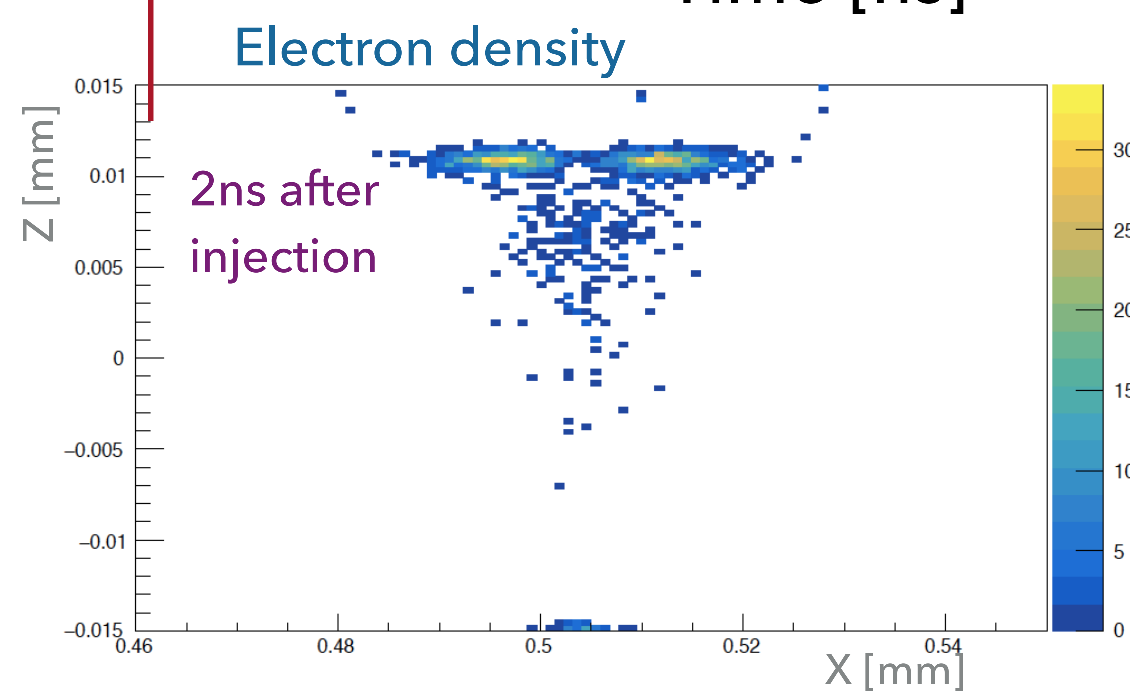
- Deviations (max. ~10 e) arise mainly from current pulse differences in the first couple of ns

VALIDATION - GAP IN N-LAYER

- A finer TCAD mesh was required to get a good agreement between APSQ+TCAD and transient TCAD for the process with gap in the n-layer
- Charge carriers propagate directly to the collection electrodes instead of a field minimum

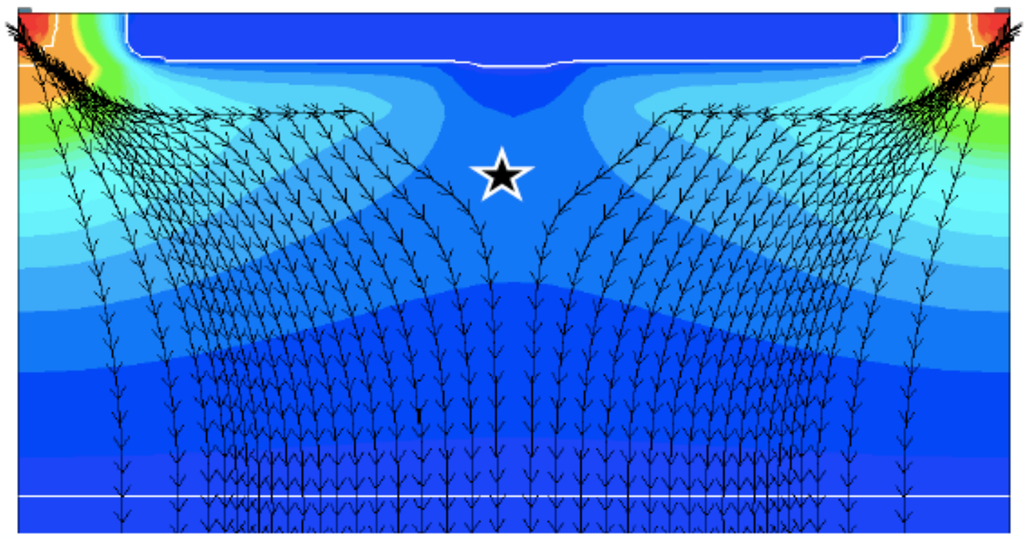






VALIDATION - GAP IN N-LAYER

Electrostatic potential:
Gap in N-type implant



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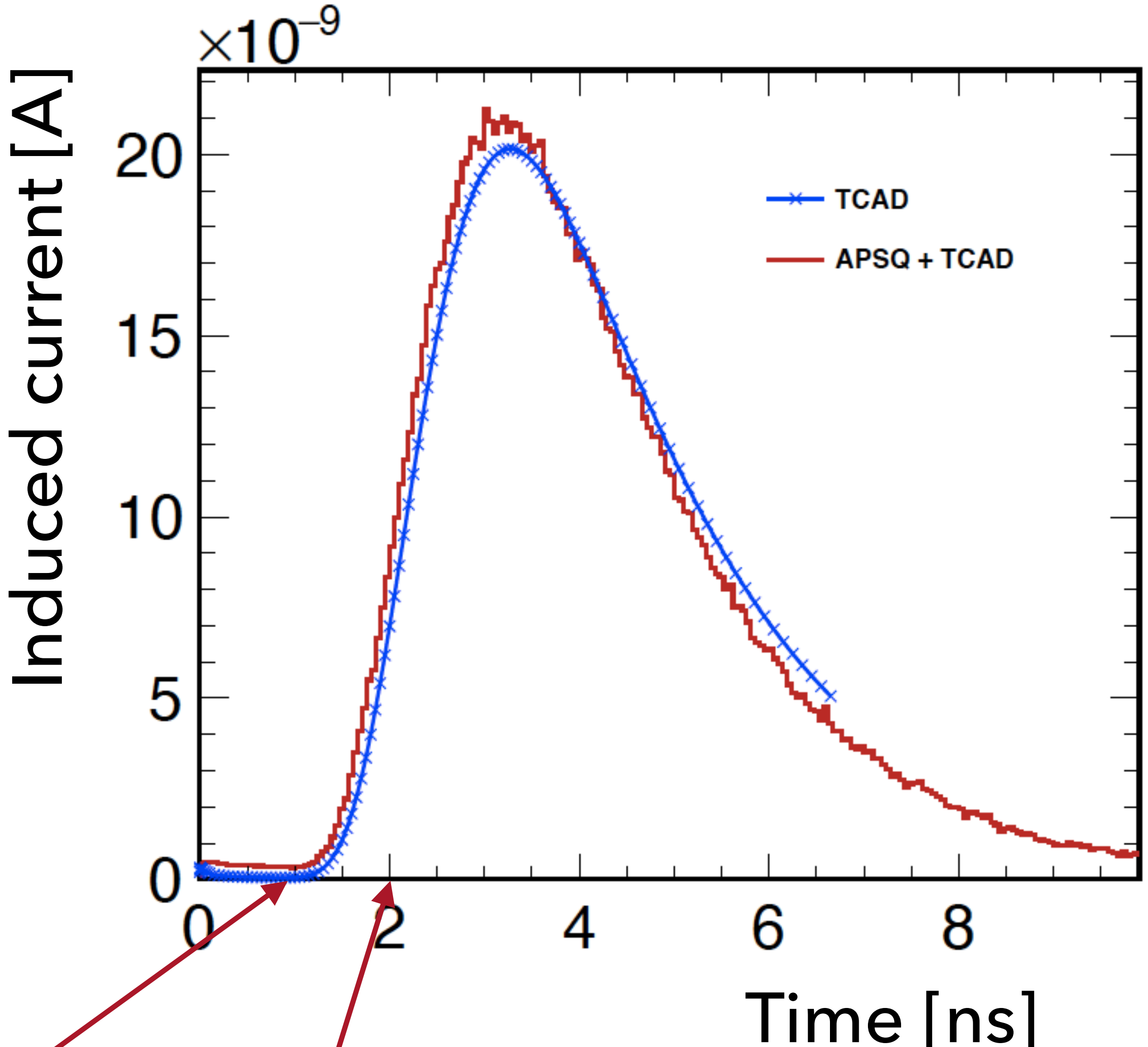
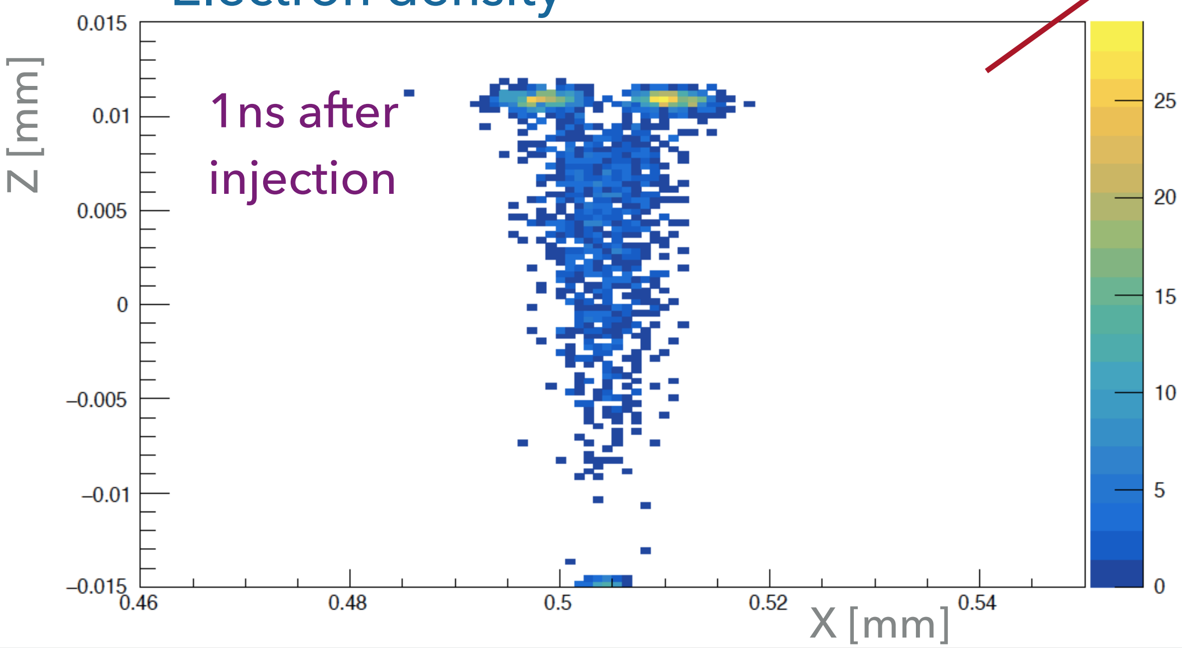
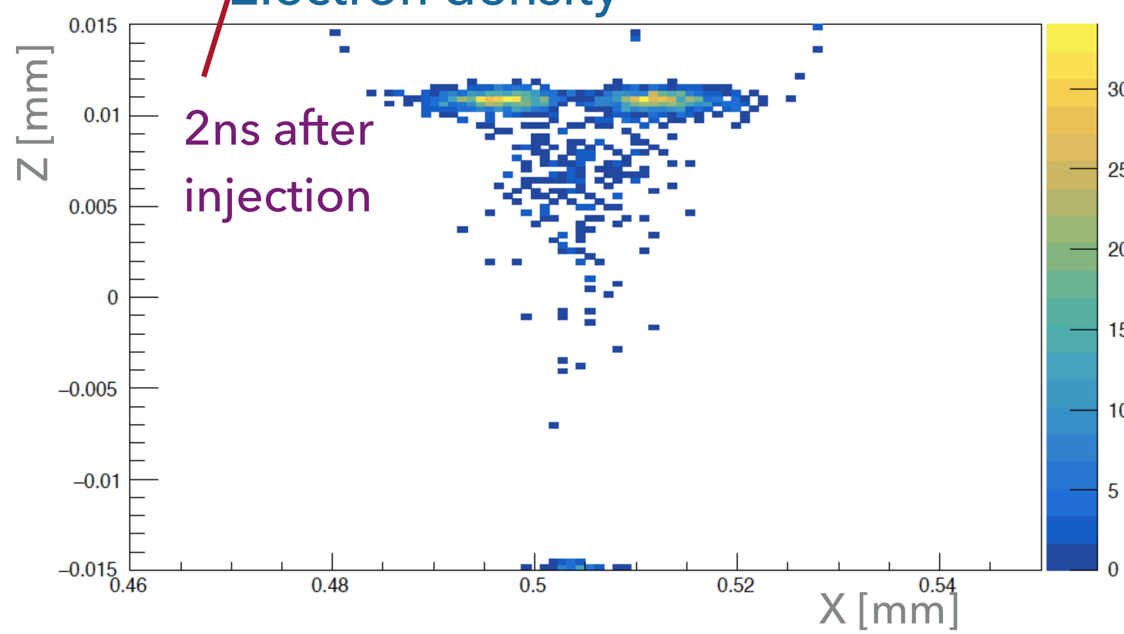
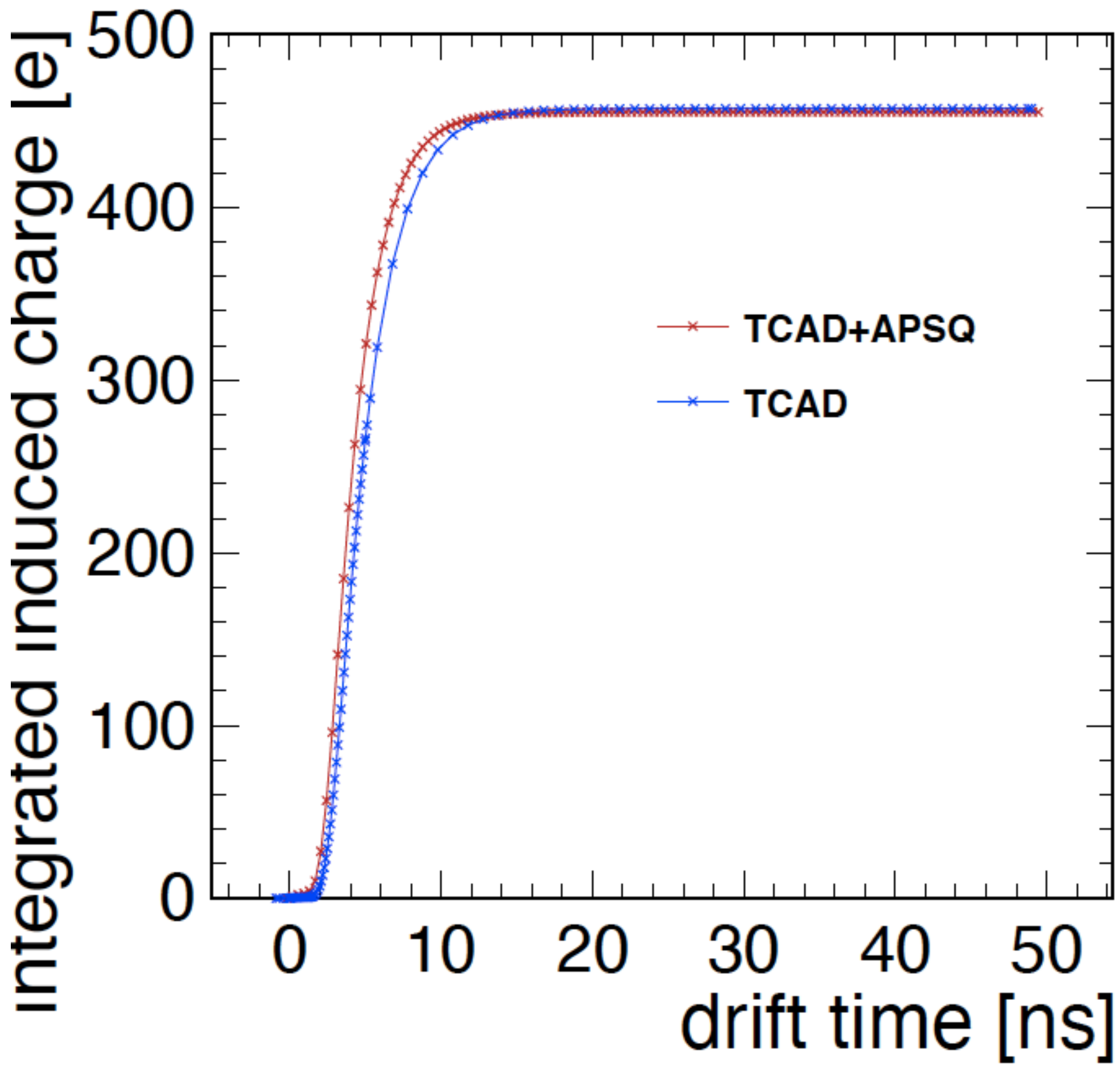






INTEGRATED CHARGE - GAP IN N-LAYER



- Faster convergence to charge saturation value
  - Onset of saturation plateau for continuous n-layer: ~30 ns
  - Onset of saturation plateau for gap in n-layer: ~10 ns

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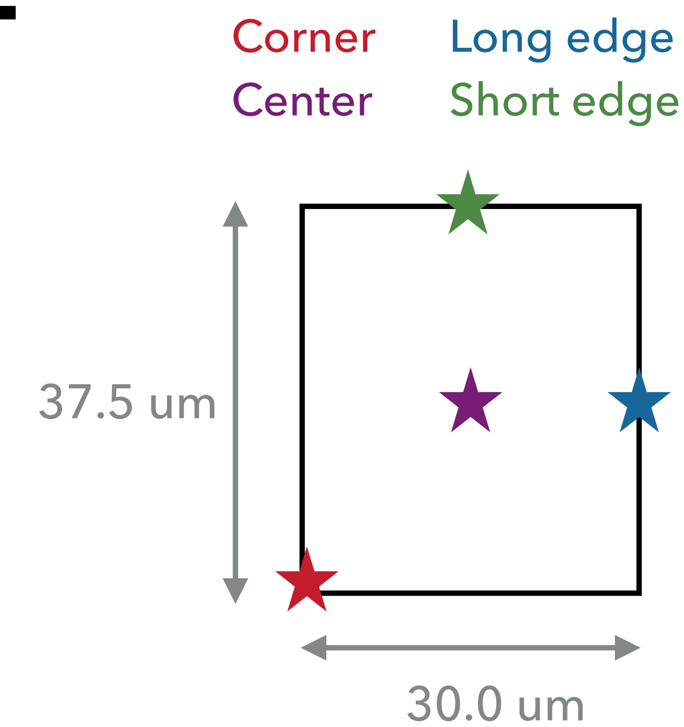
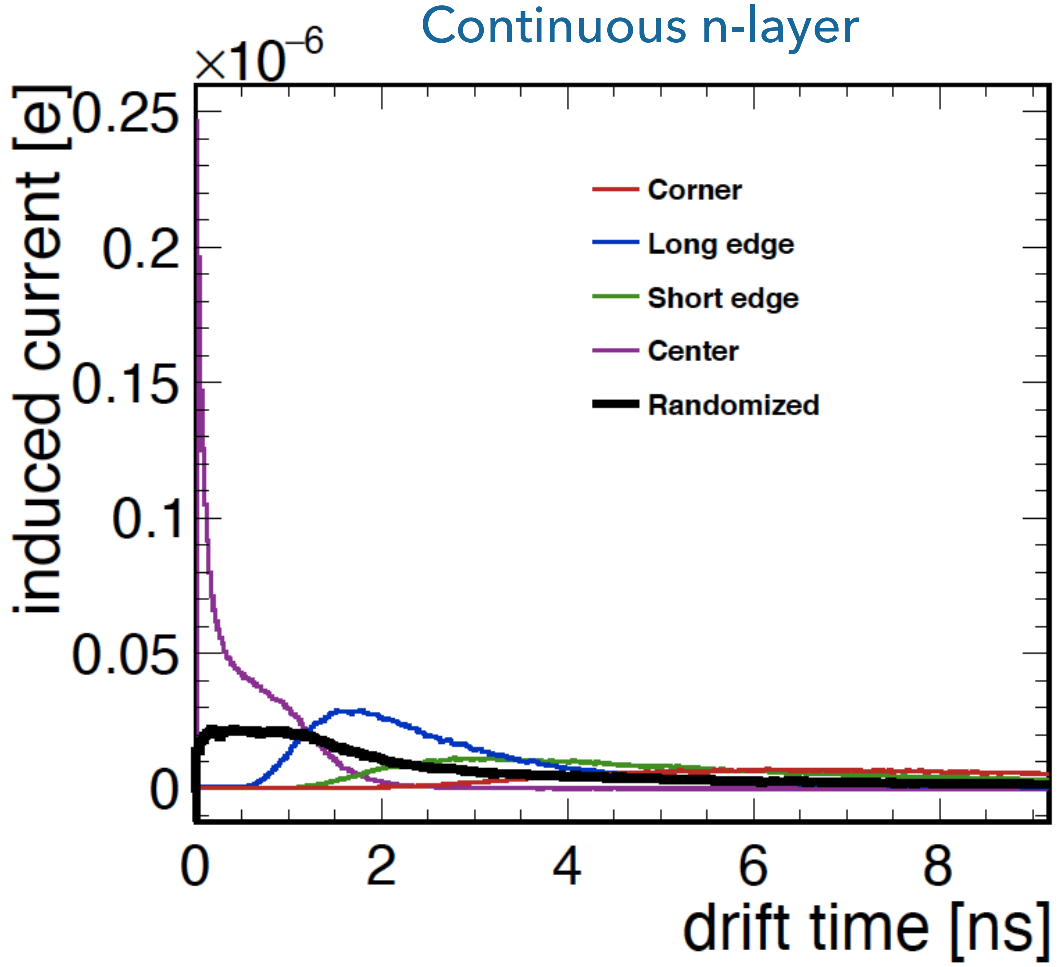
DIFFERENT INJECTION POSITIONS ACROSS PIXEL

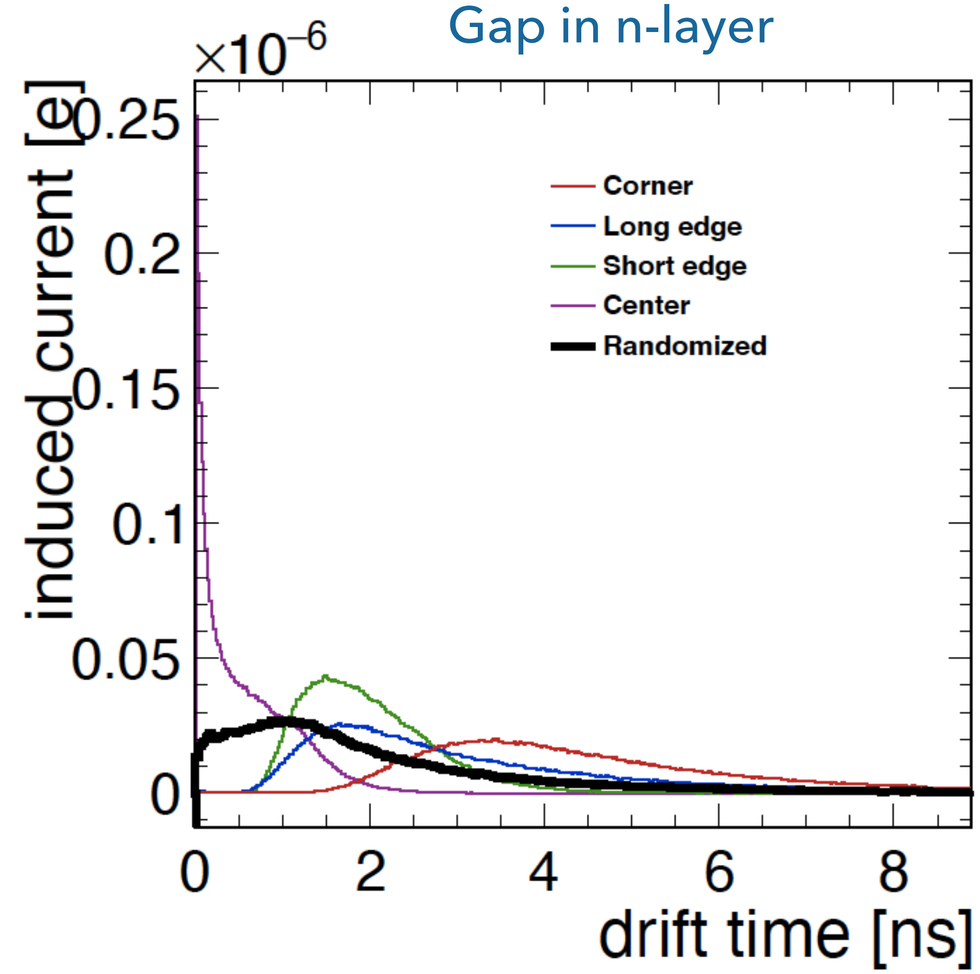
- So far, only the *worst case* (particle impinging on pixel corner) was simulated
- For a more realistic picture: four different injection positions and randomized injection over the entire pixel cell is simulated
- Same amount of charge carriers are injected (no Landau fluctuations) -> could be easily changed once simulations are validated



Continuous n-layer

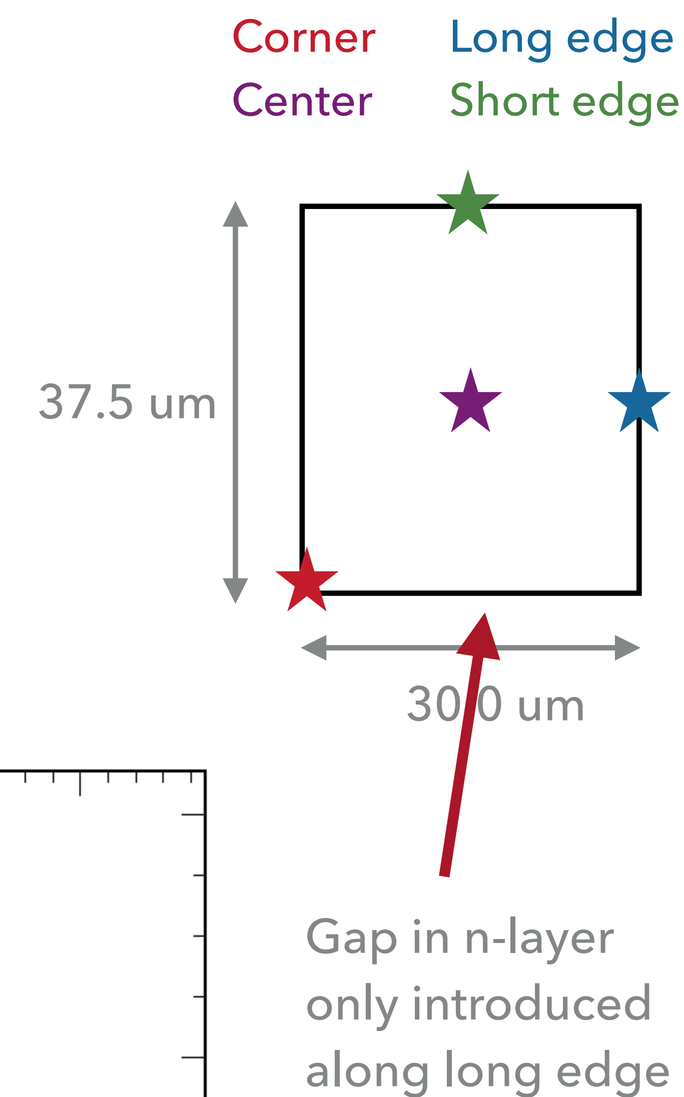


Gap in n-layer

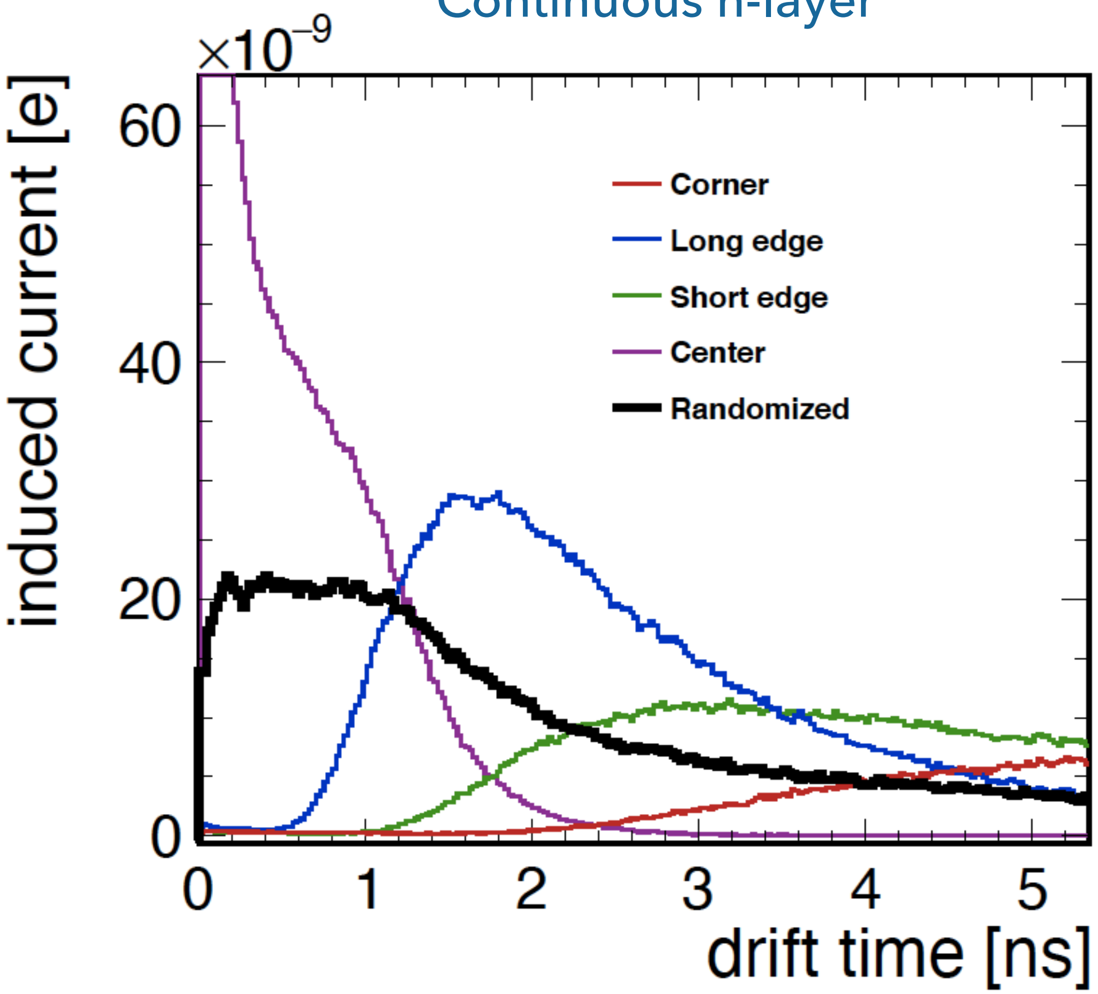


DIFFERENT INJECTION POSITIONS ACROSS PIXEL

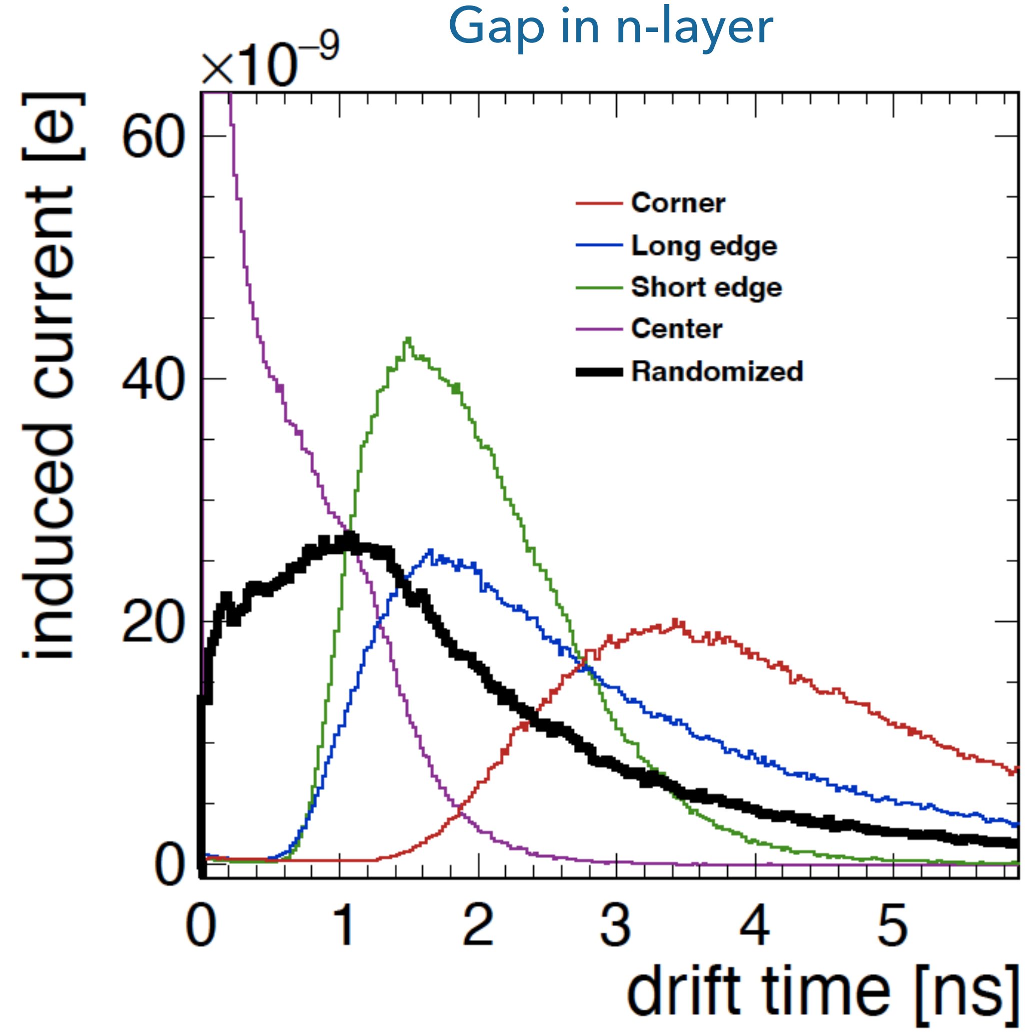
- As expected, gap in n-layer has a strong impact on current pulse for injection in pixel corner and at the short edge
- Effect on randomized injection position visible as well



Continuous n-layer



Gap in n-layer



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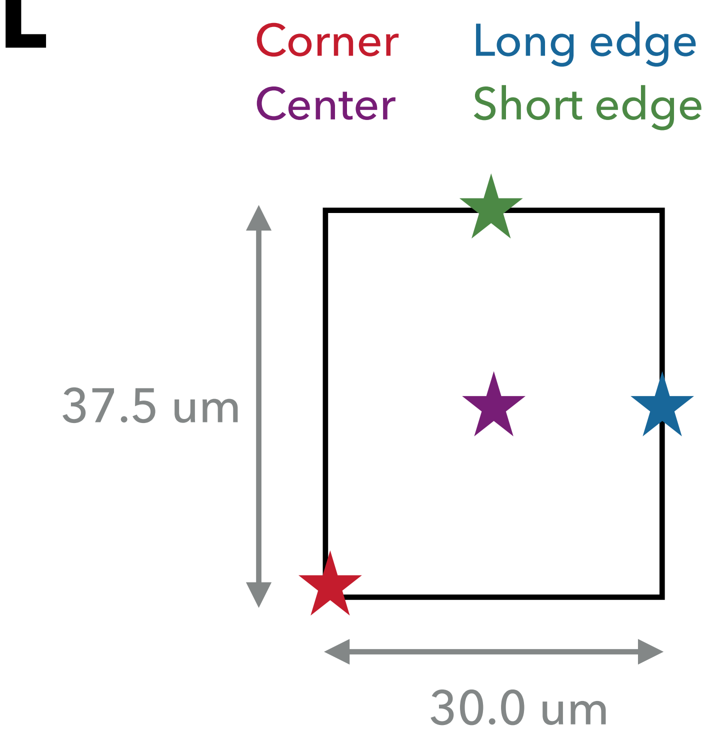
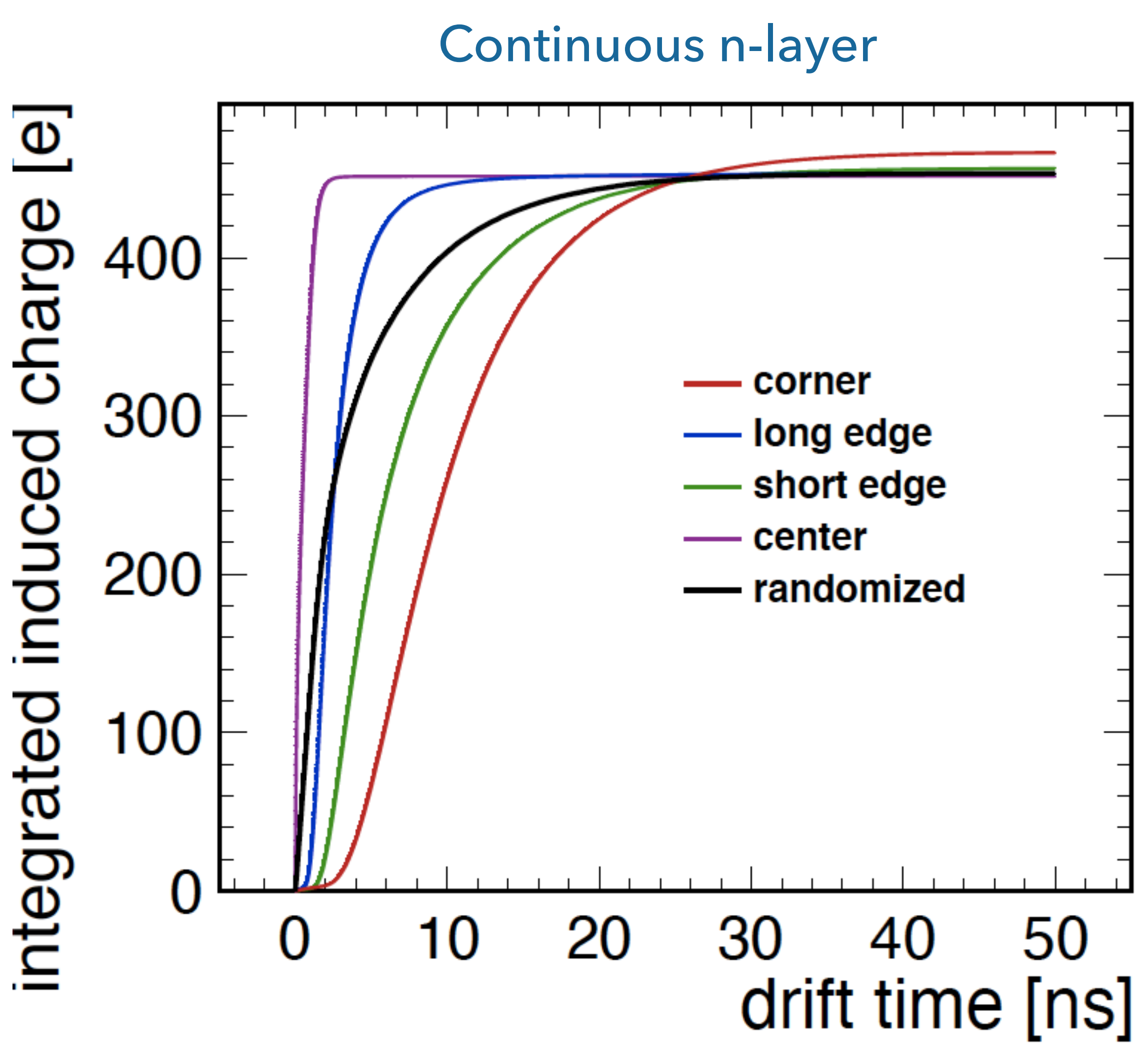
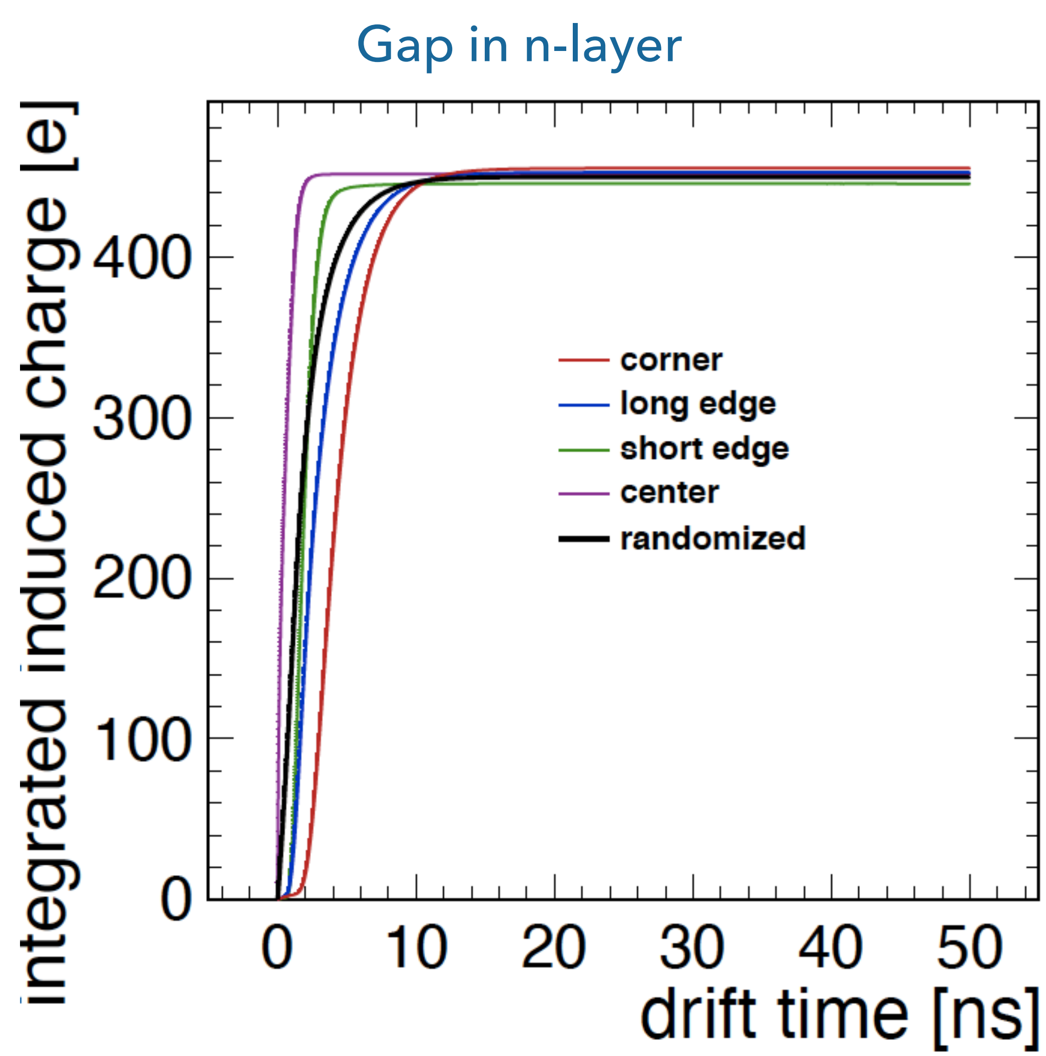
DIFFERENT INJECTION POSITIONS ACROSS PIXEL

- Integrated charge curves have less spread for gap in n-layer

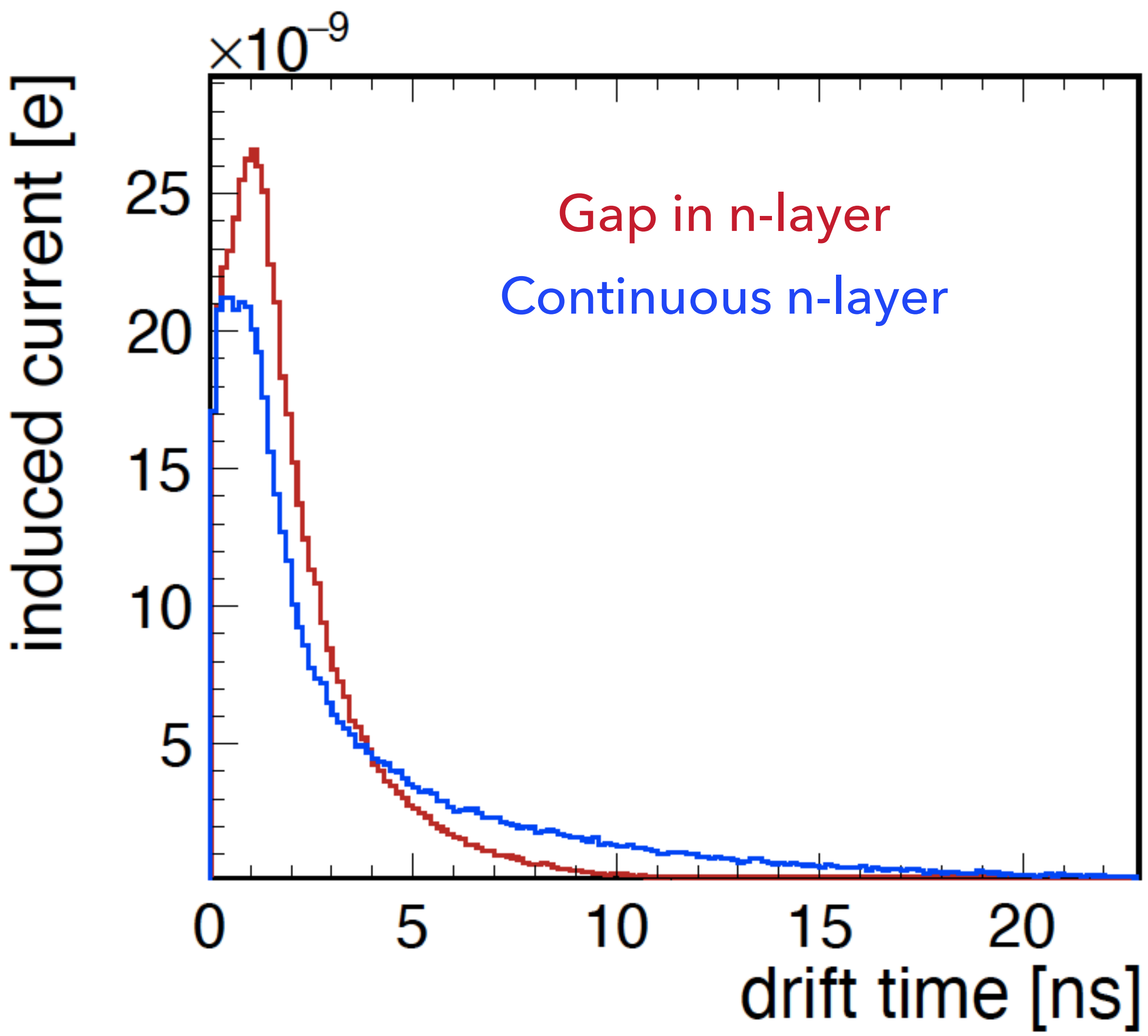
➡ Injection position in pixel has less influence on the timing spread

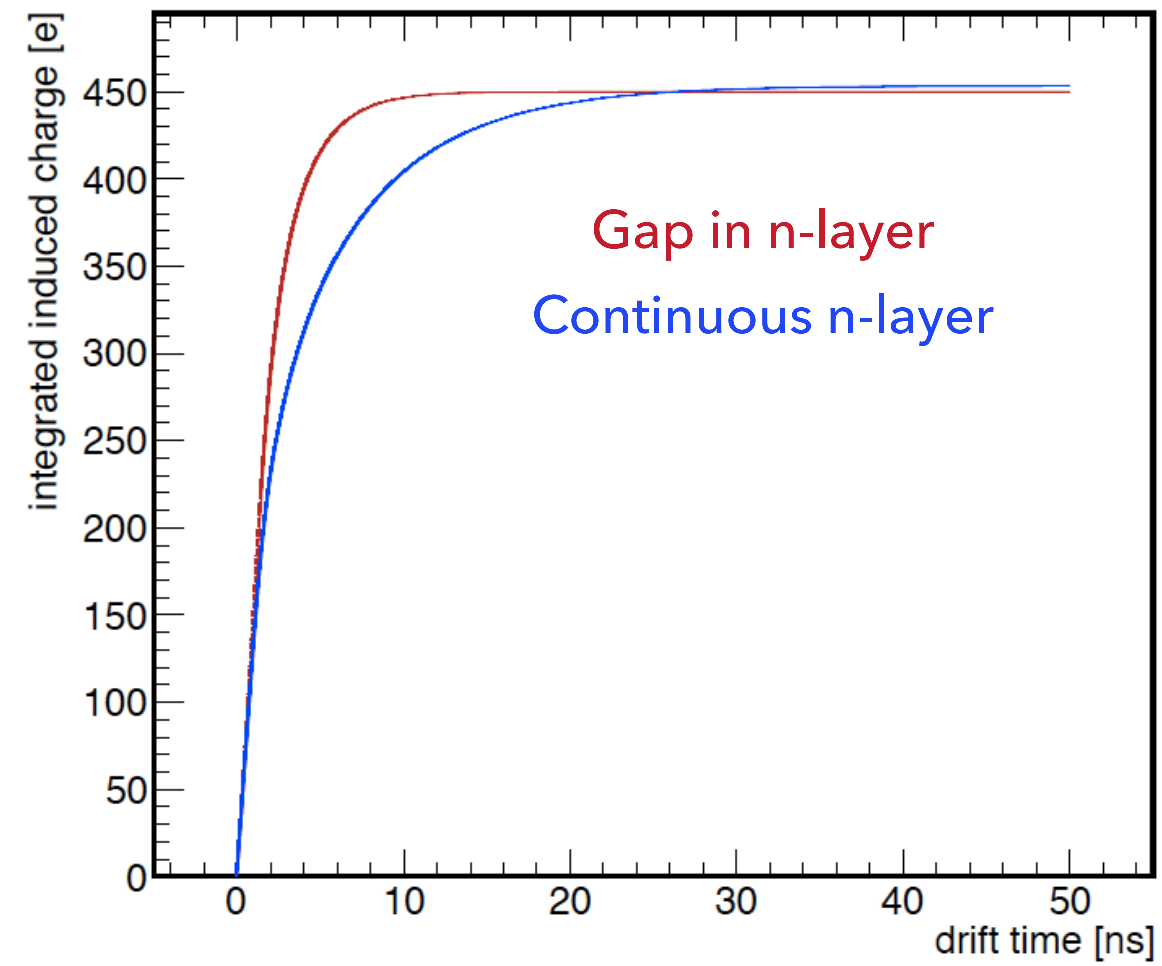






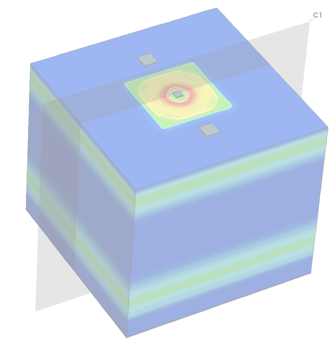
RANDOMISED INJECTION POSITIONS ACROSS PIXEL





- If injection position is randomized timing improvement by introducing the gap is still visible
- In particular, the tail to large time values is reduced

SUMMARY



- Electric field and weighting potential obtained from **electrostatic** TCAD simulations are imported into APSQ
- First transient APSQ+TCAD simulations for CLICTD exhibit good agreement with transient TCAD simulations

- Weighting potential mostly concentrated around the collection electrode
- Faster signal formation for gap in n-layer process also observable when injection position is randomized

OUTLOOK

- Simulation of lower absolute bias voltages
- Estimation of sensor timing performance to compare against test-beam and laboratory results
- Full detector simulation with minimum ionizing particles

Annika Vauth (+ APSQ DESY team) are working on the implementation of a CSADigitizer

- For this, we need a (simplified) simulation of the (CLICTD) front-end
    - Challenging for our case owing to the non-linearities in the read-out which we have seen in the laboratory

Thank you very much!

Special thank you to everybody who contributed to this work

INTRODUCTION: WEIGHTING FIELD

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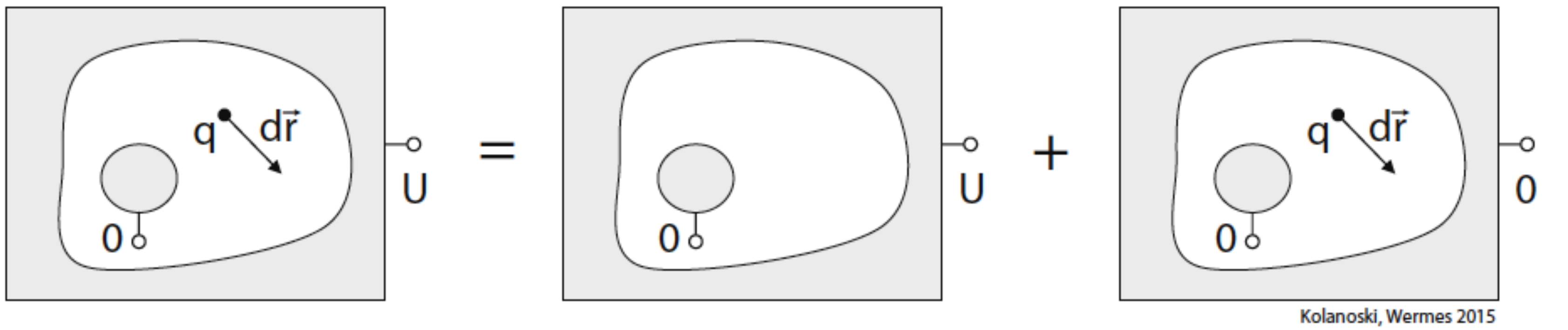
Disclaimer: This slide only motivates the basic concept of a weighting field (and the Ramo-Shockley theorem) in order to follow the talk.



total potential — potential without charge — potential of point charge

$$\phi(\vec{r}) = \phi_0(\vec{r}) + \phi_q(\vec{r})$$

- For static (or low-frequency) electric field, field energy can be separated in the same manner: $W_E = W_{E_0} + W_{E_q}$
- No change in total field energy when charge is moving:

$$0 = dW_E = dW_{E_0} + dW_{E_q} = UdQ + q\vec{E}_0 d\vec{r}$$ (External electric field assumed to be static)

$$\rightarrow dQ = -q\frac{\vec{E}_0}{U}d\vec{r}$$ (work on charge comes from the external electric field)

- By introducing a weighting field and a weighting potential: $\phi_w = \phi_0/U$; $\vec{E}_w = -\vec{\nabla}\phi_w$
- The induced current can be expressed by the propagation of the charge in the weighting field :

$$i_{id} = q\vec{E}_w\vec{v}$$

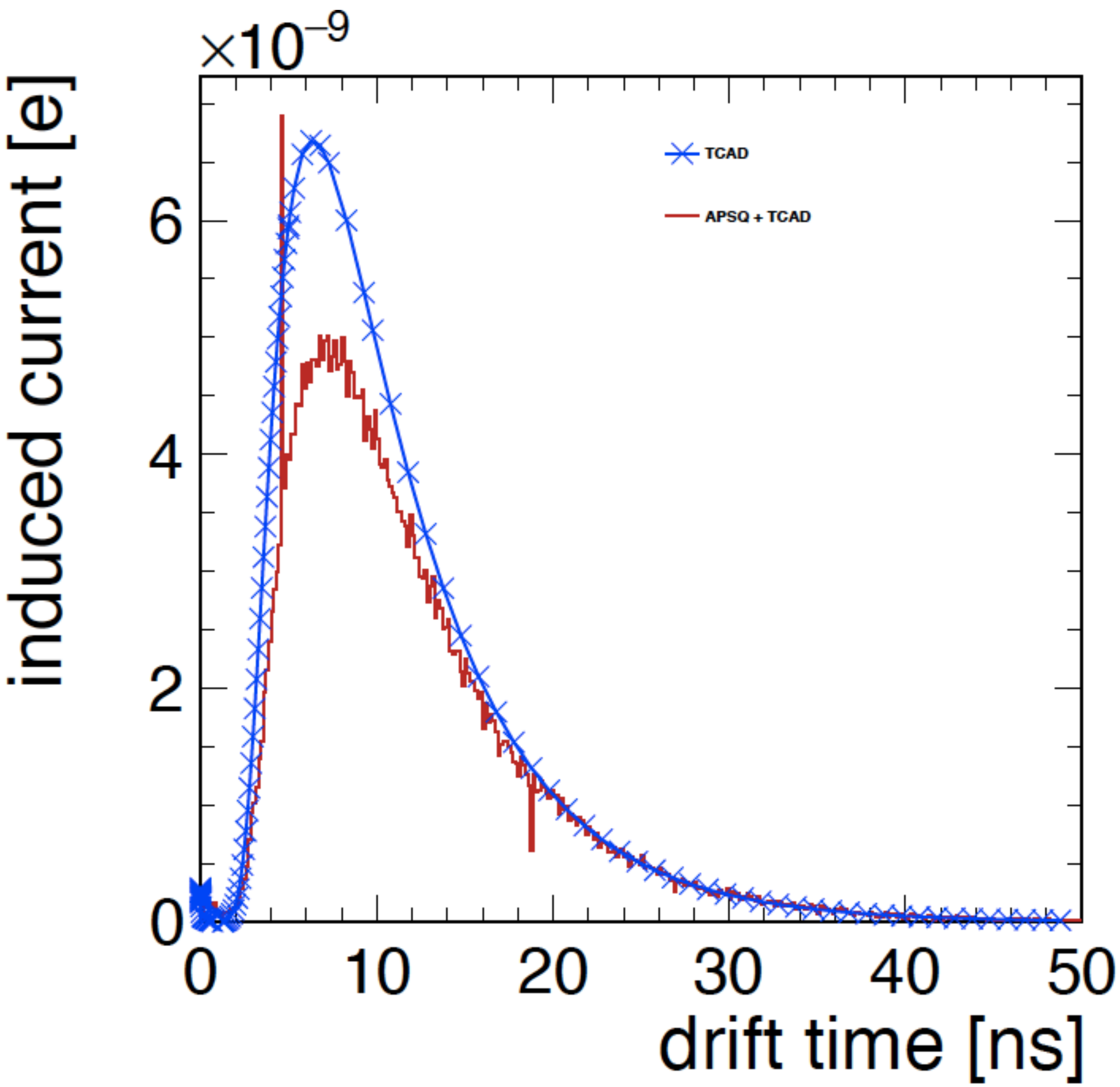
$$Q_{id} = \int_{t_0}^{t_1} = q(\phi(\vec{r}_1) - \phi(\vec{r}_2))$$

See academic training lecture by W. Riegler (https://indico.cern.ch/event/843083/)

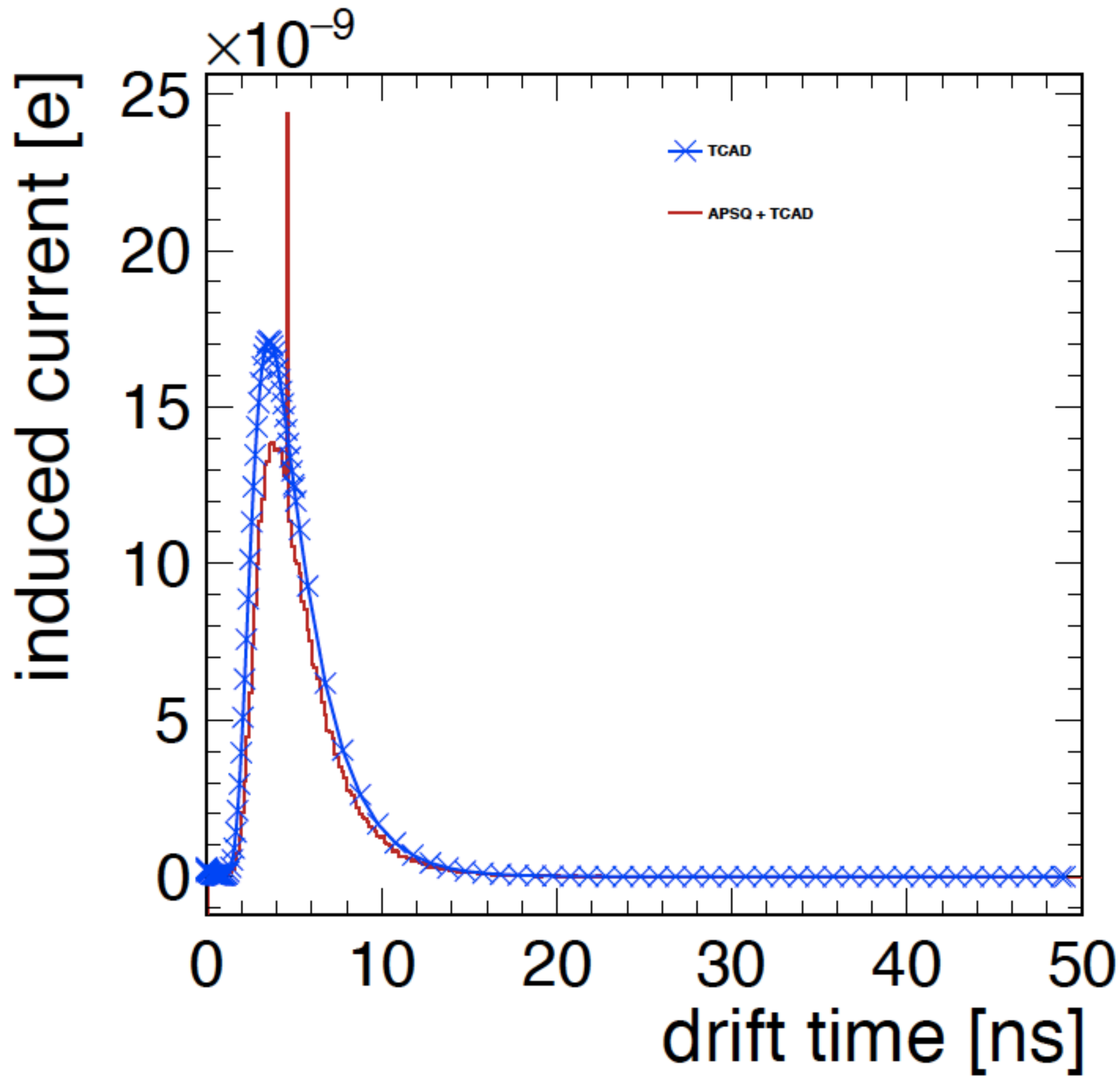
CURRENT PULSE

Step size 0.1 ns

No gap in n-layer



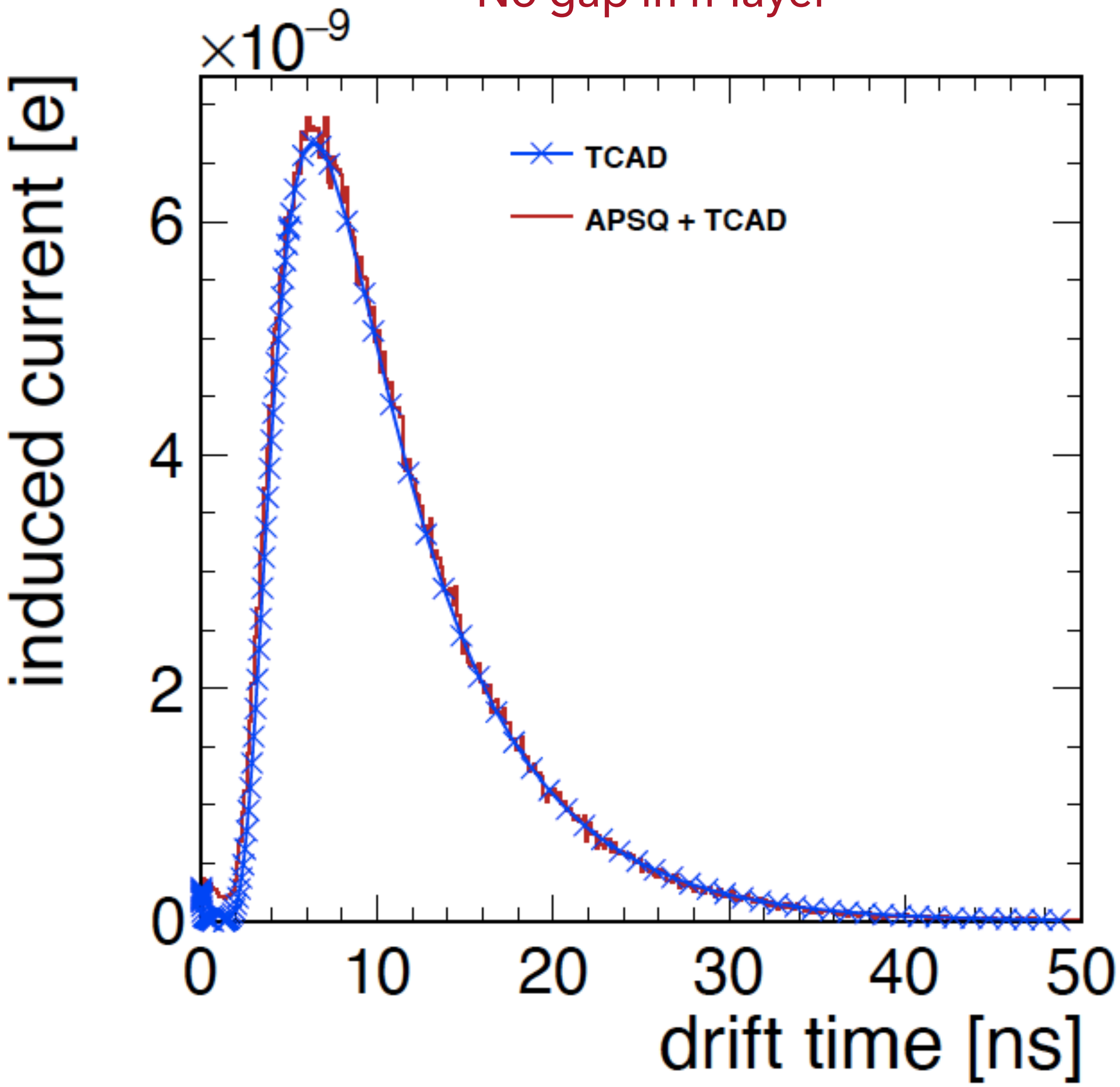
Gap in n-layer



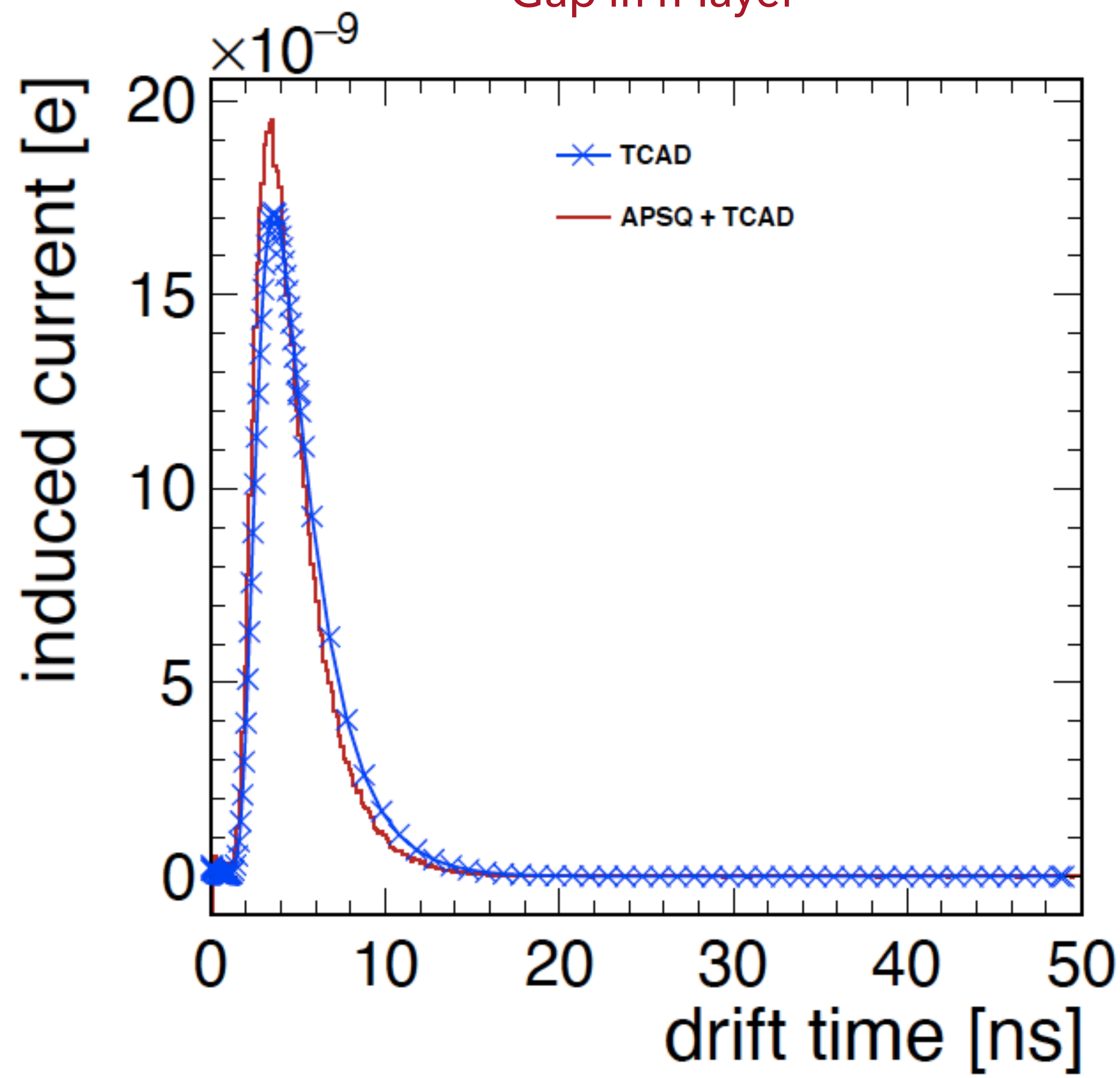
Step size 0.007 ns

CURRENT PULSE

No gap in n-layer



Gap in n-layer



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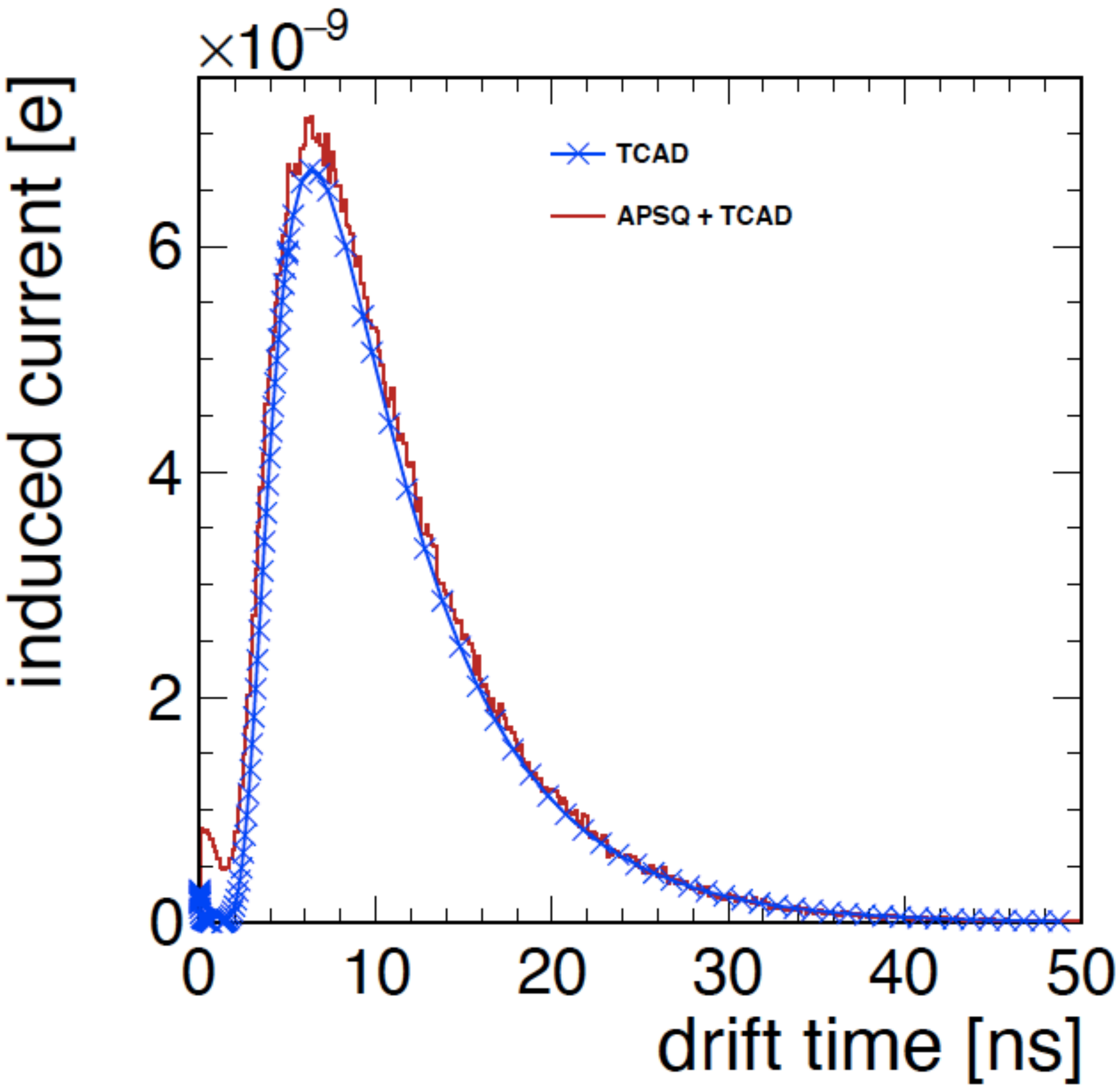
Step size 0.001 ns

CURRENT PULSE

No gap in n-layer



Gap in n-layer