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Simulations of CMOS sensors with a small collection electrode, improved for a faster charge-collection and increased radiation tolerance

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Outline:

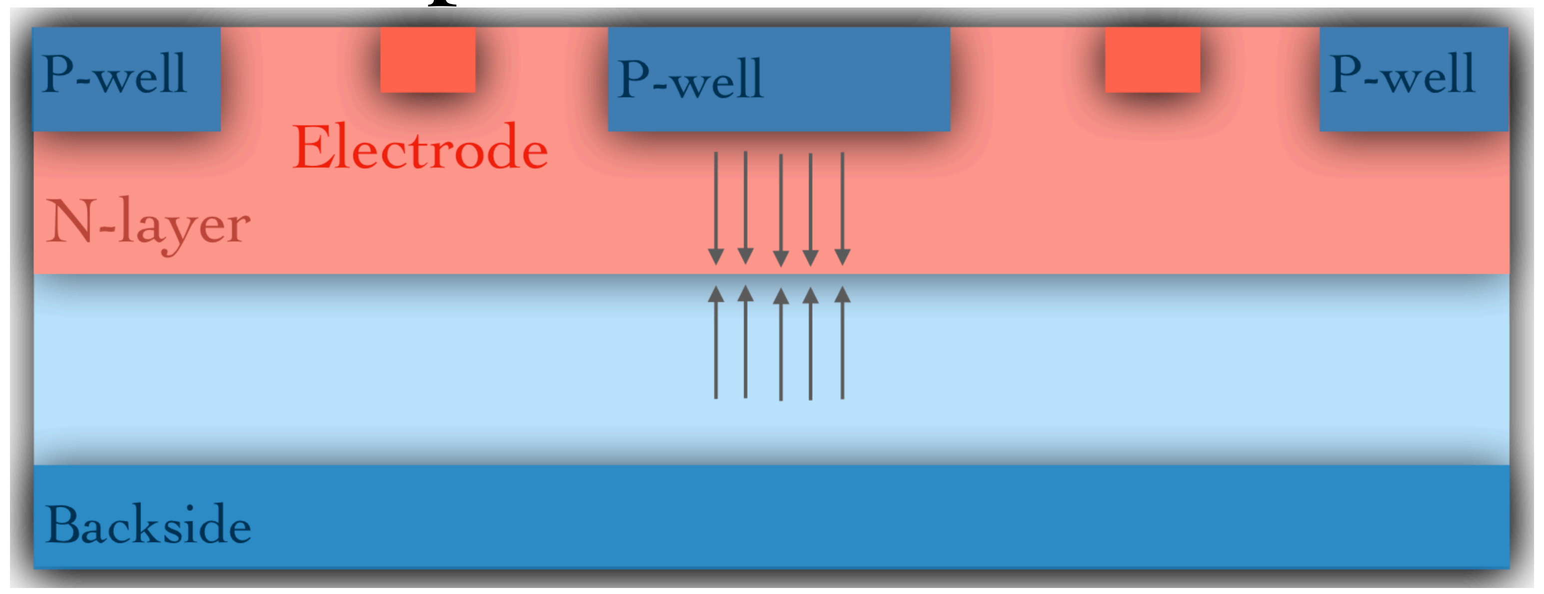
- Introduction
- 3D TCAD simulations of different sensor layouts
- 3D TCAD simulations for higher backside voltage
- Future prospects - smaller pixel sizes
- Summary

Investigated technology & motivation

Investigated technology:

- Monolithic 180 nm CMOS imaging process
- Small collection electrode design
- Implemented on high resistivity epitaxial layer
- Developed for ALICE ITS upgrade [1]:
  - Standard process (no N-layer)
  - Modified process with N-layer as a side-development

Modified process:



- N-layer to achieve full lateral depletion
- Studied for ATLAS ITk upgrade [2],[3]
- Investigated for CLIC [4]

Motivation - why do we want a faster charge collection in this process?:

Crucial to achieve a fast charge collection to benefit from the small sensor capacitance and large S/N

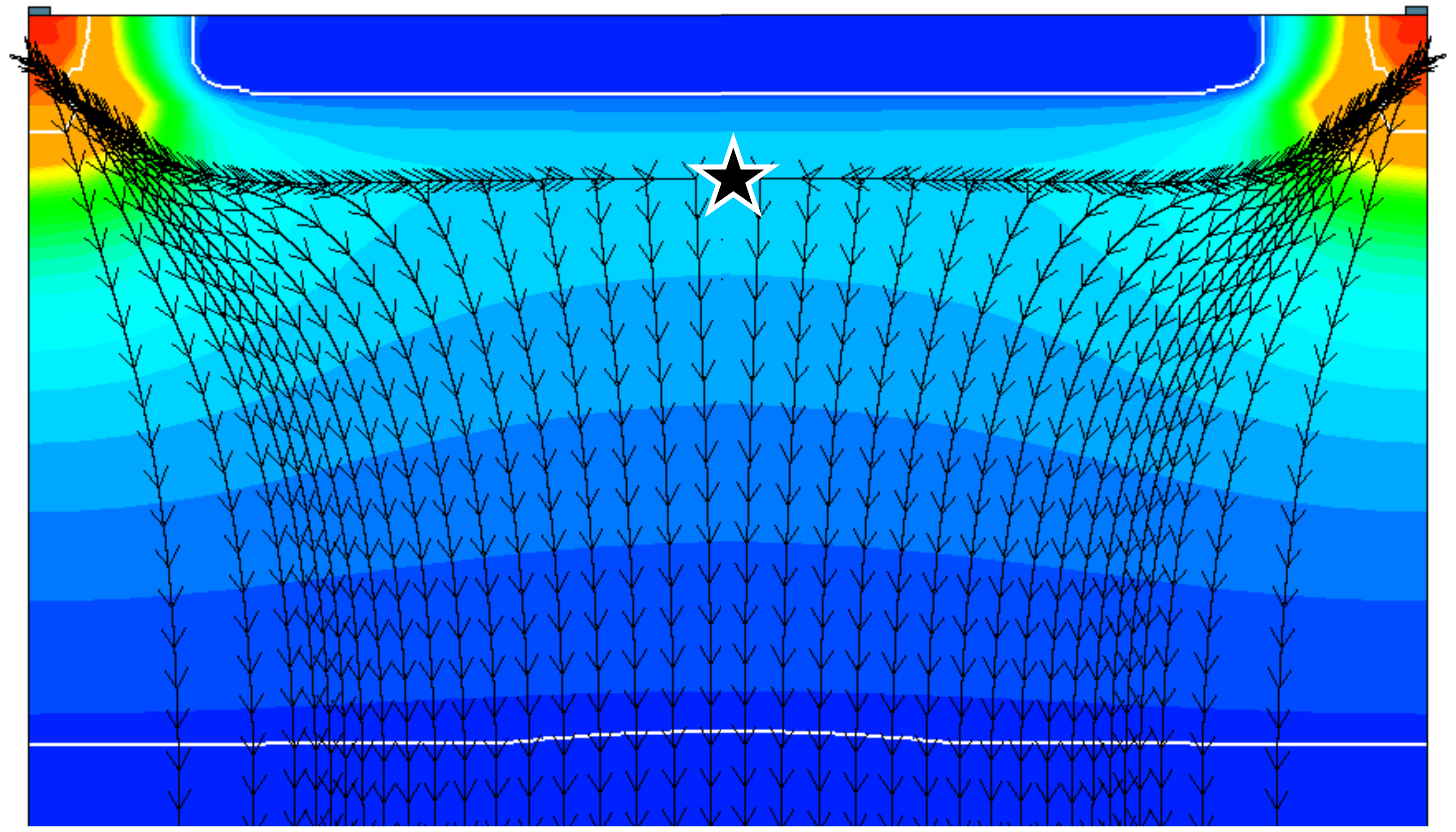
- Radiation tolerance for pixels > 30 μm [2],[3]
- Time stamping in the order of a few nanoseconds for given pixel size [4]

- Future perspectives - small pixel sizes:
  Is it possible to combine all advantages of the small collection electrode design (low material budget, low sensor capacitance, low analogue power, low threshold) with sub-nanosecond timing precision and radiation tolerance?

[1] talk by Dimitra Andreou, [2] talk by Roberto Cardella, [3] talk by Ivan Dario Caicedo Sierra, [4] talk by Mathieu Benoit

Critical sensor regions - the pixel borders

TCAD simulation - electrostatic potential minimum at pixel border:

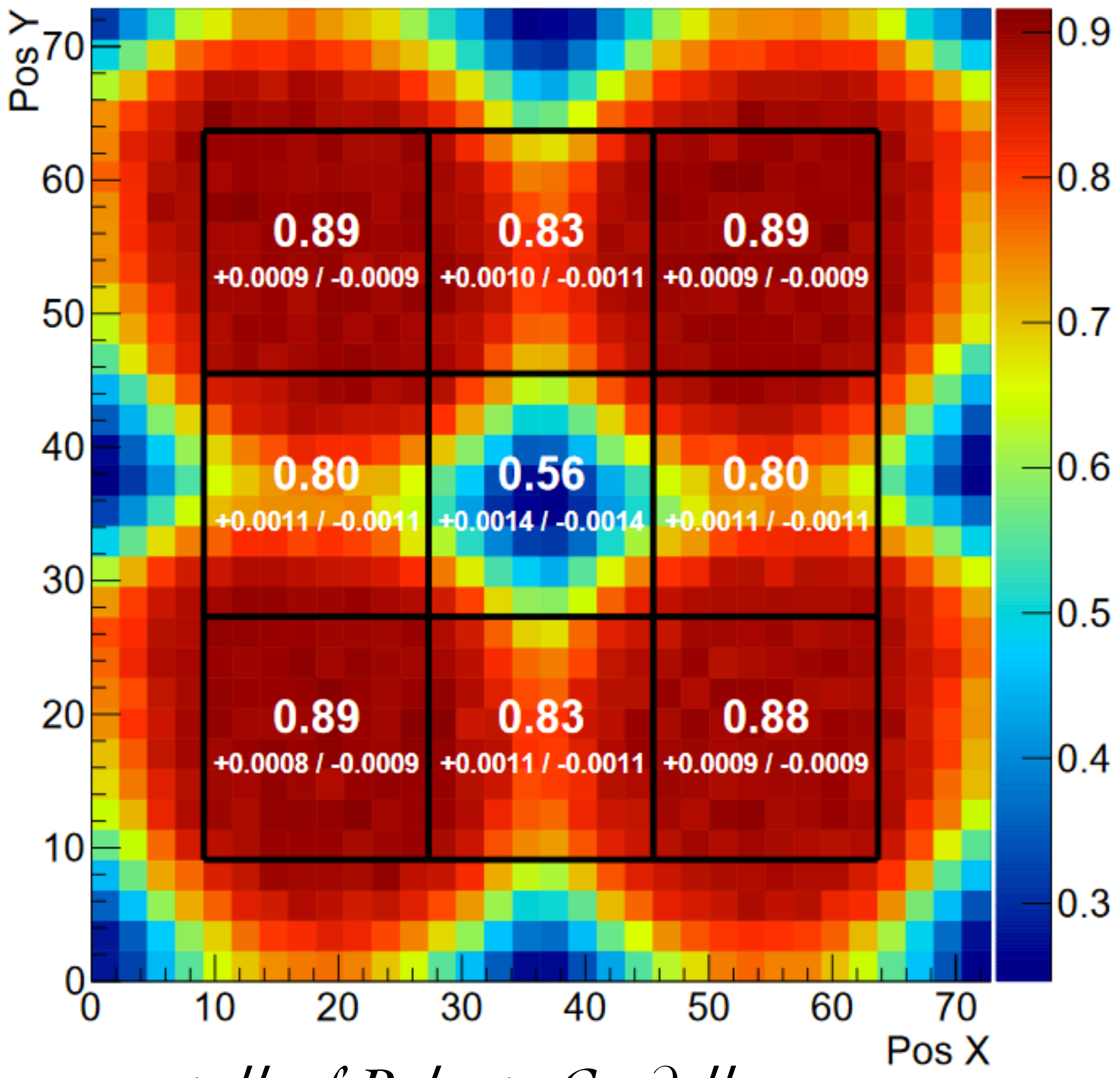


Electric field minimum (★)

—> Long drift path

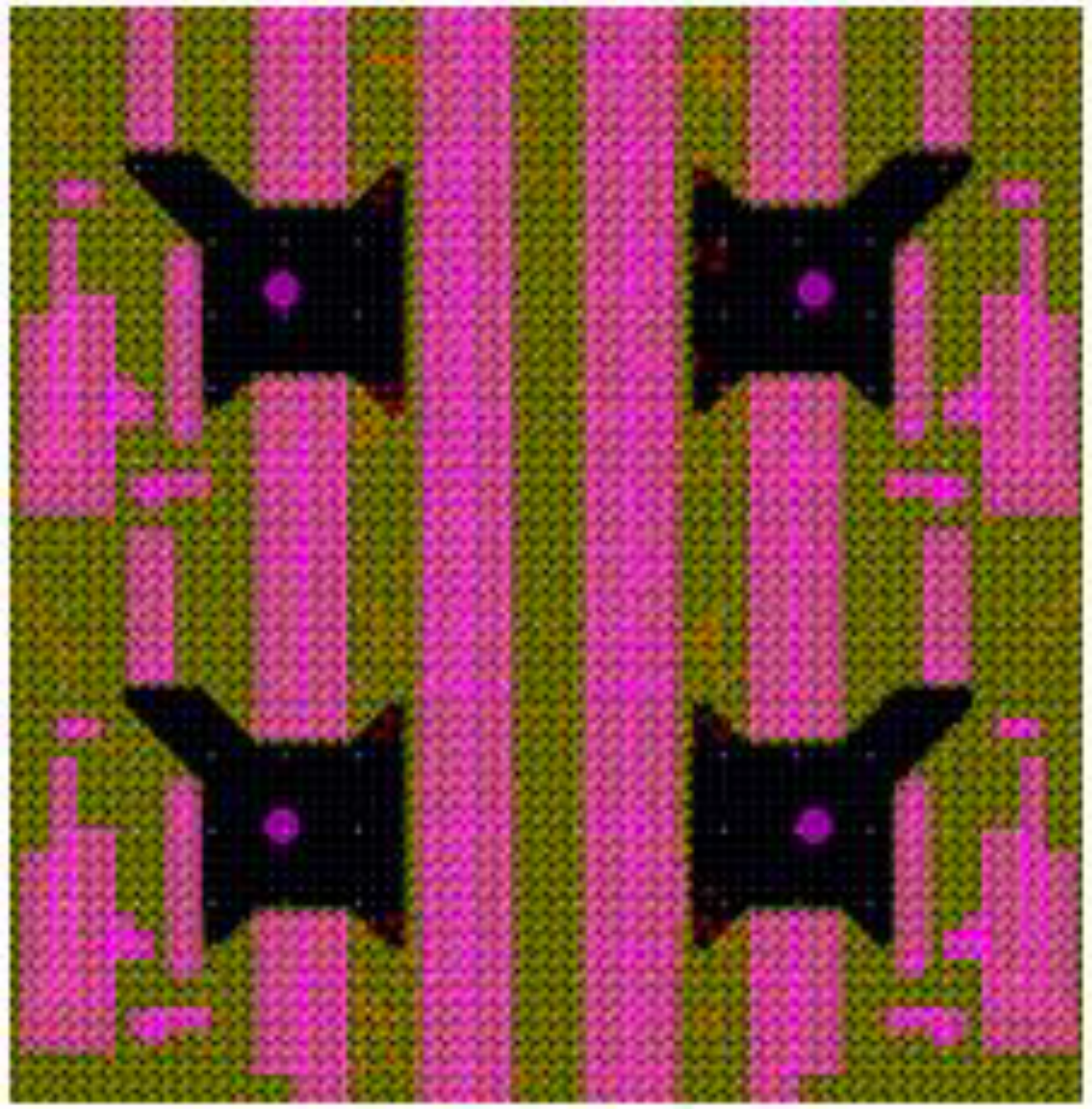
—> Efficiency loss after irradiation

MALTA in-pixel efficiency after irradiation:



see talk of Roberto Cardella

MALTA deep p-well layout:

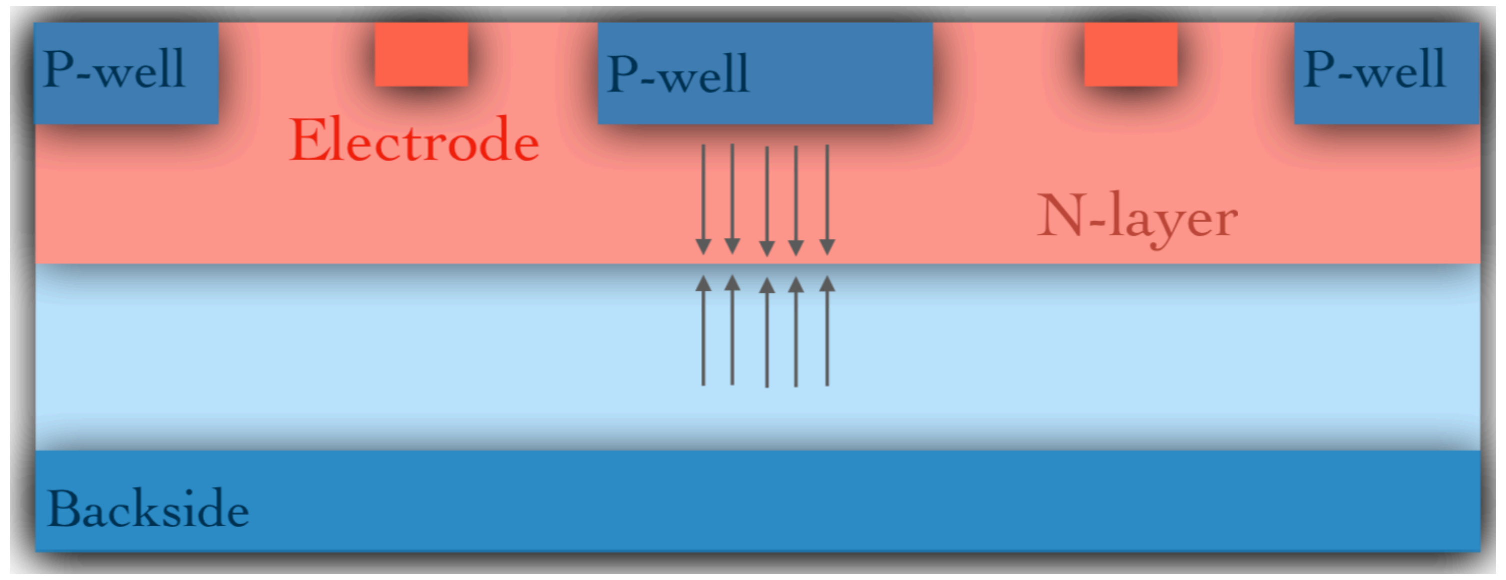


Higher efficiency in regions with less deep p-well coverage due to larger potential difference w.r.t. collection electrode

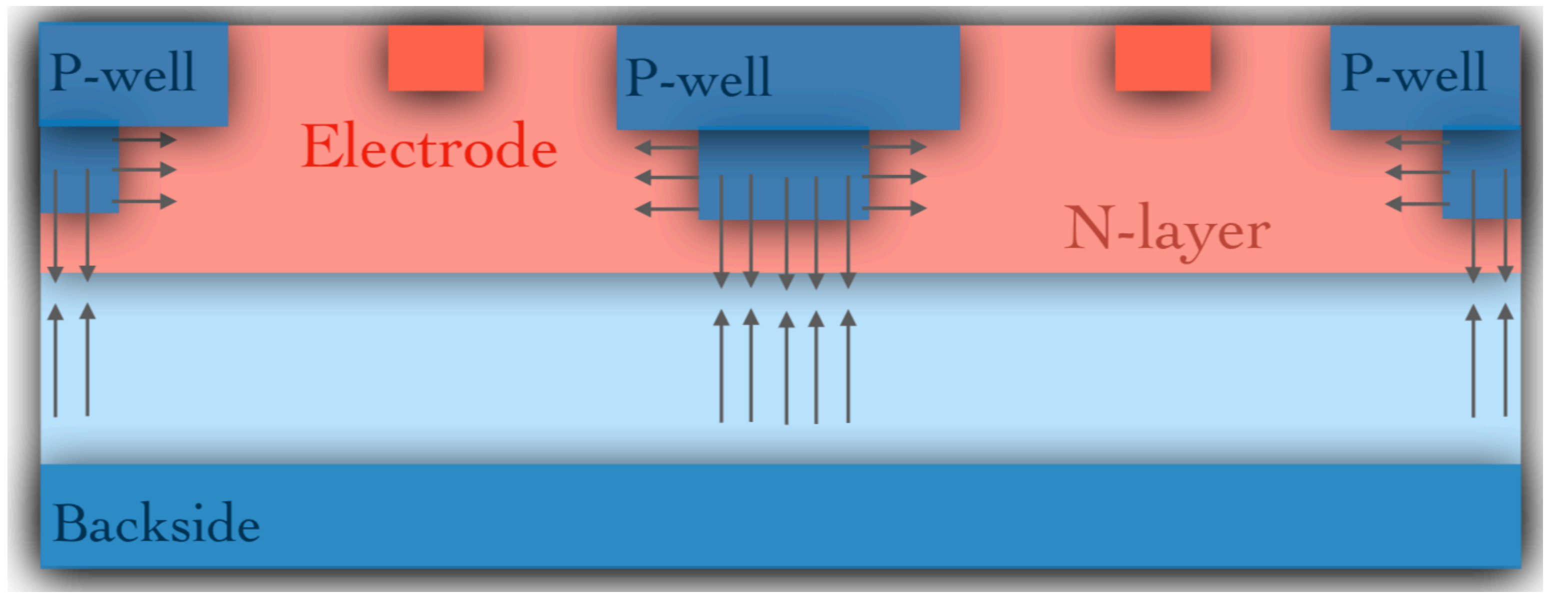
—> Use this for modifications of sensor layout

New concepts to achieve a faster charge collection

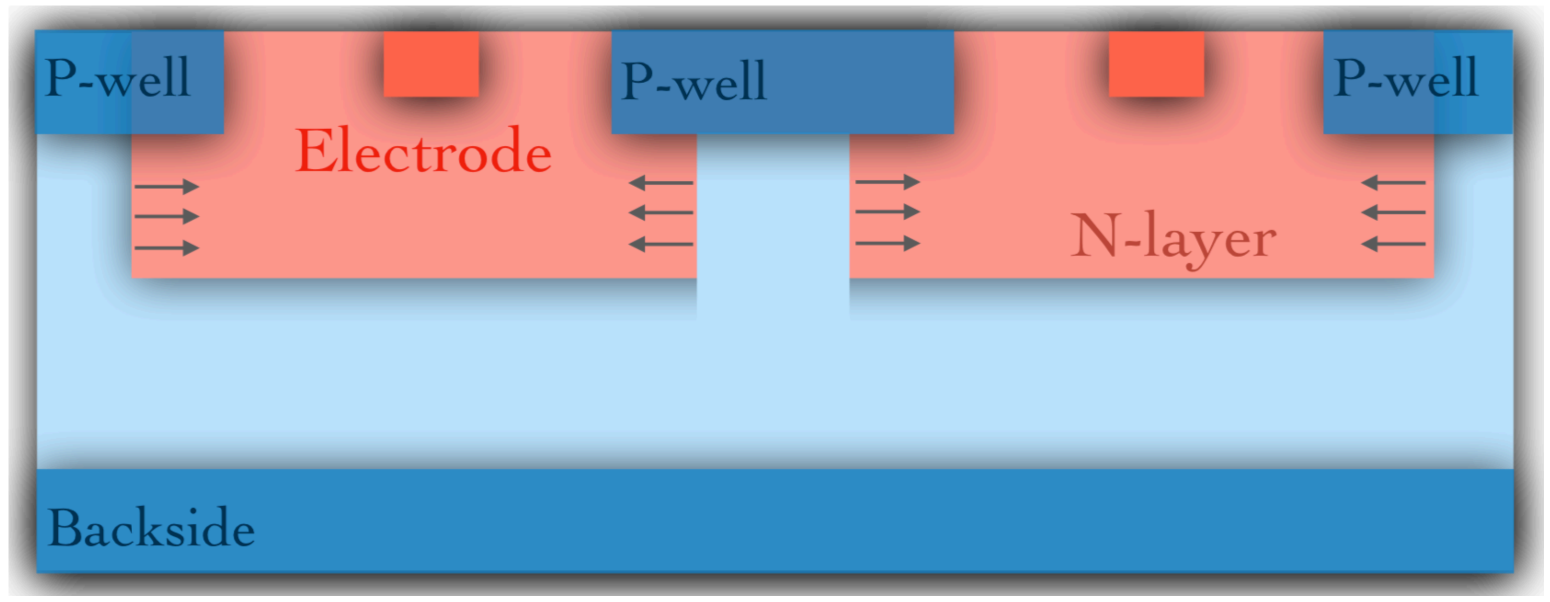
Modified process:



Modified process with additional p-implant:



Modified process with gap in n-layer:



A similar concept is being developed for image sensors for visible light:
'The Theoretical Highest Frame Rate of Silicon Image Sensors'
Goji Etoh et al., doi: https://doi.org/10.3390/s17030483

<u>Modified process:</u>

—> Electric field minimum at pixel corners

—> Charges are pushed into the minimum before they propagate to collection electrode

—> Longer drift path

<u>Additional p-implant and gap in n-layer:</u>

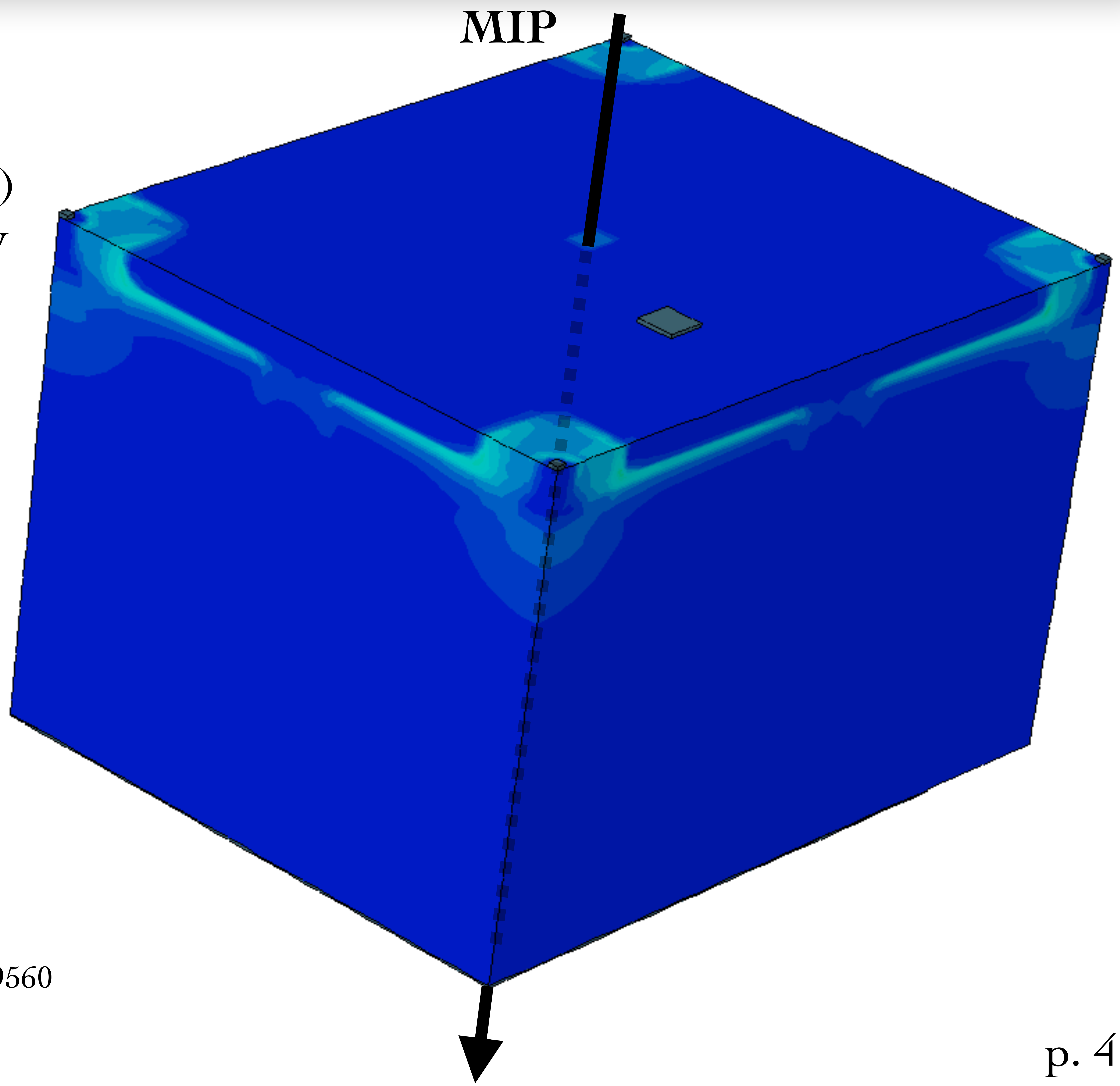
—> Bend the field lines towards the collection electrode

—> Shorter drift path

—> Increase the charge collection speed especially in the critical region of the pixel borders

3D TCAD simulation setup

- Simulated sensor:
  - Use simulated profiles
  - Pixel size of 36.4 µm^2, epi thickness of 25 µm (MALTA)
  - Voltage on p-wells of - 6 V, voltage on backside of - 6 V (if not mentioned otherwise)
  - Voltage on collection electrode of 0.8 V
  - Simulation performed at - 20 °C
- Study of worst case scenario —> pixel corner:
  - Largest distance to electrodes
  - Simulation of pixel unit cell centred around pixel corner
  - Simulation of particle incident at pixel corner
- Radiation damage model:
  - Taken from: IEEE Trans.Nucl.Sci. 63 (2016) 2716-2723, DOI: 10.1109/TNS.2016.2599560
  - Simulation of irradiation dose of 10^{15} neq/cm^2

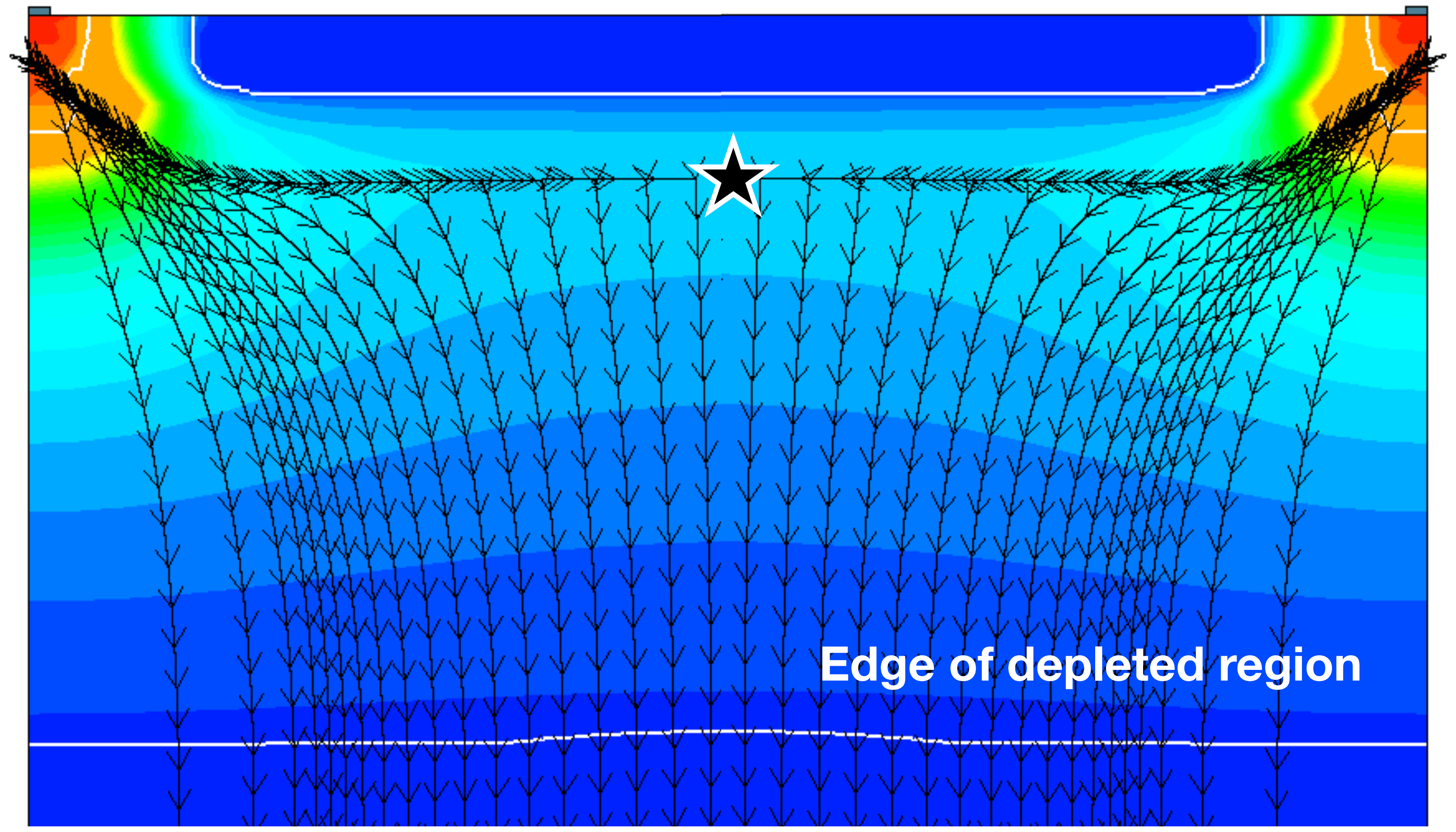


3D TCAD simulations of different sensor layouts

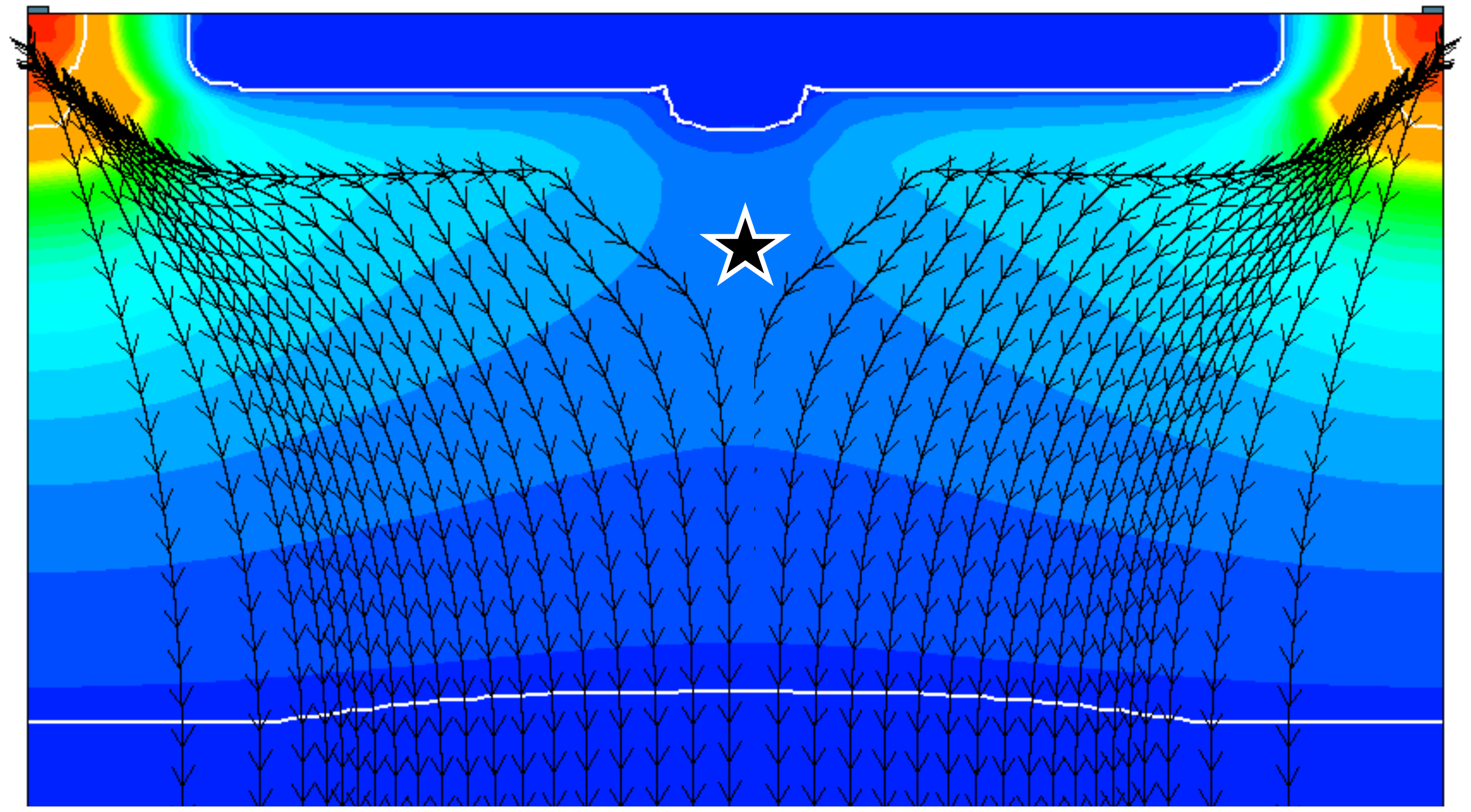
Do these proposed concepts improve timing and radiation tolerance?

Electrostatic potential and drift path

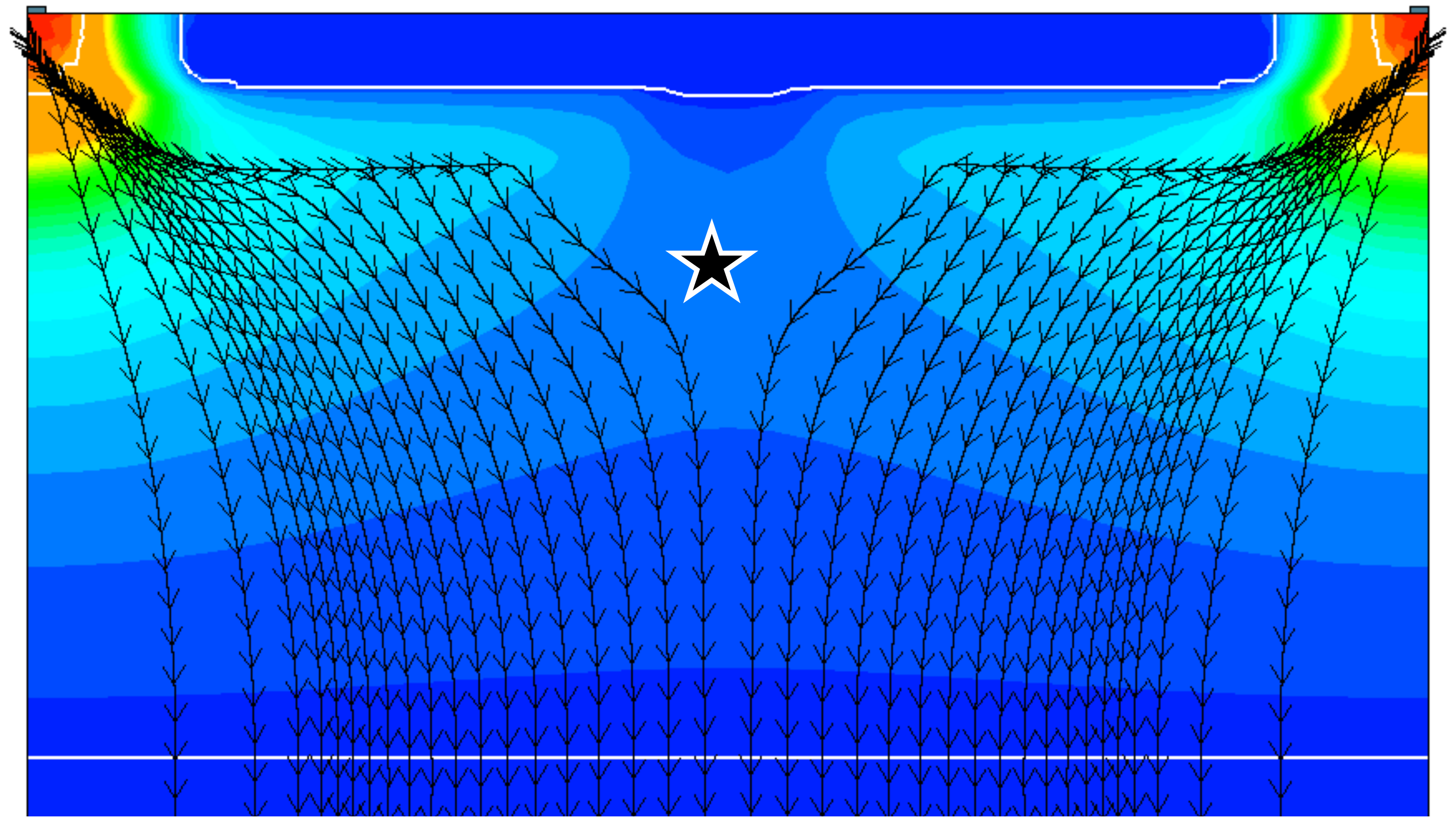
Modified process:



Modified process with additional p-implant:



Modified process with gap in n-layer:

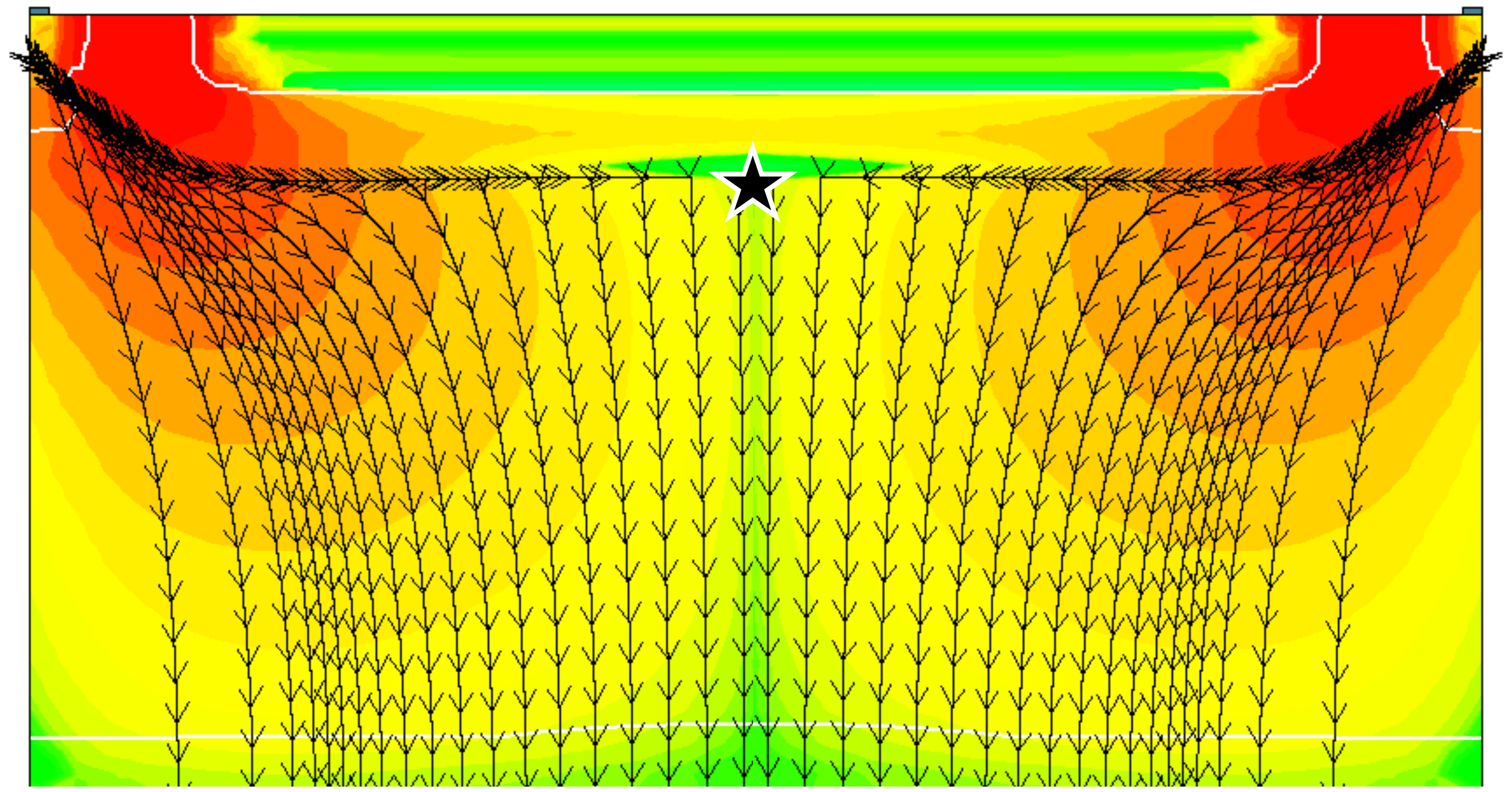


—> Constant potential at pixel border results in electric field minimum (★)

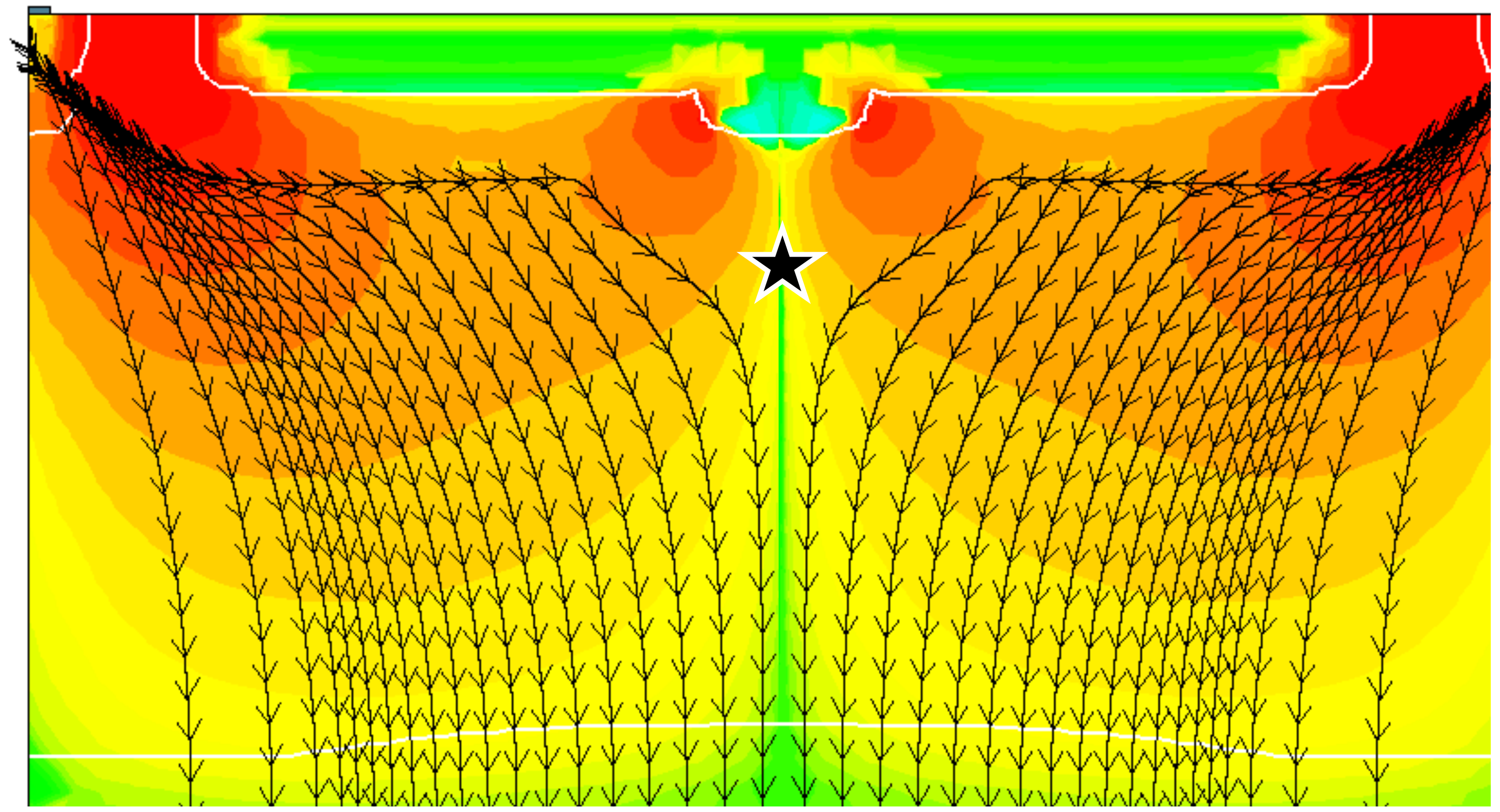
—> Additional implant & gap in n-layer create larger potential difference in lateral pixel dimension

Lateral field and drift path

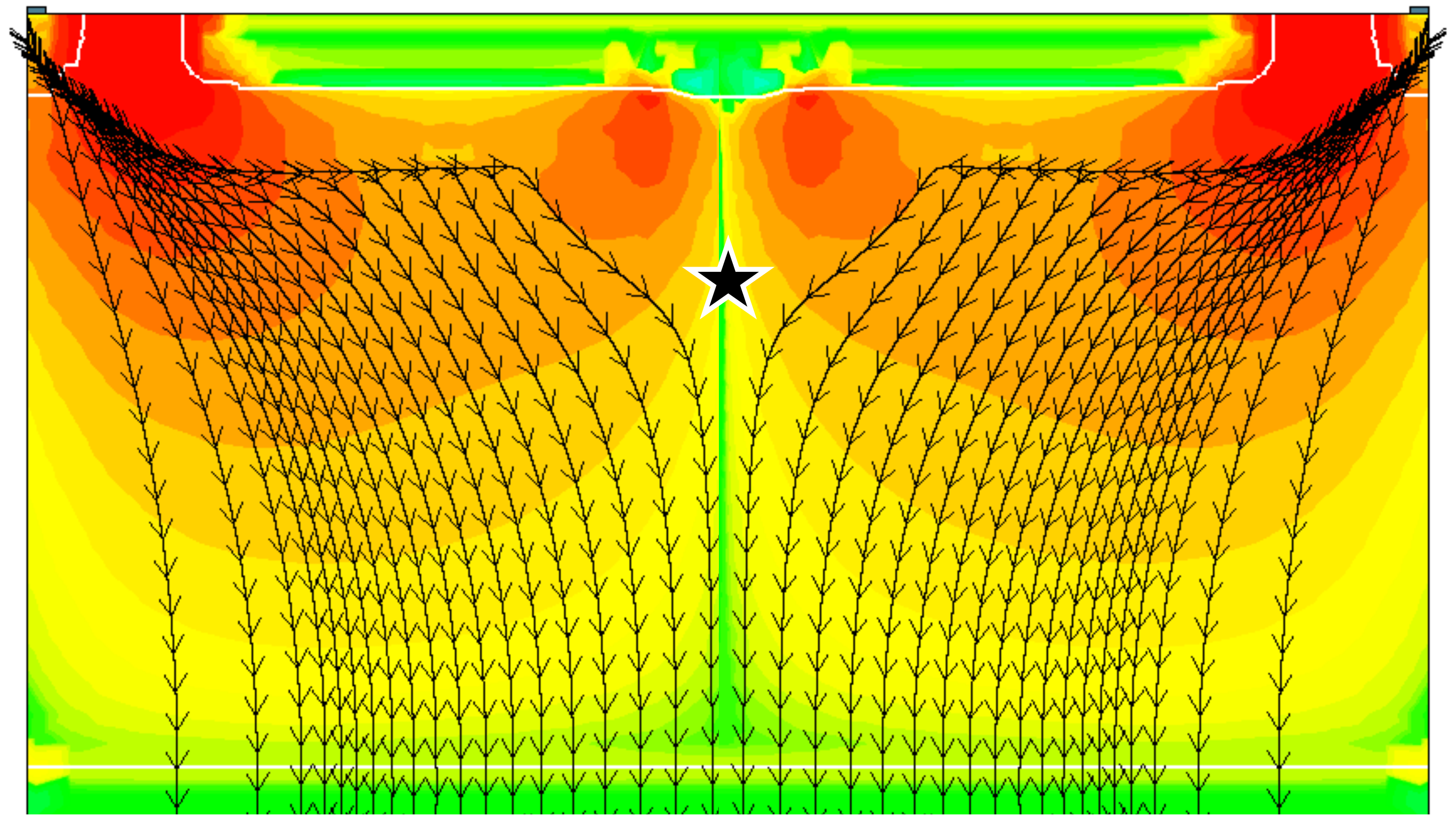
Modified process:



Modified process with additional p-implant:



Modified process with gap in n-layer:



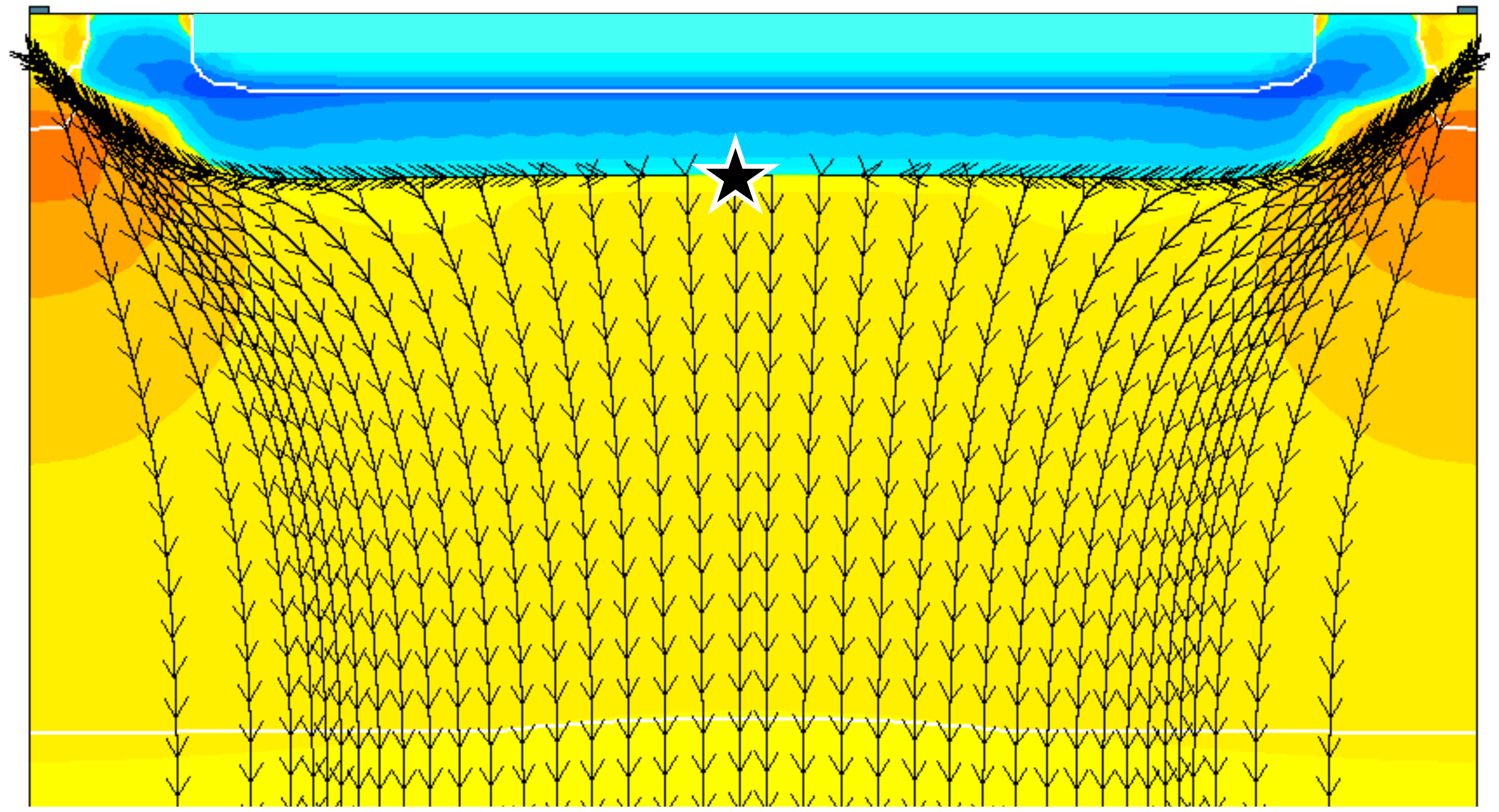
—> Constant potential at pixel border results in electric field minimum (★)

—> Additional implant & gap in n-layer create larger potential difference in lateral pixel dimension

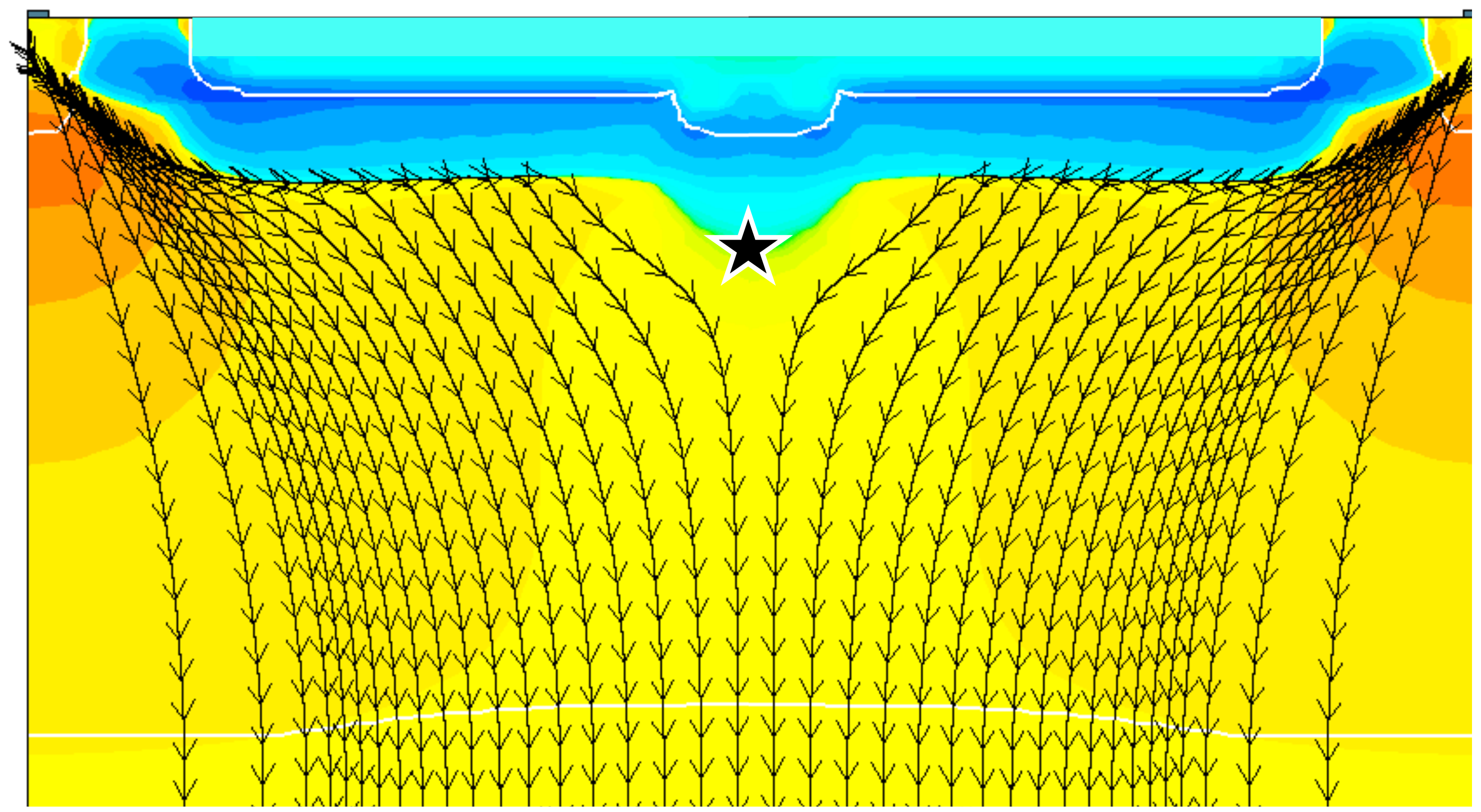
—> Higher field in lateral dimension bends the electric field lines (black arrows) toward collection electrode

Field along sensor depth and drift path

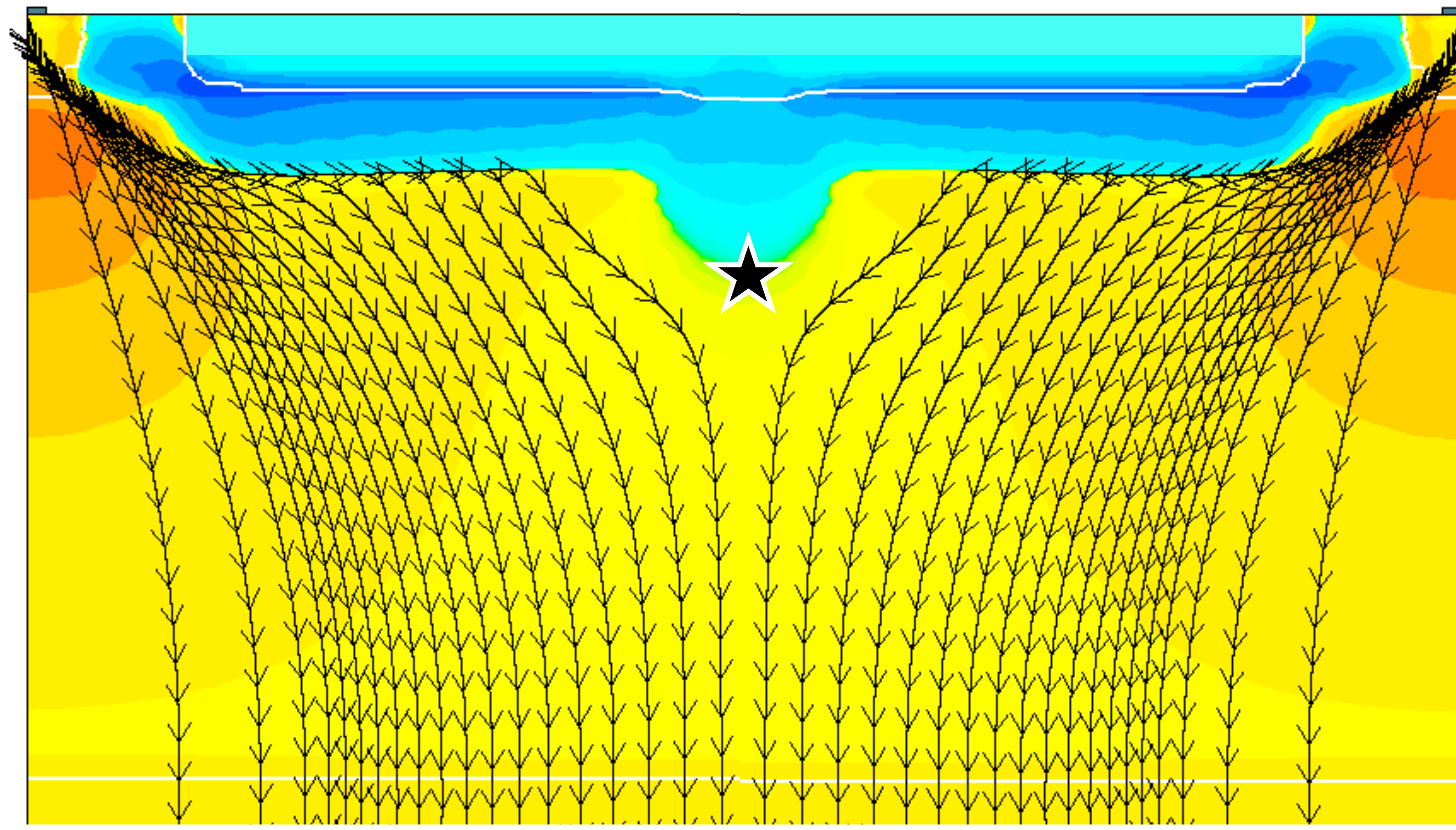
Modified process:



Modified process with additional p-implant:



Modified process with gap in n-layer:



—> Constant potential at pixel border results in electric field minimum (★)

—> Additional implant & gap in n-layer create larger potential difference in lateral dimension

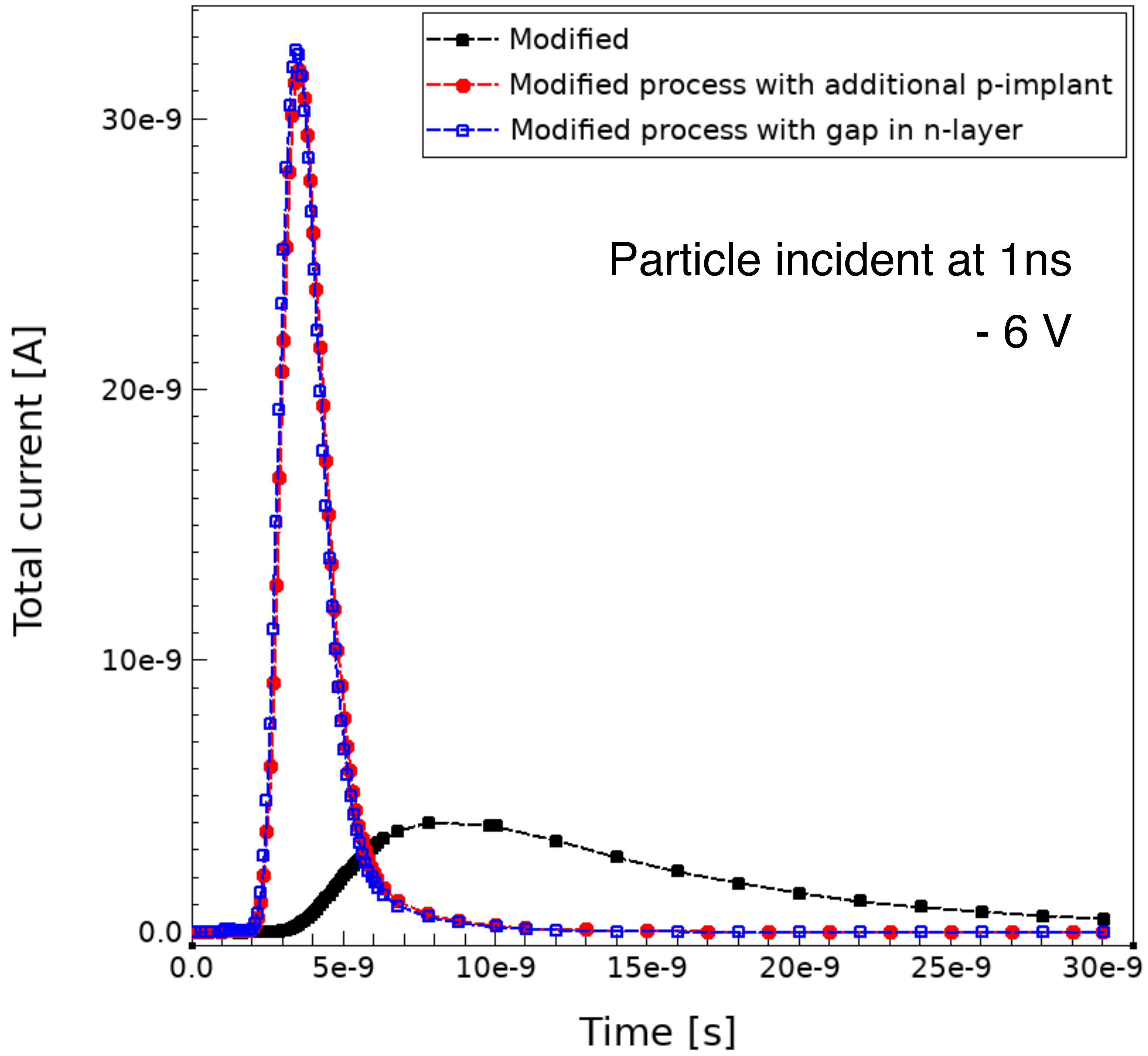
—> Higher field in lateral dimension bends the electric field lines (black arrows) toward collection electrode

—> Lower electric field along sensor depth reduces push of charge carriers into minimum

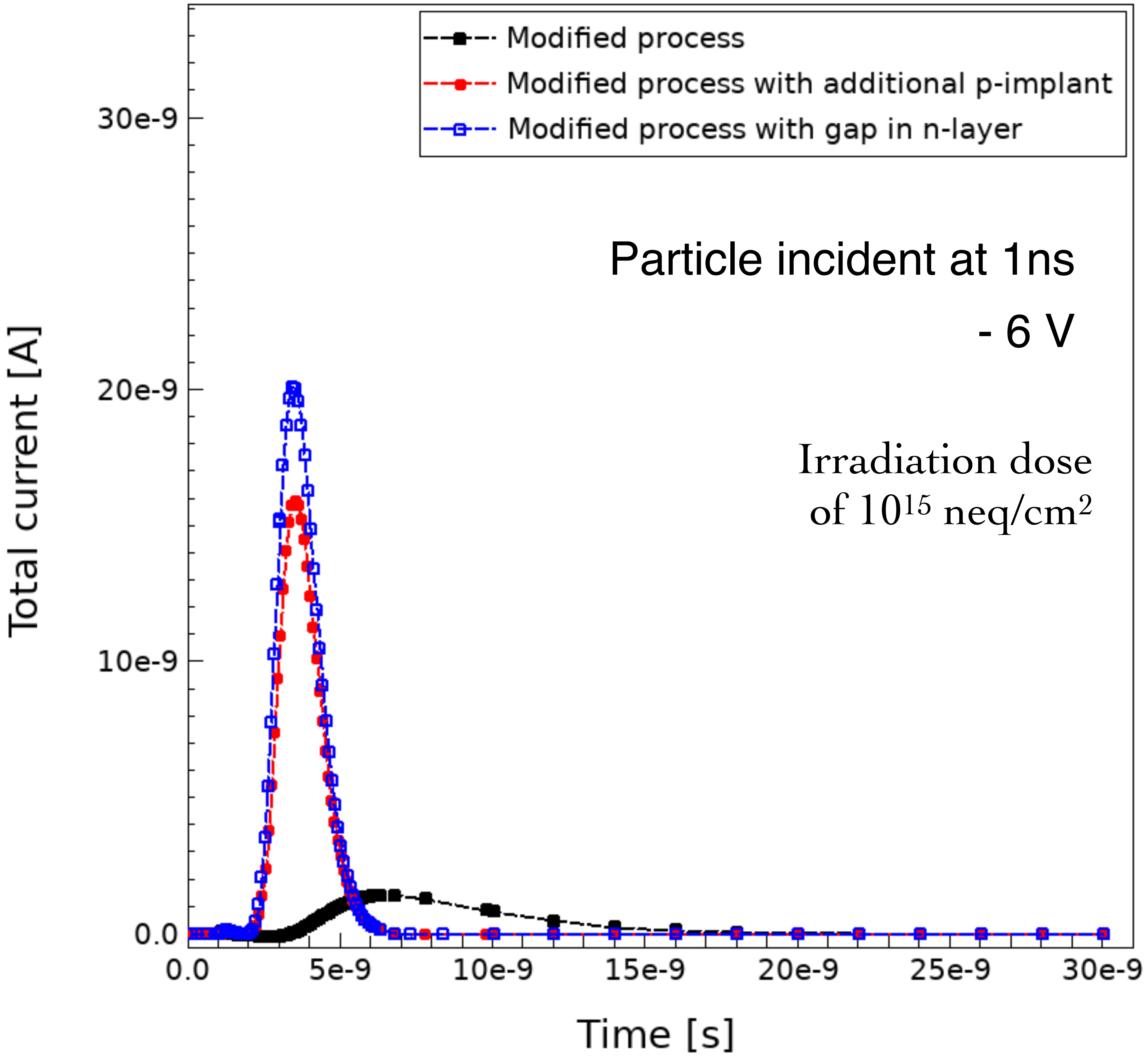
—> Electric field minimum deeper in sensor —> larger opening towards collection electrode

Current pulse signals

Before irradiation:



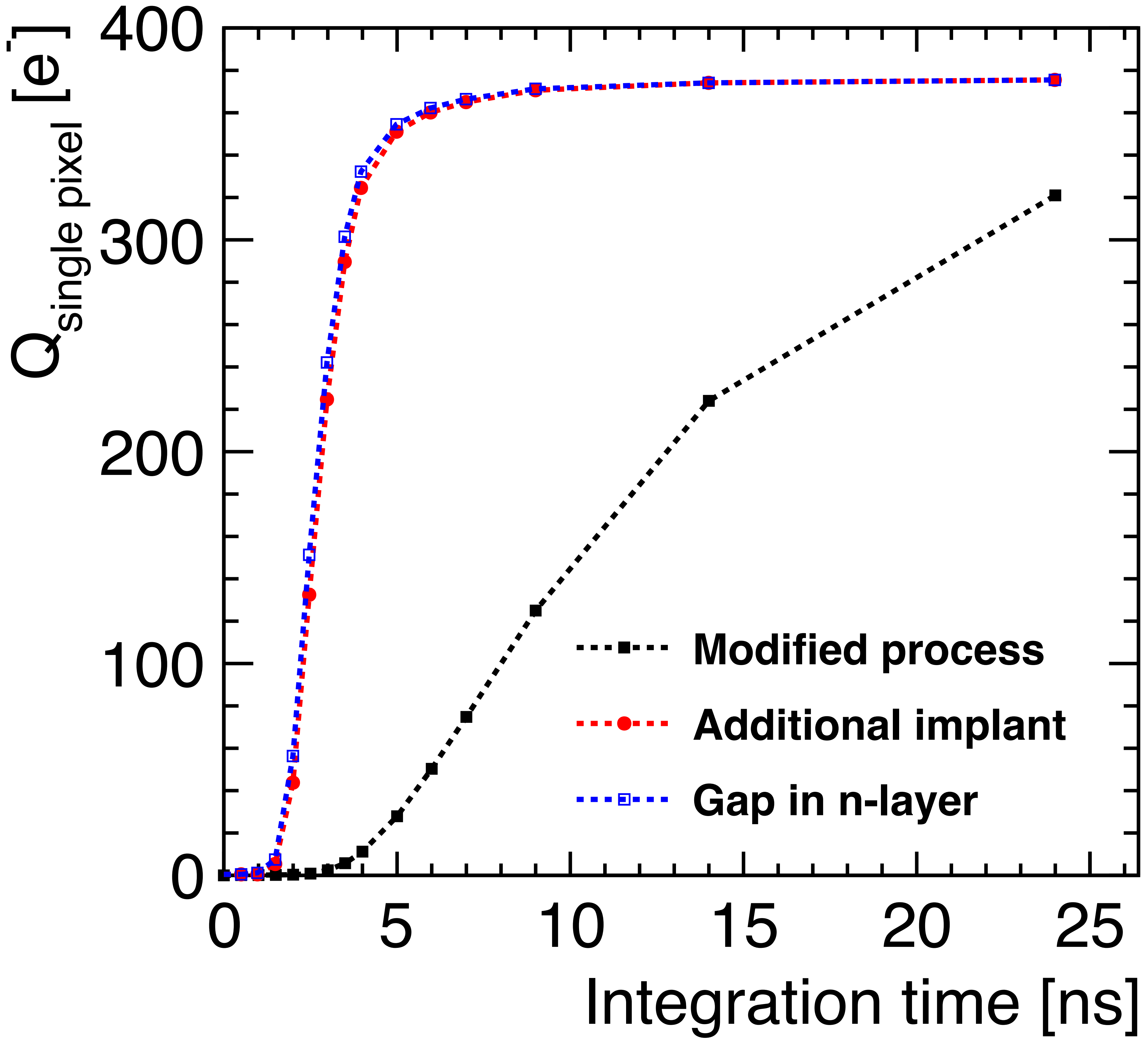
After irradiation:



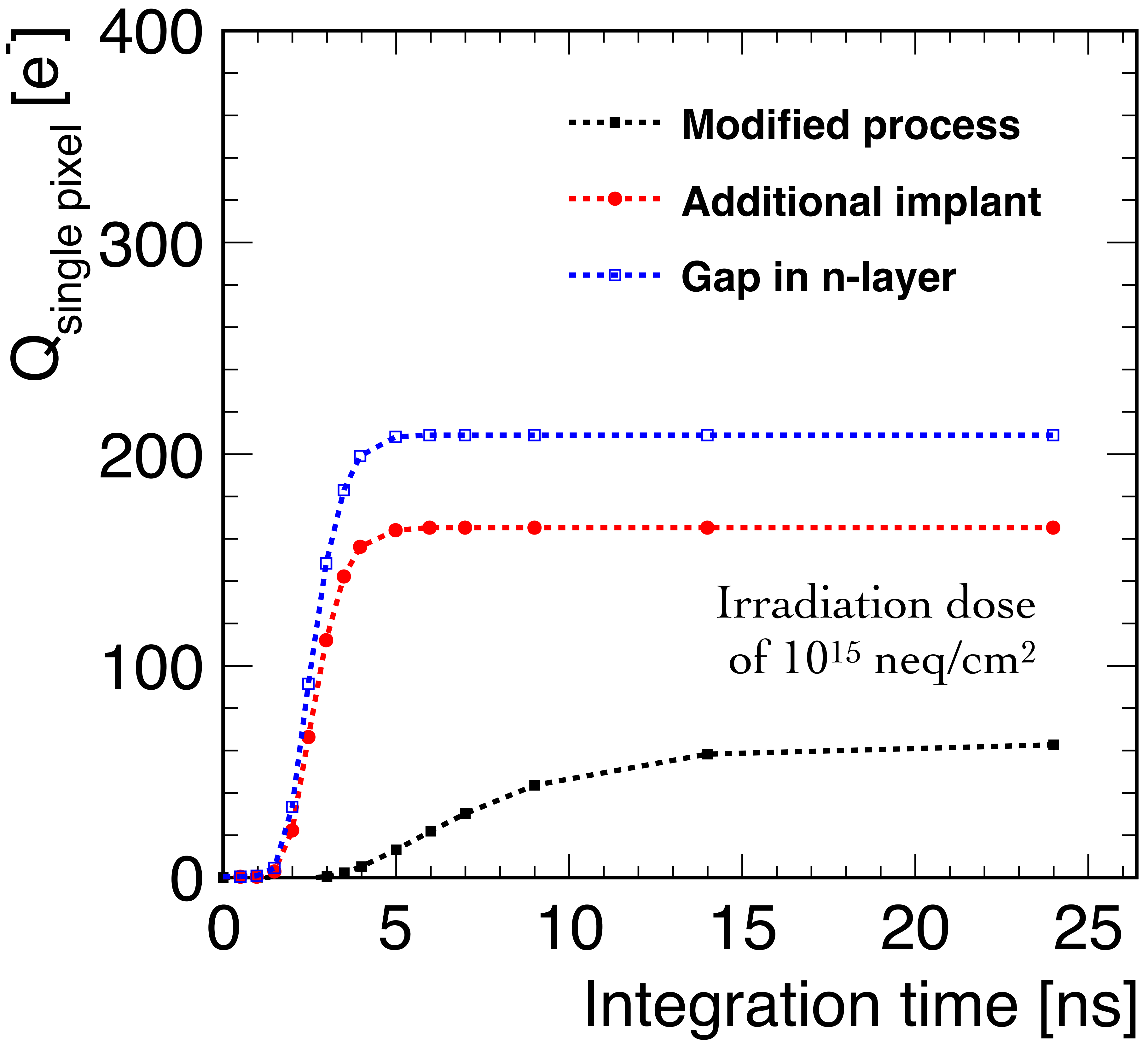
—> **Significantly faster charge collection for design with additional p-implant and gap in n-layer**

Charge versus integration time

Before irradiation:



After irradiation:



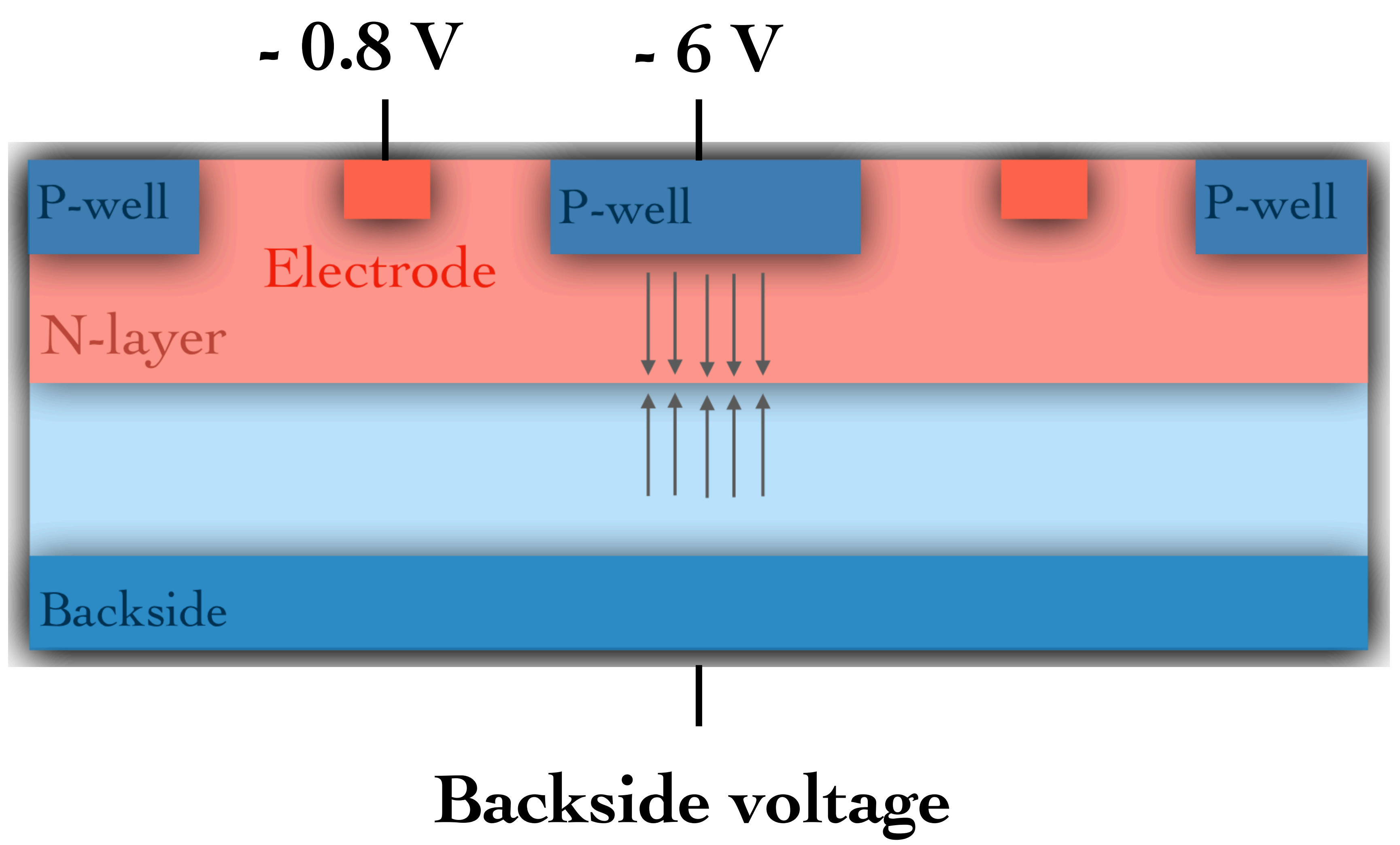
—> **Significantly larger signal after irradiation (factor of ~ 3 - 4) with additional p-implant and gap in n-layer**

3D TCAD simulations for higher backside voltage

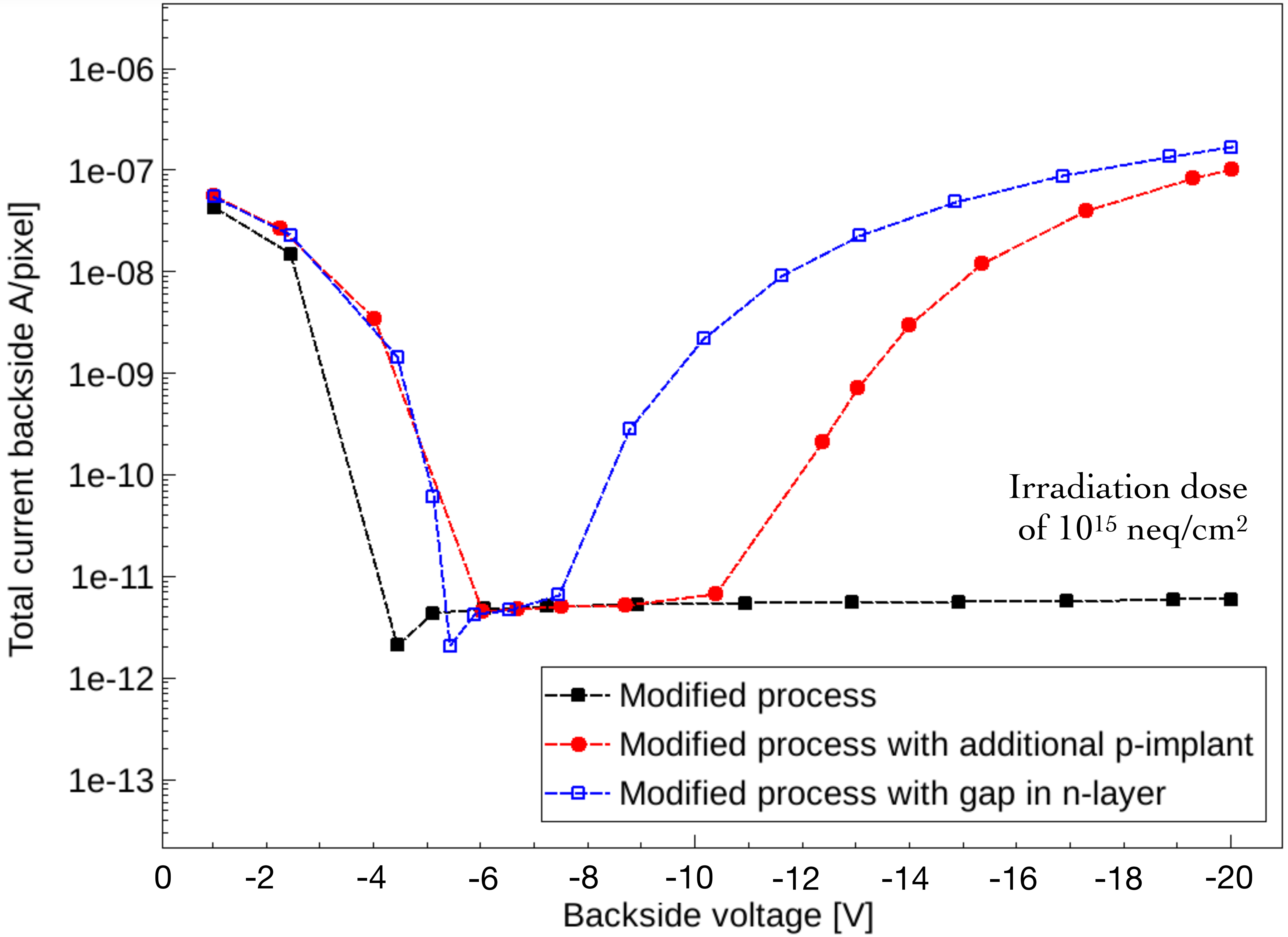
Can we achieve a faster charge collection time in the pixel corner with a higher backside voltage?

Punch through

Simulation setup:



- Fix voltage on electrode and p-wells
- Ramp up backside voltage



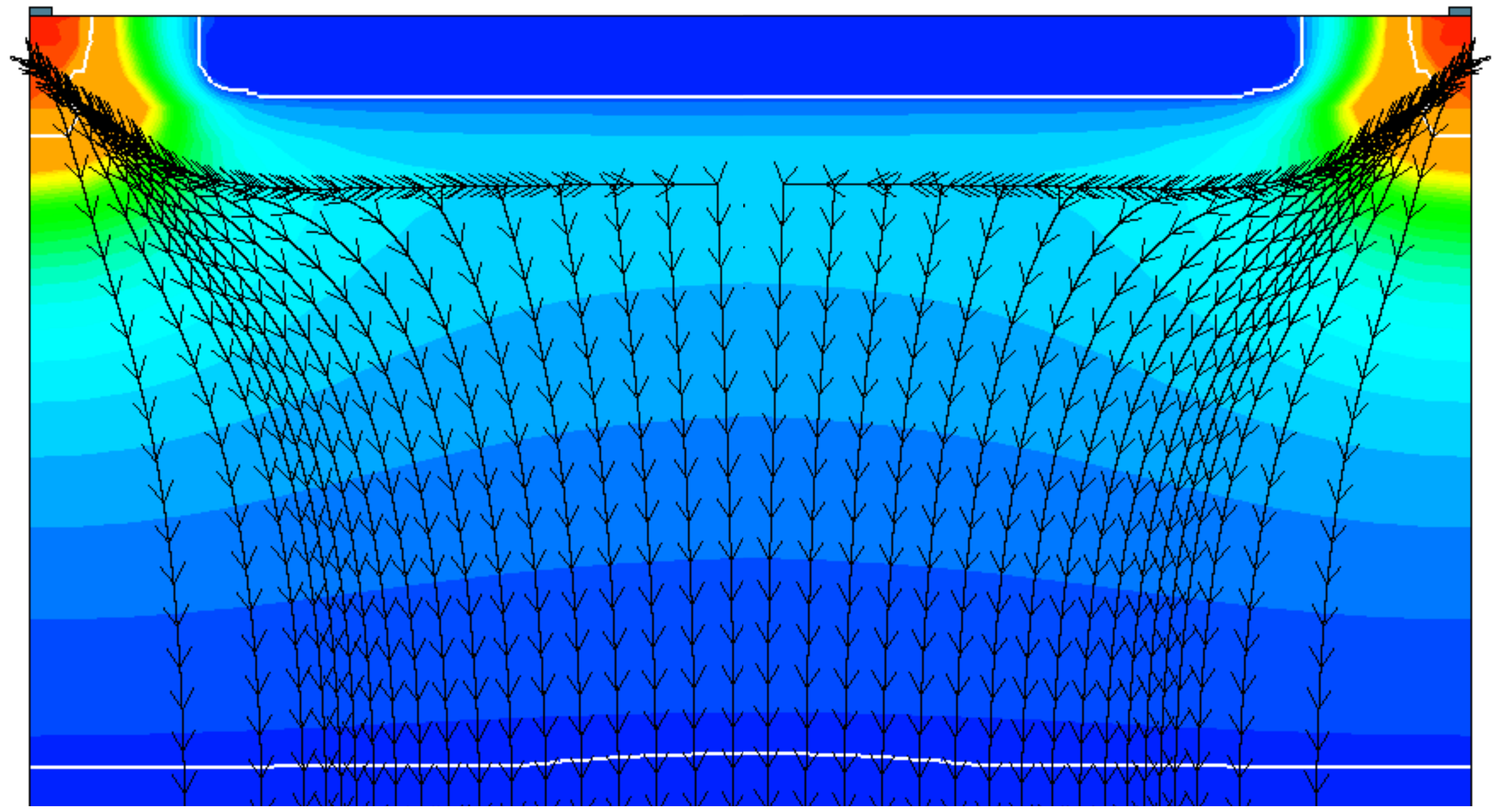
—> Punch through at lower backside voltage for additional p-implant and gap in n-layer

—> Do we gain from a higher backside voltage?

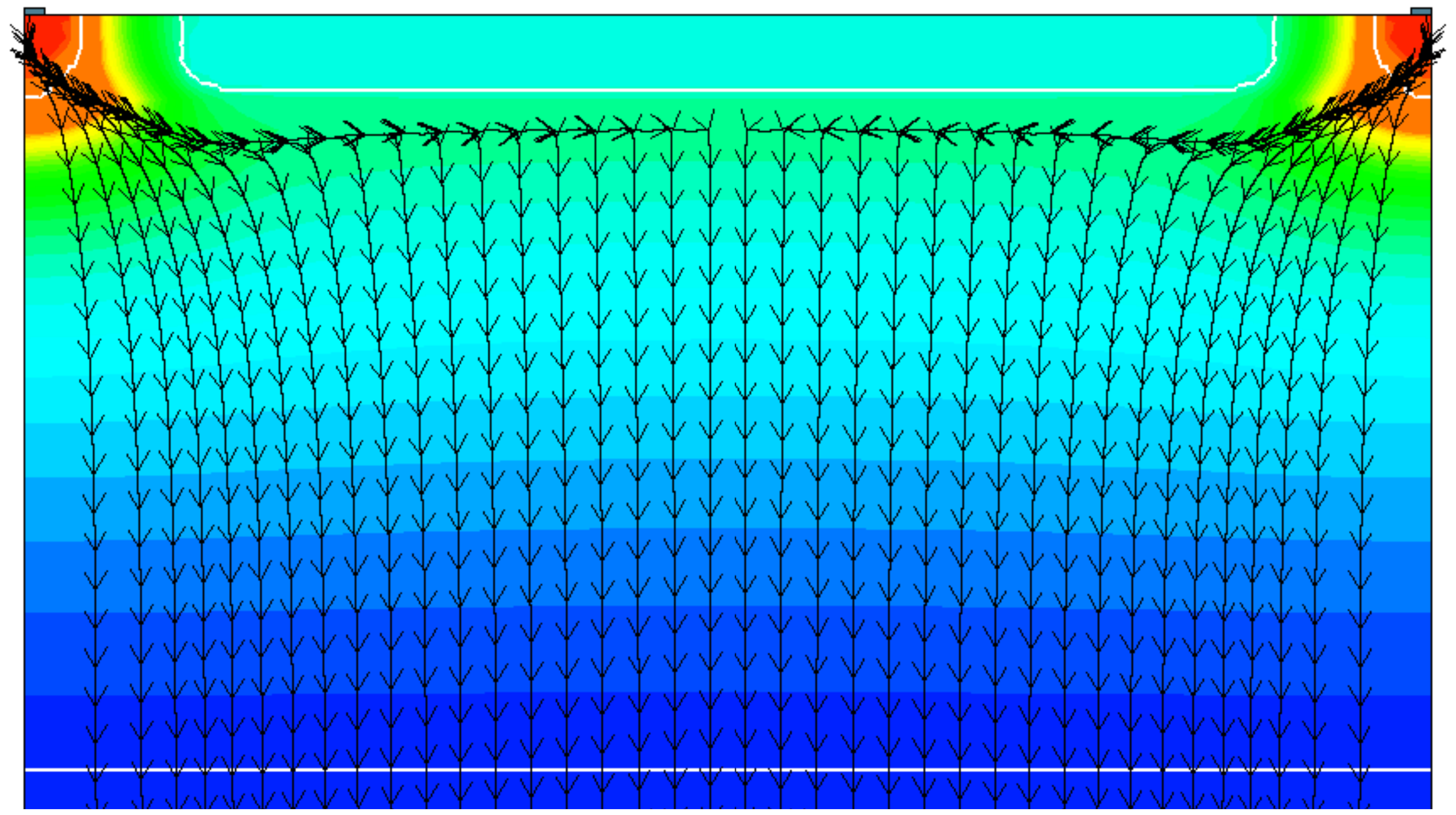
Higher backside voltage - modified process

Electrostatic potential:

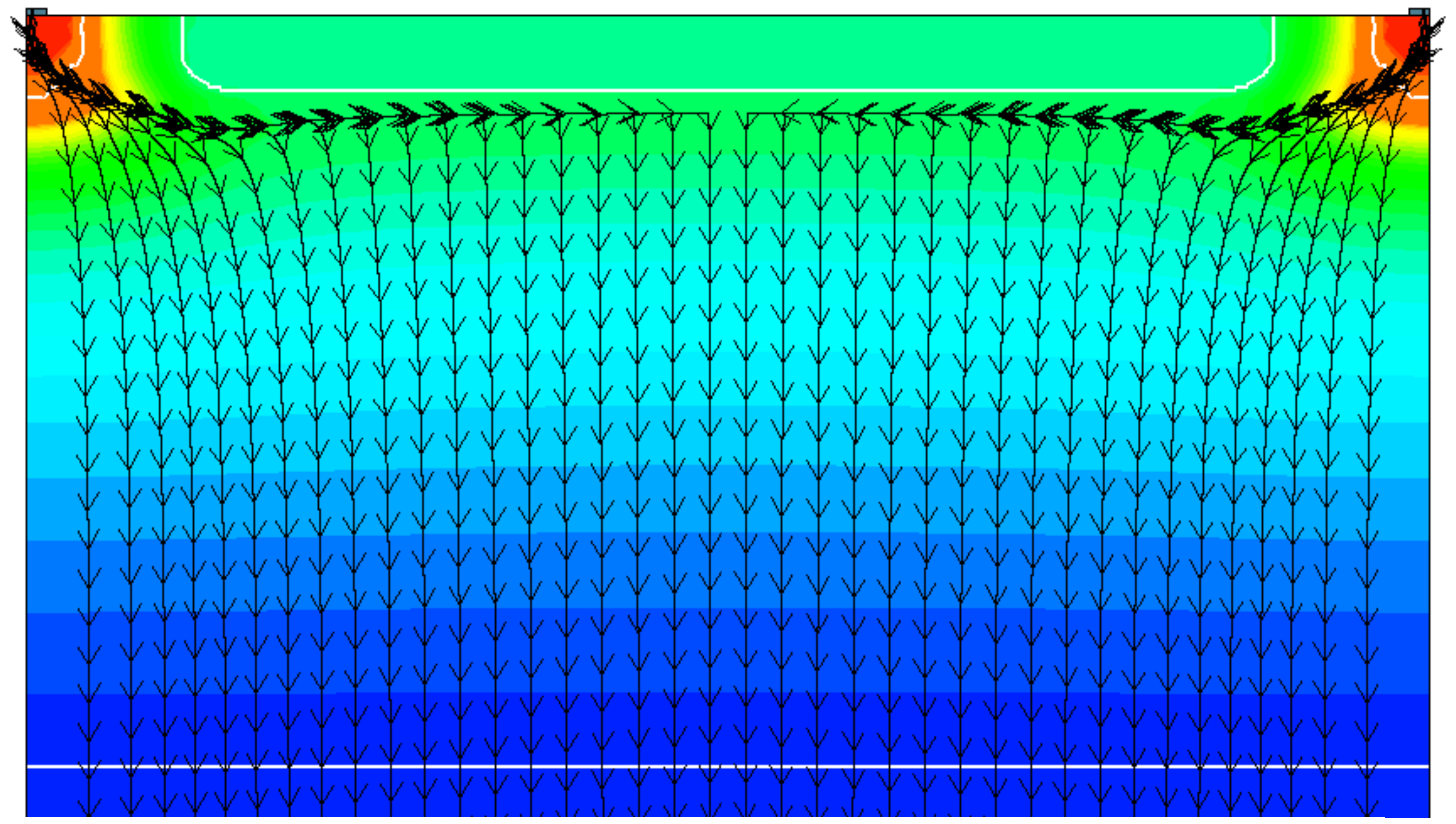
Backside voltage - 6 V:



Backside voltage - 15 V:



Backside voltage - 20 V:



Two different effects:

1. Higher backside voltage results in smaller potential variations along lateral pixel dimension:

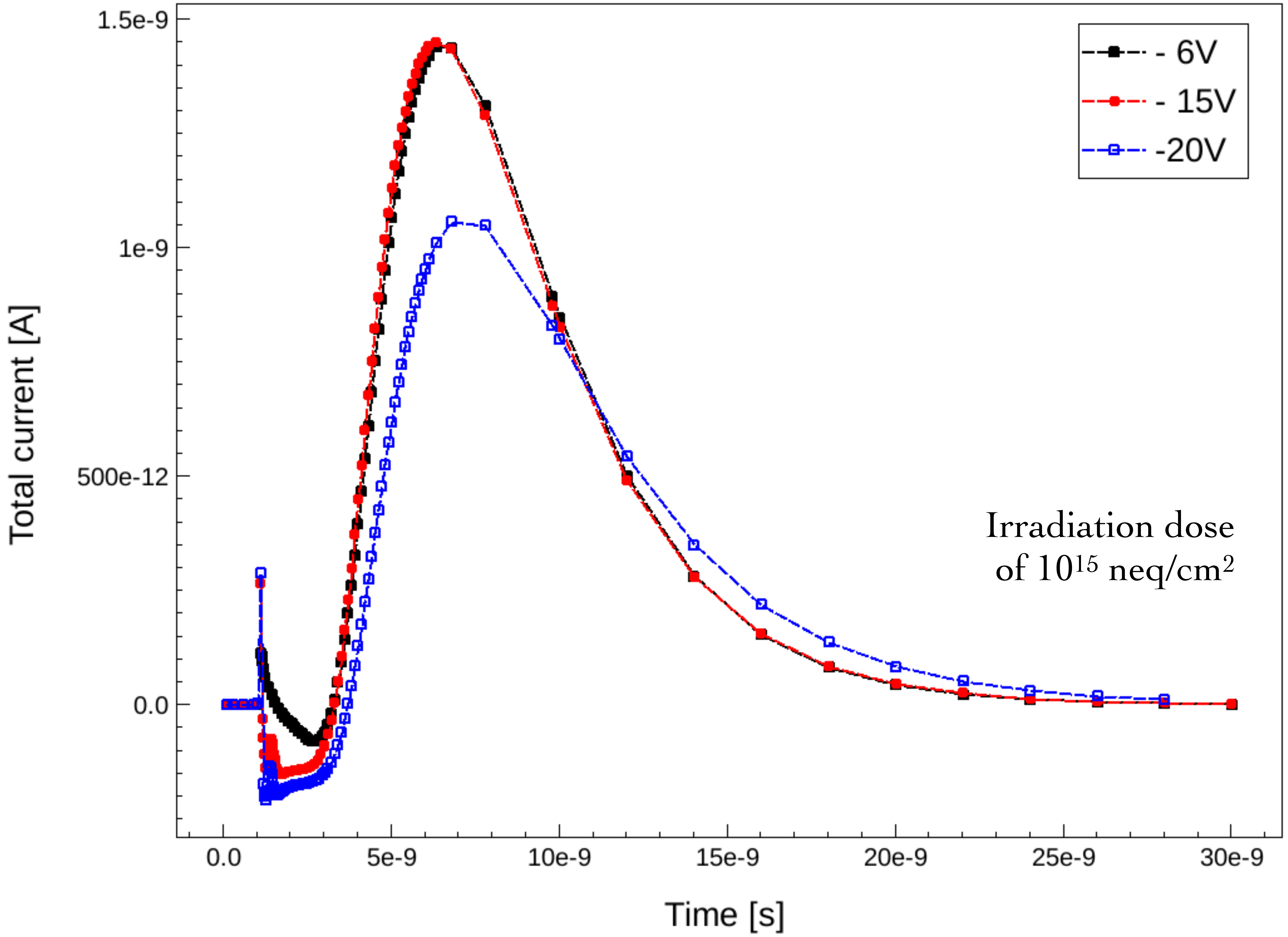
—> Electric field lines less bend towards collection electrode —> longer drift path

2. Higher backside voltage results in larger potential variations along sensor depth:

—> Enhanced electric field and faster drift along sensor depth

Higher backside voltage - modified process

Current pulses for different backside voltages after irradiation:



Dominating effect:

Higher backside voltage results in smaller potential variations along lateral pixel dimension:

—> Reduced electric field in lateral dimension

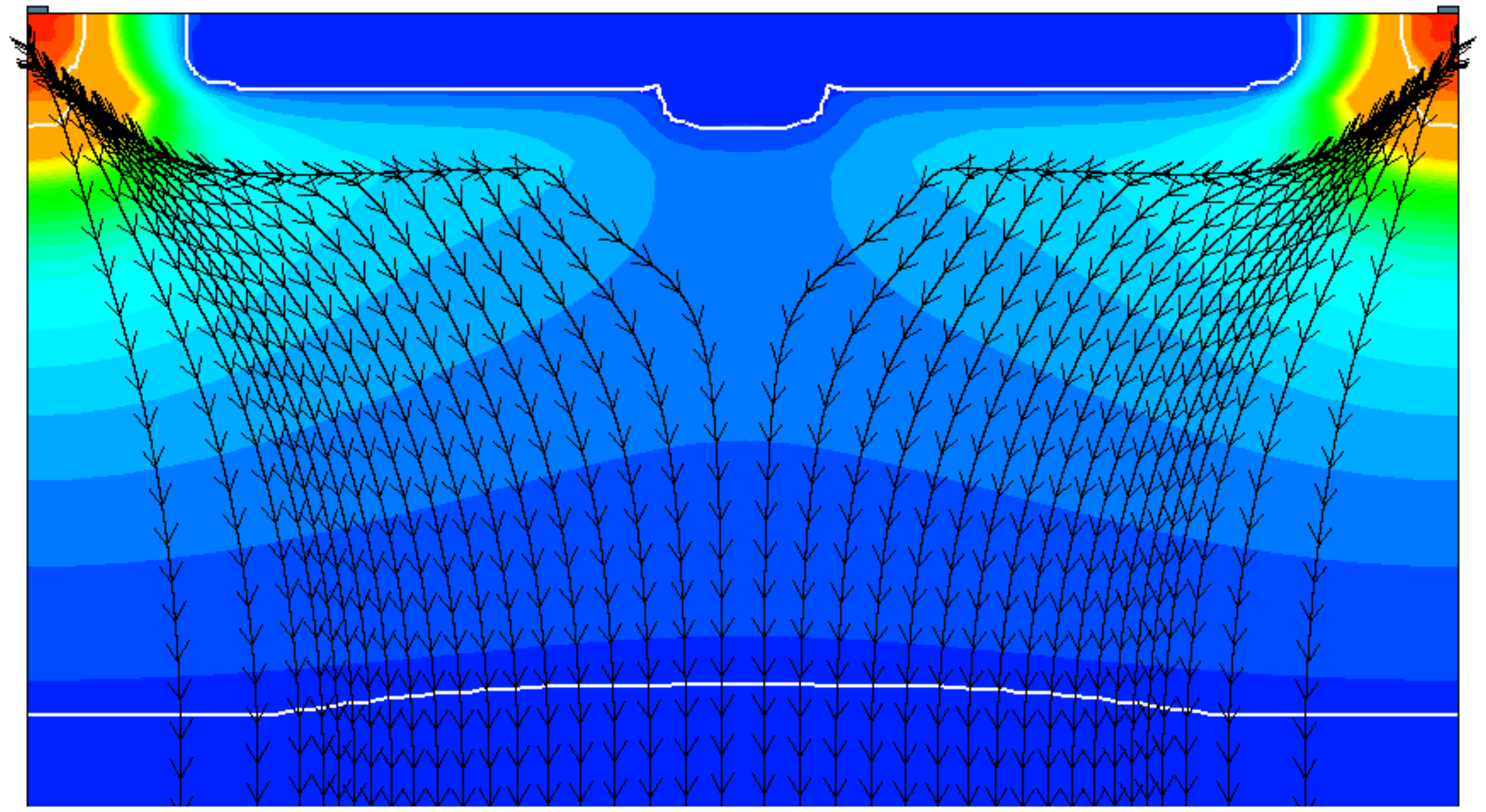
—> Slower charge collection at pixel corner

—> Reduced signal at pixel corner

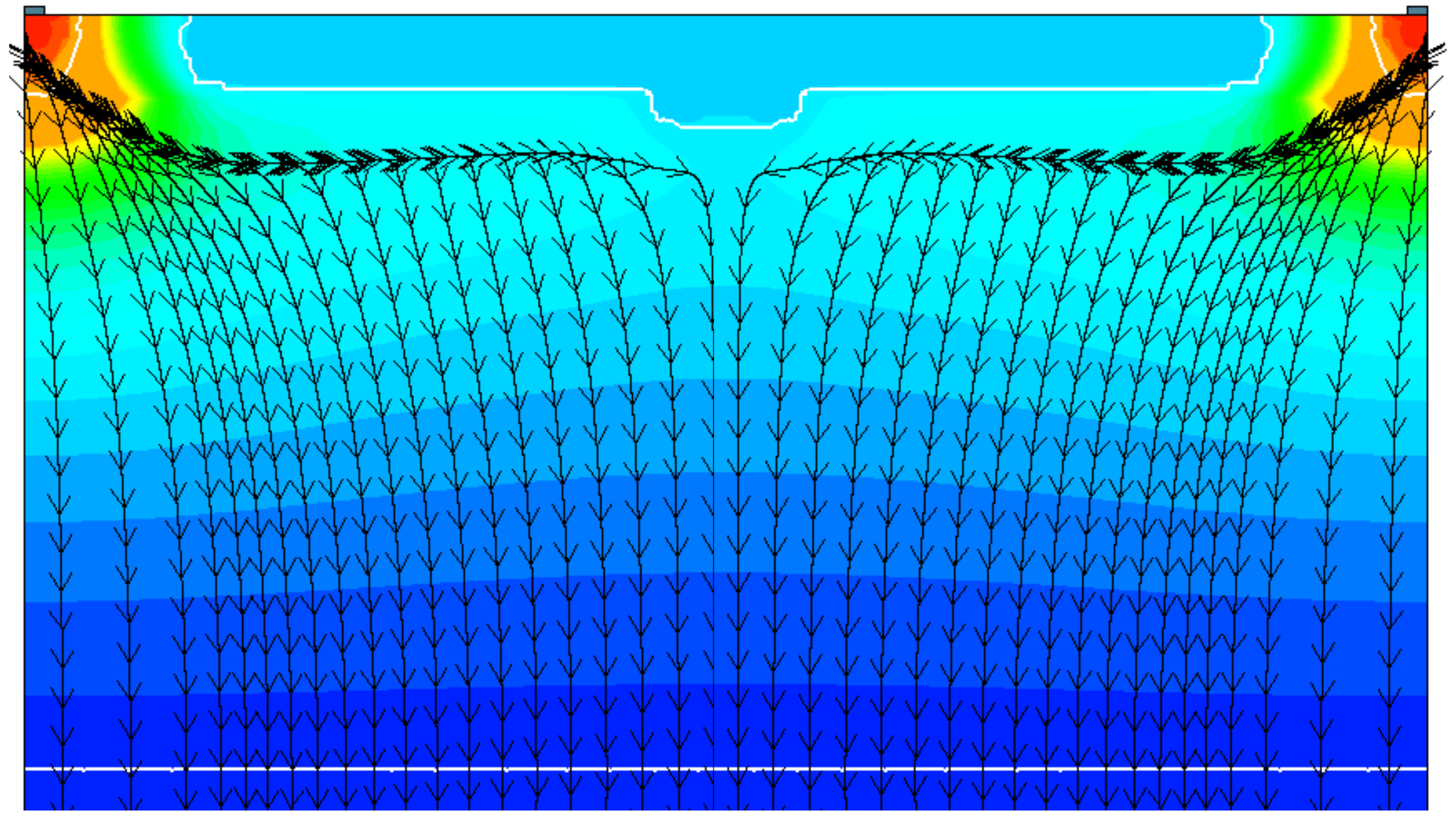
Higher backside voltage - modified process with additional p-implant

Electrostatic potential:

Backside voltage - 6 V:



Backside voltage - 9 V:



Two different effects:

1. Higher backside voltage results in smaller potential variations along lateral pixel dimension:

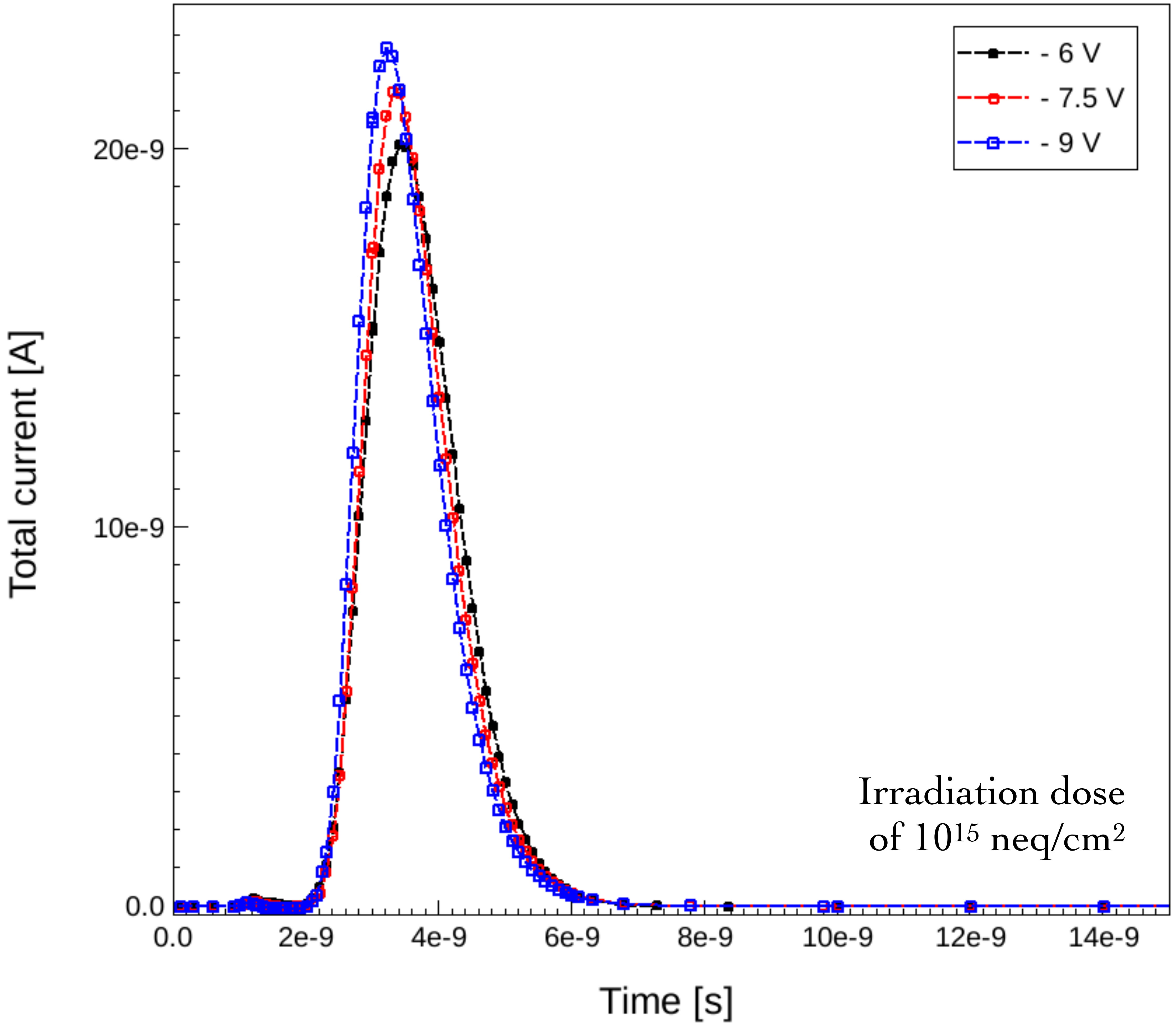
—> Electric field lines less bend towards collection electrode —> longer drift path

2. Higher backside voltage results in larger potential variations along sensor depth:

—> Enhanced electric field and faster drift along sensor depth

Higher backside voltage - modified process with additional p-implant

Current pulses for different backside voltages after irradiation:



Dominating effect:

Higher backside voltage results in larger potential variations along sensor depth:

—> Faster drift along sensor depth

—> Faster charge collection at pixel corner

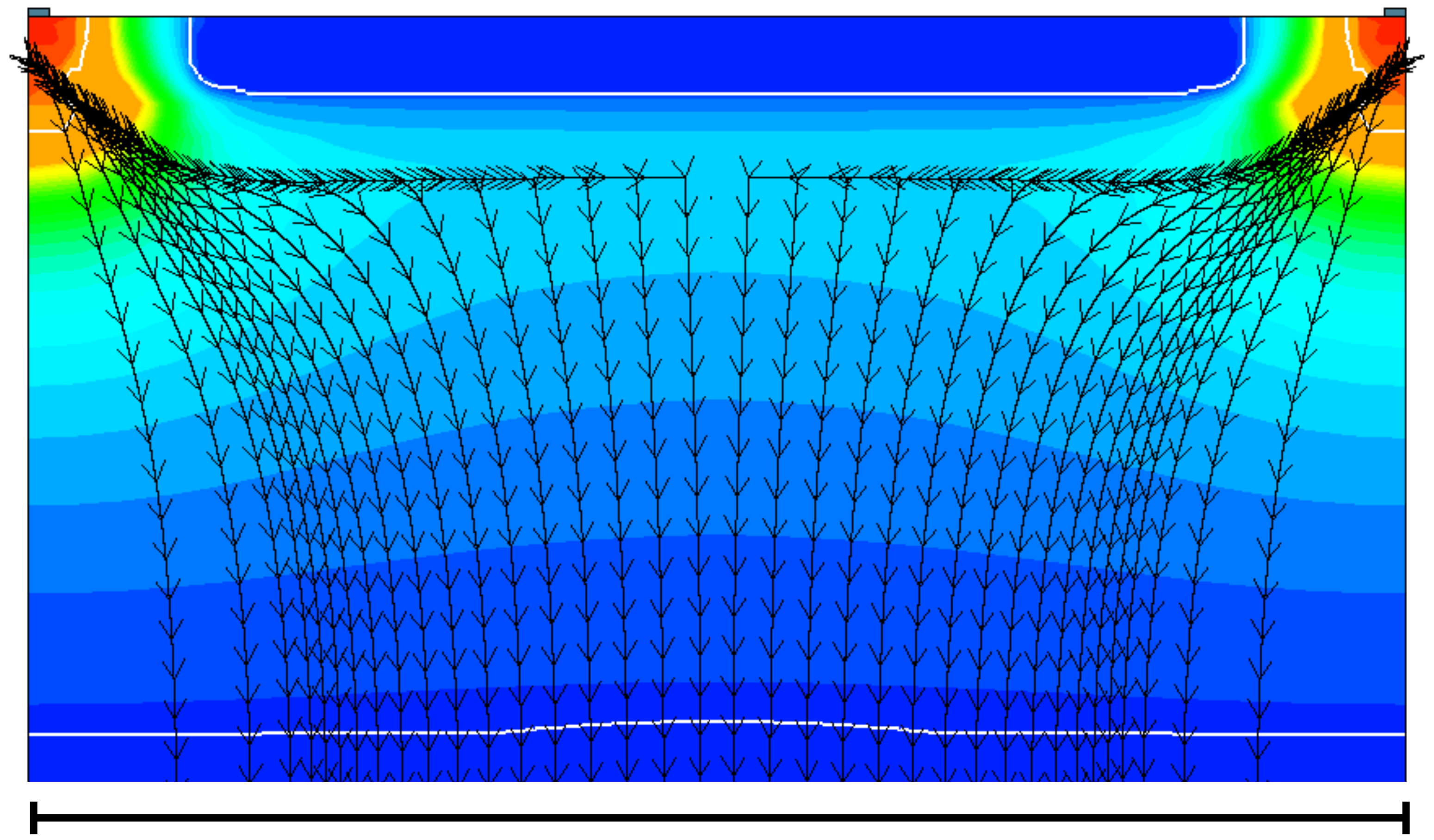
—> Increased signal at pixel corner

Future prospects - smaller pixel sizes

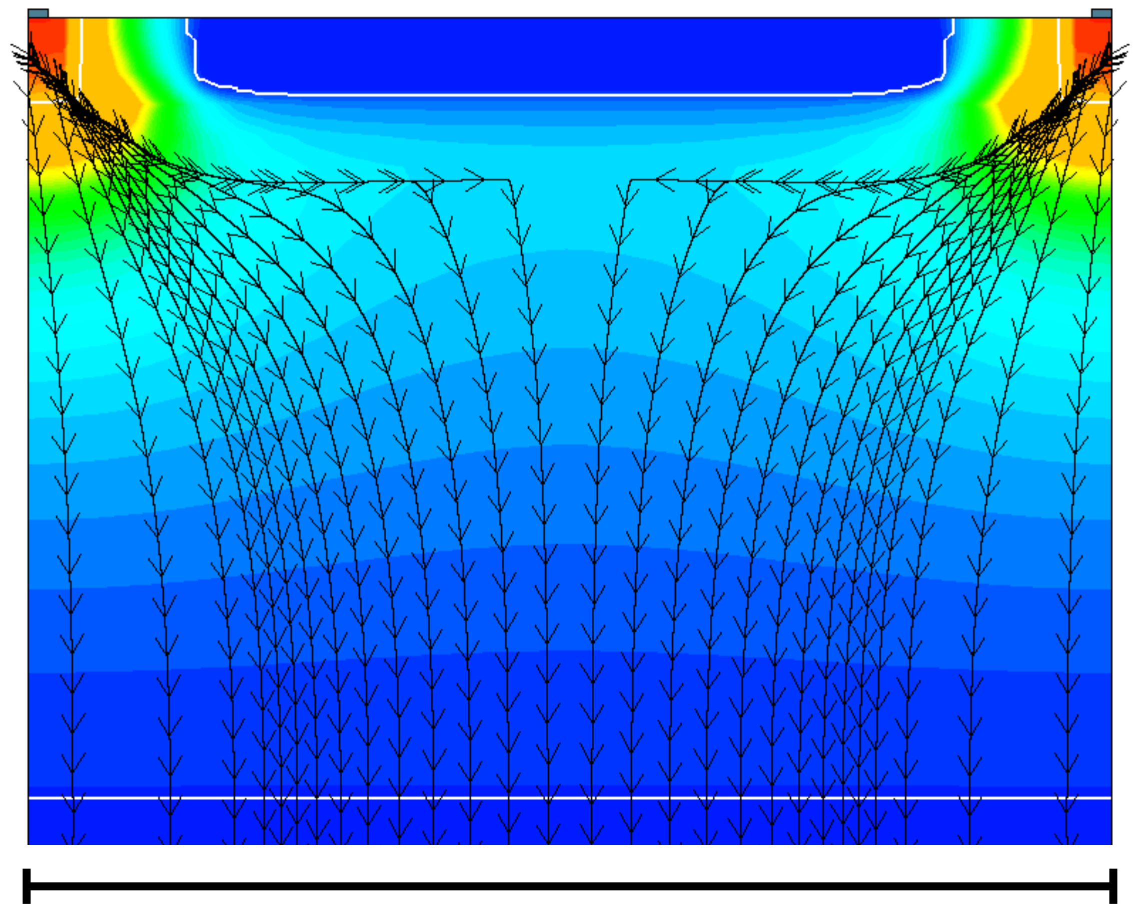
Assuming that future technologies would allow to fit all functionality in small pixels, would we still benefit from the new concepts?

Future prospects - smaller pixel sizes - electrostatic potential

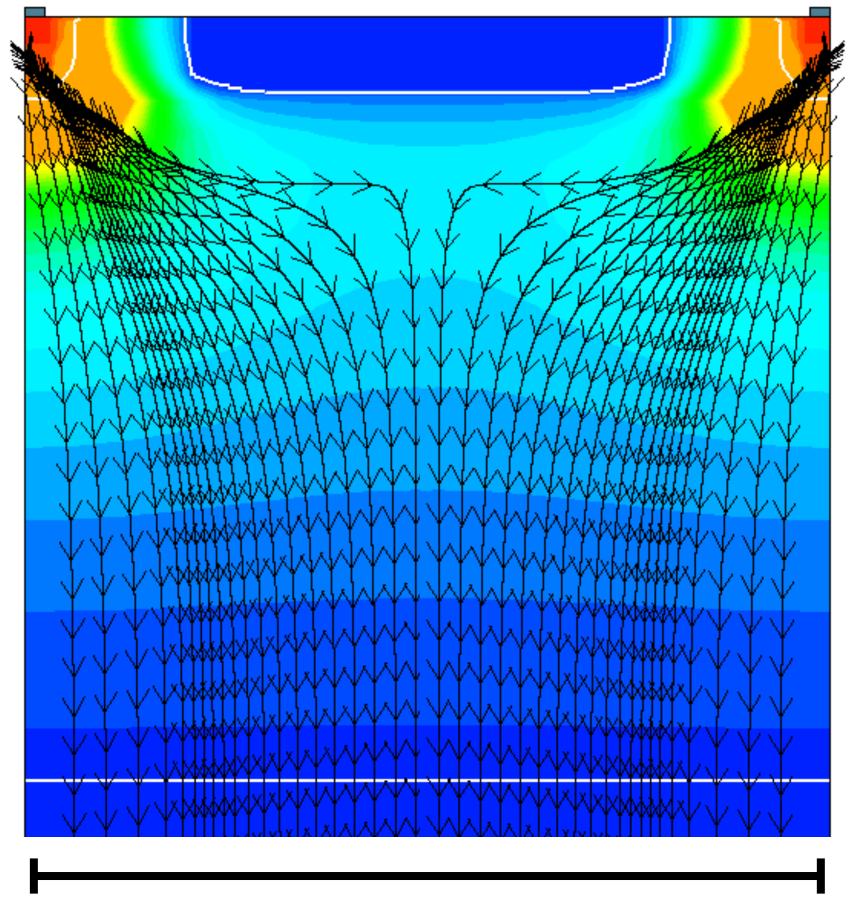
Modified process:



36.4 x 36.4 μm²

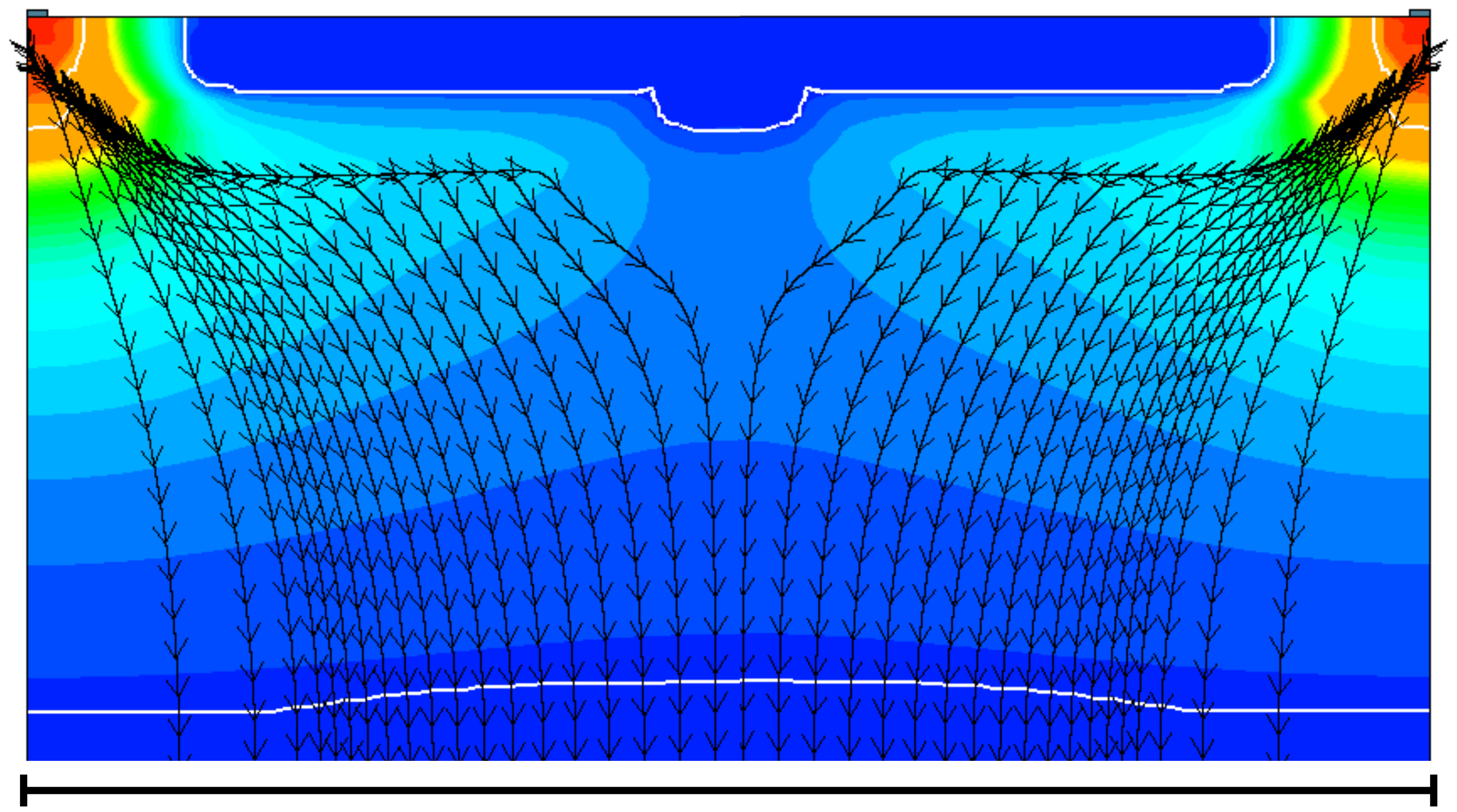


28 x 28 μm²

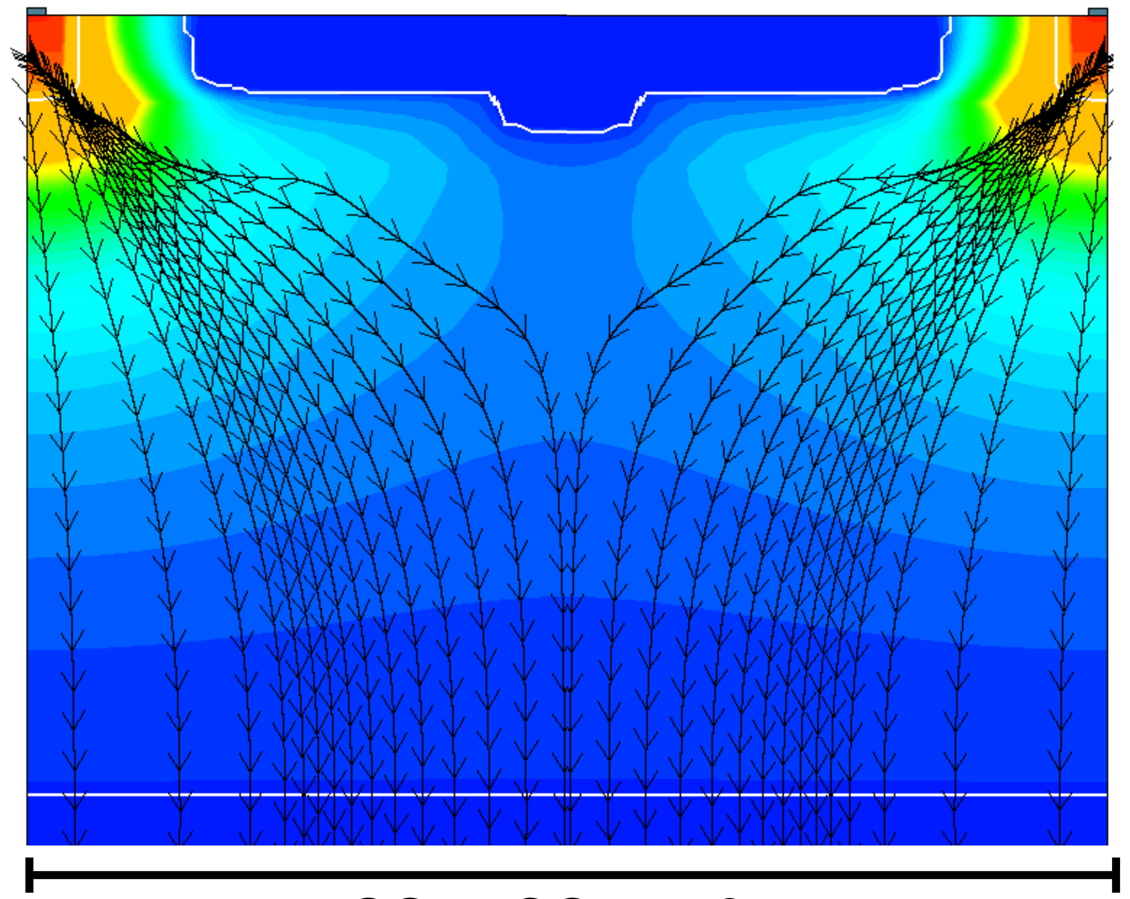


20 x 20 um²

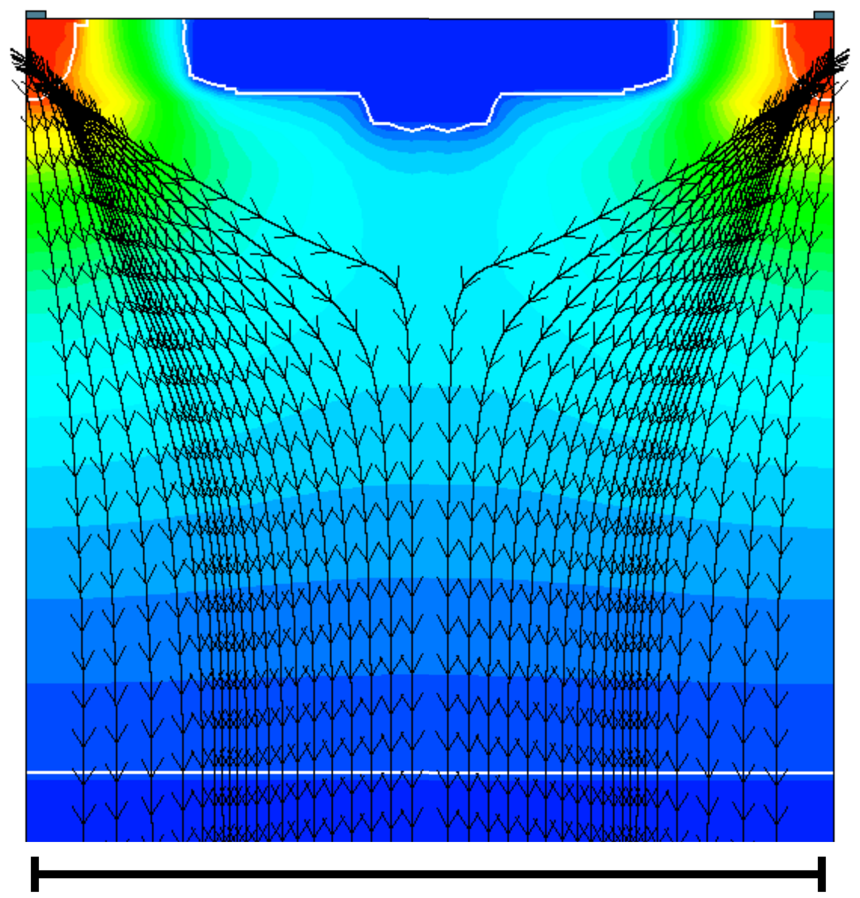
Modified process with additional p-implant:



36.4 x 36.4 μm²



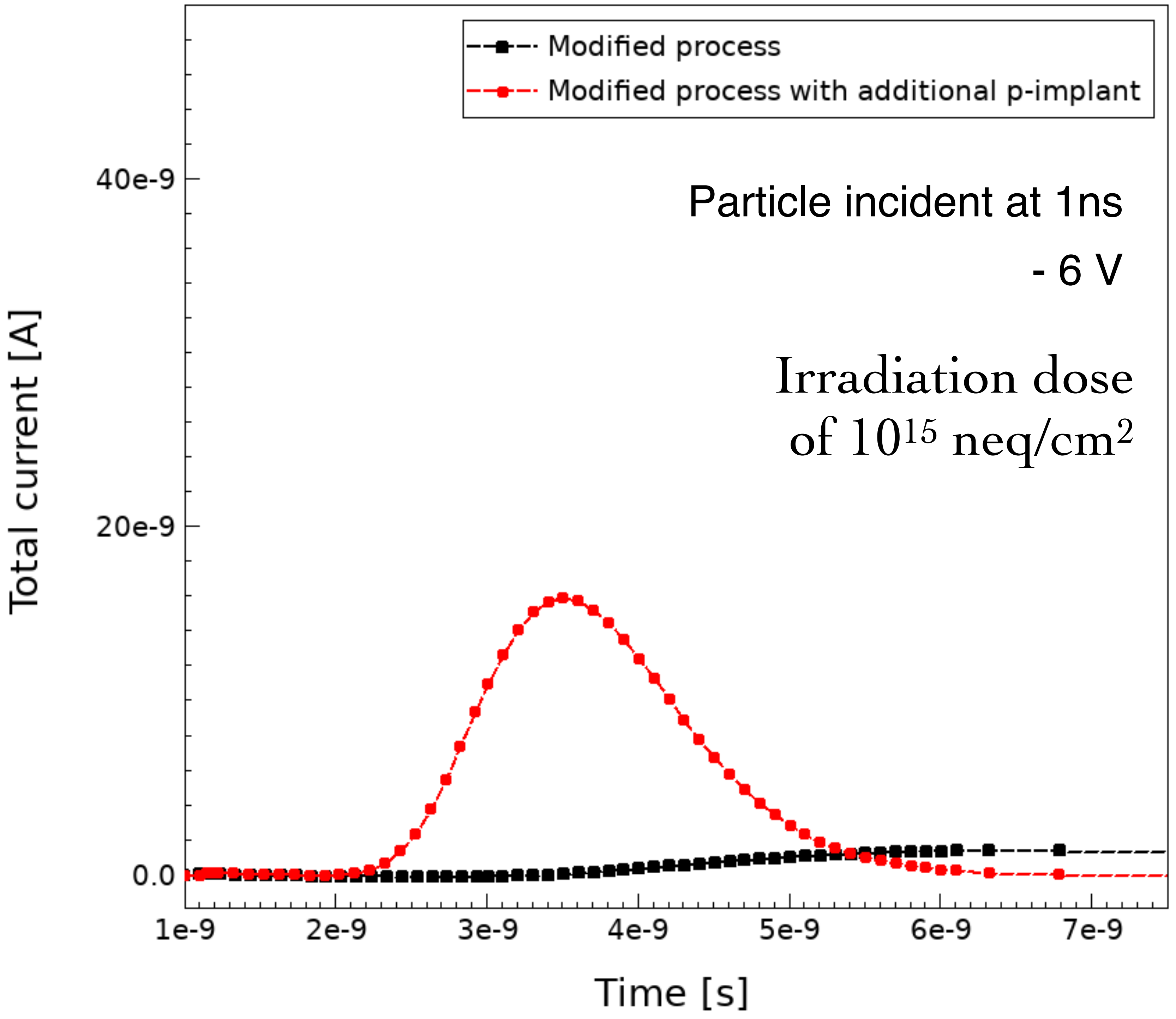
28 x 28 μm²



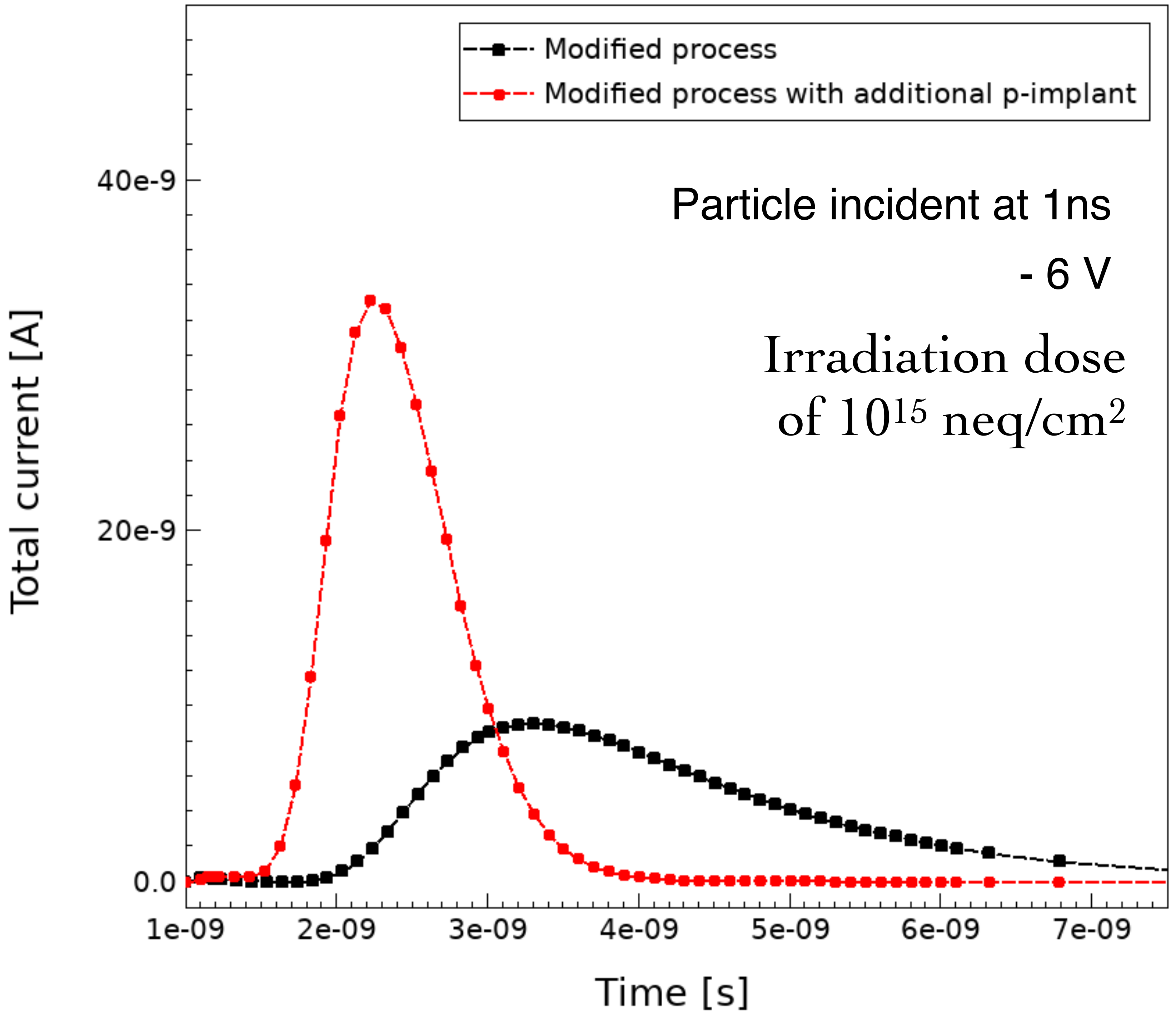
20 x 20 um²

Future prospects - smaller pixel sizes - current pulses after irradiation

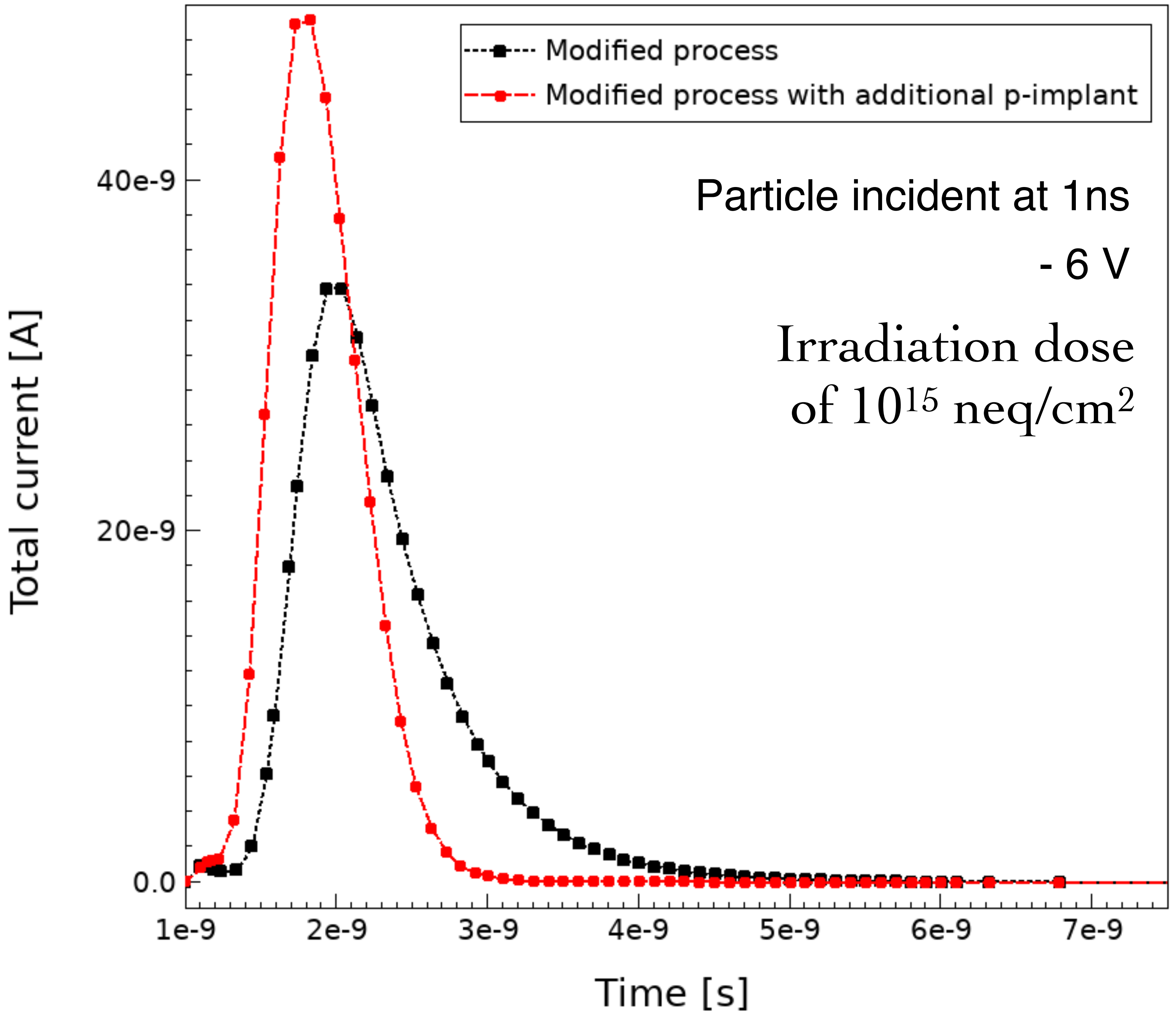
Pixel size 36.4 x 36.4 μm²:



Pixel size 28 x 28 μm²:



Pixel size 20 x 20 μm²:



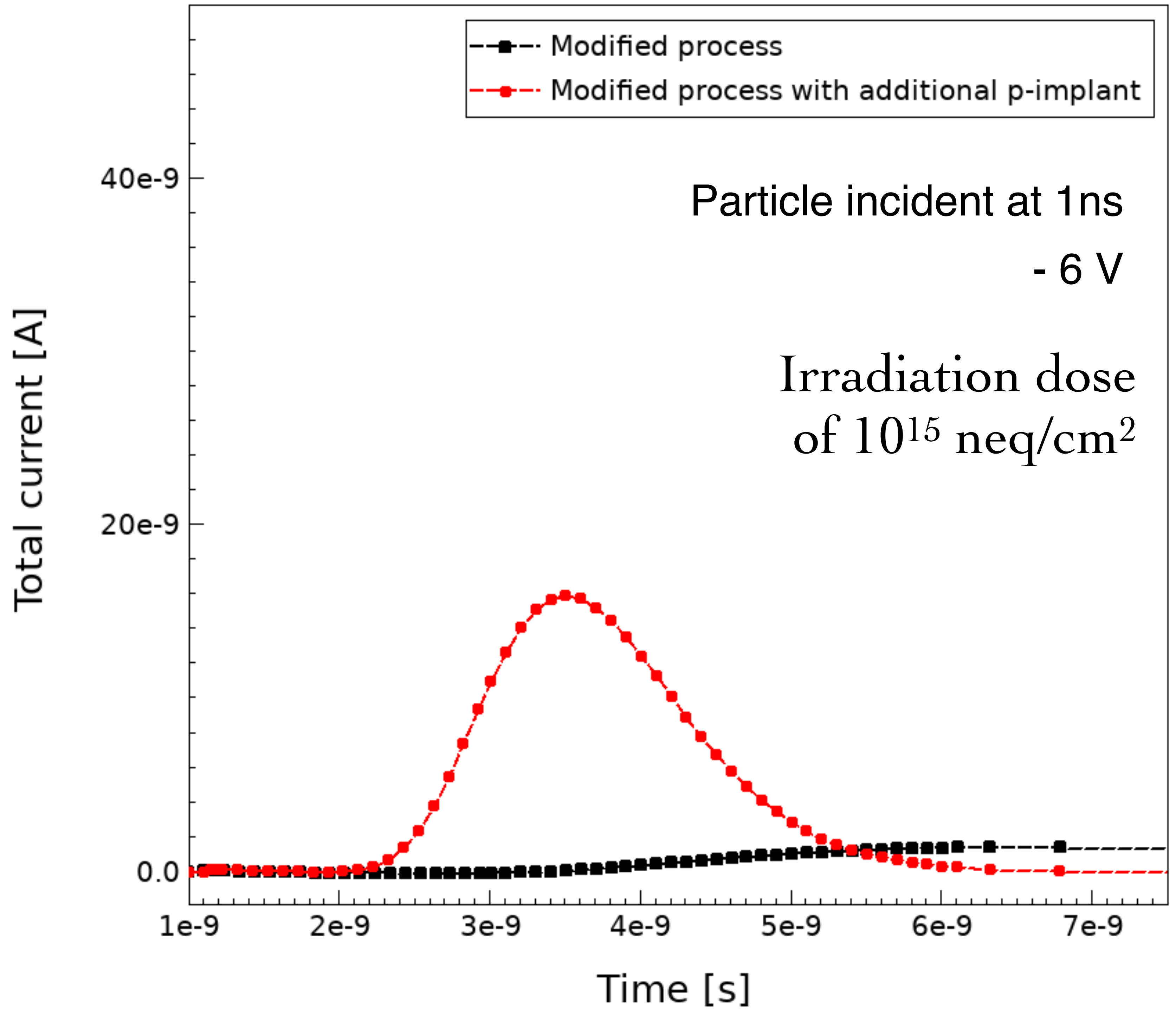
—> Significant dependancy of charge collection time on pixel pitch, especially without additional p-implant

—> No optimisation performed for smaller pixels sizes (e.g. implant or gap size)

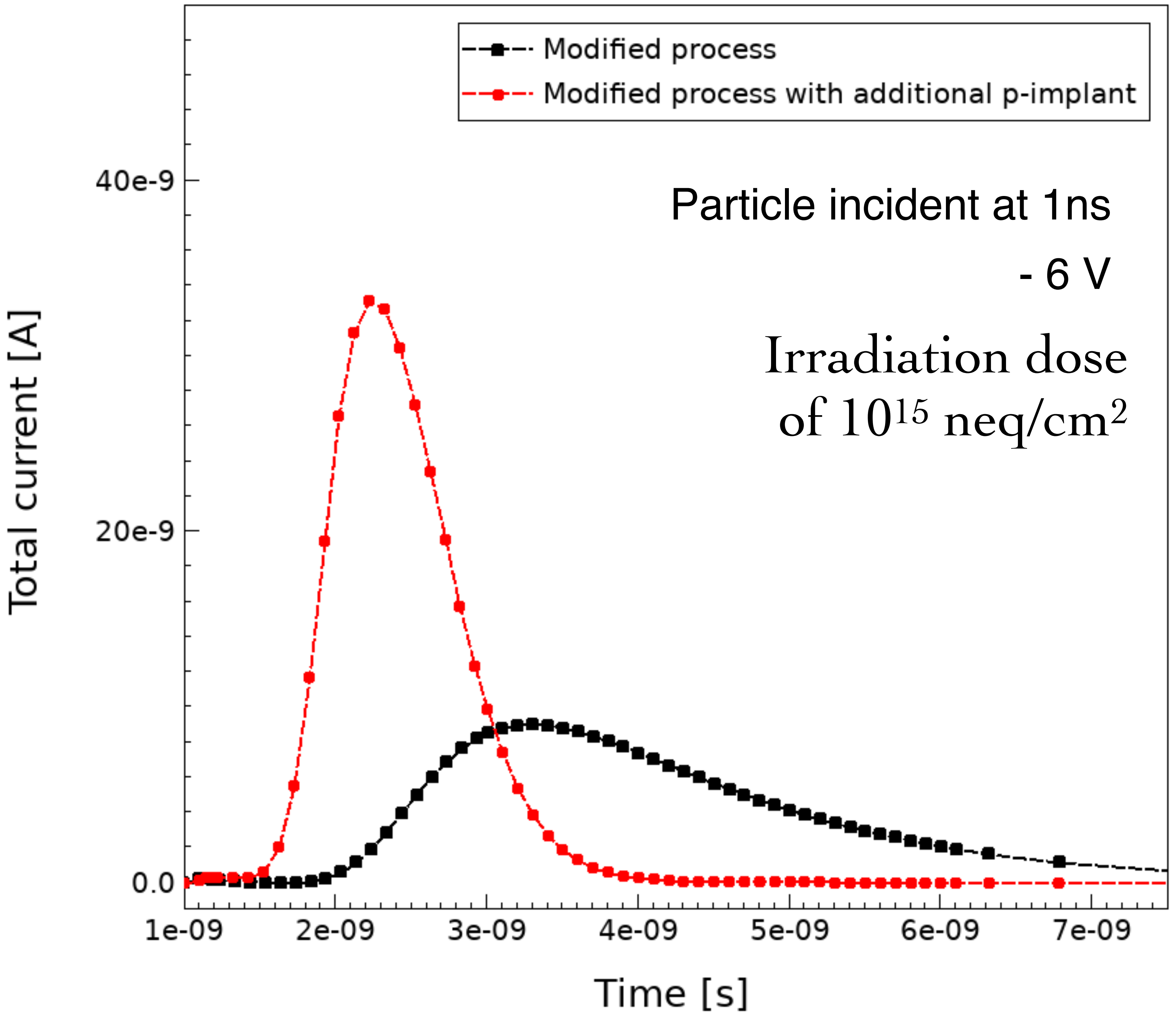
—> Room for improvement

Future prospects - smaller pixel sizes - current pulses after irradiation

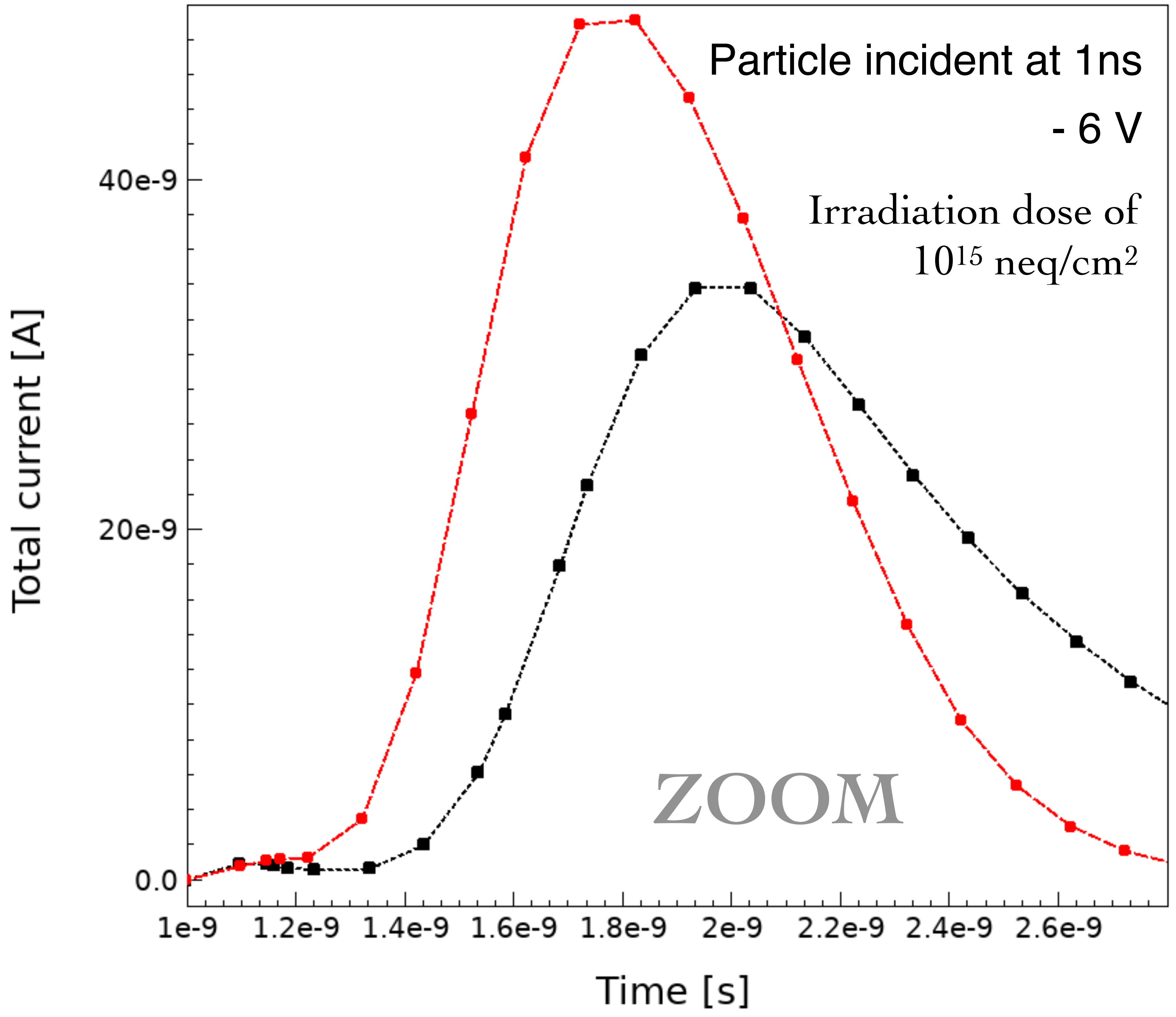
Pixel size 36.4 x 36.4 µm²:



Pixel size 28 x 28 µm²:



Pixel size 20 x 20 µm²:

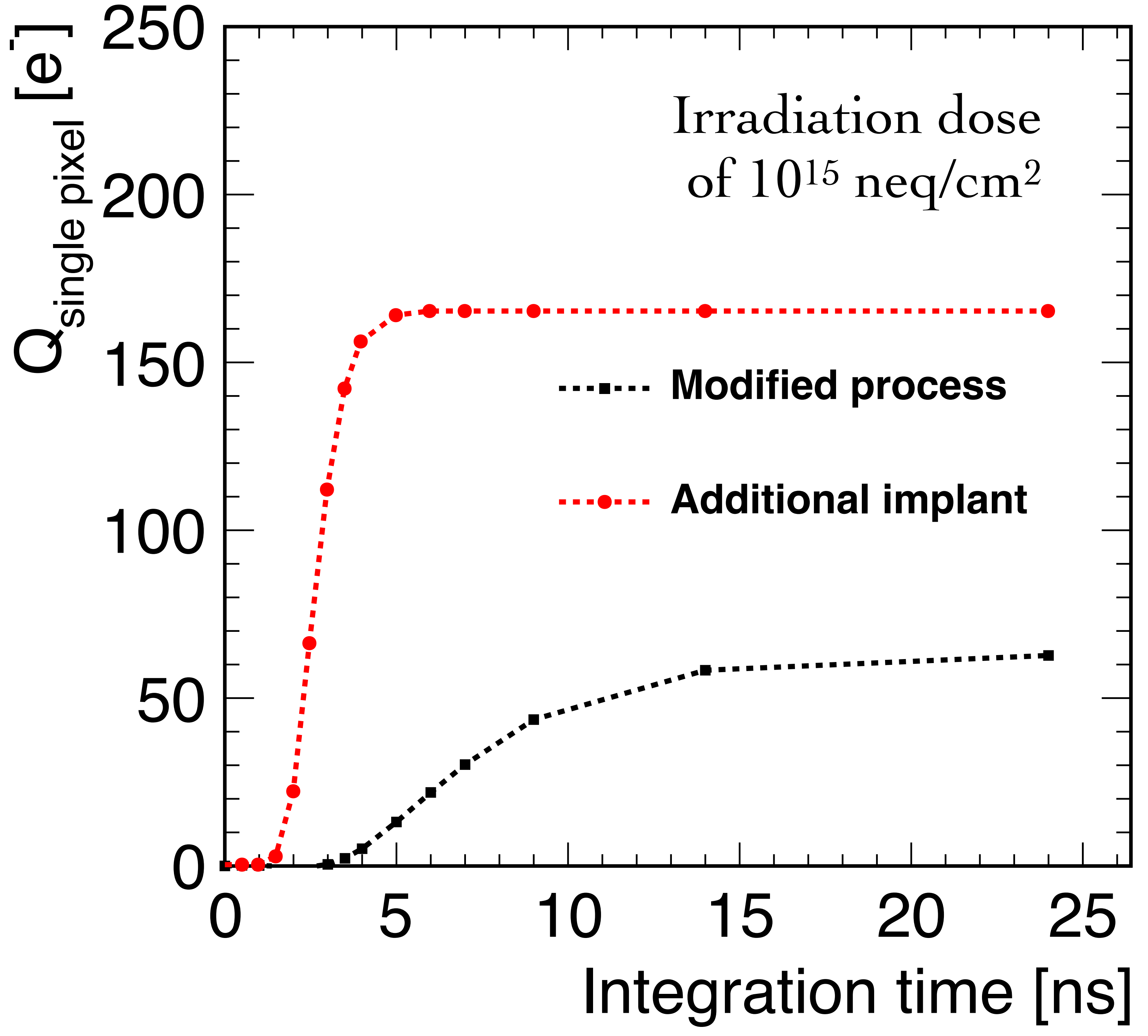


—> Even for very small pixel size of 20 µm the additional p-implant improves significantly the rise and fall time of the current pulses

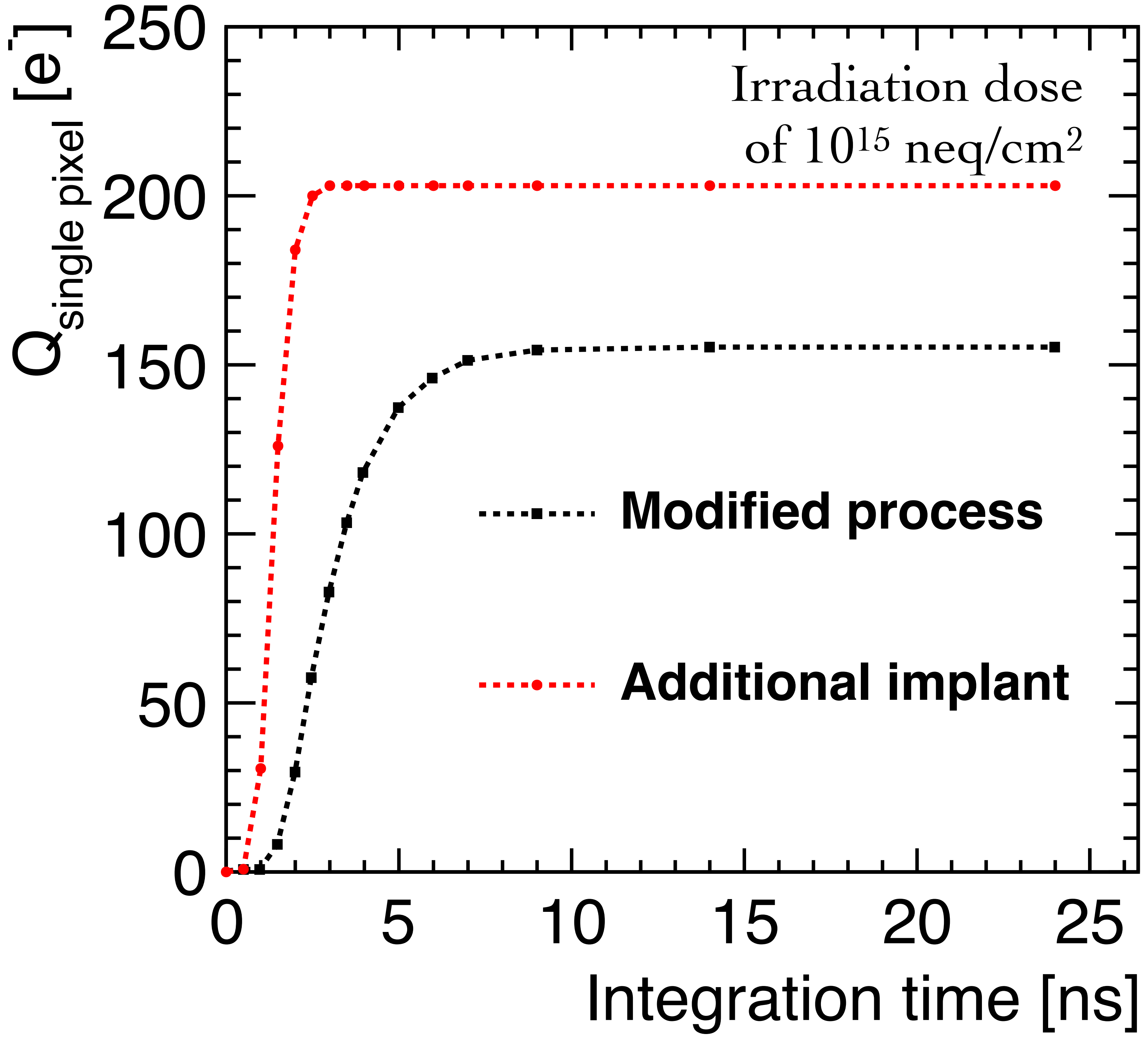
—> Potential for future technologies —> sub-nanosecond timing (room for further improvement)

Future prospects - smaller pixel sizes - charge after irradiation

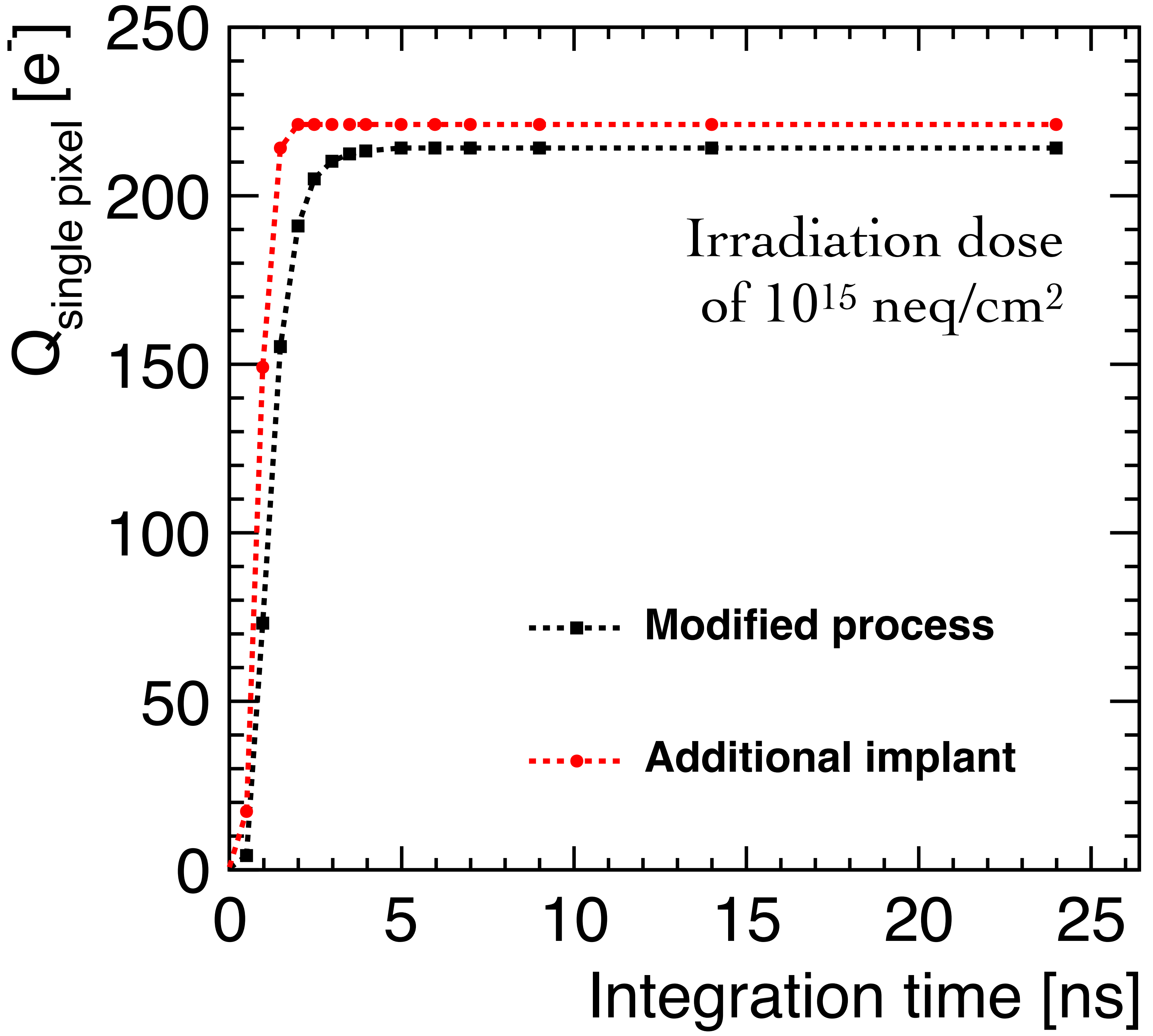
Pixel size 36.4 x 36.4 μm²:



Pixel size 28 x 28 μm²:



Pixel size 20 x 20 μm²:



—> Additional p-implant for pixel size of 36.4 x 36.4 μm² recovers charge lost due to larger pixel size w.r.t. pixel size of 28 x 28 μm²

—> Reducing pixel size gives a substantial benefit

Summary

Additional p-implant and gap in n-layer shape the field lines towards the collection electrode

—> Significant improvement of the charge collection time

—> Higher radiation tolerance and more precise time stamping capability for given pixel size

—> Implemented in ATLAS Mini-MALTA submission (*see talk of Roberto Cardella)*

Crucial to consider the lateral electric field and the vertical electric field (along the sensor depth) separately to understand and optimise performance

—> A higher backside voltage might help depending on the sensor layout and absolute value

Future prospect - smaller pixel sizes:

—> Additional p-implant and gap in n-layer significantly improve the charge collection time also for smaller pixels

Thank you!

Backup

Proposed concept

<u>State of the art:</u>
charge collection limited by pixel size

Precise timing

Radiation hardness

Fast charge collection

Smaller pixels

Challenging to fit digital functionality

Need to eliminate red links to achieve a faster charge collection for current technologies

<u>Proposed concept:</u>
achieve fast charge collection for larger pixels

Precise timing

Radiation hardness

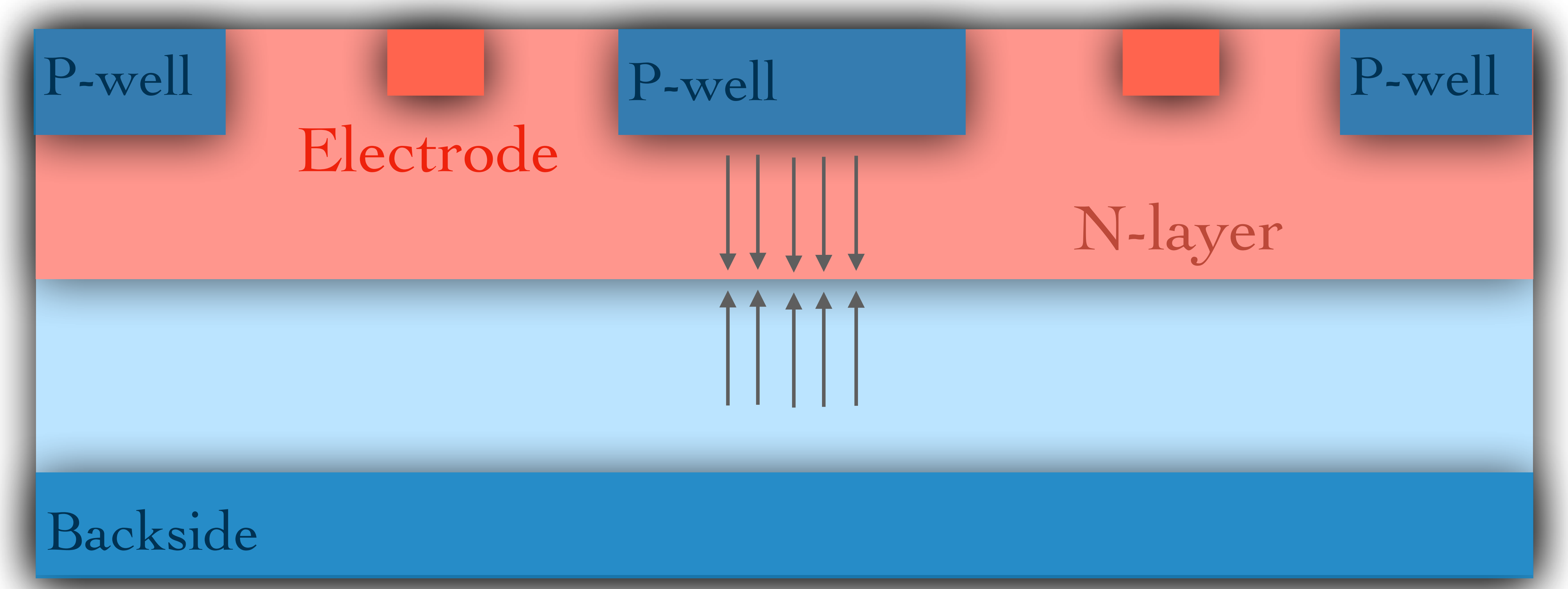
Fast charge collection

Larger pixels

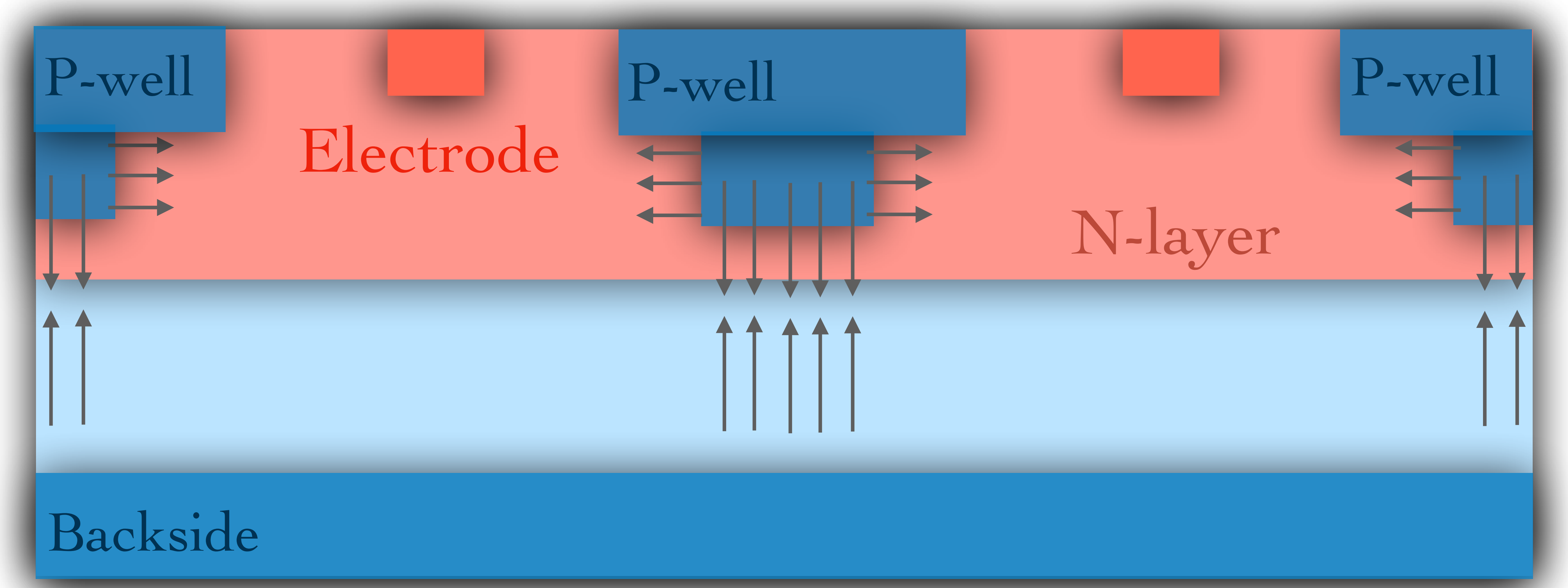
Possibility to fit digital functionality

Concept to reduce impact of electric field minimum - bending the field lines towards the collection electrode

Modified process:



Additional p-implant:



Gap in n-layer: