Tracking and Timing with Induced Current Detectors

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Introduction

There has been increasing interest in fast timing as well as “intelligent” detector systems. I would like to present some ideas for alternate designs of such systems looking at how technology for silicon-based detectors might evolve. This is a talk about the future - next generation of collider experiments.

We focus on capability enabled by new technologies that provide small pixels with low capacitance and sophisticated processing

- 3D integration of sensors and electronics
- Monolithic active devices
- Semiconductor substrate engineering

Some Basics - time resolution

- The rule of thumb for the time resolution of a system dominated by jitter is:

Jitter

$$\sigma_t \sim \sigma_{noise}\left(\frac{\partial V}{\partial t}\right) \sim t_r\left(\frac{Noise}{Signal}\right)$$

Front end noise

$$\sigma_n^2 = \frac{C_L^2(4ktA)}{g_m t_a}$$

Time resolution

$$\sigma_t \sim \frac{C_L}{\sqrt{g_m t_a}} \frac{\sqrt{t_a^2 + t_d^2}}{Signal}$$

- slew rate (dV/dt) is related to the inverse amplifier rise time, C_L is the load capacitance t_d and t_a are the detector and amplifier rise times and g_m is the input transistor transductance - related to input current, and A is a characteristic of the amplifier.
  - Fast timing -> large S/N, fast amp, small load capacitance
  - There are tradeoffs available

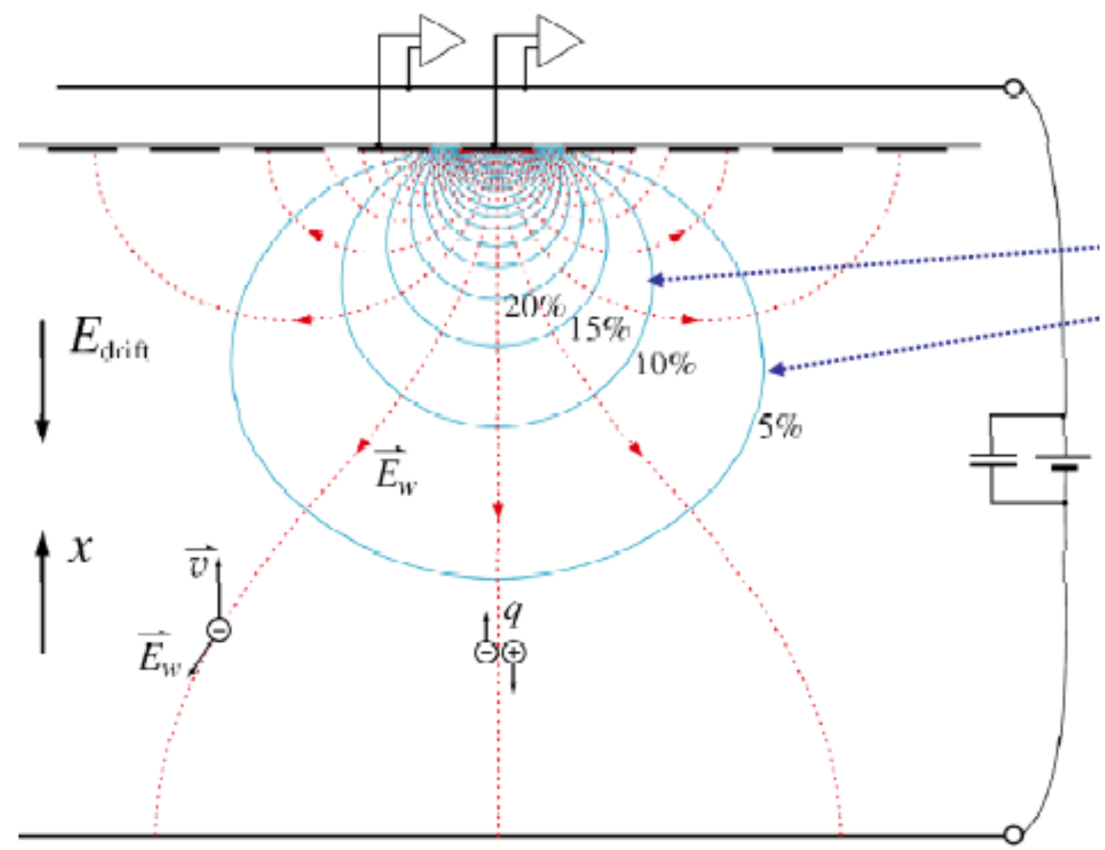
More Basics - Signal Development

- Signal induced by moving charges depends on work done by circuit. The charge induced on an electrode depends on the coupling between the moving charge and the electrode (Ramo's theorem)
- We usually work with simple parallel plate systems
- In a multi-electrode system the induced current on an electrode depends on the velocity of the charge and the value of the effective "weighting" field
- Weighting field is calculated with 1 V on measuring elected, 0 V on others
- There are fast transient induced currents on neighbor electrodes that integrate to zero - can we use them?

$$i = -q\vec{E}_w \times \vec{v}$$

$$Q_s = \int i\,dt = q\int \vec{E}_w d\vec{x}$$

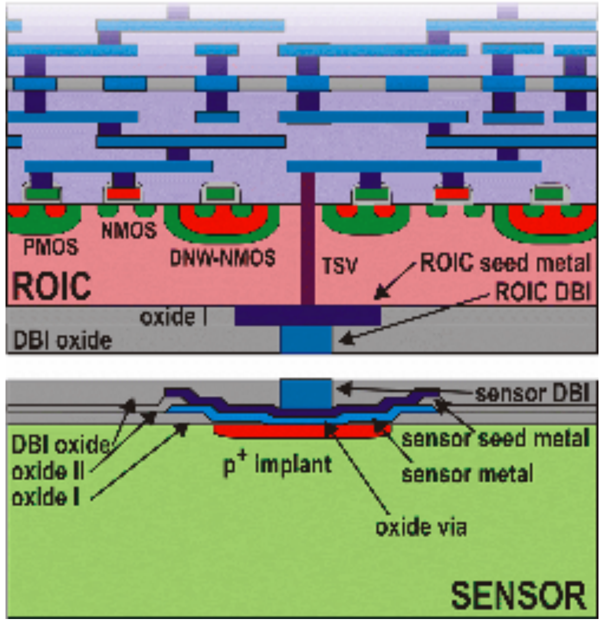
$$Q_{1\to 2} = q(V_{w2} - V_{w1})$$

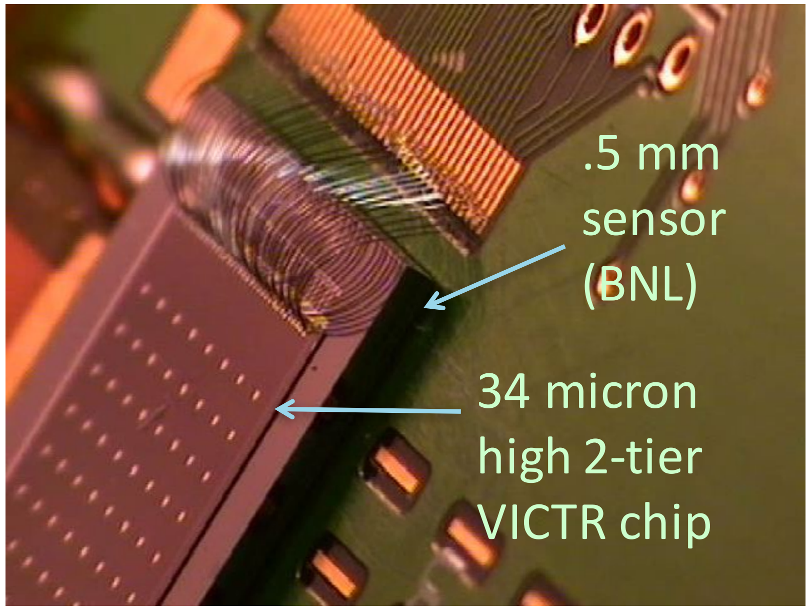


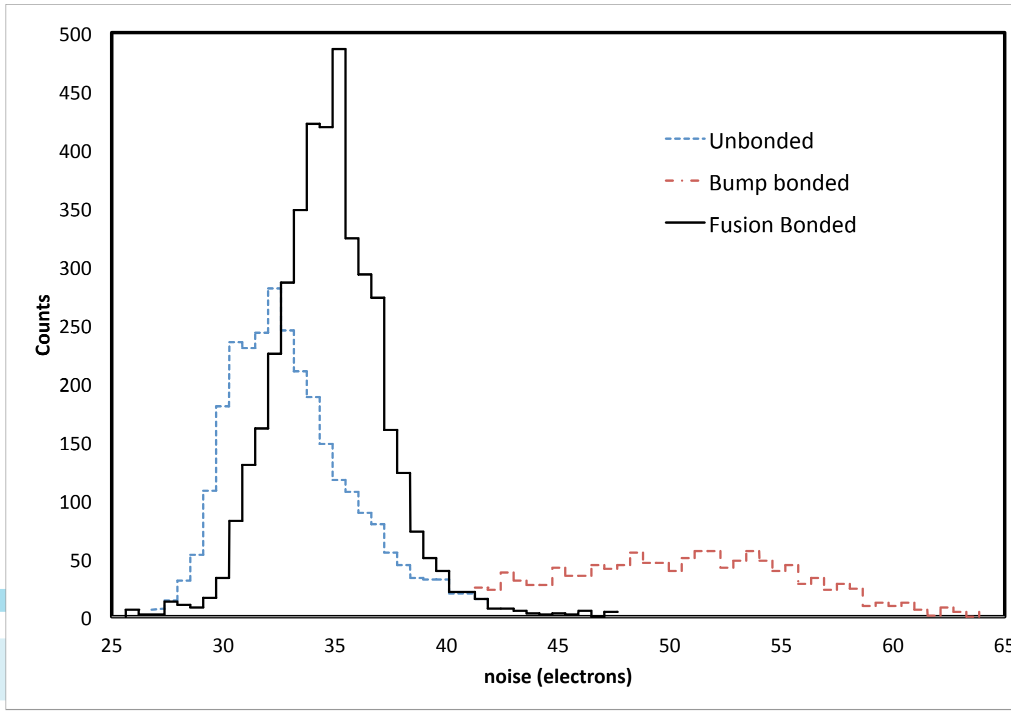
3D Integration and small pixels

Fermilab has been involved the development of 3D sensor/ASIC integration for almost a decade and have demonstrated (with industrial partners):

- Hybrid bonding technology
  - Oxide bonding with imbedded metal through silicon vias (TSV)
- Bond pitch of 4 microns
- First 3-tier electronics-sensor stack
- Small pixels with ADC, TDC (24 microns)
- Small TSV capacitance (~7 ff)
- The noise in hybrid bonded VIPIC 3D assembly is almost a factor of two lower than the equivalent conventionally bump bonded parts due to lower C_{load}





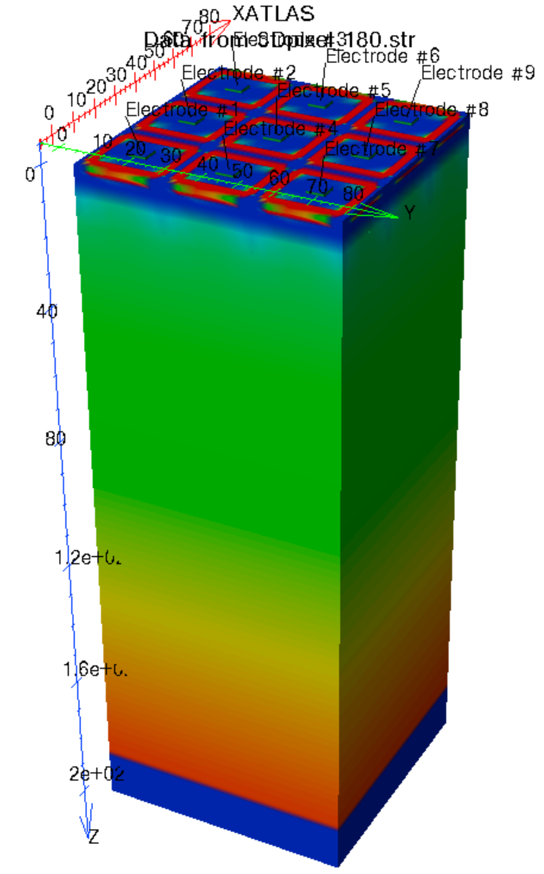


Methodology

We explore simple systems with various pixel sizes, detector thickness and pulse shapes

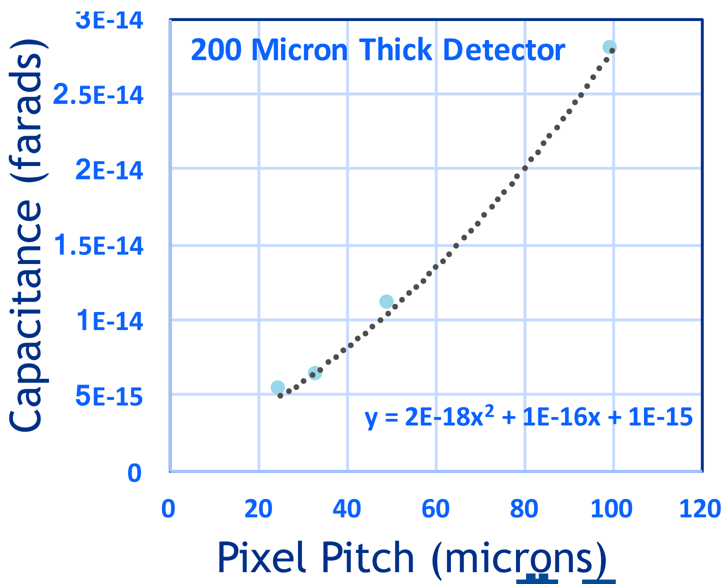
- Build a (Silvaco) TCAD (2D or 3D) detector model
- Inject a Q_{tot}=4 fc pulse
- Extract the capacitance and pulse shapes at the electrodes
- Inject the resulting pulse into a SPICE model of a generic 65nm charge sensitive amplifier including noise
- Analyze the characteristics of the resulting output pulses
- For angled track studies I use simple op amp with defined bandwidth model with adjustable bandwidth

3D 9 pixel model



Pulses from "x-ray" at~100µ 200µ thick detector

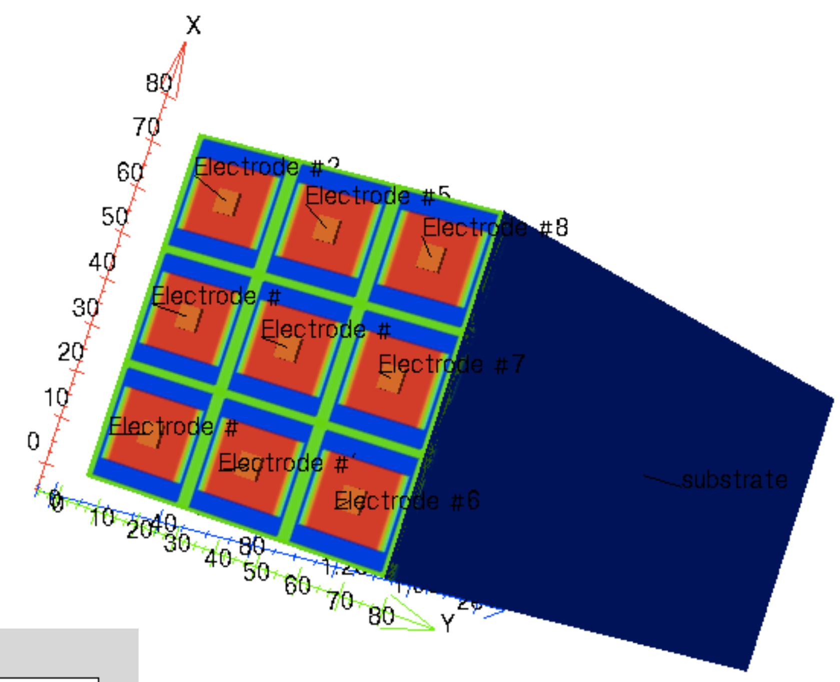
TCAD Simulation

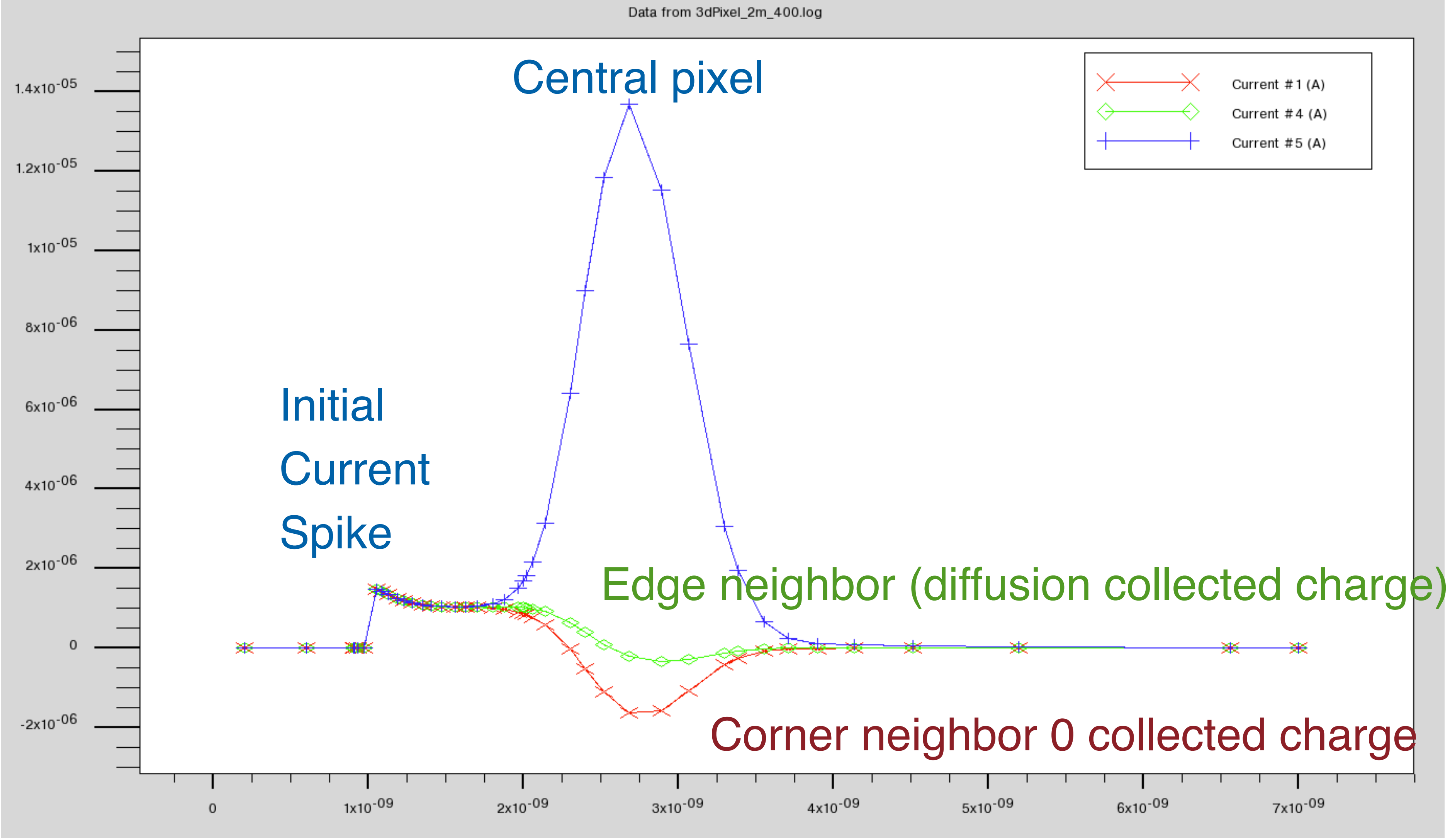


Simple Example - X-Rays

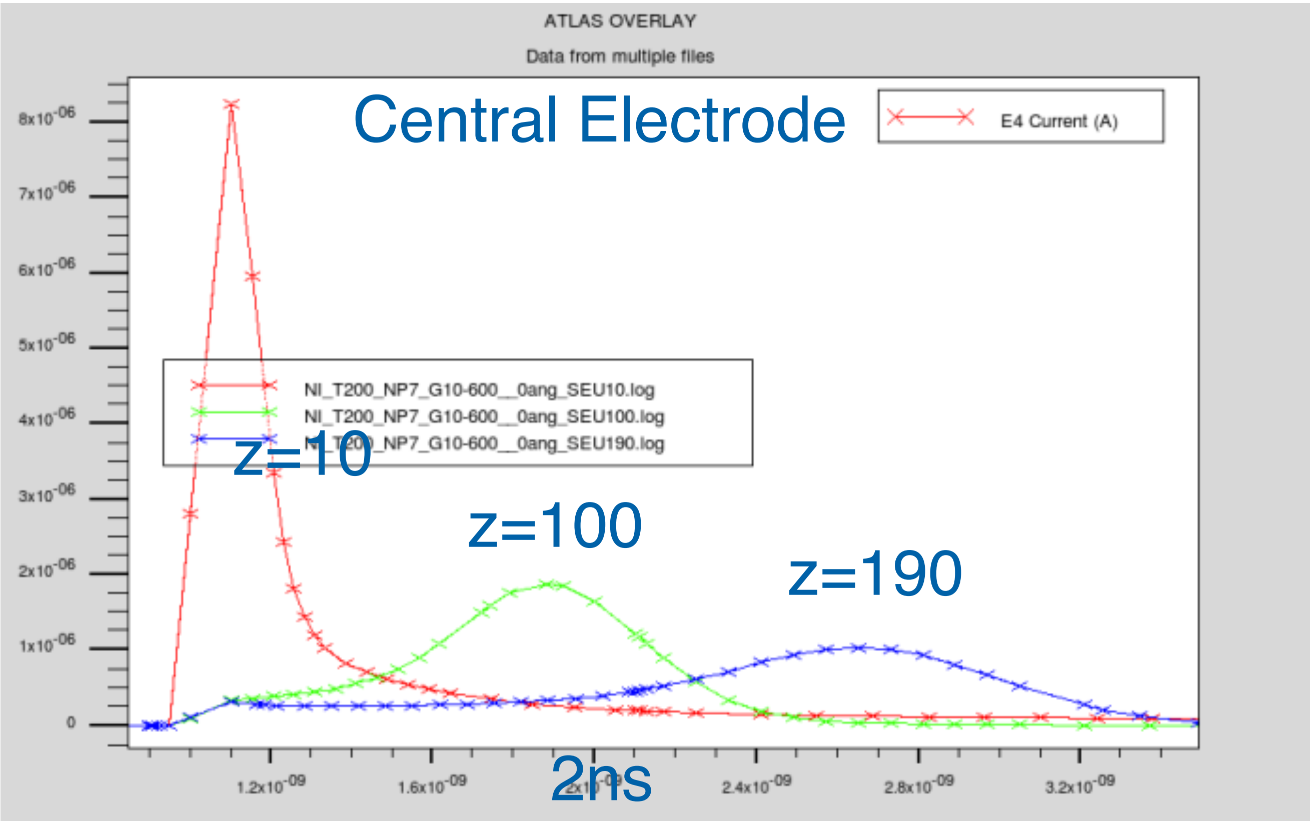
Suppose an application requires fast timing on high energy x-rays

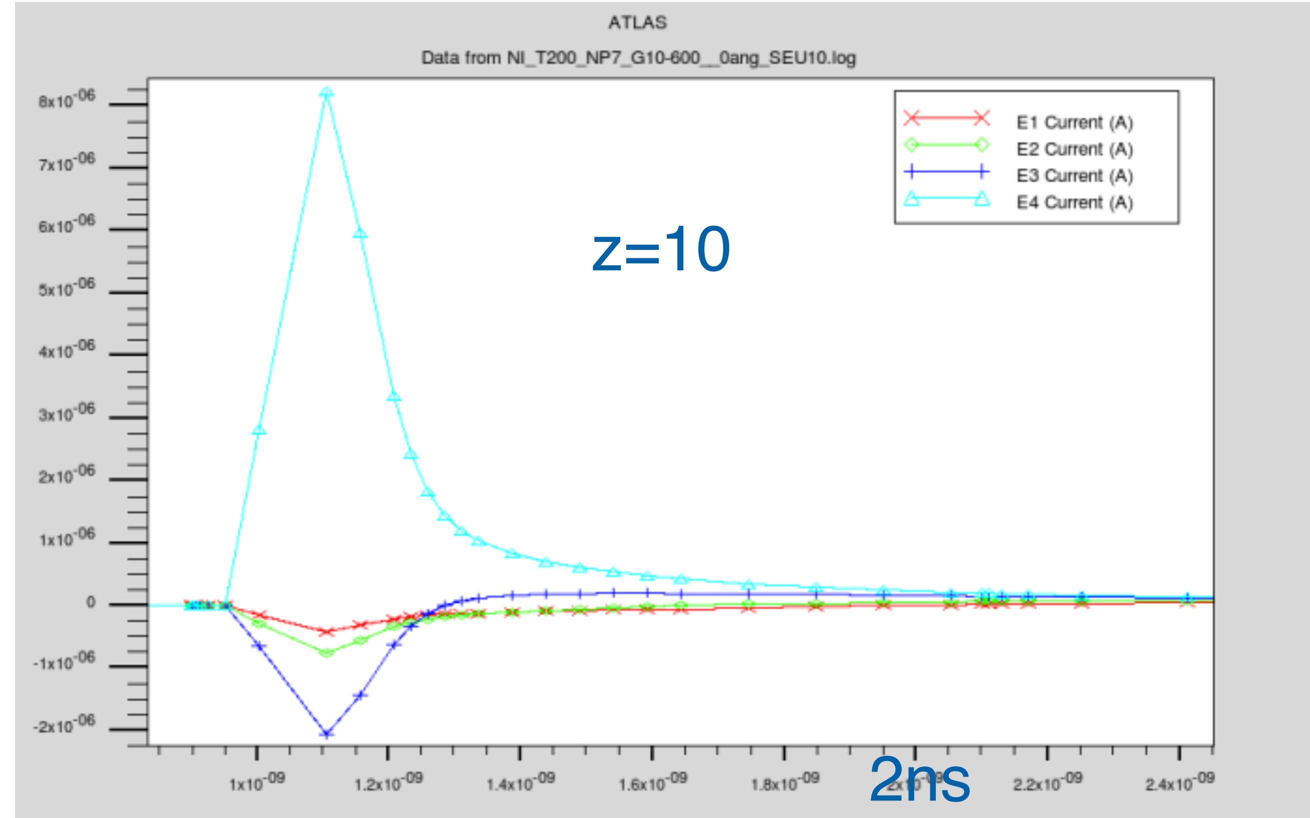
- Usually we would like thin detectors for fast timing, but thin detectors imply low efficiency - can we use induced currents to achieve time resolution in a thick detector?

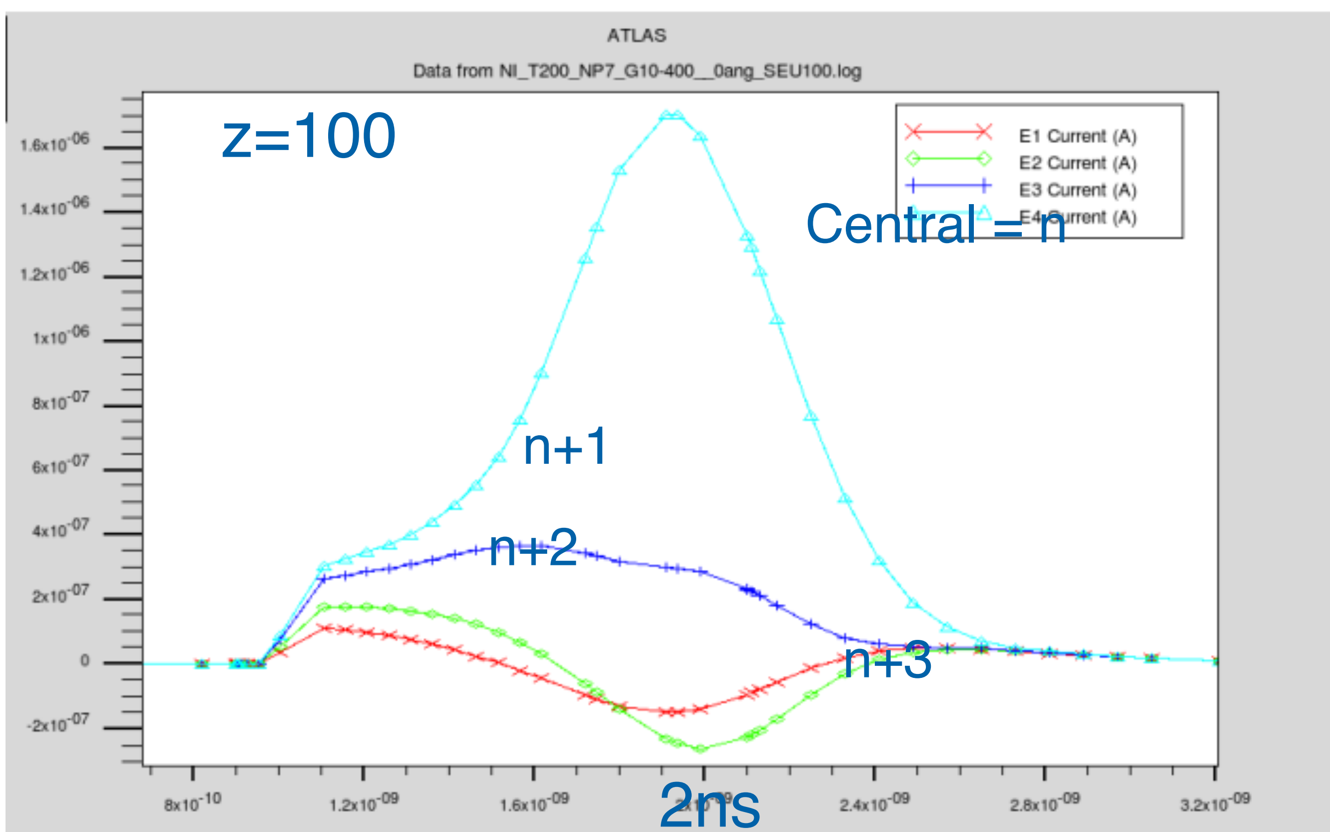


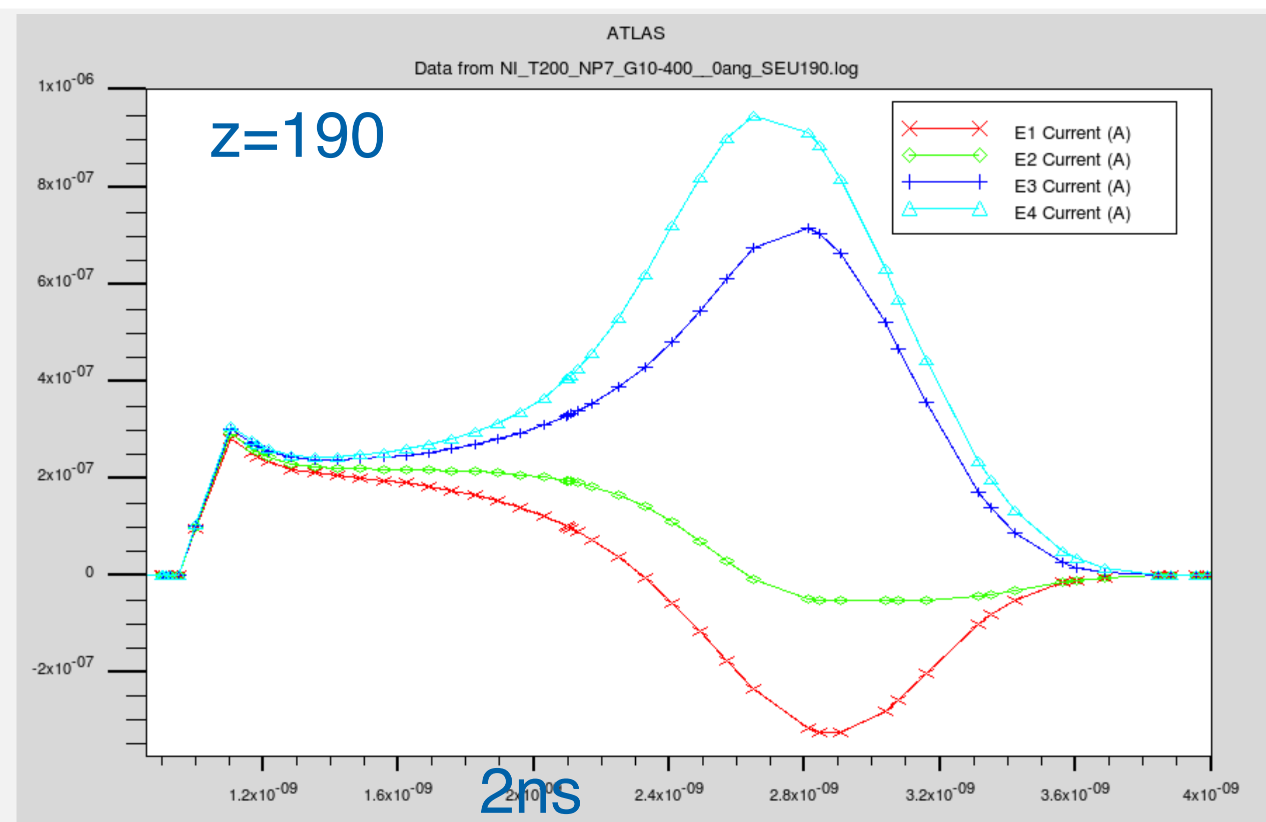


Pulse Shapes - 200 micron detector X-ray 2D Simulation



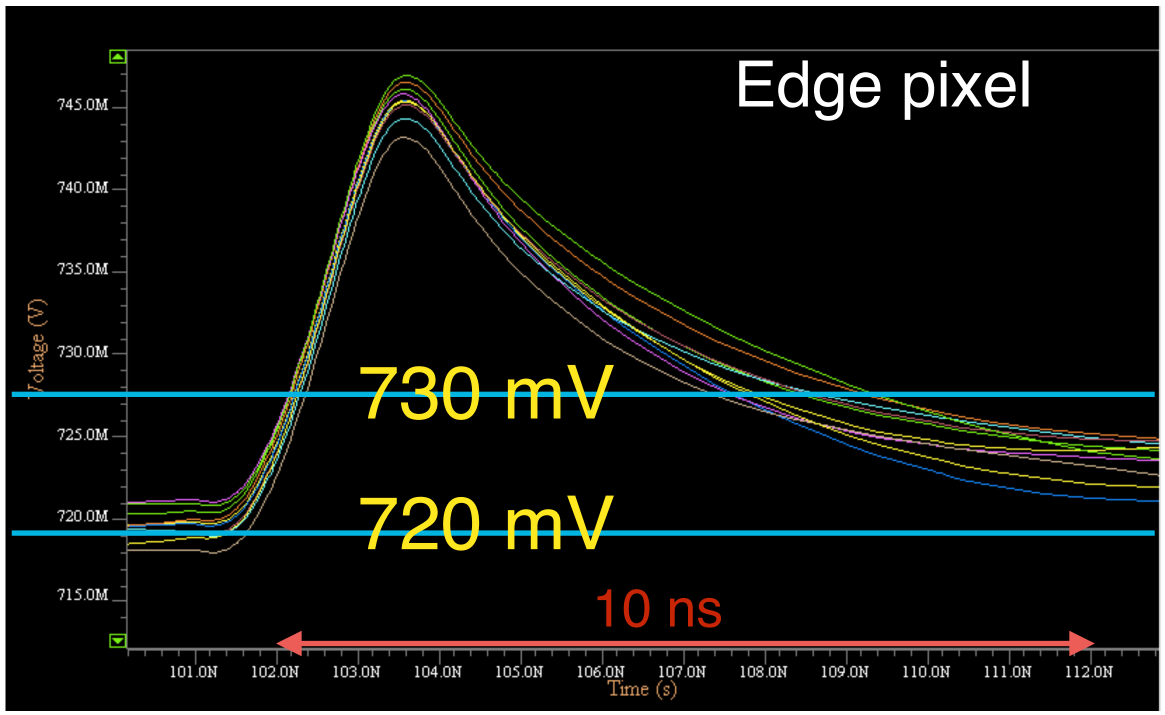


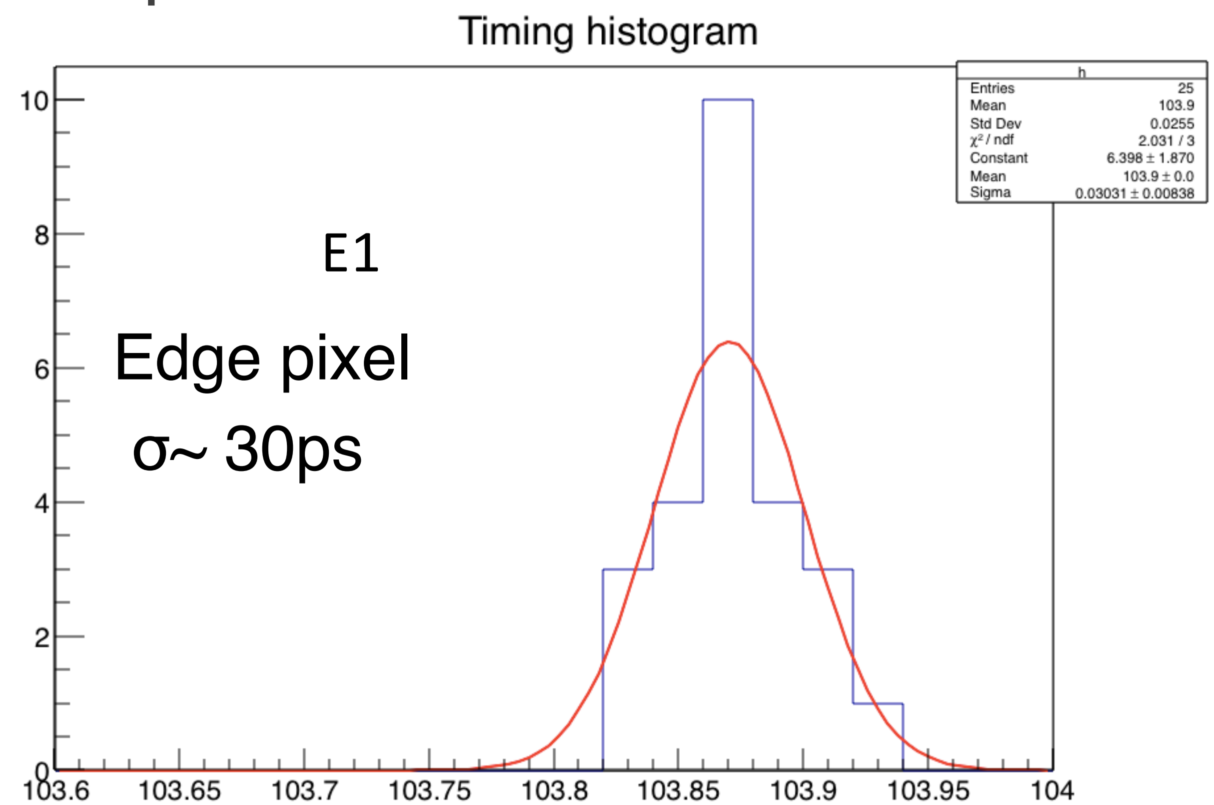


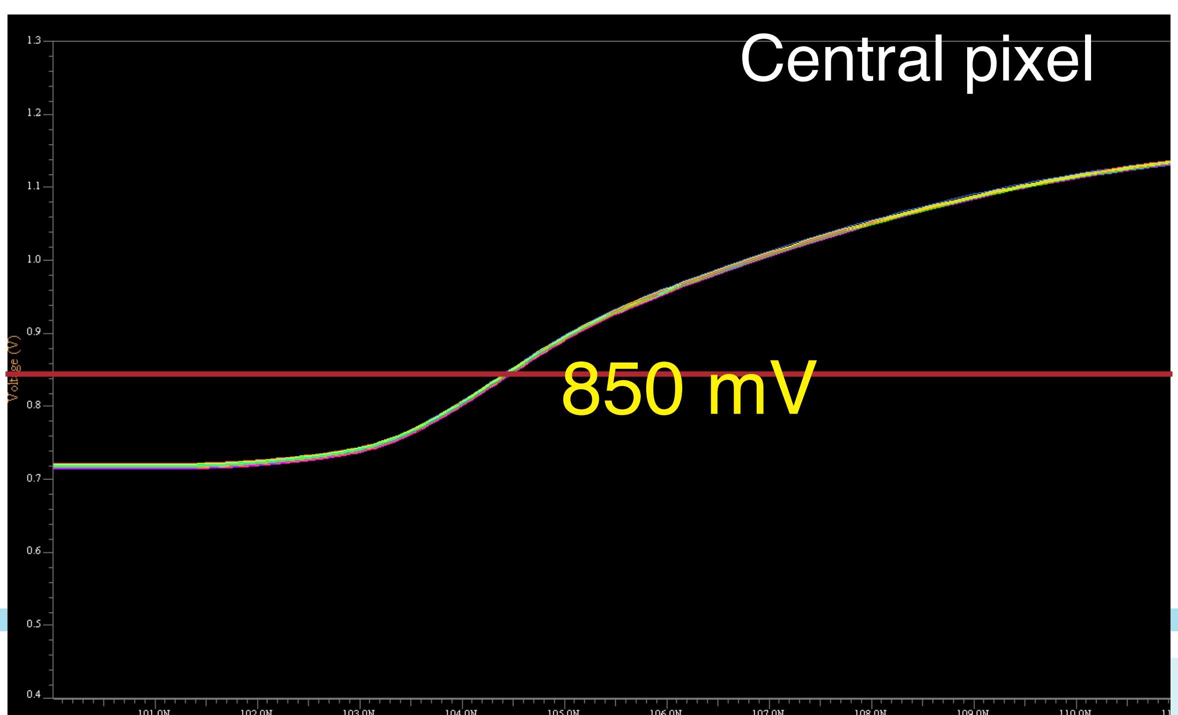


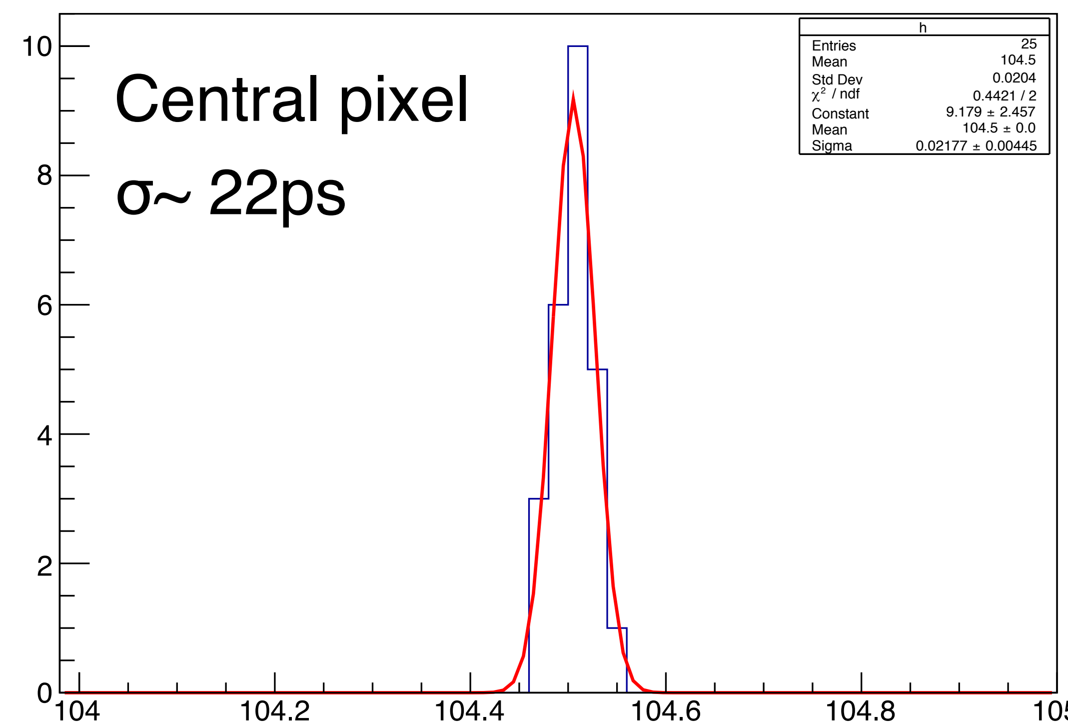
X-Ray With Noise at 185/200 micron depth

- Apply a constant threshold of E1~10 mV, E4~130 mV
- Tabulate time at threshold crossing including noise
- Edge pixel can provide a “start” time stamp if needed



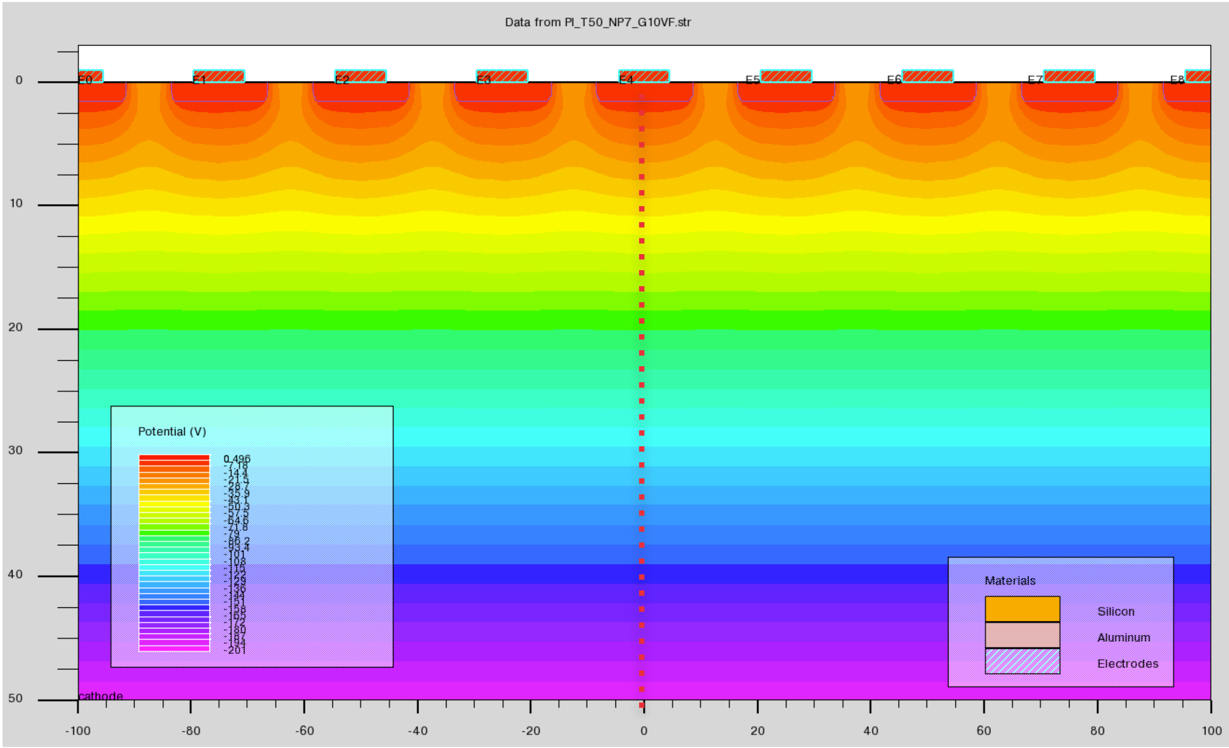




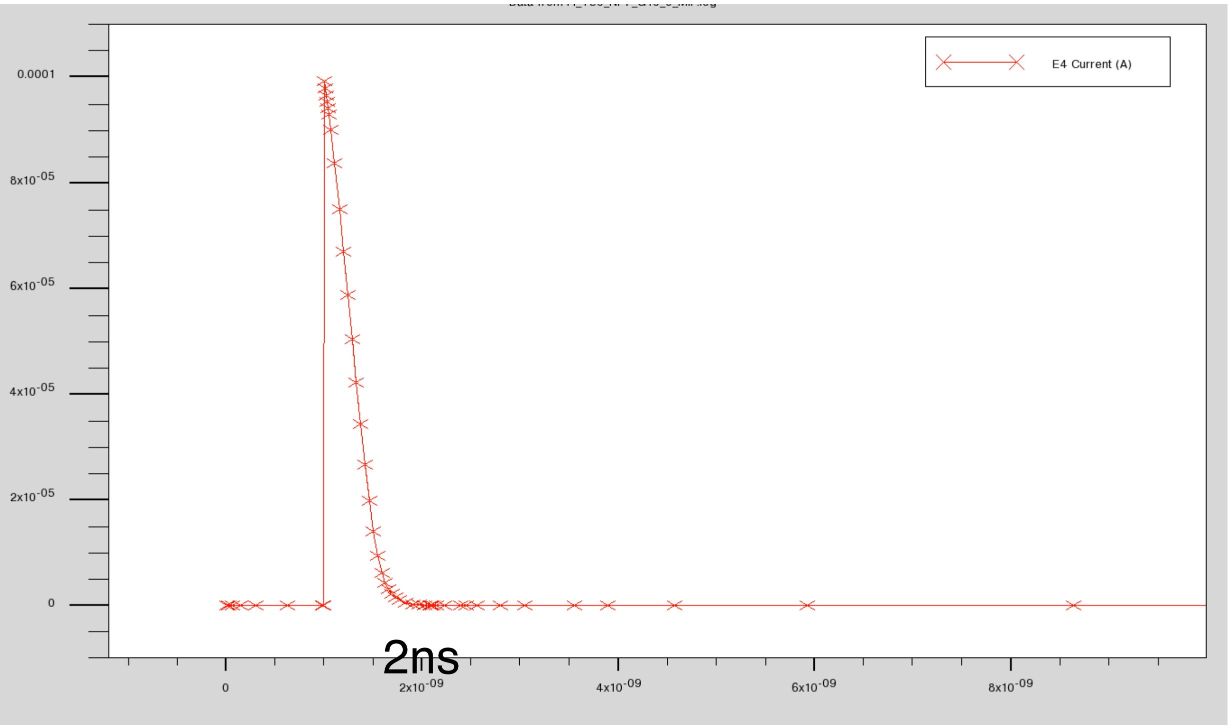


Example - MIP in a 50 micron Detector

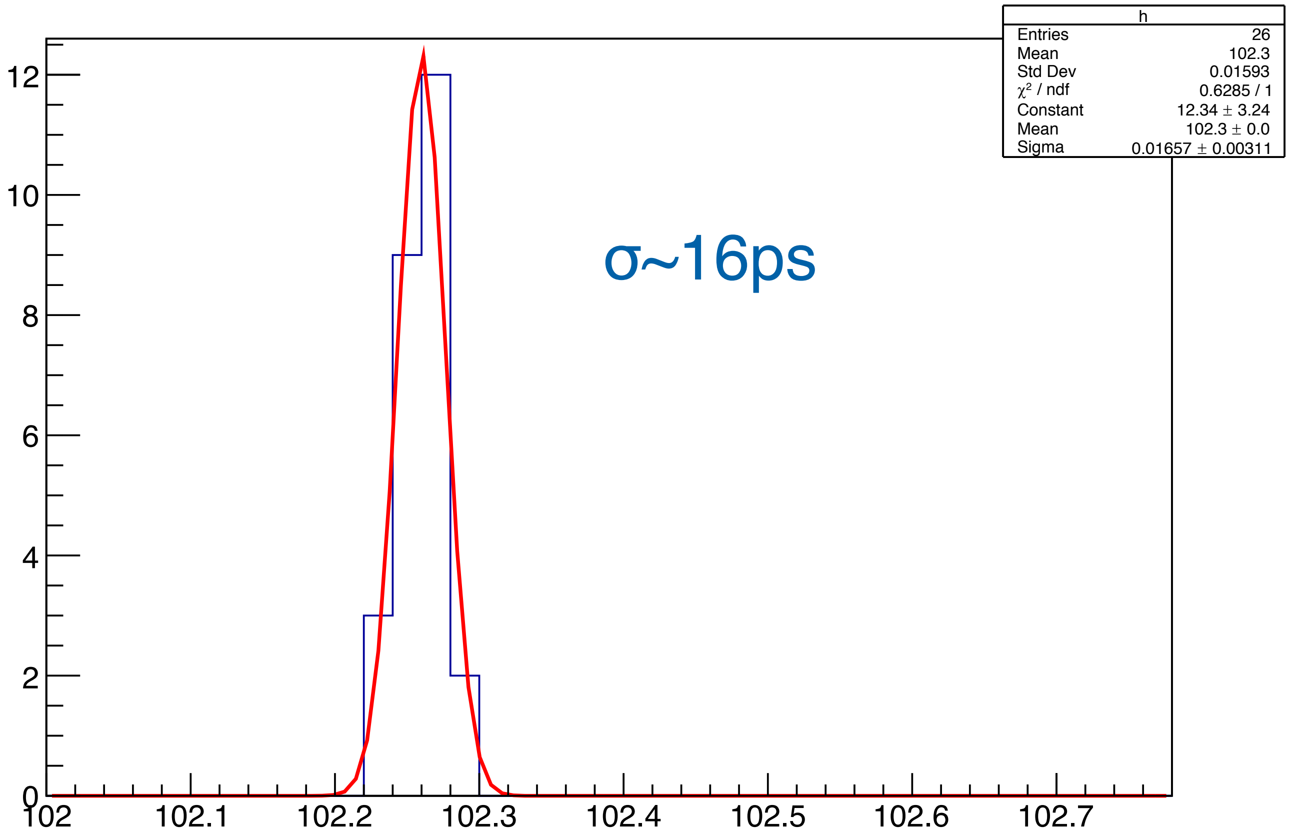
σ~25 micron pitch, 50 microns thick 200 V, sensor potential distribution



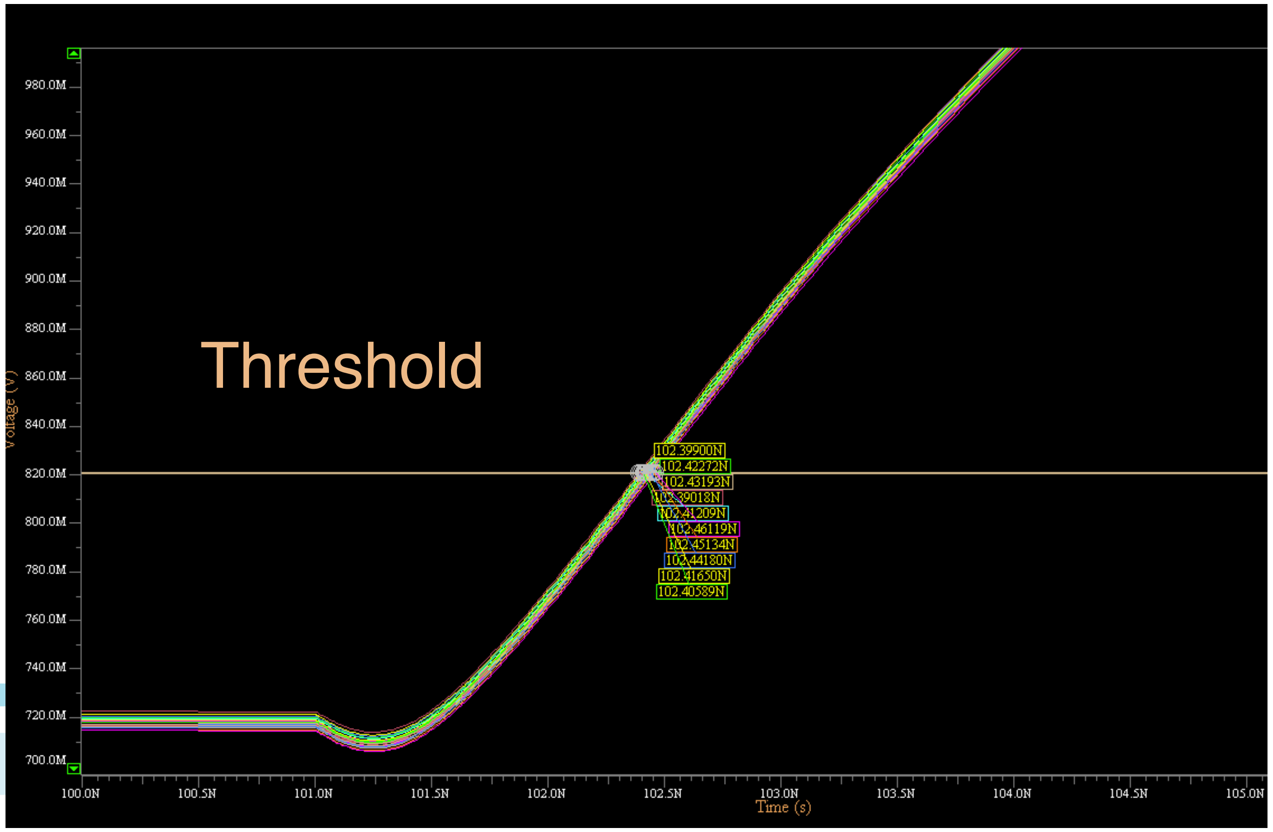
Pulse on central pixel



Timing histogram



Amplifier output with noise, 20ff load



Comments

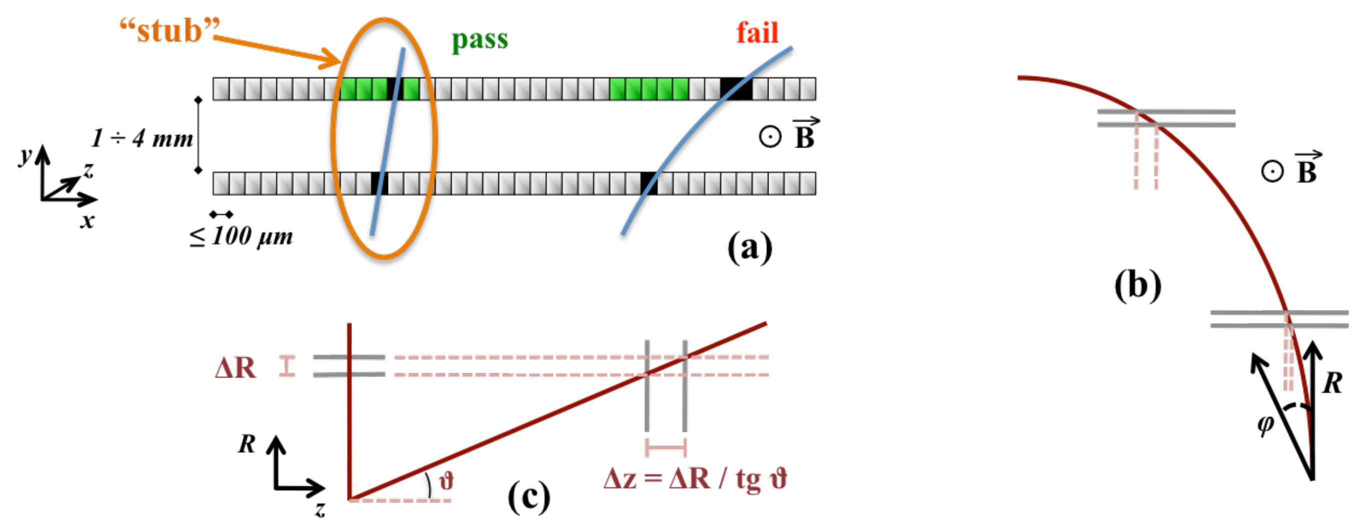
The 20-30 ps resolution will be degraded in a real system

However:

- All pixels with *spacing small compared to depth* will have similar signals ~ 16 pixels for a 25x200 micron sensor x 4 in (uncorrelated) time resolution
- The central pixel will see a large signal within a few ns of the leading edge - initial thresholds can be set low and signals latched only if a central pixel fires at a higher threshold
- The pattern of pixels will provide depth and slope information
- Multiple thresholds or more sophisticated processing can give a time walk correction
- These results are for n-on-p with maximum field at the top. n-on-n sensors have a maximum field at the bottom. The field profiles can be adjusted to suit the application by varying the applied bias

CMS “P_t module”

Pattern Recognition



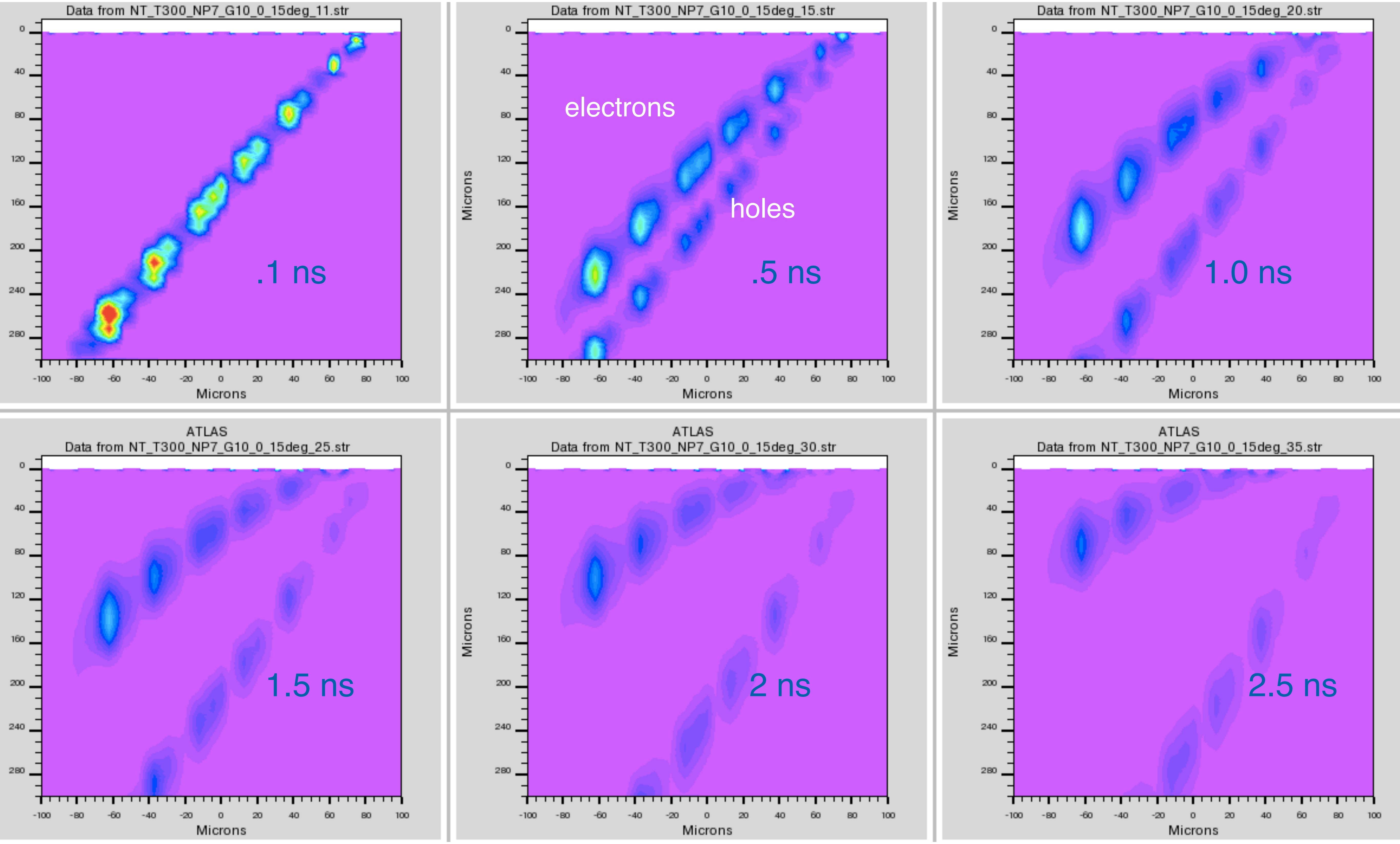
Collider based experiments have to deal with increasingly complex events

- HL LHC with ~200 interactions per crossing
  - The CMS experiment is addressing this with stacked sensor arrays to distinguish low from moderate momentum tracks
  - Can we do this in a single sensor?
- Muon collider experiments with <u>huge</u> decay backgrounds
  - Muon collider studies use timing - fall x 100 short
  - Backgrounds are from various absorber surfaces/angles
  - We can use the pattern of electrode signals to distinguish between signal and background tracks signatures

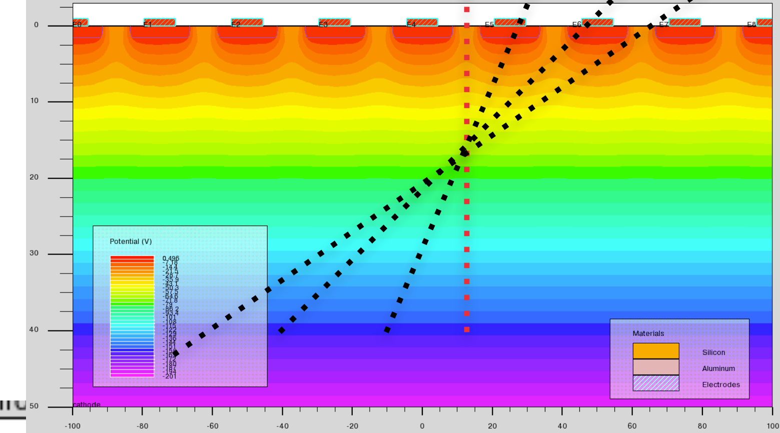
To get a feeling for this we use a 25 micron pitch electrode geometry in a ~300 micron thick sensor.

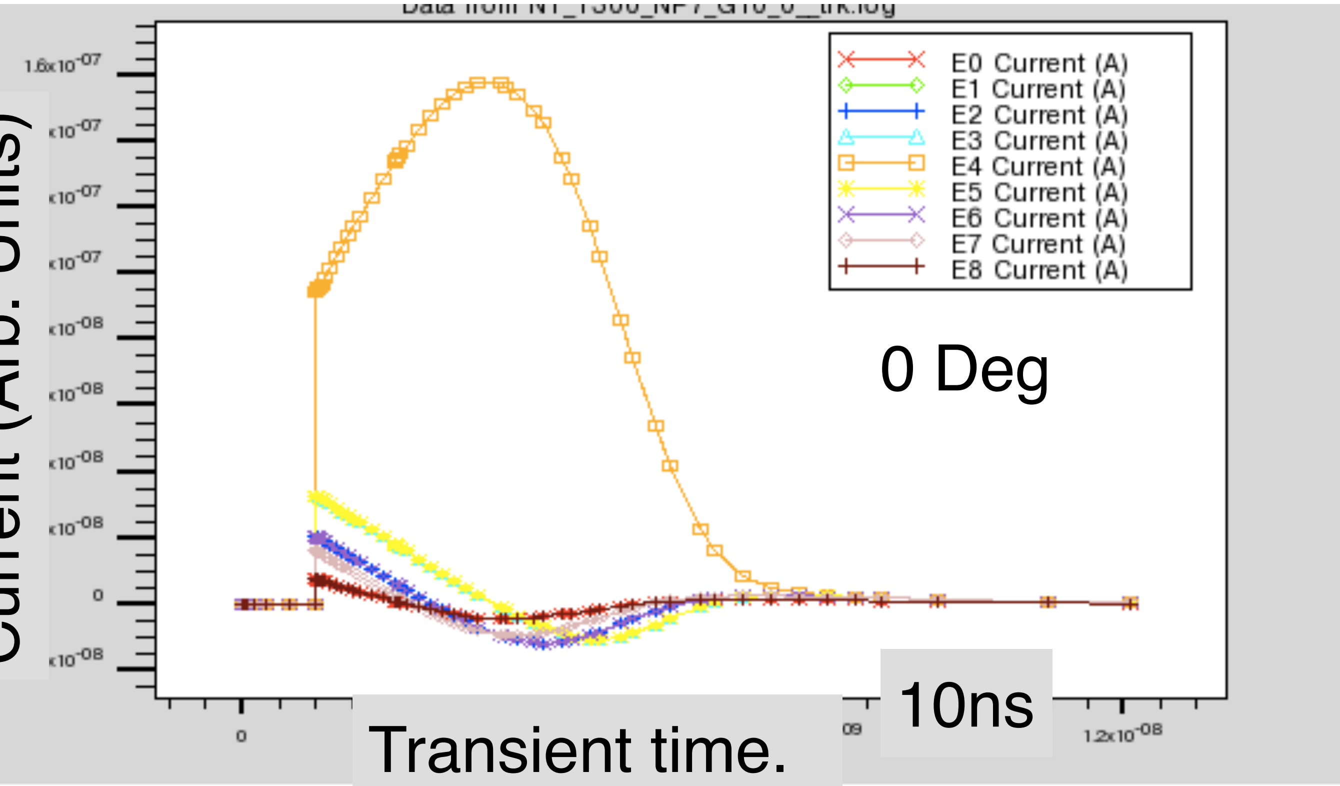
Charge Motion Visualization

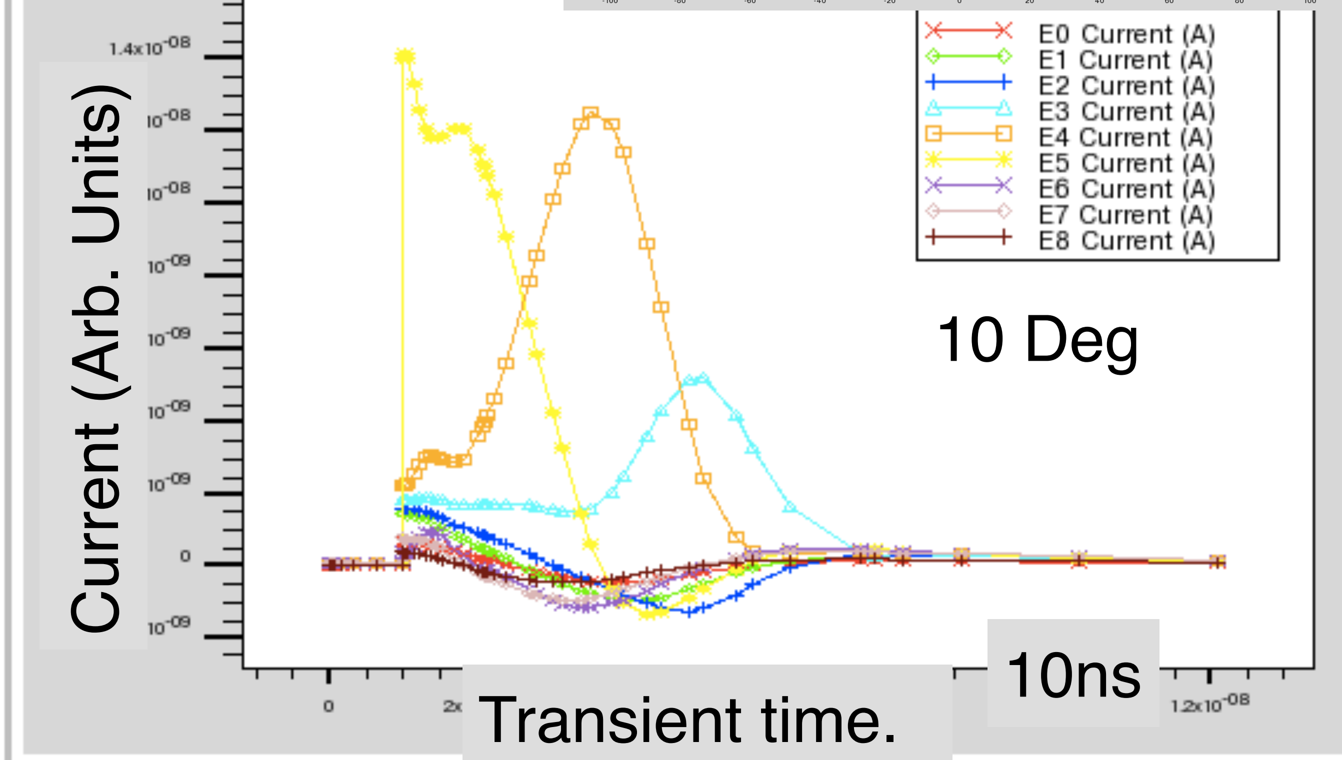
30 degree track, n on n, maximum field at bottom.

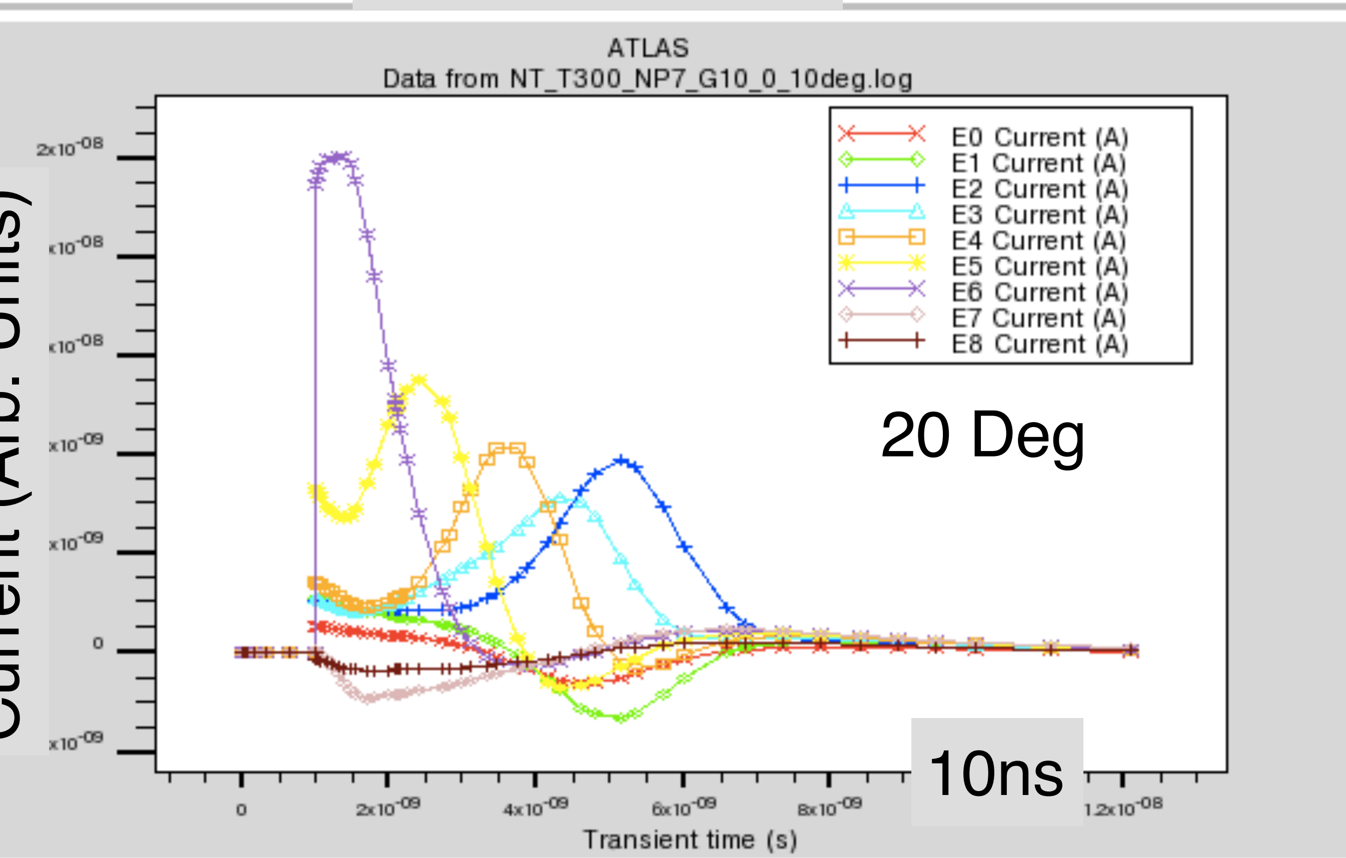


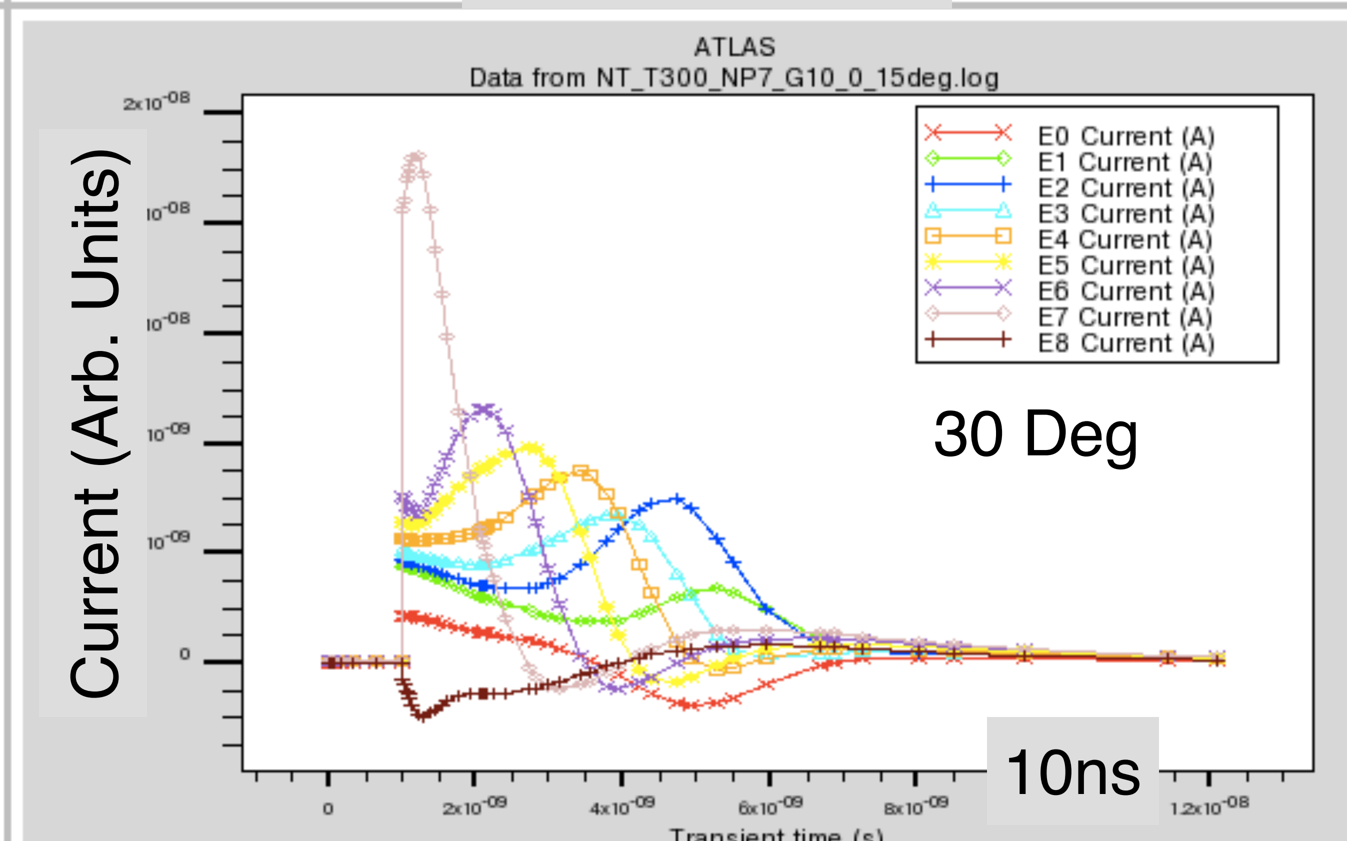
MIPs at various angles



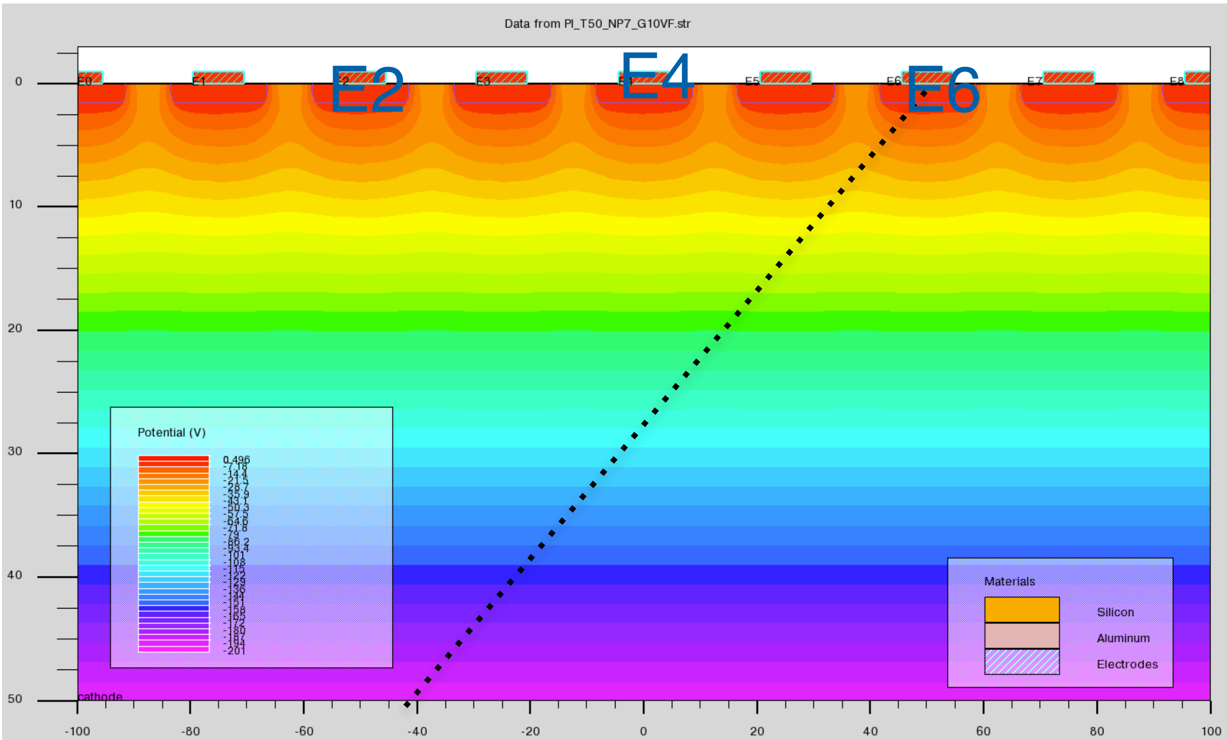


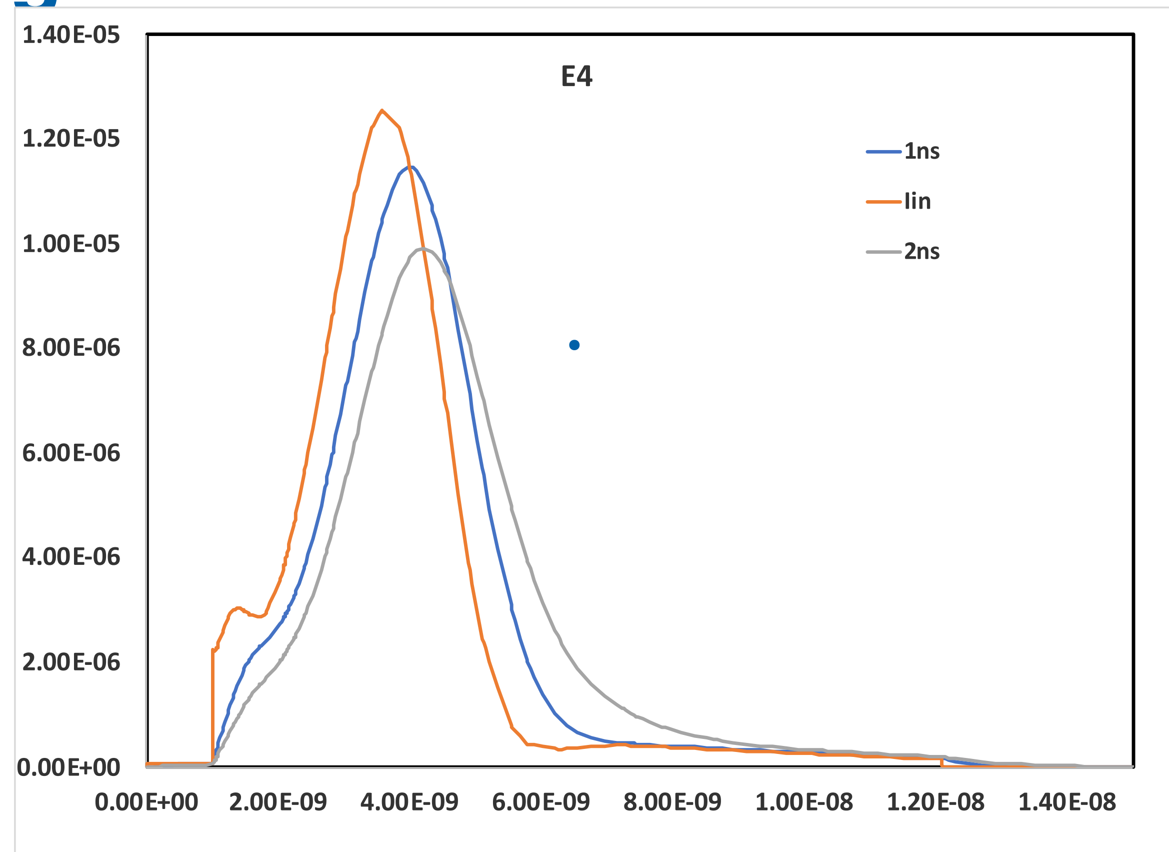






Time resolution and Pattern Recognition





Long drift

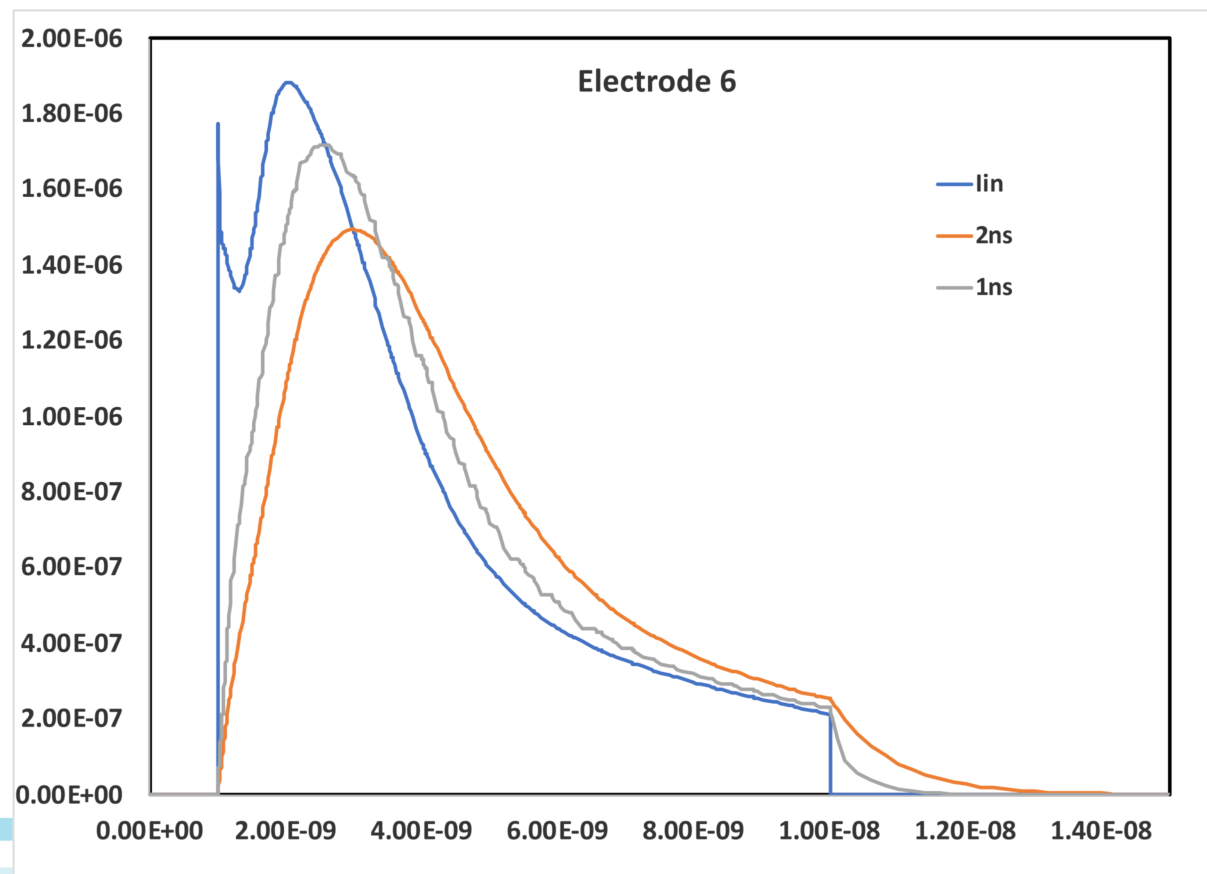
- some collected charge
- dominated by induced current
- difficult to measure secondary peak

Medium drift

- Dominated by collected charge

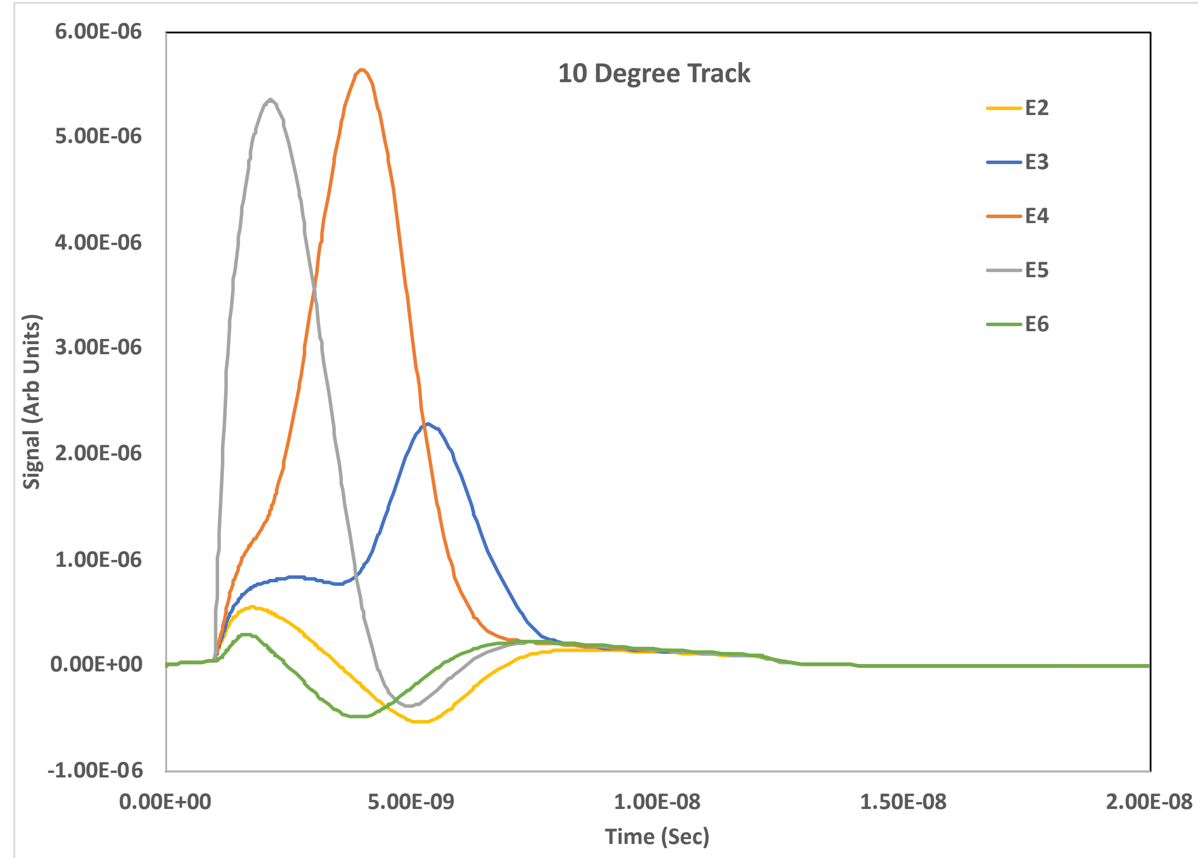
Short drift

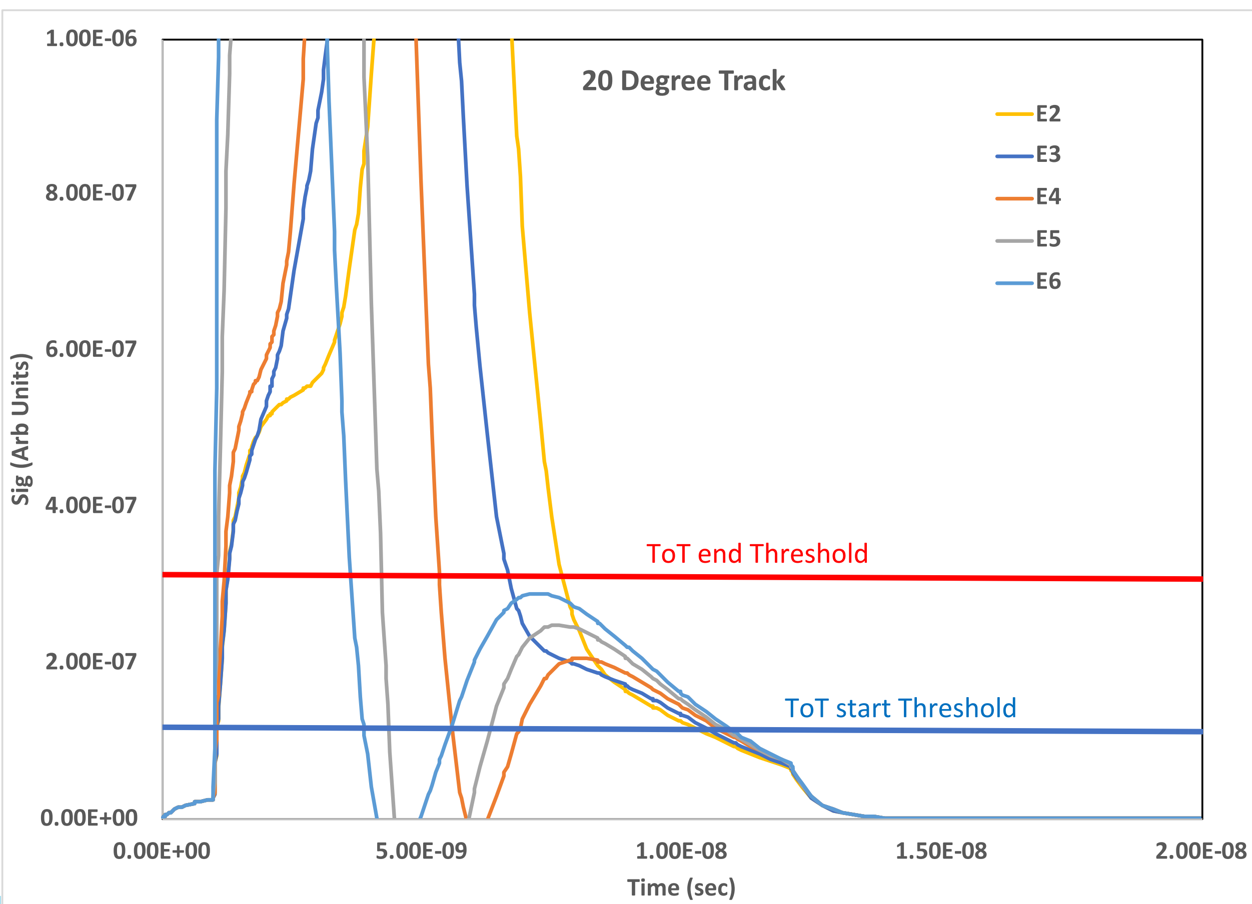
- collected charge similar to induced current
- Induced and collected signals merge

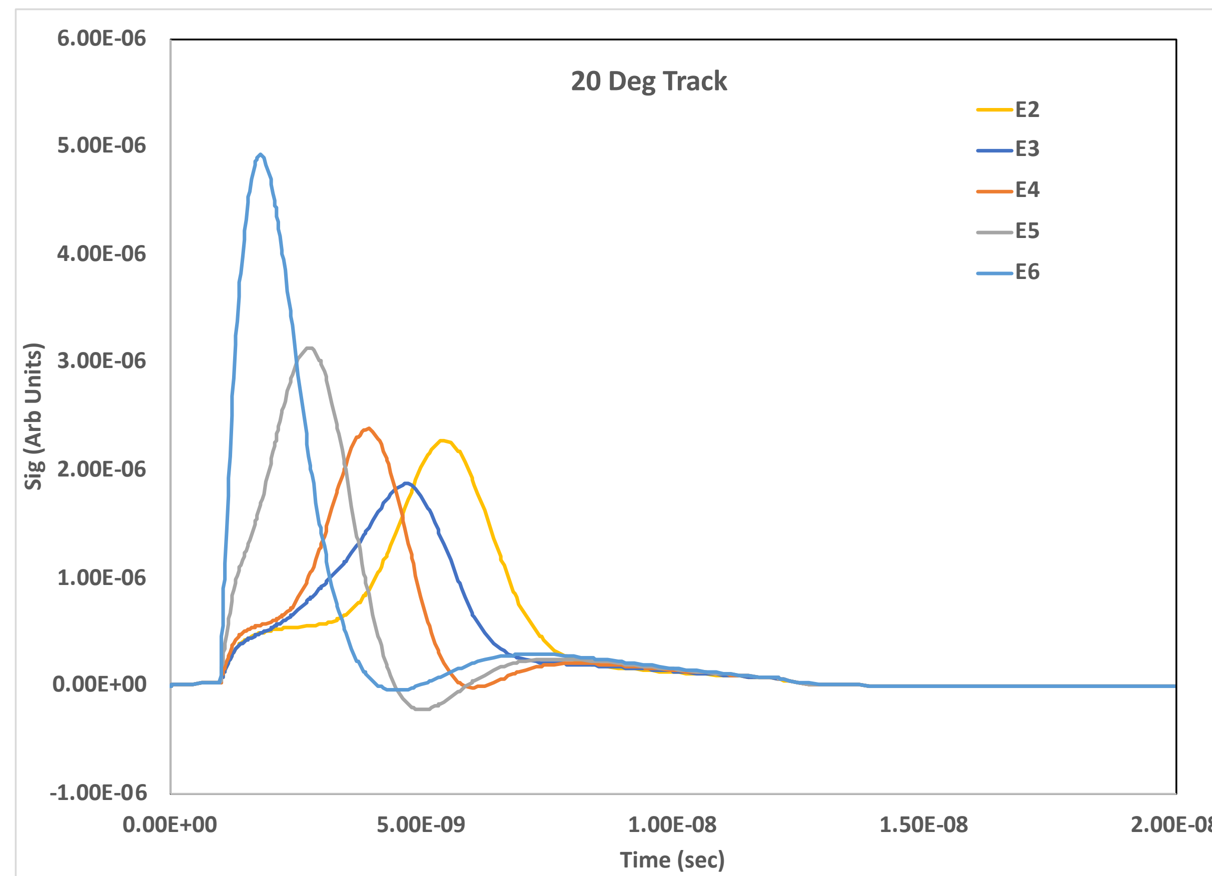


A look at angular resolution

- To try to get a feeling for what time and pulse height resolution is needed we look at 10 and 20 degree tracks
- 1 nanosecond rise time is assumed
- Lowest threshold defines time resolution and provides induced current t0
- Other thresholds provide time structure and shape of secondary peak







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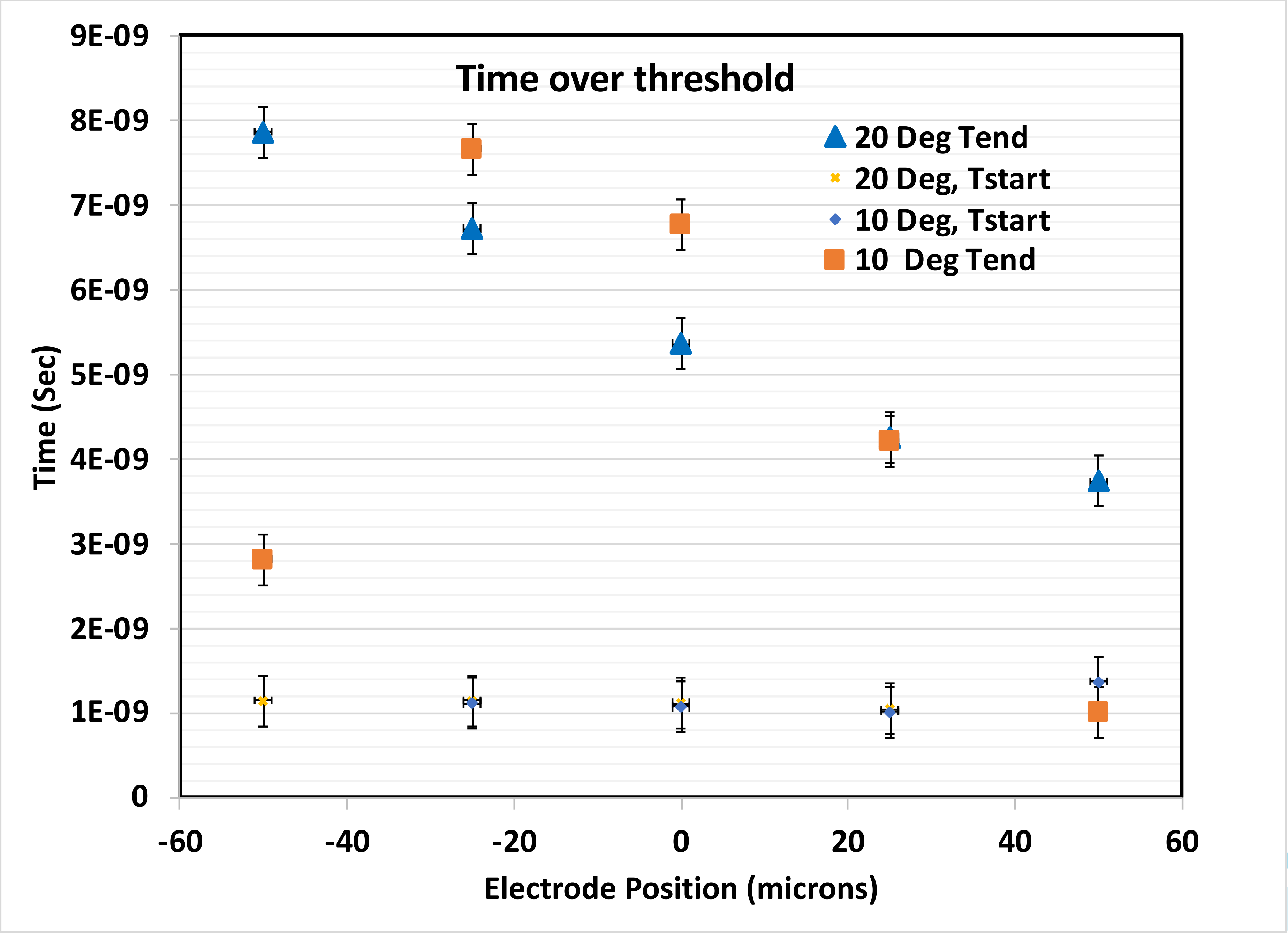
Time over Threshold

- This simple case seems to work, time stamps reflect pulse shape
- Slope indicates difference in charge drift among electrodes
- Clear cutoff in signal for 10 degree track
- Consistent start times (particle impact at 1 ns)



300ps error bars to guide the eye

Comments

Patterns of hits on pixels in "thick" detectors can provide a wealth of information - but the devil is in the details

- S/N and bandwidth are crucial
  - Information is in the first 10 ns
- This means power
- The more information about the waveforms the better
  - Time over Threshold (TOT) with multiple threshold points
    - Requires transresistance amplifier
- Simple diode arrays are more radiation hard than LGADs, but radiation will affect internal fields and charge collection
- We also need to process and transmit that information - this implies "intelligent" pixels where the information in a field of pixels can be processed and decisions made

$$\sigma_t \sim \frac{C_L}{\sqrt{g_m t_a}} \frac{\sqrt{t_a^2 + t_d^2}}{Signal}$$

$$f \sim g_m \qquad g_m \sim I_d$$

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More Work (for someone …)

This work is very much at a conceptual stage

Details will need to be understood to validate the concept and understand it's range of application

To Do:

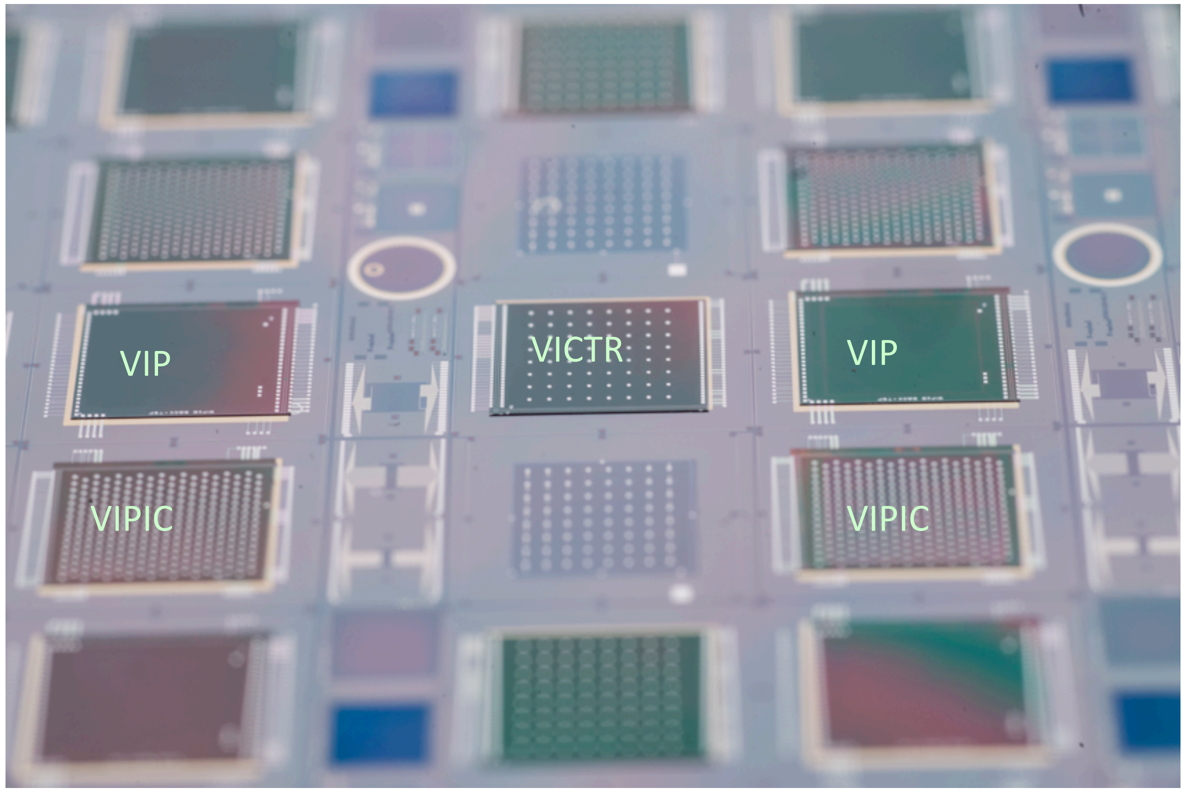
- Define an overall toy->serious algorithm
- What is the angular resolution as a function of bandwidth?
- How do Landau fluctuations affect the reconstruction?
- What is the overall time resolution?
- Implement a realistic transimpedance amplifier in 65 nm and access power requirements
- Re-acquire hybrid bonding technology for sensor/readout integration
- Access optimal detector thickness and depletion fields

Build something

Prospects

Fast timing in small pixels and thin detectors - most technologies have been demonstrated

- Thin sensors (8” wafers)
- Time of arrival (demonstrated with LGADs)
- fine pitch bonding (3D hybrid bonding)
- Chip to wafer bonding (dead regions?)



The use of induced currents

- Small signal/noise, large bandwidth
- Power consumption
- Assembly geometry and size
- Data processing - intelligent pixels to select hits around a central core
- Data bandwidth

Vendors - The basic hybrid bonding technology is now licensed to several foundries (inc MIT-LL, Sandia, IZM), used in cell phone cameras many

Conclusions

I have discussed some possible applications of small pixels enabled by emerging technologies.

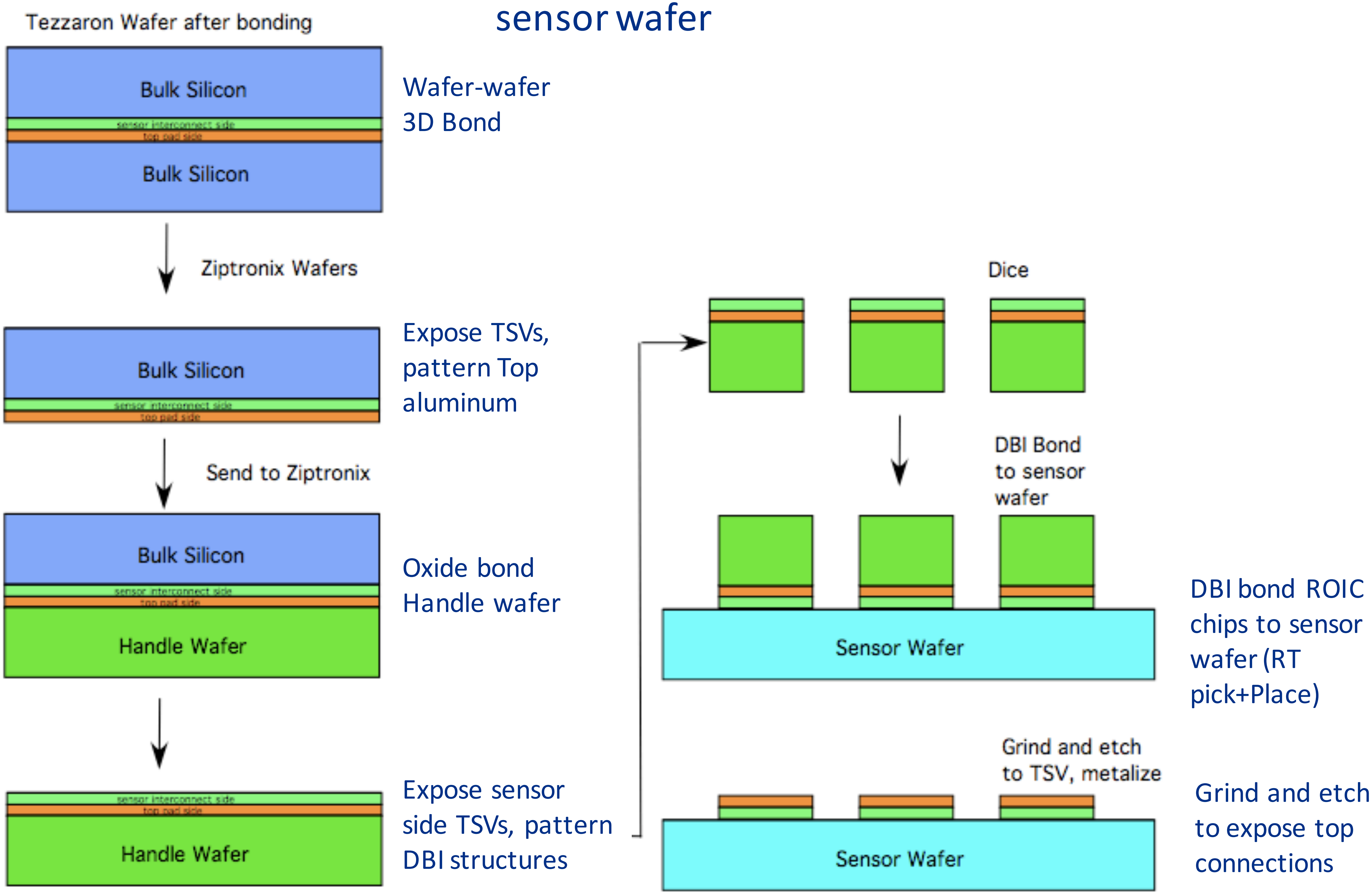
- It is one way of addressing some of the extreme challenges of future experiments (FCC, Muon Collider, EIC …)
  - Fast timing
  - Radiation hard
  - Complex event topologies
- I have presented toy models without engineering detail

To do more, a specific application and real engineering is needed

- What power is needed? Cooling mass? Support geometry
- Amplifier/discriminator design
- Design of the digital tiers
- Area to be deployed? Coverage? Cost? - What Experiment?

Chip to Wafer

DBI bonding of ROICs (VICTR, VIPIC, VIP) to BNL sensor wafer



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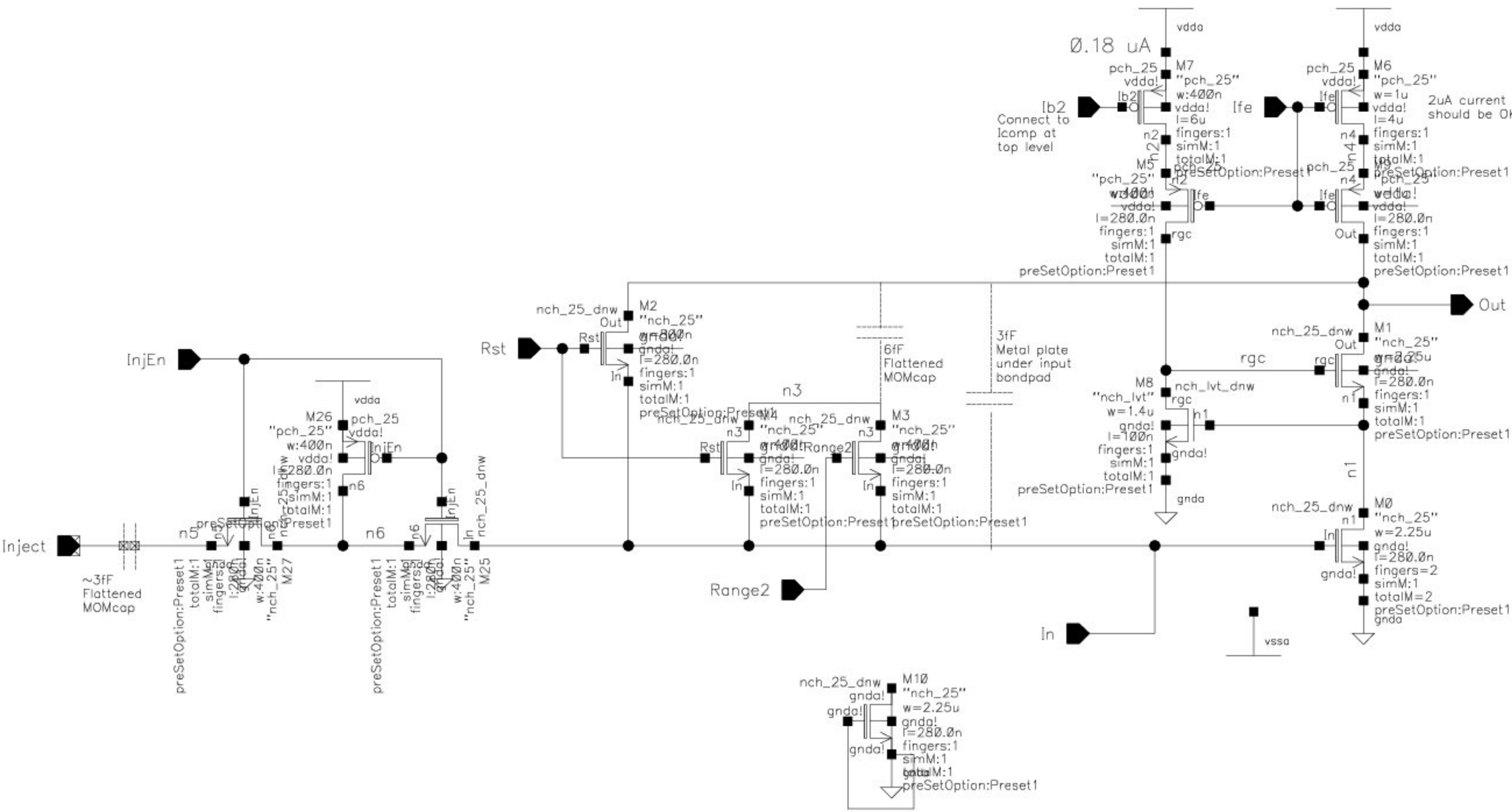
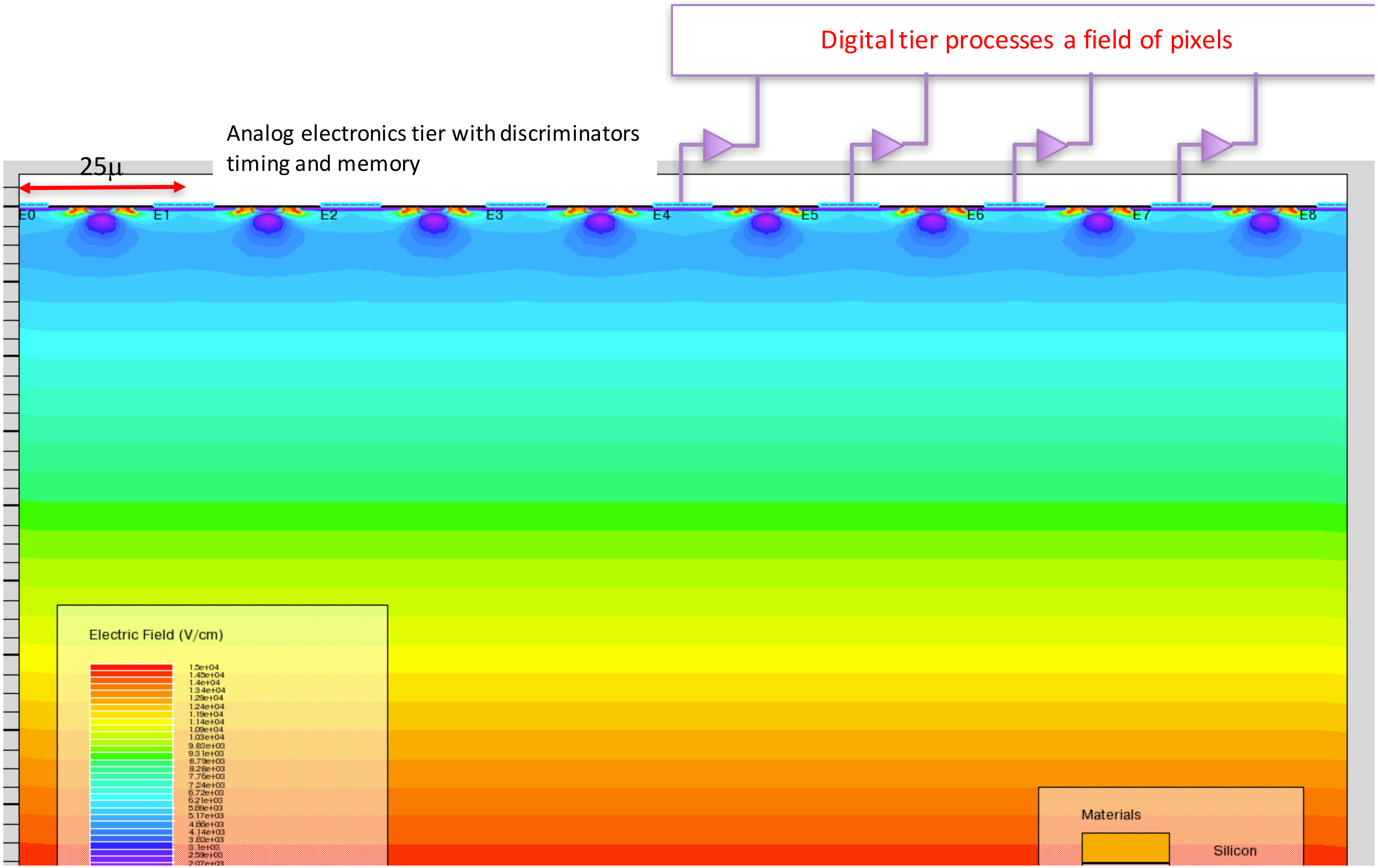
Integrator Circuit

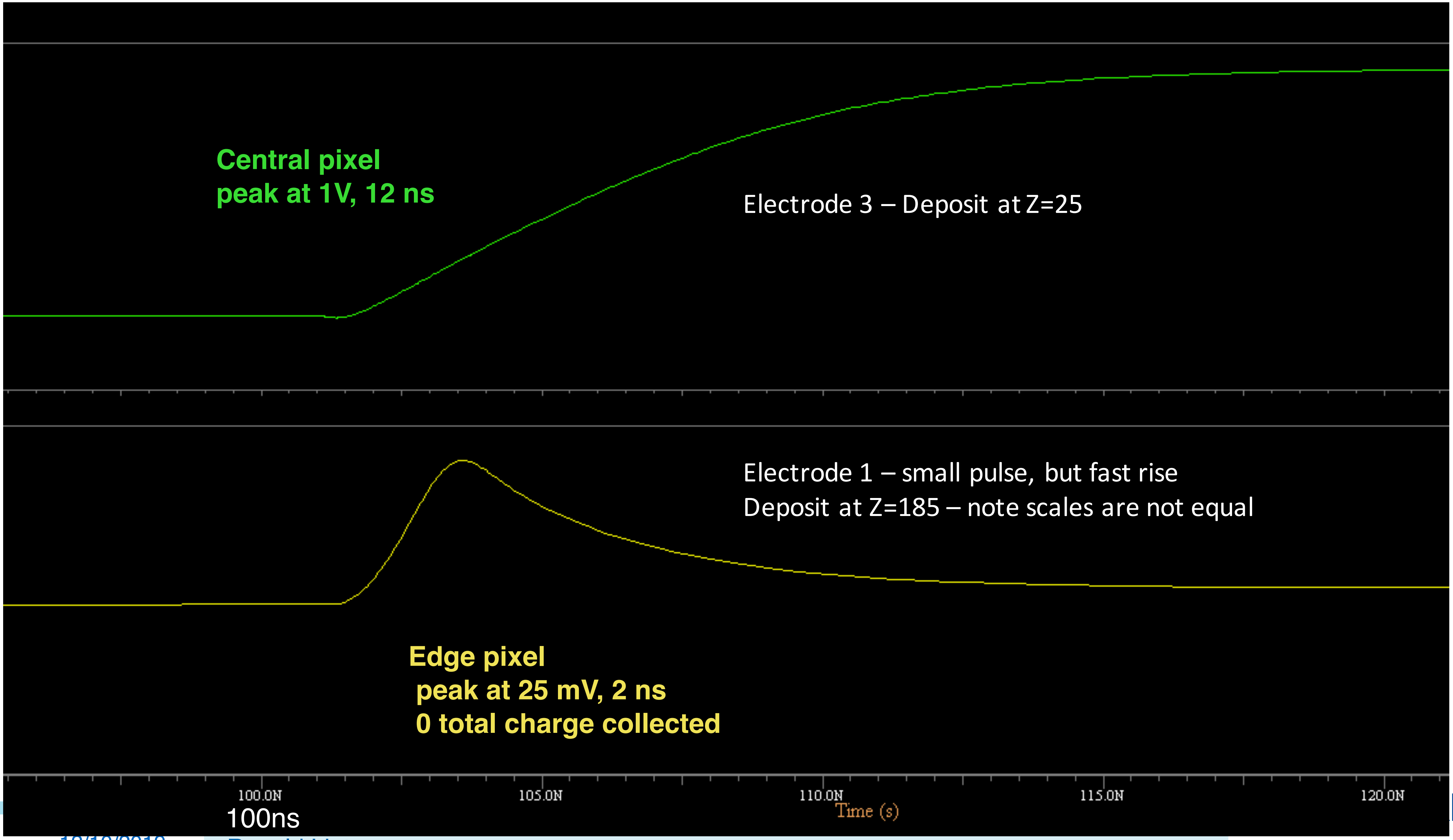


Implementation



Time resolution of a thick detector

- We use the TCAD/SPICE simulation chain to model an x-ray in the thicker detector going into a 65nm charge sensitive amplifier



Pixel Capacitance

A detector with low capacitance can provide excellent time resolution:

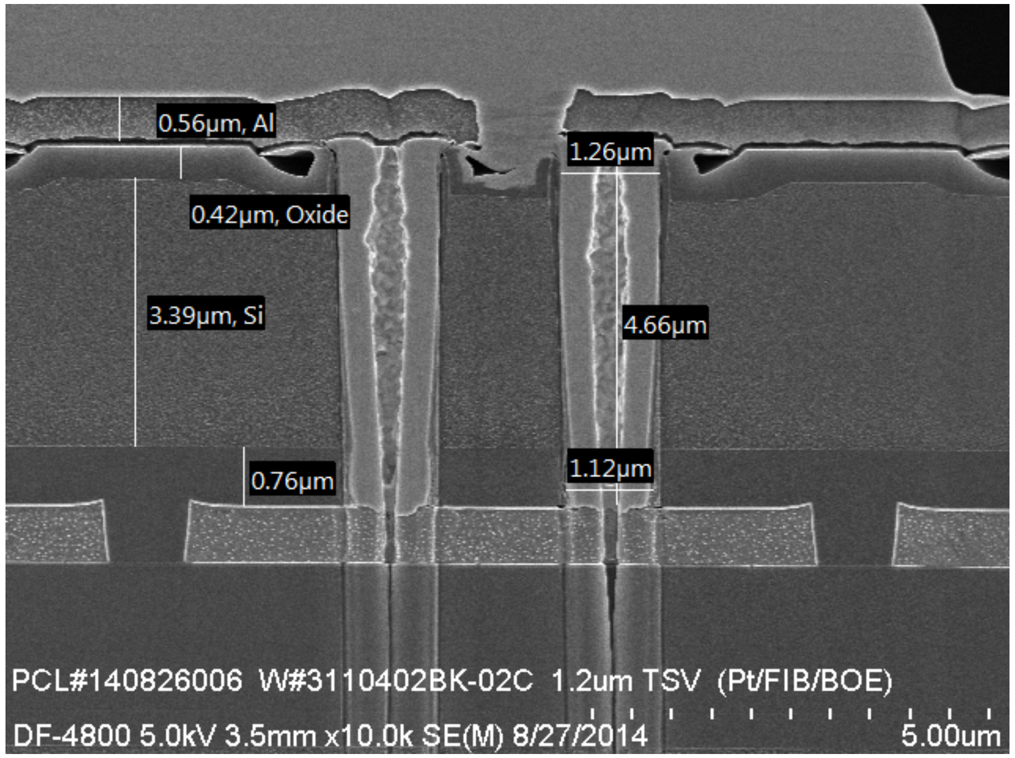
$$\frac{\sigma_{t,pixel}}{\sigma_{t,LGAD}} \sim \frac{C_{pixel}}{C_{LGAD}} \times \frac{1}{Gain_{LGAD}} \geq 10^2 \times \frac{1}{20} \sim 5$$

Before this improvement is realized other effects will dominate including charge deposition variations. Power considerations will limit front-end current which will reduce transistor transductance

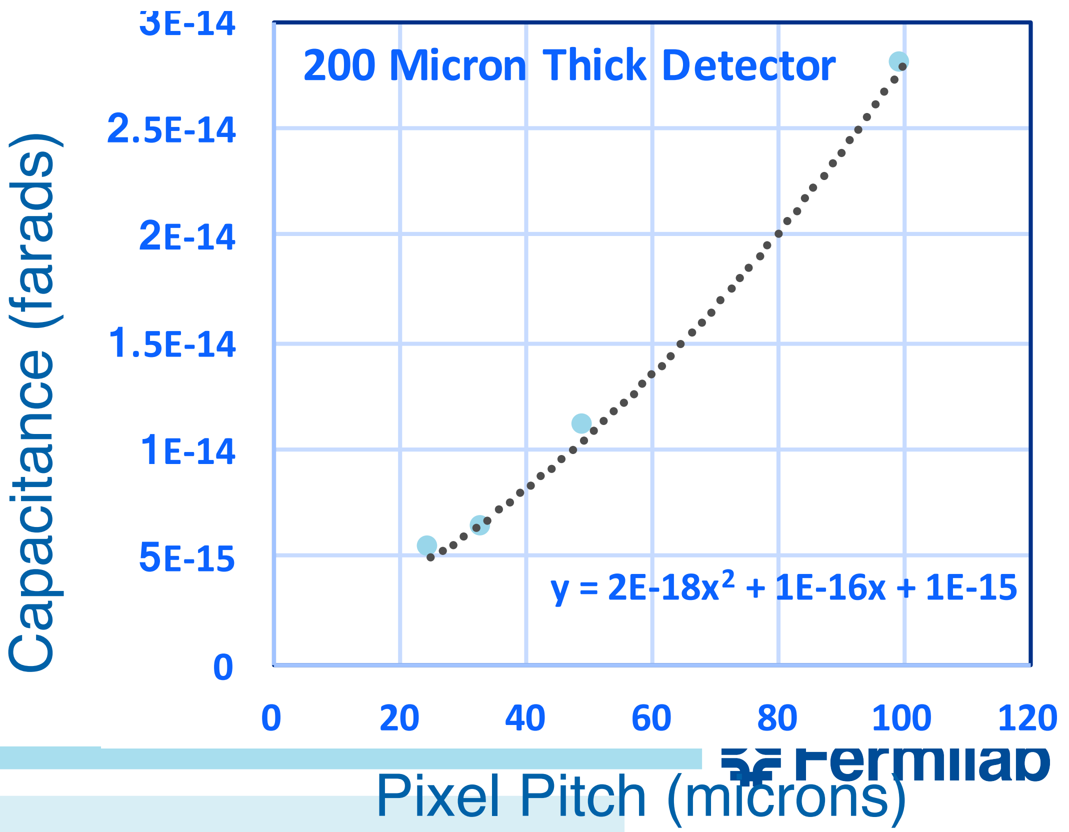
$$\sigma_t \sim \frac{1}{\sqrt{g_m}}, \quad g_m \sim I_d^{\alpha} \ (\alpha \sim 1)$$

However with "spare" margin we can become more adventurous

TSV Test Structure



TCAD Simulation



Hybrid Bonding Vendors (2019)

Vendor	*Wafer Diam*	*Wafer-Wafer*	*Die-Wafer*	*TSV*
Sony				*-*
NHanced	*8”*	✓	✓	*~1 um?*
Teledyne Dalsa	*6”, 8”*	✓		*~5 um*
Sandia	*6”->8”*	*developing*	✓	*no*
IZM	*12”*	✓	*no*	*~5 um*
Raytheon	*8”*	✓		*-*