Signal Formation & Timing
in
Conventional P-I-N Diodes

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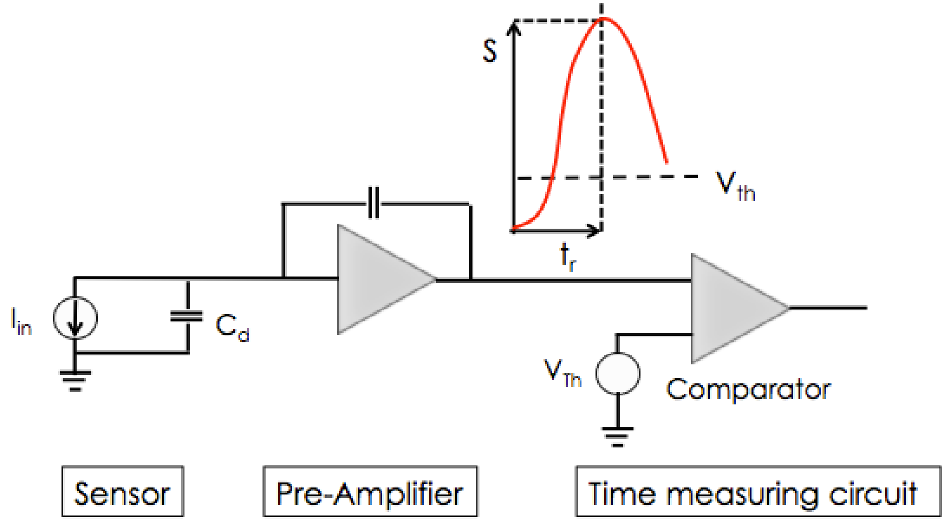
Constraints for precision timing
  from sensors (currents)
  from pre-amplifier (voltages)
Noise and pulse shaping in Broad-Band amplifiers
Simulations of Pulse shapes with Weightfield 2 (WF2)
Pivotal role of detector capacitance
Case study: Simulation of recently reported MIP timing measurements

A time-tagging detector



For calorimeter applications, the sensors are un-segmented n-in-p pads with C_d=A/w. (Area =L^2 , thickness w)
Will consider a broad-band pre-amplifier (BB) which contributes the input impedance (e.g. R=50Ω) to the crucial time constant R*C_d.
The discussion of the time measuring circuit is left to experts like Christophe.

Timing error:

$$\sigma_t^2 = \sigma_{TW}^2 + \sigma_J^2 + \sigma_L^2 + \sigma_{TDC}^2$$

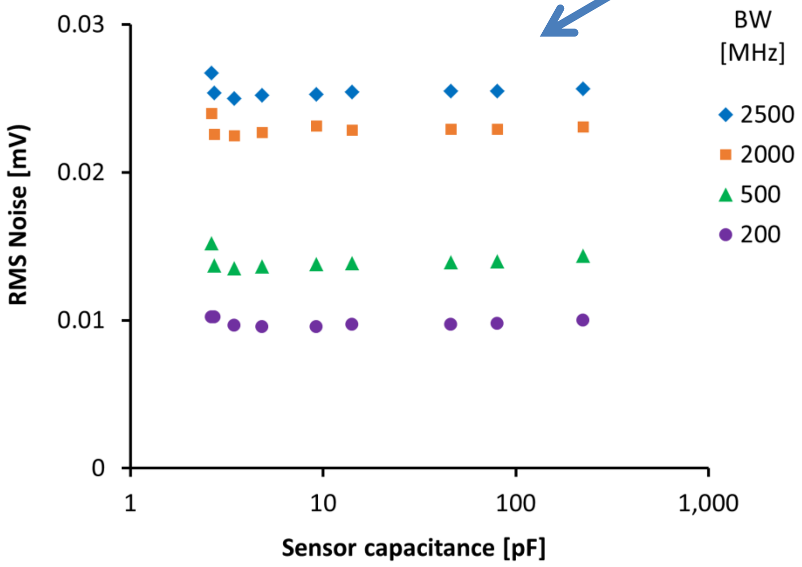
The pulse **slew-rate (slope) dV/dt** is the critical parameter for timing consideration
For signals of many MIPs, only jitter σ_j = Noise/(slope) is relevant if the time measuring circuit is under control.

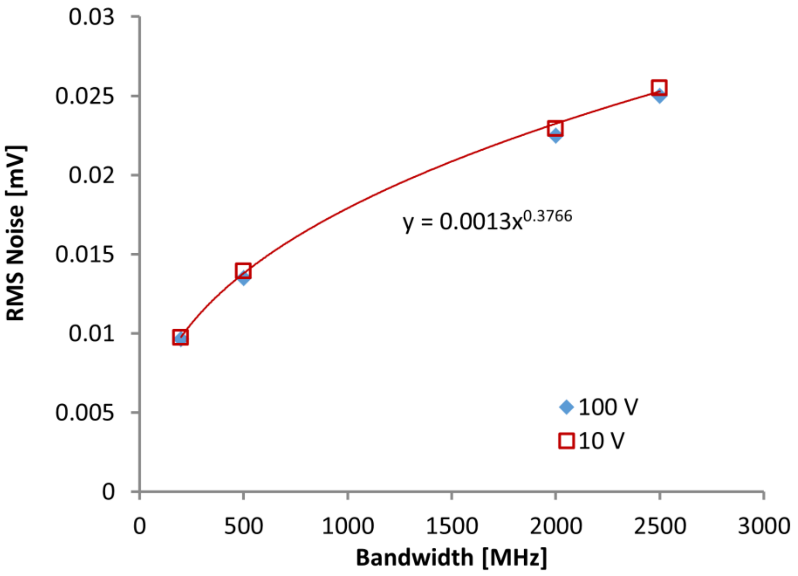
Note that for N concurrent MIPs, the jitter is **σ_j (N) = 1/N* σ_j (MIP)**

The is the “root cause” for the good timing resolution in calorimeters.

Noise and Signal in an Broad Band Amplifier (BB)

With a charge sensitive amplifiers (CSA), aka a “Capacitor”, the output signal does not depend on the detector capacitance C_d , but the noise does.
With a broad-band amplifier (BB), aka a “resistor”, it will be shown that the signal height depends on C_d via the R*C at the amplifier input and that the noise is independent of the capacitance, as measured with a bias scan of the sensor.

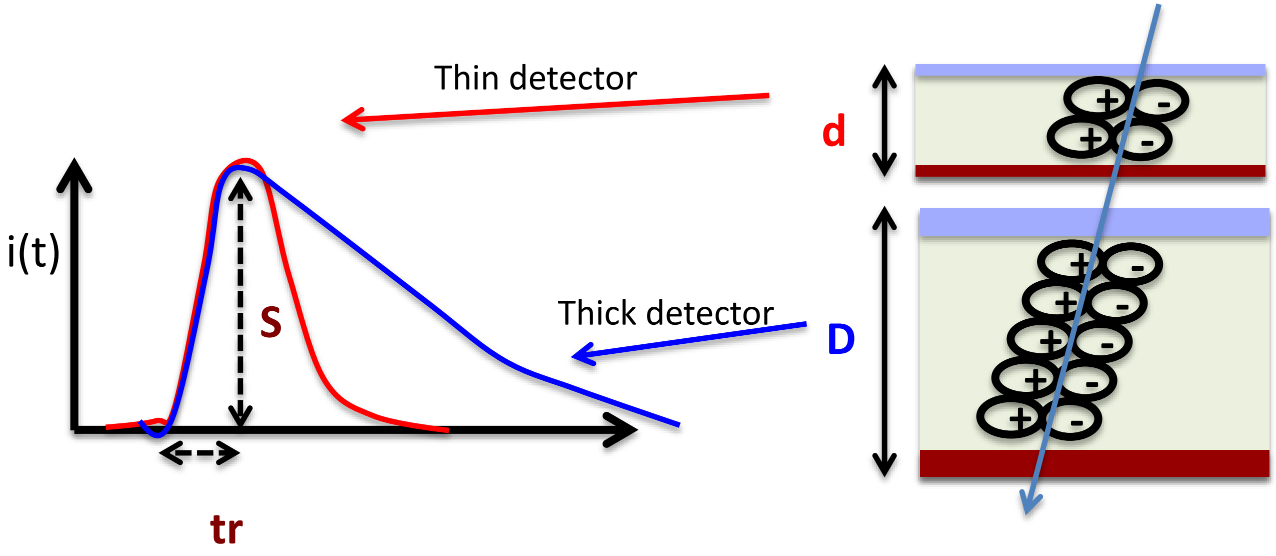




The amplifier noise is crucial parameter, since it causes the time jitter, which can be the dominant part of the timing resolution.

Jitter = Noise/slope = Noise /(dV/dt)

Thin vs Thick detectors



Ramo's Theory predicts the detector current (the weighting field E_w =1/d for pads):

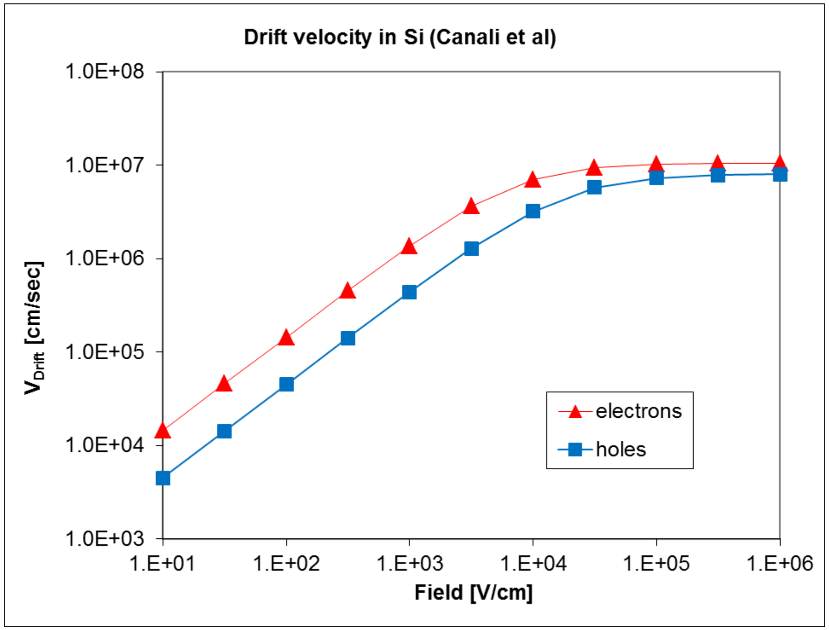
$$i = q * v * E_w$$

The current is proportional to the sum of the velocities of all moving charges.

Highest at t=0 when all charges all still moving, and v is saturated.

Lower if the bias is too low such that there is a velocity gradient.

Charge Collection Time in Si Sensors



Drift velocity saturates for both electrons and holes!

-> **need thin sensors or large over-depletion for fast charge collection**

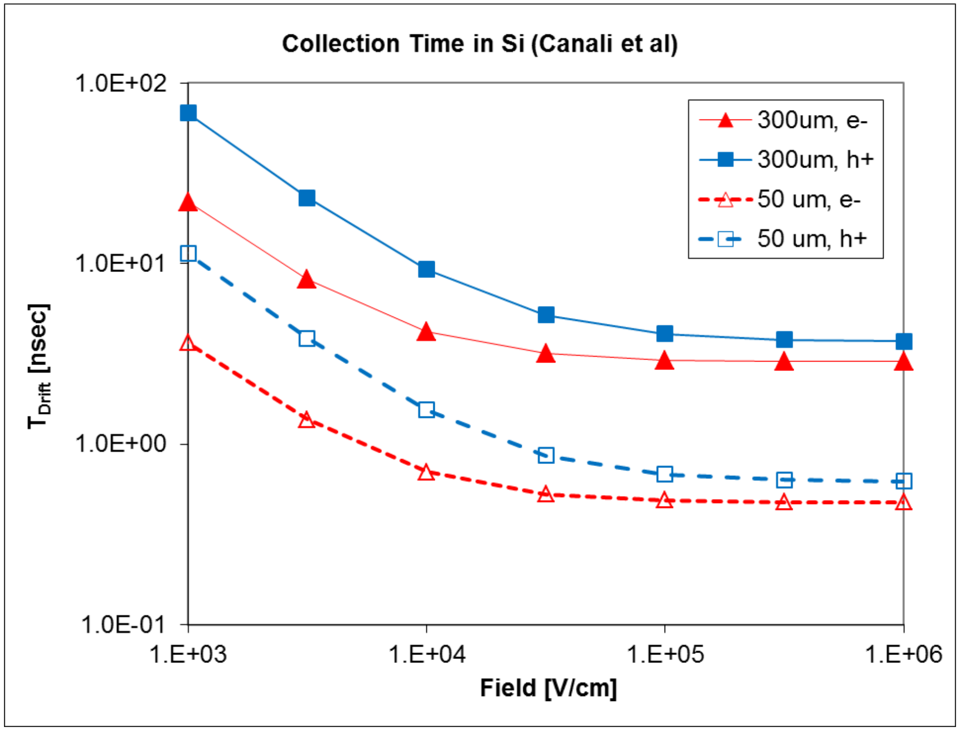
Collection time is close to minimum when E-Field ≥ 20 kV/cm

For 300um Si

Collection time ~ 4 ns (h), ~ 3 ns (e)

For 50um Si

Collection time ~ 0.7 ns (h), ~ 0.5 ns (e)



Sensor: Simulation

Nicolo Cartiglia developed a full sensor simulation to optimize the sensor design

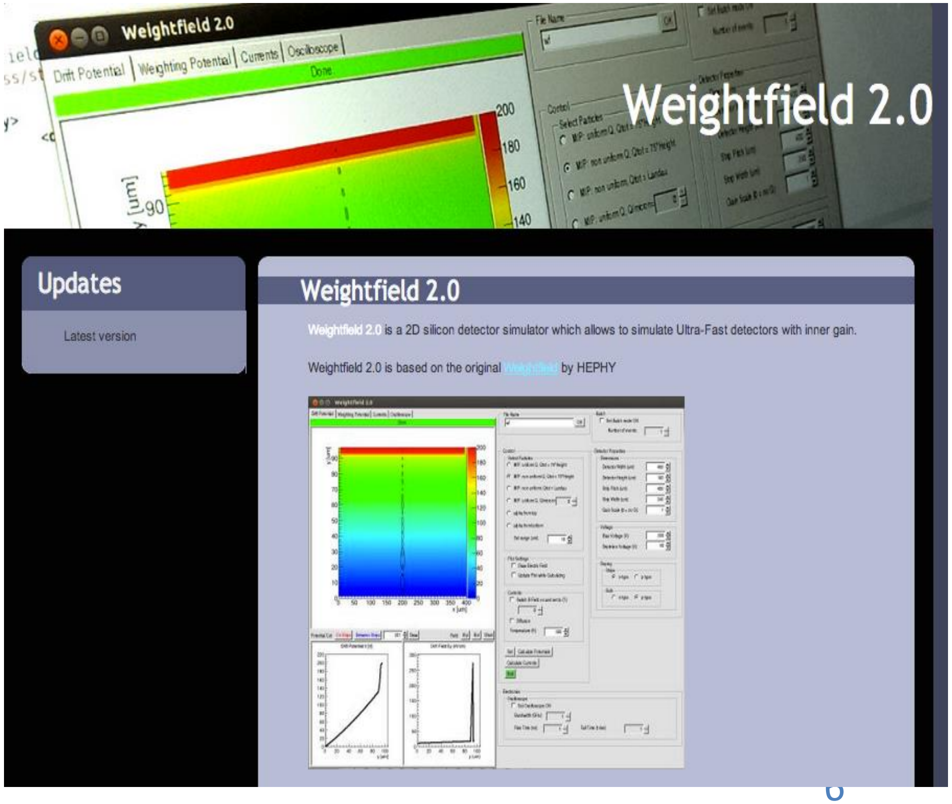
WeightField2, F. Cenna, N. Cartiglia 9th Trento workshop, Genova 2014

Available at http://personalpages.to.infn.it/~cartigli/weightfield2

It includes many “bells & whistles” required for the detailed description of the signals, i.e. charge generation, drift and collection.

It allows to separate the properties of the current source from the amplifier shaping.

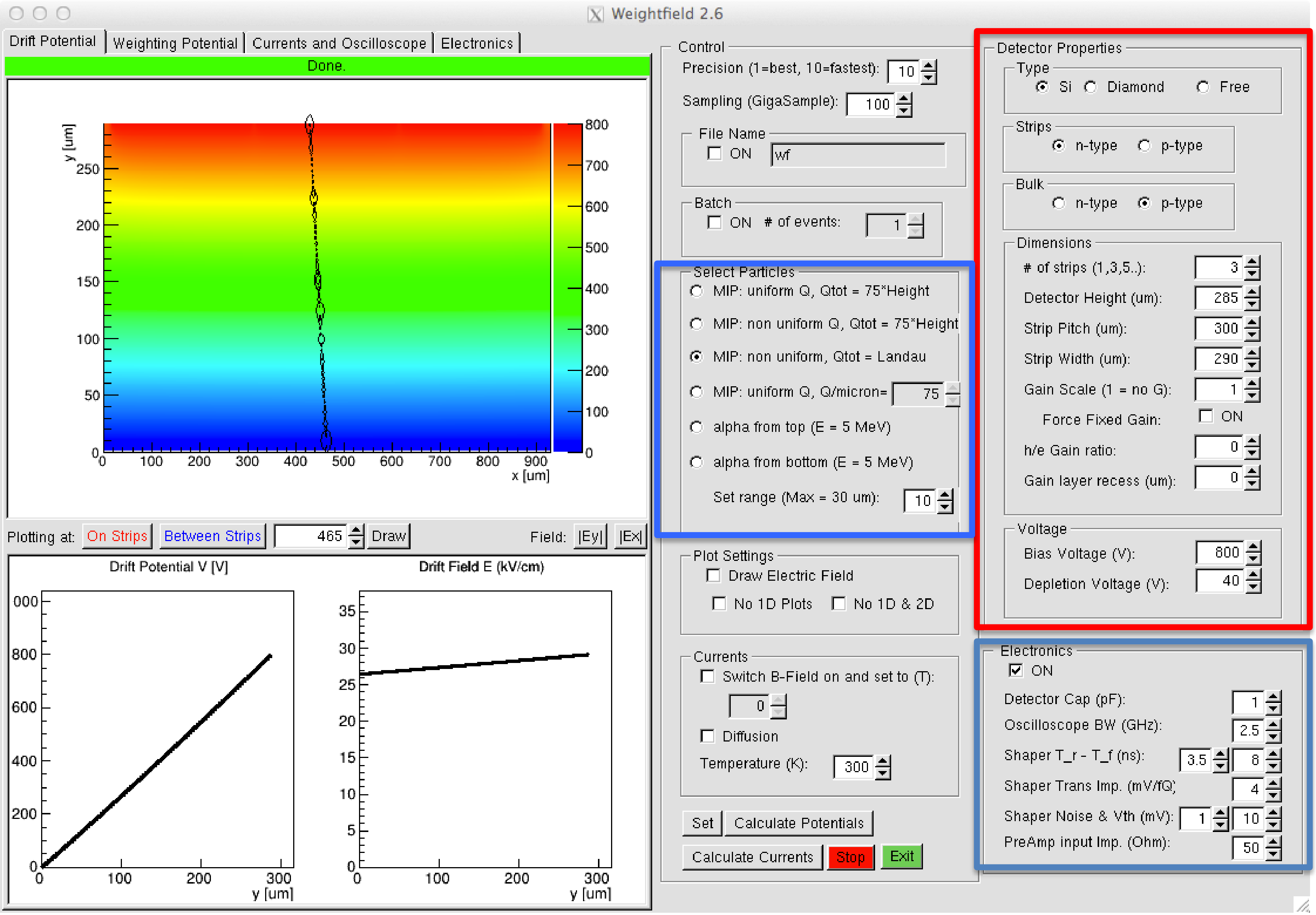
(Perfect to teach and learn about silicon sensors)



Weightfield 2.0 is a 2D silicon detector simulator which allows to simulate Ultra-Fast detectors with inner gain.

Weightfield 2.0 is based on the original Weightfield by HEPHY

WeightField2: the Silicon Detector Simulator



Plotting at: On Strips Between Strips 465 Draw Field: |Ey| |Ex|

Control

Precision (1=best, 10=fastest): 10

Sampling (GigaSample): 100

File Name

☐ ON wf

Batch

☐ ON # of events: 1

Select Particles

- ○ MIP: uniform Q, Qtot = 75*Height
- ○ MIP: non uniform Q, Qtot = 75*Height
- ● MIP: non uniform, Qtot = Landau
- ○ MIP: uniform Q, Q/micron= 75
- ○ alpha from top (E = 5 MeV)
- ○ alpha from bottom (E = 5 MeV)

Set range (Max = 30 um): 10

Plot Settings

☐ Draw Electric Field

☐ No 1D Plots ☐ No 1D & 2D

Currents

☐ Switch B-Field on and set to (T): 0

☐ Diffusion

Temperature (K): 300

Detector Properties

Type

● Si ○ Diamond ○ Free

Strips

● n-type ○ p-type

Bulk

○ n-type ● p-type

Dimensions

# of strips (1,3,5..): 3

Detector Height (um): 285

Strip Pitch (um): 300

Strip Width (um): 290

Gain Scale (1 = no G): 1

Force Fixed Gain: ☐ ON

h/e Gain ratio: 0

Gain layer recess (um): 0

Voltage

Bias Voltage (V): 800

Depletion Voltage (V): 40

Electronics

☑ ON

Detector Cap (pF): 1

Oscilloscope BW (GHz): 2.5

Shaper T_r - T_f (ns): 3.5 8

Shaper Trans Imp. (mV/fQ): 4

Shaper Noise & Vth (mV): 1 10

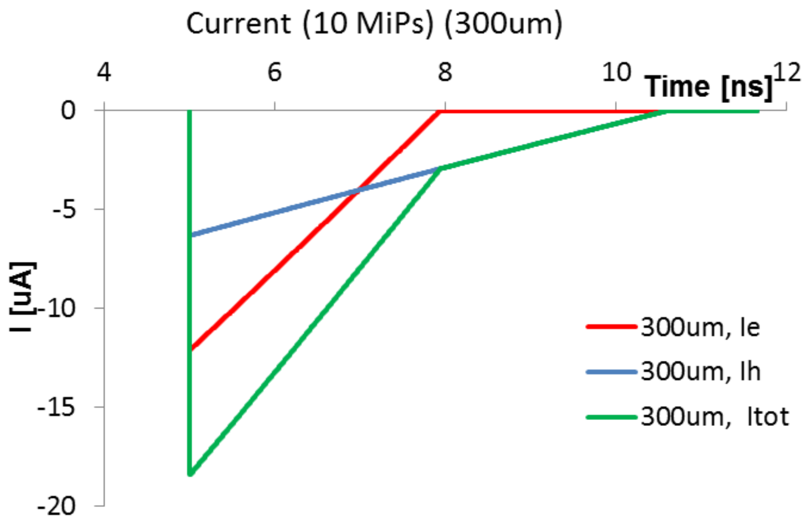
PreAmp input Imp. (Ohm): 50

The Current Source: Current from 10 MIPs

In the following simulate the signal from 10 MIPs

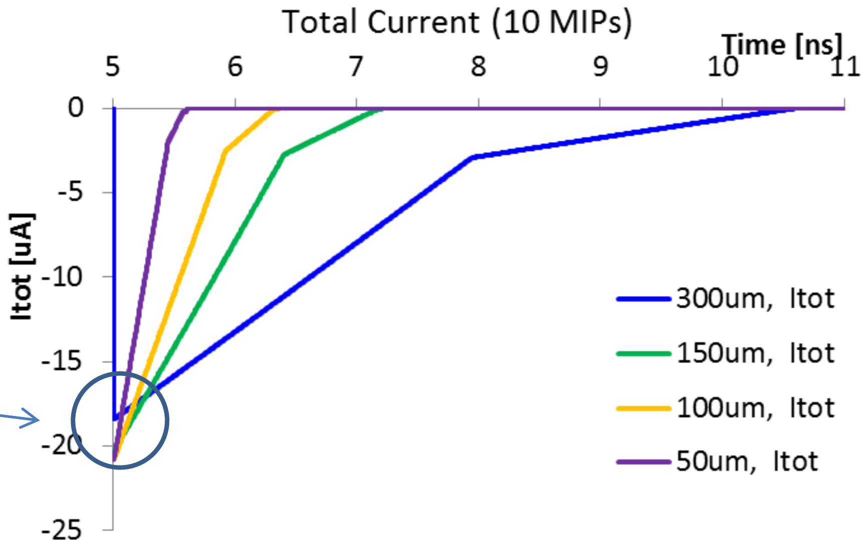
Total current = electron current + hole current
Drift time difference electrons-holes clearly visible

Most importantly:
The current peaks at t=0 where we want to make the time measurement



The current signal of sensors with different thickness' show that the height of peak at t=0 is independent of the detector thickness! Thick detectors contribute to the tail.

The 300µm sensor is not sufficiently over-depleted to reach saturation velocity, in contrast to the thinner ones.



Simulations by Charilou Labitan

WF2 : Radiation Effects on Signal Current

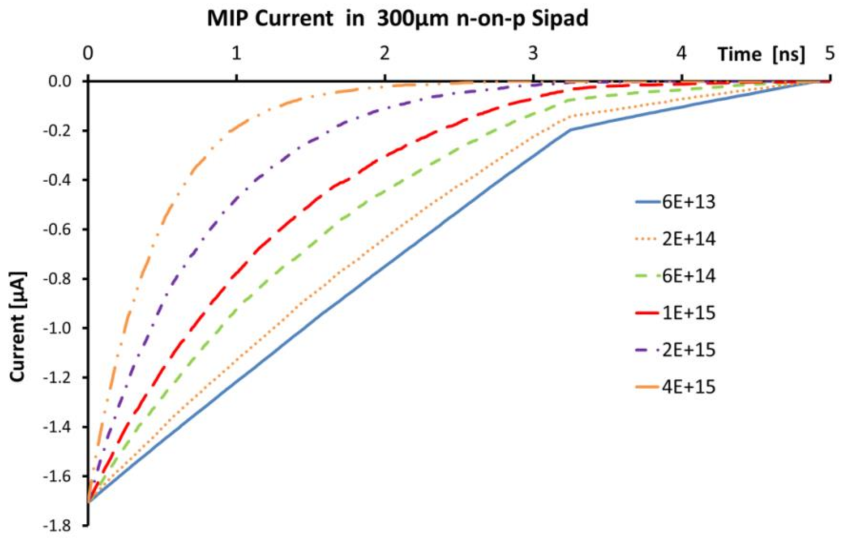
Radiation damage are increase of leakage current and trapping (loss of charge).

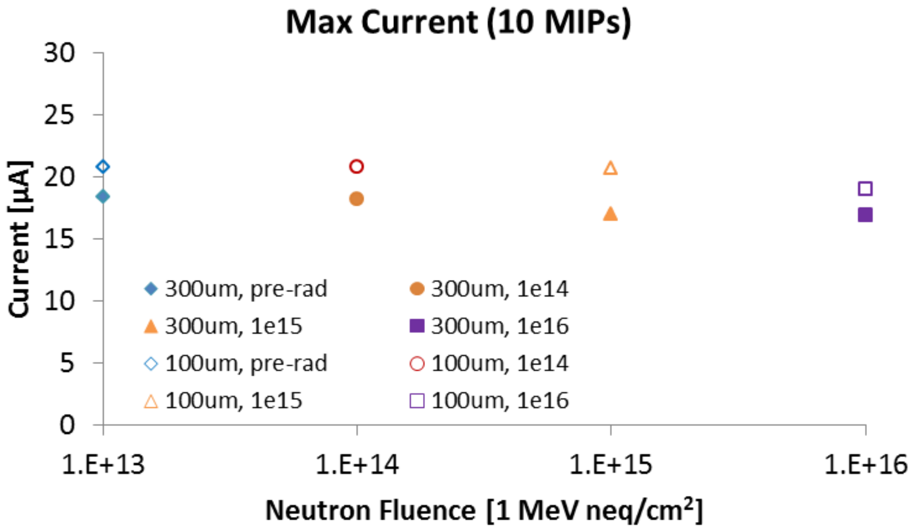
Since trapping is characterized by a characteristic time of ~50ps (and thus a characteristic distance of ~50µm at saturated drift velocity) only the later part of the pulse is affected which is not used for timing (unless TOT is used!).

The current maximum at the pulse front is preserved.

A pulse from 300µm sensor resembles one from a 50µm sensor after a fluence of several 10^{15} neq/cm^2

High bias operation is preferred to decreased the drift time.



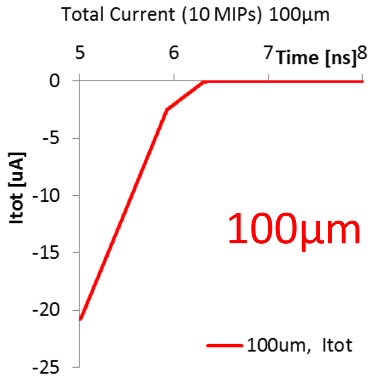


Simulations by Chiara Baldassarri & Niamh Maher

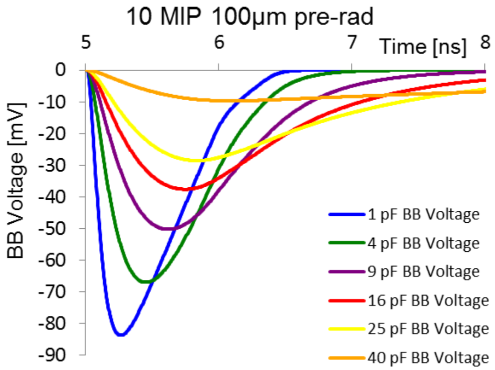
WF2: Radiation Effects on Voltage Pulse Shape

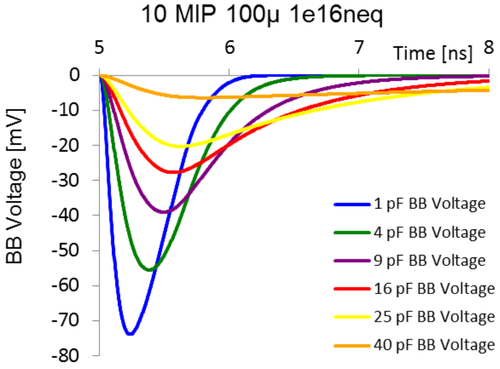
Assume BB amplifier with 50Ω input impedance and gain of 100.
Vary: pad size A: 1x1, 3x3, 5x5 mm^2.sensor thickness w:100µm, 300µm
This samples different detector capacitance C_d-= A/w from 0.3 to 40pF

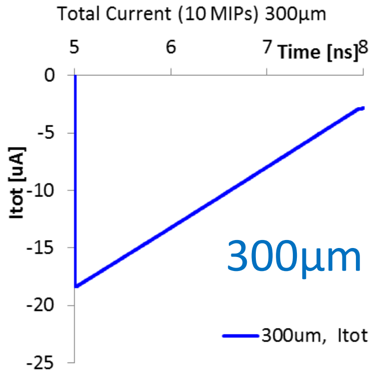
Solid State Physics **convolution** **Electronics**
Current **RC →** **Voltage** **→** **Radiation effect**



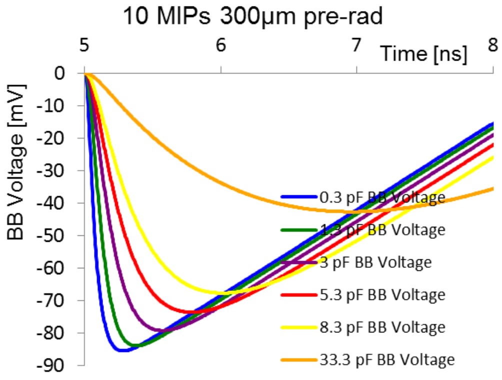
RC

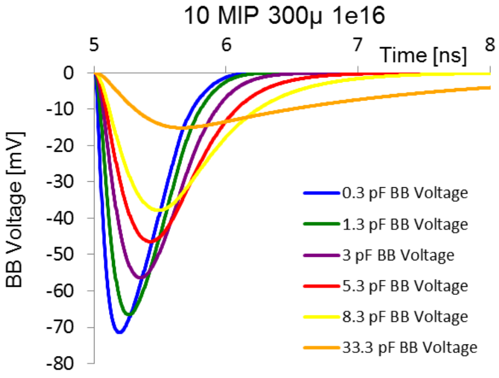






RC

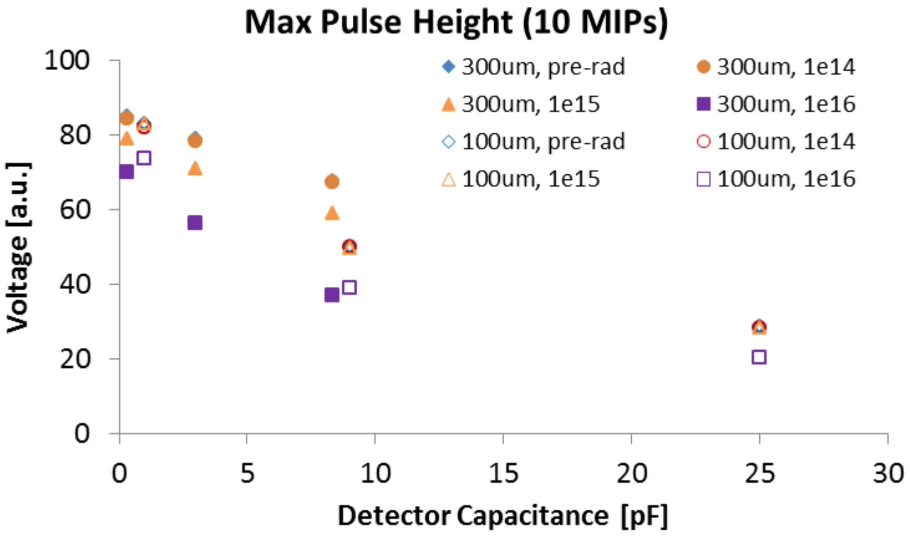




Simulations by Charilou Labitan

WF2: Radiation Effects on Voltage Pulse Shape

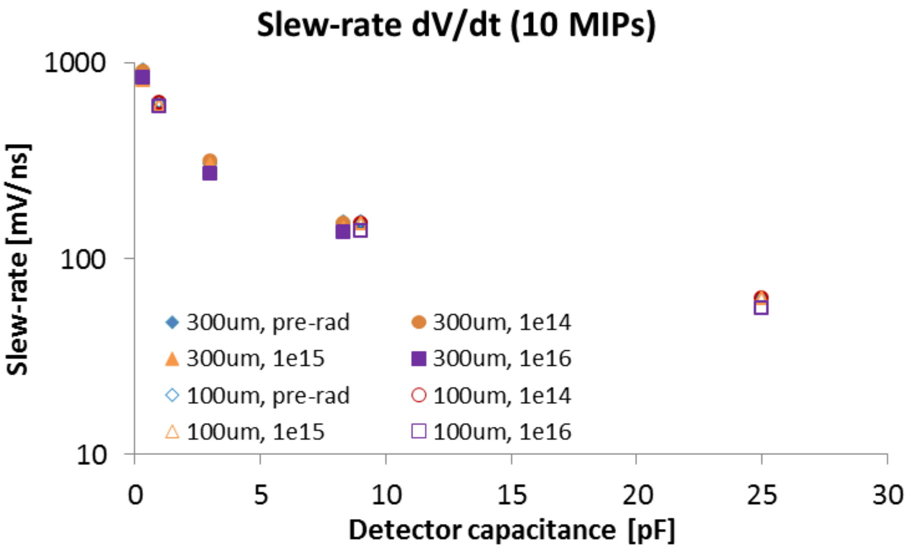
The pulse height
varies both with the detector
capacitance and the radiation



The slew-rate (20% - 80%) depends universally on detector capacitance
e.g.
dV/dt(5mm/300μm) ≈ dV/dt(3mm/100μm)

No radiation effect on slew-rate dV/dt!

Prefer thinner sensors because of leakage current

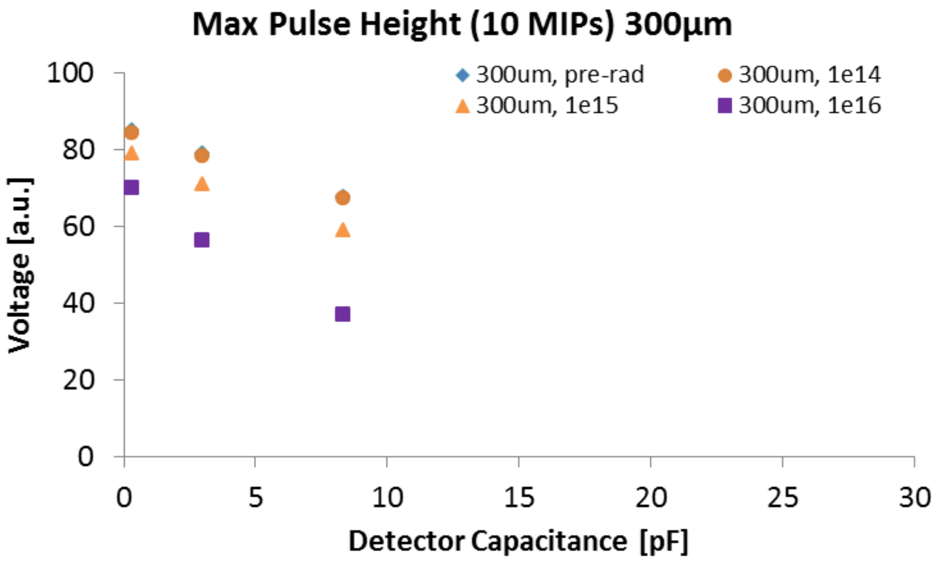


Simulations by Charilou Labitan

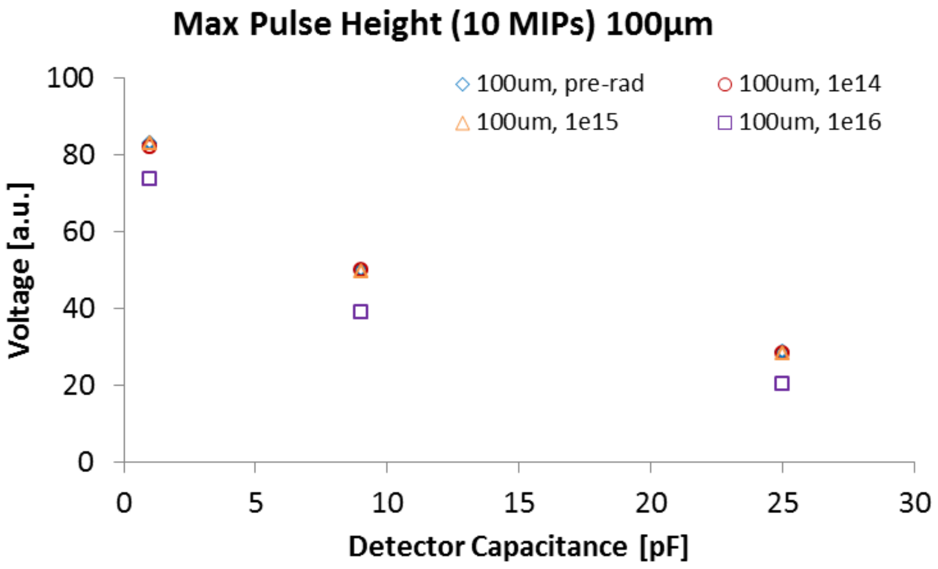
Hartmut F.-W. Sadrozinski, Energy & time with HGSD, 6/13/2016

WF2 Simulation: Radiation Effects on Signal Voltage

Pad size dimension 1x1, 3x3, 5x5 mm^2
Sensor thickness 100µm, 300µm



Radiation effects on signal voltage are small up to 1e16



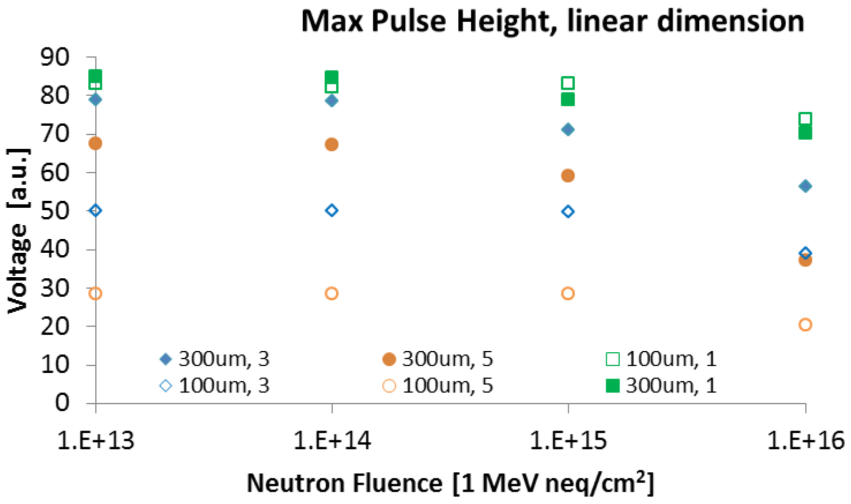
Need small detector sizes,
small input impedance R for RC < 100ps
to get large dV/dt

Simulations by Charilou Labitan

WF2: Radiation Effects on Pulse Height and dV/dt

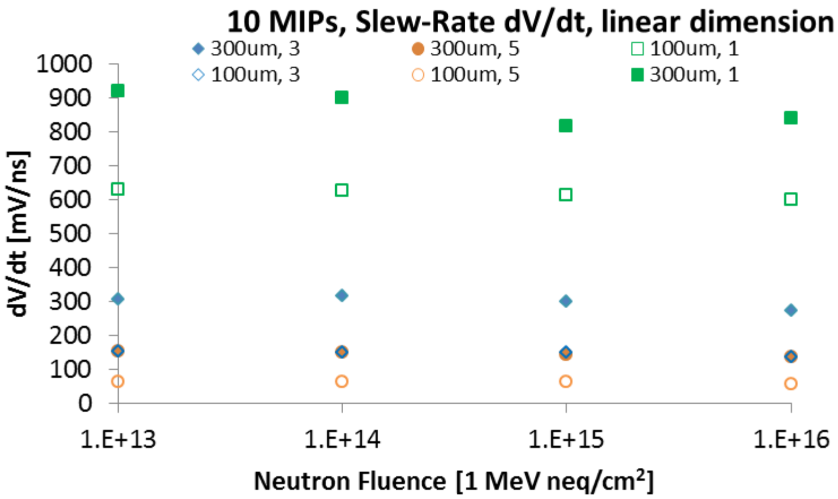
Pad size dimension 1,3,5 mm are indicated for 2 sensor thickness’ 100µm, 300µm

Max pulse voltage depends on capacitance
Small dependence on radiation level



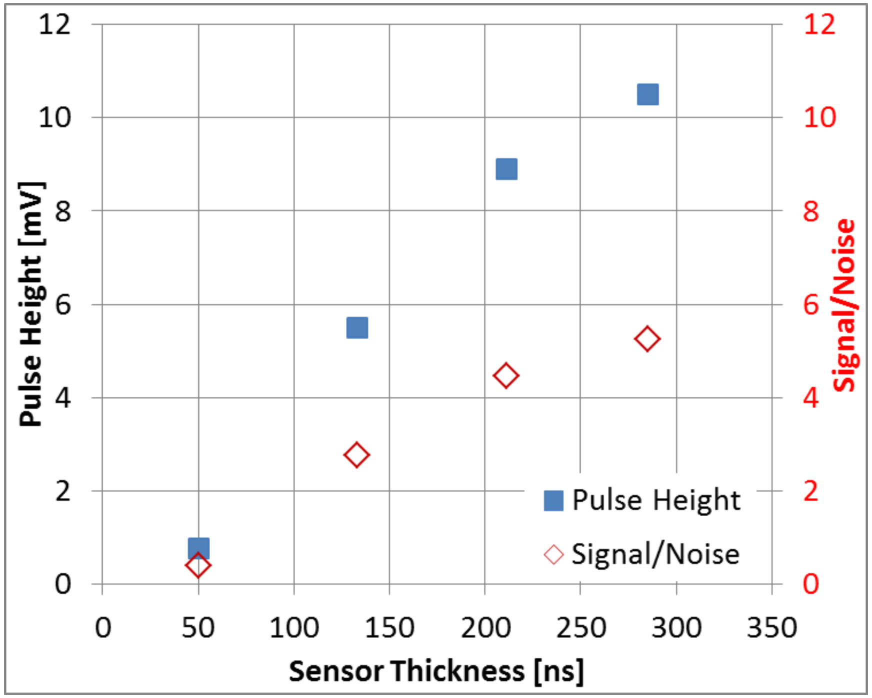
Slew-rate dV/dt depends on the pad capacitance.
Small dependence on radiation level

Need small detector sizes,
small input impedance R for RC < 100ps
to get large dV/dt.

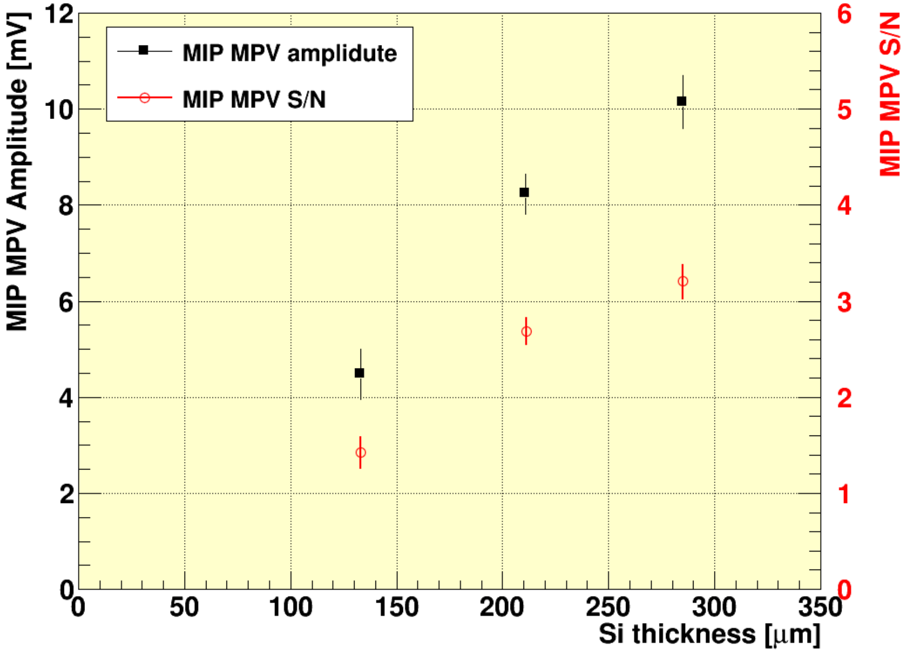


Simulations by Charilou Labitan

Sensor Thickness Dependence of MIP: WF2 vs. Data



Simulations by Nicolo Cartiglia
BB gain ~150, noise = 2 mV



N. Akchurin etal.
A. Bornheim et al
E. Currás etal

shown by Marcello, Arabella

Very good agreement of the WF2 simulation and the MIP MPV data.

The apparent increase of the MIP MPV with sensor thickness is caused by the sensor capacitance, not by an increase in the sensor current!

Careful investigation of the impact of various sensor-BB amp options with different RC values should be considered.

(N.B. how was the S/N in the data calculated when the noise was quoted as 2mV?)

Conclusions

- The P-i-N diodes present a unique opportunity for fast timing given their pulse shape
- The fast rising edge of the current pulse from SiPads of all thicknesses and areas are identical with sufficient over-depletion of the sensors.
- The rising edge of the voltage pulse is shaped through the RC of the SiPad capacitance and the input impedance of the broad-band amplifier.
- Since the time jitter depends inversely on the slew-rate, lower sensor capacitances are preferred since they result in higher slew-rate.
- Concurrent pulses from N MIPs have N-times the slew rate and thus 1/N the time jitter
- The data on time resolution of multiple MIP events in SiPad presented today are reproduced by the simulations using the Weightfield2 (WF2) program.
- Given that the capacitance of the pads depends both on area and thickness of the SiPad, it opens the opportunity to optimize the geometry of the sensors depending on Physics and detector performance; e.g. 5mmx5mm, 300µm thick sensors have ≈ the same capacitance as 3mmx3mm, 100µm and thus the same slew-rate dV/dt and timing resolution.
- To match the jet size one might go with the 5mmx5mm pad, or for radiation mitigation one might opt for the thinner bulk of 100µm pads with better radiation tolerance and tighter jet confinement.
- Thinner sensor will have less leakage current and less leakage current induced noise, although with cooling and the short shaping times this might not be an unsolvable issue.
- We should look forward to see how our electronic colleagues will face the challenges to minimize noise and power as well as optimize the time measuring systems.