

A novel simulation approach for full-carbon 3D diamond sensors

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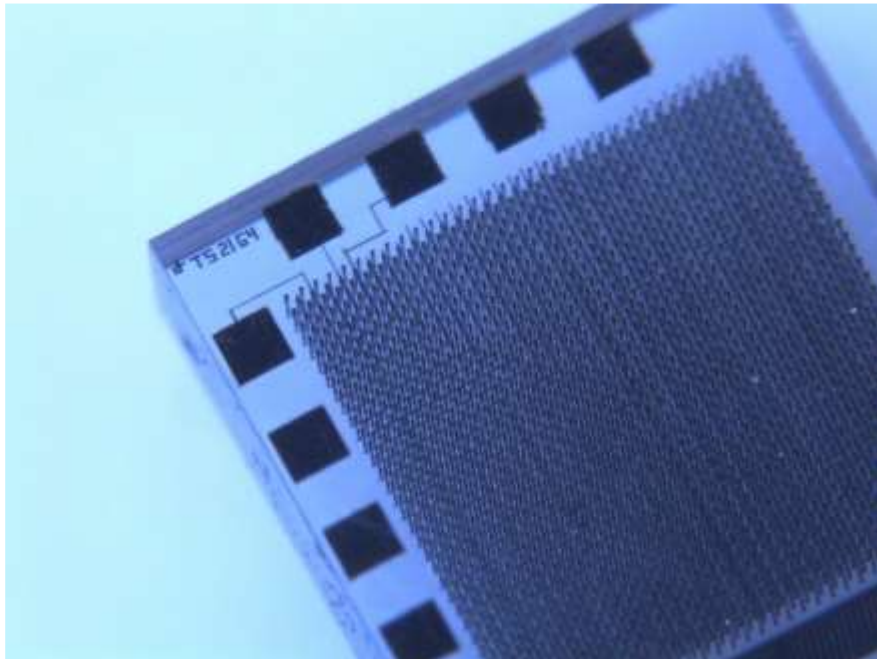
3D DIAMOND DETECTORS

The current challenge in the field of solid-state detector development is to obtain devices capable of operating under extreme radiation conditions: **excellent time performance** and **high radiation resistance**

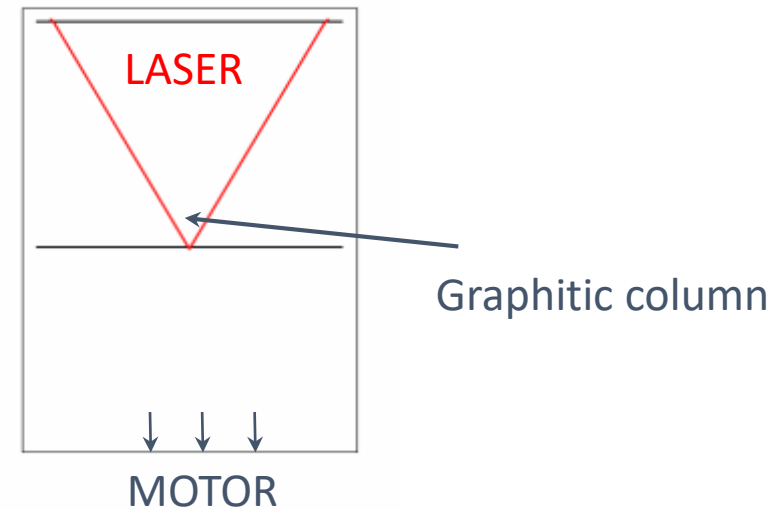
DIAMOND IS AN INTERESTING CANDIDATE!

- high separation energy
- high charges mobility and saturation velocity
- strong chrystalline bonds
- 3D geometry thanks to graphitization

Physical properties	Diamond	Silicon
Separation Energy (eV)	5.5	3.6
Electron mobility ($\text{cm}^2/\text{V} \times \text{s}$)	4551	1350
Hole mobility ($\text{cm}^2/\text{V} \times \text{s}$)	2750	480
Electron saturation velocity (cm/s)	2.6×10^7	10^7
Hole saturation velocity (cm/s)	1.6×10^7	7.5×10^6
Limit energy of dislocation (eV)	37.5-47.6	36



COLUMN FABRICATION PROCESS FOR 3D DIAMOND SENSORS



SIMULATION

Output signal is generated by the motion of charge carriers in the sensor and in the case of perfectly conductive electrodes can be calculated through the Ramo-Shockley theorem

$$I_n^{ind}(t) = -\frac{q}{V_w} \vec{E}_{w,n}(\vec{x}(t)) \cdot \dot{\vec{x}}(t)$$

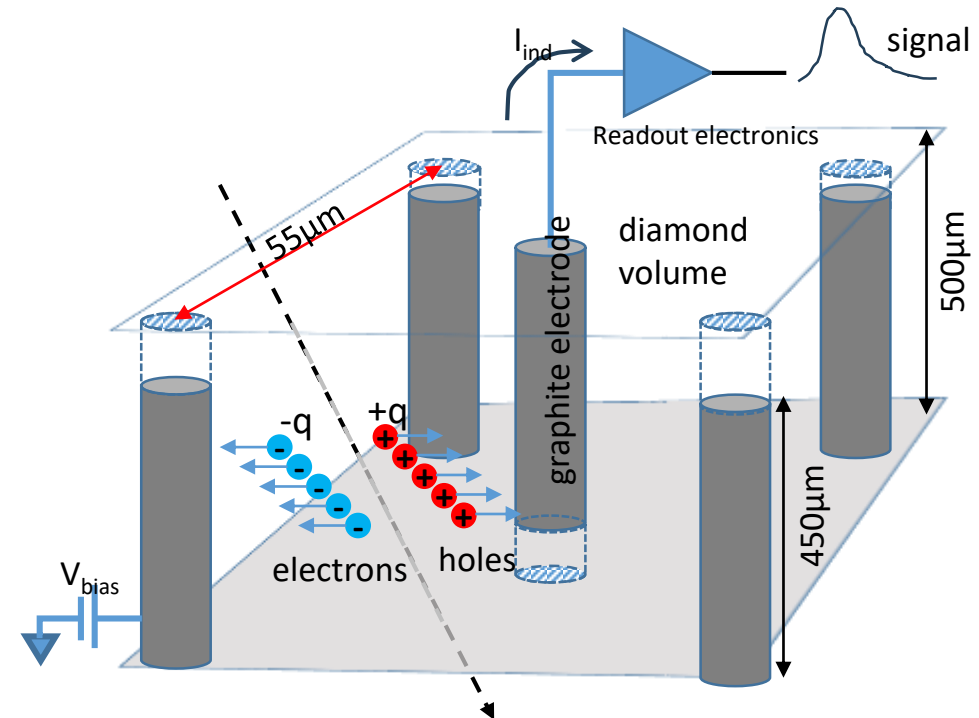
Assumptions to find the weighting field $\vec{E}_{w,n}$:

- Electrode n is at fixed voltage V_w
- All the others electrodes are at zero voltage
- Any charge trapped in the volume is neglected

➤ **COMPLEXITY: graphite cannot be approximated by an ideal conductor (resistivity $20 \mu\Omega \times m$)**

The presence of graphite causes a slowdown in signal transmission along the electrode. **Carrier transport and signal propagation through the resistive electrodes** introduce effects detrimental to the timing performance, of the same order of magnitude

➔ **WE NEED A SIMULATION APPROACH MODELING BOTH**



SIMULATION OF THE SIGNAL TRANSMISSION

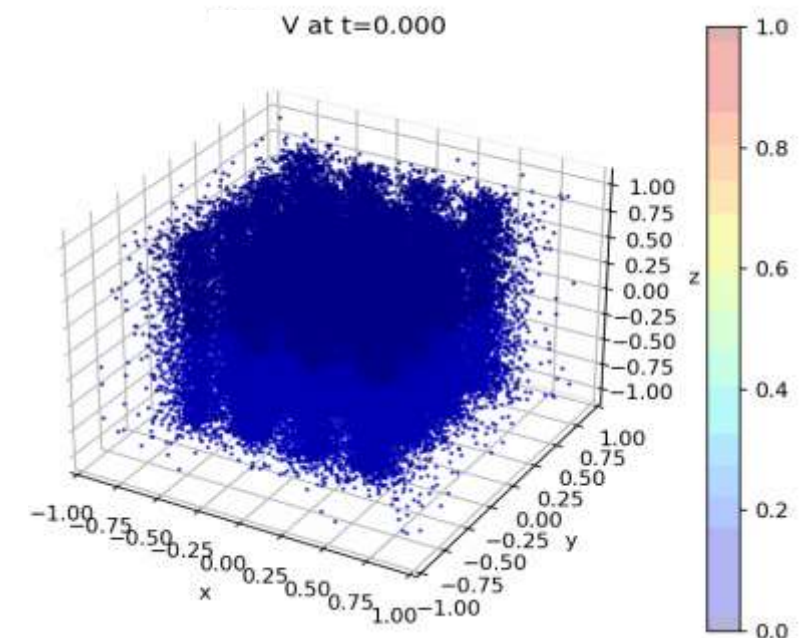
- **old approach:** decoupling contributions to the signal. The effect due to graphite electrodes can be approximated by that of a TRANSMISSION LINE

$$I_n^{ind}(t) = i(t) * F(t)$$

$i(t)$ signal with Ramo-Shockley theorem
 $F(t)$ transmission line transfer function

- **NOVEL APPROACH:** D. Jassensen et al. studied an extension of the Ramo-Shockley theorem for detectors with resistive materials inside

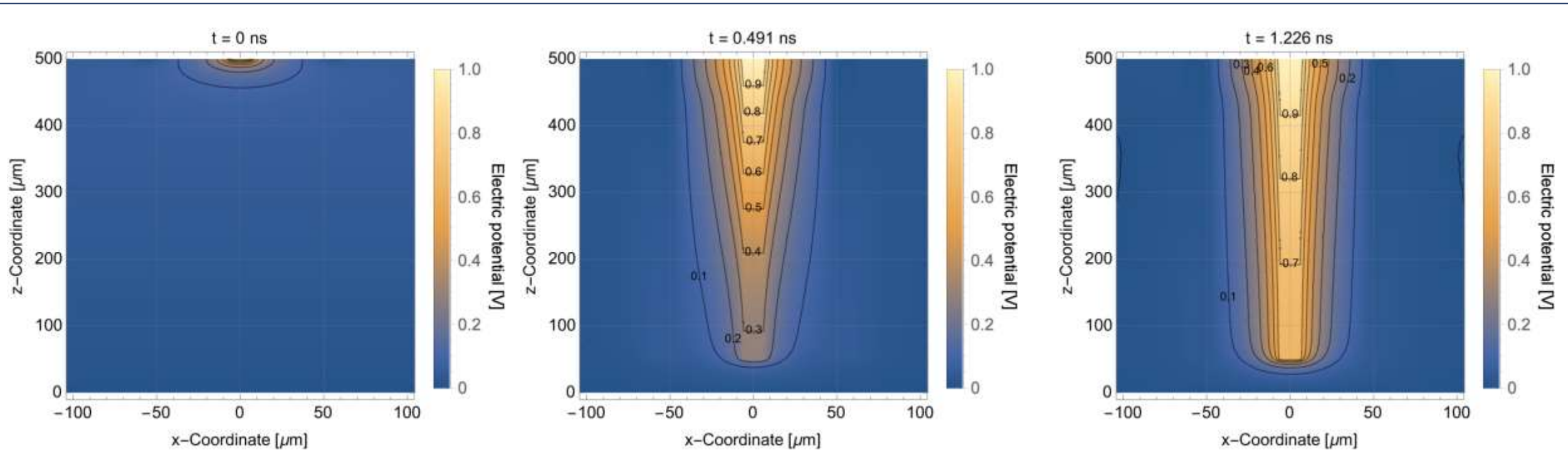
$$I_n^{ind}(t) = -\frac{q}{V_w} \int_0^t \vec{E}_{w,n}(\vec{x}(t'), t - t') \cdot \dot{\vec{x}}(t') dt'$$



D. Jassensen et al. ,(VCI 2022) <https://doi.org/10.1016/j.nima.2022.167227>

SIMULATION SOFTWARE

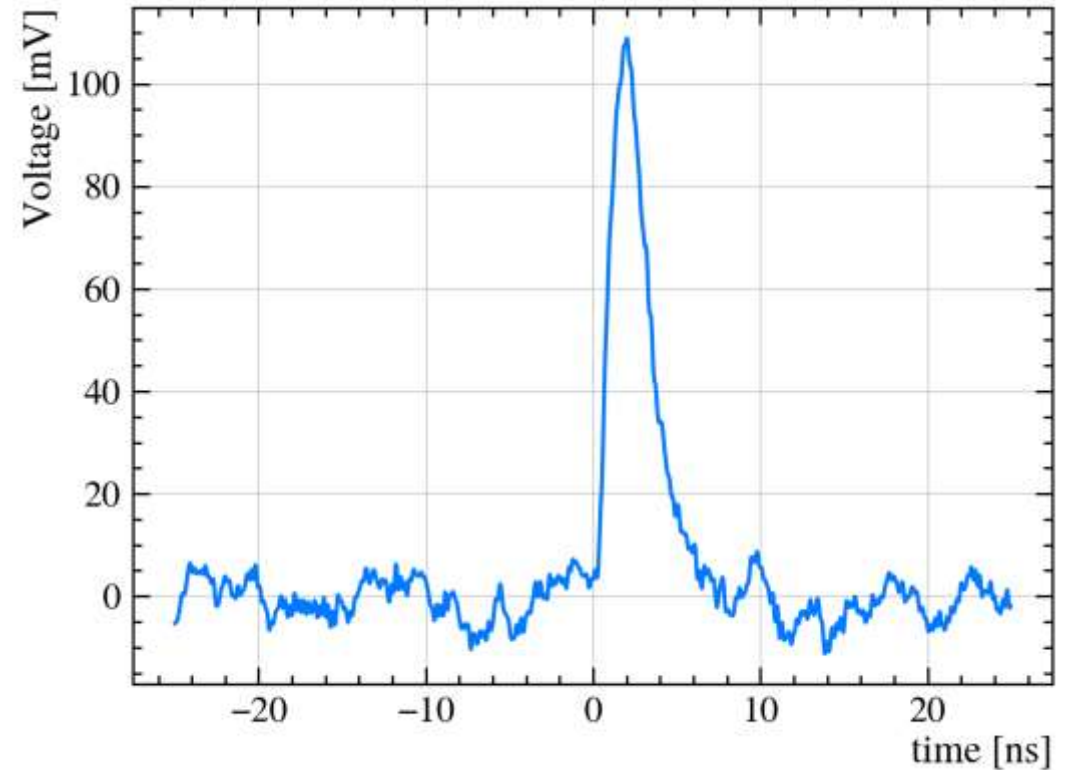
- Time-dependent weighting potential maps are made using COMSOL Multiphysics (<https://www.comsol.com/comsol-multiphysics>)
- Output signal from the sensor is simulated using Garfield++ (<https://garfieldpp.web.cern.ch/garfieldpp/>)



D. Jassensen, PhD Thesis, 2023, <https://cds.cern.ch/record/2890572>

READOUT ELECTRONICS AND SIGNALS

- The signal output from Garfield++ is convolved with the transfer function of the readout electronics (LTSpice software)
- Noise from the readout electronics was also added to each signal



RESULTS AND VALIDATION

To validate the simulation, the results of the analysis can be compared with those of a beam test, organized by the TIMESPOT organization, that occurred in 2021 at the SPS at CERN <https://web.infn.it/timespot/>

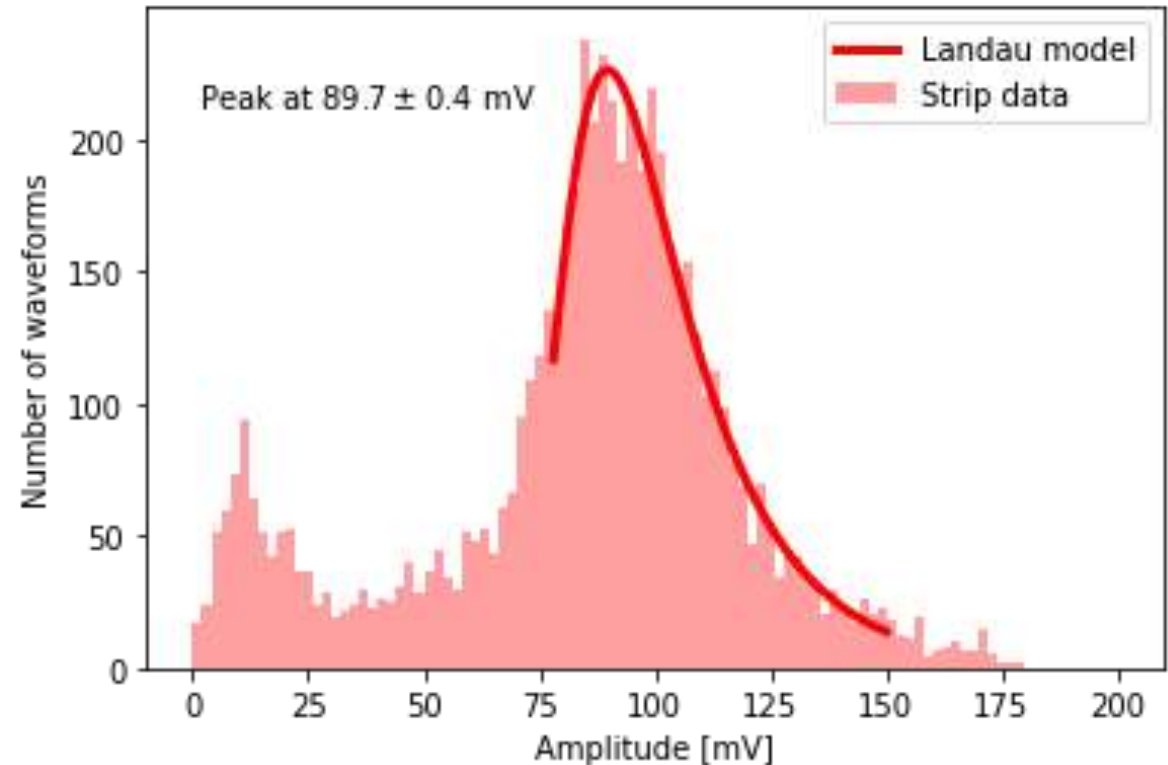
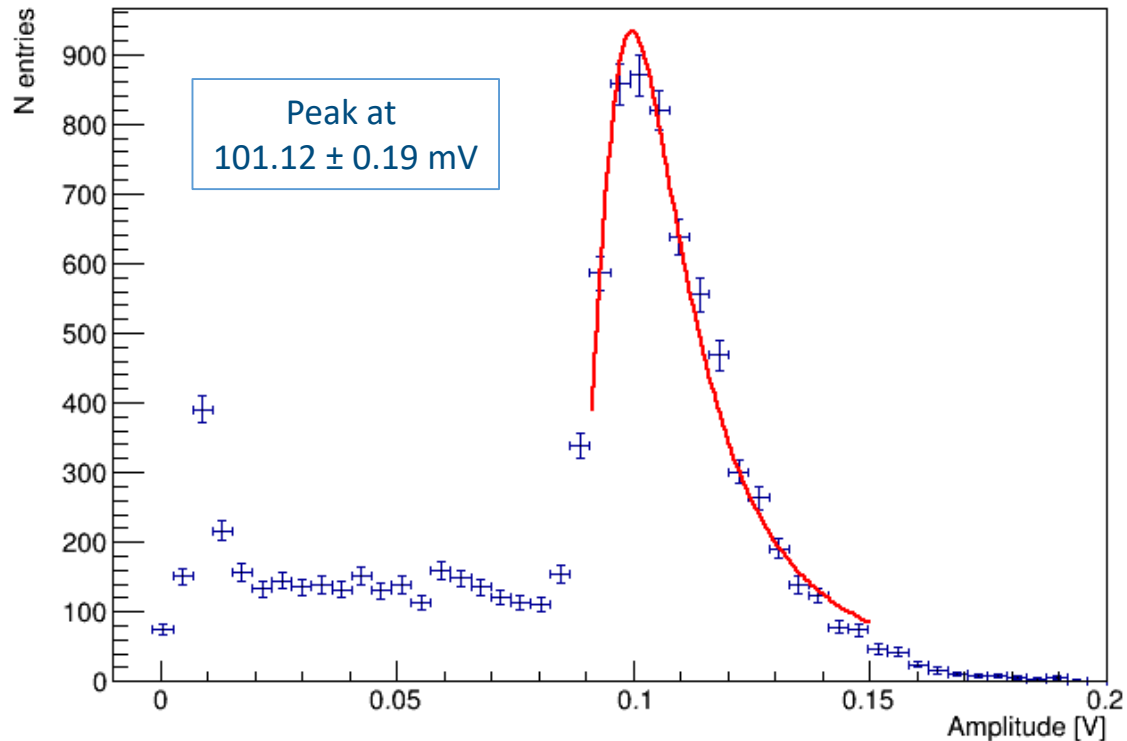
BEAM:

- 180 GeV/c hadrons
- Gaussian angular distribution: $\sigma_x = 14.9$ mrad e $\sigma_y = 31.8$ mrad

DETECTOR:

- Matrix 6x6 pixel 55 μm x 55 μm
- electrode resistance = 30 k Ω

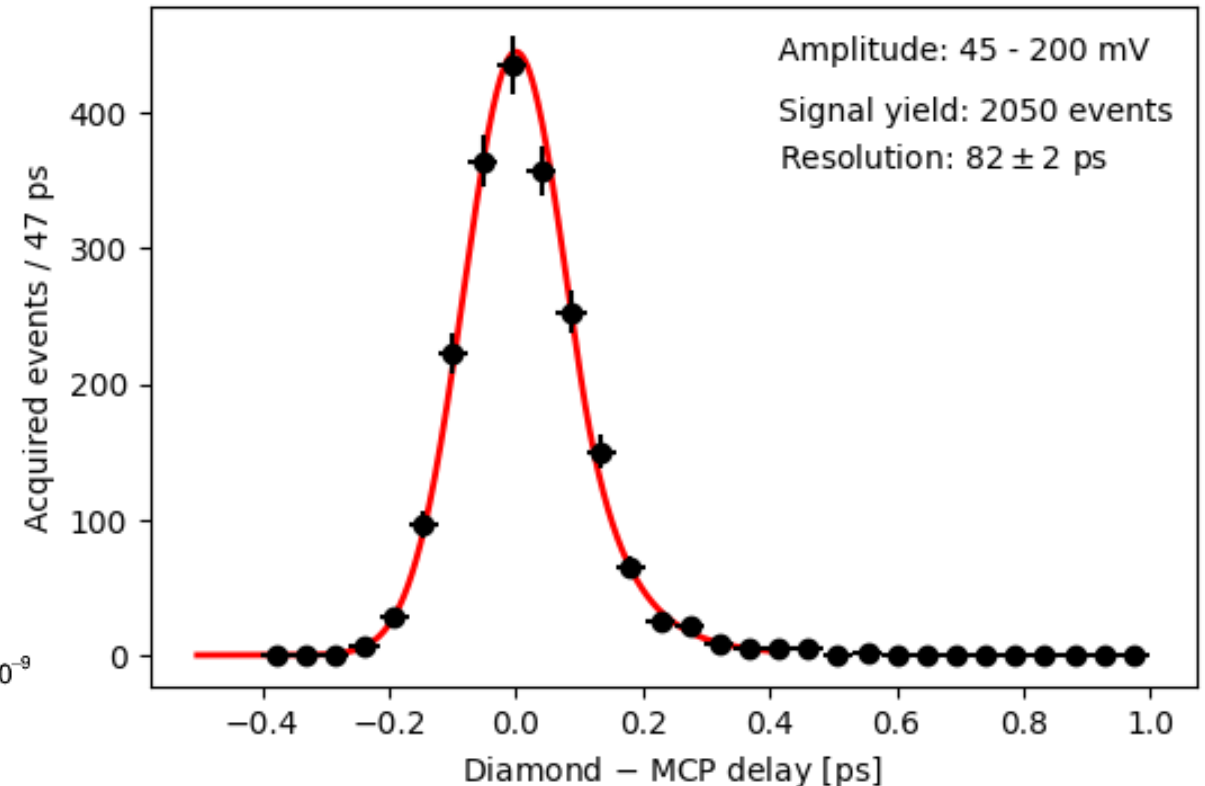
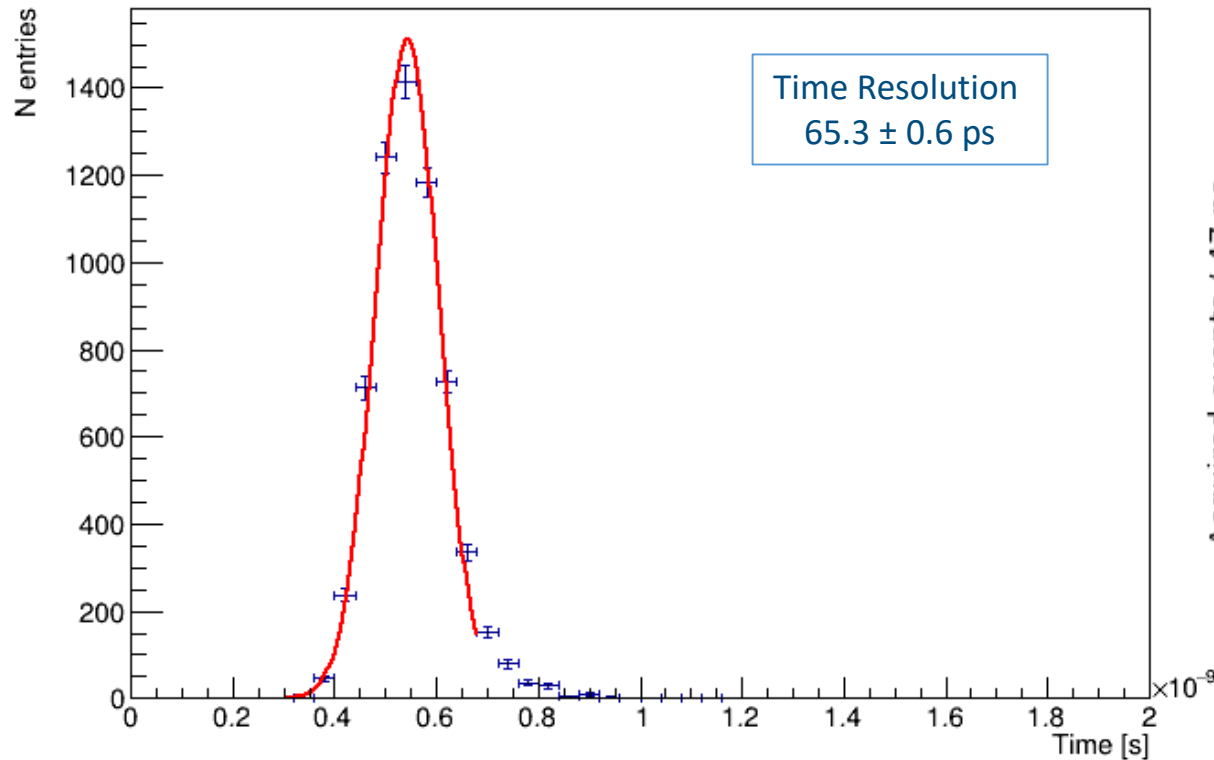
Simulated signals amplitude



RESULTS AND VALIDATION

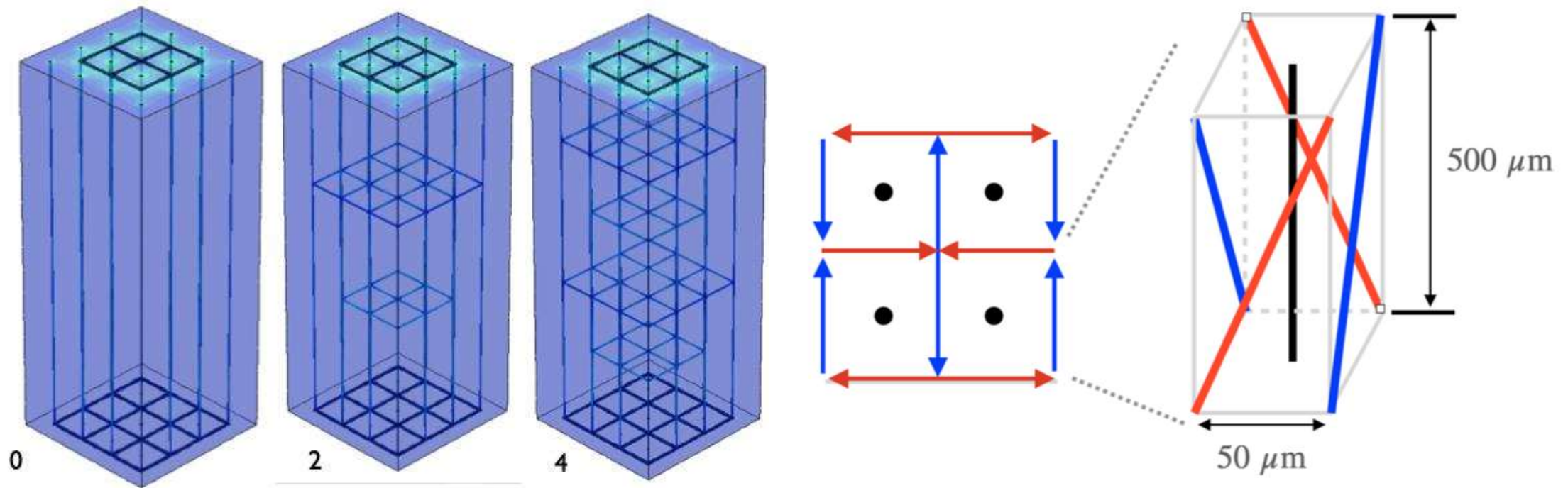
- Time resolution of the beam test results is computed on the time interval between two different time markers, set on the diamond structure and on a microchannel plate photomultiplier tubes (MCP-PMT) used as time reference
- Time resolution of the simulated detector is evaluated as the width of the Gaussian fit over the distribution of time markers of the signals obtained by a digital CFD

Amplitude > 90 mV



CONCLUSIONS AND FUTURE DEVELOPMENTS

- Simulation with the novel approach reproduces experimental data well
- The simulation can be exploited for design optimization: to predict detector performance as electrode resistance decreases and by changing the sensors geometry

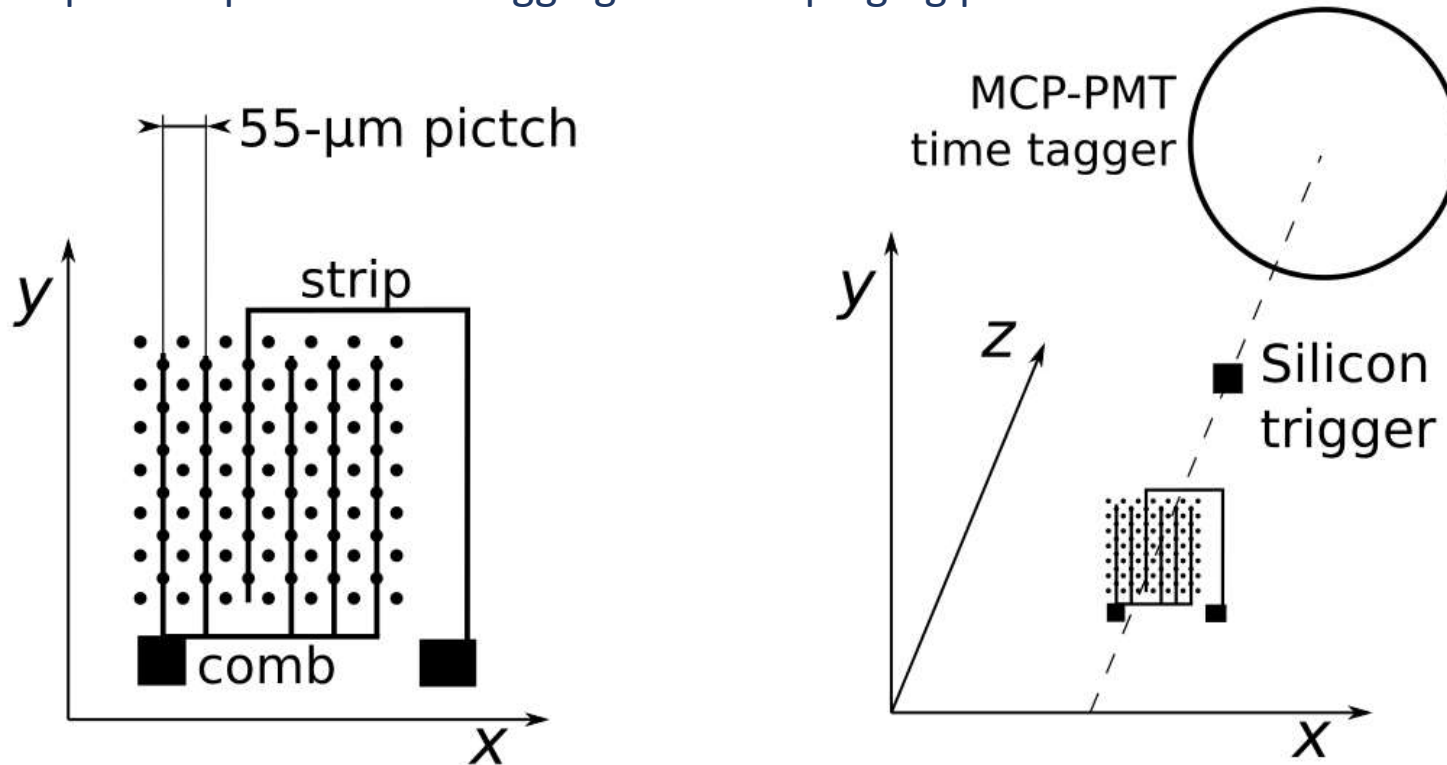


https://indico.cern.ch/event/1402825/contributions/5998324/attachments/2881611/5048654/diamond_DRD3_240620.pdf

BACK-UP SLIDES

TEST BEAM 2021

- The trigger condition is based on simultaneous signals observed in the silicon device and in a downstream MCP-PMT device acquired to provide precise time tagging of the impinging particles

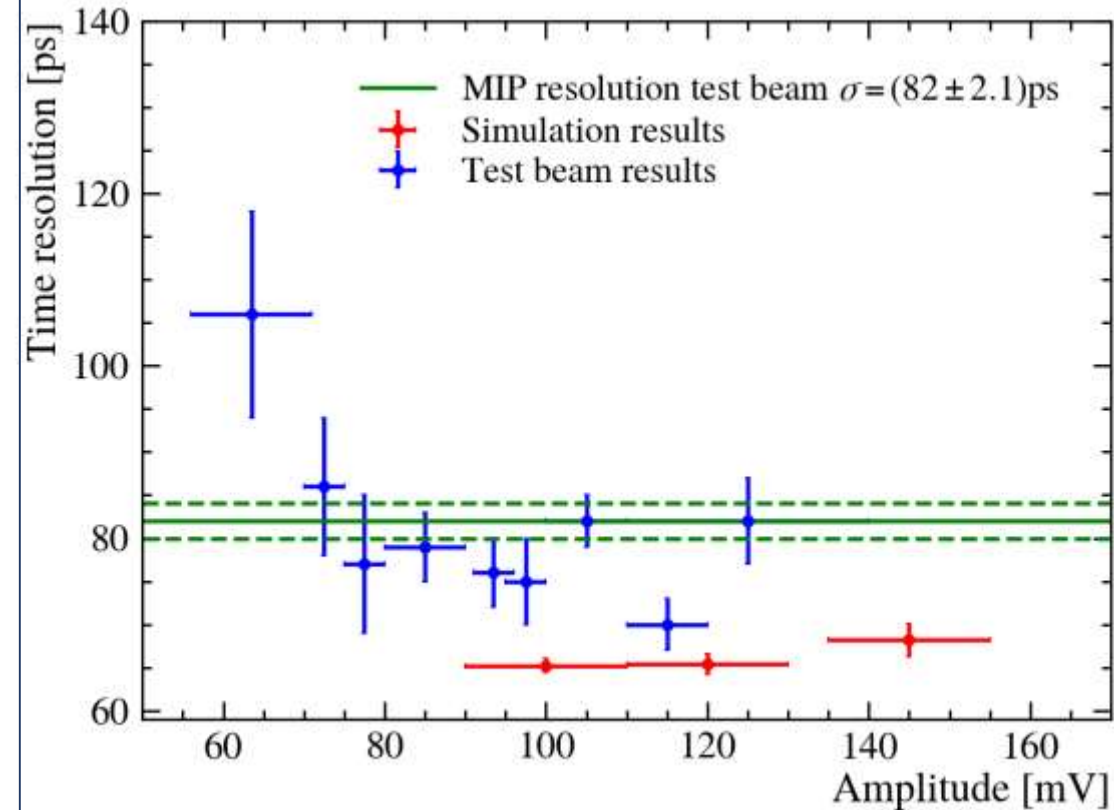
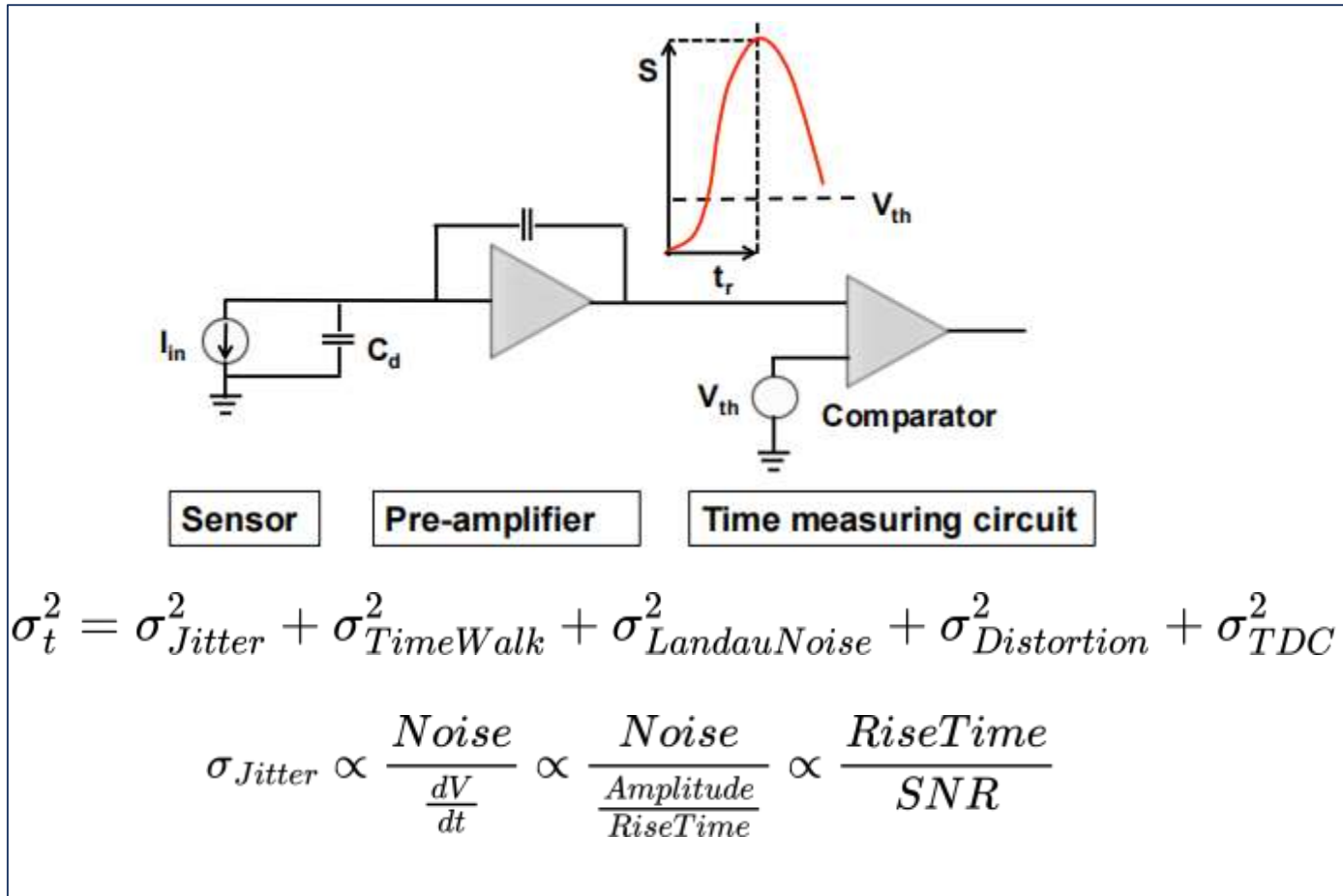


- Time resolution is computed on the time interval between two different time markers, set on a diamond structure and on the MCP used as time reference



TIME RESOLUTION AS A FUNCTION OF THE SIGNAL AMPLITUDE

Time resolution decreases as signal amplitude increases; in fact, the contribution of noise to resolution is expected to decrease



TIME RESOLUTION PERFECTLY CONDUCTIVE ELECTRODES

The time resolution obtained in the case of totally conductive electrodes is far better. The major contribution to the temporal resolution of the detector is due to the resistance of the electrodes

Threshold crossing time (static weighting potential maps)

$$\sigma_t^2 = \sigma_{geometry}^2 + \sigma_{resistance}^2$$
$$\sigma_{resistance} = \sqrt{\sigma_t^2 - \sigma_{geometry}^2} \simeq 60ps$$

