Characterisation of the transient response of diamond and SiC detectors with short intense electron pulses

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Diamond vs Silicon vs SiC

Properties	Diamond	Silicon	4H-SiC
Energy gap [eV]	5.45	1.12	3.26
Hole lifetime [s]	10^{-9}	2.5×10^{-3}	6×10^{-7}
e-h ionisation energy [eV]	13	3.66	7.78
Density [g/cm³]	3.52	2.33	3.21
Thermal conductivity [W/cm °C]	20	1.5	3 - 5
Electron mobility [cm²/Vs]	1800-2200	1400-1500	800-1000
Hole mobility [cm²/Vs]	1200-6000	450-600	100-115
Breakdown electric field [MV/cm]	10	0.2 - 0.3	2.2 - 4.0
Max working temperature [°C]	1100	300	1240
Displacement [eV]	43	13 - 20	25

Wide bandage:
Lower leakage current than silicon

High signal (MIP):
Diamond ⇒ 16 e/μm
Silicon ⇒ 89 e/μm
SiC ⇒ 51 e/μm

Fast time response

High radiation hardness

Diamond detectors

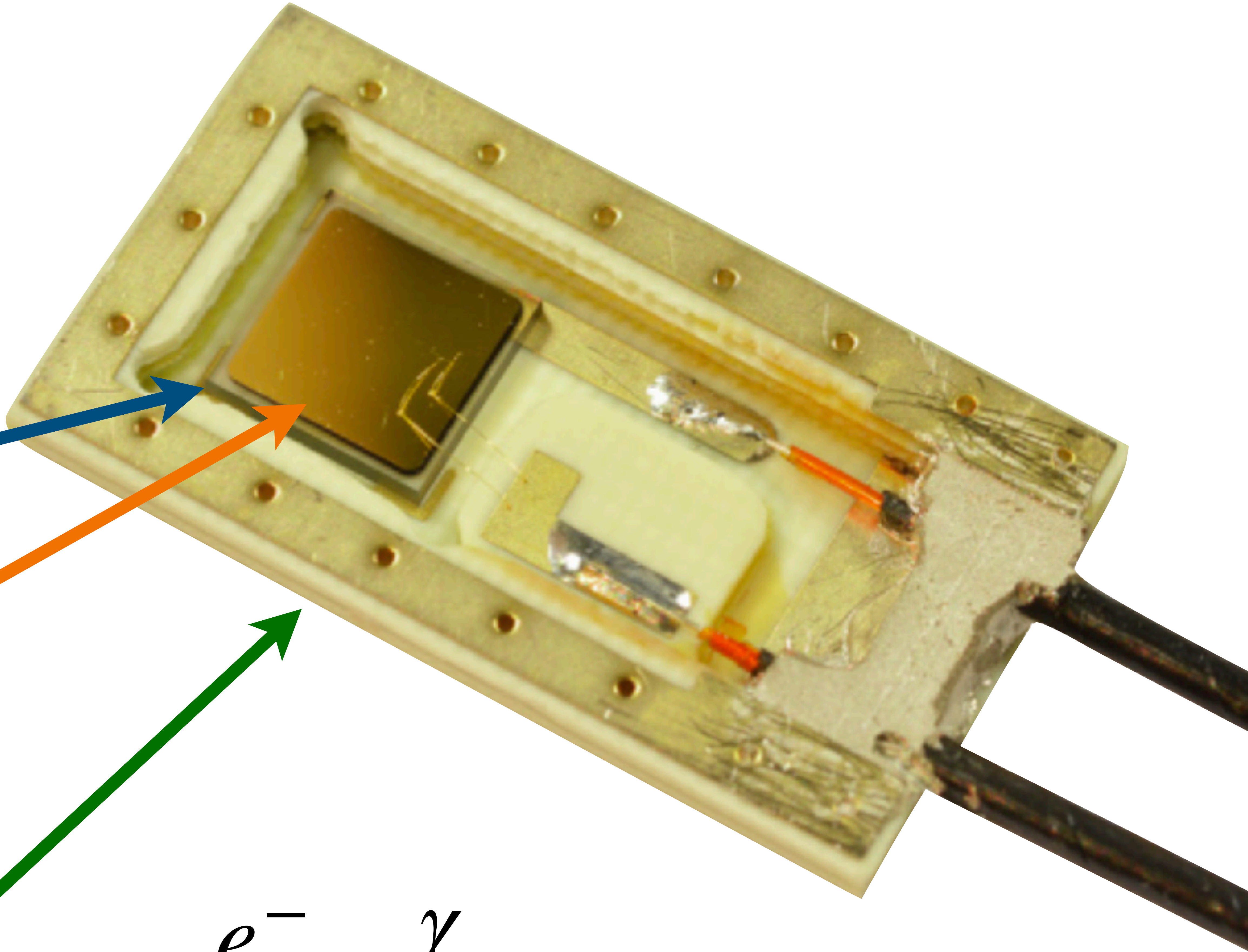
- **sCVD single crystal diamond sensors:**

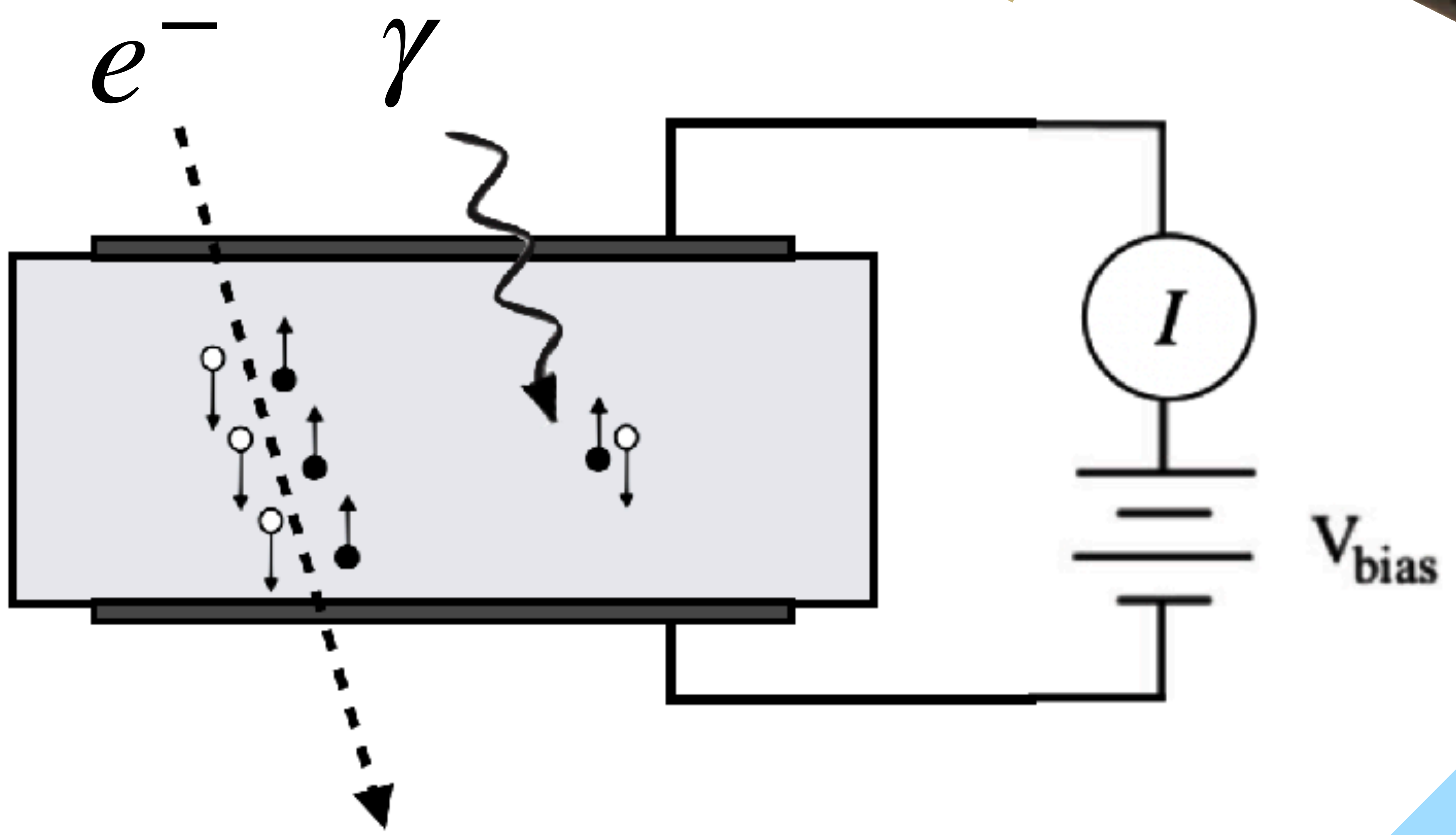
  ⇒ (4.5 × 4.5) mm^2 **crystal** faces and 0.50 mm thickness

  ⇒ (4.0 × 4.0) mm^2 **electrodes** on both faces, made of Ti+Pt+Au layers with (100 + 120 + 250) nm thickness

- Rad-hard ceramic-like (Rogers) printed-circuit board (**PCB**)

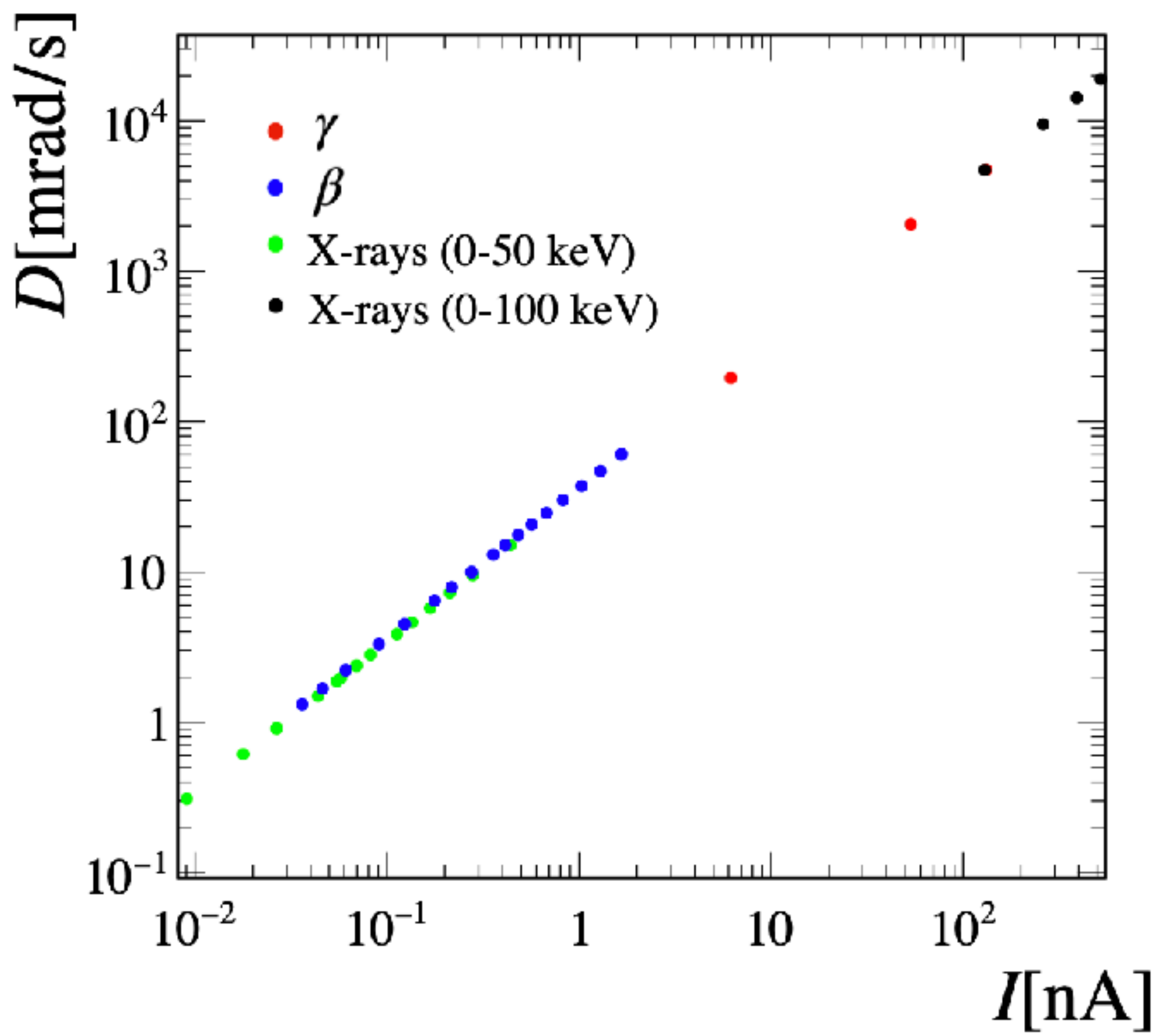
- Aluminium cover ($\sim 180\,\mu m$) placed in front of the detector to complete the mechanical and electrical shielding





Measured linearity

- **Calibration with different steady radiations**
  - ⇒ β radiation (^{90}Sr): 10 pA - 2 nA
  - ⇒ γ radiation (^{60}Co): 10 nA - 100 nA
  - ⇒ X radiation (0 - 50 keV): 10 pA - 1 nA
  - ⇒ X radiation (0 - 100 keV): 100 - 500 nA



Full charge collection efficiency over a wide range of bias voltages 40 ÷ 600V

More details about calibration: NIM-A 2021.165383 (July 2021)

Measured linearity

- **Calibration with different radiation sources**
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  - ⇒ γ radiation (^{60}Co): 10 nA - 100 nA
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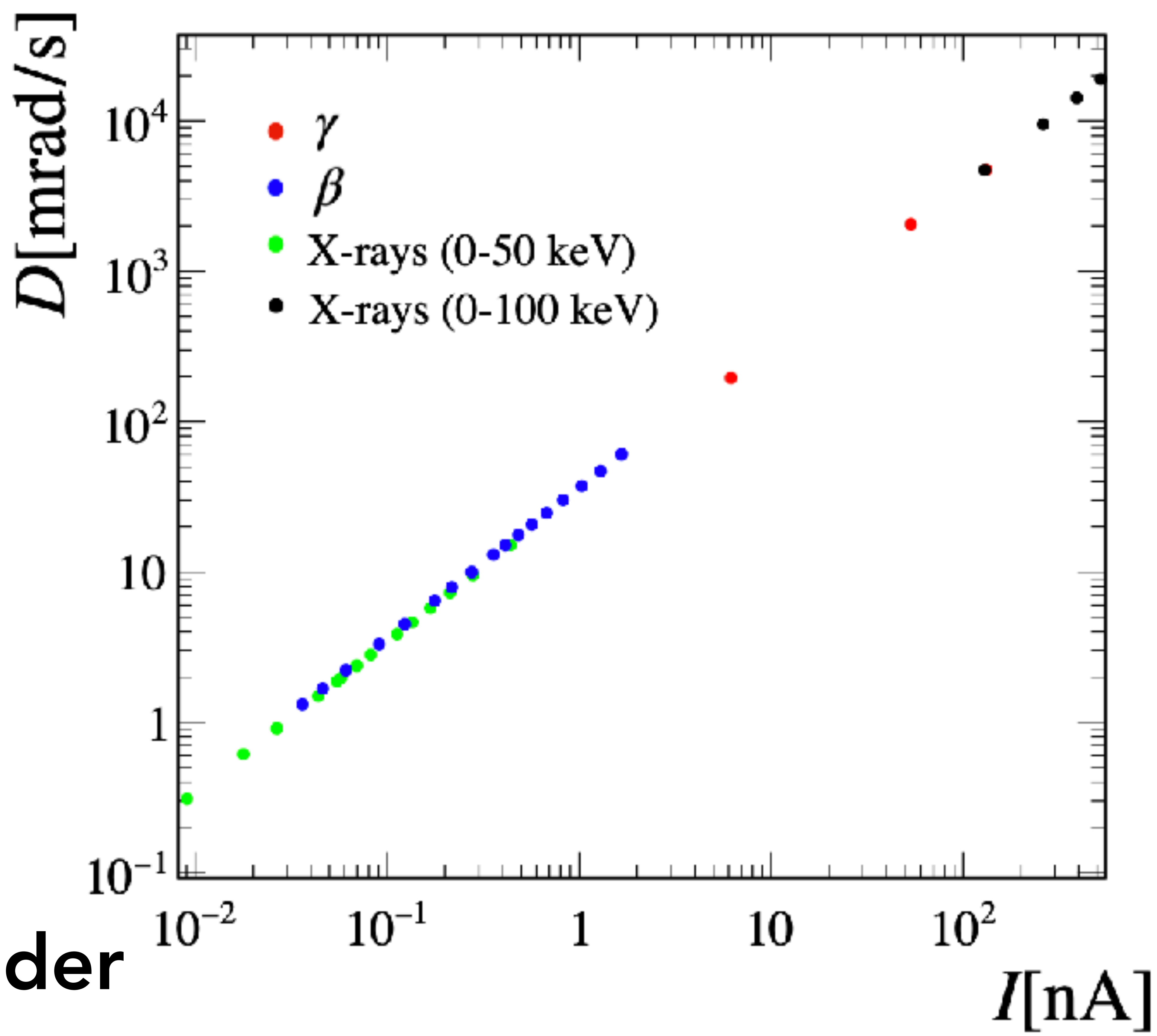


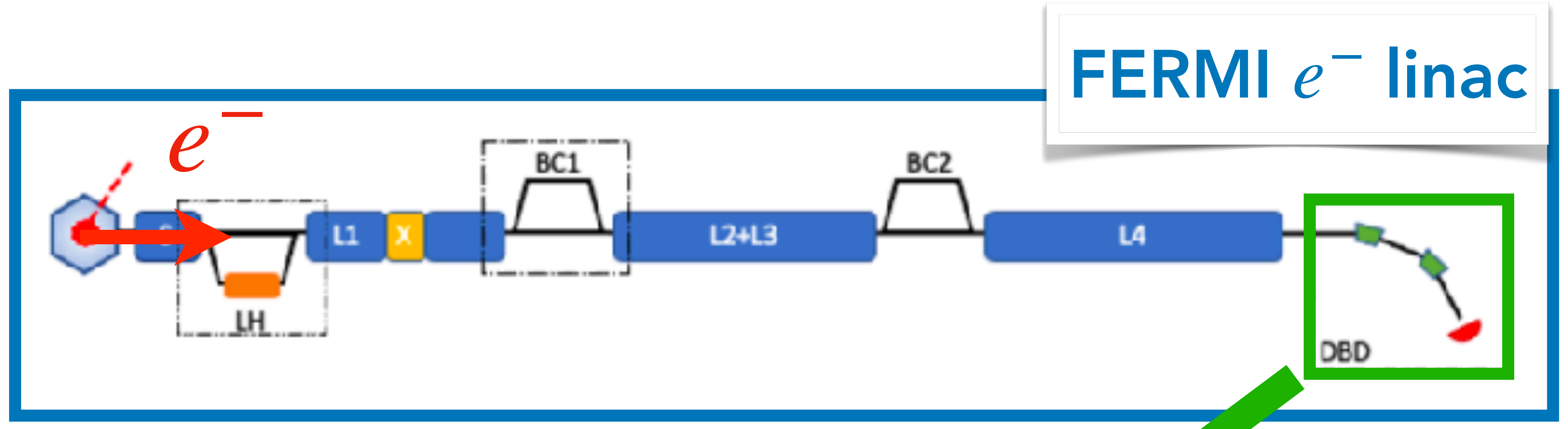
- **Belle II radiation monitor at SuperKEKB e^+e^- collider**
  - ⇒ stationary regime (background in collisions): $\mathcal{O}$(nA)
  - ⇒ continuos injection: $\mathcal{O}(\mu$A) in 300 μs
  - ⇒ huge beam losses: $\mathcal{O}$(mA) in 10 μs

Saturation effects?

Need to test the transient response for high intensity pulses

Experimental setup

Elettra Sincrotrone Trieste



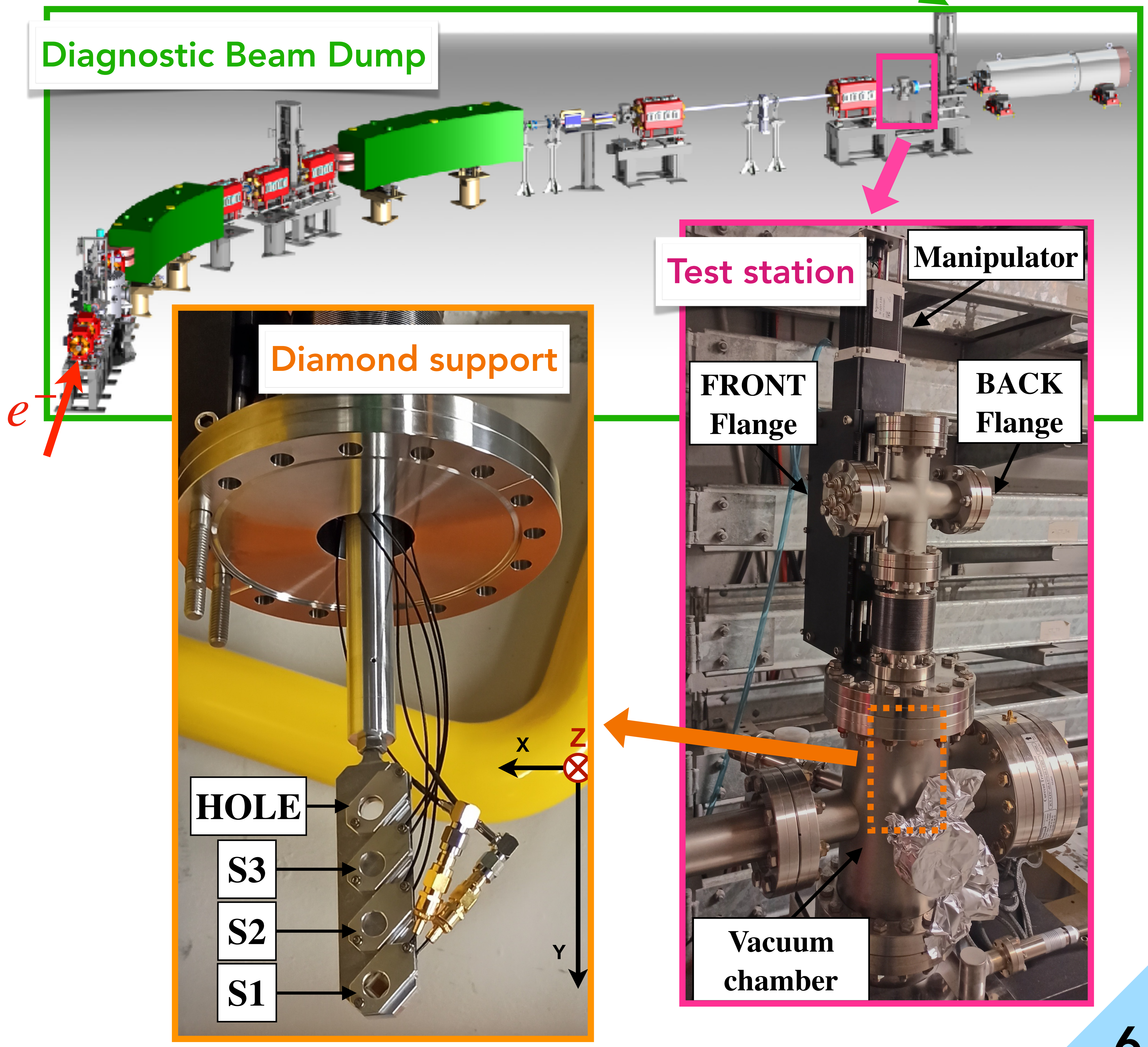
- FERMI e^- linac: $1\,\mathrm{GeV}$ electrons short bunches of $1\,\mathrm{ps}$ duration and transverse size down to $\sim 100\,\mu\mathrm{m}$, with adjustable bunch charge from ten to hundreds of pC

- **Main goal**: study possible non-linearity in the diamond response due to a very high charge carrier density in the diamond bulk

- **Several sets of measurements:**

  ⇒ changing beam parameters

  ⇒ varying detector bias voltage and vertical position

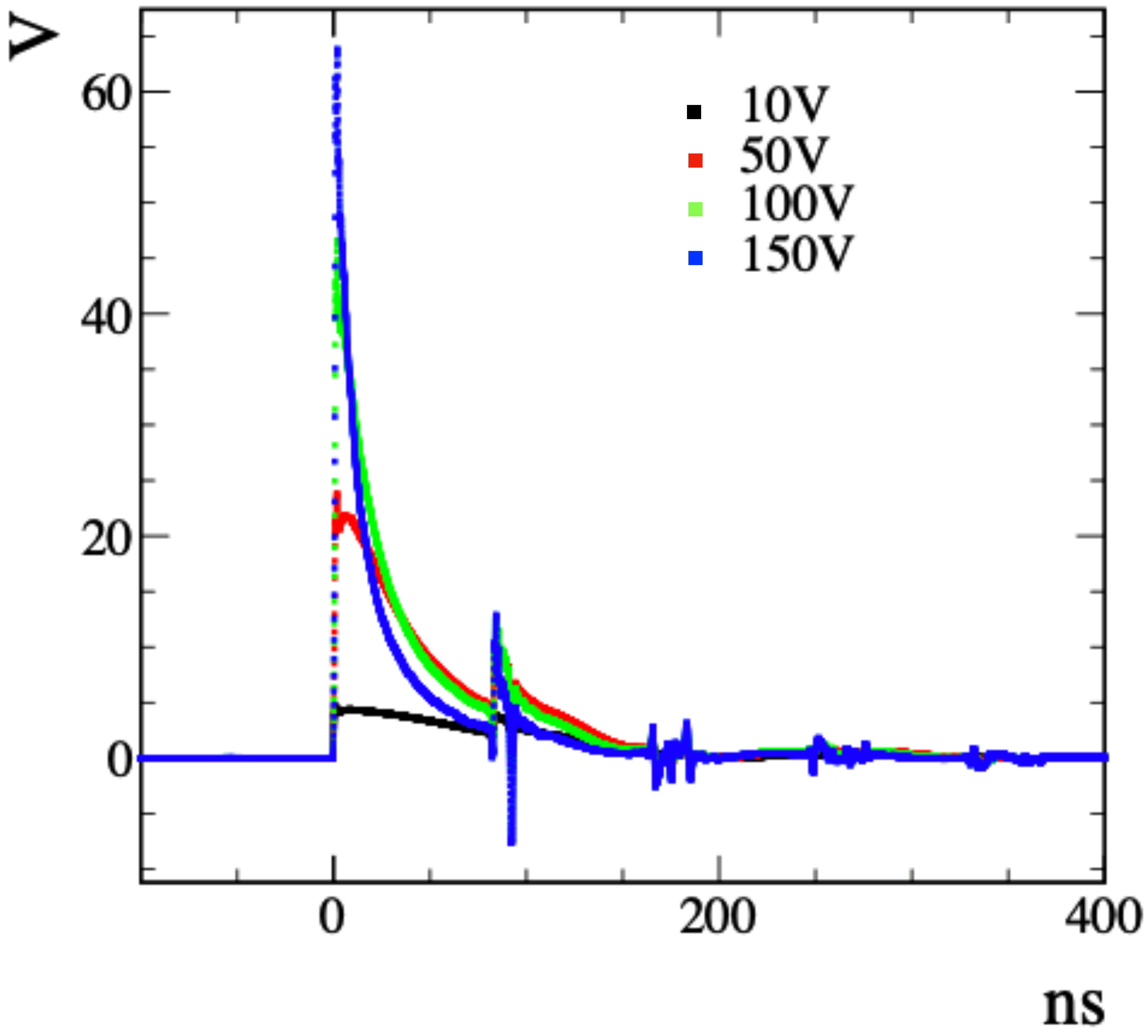


Diamond response

- **Induced signal:** characterised by a fast rise time of ~100ps, tails of hundreds of ns and reflections due to impedance mismatches

- Signal **amplitude** and **integral** change as a function of the beam shape and bunch charge

Measured signals for e^- bunches of 35pC, at four different bias voltages



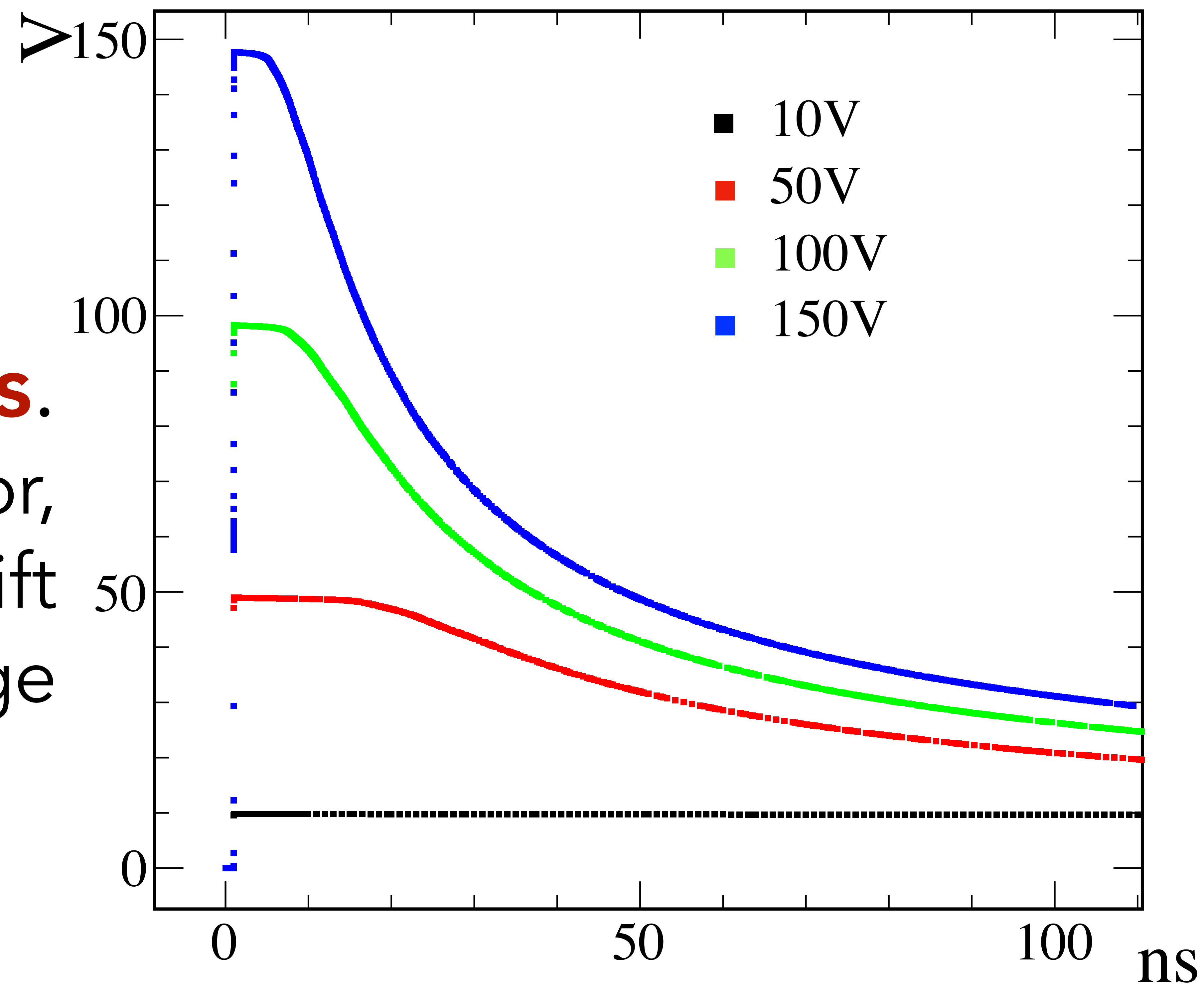
Two-step numerical simulation

A two-step numerical approach to simulate the time response of the diamonds:

- Signal formation on the sensor by **TCAD-Sentaurus**.
  It includes the interaction of the radiation with the sensor, the generation of e-h pairs by impinging radiation, the drift of charge carriers and the evolution of the induced voltage drop on the electrodes

- Detector-readout circuit in **LTspice**.
  It gives a modelling of diamond resistance, coaxial cables, power supply, and oscilloscope input. It takes into account effects of electronic circuit on signal, such as reflection, attenuation and distortion

More details: **NIM-A 2023.168259 (July 2023)**

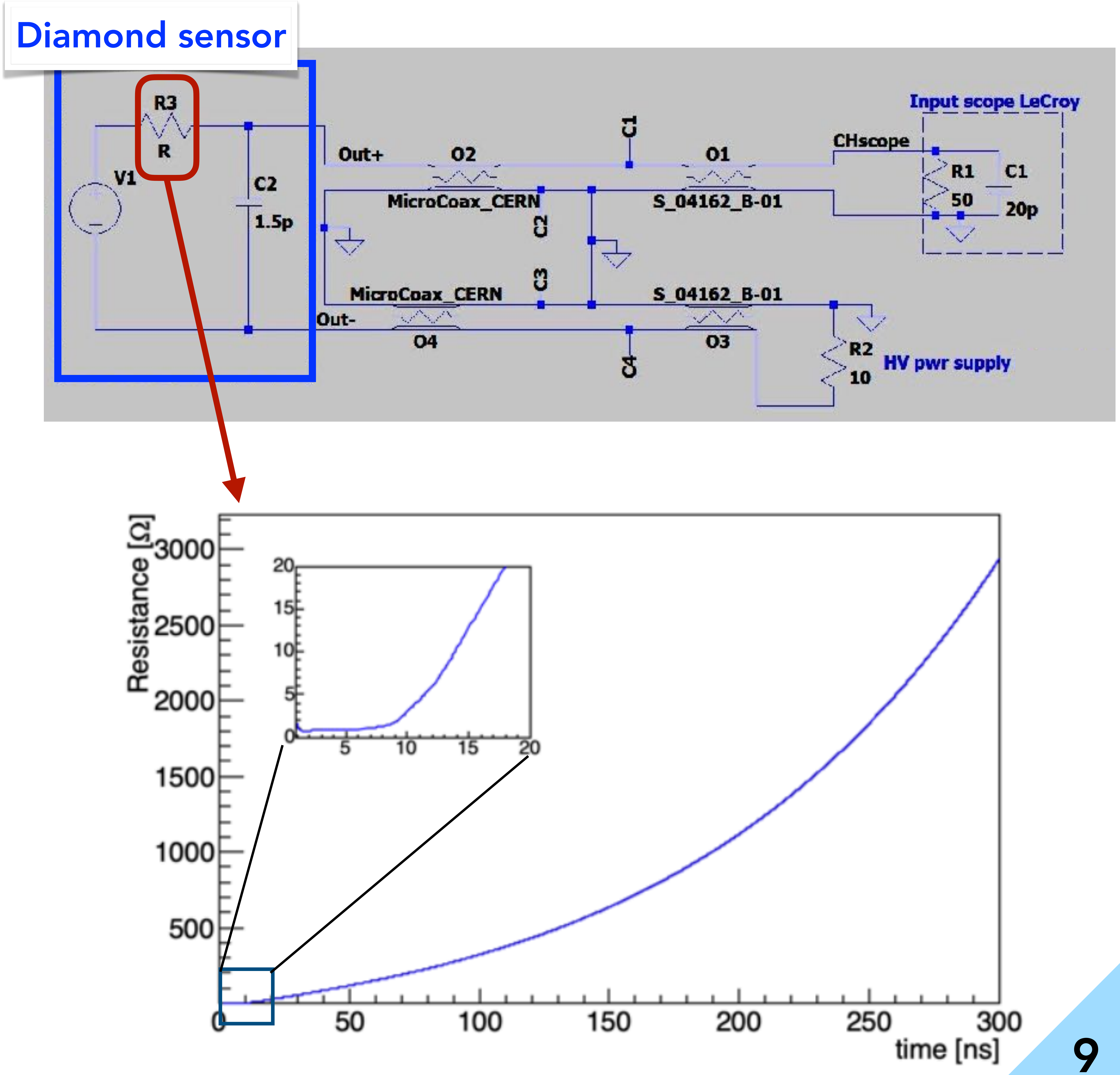


TCAD output signals obtained for e^- bunches of 35 pC at different bias voltages

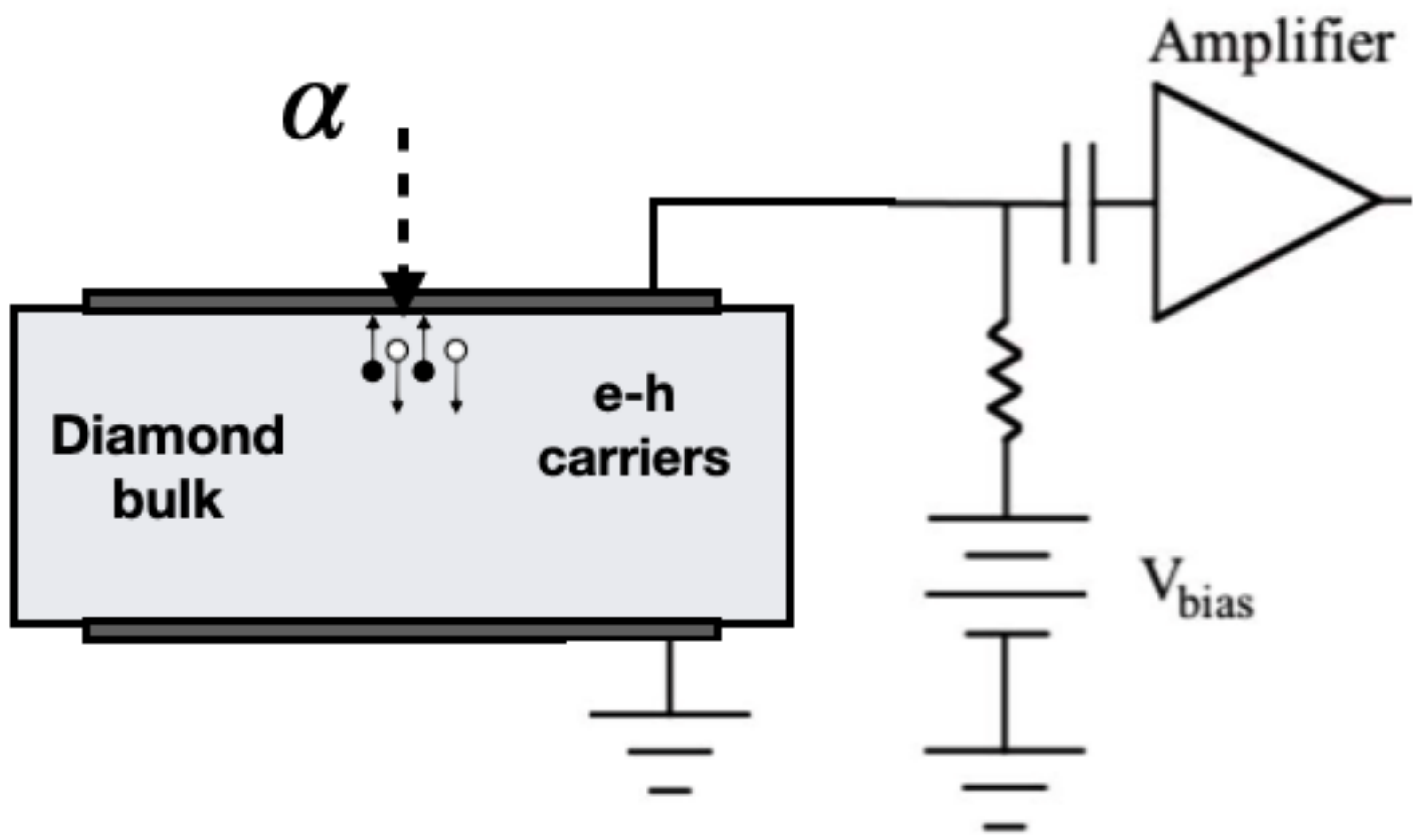
Transient on diamond properties

The sensor can be modelled as a capacitor and a variable resistance

- A bunch carrying a charge of $1\,\mathrm{pC}$ can inject e-h concentration of about $10^{15}\,\mathrm{cm}^{-3}$ in a limited volume and in a short time interval
- The high density of charge carriers generated by ionisation in the diamond bulk causes a transient modification of electrical properties of diamond sensor (e.g., resistance), which in turn affects the signal shape
- **Variable diamond resistance** has been modelled as a function of the charge carrier density in the diamond bulk

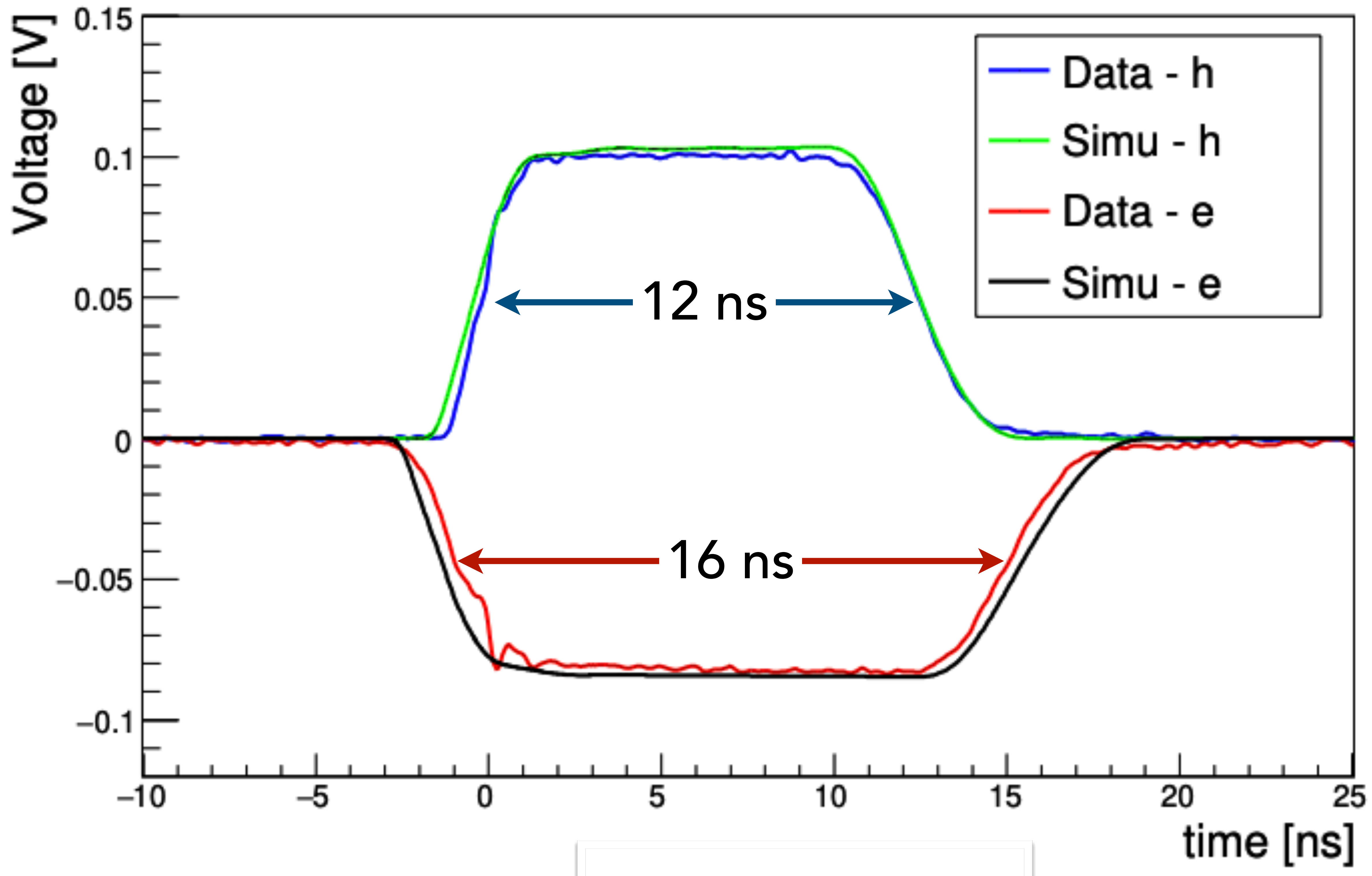


Validation with TCT



Simulating the time response of diamond detector for Transient Current Technique (TCT) measurements with monochromatic (~5 MeV) α particles:

- Good agreement between results of numerical simulation and experimental data, on both the amplitude and the shape of the pulse, validating the two-step simulation of our diamond sensors.
- Charge carrier parameters used in simulation well describe our diamond sensor.



$V_{bias} = \pm 150\,\mathrm{V}$

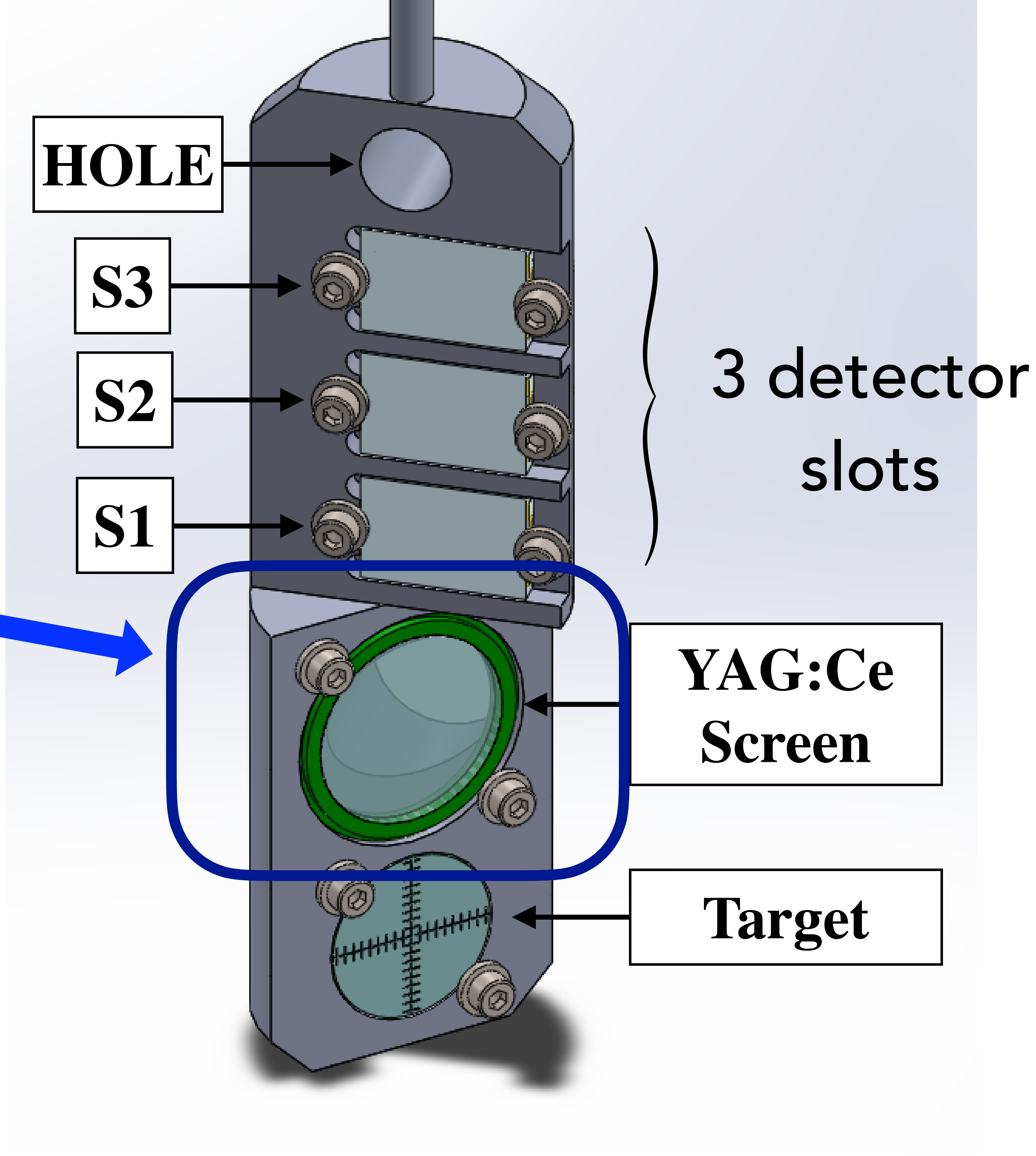
Measurement vs simulation

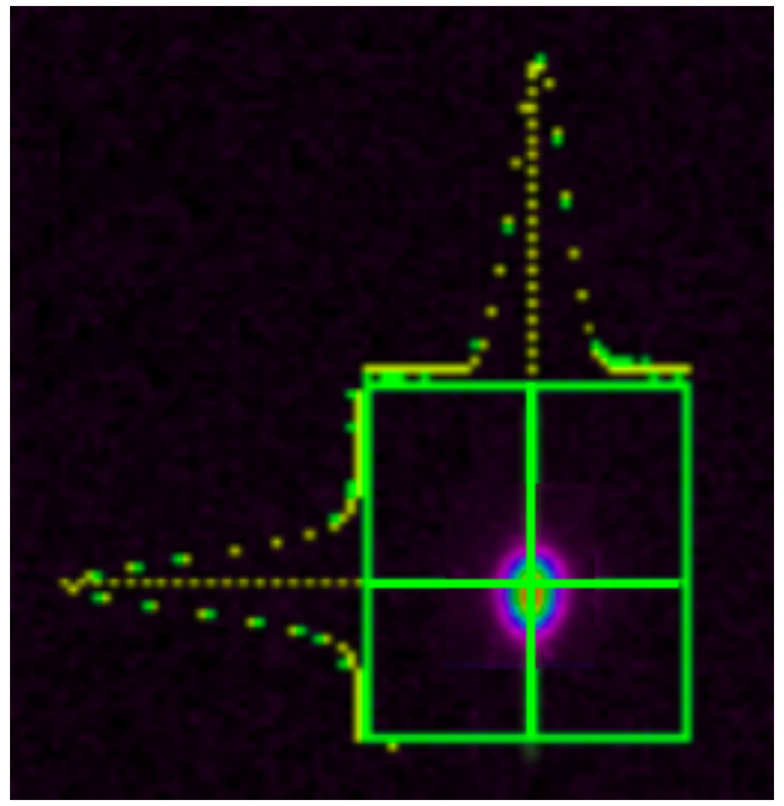
- Fair agreement between measurement and simulation (same amplitude and reflection time) at different bias voltages
- The results are obtained for a recombination time $\tau = 50\,\mathrm{ns}$

Comparison for e^- bunches of 35 pC at different bias voltages

Optimised setup

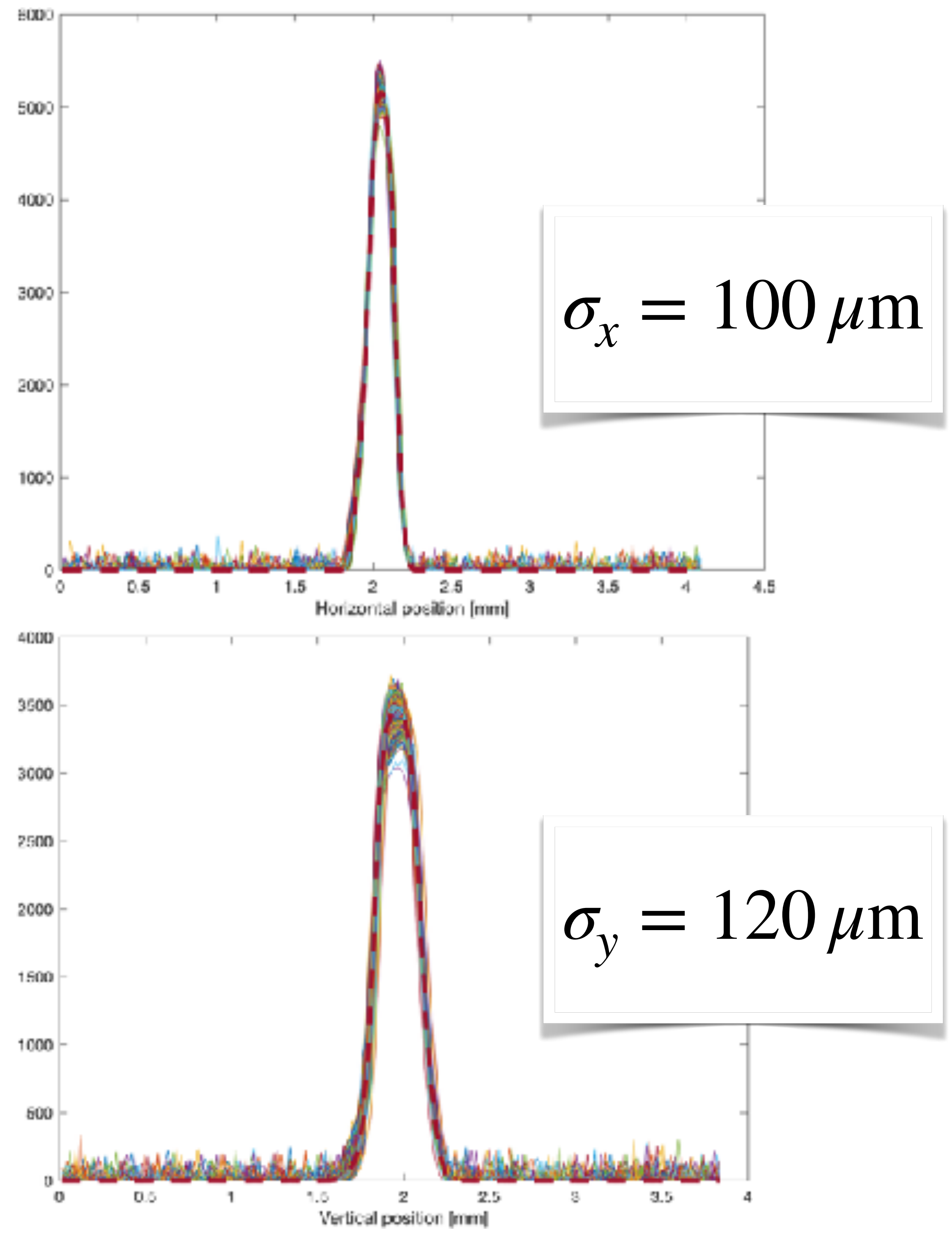
- Added a **YAG:Ce fluorescent screen** with a CCD camera realtime readout system





Real time image acquired by CCD

Acquired 1000 shot-to-shot images



Offline analysis

- **Improvements:**

  ⇒ better knowledge of the beam profile and position on the detector under test (online)

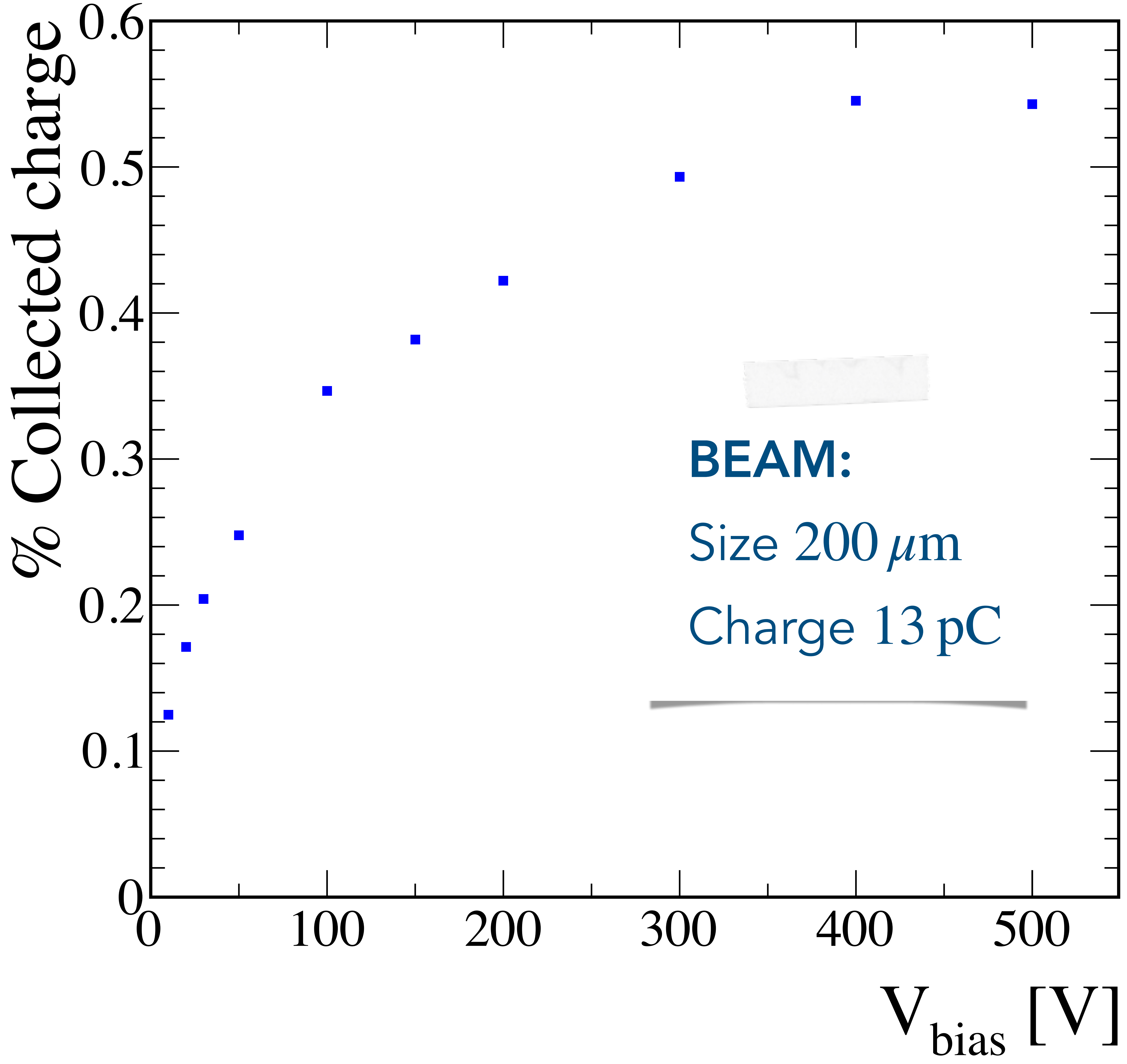
  ⇒ measurement of beam dimensions

Non-linearity of charge collection

- **High voltage scan** for different beam charges with fixed beam parameters and beam centred on the diamond sensor

- A small fraction of the total ionisation charge is collected (max ~0.6%), that is an indication of relevant charge carrier losses by recombination

- Moreover, collection efficiency depends on the beam size



Silicon Carbide

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Wide bandage:
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High signal:
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SiC ⇒ 51 e/μm

Fast time response

High radiation hardness

- Often used for power electronics (military and space applications)
- Lower cost but even more difficult to procure high quality crystals compared to diamonds

SiC detector

- **Geometry similar to diamond sensor:**

  $\Rightarrow (5.0 \times 4.5)\,\mathrm{mm}^2$ **crystal** faces and 0.50 mm thickness

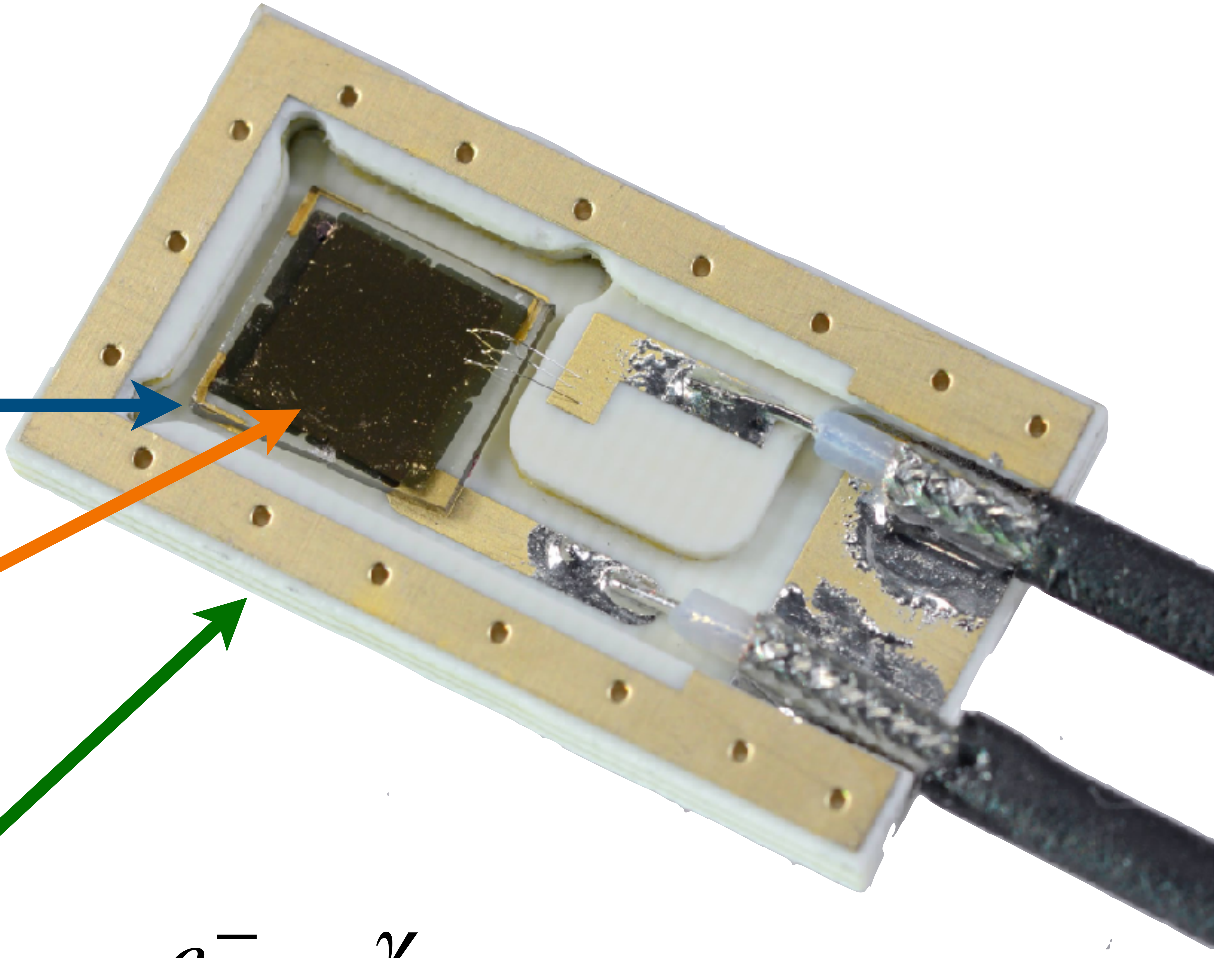
  $\Rightarrow (4.1 \times 4.1)\,\mathrm{mm}^2$ **electrodes** on both faces, made of Cr+Au layers with (5 + 50) nm thickness

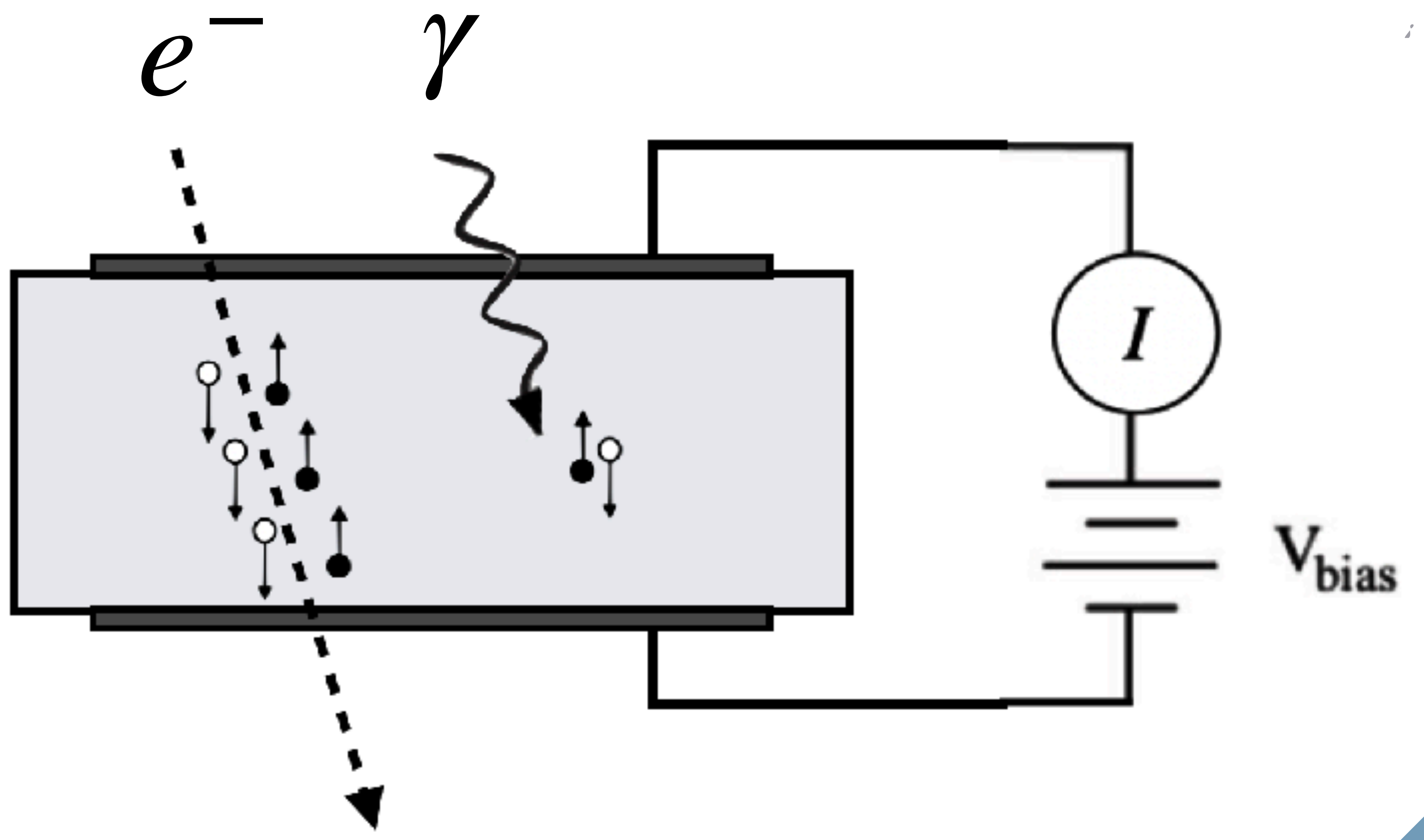
- Rad-hard ceramic-like (Rogers) printed-circuit board (**PCB**)

- **SiC crystal:**

  Type : 4H-SiC semi-insulating

  Nominal resistivity: $>10^5\,\Omega\mathrm{cm}$

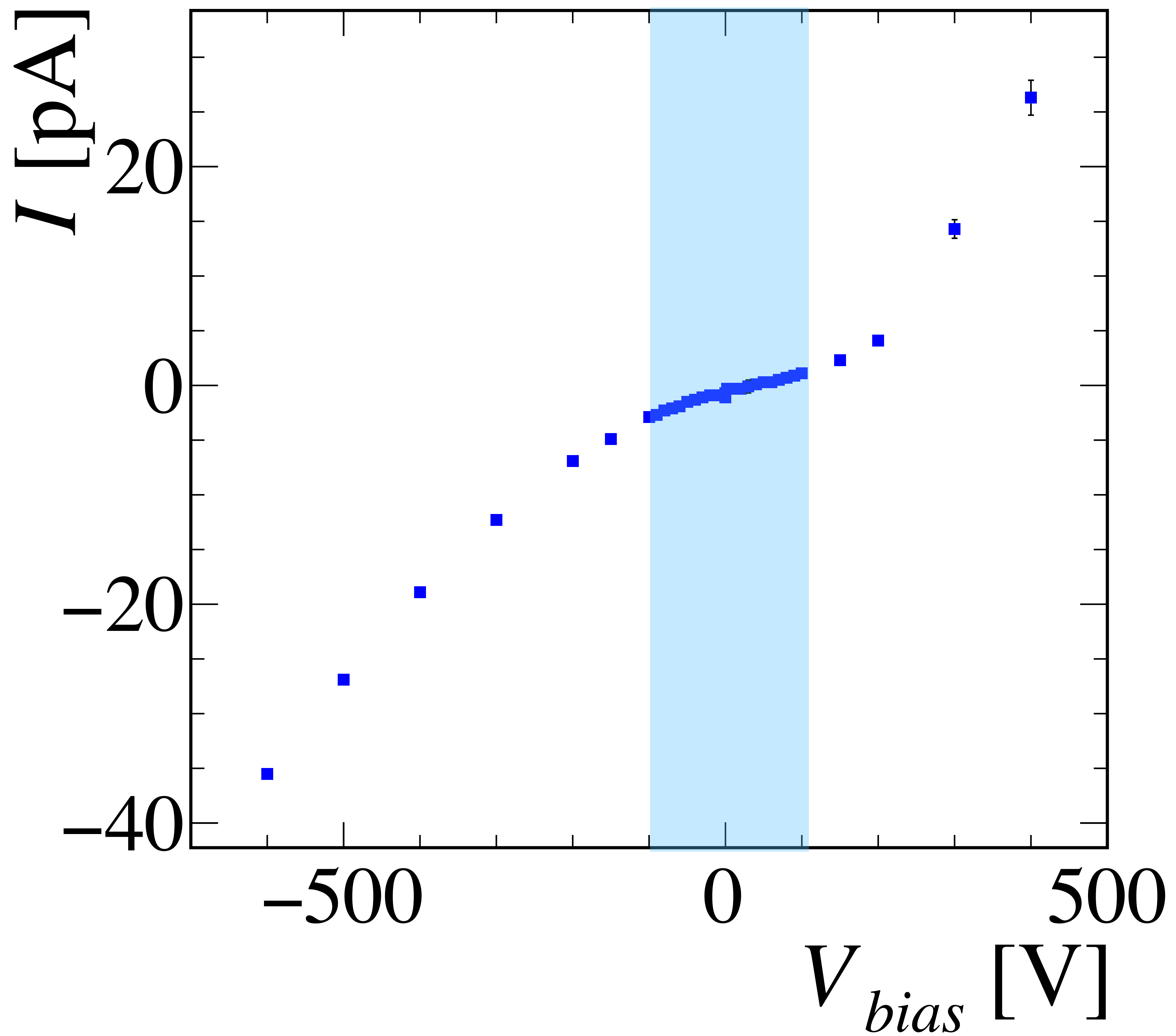




Preliminary characterisation

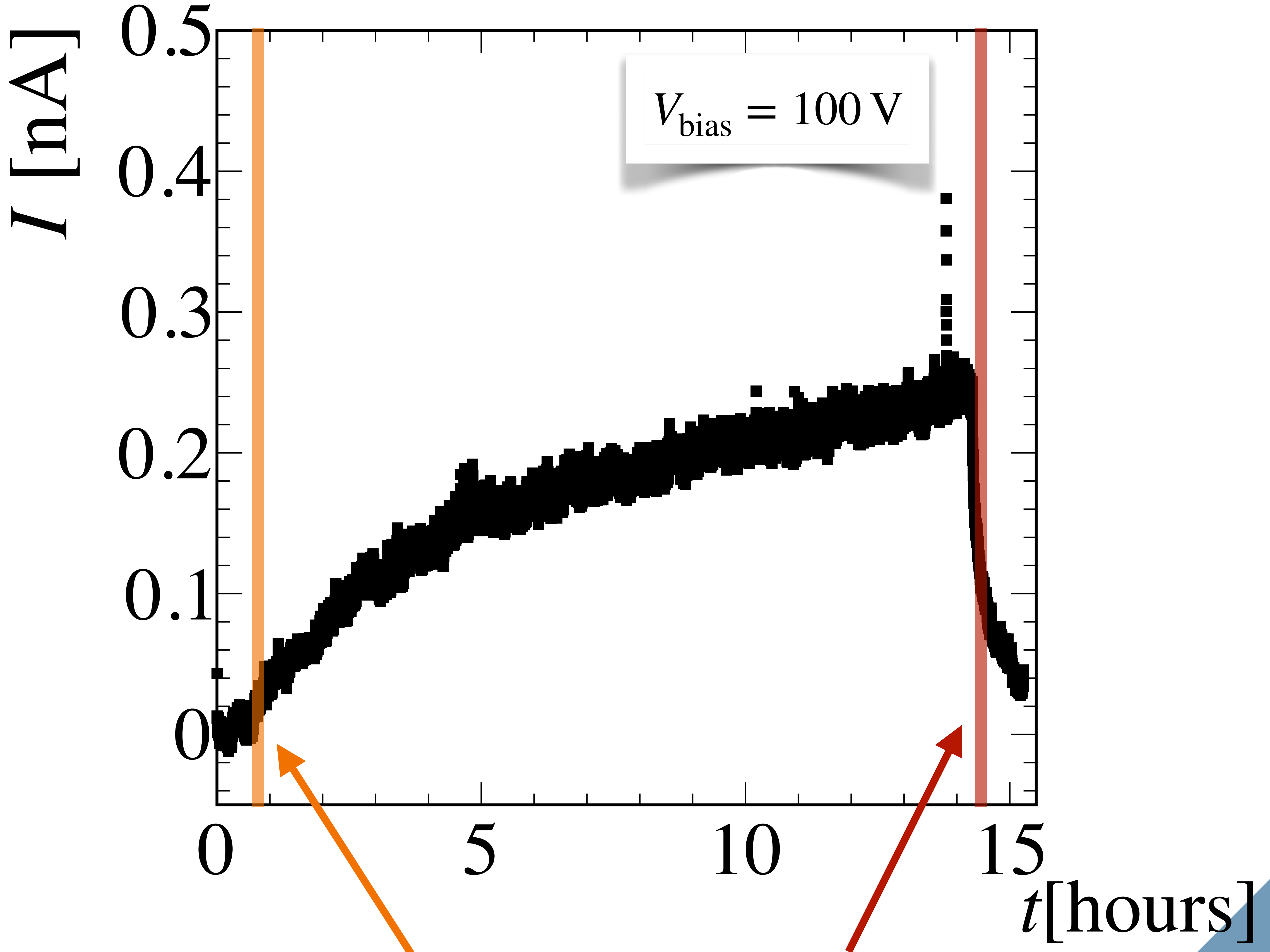
- **Dark IV:** resistivity higher than the nominal value ($\rho_{meas} > 10^{12}\,\Omega\mathrm{cm}$)

  ⇒ Leakage current ~10x diamond



- **Stability of the response** in time under a steady β irradiation:

  ⇒ 1÷25% charge collection efficiency



Shutter removal and insertion time

SiC response to intense e^- bunches

- **Clear induced signal:**

  ⇒ Fast rise time ~100ps

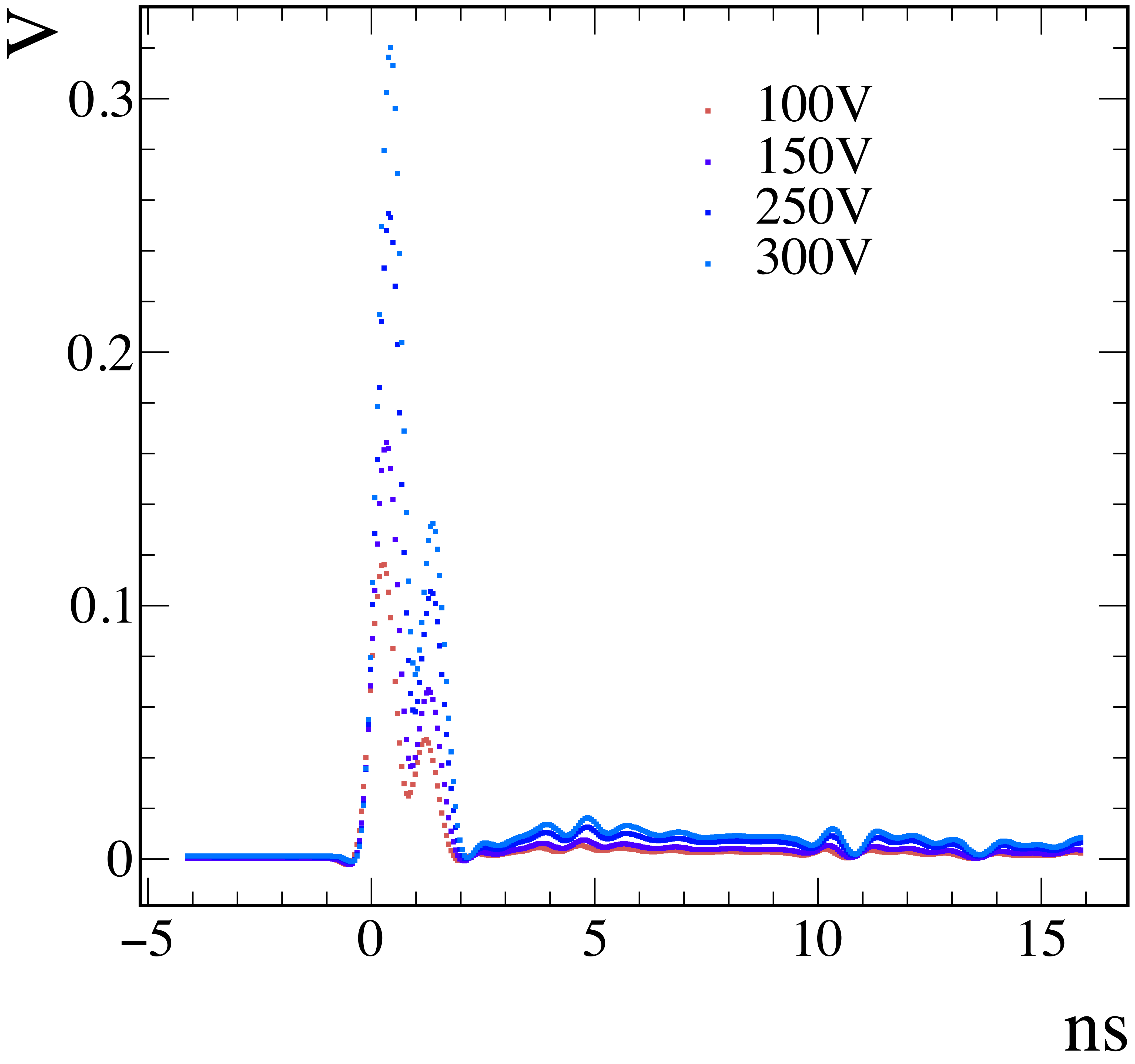
  ⇒ Amplitude 1/20 of diamond's

  ⇒ Signal width of few ns, that is an indication of strong recombination

- **Limited crystal quality:**

  ⇒ As expected traps, impurities and dislocations reduce the charge collection efficiency

- Simulations and other investigations on other samples are ongoing



Measured signals for e^- bunches of 15pC, at four different bias voltages

Summary

- Diamond detectors show a linear response over a wide range of measured steady currents. However, large transient localised ionisation density in the diamond bulk might cause non-linearity in the detector response

- We designed and installed a test station on the FERMI e^- linac to test the transient response of our detectors to ultra-short collimated ~1GeV e^- bunches

- A two-step numerical simulation approach has been implemented to the time response of the detector to different radiations and measurements are in agreement with simulations

- Non-linearity in the response of diamond to ultra-fast and intense pulses due to charge recombination in the diamond bulk

- Preliminary results on a first sample of silicon carbide presented

Acknowledgement

S. Bassanese[c], L. Bosisio[a], A. Bryne[c], G. Cautero[c], P. Cristaudo[a], S. Di Mitri[c], M. Ferianis[c], A. Gabrielli[a,b], D. Garzella[c], D. Giuressi[c], Y. Jin[a,d], L. Lanceri[a], M. Marich[c], G. Perosa[c,e], L. Stebel[c], L. Vitale[a,b]

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[d] *Now at Brookhaven National Laboratory, USA*

[e] *Now at Uppsala University, Sweden*

Backup

Diamond resistivity

- In the absence of ionisation: typically $\rho > 10^{11}\Omega \cdot \mathrm{cm}$ $\Rightarrow$ **Insulator**

- For diamond treated as an intrinsic semiconductor, the resistivity is given by

$$\rho = \frac{1}{q_e(n_n\mu_n + n_p\mu_p)}$$

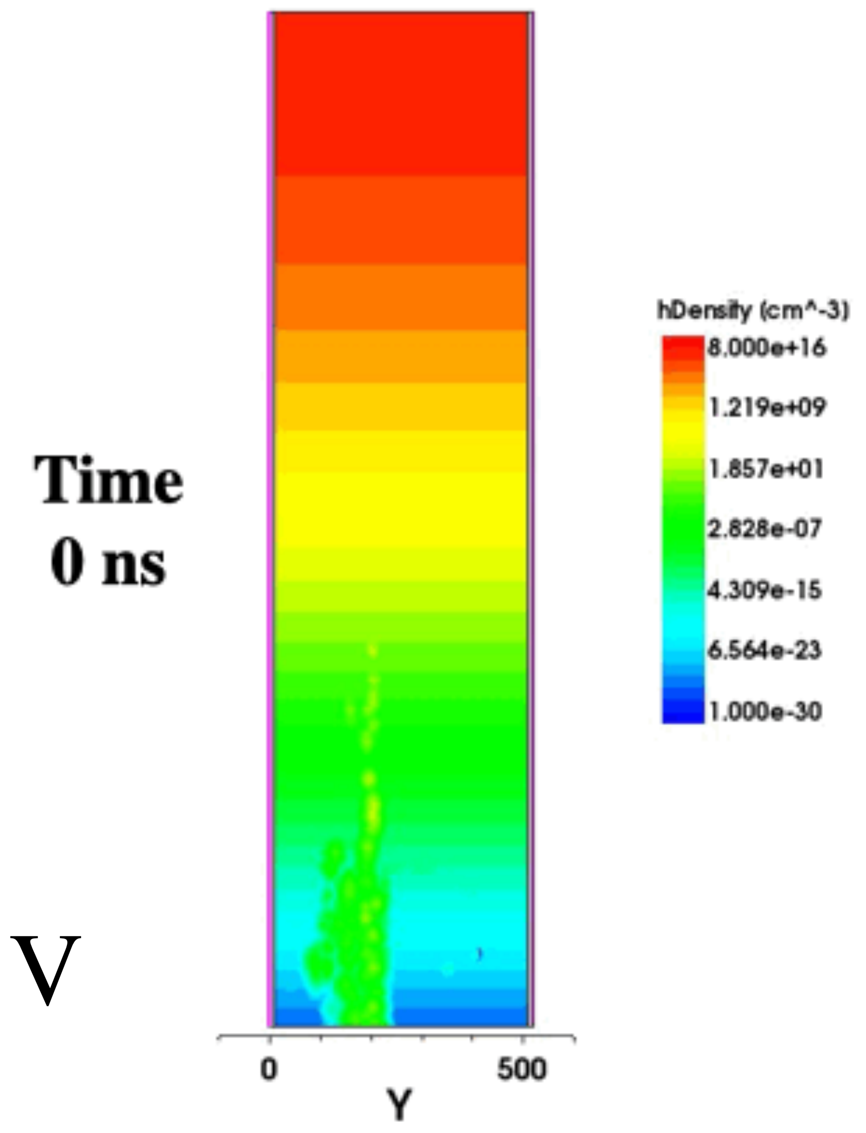
With $n_n = n_p = 10^{15}\mathrm{cm}^{-3}$, $\mu_n = 1800\,\mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$, $\mu_p = 1200\,\mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$ and$q_e = 1.6 \times 10^{-19}\,\mathrm{C}$

- This scales inversely with the assumed carriers concentration:

$$n_n = n_p = 10^{16}\,\mathrm{cm}^{-3} \Rightarrow R = 0.06\,\Omega$$

$$n_n = n_p = 10^{15}\,\mathrm{cm}^{-3} \Rightarrow R = 0.66\,\Omega$$

For thickness $d = 5 \times 10^{-2}\,\mathrm{cm}$ and area $S = 0.16\,\mathrm{cm}^2$



$V_{bias} = 10\,\mathrm{V}$

Simulations for different τ

- Comparison between measurement and simulation for three different recombination times τ

Comparison for e^- bunches of 35 pC at different bias voltages