Diamond detector's response to intense high-energy electron pulses

15th Pisa Meeting on Advanced Detectors, La Biodola, Isola d'Elba, Italy, 22-28 May 2022

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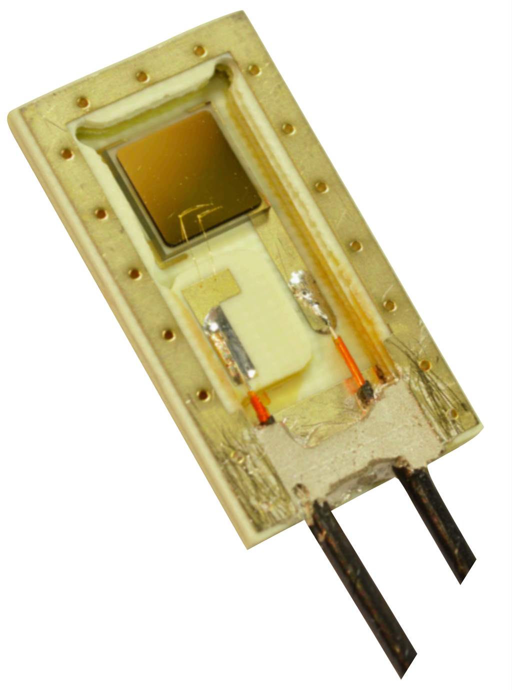
Introduction

Owing to their excellent radiation hardness, synthetic diamond crystals have been widely used as solid state particle detectors, beam loss monitors and dosimeters in high-radiation environments, such as particle colliders. To assess the crystal quality and the response of our devices, we carried out several tests using different radiation sources. In order to use them as radiation and beam-loss monitors, a characterisation and calibration procedure is mandatory to obtain consistent results.

We devised a current-to-dose-rate calibration method that uses a silicon diode as a reference, to reduce uncertainties associated with the source activity and with the setup simulation. The method has been validated by measuring the calibration factors with X and β radiation, spanning a dose-rate range from hundreds of nrad/s to tens of rad/s. Nevertheless, also the transient response must be investigated. For this reason, we designed an ad-hoc experimental setup that uses a collimated, sub-picosecond, 1 GeV electron beam, with a bunch charge of tens of pC, provided by the FERMI electron linac in Trieste, Italy.

Diamond detector

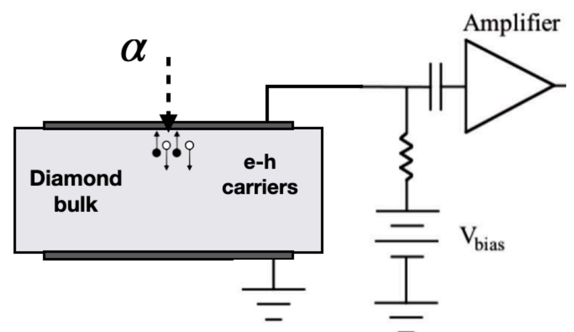


- sCVD single crystal diamond sensors:
- → (4.5 × 4.5) mm^2 crystal faces and 0.5 mm thickness
- → (4.0 × 4.0) mm^2 electrodes on both faces, made of Ti+Pt+Au layers with (100 + 120 + 250) nm thickness
- Rad-hard ceramic-like printed-circuit board (PCB)
- An aluminium cover ~ 180 μm completes the mechanical and electrical shielding
- Optimal operation voltage V_{bias} = 100 V

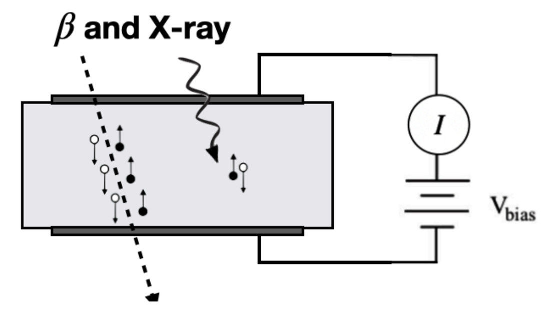
Characterisation procedure

- Our sensors are characterised with different sources:

→ α **irradiation**: measurement of e-h properties (mobility, mean ionisation energy) with TCT (Transient-Current Technique) to assess crystal quality and detector homogeneity



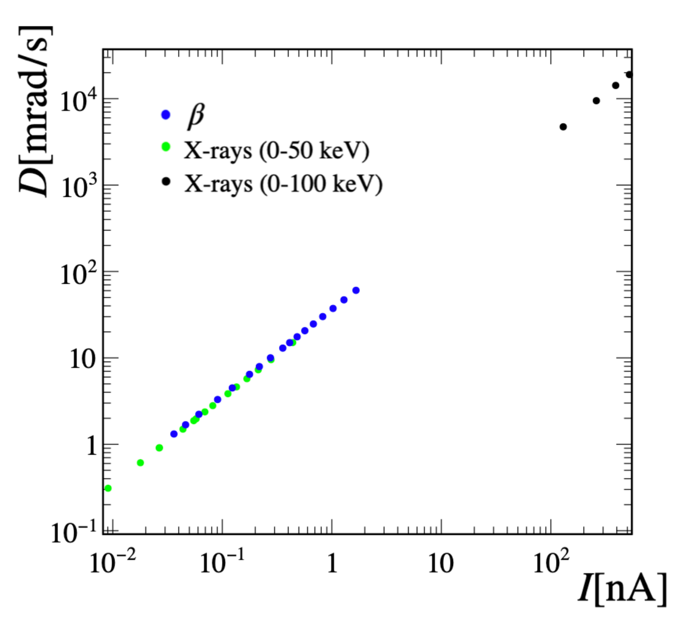
→ β **and X irradiation**: stability of sensor response under steady irradiation, choice of best bias polarity and Current-to-Dose-rate calibration



- Each part of the procedure has a dedicated simulation of the experimental setup in FLUKA

Calibration procedure

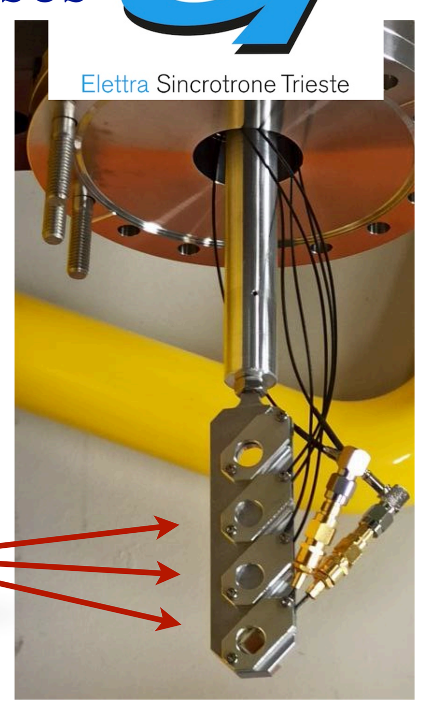
- New Diamond-to-Diode comparison method, assuming a good knowledge of the silicon diode response [1];
- Employing a silicon diode as a reference greatly reduces the uncertainties associated with the source activity and the setup simulation
- All measurements agree with the simulation, covering a dose rate range from hundreds of nrad/s to tens of rad/s.



High intensity e^- pulses

- Three diamond sensors are irradiated with collimated ~ 1 GeV electrons bunches of 1 ps duration, on the linac Beam-Dump line of the FERMI@Elettra FEL [2] in Trieste.

Diamond detectors on their support (in vacuum)

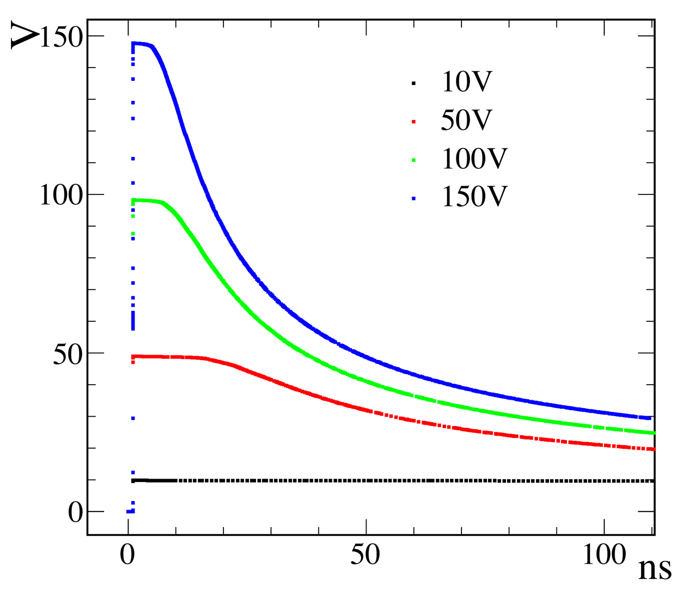


- Two sets of measurements are obtained :
  ⇒ changing the bunch charge from a few pC to about 50 pC
  ⇒ varying the bias voltage from 10 V to 150 V
- The goal is to test the diamond transient response for very high intensity pulses and to study possible saturation effects due to a very high charge carrier density in the diamond bulk

Two-steps numerical simulation

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

- **Signal formation on the sensor by TCAD-Sentaurus.** It includes 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.



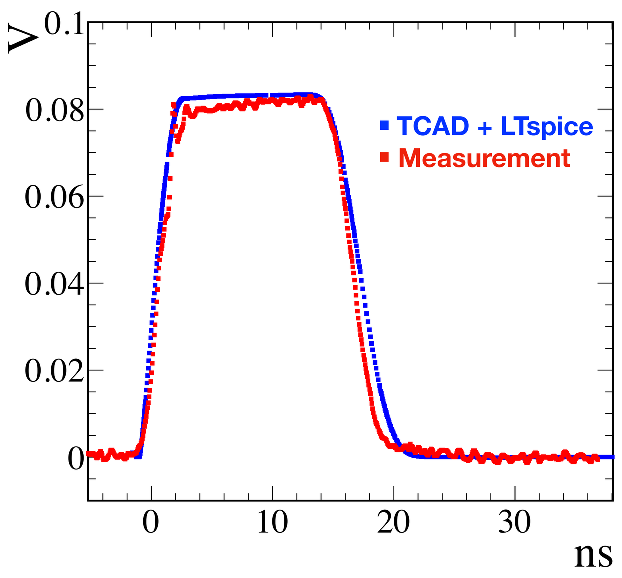
TCAD output signals obtained for e^- bunches of 35 pC at different bias voltages

- **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.

Validation of simulation

Simulating the time response of diamond detector for TCT measurements with α particles:

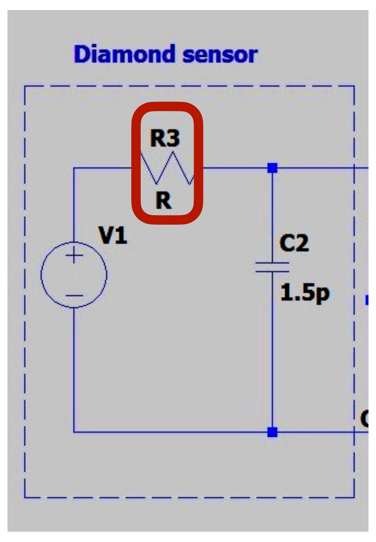
- Good agreement between results of numerical simulation and experimental data, on both the amplitude and the shape of the pulse, validating the two-step simulation of our diamond sensors.
- Charge carrier parameters used in simulation well describe our diamond sensor.



Time development of the signal induced by electrons in a diamond sensor, at a bias voltage of +150 V

Transients on diamond properties

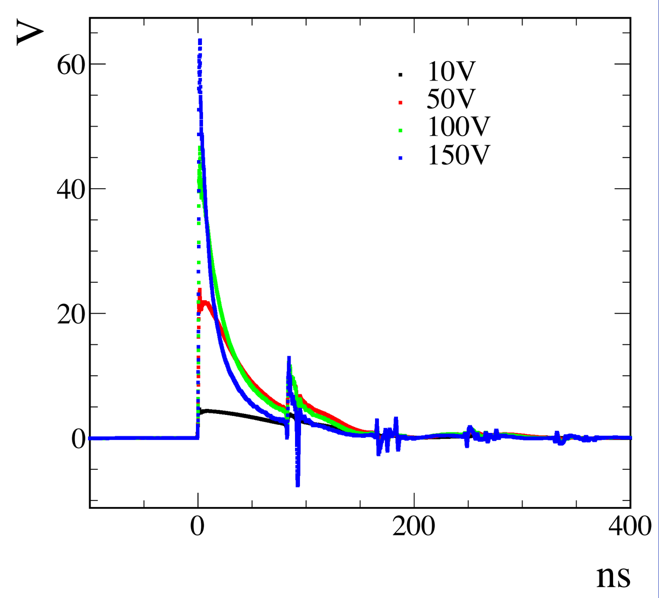
- The high density of charge carriers generated by ionisation in the diamond bulk causes a transient modification of electrical properties of diamond sensor (e.g., resistance), which in turn affects the signal shape
- **Variable diamond resistance** has been modelled as a function of the charge carrier density in the diamond bulk.



LTSpice circuit for diamond sensor

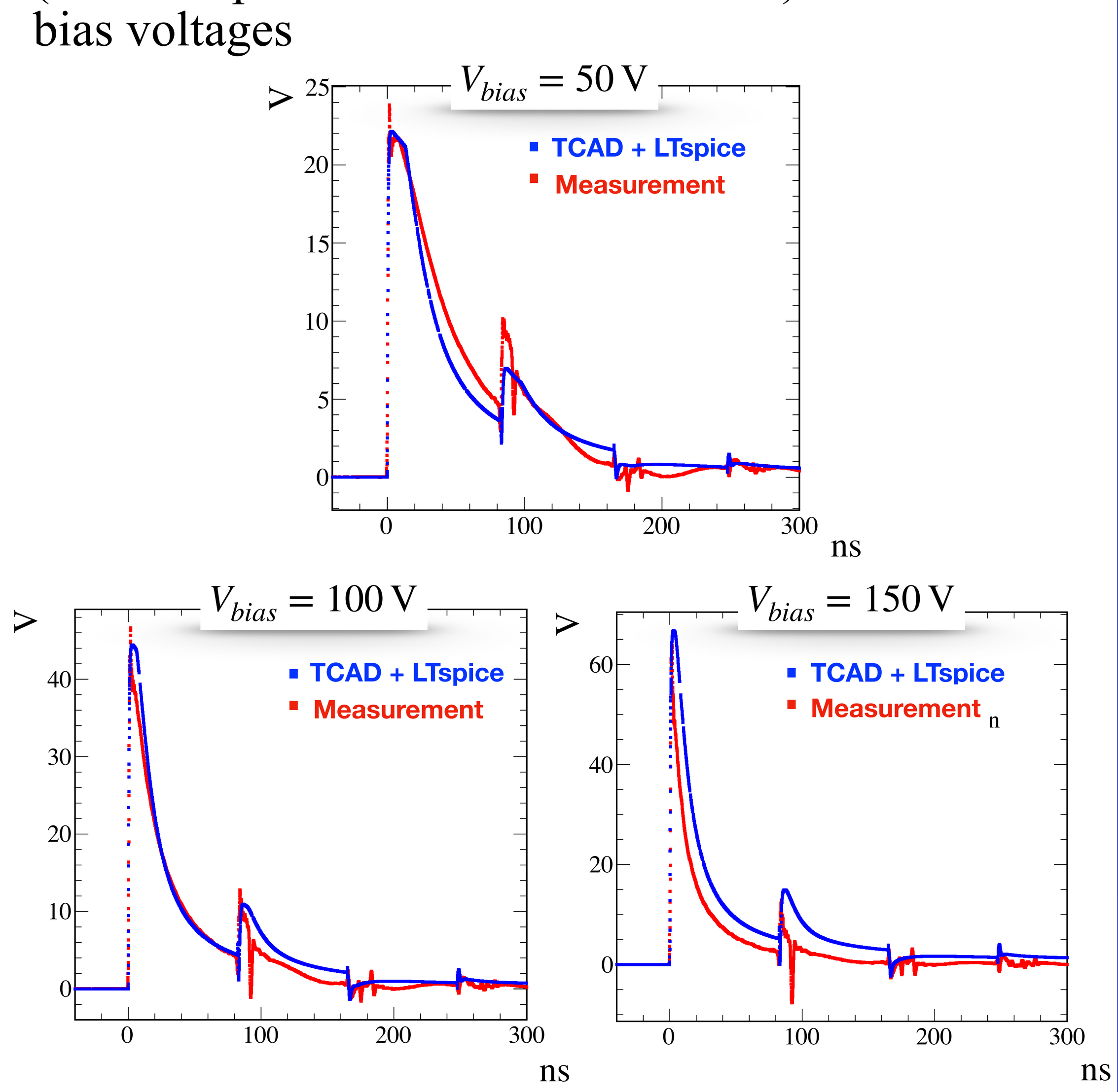
Preliminary results

- The diamond detectors show a predictable response to these high intensity electron bunches, with signal pulses characterised by fast rise-time, tails hundreds of ns, and reflections due to small impedance mismatches.



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

- Measurement and simulation fair agreement (same amplitude and reflection time) at different bias voltages



References

1.G. Bassi, et al., Calibration of diamond detectors for dosimetry in beam- loss monitoring, Nucl. Instrum. Meth. A 1004 (2021) 165383. doi:10. 1016/j.nima.2021.165383.

2.E. Allaria, et al., The FERMI free-electron lasers, Journal of Synchrotron Radiation 22 (3) (2015) 485–491. doi:10.1107/ S1600577515005366.

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