In-depth characterization of diamond sensors for dosimetry in beam-loss monitoring

Alice Gabrielli

alice.gabrielli@ts.infn.ts

VCI2022 - 21-25 February 2022, Vienna

Our diamond sensors

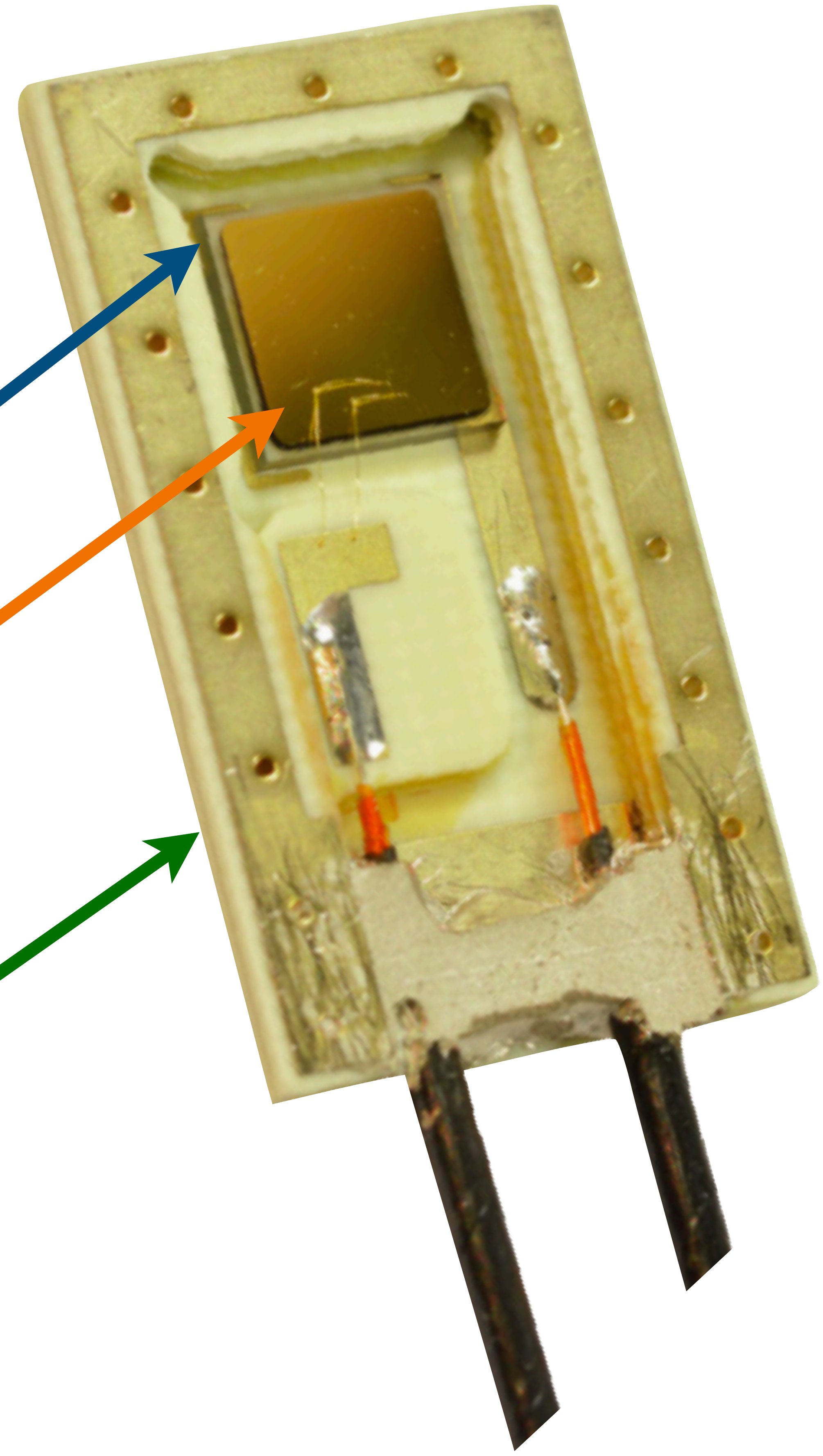
- **sCVD single crystal diamond sensors:**

—> (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 ($\sim 180\,\mu\mathrm{m}$) placed in front of the detector to complete the mechanical and electrical shielding



Used in the Belle II radiation monitor and beam abort system

10 new sensors assembled and tested, to be installed on the new beam pipe in the LS1 shutdown (fall 2022)

Radiation monitor and beam abort system

- 28 synthetic diamond sensors installed around the interaction region and the Belle II Silicon Vertex Detector (SVD)

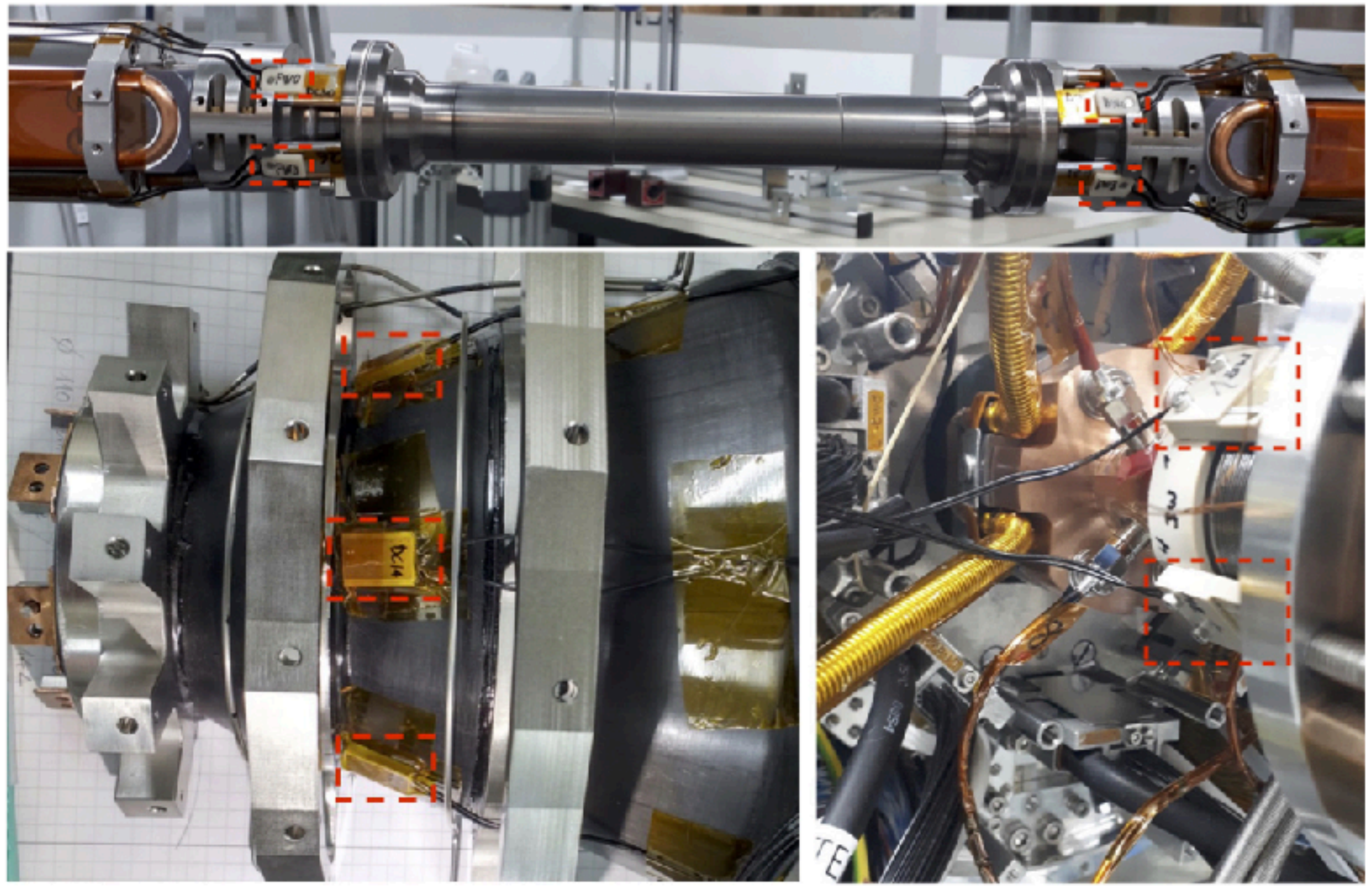
- 24 sensors → Measure dose rates and provide feedback to fix beam conditions ($10\,\mathrm{Hz}$ readout)

- 4 sensors → Beam abort ($400\,\mathrm{kHz}$ readout)

- Main requirements:

—> a wide range of radiation dose rates ($\mu\mathrm{rad/s}$ - $100\,\mathrm{krad/s}$)

—> performance stability in time (expected integrated dose of $10\,\mathrm{Mrad}$)

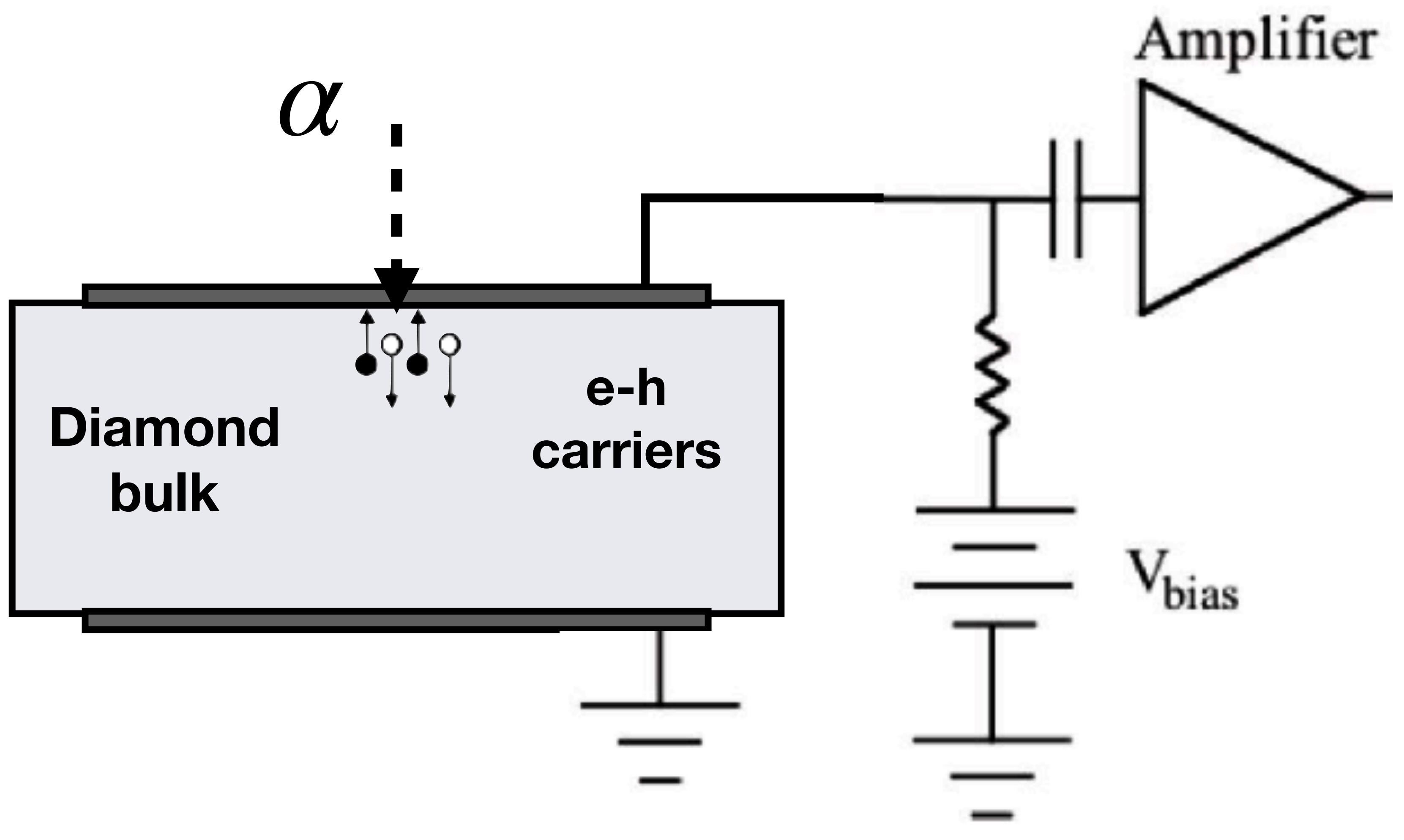


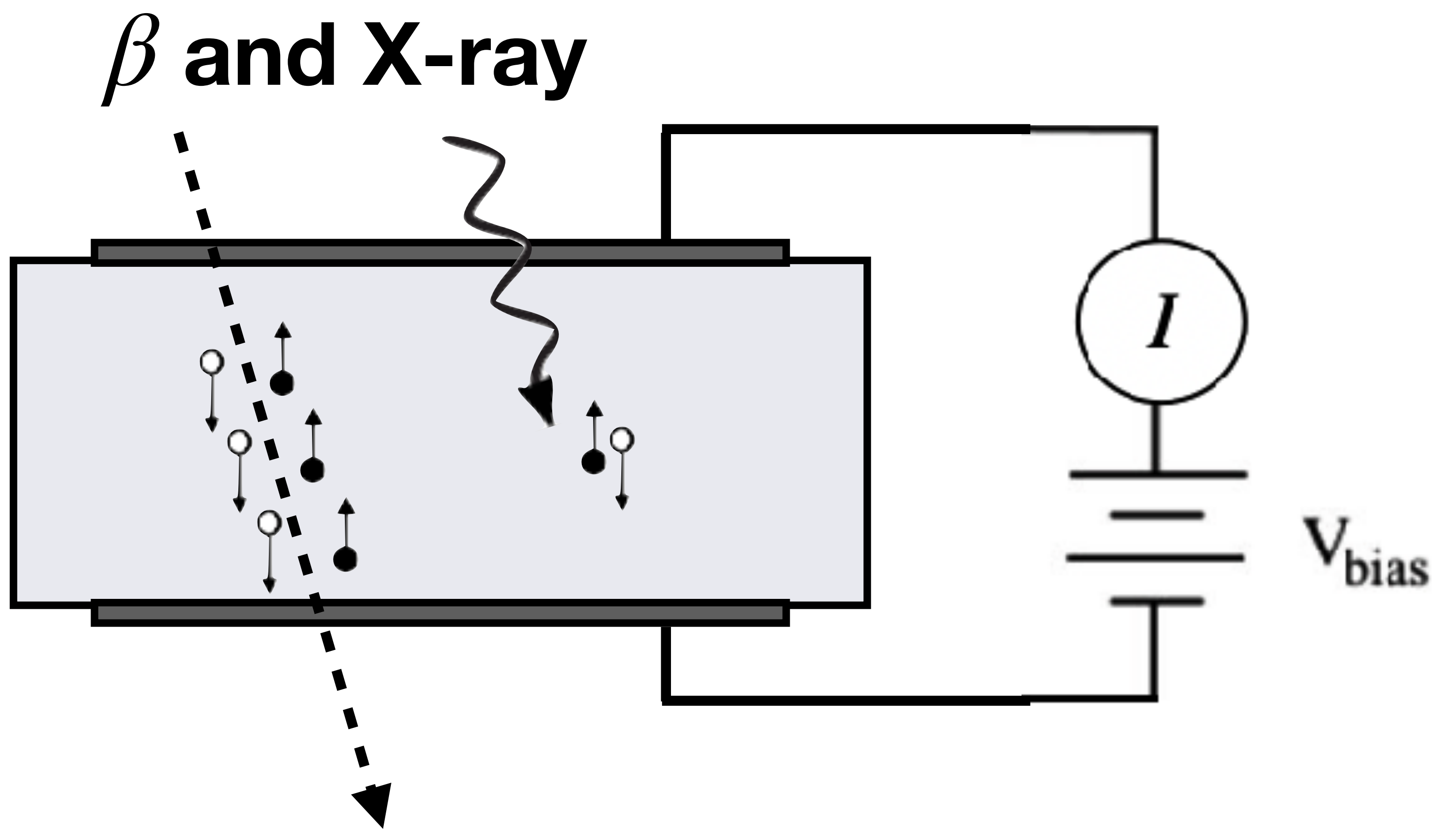
Diamond sensors characterization

- Our diamond sensors are characterized with different sources:

  → α **irradiation:** measurement of e-h properties (mobility, mean ionization 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

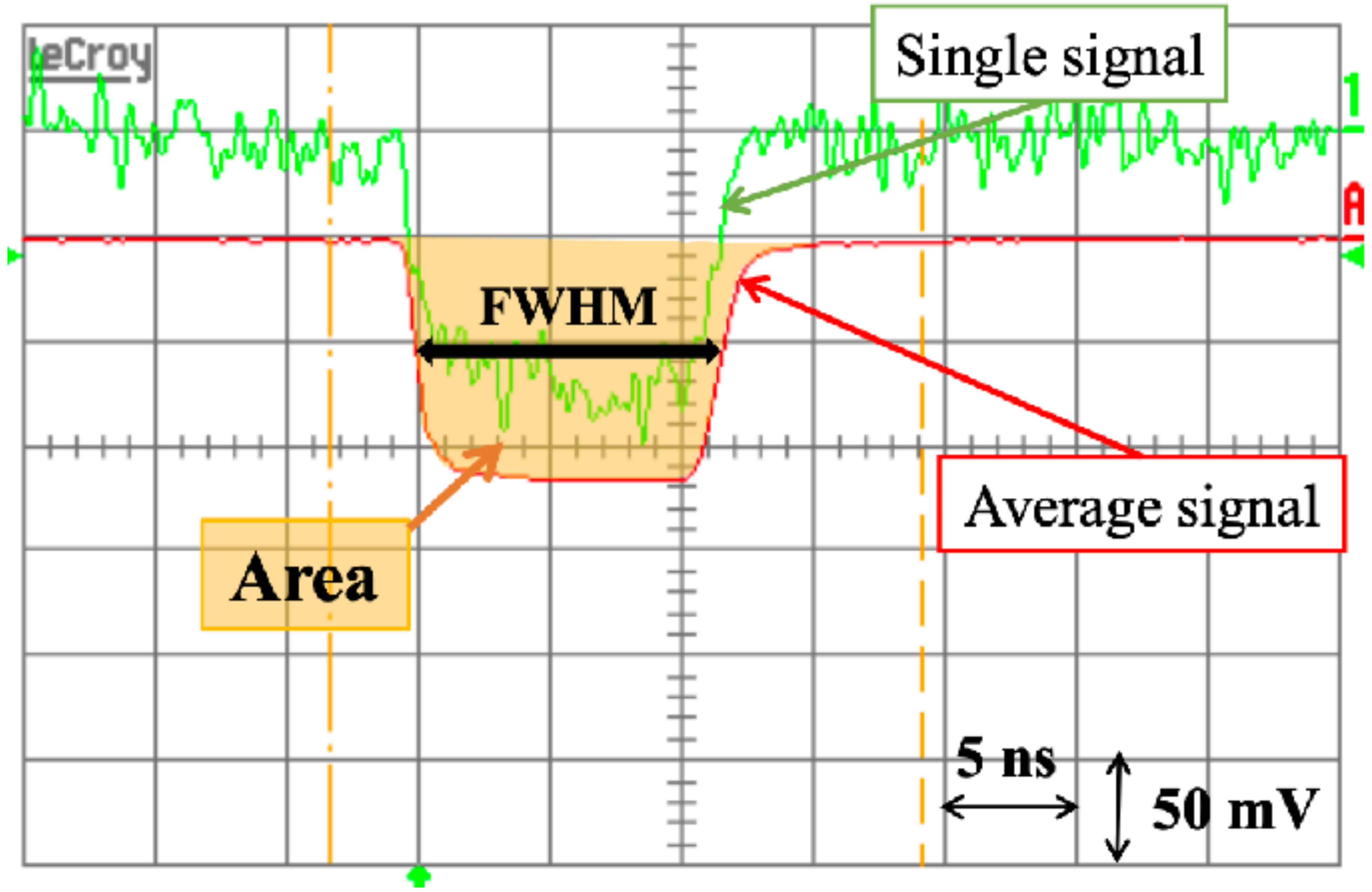


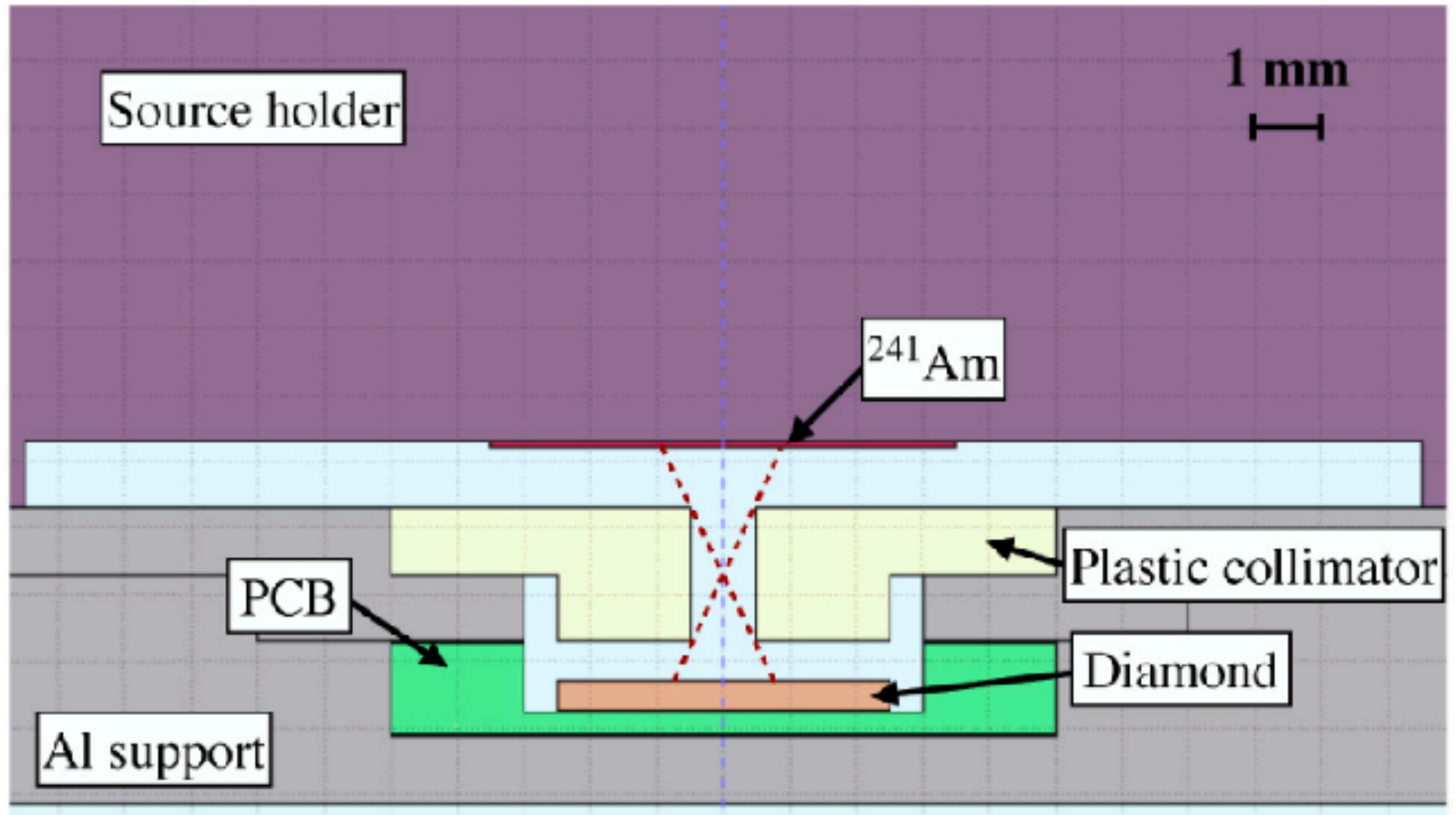


Transient Current Technique - TCT with α

Monochromatic α particles ($\sim 5.4\,\mathrm{MeV}$) generate e-h pairs at a small depth in the diamond bulk (within $\sim 14\,\mu\mathrm{m}$), very close to the crossed electrode.

- Measurement of the shape of the current pulse induced by the drift of charge carriers moving in a uniform electric field, varying the bias voltage from $100\,\mathrm{V}$ to $800\,\mathrm{V}$, for both polarities
- Detailed FLUKA simulation to calculate the average energy deposited by α particles in the diamond bulk.





TCT results

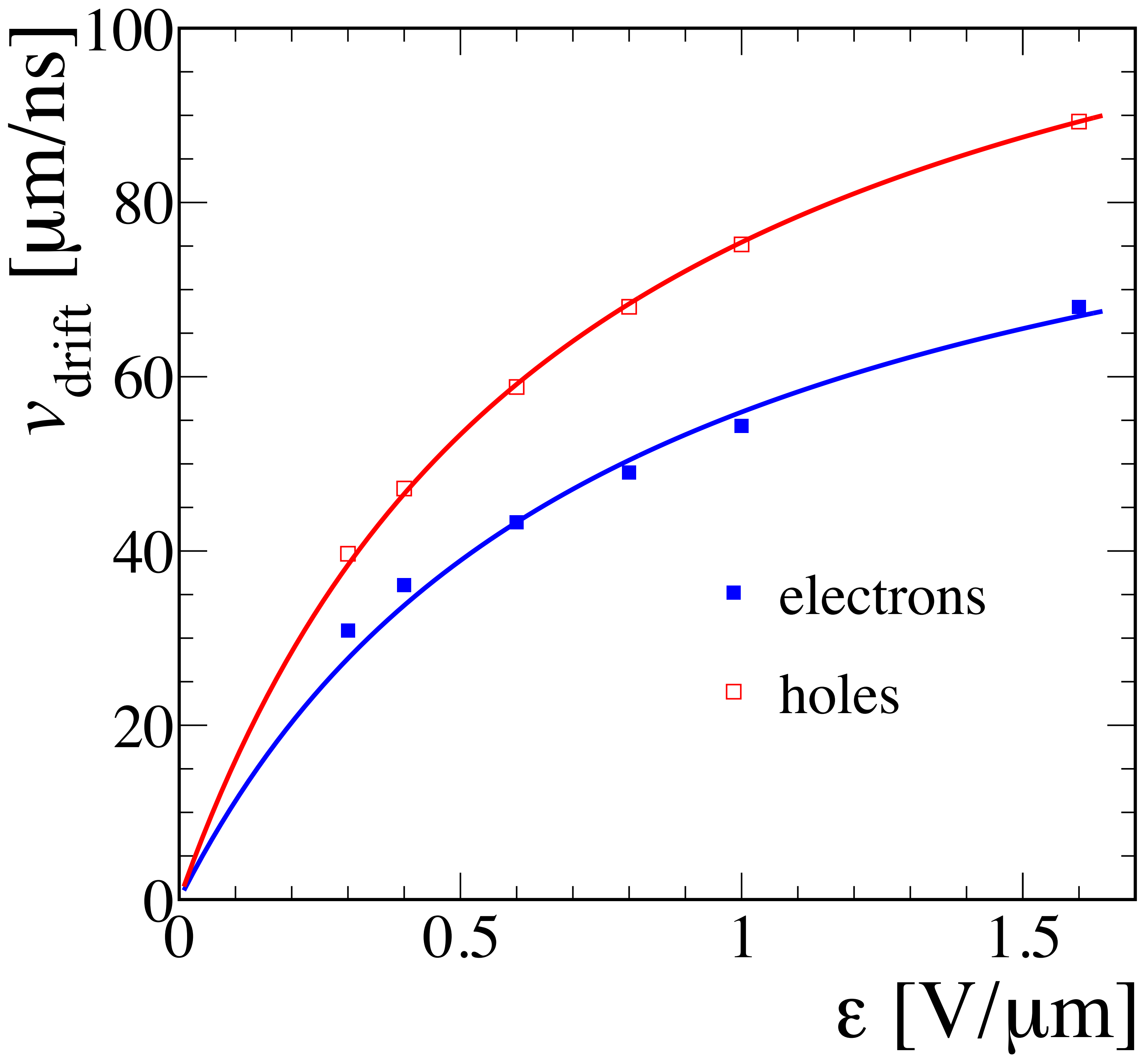
- The drift velocity is calculated dividing the diamond thickness by the FWHM of the measured pulse

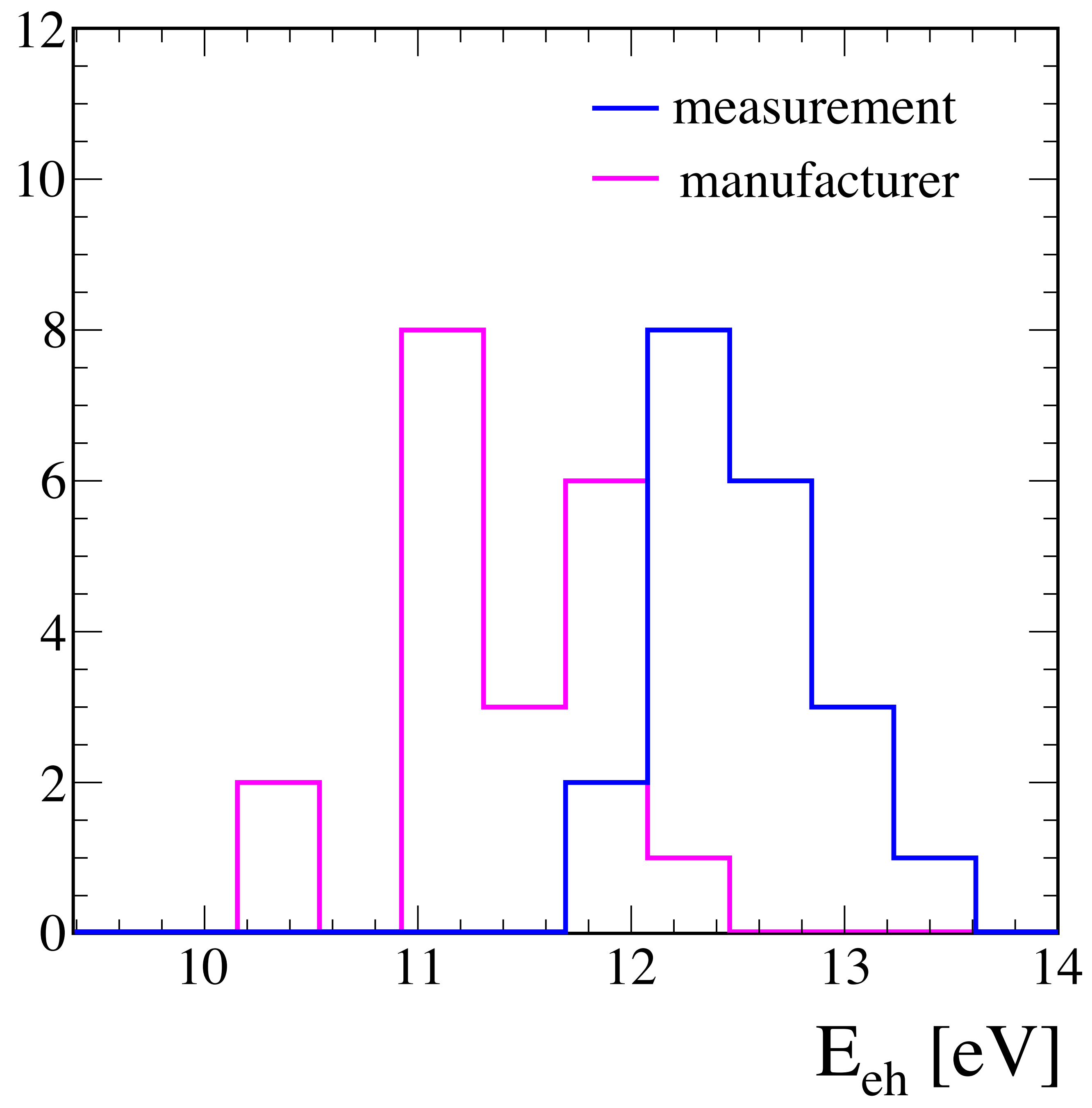
- The average ionization energy E_{eh} is obtained from the ratio between the simulated energy deposited and the measured collected charge (proportional to the signal Area)

- Diamond mobilities and drift velocities are consistent among all diamonds, supporting the detector homogeneity

- Average ionization energy of $12.6 \pm 0.4\,\mathrm{eV}$ for the 10 diamond sensors, in agreement within 9% with the value given by the manufacturer

- **Method validated** by using a silicon diode: silicon ionization energy consistent with the nominal value $3.66\,\mathrm{eV}$ within 7%



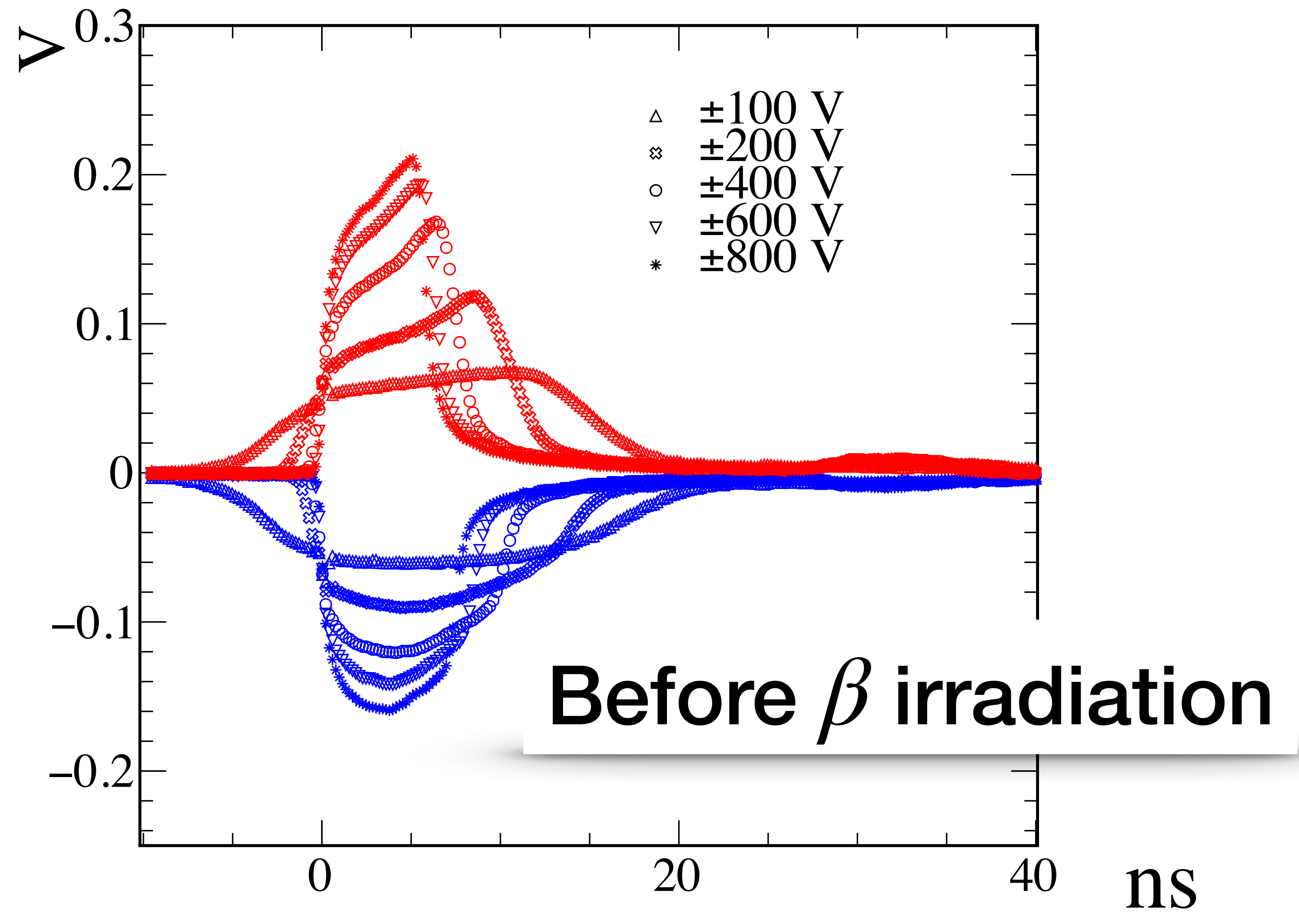


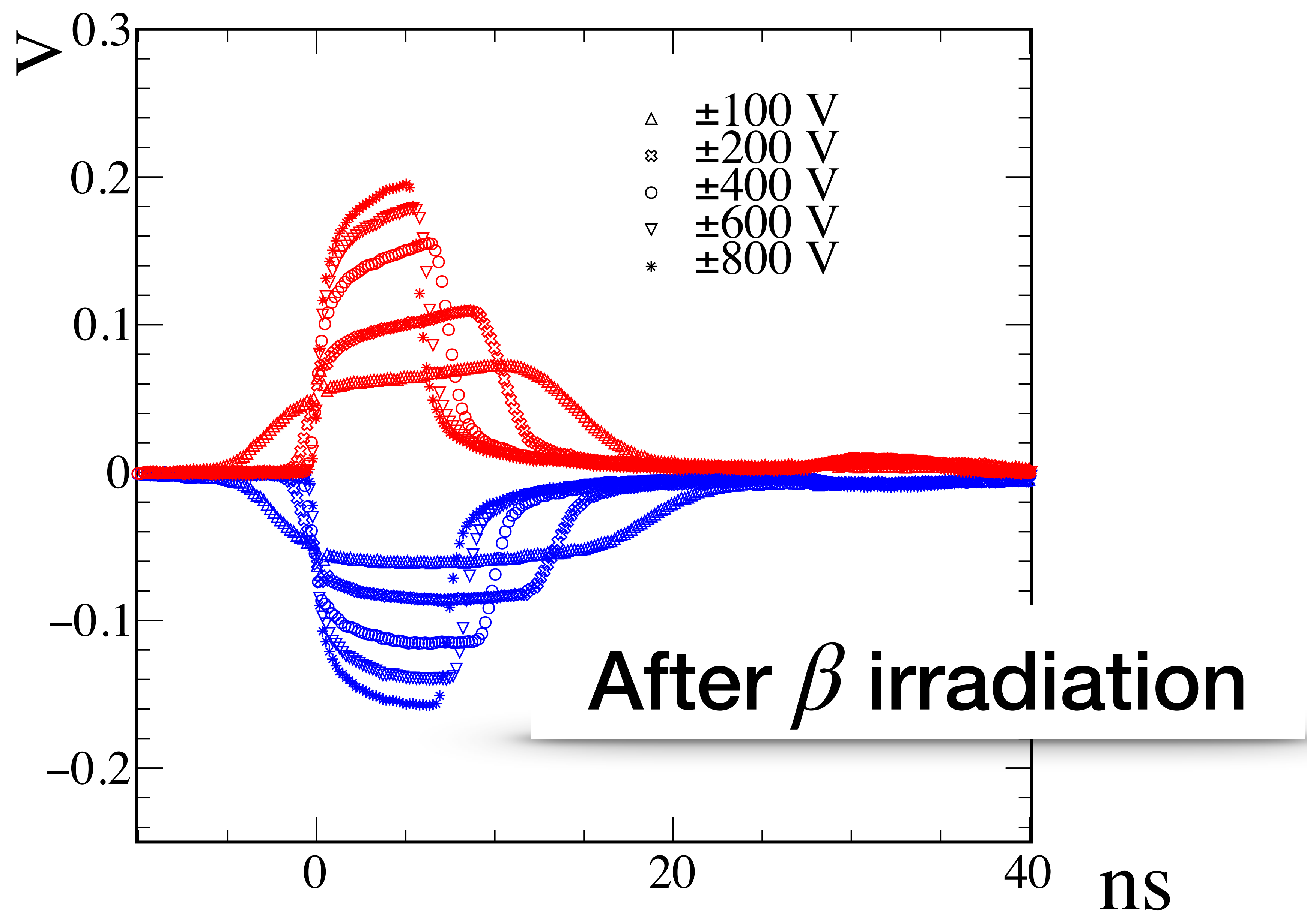
Irradiation effects on pulse shape

The shape is related to the uniformity of the electric field in the diamond bulk

- A slope in the plateau region is related to a non uniform electric field, due to the presence of a fixed space charge density in the diamond bulk

- Visible signal shape deformation, due to defects or imperfections of the crystal, is reduced after sensor β irradiation





TCT simulation - TCAD

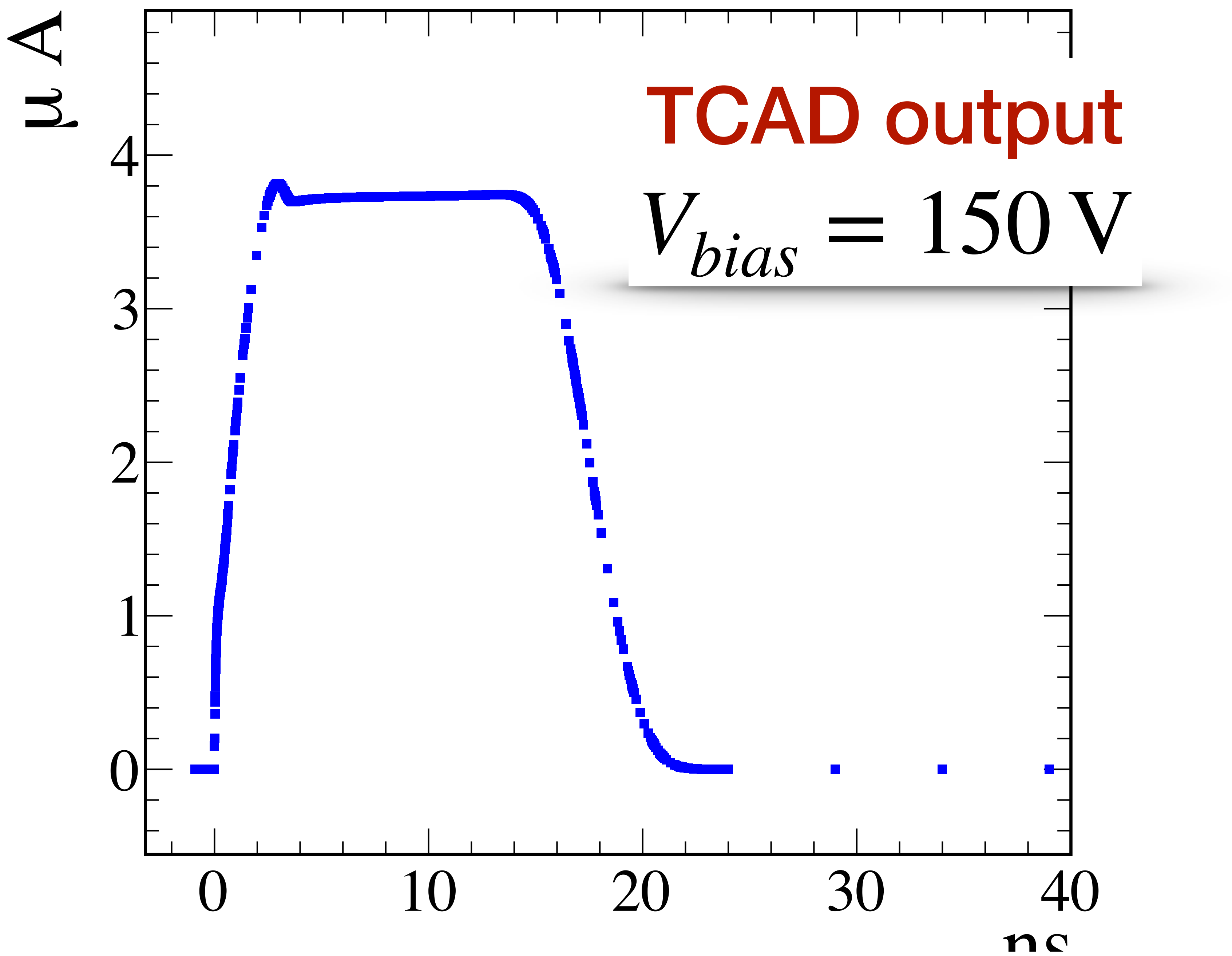
A two-step numerical simulation approach is improved to study the time response of the diamond detector:

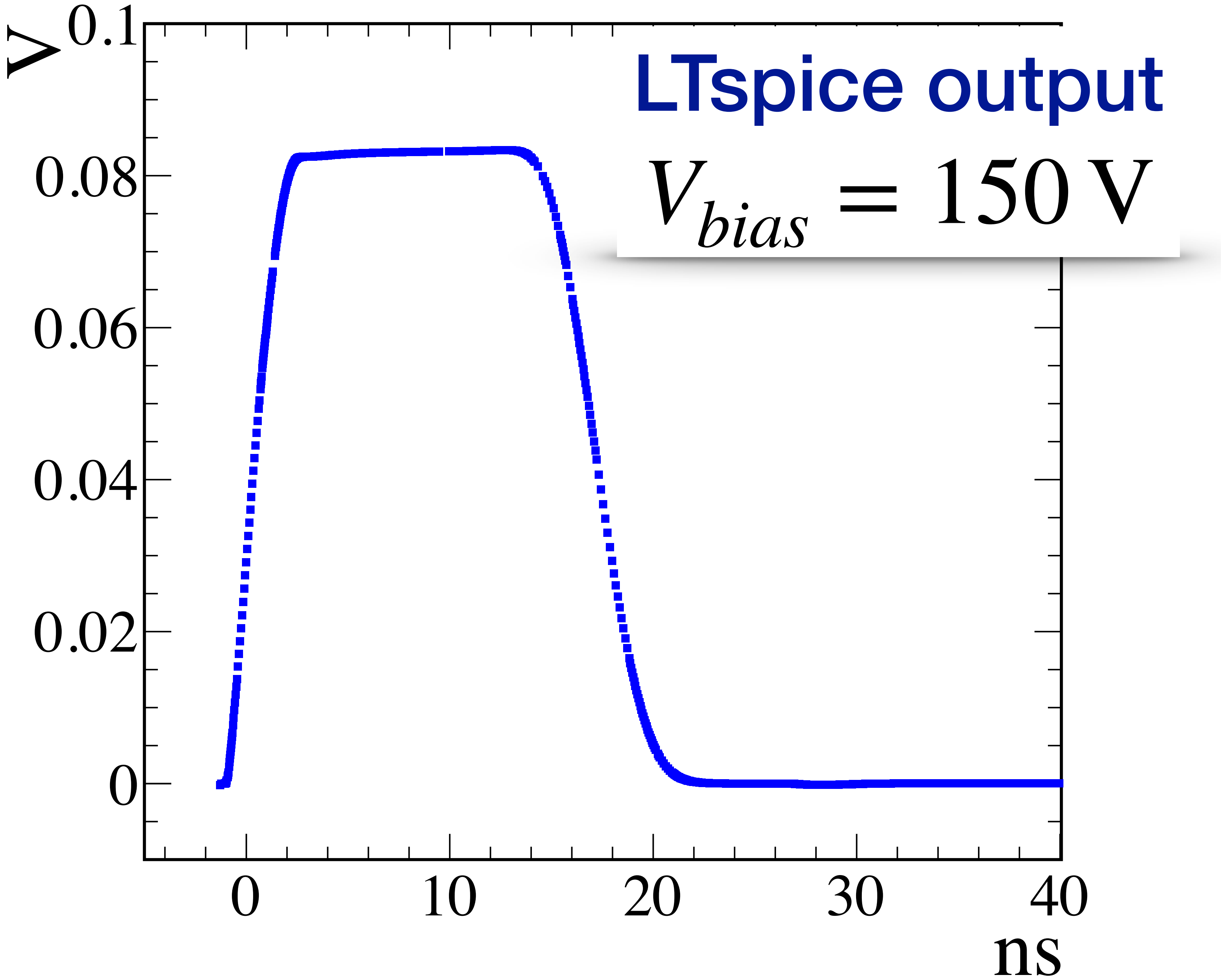
- **TCAD-Sentaurus** which includes the process of α interacting with diamond bulk, e-h generation, carrier drifting, voltage drop on electrodes;

  →Gives the time response of the detector, using the e-h properties measured with TCT as input;

- **LTspice** with a proper modeling of coaxial cables, power supply, and oscilloscope;

  →Takes into account the effects of the electronic circuit on signal, such as reflection, attenuation, distortion, etc.



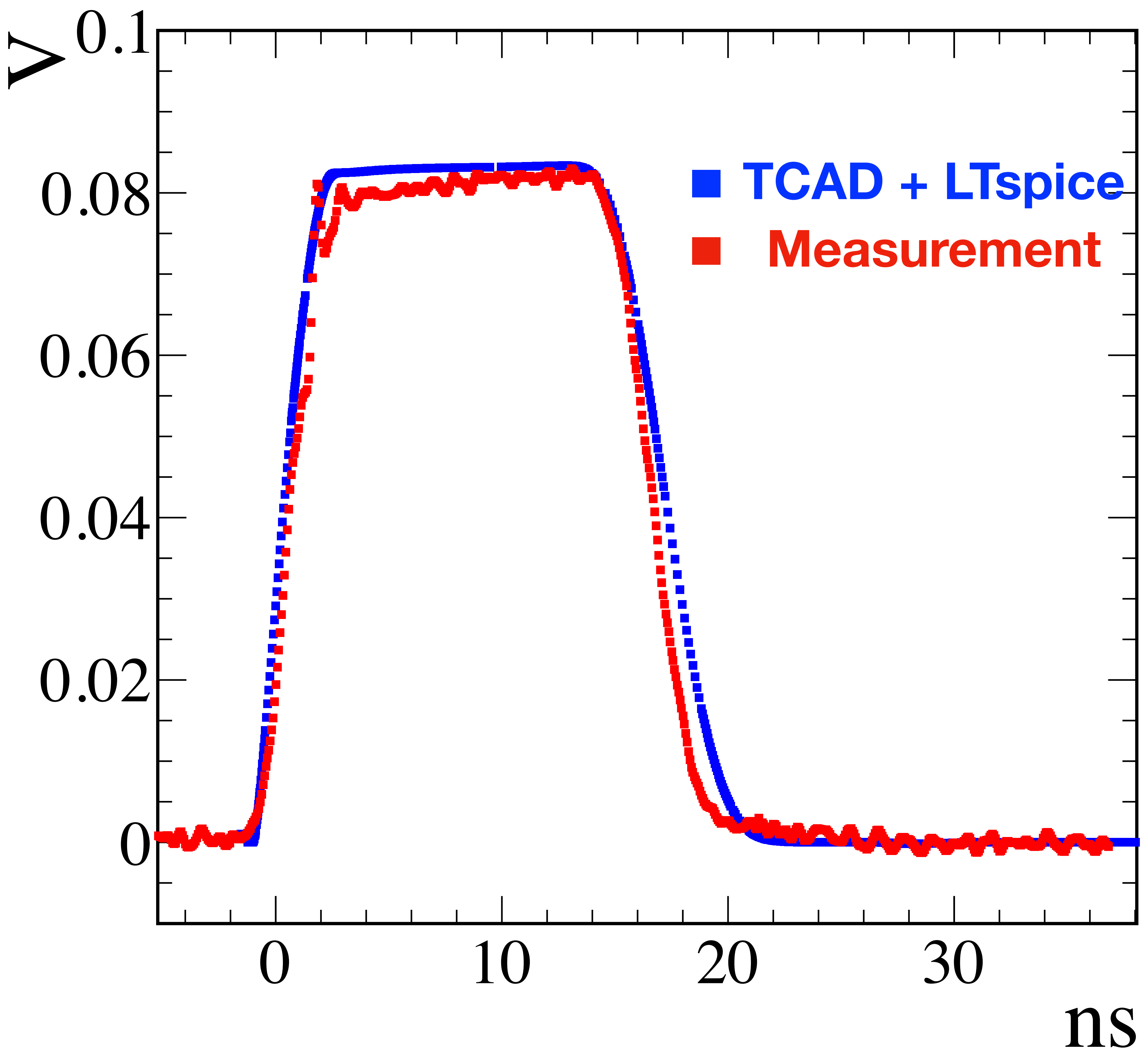


TCAD simulation results

- Good agreement between the numerical simulation and the measurement, on both the amplitude and the shape of all signals under different bias voltages;

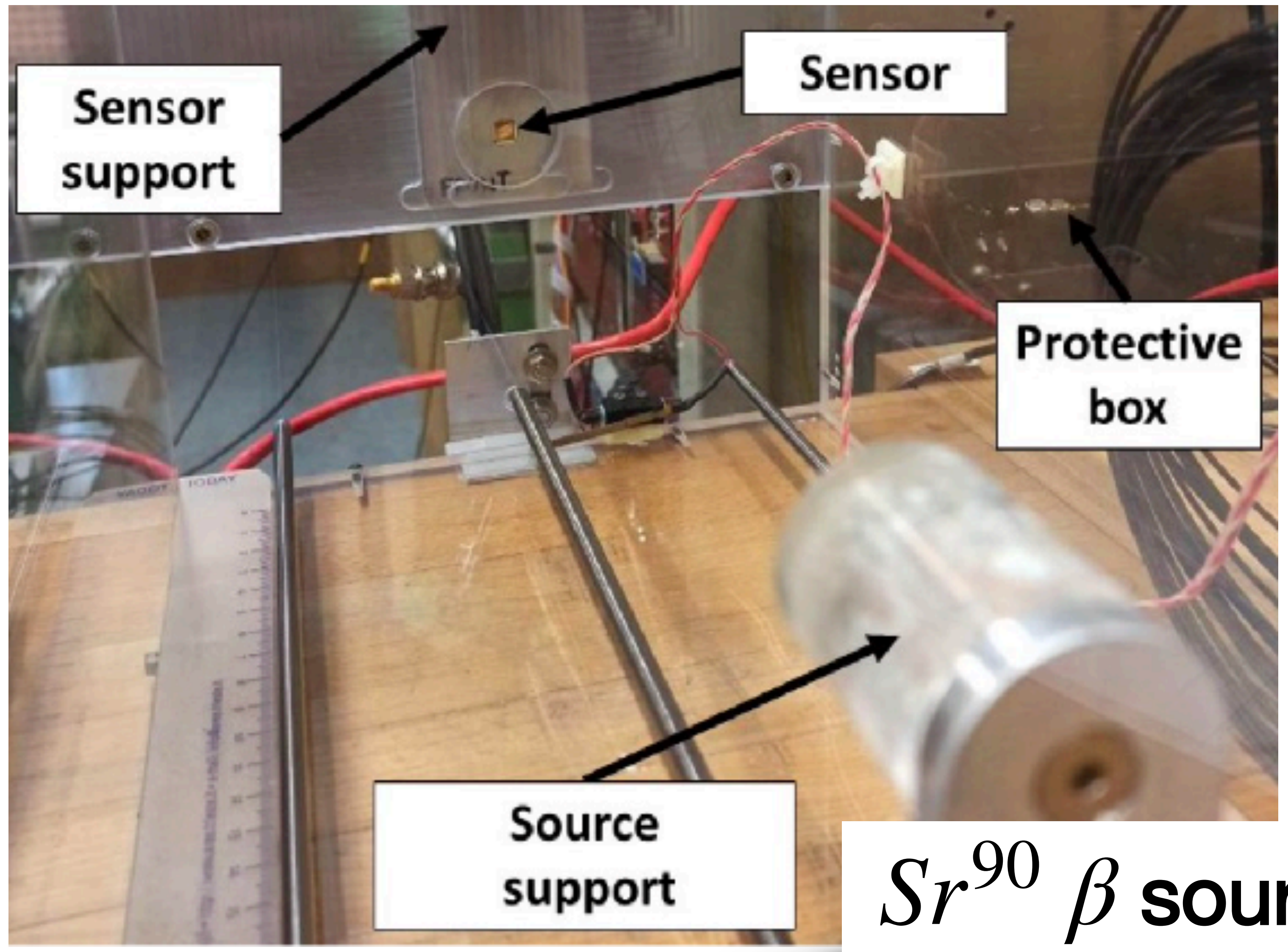
⇒ charge carrier parameters used in simulation well describe our diamond sensor;

⇒ A further validation of the TCT measurement procedure

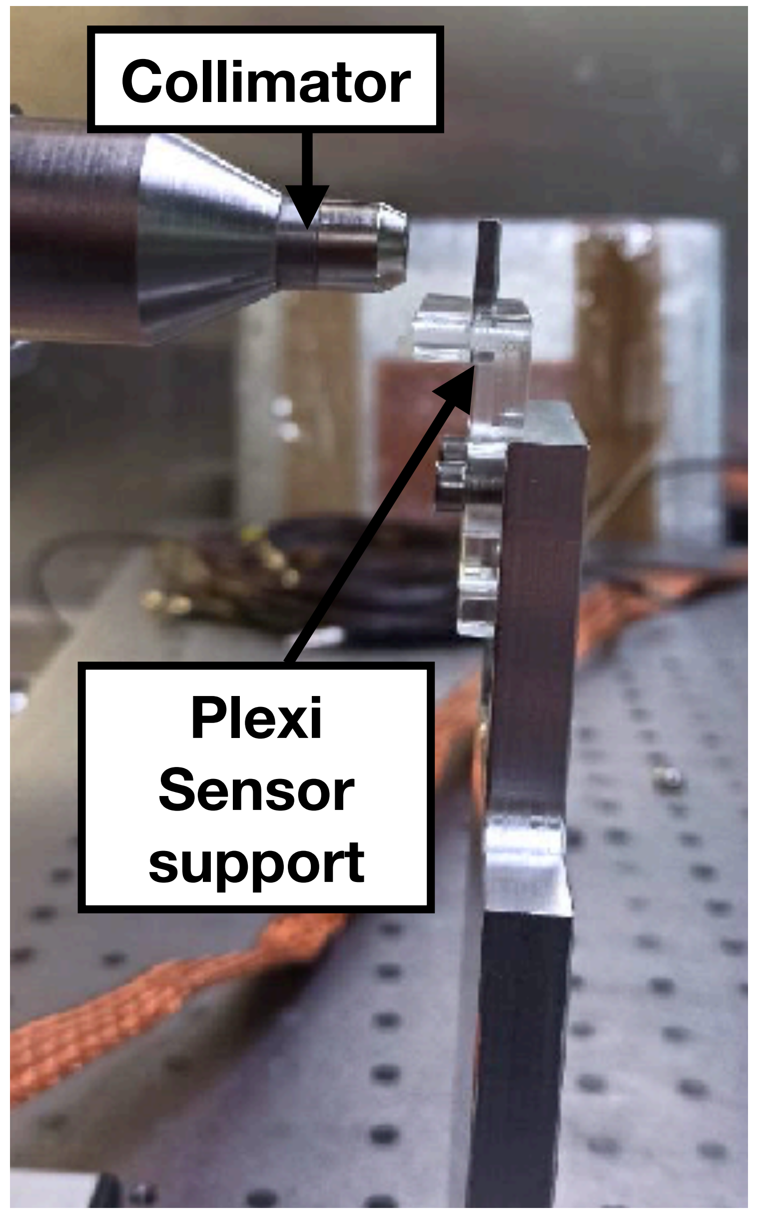


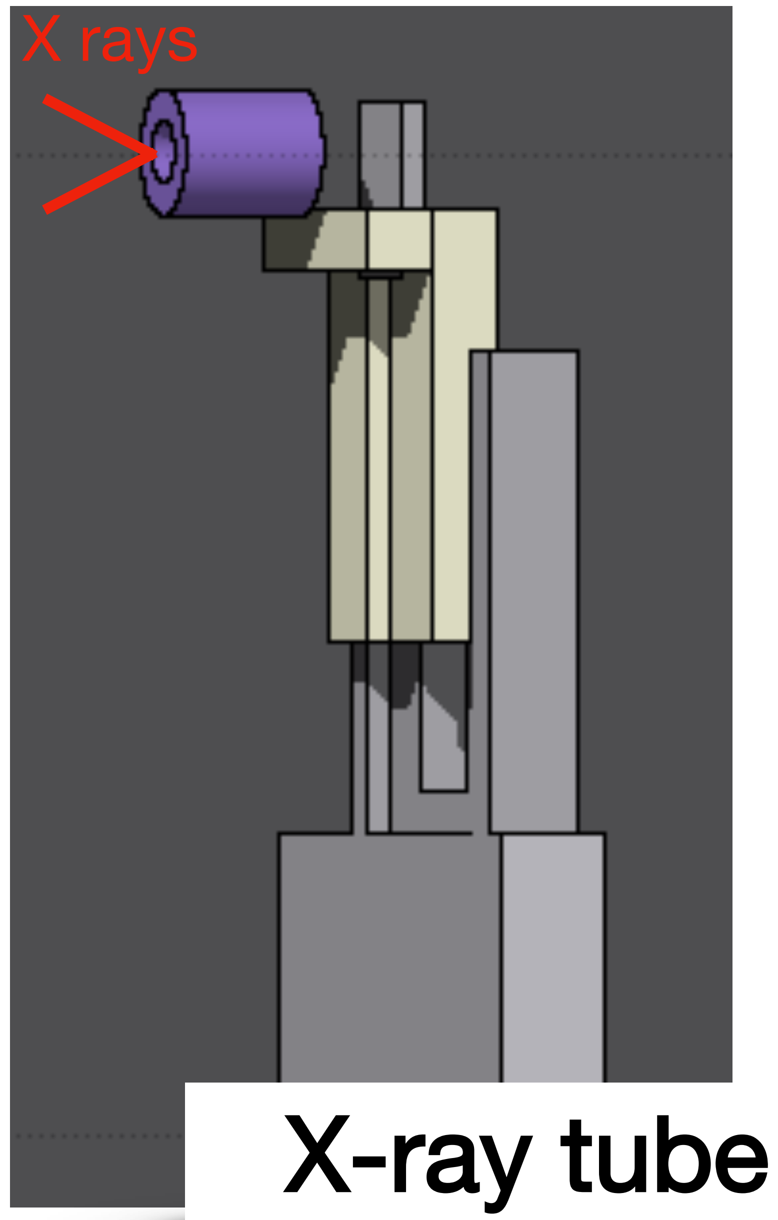
Calibration procedure

- New Diamond-to-Diode comparison method, assuming a good knowledge of the silicon diode response, described in NIM-A 2021.165383 (July 2021).
- Irradiate the sensor and measure the generated current I^{Det} under steady irradiation (β and X) at $|V_{bias}| = 100\,\mathrm{V}$
- Determine the ratio R between the diamond current and that of the reference diode.
- Compare the measured ratio R to the ratio R_{exp} expected from a detailed simulation of the experimental setup (FLUKA).



Sr^{90} β source





X-ray tube

This procedure reduces uncertainties associated to the radiation source

X and β radiation

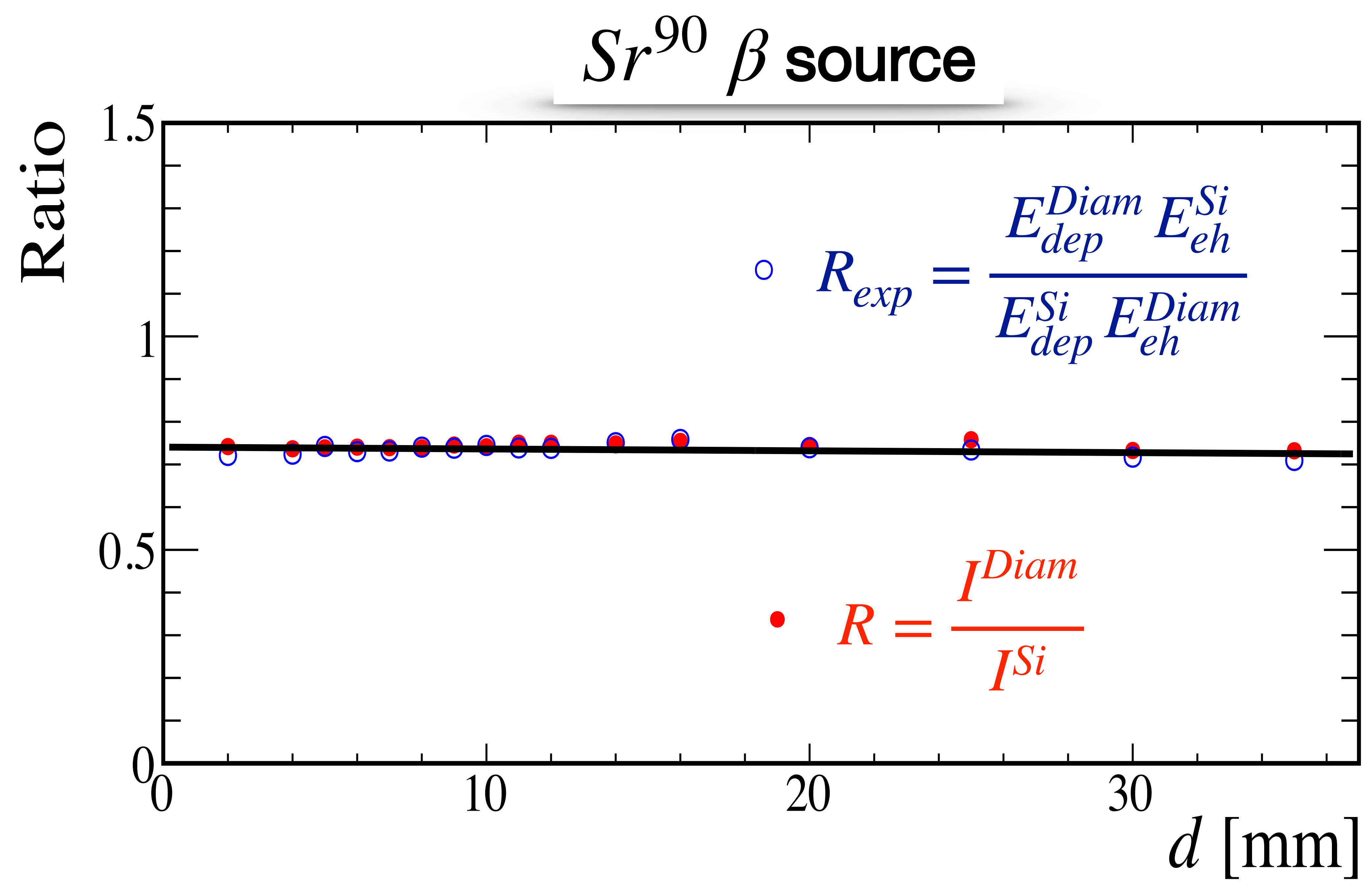
- All measurements are repeated for different source conditions:

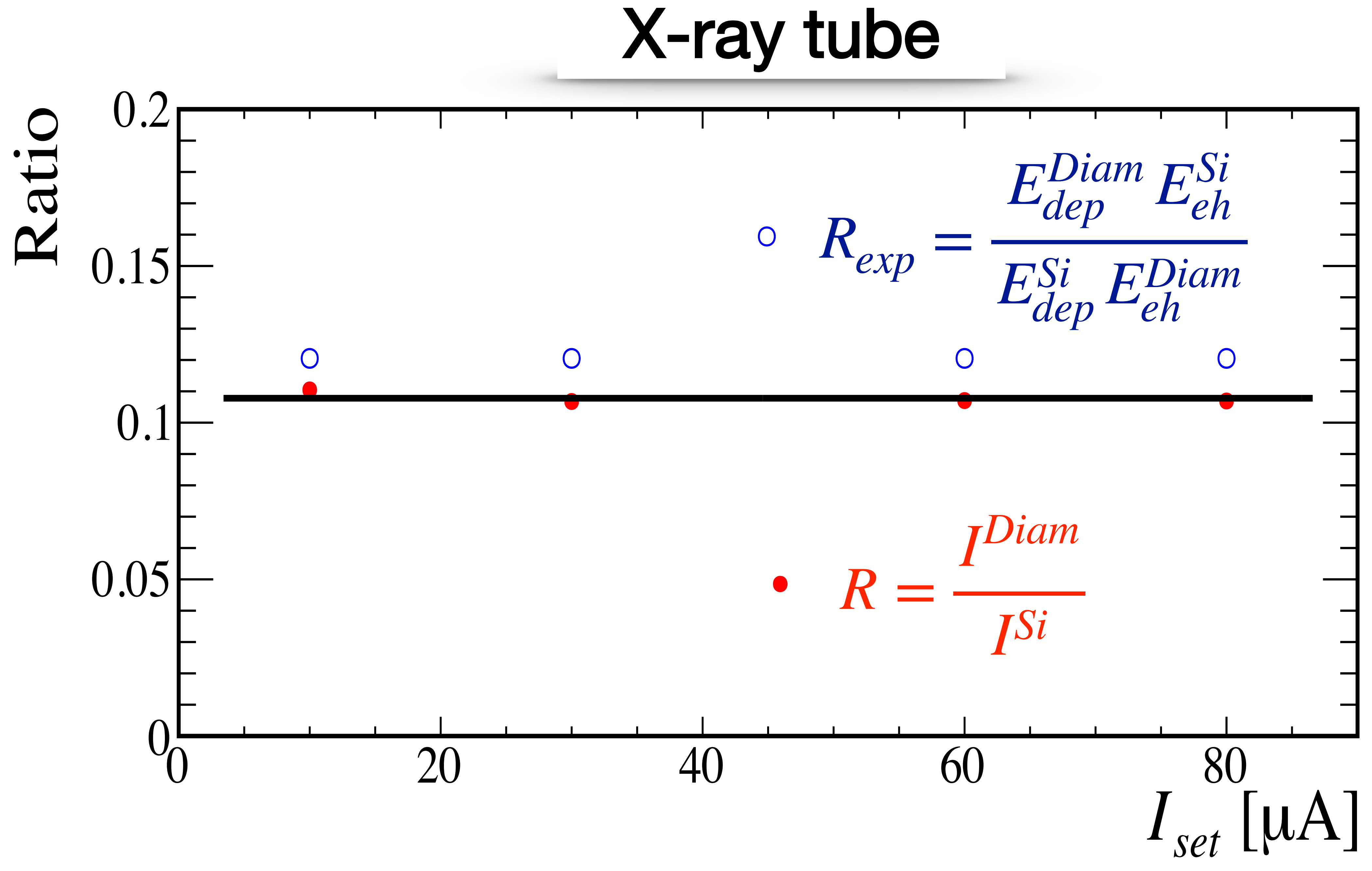
  β : source-detector distance d

  X : tube current I_{set} ($\propto$ photon flux)

- Simulation and measurements are in good agreement for the β source within 3%, which corresponds on average to fully efficient detectors, with uniform good quality crystal

- X-ray shows an agreement at 10% level between simulation and measurements



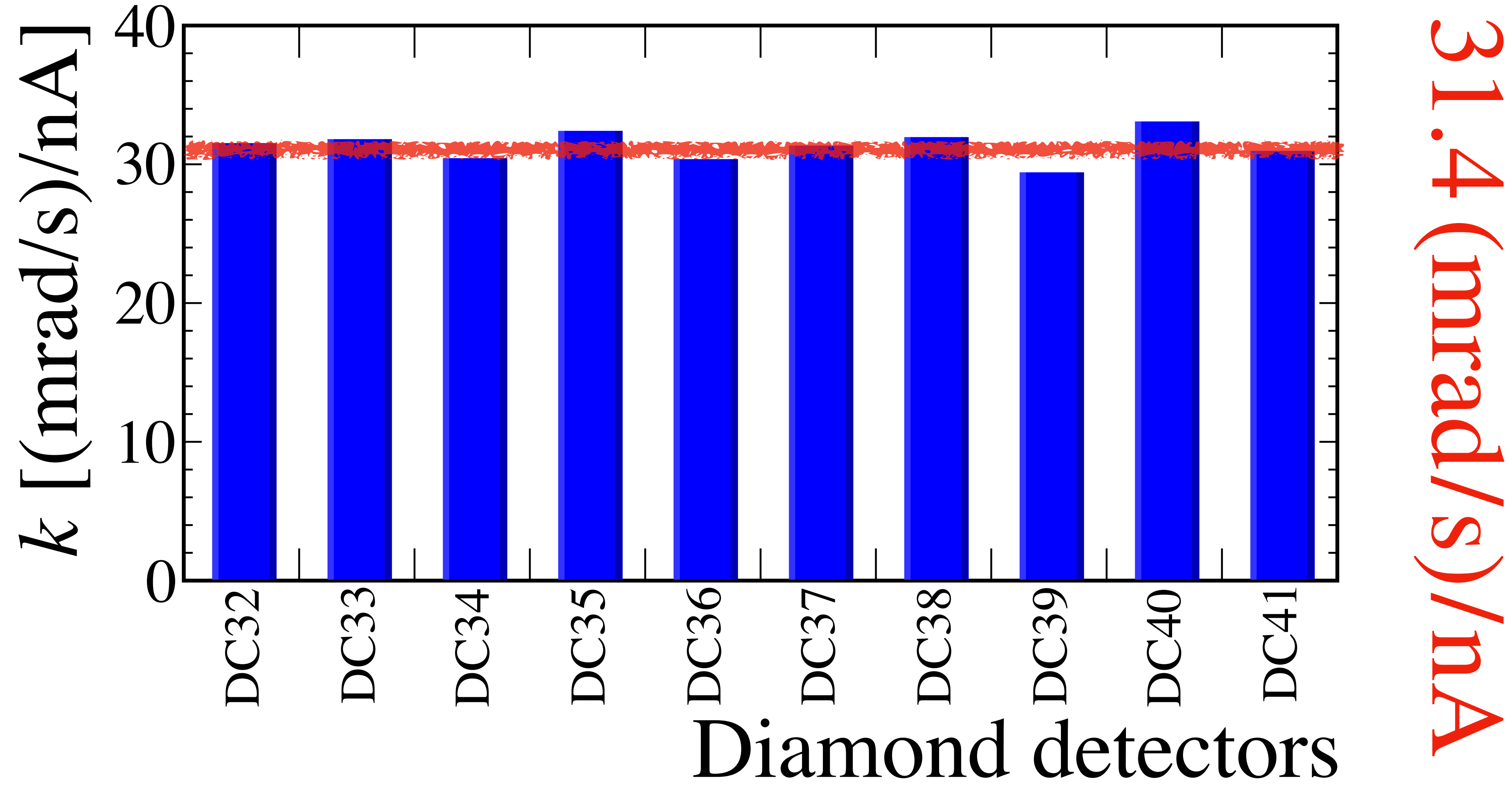


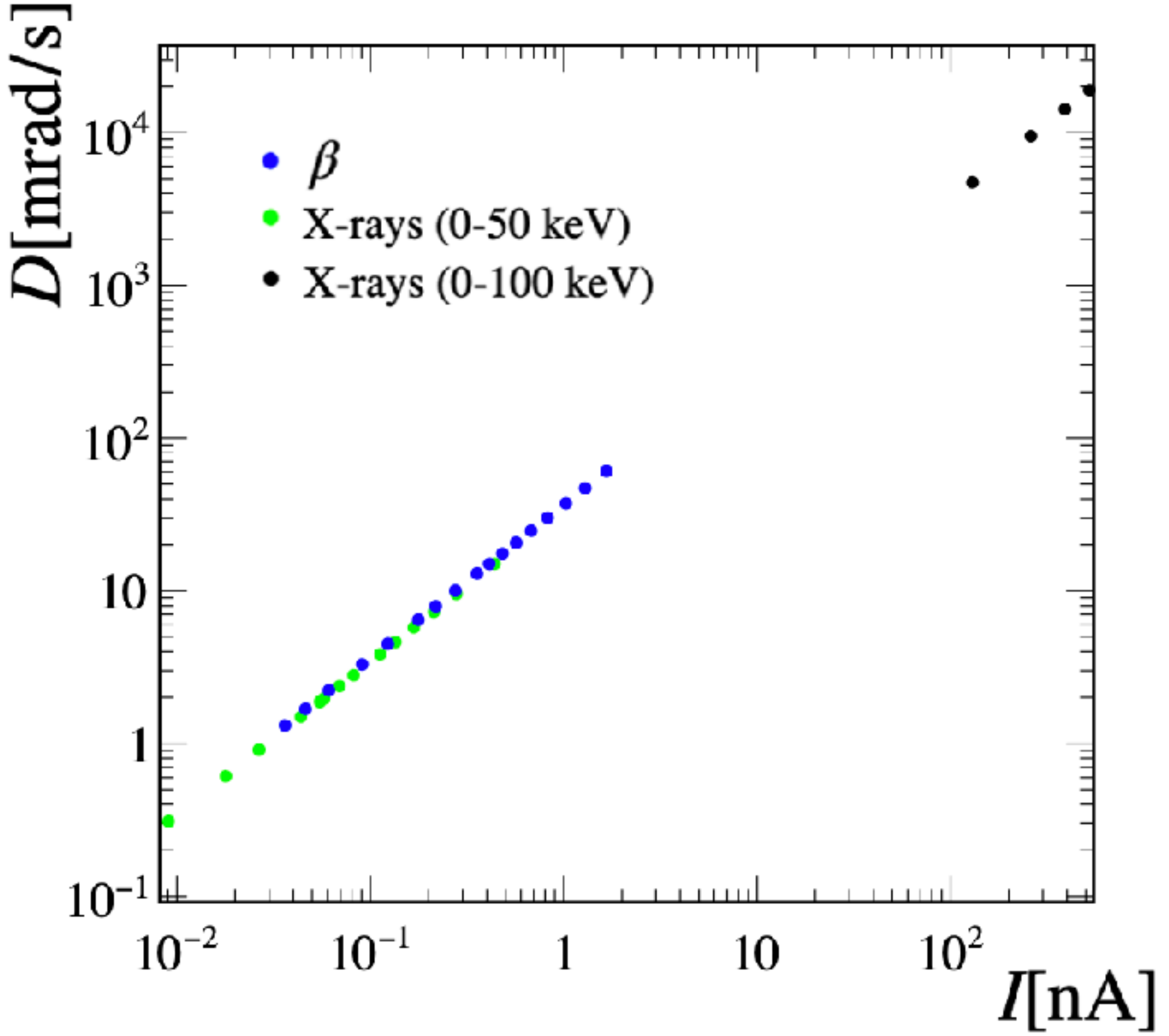
Calibration results

- The average current to dose rate calibration factor $k = 31.4 \pm 0.3\,(\mathrm{mrad/s})/\mathrm{nA}$

- Calibration with the different radiation sources cover the current range from a few pA to hundred nA

- Great consistency of the linear calibration from different sources over 4 orders of magnitude





High intensity e^- pulses

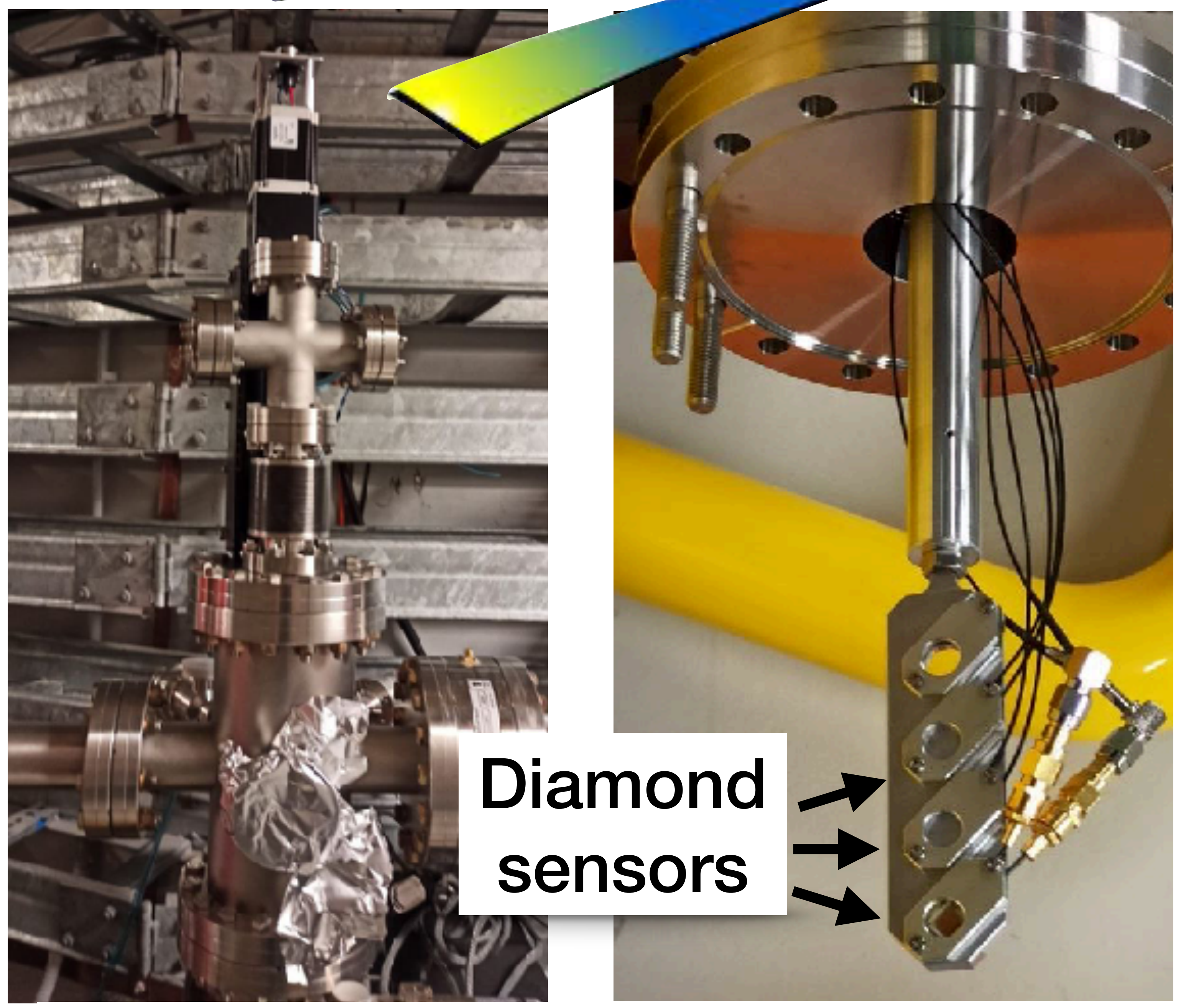
- Beam test at FERMI@Elettra FEL with $1\ \mathrm{GeV}$ electrons short bunches of $1\ \mathrm{ps}$ duration and vertical size of $0.1\ \mathrm{mm}$, with bunch charge from one to hundreds of pC.

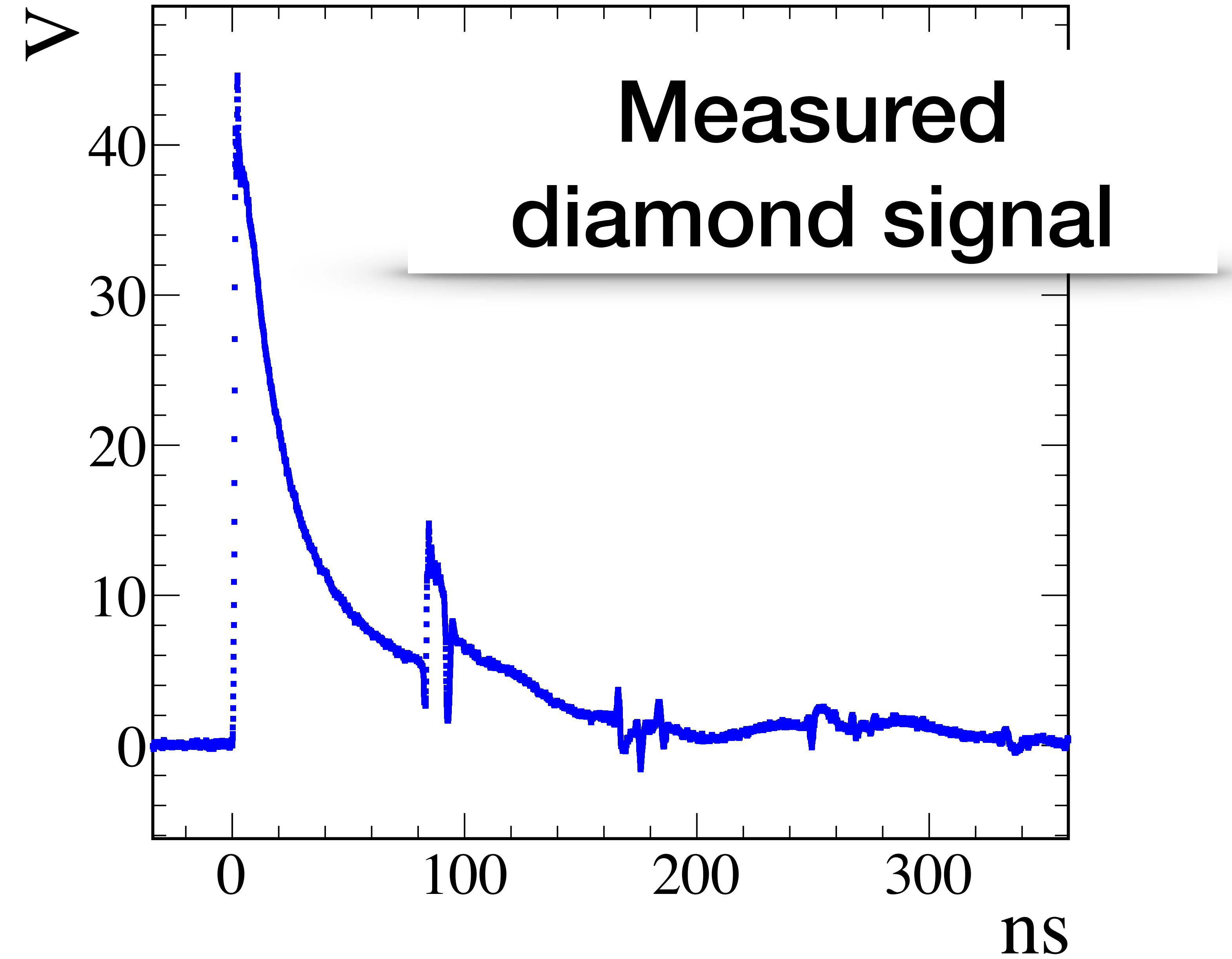
- Two sets of measurements are obtained :

  ⇒ changing the bunch charge

  ⇒ varying the bias voltage

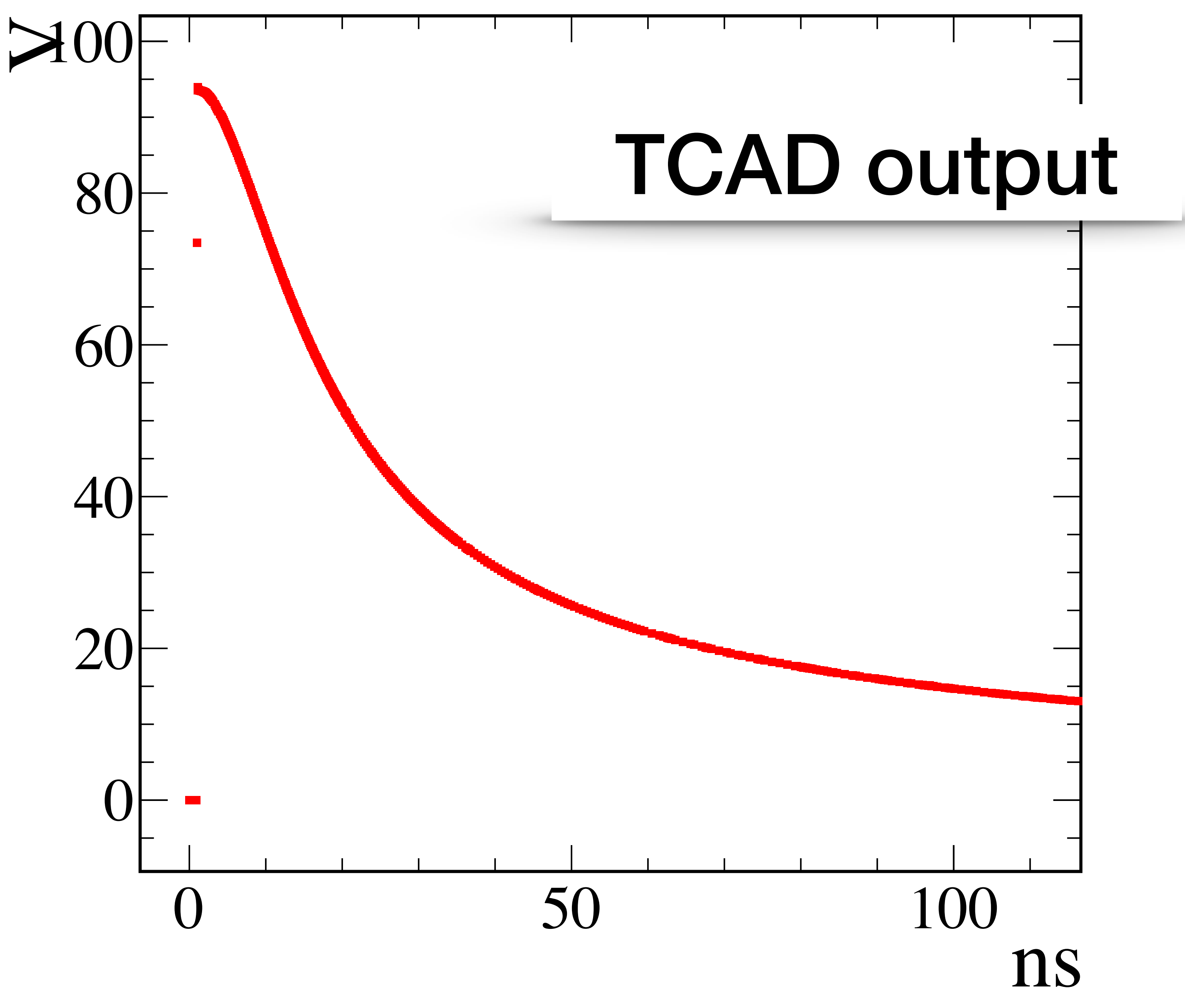
- The goal is to test the diamond transient response for very high intensity pulses and to study possible saturation effects due to a very high charge carrier density in the diamond bulk

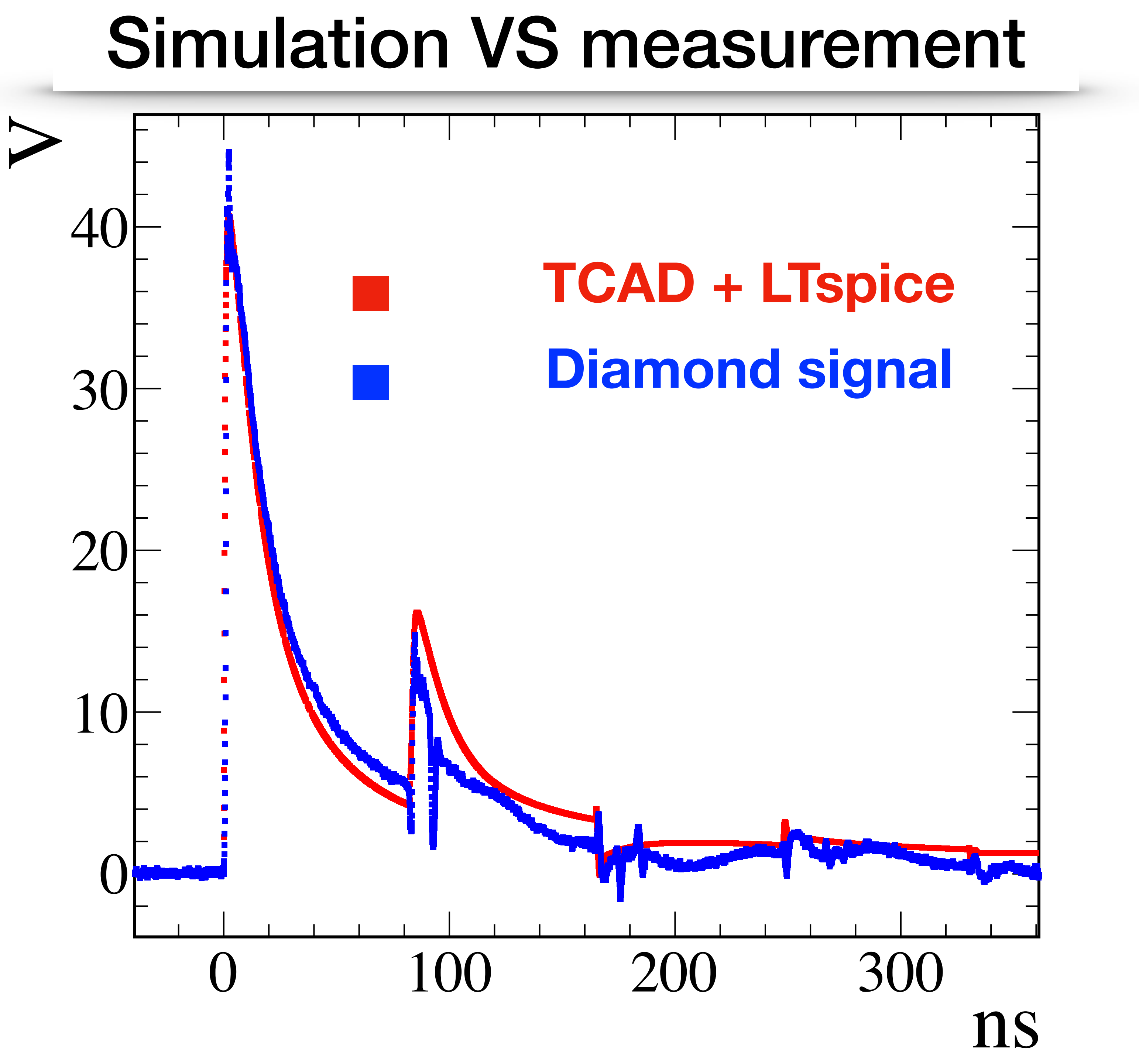




Preliminary results vs simulation

- Very clear measured signal with fast rise time, hundreds ns tails and multiple reflections due to impedance mismatching
- Two-step numerical simulation approach (TCAD + LTspice) to simulate the diamond detector's response in time
- Modeling of the diamond resistance as a function of the charge carrier density in the diamond bulk. A resistance variable in time is set for the diamond sensor.
- Measurement and simulation good agreement (same amplitude and reflection time)





Summary

Contacts:
Alice Gabrielli
alice.gabrielli@ts.infn.ts
Skype: live:gabrielli.alice

- Our diamond sensors are characterized using different radiation sources, and all the procedures are validated using a silicon diode as a reference;
- Good control of FLUKA simulation of the diamond sensors for charge particles, with possible improvements for X-ray;
- The two-step numerical simulation approach (TCAD + LTspice) gives the time response of the detector for two different radiation sources, in good agreement with the measurements;
- The diamond sensor has a very fast response for high intensity bunches of electrons of about $1\,\mathrm{GeV}$ energy. Preliminary results show a good agreement between measurements and simulation.