Characterisation of the transient response of diamond sensors to collimated, sub-picosecond, 1 GeV electron bunches

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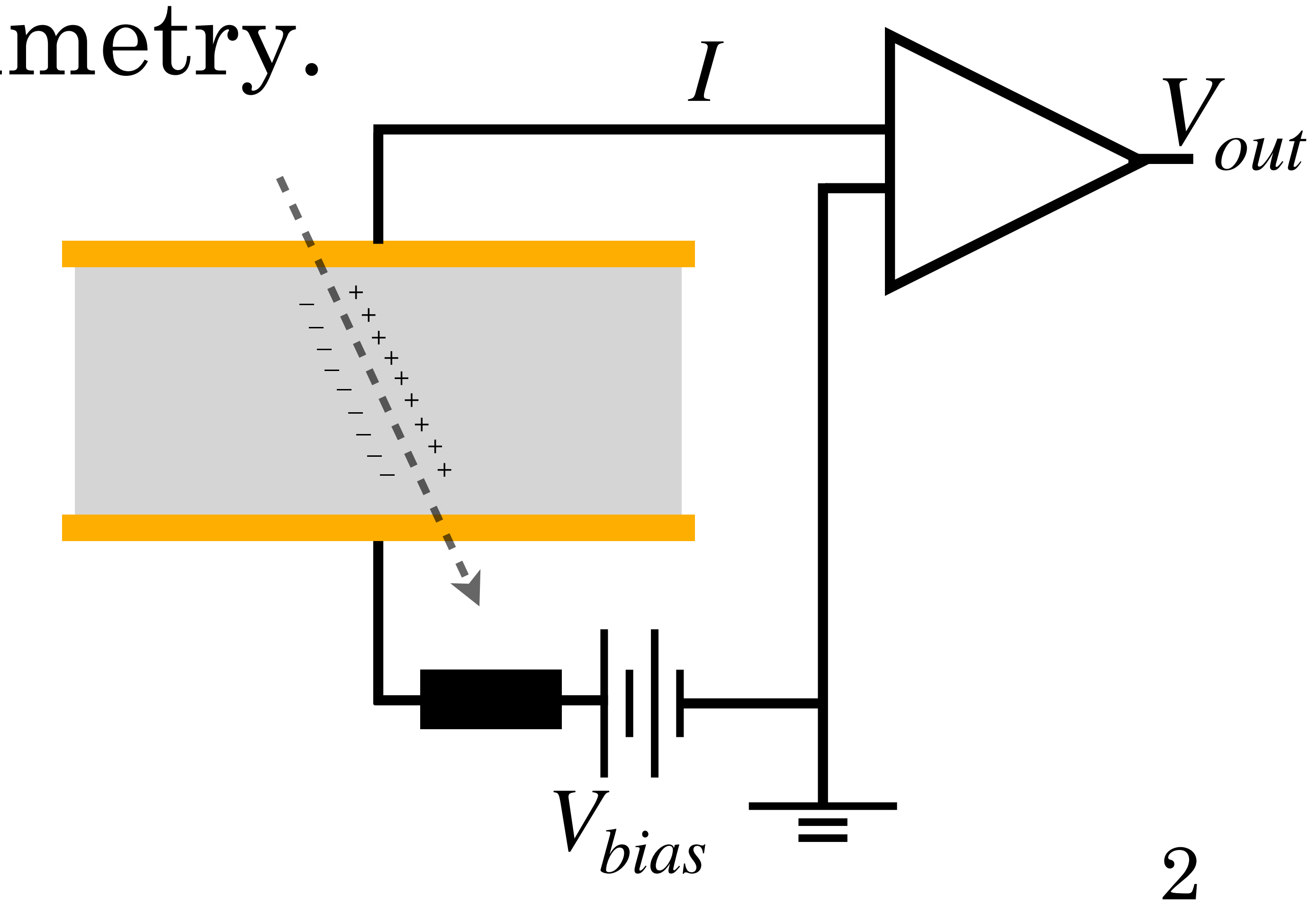
Diamond sensors

- Synthetic chemical-vapor deposition (CVD) diamond sensors are widely used in HEP experiments.

- As a semiconductor material, it has high charge carrier mobility → fast signal; wide bandgap → excellent radiation hardness.

- Often serve as solid-state ionisation chamber for radiation dosimetry.

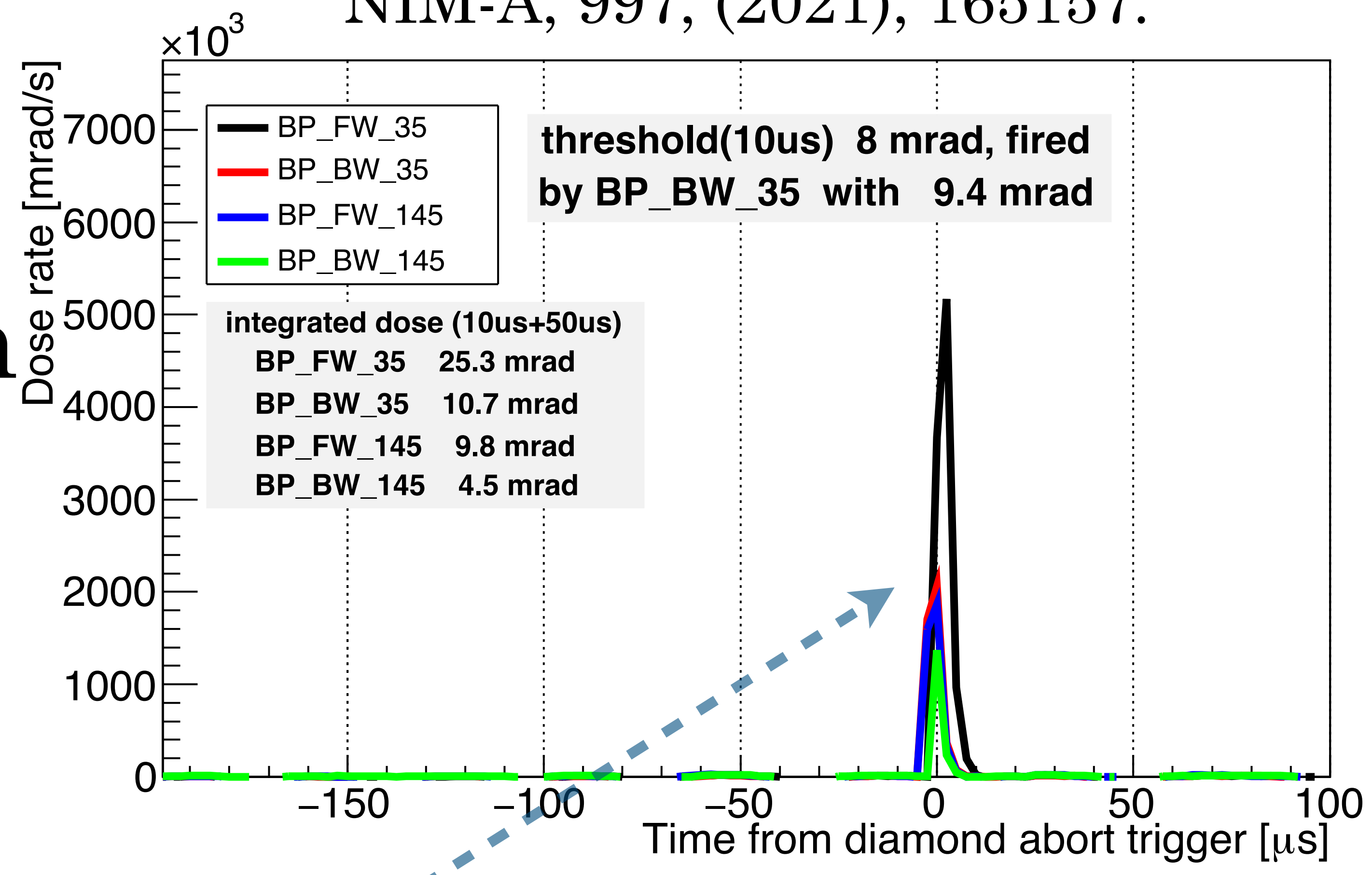
  (In some applications, also as tracker.)



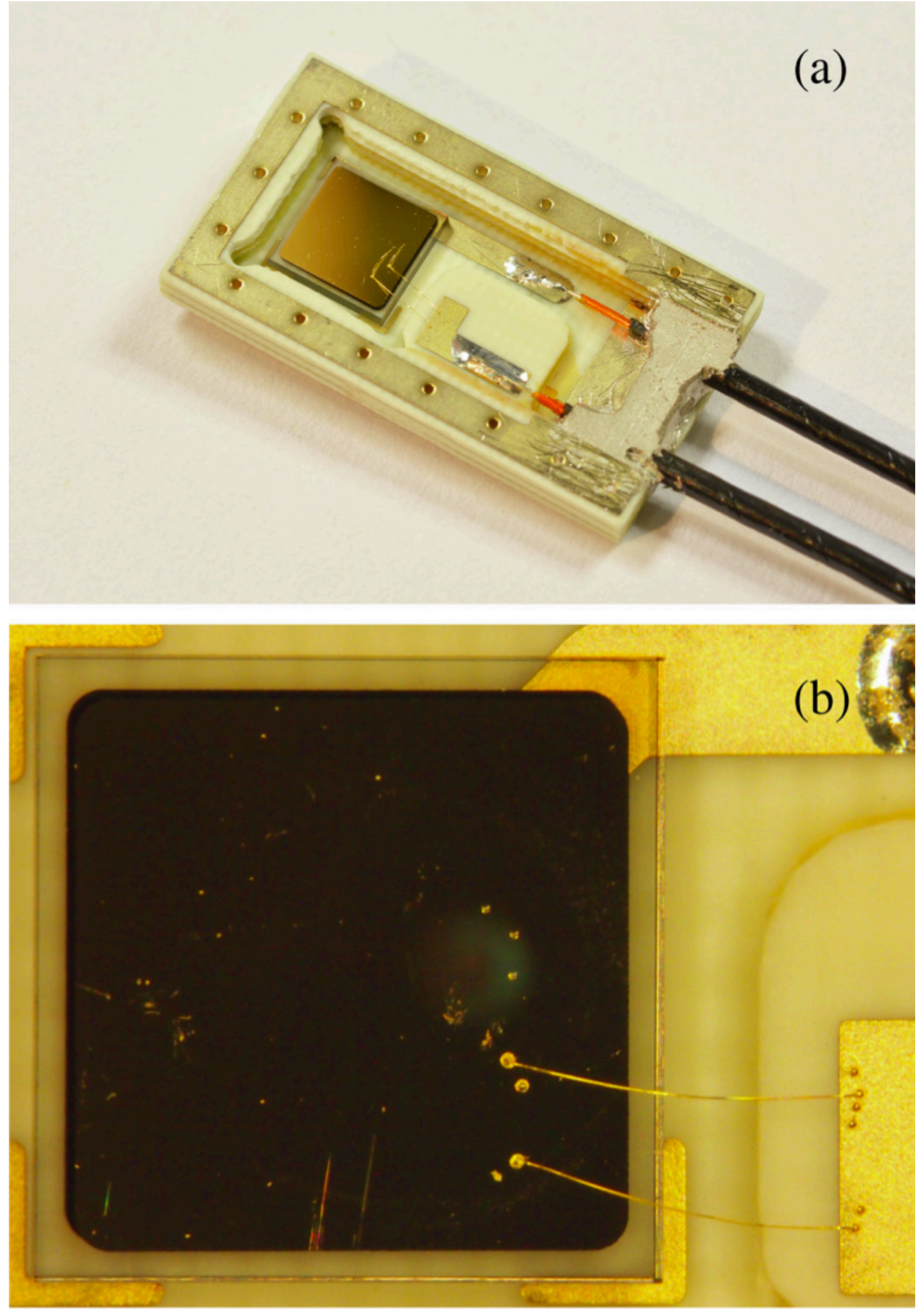
Radiation monitor @ Belle II

- We have developed and installed a diamond-based radiation monitor on Belle II detector at SuperKEKB e^+e^- collider.

NIM-A, 997, (2021), 165157.



(4.5 x 4.5 x 0.5) mm^3 sCVD crystals



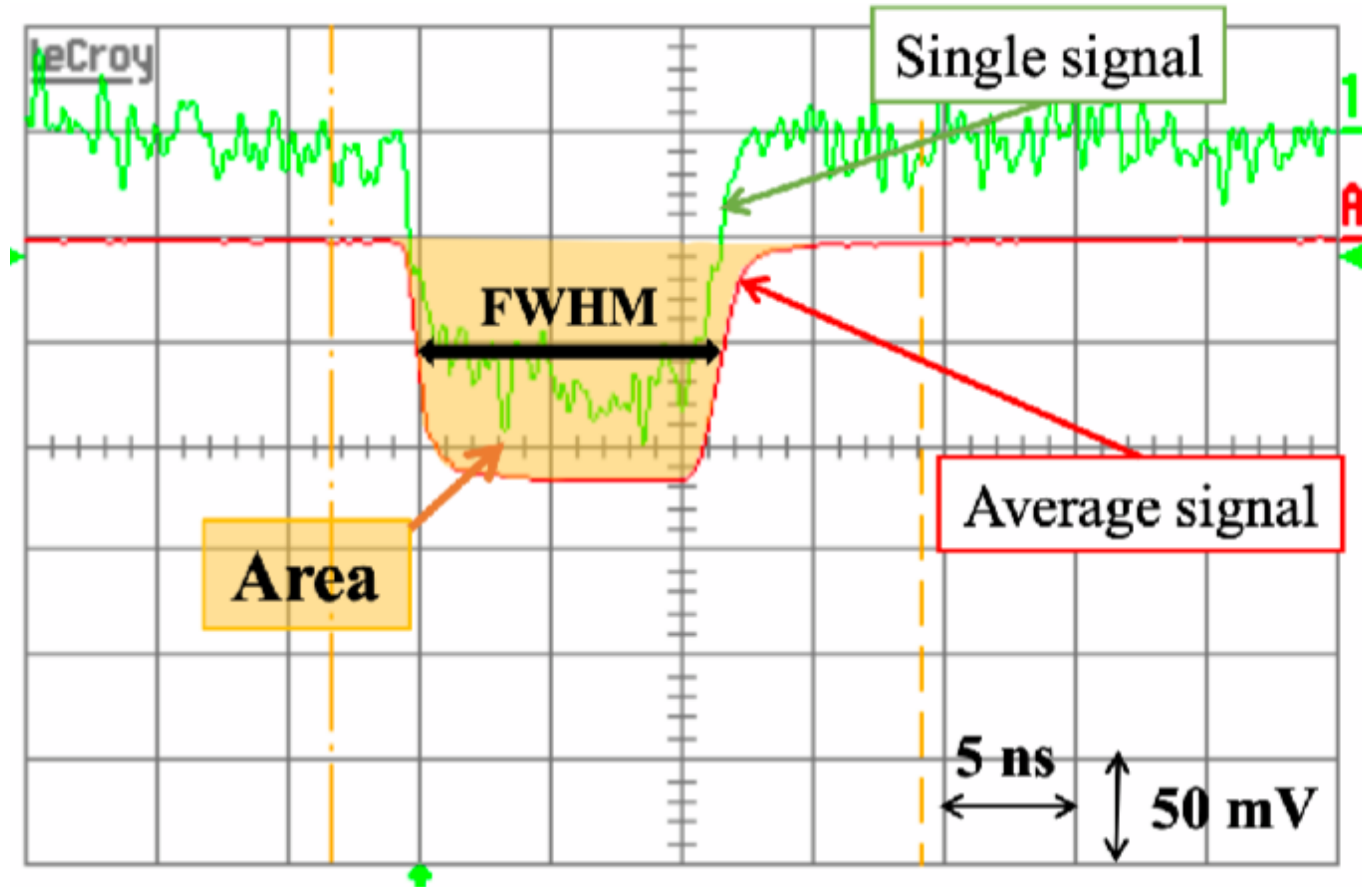
NIM-A, 1004, (2021), 165383.

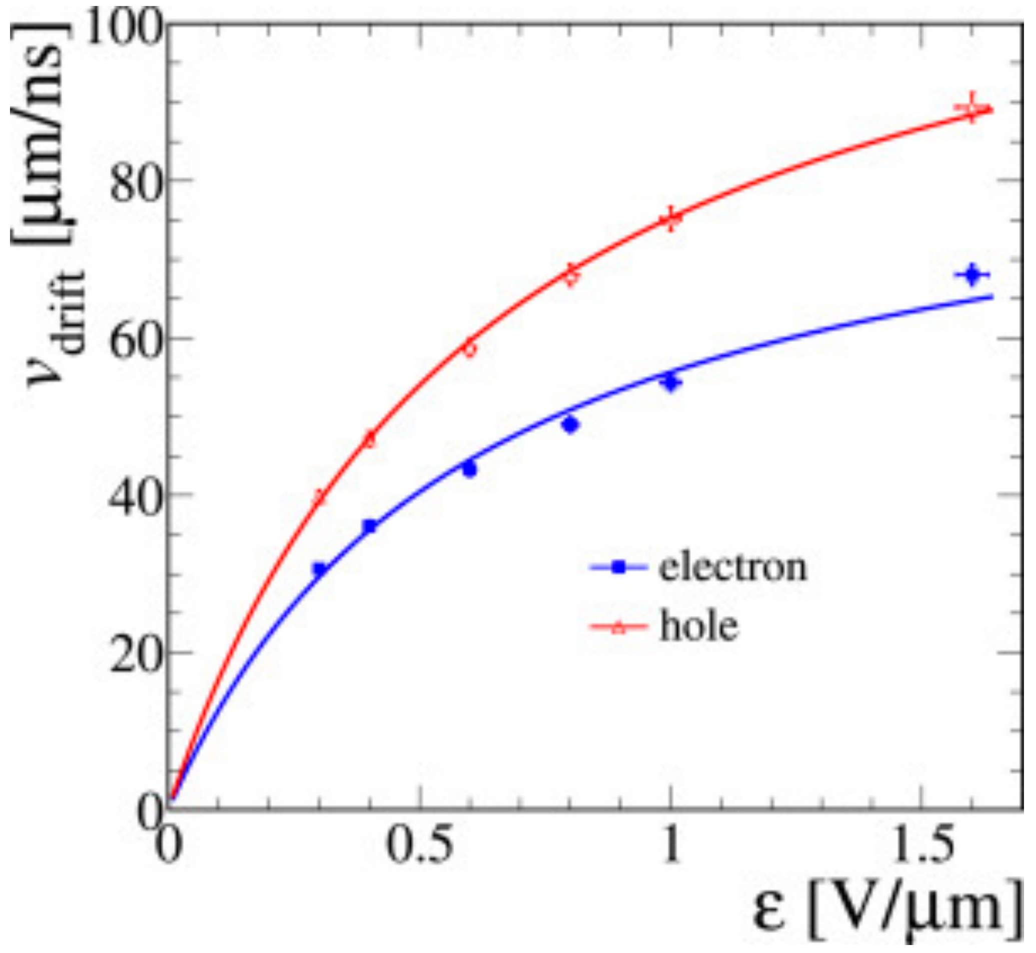
- With the increase of SuperKEKB instantaneous luminosity (new world record $4.7 \times 10^{-35}\ cm^{-2}s^{-1}$), the beam background is more severe. Bunch charge 4 nC. Radiation bursts occur due to the beam hitting dust.

- This urges an investigation of the response of diamond sensors to ultra-fast and intense electron pulses (tens of pC). On the other hand, the beam background due to neutrons and pions is still tolerable at this e^+e^- collider.

Crystal assessment

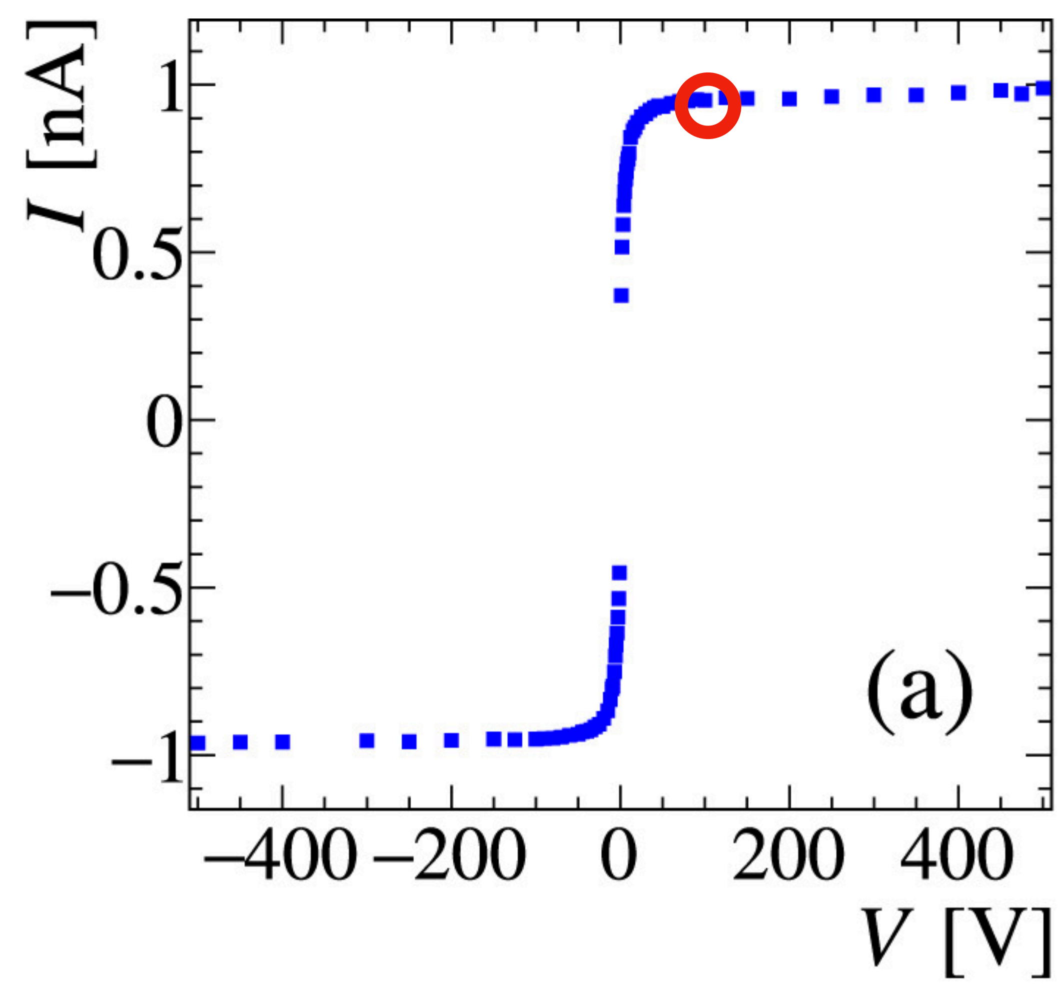
- Transient current technique (TCT) with α particle source has been used to measure the mobility and drift velocity of charge carriers, and the energy to create an e-h pair in diamond ($E_{eh} \approx 13 eV$).

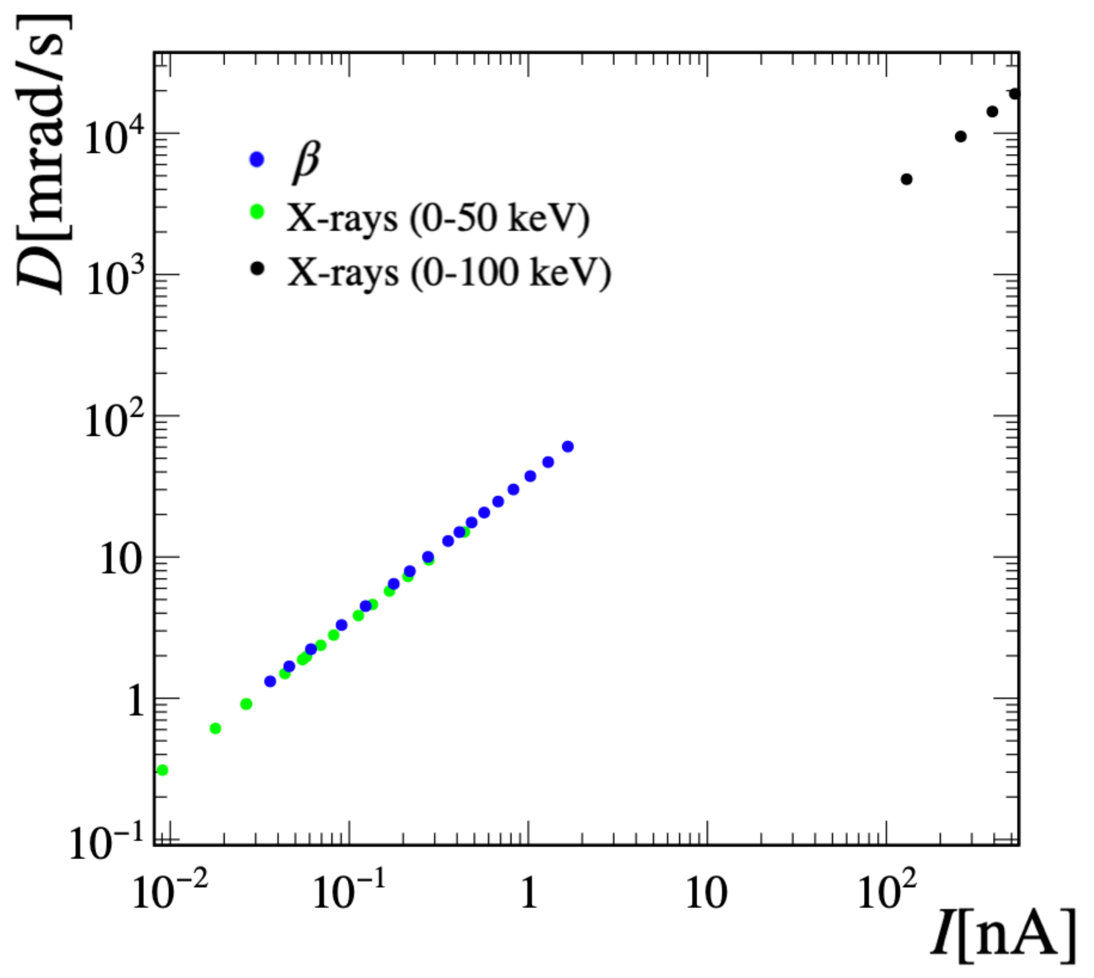




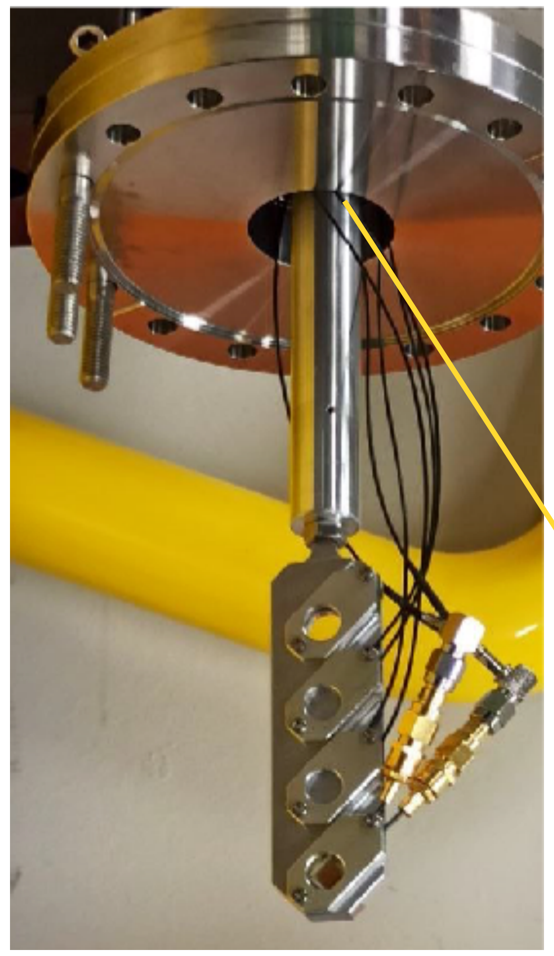
NIM-A, 1004, (2021), 165383.

- Using $\beta-$ and $X-$ ray, the stability of diamond sensor's response to steady irradiation has been investigated; calibration factor, from current I to dose rate D, measured over a wide range. A silicon diode is used as reference to reduce uncertainty of radiation source.

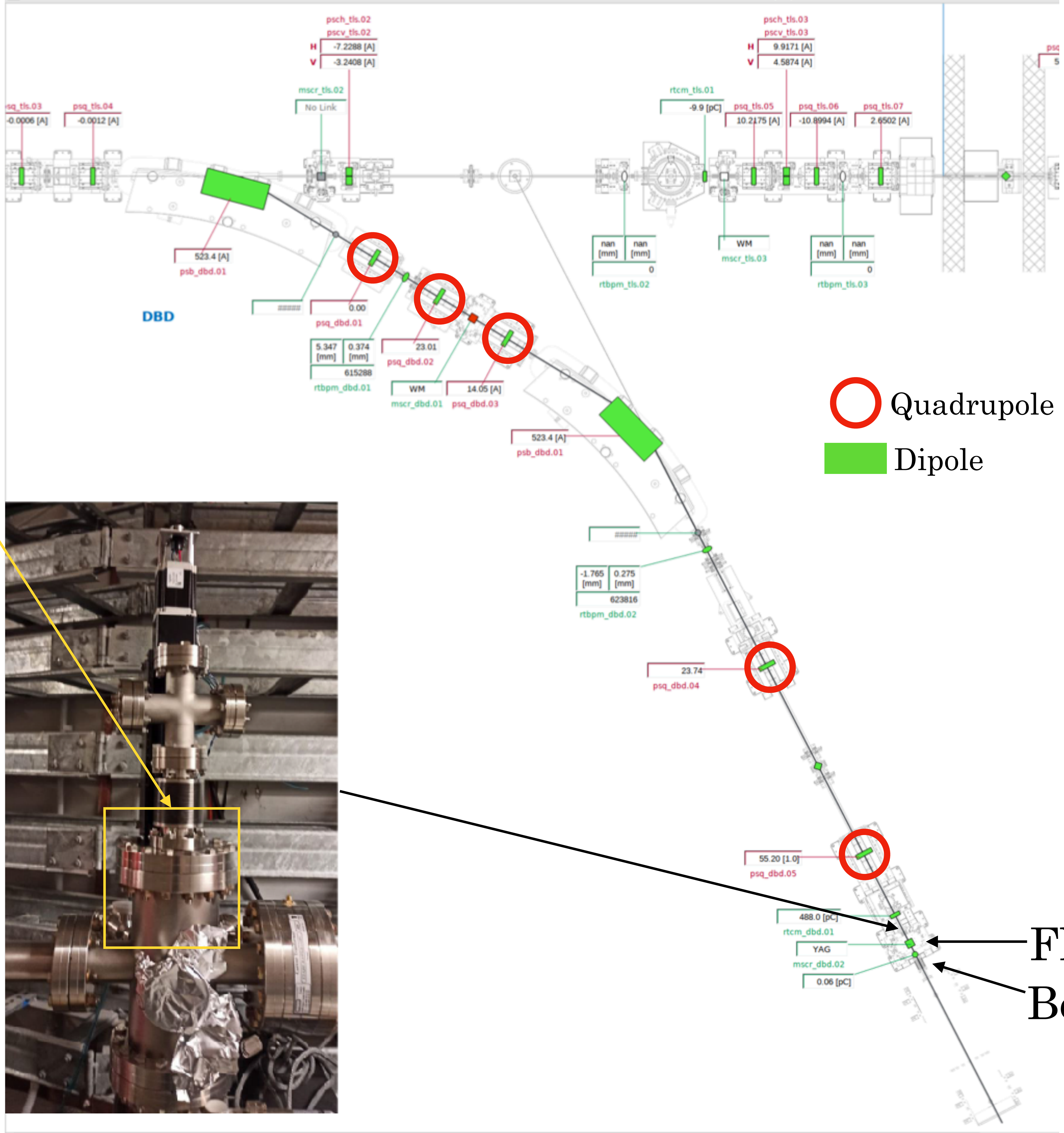




Exp. set-up @FERMI Linear Accelerator, Elettra



can move vertically



- ~1 GeV energy electron bunches,
- Variable charge from 20 to 500 pC,
- ~0.1 mm transverse size,
- Duration <1 ps, rate 50 Hz.

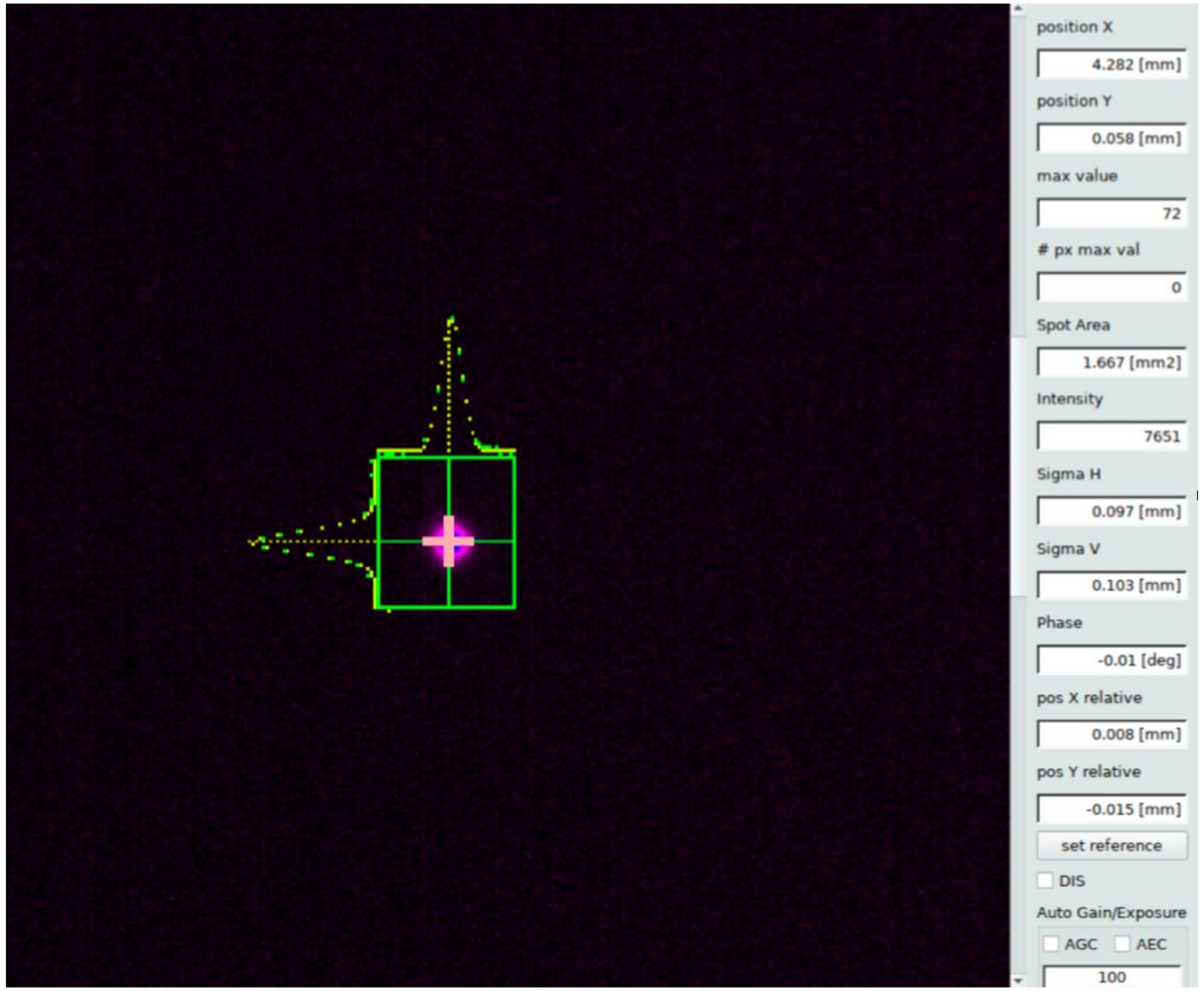
← **Experimental layout**

←← **Diamond sensors**

Fluorescent screen → beam profile

Beam current transformer → bunch charge

Data taking



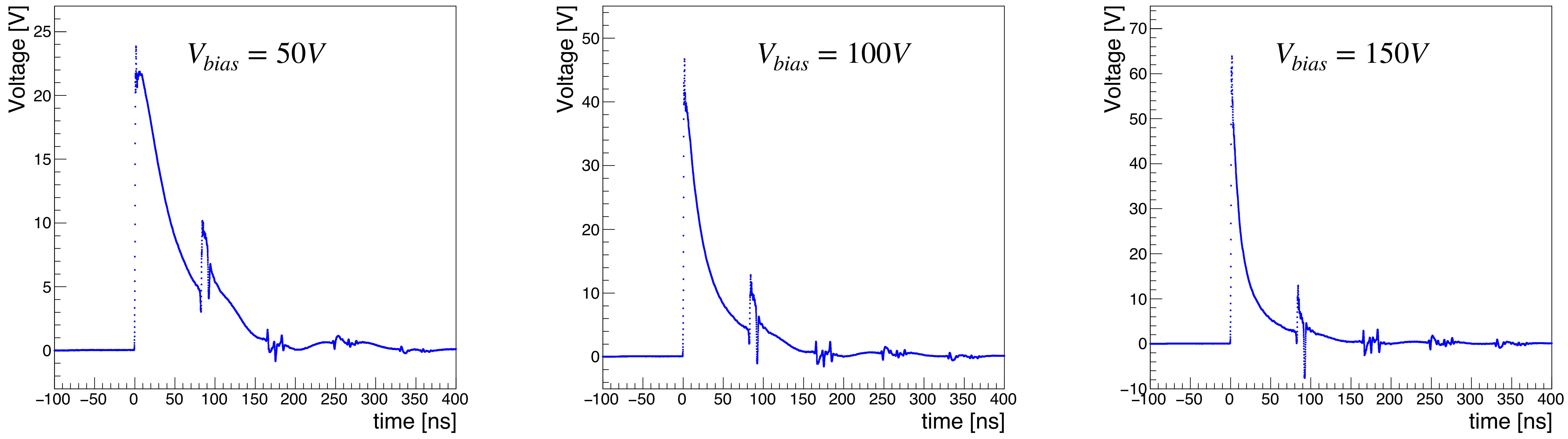
Fluorescent screen: beam profile

- V_{bias} on the electrode: 50 V, 100 V, 150 V.
- For small bunch charge, thorough beam tuning and optics simulation are needed.
- After achieving satisfactory beam condition, beam scan on the diamond is carried out.
- Data sets: 35 pC, 50 pC.

Response to electron bunches

- Assuming collision energy loss for incoming electrons $\triangle E = 0.35$ MeV [1], a 35pC electron bunch traversing 0.5 mm thickness generates 5.9×10^{12}e-h pairs → expected total signal charge : 9.4×10^{-7} C.

- Experimental data (voltage on the electrode measured by oscilloscope):



- Integrated current (voltage/50Ω termination), a measure of collected charge, gives : 2.7×10^{-8} C, 3.0×10^{-8} C, and 2.4×10^{-8} C. **Non-linearity is manifest.**

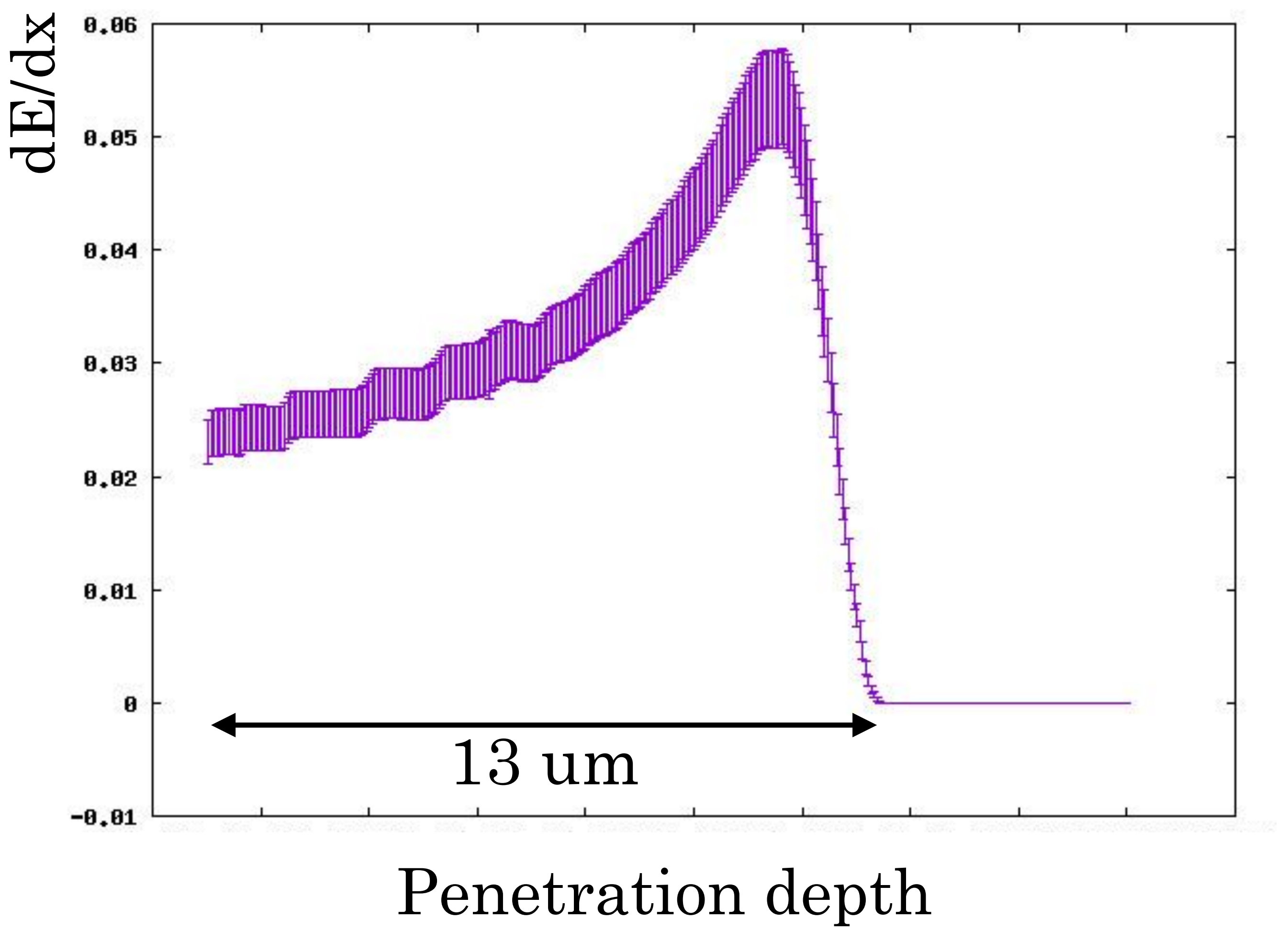
1, NIST Standard Reference Database 124

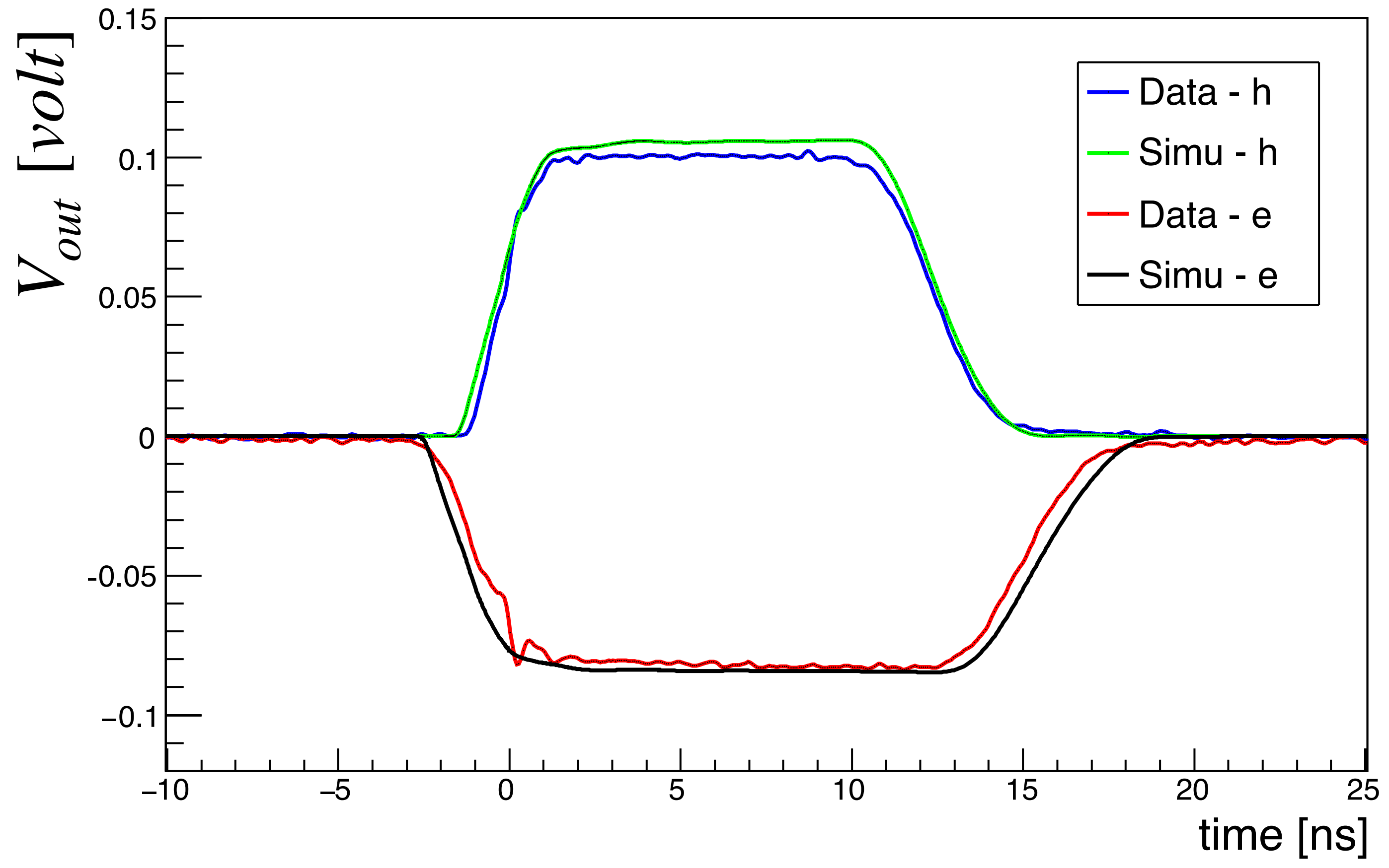
Simulation workflow

- A two-step simulation (TCAD+LTspice) was established prior to data-taking.
- The diamond detector → voltage source? current source?
- Using TCAD-Sentaurus [1]: a beam interacting with the diamond crystal, the creation of electron-hole pairs, the drift of charge carriers, and the evolution of the induced voltage drop on electrodes. In addition, evolution of the concentration of charge carriers inside the diamond crystal.
- The simulated voltage drop on the electrode is input to LTspice [2]. Coaxial cables, power supply, and oscilloscope all are modelled to take into account the transmission effects on the electrical signal such as reflection, attenuation, distortion, etc.

1, https://www.synopsys.com/silicon/tcad.html
2, https://www.analog.com/en/design-center/design-tools-and-calculators/ltspice-simulator.html

Validation of simulation approach



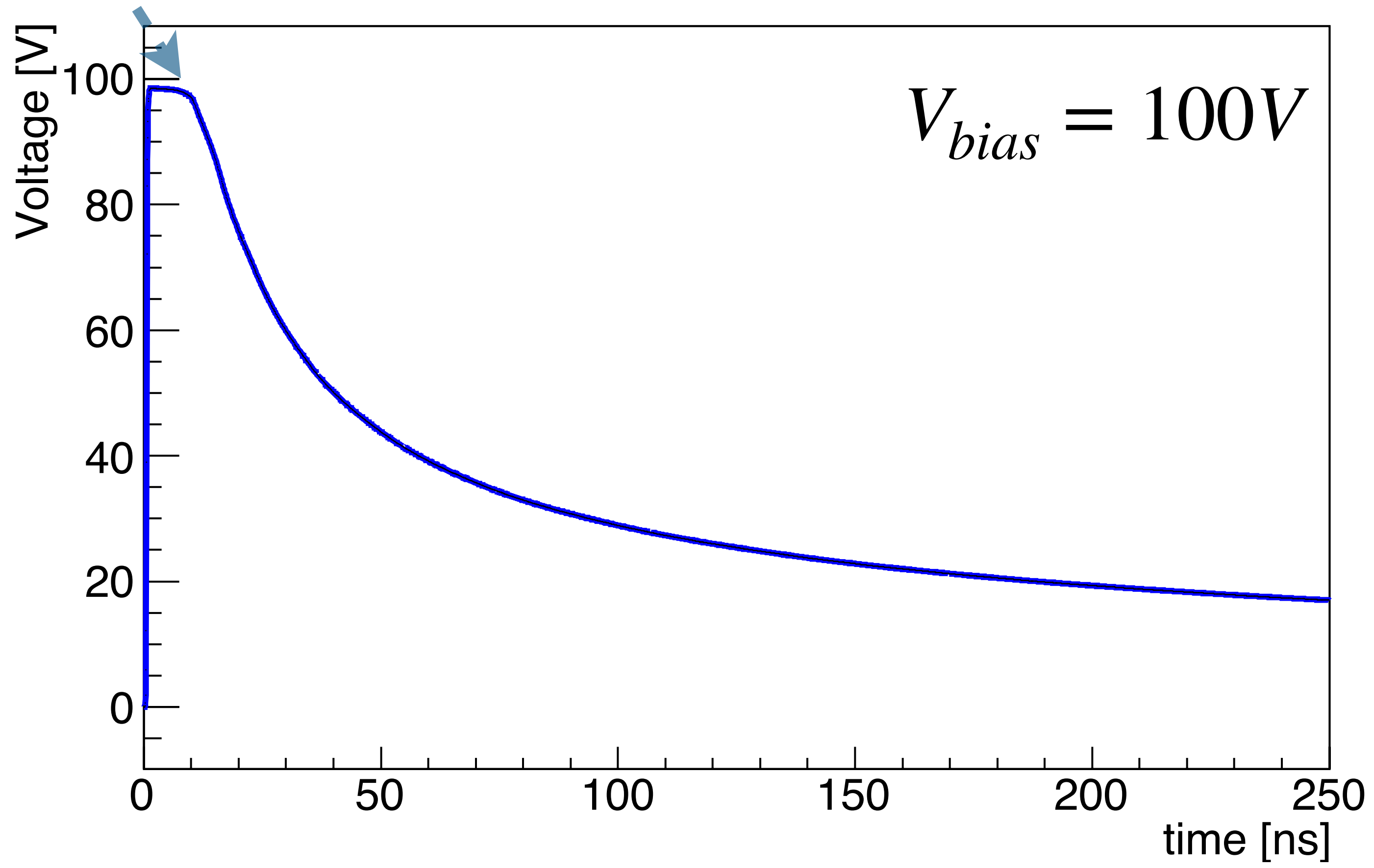


- Using TCT measurement, the simulation is validated.
- The deposit energy of α particles in the diamond bulk is simulated using FLUKA. The obtained distribution is input to TCAD.
- The measured values of charge carrier mobility and saturation velocity are input to TCAD. The lifetime of charge carriers (2 μs) is taken from Element Six handbook.
- Contact between diamond and Ti-Pt-Al electrodes is set "ohmic".
- The diamond sensor is modelled as a current source here.
- Good agreement between simulation and experimental data is observed.

Outcome of TCAD

- A distinct "knee" feature exists in the voltage evolution. Due to the large concentration of excess charge carriers, diamond is a "conductor" for a short time. As carriers start to drift, an internal E field is established by the space charge, which cancel off the external E field, slowing down the charge collection.

- The concentration of charge carriers near the injection path is up to $10^{17} cm^{-3}$! Thus the previous value of lifetime no longer makes sense, ie, additional recombination occurs[1]. Temperature increase also reduces lifetime. Realistic lifetime could be one order smaller[2].

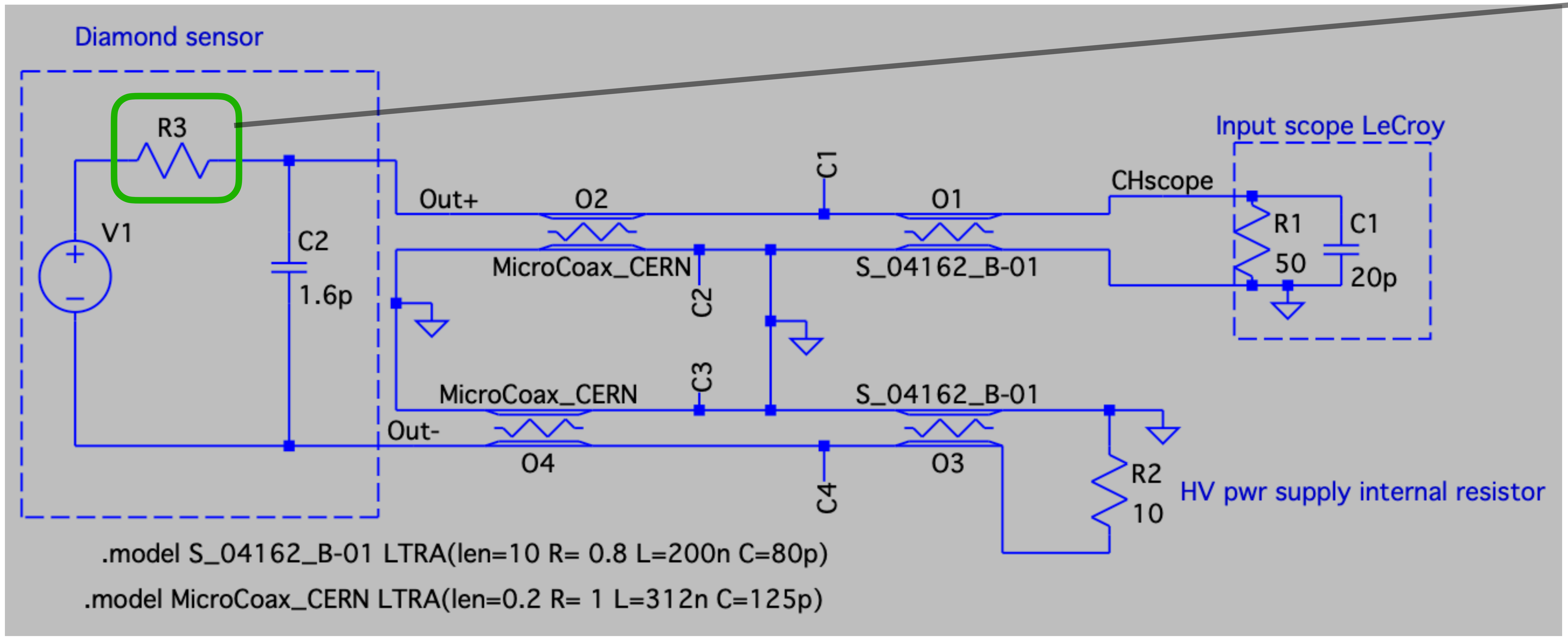


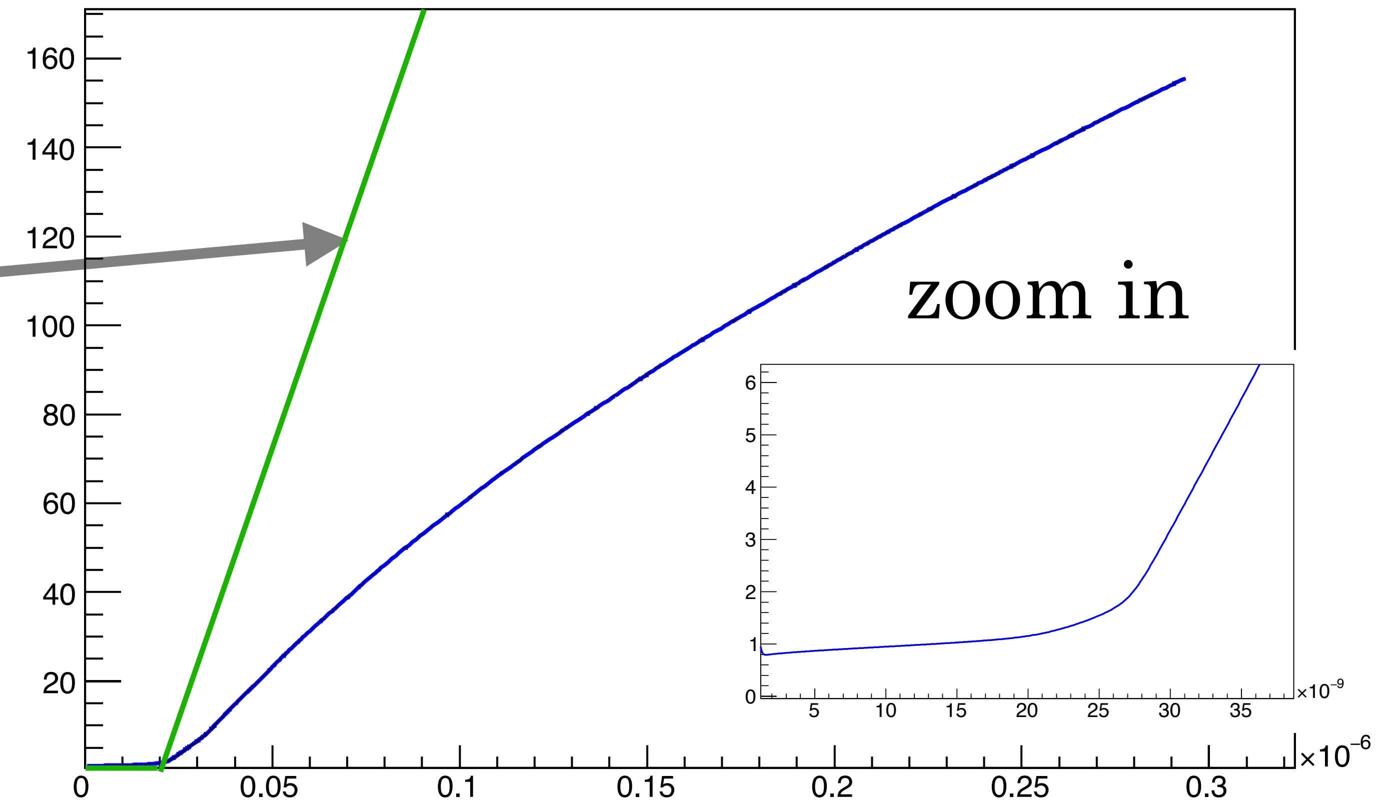
Attention: amplitude $\rightarrow V_{bias}$!

1, DOI: 10.5772/65064
2, DOI: j.nima.2015.04.002

Modelling of diamond sensor in circuit

$$R = \frac{V_{TCAD}}{I_{TCAD}}$$

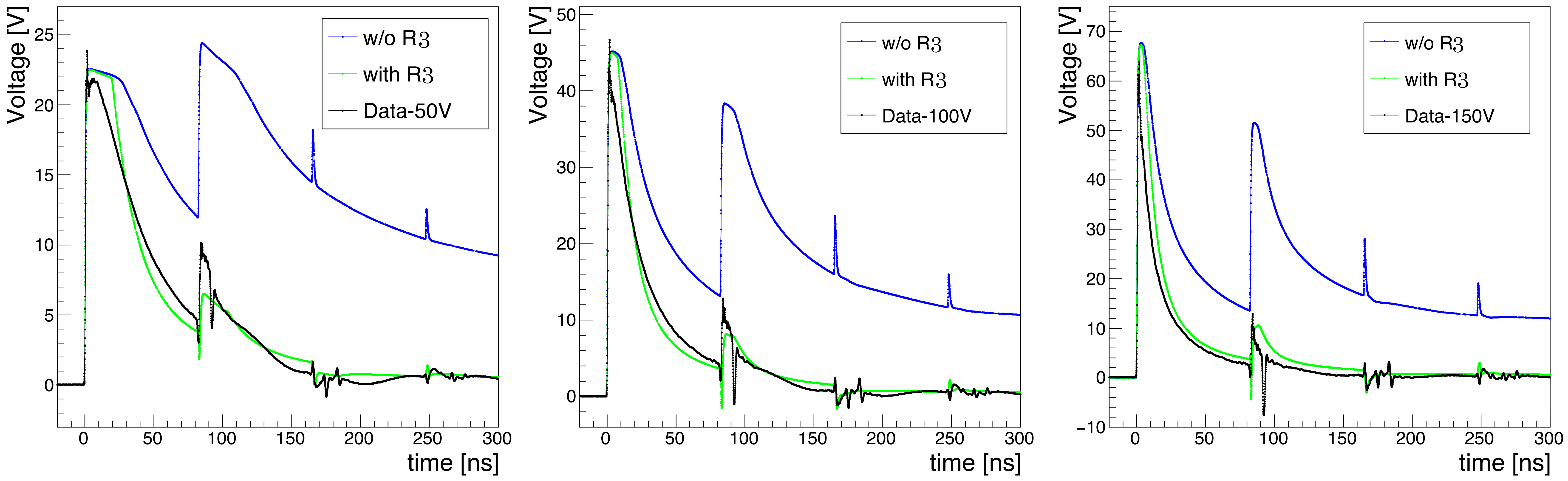




- A variable effective resistor (R3) is introduced to account for the variable impedance and additional recombination of charge carriers. It has a 10 times higher slope w.r.t the resistance (R) obtained from TCAD.

Outcome of LTspice

$V_{bias} = 50V$ $V_{bias} = 100V$ $V_{bias} = 150V$



- The amplitude (about half of V_{bias}) is determined by the circuit impedance.
- The time gap between reflections is also well-reproduced.

Summary & outlook

- Non-linearity does exist in diamond's response to ultra-fast and intense e pulses.

- Underlying mechanism has been investigated:

- The signal amplitude is determined by circuit impedance.

- The long tail is due to the screening effect of space charge, which delays the collection of charge carriers at the electrodes.

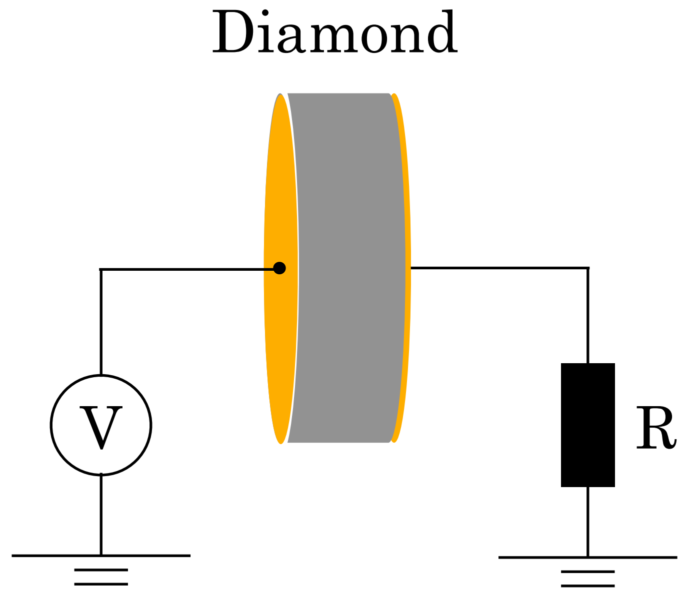
- The tail slope is mainly determined by the presence of substantial recombination of charge carriers (with lifetime much shorter due to their high initial concentration).

- We have collected data at 35 pC and 50 pC, can use our model to extrapolate the detector's response to similar conditions.

- More datasets are planned (aiming at lower charge).

Thank you!

Backup



Mass collision stopping power of diamond 2 $MeV \cdot cm^{-2} \cdot g^{-1}$

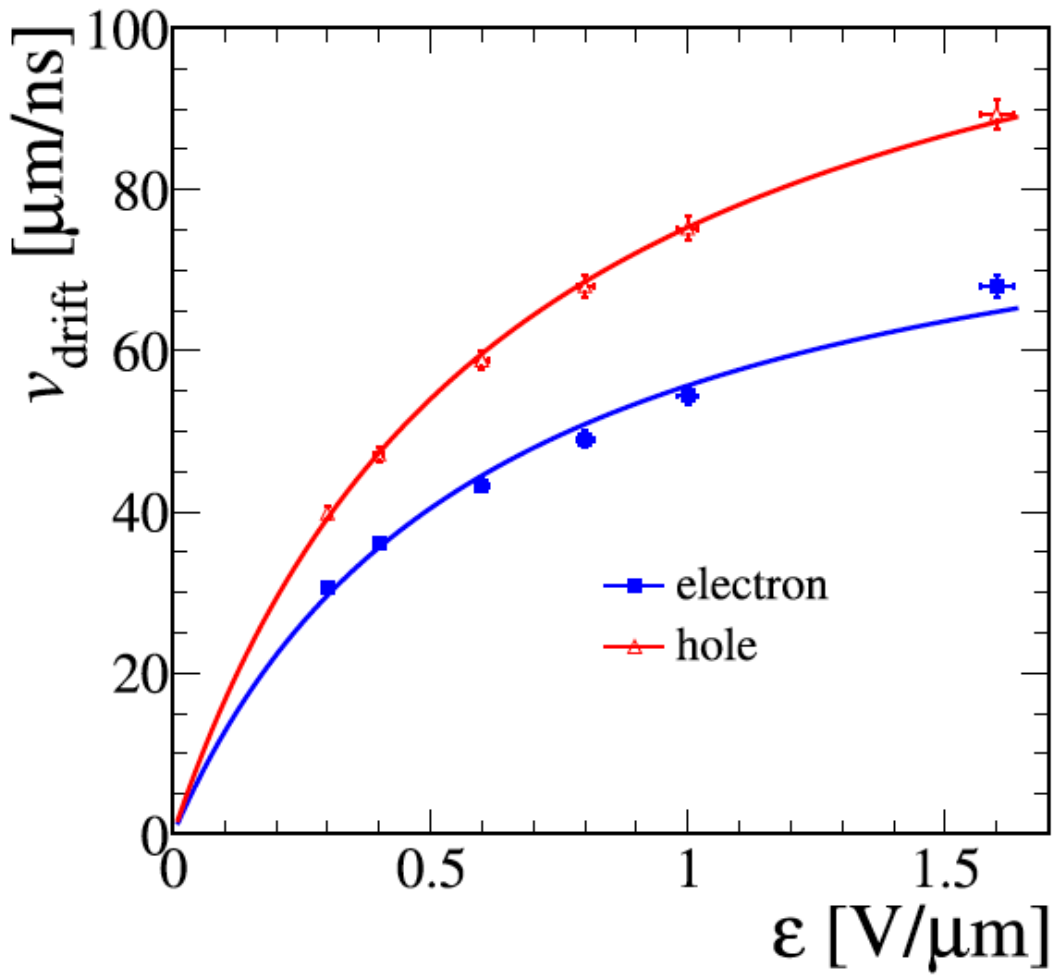
Diamond density 3.5 g/cm^3

Deposit energy 2 $MeV \cdot cm^{-2} \cdot g^{-1}$ x 3.5 g/cm^3 x 0.05 cm = 0.35 MeV

$$N_{eh} = \frac{DepositEnergy}{E_{eh}} \cdot N_{e-in-a-bunch} \cdot q = 5.9 \times 10^{12} \ (9.4 \times 10^{-7}\ \mathrm{C})$$

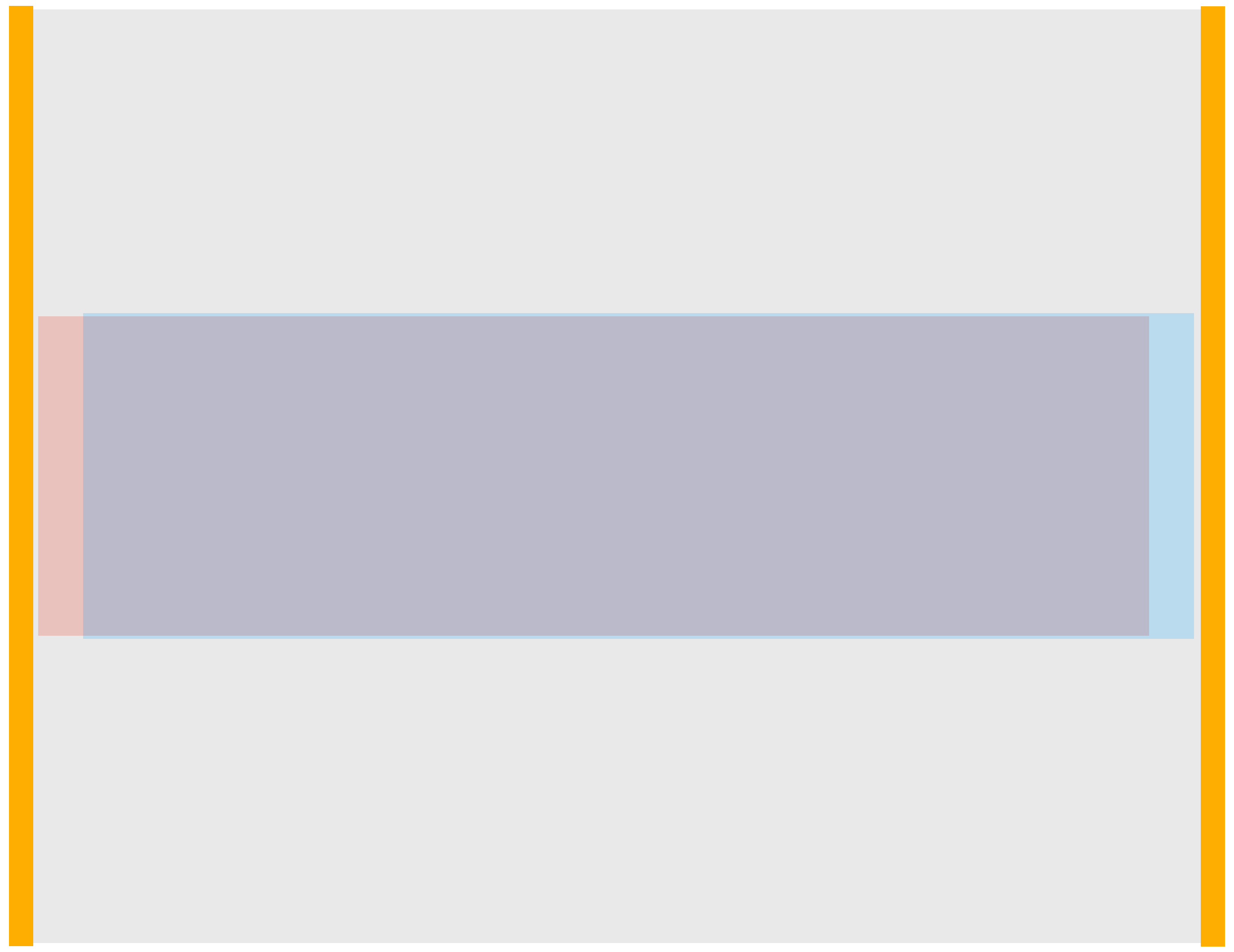
$$R = \frac{\rho \cdot d}{s} = \frac{1}{qn_e\mu_e + qn_h\mu_h} \cdot \frac{d}{s} = \frac{1}{qN_{eh}\mu_e/V + qN_{eh}\mu_h/V} \cdot \frac{d}{s} = \frac{1}{qN_{eh}\mu_e + qN_{eh}\mu_h} \cdot d^2$$

For 50 V bias, $\mu_e + \mu_h = 3000$
For 100 V bias, $\mu_e + \mu_h = 2650$
For 150 V bias, $\mu_e + \mu_h = 2600$



$R = 1\Omega$ for 35 pC
S cancel out in the calculation.
Note that we do not assume e-h distribute over all diamond, we assume they are confined in a certain region and the border of concentration is sharp.

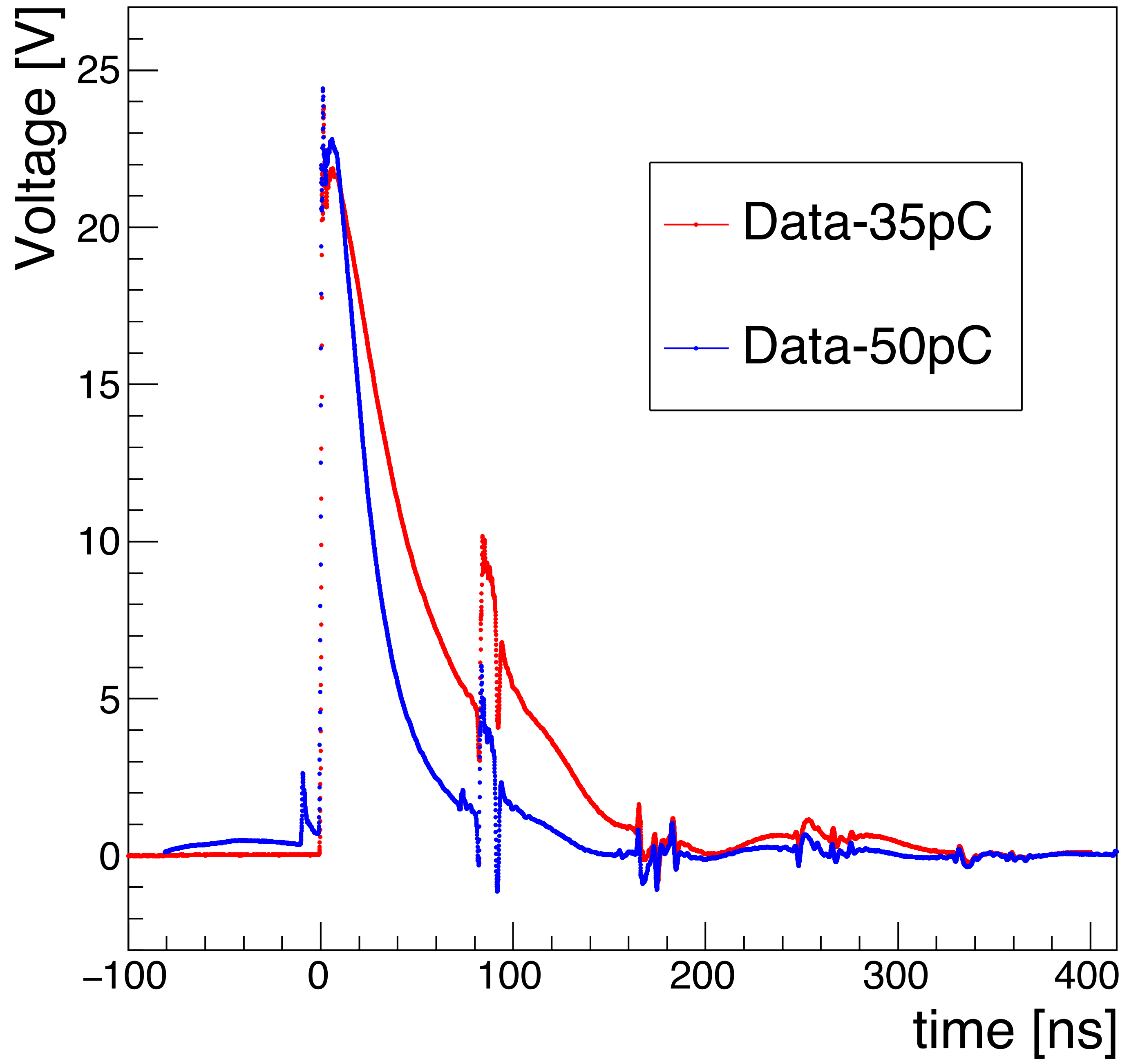
Internal E field



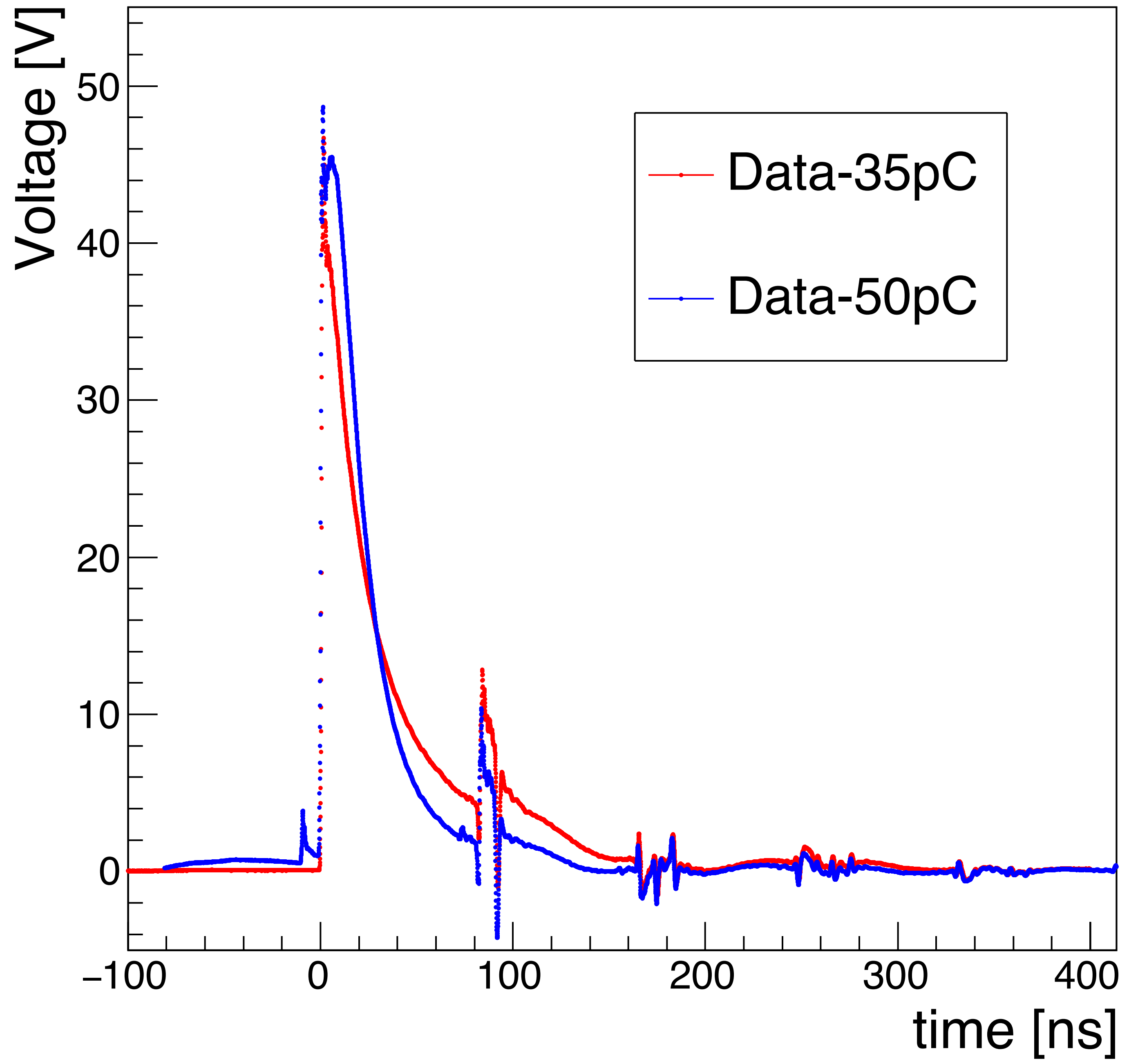
When e and h start to separate, a thin layer of e, a huge bulk of neutral region in the middle, and a thin layer of h.

Data taken with 50 pC

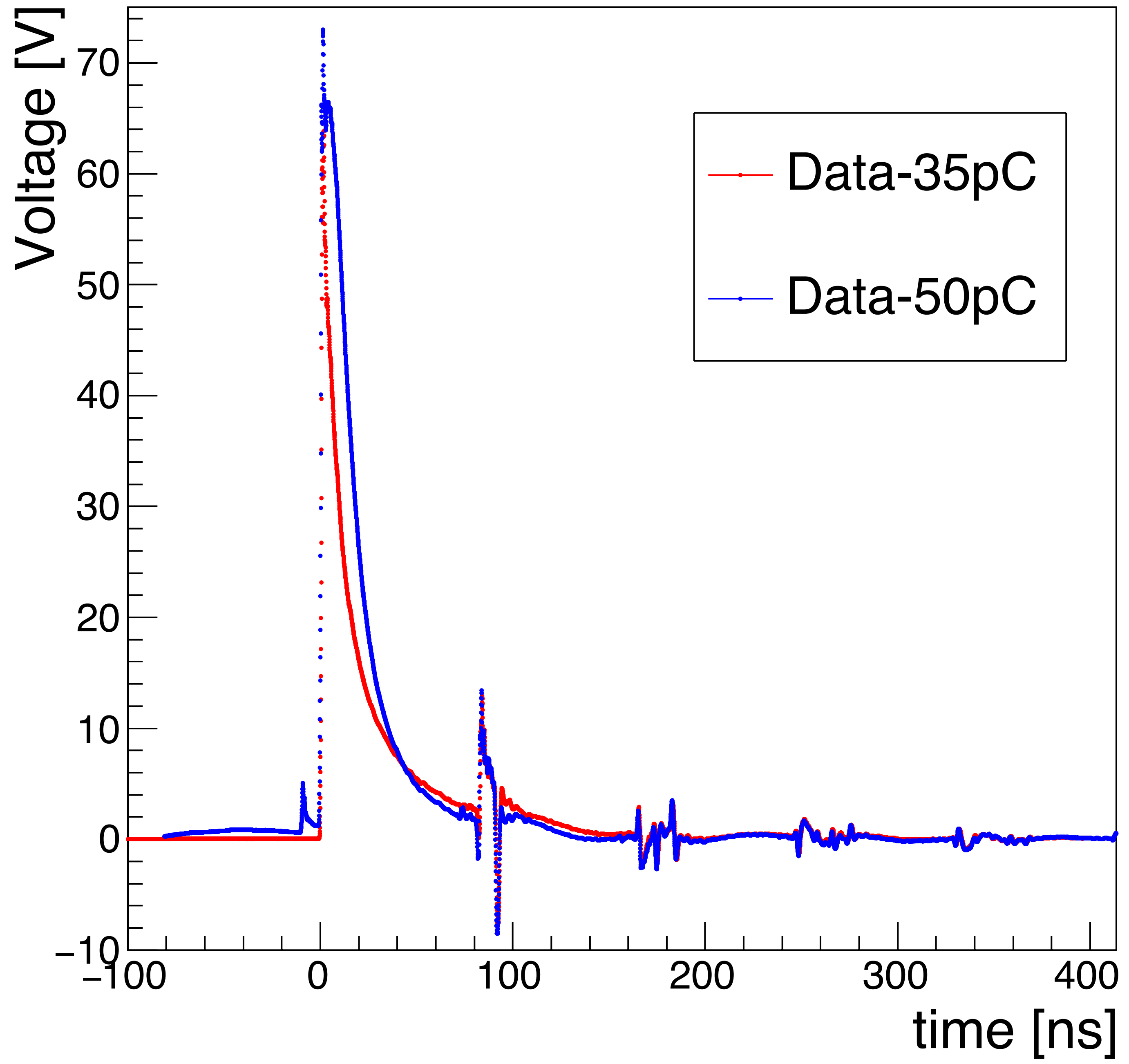
$V_{bias} = 50V$



$V_{bias} = 100V$

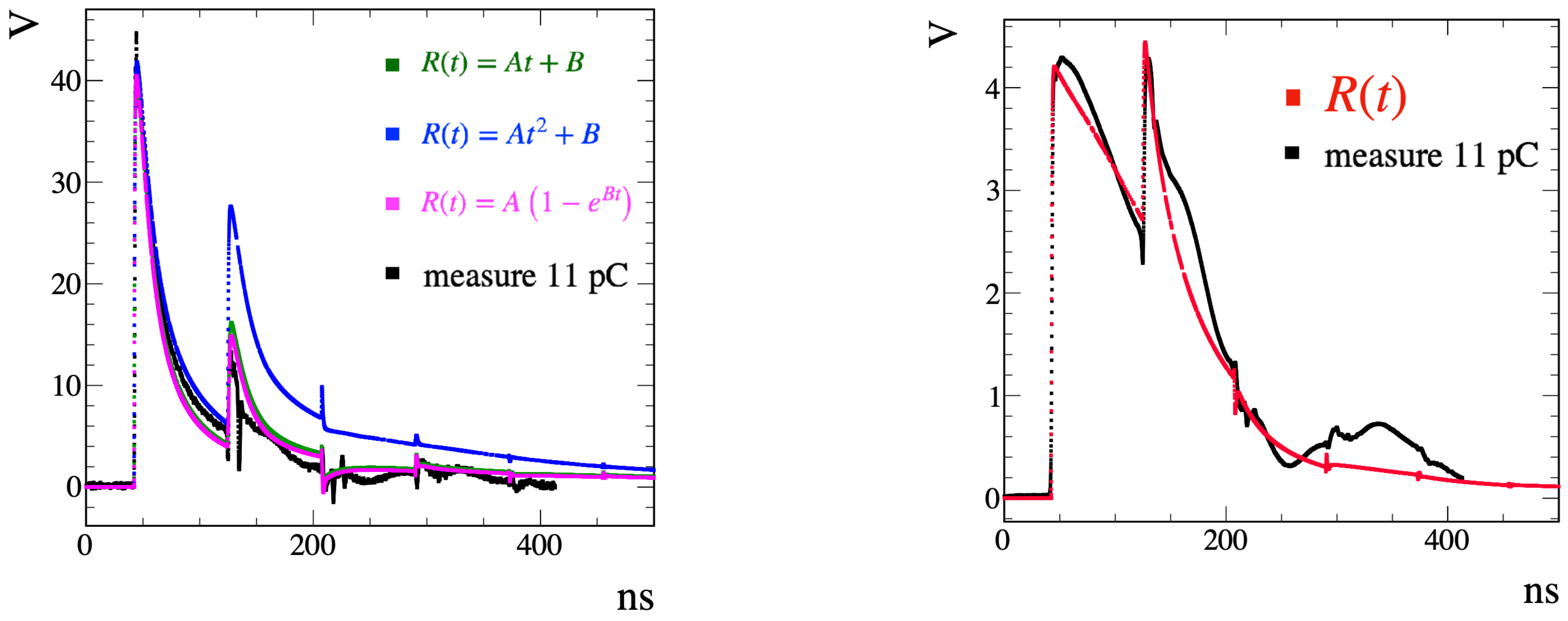


$V_{bias} = 150V$



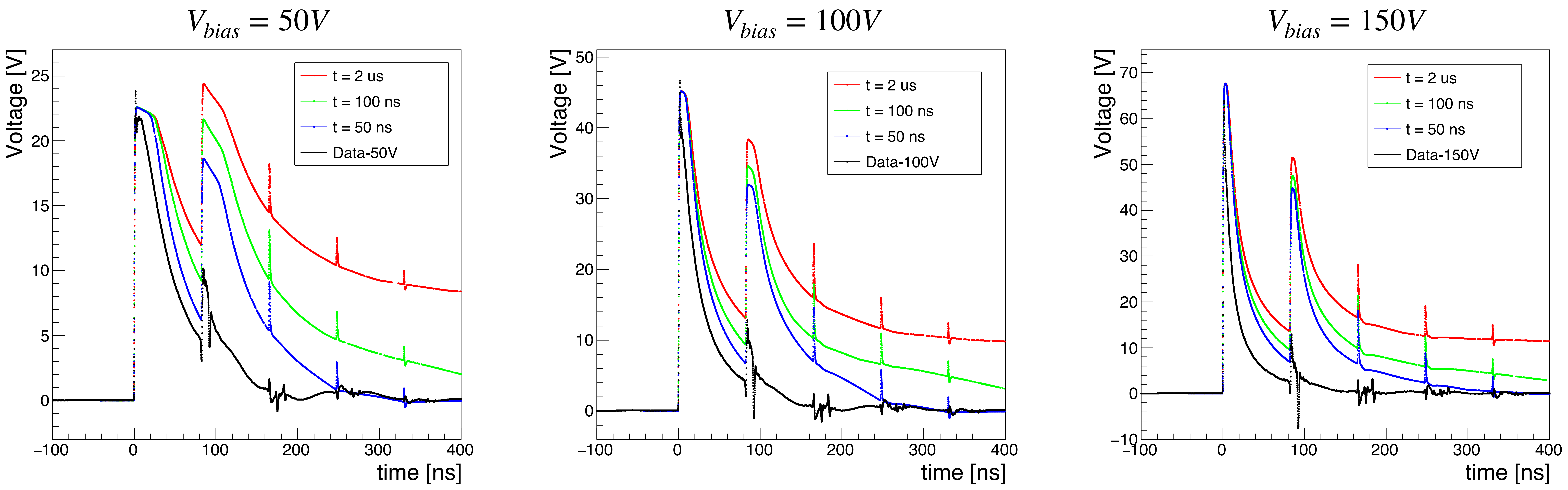
A dataset taken recently, with bunch charge 50 pC.

Data taken with 11 pC



A dataset taken at the begining of the project, with transverse dimension $\sigma = 1$ mm.

w/o R in LTspice



Removing the R in LTspice and setting directly a shorter lifetime in TCAD, the reflection cannot be reproduced well.