Characterization of Single-Crystal Diamond Sensors for Radiation Monitoring in the Belle II Experiment

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Belle II and its Vertex Detector

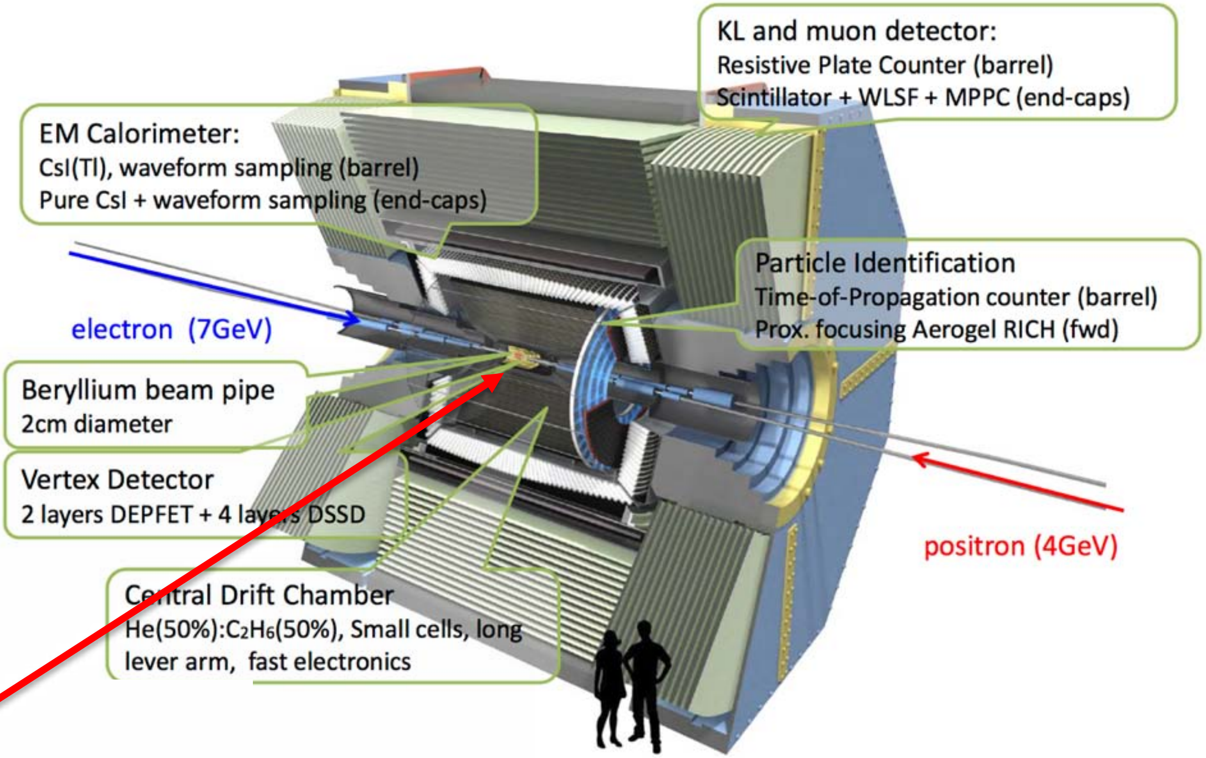
Belle II Detector

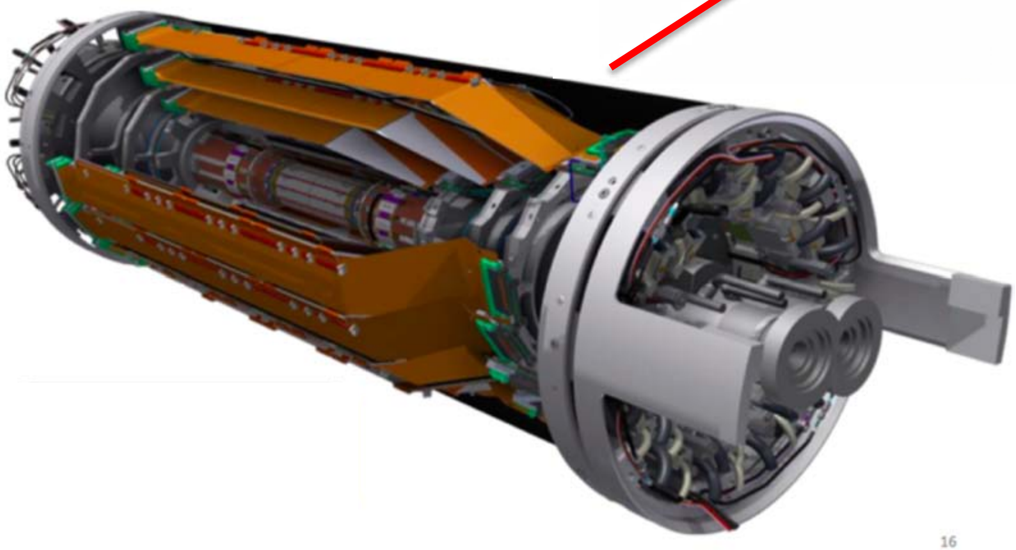
at the SuperKEKB

e^+-e^- collider

$L_{peak} = 8 \times 10^{35}\ cm^{-2}s^{-1}$

$L_{int} = 50\ ab^{-1}$ by 2025





Silicon Vertex Detector (SVX)

- Two layers of DEPFET pixels (PXD)
- Six layers of double-sided microstrips (SVD)

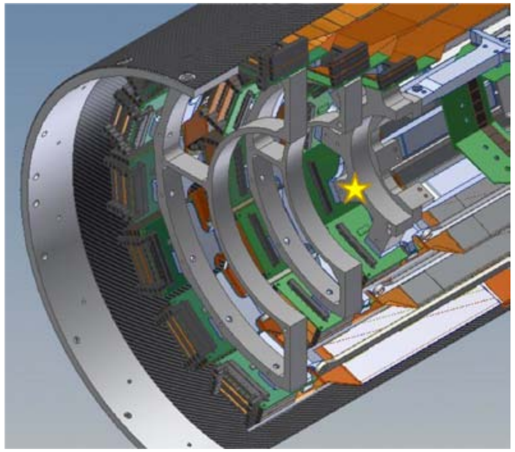
Radiation Detection System

Dual-purpose system:

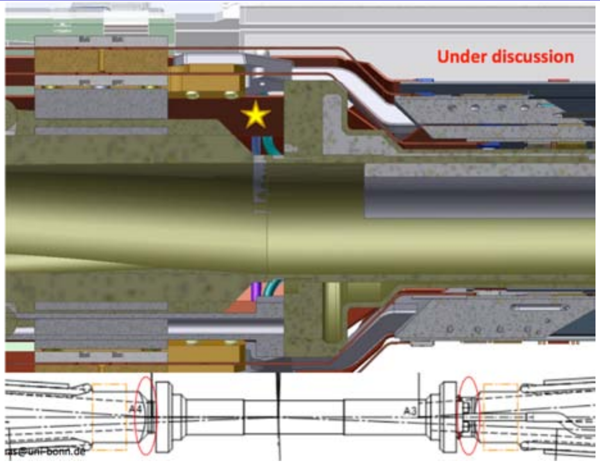
1. Providing long-term monitoring of integrated radiation doses at several places in the vertex detector
2. Providing interlock signals for beam abort in case of potentially damaging radiation levels

Sensor current is measured and sampled, providing fast (100 kHz, higher dynamic range) and a slow (10 Hz, higher sensitivity) data output streams

28 Diamond Sensors installed

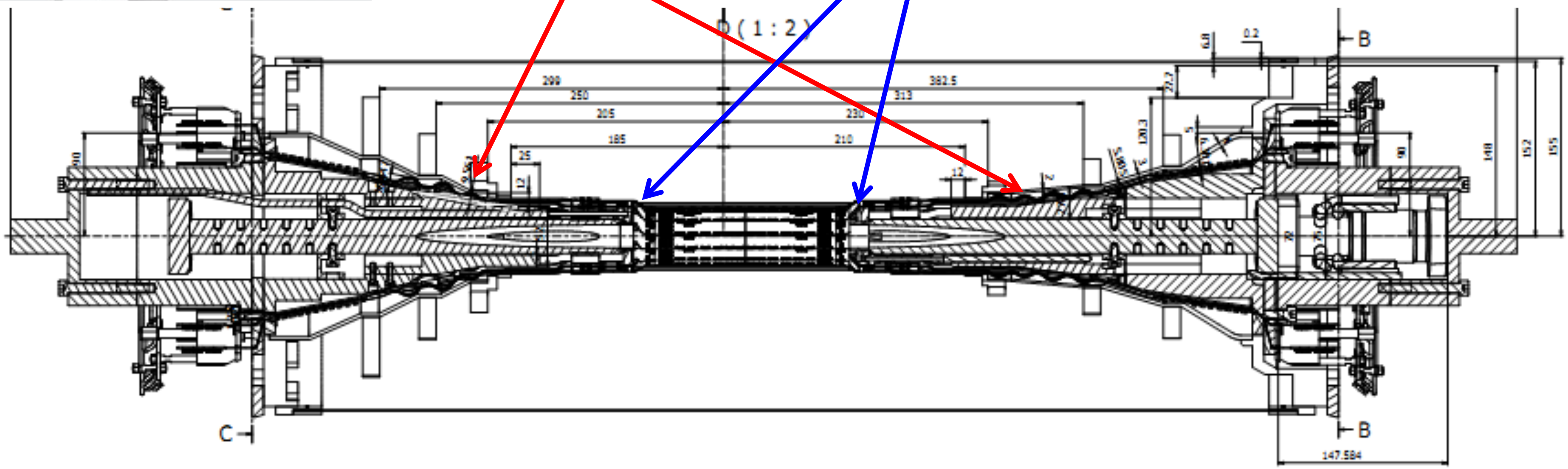


20 sensors at the SVX



6 + 6 sensors close to SVD L3 support rings

4 + 4 sensors at PXD-beam pipe

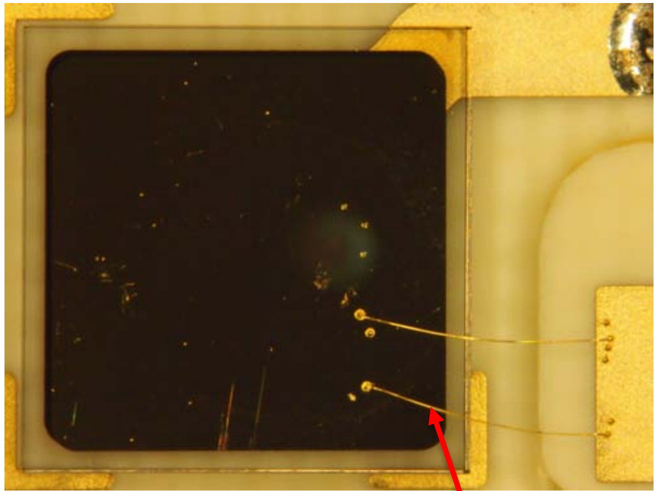


Plus 4 + 4 sensors at the nearest quadrupoles

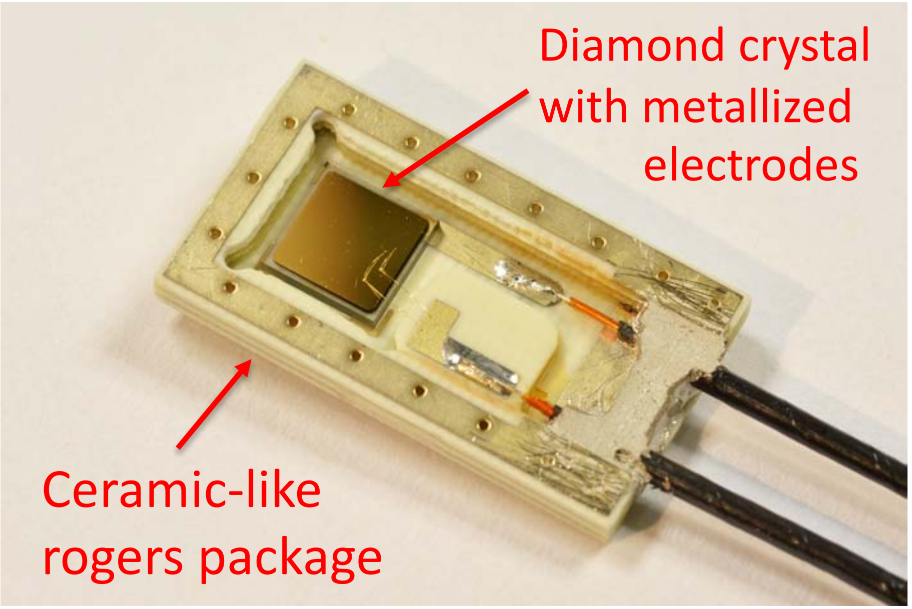
=> 28 Diamond Sensors in total

Diamond Sensors + Package

- Diamond sensors supplied by Cividec
- (4.5 x 4.5 x 0.5) mm^3 single-crystal diamond
- Ti + Pt + Au metallization (100 + 120 + 250) nm



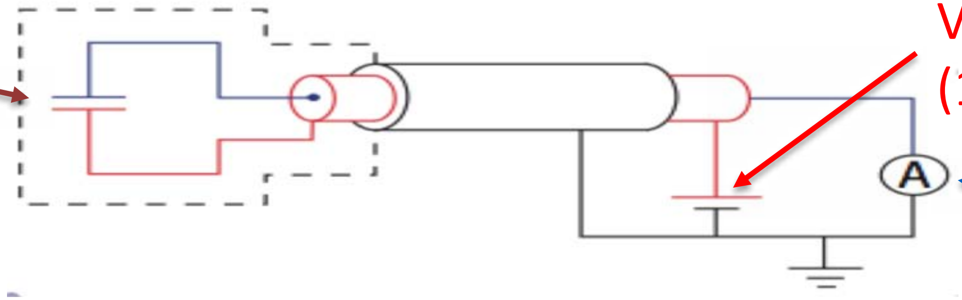
Ball-bonded gold wires



Shielding is completed by a thin Al cover

Miniature coaxial cables 2.5 m long + standard cables 25 m long

Shielded diamond sensor in package

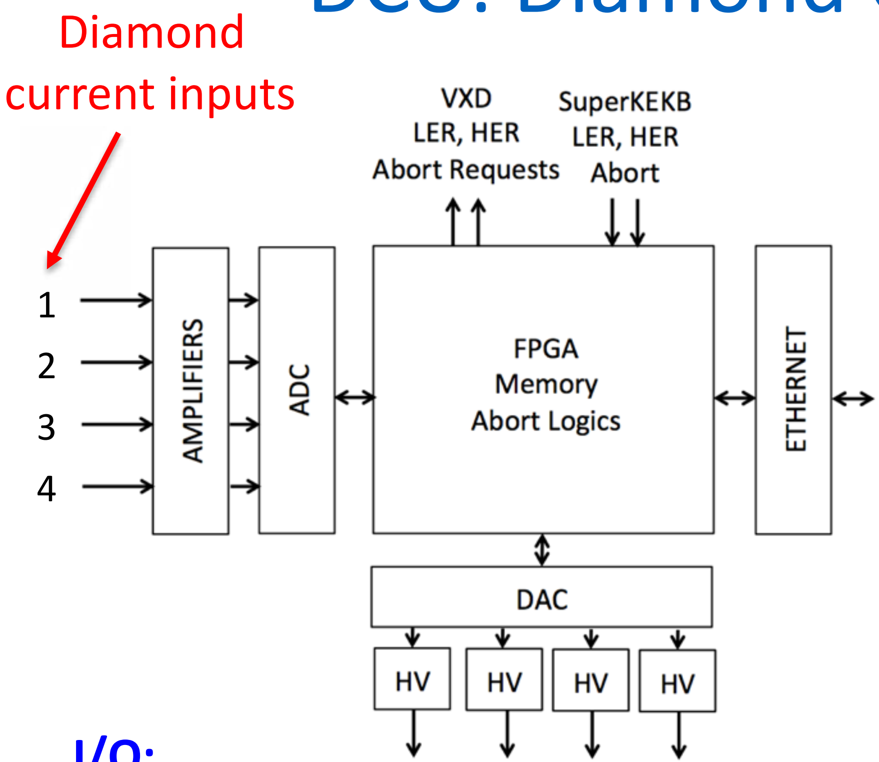


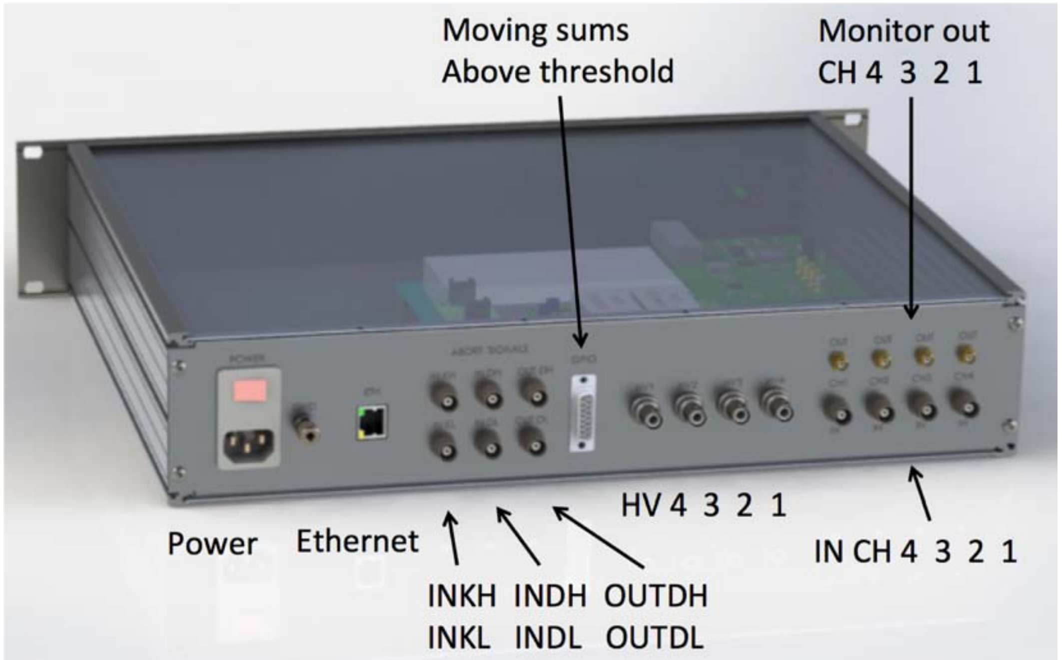
Voltage source (150÷500 V)

pA–meter

Readout Electronics

DCU: Diamond Control Unit (4 channels)





Back panel: connectors

I/O:

Ethernet

DAC + 4 HV modules: HV bias to diamond sensors

4 Amplifiers + ADCs: currents digitization at 50 MHz

FPGA:

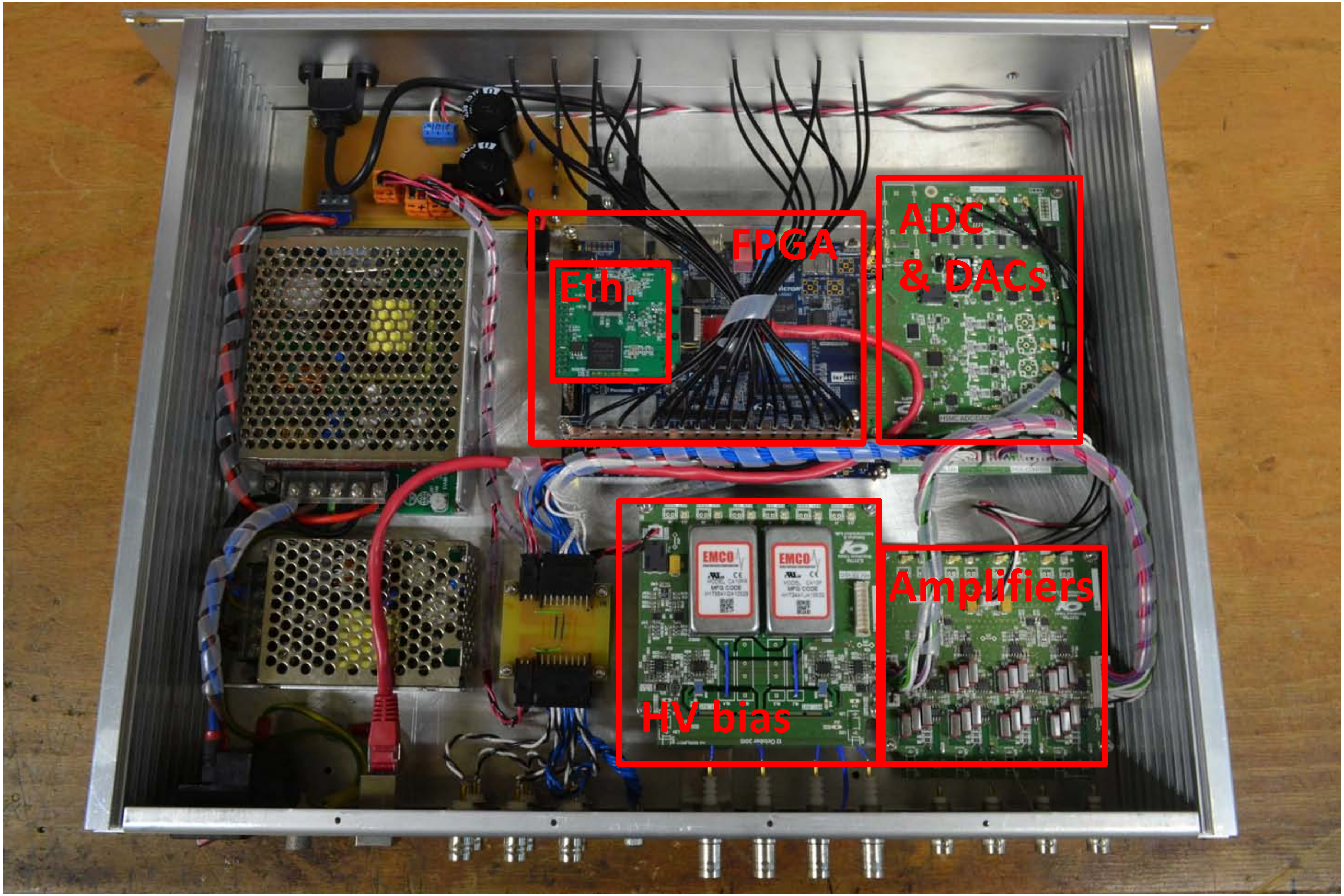
HV setting, Amplifier range selection, thresholds

Moving sums and abort logics at 100 kHz

Monitoring data at 10 Hz

Developed by
Elettra Sincrotrone Trieste ScpA

Diamond Current Unit



Diamond sensor test by Cividec

Cividec provided data sheets for each sensor, including:

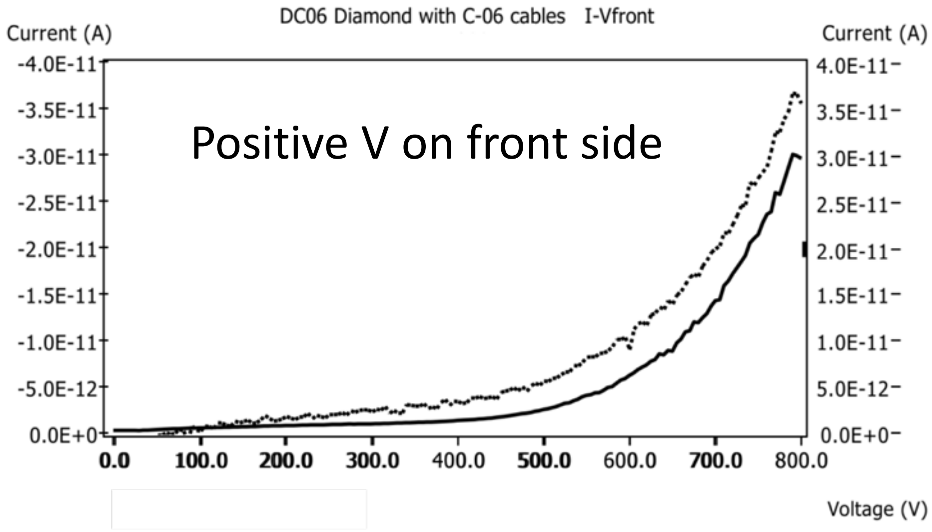
- Alpha-TCT
- *I-V* dark
- *I-t* stability with Beta irradiation (±100 V, −200 V, 10 min, +200V, 1h)

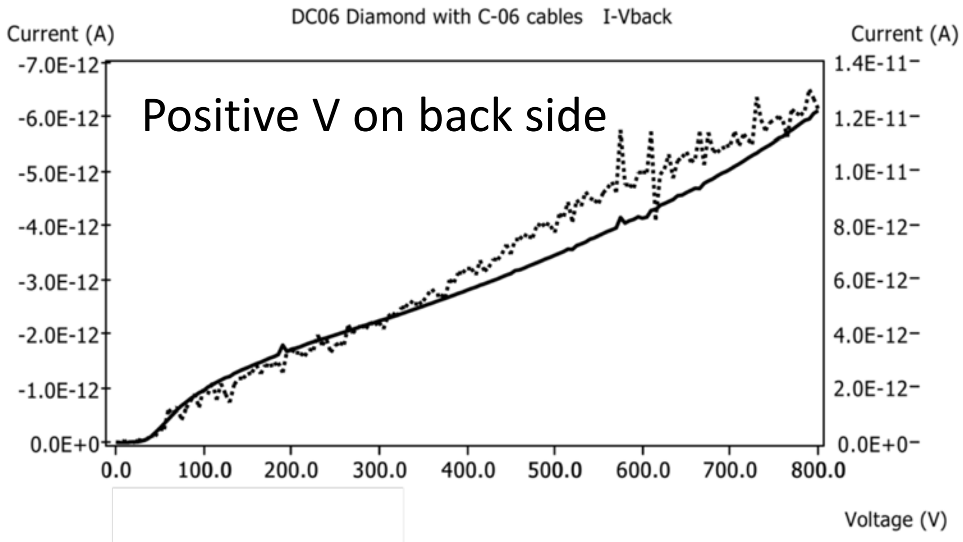
Our measurements – outline

- *I*-*V* dark current
- Alpha TCT
- Current stability under steady beta irradiation
- *I*-*V* with beta irradiation
- Current to dose-rate calibration:
  - *I* vs *d* (source distance)
  - Fluka simulation of *I* vs dose-rate
  - => Effective Gain factor

Dark *I-V* measurements

- Measured up to 800 V, both polarities



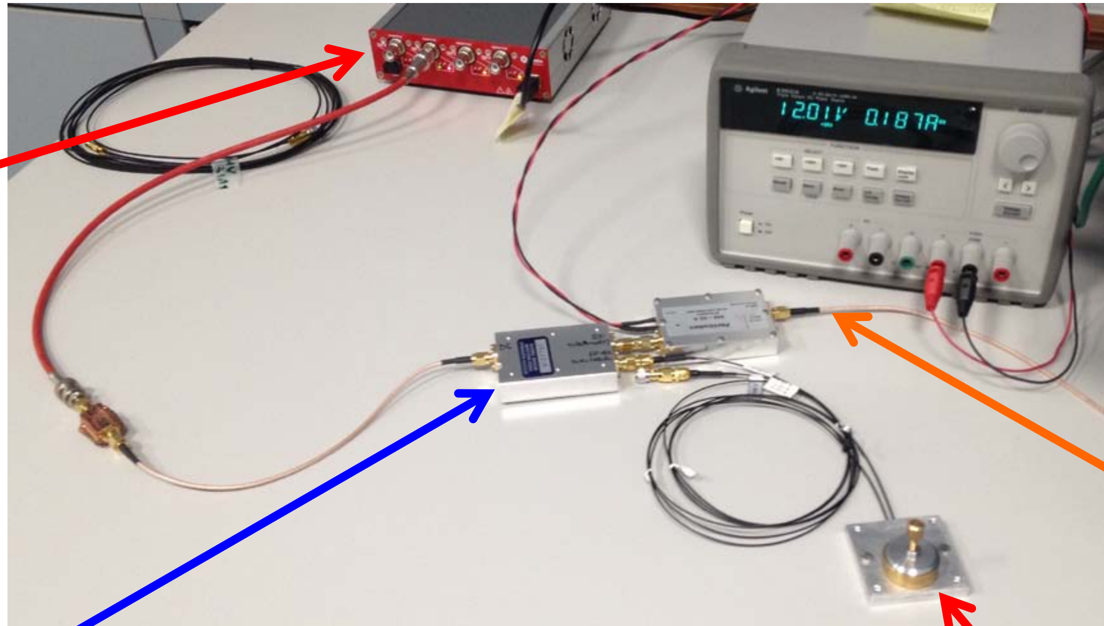


Large variations, but:

- measurement not slow enough to reduce memory effects
- all currents within a few pA at 500 V

Alpha TCT : Set-Up

HV Power Supply
(- 800 V ÷ + 800 V)

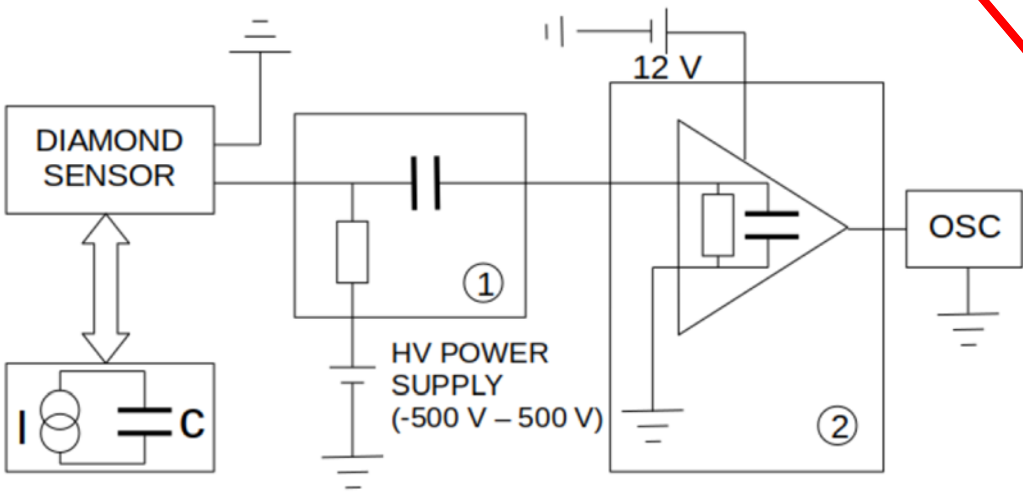


Power Supply for Amplifier (12 V)

Signal to Oscilloscope

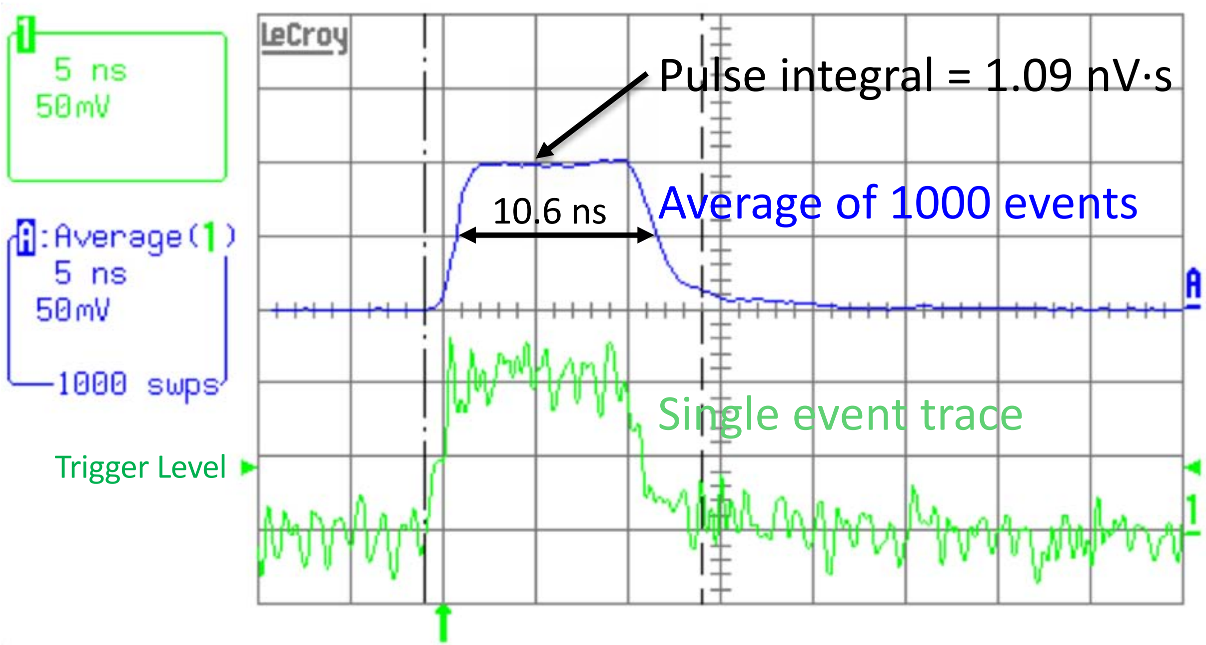
Holder of Diamond Sensor and Alpha Source

BIAS-T (1) and
AMPLIFIER (2)
(by Particulars d.o.o.)



Examples of TCT measurements - 1

Scope screenshot, + 200 V bias => hole drift



- E = 200 V/0.5 mm
  = 4.0 x 10^3 V/cm
- v_{drift} = 0.5 mm/10.6 ns
  = 4.7 x 10^7 cm/s
- μ_h = 1.2 x 10^3 cm^2/(V·s)
- Amplifier voltage gain:
  G_{amp} = 52 dB $\simeq$ 400
- Amplifier Z_{in} = 50 Ω

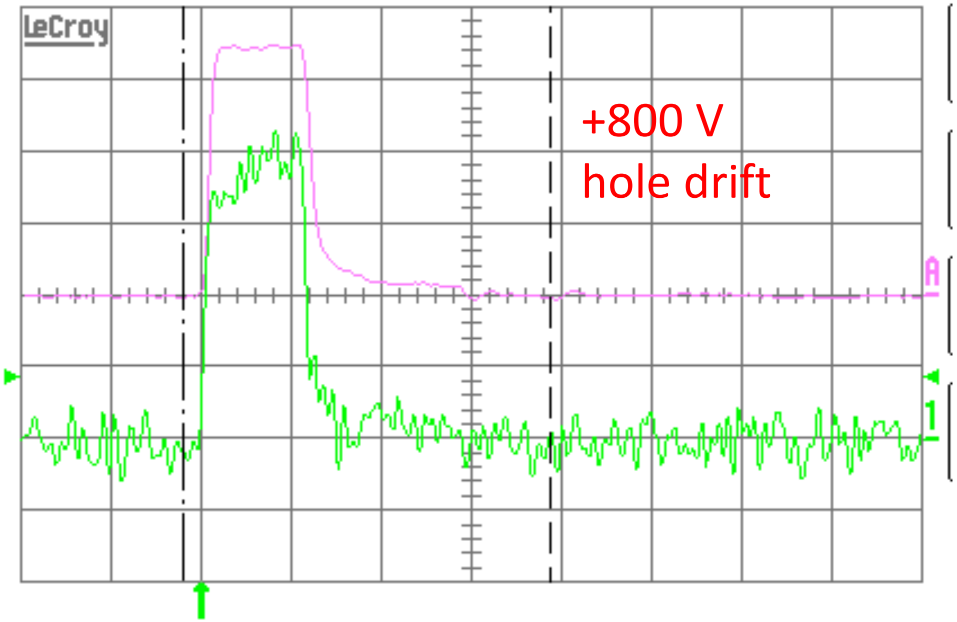
- $Q_{collected}$ = Pulse Integral/G_{amp} / Z_{in} = 5.45 x 10^{-14} C
- Q_{gen} = q_e · 5.17 x 10^6 eV / 13 eV = 6.36 x 10^{-14} C
- CCE = $Q_{collected}$/ Q_{gen} = 86%

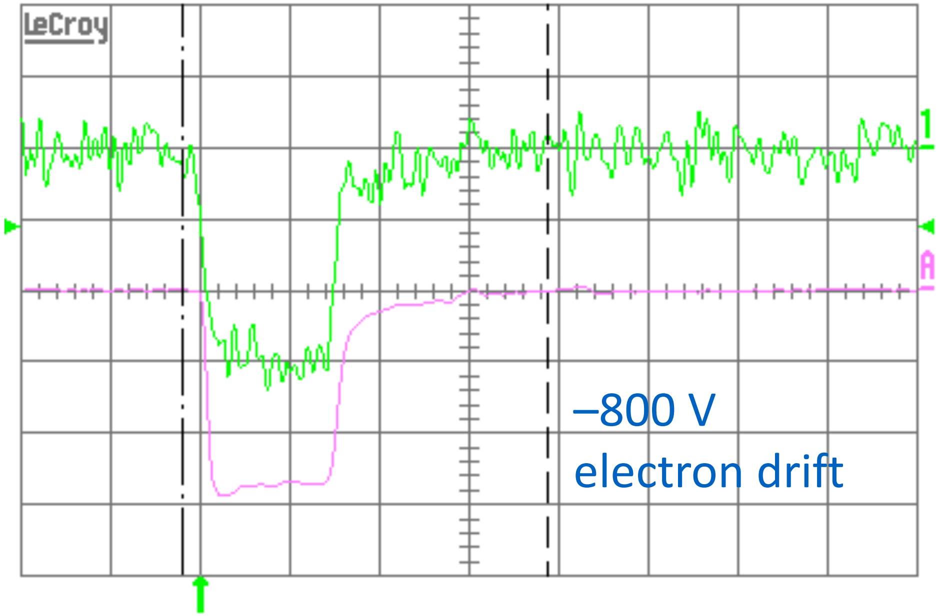
But there is some uncertainty in amplifier gain and Z_{in} ,
plus some attenuation (~ 1dB ?) from the 2.5 m long, thin cable

=> under investigation

Examples of TCT measurement-2

Measurement at +/– 800 V bias

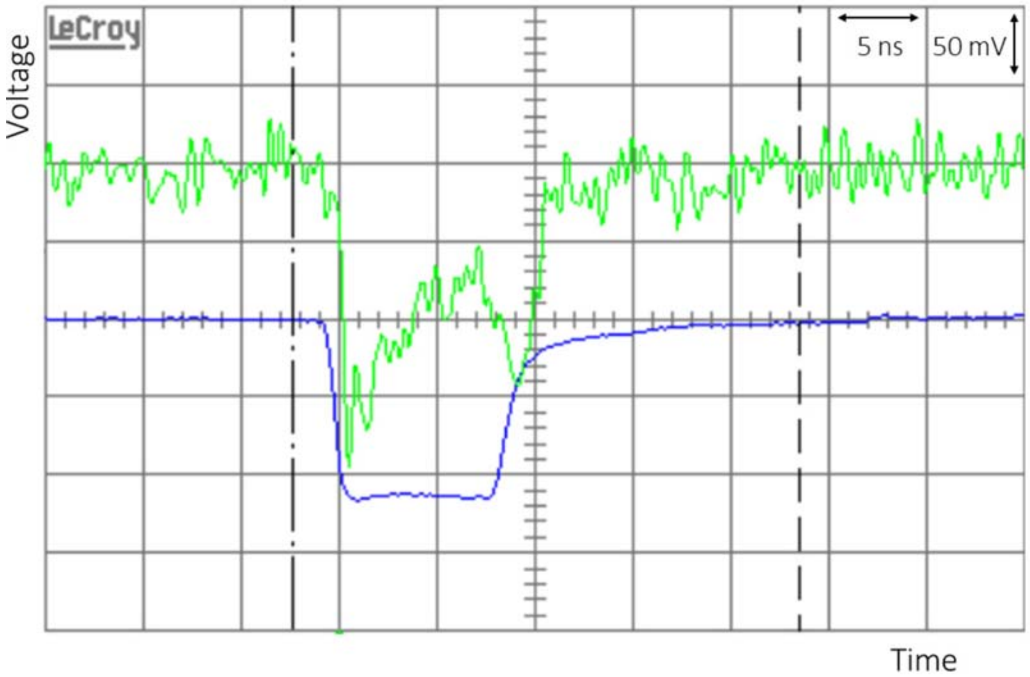




- Higher drift speed consistently obtained for holes
- Trailing edge has rather long tail
    - cannot be explained by carrier diffusion (much smaller effect)
    - possibly due to parasitics introduced by the sensor assembly

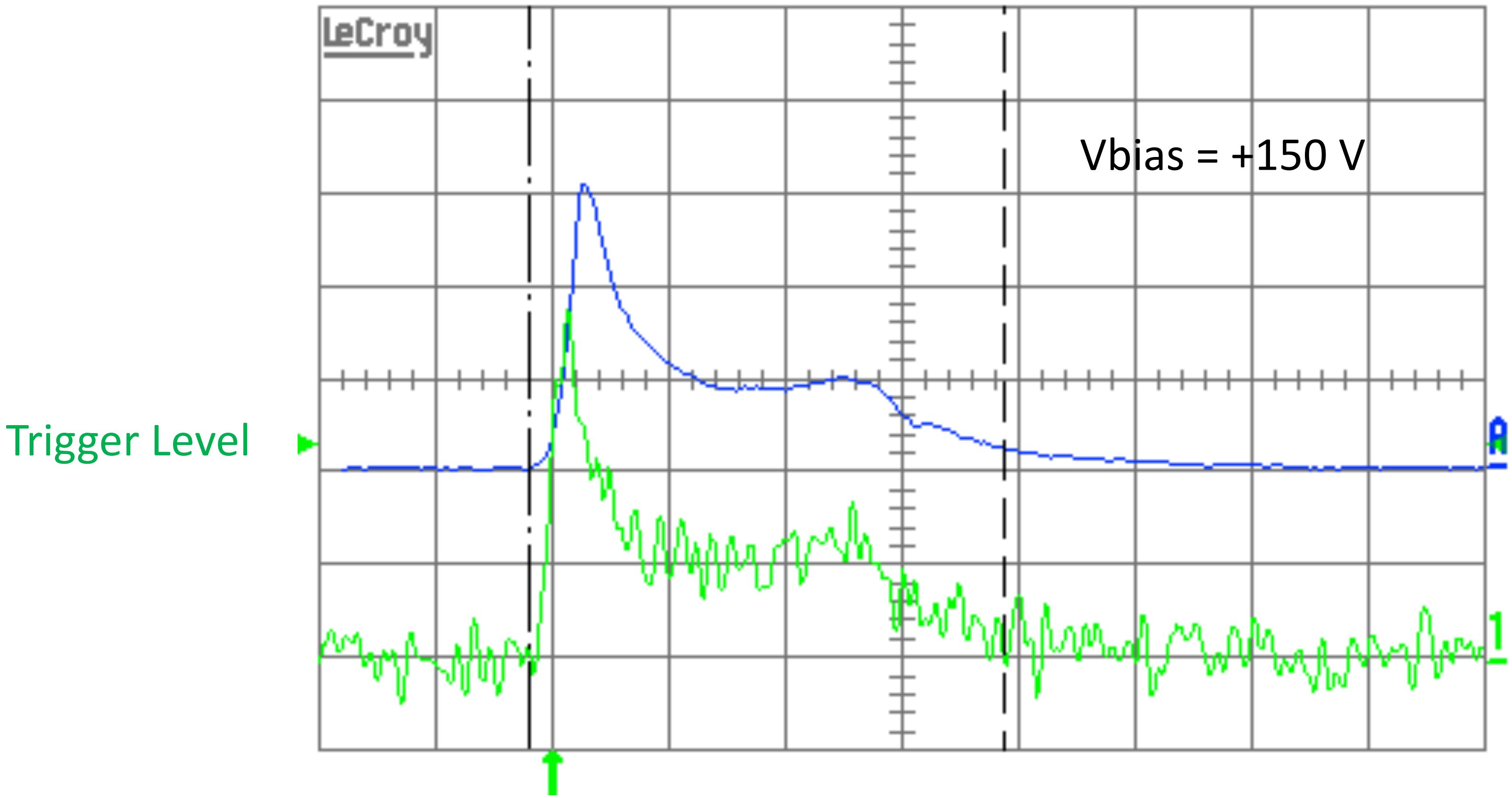
Examples of TCT measurement-3

- Some signals show spikes at the rising or falling edge, or both:



Examples of TCT measurement-4

- By rising the trigger level, we can single-out these signals

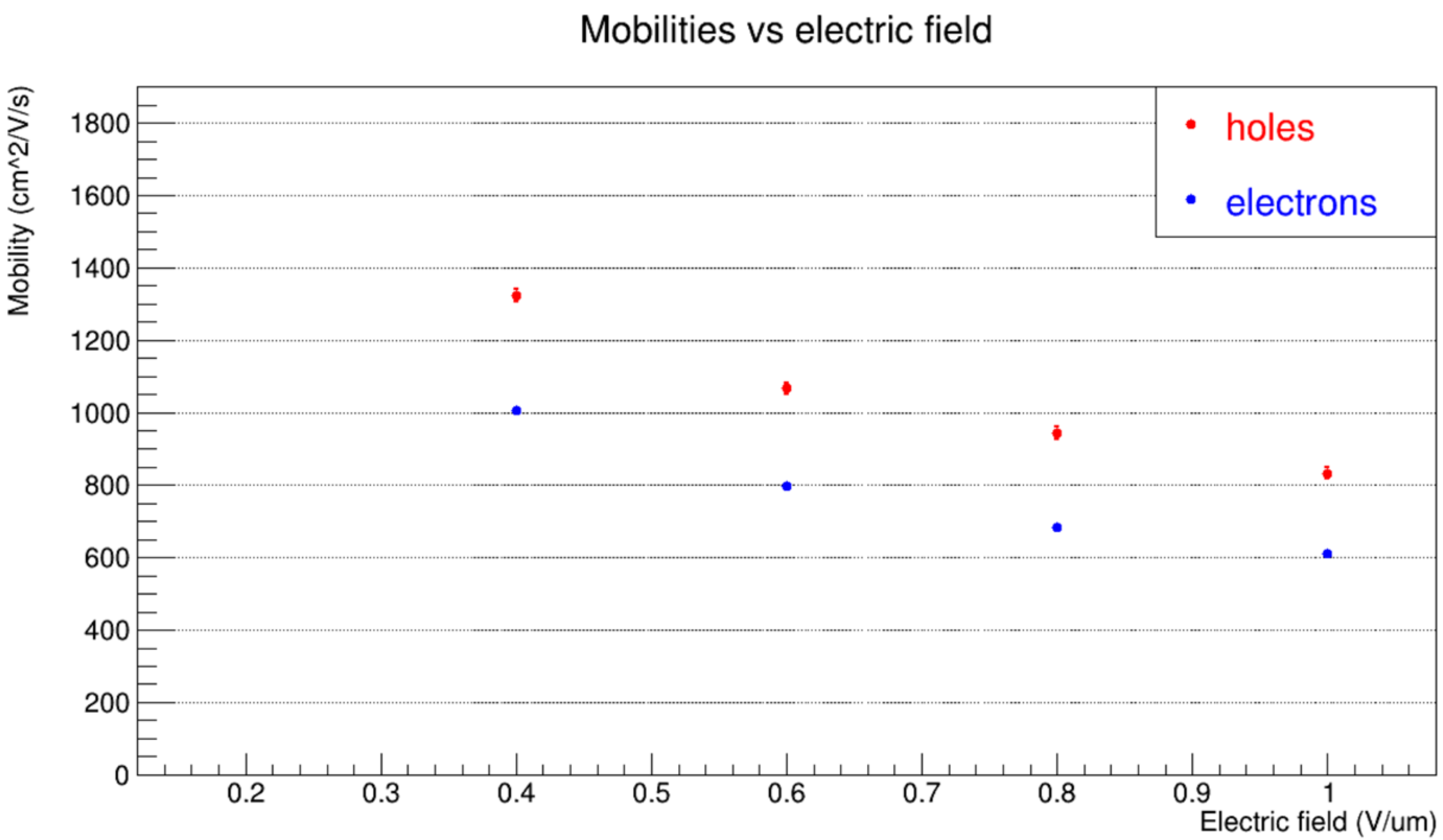


Possible explanation:

- Charge build-up in localized areas and close to the surfaces ?
- Edge effects due to insufficient collimation of alpha particles ?

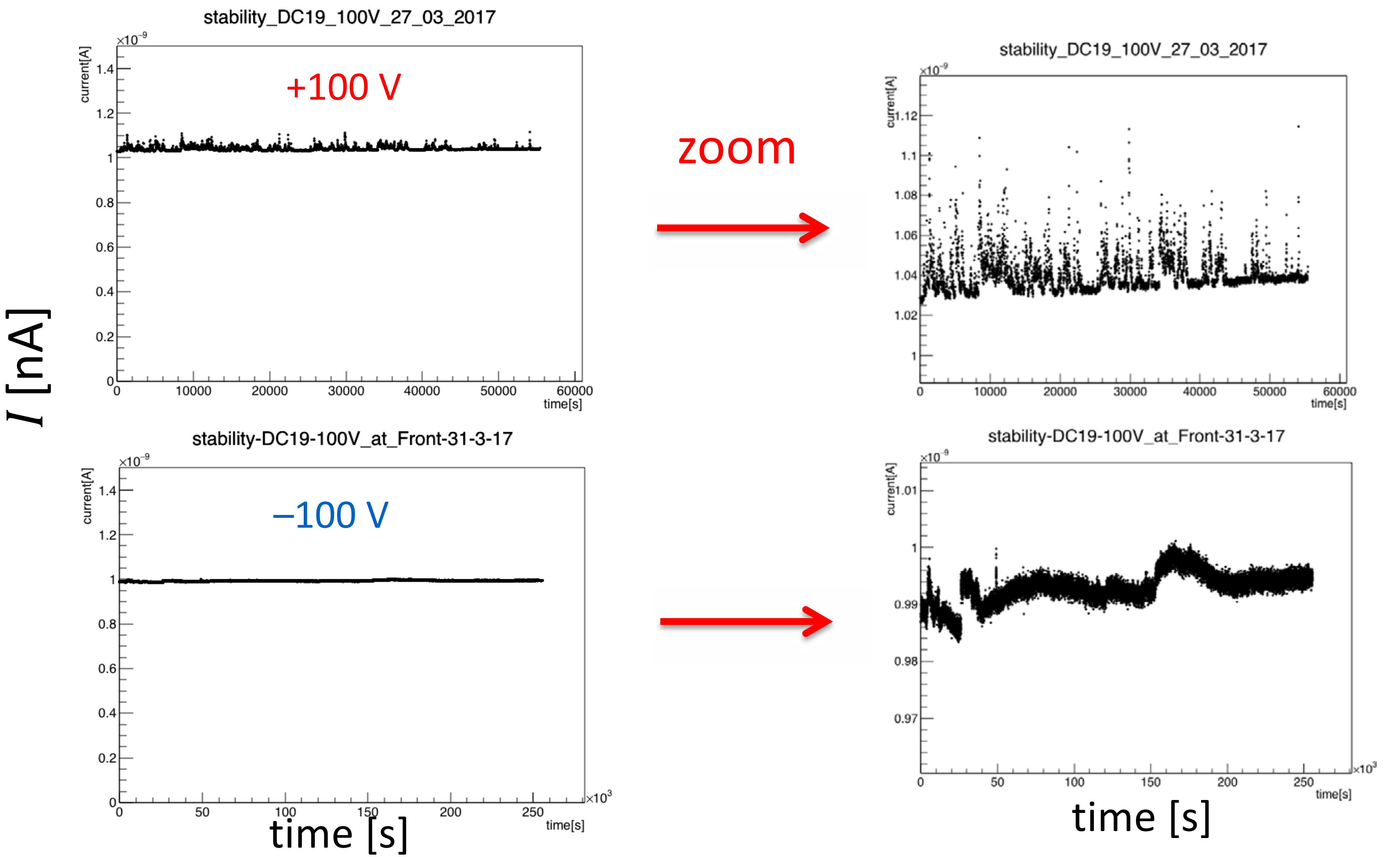
Carrier Mobilities from TCT

- From the TCT measurements we obtain the 'field-dependent mobilities'



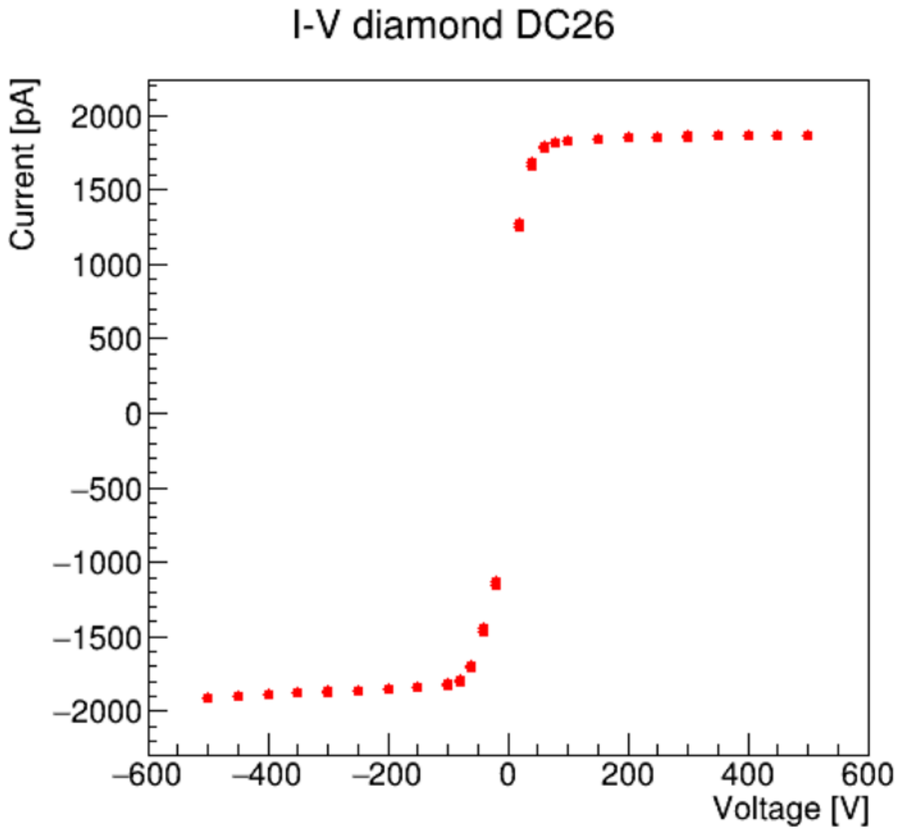
Current stability under beta irradiation

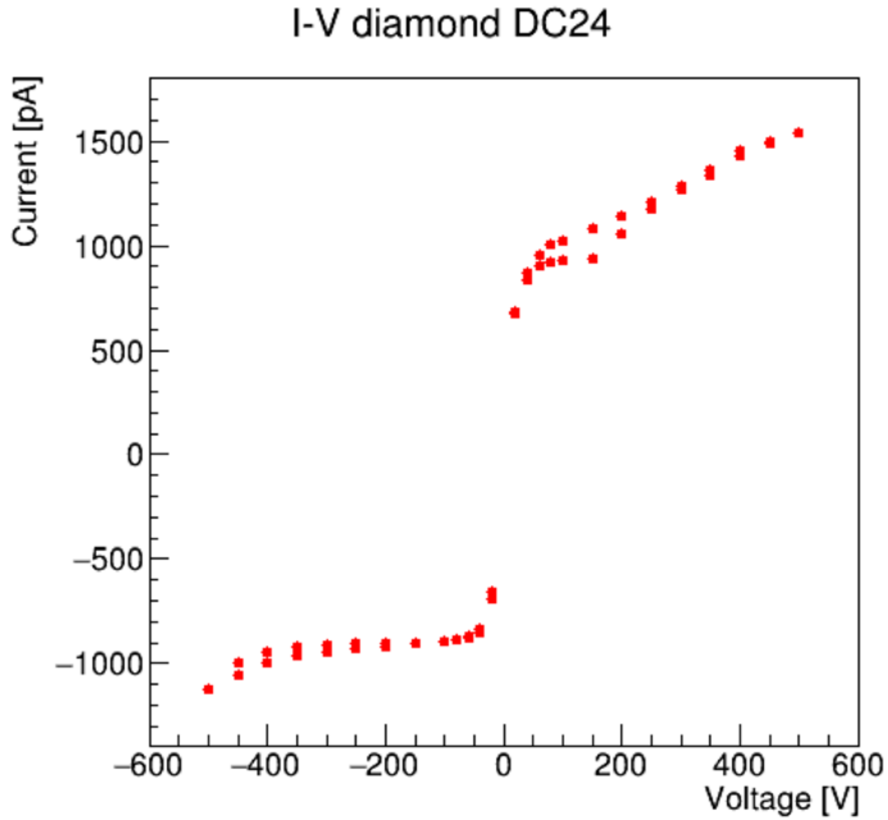
The current is measured vs time at +/- 100 V bias, for times of ~ 1 day, with beta irradiation giving ~ 1 nA current.
Results are used to choose the bias polarity to be used for each sensor.



I-V curves under beta irradiation

- Measured from 0 to ± 500 V and back to 0 V
- Source at short distance to the sensor (~ 2 mm)





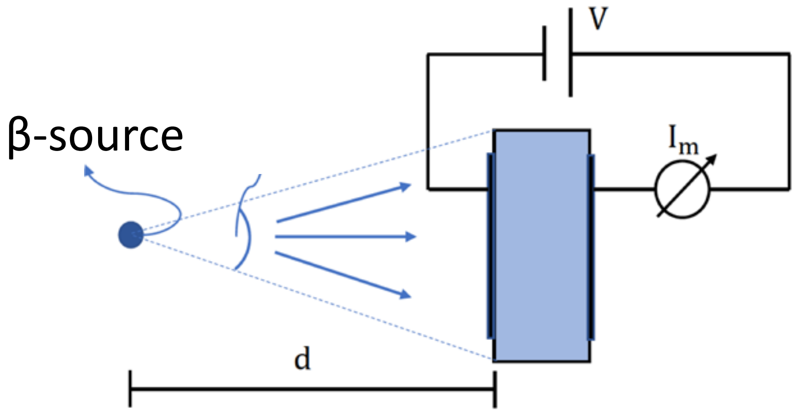
- Some sensors show lack of saturation and hysteresis effects
- These curves are also used to select the bias polarity for each sensor

Dose-rate vs current calibration

Obtained with beta irradiation, by:

- Measuring the current versus source-detector distance *d*, at ± 100 V bias
- Simulating with FLUKA the energy deposited in the sensor per unit time, and converting it into current, assuming $\varepsilon_{e\text{-}h} = 13$ eV
- Comparing the two currents, to get an 'effective' gain *G*, accounting for both the photoconductive gain and a possible defect in CCE
- Relating the simulated energy deposit to dose, using the sensor mass

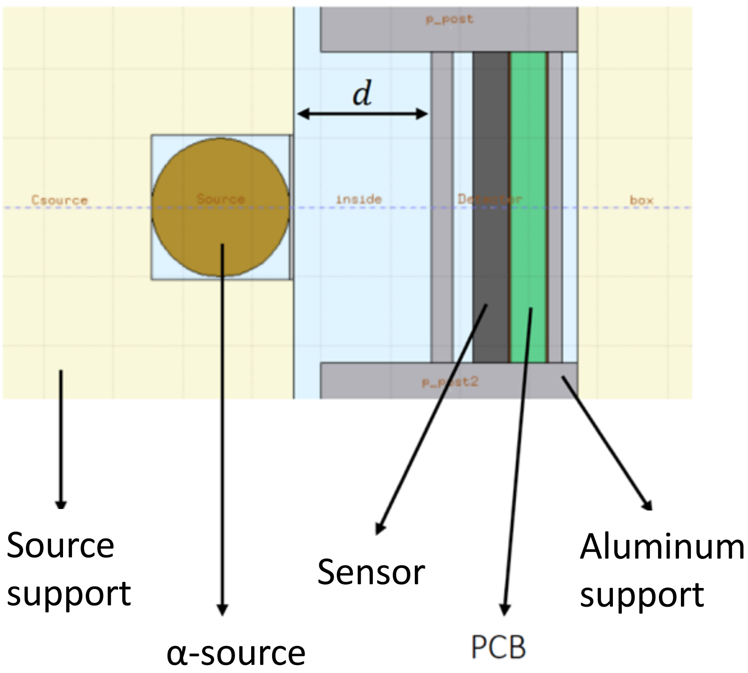
Measured and simulated currents



Measured current I_m vs distance,
≈ point-like source:

$$I_m(d) \propto \text{solid angle}$$

Simulated energy deposit (dose rate)
⇒ Simulated current I_s vs distance
⇒ assuming gain $G = 1$



α-source

Average energy deposit per emitted β electron

$$I_s(d) = \frac{\langle E(d) \rangle}{\varepsilon_{e-h}} A q_e$$

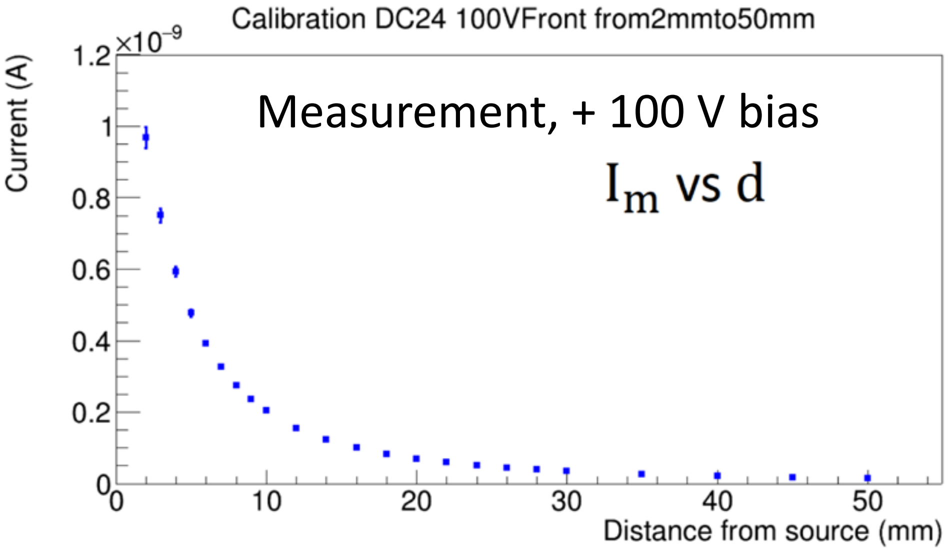
Source activity (3.2 MBq)

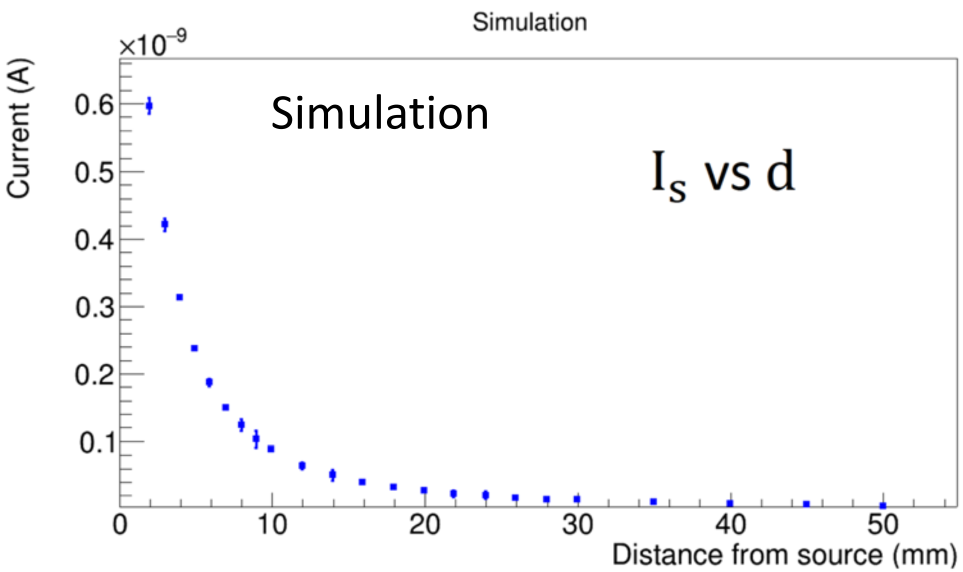
elementary charge

Average energy deposit per generated e-h pair, assumed to be 13 eV

Current to Dose-Rate Conversion

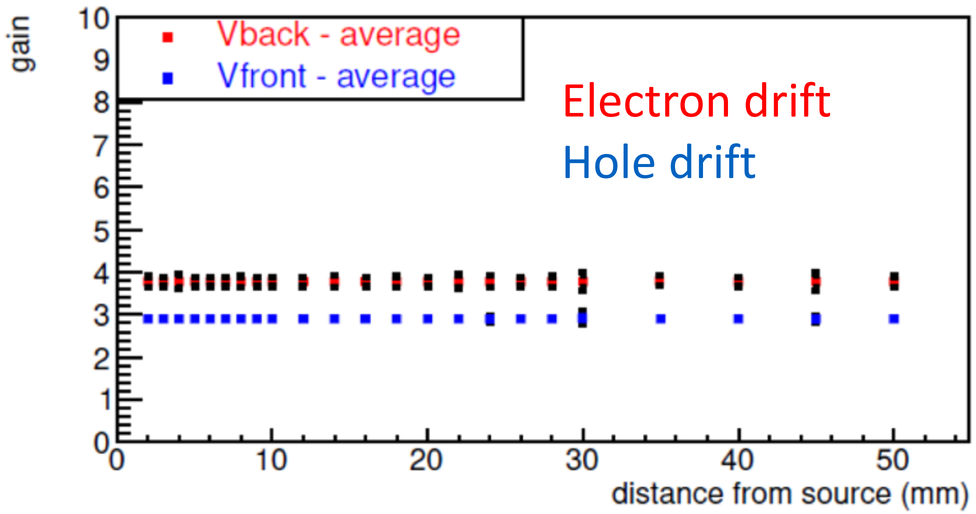
Current is measured vs source-detector distance and confronted with simulation





'Effective' photo-conductive gain G (includes also possible CCE defect):

$$\frac{I_m(d)}{I_s(d)} = G > 1$$

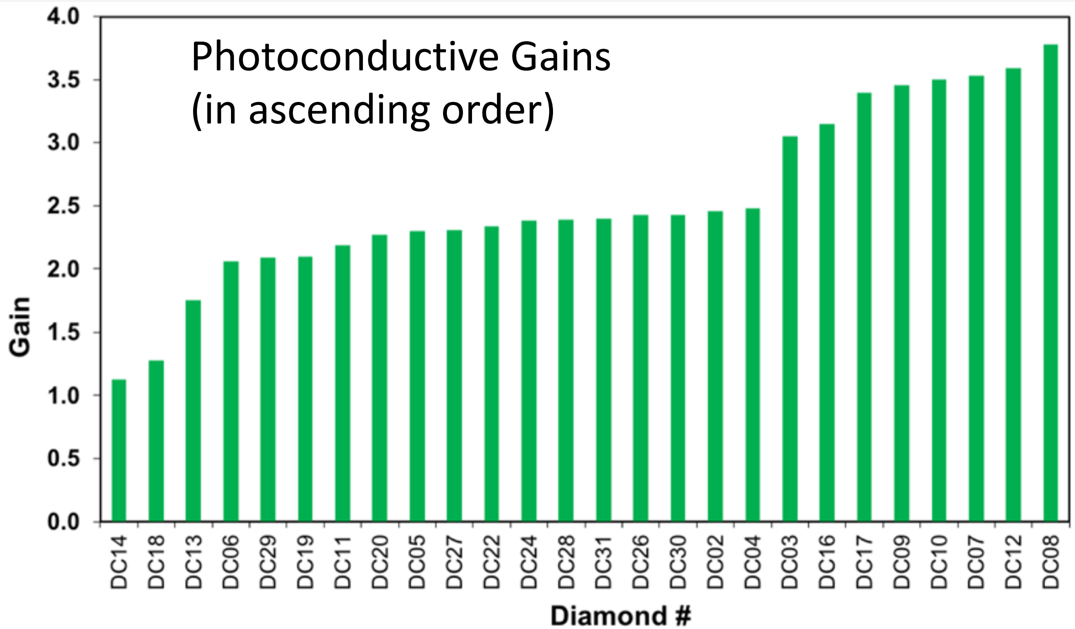


Conversion: current => dose-rate:

$$\frac{dD}{dt} = \frac{F}{G} I_m \qquad F = \frac{\varepsilon_{e-h}}{m} \frac{1}{q_e}$$

sensor mass

Calibrations summary on 26 detectors

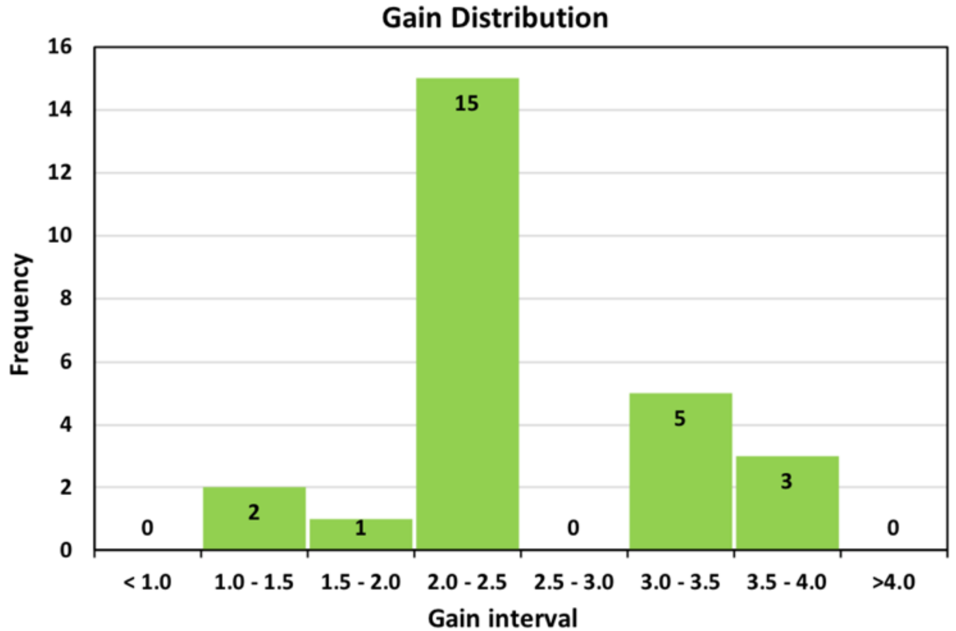


- F = 36.5 (mrad/s)/nA
- G ≈ 2 – 3

(very approximately)

$$\frac{dD}{dt}\left[\mathrm{mrad}/s\right] \approx$$

$$\approx 10\left[\frac{\mathrm{mrad}/s}{\mathrm{nA}}\right] \times I_m\left[\mathrm{nA}\right]$$

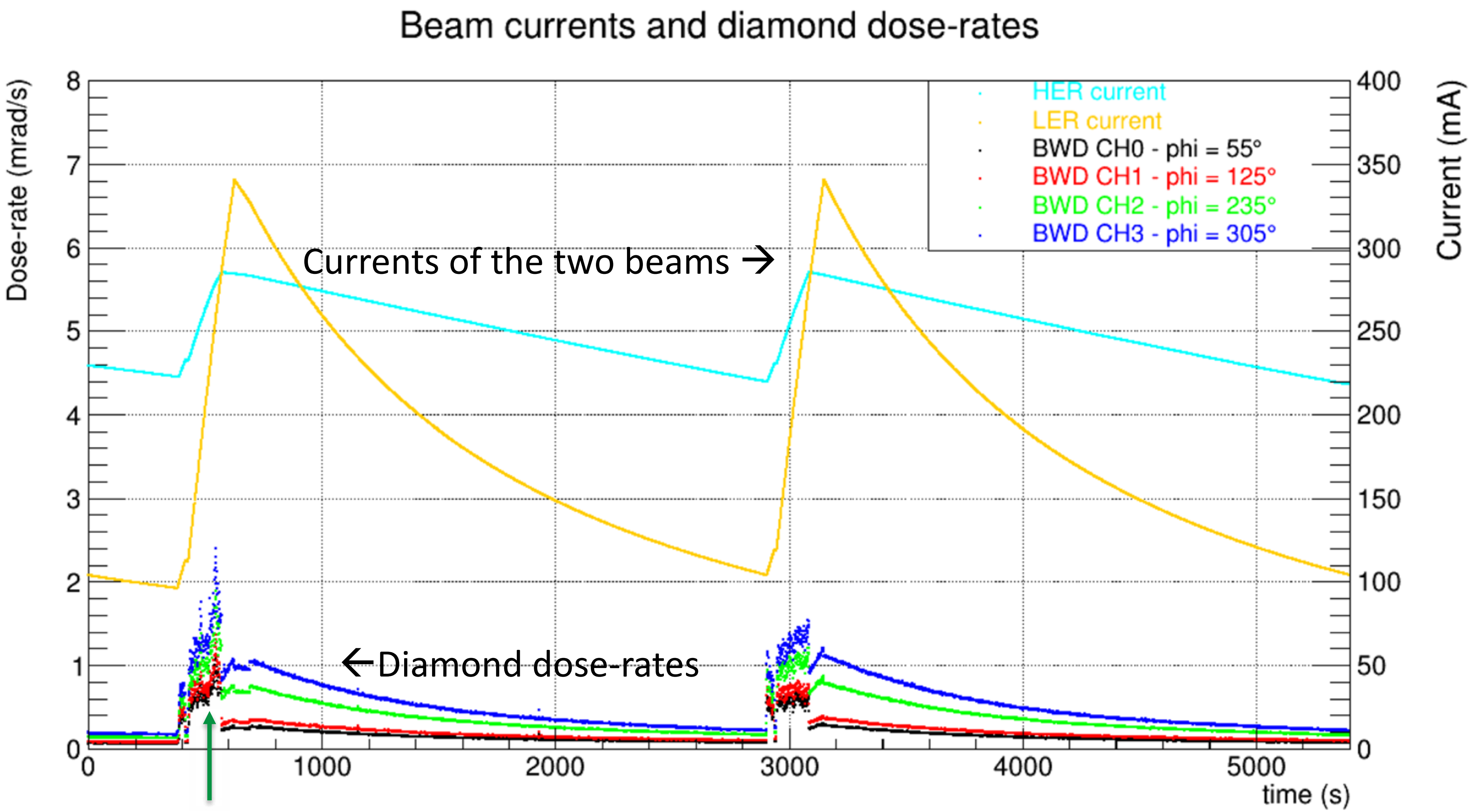


Temporary estimate of systematic relative uncertainty on F/G: about 17%
(under study)

Origin of systematic uncertainty	$\delta G/G$ [%]
Source-diamond sensor distance	10
Diamond sensor active volume	10
Diamond sensor priming or pumping	5
Source activity	7
FLUKA simulation statistics	1
HV reproducibility	1
Combination in quadrature	17

Example of diamond results at SuperKEKB

Correlation between beam currents and diamond dose-rates during Phase 3 commissioning of SuperKEKB and Belle II



The spikes from diamonds are due to transient increases of radiation during injections

Conclusions

- A relatively large number of diamond sensors has been procured, assembled and characterized for radiation monitoring in Belle II experiment.
- The application required measuring sensor currents, and a very compact sensor package, with long, thin cables.
- Characterization emphasis was on measurement of radiation-induced current, not on single-particle signals, for which the sensor assembly was not well suited.
- More detailed investigations of sensor characteristics are planned, together with a comparison with SiC sensors.