Synthetic Diamond Radiation Detection

Doctoral Research Project

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&
Diamond Detectors Ltd

Outline

- The wonders of diamond
  - The pros and cons of diamond vs. silicon
- Introduction to diamond radiation detectors
  - Basic principles of operation, different types of diamond
- Measuring the quality of your diamond
  - Different types of synthetic diamond and how they differ
- Building an amplifier to get the most out of your diamond
  - Spectroscopy at very high count rates
- Future work here at BNL

Amazing, paradoxical diamond

- Diamond is amazing!
  - Hardest material in the world
    - Grinding & cutting, anvil cells for extreme pressures
    - Also means radiation hardness for detectors → beam monitors, tracking etc
  - Best thermal conductor in the world, also great thermal tolerance
    - No need for heat spreaders, can operate *hot*
  - Amazing insulating properties > 1GV/m before breakdown!
    - Can operate at very high fields
  - Very high charge carrier mobilities and saturation velocities
    - Doesn't conduct, but when it does, it really does!
  - Almost transparent to X-Rays so good for synchrotron windows
    - Not to mention myriad other synchrotron applications – just ask John Smedley
  - Too many others to list but includes…
    - Tissue equivalence for dosimetry, NEA for electron amplification, solar blind pixel detectors, fast operation for spectroscopy, high-temp for drilling, quantum information with nitrogen vacancies, high frequency FETs, high voltage switching, etc…

Properties rarely seen together!

Properties almost mutually exclusive!

Semiconductor Radiation Detection 101

- Semiconductors can be used to detect radiation
  - Measured signal is a charge pulse from the movement of excited charge carriers

- Factors that limit performance
  - Noise - Thermally activated (intrinsic) charge carriers
  - Noise - Capacitance of the detector
  - Pulse shape due to the semiconducting medium

- For traditional silicon detectors
  - Many free charge carriers at room temperature → need P-N junctions to deplete
    - Non-trivial fabrication (and utilisation)
  - (Relatively) slow charge collection
  - (Relatively) high capacitance (for a given geometry)

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- For diamond detectors
  - ~ No free charge carriers at room temperature
    - Trivial fabrication and utilisation (just metalise and plug it in!)
  - Fast charge collection → high count rates possible
  - Low capacitance → fast, low noise electronics

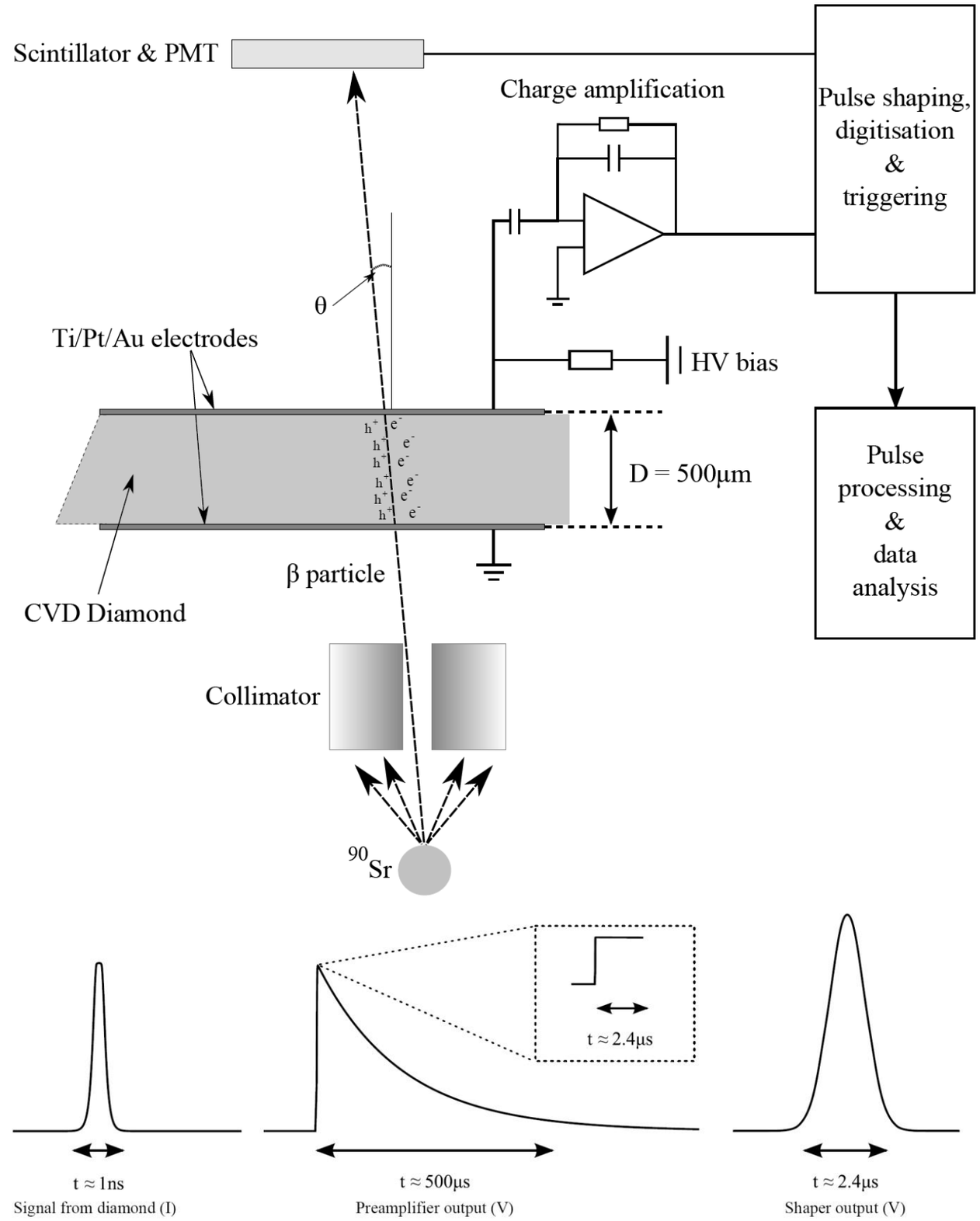
Diamond as a semiconductor

- Many interesting properties make it an excellent detector medium
  - ~ No free charge carriers at room temperature
    - Large band gap → Very few thermally generated charge carriers
      → Extremely low leakage current
      → Low noise detectors
  - Low dielectric constant
    - Low capacitance → Low noise detectors
  - Very fast signals
    - Ability to perform high count-rate spectroscopy
  - Insensitive to visible light
    - No need for light shielding
  - Extremely radiation hard

Property	Diamond	Silicon
E_g (eV)	5.5	1.12
μ_e (cm^2 V s^{-1})	1800	1500
μ_h (cm^2 V s^{-1})	1200	450
e/h energy (eV)	13	3.6
Displacement (eV)	43	13-20
Density (g cm^{-3})	3.52	2.33
Rad length X_0 (cm)	12.2	9.4
Dielectric constant	5.7	11.9
Max E-Field (V/um)	1000	30
Resistivity (Ω/cm)	$>10^{15}$	10^5 - 10^6

Semiconductor Radiation Detection 101

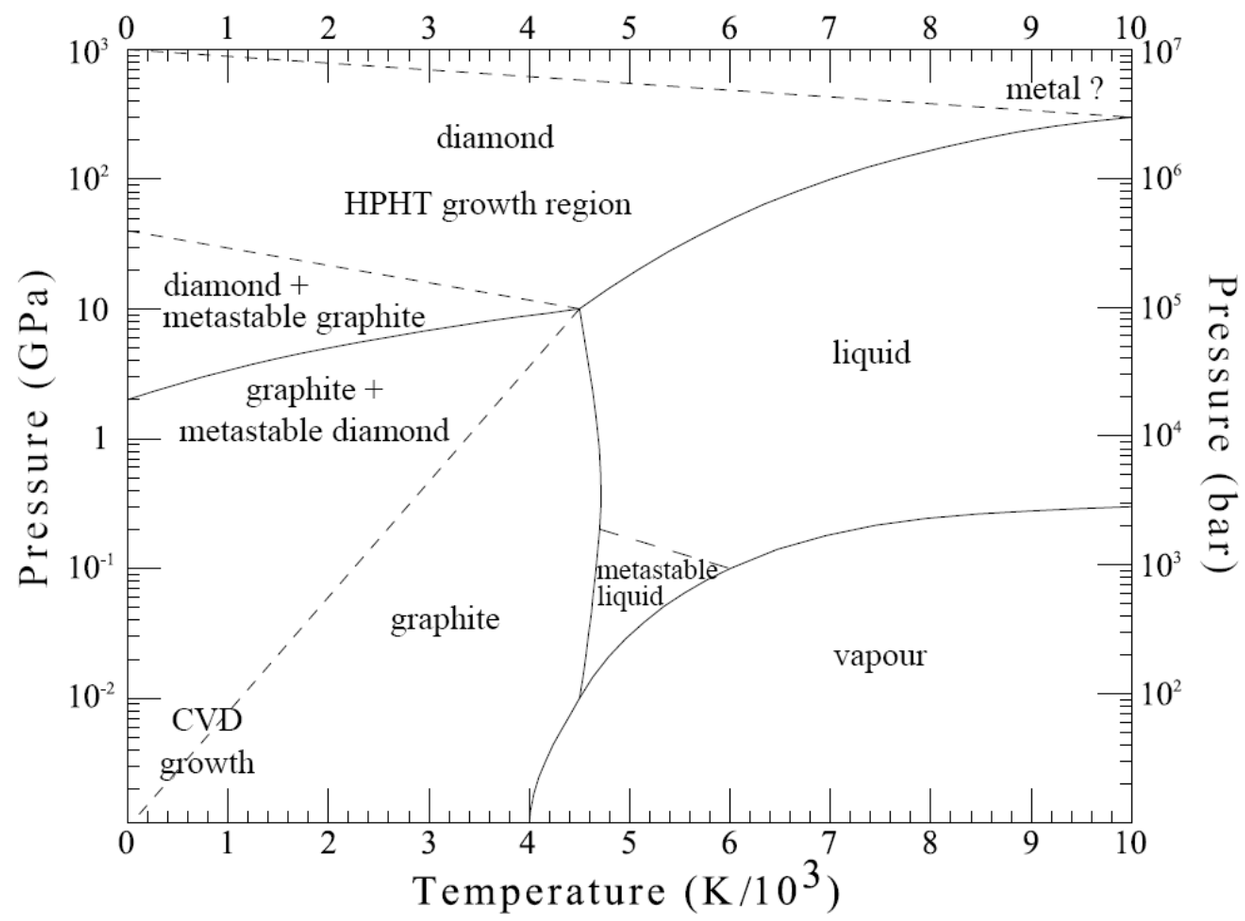
- Radiation leaves ionisation trial in the diamond
  - Electrons excited from valence band into conduction band
    - Free charge carriers are generated
    - Drift → signal
- Applied electric field moves the generated charges towards electrodes on the diamond's surface
  - But… trapping!
- Charge pulse is detected by a charge sensitive amplifier then shaped
- Readout electronics register digitise the output voltage pulse
  - Pulse height and timing information is extracted



Fabrication of Diamond

- Can't dig them out of the ground
  - "Every diamond is unique"
  - Unique means great for jewellery, but bad for science!

- It's not easy, but diamond *can* be synthesised
  - Two methods exist, HPHT and CVD



- HPHT is no good for making detectors of reasonable size

- CVD is the way…

CVD Diamond growth

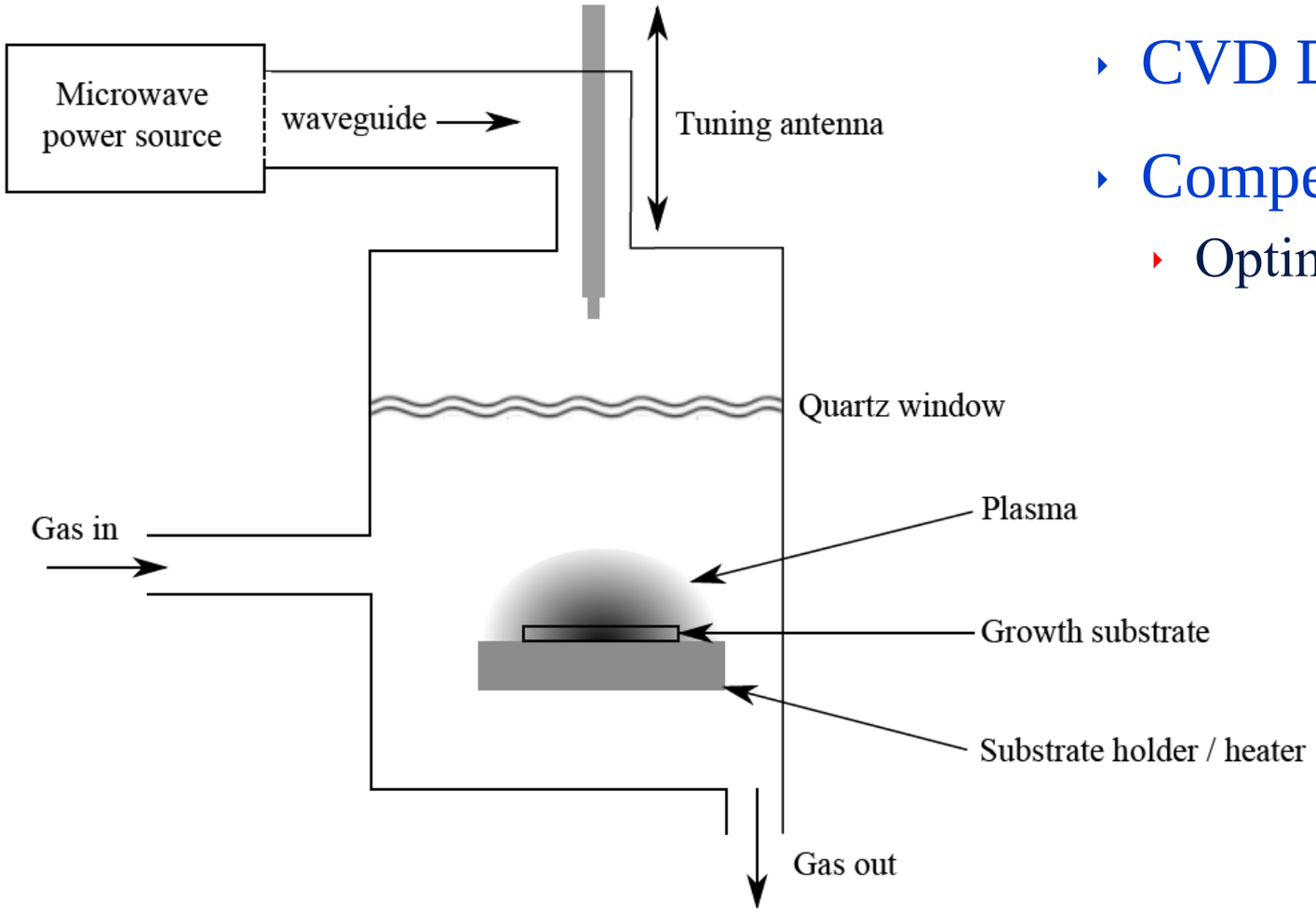
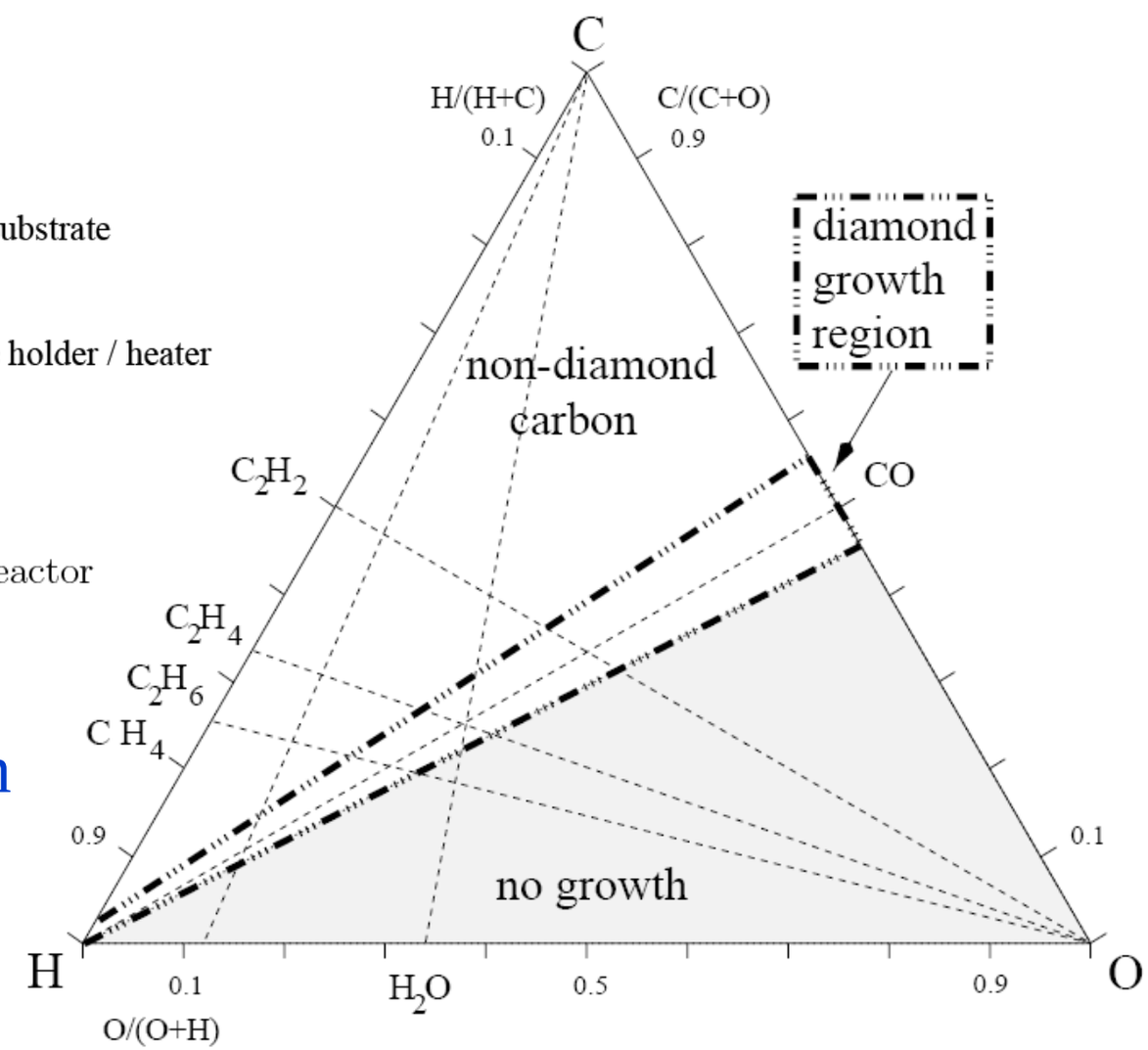


Diagram of a microwave plasma chemical vapour deposition reactor

- CVD Diamond growth is non-trivial
- Competing processes – hard to optimise
  - Optimisation proceeds via “black magic”



- Industrial secrecy, minimal competition
  - High cost and poor availability
  - No ability to control growth parameters

Types of CVD Diamond

Single Crystal CVD Diamond

- Homoepitaxial growth
  - Diamond on diamond
- Full charge collection
  - → Large signal
  - → Best signal to noise ratio
- Signal amplitude constant in time
- Maximum detector area
  - ~ size of a penny
- Extremely expensive!

Polycrystalline CVD Diamond

- Heteroepitaxial growth
  - Diamond on silicon
- Only partial charge collection
  - → Smaller signal
  - → Worse signal to noise ratio
- Signal increases with irradiation
- Maximum detector area
  - ~ size of a DVD!
    - (*in theory*)

- Slightly less expensive…
  - But still not cheap!

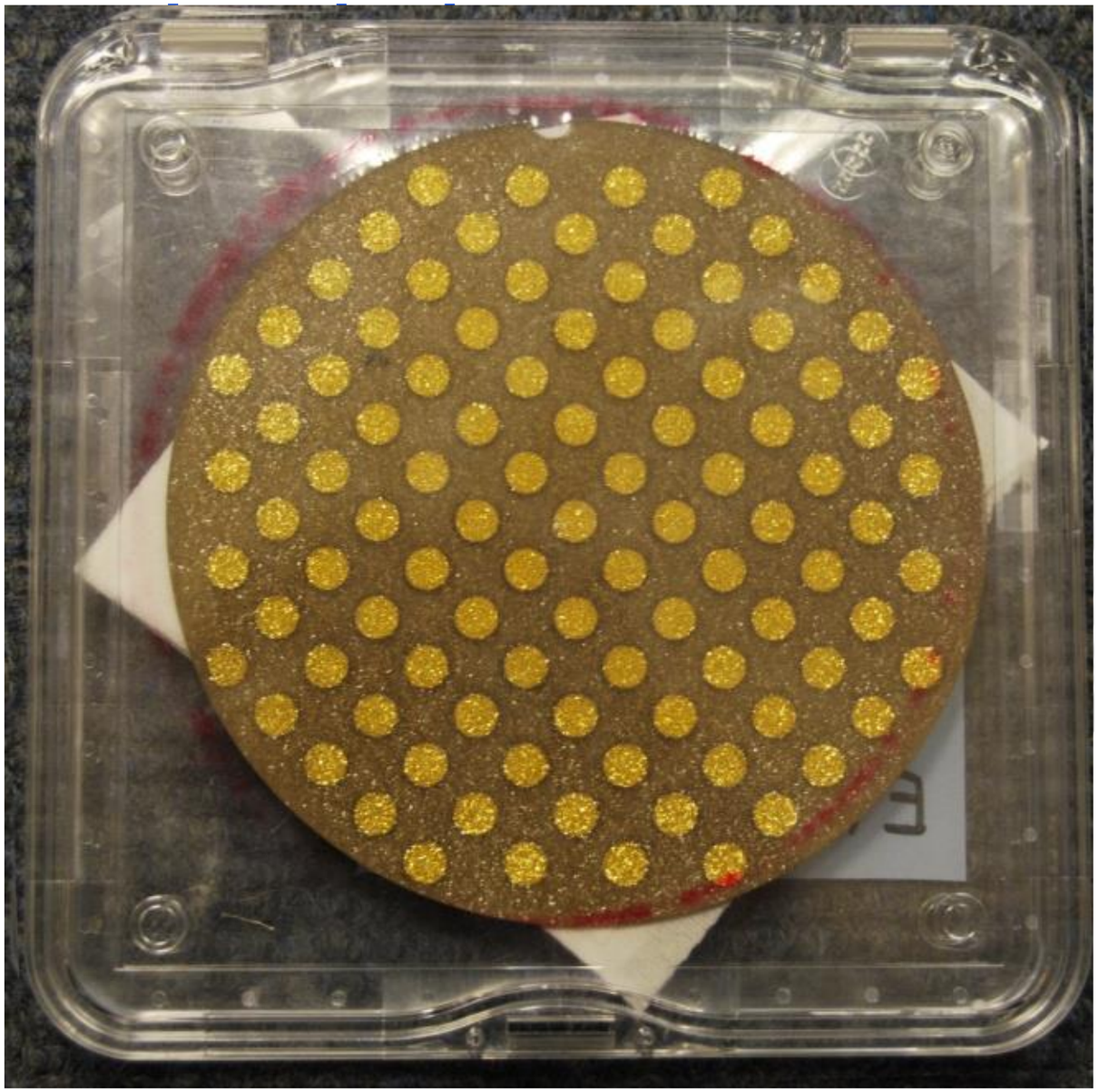
Detector size and quality

Single Crystal CVD Diamond

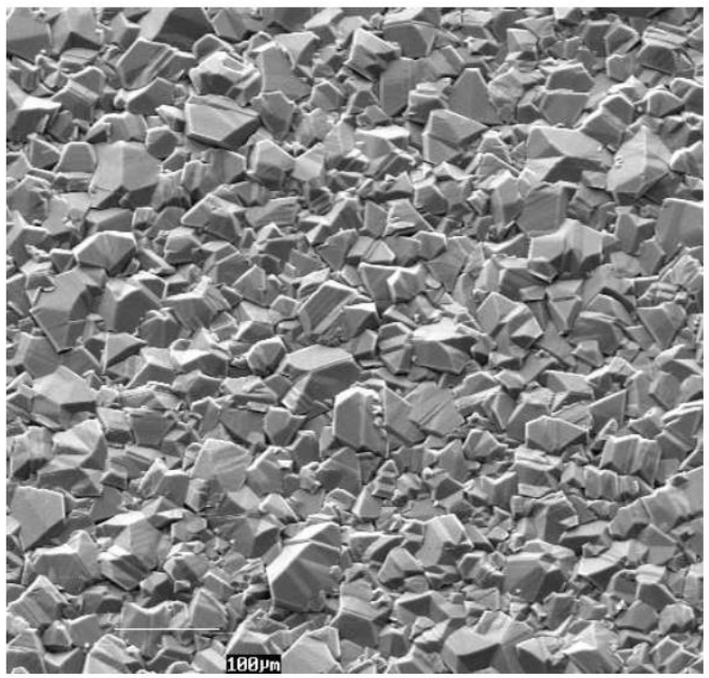
- Quality: ~ 100%
  - No dependence on thickness

- Size: cannot be grown much larger than a penny
  - Limiting factor is the size of the largest available seed crystal
    - It (currently) has to be a diamond!

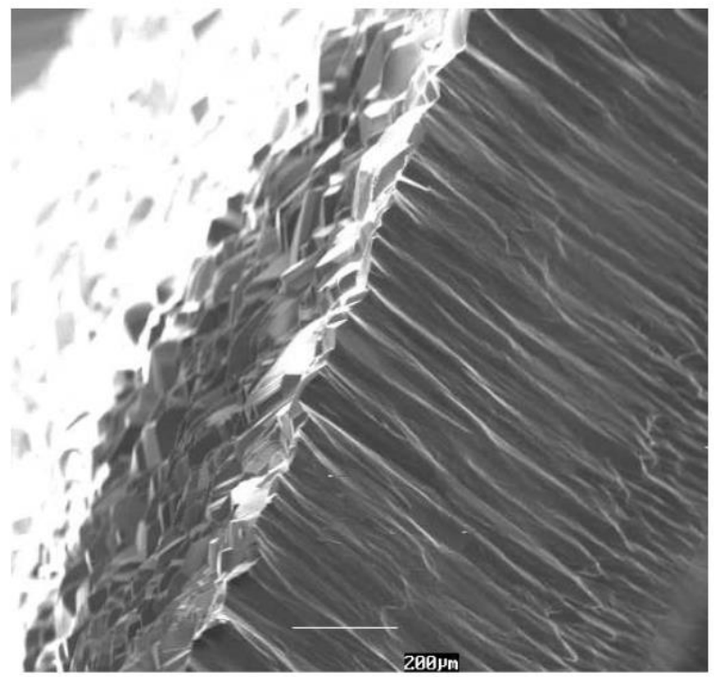
Polycrystalline CVD Diamond



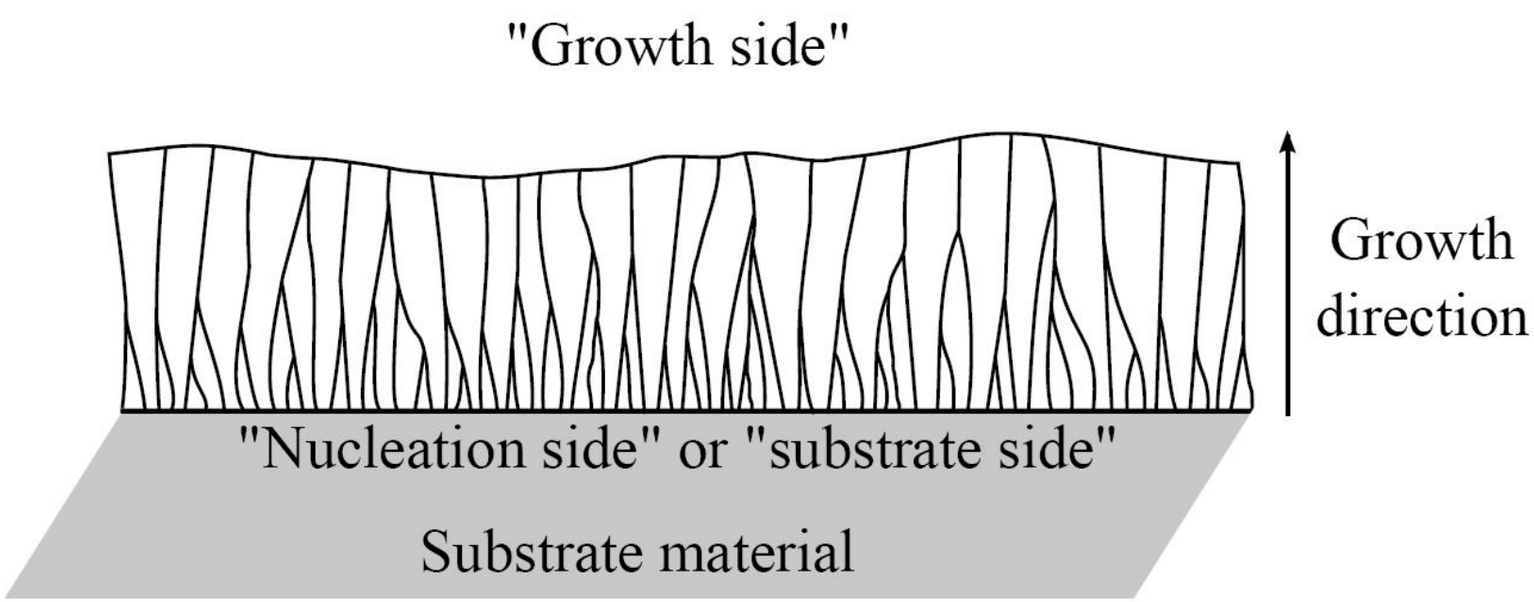
Grain Structure in Polycrystalline Diamond



(a) Scanning electron microscope image of the growth side of a polycrystalline diamond film.



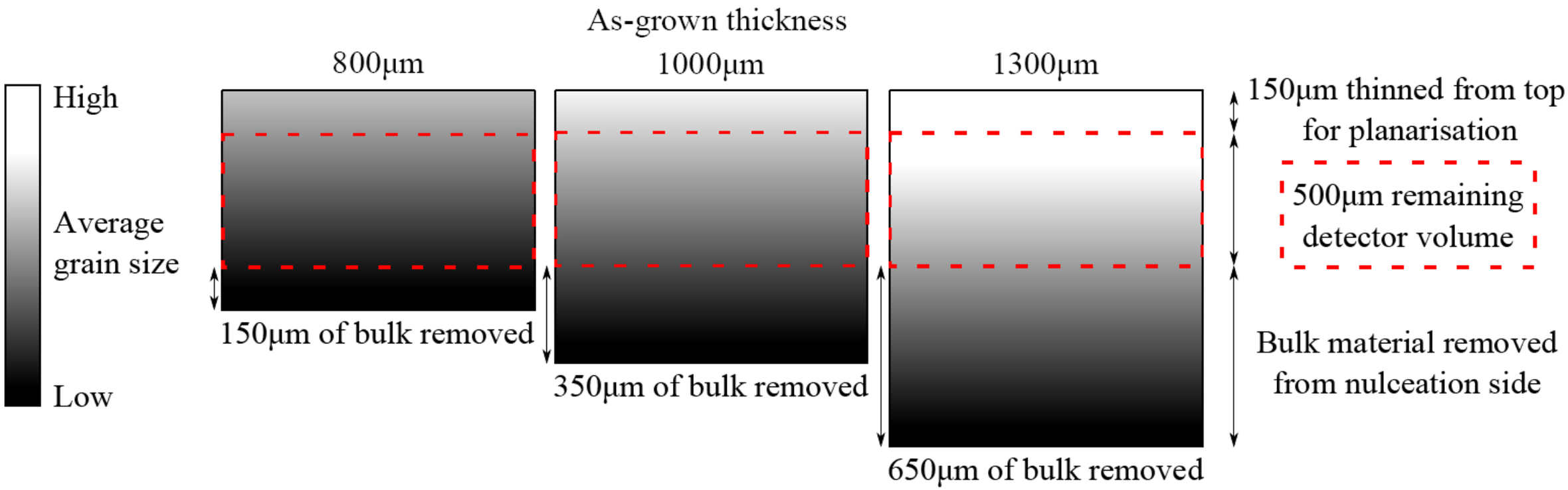
(b) Cross-sectional view of a polycrystalline diamond film showing the increase in grain size with crystal thickness.

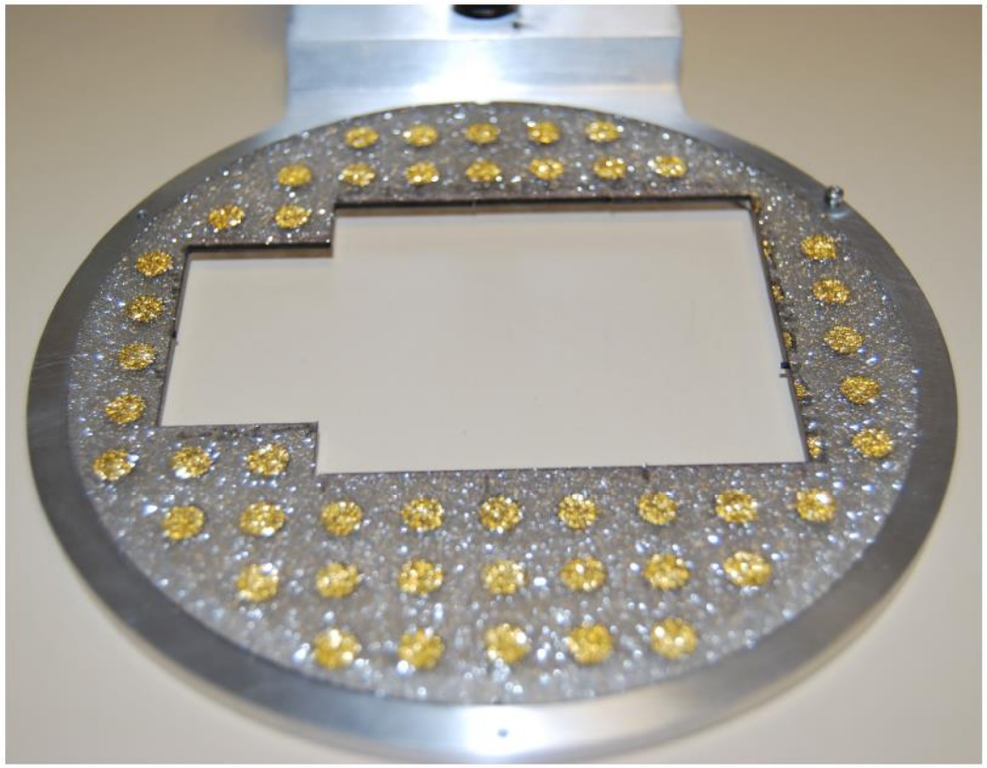


(c) Illustration of grain coalescence in polycrystalline diamond film growth.

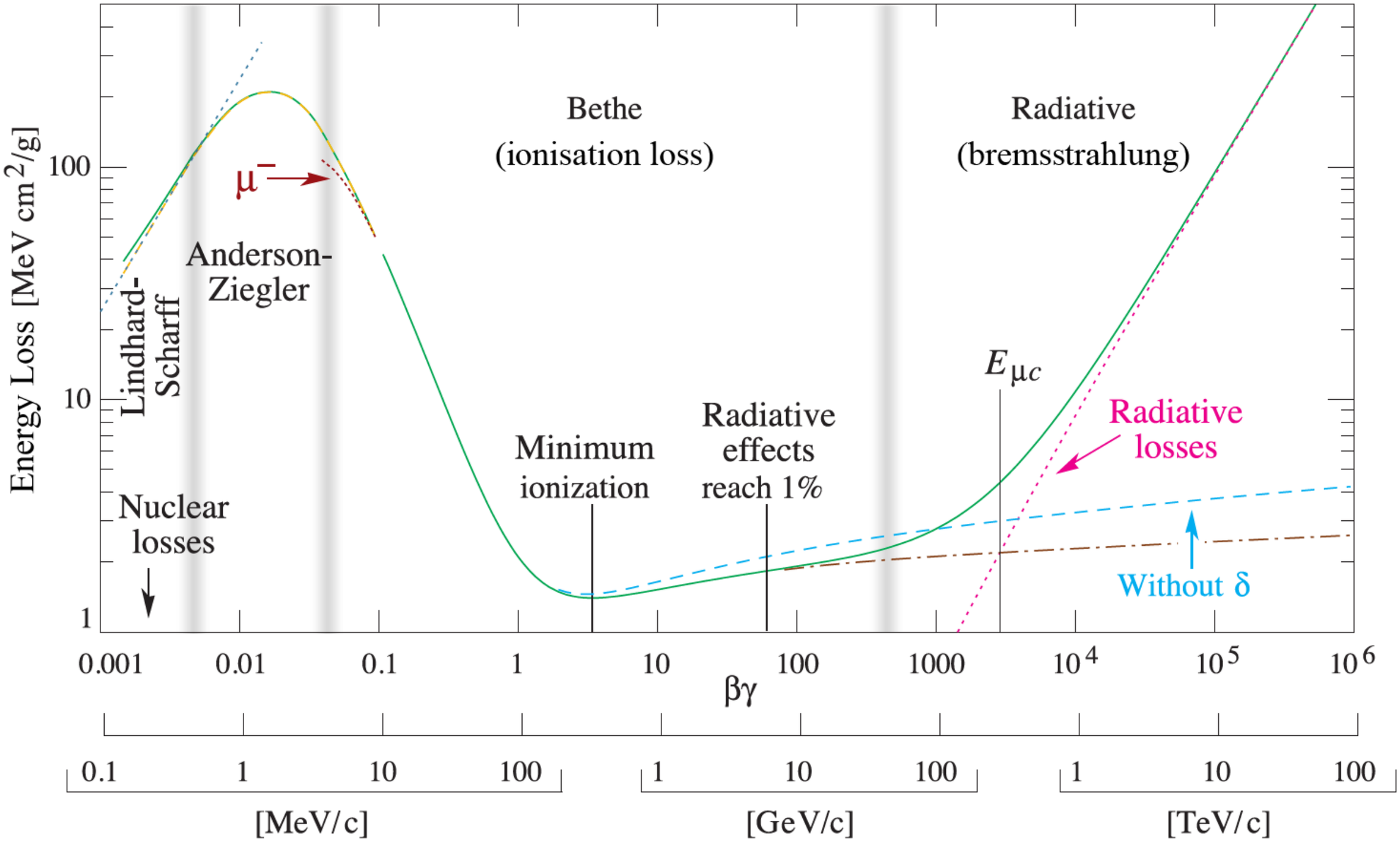
- Small grains
  - → Bad performance
- Big grains
  - → Good performance
- Approximately linear increase in grains size with crystal thickness
- Grow thick and throw away the bad stuff!

Detector thinning





Diamond Characterisation



Energy Distribution

- Landau Distribution

$$f(x,\Delta) = \phi(\lambda)/\xi$$

$$\phi(\lambda) = \frac{1}{\pi}\int_0^\infty e^{-u\ln u - u\lambda}\sin(\pi u)\,\mathrm{d}u$$

$$\lambda = \frac{1}{\xi}[\Delta - \xi(\ln\xi - \ln\epsilon + 1 - C)]$$

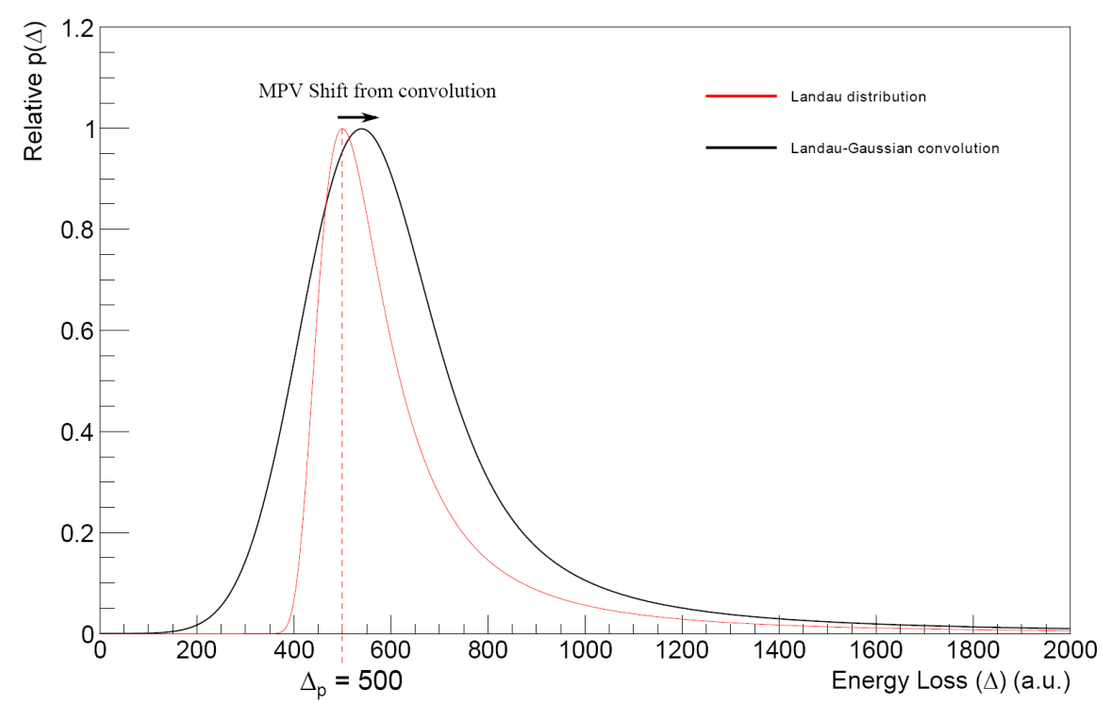
$$\ln\epsilon = \ln\frac{(1-\beta^2)I^2}{2mc^2\beta^2} + \beta^2$$

$K = 2\pi N_0 r_e^2 m_e c^2 = 0.1535\mathrm{MeV}c^2/\mathrm{g}$;
x is the path length in g/cm^2;
$r_e = \frac{e^2}{4\pi\epsilon_0 m_e c^2} = 2.8179\ \times 10^{-13}$ cm is the classical electron radius;
m_e is the mass of the electron;
N_0 is Avagadro's number, $6.022\ \times 10^{23}$;
I is the mean excitation energy averaged over all electrons in eV;
Z is the atomic number of the medium;
A is the atomic weight of the medium;
ρ is the density of the medium;
z is the charge of the incoming particle;
$\beta = v/c$ is the ratio of the incoming particle to the speed of light;
γ is the Lorentz factor $\frac{1}{\sqrt{1-\beta^2}}$;
δ_{ion} is a density correction;
C is a shell correction;

- Peak Energy loss

$$\Delta_p = \xi\left[\ln\frac{2mc^2\beta^2\gamma^2}{I} + \ln\frac{\xi}{I} + j - \beta^2 - \delta_{ion}(\beta\gamma)\right]$$

$$\xi = x\cdot\frac{K}{2}\frac{Z}{A}\frac{1}{\beta^2}\,\mathrm{MeV}$$



Charge Collection Distance

- Plugging in numbers for:
  - Parameters of diamond as a material
  - Detector thickness of 500 μm
  - Relativistic properties of a ^{90}Sr β particle

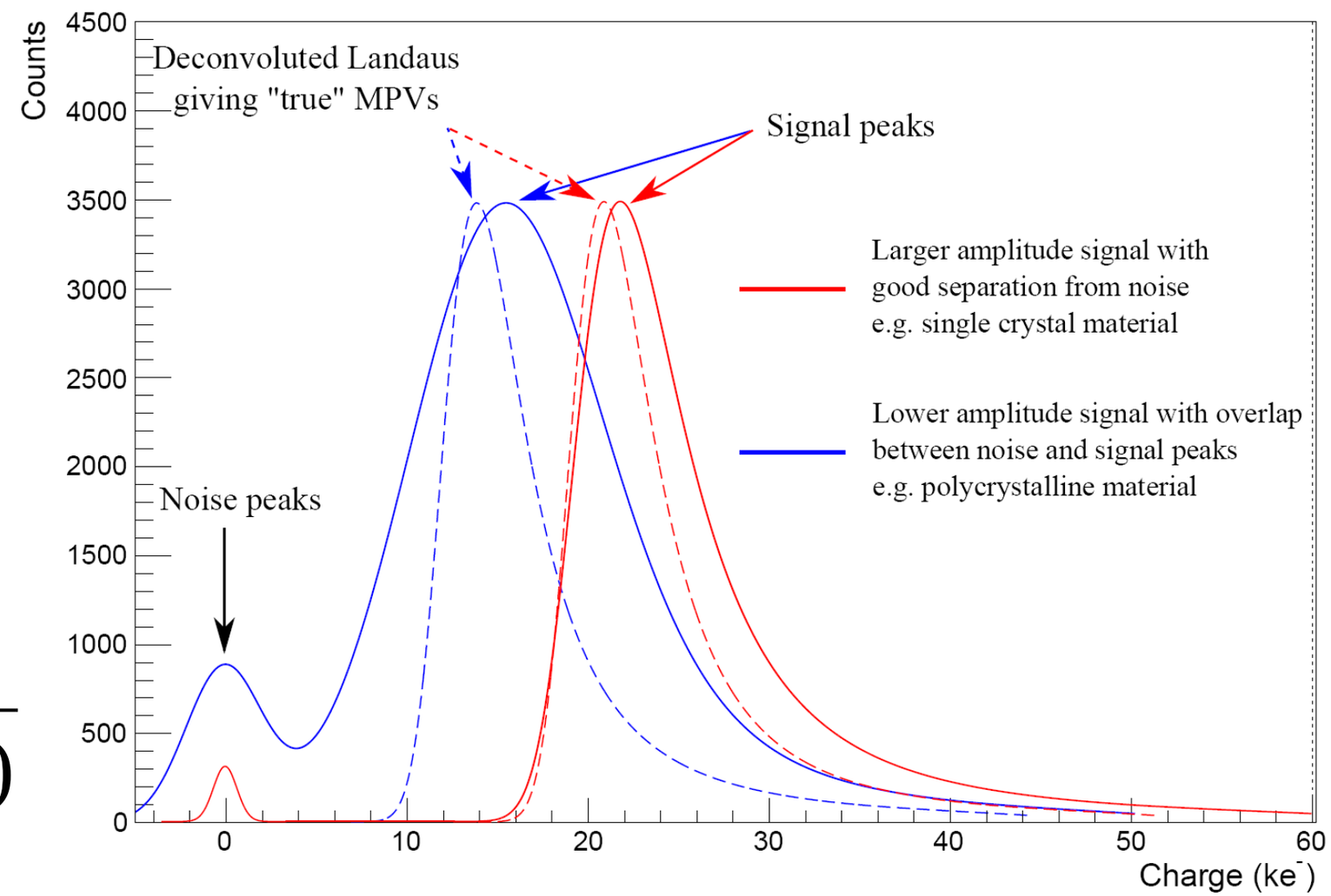
$$\rightarrow \Delta_p = 239.7\text{keV}$$

$$\rho_Q = 36e/h \cdot \mu m^{-1}$$

$$\epsilon_Q = \frac{Q_{col}}{Q_{gen}} = \frac{Q_{col}}{\rho_Q \cdot d}$$

$$CCD = \frac{Q_{col}}{\rho_Q} = d \cdot \epsilon_Q$$

$$CCD(\mu m) = \frac{\langle Q \rangle (e^-)}{36(e^- / \mu m)}$$

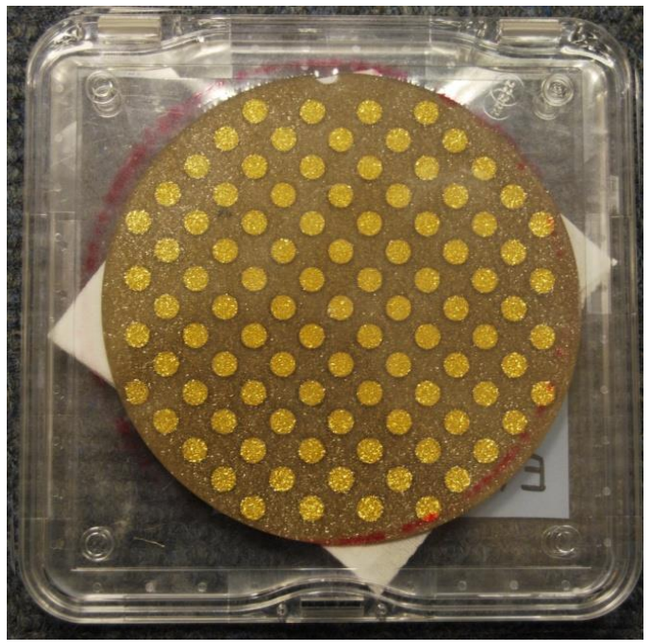


How good is your diamond / detector?

Single crystal diamond

- How much charge can be collected?
- How much voltage is needed for full collection?
- How much voltage can you apply before it shorts?
- Was your metallisation successful?

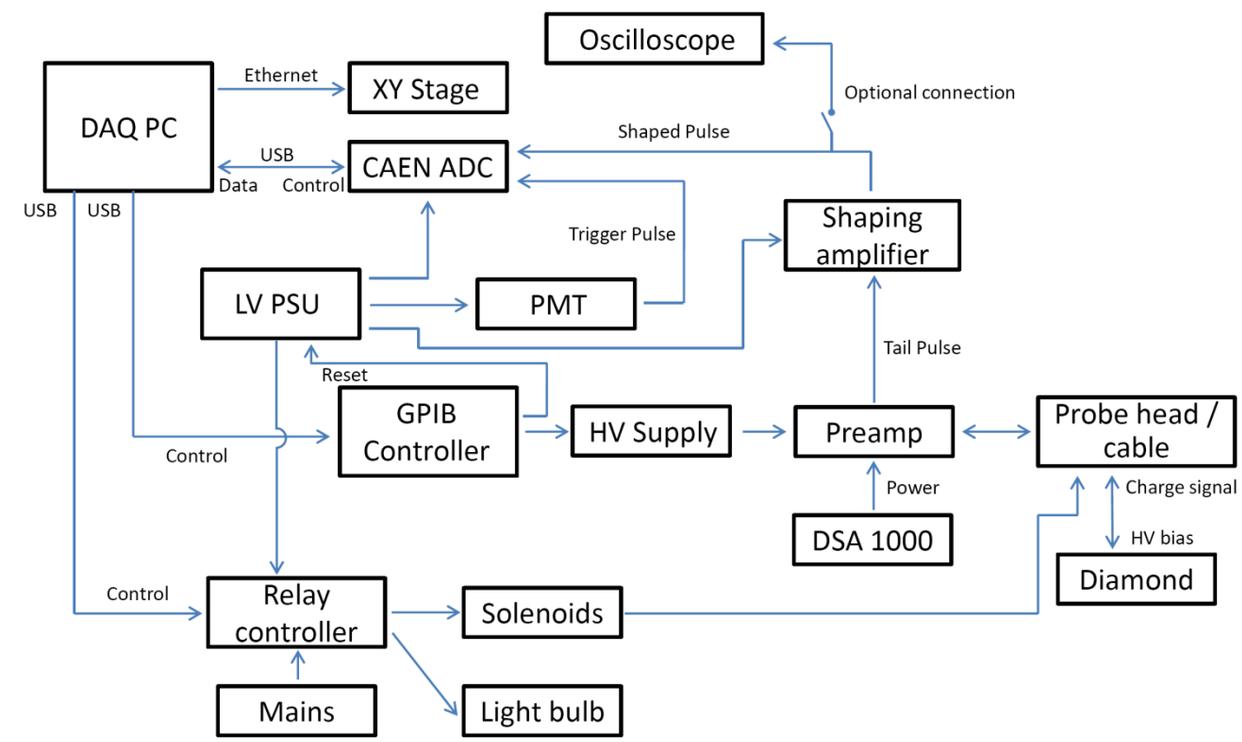
Polycrystalline diamond



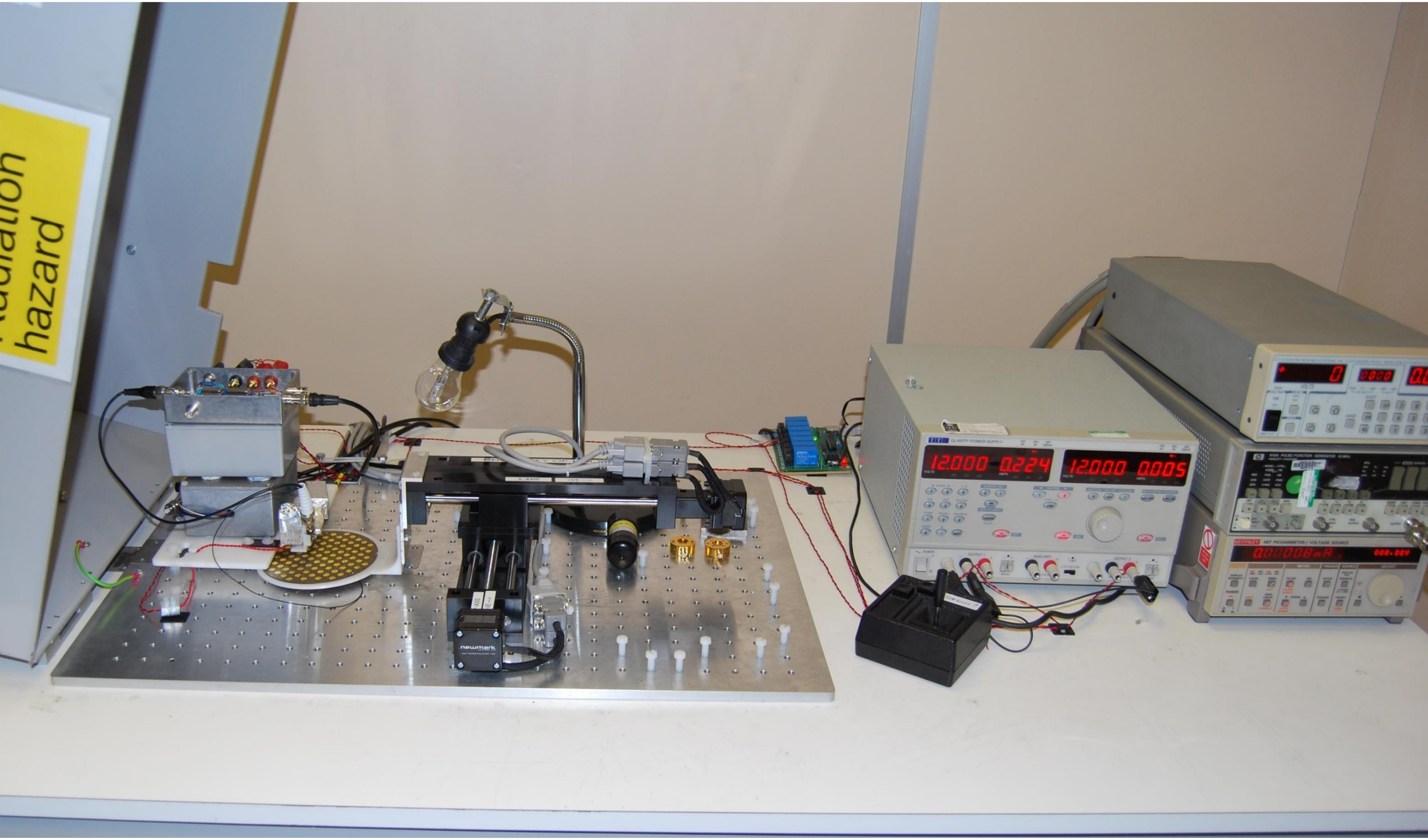
- How does signal vary with irradiation? (pumping)
- Does the applied electric field affect the pumping?
- Which are the good areas on your wafer?

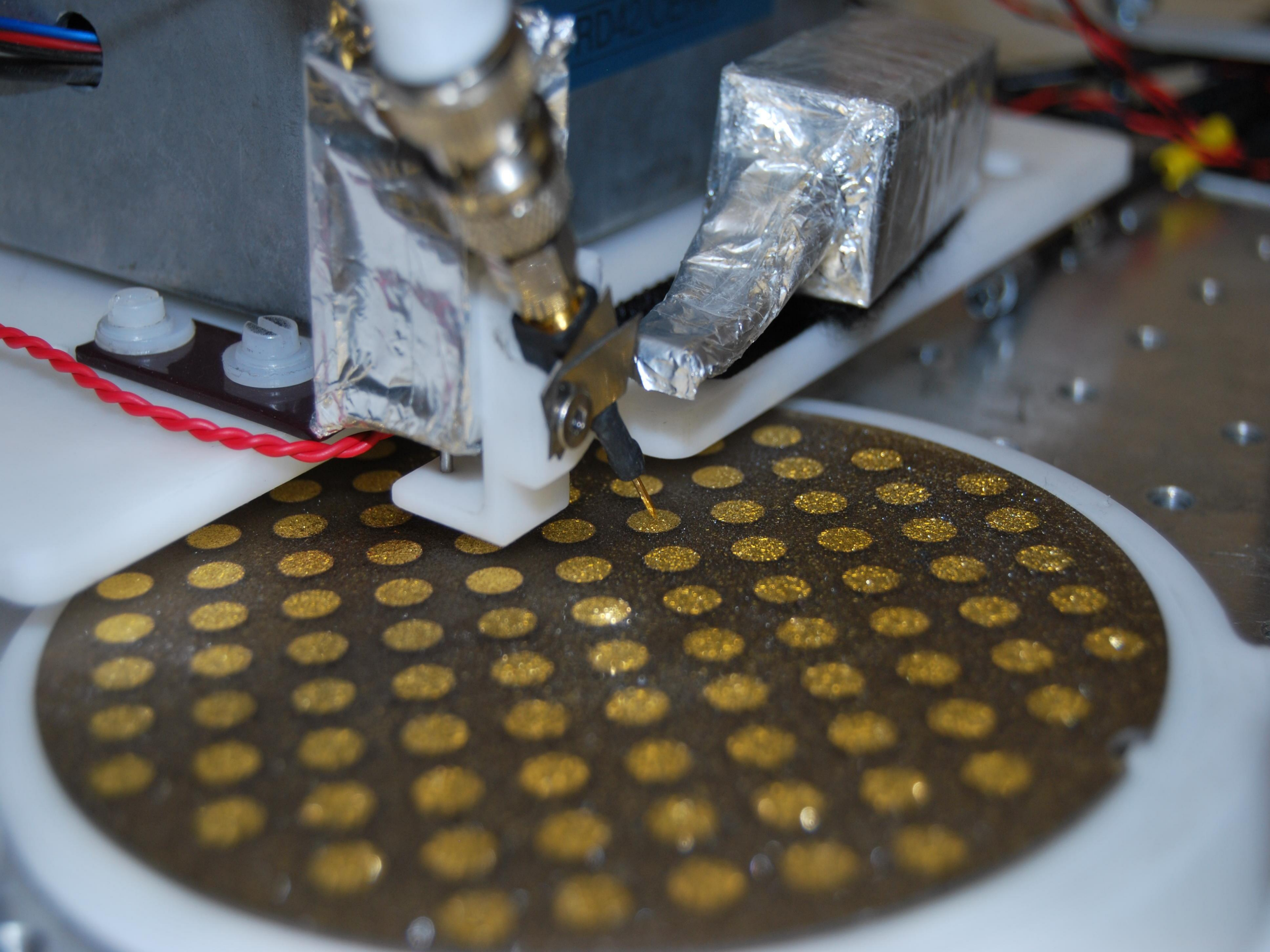
System components

- HV sources (± 500V, +/- 5000V)
  - GPIB controlled
- XY Stage
  - Ethernet controlled with routines written to allow programming of set movement patterns
- Desktop digitiser (CAEN DT5720)
  - Data acquired through customised control software
  - Automated resets performed via relays
- Photomultiplier for triggering
- Halogen light bulb for de-pumping
  - Automated with relays
- Roving probe head for contacting wafer
  - Actuated via computer controlled solenoids
- Post processing performed on DAQ PC



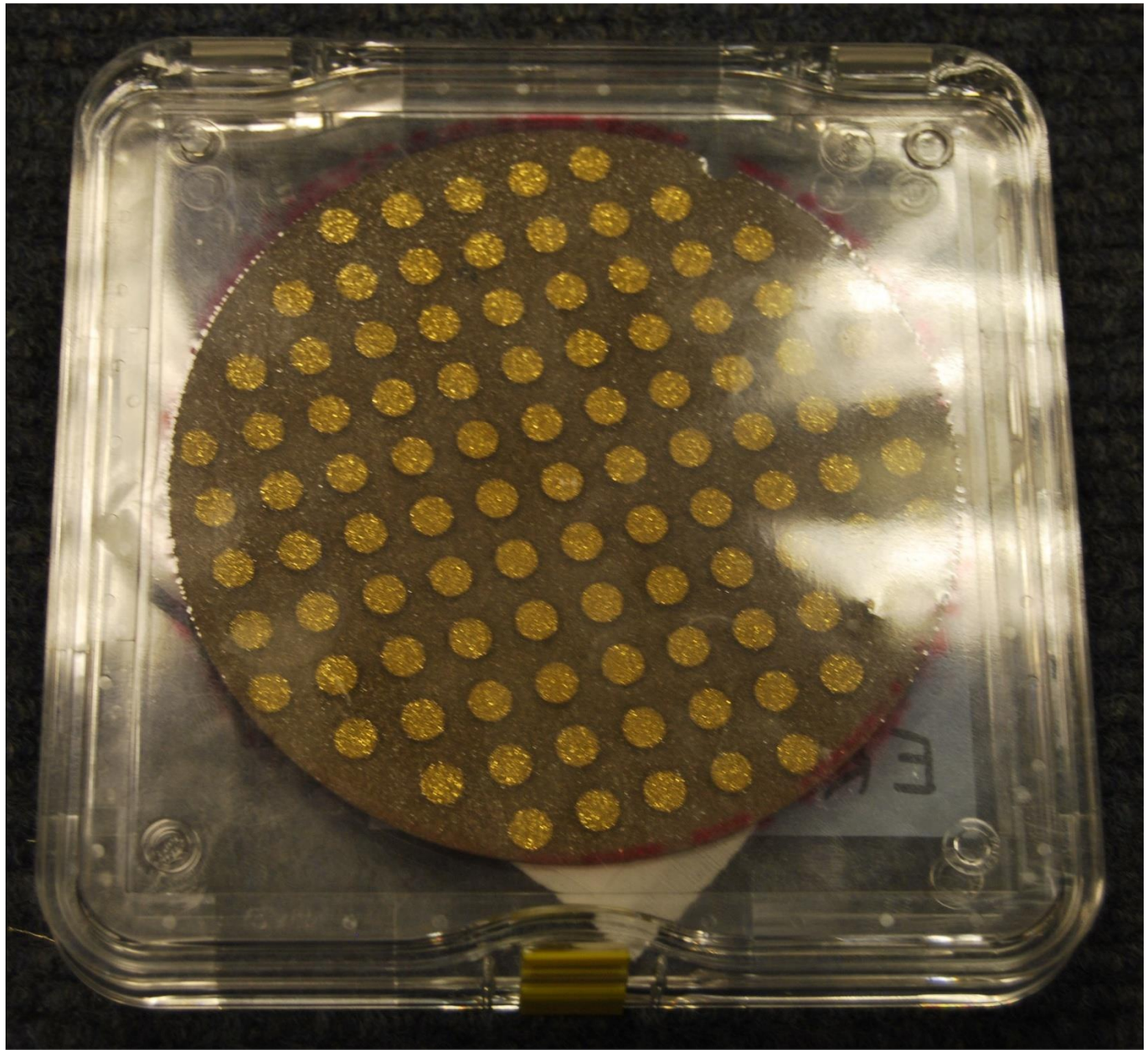
Measurement System





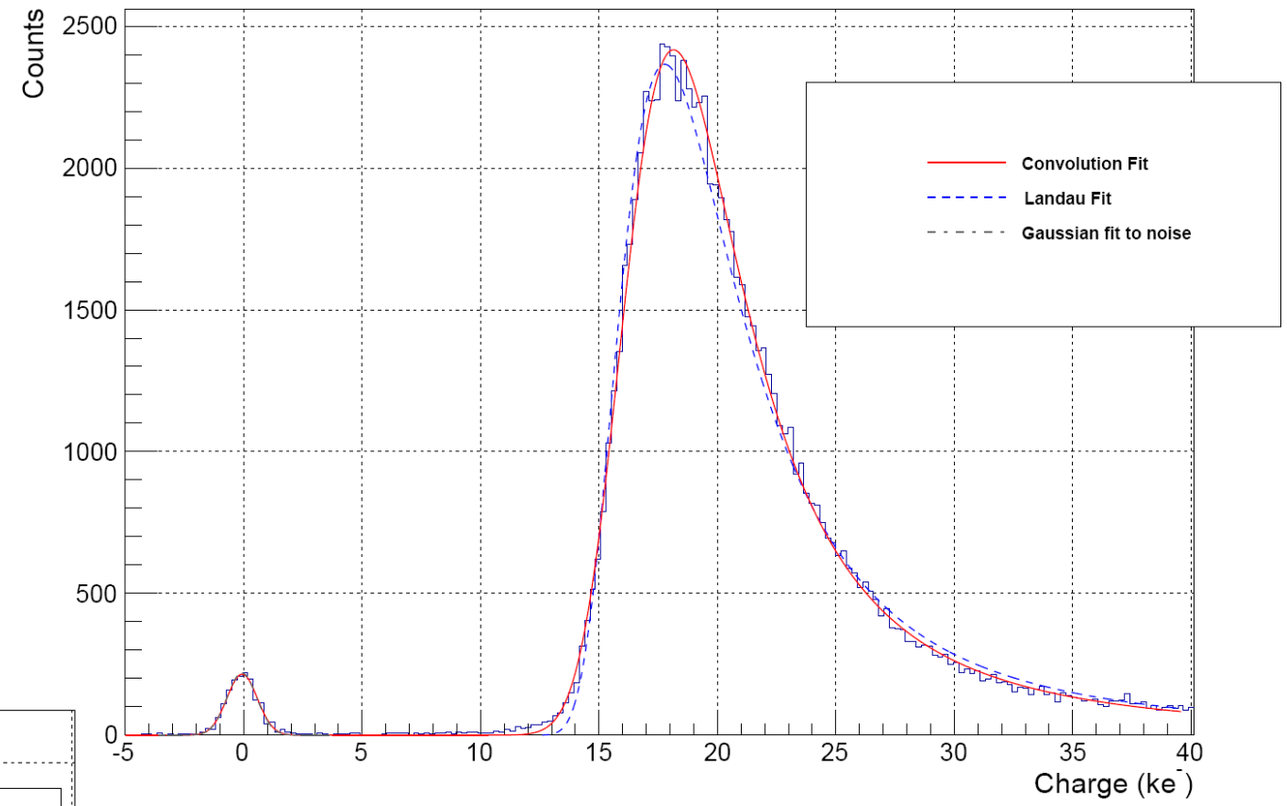
Wafer mapping

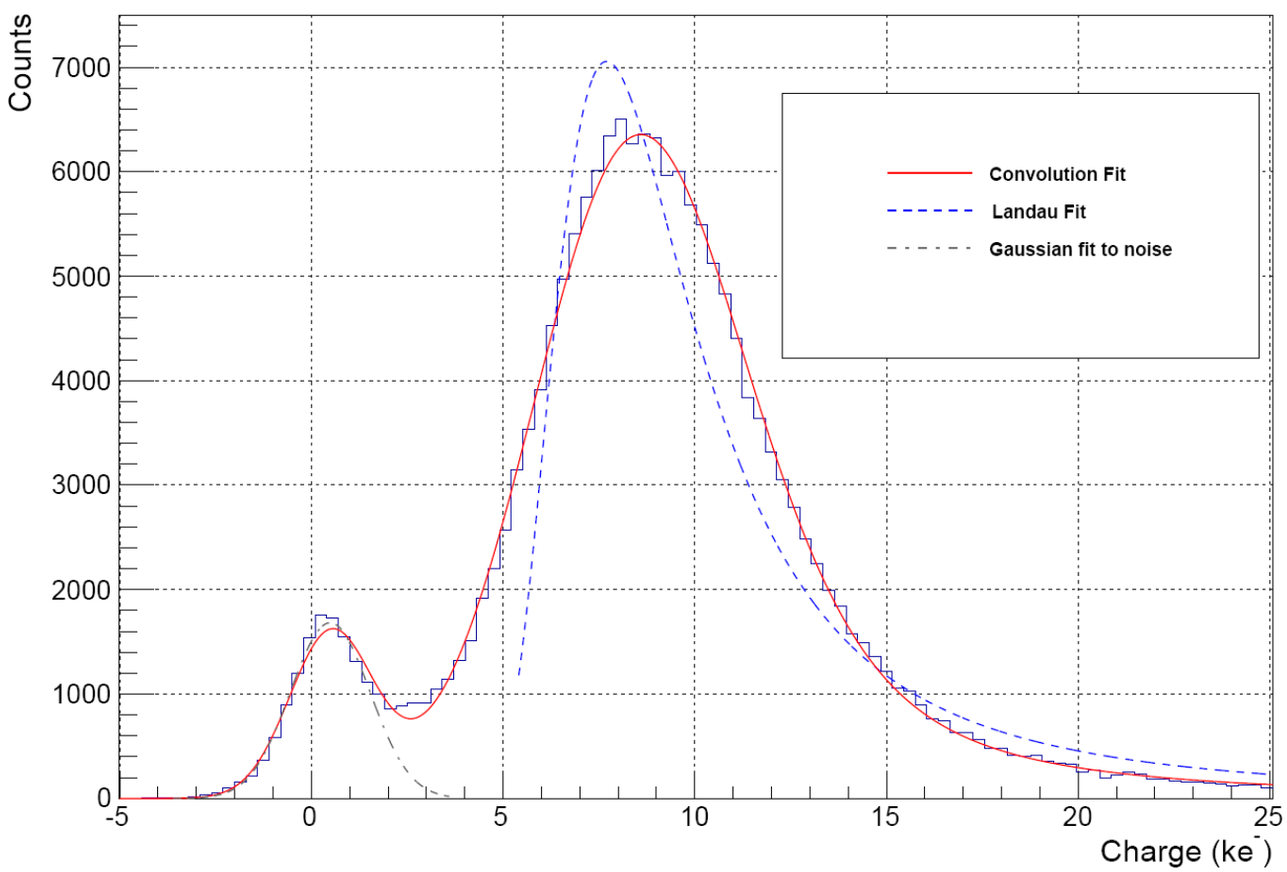
- Each point on the wafer analysed in turn
  - Pulse height distribution produced and fitted
  - CCD calculated using system gain
- Wafer map produced and viewed through GUI
- Allows for material choice before cutting of detector area



Pulse Height Distributions

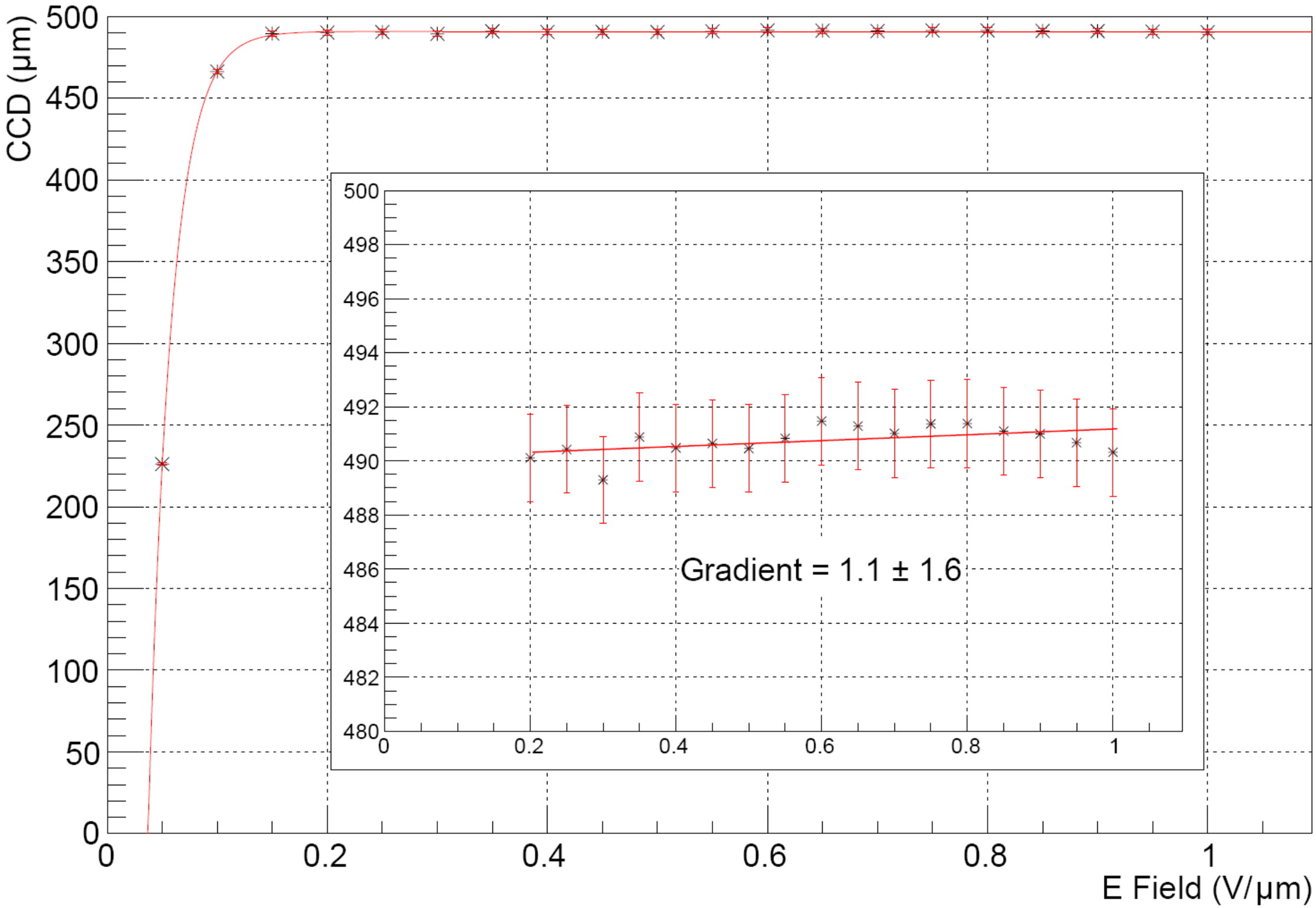
Single crystal diamond →



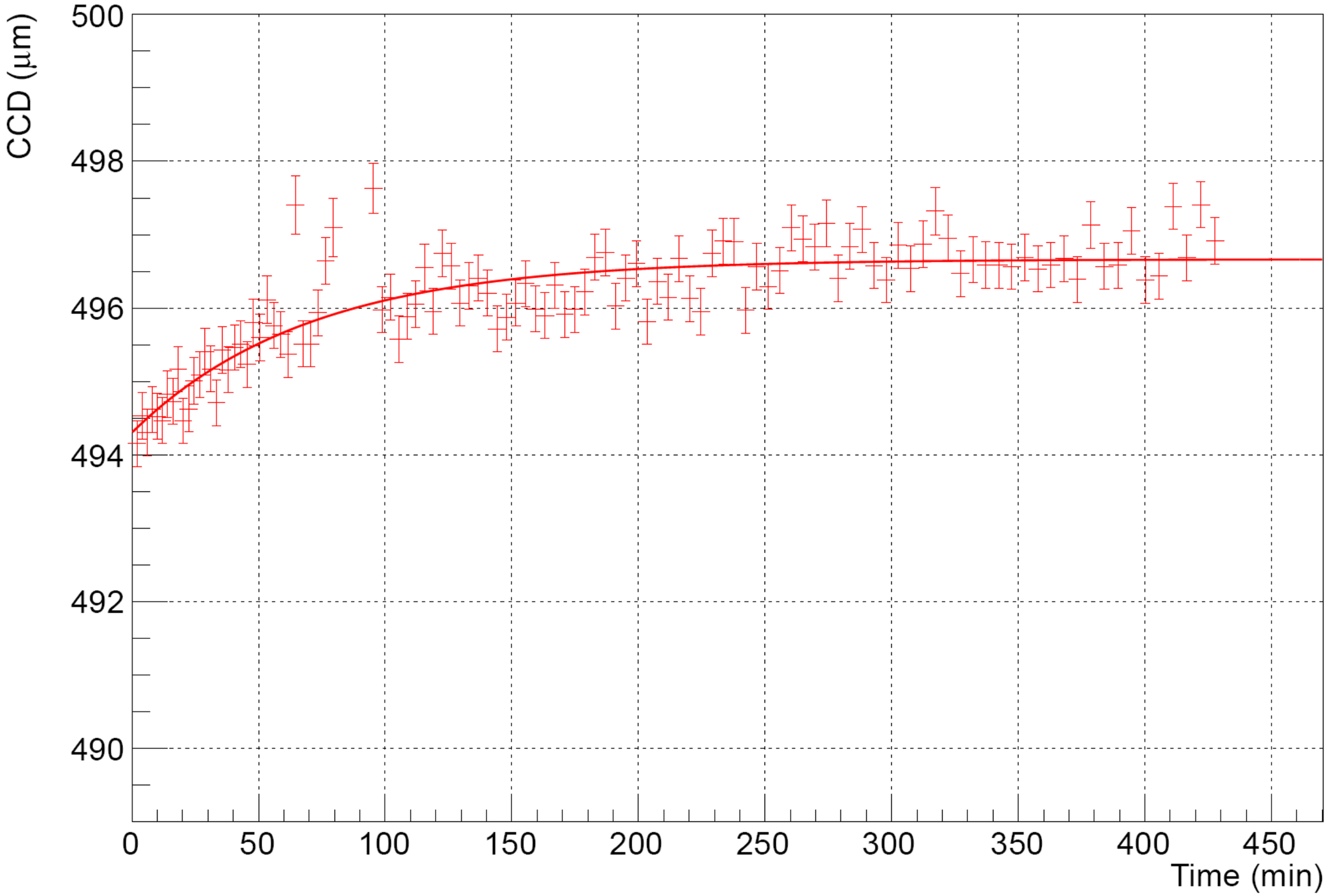


← Polycrystalline diamond

Field Strength in single crystal diamond



“Pumping” in single crystal diamond



Ionisation potential and density

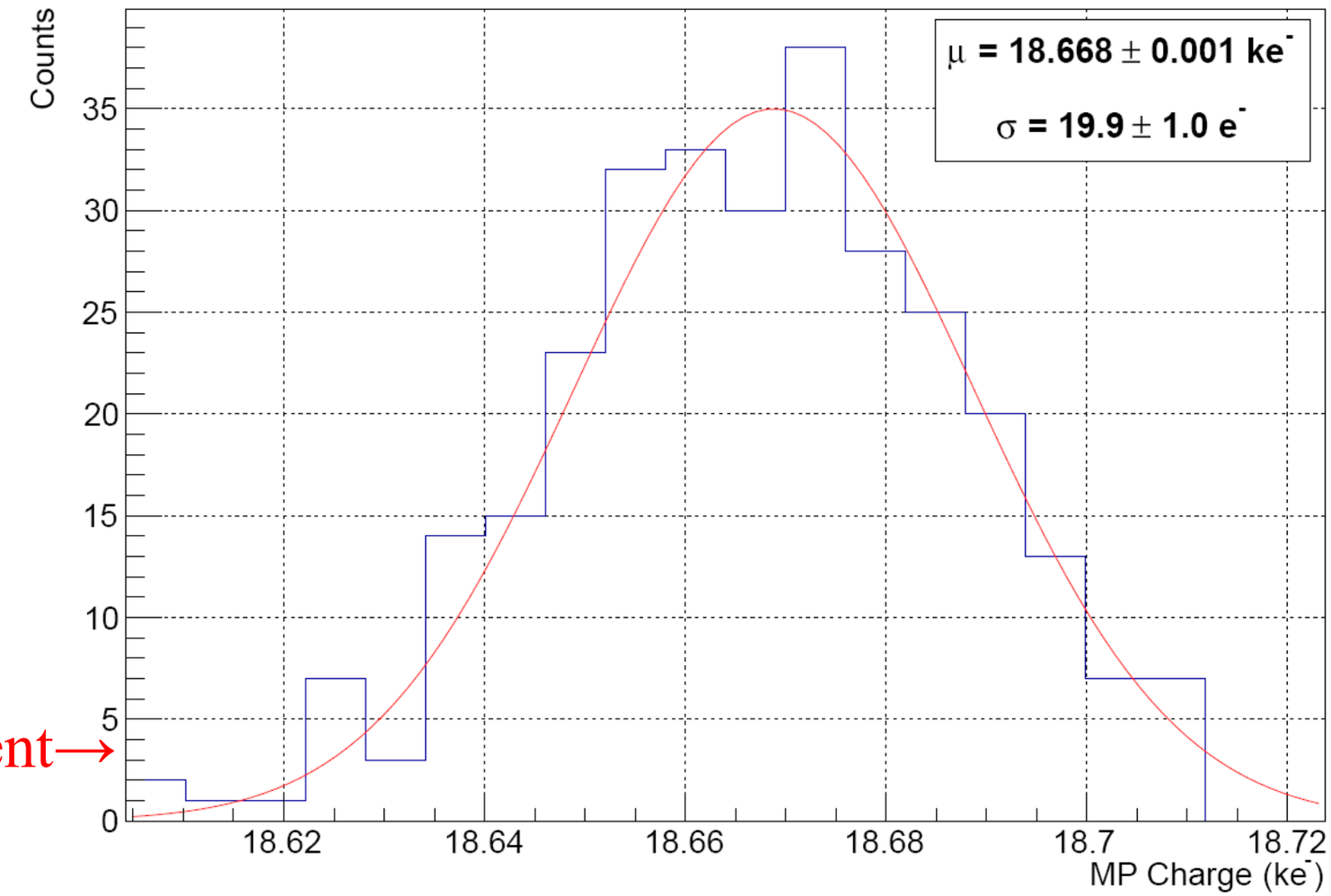
$$CCD = \frac{Q_{col}}{\rho_Q} = d \cdot \epsilon_Q$$

$$\epsilon_Q = \frac{Q_{col}}{Q_{gen}} = \frac{Q_{col}}{\rho_Q \cdot d}$$

$$\epsilon_\beta = \frac{\Delta_p}{\hat{Q}_{col}}$$

← From theory

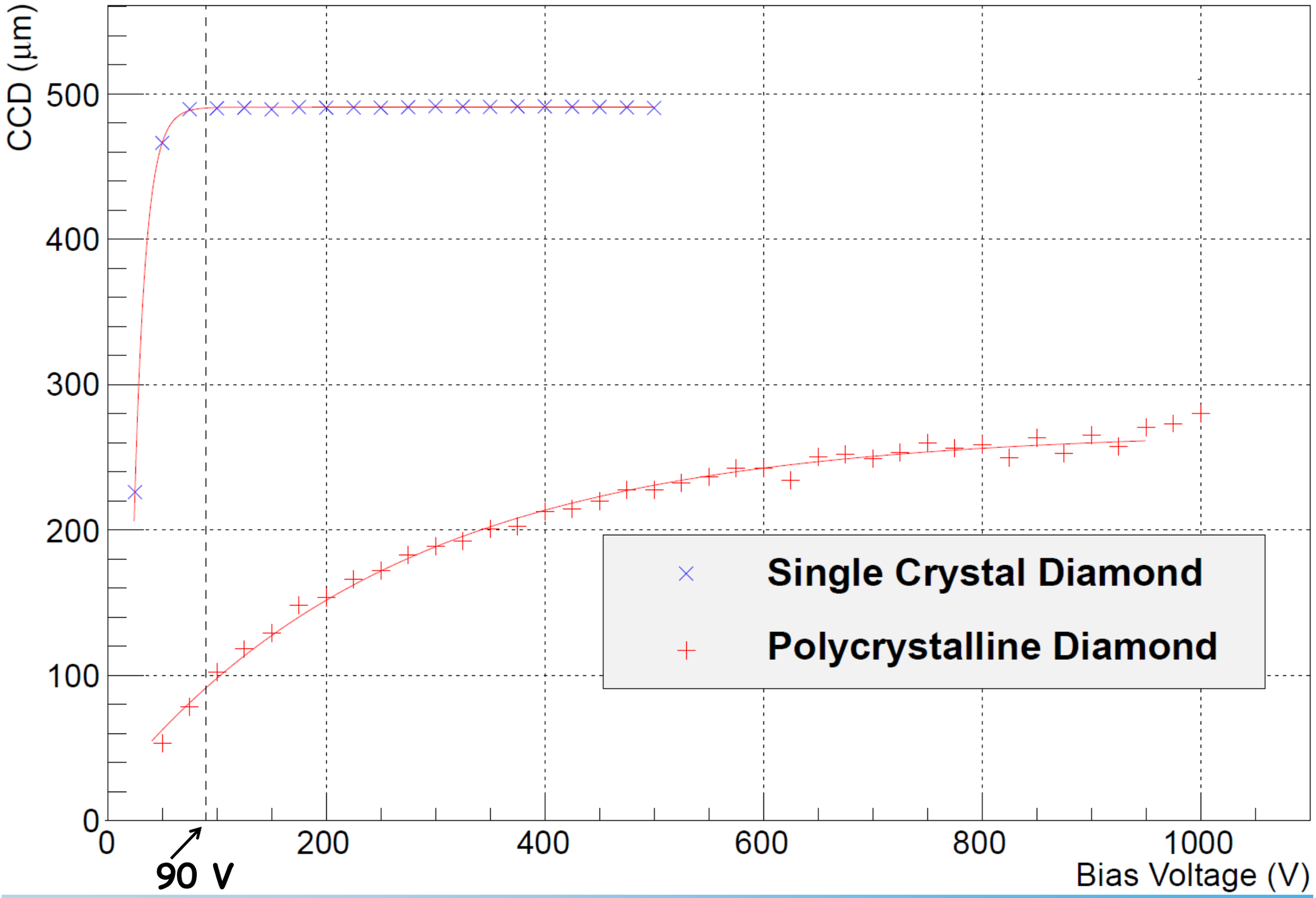
← From experiment→



$$\epsilon_\beta = \frac{239.7 \text{ keV} \cdot \frac{508\mu\text{m}}{500\mu\text{m}}}{18,668 \pm 59 \text{ e}^-} = 13.05 \pm 0.05\text{eV}$$

$$\hat{\rho}_Q = \frac{\hat{Q}_{col}}{d} = \frac{18,668 \pm 59 \text{ e}^-}{508 \pm 1\mu\text{m}} = 36.75 \pm 0.14 \text{ e/h pairs / } \mu\text{m}$$

Electric Field Strength



Polycrystalline Field Strength

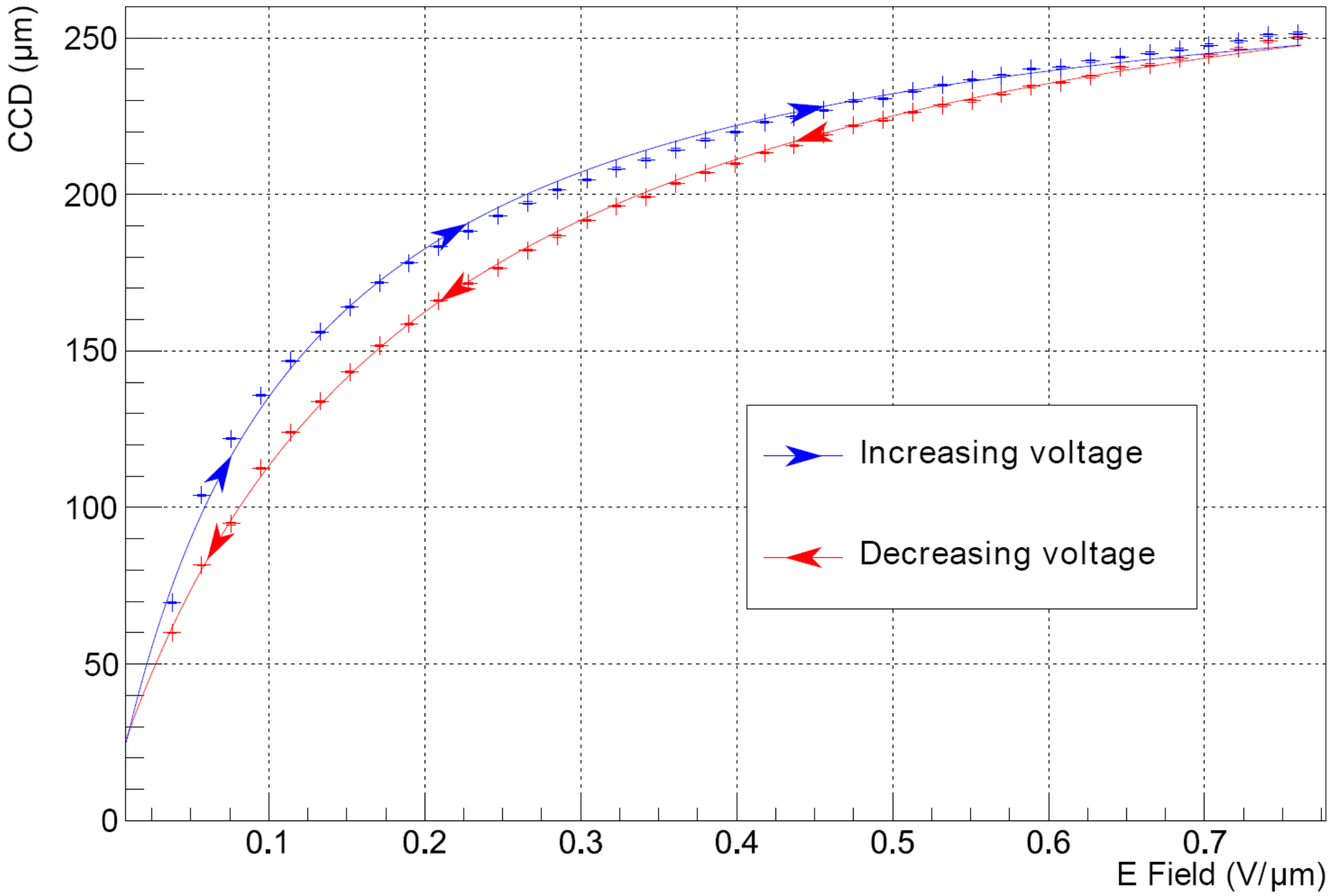
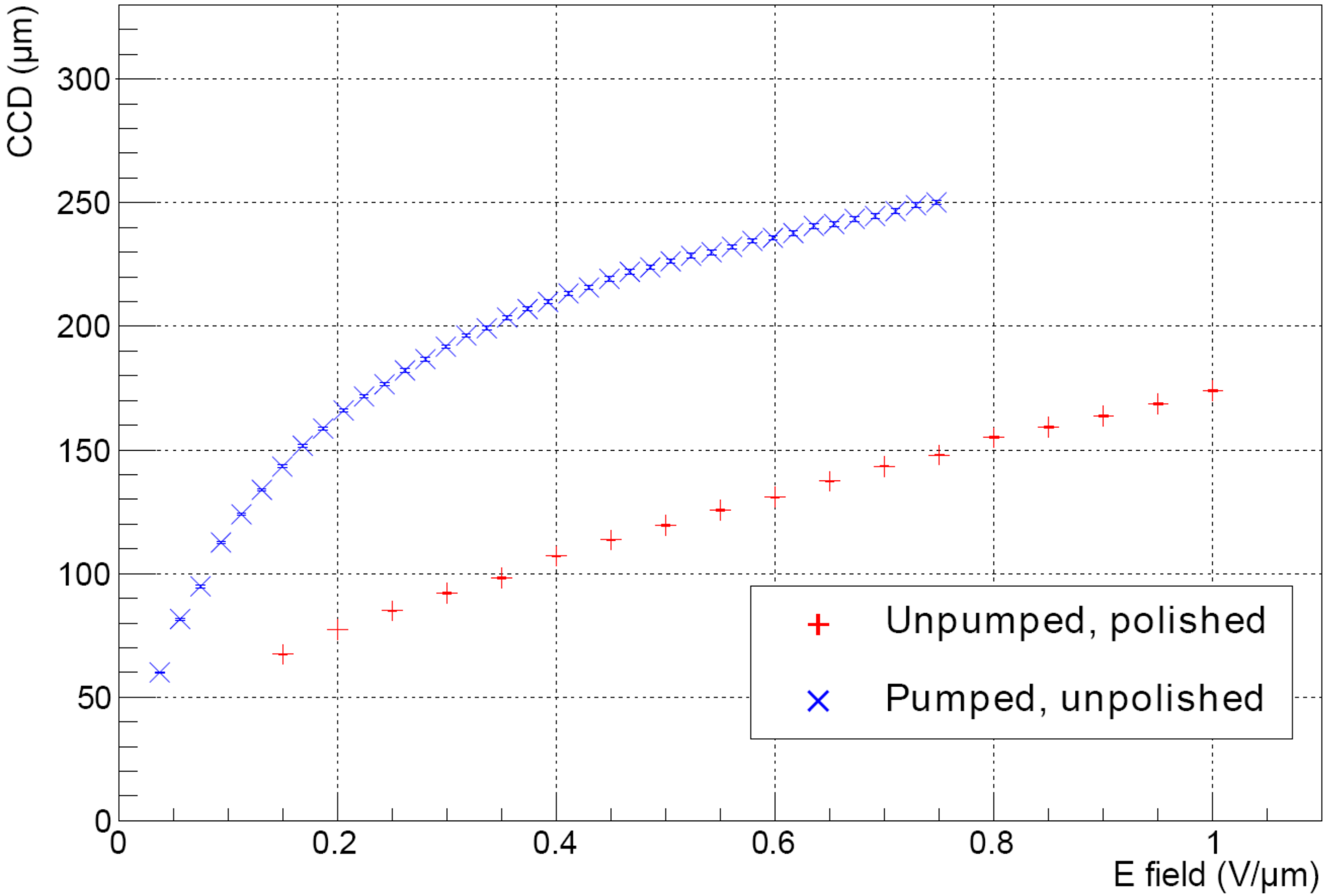
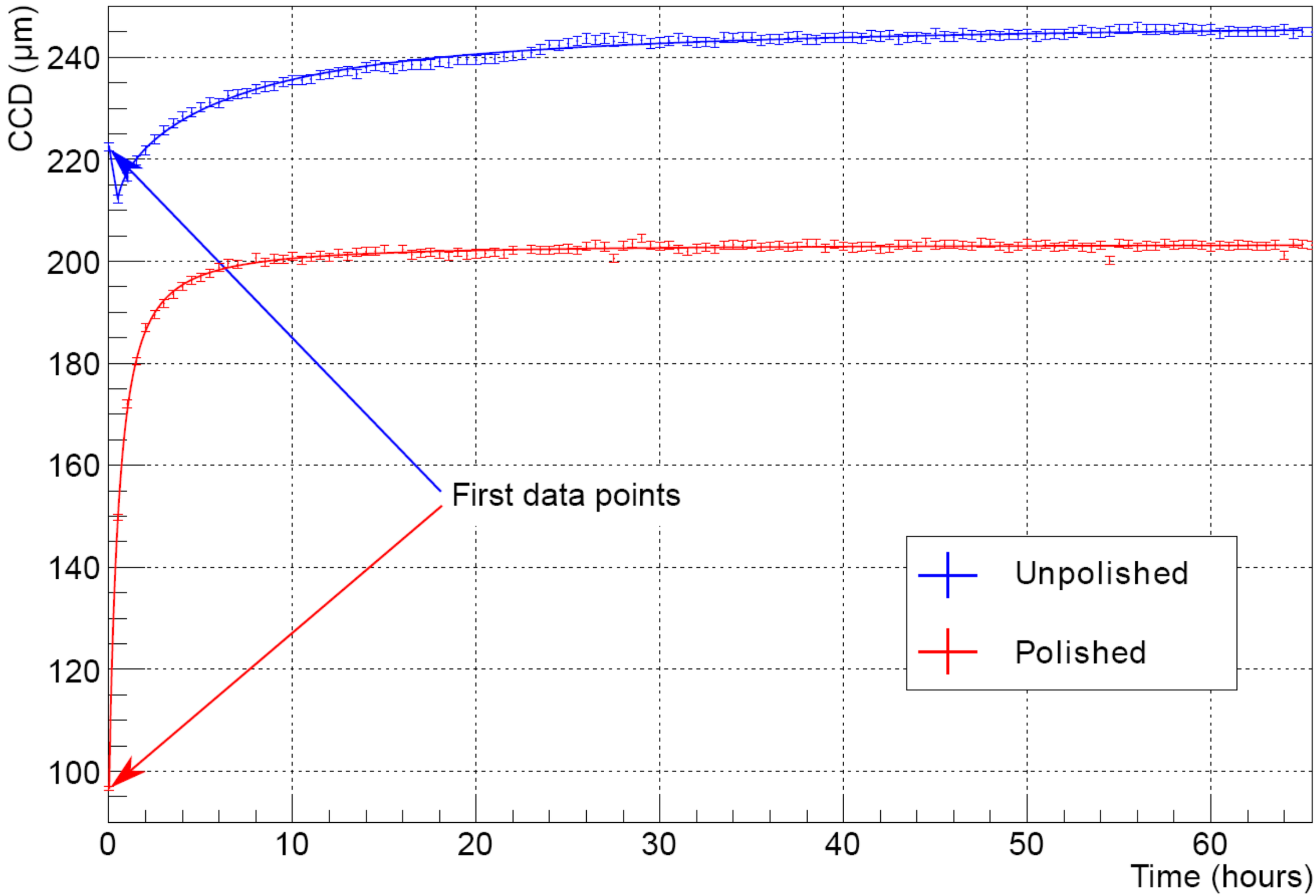


Figure 4.4: Hysteresis in the charge collection behaviour of a pumped, unpolished polycrystalline detector.

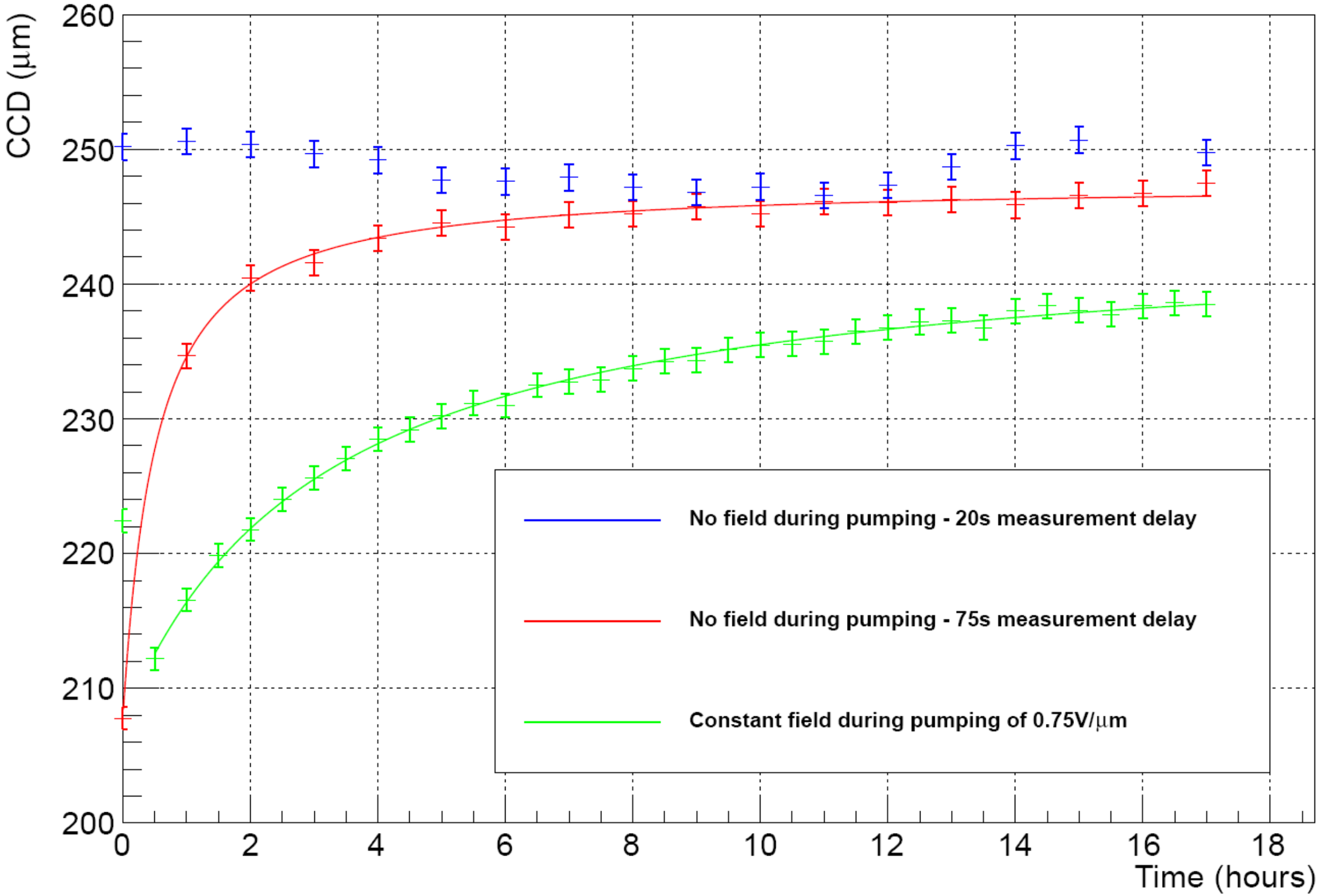
Field wrt pump state



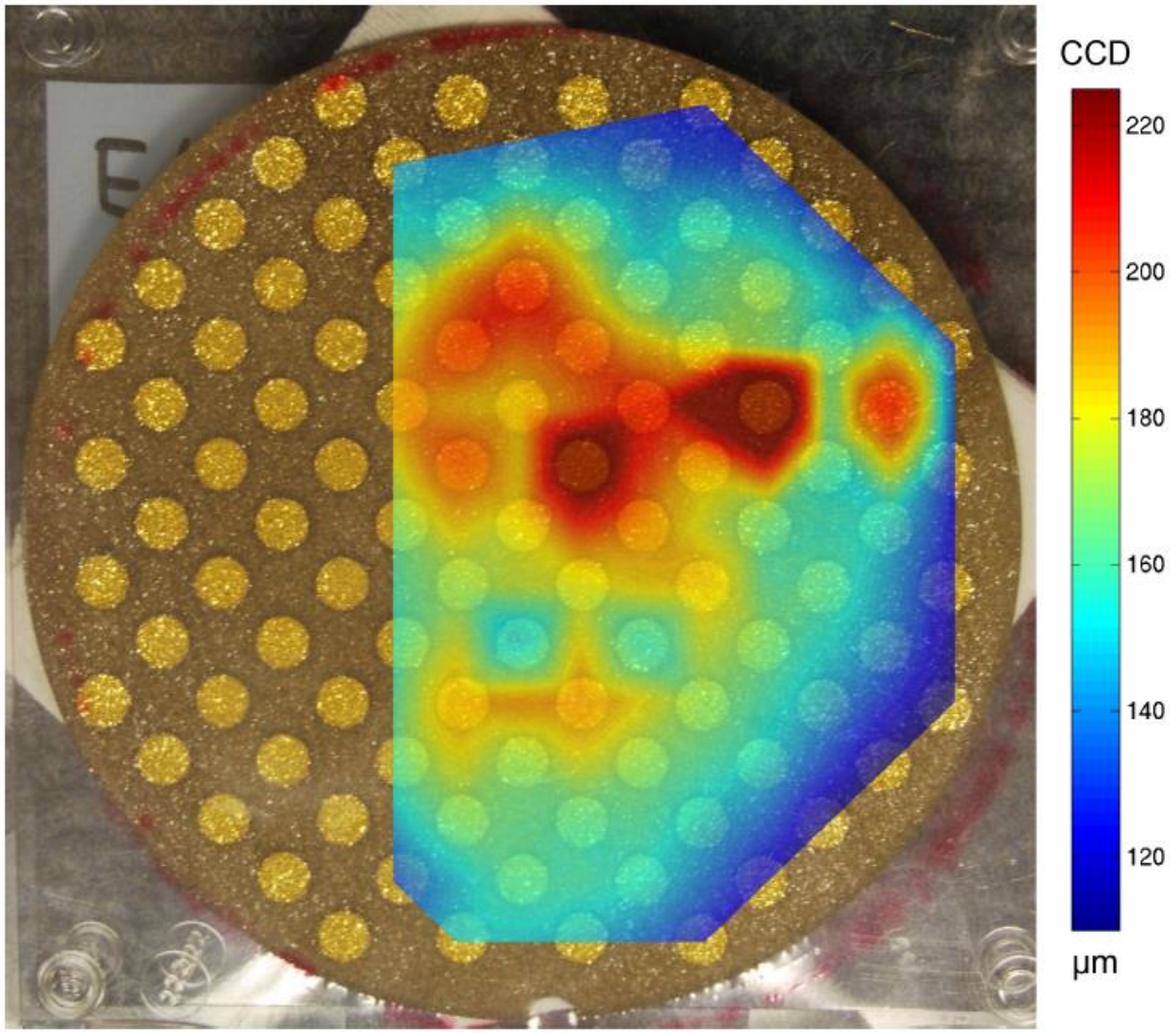
“Pumping” effect



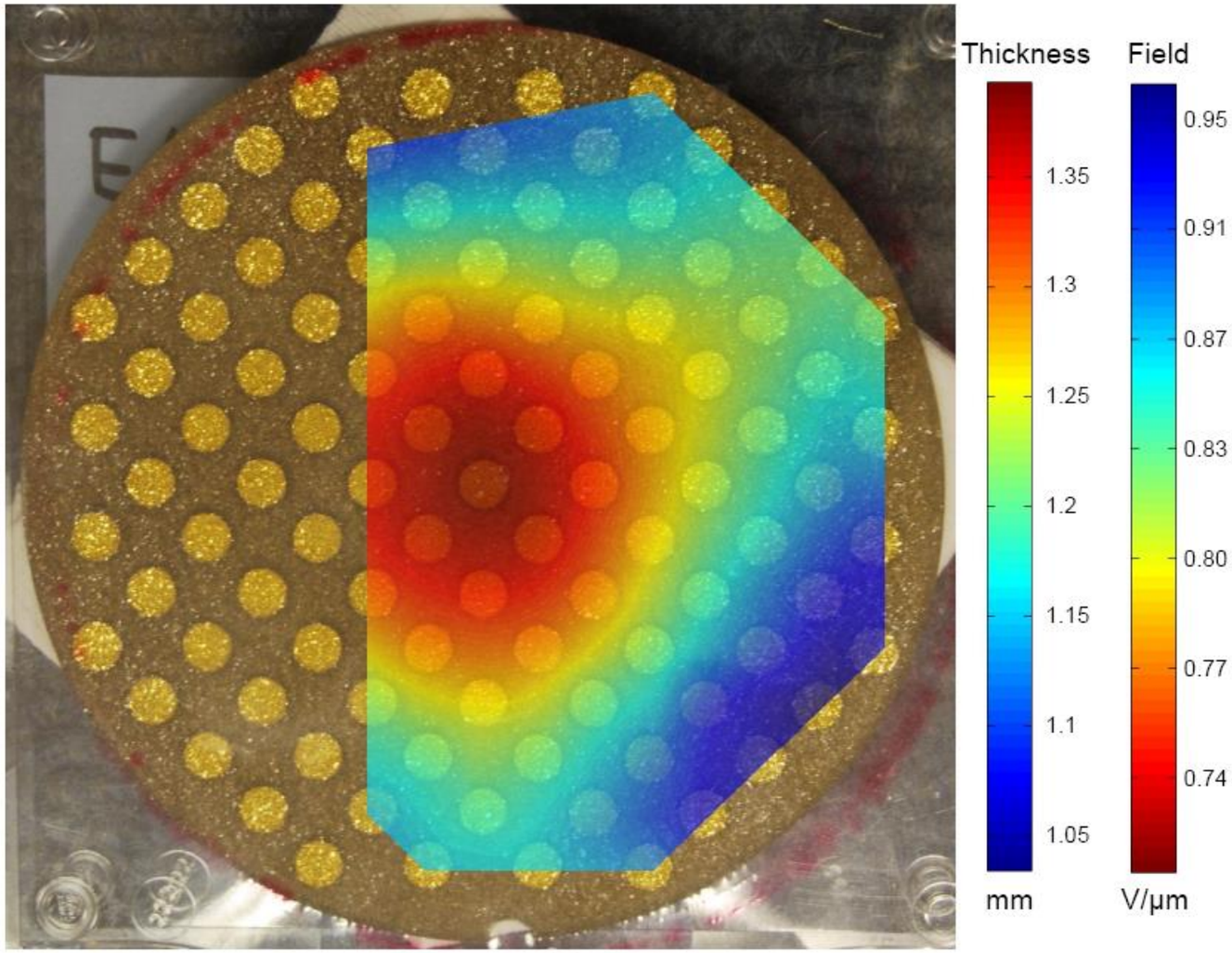
Dependence of pump rate on E-field



Wafer mapping



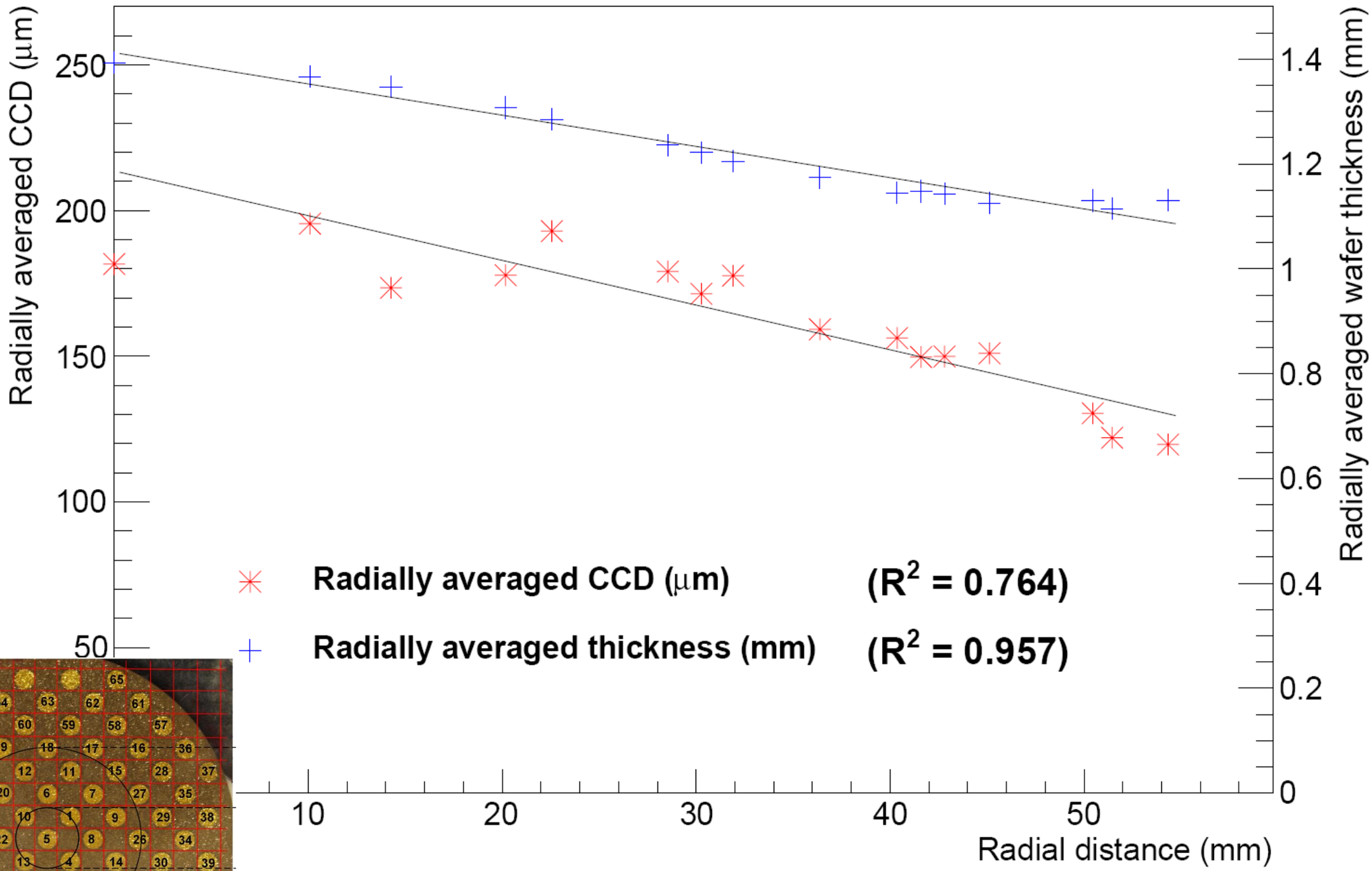
(a) CCD

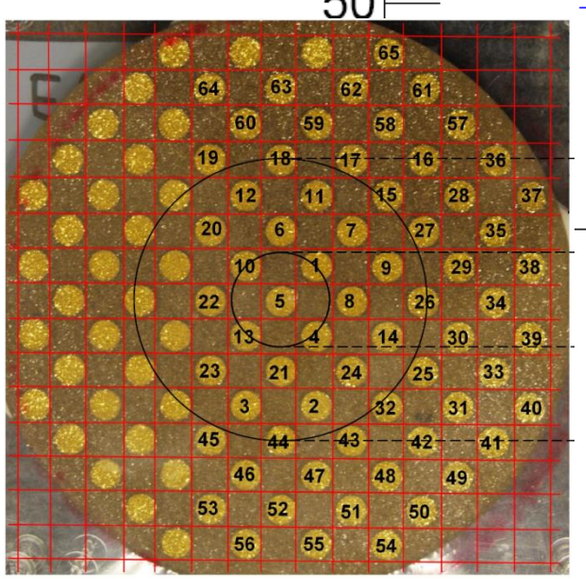


(b) Thickness

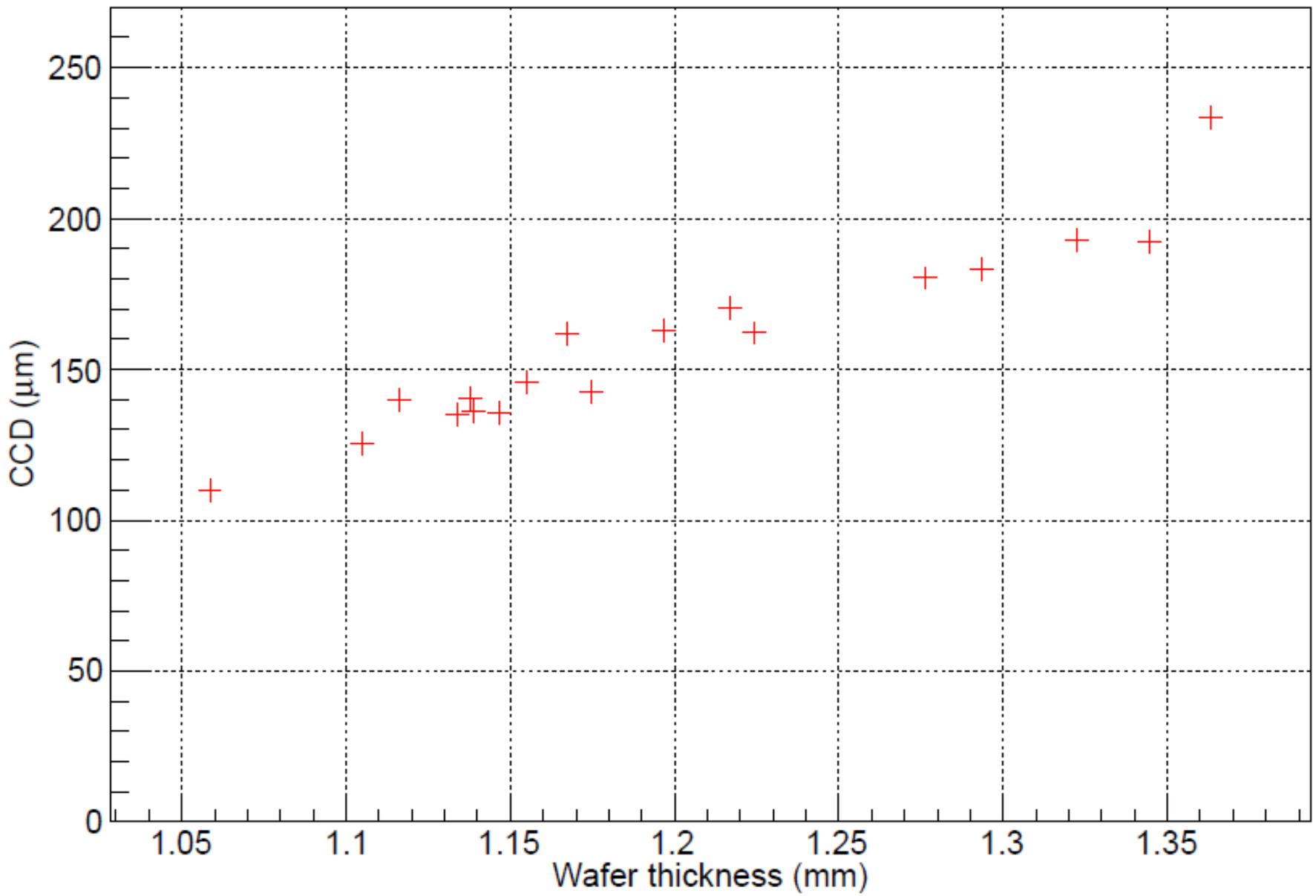
- Diamond quality (CCD) measured with wafer measurement system
- Thickness of diamond wafer measured with a digital micrometer

Radial CCD and Thickness





Radial CCD dependence



Correlation between wafer thickness and CCD using radially averaged values

Conclusion

- A fully automated system was produced to allow for full wafer measurement inc. pumping, electric field sweeps etc.
- Interesting results produced with minimal effort
  - Allows for routine profiling of diamond material before it is sold
- System results well received by customers/end-users
  - DDL was sending out pulse height distributions on their datasheets and received very positive feedback on giving out this information (despite charging for it!)
- Many prior science results confirmed with much improved precision
  - Definite radial distribution of diamond quality shown
    - However, with significant departures from a perfect distribution
  - Quality can be probabilistically improved by taking material from central regions, but to get the best material the only way is to test before cutting

Amplifier design

Amplifiers for Diamond Spectroscopy

- Creation of an amplifier for use with scCVD diamond
  - Diamond is low capacitance and has fast signal collection
    - We can use it for fast spectroscopy (potentially at 100s of MHz!)
    - Plus it can handle the dose…
  - Amplifiers need to be customised to capitalise on diamond's properties

- Preamplifier needs to be high-bandwidth
  - Need custom shapers for fast baseline restoration
  - Need high-frequency, high-voltage bias tee
    - Full charge collection @ 1V/μm (after damage / in poly)
    - 500μm thick diamond → need 500V bias tee
  - Amplifier performance modelled in SPICE
    - Followed by an iterative design process

Traditional circuit topology

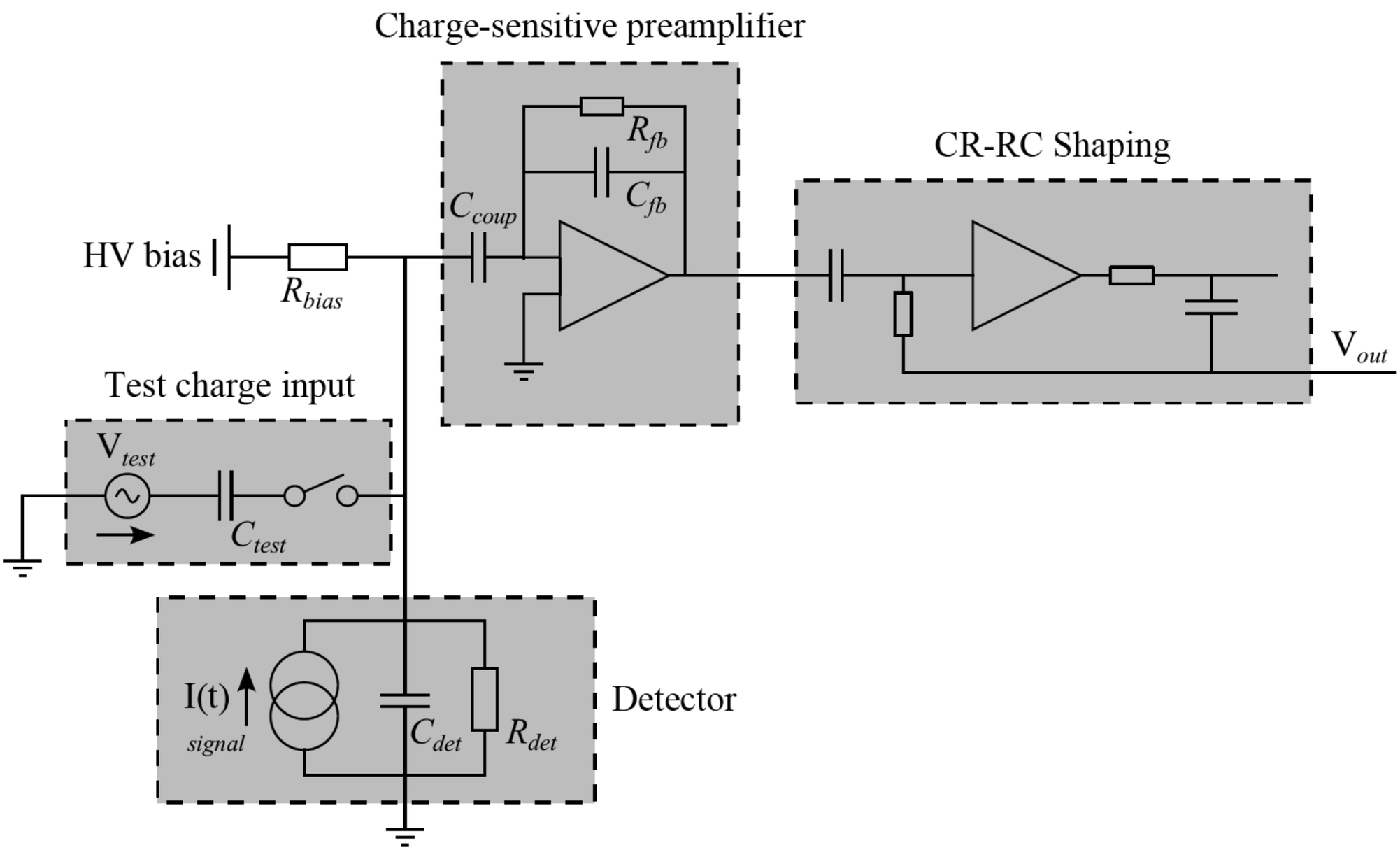
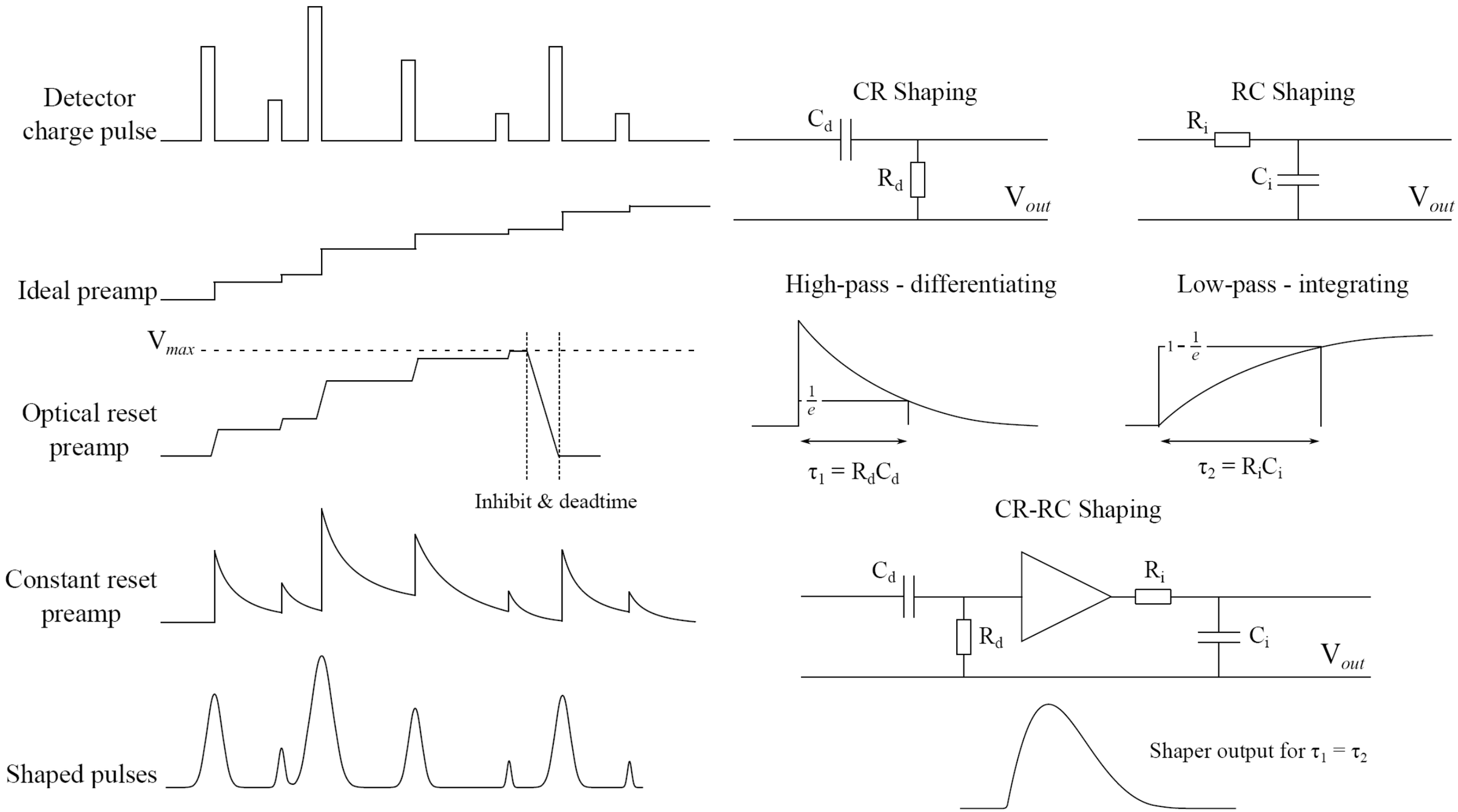


Figure 5.2: Electrical model of a semiconductor radiation detector connected to a charge sensitive amplifier and shaping amplifier.

Single Pole CR-RC Shaping



Differentiating - high / low rate configurations

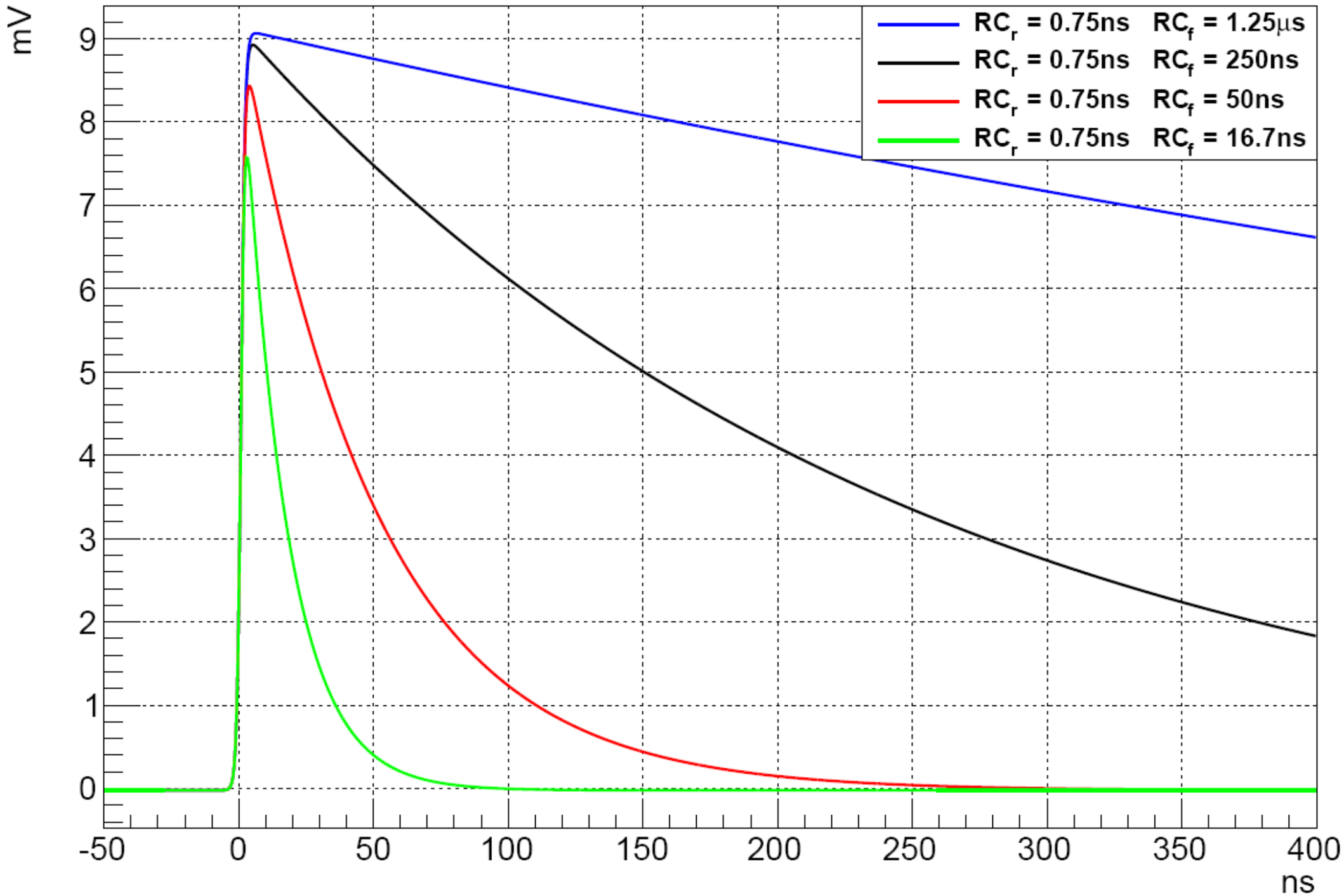
"Low" rate

- *High* value R_{fb}
- Preamplifier has *slow* return to baseline
- Differentiator gives a *unipolar* output pulse
- Shaped output returns to baseline much faster than preamplifier
  - High instantaneous rates possible
  - High sustained rates not possible

High rate

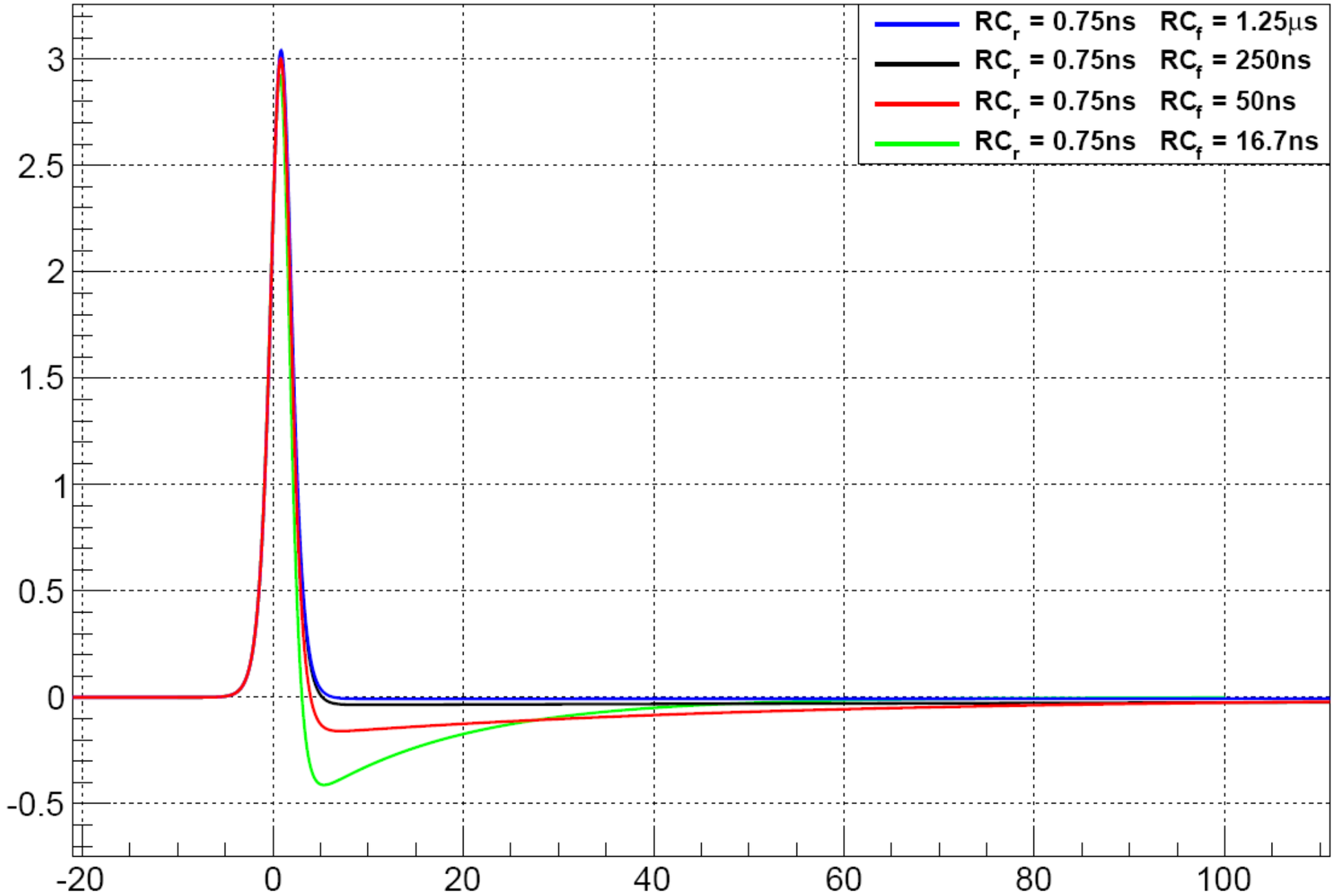
- *Low* value R_{fb}
- Preamplifier has *fast* return to baseline
- Differentiator gives a *bipolar* output pulse
- Shaped output returns to baseline with preamplifier
  - Lower instantaneous count rate
  - Much improved sustained count rate

Signal amplitude w.r.t Rise/Fall ratio



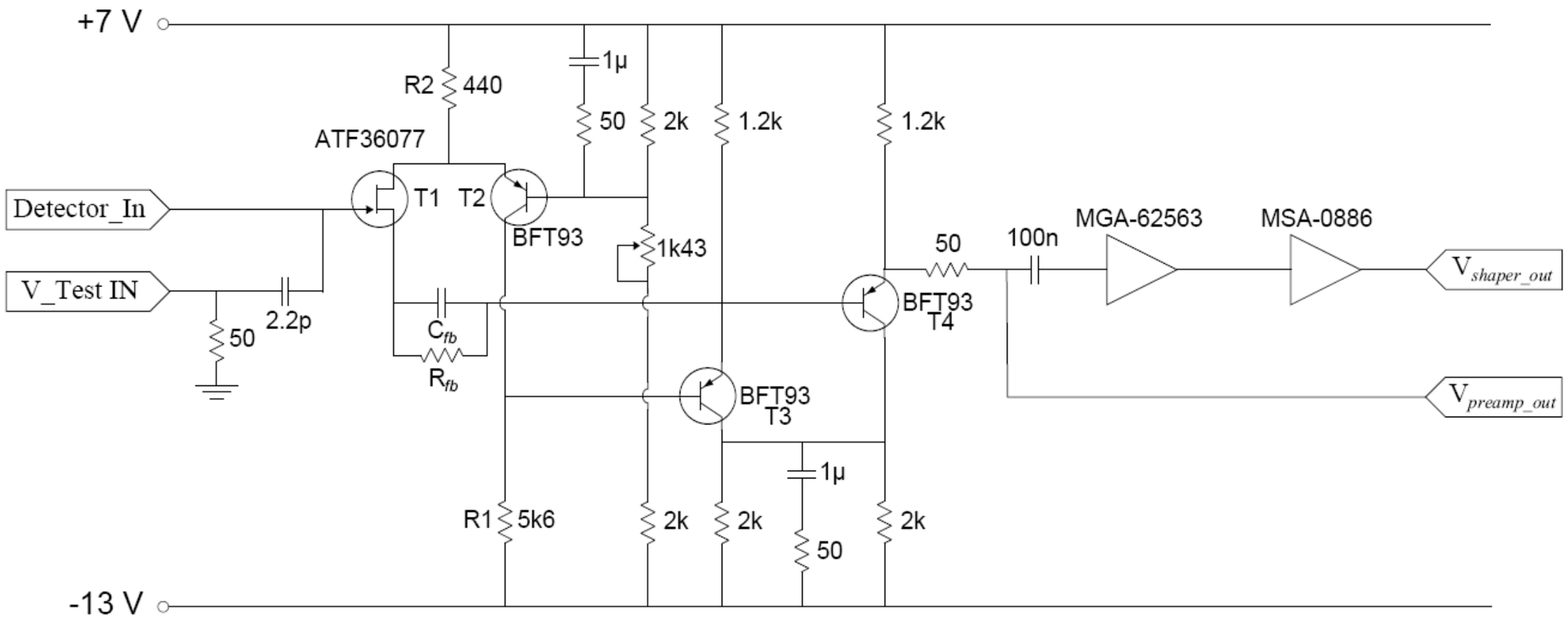
(a) Preamplifier output for several RC time constants.

Preamplifier Differential



(b) Differential of the preamplifier output.

Circuit topology



- Adaptation from a previous design [1] which achieved 139 e⁻ RMS (inc. shaping)
  - 20ns shaping & 25µs tail pulse
- Adapted to work with modern transistors
- HEMT transistor at input
- > ± 1kV HF bias tee

Component	Type	Gain @ Frequency	Noise @ Frequency	Role
ATF-36077	HEMT	17.0dB @ 4GHz	0.3dB @ 4GHz	Front-end
BFT93	PNP	16.5dB @ 500MHz	3.0dB @ 1GHz	Cascode
MGA-62563	MMIC	13.0dB @ 3GHz 20.0dB @ 1GHz 23.5dB @ 100MHz	1.5dB @ 3GHz 0.9dB @ 1GHz 1.1dB @ 100MHz	Differentiator
MSA-0886	MMIC	12.9dB @ 3GHz 22.5dB @ 1GHz 32.5bB @ 100MHz	- 3.3dB @ 1GHz 3.1dB @ 100MHz	Gain

[1] Adaptation of the preamplifier circuit in G. Bertuccio and A. Pullia; *An HEMT Input Charge Preamplifier for Nanoseconds Signal Processing Time; IEEE Trans. Nucl. Sci. Vol. 42, No. 2,* April (1995) 66.

SPICE Simulation

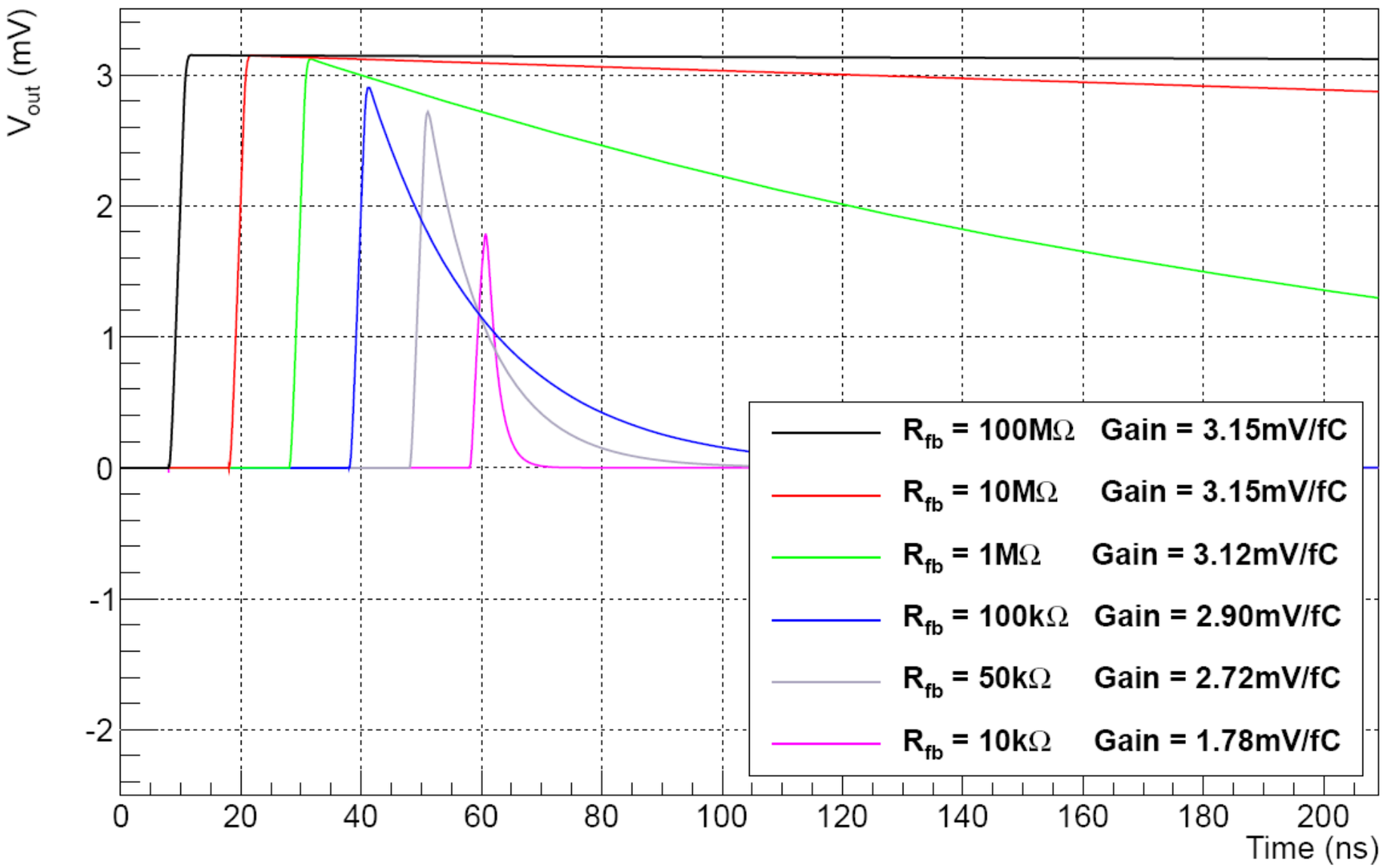
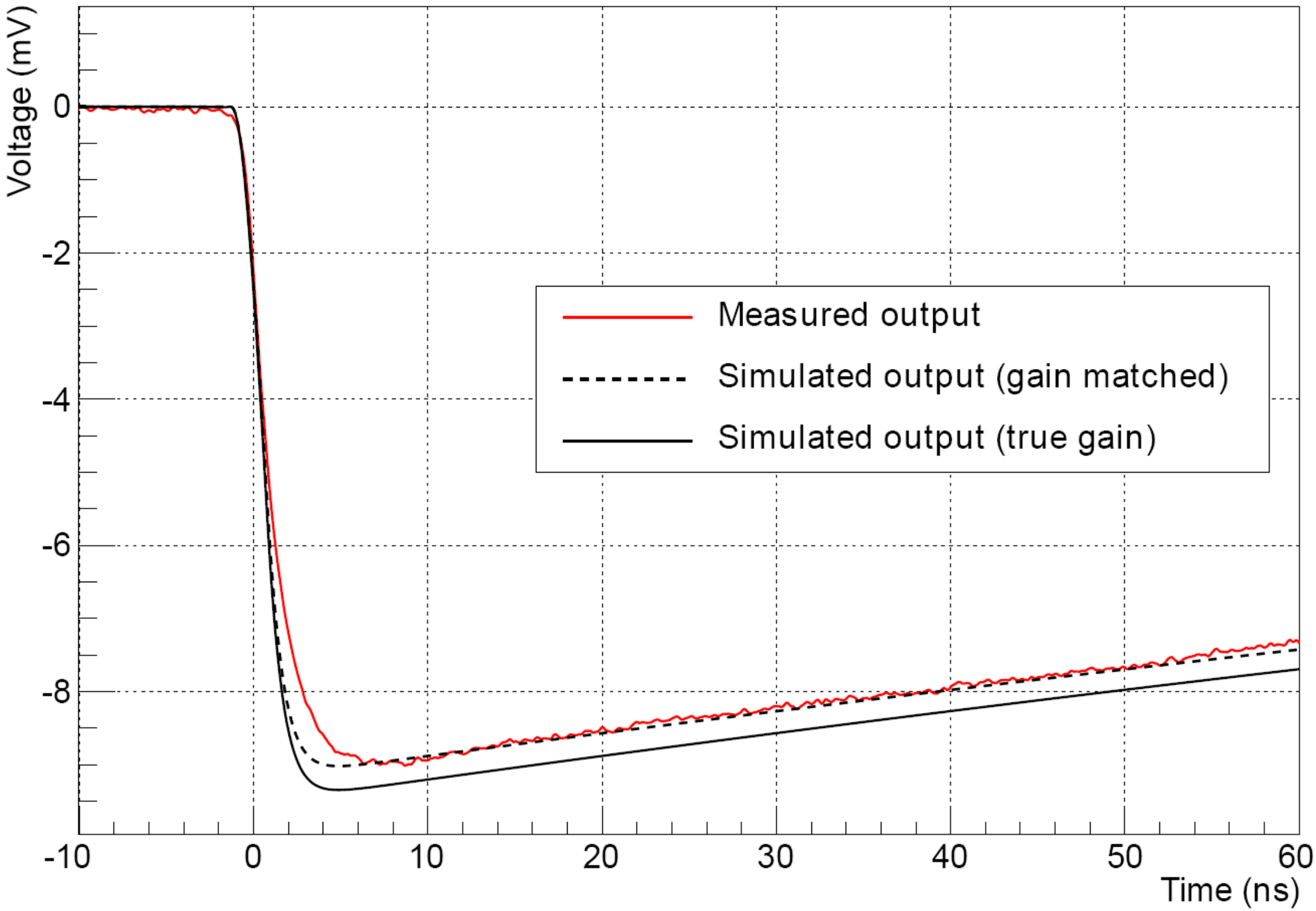


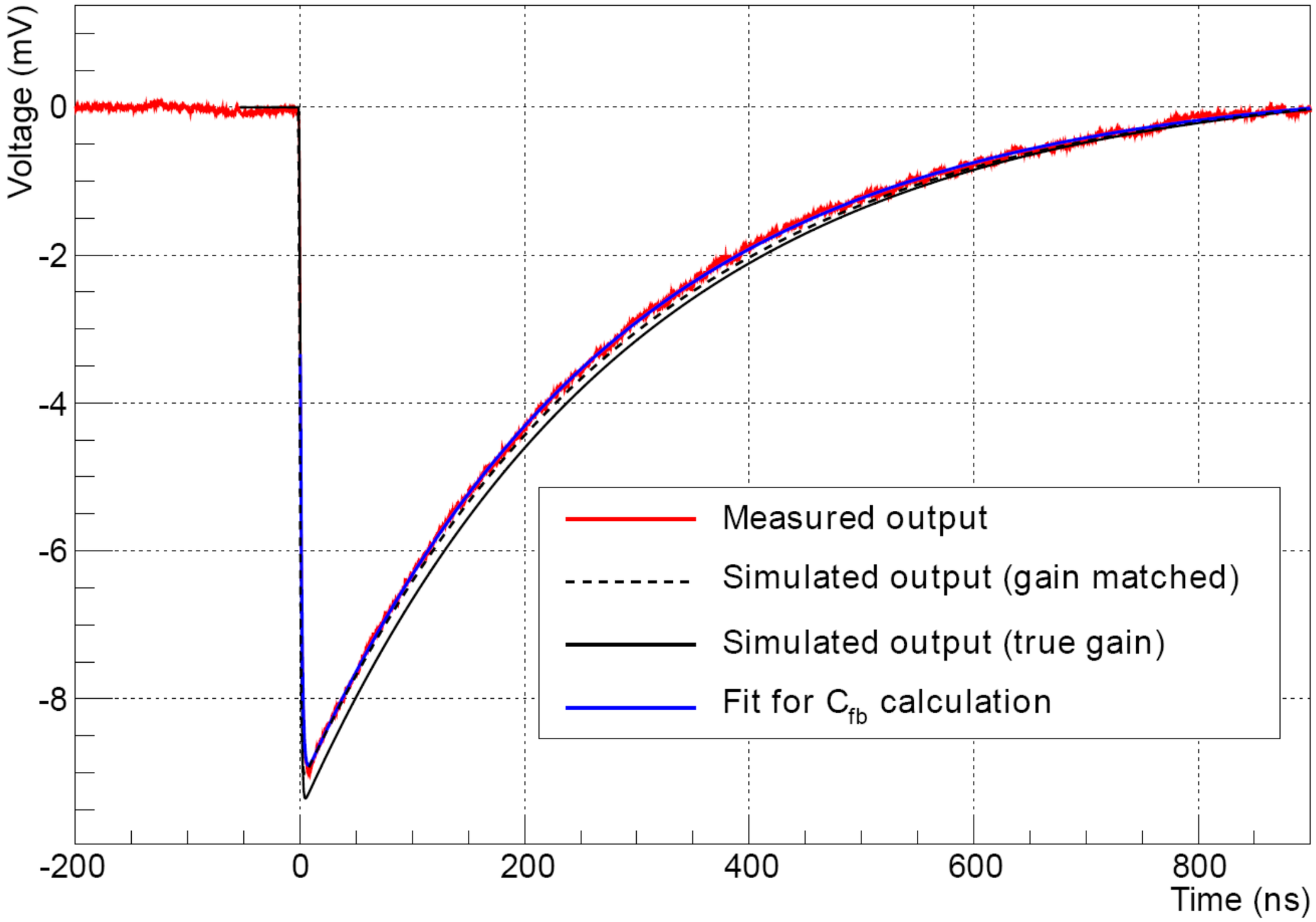
Figure 5.8: SPICE simulation of the preamplifier's performance for various R_{fb} values with a constant value of $C_{fb} = 0.28$pF. The injected charge is 1fC, with the height of the peak defining the gain. A 10ns time offset has been applied to each of the series to help aid comparison.

Preamplifier performance



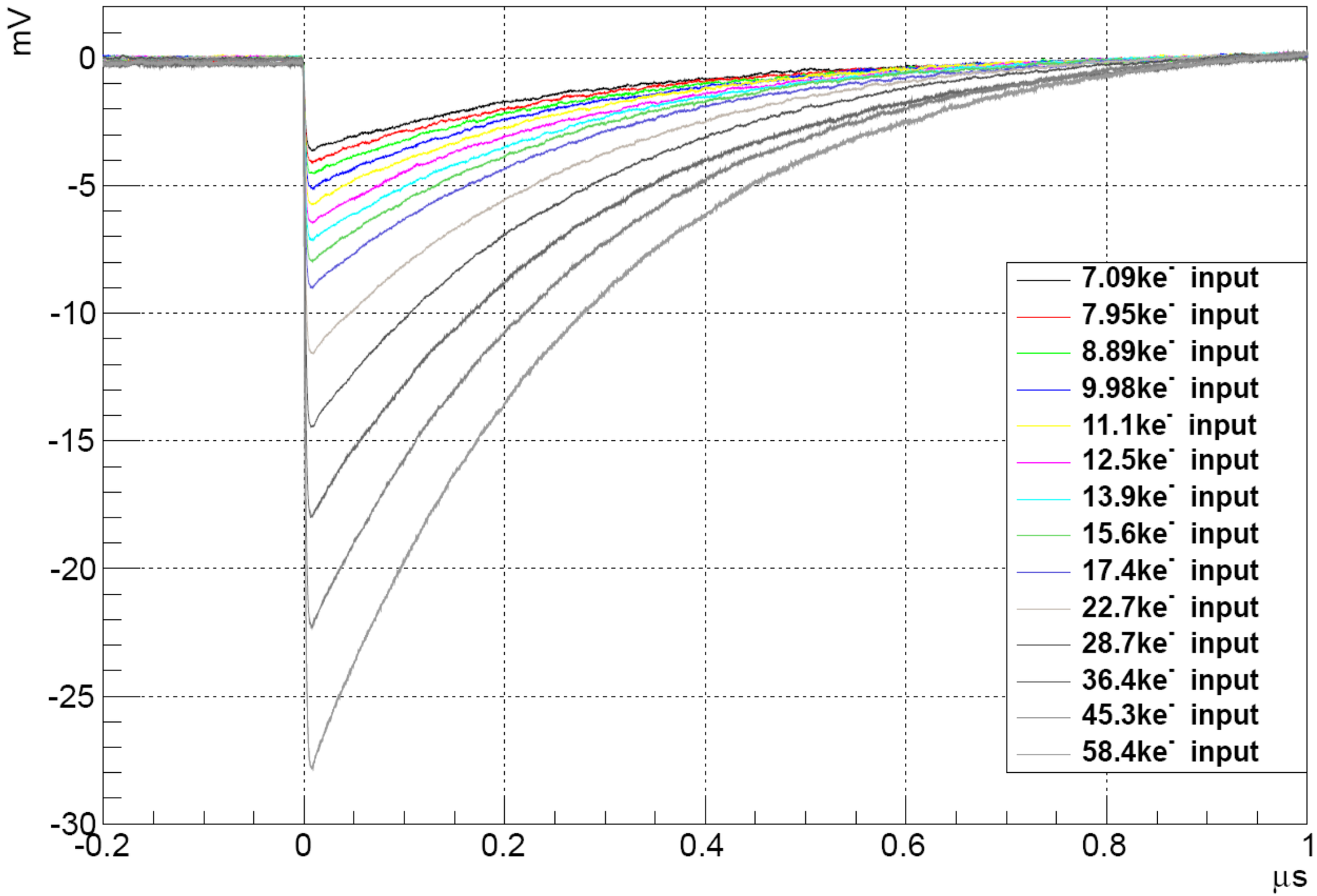
(a) Short timebase

Preamplifier performance



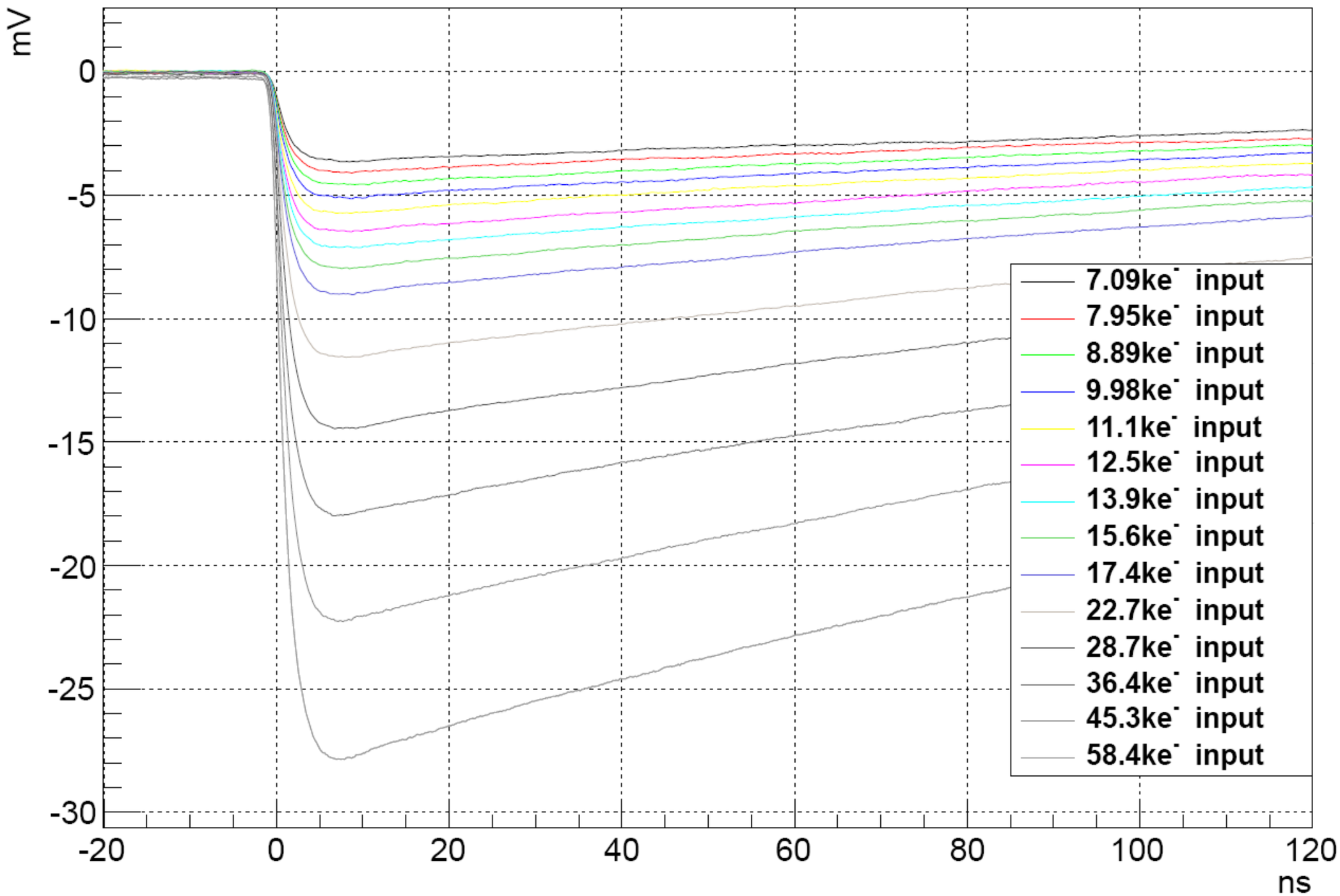
(b) Long timebase

Preamplifier performance



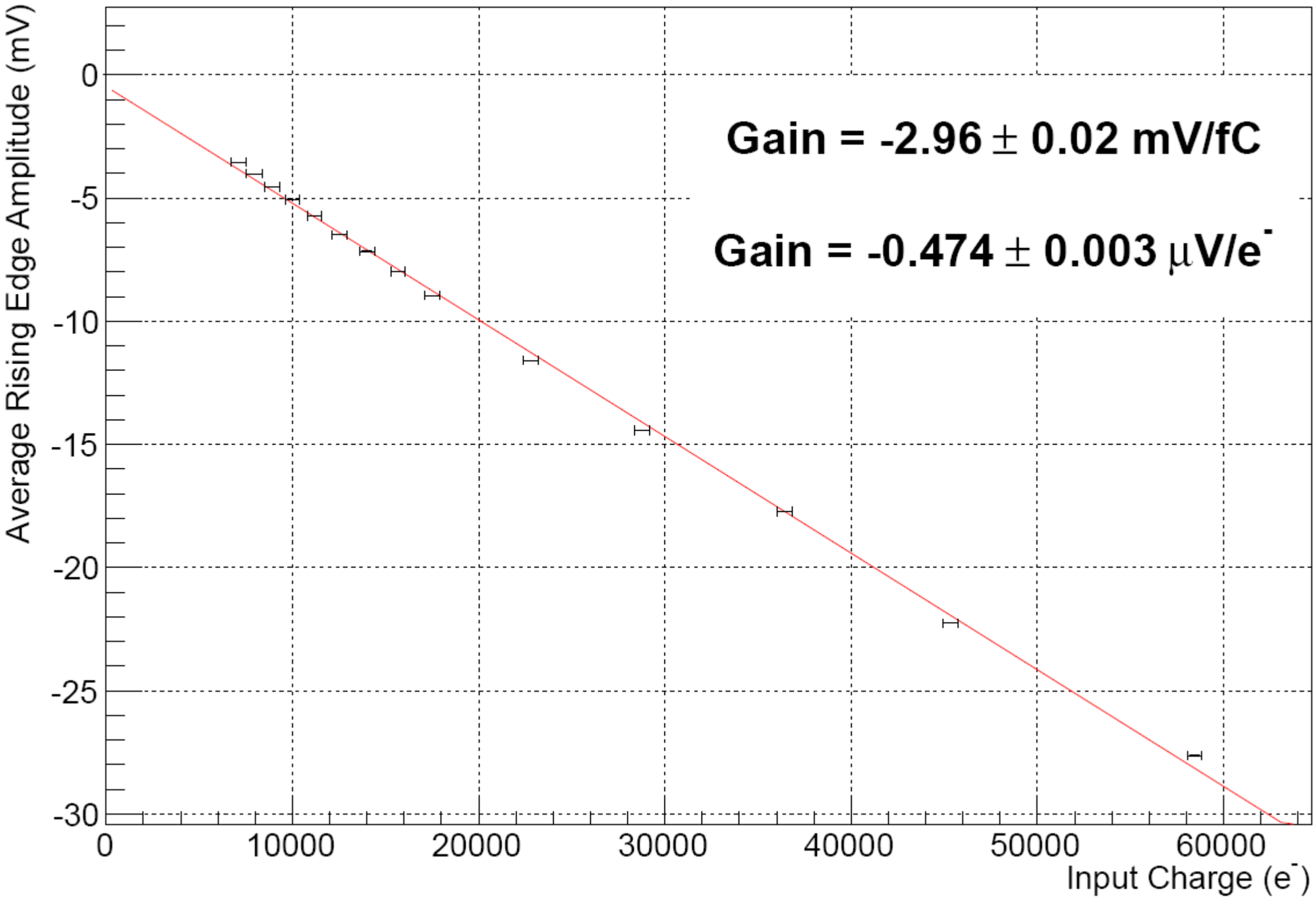
(a) Long timebase

Preamplifier performance



(b) Short timebase

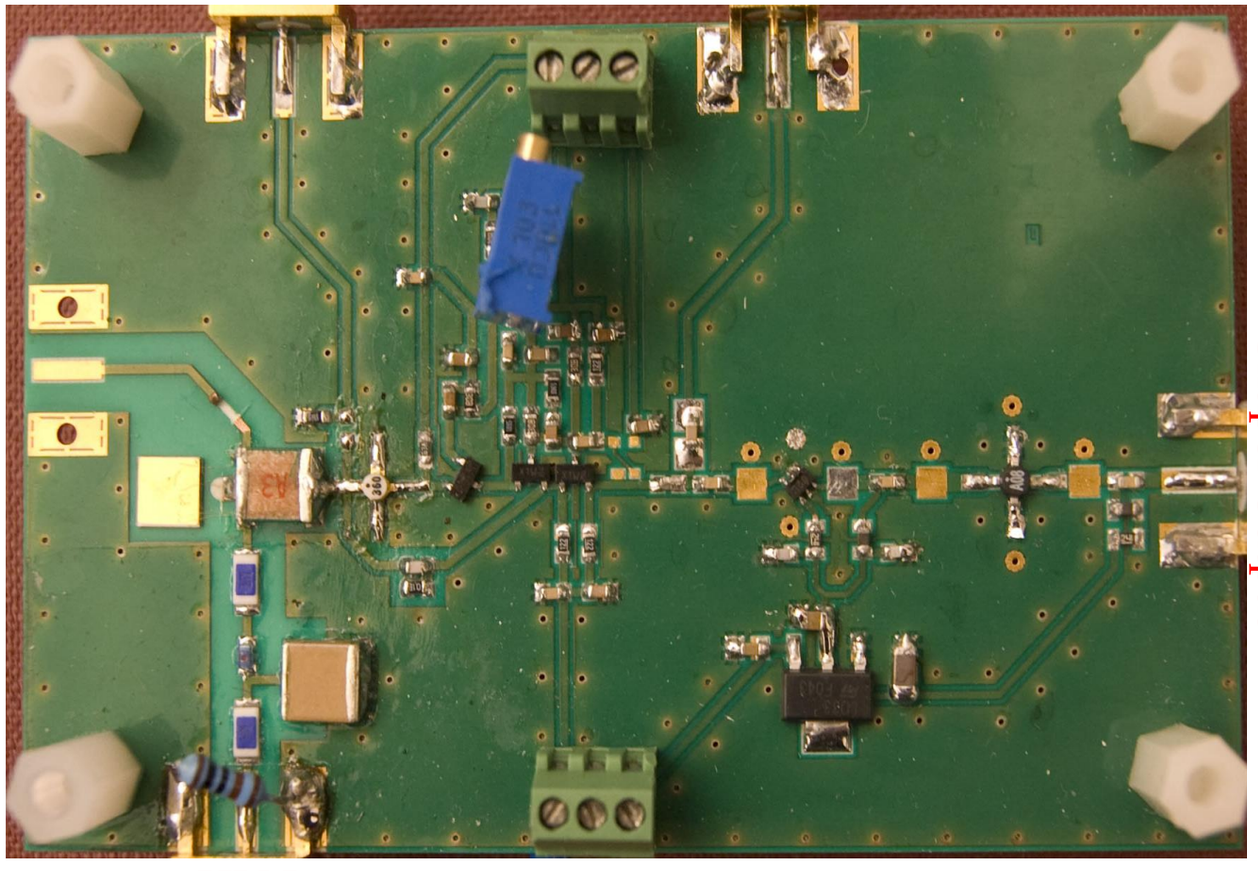
Gain measurement



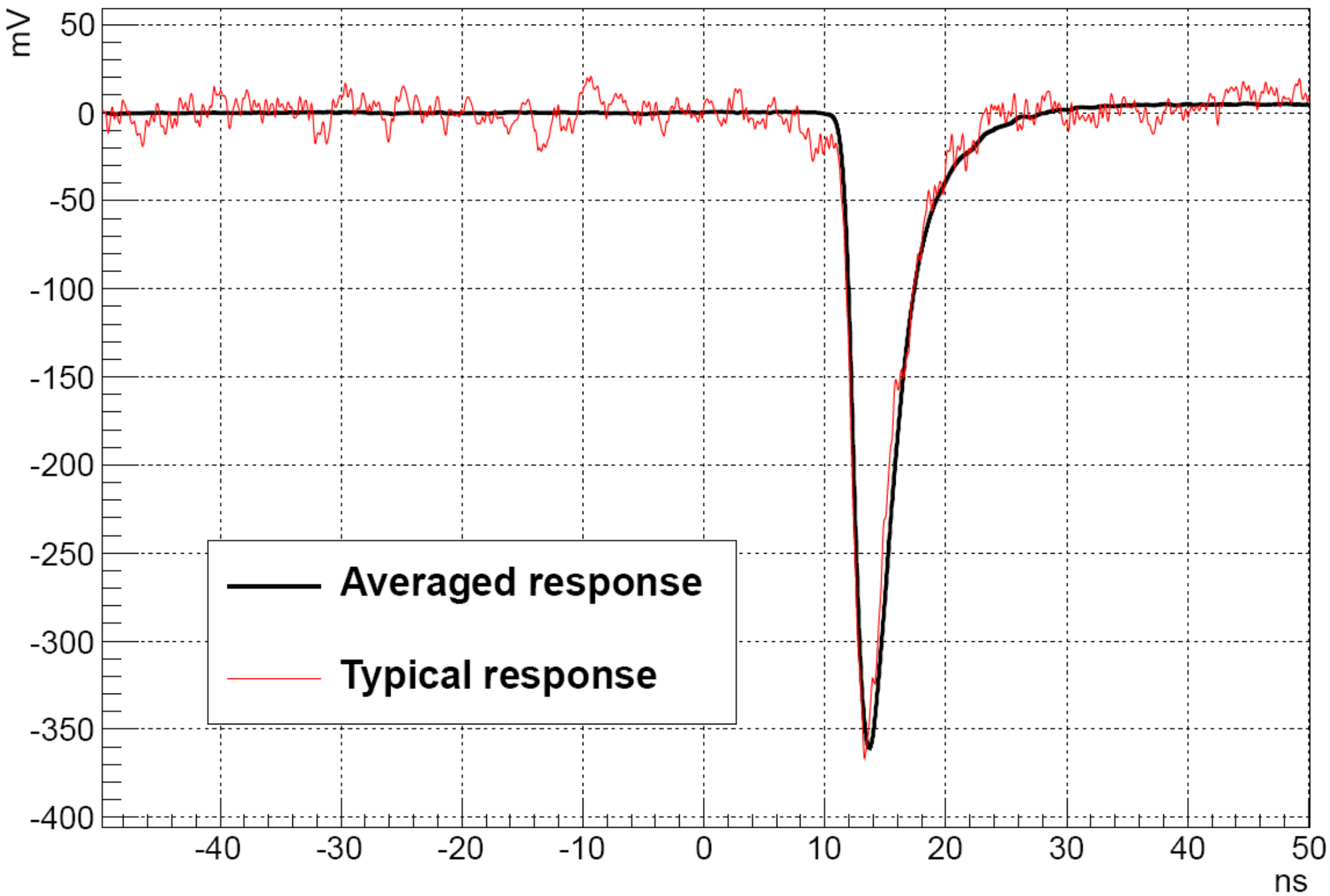
Preamplifier performance comparison

	Configuration	Units	Simulation	Measured
Gain	0.28pF// 1MΩ	mV/fC	3.12	2.96

Measurement	Simulation	Measured
Rise time - 10%-90%	2.1 ns	3.4 ns
Rise time - 20%-80%	1.7 ns	2.2 ns

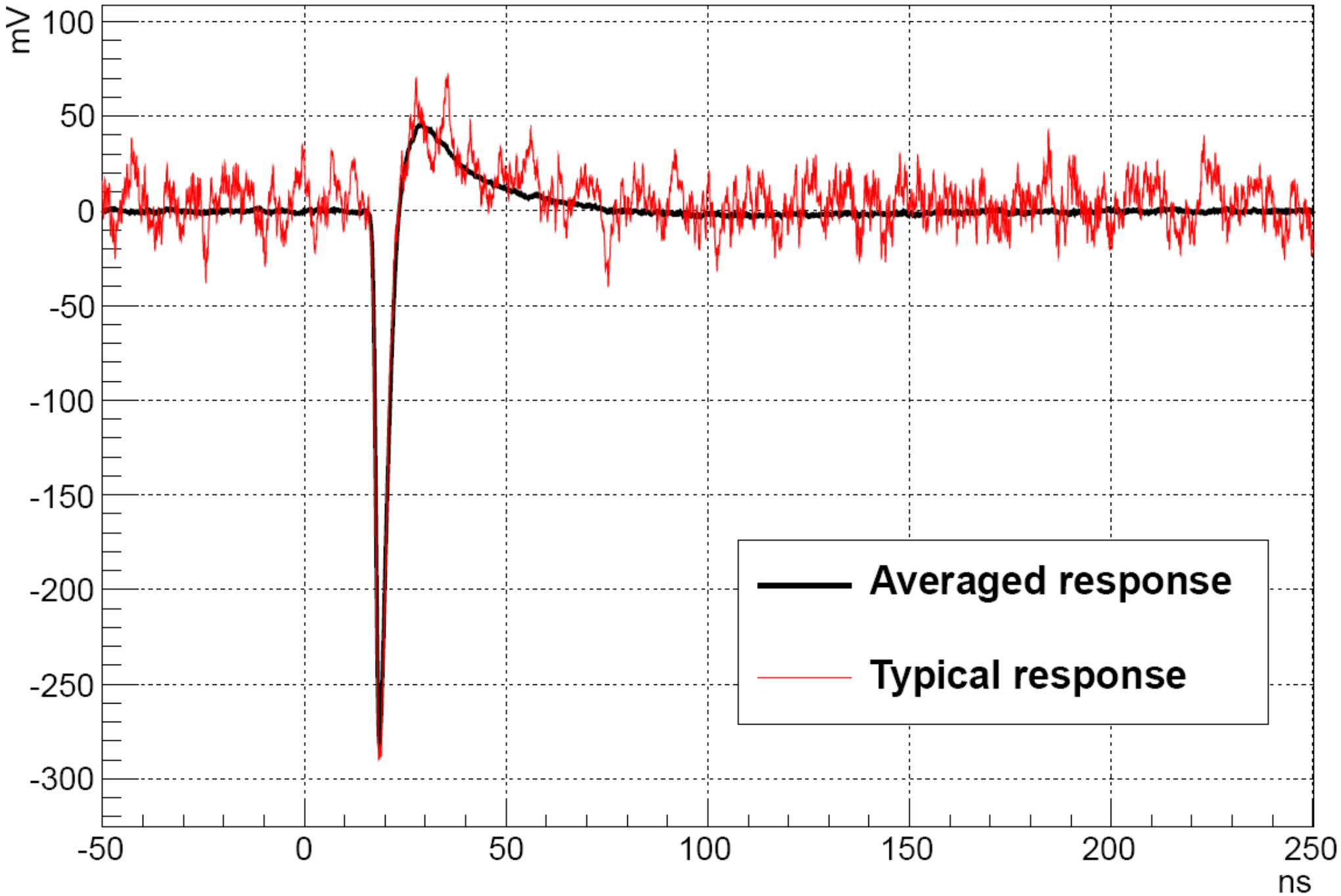


Low rate (unipolar) MIP Response



(a) Long preamplifier time-constant configuration of 0.28pF//1MΩ giving a unipolar shaped output.

High rate (bipolar) MIP Response



(b) Short preamplifier time-constant configuration of 0.28pF//50kΩ giving a bipolar shaped output.

Timing a bipolar output

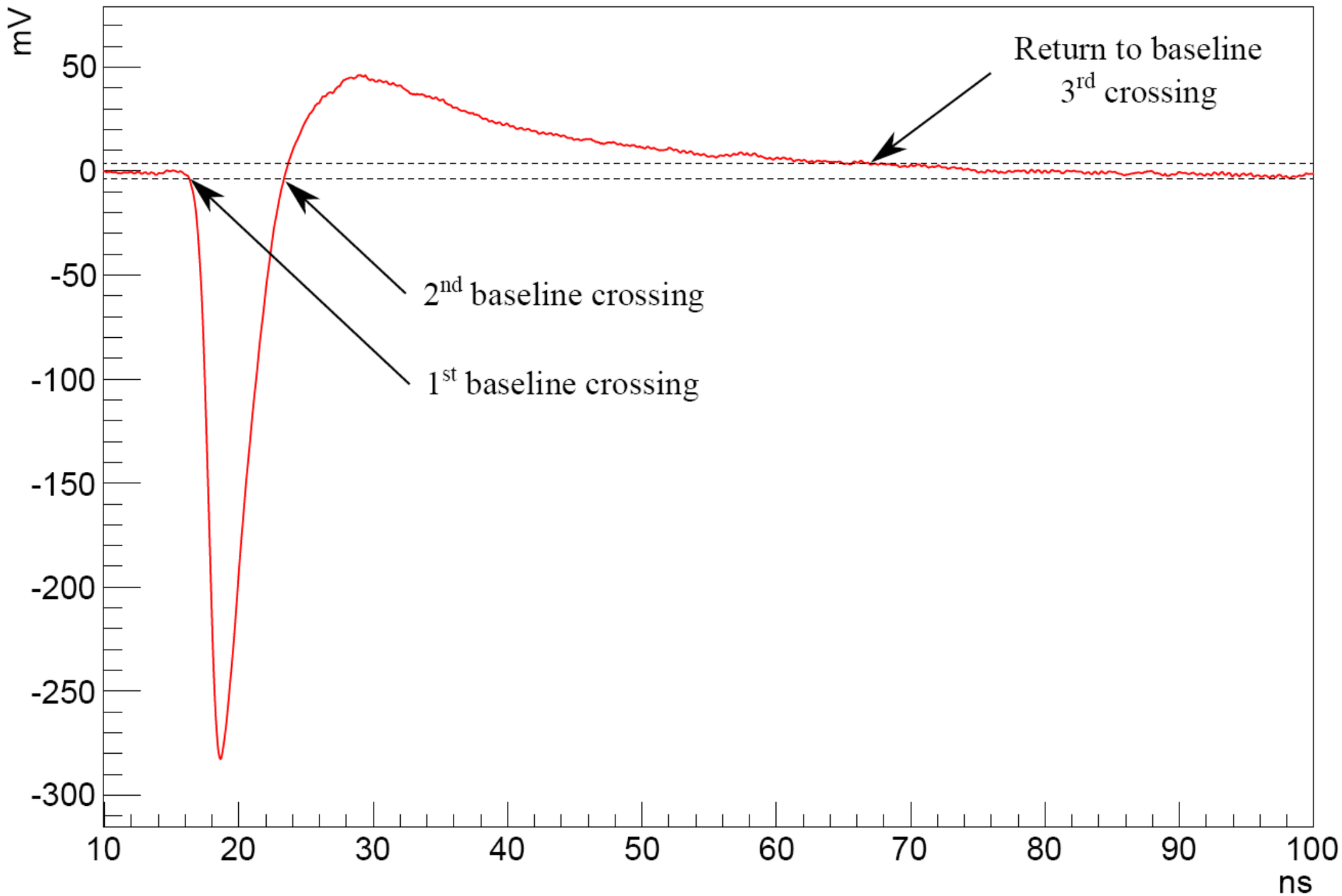


Figure 5.15: Definitions used for timing measurements of the bipolar pulse output.

Shaper timing performance

	FWHM (ns)	20-80% (ns)	10-90% (ns)	Baseline 2% (ns)	Baseline 1% (ns)
Unipolar	3.75	1.0	1.6	13.9	15.0
Bipolar	2.95*	0.9*	1.3*	44.8	52.7

Table 5.5: Combined preamplifier/shaper timing performance. The baseline calculations for the bipolar pulse use the definitions given in Fig. 5.15.
* FWHM and rise time measurements for the bipolar pulse shape are made using the first (negative-going) portion of the pulse for comparison with the unipolar output.

Combined Amplifier Gain vs Noise

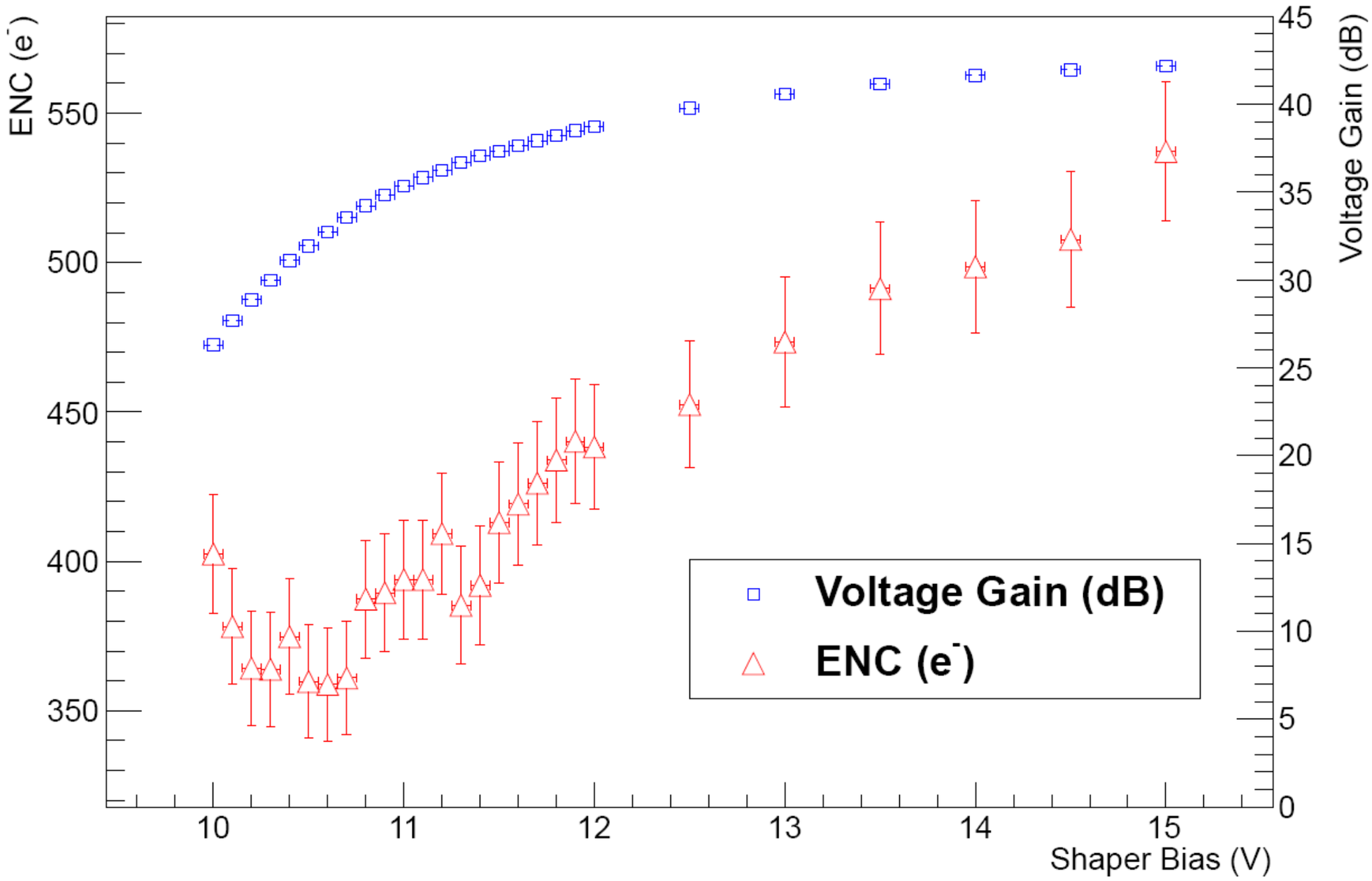
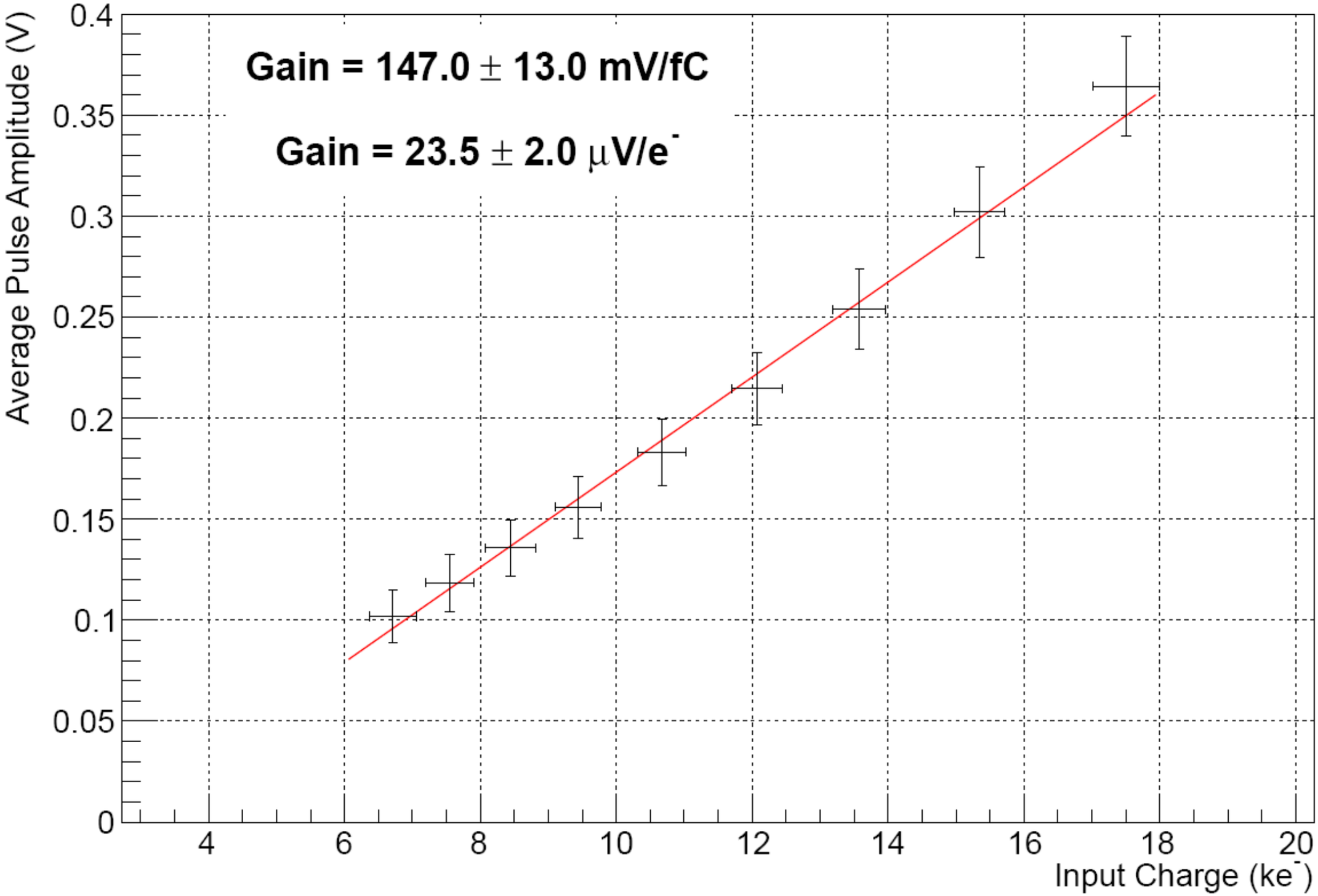
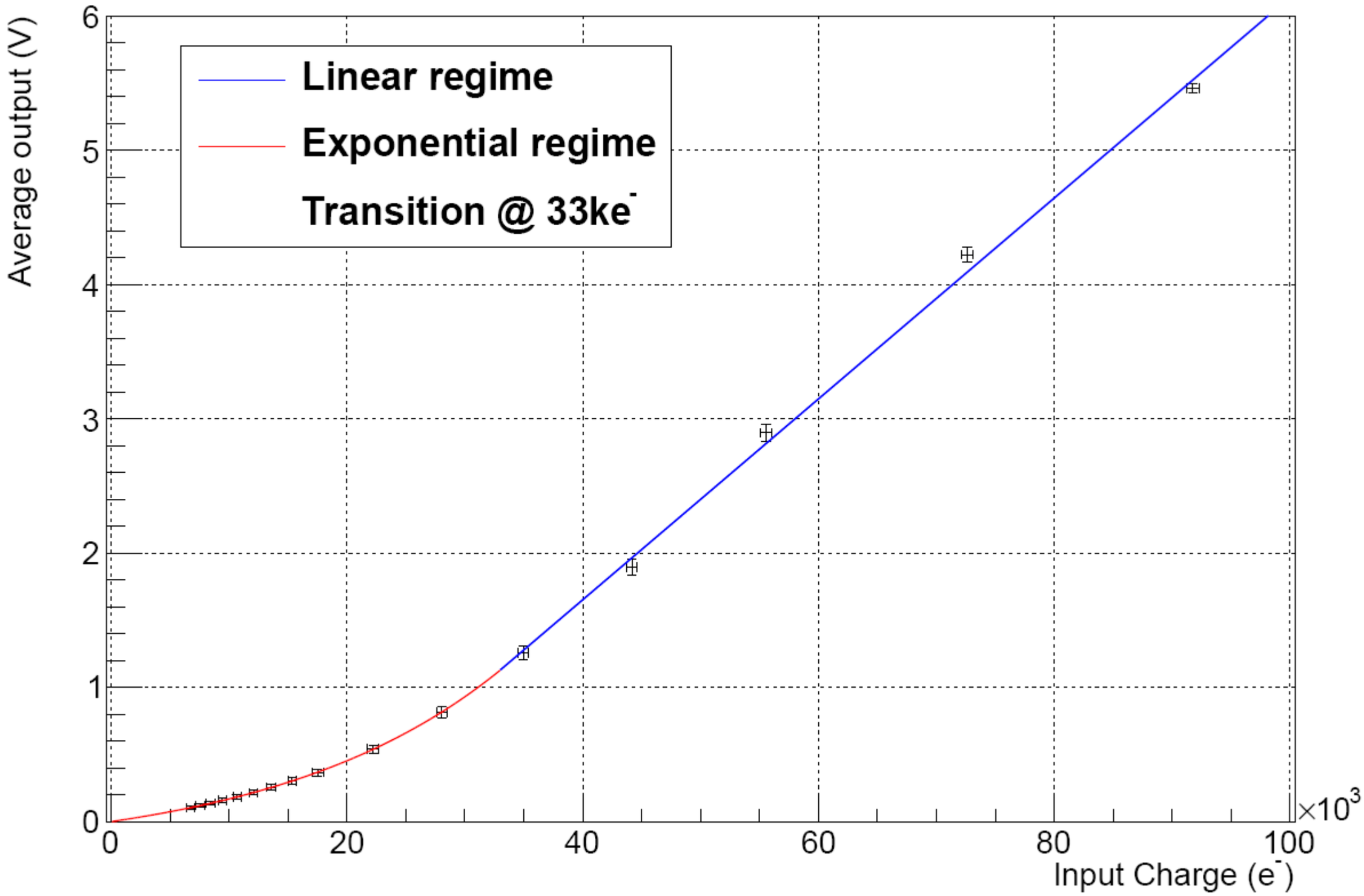


Figure 5.19: ENC and voltage gain of the combined preamplifier and shaper as a function of the shaper supply voltage. A fixed input charge of 2.88fC was used as the input.

Total system gain



Total system linearity



Comparison with commercial products

Amplifier	Type	ENC (e^-)	Gain (mV/fC)	Rise Time (ns)	FWHM (ns)
Cividec C6 [90]	Preamp & shaper	1000	4.4	3.5	10
Cividec Cx [90]	Preamp & shaper	300	8.3	80	180
eV-5091 [91]	Preamp & shaper	~550	1	20	25,000
Amptek A250 & A275 [92]	Preamp & shaper	~150	1	>20	250
Amptek A225 [92]	Preamp & shaper	280	5.2	2400	>4,000
Amptek A250 [92]	Preamplifier only	100	1	2.5	n/a
Design from [94]	Preamp & shaper	139	unknown	2.8	~38
This work [100]	Preamp & shaper	293	146.8	2.12	3.75

- Whilst some properties are matched by commercial solutions, not all can be found in one package
  - Comparable ENC to leading commercial amplifiers
  - Fast leading edge response
  - Narrow pulse widths
  - Very high gain

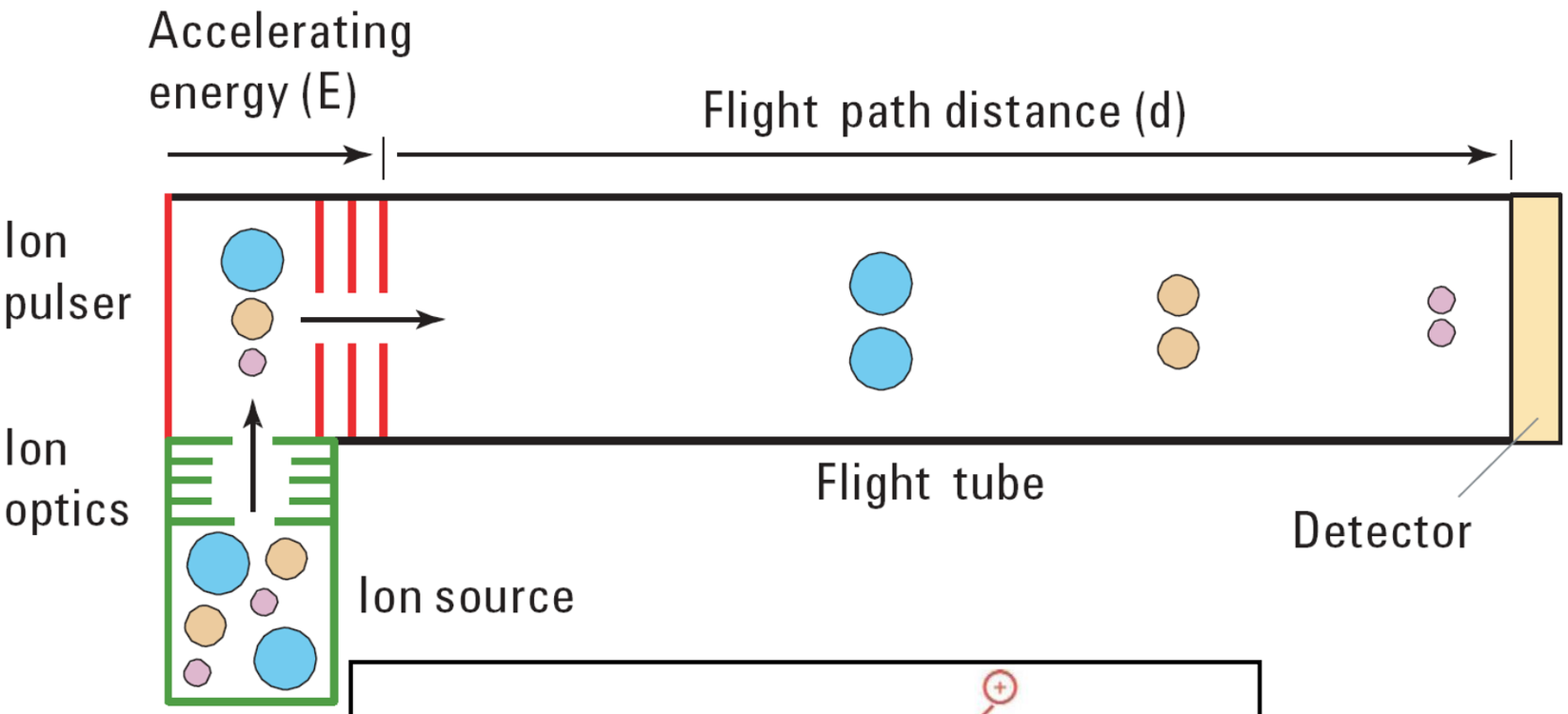
[100] M. Fisher-Levine, J. Velthuis, D. Cussans, and S. Nash, "A fast analogue front end for a diamond radiation spectrometer." *Nuclear Science, IEEE Transactions on*, 2013, vol. PP (99): pp. 1–5, ISSN 0018-9499. http://dx.doi.org/10.1109/TNS.2013.2280972

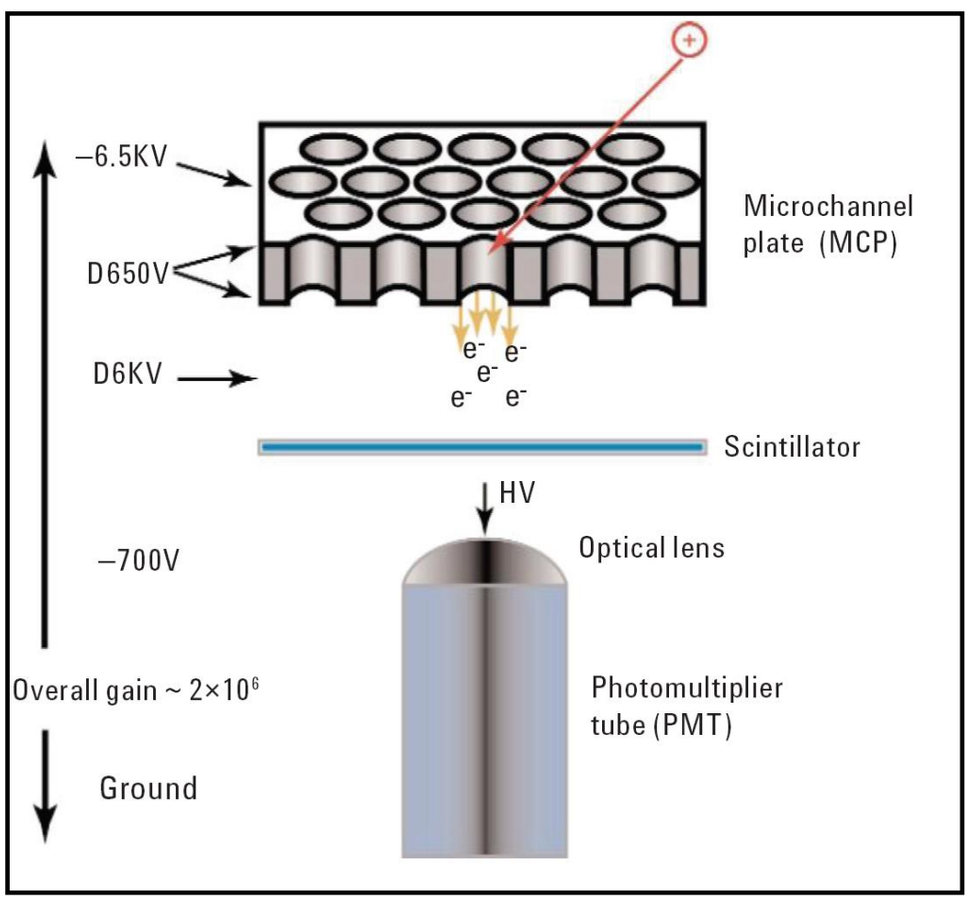
Conclusion

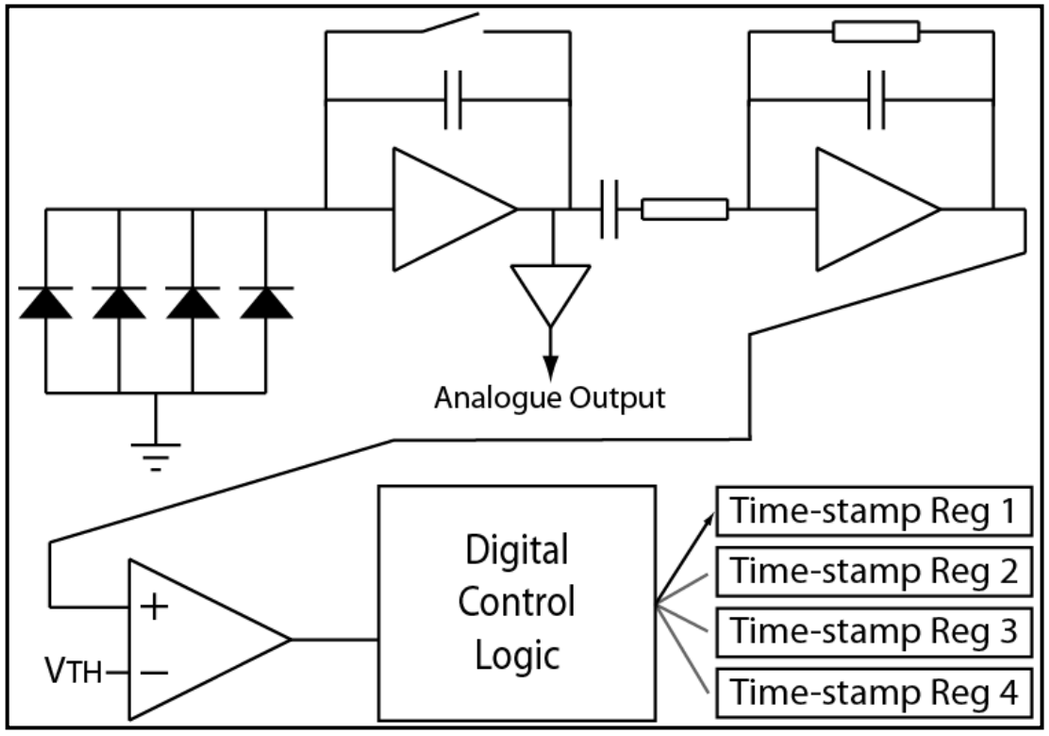
- Synthetic diamonds can be used for radiation detection
  - Many advantages over silicon and other materials
- An automated system was built to measure diamond quality
- A fast charge sensitive and shaping amplifier was built using discrete components
  - 2.1ns rise and 3.75ns FWHM signal times achieved
- High gain and good noise performance was achieved with fast pulse shaping
  - 147mV/fC and 293e^- RMS
- Combines many commercially available specifications into one device

Future Work at BNL

PImMS – A time-stamping pixel detector

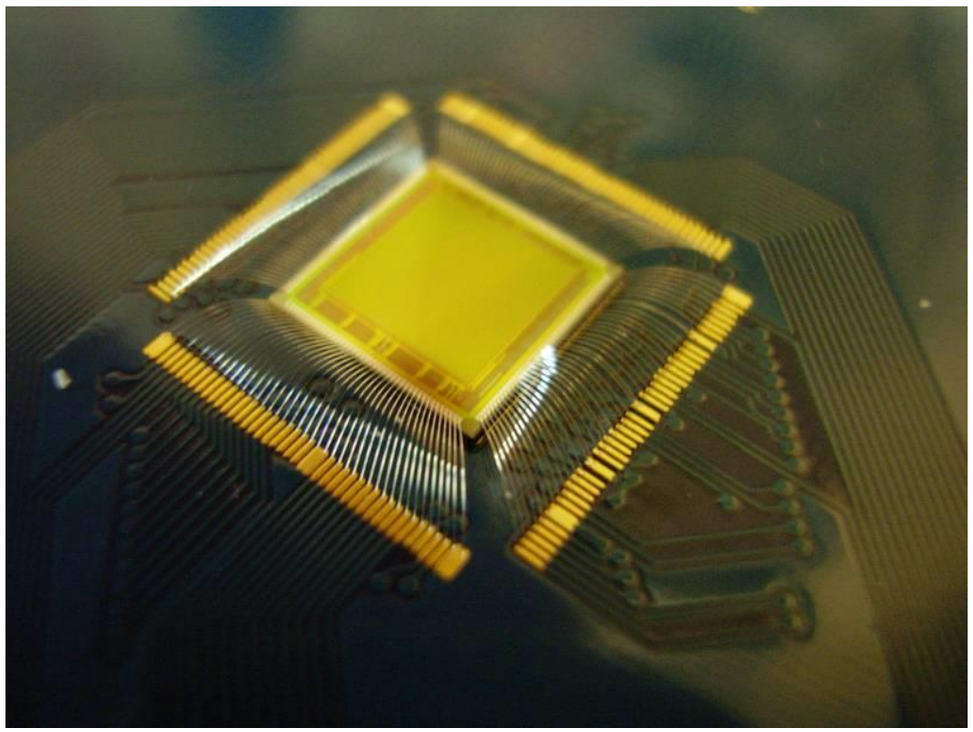


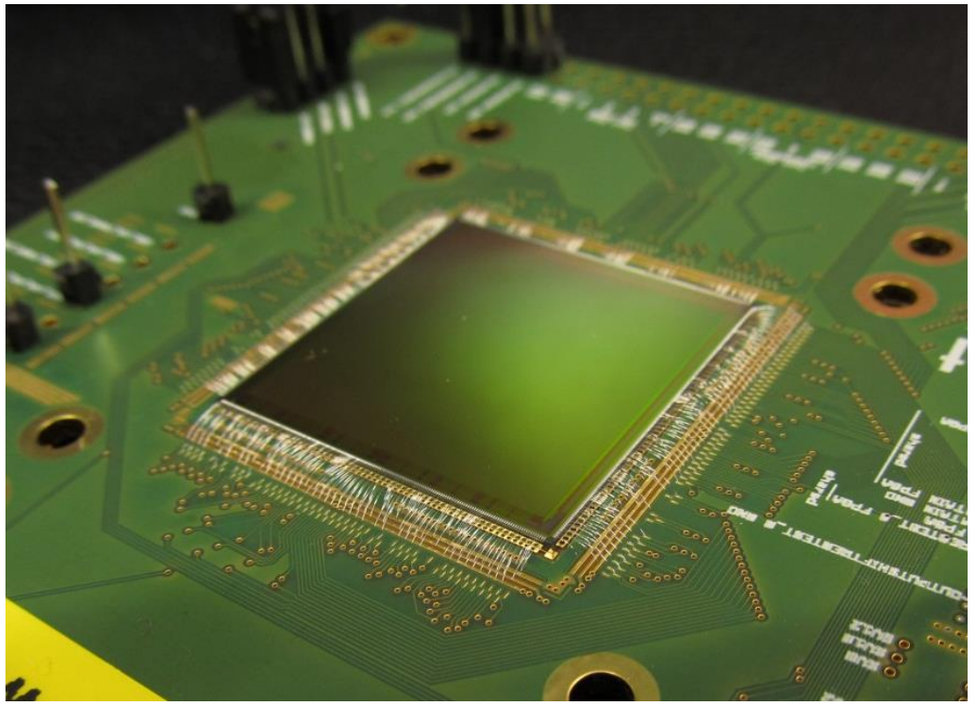




Fast Imaging with PImMS

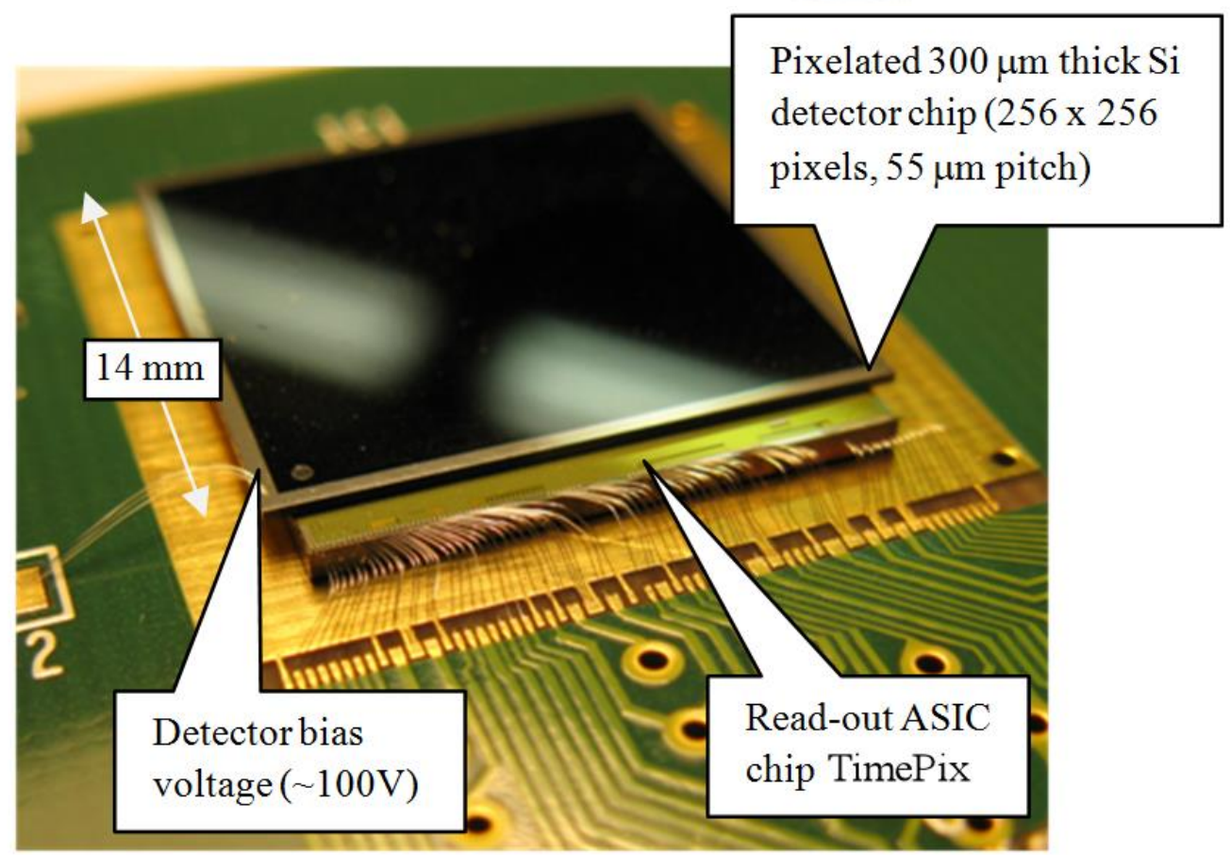
- Pixel Imaging Mass Spectrometry (PImMS)
  - INMAPS CMOS sensor
- 324 × 324 pixel array
- 70μm × 70μm pixels
- 80MHz clock
  - →12.5ns time resolution
- 12 bit timestamp register
  - 50μs experimental window at full speed
- Multi-hit capability
  - 4 timecodes per pixel





Fast Imaging with Timepix

- Timepix sensor bump-bonded to silicon pixel sensor
- 256 × 256 pixel array
- 55μm × 55μm pixels
- 100MHz clock
  - →10ns time resolution
- ~14 bit timestamp register
  - 118μs experimental window at full speed
- No multi-hit capability
  - Use it once and it won't record again



Synergy with LSST & NSLS-II

- Using LSST data analysis software (DMstack) for analysis of mass spec data
  - Similar requirements of cluster finding etc

- Time resoloved x-ray imaging for NSLS-II
  - 10ns is orders of magnitude better than is currently available!

From Bristol & DDL, many thanks to:

Jaap Velthuis
Dave Cussans
Kevin Oliver
RD42 Collaboration
Steve Nash
Scott Kolya
Magnus Loutit

and many others for all their help and support with this work and to

Andrei Nomerotski & Brookhaven Lab

for my new job!

Thank you for listening!

Any questions?