Survey of edge-TCT measurements at CERN

Irena Dolenc Kittelmann,
M. Moll, M. Gabrysch, N. Pacifico
CERN

Outline

- Extraction of trapping time profiles from eTCT measurements
  - 2 methods proposed
  - Extraction of electric field profile from measured drift velocity profile (electric field profile required by both methods)
  - Determination of transfer function of the measurement system (required for 1. method)
  - An example of 2. method (1. method presented at 19th RD50 workshop)

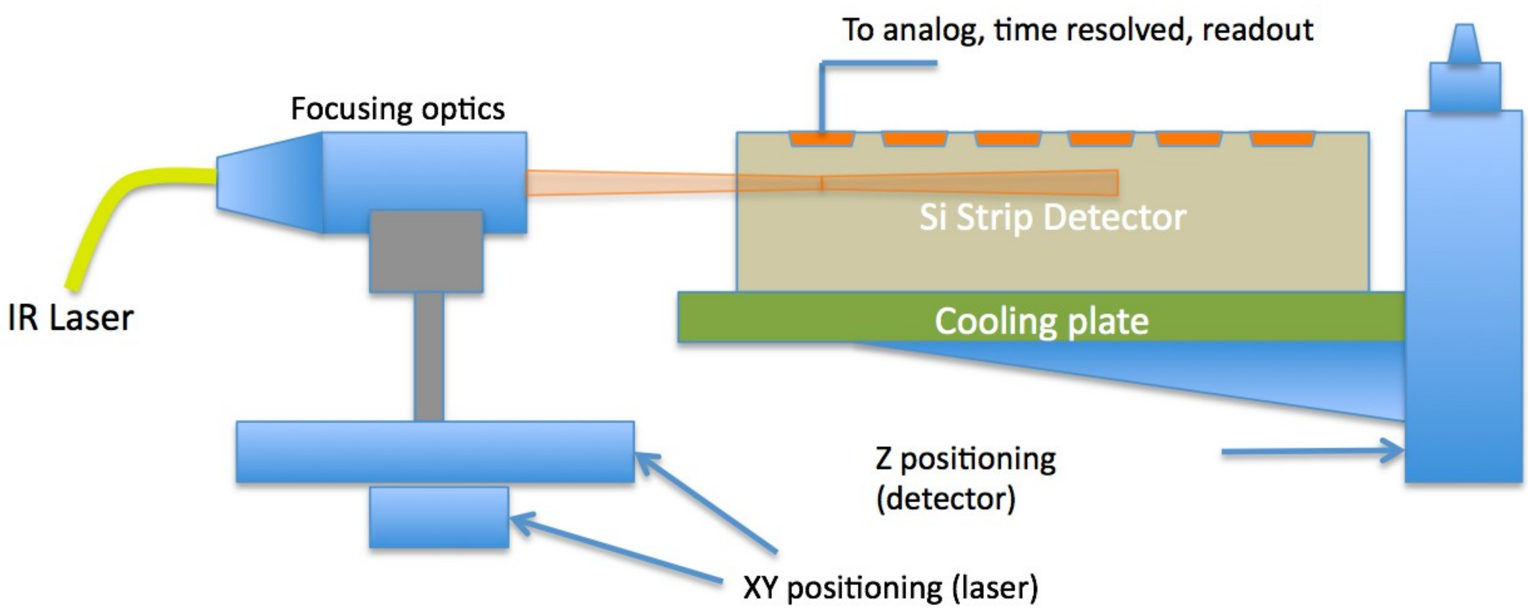
- eTCT measurements with p-type strip detectors after proton irradiation (*N. Pacifico*'s PhD, also presented at 19th RD50 workshop)
  - Study of annealing development of drift velocity and efficiency profile behavior in FZ and MCz p-type detectors
  - Study of effect of oxygen enrichment on drift velocity and efficiency profiles

Part 1:
Trapping time extraction from eTCT measurements

τ extraction from eTCT measurements

- Classical TCT measurement with red laser:
  - Offers trapping time determination with the assumption: $\tau_{e,h}(E) = \text{const.}$
  - Difficulties with trapping time extraction for highly irradiated detectors → $\tau_{e,h}(E) \neq \text{const?}$
- eTCT measurement:
  - Offers $v_{dr}(z)$ extraction → $\tau_{e,h}(E)$
  - Investigating 2 different methods

eTCT technique



- For details on eTCT and related analysis see [1]
- Drift velocity profile:
  - Integration window of 0.5ns from beginning of signal
- Efficiency profile:
  - Integration window of 25ns around the signal

[1] G. Kramberger et al., IEEE TNS, vol. 57, no. 4, August 2010, p 2294

Drift velocity deconvolution (1/5)

- Extraction of point charge $v_{dr,t}(z)$ required → deconvolution of measured $v_{dr,m}(z)$

- General remarks on deconvolution:

$$g(z)=h(z)*f(z)$$

  - Problem: deconvolution most often ill posed problem
    - In Fourier space $G(\omega)=H(\omega)F(\omega) \rightarrow F(\omega)=G(\omega)/H(\omega)$
    - $H(\omega)$ is typically a low pass filter, the inverse $1/H(\omega)$ is a high pass filter → amplifies noise and numerical errors!

  - Methods
    - Regularization (filtering)
    - "Fitting": take model function for *f* and vary parameters to fit the measured data, gives best results, if the model function is known...

Drift velocity deconvolution (2/5)

$$v_{dr,m}(z) = G(0,\sigma) * v_{dr,t}(z)$$

- Assuming Gaussian smearing function (laser beam, imperfection due to polishing)
- Tried several regularization methods
  - Problems: not edge preserving, can be time consuming, no reliable automatic algorithm for determination of regularization constants found …
- Decided to use “fitting” strategy
- $v_{dr,t}(z)$ function is modeled with N parabolas/lines applied to different regions of detector
- Least squares minimization with TMinuit is performed: typically Simplex method is used to bring initial guess closer to solution, followed by Migrad minimization to improve the result
- Parameters
  - σ of Gaussian smearing function
  - Points (z, v_{dr}) determining the N regions with different parabolas/lines
  - Constant a or b ($v_{dr}(z) = az^2 + bz + c$) for each parabola
  - Depending on the problem, some can be fixed before Migrad and/or Simplex minimization

Drift velocity deconvolution (3/5)

- Use deconvoluted $v_{dr,t}(z)$ → calculate $v^e{}_{dr,t}(z)$, $v^h{}_{dr,t}(z)$, $E(z)$

- Extracted deconvoluted $v_{dr,t}(z)$ in arbitrary units

- Constraint $\int E(z)dz = U_{bias}$ to determine the absolute scale
  - Fix normalization A of $v_{dr,t}(z)$ and calculate $v^e{}_{dr,t}(z)$, $v^h{}_{dr,t}(z)$, $E(z)$

    $$A \cdot v_{dr,t}(z) = (v^e{}_{dr,t}(z) + v^h{}_{dr,t}(z)) = E \cdot (\mu_e(E) + \mu_h(E))$$

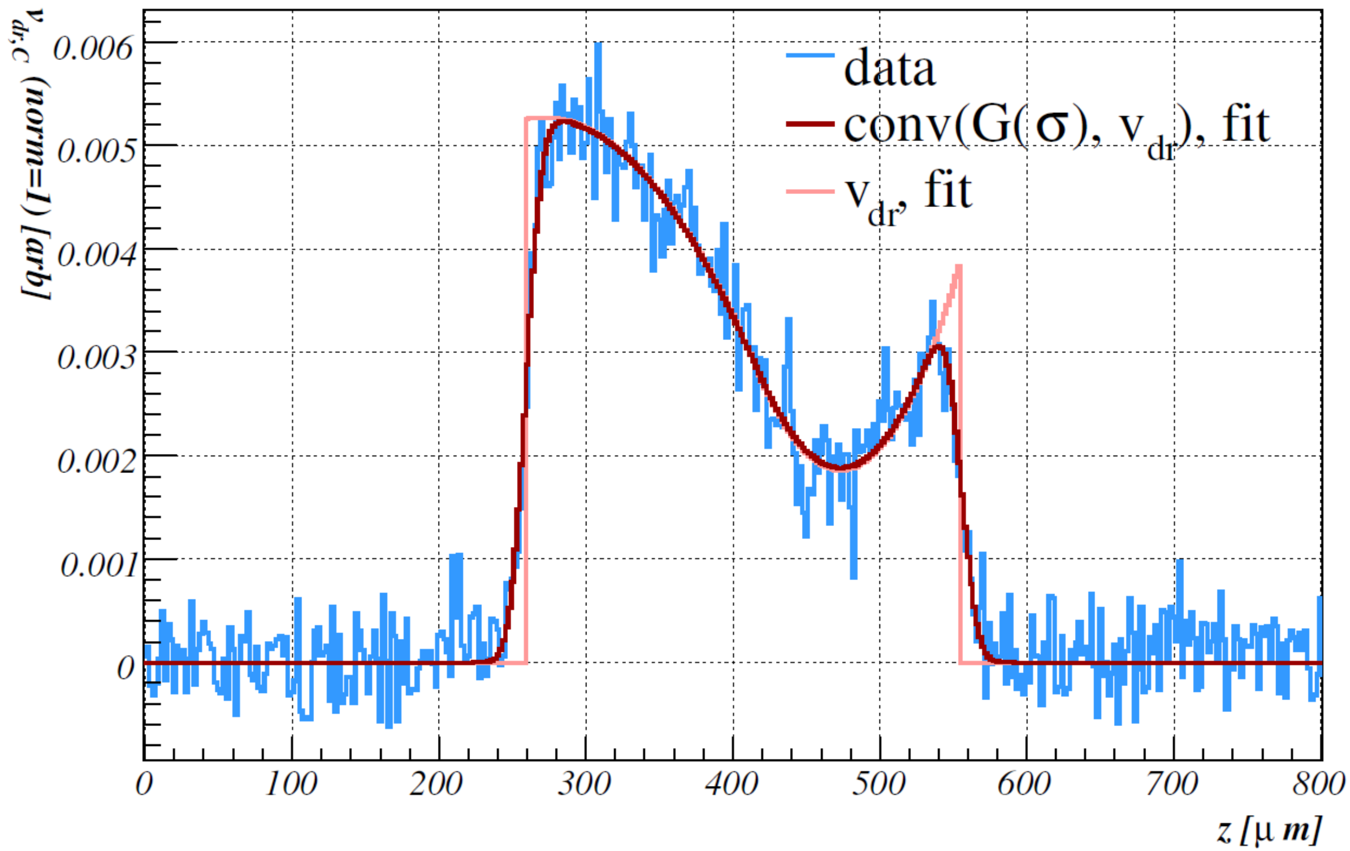
    $\rightarrow$ requires "bisection" like method at each z due to nonlinear mobility dependence on field
  - "Bisection": vary A until the constraint is $\int E(z)dz = U_{bias}$ is met

  - Limitations: fails at very high fields where both electron and hole drift velocities are saturated

Drift velocity deconvolution (4/5)

Example:

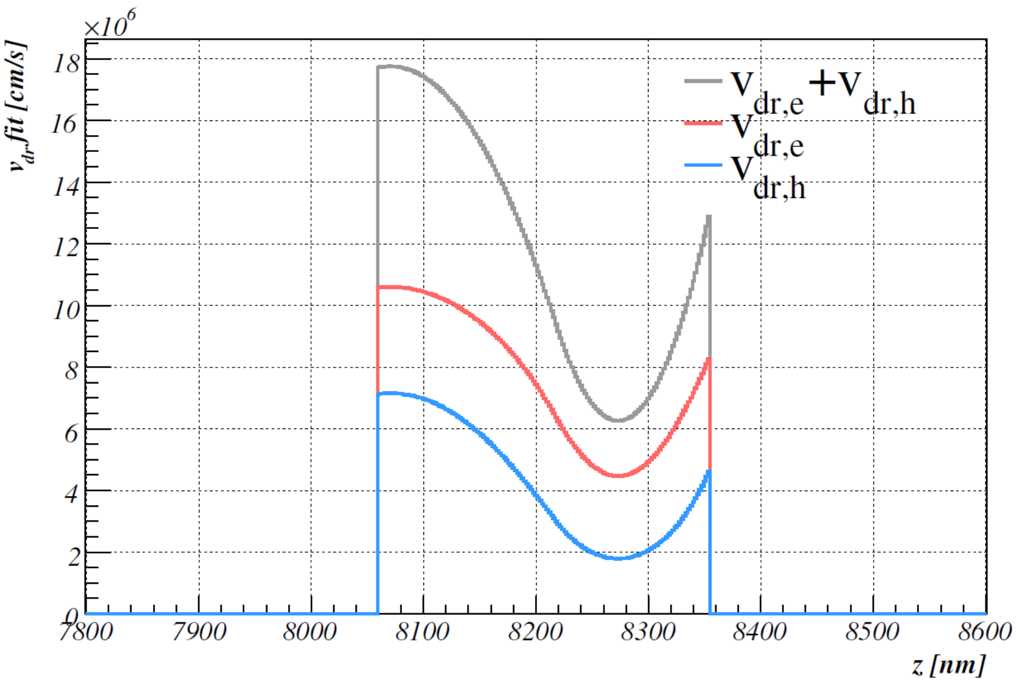
- Micron FZ-p strip detector, $\Phi=2\times10^{15}$protons/cm^2, in annealing minimum, U_{bias}=500V, measurement T=–25^{o}C
- Model function: 2 parabolas in 2 different regions
  - Gaussian smear: $\sigma_{best}=8.6\mu$m (laser σ=7.5-8μm)
  - Active region: $d_{best}=292\mu$m
- Calculated $E(z)$ and $v^e{}_{dr,t}(z)$, $v^h{}_{dr,t}(z)$ on next slide...



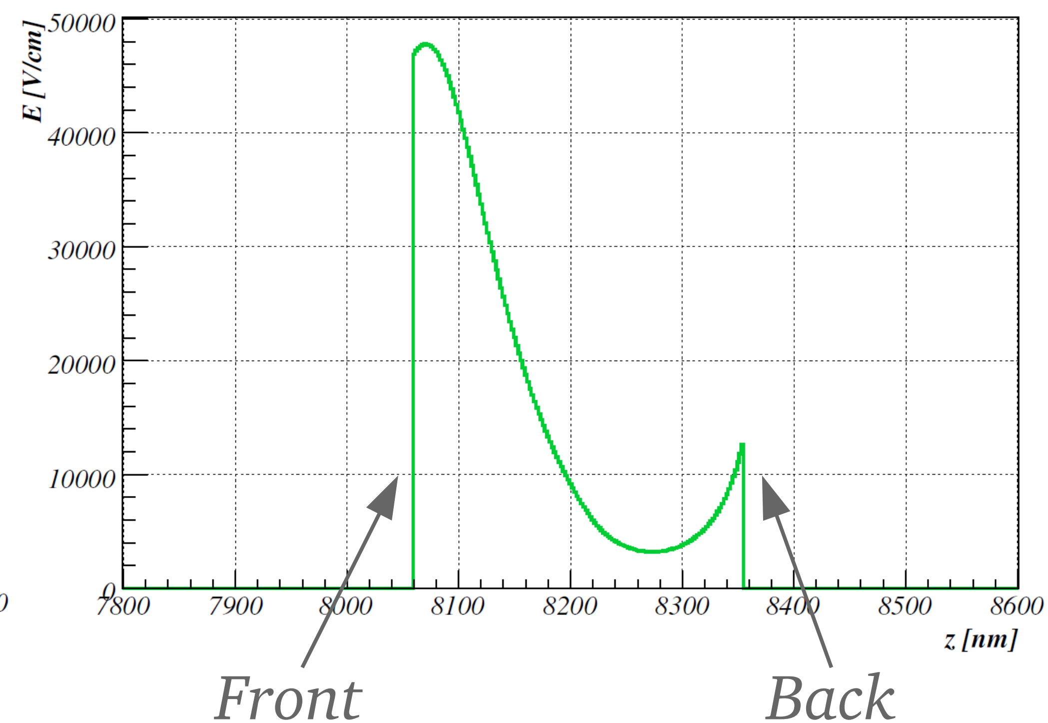
Drift velocity deconvolution (5/5)

- Calculated $v^e_{dr,t}(z)$, $v^h_{dr,t}(z)$, $E(z)$
- Mobility model: Jacoboni [2]

$v^e_{dr,t}(z)$, $v^h_{dr,t}(z)$



$E(z)$



[2] C. Jacoboni et al., Solid State Electronics, 1977, Vol. 20, 77-89

τ extraction: method 1

- Procedure:
  - Consider front/back injection (only one type of charge drifting)
  - *E(z)* → calculate induced current, assume Gaussian laser beam profile with σ as extracted from the deconvolution of $v^{e}_{dr,t}(z)$
  - Add trapping, convolve with transfer function and vary trapping model parameters to fit the result to measured waveform in the least squares sense (Minuit minimization)

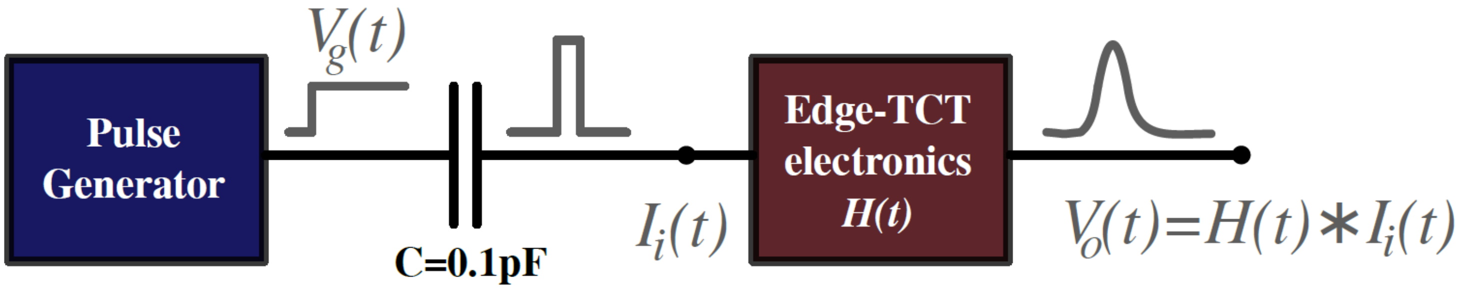
- Fit parameters:
  - Normalization constant (can be fixed, depending on the transfer function used)
  - Parameters for $\tau_{e,h}$ modeling

- $\tau_{e,h}$ modeling:
  1) Divided detector in *n* equidistant regions with different trapping time for each region
  2) Assume some other dependence on electric field (linear, exp...)

Transfer function of the meas. system (1/5)

- Method 1) for trapping time extraction requires knowledge of transfer function of the measurement system

- Option: measured I_i and V_o(2.5GHz scope,Agilent DSO9254A):



I_i δ-like current spike
V_g: step-like voltage pulse

- H calculated in Fourier space (Riad-Parruck method [3]):

$$H(\omega) = \frac{V_o(\omega)}{I_i(\omega)} S(\omega)$$

- Filter (regularization):

$$S(\omega) = \frac{|I_i(\omega)|^2}{|I_i(\omega)|^2 + \lambda}$$

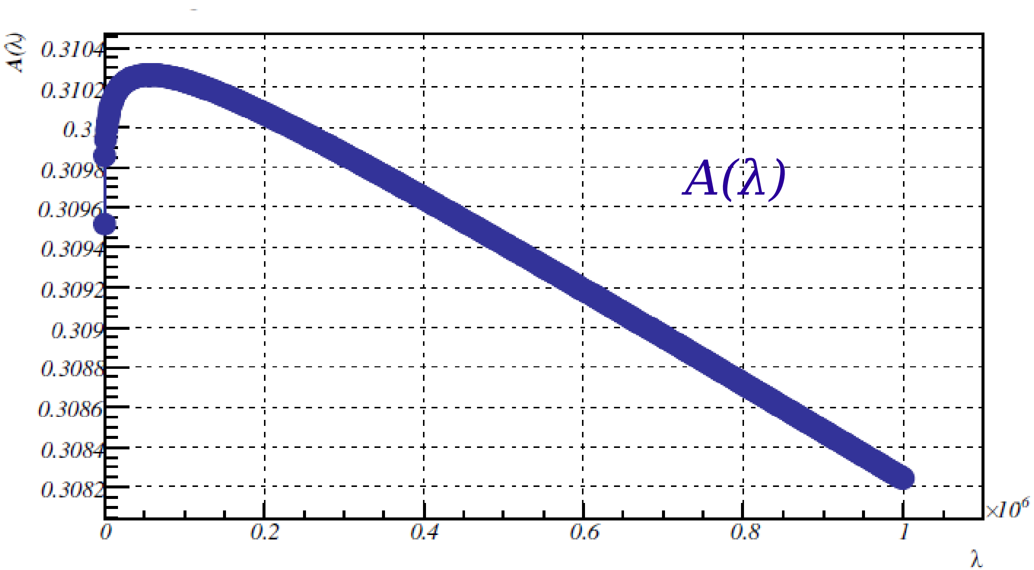
[3] B. Parruck, S. M. Riad, 1EEE Trans. Instr. & Meas, vol. IM-32, no. 1, pp. 137-140,. Mar. 1983

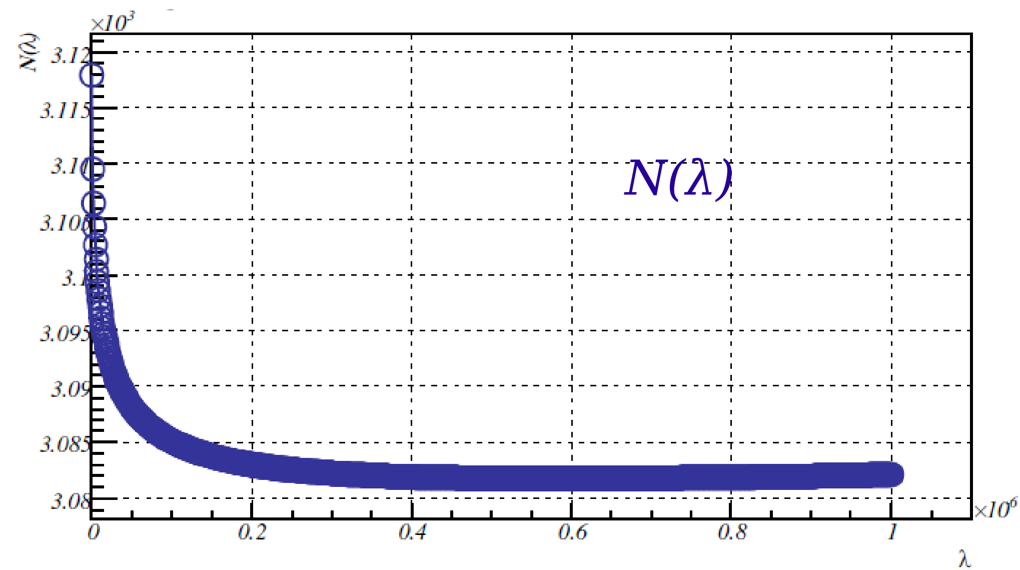
Transfer function of the meas. system (2/5)

- Optimal regularization constant λ determination:
  - For <u>each</u> λ:
    - Check the integral of calculated $H(t)$ to get a smooth step-like waveform (less sensitive to noise), $\int H(t)dt$
    - check mean, $A(\lambda)$, and RMS, $N(\lambda)$, in the tail part of the step-like response $\int H(t)dt$
  - <u>Optimum</u> λ_{opt}:

$$\frac{A(0) - A(\lambda_{opt})}{A(0)} \ll 1$$

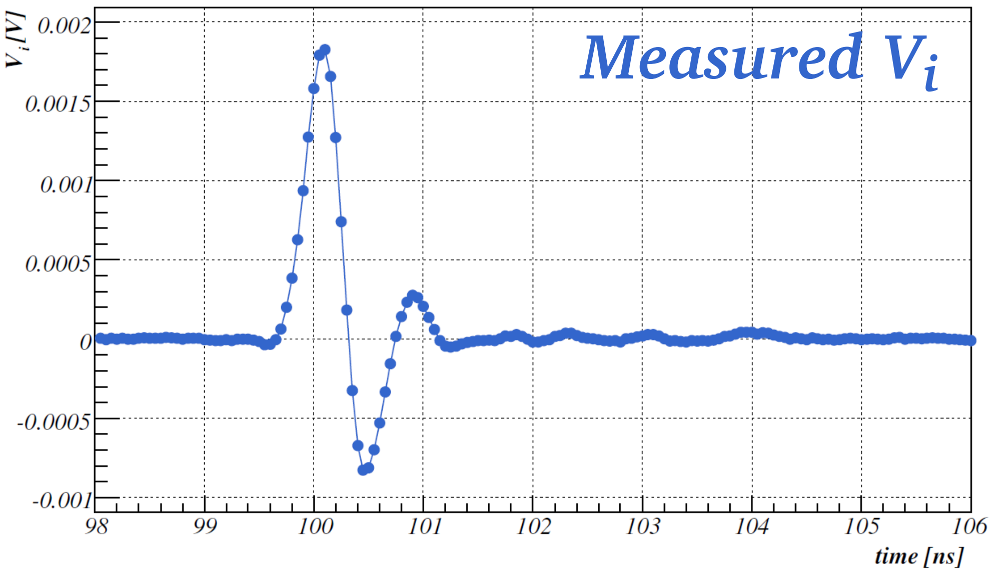
$$N(\lambda_{opt}) \ll N(0)$$

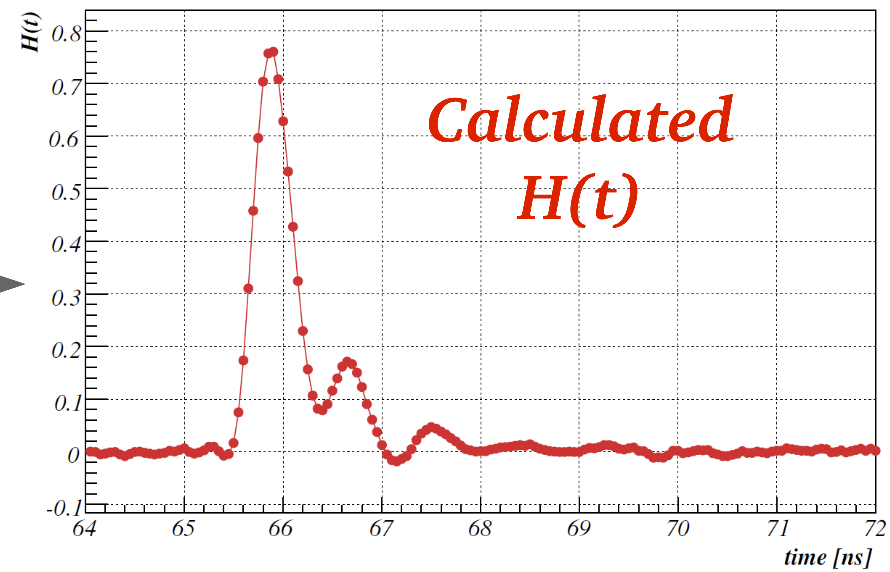


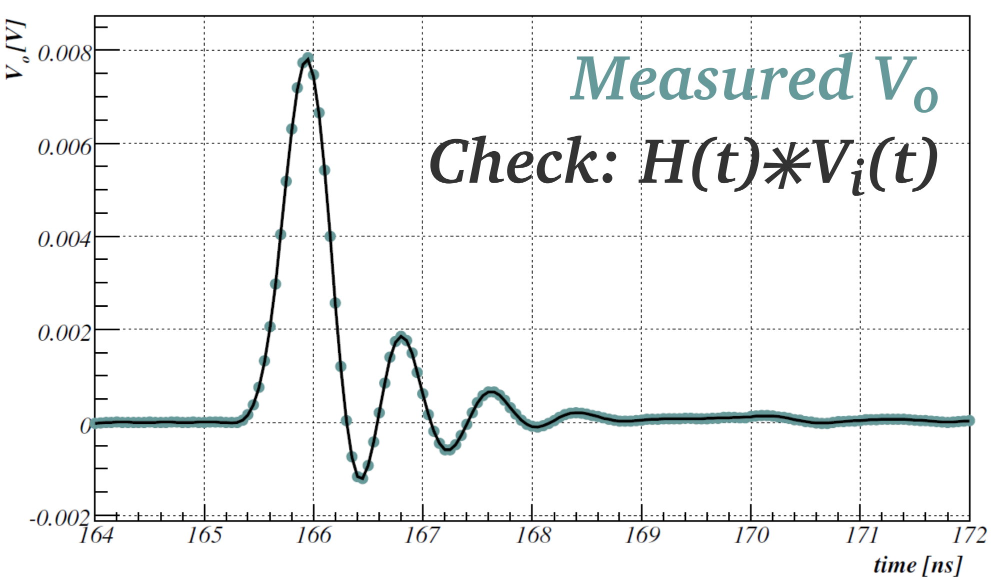


Transfer function of the meas. system (3/5)

Result

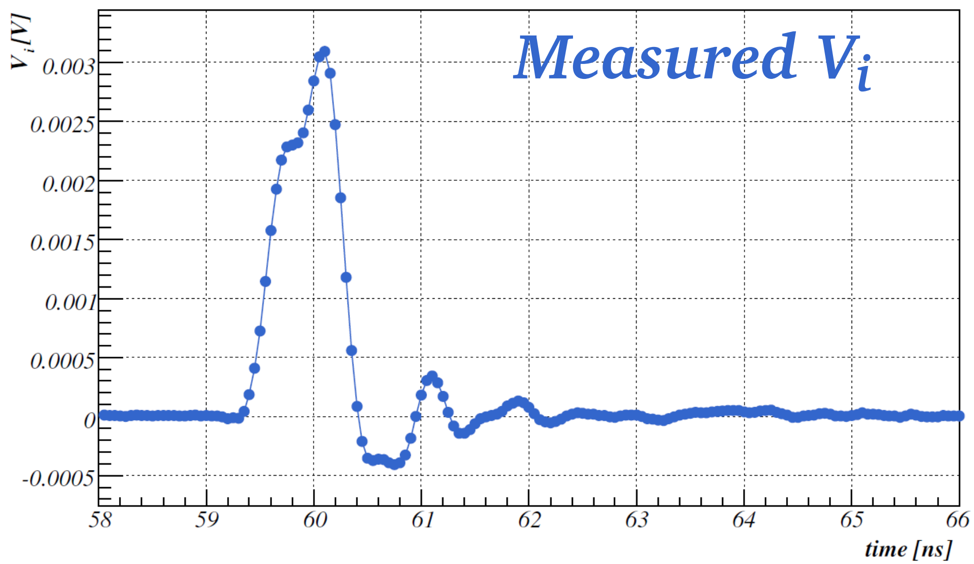


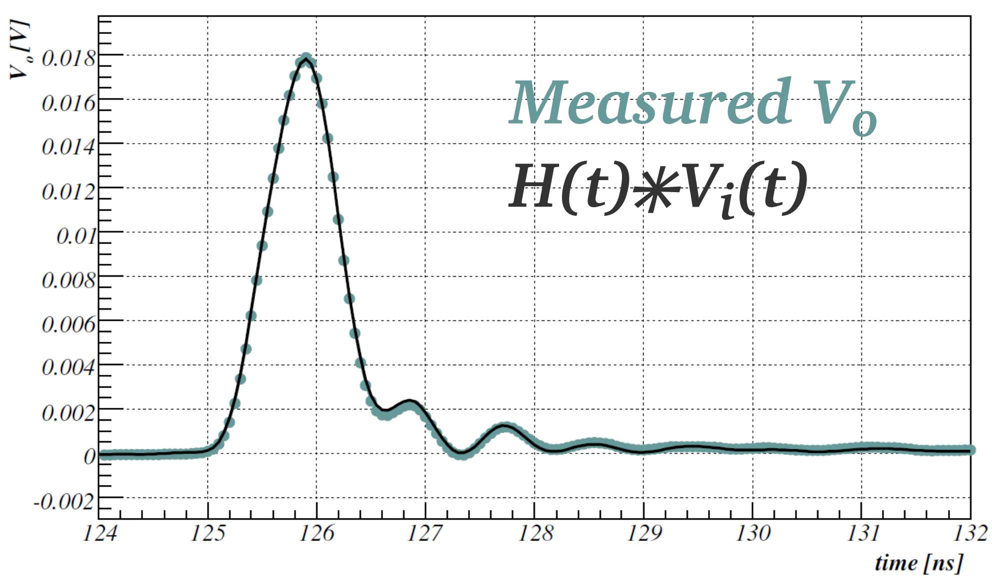




Transfer function of the meas. system (4/5)

Check: how calculated $H(t)$ transforms a different V_i?





Looks good

- Extra check: for detector irradiated to 2×10^{14}pions/cm2 compared calculated signal with measured ones, shapes matched well
- Different strategy for transfer function extraction presented on the next slide...

Transfer function of the meas. system (4/5)

- Unirradiated sensor: take calculated signal as input and measured signal as output to calculate the transfer function

- Problem: measured signals were too noisy… high value for regularization constant needed for Riad-Parruck method to work, but this alters the calculated transfer function too much for our needs…

- Tried with no filtering and average over the transfer functions calculated at different positions z in the detector
  - Still not good enough results…
  - Noticed that while transfer functions calculated from the central regions of detector match well, the ones from the edges look different… problems with model of the laser beam?

τ extraction: method 2

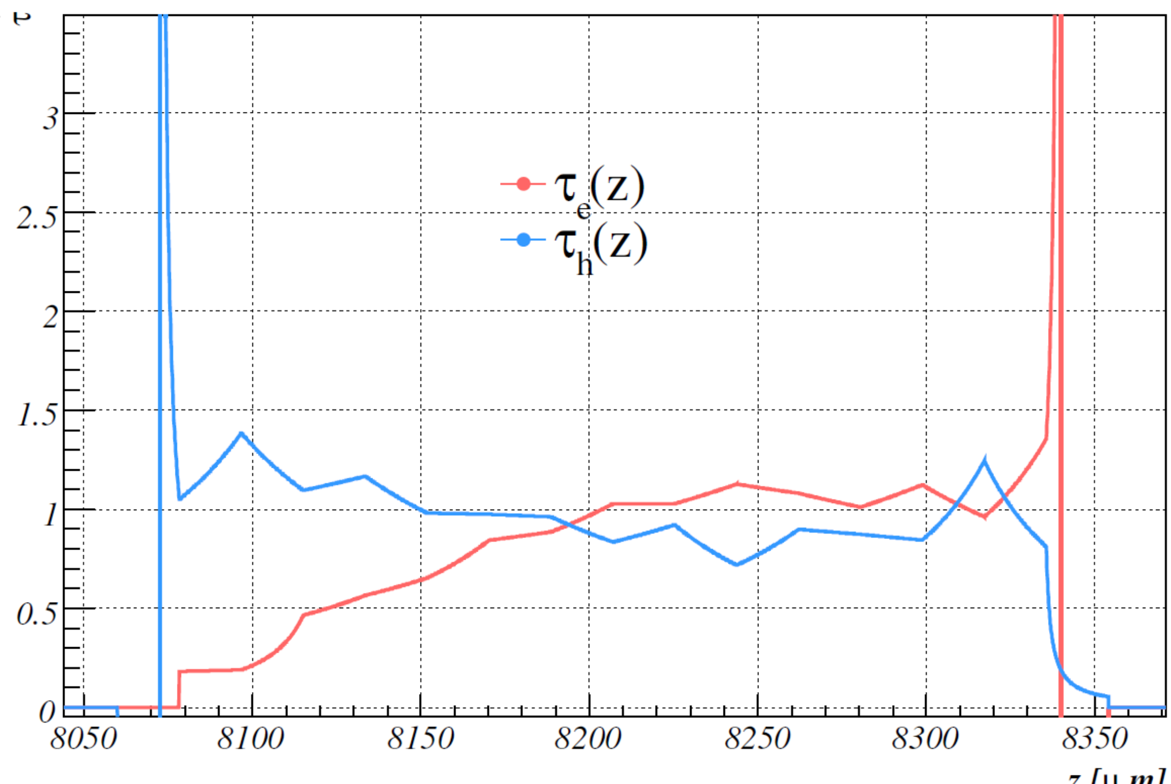
- Procedure: iterative process
  - Calculate the efficiency profile and compare it to the measured one
  - Divide the detector width in N equidistant regions with linear $1/\tau_{e,h}$
  - $E(z)$ → calculate induced current at each point z inside the detector
    - assume Gaussian laser beam profile with σ as extracted from the deconvolution of $v^{e}_{dr,t}(z)$
    - Apply some initial values of $1/\tau_{e,h}$ for each of the points bounding the regions
    - Extract the integral of this signal (charge) → efficiency profile
    - Apply same normalization factor on the calculated efficiency profile as extracted from measured one
  - Vary $1/\tau_{e,h}$ for each of the points bounding the regions (and each of the charge type) separately (while keeping others constant) to minimize the χ^2
  - Repeat until desired accuracy is reached

- No need for transfer function
- No model function for $\tau_{e,h}(E)$ needed
- Much more time consuming than method 1...

τ extraction: method 2

Example (not final result)

- FZ-p strip detector $\Phi=2\times10^{15}$protons/cm^2, U_{bias}=500V, (electric field on p10):
  - Detector divided in 16 regions
  - Expected from [4]: τ_e~0.5ns, τ_h~0.4ns
- Observations:
  - Tried with different initial conditions and get approximately same result (in the central part)
  - Less trapping close to front/back edges (higher el. Field) for holes/electrons?
  - Holes: shape follows the electric field (apart from points at the back...) and seams as one would expected intuitively
  - Electrons: opposite behavior than with holes
  - Problems with edge points...
    - Wrong laser beam shape modeling?
  - More investigation needed to see if this makes sense and if the method can work...

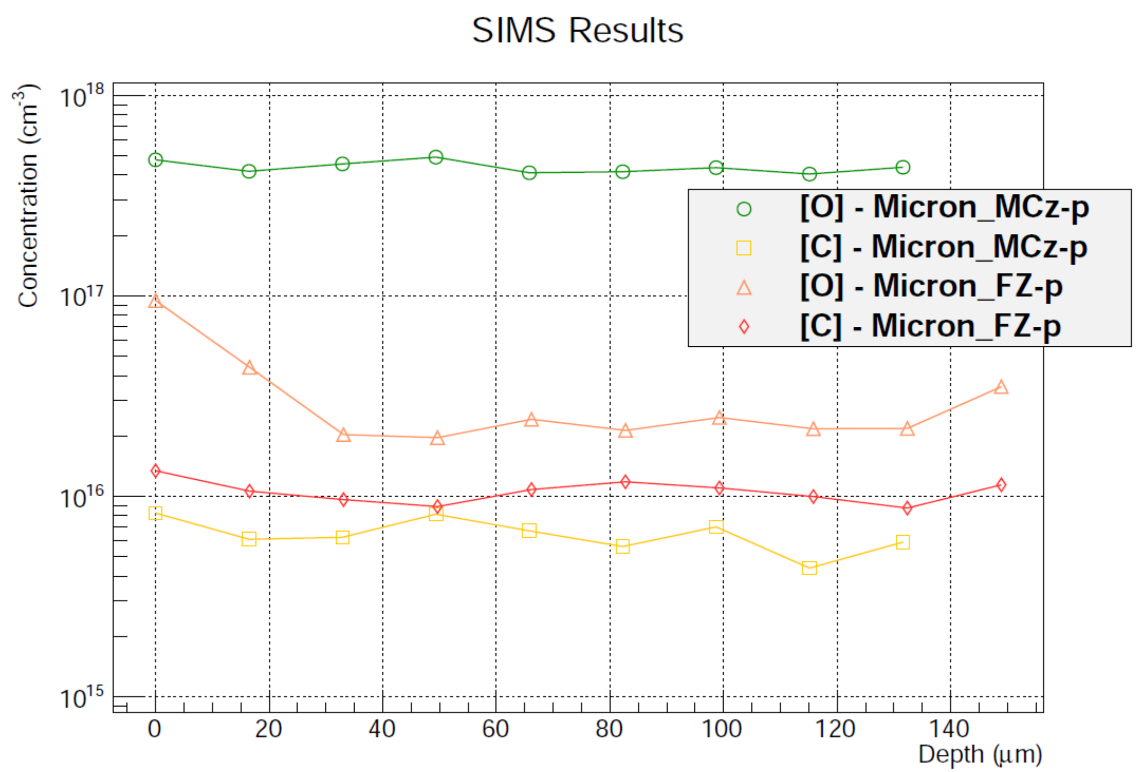


[4] G.Kramberger et al, NIM A,Vol.481, Issues 1-3, 1. April 2002, p. 297-305

Part 2:
Annealing study

Annealing study: samples & irradiations

- Detectors:
  - 2010 Micron RD50 production
  - FZ-p and MCz-p strip detectors
  - 300 μm thick
  - Strips: 80 μm pitch, 20 μm width
  - SIMS measurements
    - MCz: uniform oxygen concentration
    - FZ: higher oxygen concentration close to the implant, but still orde of magnitude lower than in MCz



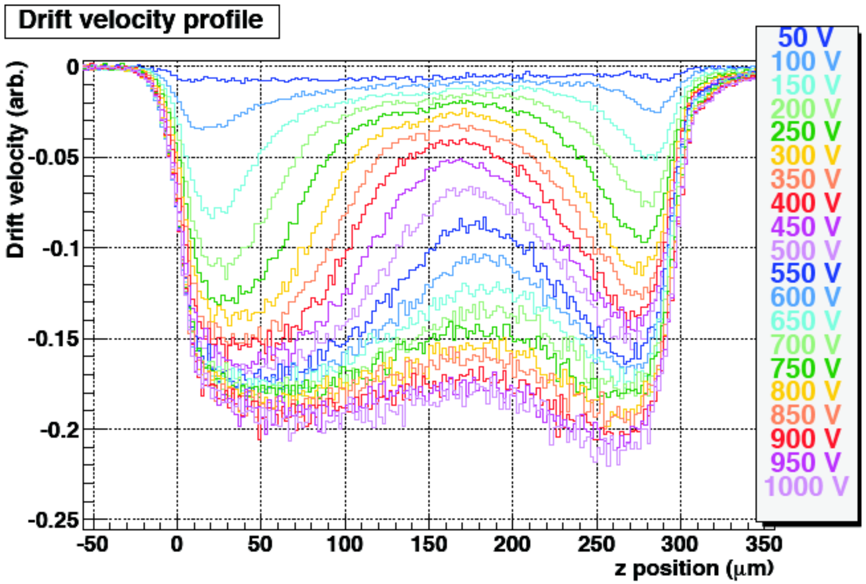
- Irradiations
  - Irradiated with 24GeV/c protons (CERN PS)
  - $\Phi=10^{16}$p/cm^2 ($\Phi_{eq}=6.2\times10^{15}n_{eq}$/cm^2)

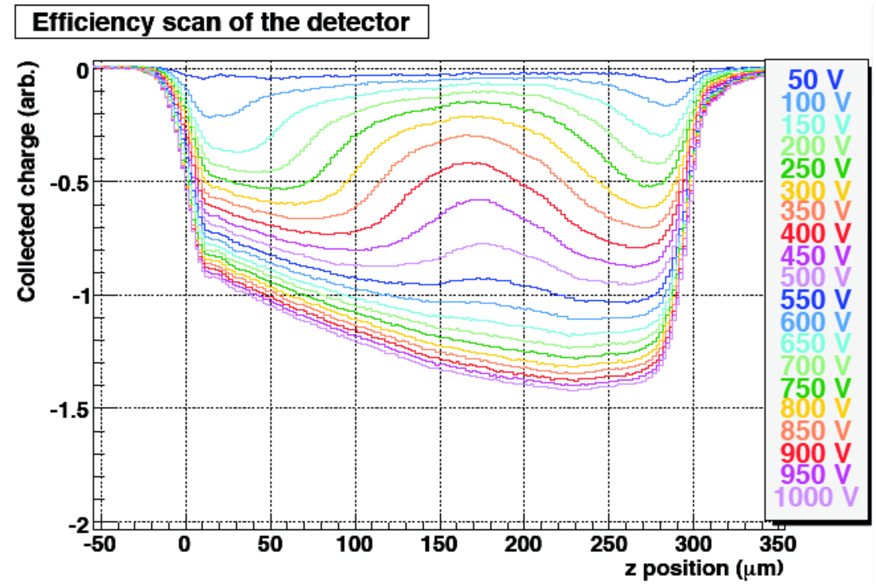
Annealing study: procedure

- After each annealing step devices were characterized with eTCT, for details on eTCT and related analysis see [1]
- Measurement temperature -25^{o}C
- Drift velocity profile:
  - Integration window of 0.6ns from beginning of signal
- Efficiency profile:
  - Integration window of 25ns around the signal
- Annealing:
  - @ temperature 60^{o}C
  - Up to maximum annealing time of 10^4min
  - On-board, without changing laser parameters (focusing distance, power, etc) → possible comparison between measurements on same detector

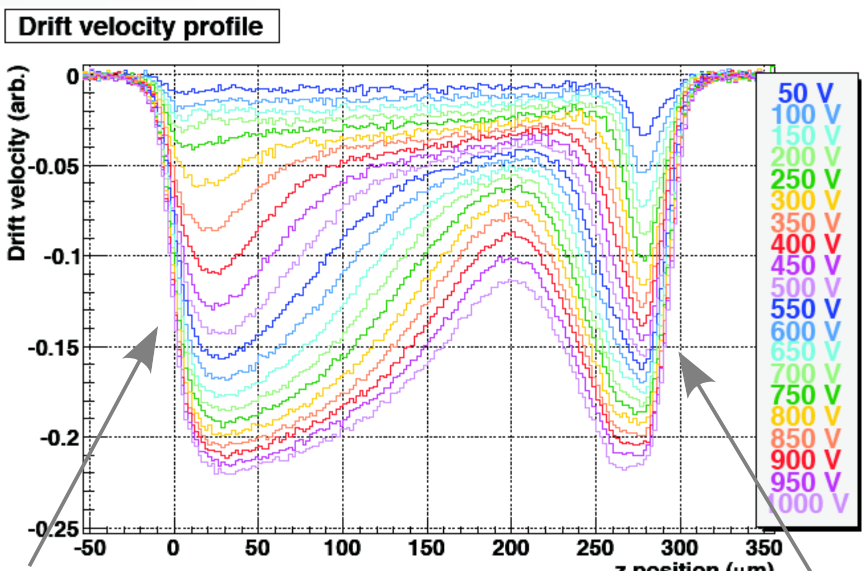
[1] G. Kramberger et al., IEEE TNS, vol. 57, no. 4, August 2010, p 2294

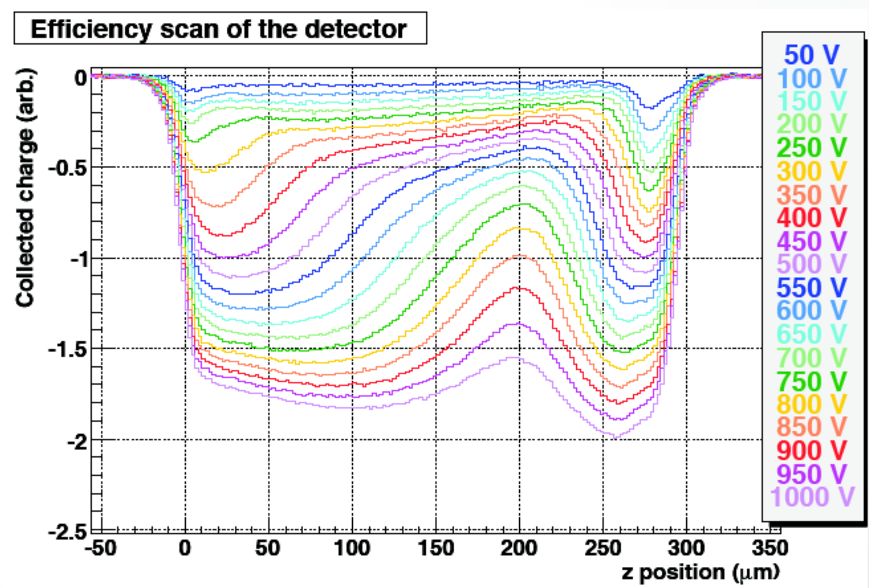
Annealing study: no annealing





FZ



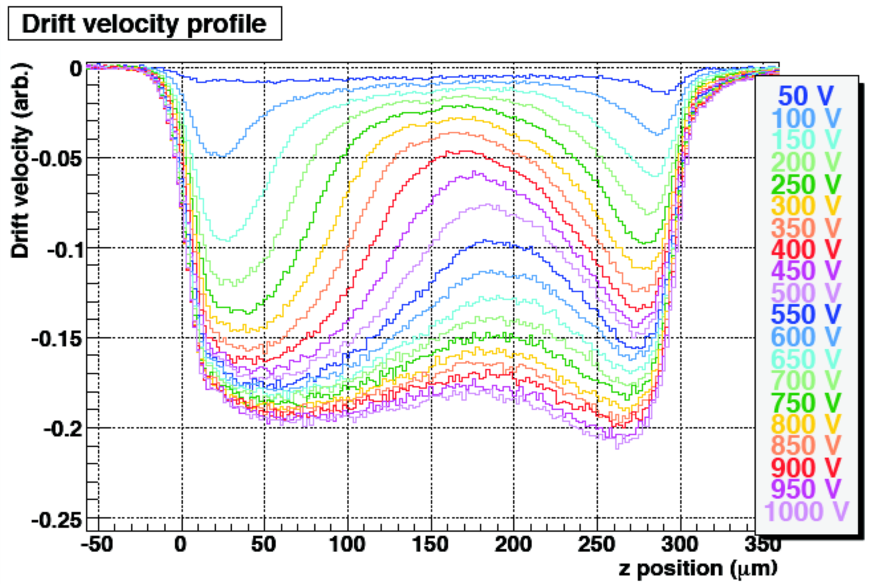


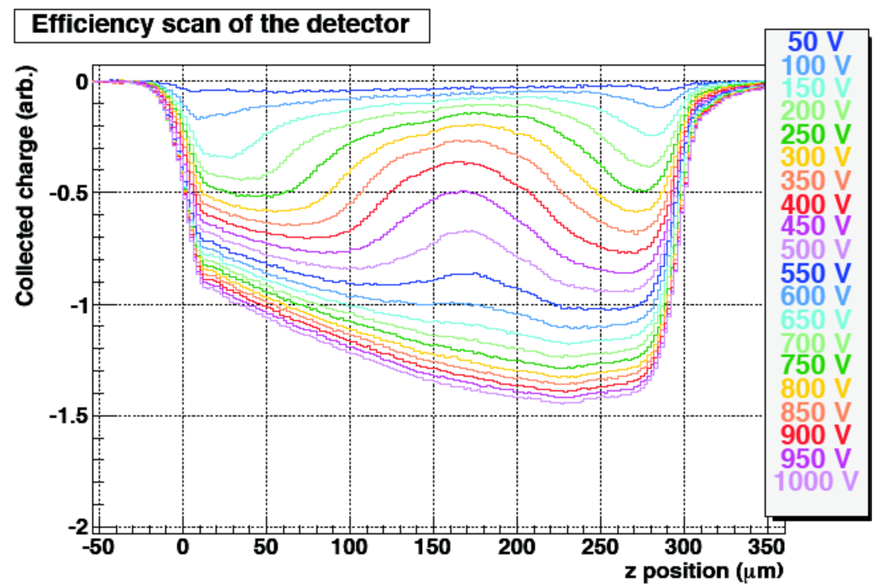
MCz

front

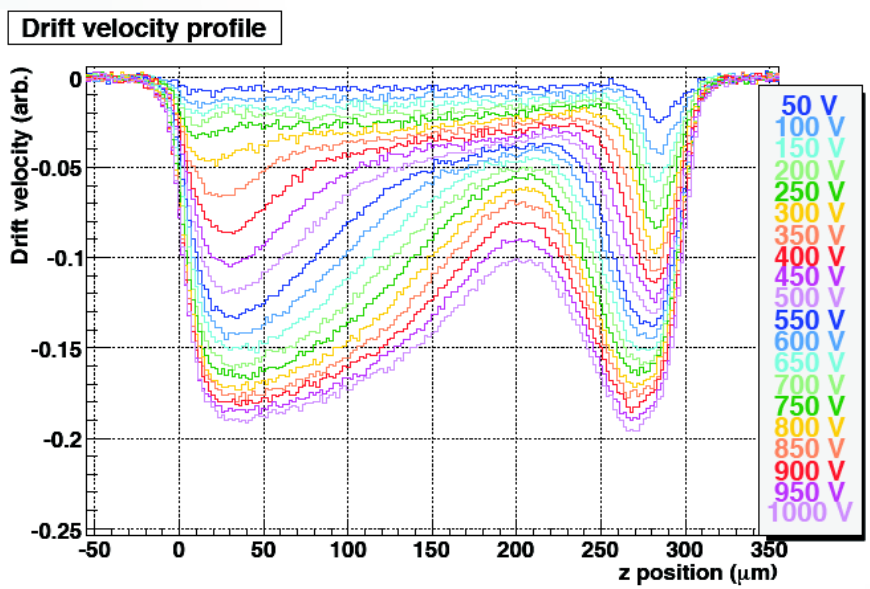
back

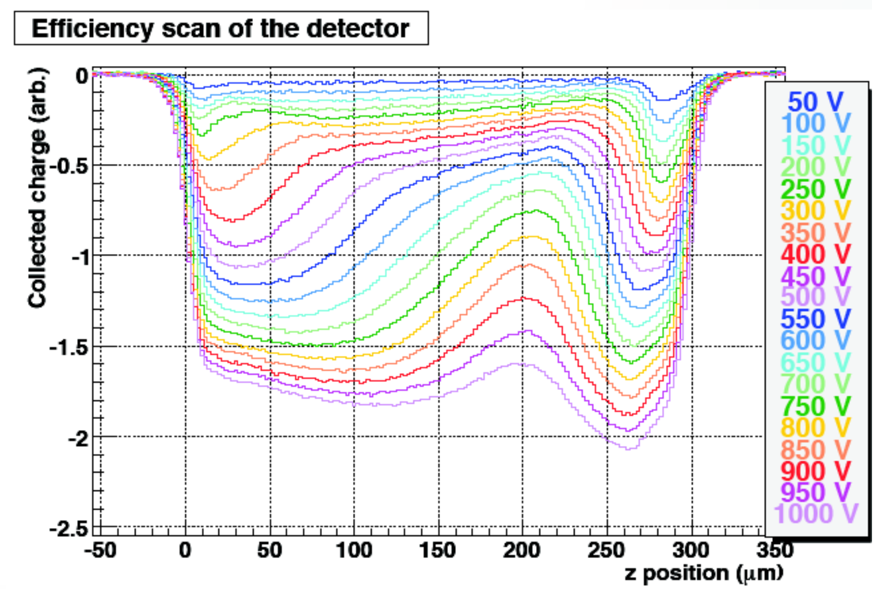
Annealing study: 80 min annealing





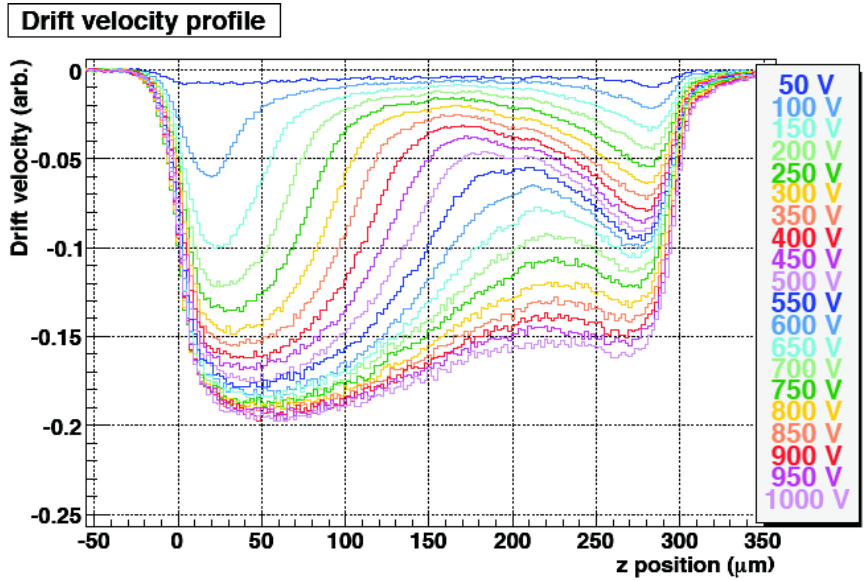
FZ

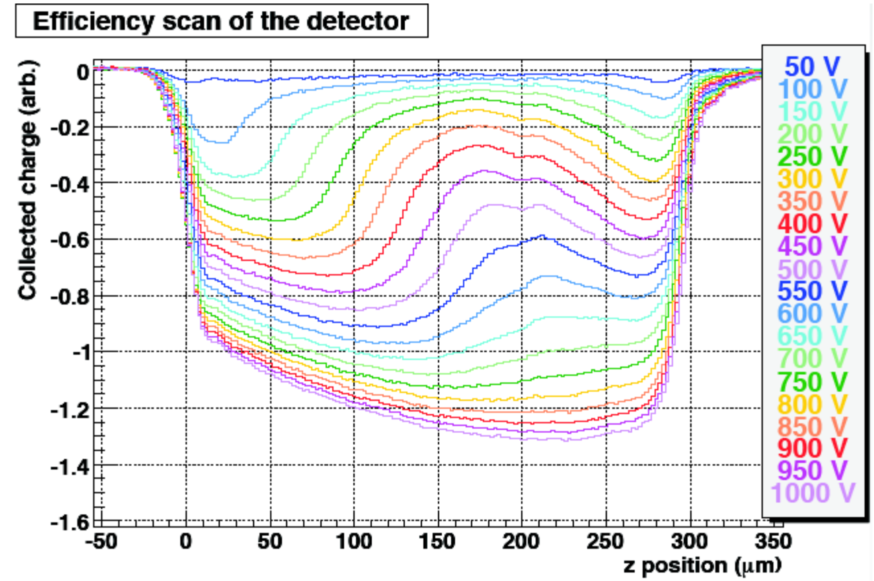




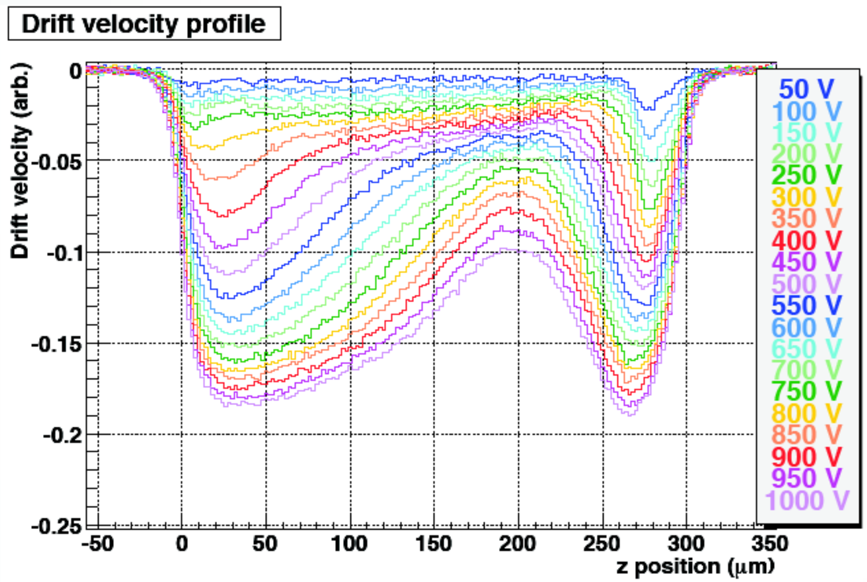
MCz

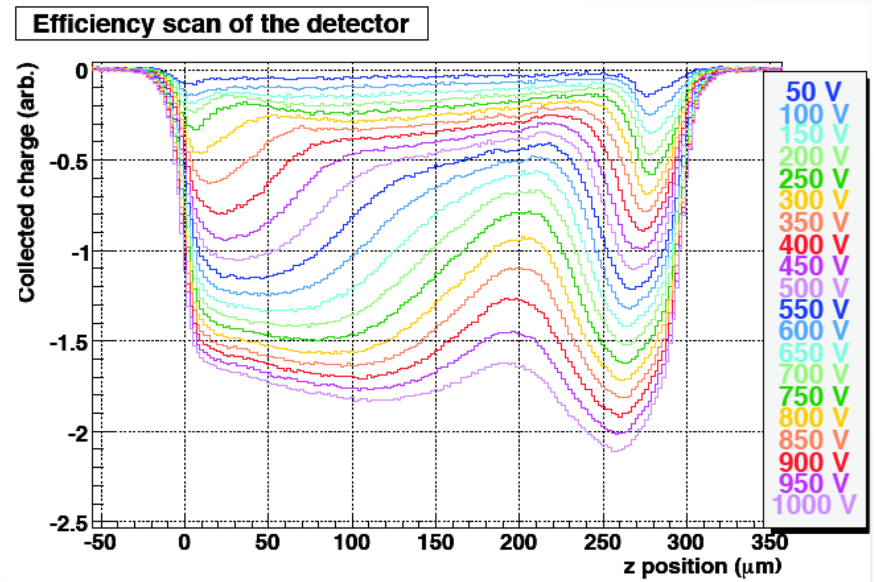
Annealing study: 240 min annealing





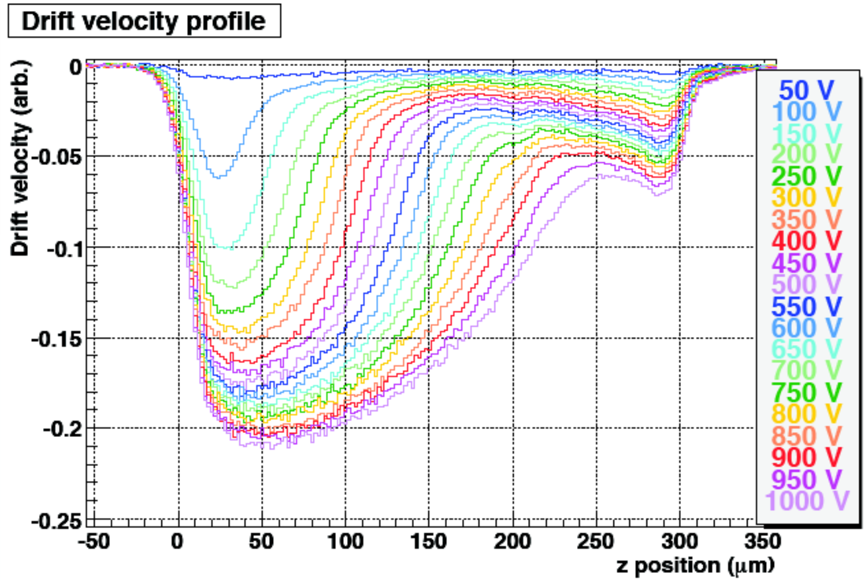
FZ



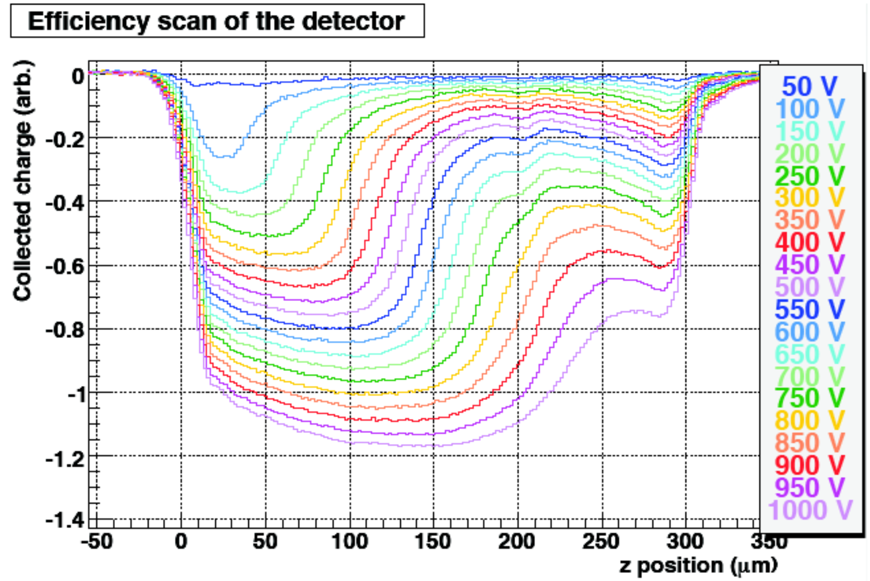


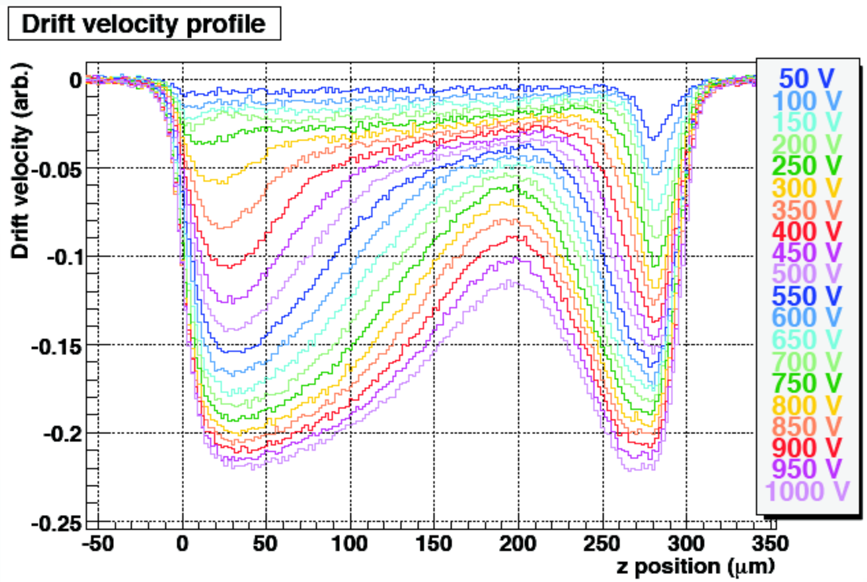
MCz

Annealing study: 560 min annealing

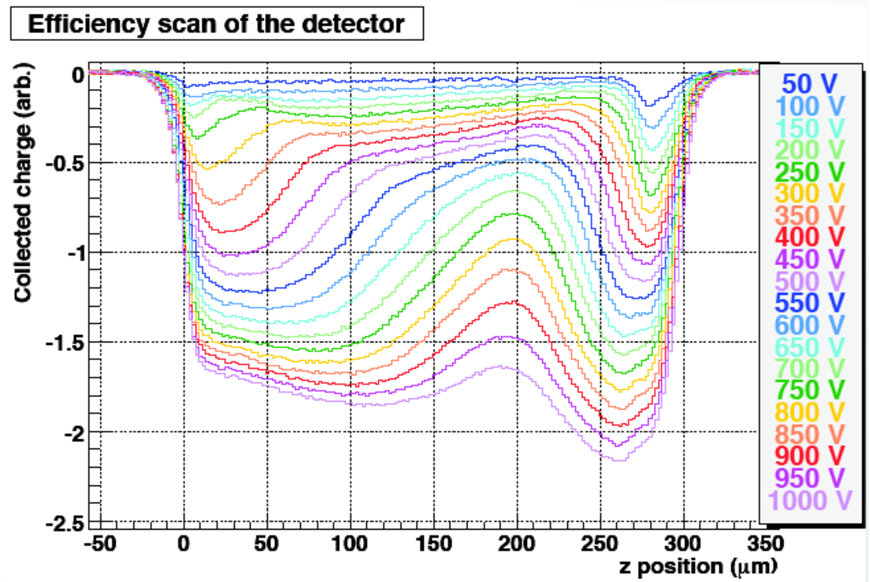


FZ

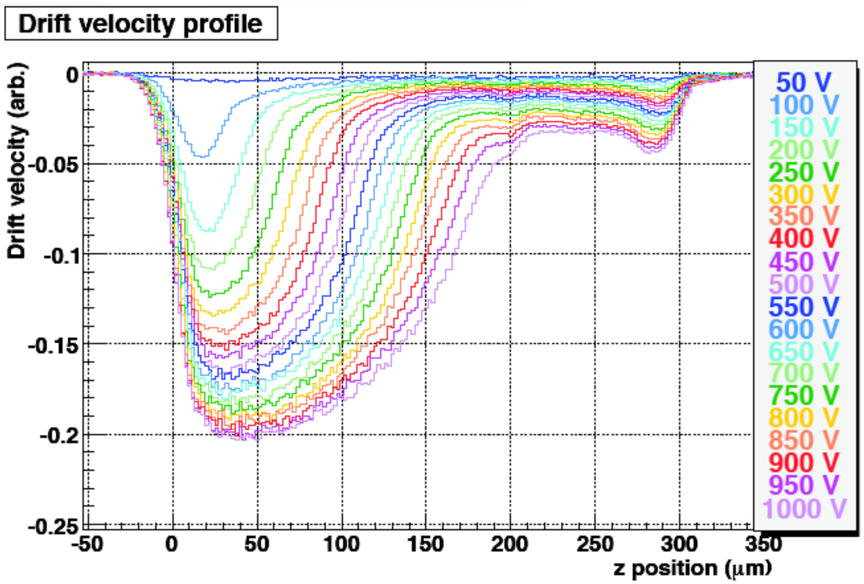


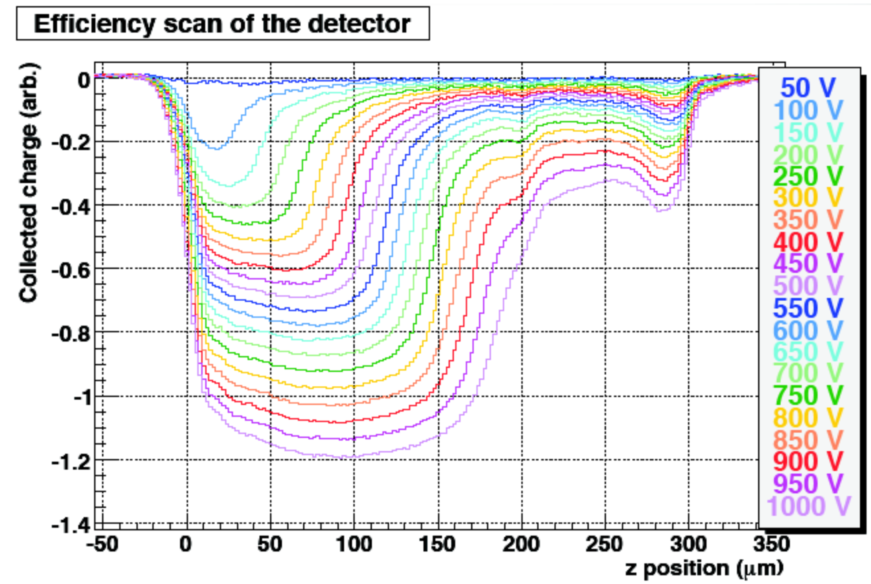


MCz

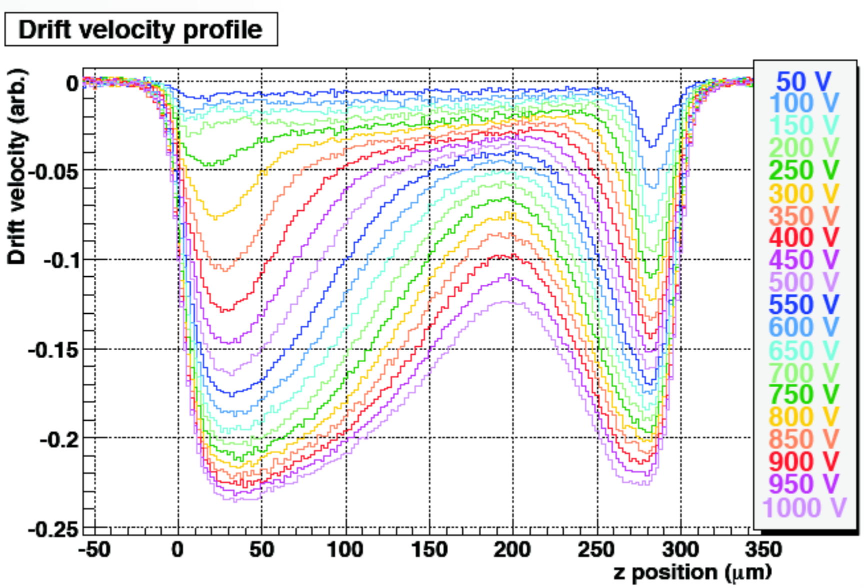


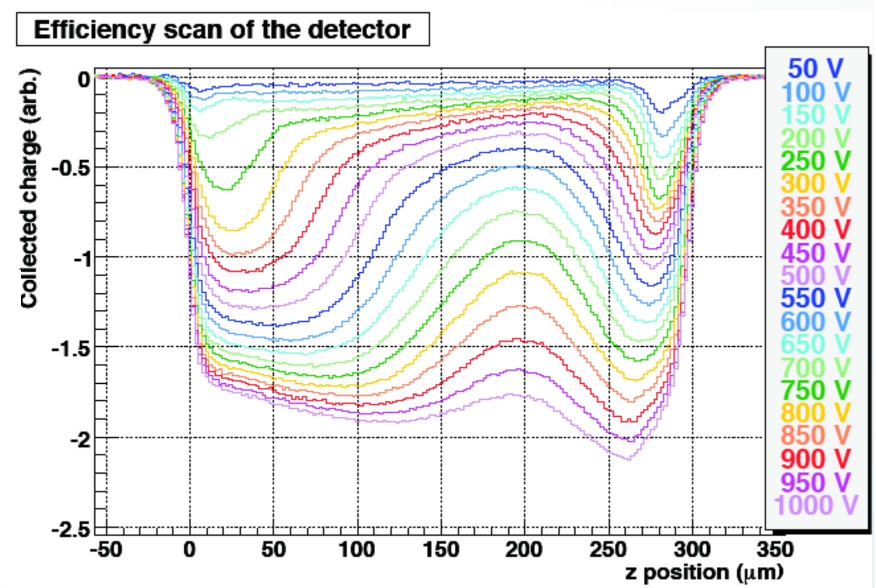
Annealing study: 1200 min annealing





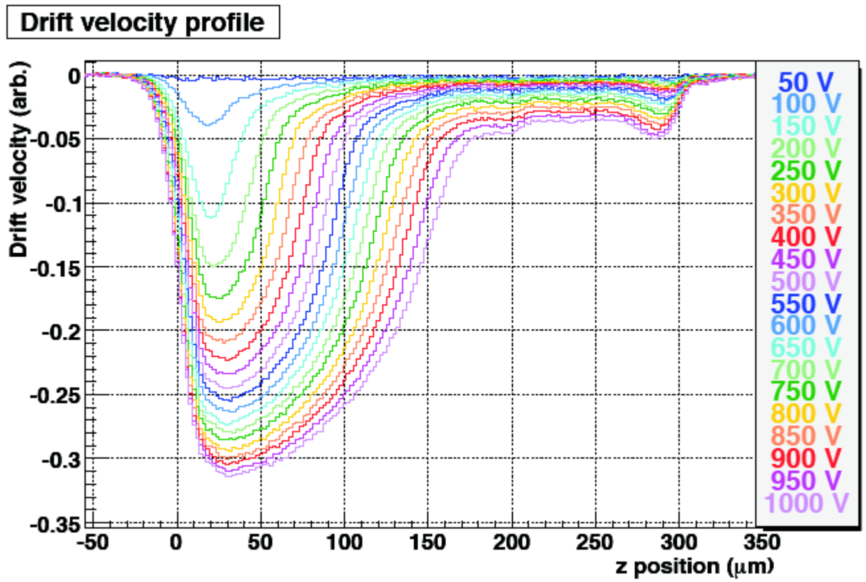
FZ

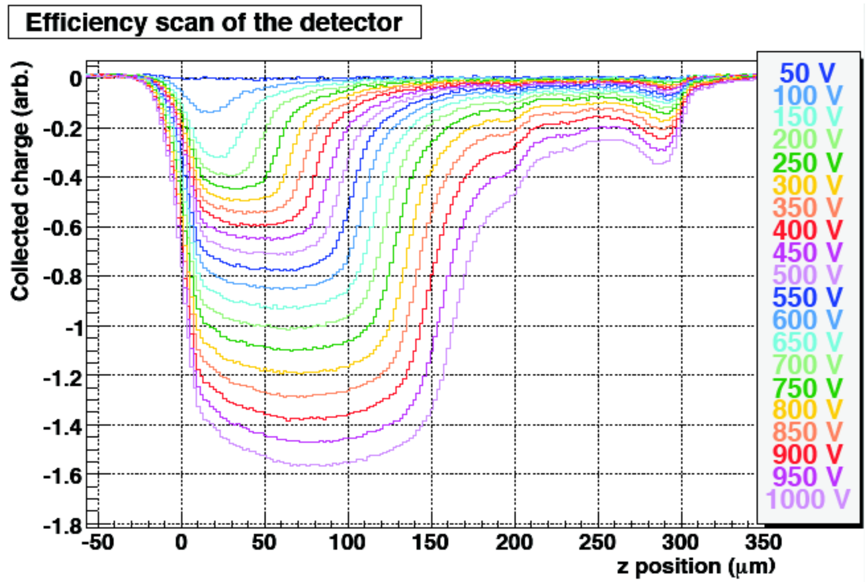




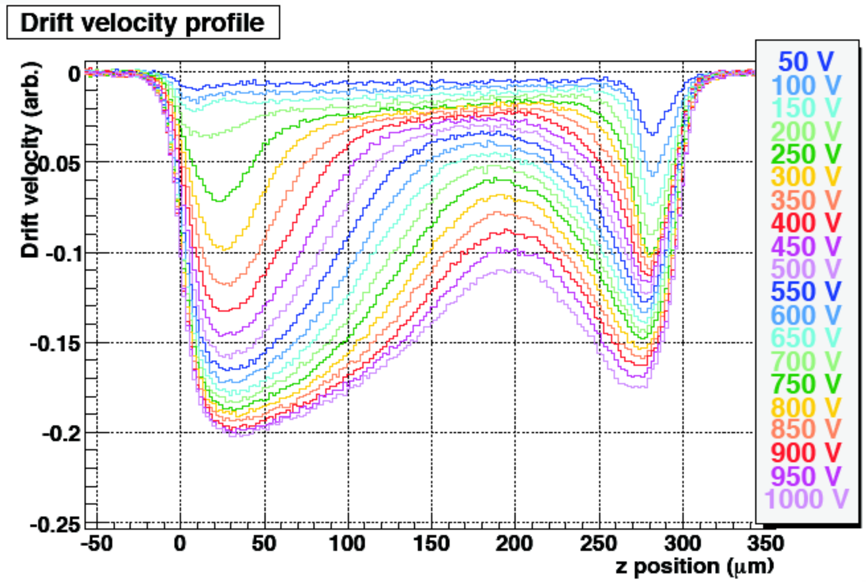
MCz

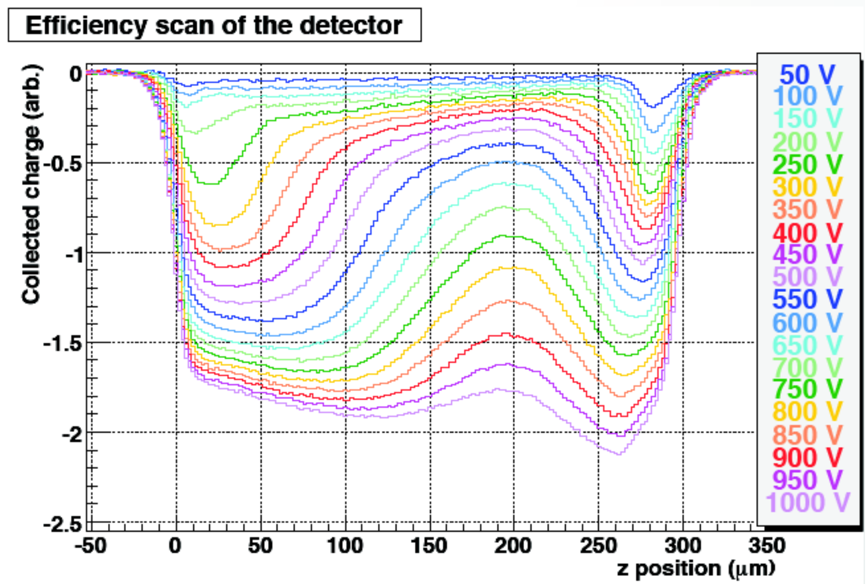
Annealing study: 2480 min annealing





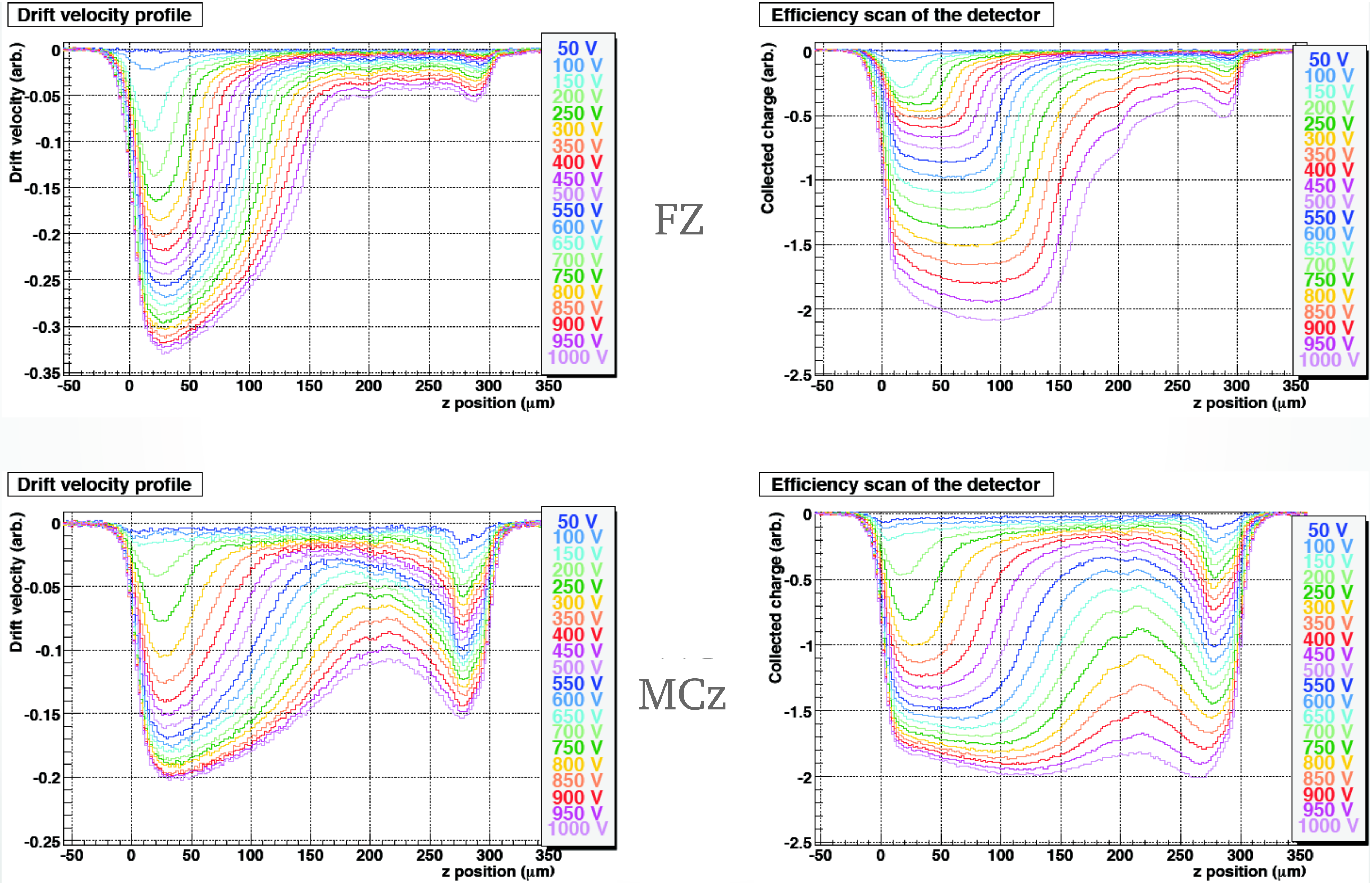
FZ



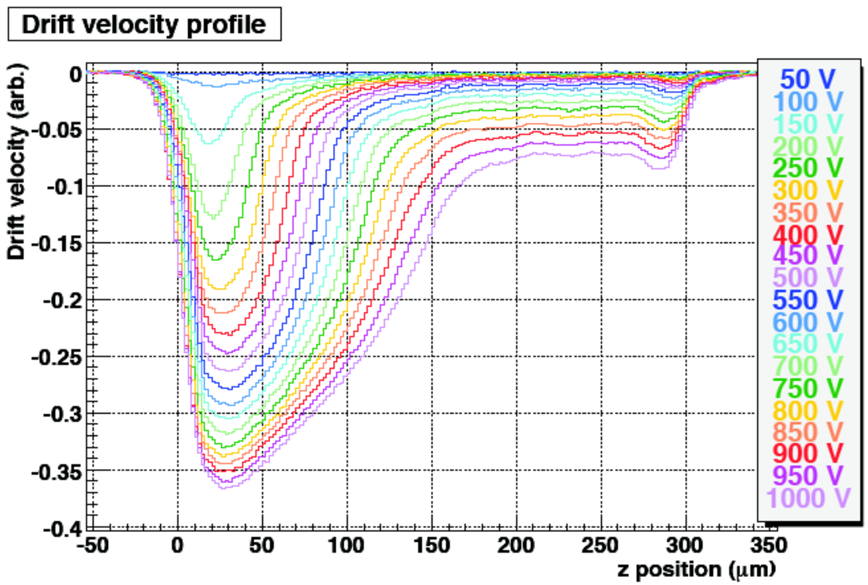


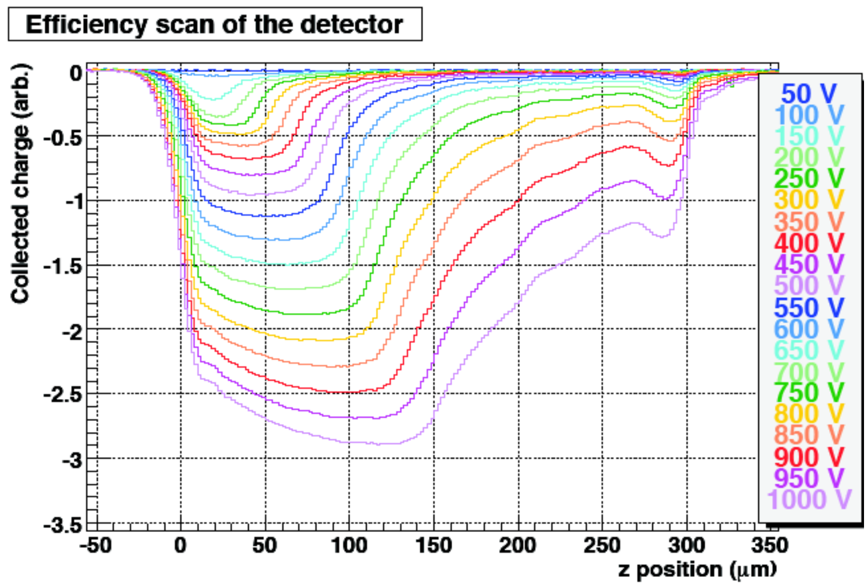
MCz

Annealing study: 5040 min annealing

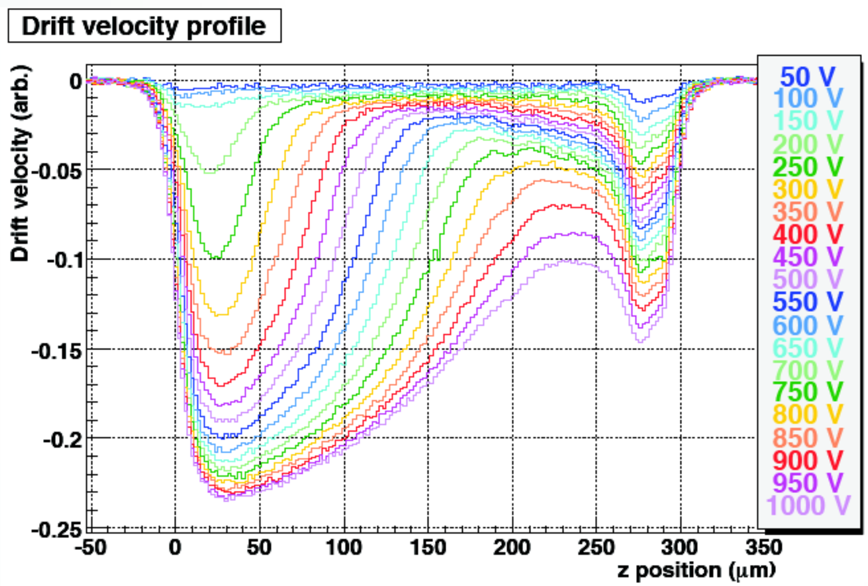


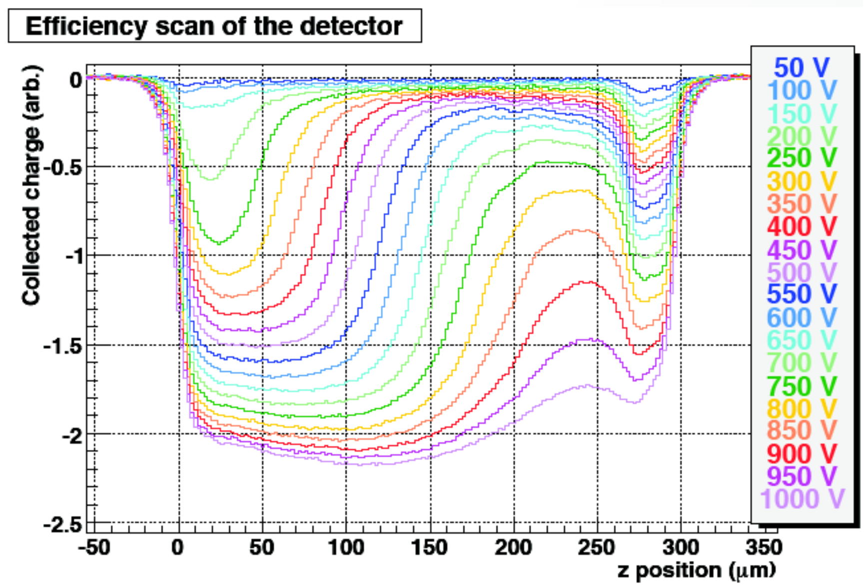
Annealing study: 10200 min annealing





FZ





MCz

Annealing study: comments

- Drift velocity profiles
  - Immediately after the irradiation for both FZ and MCz: double peak configuration with higher peak on the back → indication of introduction of donor like defects
  - Decrease of the field strength on the back with annealing, field concentrated on the front → introduction of acceptor like defects with annealing
  - Shapes for FZ and MCz comparable at end of annealing
  - Before annealing lower field in the central more pronounced for MCz than for FZ → lower introduction rate of space charge with irradiation in FZ, which is then compensated with annealing when the net acceptor introduction rate appears to be higher

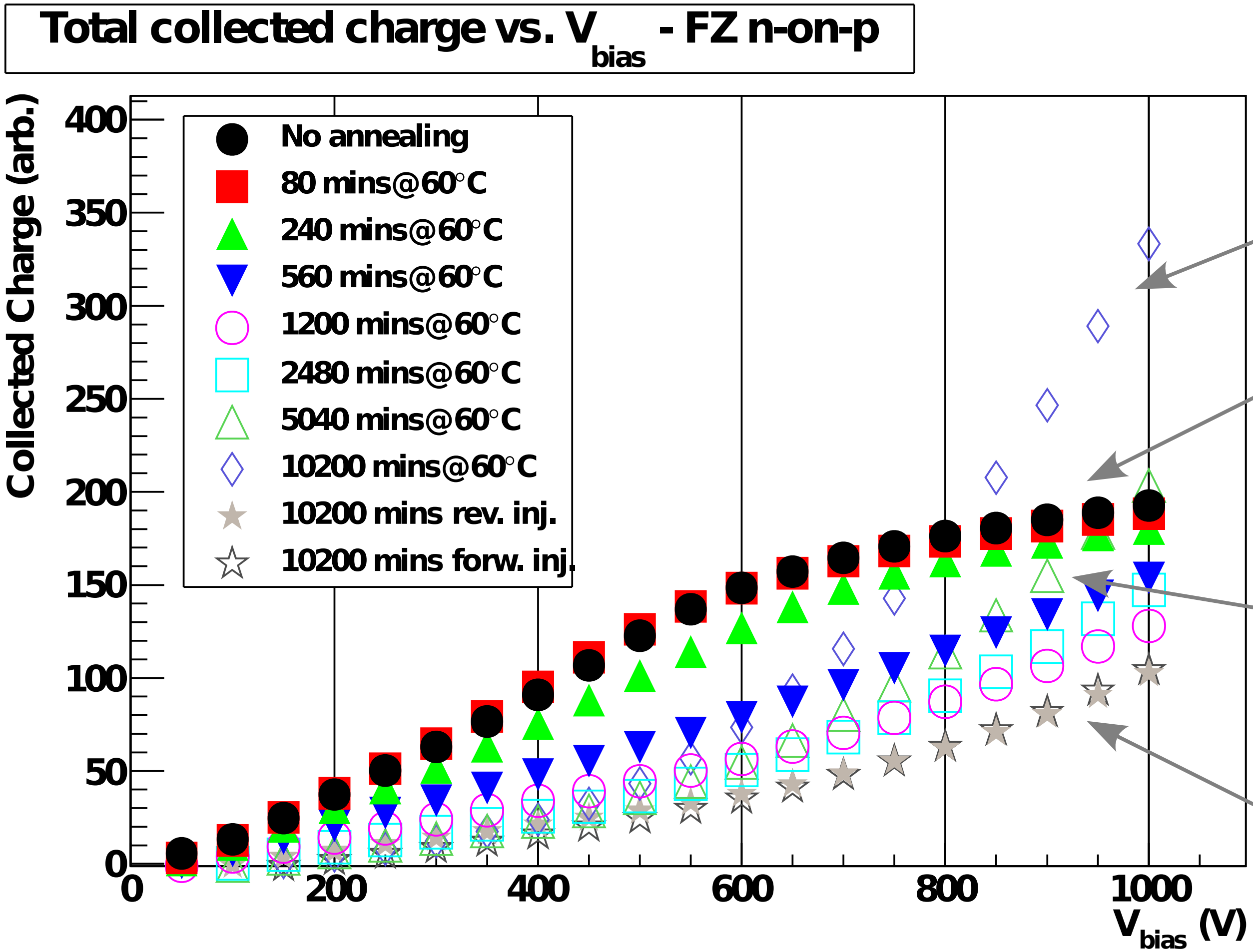
- Efficiency profiles:
  - Prior to annealing: region with maximum efficiency close to back side for both FZ and MCz (slightly higher filed on the back)
  - FZ
    - Decrease of active region width with annealing up to annealing 5040min annealing step
    - After 5200 min step: increase of collected charge value, more prominent close to the back → onset of charge multiplication of electrons traveling towards front
  - Mcz
    - Almost no change up to to the last annealing step where detector starts to be more efficient in front

Annealing study: CM “quenching” in FZ

- After 10200min of annealing, FZ was observed to develop “memory”...
- Charge multiplication “turned off” by high current injection, performed either with forward injection at low temperature or reverse at high temperature (~700μA), plots on the next slide
- The effect can be reversed by leaving the detector at room temperature over night
- The defect(s) can stay in its active state for more than 2 days at -25C...
- An explanation for slow de-excitation rate could lie in the change of chemical configuration of defect (bistable behavior)

Annealing study: Total charge collected, FZ

Total collected charge (integral of efficiency profile over z) as function of bias



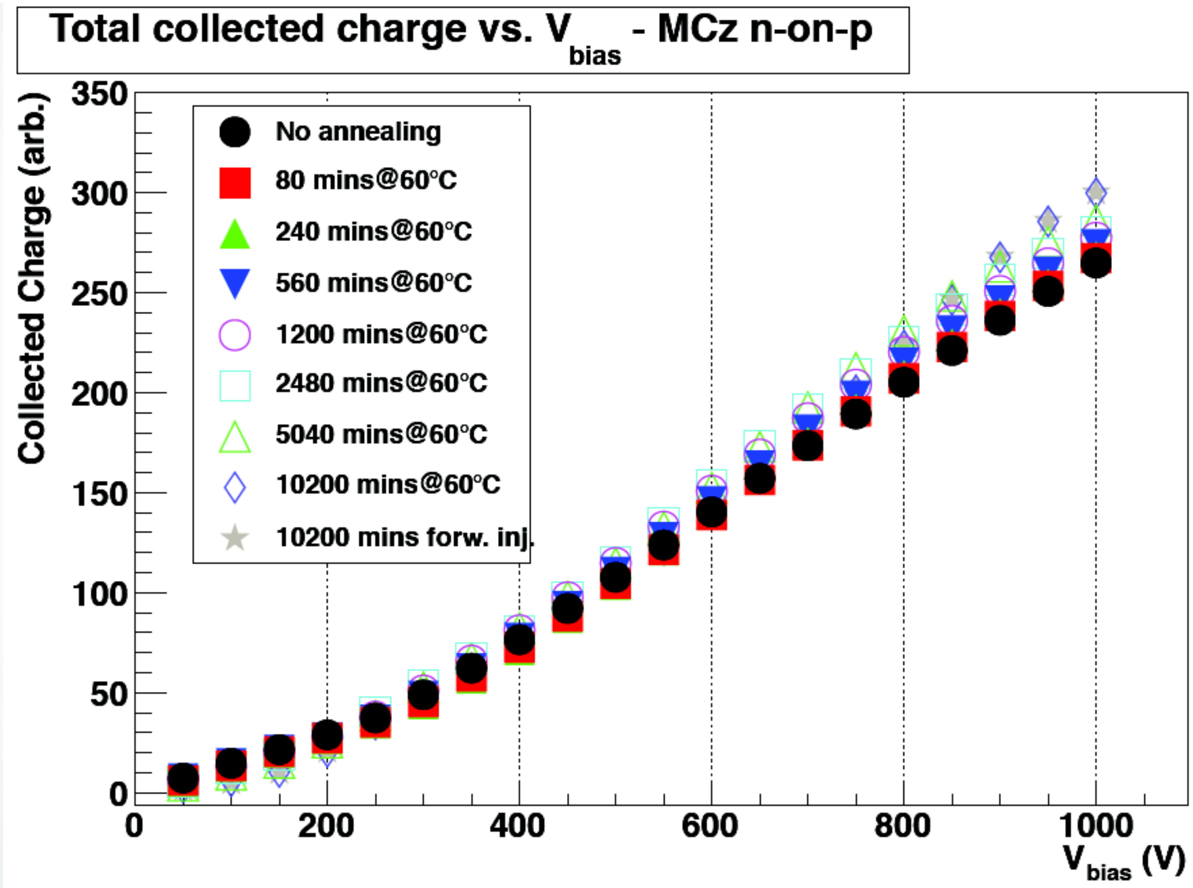
Strong CM in the last annealing step

Typical "depleted" CCE behavior

Onset of CM

Bistable defect turning of noticeable part of CM

Annealing study: Total charge collected, MCz



- Annealing seems to have little influence
- No evidence of CM
- No evidence of bistable defect

Summary (part 1)

Trapping time extraction from eTCT measurements

- 2 methods proposed
  1) Comparison of measured and calculated signals at the edges of detector
  2) Comparison of measured and calculated efficiency profiles
  - Both seem to have troubles close to the detector edges...

- Future plans:
  - Check modeling of laser beam
  - Try method 1) for number of positions in the middle of detector
  - Try method 2) but exclude regions close to edges when comparing measured/calc. Signal

Summary (part 2)

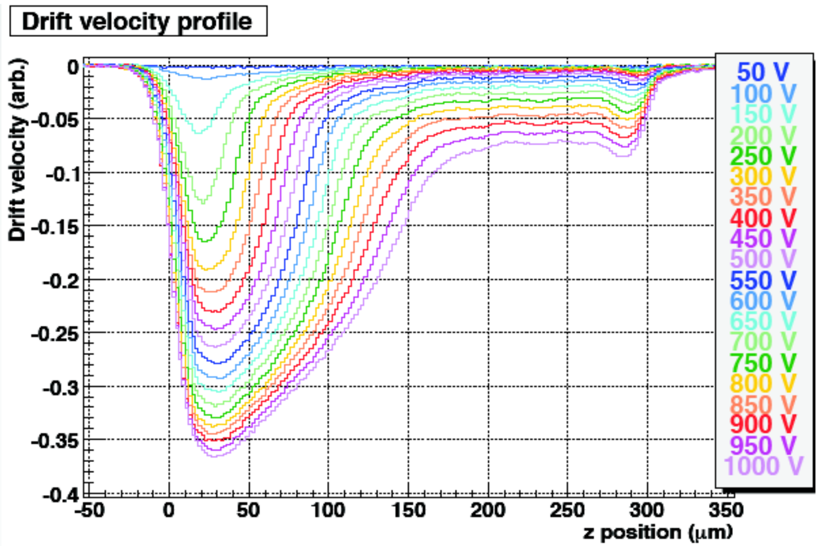
eTCT measurements at several annealing steps of FZ and MCz p-type strip detectors irradiated to $\Phi = 10^{16} p/cm^2$

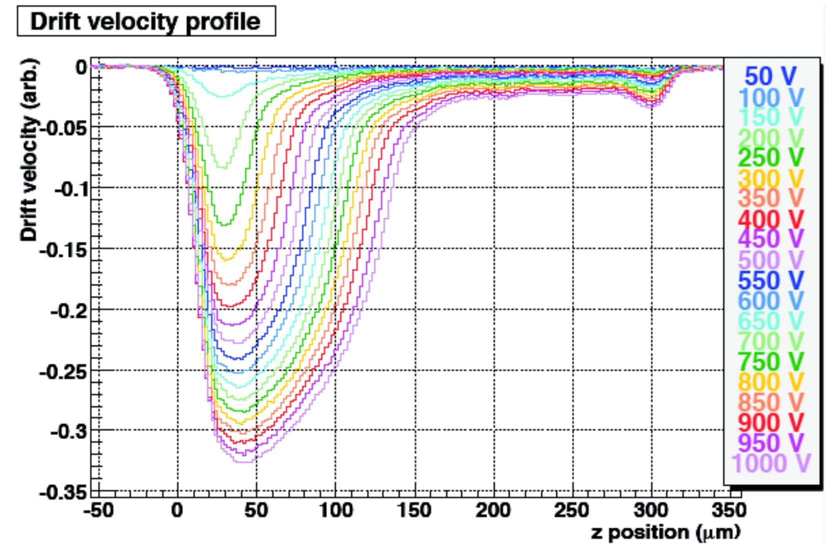
- FZ:
  - Devices show double junction field configuration
  - Acceptor introduction with annealing, at higher annealing times virtually all the field is concentrated in the front
  - Onset of charge multiplication
  - Bistable defect observed, decreasing both charge multiplication

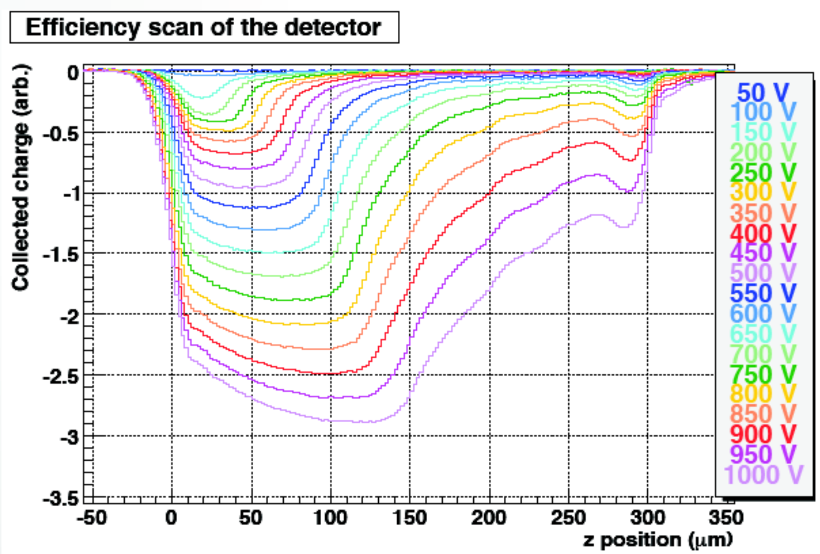
- MCz by far less sensitive to annealing:
  - Collected charge almost unaffected even at higher annealing times
  - No evidence of charge multiplication
  - No bistable defect observed – most probably high O concentrations are gettering the defect observed in FZ

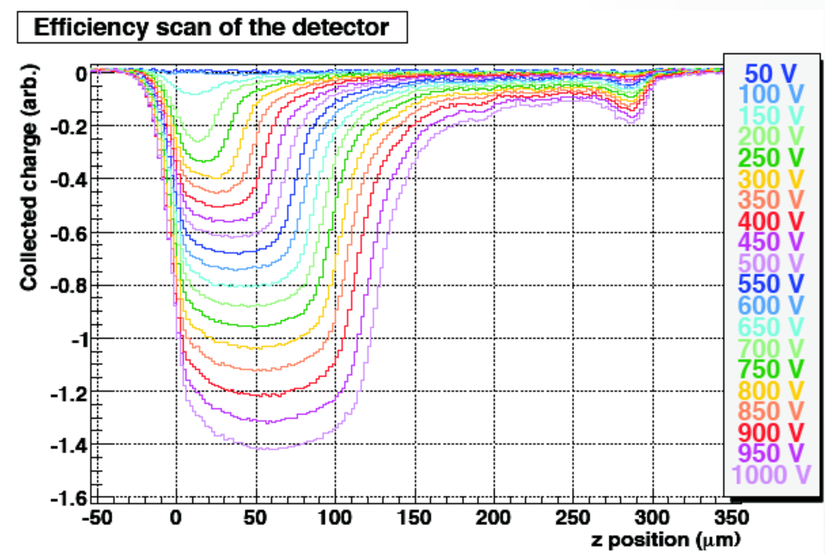
Back up slides

eTCT measurements: CM "quenching" in FZ



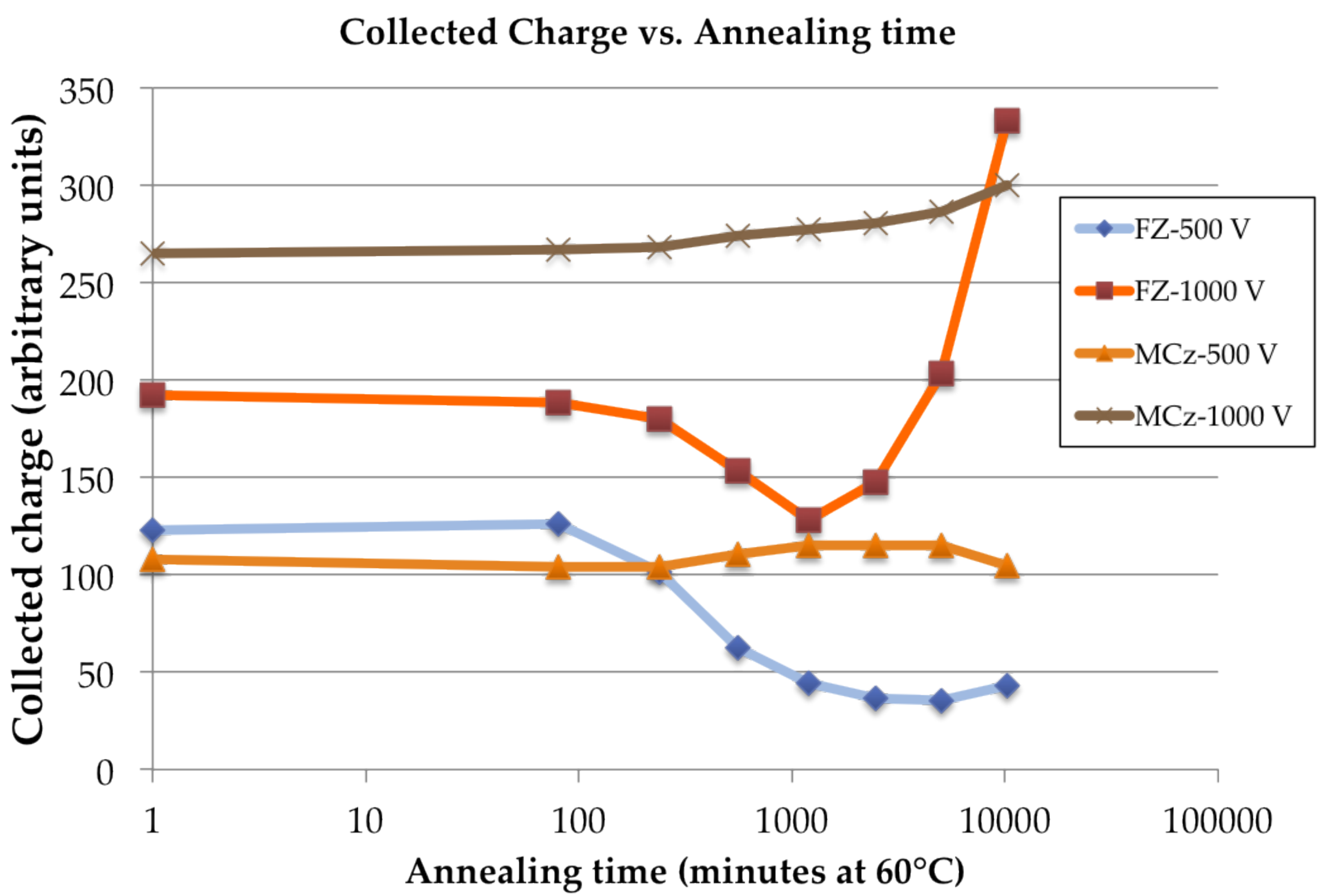






Immediately after annealing

After ~700μA forward injection


Collected Charge vs. Annealing time
Collected charge (arbitrary units)
350
300
250
200
150
100
50
0
1
10
100
1000
10000
100000
Annealing time (minutes at 60°C)
FZ-500 V
FZ-1000 V
MCz-500 V
MCz-1000 V