Determination of E-field in Two-Photon TCT: application to the E-field mapping of irradiated LGADs

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Outline

Motivation

Transient Current Techniques: TPA-TCT

Calculation of E-field, the scaling problem

Examples of E-field calculation

- Edge-TCT on **diodes**
- TPA-TCT on **diodes**
- TPA-TCT on **LGAD**

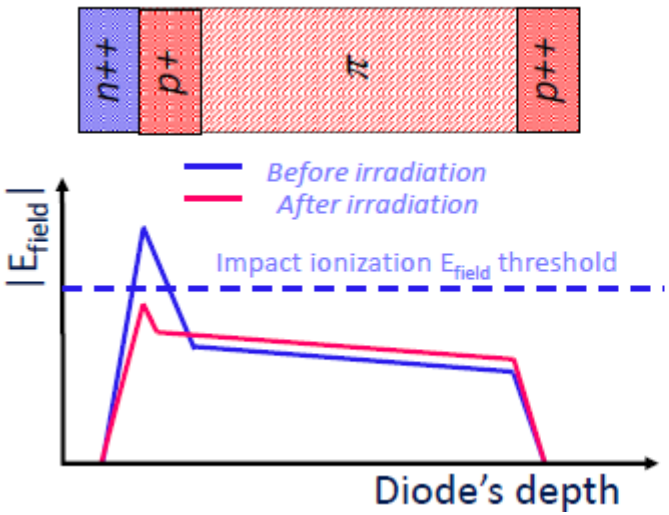
Work carried out within RD50 collaboration

Motivation

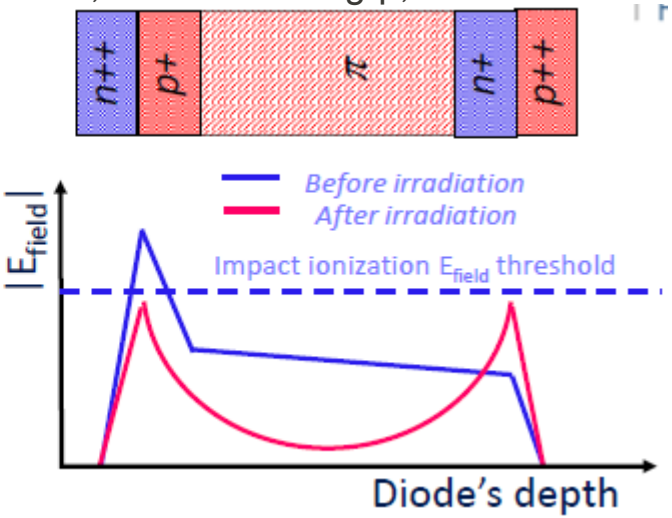
Two (not excluding) hypothesis for gain reduction in LGADs.:

1) Acceptor removal in the gain layer or

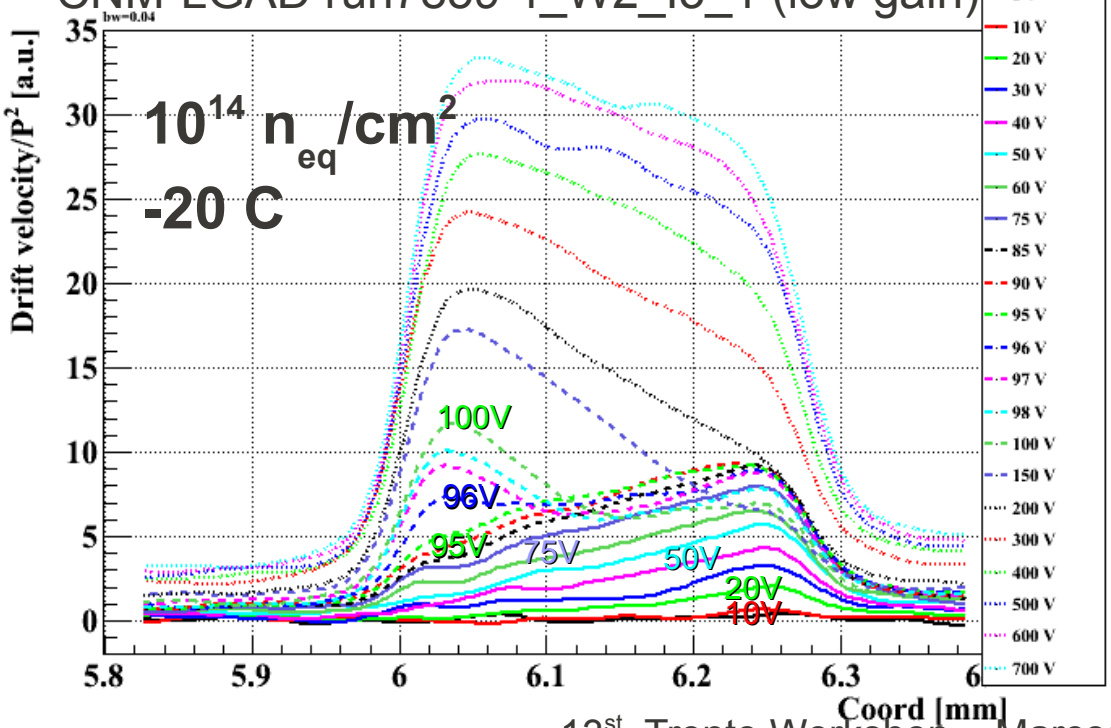
2) Double Junction mechanism



I. Vila,ETL sensor wkgrp, Oct 2017



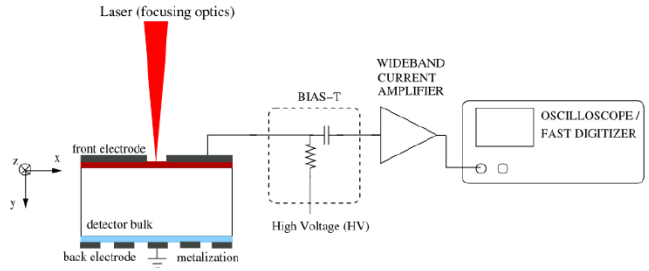
CNM-LGAD run7859 4_W2_I3_1 (low gain)



Two-Photon-Absorption TCT measurement of CNM-LGAD irradiated to 10^{14} n_{eq}/cm^2 shows:

0-95 V: depletion starting from the backside
96-100 V: double junction shape
>100V: junction at the front and develops to the backside

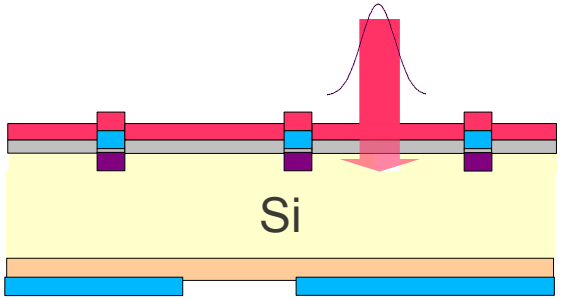
How sound is this E-field calculation?



Transient Current Techniques

Technique that allows to study the **current induced** by excess charge carriers produced, typically, by a **laser**.

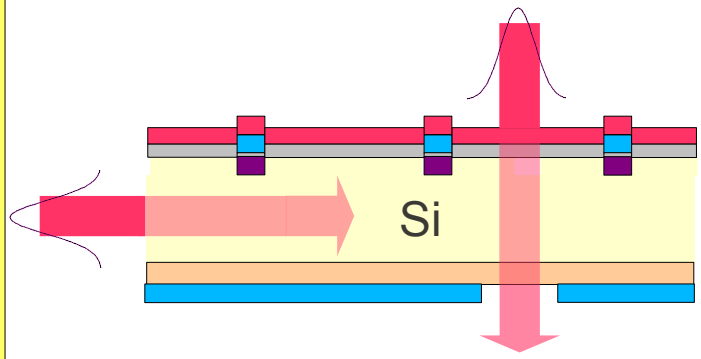
Laser characterization techniques



SPA-TCT Red

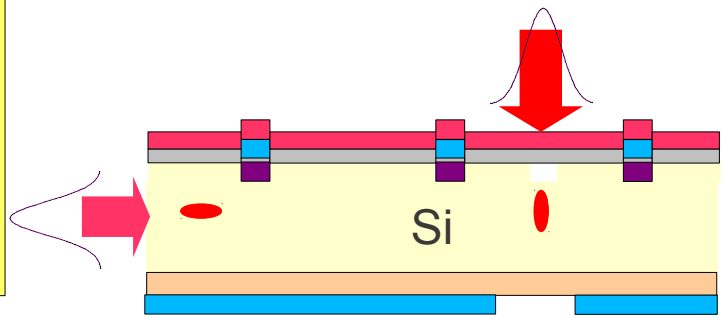
Employing short absorption length laser (red for Si), all carriers deposited in few µm from surface.
Allows to study drift of one kind of carriers.
No spatial resolution along beam direction.
1 photon=1 e-h pair

SPA: Single Photon Absorption
TCT: Transient Current Technique



SPA-TCT Infrared

Using long absorption length laser (infrared for Si).
Homogeneous distribution along “Rayleigh length”.
Similar to MIPs, though different dE/dx.
Incidence can be from **top, bottom** or **edge.**
Edge: lateral spatial resolution.
1 photon=1 e-h pair



Two Photon Absorption (TPA-TCT)

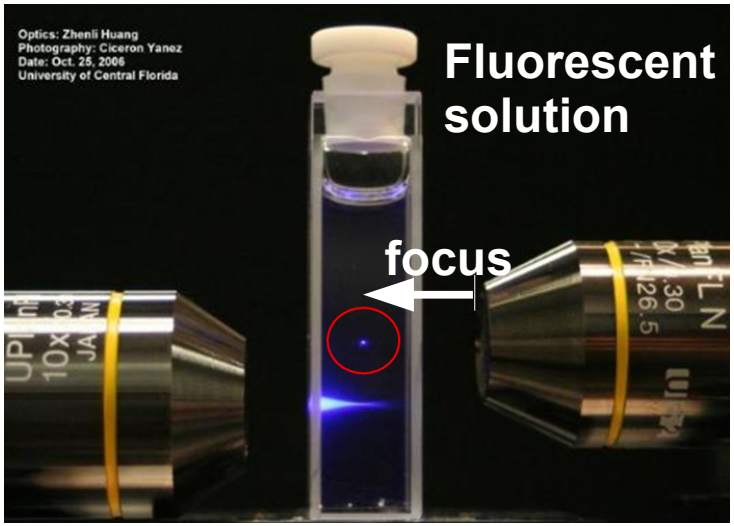
Point-like energy deposition → 3D spatial resolution
Novel technique developed by **IFCA, CERN, US, UPV**
2 photons=1 e-h pair

Two Photon Absorption-TCT

SPA

Single Photon Absorption

Continuous energy deposition

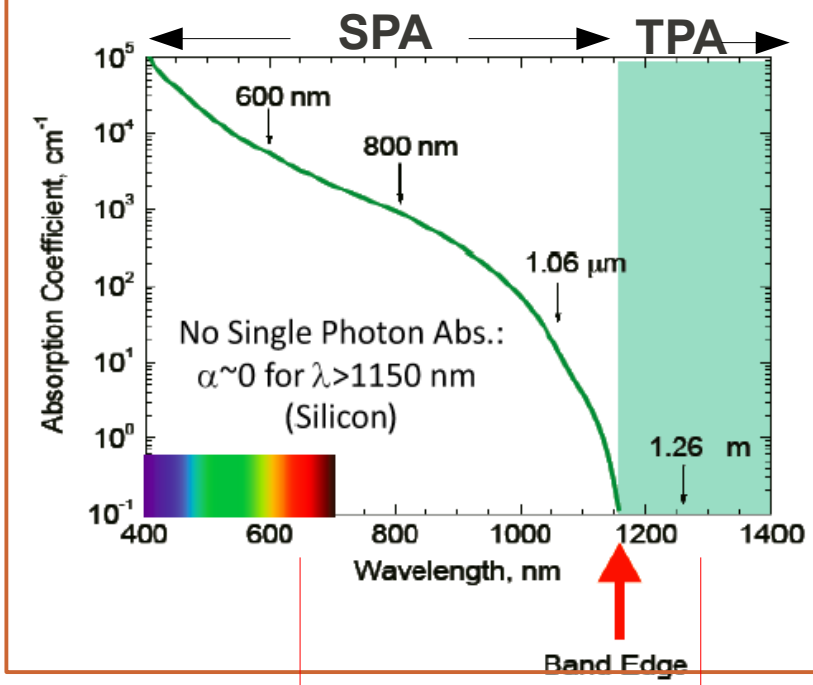


TPA

Two Photon Absorption

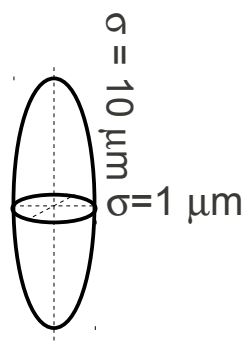
Energy confinement

Absorption in Si



Spot size

Two Photons ($E>E_{gap}/2$) must be **coincident in time** (pulsed **mode-locked** lasers) and in **space** (**microfocusing**) ×**100** objective



$$\frac{dN(r,z)}{dt} = \alpha \frac{I(r,z)}{\hbar\omega} + \frac{\beta_2 I^2(r,z)}{2\hbar\omega}$$

Single **P**hoton **A**bsorption
No spatial resolution along the beam propagation direction

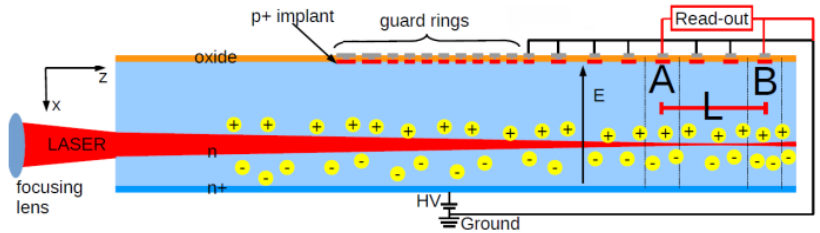
Two **P**hoton **A**bsorption
Point-like resolution

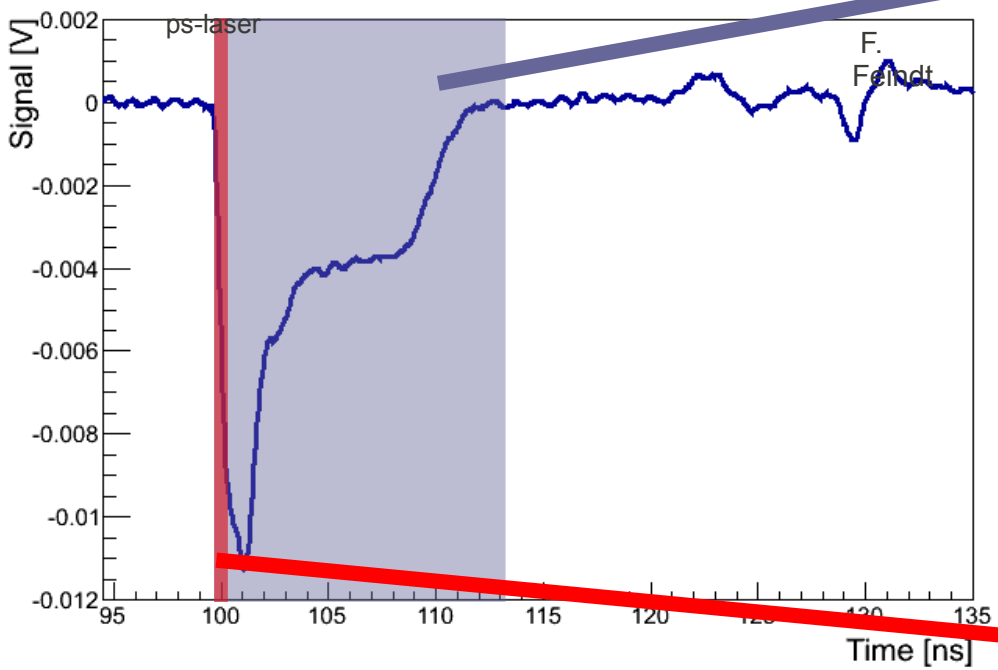
Boosted by getting away from SPA region and increasing irradiance so I2>>I.

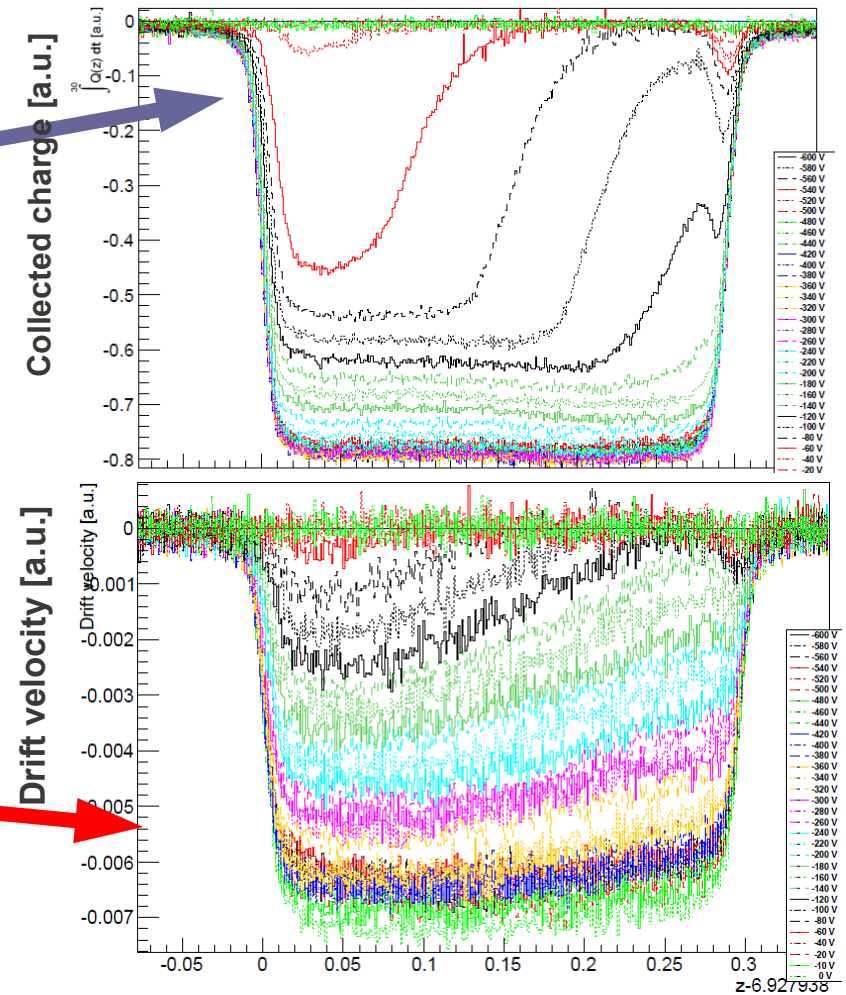
Handle: use fs laser

Laser facility at Bilbao (Spain) UPV
Access granted thanks to RD50 collaboration

The problem: calculate E-field in absolute units





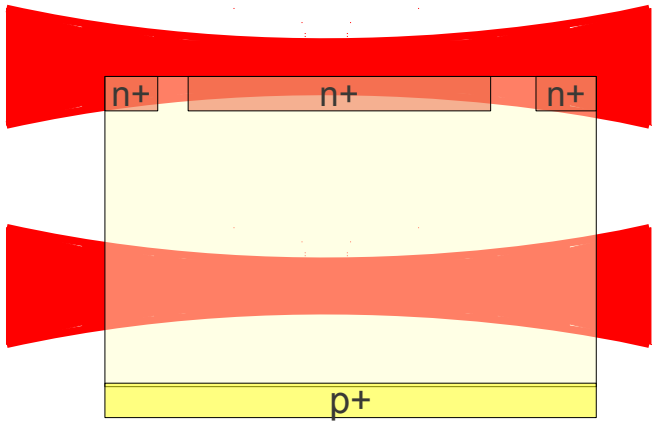


Detector response to a pulse of light

$$I_{total}(t) = N_{e,h} q_e A \cdot e^{\frac{-t}{\tau}} \cdot \vec{v} \vec{E}_W$$

Charge scale can be fixed comparing with a MIP and using 1 MIP=76 e-h/μm.
This does not hold for irradiated detectors
Scaling for drift velocity is not straightforward

Systematics for the calculation of E-field scale



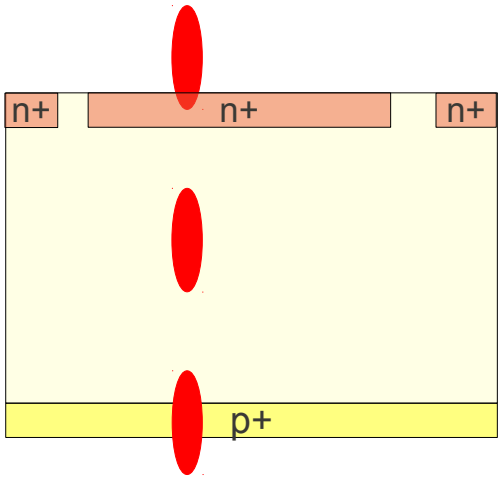
SPA edge-TCT:

Reflections at the air-surface interface (inward and outward) → number of photons is not constant.

Attenuation depth along direction of propagation (mm) modify number of photons

Mitigated using strip detectors + weighting field

Illumination below GR and unactive regions for detection



TPA-TCT:

Only normal reflections.

Attenuation along beam direction is **minimal** because of small detector thickness.

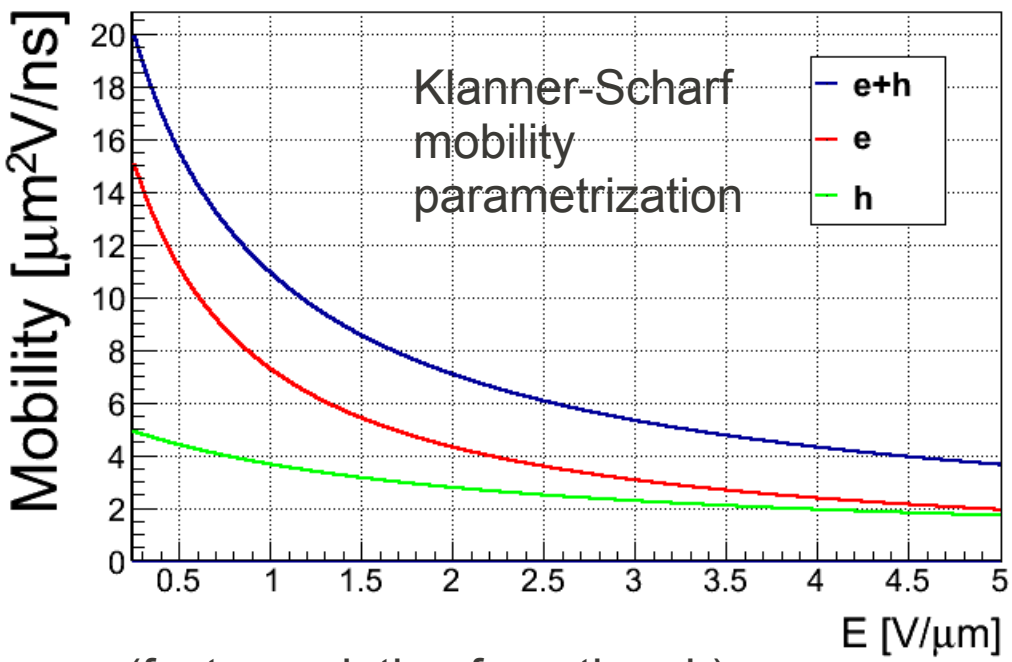
A diode is the best geometry because of **constant weighting** field.

Scaling of drift velocity (I)

As a **first approach**, we will use the prompt method (Kramberger, IEE TNS vol57 4, 2010), based on Ramo's current. For a diode (E_w=1/d) and constant mobility, the total induced current is:

$$I_{total}(t) = \underbrace{\frac{N_{e,h} q_e A}{d}}_{constant} \cdot e^{\frac{-t}{\tau}} \cdot (\mu_e E(z) + \mu_h E(z))$$

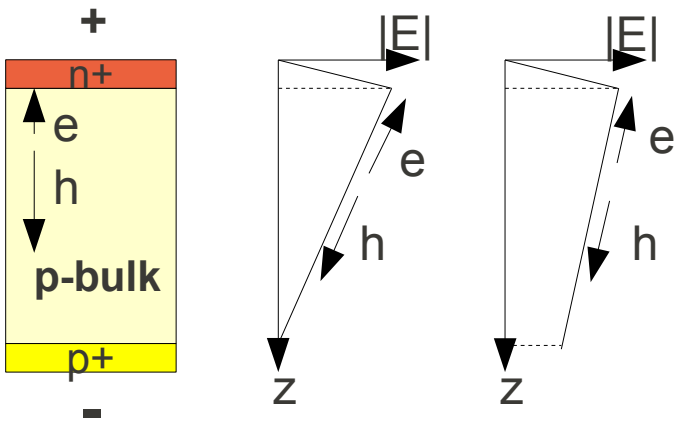
First simplification: mobility is constant. $I_{total}(t) = k\, e^{\frac{-t}{\tau}} (\mu_e + \mu_h) E(z)$



(faster variation for e than h)

For a fixed bias E<1 V/μm in a diode→ $\mu_e(\mu_\eta)$ typically varies ~20%(10%).

Better applicability for overdepleted detectors with"flat" velocity profiles ("small" Neff, high resistivity)



Scaling of drift velocity (II)

For t~0:

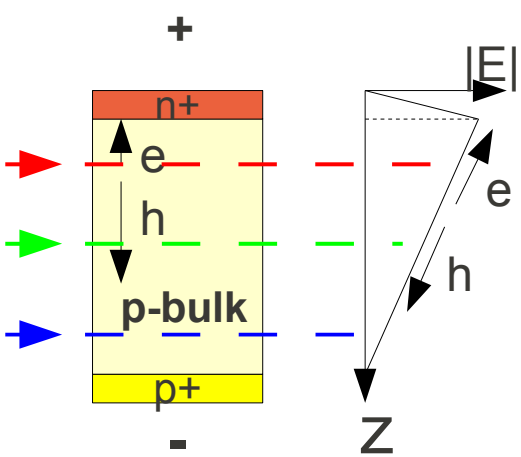
$$I_{total}(t\sim 0) = \underbrace{k(\mu_e+\mu_h)}_{k'} E(z) = k' E(z) \quad \Rightarrow \quad E(z) = \frac{I_{total}(t\sim 0)}{k'}$$

Prompt method:
Drift velocity profile can be calculated except for a proportional factor from the **rising edge** of the induced current

To calculate k' we use the **constraint** that the electric field integrated over the thickness of the detector gives the bias. **Experimentally** this can be realized as a **Z-scan** in edge-TCT or a normal scan in TPA.

$$V_{bias} = \int_0^{w(V)} E(z)\,dz = \int_0^{w(V)} \frac{I_{total}(t\sim 0)}{k'}\,dz \quad \Rightarrow \quad k' = \frac{\int_0^{w(V)} I_{total}(t\sim 0)\,dz}{V_{bias}}$$

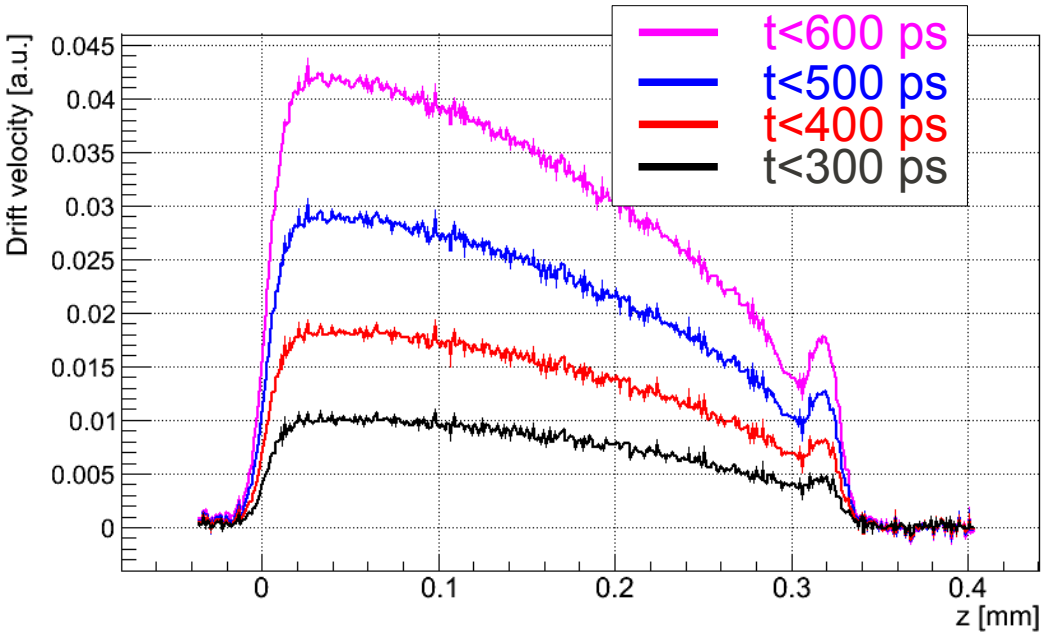
Different k' for each bias



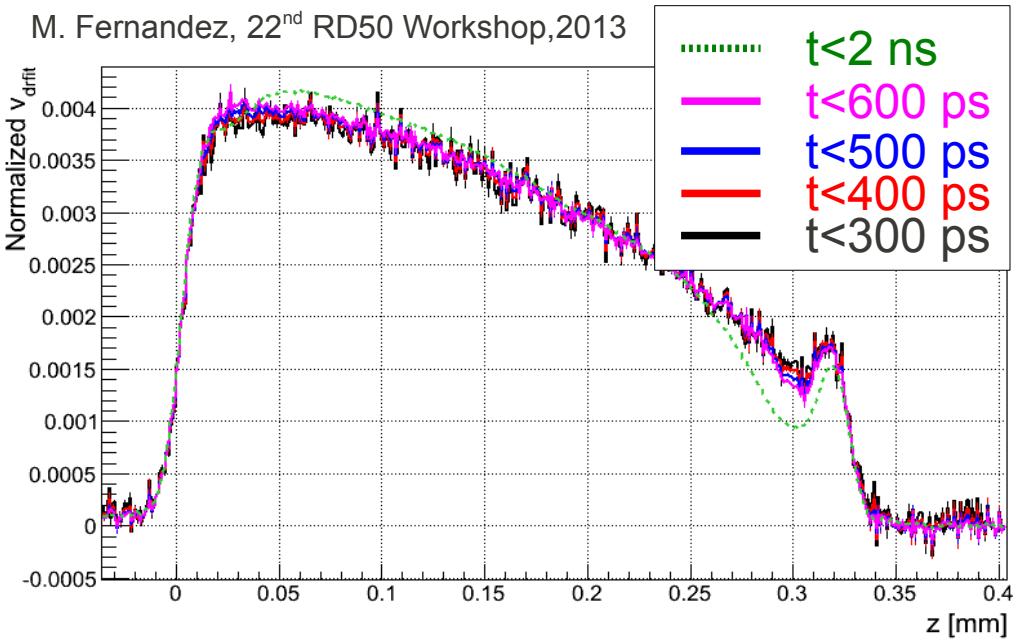
$$E(z) = \frac{I_{total}(t\sim 0)}{k'} = \frac{I_{total}(t\sim 0)}{\int_0^{w(V)} I_{total}(t\sim 0)\,dz} \cdot V_{bias}$$

By construction: $V_{bias} = \int_0^{w(V)} E(z)\,dz$

Meaning of t~0



Absolute vdrift ([a.u.]) for different averaging times

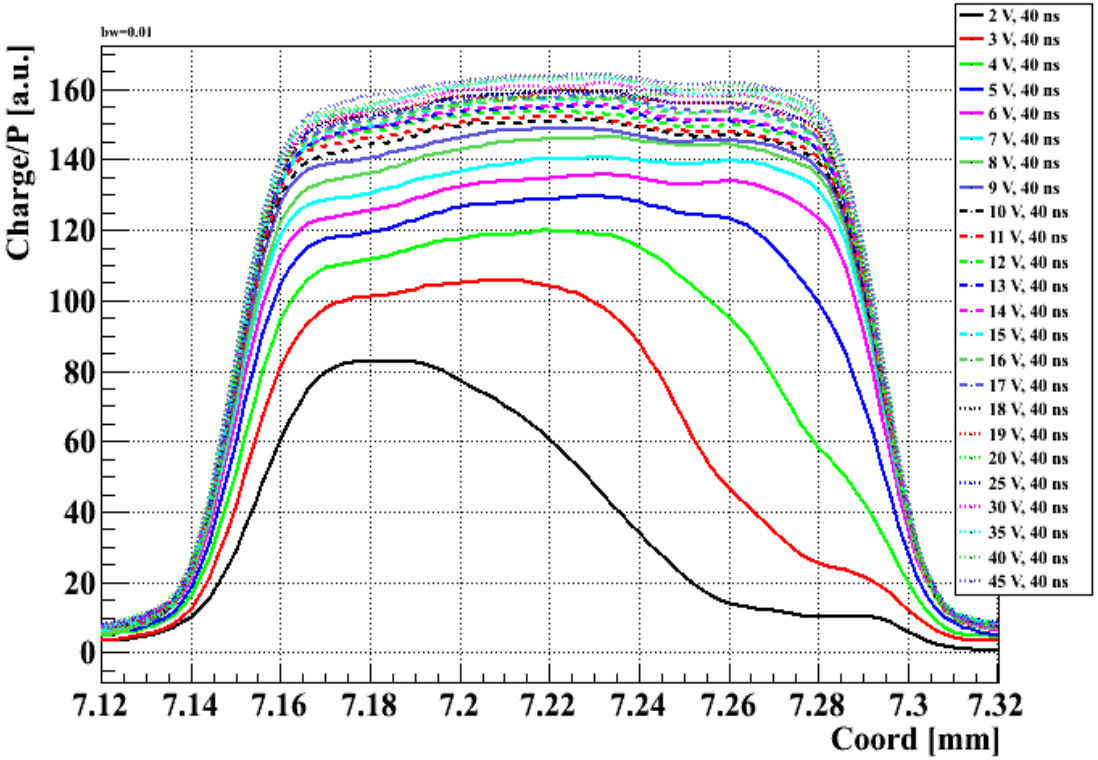


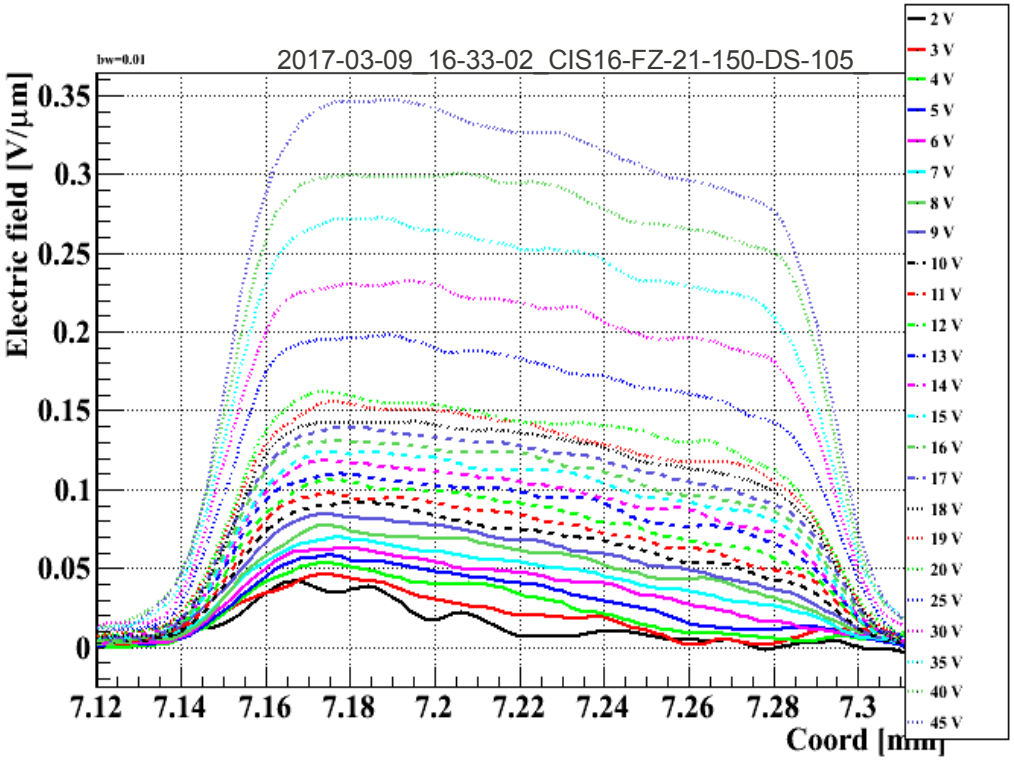
Normalized vdrift ([a.u.]) for different averaging times

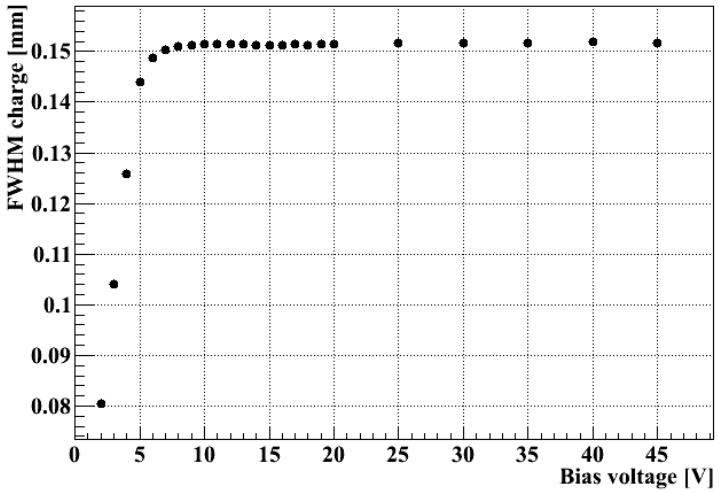
The picture obtained for different (t~0) is the same except for a normalization constant

E-field calculation in SPA edge-TCT

SPA edge-TCT of CIS16-FZ-21-150-DS-105 **diode (measurements at CERN-SSD)**







The resistivity calculated from Vdep~5 V gives a resistivity of 14.5 kΩ.cm.

Nominal is >10 kΩ.cm.

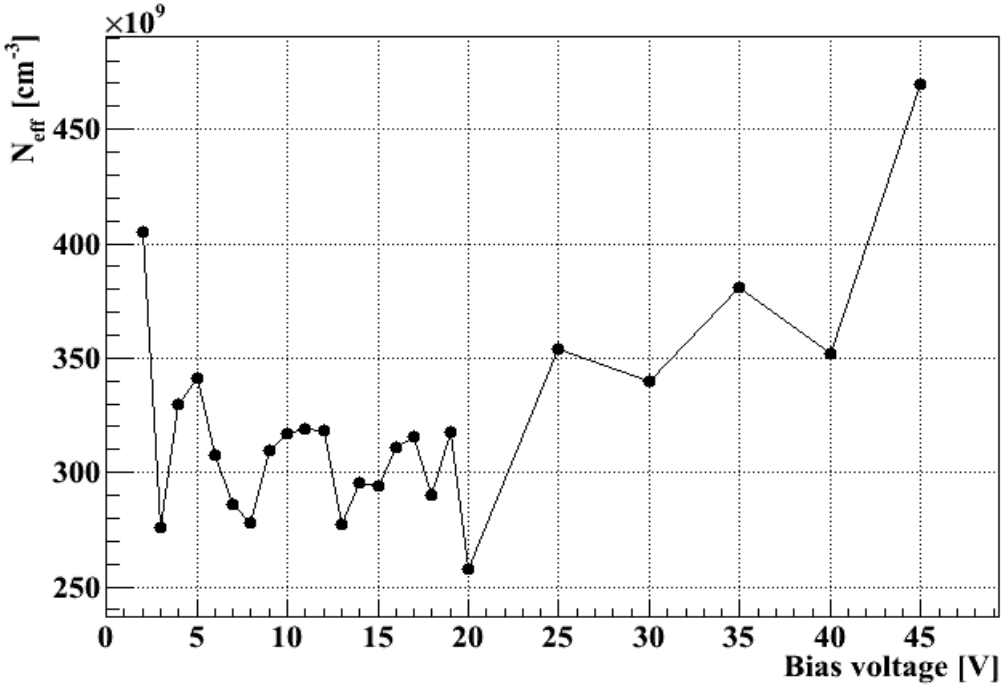
Edge-TCT: Neff calculation from E-field

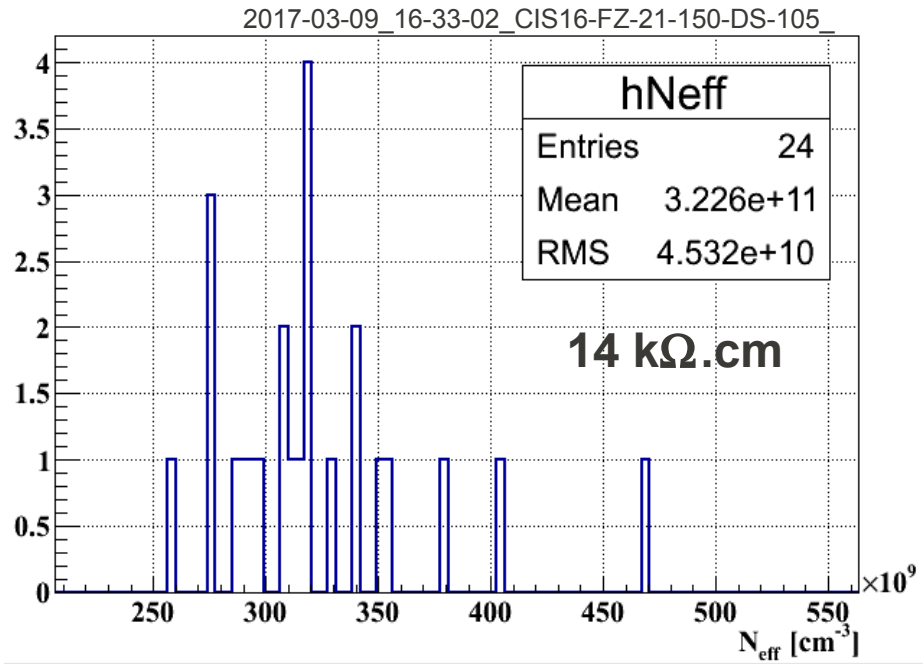
Doping resistivity can be calculated from the slope of the E-field, once the scale is known.

$$E(x) = \frac{2V_{di}}{d}\left(1 - \frac{x}{d}\right) + \frac{V_b - V_{di}}{d}$$

$\Rightarrow$ slope=$2V_{dep}/d^2$ $\rightarrow$ $N_{eff} = \frac{\epsilon}{e} \cdot slope$

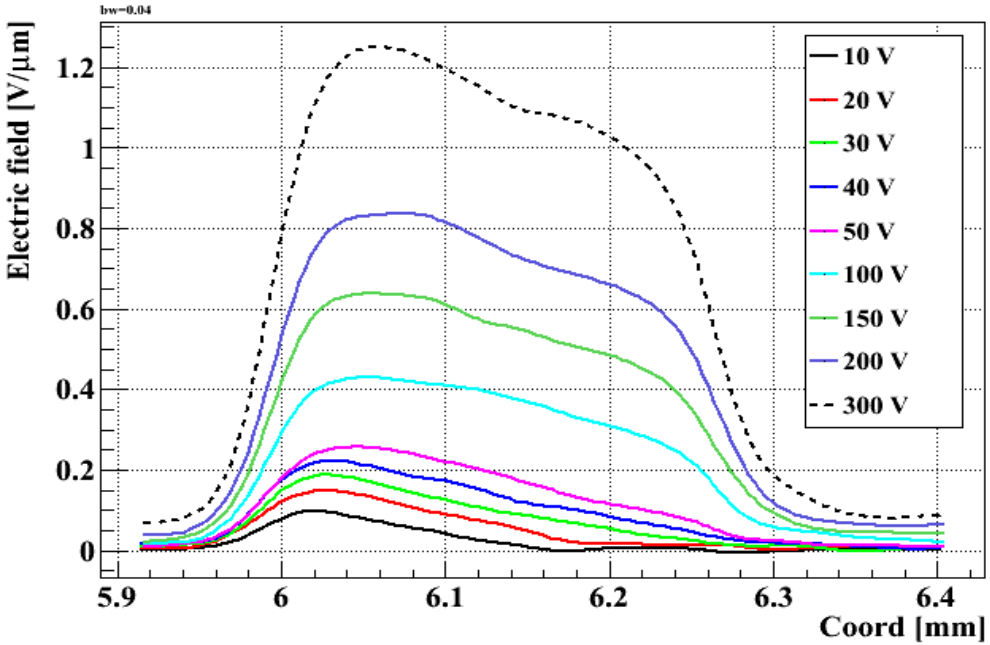
The result for this detector is 14 kΩ.cm

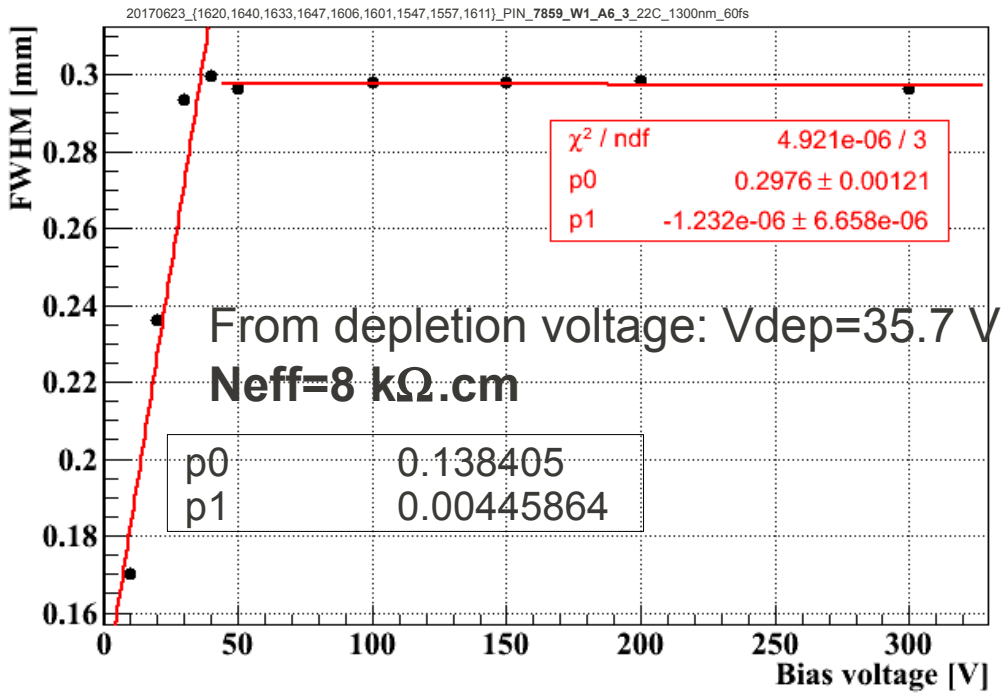


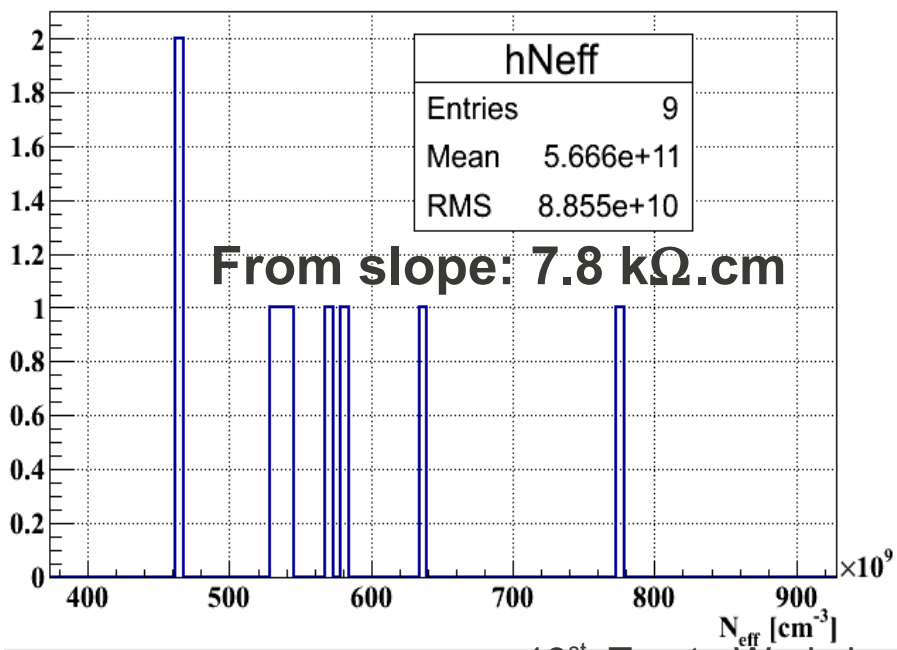


However this method is not robust. A small change in the slope gets amplified by the ε/e factor (error is roughly x10 bigger than from Vdep method).

E-field calculation in TPA top-TCT







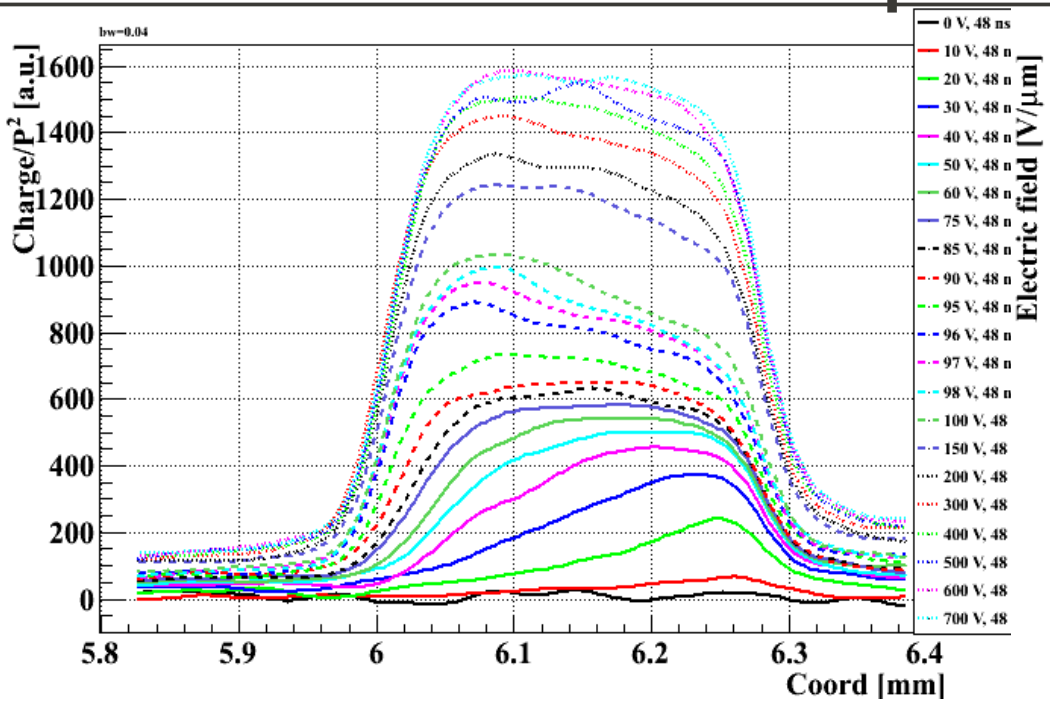
PiN 7859_W1_A6_3 (different detector)

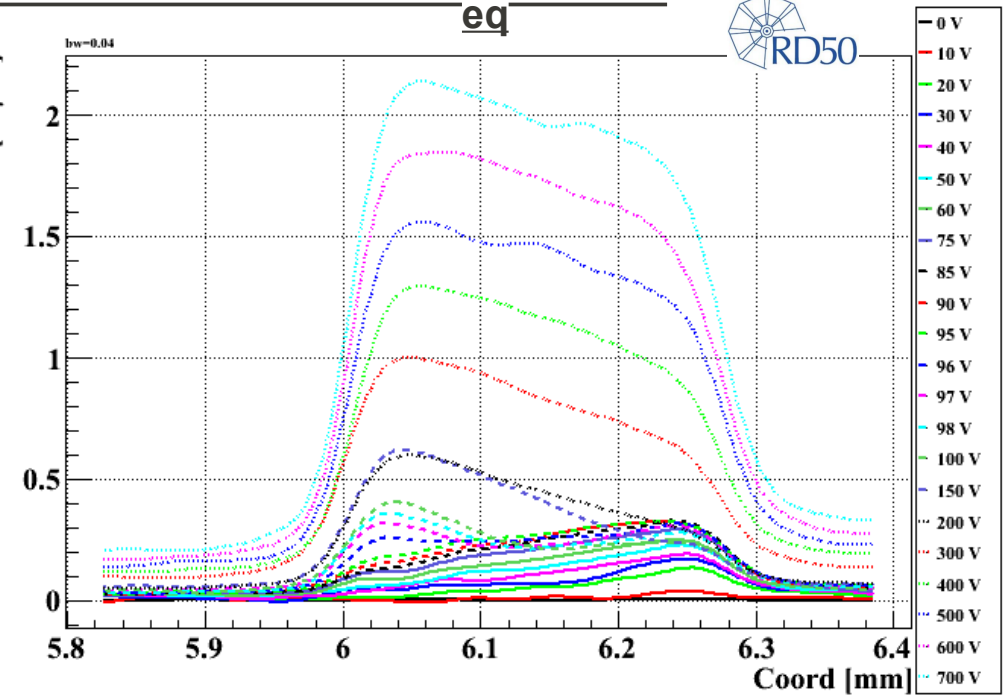
Two independent estimations of the nominal resistivity (12 kΩ.cm):

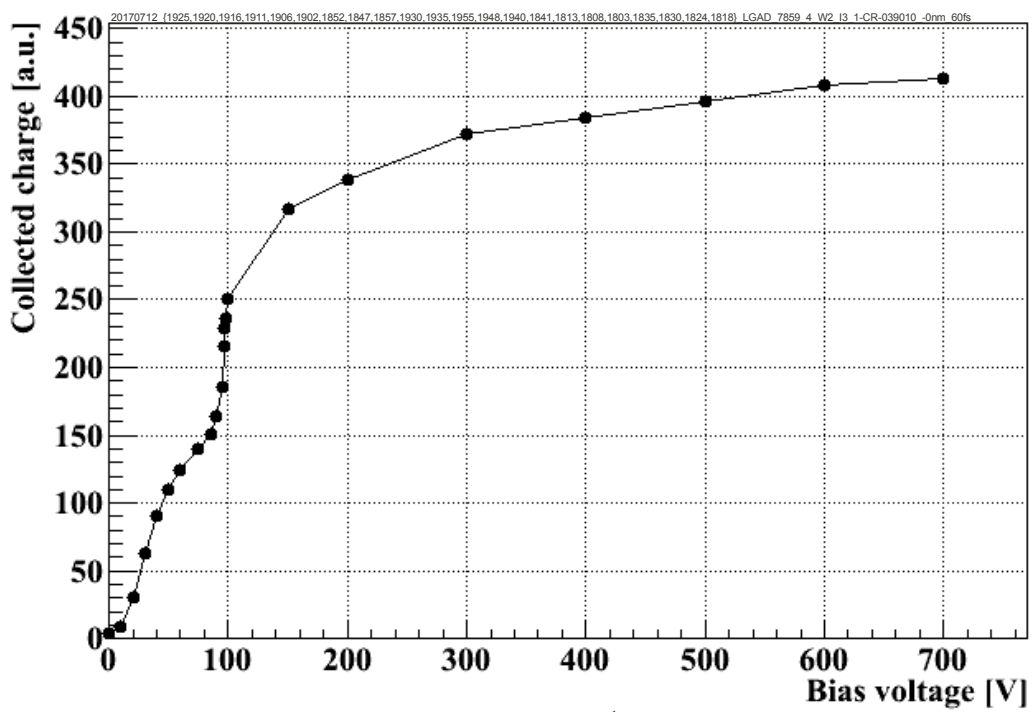
From depleted width (CV-like): 8 kΩ.cm

From E-field slope: 7.8 kΩ.cm

E-field calculation in LGAD p-irradiated 1e14 n_{eq}/cm2

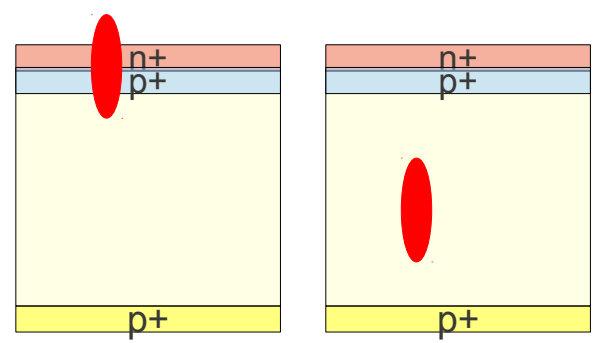






Gain at the front does not seem to impact drift velocity/charge profiles.

Drift velocity scaling calculated discarding Gain



At t~0 $N_e + GN_h$ $N_e + N_h$

Conclusions

Thanks to the **point-like** excitation volume inherent to TPA the problem of calculation of Electric field inside a detector using Ramo theorem is simplified.

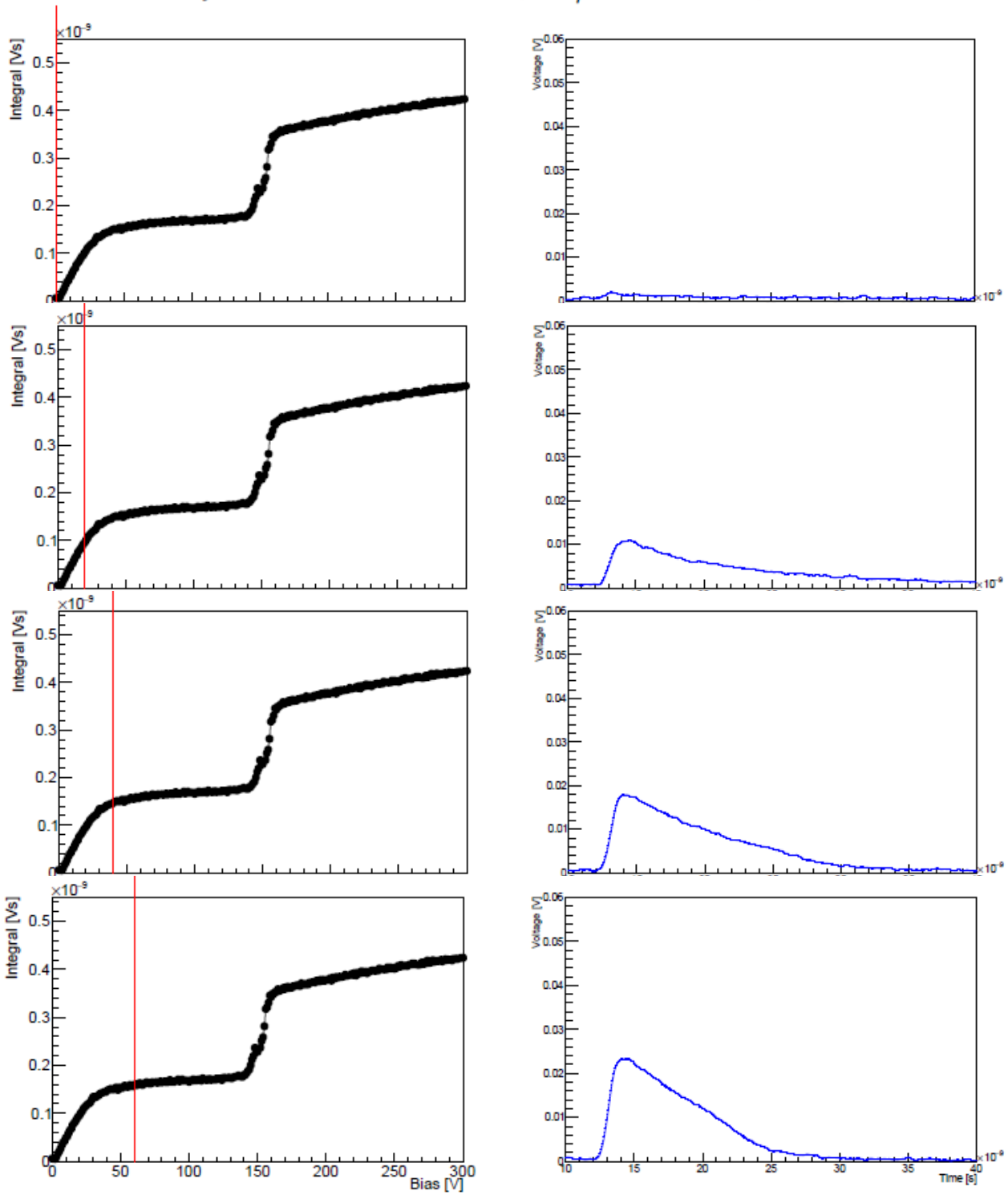
As a **first attempt**, we used the current prompt method and the bias constraint to extract the proportionality factor. Electric field and doping concentration calculated for **diodes** and an irradiated **LGAD**.

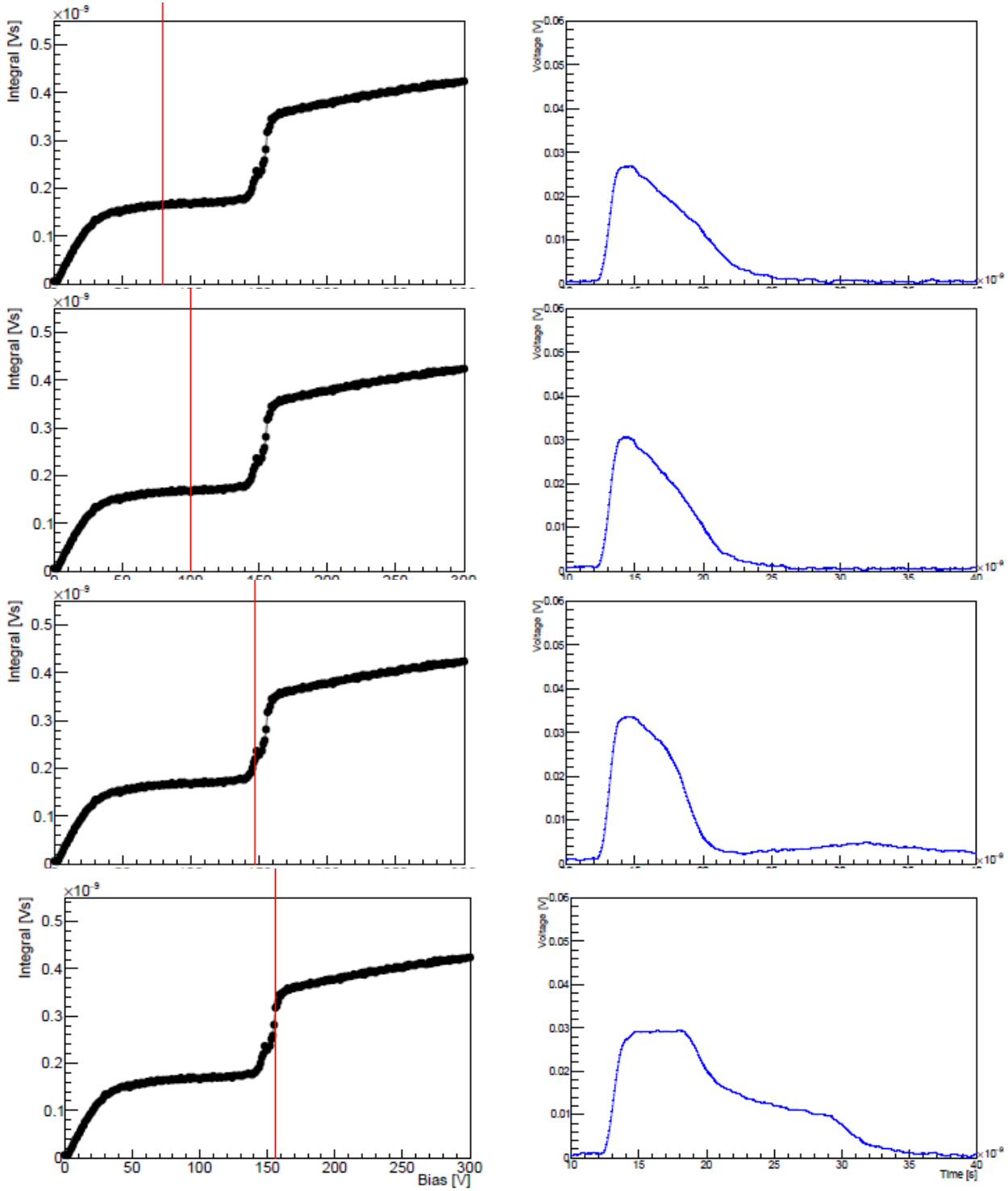
Next: use simulation package TRACS to account for mobility changes with E-field and fit for effective space charge.

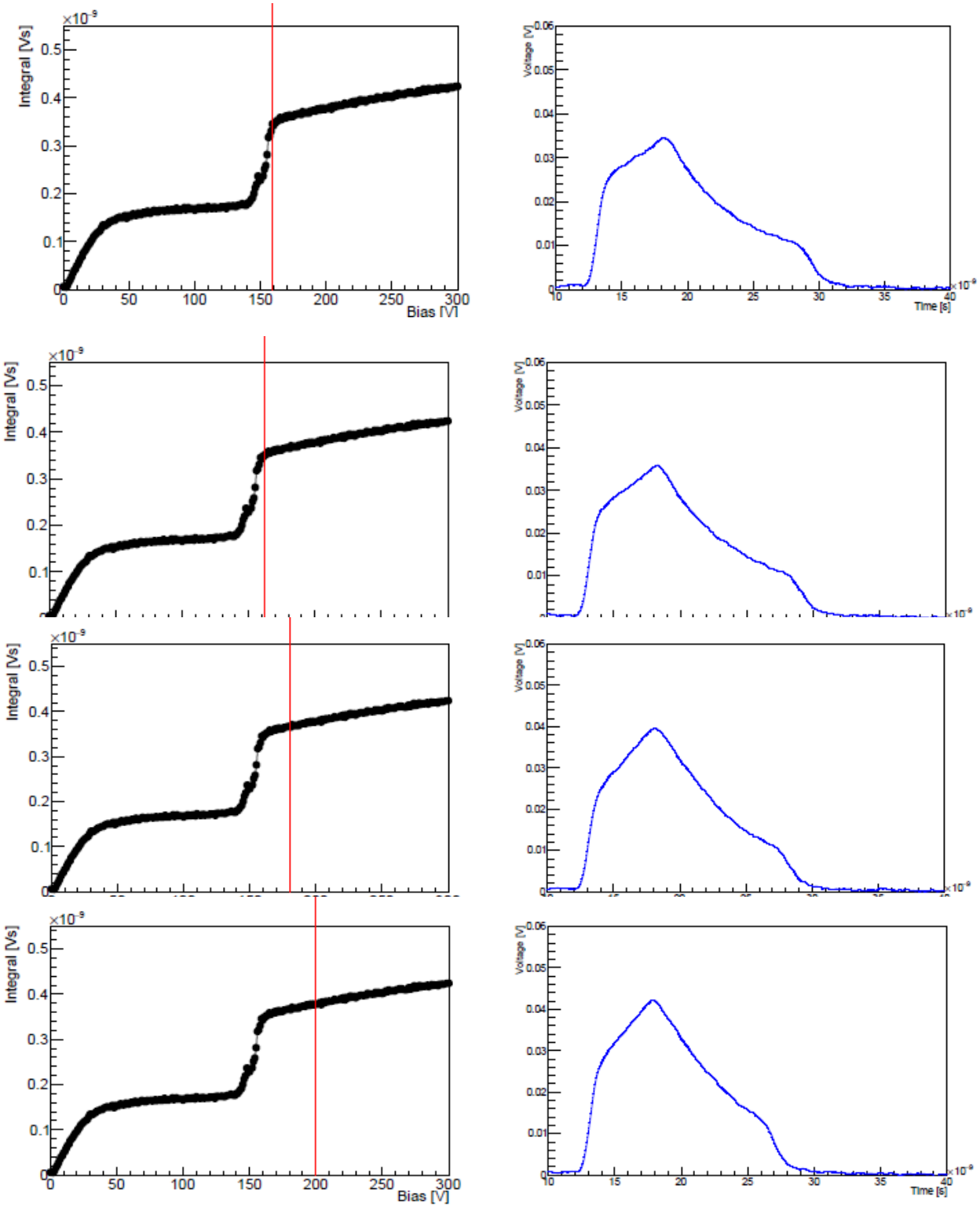
A TPA-TCT system is being built at CERN-SSD and will be commissioned at the end of 2018, thanks to CERN-KT funding.

Backup

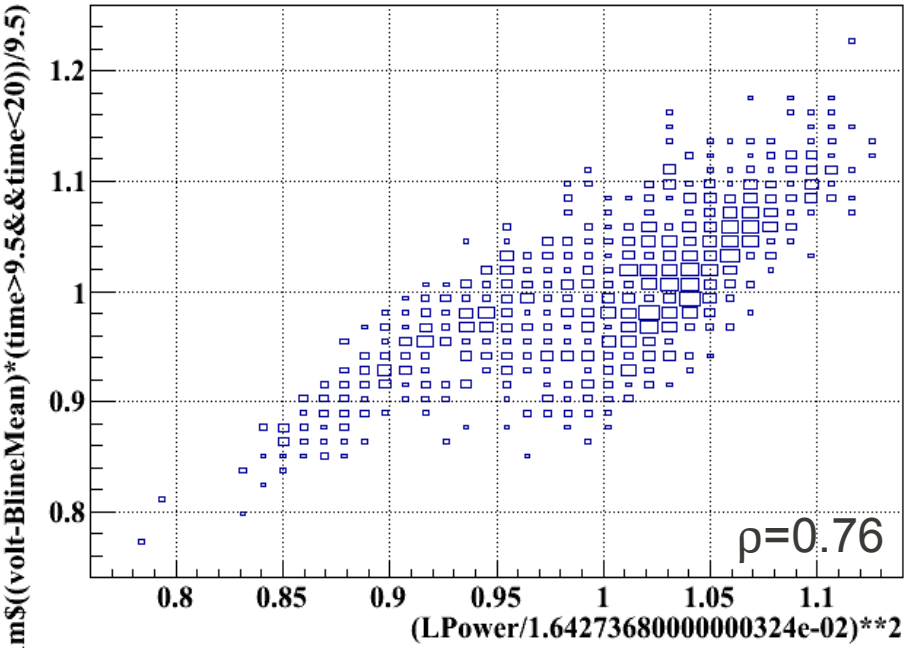
Mult. layer dose $1.8 \cdot 10^{13}\,\mathrm{cm}^{-2}$, $\Phi_{eq} = 10^{14}\,\mathrm{cm}^{-2}$, $T = -20^{\circ}\mathrm{C}$



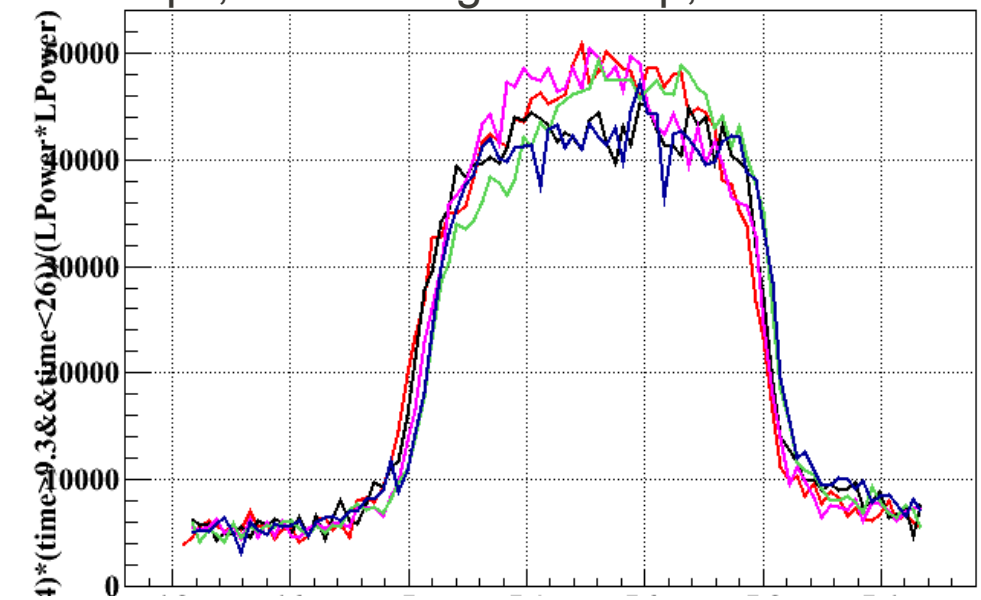

Integral [Vs]
×10⁻⁹
Bias [V]
Voltage [V]
Time [s]

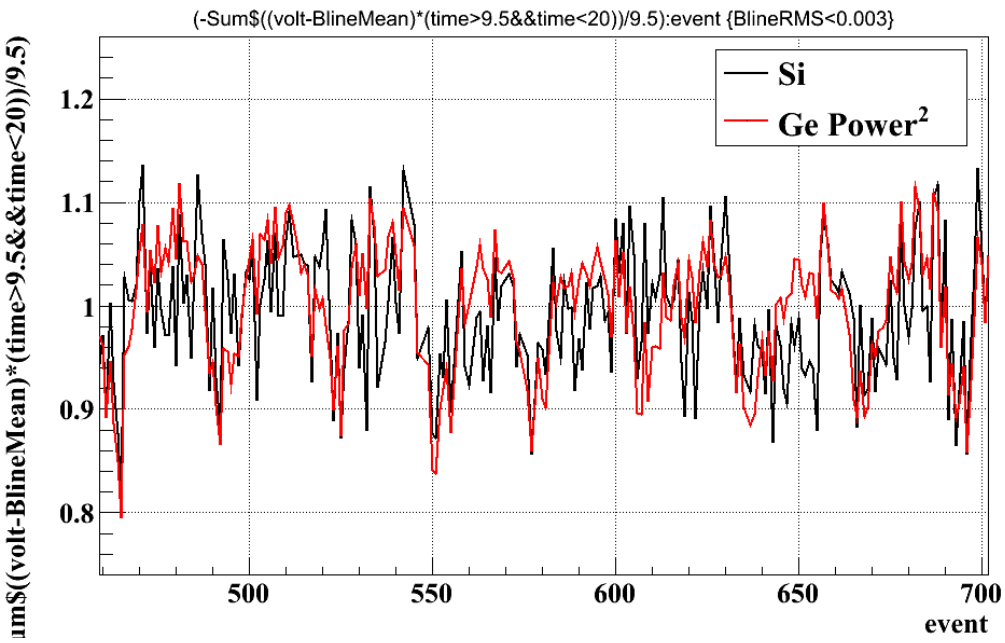

Integral [Vs]
×10⁻⁹
Bias [V]
Voltage [V]
Time [s]
×10⁻⁹

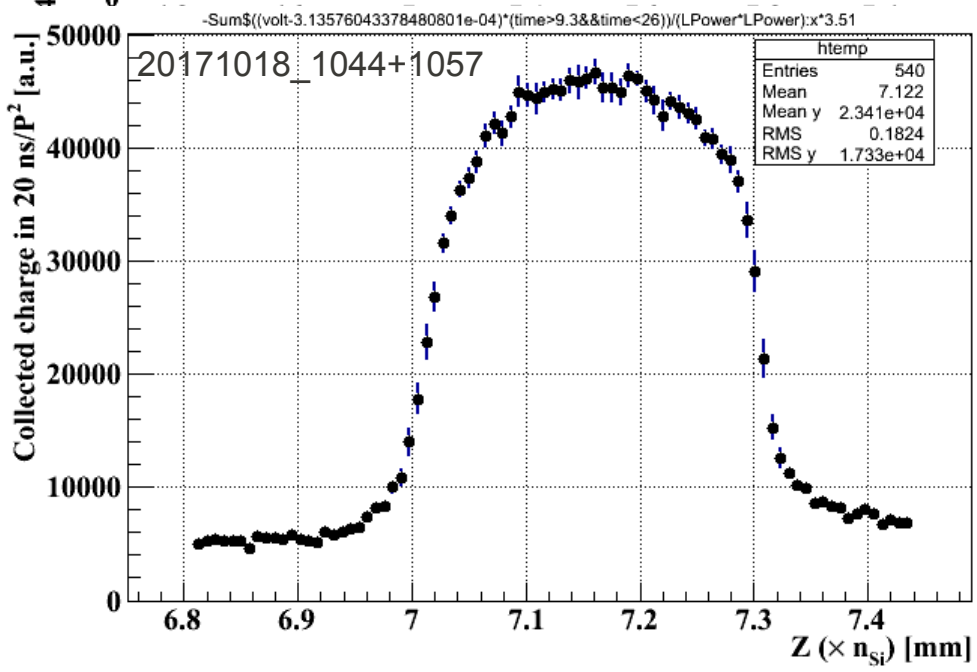
Sweeping vs averaging



5 sweeps, 128 averages/sweep, LPower=0.011







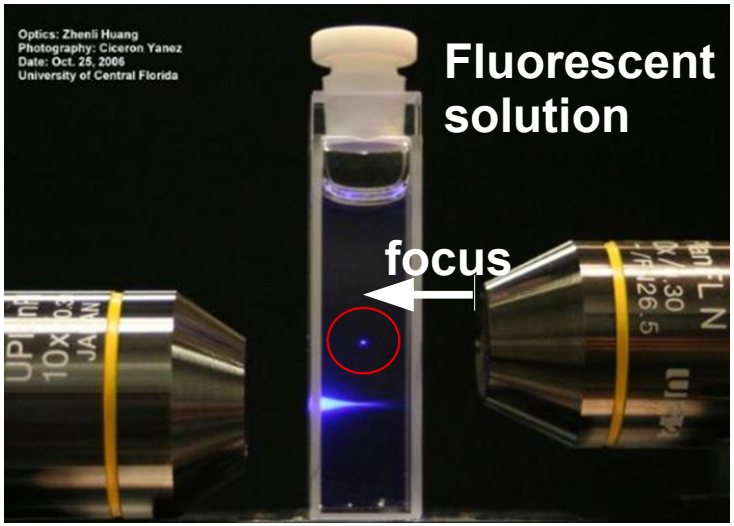
Short sweeps average laser power oscillations

Two Photon Absorption-TCT

SPA

Single Photon Absorption

Continuous energy deposition

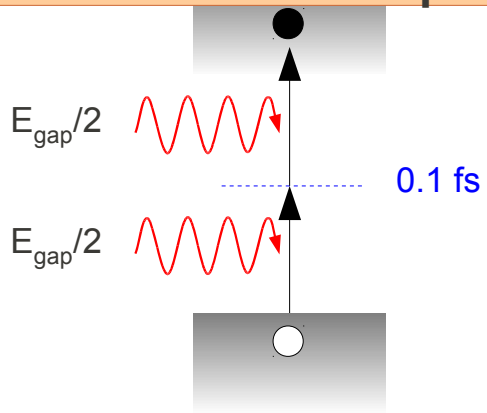


TPA

Two Photon Absorption

Energy confinement

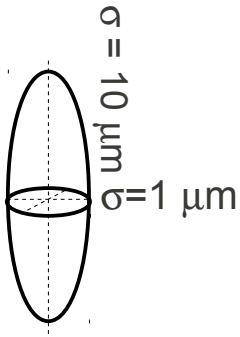
Two Photon Absorption



Non-irradiated

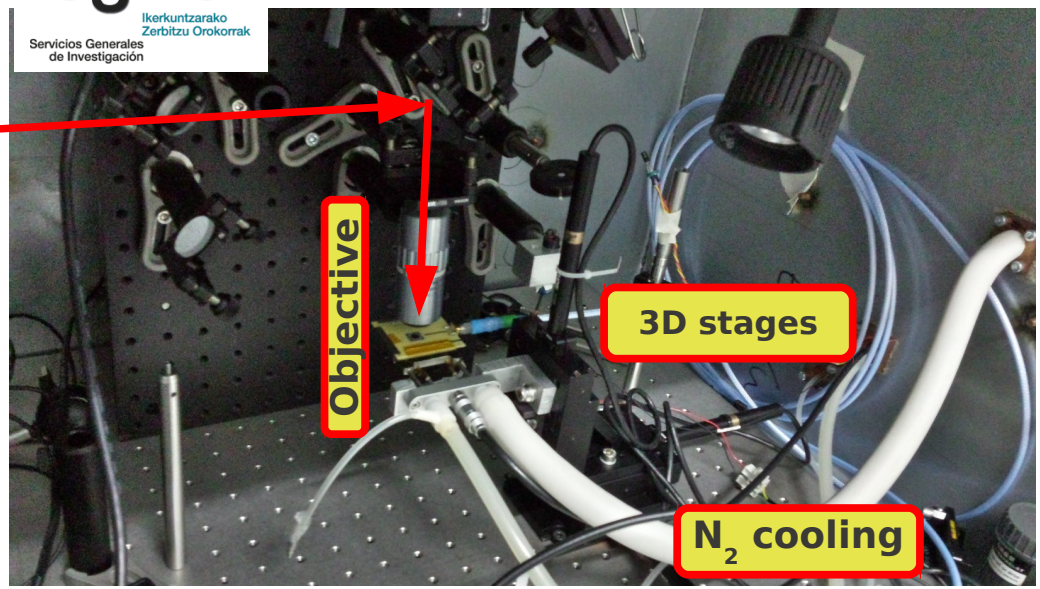
Spot size

Two Photons must be **coincident in time** (pulsed **mode-locked** lasers) and in **space** (**microfocusing**)



×**100** objective

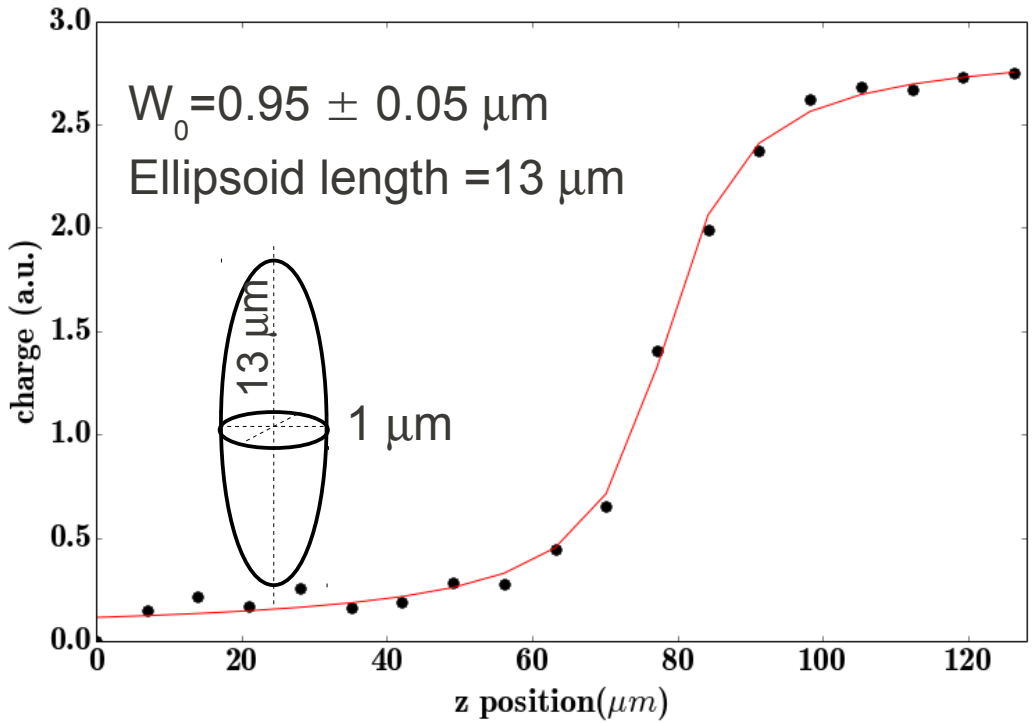
Setup



Evidences for TPA process

1) Collected charge varies quadratically with power
2) Z-scan is not Z-invariant.

Then characterize the excitation volume:



Ellipsoid is completely described by waist (w_0), λ and β.

$$w(z) = w_0 \sqrt{\frac{\lambda z}{\pi w_0^2 n}}$$

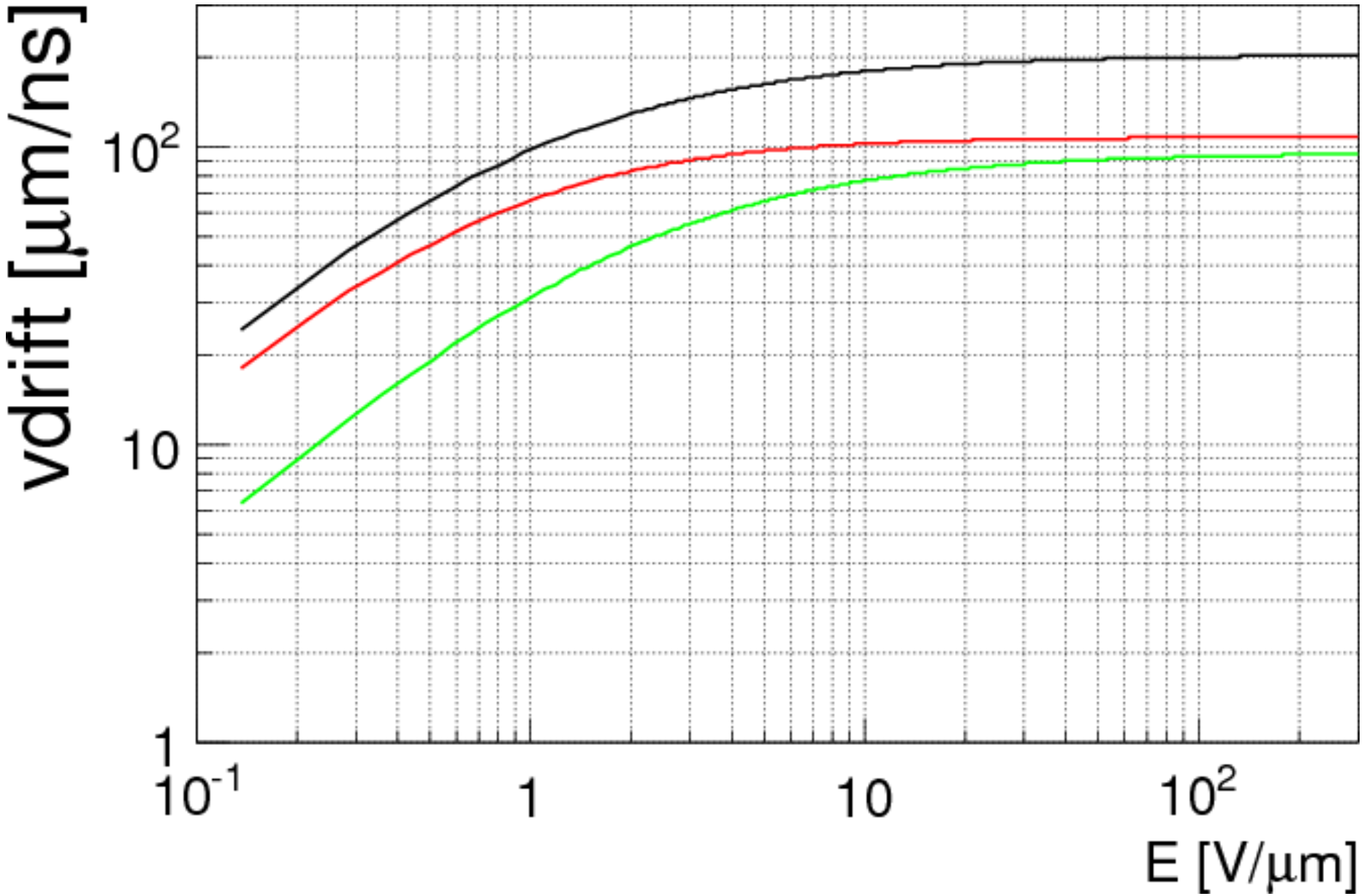
$$I(z) = \frac{2P}{\pi w^2(z)} e^{\frac{-2r^2}{w^2(z)}}$$

$$\frac{dN(r,z)}{dt} = \frac{\beta_2 I^2(r,z)}{2\hbar\omega}$$

$$t \sim t_p \rightarrow N(z) = \int_{-\infty}^{\infty} 2\pi r \cdot t_p \cdot N(r,z)\, dr$$

An **edge-TPA** scan is optimum, because spatial resolution is **~1 μm**
Try to scan **pads from the edge** → Get active area very close to the border

New RD50 project to perform edge-TPA on irradiated diodes


vdrift [μm/ns]
10^2
10
1
10^{-1}
1
10
10^2
E [V/μm]