SÉMINAIRE DE PHYSIQUE CORPUSCULAIRE

RD50

IFCA
Instituto de Física de Cantabria

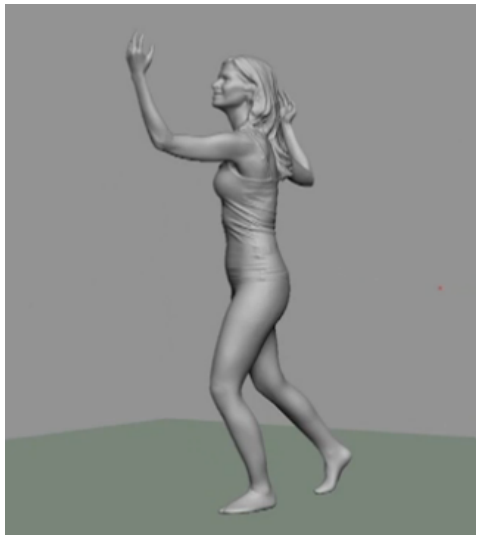
3D Laser characterization of semiconductor devices

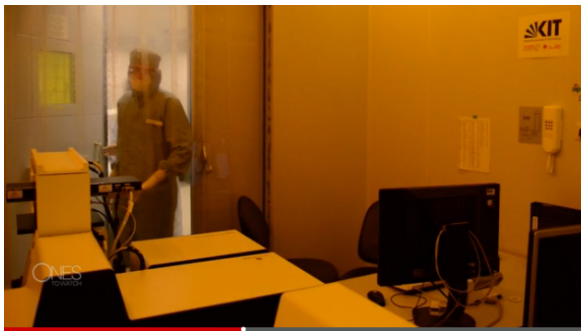
Marcos Fernández García
IFCA-Universidad de Cantabria (Spain)
Visitor scientist at CERN SSD

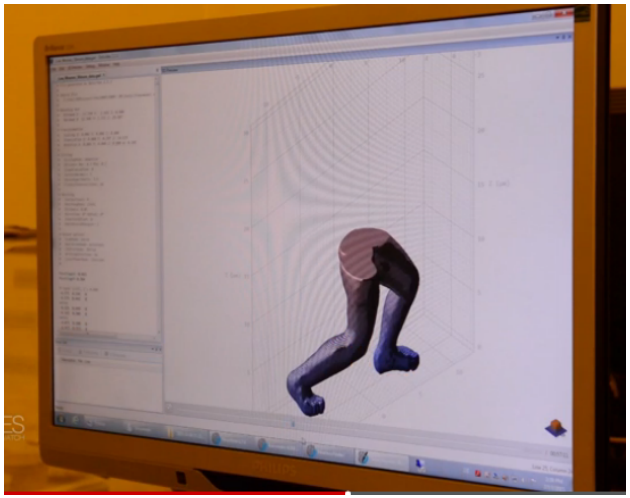
10 µm

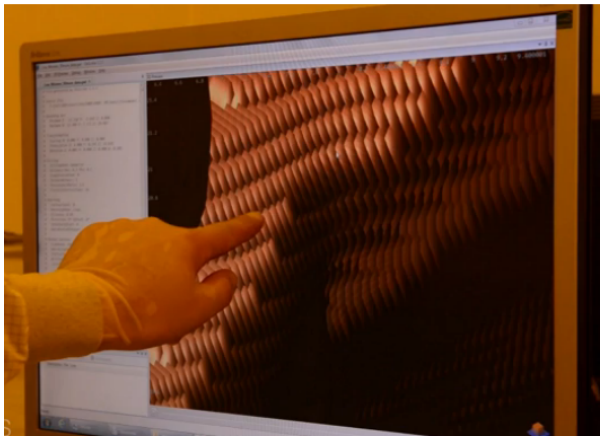
http://www.jontyhurwitz.com

3D microfabrication: using **focused ultrashort laser pulses** on the volume of a **photoresist**, the pulses initiate **polymerization**. After illumination of the structure and **development** (washing out the non-illuminated regions) the **polymerized** material remains in the prescribed **3D** form.









Screenshots from "**Is this the world's smallest sculpture?**" CNN "Ones to watch"

Further reading:**Two Photon Polymerization: a New Approach to Micromachining**, Photonics spectra, October 2006

Outline of this talk

3D laser testing = TPA-TCT

What is TPA? **What is TCT?**

TPA-TCT on:

Diodes **HVCMOS** **Diamond**

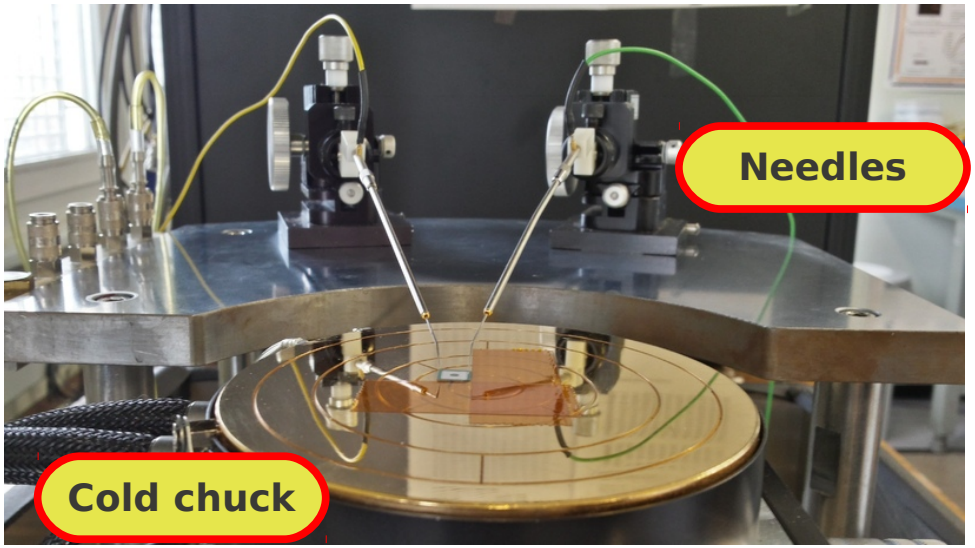
Not irradiated / irradiated (n)

Common characterization techniques of semiconductor radiation detectors

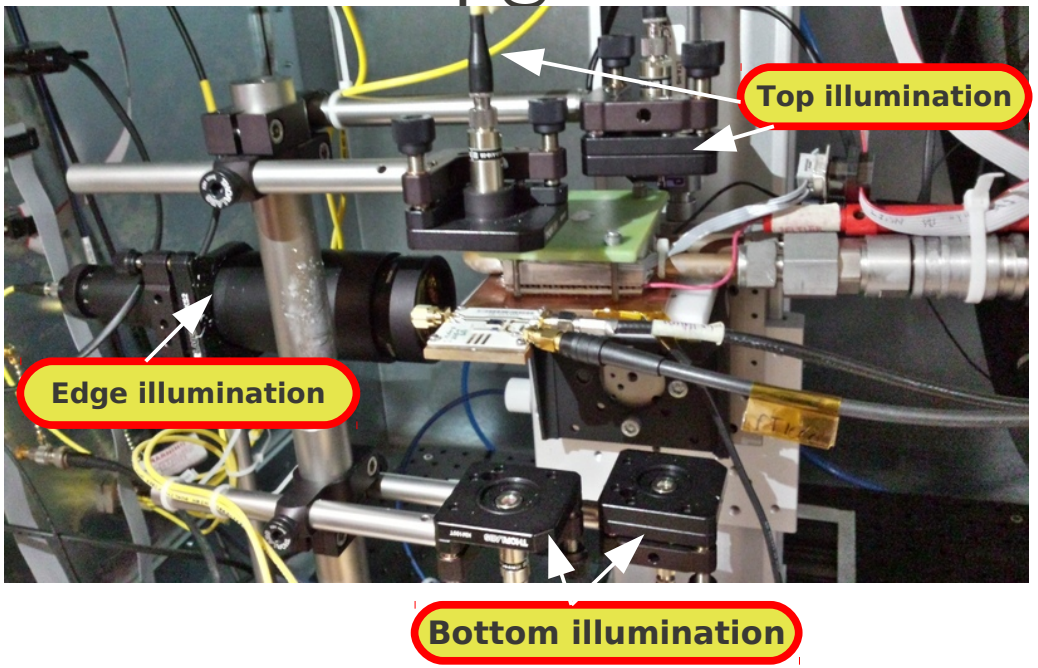
Technique	Type	Spatial resolution	Efficiency	Reach	Requirements
IV/CV	Electrical	Not applicable	No	I_{leak}, $V_{dep}(\propto N_{eff})$, V_{br}, C_{end}	Needle system Cold chuck pA-meter, LCR meter...
TCT (Transient Current Technique)	Optical	2D	Yes	N_{eff}, $\tau_{e,h}$ (low Φ_{eq}) uniformity	ps-pulsed laser stepper motors Amplifier, scope
Radioactive source	Source	None	Yes	V_{dep}, CCE	Radioactive source, trigger system
IBIC	Source	2D	Yes	2D CCE	Accelerator
Test beam	Source	2D	Yes	Setup/sensor dependent: 2D CCE,...	Accelerator, beam time, telescope, trigger,

MIP capabilities: Test beam, infrared TCT

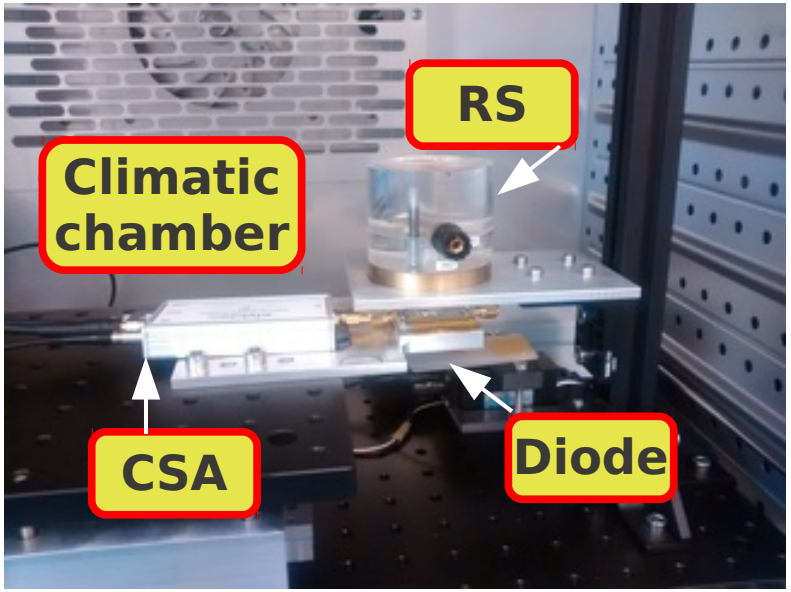
IV/CV @ CERN-SSD



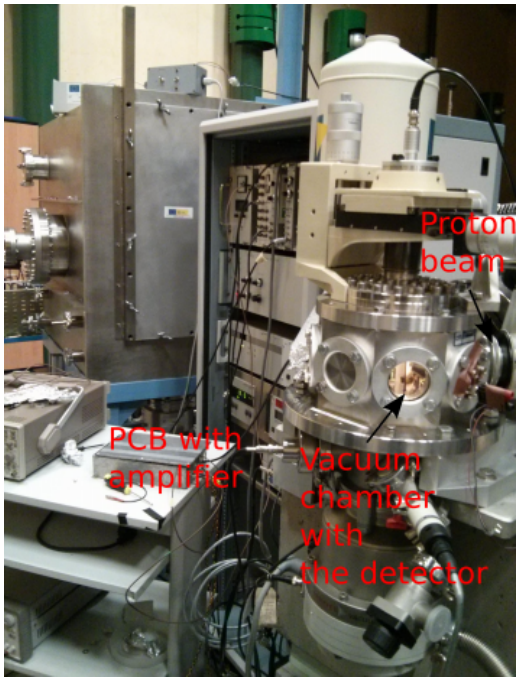
TCT+ setup @ CERN-SSD



CSA setup @ CERN-SSD



IBIC @ CNA-Sevilla



Test beam @CERN SPS

Is there any technique providing 3D spatial resolution ?

Is there any technique providing 3D spatial resolution ?

Yes

The answer to the question is: **Two Photon Absorption TCT**

As of now (2016), the only existing demonstrator of the technology has been built in a laser facility in Spain.

What can it offer?

- **True 3D** spatial resolution (only technique achieving this)
- Repeatability
- Easy triggering
- High S/N

} Laser

Next steps:

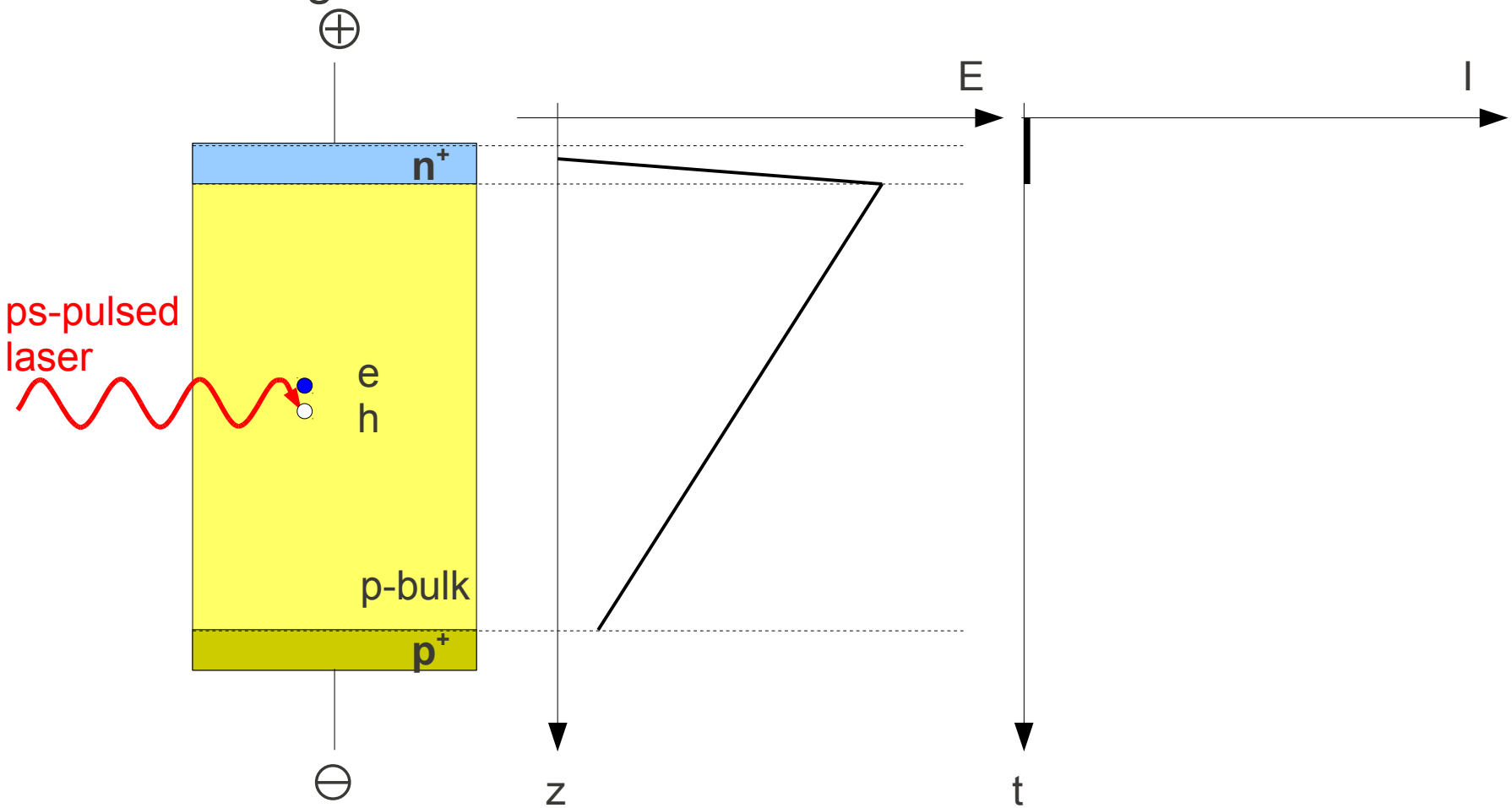
1) What is TCT?
2) What is TPA?
3) TPA TCT

What is TCT?

Powerpoint physics

TCT: Transient Current Technique

Allows to probe the space charge of a detector by measuring transport of induced charge carriers

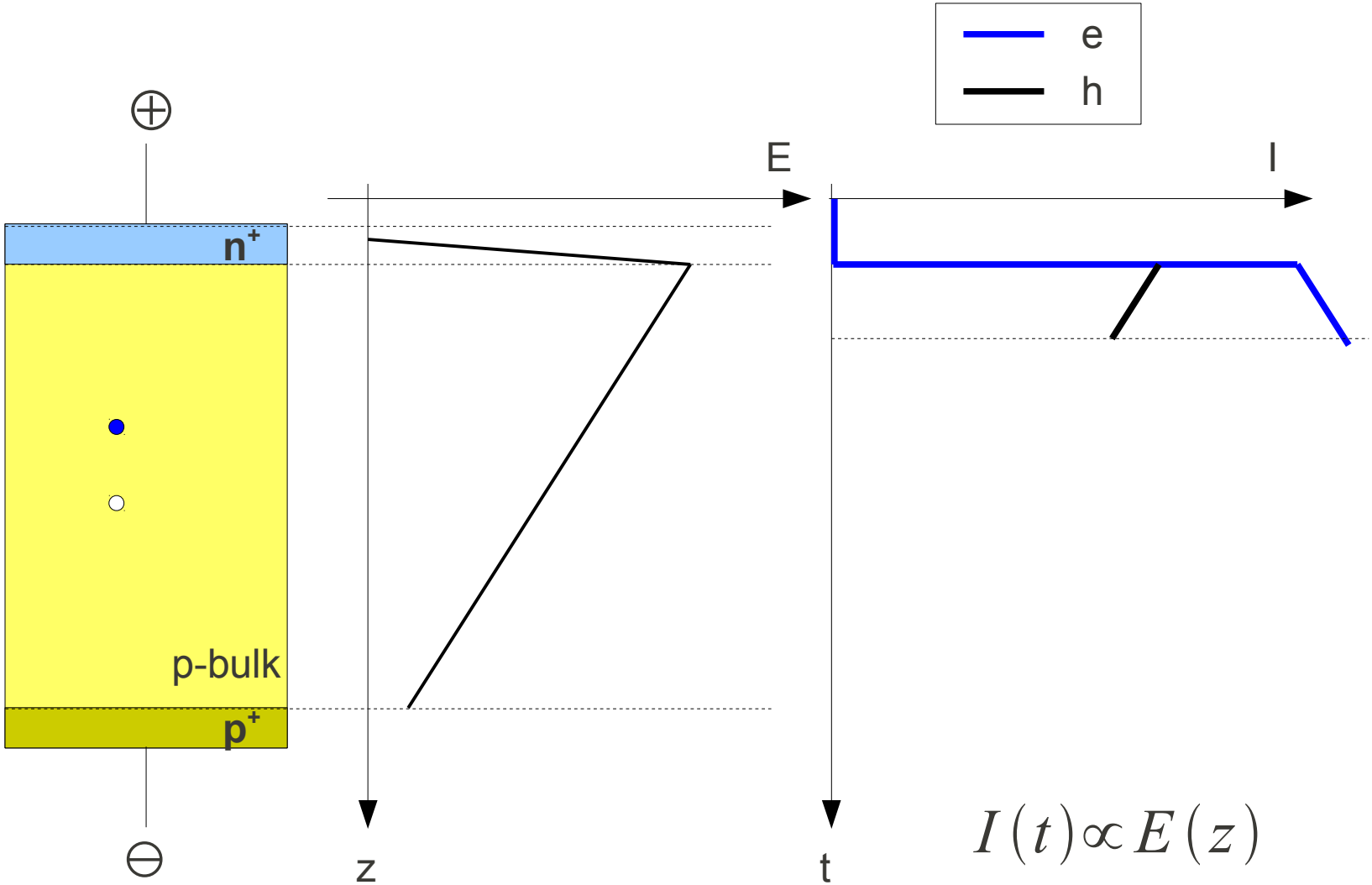


$$I(t) = N_{eh} A q_e v_{drift} E_W \propto v_{drift} = \mu(E) E \Rightarrow I(t) \propto E(z)$$

Assumption: overdepleted, non-irradiated diode

t = -0 ns

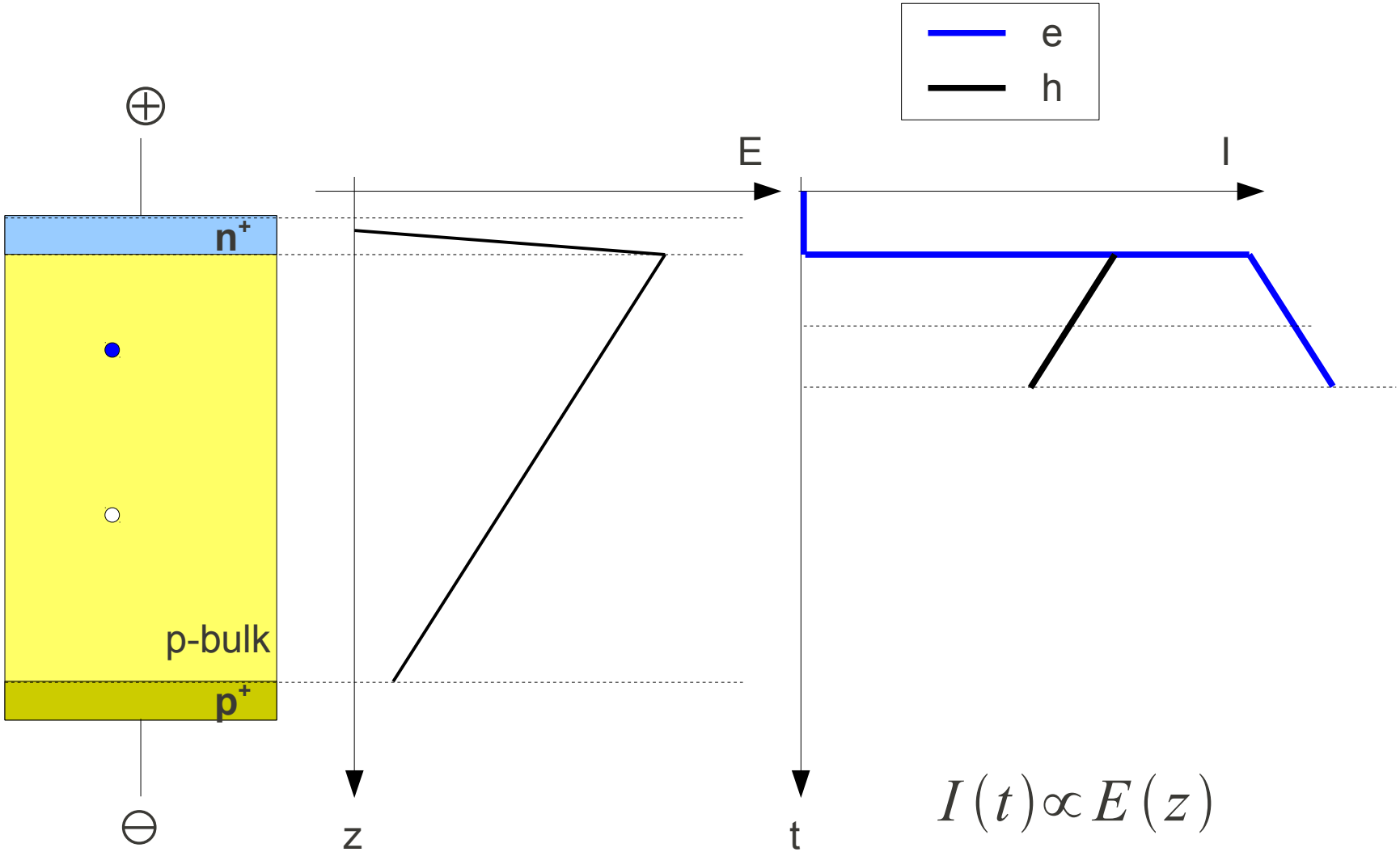
TCT: Transient Current Technique



$$I(t) \propto E(z)$$

t = 1 ns

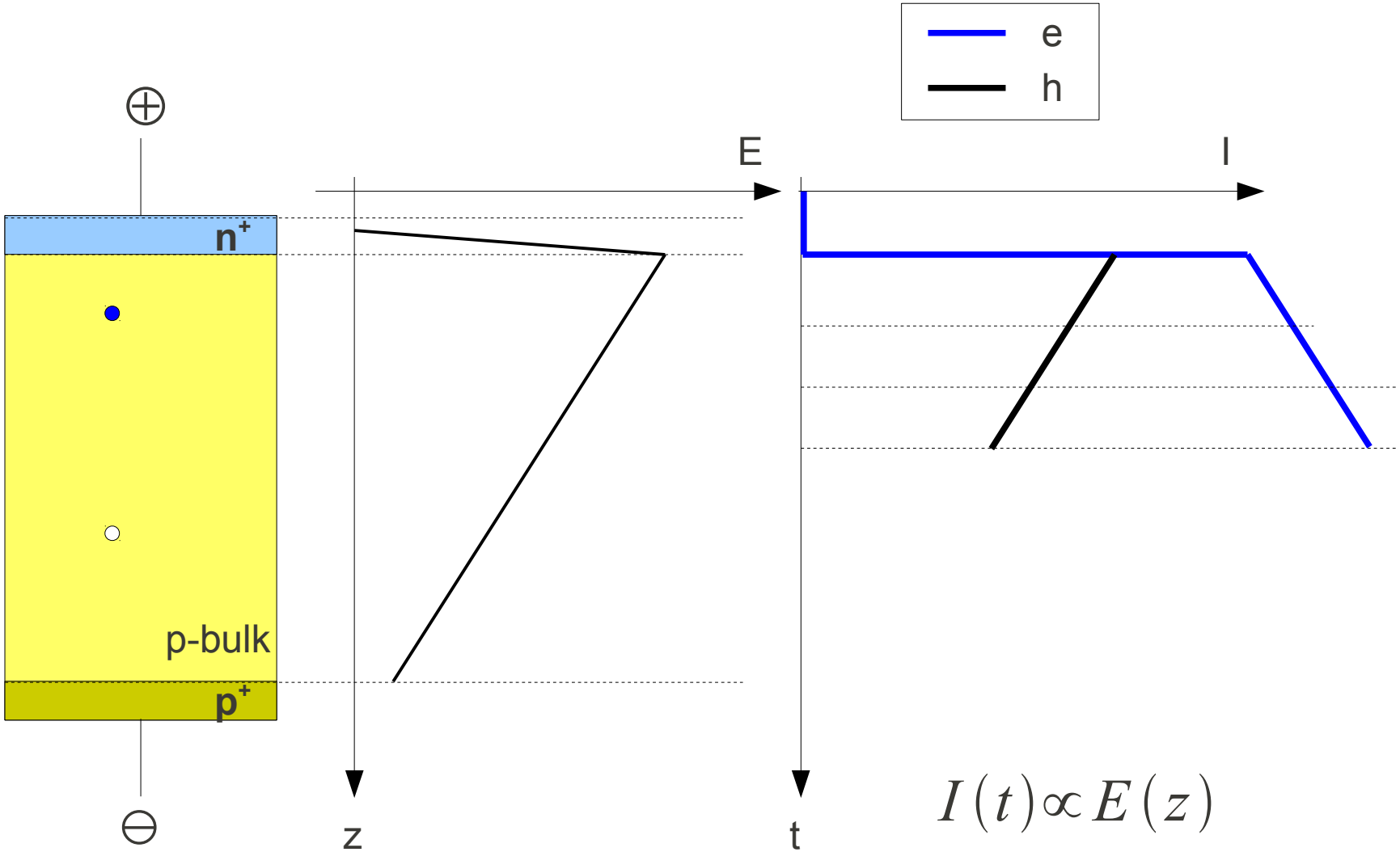
TCT: Transient Current Technique



$$I(t) \propto E(z)$$

t = 2 ns

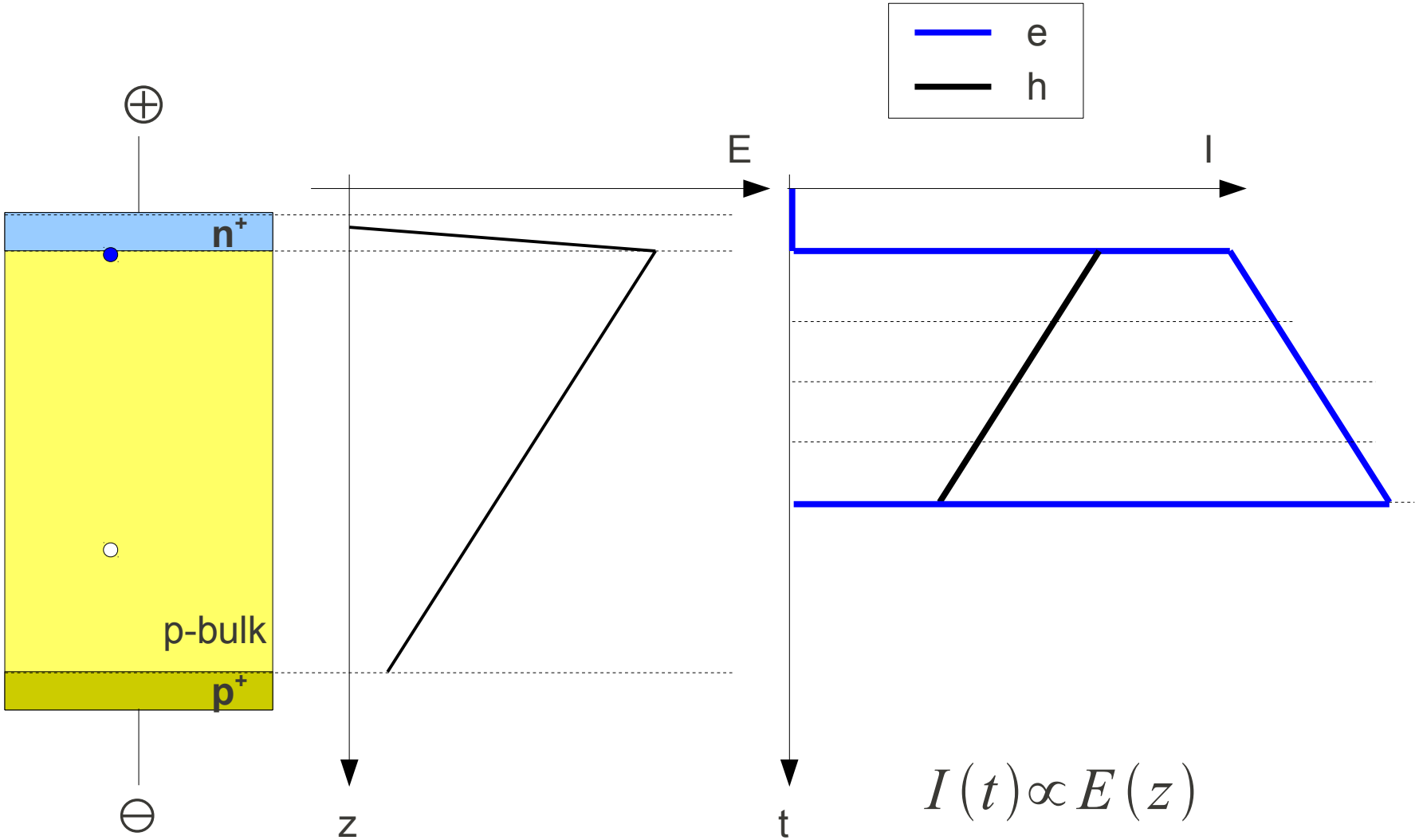
TCT: Transient Current Technique



$$I(t) \propto E(z)$$

t = 3 ns

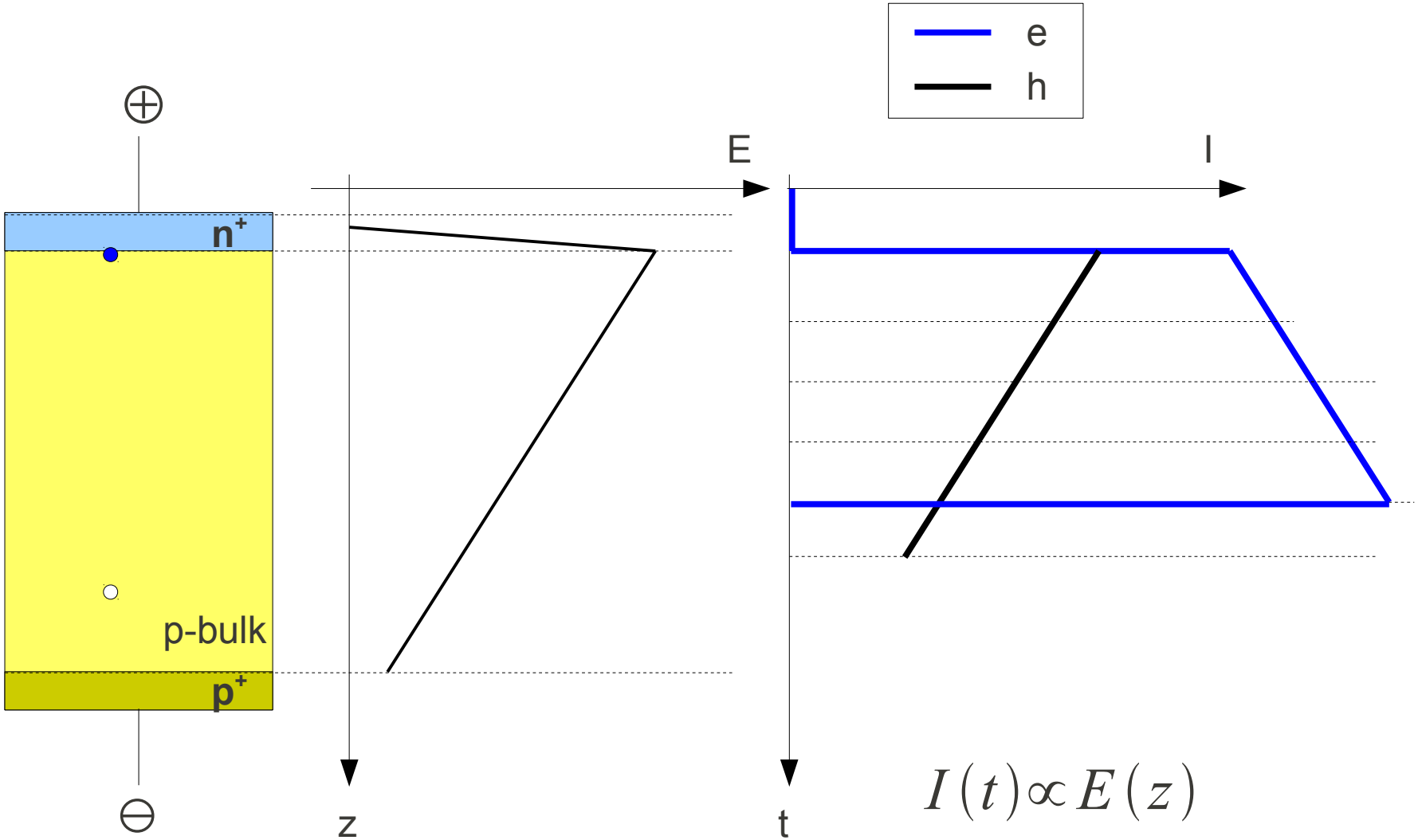
TCT: Transient Current Technique



$$I(t) \propto E(z)$$

t = 4 ns

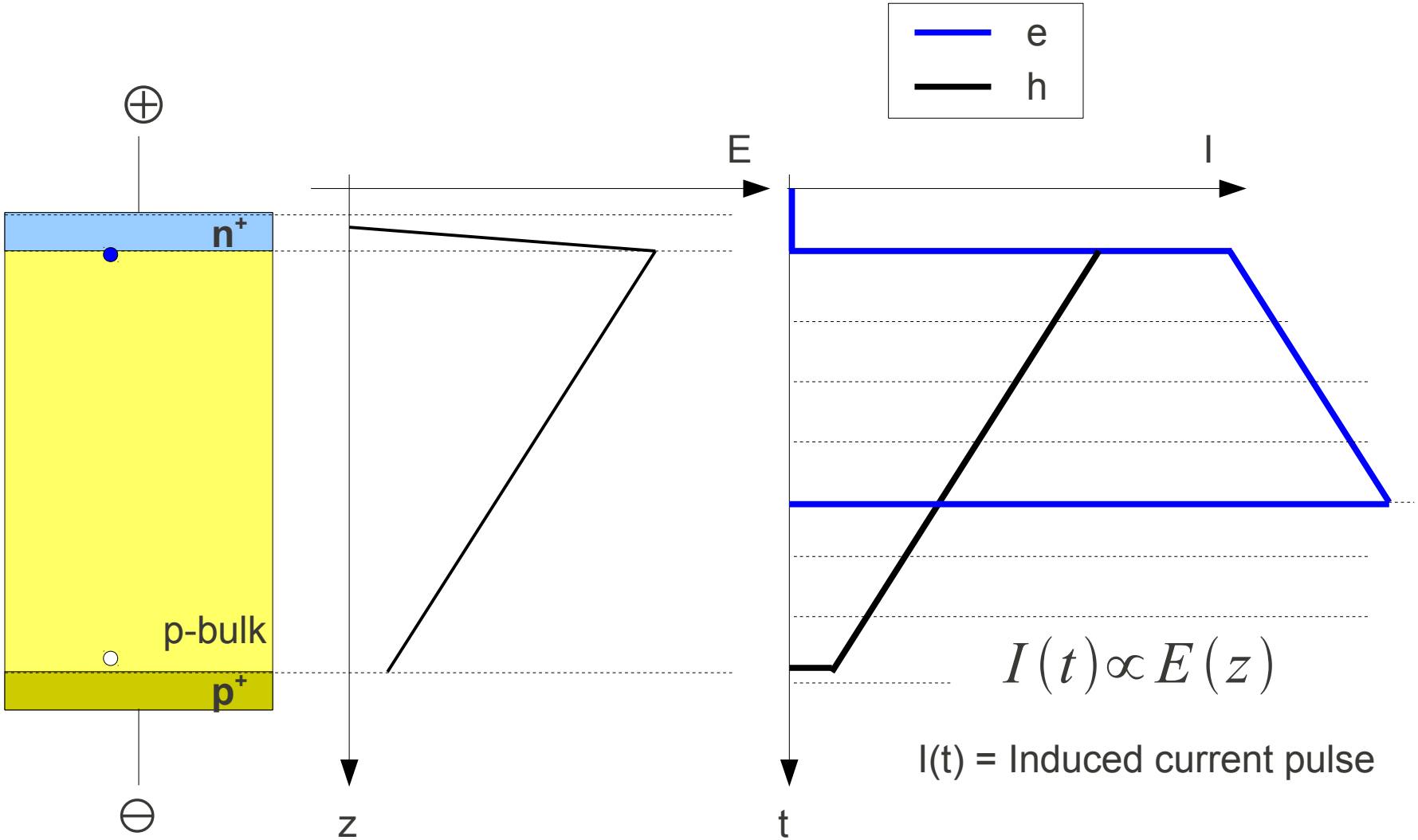
TCT: Transient Current Technique



$$I(t) \propto E(z)$$

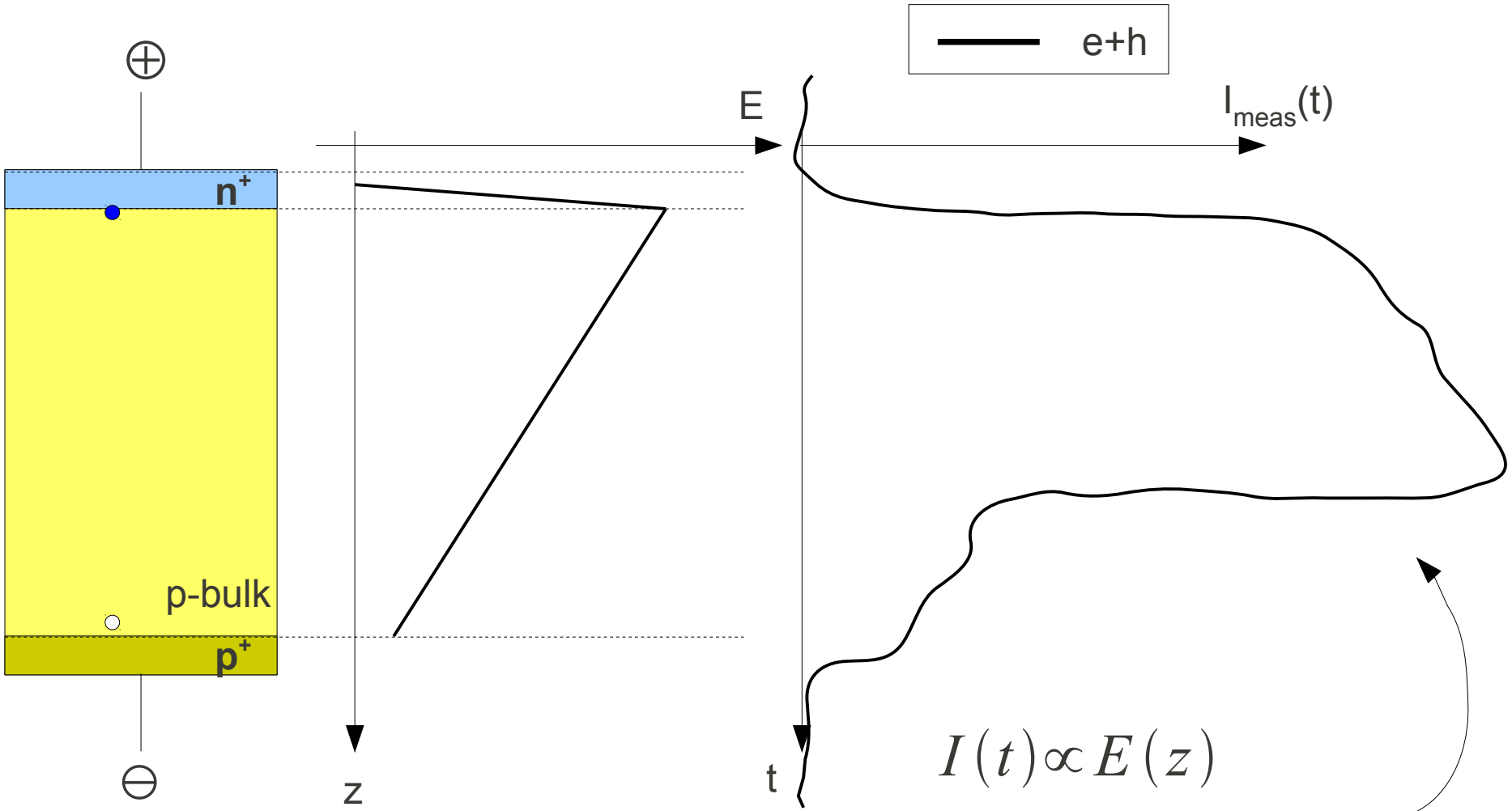
t = 6 ns

TCT: Transient Current Technique



t = 12 ns

TCT: Transient Current Technique



$$I(t) \propto E(z)$$

Measured pulse shows a “picture” of the electric field the carriers encountered during drift.

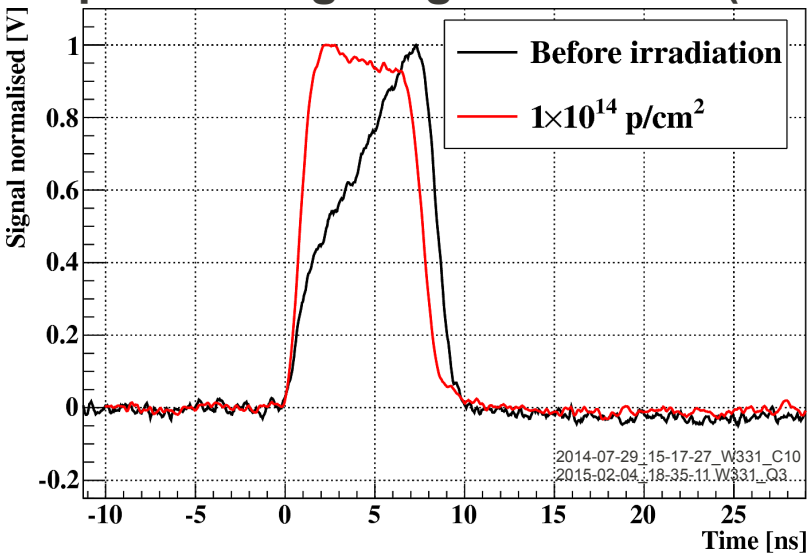
For an **irradiated** detector, the picture gets **distorted** due to **trapping** of charge carriers. Carriers do not “**see**” the full E-field profile.

Measured pulse convolutes:

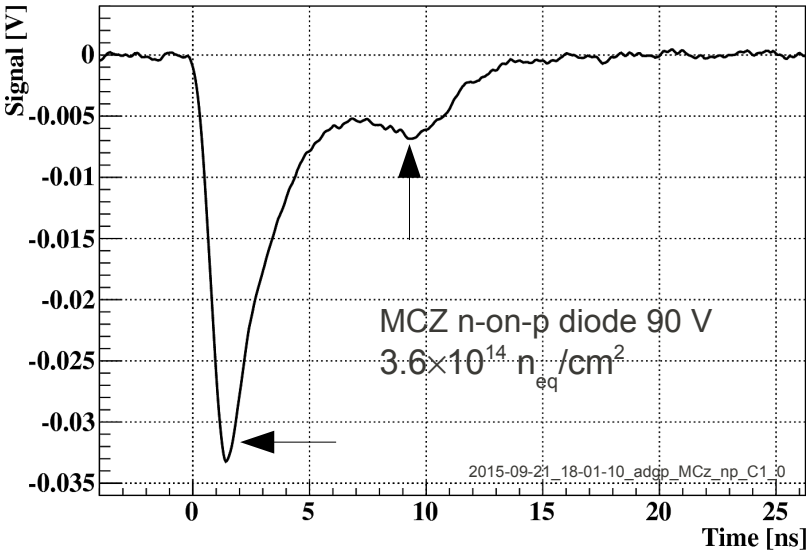
1) EM noise
2) $RC_{detector}$ (low pass filtering)
3) Amplifier transfer function

Examples of TCT performance: measured waveforms

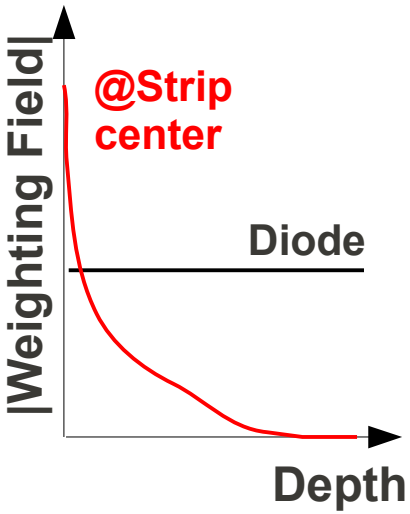
Space Charge Sign Inversion (SCSI)

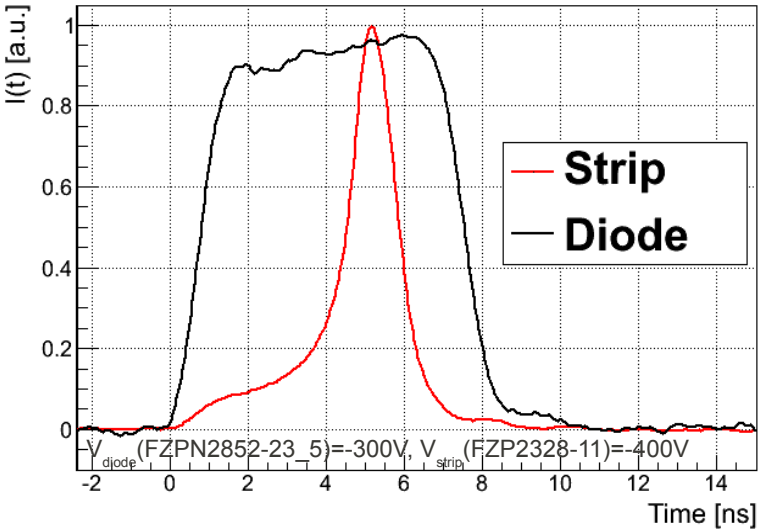


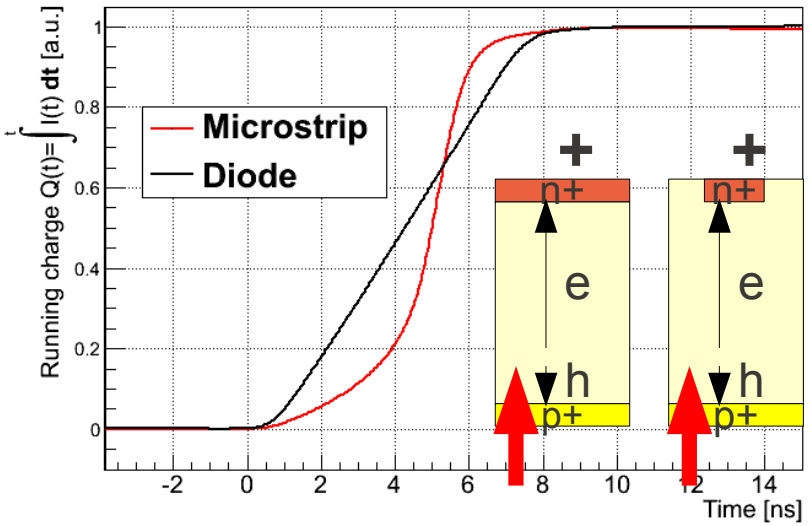
Double Junction effect



Difference between strip and diode (**bottom red** injection)
Most of the charge for a strip is induced near the strip → **Weighting field**







What is TPA-TCT?

TPA-TCT: A Two Photon Absorption Transient Current Technique

- TPA-TCT is a **new TCT method** to characterize semiconductors.

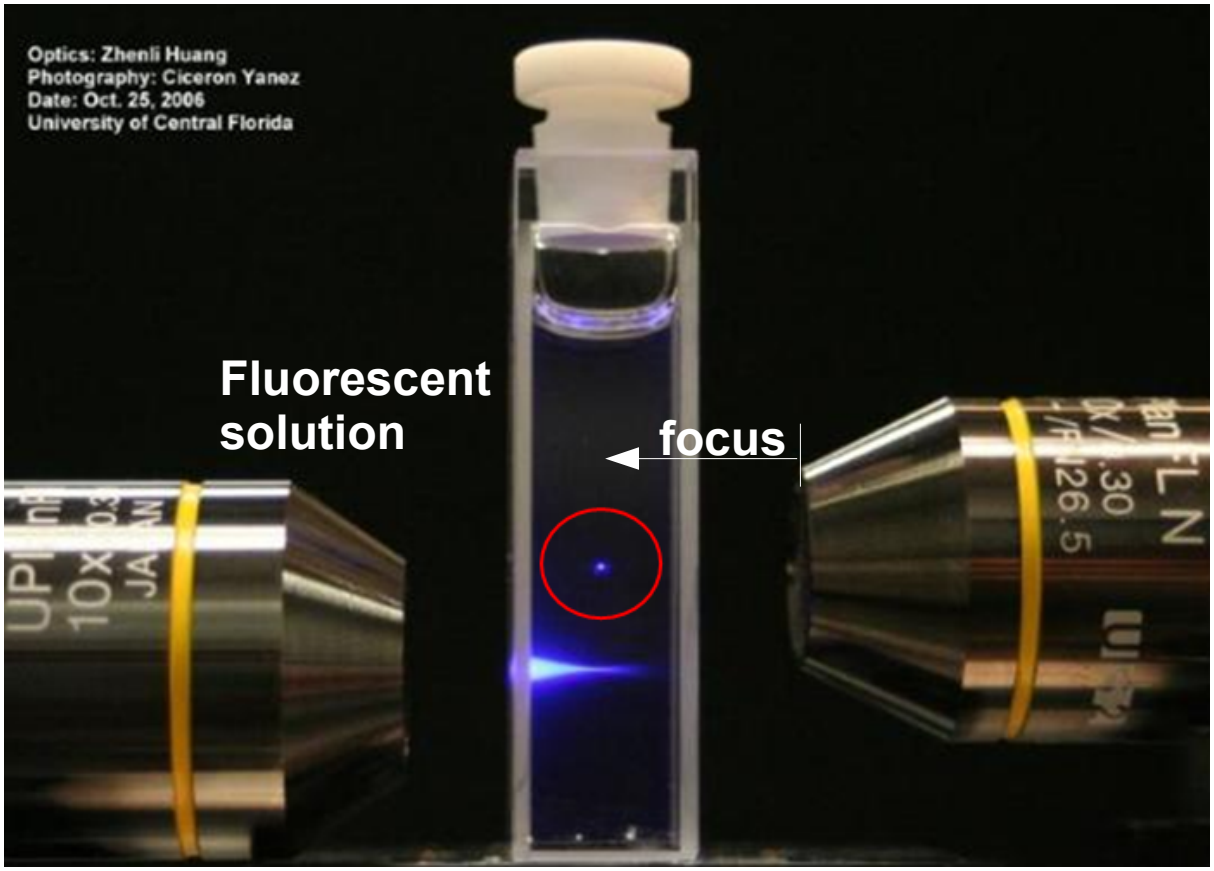
- **In standard TCT** a laser is used to excite the material and create a signal. The signal is however produced across the **full laser path**. TPA-TCT uses a laser to create a **point-like** (new!) signal generation volume. This point-like probe can then be **3D scanned** across the volume of the sensor.

- The physical phenomena exploited is the **simultaneous absorption of 2 photons** in the material

OLD

Single Photon Absorption

Continuous energy deposition



NEW

Two Photon Absorption

Energy confinement

Two photons from one laser !!

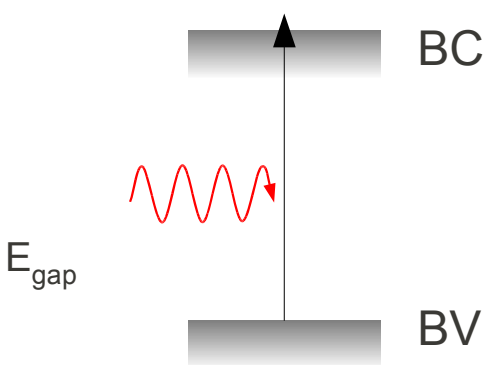
TPA: physics background (I)

- TPA-TCT exploits a **non-linear effect** shown by any material when illuminated with a **high intensity** source (for instance, a laser). For certain wavelengths, light absorption (=signal) only happens **at the focus** of the beam. No photons are absorbed "out of focus". The more light is focused, the better "point-like" signal generation volume.

- The energy of each photon is **smaller than the bandgap** (so individually they can not create an e-h pair), but **the sum of both** is enough to produce one e-h pair → signal.

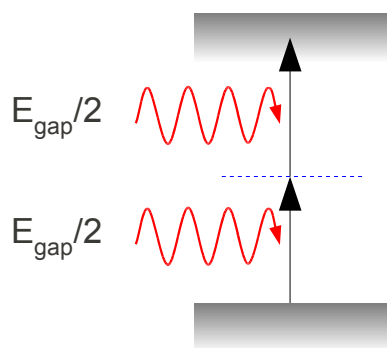
SPA

SPA: $E_{photon} \geq E_{gap}$~1.12 eV



TPA

TPA: Conventionally, no excitation if E_{photon}<E_{gap}~1 eV. But, if **TWO** photons arrive in ~100 attoseconds:

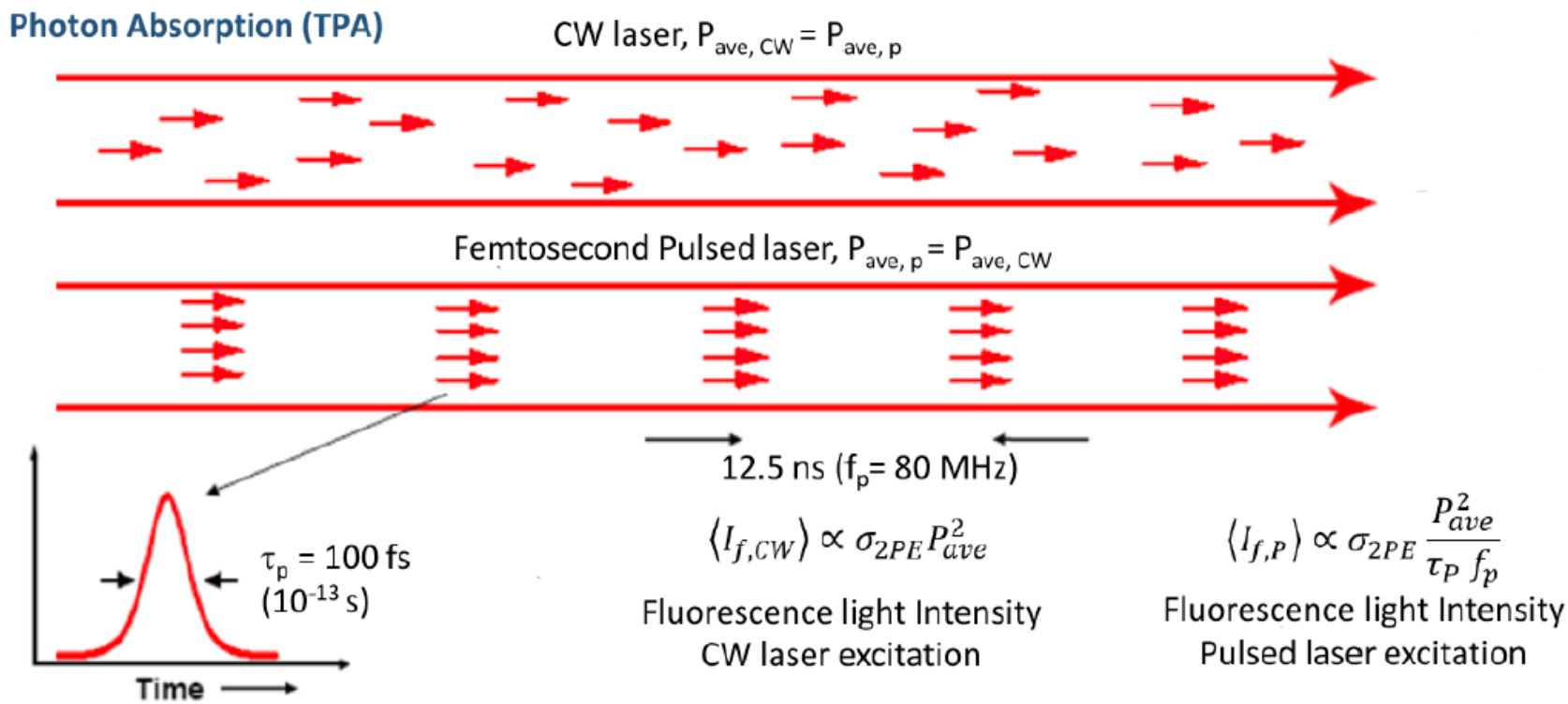


Virtual state

$$\tau_{virtual} \approx \frac{\hbar}{E_{gap}/2} \approx 0.1\ fs$$

TPA: physics background (II)

- To have simultaneous absorption of 2 photons we need them to be **"packed"** in space (=focus → use high N.A. objectives) and time. Time packaging provided by ***femtosecond*** (fs) pulsed mode locked lasers.



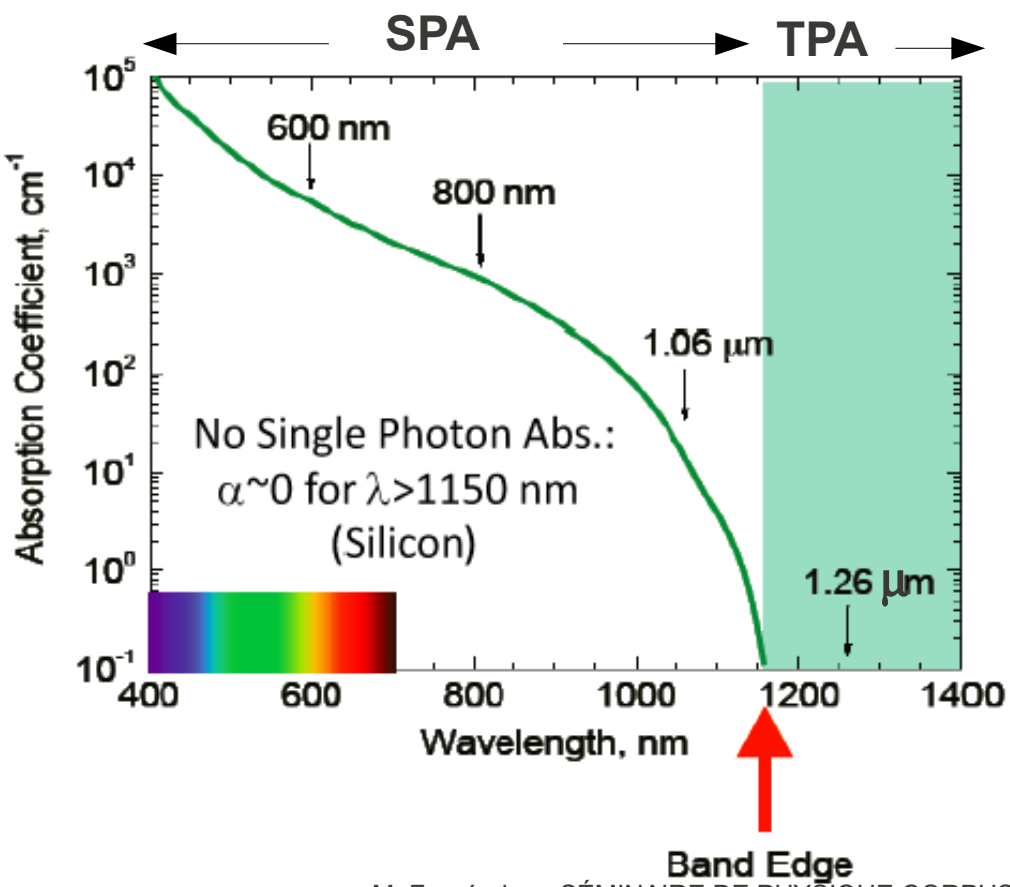
- **Mode locking** is a way to induce a fixed-phase relationship between the longitudinal modes of the laser's resonant cavity

TPA: physics background (III)

- **SPA: Probability to create e-h** pair is proportional to intensity $\propto \mathbf{I}$.

In **TPA** we need 2 photons, so the **probability is** $\propto \mathbf{I}^2$. The carrier production rate:

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

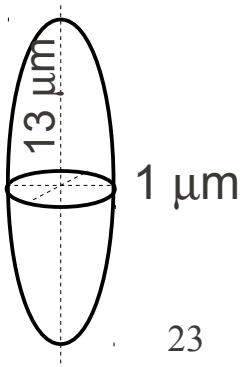


- We work in a wavelength region where α is very small. Since light is focused $I^2 >> I$ and the second term will be predominant.

- The **power of this method** depends on $\alpha I << \beta I^2$.

- Special attention must be payed to **irradiated** detectors where α **increases with fluence!**

- Our measured signal generation volume is an **ellipsoid of 1 µm section and 10 µm length** (see backup)



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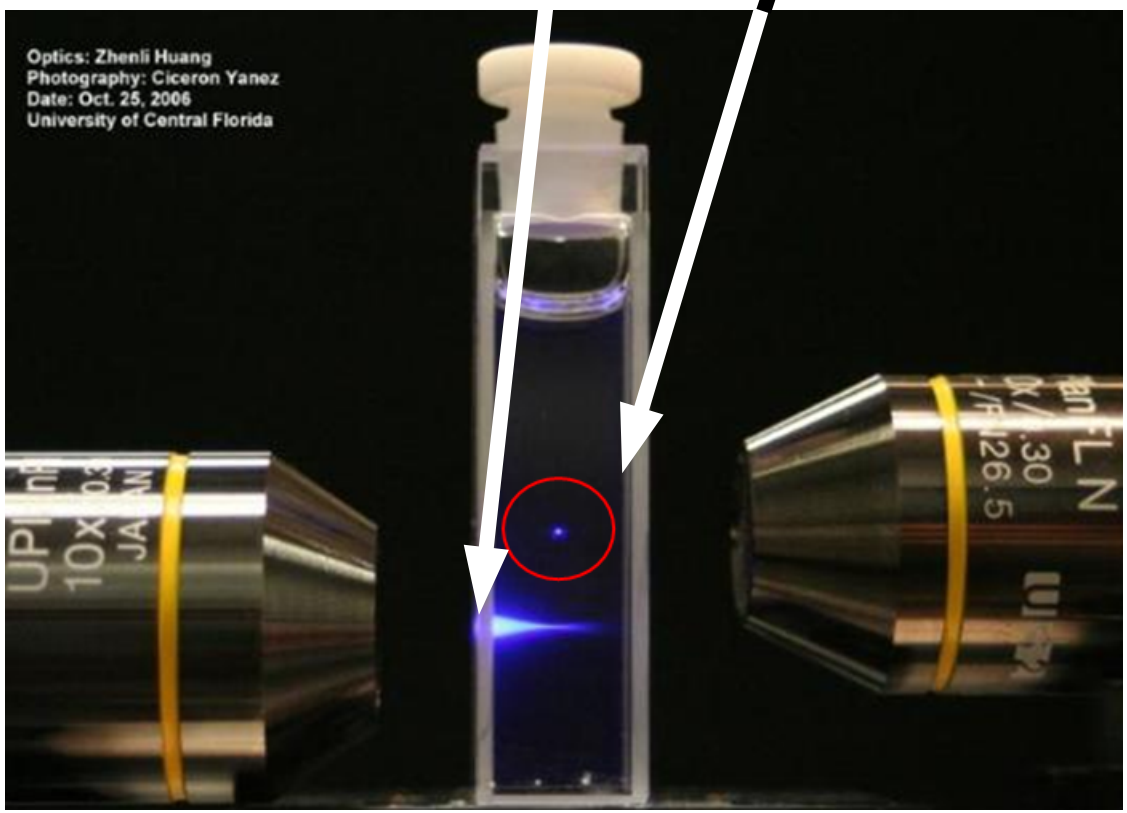

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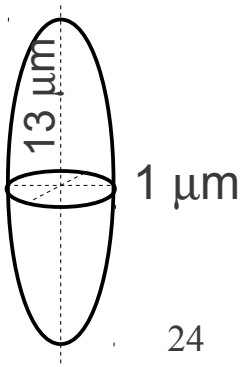
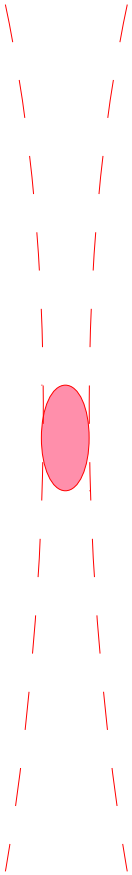


Understanding (nano-)women...



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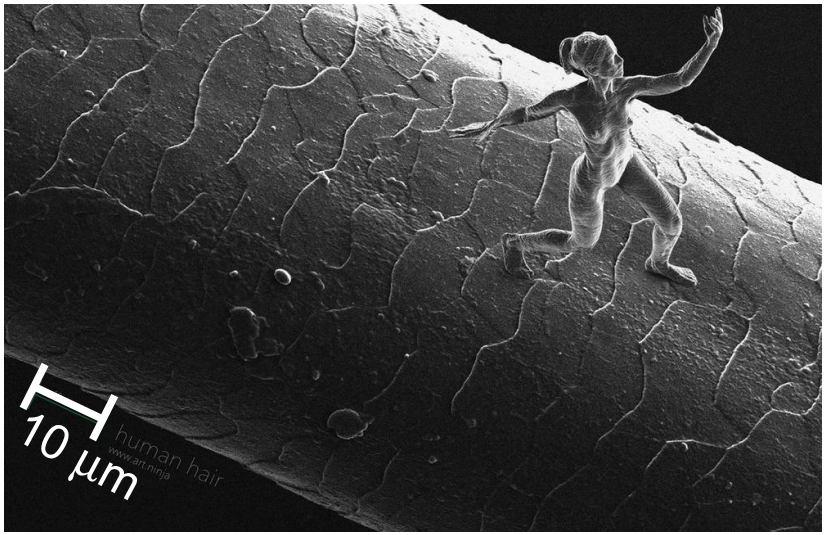
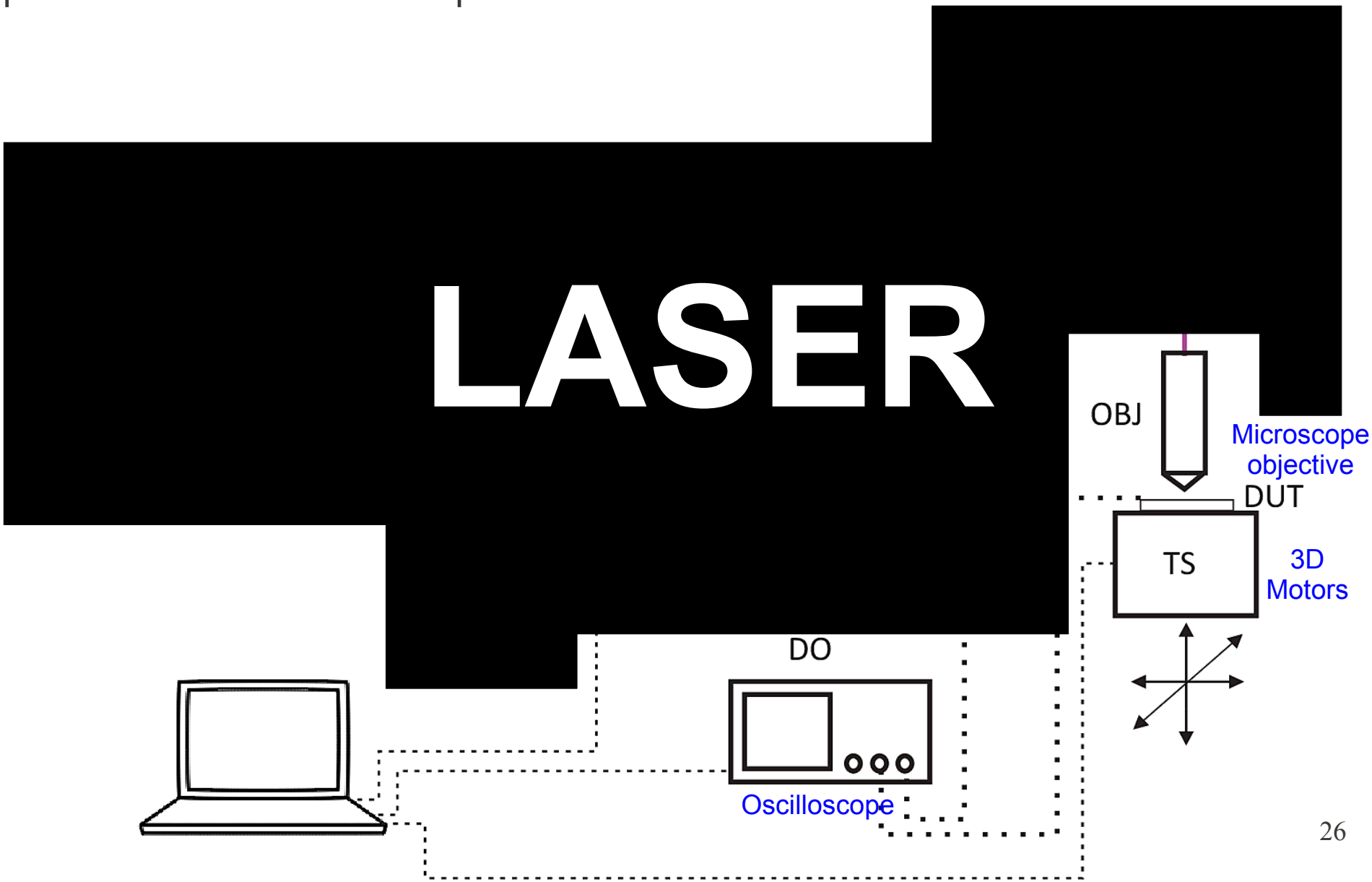


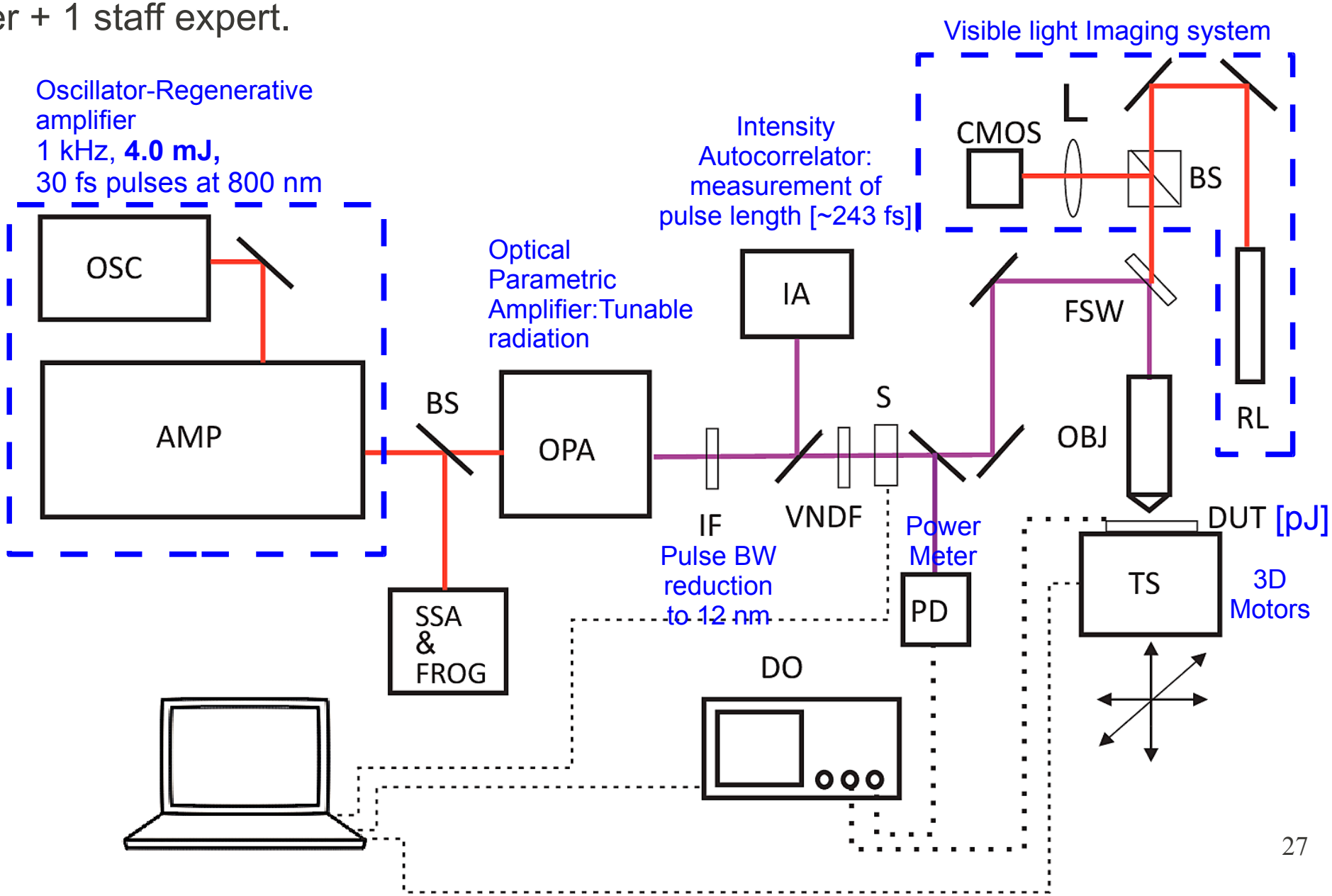
TPA-TCT at the SGIKER laser facility

- **Tunable** wavelength, energy for the sensor (after attenuation) [~pJ]. Then typical **TCT readout**: top/side injection, 3D system, current amplifier and fast readout scope.



TPA-TCT at the SGIKER laser facility

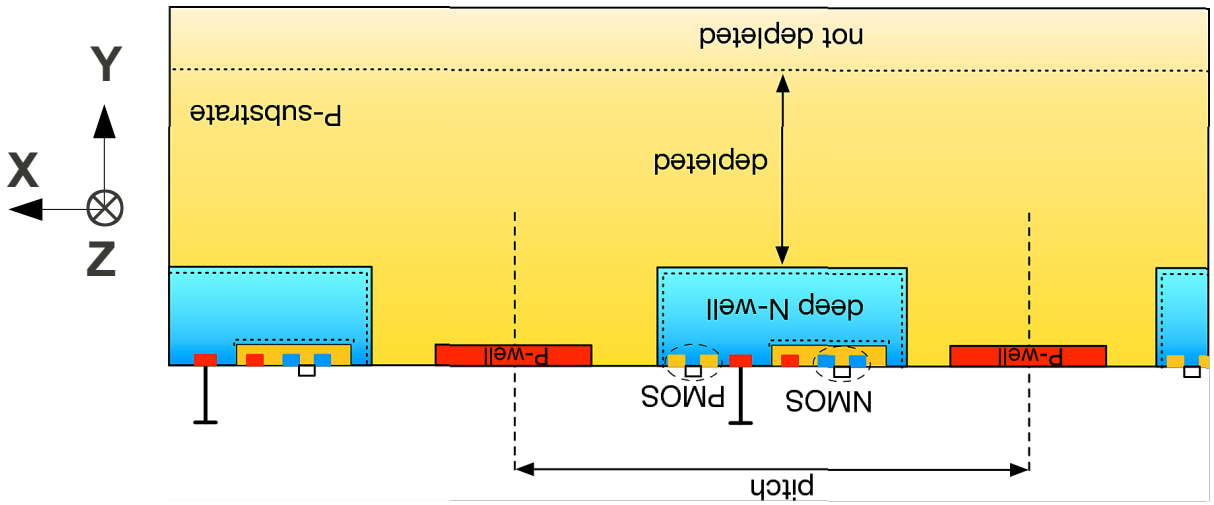
- **SGIKER** laser facility in Bilbao (Spain) is a service of the UPV for the academic community. Granted access via **RD50** to the R&D laser + 1 staff expert.



TPA of an HVCMOS (CCPDv3, HV2FEI4)

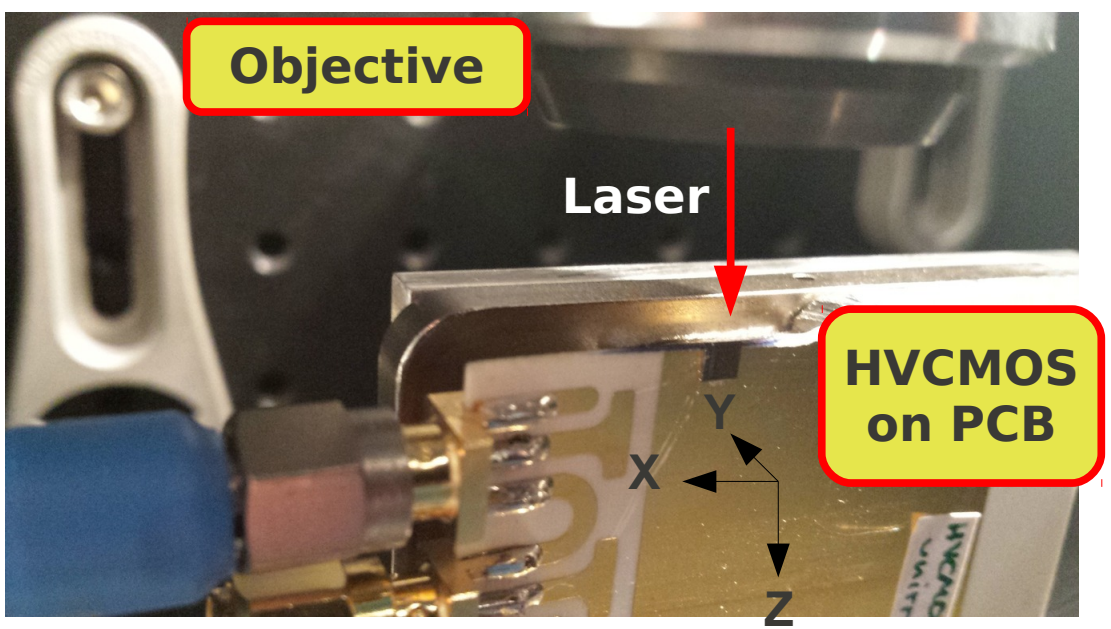
λ=1300 nm, Δt=240 fs

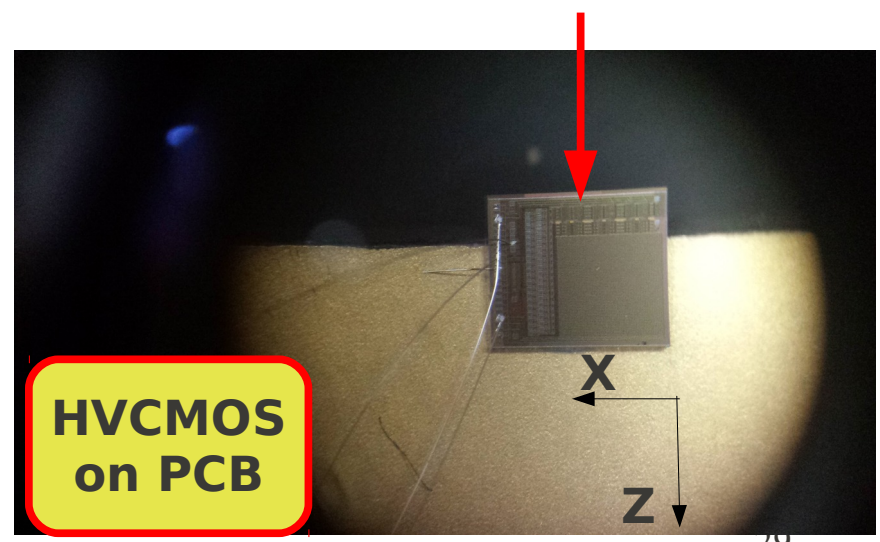
TPA on HVCMOS: geometry



Edge-TPA scan:
Z propagation direction
Next slides XY scans
$\sigma = 1\ \mu m$ (beam waist)

- We measure optical test structures. Only DNW, no NMOS/PMOS inside!!



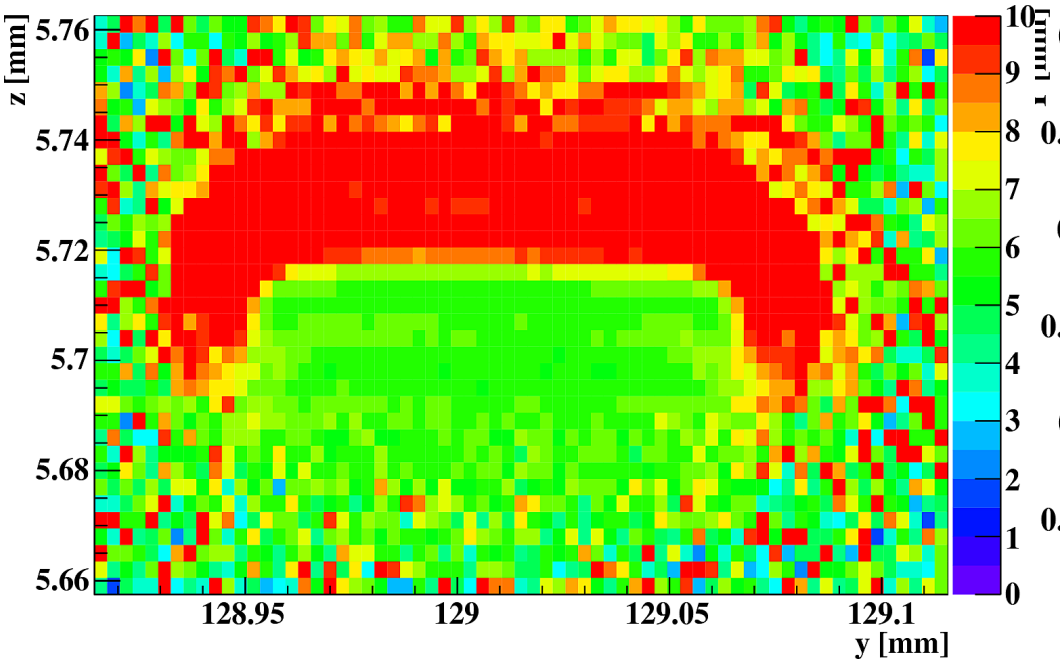


Application examples: unirradiated HVCMOS

- HVCMOS is a partially depleted sensor, built on commercial CMOS technology (industrial!) Substrate of very low resistivity → very narrow depletion width (~10 μm at 100 V). Challenging detector

- Showing 2D map of the **collection time** of charge carriers (time lapse till 98% charge is collected)

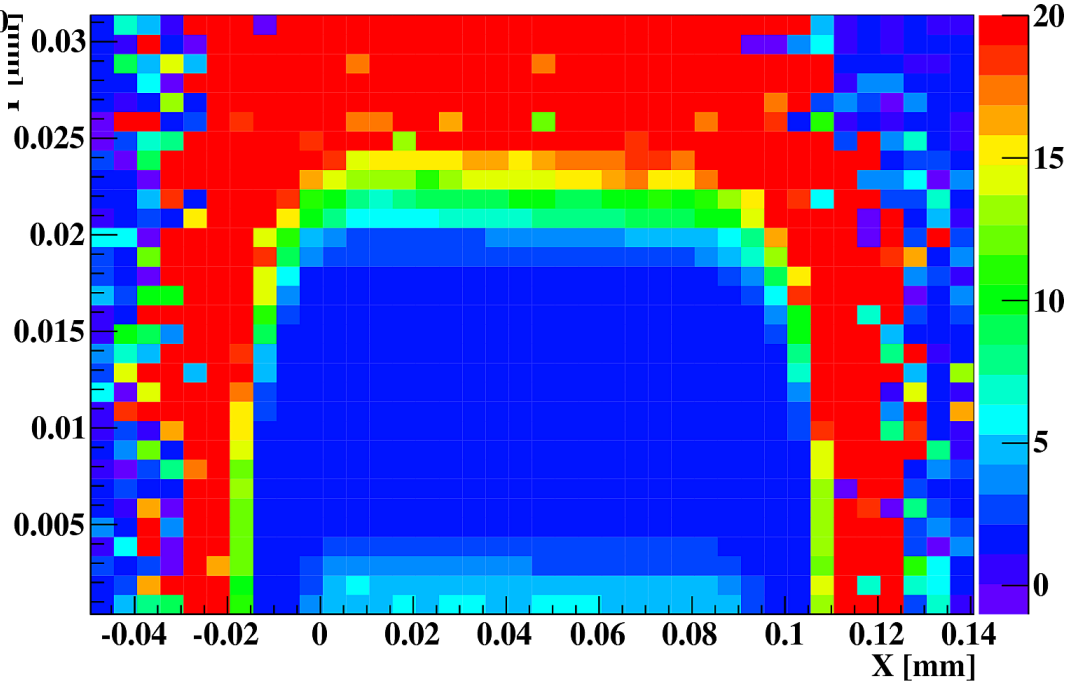
Standard SPA-TCT



Spatially continuous laser source, ps pulses

λ=1064 nm, σ=10 μm, **200 ps**-pulsed laser

TPA-TCT

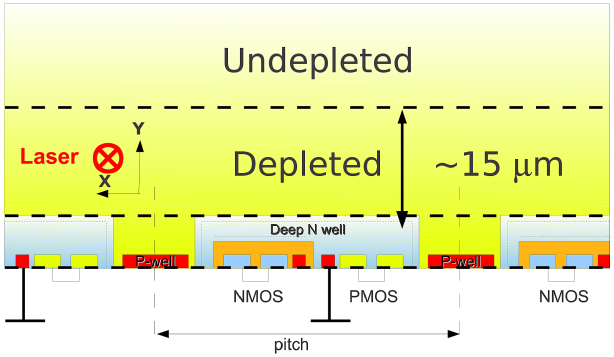


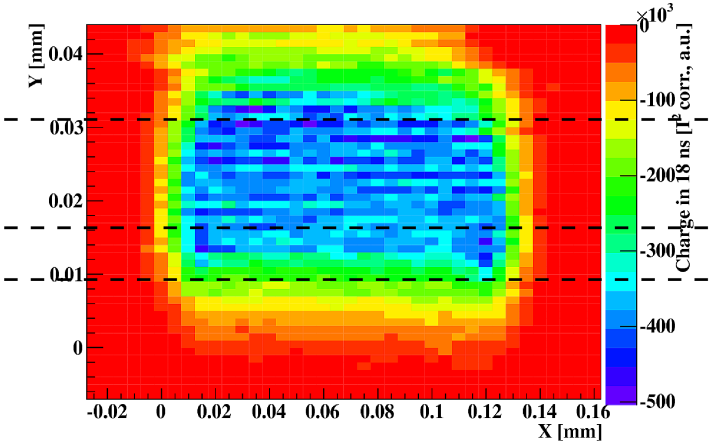
Point-like laser source, fs pulses

λ=1300 nm, σ=1 μm, **200 fs**-pulsed laser

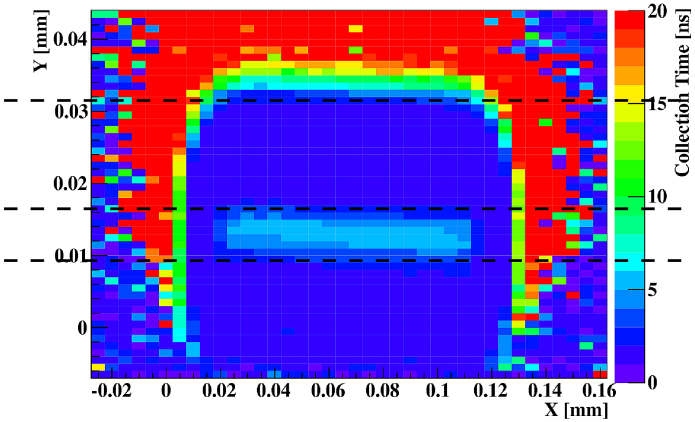
Substructures resolved with TPA-TCT

Substructures identified



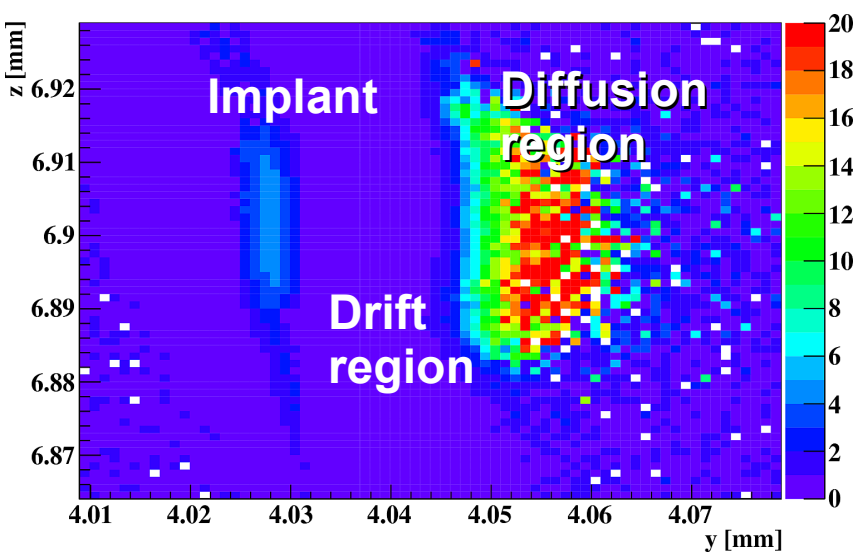


Collected charge map (XY)

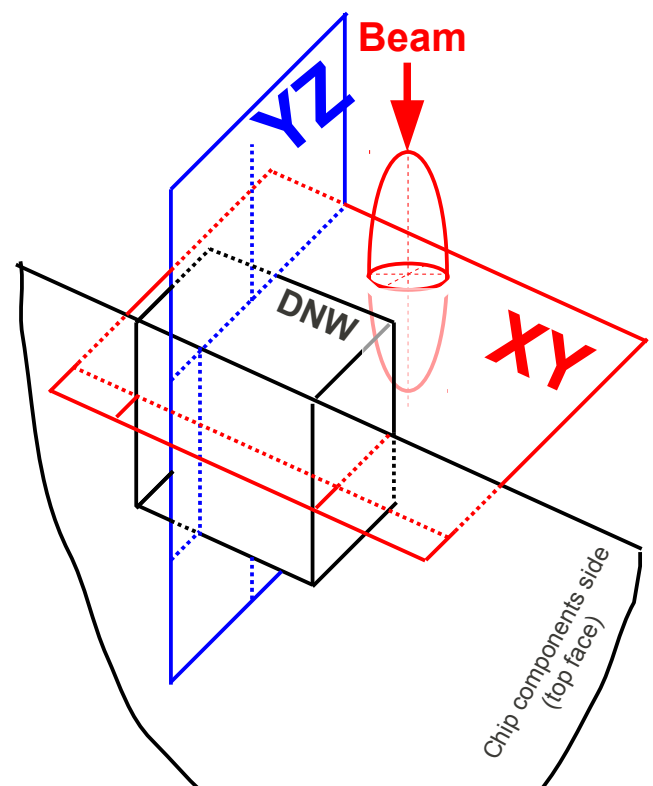


Collection time map (XY)

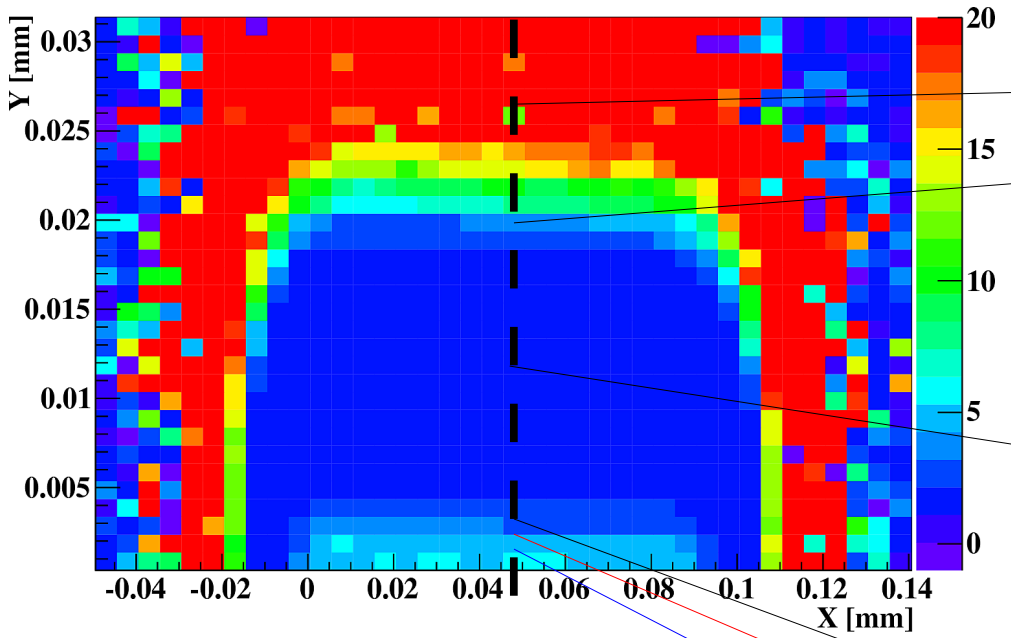
In 3D !

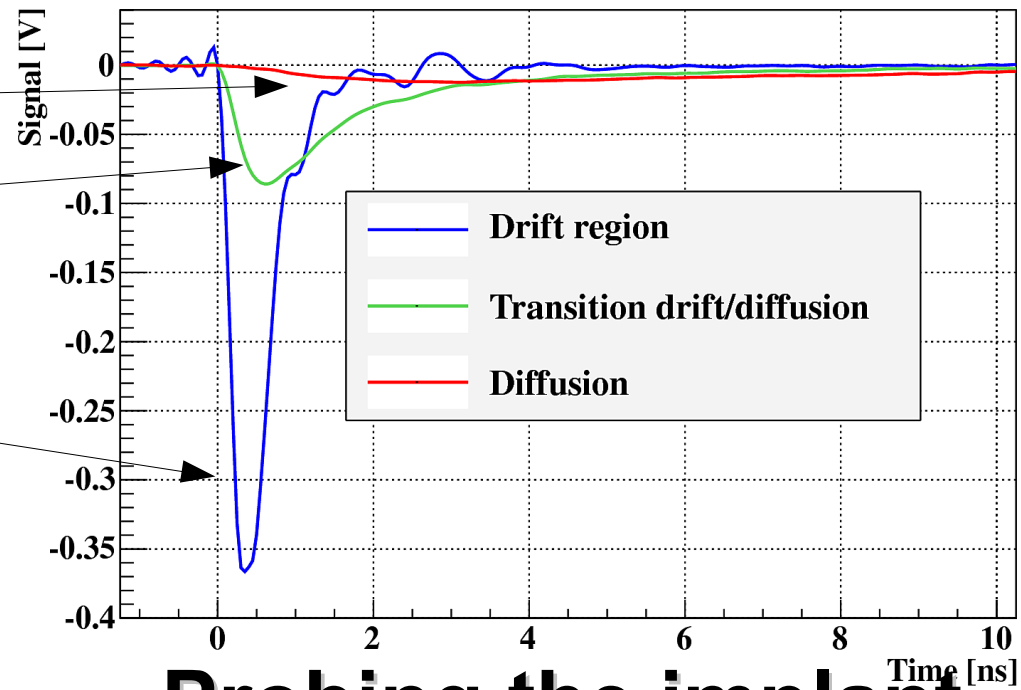


Collected charge map (YZ)

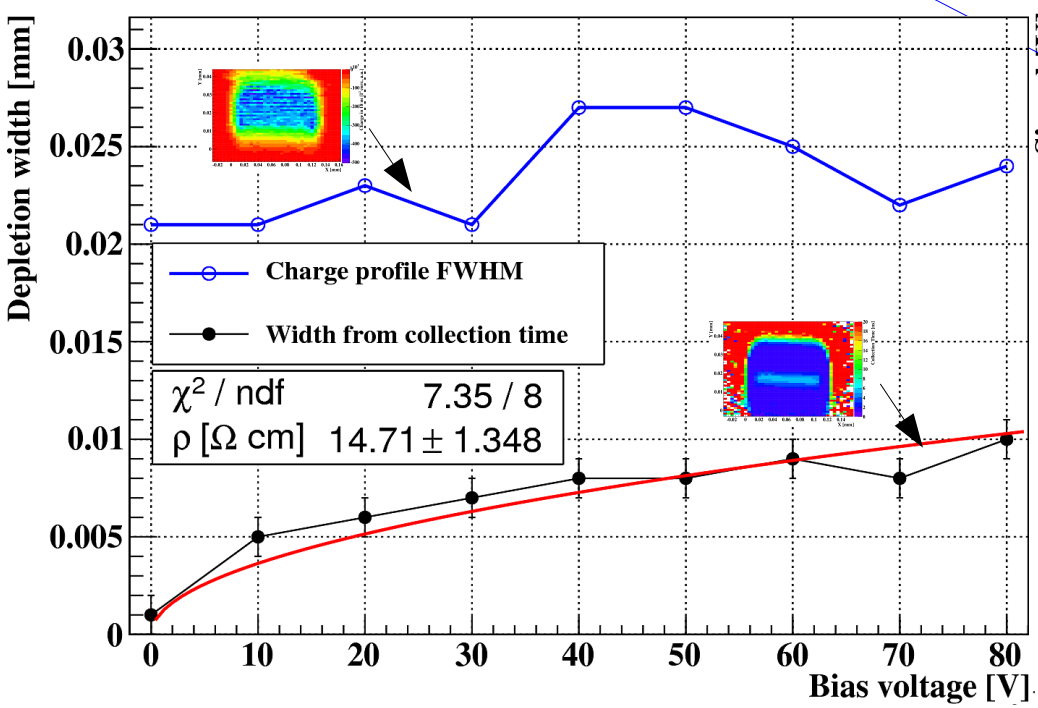


Drift/diffusion discrimination

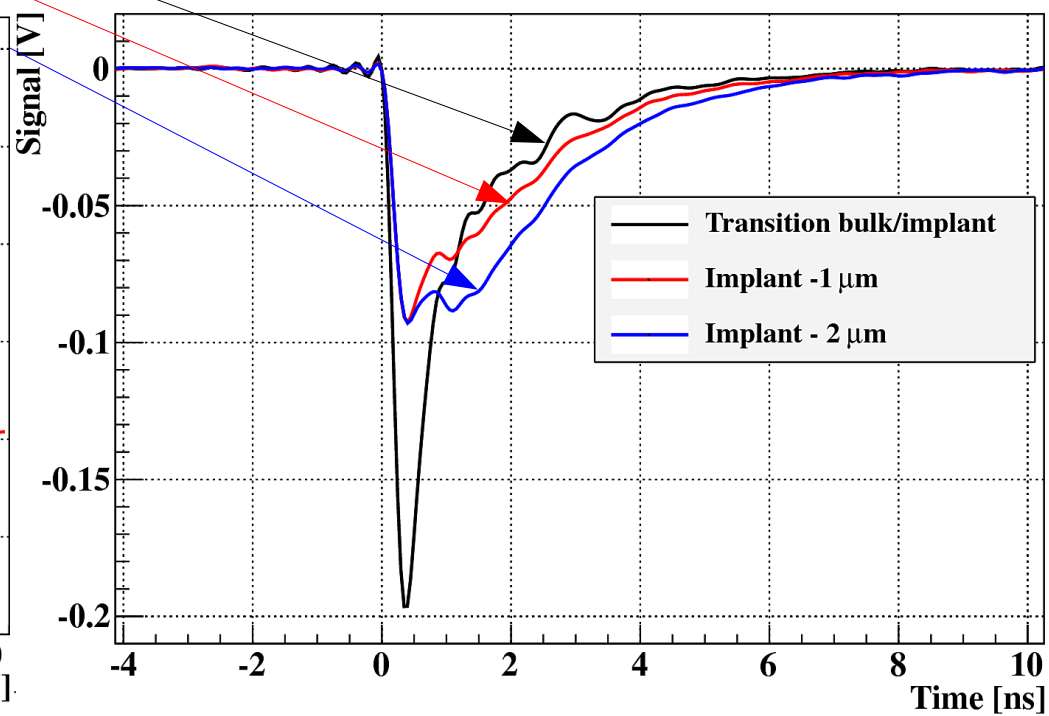




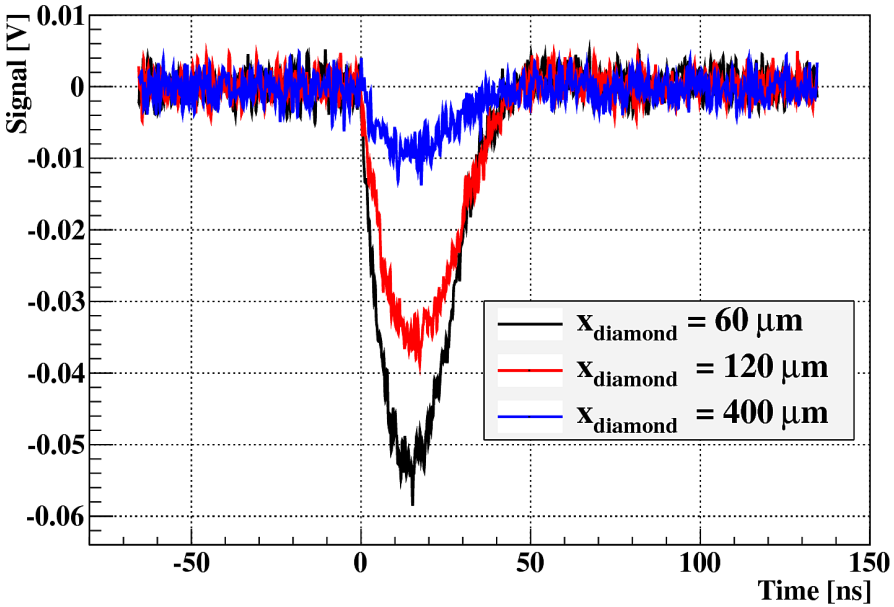
Doping concentration



Probing the implant



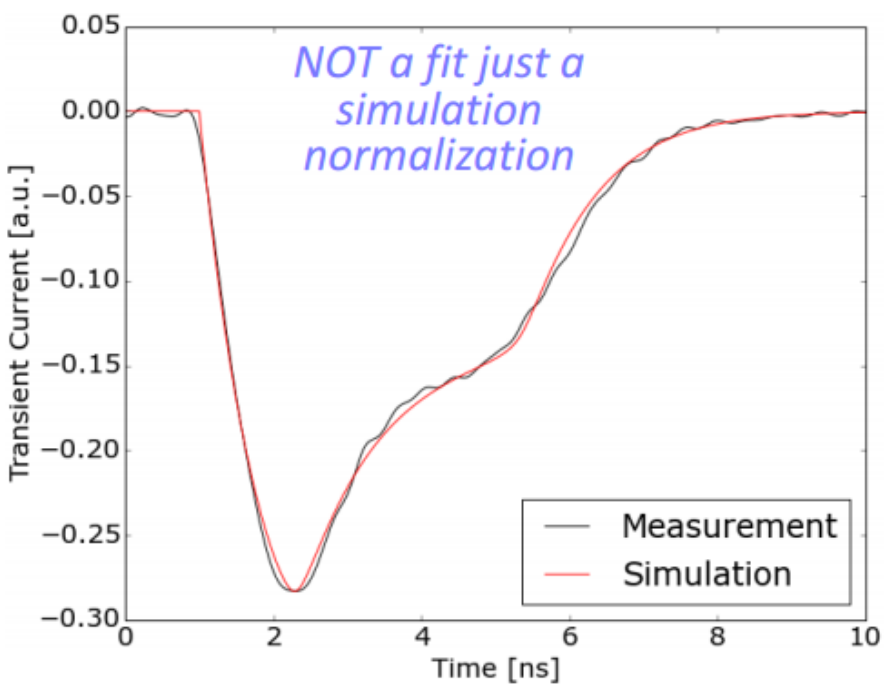
TPA in diamond



- Applying standard TCT to diamond because would require a **UV laser.**
- Using λ_{TPA}= 400 nm we did TPA-TCT in diamond
- Picture to the left is just a proof of principle: we got a signal in a diamond device.

That's a first laser TCT in diamond ever !

DAQ, simulation and analysis packages



- We have **developed** a simulation package called **TRACS**:

https://github.com/JulesDoc/Tracs

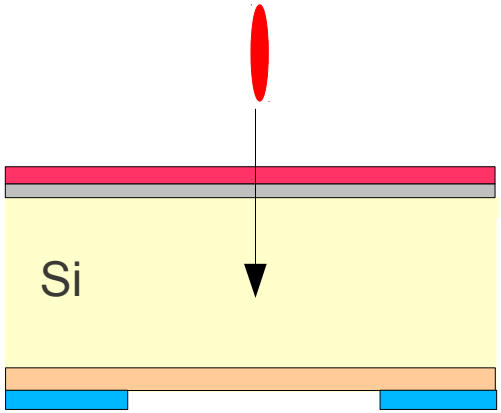
that simulates any TCT, including TPA-TCT.

- We also have a complete **ROOT-based** software package to do **3D analysis** of TPA data.
- DAQ is **Labview** based

TPA of neutron irradiated:
- Diodes
(10^{13}-10^{16} n_{eq}/cm^2)

λ=1300 nm, Δt=240 fs

TPA on irradiated diodes



FZ **diodes** produced by **CNM-Barcelona**
Φ_{eq}=10^{13}-10^{16} n_{eq}/cm^2 (**neutron** irradiation at **Ljubljana**)
Measurements at -15 ºC

What do we expect for irradiated sensors?

For the intensity regime where we operate there are linear ($\alpha \rightarrow 0$) and quadratic (β) absorption terms..

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

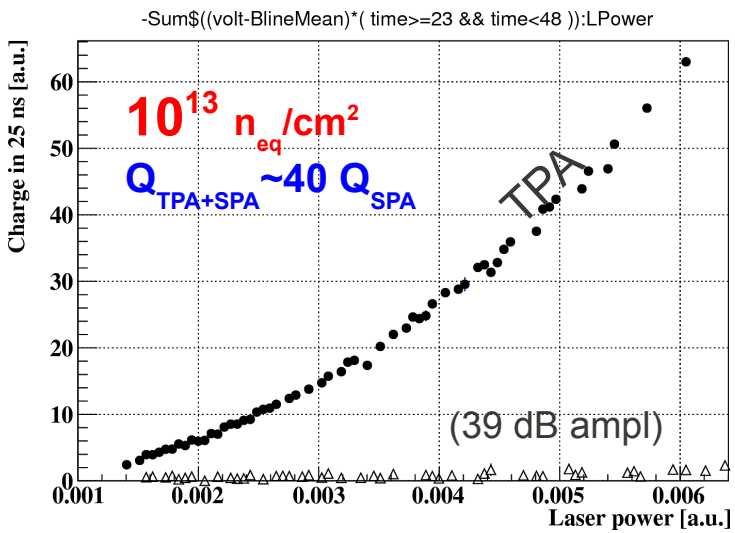
Linear absorption in Si has been measured to grow with irradiation.

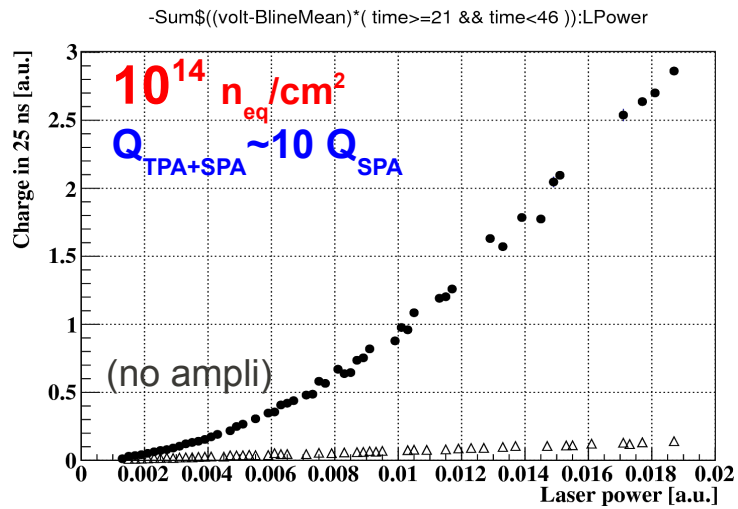
Having a sizable α contribution to the signal will spoil the spatial resolution along the beam (continuous energy deposition)

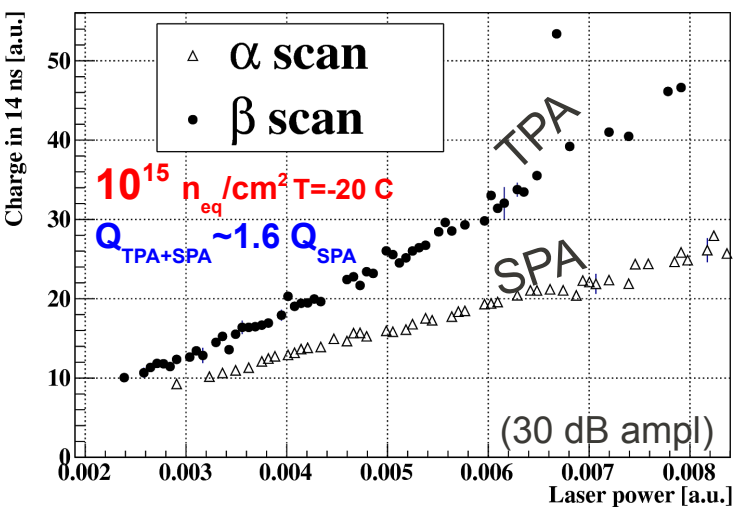
Let's see how much linear absorption we have in the irradiated diodes

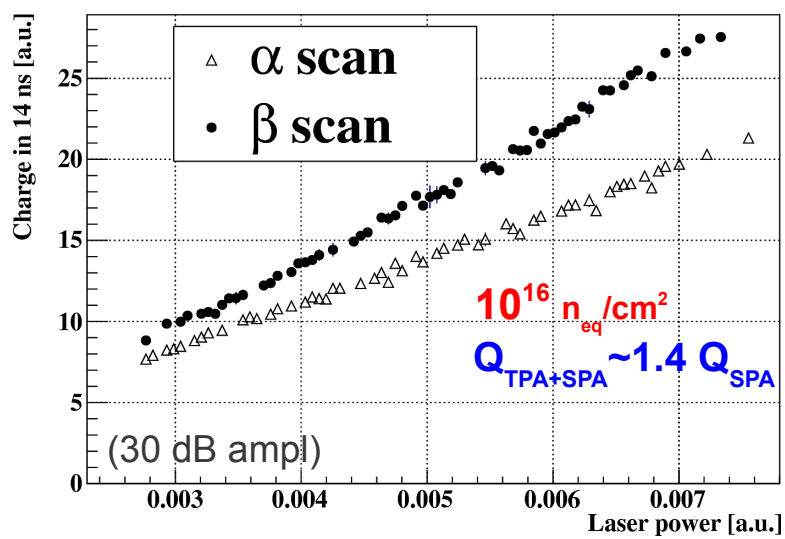
Irradiated diodes: intensity scan

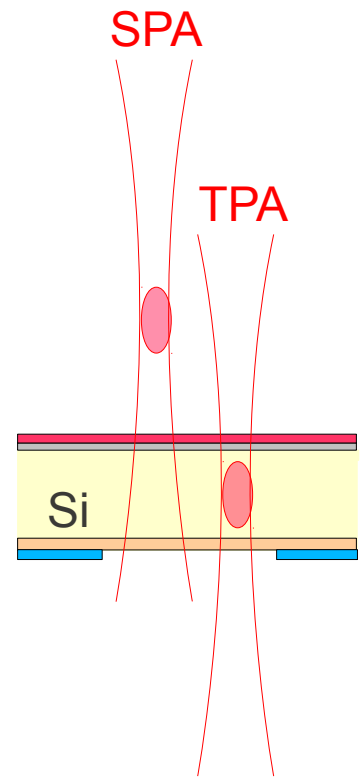
$$\frac{dN(r,z)}{dt} = \alpha \frac{I(r,z)}{\hbar\omega} + \frac{\beta_2 I^2(r,z)}{2\hbar\omega}$$





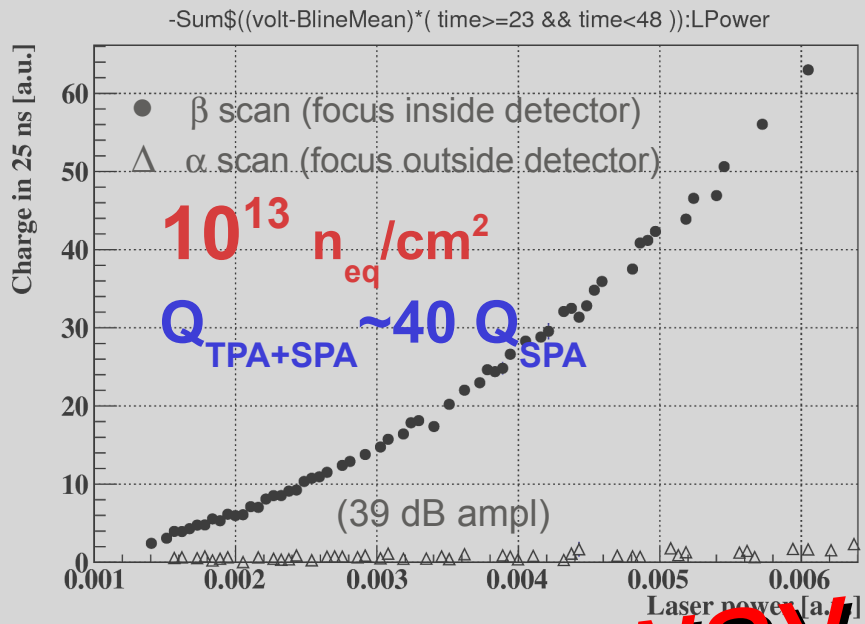


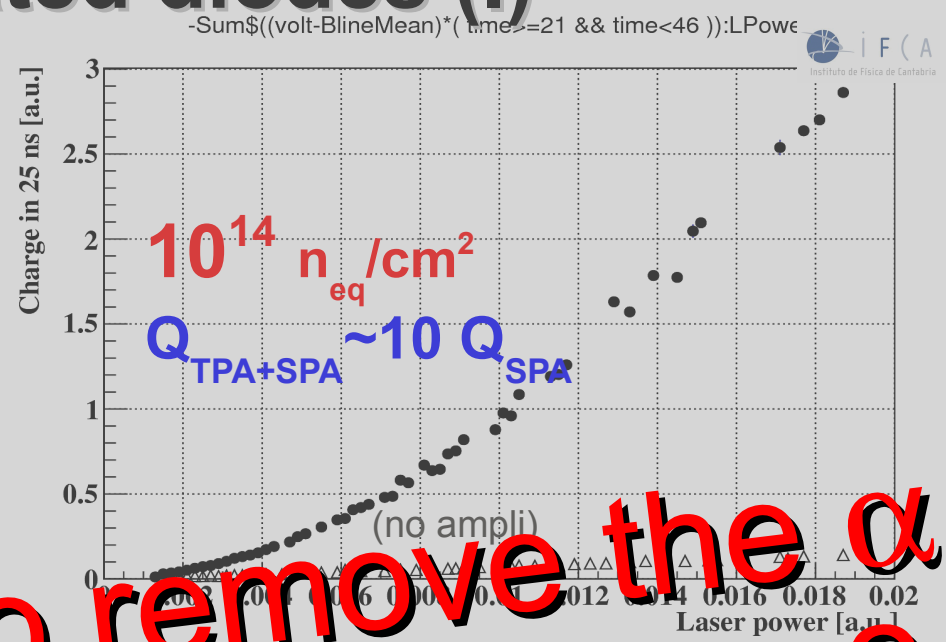




TPA intensity scan done with **focus inside** the detector
SPA intensity scan done with **focus outside** the detector

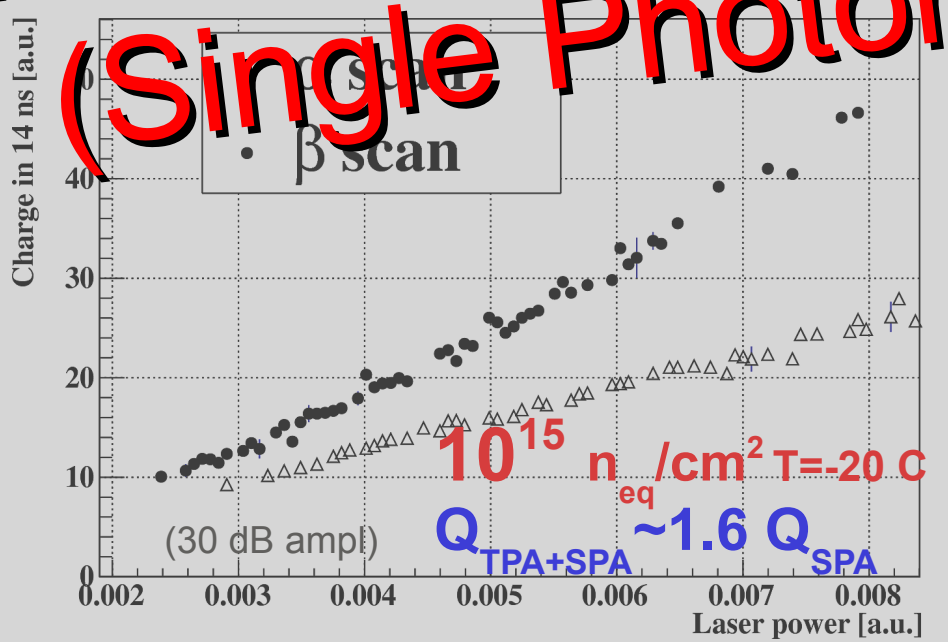
TPA on irradiated diodes (I)

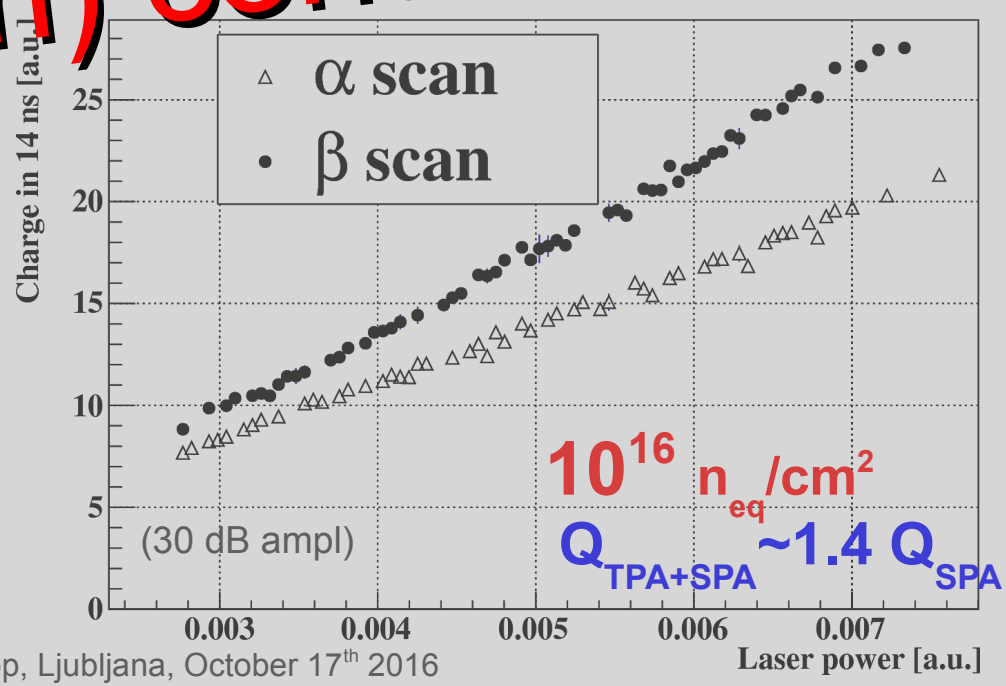




Is there a way to remove the α (Single Photon) contribution?

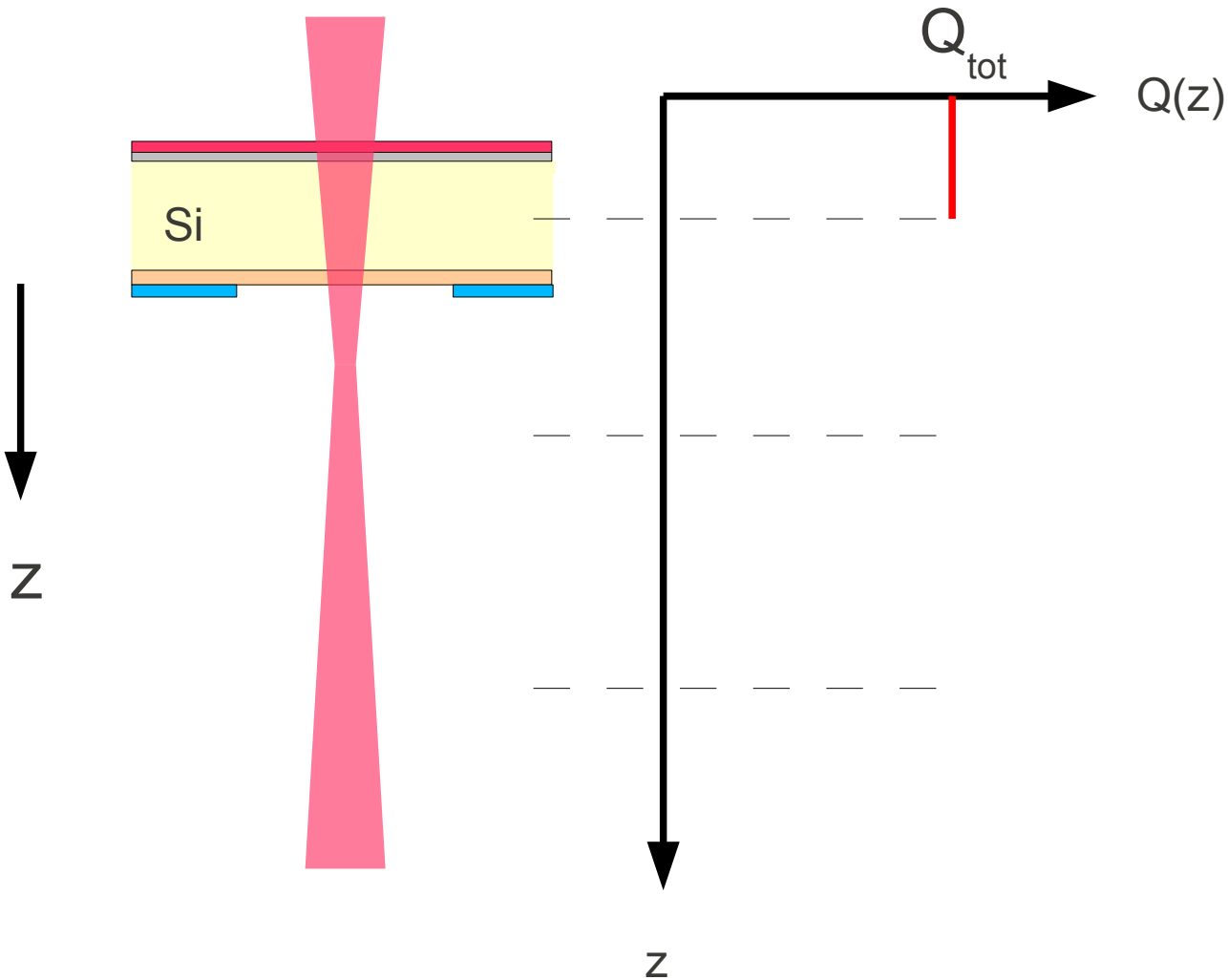
Ratio a Laser Power=0.06





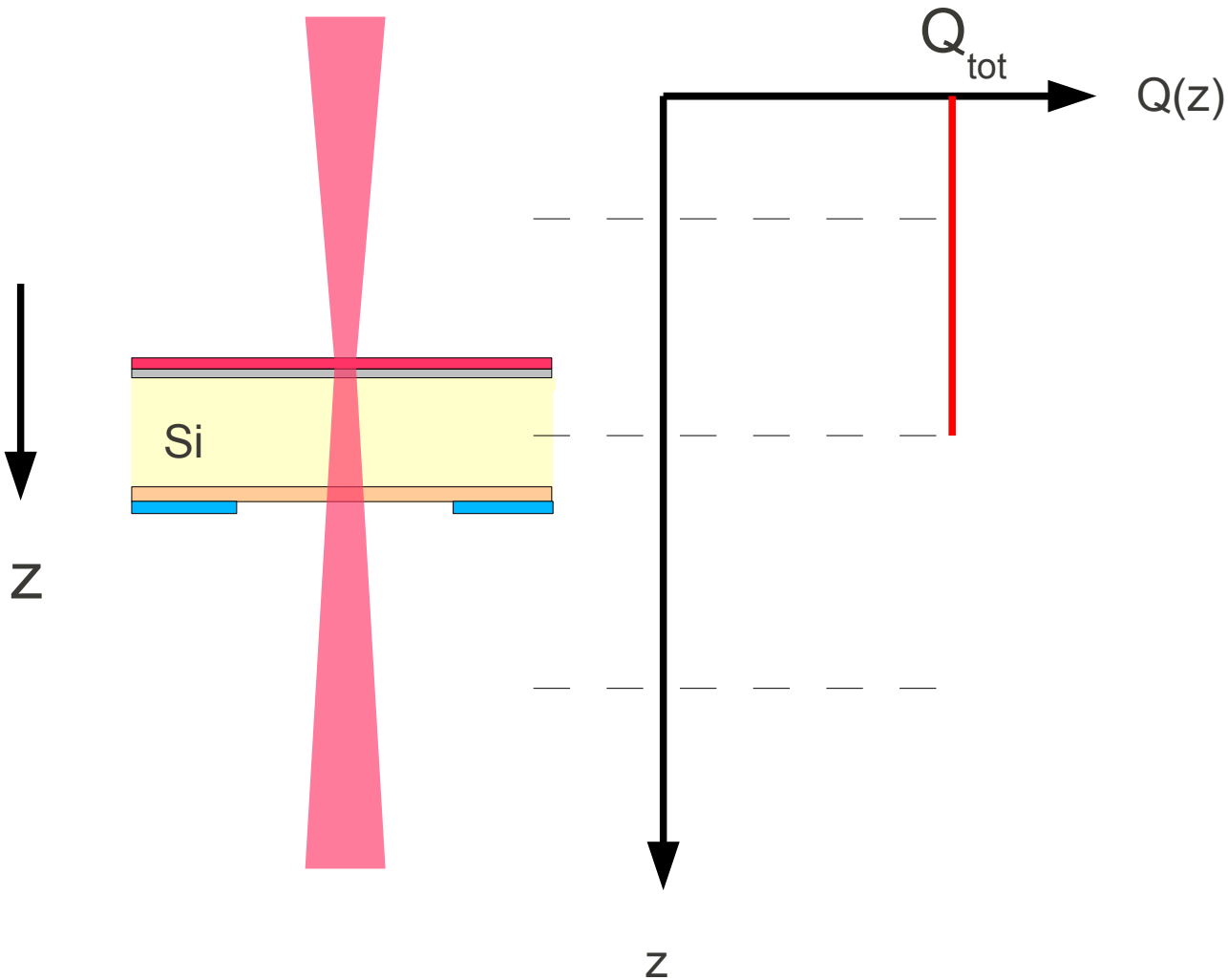
SPA: Vertical scans
...more Powerpoint physics

Let's do a vertical scan. How does it look like in case of SPA for non irradiated?
TCT → **induced current** → Q(z) = integrated current as a function of detector position



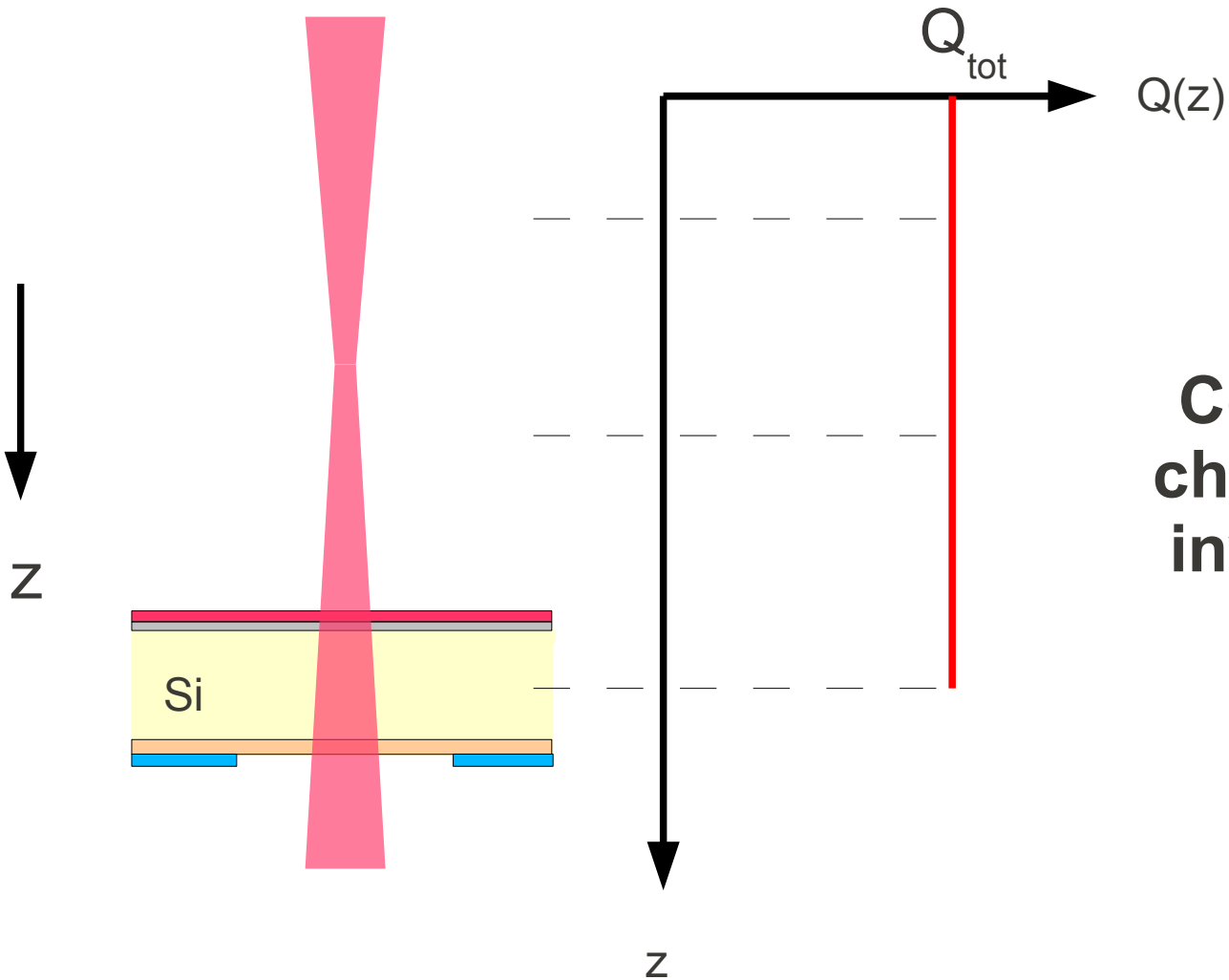
SPA: vertical scans

- **SPA:** IR vertical (z) scan. Assuming depleted detector.



SPA: vertical scans

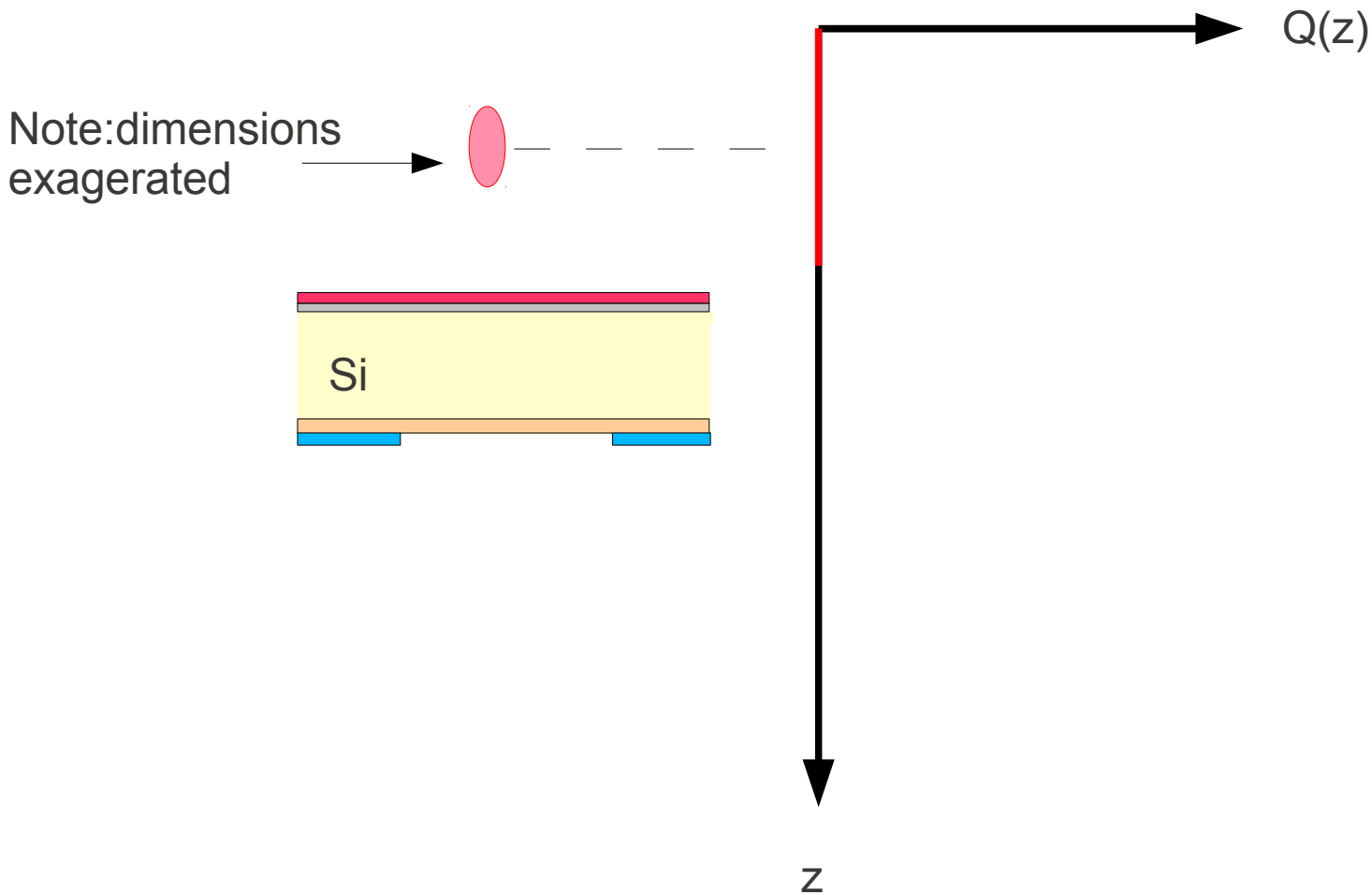
- **SPA:** IR vertical (z) scan. Assuming depleted detector.



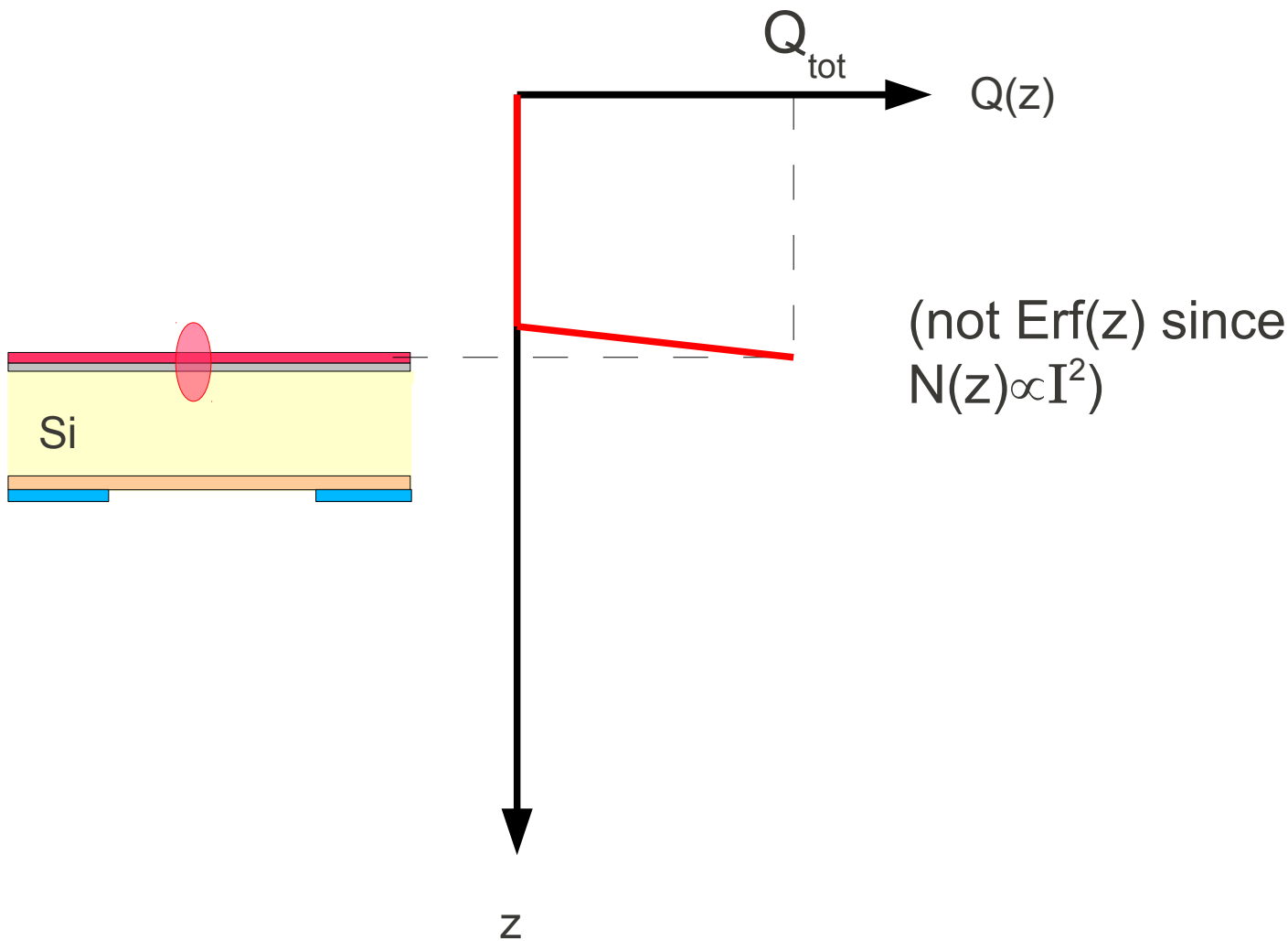
Collected charge is Z invariant !

TPA: vertical scans

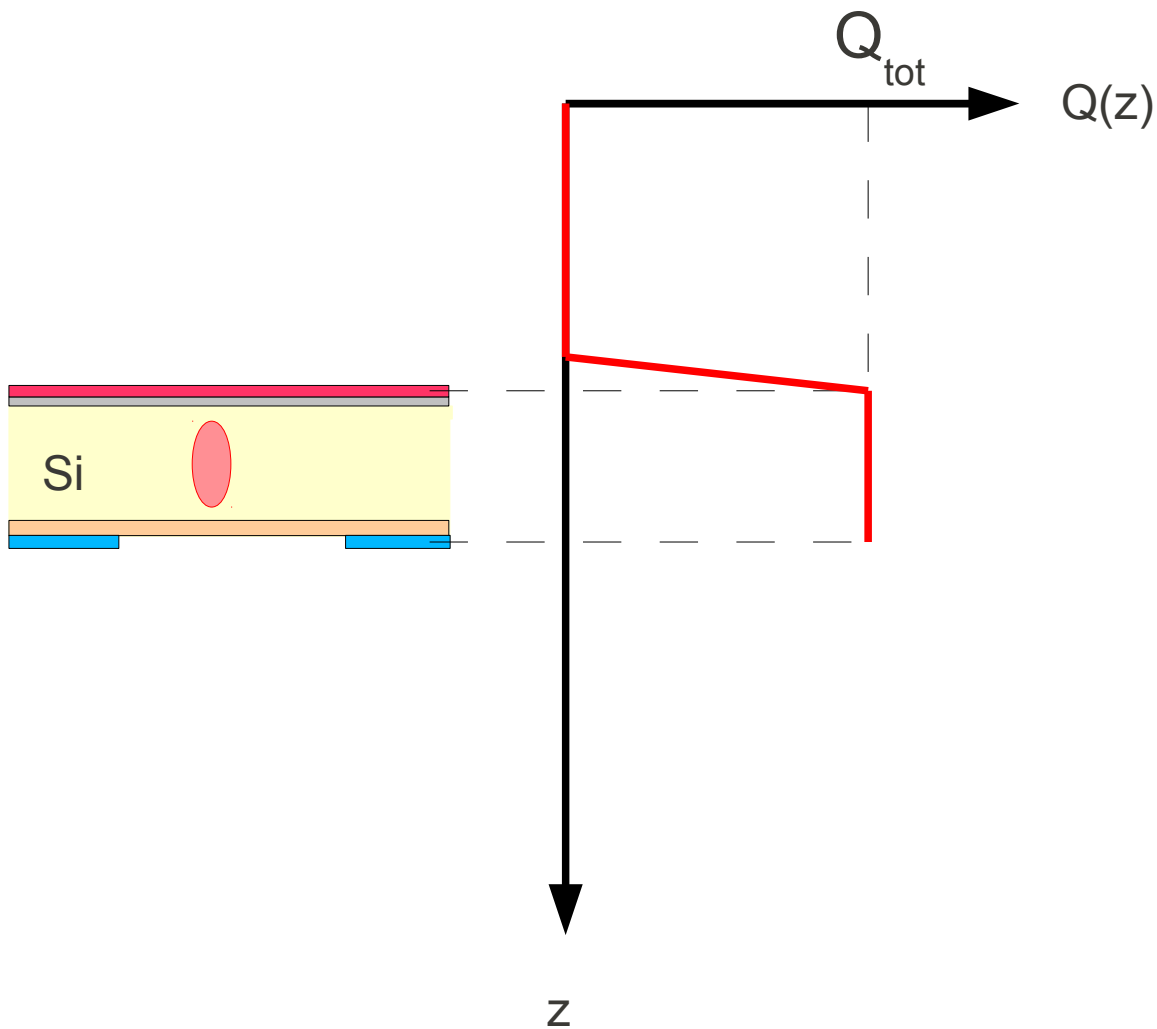
- **TPA:** Ellipsoidal excitation volume. In reality the detector is moved. Here, moving the laser voxel. Detector not irradiated: $\alpha I << \beta I^2$.



TPA: vertical scans

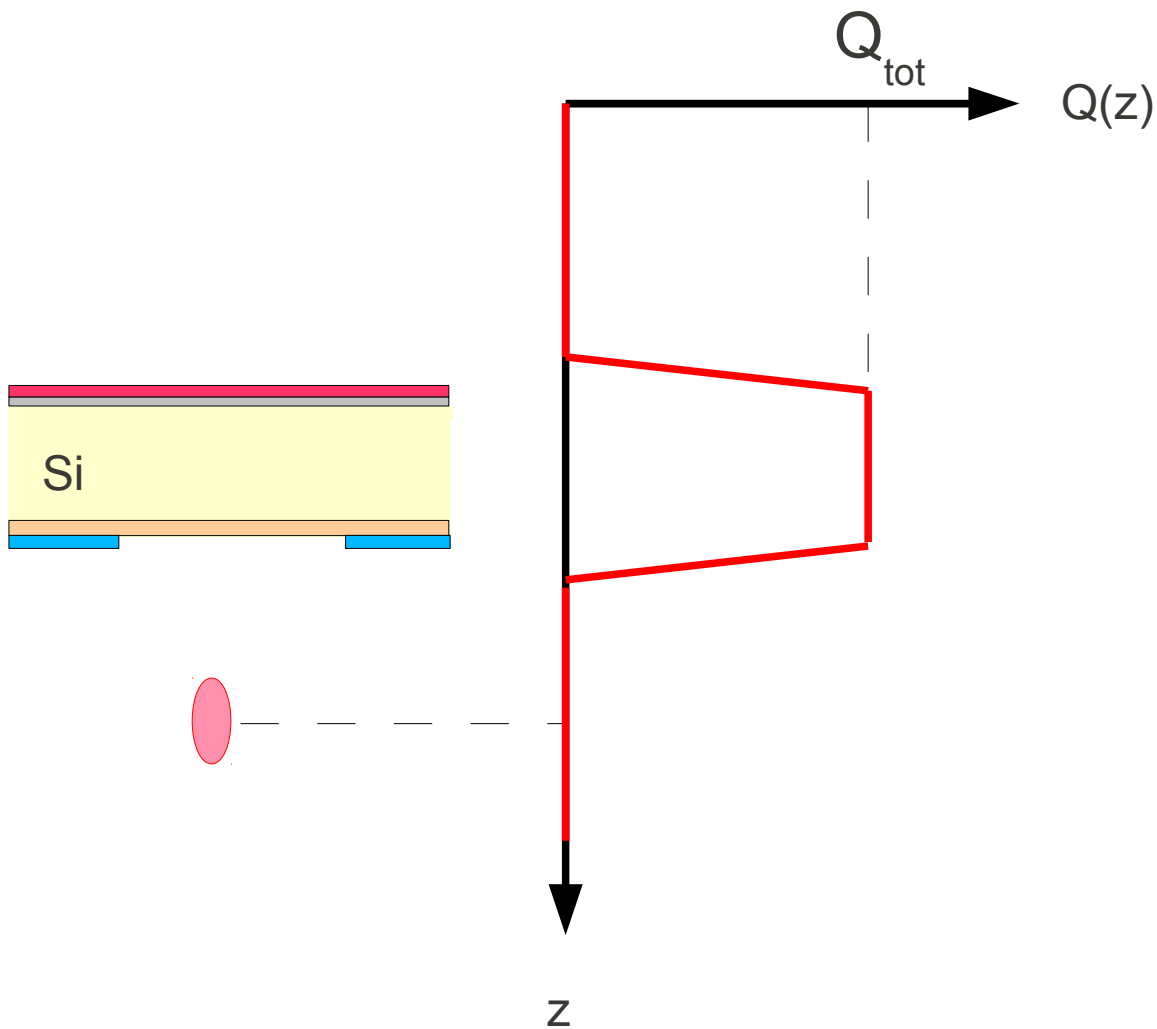


TPA: vertical scans



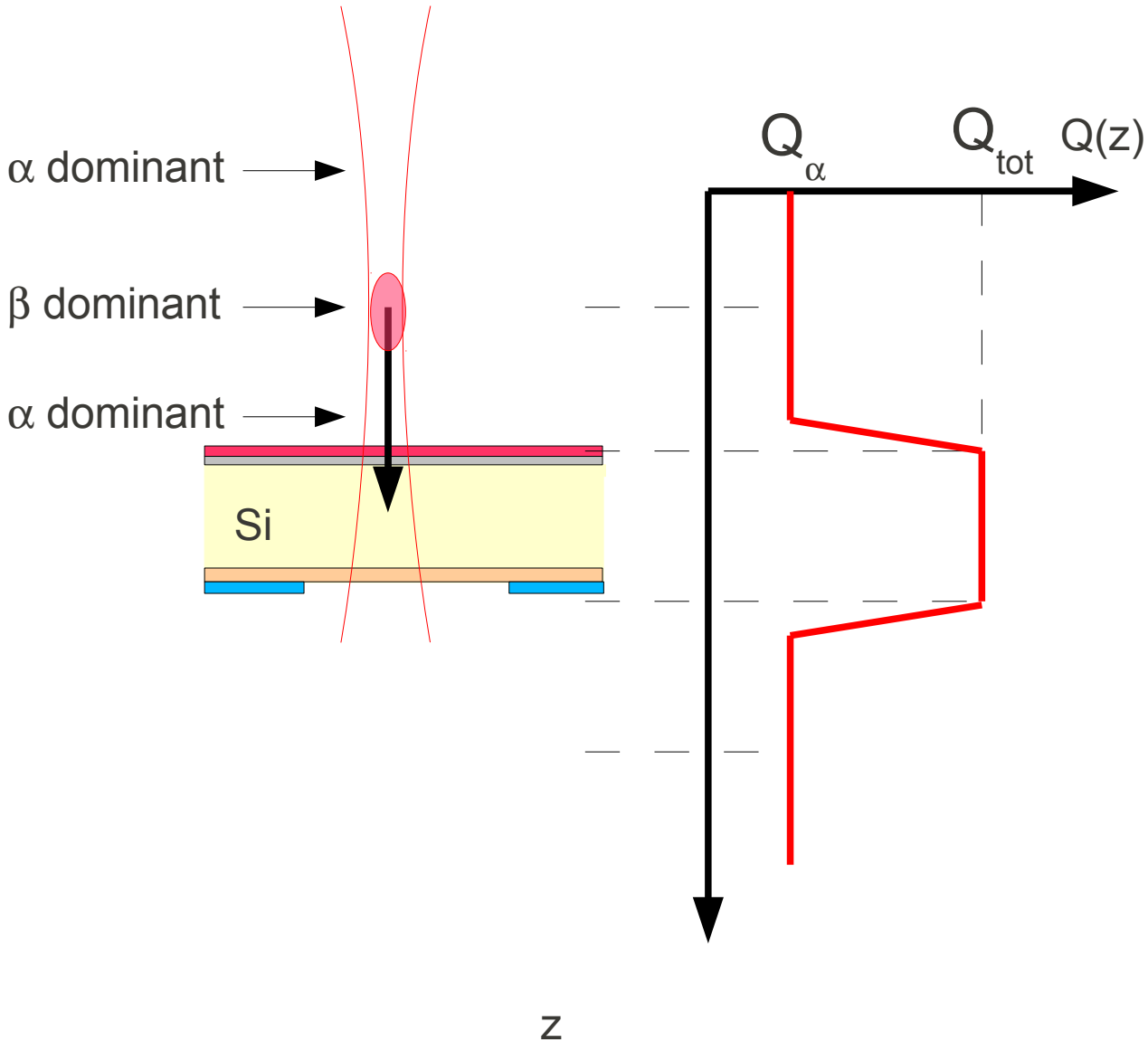
SPA: vertical scans

- **TPA:** Vertical Z-scan**: no light absorbed before/after** the focus !!



Vertical scan of an irradiated detector

- **TPA:** In case of irradiated detectors, $\alpha(\lambda)$ increases with fluence, leading to a reduced β/α contrast.



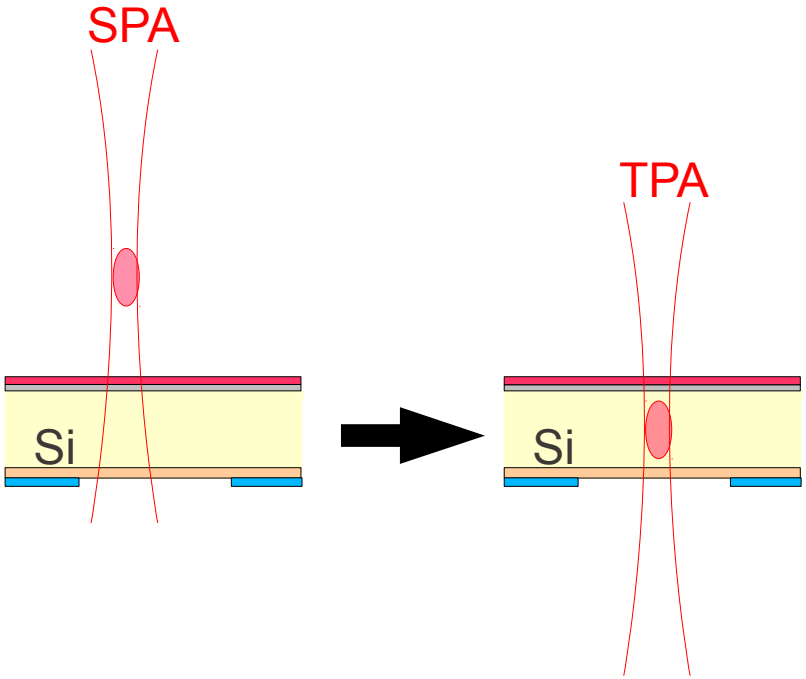
Subtraction of linear absorption

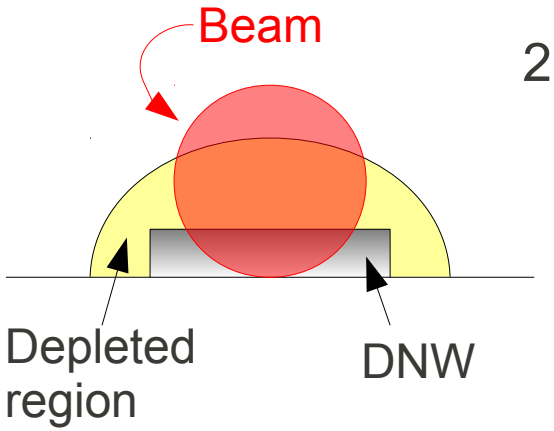
- SPA contribution can be removed cause it is z-invariant!

Two correction algorithms are possible

1) If the depletion width > beam diameter:
Z-scan method

- Focus beam outside → measure α contribution.
- Focus beam inside → measure $\alpha + \beta$ contribution
- Correct data (focus inside) at waveform level.



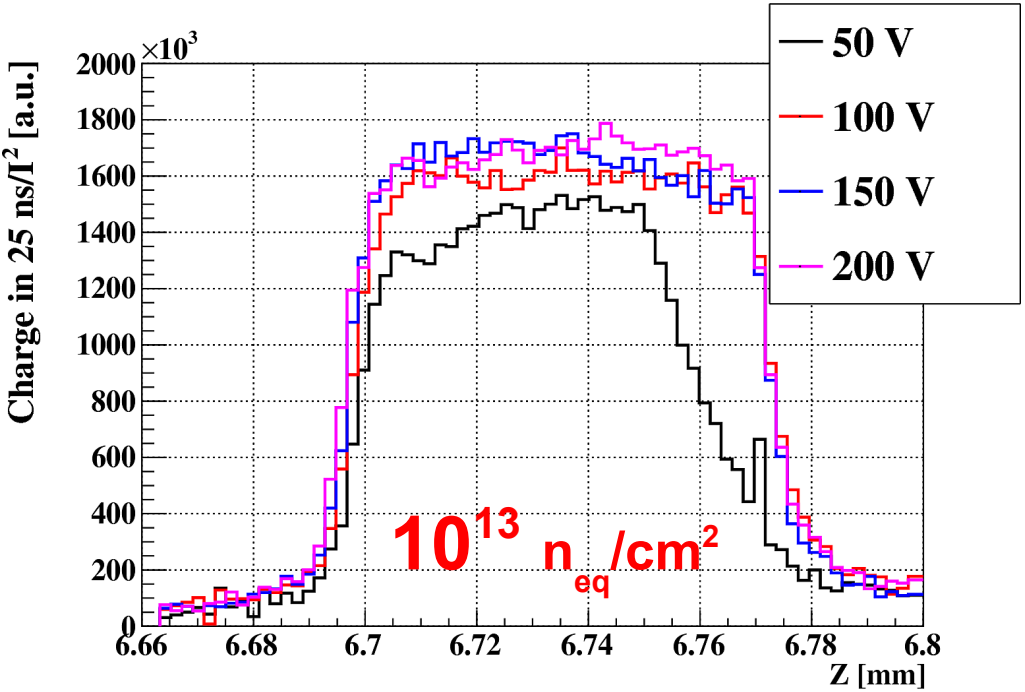


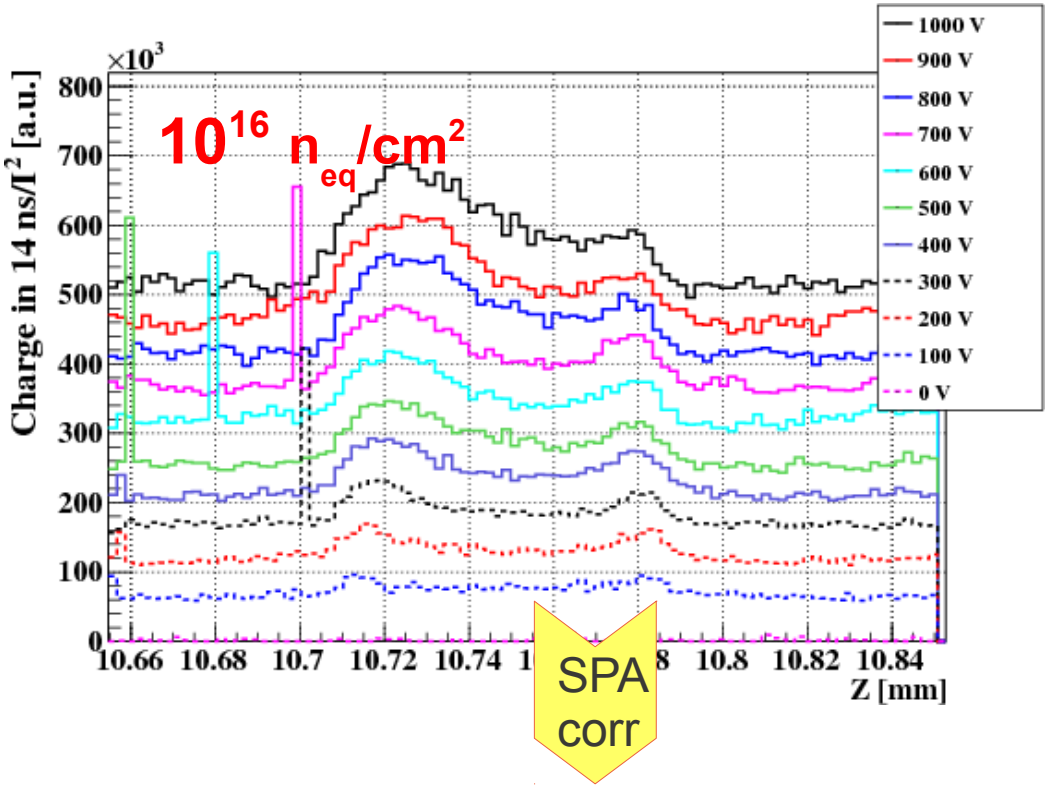
HVCMOS Top view

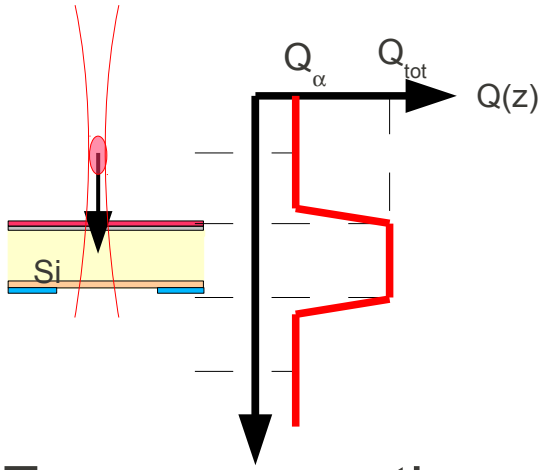
2) If the beam diameter is bigger than the depletion region:
Intensity method

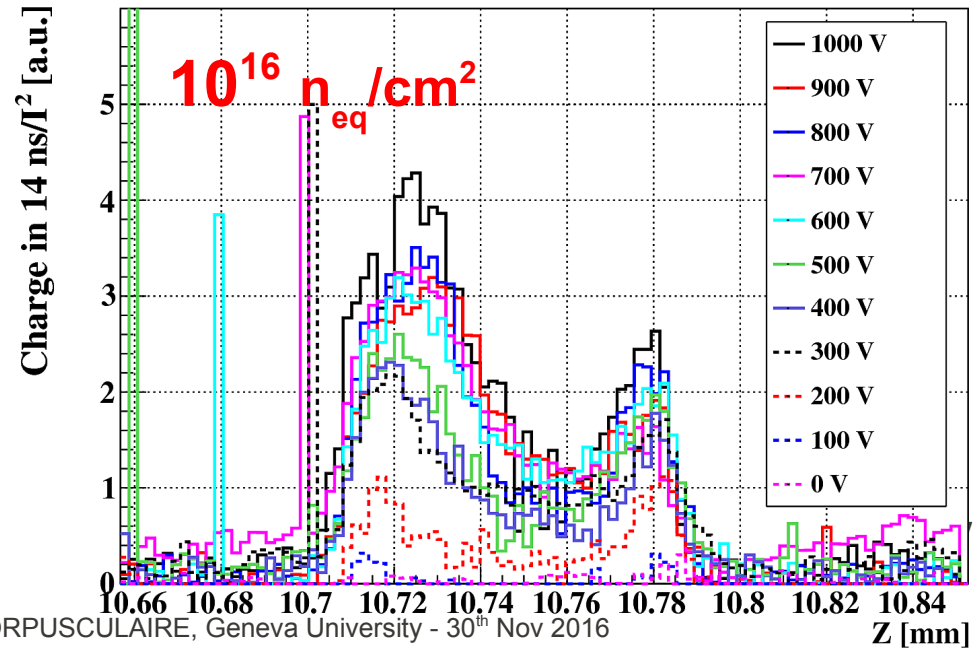
- Focus beam inside the detector
- Reduce intensity (so $\alpha I \geq \beta I^2$) → measure α contribution
- Do **not** move the focus. Increase intensity and measure $\alpha+\beta$.
- Substract α

Diodes: SPA subtraction









- SPA Z-scan correction works

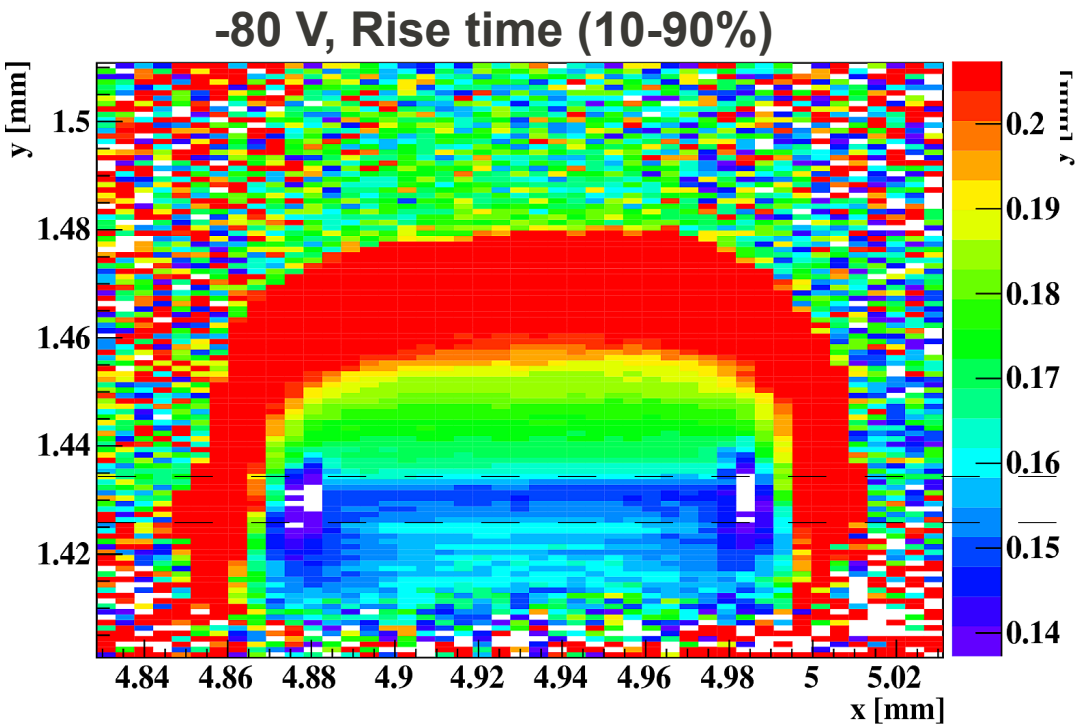
Corrections are done at waveform level

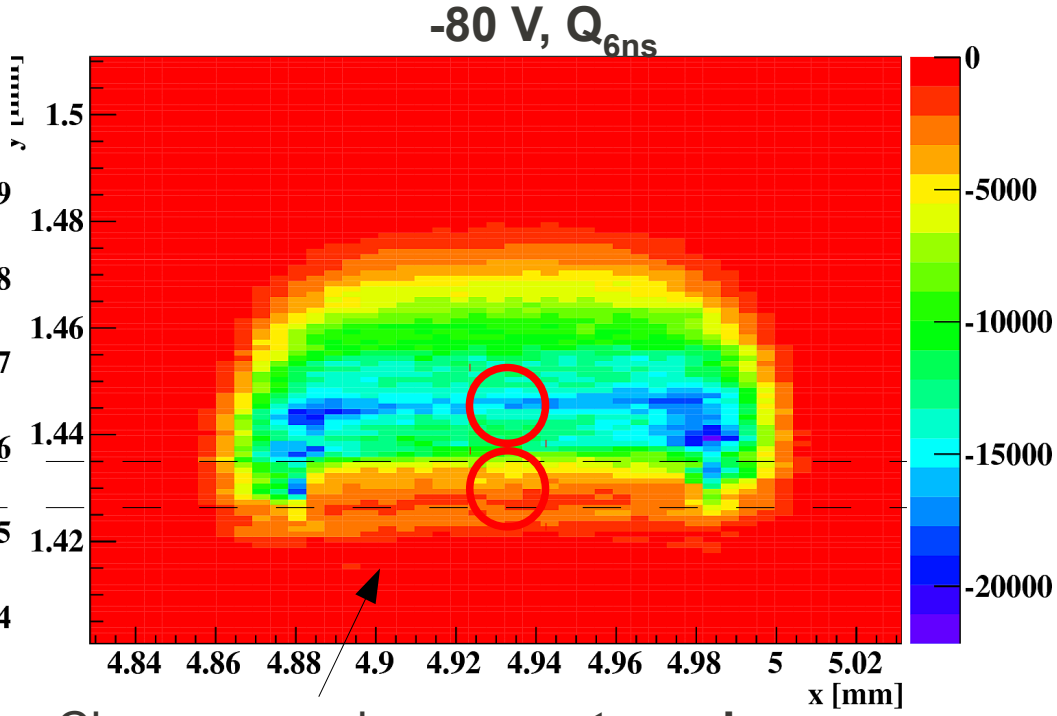
TPA of neutron irradiated:
- HVCMOS (CCPDv3)
(7×10^{15} n_{eq}/cm^2)

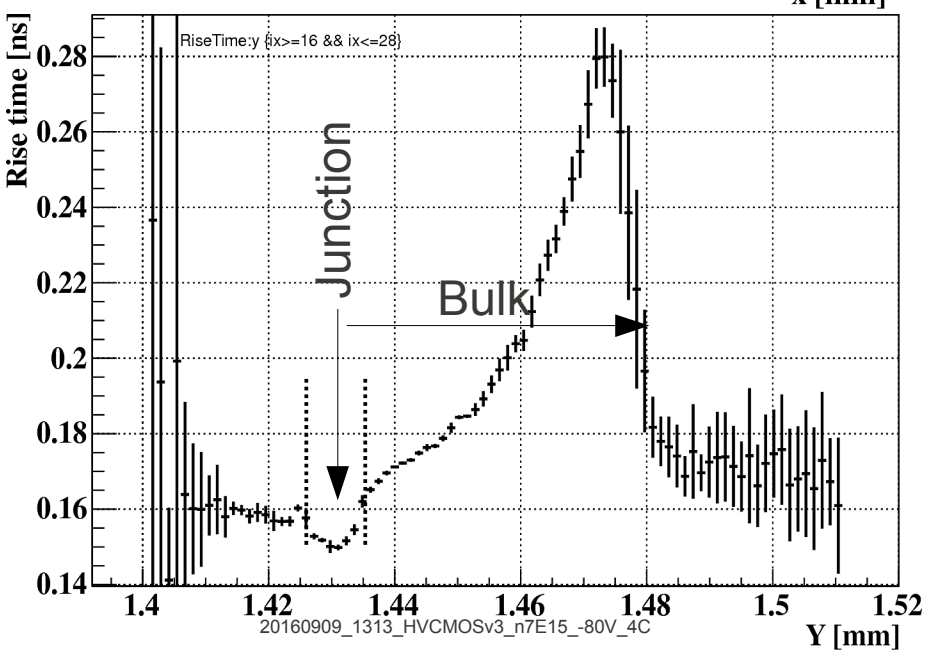
[no SPA correction accomplished yet]

λ=1300 nm, Δt=240 fs

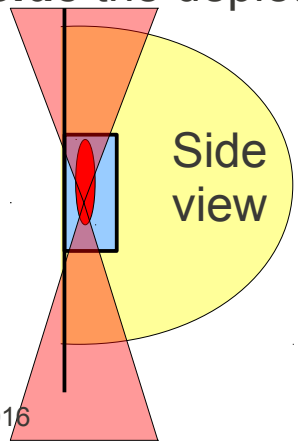
HVCMOS 7×10^{15} n_{eq}/cm^2 -80V

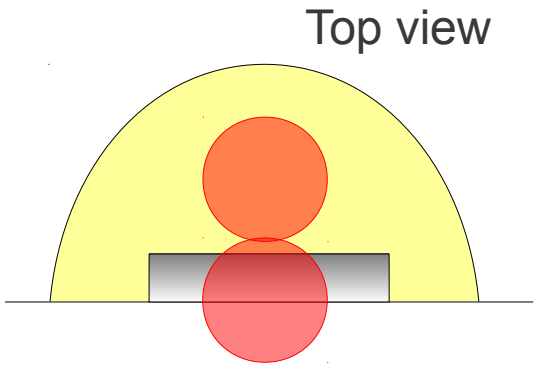






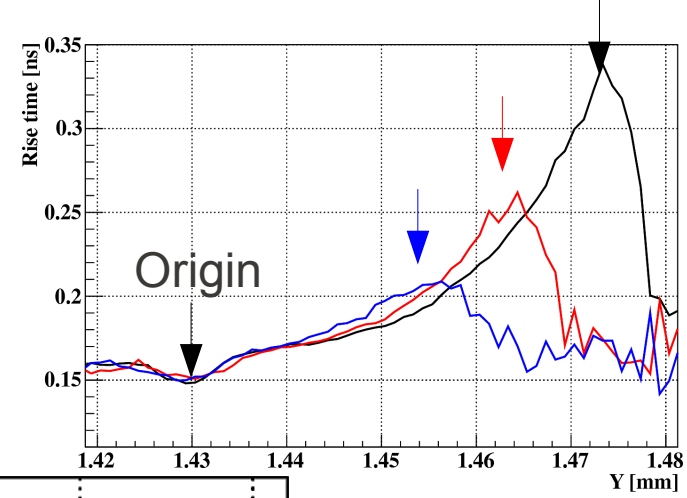
Charge map shows a r**ectangular region** with increased charge collection shifted away from junction border. Most likely due to **full beam** there being **inside** the depleted region

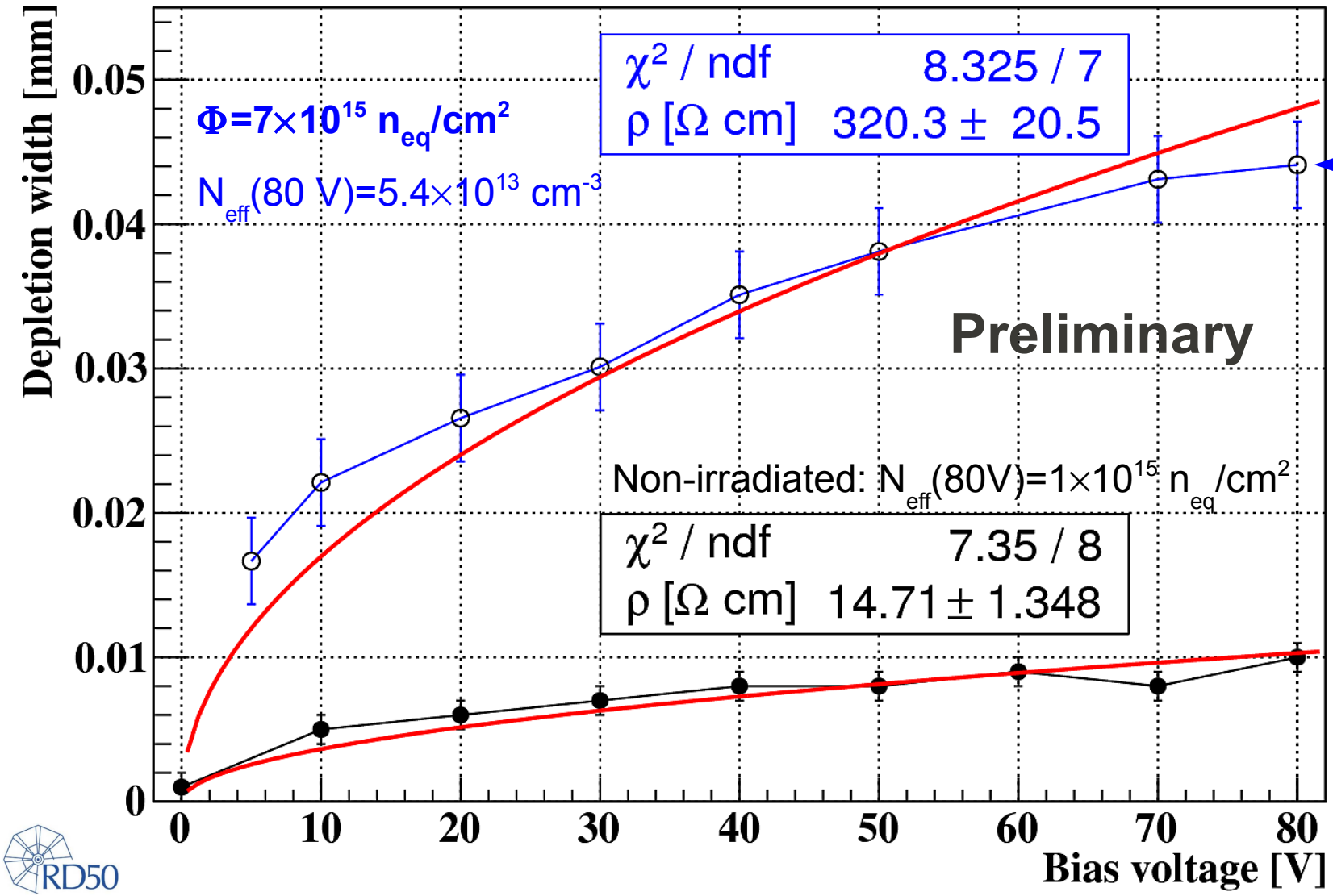




Depletion depth

- **Criteria**: End of depletion region is calculated fitting the rightmost "**bump**" in rise time. **PN junction** origin assigned to **minimum** of rise time bump.





Note: using other estimators for depleted width (collection time, for instance), we arrive to different numbers. Resistivity can change up to $\Delta\rho$=100 Ω.cm

RD50

IFCA Instituto de Física de Cantabria

Past / Present / Future

- Idea of TPA-TCT came **during a seminar** about TCT (!!) in 2012.

Sometimes, seminars are more useful for the speaker than for the audience

- Simulation of the system and **first measurements accomplished by 2014**

TPA **officially** presented at **25th RD50 workshop** at CERN (Nov. 2014)

- Since then we measured: silicon diodes, LGADs, diamond, HVCMOS

- Some **improvements** to current setup are on the way:
  - Sub-µm stepping motors
  - Pitch and Jaw platforms

- TPA presented in EP-**Knowledge Transfer** day → Selected and presented for **KT Fund Selection Committe**. Now waiting an answer:
  - TPA can be used in industry as a doping/E-field profiler
  - Design debugger
  - Live imaging of functioning device
  - ...

- Alternatively, we would also like to have a TPA-TCT setup at CERN. **Market survey** of components to setup a desktop TPA-system at CERN.

Wrapping up...

Transient Current Technique

R&D on radiation hardness of Si sensors

+

Two Photon Absorption

Test of Single Event Effects on electronics

Ultrafast molecular spectroscopy

UPV EHU

CERN: Michael Moll

IFCA: Marcos Fernández, Richard Jaramillo Iván Vila

TPA-TCT

UPV: Raúl Montero

US: Rogelio Palomo

This mixture has been possible via **CERN-RD50** collaboration

Summary

- The opening question of this talk "**Is there any technique providing 3D spatial resolution ?**" has been answered positvely:
  - **Two Photon Absorption-TCT** is a new semiconductor characterization technique that allows for **3D spatial resolution ($1 \times 1 \times 10\ \mu m^3$).**

Successfully tested on Si and diamond detectors

- On **unirradiated** devices TPA shows its full power. We resolved the deep implant of an HVCMOS and even measured inside of it.

- In **irradiated** devices, the **radiation-induced** linear absorption smears the contrast of TPA-TCT. Corrections tested and working.

  Can we try to minimize α-contribution? We are commissioning the fs-laser facility in Bilbao to operate at λ=1.5 μm, because of the lower linear absorption

- Access to a **fs-laser** is still reduced in our community. We will try to have a table-top fs-laser (fixed λ) at CERN-SSD

- New **RD50 project** to measure non-irradiated / irradiated **HV/HRCMOS** (different resistivities, collecting electrode geometries...).

Institutions welcome to join.

THANK YOU FOR YOUR ATTENTION

http://www.jontyhurwitz.com/eyelash-surfer/

SP
AR
ES

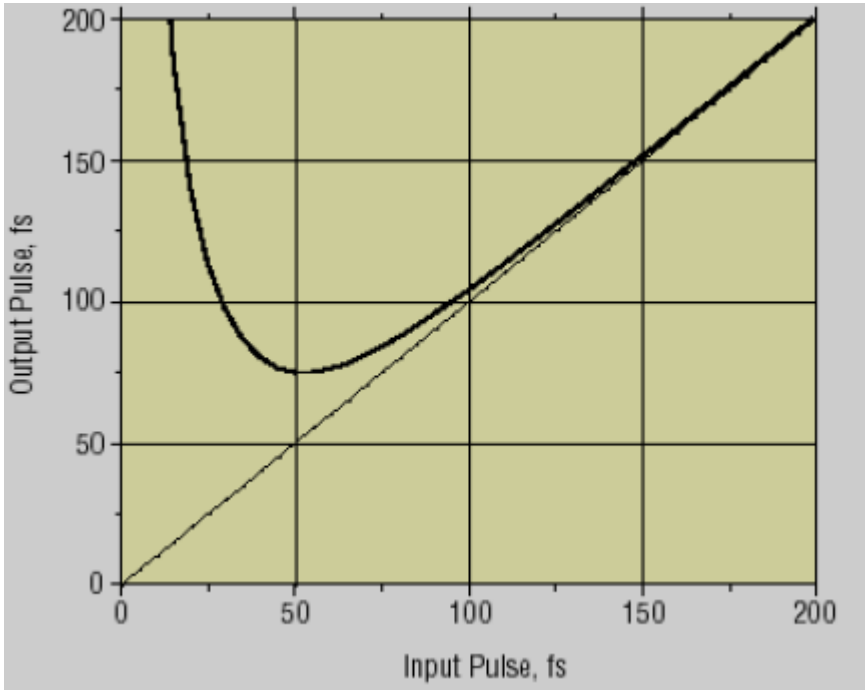
fs laser facts for ps laser users

- **Pulse stretching:** Short pulse → Wide spectrum → different frequencies travel at different speed → dispersion. When a fs pulse **traverses material**, the pulse length **increases**. This is not important for ps pulses.

  - Luckily, this broadening **can be corrected** (within limits). Careful choice of optics is needed. Lenses are forbidden. Use mirrors.

- **Wavelength tunability**: Non-linear effects allow to tune the wavelength of the pulse. Second (**2ω**) and higher order **harmonics** (**3ω**...) are easily generated. NIR → Vis (2ω) → UV (3ω)

Pulse width broadening after 20 mm of BK7 for an input pulse of 100 fs



- Getting higher wavelengths from a lower one needs of expensive hardware: parametric amplifiers and sufficient energy (≥μJ). Table-top (cheap) lasers will be bounded to the wavelength chosen and to the harmonics below.

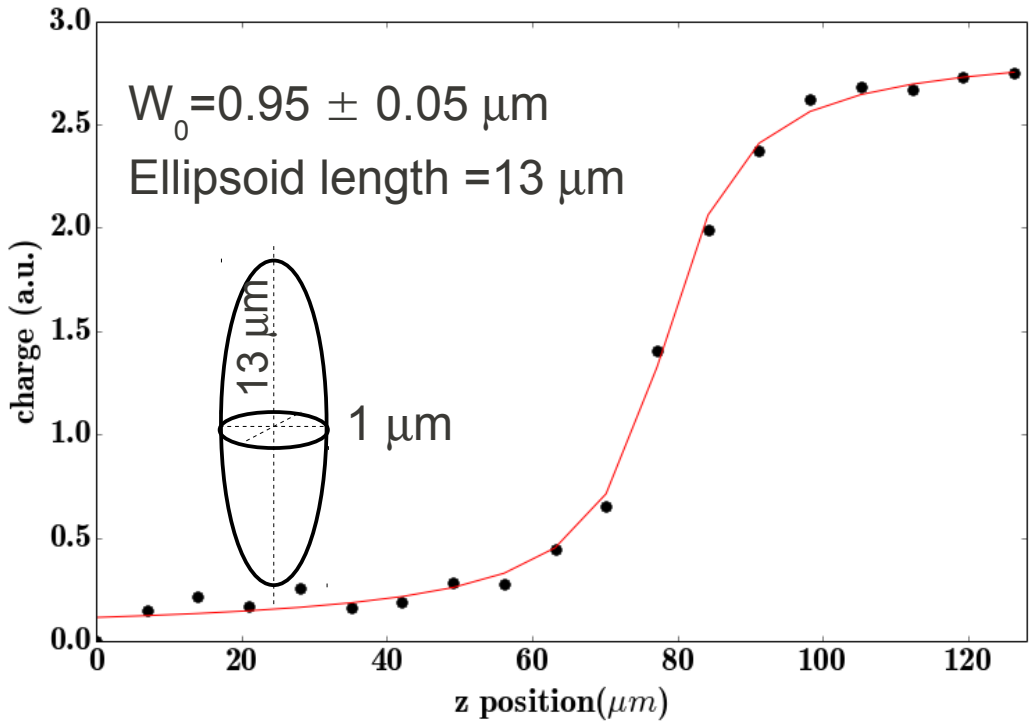
Careful: fs-laser can **vaporize** the detector (Si ablation~45 $\mu J/\mu m^2$, μJ/fs=1 GW)

In general, do not reach nJ pulses for Silicon

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.

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

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

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

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

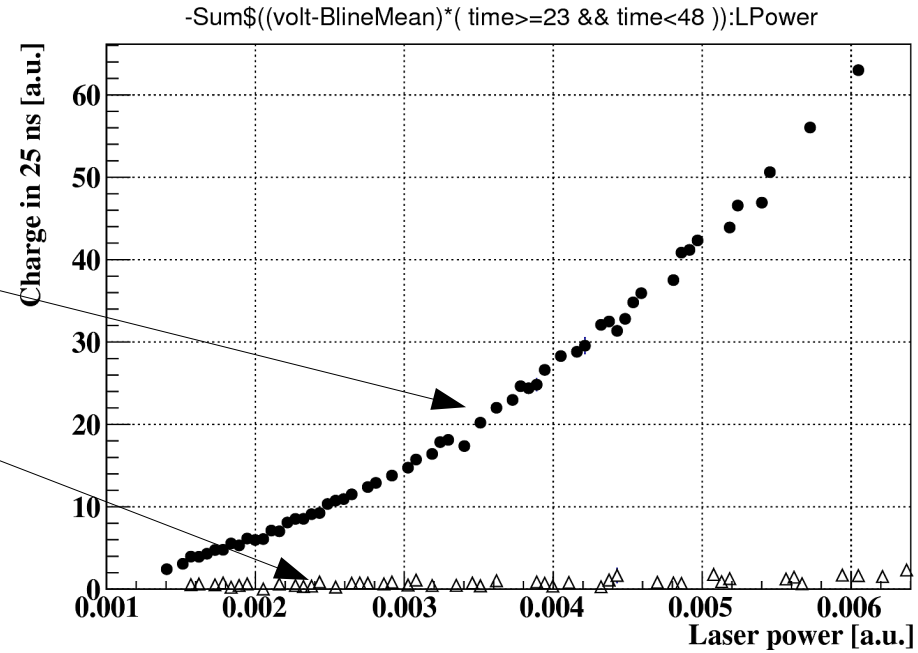
An **edge-TPA** scan is optimum, because spatial resolution is **~1 μm**
Try to scan **pads from the edge** → Get active area very close to the border

New RD50 project to perform edge-TPA on irradiated diodes

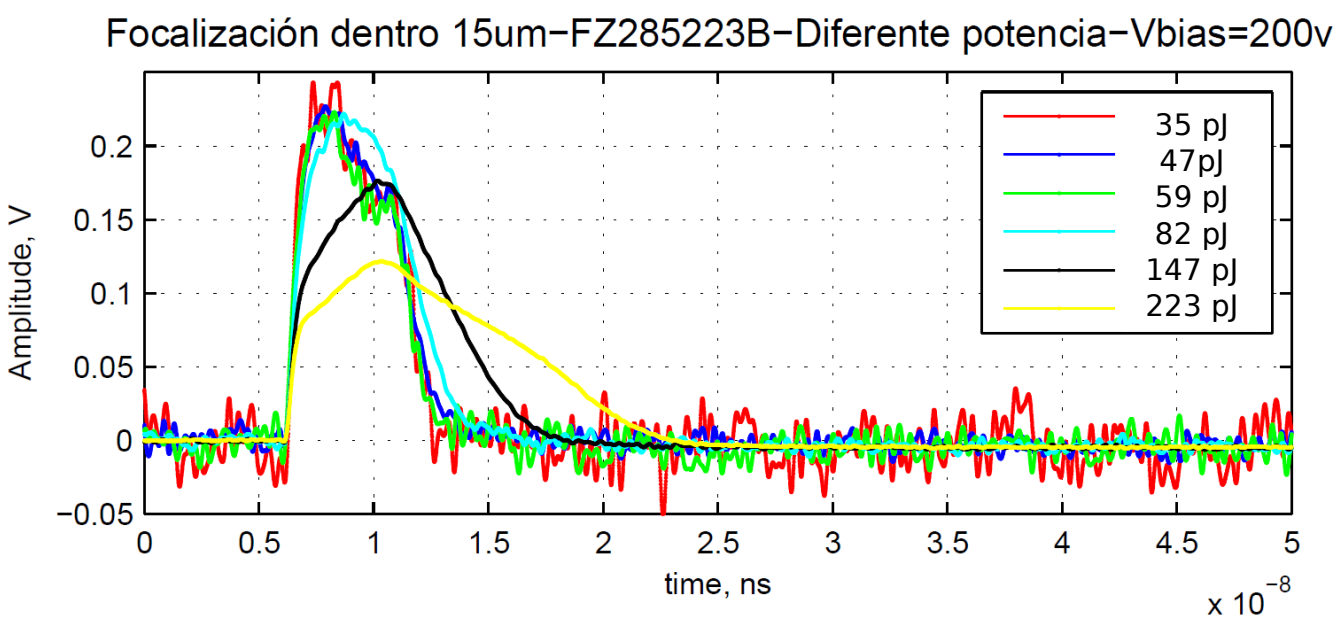
Differences between TPA and SPA scans (I)

TPA: collected charge increases **quadratically** with power

SPA: collected charge increases **linearly** with power.



⇒ Work in a power regime where **β>>α** but **without** producing **plasma**.

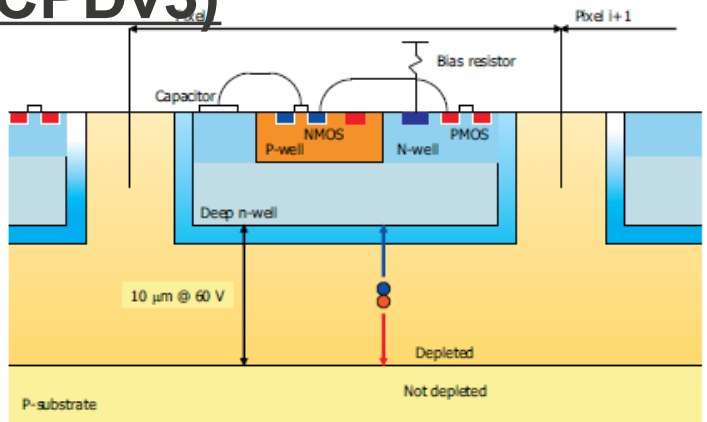


- For this detector. Laser power<80 pJ ⇒ no plasma effect

Tested device: HVCMOS HV2FEI4 (aka CCPDv3)

- HVCMOS sensors are partially depleted MAPS implemented in **low resistivity** CMOS technology, able to withstand voltages **up to 100 V**.

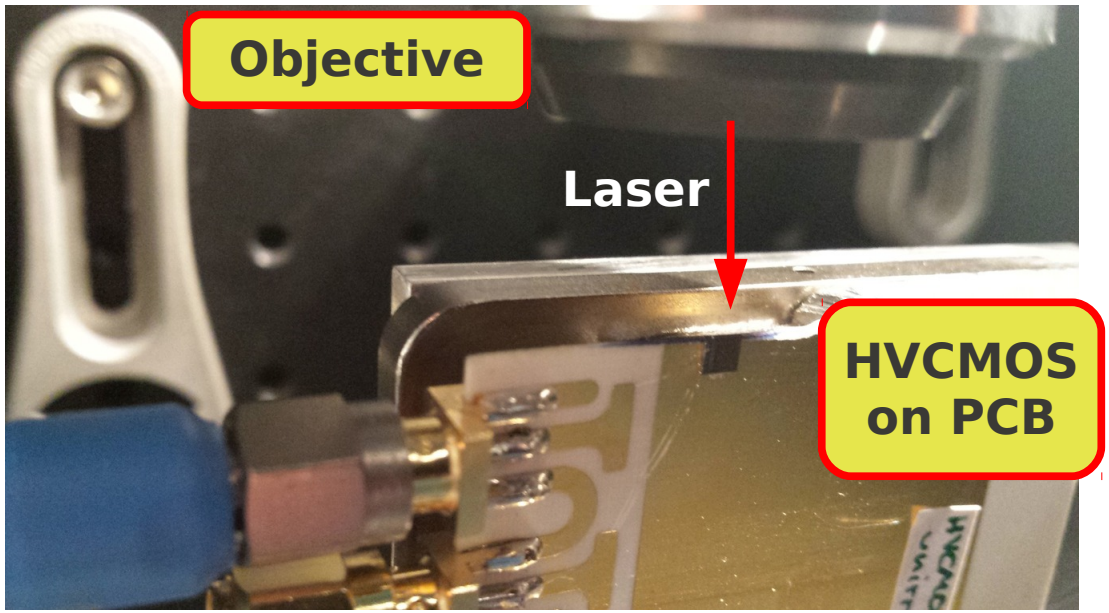
- The deep n-well (DNW) is both the substrate for shallow transistors and the collecting diode.

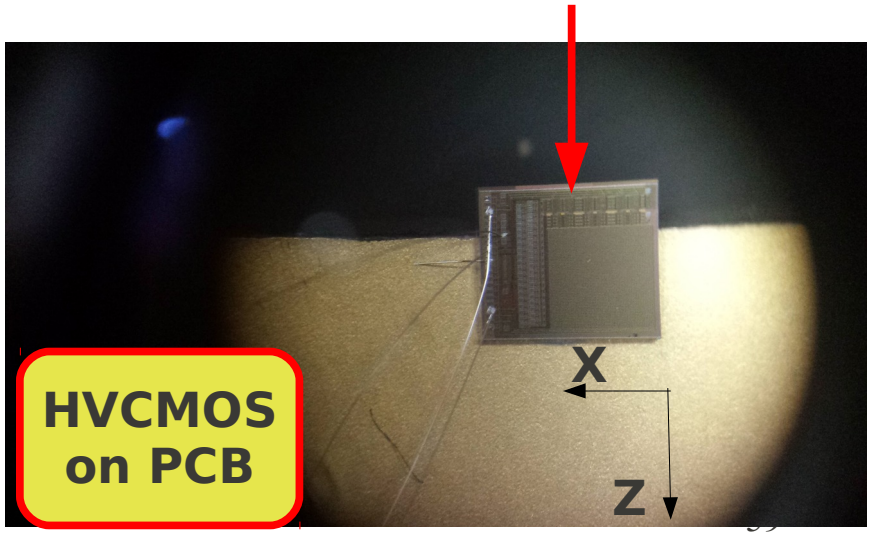


I. Peric doi:10.1088/1748-0221/7/08/c08002

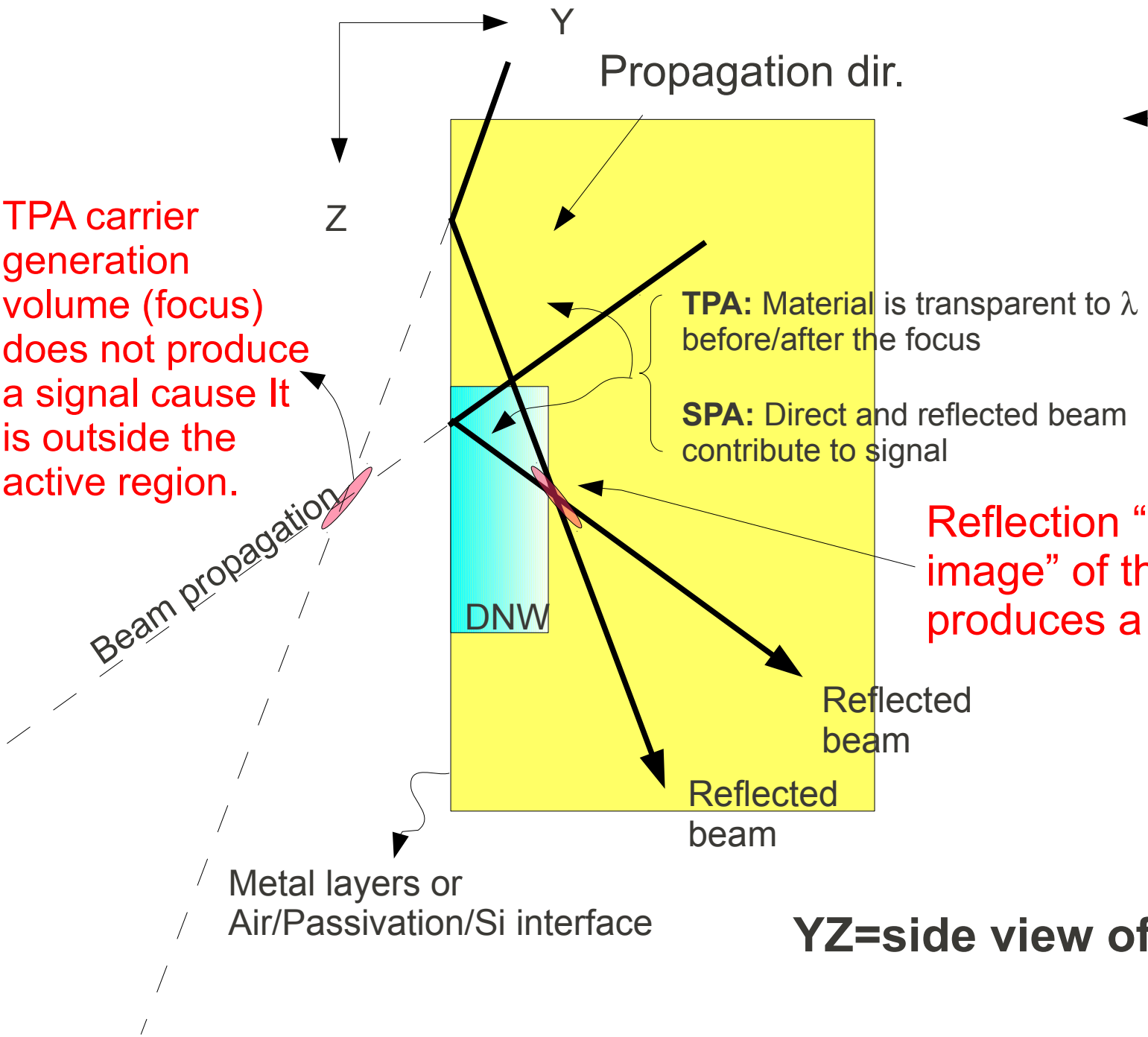
- Due to the low resistivity and maximum voltage granted by the technology, the maximum depletion depth is of the order of 10 µm ← **Tough for SPA methods**

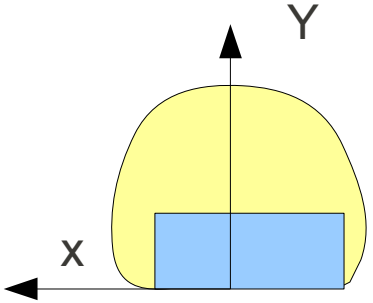
- For this experiment, laser illumination from the **edge of the detector.**





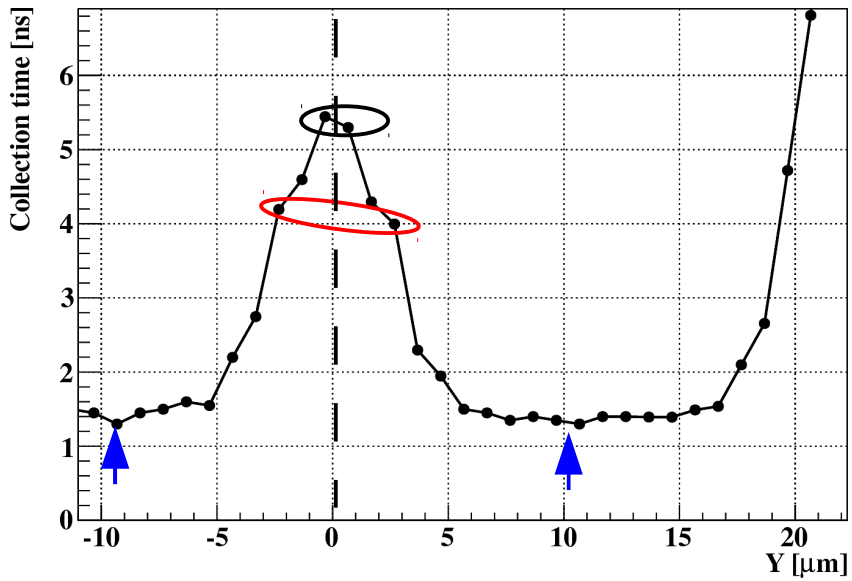
Beam reflection at interfaces





YZ=side view of the implant

Comparison of direct and ghost signals



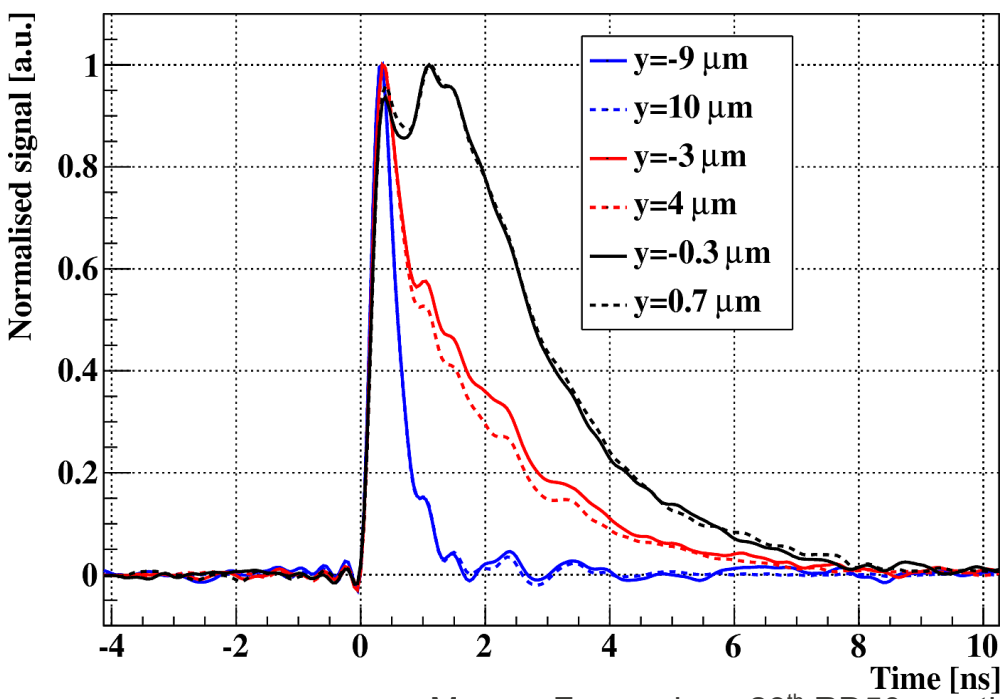
Choosing pairs of waveforms:

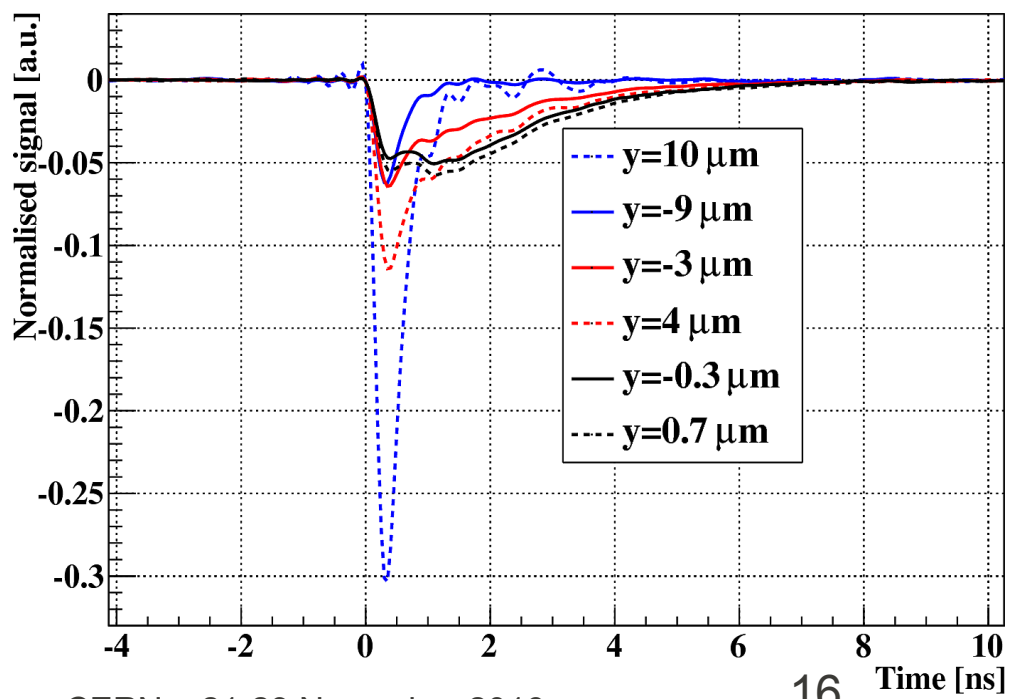
1) at the interface
2) ±2 μm away
3) ±10 μm away

Seen reflection of pulses well inside the bulk.

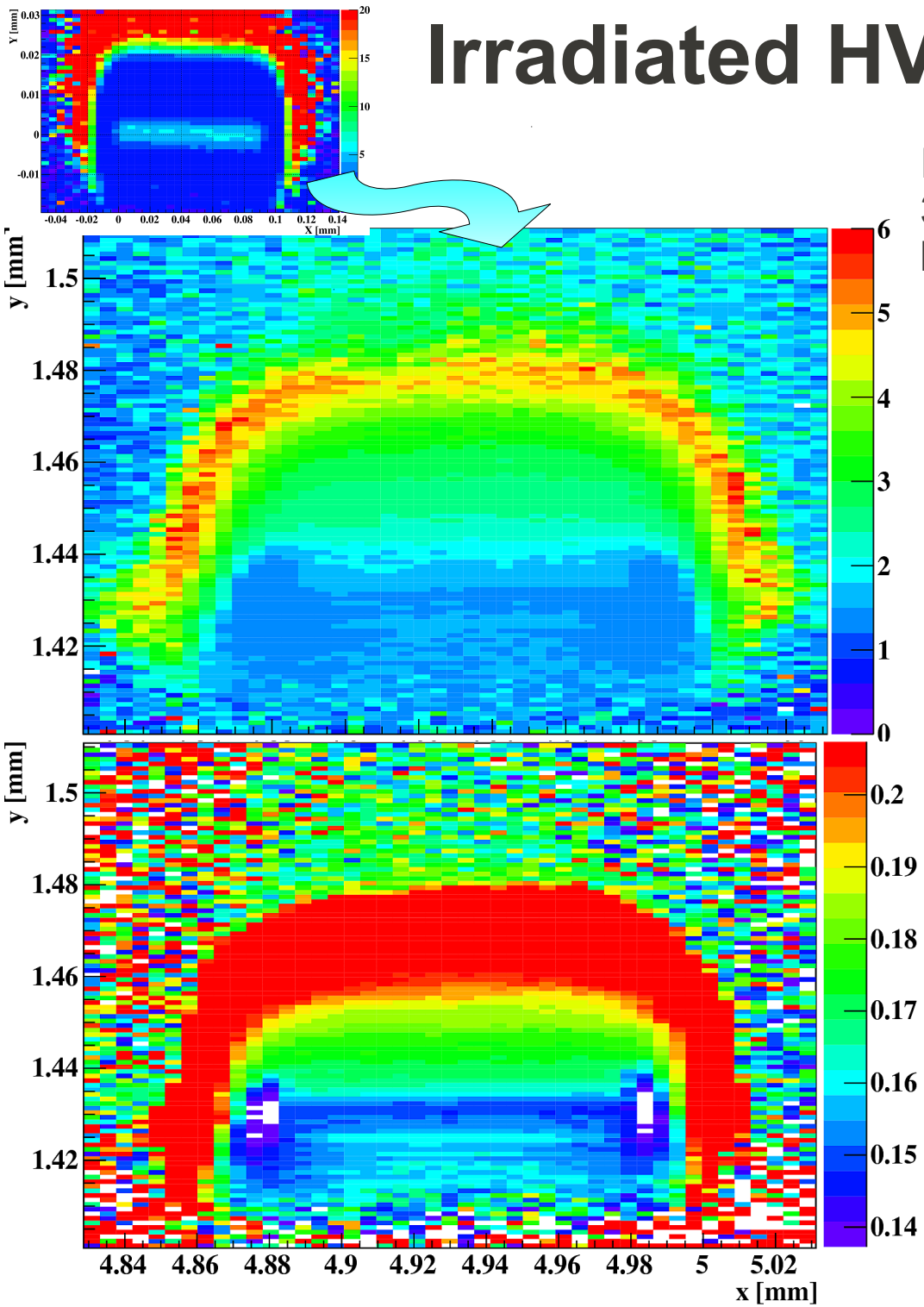
In SPA-edge-TCT this reflection can not be easily resolved because the beam is continuous.

I. Vila, proceedings Pixel 2016, Sept. 2016

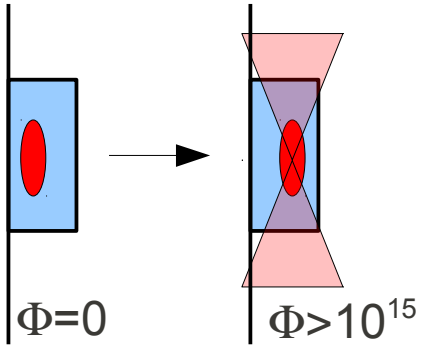




Irradiated HVCMOS, time variables



In irradiated Si, linear absorption **α grows**: 3D resolution in TPA of irradiated detectors looks more like a 2D resolution



[See backup for correction method in diodes]

Collection time map is **smeared** by charges coming from above/below focus point.

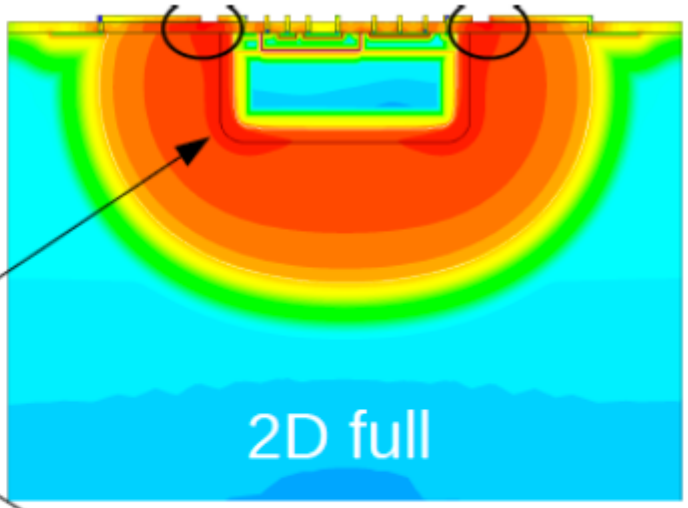
Testing **Rise Time** (RT, 10-90%) as **estimator** to **identify** junction position.

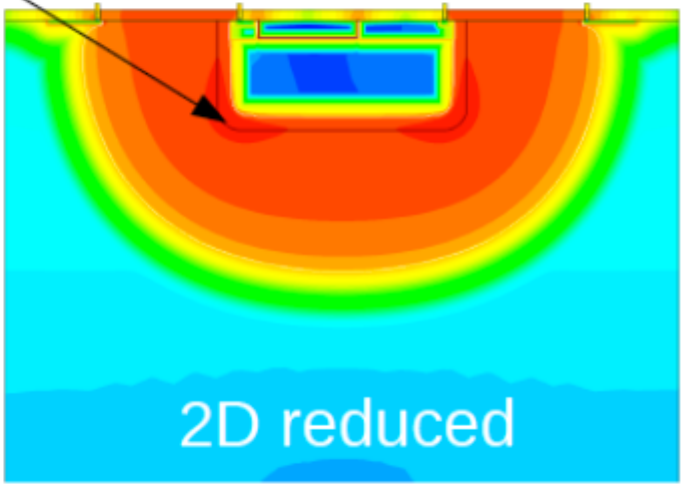
E-field ∝Rise Time:
Higher E-field → faster pulses → Smaller RT

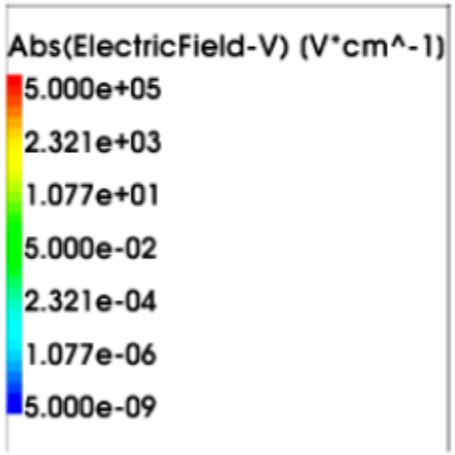
Expecting **lowest RT at junction border**.

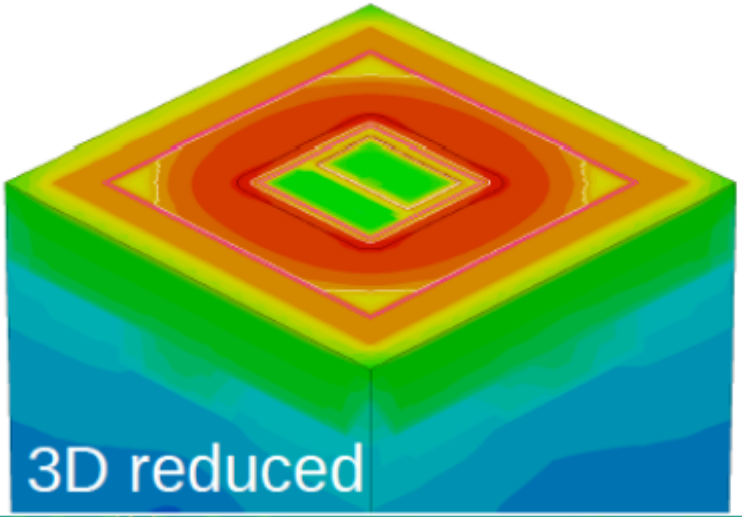
E-field comparison

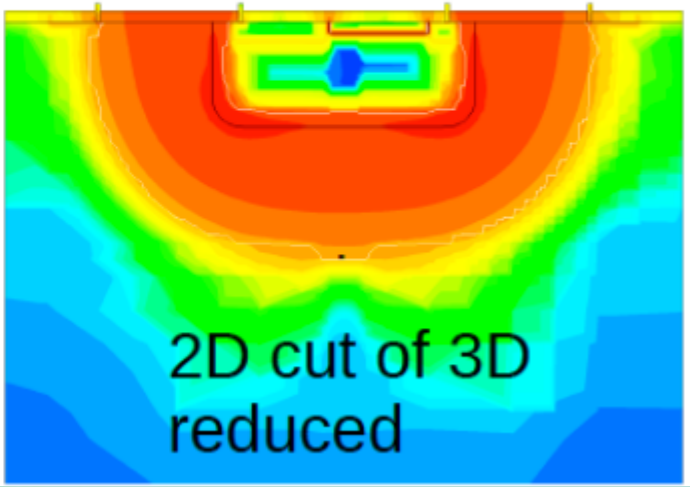
- Biased to -60V, operating voltage of device
- All electric fields are roughly the same:
  - higher value at edges of the deep n-well
  - Lower value in deep n-well and outside depletion
- One difference: 2D full model has a higher electric field value in the oxide because of the metal layer











Z scan Technique
Funny and Useful!

SubSurface Laser Engraving (SSLE)

Tipically in BK7 Glass (Borosilicate doped with potassium)

Also with pure quartz (SiO_2)

Pico or FemtoSecond Laser, 1064 nm (SiO_2), 532 nm (BK7)

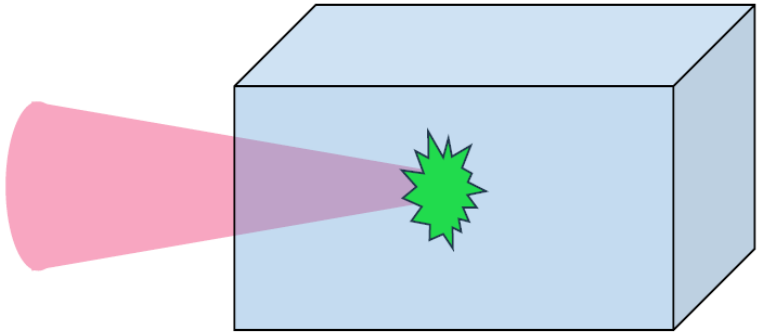
Multi-Photon Absorption

Free electron creation in the focus point

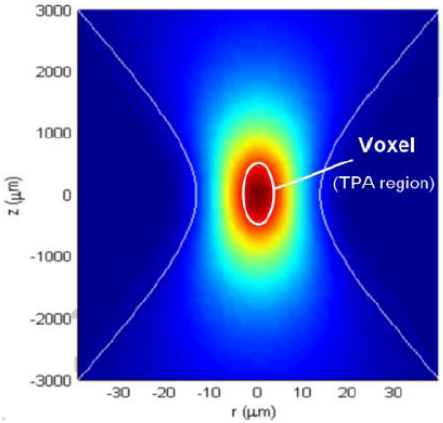
FotoChemistry in Solids:

Index of refraction changes,

Color centers



TJDP-532K Machine (532 nm, BK7 crown glass)
http://www.tianjunlaser.com/



Two-Photon Photopolymerization and 3D Litographic Microfabrication. H.B.Sun and S.Kawata. APS (2004) 170 pp 169-273, Springer-Verlag.
Femtosecond Laser Litography in Organic and Non-Organic Materials, F.Jipa et al., Chap.3, Nanotechnology and Nanomaterials, "Updates in Advanced Litography", ed. by S.Hosaka, INTECH, 2013.