TPA - TCT
Two Photon Absorption - Transient Current Technique

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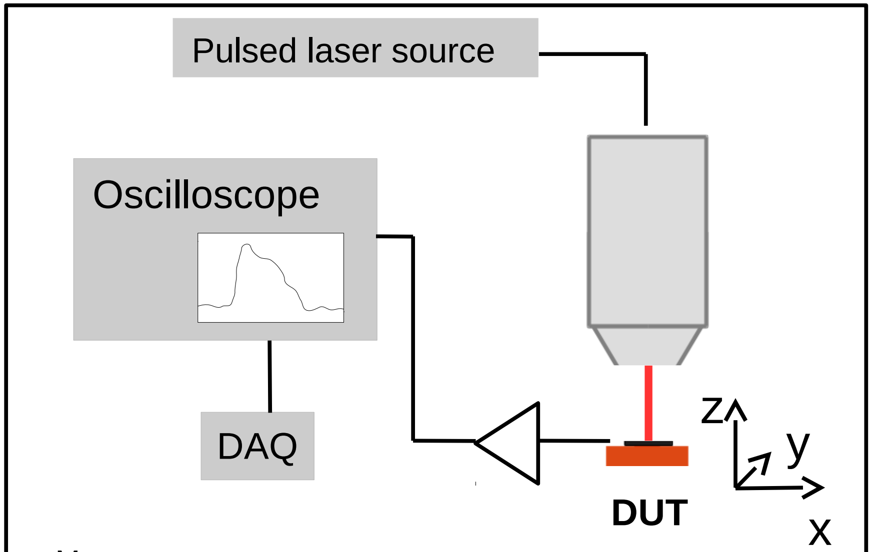
36th RD50 Workshop

Outline

- Gaussian Beam Optics
- Charge Generation via TPA
- Z-scan
- X-Z-scan

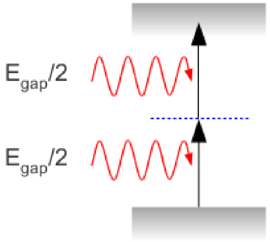
TPA-TCT: Reminder

Characterization of un-/irradiated silicon detectors with strong focusing of fs-laser pulses
Advantage of TPA: – charge generation only at focal point – very good spatial resolution – 3D mapping of sensor



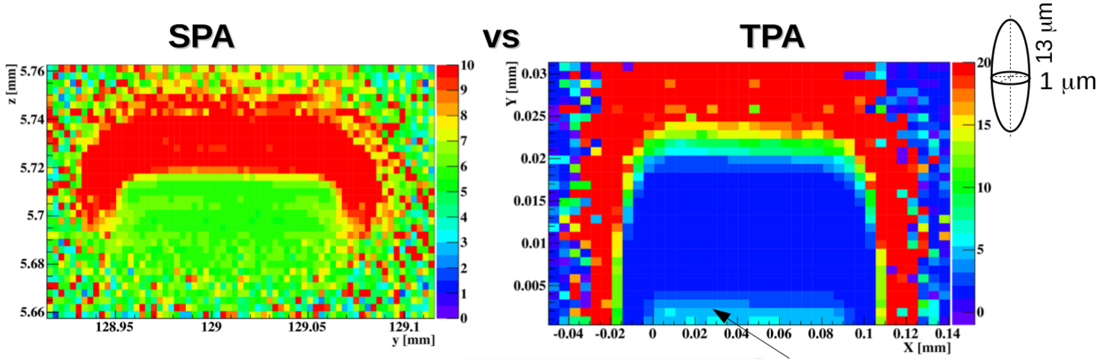
Measure:

- signal / noise
- charge collection time
- charge collection homogeneity
- electric field profile
- effective doping concentration
- ...



- Resolving sensor properties along beam direction: only possible with TPA
- Resolution perpendicular to beam ~1-2µm

- <u>Irradiated detectors tested:</u>
  defects induce SPA –Single Photon Absorption;
  correction methods have been developed
- It is planned to use setup also for <u>SEU testing</u>



deep n-well in HVCMOS
Not resolved in SPA-TCT

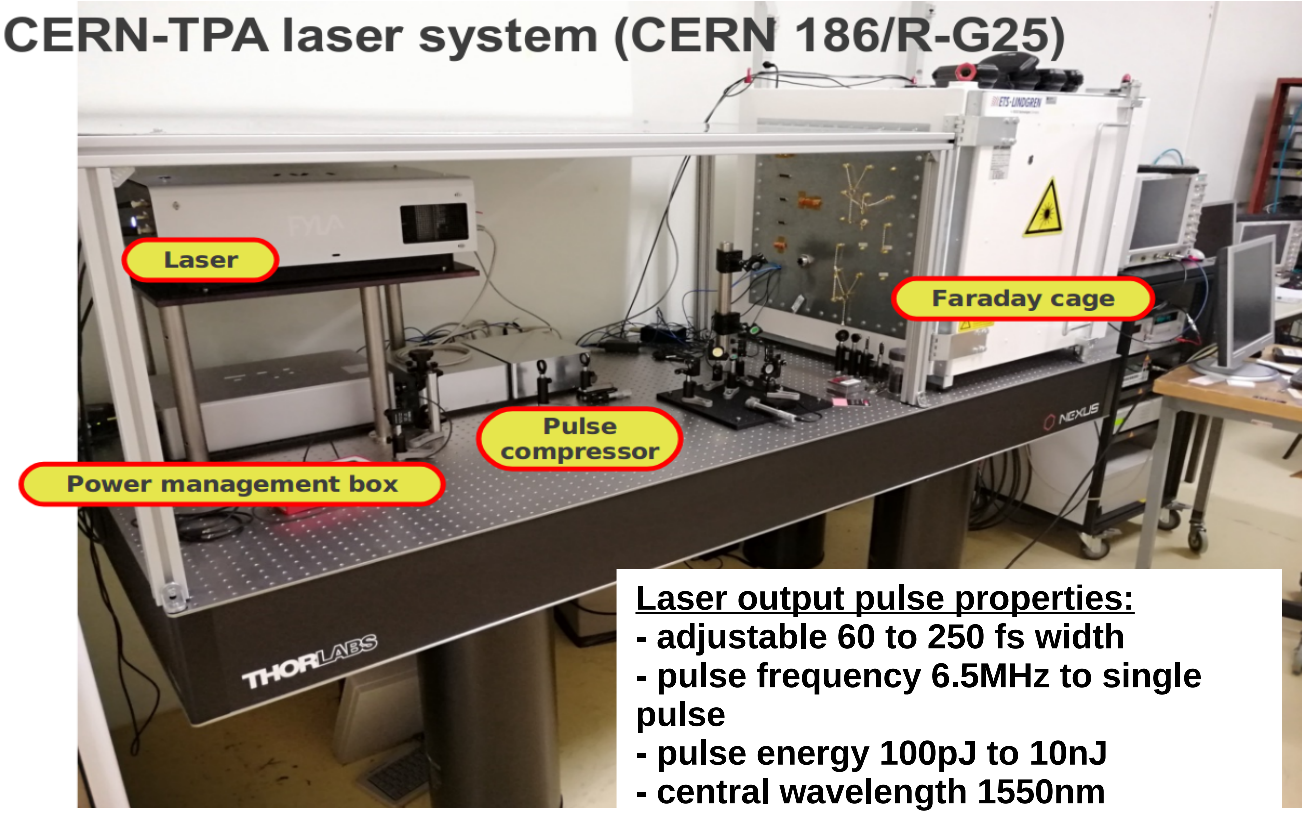
HVCMOS sensor
100 µm x 100 µm;
10 µm depleted;
Imaged by edge-TCT (left)
and TPA-TCT (right|)

TPA-TCT at CERN

2nd July 2019: delivery of laser and first signal

see also 35th RD50: *https://indico.cern.ch/event/855994/contributions/3637067/*

commissioning ongoing...



CERN-TPA laser system (CERN 186/R-G25)

Laser output pulse properties:

- adjustable 60 to 250 fs width
- pulse frequency 6.5MHz to single pulse
- pulse energy 100pJ to 10nJ
- central wavelength 1550nm

Several delays since last RD50:

- CERN Laser Safety
- Laser stability
- DUT/reference correlation

→ coupling of light to objective

- defects in pulse compressor module

Gaussian Laser Beam

Irradiance [I(r,z,t)]=J/m²s

$$I(r,z,t) = \frac{E_p}{\tau}\frac{4\sqrt{\ln 2}}{\pi^{\frac{3}{2}}w^2(z)} \exp\left[-\frac{2r^2}{w^2(z)}\right] \exp\left[-4\ln 2\frac{t^2}{\tau^2}\right]$$

Normalization of I(r,z,t) is such that

$$E_p = \int_{-\infty}^{\infty}\int_0^{2\pi}\int_0^{\infty} I(r,z,t)\, r dr\, d\phi\, dt$$

Ep: Pulse Energy

Gaussian spatial term

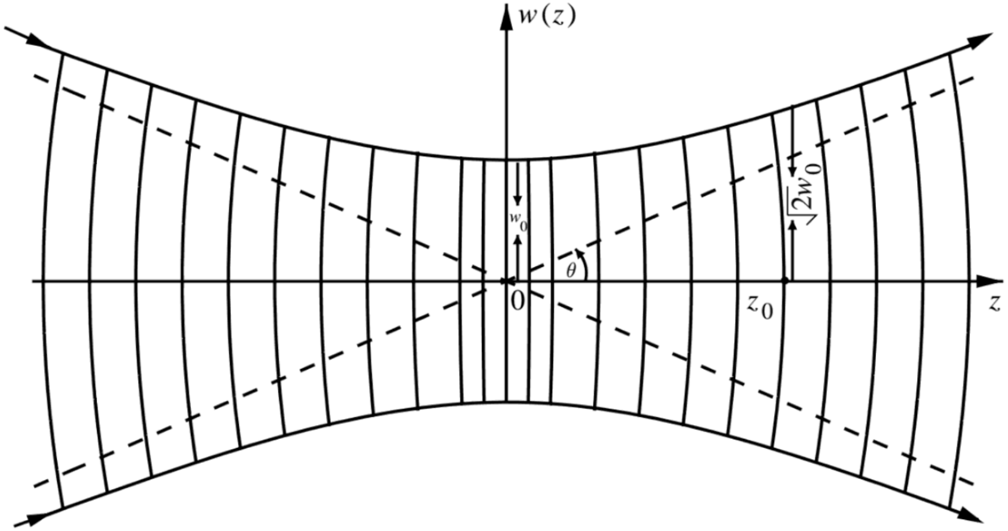
Beam radius w $w(z) = w_0\sqrt{1+\left(\frac{\lambda z}{\pi w_0^2 n}\right)^2}$

Rayleigh length z0 $z_0 = \pi w_0^2 n/\lambda$

w is the 2σ radius of the intensity profile and $w(z_0) = \sqrt{2}w_0$

Gaussian temporal term

τ = FWHM pulse temporal width



Numerical aperture defined by beam divergence

$$NA = n\sin\theta$$

beam radius w increases linearly at large z

$$\tan\theta = \lim_{z\to\infty}\frac{dw(z)}{dz} = \frac{w_0}{z_0}$$

Two Photon Absorption

Change of irradiance along beam direction **due to absorption** (SPA, TPA, free carrier absorption)

$$\frac{dI(r,z)}{dz} = -\alpha I(r,z) - \beta_2 I^2(r,z) - \sigma_{ex} N I(r,z)$$

linear Term, **SPA**
not contributing
(for unirradiated sensor)

quadratic term, **TPA**

free carrier absorption
neglected

depletion of the beam:

absorbed photons << total flux
beam depletion is **neglected**

$$I(z) = \frac{I_0}{1 + \beta_2 I_0 z}$$

creation of charge carriers:

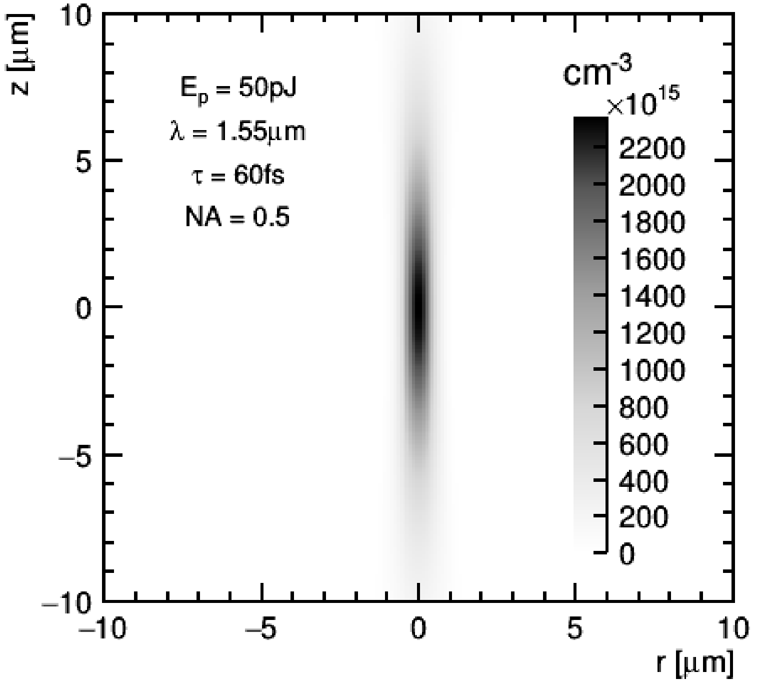
$$\frac{dn(r,z)}{dt} = \frac{\beta_2}{2\hbar\omega} I^2(r,z,t)$$

inserting irradiance (Gaussian beam),
integration over time
→ **charge carrier density**:

$$\boxed{n_{tpa}(r,z) = \frac{E_p^2 \beta_2\, 4\ln 2}{\tau\,\hbar\omega\,\pi^{\frac{5}{2}}\, w^4(z)\,\sqrt{\ln 4}} \exp\left[-\frac{4r^2}{w^2(z)}\right]}$$

spatial integration
→ **total number of charge carriers**:

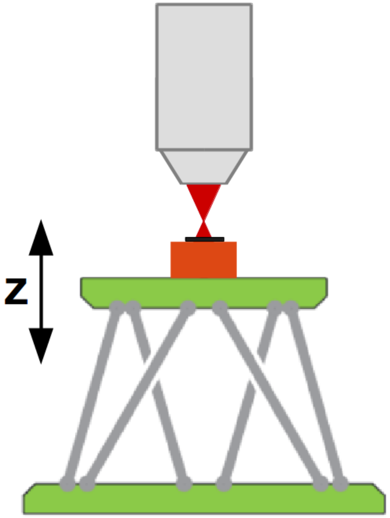
$$N_{tpa} = \int_V n_{tpa}(r,z)\, dV = \frac{E_p^2 n^2 \beta_2 \ln 2}{2\hbar c\tau \sqrt{\pi \ln 4}}$$

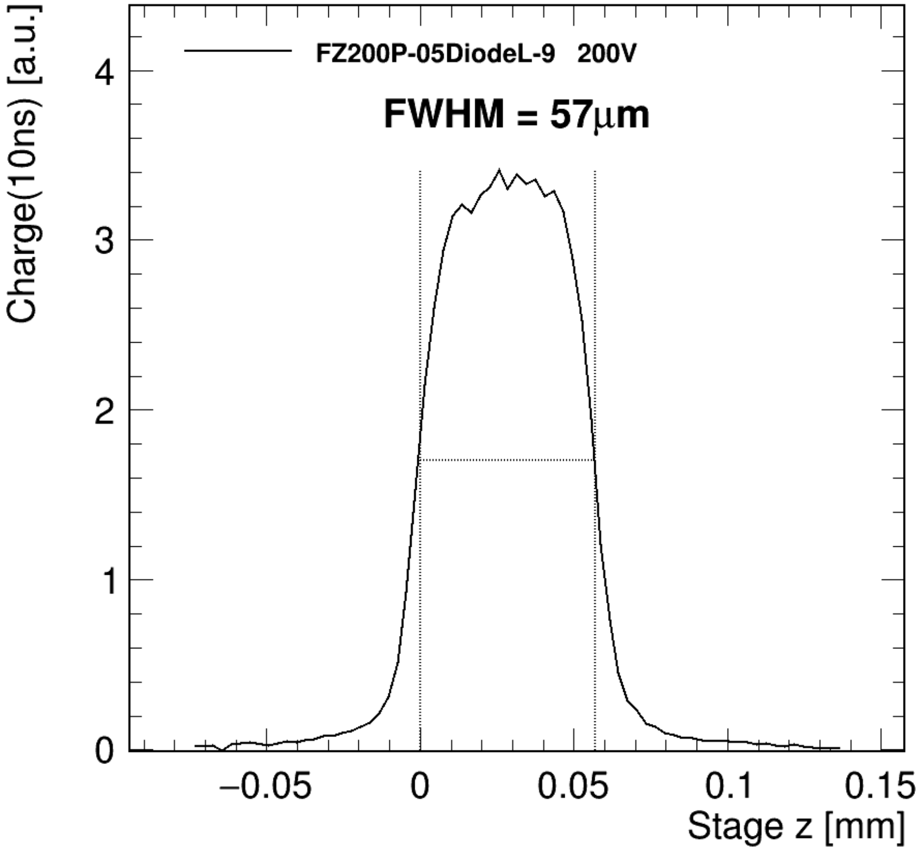


Charge carrier density in silicon β2 = 1.5cm/GW

Z-scan..

This sensor is ~200µm thick





movement of positioning stage ≠ movement of focal point

Z-scaling

I. **Refraction: Beam appears elongated** in silicon
→ Rayleigh length z0 is different in si/air

‘Scaling’ of z depends on focusing optics: NA or z0
(here z0 is the value in silicon!)

$$z' = z \cdot \sqrt{\frac{z_0 \pi n^3}{z_0 \pi n - \lambda n^2 + \lambda}}$$

derived from

$$\sin\theta = n \sin\theta'$$
$$\tan\theta' = w_0/z_0$$
$$z_0 = \pi n w_0^2/\lambda$$

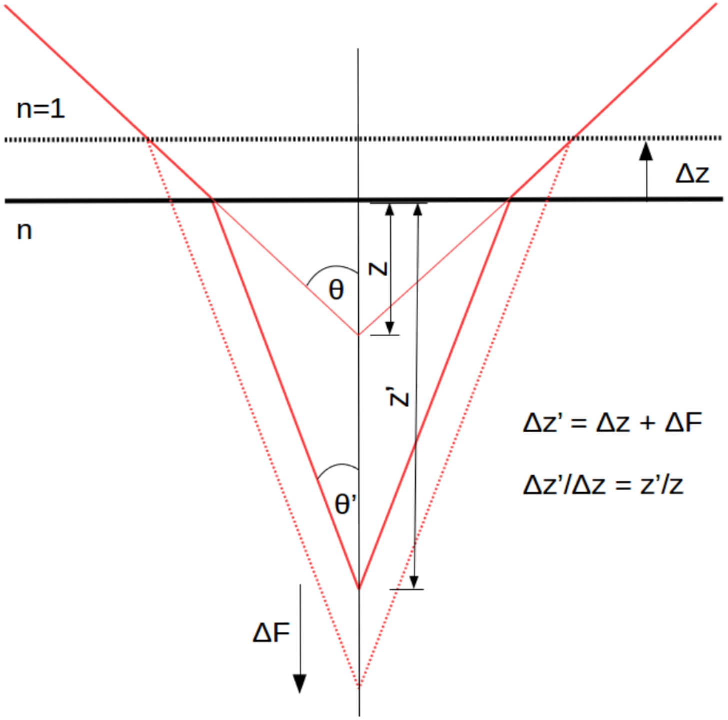
alternative using NA=n sinθ

$$z' = z\sqrt{\frac{n^2 - NA^2}{1 - NA^2}}$$

II. Stage movement by Δz
→ focal point movement ΔF

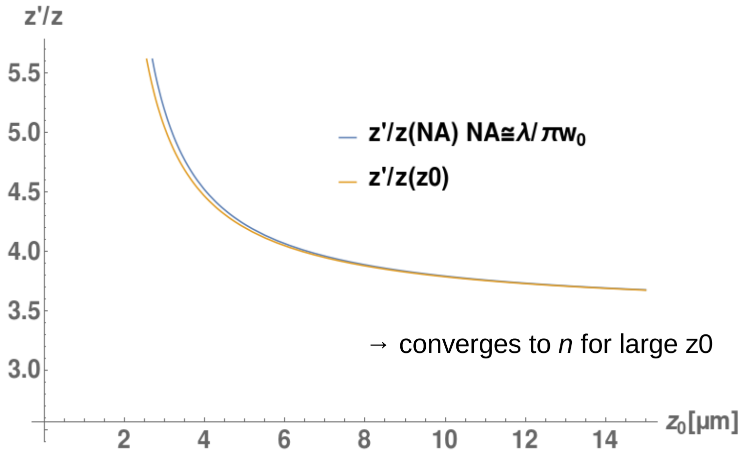
focal point to sensor surface changes by
Δz’ = Δz + ΔF

same scaling applies for Δz to Δz’ as for z to z’



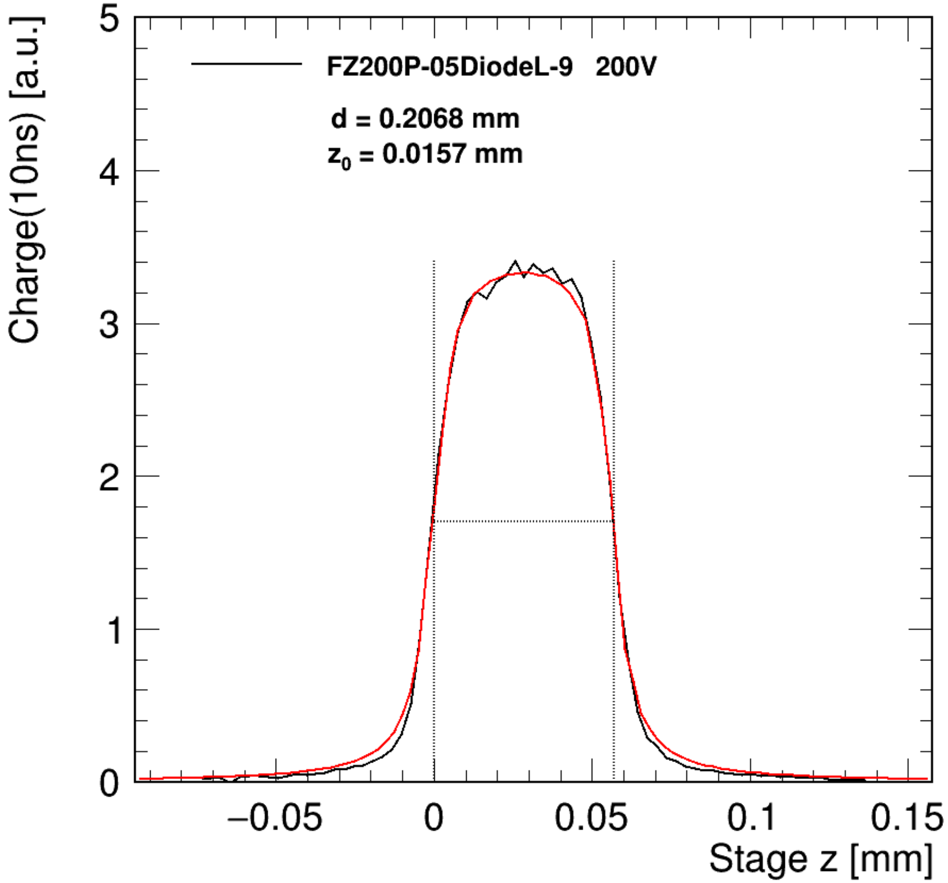
Δz’ = Δz + ΔF

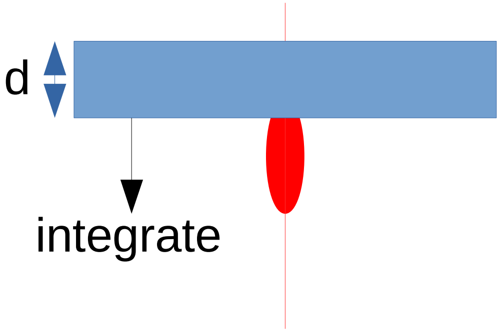
Δz’/Δz = z’/z



→ converges to *n* for large z0

Z-scan





Fit with:

$$N^d_{tpa}(z) = 2\pi \int_{z-d}^{z} \int_0^{\infty} n_{tpa}(r, z')\, r dr\, dz'$$

$$= \frac{E_p^2\, n^2\, \beta_2 \sqrt{\ln 4}}{4\, c\, \hbar\, \pi^{\frac{3}{2}}\, \tau} \cdot \left[\tan^{-1}\left(\frac{(d - z)}{z_0}\right) + \tan^{-1}\left(\frac{z}{z_0}\right) \right]$$

- account for refraction: replace z → z’
- d [mm] is sensor thickness
- z0 is the Rayleigh length in silicon

$$z' = z \cdot \sqrt{\frac{z_0\, \pi n^3}{z_0 \pi n - \lambda n^2 + \lambda}}$$

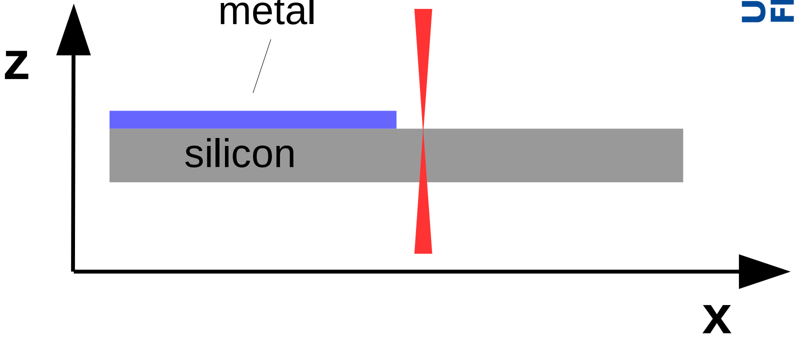
Technicality:
Horizontal axis not scaled to include z0 into fit

<u>Result</u>
d = 207µm
z0 = 15.7µm → w0 = 1.5µm
$NA = n \sin\theta \approx \lambda / \pi w_0$ = 0.33

d as expected
CV measurement: 209µm

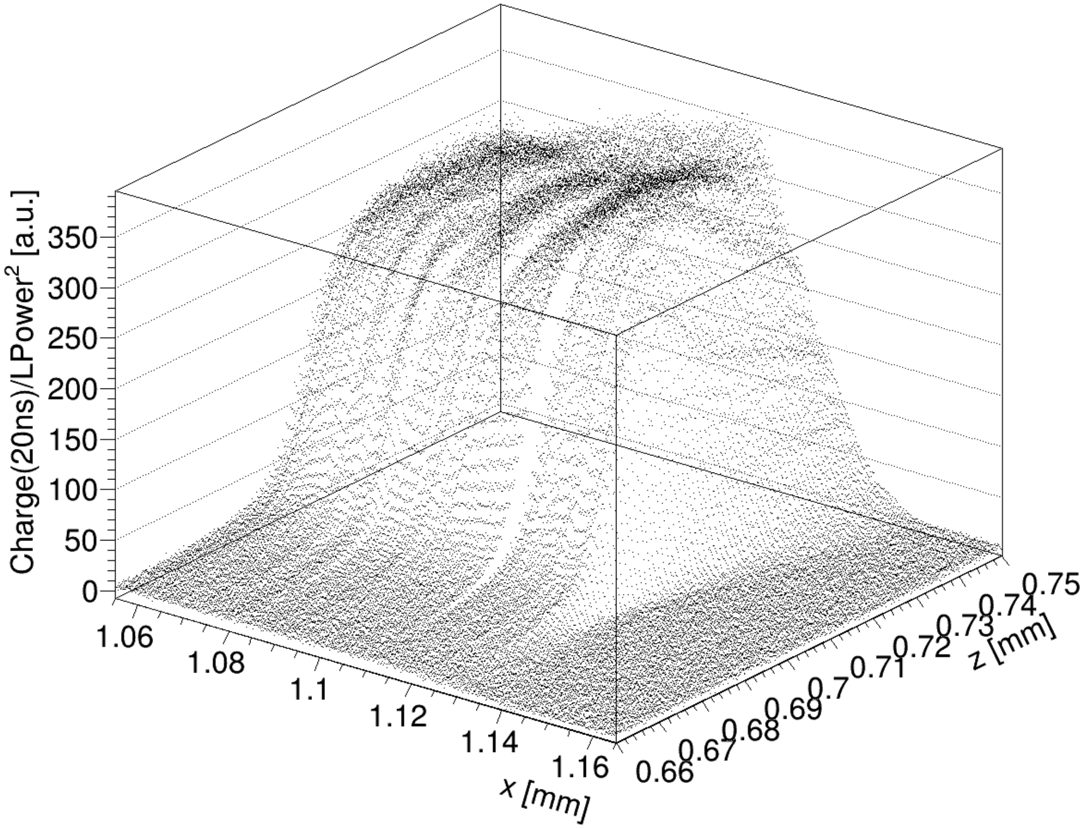
but nominal NA=0.5
→ w0 = 1µm, z0 = 6.9µm
→ focusing not as good as it could be?

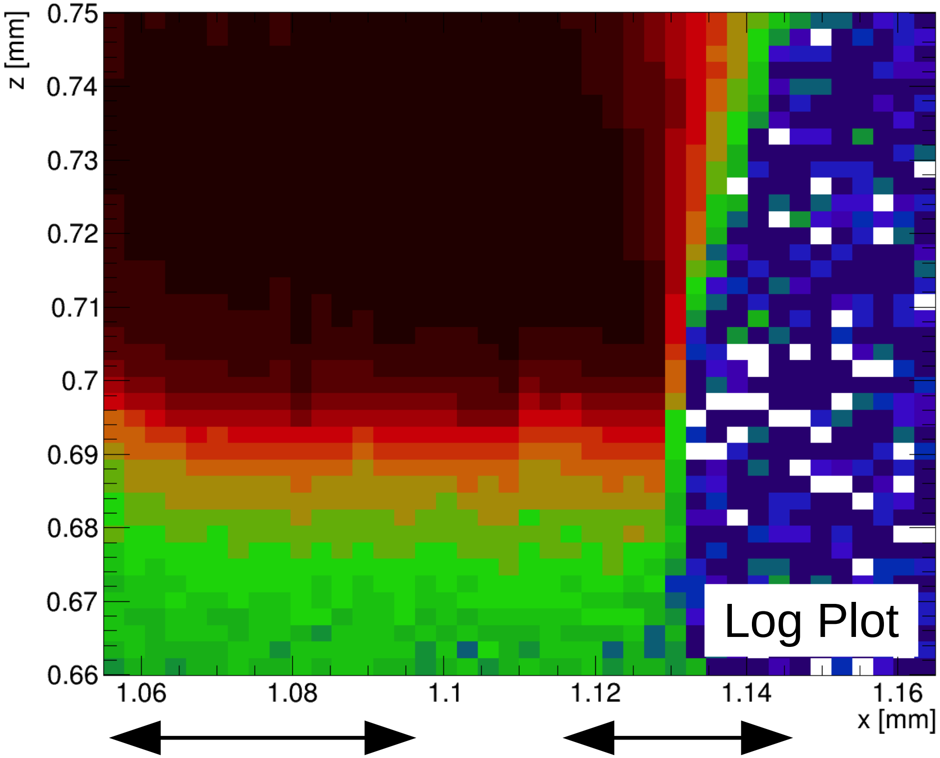
X-Z-scan



Sensor: FZ200P_05_DiodeL_9

300V bias voltage, 200Hz, 150° NDF (about 0.2nJ/pulse)
scan direction: z-scan for different x positions
x-increment: 0.2µm
z-increment: 1µm

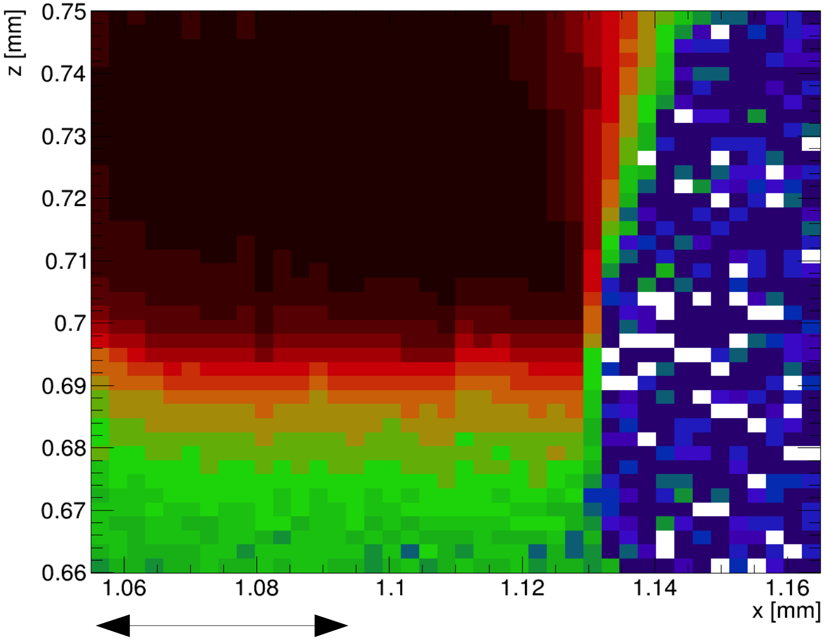




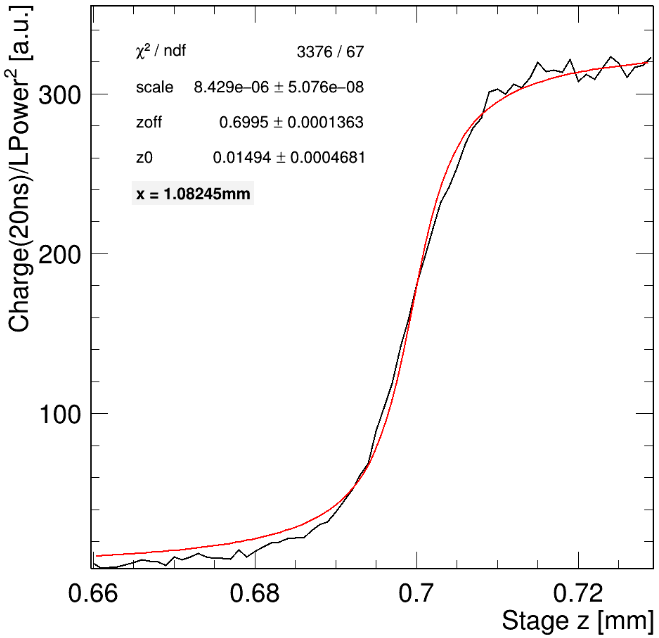
1. no metal
fit z-scans
→ obtain z0

2. metal: knife-edge
fit x-scans
→ obtain w(z)

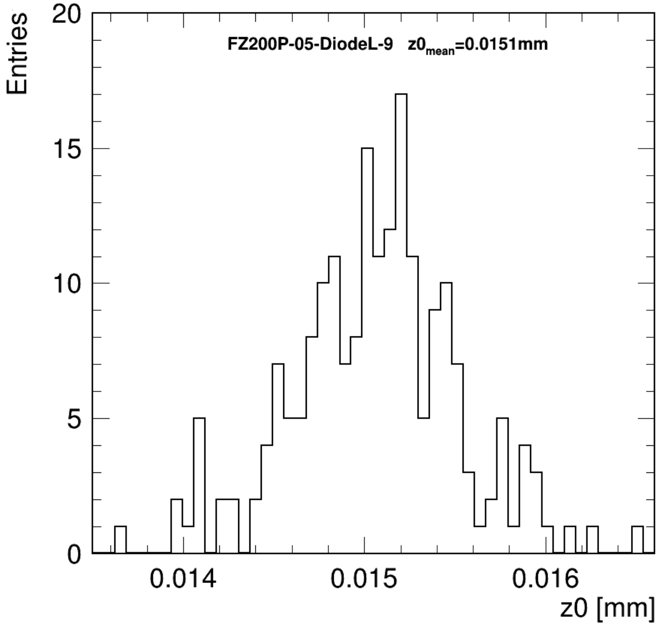
X-Z-scan – Rayleigh Length



fit each z-scan



z0 histogram



1.0550 < x < 1.0950

Range in x with beam inside active area
- correct z for refraction, z'=K*z
- fit z-scan with:

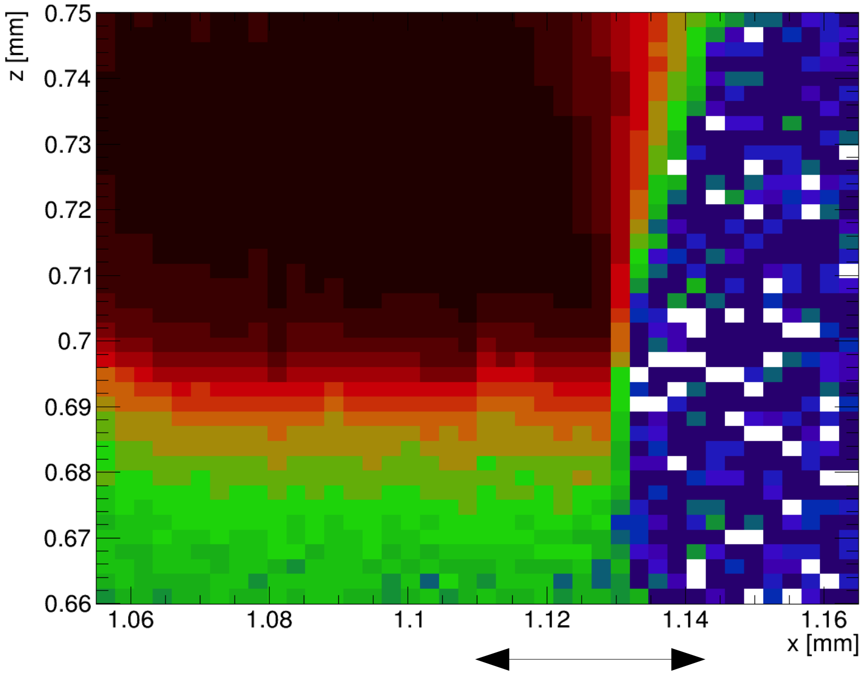
$$K = \sqrt{\frac{z_0\,\pi n^3}{z_0 \pi n - \lambda n^2 + \lambda}}$$

arctan[K*(z-zoff)/z0]

$$2\pi \int_{-\infty}^{z} \int_{0}^{\infty} n_{tpa}(r, z')\, r\, dr\, dz' = \frac{E_p^2\, n^2\, \beta_2 \sqrt{\ln 4}}{8\, c\, \hbar\, \pi^{\frac{3}{2}}\, \tau} \cdot \left[\pi + 2\tan^{-1}\left(\frac{z}{z_0}\right)\right]$$

Mean **z0 = 0.0151mm** → **NA ~ 0.34**

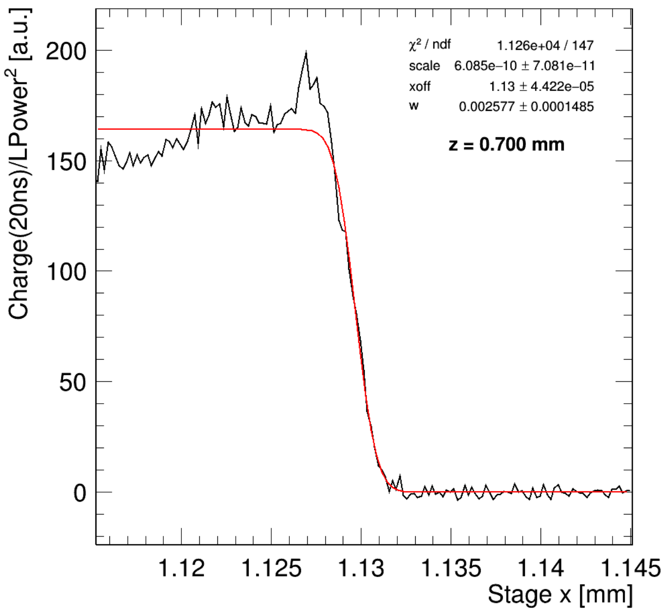
X-Z-scan – Beam Radius



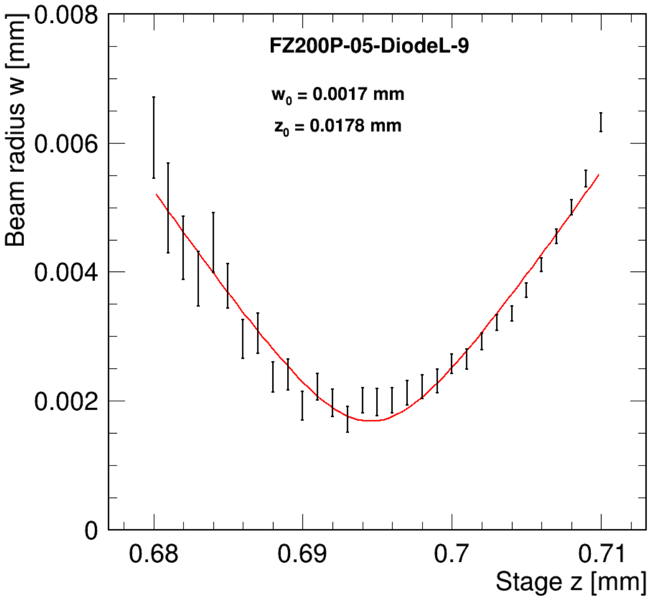
1.115 < x < 1.145

0.68 < z < 0.71

fit each x-scan



plot w(z)



Range in x at edge of active area
- fit x-scan with:

$$\int_{-\infty}^{x}\int_{-\infty}^{\infty} n_{tpa}(x',y,z)\,dy\,dx' = \frac{E_p^2\, n\, \beta_2\, \lambda \sqrt{\ln 4}}{8\, c\, \hbar\, \pi^{\frac{5}{2}}\, \tau w^2(z)} \cdot \left[1 + 2\,\mathrm{erf}\left(\frac{2x}{w(z)}\right)\right]$$

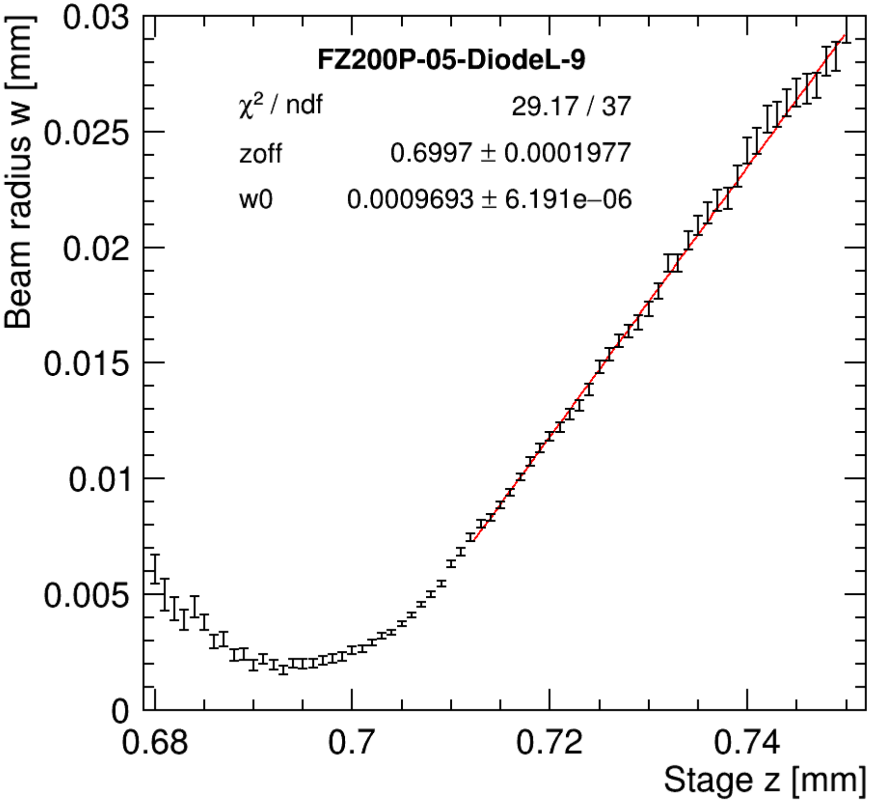
note: only 2d integral,
→ unit is Q/m

- correct z for refraction
- fit beam radius with:

$$w(z) = w_0\sqrt{1 + \left(\frac{z}{z_0}\right)^2}$$

z0 = 0.0178mm
w0 = 0.0017mm → **NA ~ 0.3**

X-Z-scan – Beam Radius



The linear part is fitted with function

$$w(z) = z \cdot \tan\theta = z \cdot \frac{w_0}{z_0} = z \cdot \frac{\lambda}{w_0 \pi n}$$

with z corrected for refraction

Fit results in w0 = 0.97µm → NA = 0.5

(note: objective nominal NA = 0.5)

<u>But not in agreement with results at focal point</u>.

Conclusions:

<u>At the focal point:</u>
- z-scans result in NA = 0.34
- beam radius at waist w0=1.7µm → NA = 0.3

<u>Some distance to the focal point:</u>
- linear increase of w with z → NA = 0.5

- Spatial distribution of charge well understood

- Behavior of laser beam well understood

- For this measurement the focusing (coupling of beam to objective) was not optimal

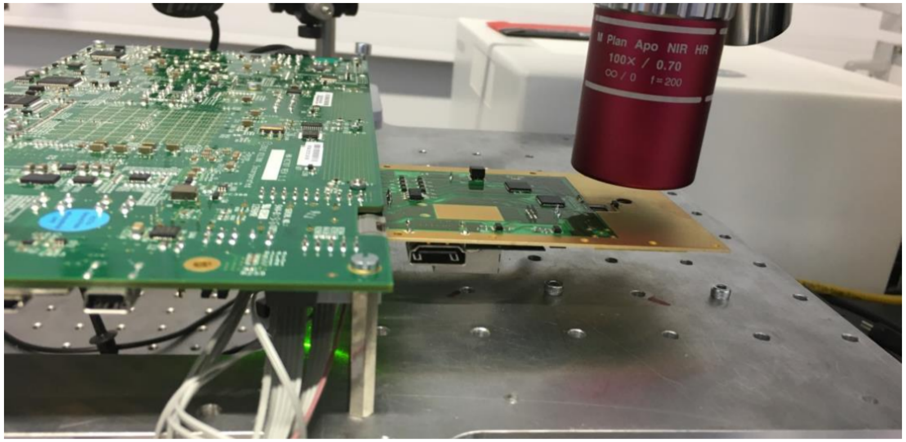
Thanks for your attention!

Additional Use-case for TPA

CERN Electronic Systems for Experiments (CERN-EP-ESE)

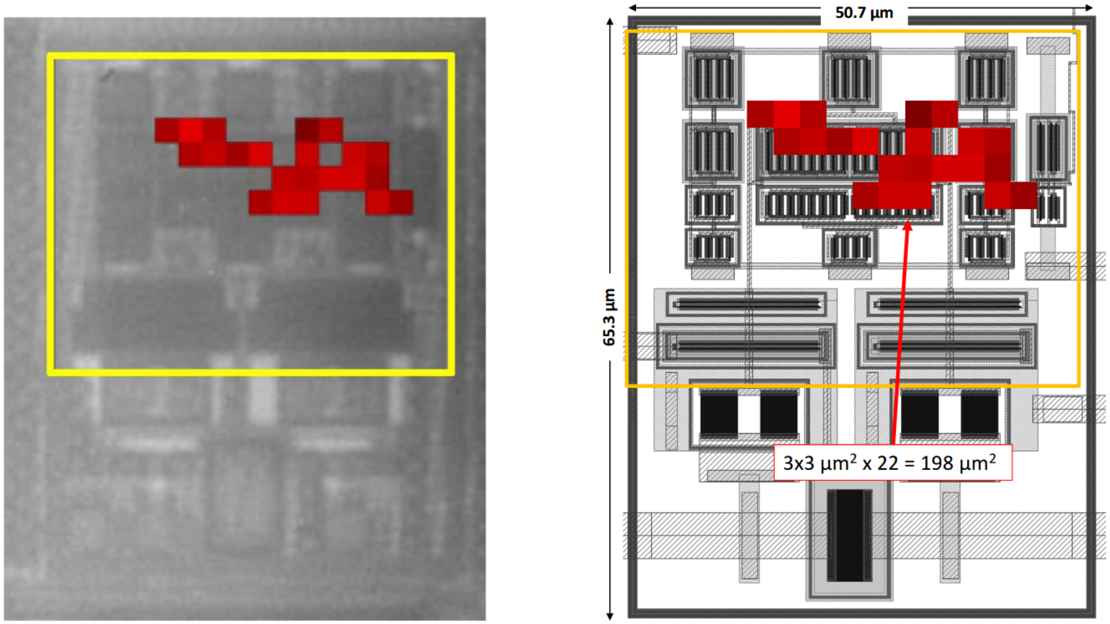
Single Event Upset (SEU) test with TPA, performing measurements in Montpellier

Can this be done at CERN with TPA-TCT-setup?



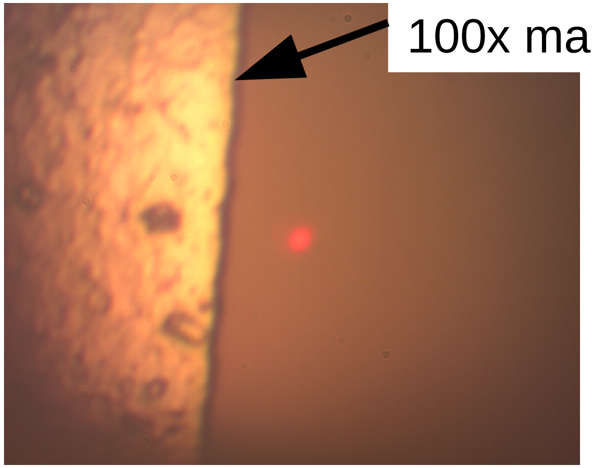
Method:
- flip electronics chip upside-down
- image chip with IR illumination/camera
- perform high spatial precision SEU test

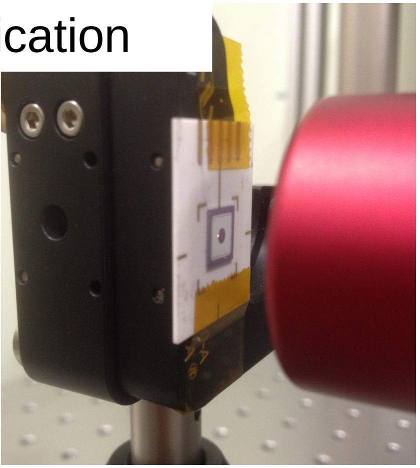
Requirement for CERN TPA-TCT-setup:
- employ IR microscopy



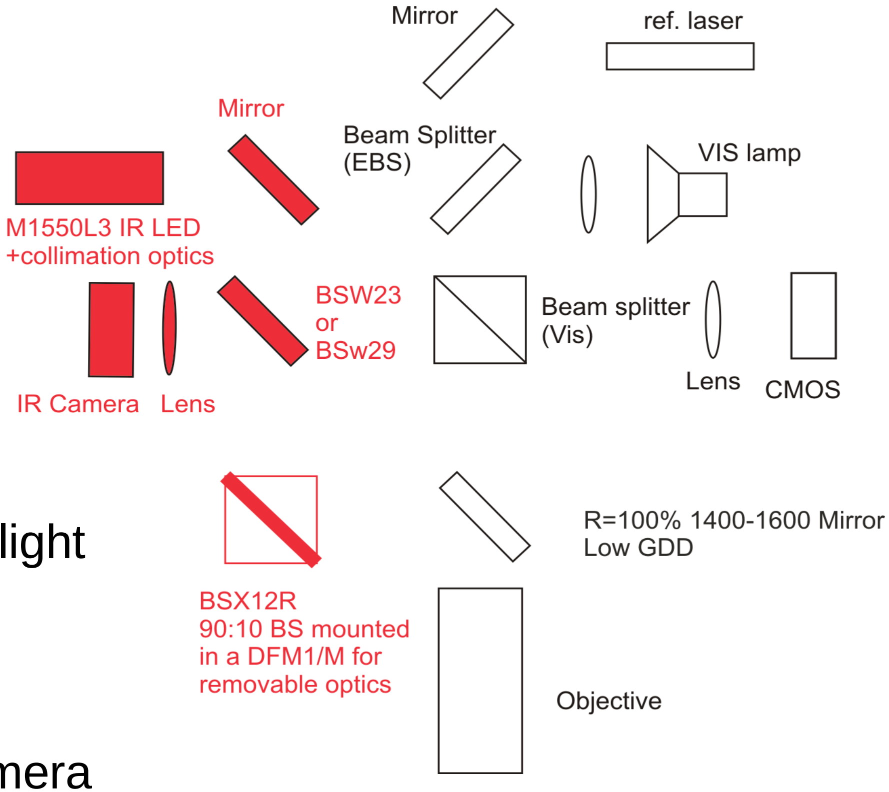
Montpellier Laser Scan Results
X. Llopart, CERN Electronic Systems for Experiments

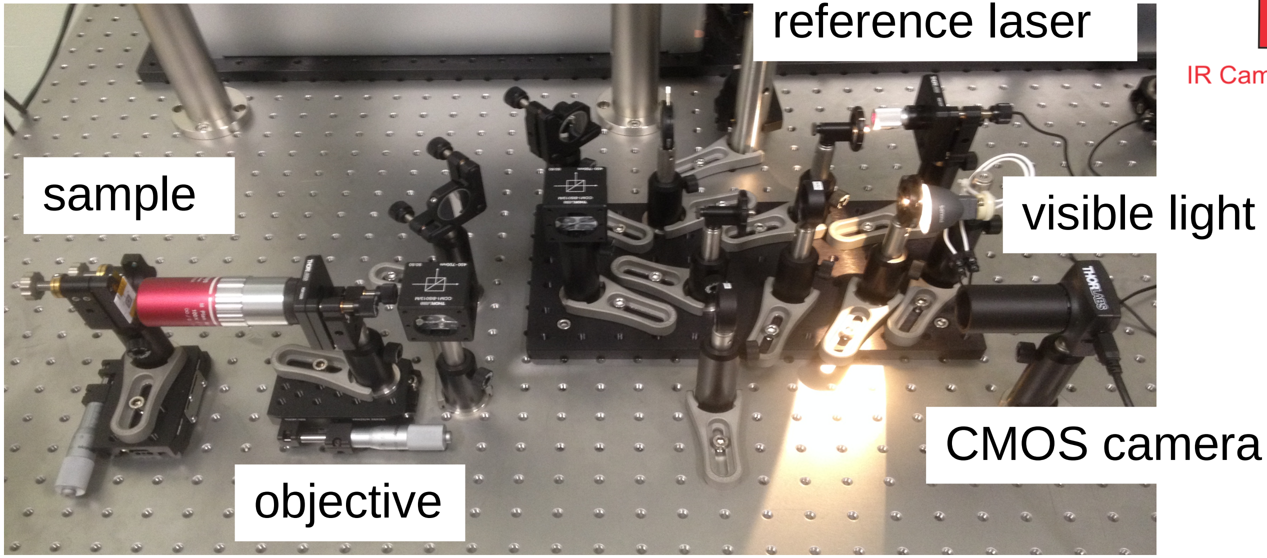
IR + VIS Microscopy





planned components for IR image in red



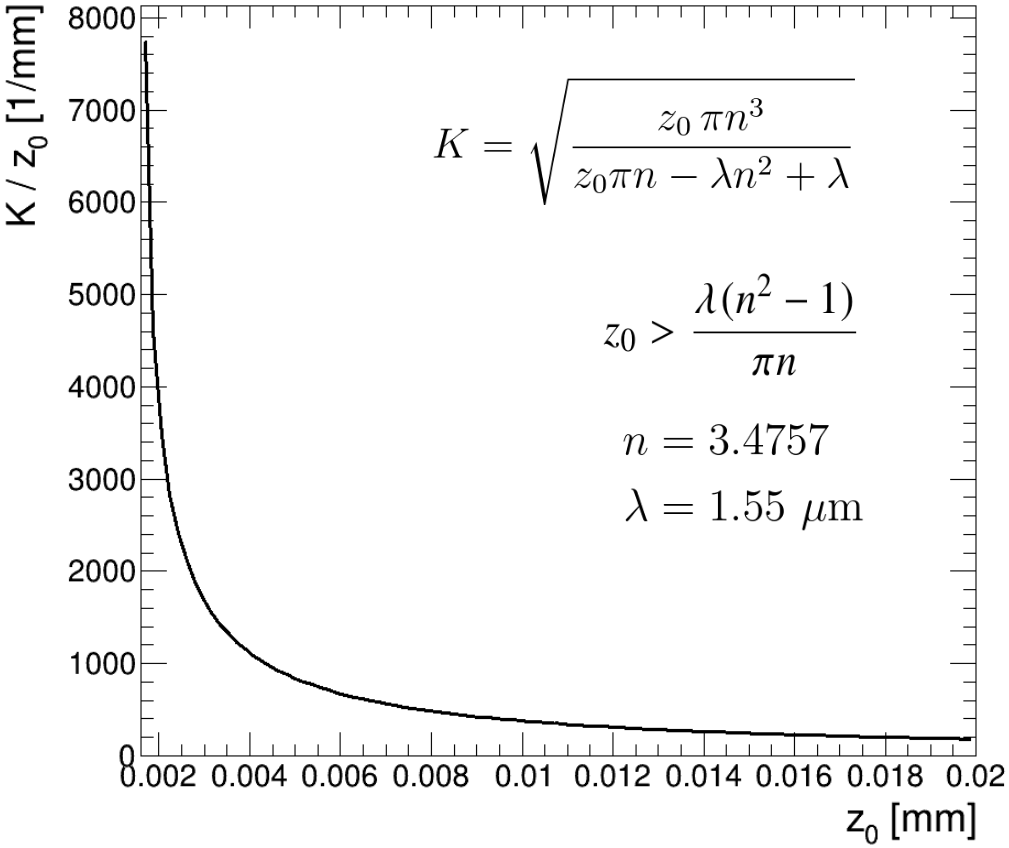


microscope setup mounted on optical table for educational purposes

Backup: z-scan fit

z0 affects
- the width of the arctan function
- the scaling of the horizontal axis

The z-scan fits are done with arctan(K*z/z0)



$$K = \sqrt{\frac{z_0\, \pi n^3}{z_0 \pi n - \lambda n^2 + \lambda}}$$

$$z_0 > \frac{\lambda(n^2 - 1)}{\pi n}$$

$$n = 3.4757$$

$$\lambda = 1.55\ \mu\text{m}$$

Can z0 be found unambiguously from a single z-scan?

Yes, since K/z0 as a function of z0 is strictly monotone.