WP4.4 - Design & Development of a New Sensor Characterization System based on TPA-TCT Technique

AIDAinnova 3rd annual meeting, 18.-21. March 2024, Catania

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1) Vienna University of Technology (TU Wien)
2) CERN

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Outline

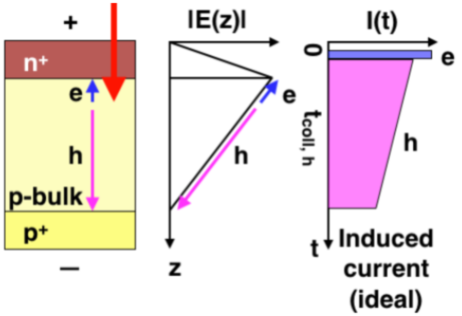
- Brief introduction to TCT and TPA-TCT
- The AIDAinnova TPA-TCT project
  - Examples of recent TPA-TCT applications
  - Measurement technique improvements
- Ongoing developments
  - A new compact TPA-TCT laser system
- Summary and Outlook

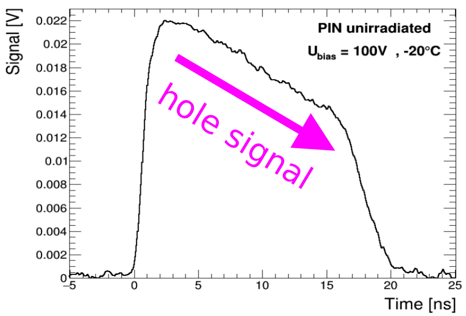
Transient Current Technique

- Transient Current Technique (TCT) for characterizing silicon sensors: pulsed laser induces generation of charge carriers
- Illumination with laser light pulse (<1ns) → recording the resulting current transient

Example 1:
mode: “top TCT”

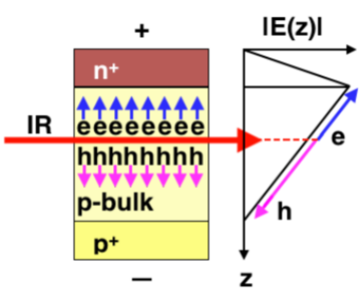
red laser
(e.g. 660nm)

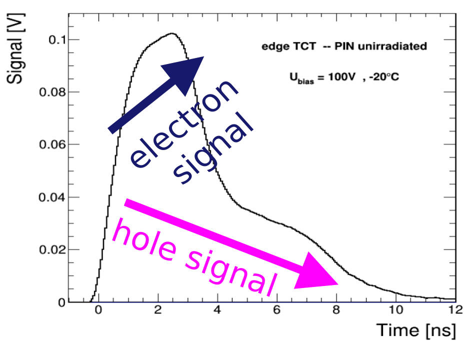




Example 2:
mode: “edge TCT”

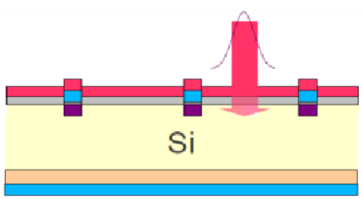
infrared laser
(e.g. 1060nm)





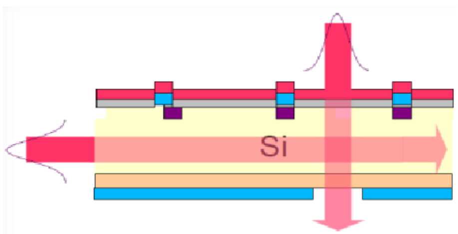
Transient Current Technique

TCT (red light)



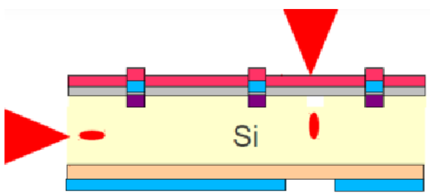
- Short penetration length (650nm = 1.9eV)
- Carriers deposited in a few µm from surface
- Front & back TCT: study electron & hole drift separately
- 2D spatial resolution (5-10µm)

TCT (infrared light)



- Long penetration (1064nm = 1.17eV)
- Similar to MIPs (though different dE/dx)
- Top and edge TCT
- 2D spatial resolution (5-10µm)

TPA-TCT (far infrared)



- No single photon absorption in silicon (1550nm = 0.8eV)
- 2 photons produce one electron-hole pair
- Point-like energy deposition in focal point
- **3D** spatial resolution (1 x 1 x 10µm)

TCT "invented": 1996

edge-TCT invented within RD50: 2010

TCT commercialized: 2013

TPA-TCT: Proof of concept presented by RD50 in 2015

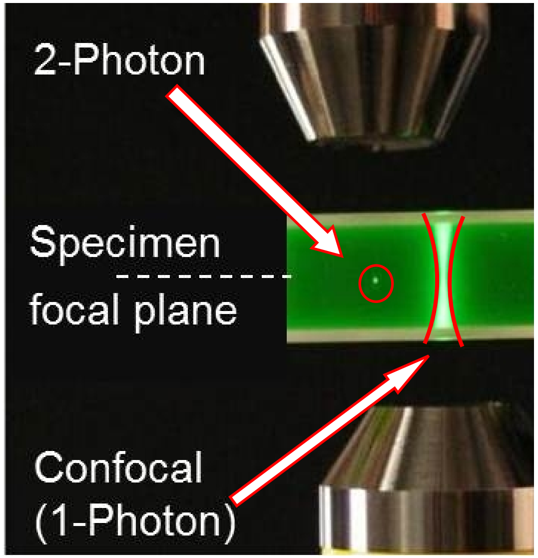
Table-top TPA-TCT laser commercialized: 2020/21

Table-top TPA-TCT system

All fiber based table-top TPA-TCT laser/system

Two Photon Absorption - TCT

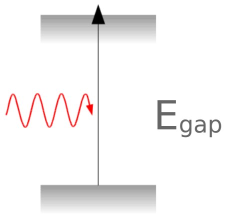
- TCT: Single Photon Absorption (SPA) – continuous energy deposition along beam
- TPA-TCT: Two Photon Absorption (TPA) – absorption only in focal point
- Energy of each photon (λ=1550nm) is smaller than the bandgap (individually they can not create an e-h pair), two photons needed to create an e-h pair



[Photo: C.Yanez, Uni of Central Florida]

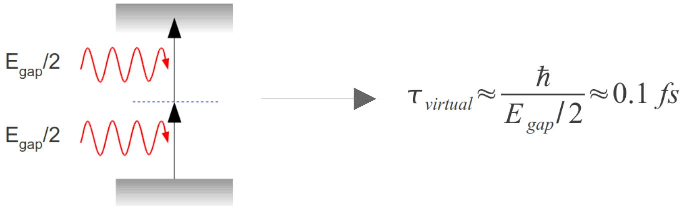
SPA:

$E_{photon} \geq E_{gap} \sim 1.12\text{eV}$



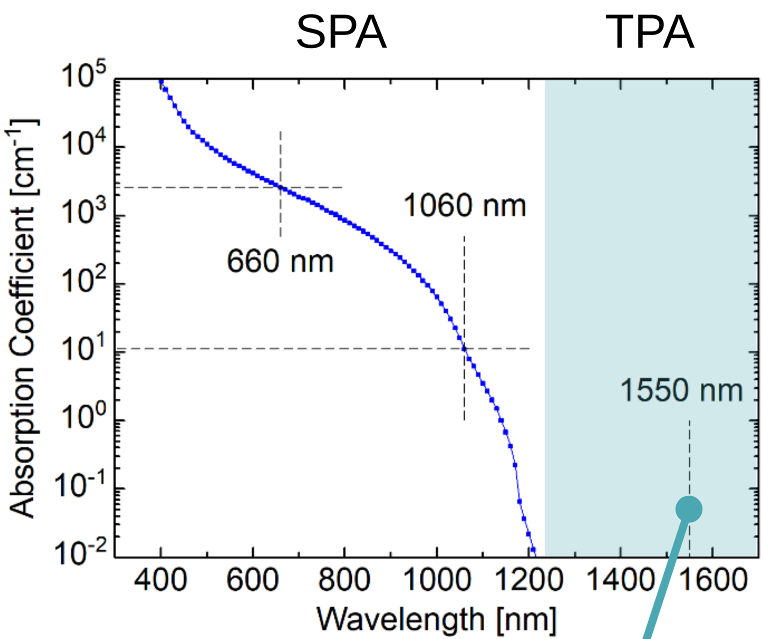
TPA:

No excitation if $E_{photon} < E_{gap} \sim 1\text{eV}$. But, if **two** photons arrive in ~100 attoseconds:



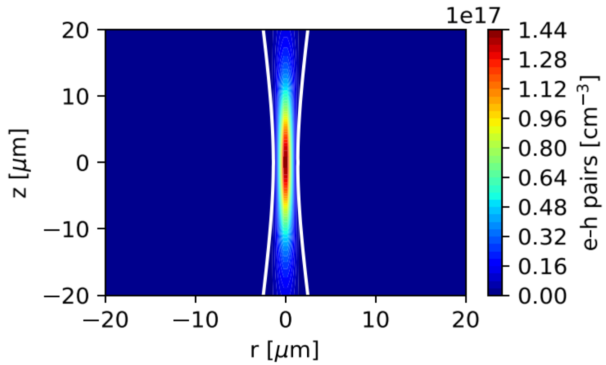
Two Photon Absorption - TCT

- SPA: Probability to create an e-h pair is proportional to ∝ I
- TPA: 2 photons are needed, the probability is ∝ I^2

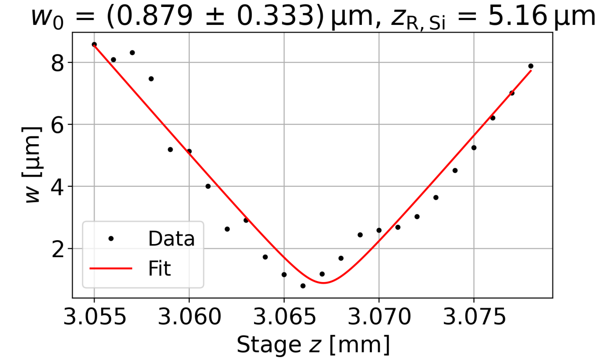


$$\frac{dI(r,z)}{dt} = -\alpha I - \beta I^2(r,z)$$

Simulation of TPA charge carrier density, λ=1550nm



Measurement:
Beam waist < 1μm
z_r~5μm



S. Pape, 38th RD50 workshop

TPA-TCT development history

- **Since 2015:** TPA-TCT measurements performed at laser facility (in Bilbao)
  - Proof of concept, demonstration of 3D resolution and feasibility to study irradiated sensors
- **2017:** CERN KT-fund approves & funds a project to develop a table-top TPA-TCT system
  - **2017-18:** development of specs, discussions with laser experts, market survey, …
    - 03/2018: Call for Tender
    - 06/2018: Order to Fyla
    - **04/2019:** 1st prototype arrived at CERN, installation problem & transport damage
    - 07/2019: 2nd delivery; installation successful, commissioning, system debugging, …
    - 10/2019: power cut damages laser, repair
    - 12/2019: replacements of components
    - 07/2020: power stability issues detected, laser returned to FYLA, upgraded
    - **01/2021:** new generation prototype delivered to CERN; since then: data taking
- **AIDAinnova WP4.4.:** further improvements

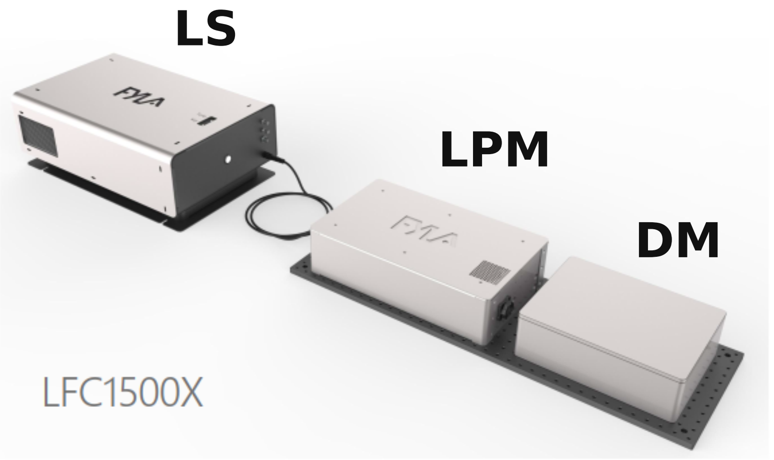
  & user community system development & all fiber laser system

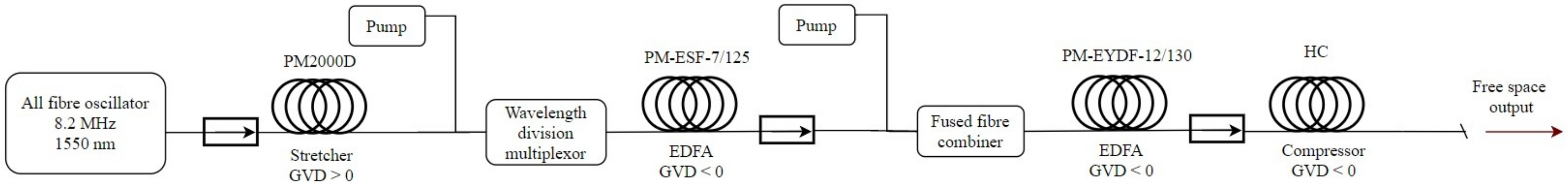
Development of FYLA LFC1500X

Laser system schematics

Modular femtosecond laser system:

- Laser Source (LS)
  - 10MHz, 1550nm, 300fs
- Laser Pulse Management (LPM)
  - 10pJ - 10nJ, 10MHz to single shot
- Dispersion management (DM)
  - 300 – 600fs, pulse characterization





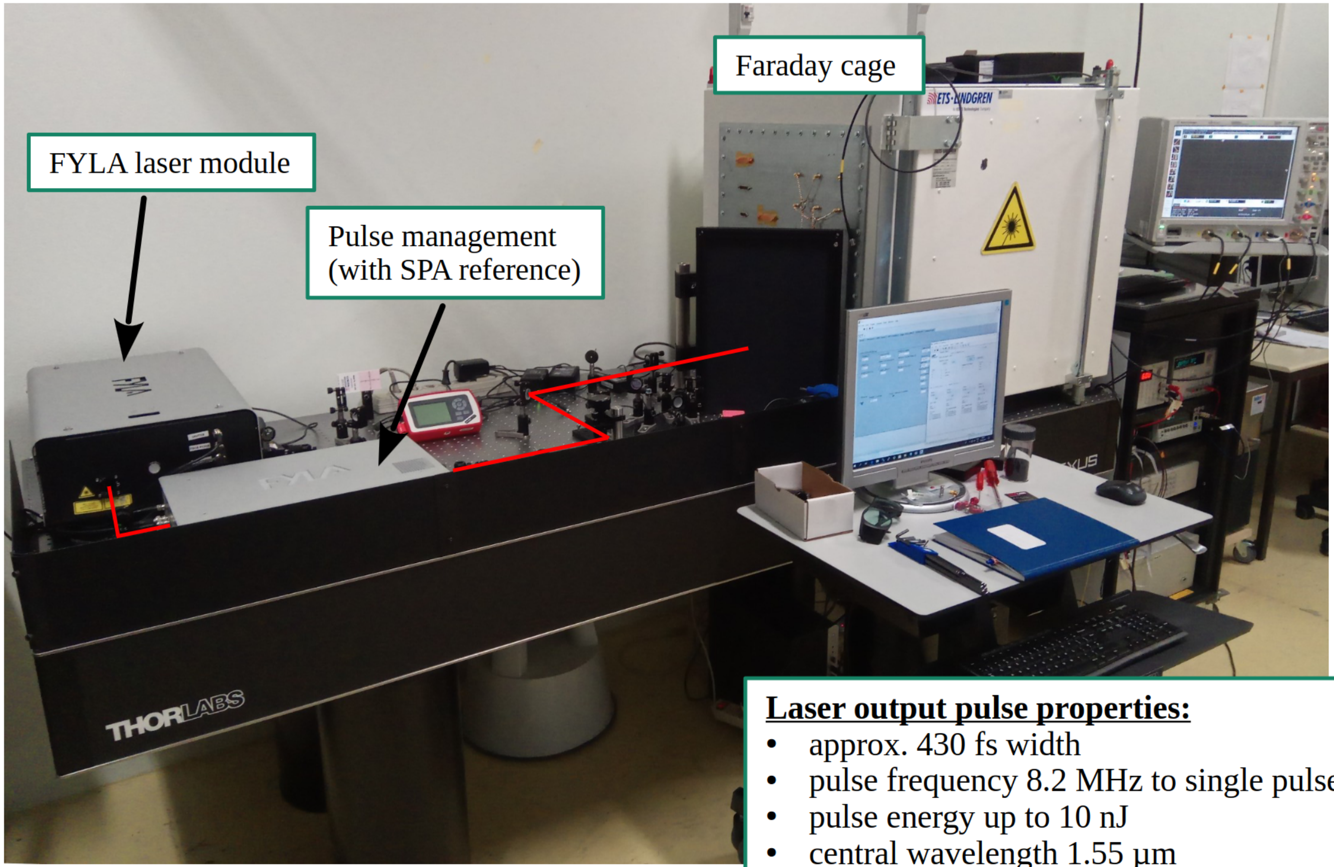
Details:

Fiber Laser System of 1550 nm Femtosecond Pulses with Configurable Properties for the Two-Photon Excitation of Transient Currents in Semiconductor Detectors; *Azahara Almagro-Ruiz, Sebastian Pape, Hector Muñoz, Moritz Wiehe, Esteban Curras Rivera, Marcos Fernández-García, Michael Moll, Raúl Montero Santos, Rogelio Palomo, Cristian Quintana, Iván Vila Álvarez, Pere Pérez-Millán;* Applied Optics 61, 9386-9397 (2022); https://doi.org/10.1364/AO.470780

TPA-TCT at CERN SSD (EP-DT)

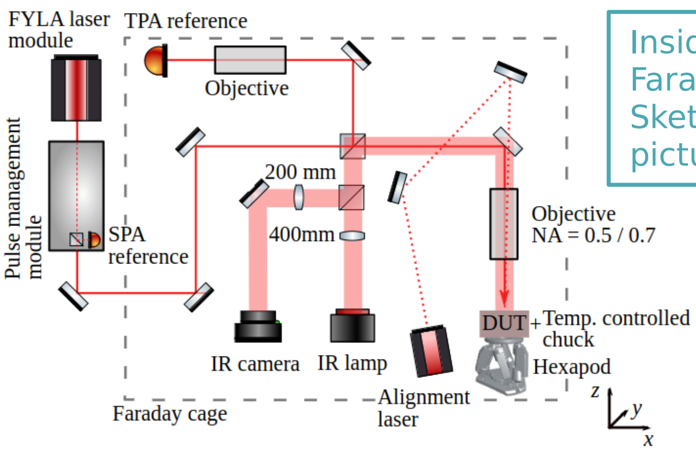
- **CERN:** TPA-TCT at the Solid State Detectors (SSD) lab of the EP-DT group (Laser laboratory with interlocked access and personal protection equipment)

[M.Wiehe et al.: Development of a Tabletop Setup for the Transient Current Technique using Two-Photon Absorption in Silicon Particle Detectors, IEEE TNS, Vol.68, Issue.2, Feb.2021, pages 220-228]



Laser output pulse properties:
- approx. 430 fs width
- pulse frequency 8.2 MHz to single pulse
- pulse energy up to 10 nJ
- central wavelength 1.55 µm

TPA-TCT at CERN: Calibration



Inside the Faraday cage: Sketch and picture

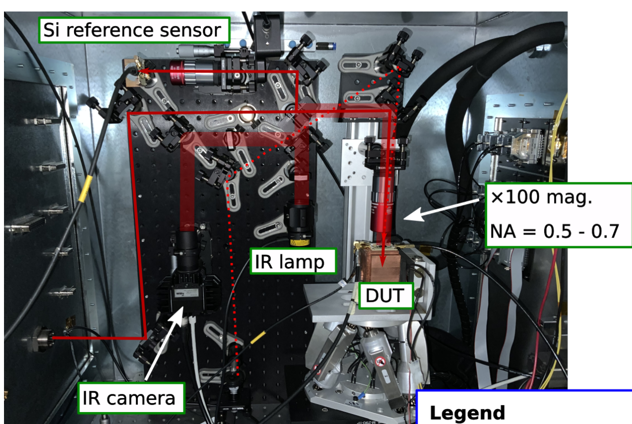
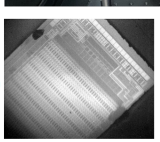
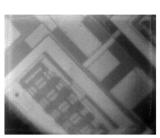


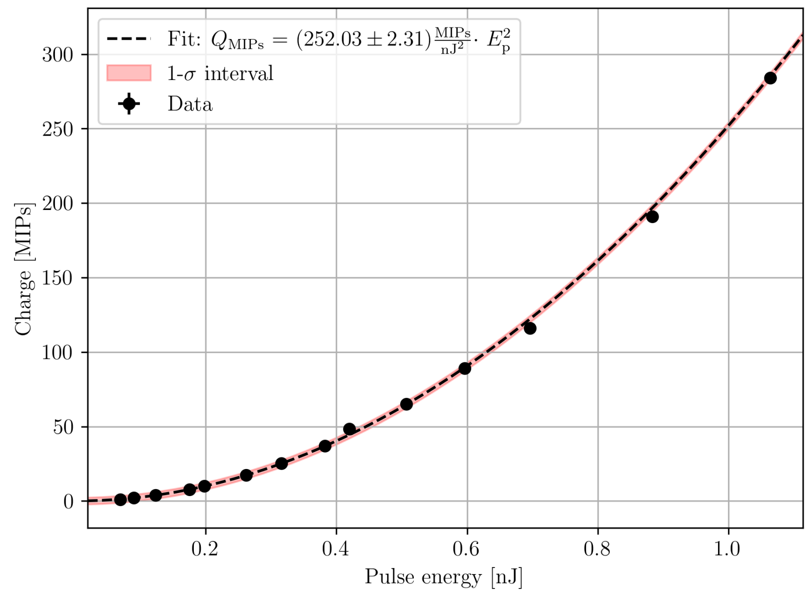
image from rear through bulk



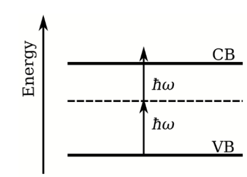


Calibration against MIP (^{90}Sr):

- Pulse energy against generated charge (285µm PIN; NA = 0.5 at 20°C and 0% humidity)
- The pulse energy is measured with a S401C thermal power sensor from Thorlabs.



$$\frac{dI(r,z)}{dt} = -\cancel{\alpha I} - \beta I^2(r,z)$$



AIDA innova

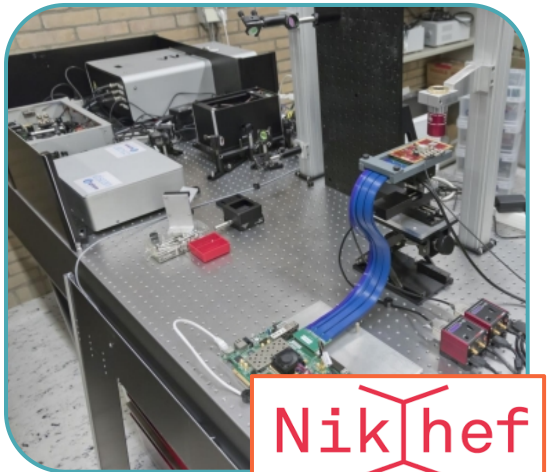
TPA-TCT at other institutes

TPA-TCT systems with the LFC1500X or new “Pulsar” laser system at several institutes:

CERN

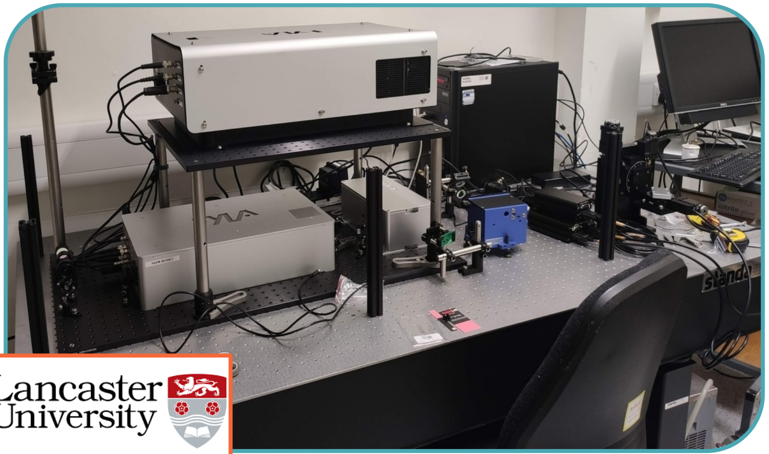
UNIVERSITY OF OXFORD

(In setup phase)

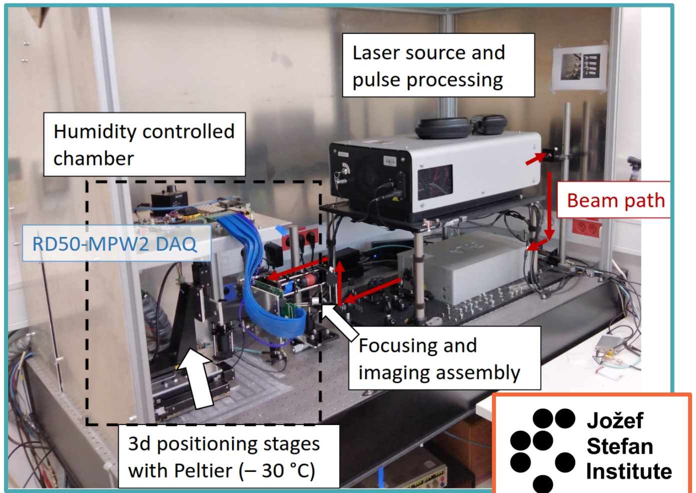


Nikhef

IFCA



Lancaster University



Jožef Stefan Institute

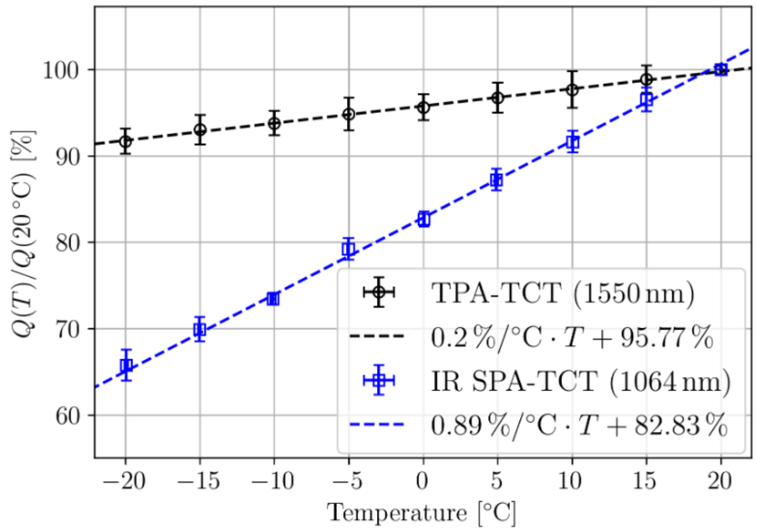
Examples of recent TPA-TCT applications & Measurement technique improvements

Influence of temperature on TPA-TCT

- Charge generation decreases with temperature
  - Less phonons available
  - Increasing band gap (~1meV)
  - Change in refractive index: n(-23°C)/n(20°C) = 99.8% → negligible
- Dependence is sensitive to wavelength
- Charge generation is given by:

$$Q_{TPA}(T) \sim n_{Si}(T)\beta_2(T)$$

$$Q_{SPA}(T) \sim (1 - \exp(-\alpha(T) \cdot d))$$



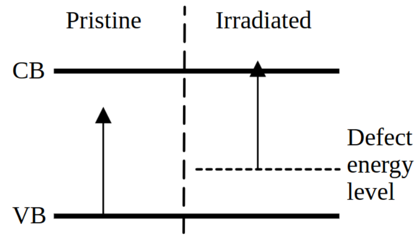
Charge collection efficiency measured with SPA- and TPA-TCT at different temperatures.

- Temperature dependence in relevant for measurements of irradiated samples (measured at -20°C to decrease the leakage current)

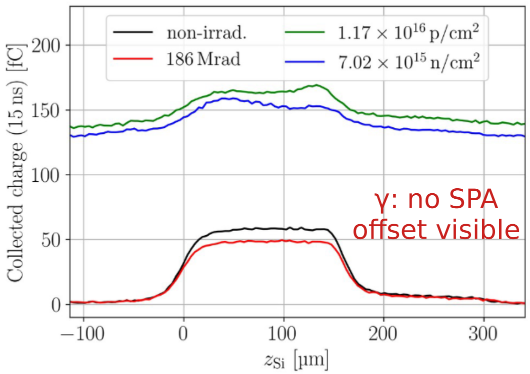
Influence of temperature on measurements of the Two Photon Absorption – Transient Current Technique in silicon planar detectors using a 1550 nm femtosecond fibre laser; S. Pape at al., 2023, https://doi.org/10.1016/j.nima.2023.168387

Influence of radiation damage on TPA-TCT

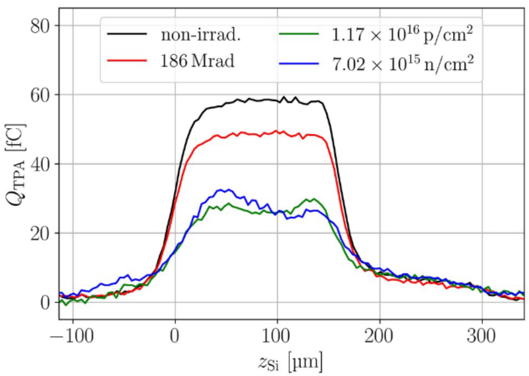
- Radiation damage can introduce new energy levels in the band gap that trap charge carriers
- Trapped charge carriers can be excited by a single 1550nm photon
- This enables a parasitic single photon absorption component to the TPA-TCT measurement (SPA component is found as a offset, as it is not depth dependent $Q_{SPA}(z)$ = const.)



Systematic study of influence of radiation damage on the TPA-TCT
→ n, p, γ



→ SPA corrected



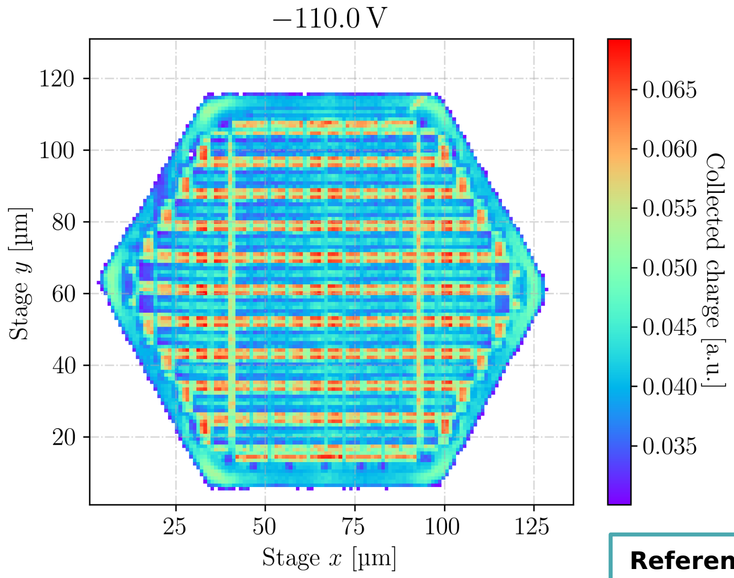
Plot from S. Pape Thesis (2024)

- Increasing hadron irradiation increases the SPA background, γ does not
- **SPA background probably related to NIEL!**

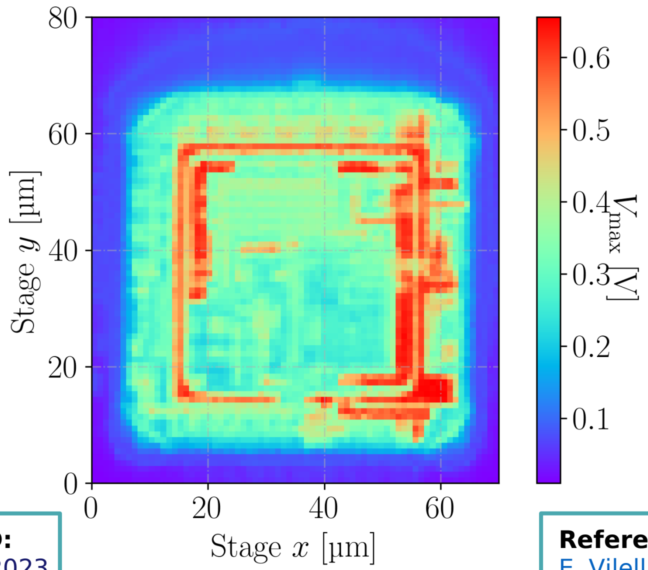
S. Pape, 43rd RD50 workshop

TPA-TCT as high precision scanning tool

- The examples show the probing of the top side metals of monolithic detectors. Regions with metal have an increased charge collection due to reflection.
- Features in the µm scale are well resolved (~60 x 60µm² pixels)!



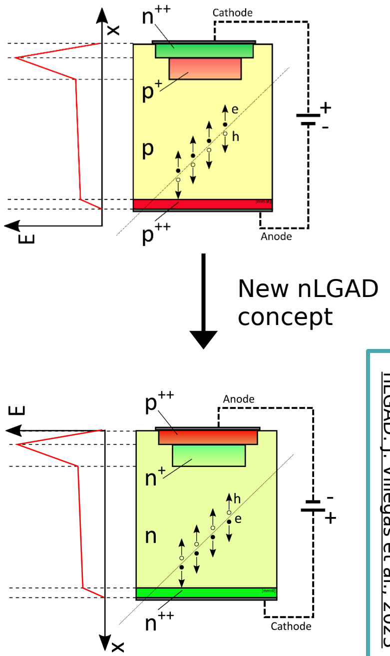
Reference PicoAD:
M. Milanesio et al. 2023
R.Cardella et al. 2022



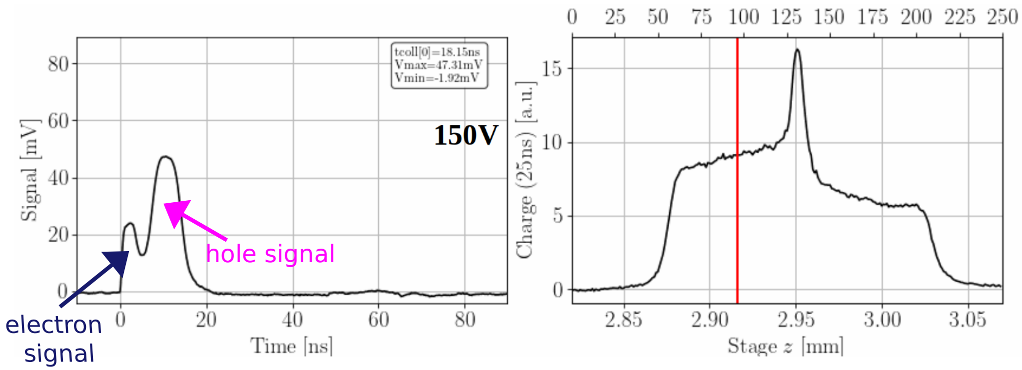
Reference MPW2:
E. Vilella 2022

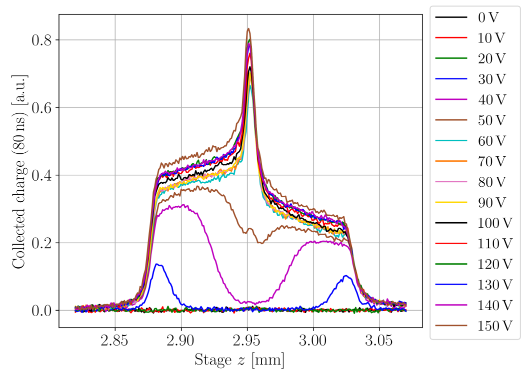
TPA-TCT testing of nLGADs

- Low Gain Avalanche Detectors (LGAD), implemented as $n^{++}-p^{+}-p$, show outstanding performance when detecting high-energy charged particles
- Due to the difference in multiplication mechanism for holes and electrons, the detection performance for low penetrating particles (e.g low-energy protons or soft x-rays) is significantly reduced
- A novel design of an LGAD detector, the nLGAD, was designed and fabricated at CNM and first tested at CERN with the TPA-TCT



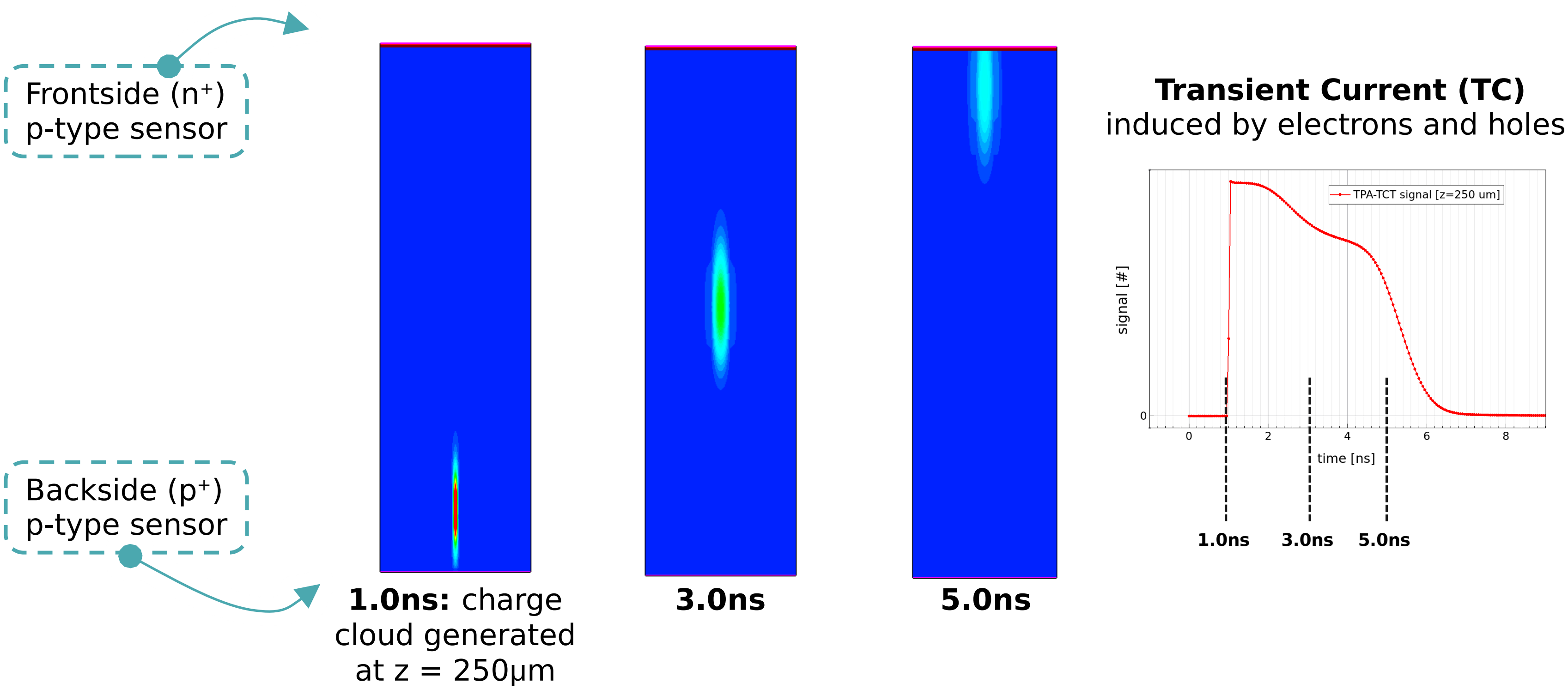
nLGAD: J. Villegas et al., 2023





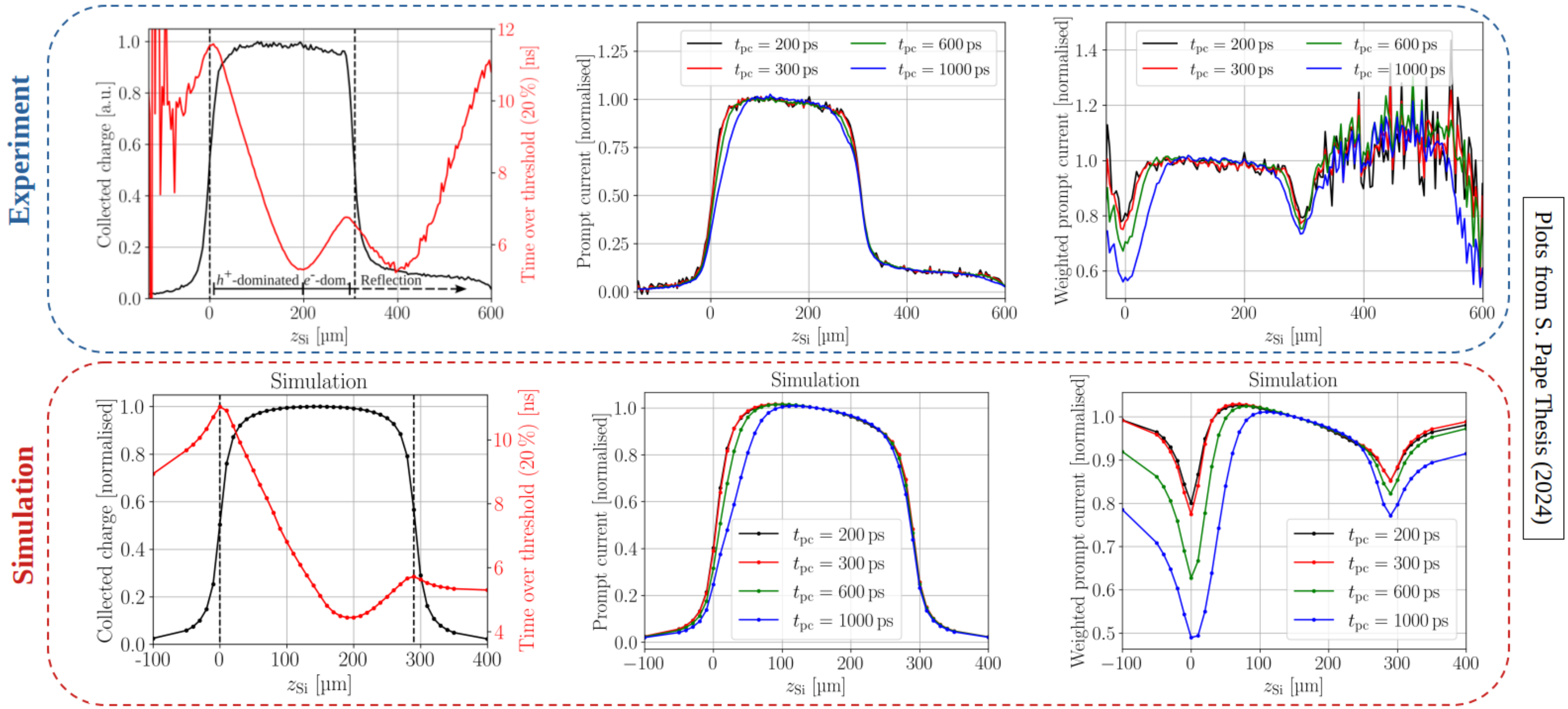
Advances in TCAD simulations

- Simulation of TPA-TCT
  - Charge cloud generated around focal depth of 250μm at t=1ns
  - Visualisation of electron cloud moving through PIN detector (holes not shown)



Advances in TCAD simulations

- Comparison of data extracted from experimental current transients versus data extracted from simulated transients taken on a 300µm thick PIN sensor

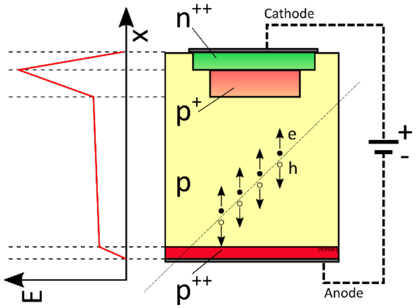


Advances in TCAD simulations

- Gain suppression in LGADs:
  - The gain in Low Gain Avalanche Diodes (LGADs) depends on the charge density entering the Gain Layer (GL)
  - **Low charge density** in GL: negligible gain suppression

    High charge density in GL: drop in the E-field (less amplification)

    → reduction in the gain
  - Effect relevant for characterization and operation of LGADs for the HL-LHC ATLAS/CMS timing experiments

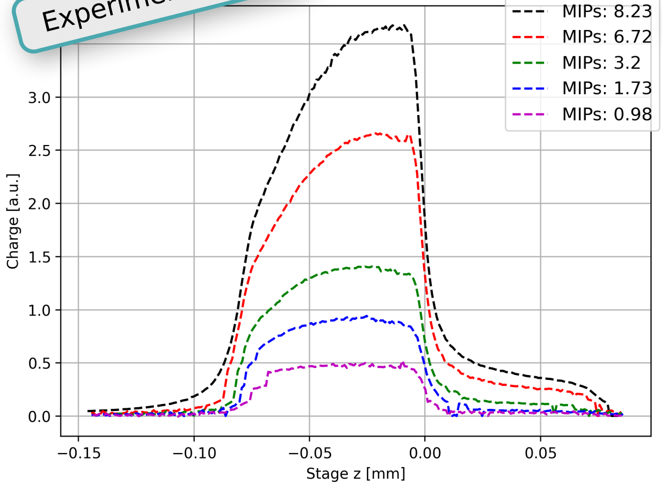


TPA-TCT measurements and simulations on CNM 8622 devices (illumination from top)

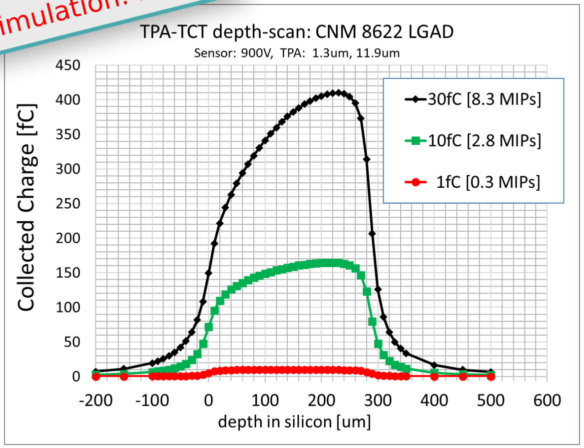
M. Moll, 43rd RD50 Workshop

Experiment: LGAD

1 MIP ≈ 3.6fC



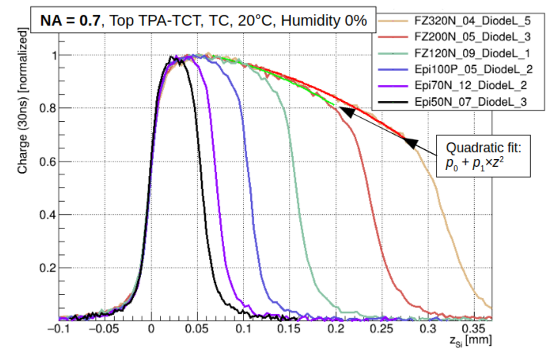
Simulation: LGAD

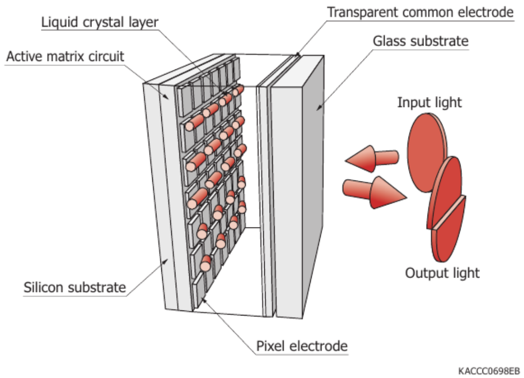


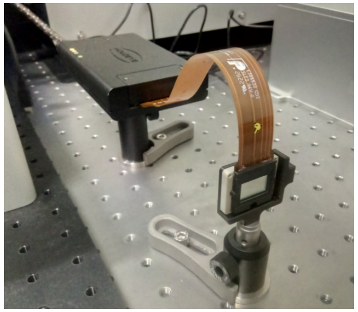
Spatial Light Modulation

- Radiation hardness demands thin detectors, the longitudinal resolution in TPA is improved using objectives with NA>0.5 (=TPA baseline)
- Using highly focusing objectives (NA=0.7) for thin devices, spherical aberration occurs
- Dynamic aberration correction via a Spatial Light Modulator (SLM)
- An applied voltage to a pixel changes it's refractive index:
  - The Phase front of the beam can be changed
  - In many applications in industry and science, micro-machining, microscopy, optical tweezers, etc., SLMs are used to improve the beam quality
- **Status at CERN SSD:**
  - Holoeye PLUTO-2.1-TELCO-142 Phase only LCOS SLM,

    1920 x 1080 pixels, 8µm pitch, 15.36mm x 8.64mm active area, 256 phase levels
  - Purchased and delivered
  - Commissioning started

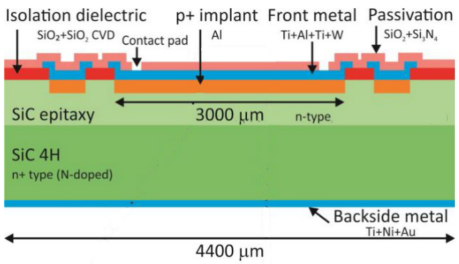


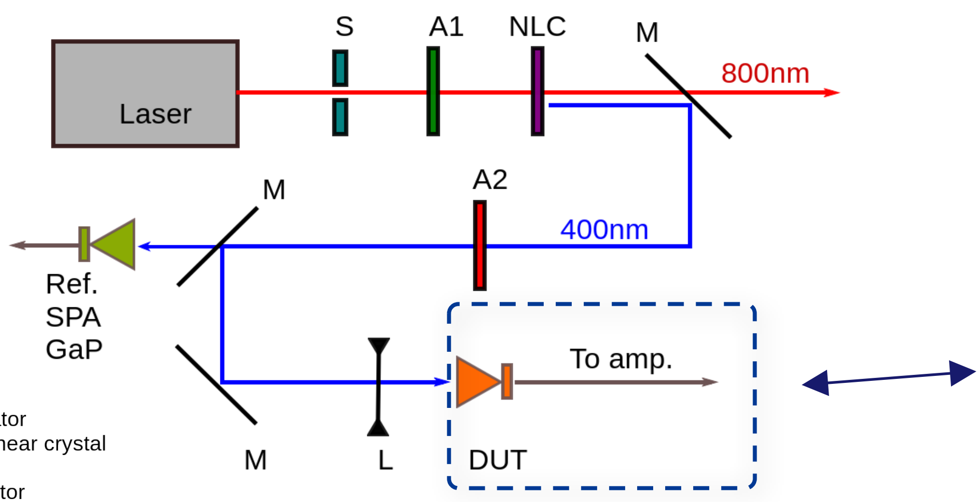




TPA-TCT testing of SiC

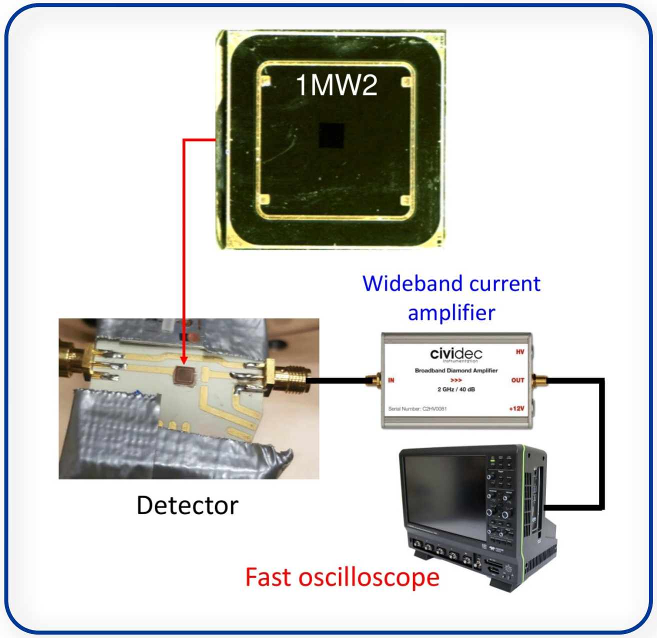
- Extension of TPA-TCT to other semiconductors
  - Si (1.12eV); **SiC (3.26eV)**; Diamond (5.46eV)
- SiC sensor study at UPV/EHU laser facility in Bilbao
  - Sensor: CNM planar p-in-n SiC epitaxial (50μm) sensor (N_{eff}=1.5e14cm^{-3})





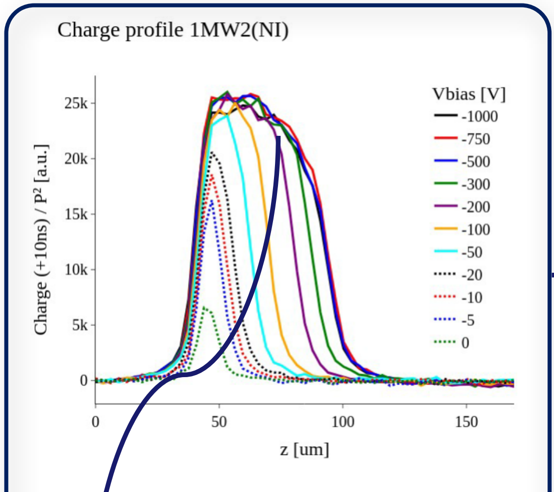
S: Shutter
A1: Attenuator
NLY: Non linear crystal
M: Mirrors
A2: Attenuator
Ref.: Laser power reference
L: focusing lens
DUT: Device under test

Readout for TPA-TCT

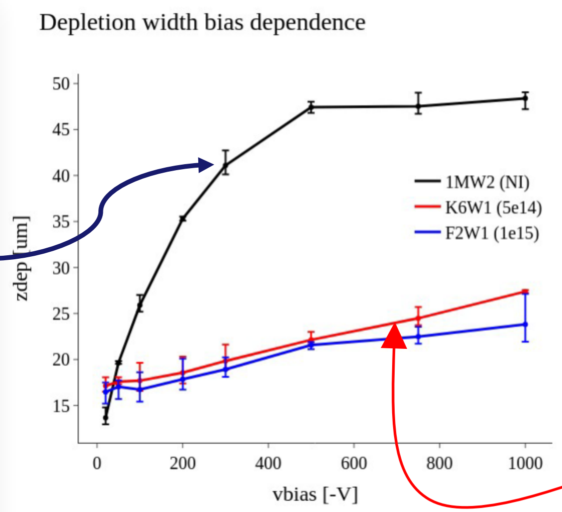


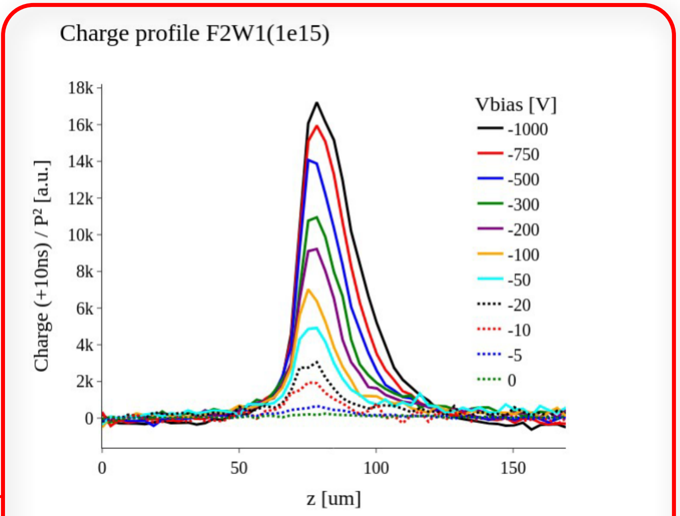
TPA-TCT testing of SiC

- SiC sensor study at UPV/EHU laser facility in Bilbao
  - Sensor: CNM planar p-in-n SiC epitaxial (50μm) sensor (N_{eff}=1.5e14cm^{-3})



before irradiation





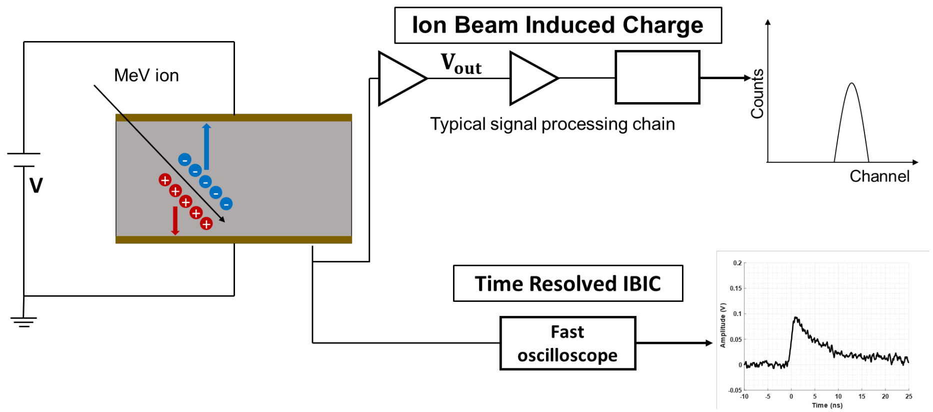
after irradiation to 10^{15} n_{eq}/cm^2

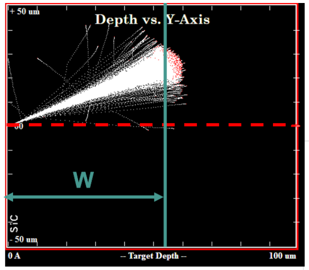
The in-depth charge profile was significantly influenced by **spherical aberration**. Specifically, the effect was more pronounced as the focal point became deeper.

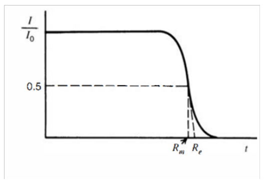
Details: C.Quintana "**Update on the characterization of neutron irradiated IMB-CNM SiC planar diodes**", presented on 41st RD50 Workshop, November 2022

TPA-TCT testing of SiC

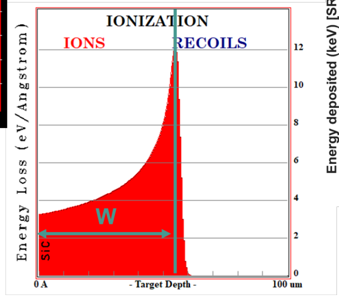
- Validation of the experimental results using the **Ion Beam Induced Charge Method** (IBIC) measured at CNA in Seville (microprobe at Tandem)

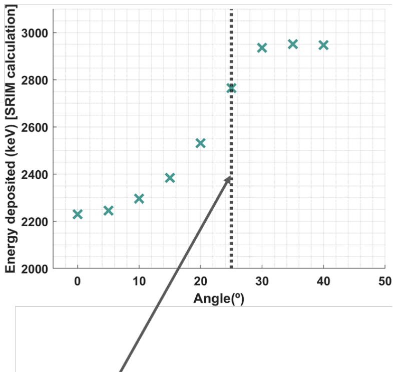






$$E_{dep}(W,\theta) = \int_0^W \frac{dE}{dx}(\theta)dx$$





$W[\mu m] = \mathrm{Range}(E(\theta)) \times \cos(\theta)$

$\theta \rightarrow$ critical angle

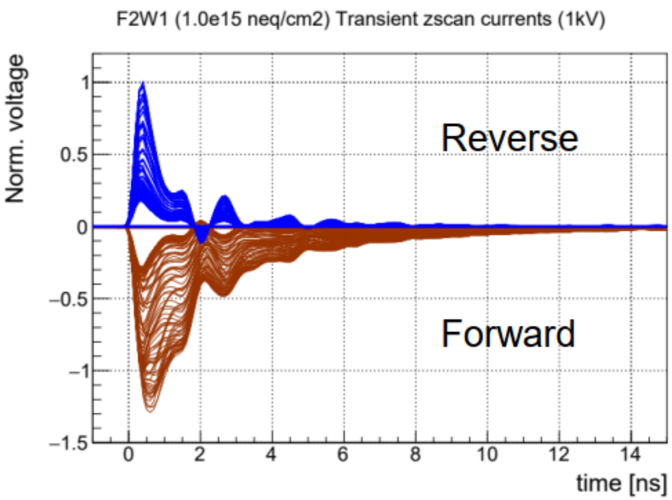
Detector	Bias (V)	(W-IBIC±1) (µm)	W-TPA (µm)	W-CV (µm)
Pristine	350	46	43	39
	200	37	36	32
	100	27	27	23
$4 \times 10^{14} n_{eq}/cm^2$	800	20-25	25	45
	300	15-20	20	46
$1 \times 10^{15}\ n_{eq}/cm^2$	400	20-25	20	44
	200	15-20	17	44

Validation of the TPA results using the IBIC method!

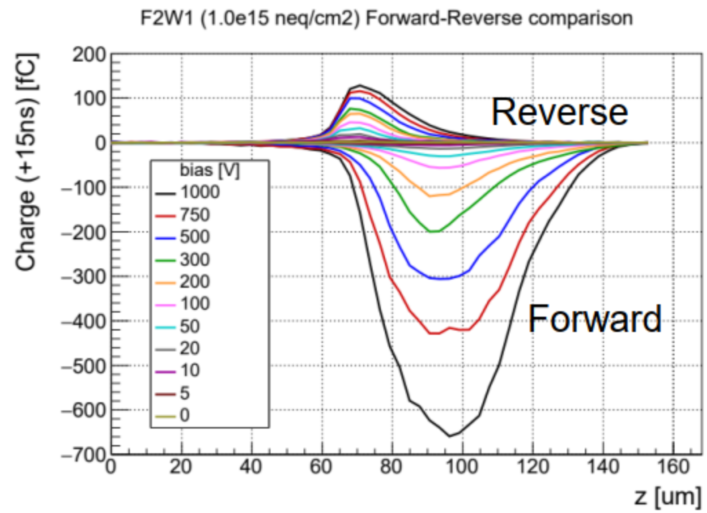
TPA-TCT testing of SiC

- SiC sensor study at UPV/EHU laser facility in Bilbao
  - Sensor: CNM planar p-in-n SiC epitaxial (50µm) sensor (N_{eff}=1.5e14cm^{-3})

Signal



Charge profiles



Interesting observations when forward biasing the irradiated diodes:

- Comparison between two z-scans at same HV bias but opposite polarization
- The signal amplitude is significantly greater in forward biasing than reverse biasing
- Large increase of the depletion width

Details: I.Vila **"Raidation Tolerance Study of neutron-irradiated SiC pn planar diodes"**, presented on TREDI 2023, Trento, March 2023

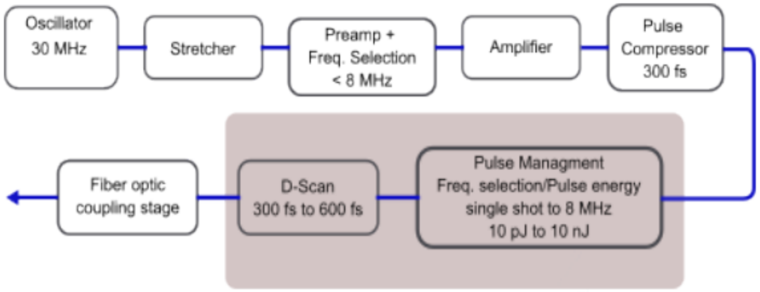
Towards a new, more compact laser system

System development

- Re-designed Laser system at Fyla – Status 2024
- The new "Pulsar" laser system was manufactured
  - The system fully integrates the laser pulse source (LPS), the pulse management module (LPM) and the dispersion compensation module (D-scan) in a single box component with fiber optic beam delivery.
  - The system "Pulsar" presents robustness and great stability in optical and temporal properties.
  - "Pulsar" provides beam delivery through 3m of optical fiber with coupling efficiency of ~70% (currently: under test and improvement)

"Pulsar" system specifications

- **LPS:** Laser Pulse Source
  - All-fiber CPA femtosecond pulses generation
  - Pulse rep rate selection. **Single shot to 8MHz**
- **LPM**: Laser Pulse Management module
  - Pulse energy modulation: **10pJ to 10nJ**
  - Synchronized shutter, **rise/fall time < 1μs**
- **D-SCAN:** Dispersion scanning
  - Pulse duration tuning: **300fs to 600fs**
  - Pulse temporal properties characterization



PULSAR

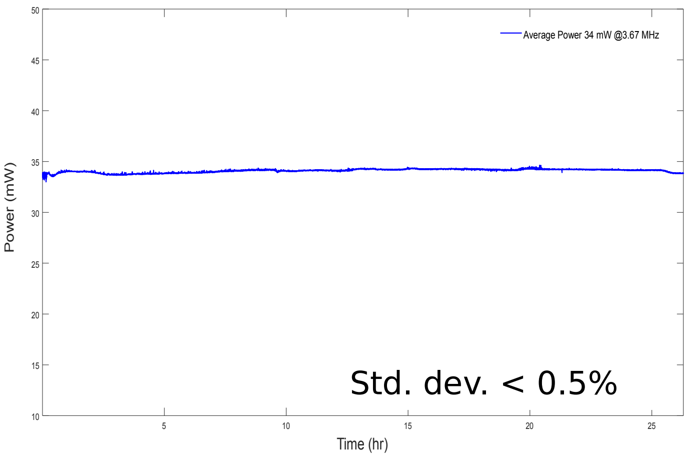
Dimensions:

Length: 91 cm
Width: 62 cm
Height: 22 cm

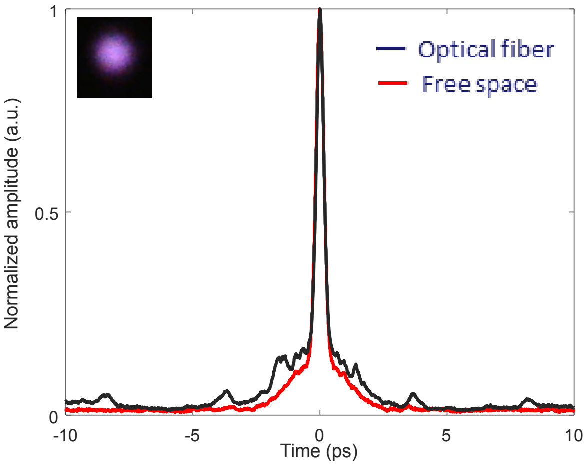
Fiber based TPA-TCT system

- Testing the "Pulsar" laser performance

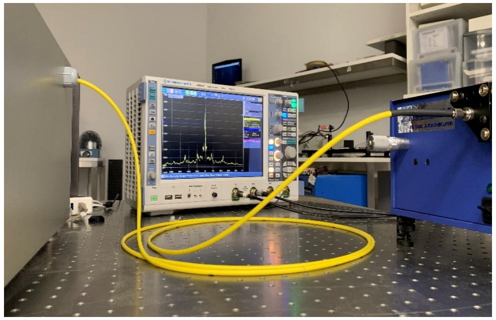
Power stability



Pulse profile



Beam delivery



Beam delivery through optical fiber, coupling efficieny ~70%

- Beam delivery through optical fiber (under test and improvement)
  - Coupling efficiency of ~ 70% to Kagome fiber under improvement
  - Studying new possibilities for beam delivery through optical fiber
- Difficulties with fiber beam delivery
  - Bending losses (20%)
  - Higher order (non-Gaussian) mode coupling when manipulating the output fiber

Summary: WP4.4. TPA-TCT development

- **WP4.4 - Design & Development of a TPA-TCT Sensor Characterization System**
  - **Scope:** Development of a customizable and user friendly Two Photon Absorption – Transient Current Technique (TPA-TCT) system for the characterization and testing of silicon devices
  - **Beneficiaries:** CERN (task leader); CSIC-IFCA (Santander, ES); Fyla (Valencia, ES)
  - **Deliverables/Milestones:**
    - MS16 (M23–February 2023) – Commissioning of complete TPA-TCT system [**Done**]
      Milestone Document report: https://zenodo.org/records/8027093
    - D4.4. (M46–January 2025) Publications & systems operational at several institutes [**Well on track**]
- **Status March 2024:**
  - **Laser systems:**
    - Fyla LFC1500X at CERN, IFCA (ES), JSI Ljubljana (SI), NIKHEF (NL), Lancaster (UK)
    - Fyla "Pulsar" in setup phase at Oxford (UK)
  - **Work of last 12 months:** see publication list in Annex
  - **New compact laser system developments**:
    - 2023: Work started at Fyla on new design
    - 2024: System "Pulsar" presents robustness and great stability in optical and temporal properties; beam delivery through 3m of optical fiber with coupling efficiency of ~70%
  - **User community:**
    - TPA-TCT lasers have been delivered to 6 HEP institutes; CERN/IFCA/Fyla provided consulting for setting up the systems
    - TPA-TCT common effort presented as example for collaborative efforts for new R&D collaboration (DRD3) in ECFA Detector R&D roadmap implementation plan.

Annex

AIDAinnova proposal: WP4.4.

- Objectives:

Task 4.4 Design & development of a new sensor characterisation system based on the TPA-TCT technique

- Complete the development from the proof-of-concept installation towards a customisable user friendly Two-Photon Absorption (TPA) Transient Current Technique (TCT) system with data acquisition and data analysis tools
- Support the evaluation of newly developed sensors (Low-Gain Avalanche Detectors and depleted CMOS devices) developed in WP5 and WP6
- Offer support towards the implementation of similar systems in other European institutions

- Description of work:

Task 4.4 Design & Development of a New Sensor Characterisation System based on TPA-TCT Technique (CERN, CSIC-IFCA, *FYLA*)

The Transient Current Technique (TCT) as a tool for studying signal formation in solid-state detectors is limited in resolution and allows for two-dimensional scans only. Two-Photon Absorption (TPA) TCT overcomes this limitation by employing a femtosecond laser pulse that creates charges only in a tiny voxel in the focal point of the laser beam, allowing, for example, small volume pixel detectors. This task will thus develop a novel very powerful tool for precise characterisation of semiconductor devices and offer it to the community for testing newly developed sensor technologies. FYLA will improve the performance and usability of the fiber laser for the TPA-TCT by increasing the laser stability and using a new fibre-based beam delivery system.

- 1 Milestone:

MS4.5	Commission a complete TPA-TCT system	4.4	M23	Report

- 1 Deliverable:

D4.4: Support towards the implementation of TPA-TCT systems and contribute to the evaluation of newly developed sensors technologies *Publication on TPA-TCT evaluation of sensors (task 4.4)*	46

January 2025

Publications

AIDAinnova publications (task 4.4.):

- **Influence of temperature on measurements of the Two Photon Absorption – Transient Current Technique in silicon planar detectors using a 1550 nm femtosecond fibre laser**; *S. Pape, E.Currás, M.Fernández García, M. Moll, M. Wiehe,* Nuclear Instruments and Methods in Physics Research Section A: Accelerators Spectrometers Detectors and Associated Equipment, Volume 1053, August 2023, 168387*;* https://doi.org/10.1016/j.nima.2023.168387
- **Technique for the investigation of segmented sensors using the Two Photon Absorption – Transient Current Technique**; *Sebastian Pape, Esteban Currás, Marcos Fernández García, Michael Moll*; Sensors 2023, 23(2), 962; https://doi.org/10.3390/s23020962
- **Fiber Laser System of 1550 nm Femtosecond Pulses with Configurable Properties for the Two-Photon Excitation of Transient Currents in Semiconductor Detectors***; Azahara Almagro-Ruiz, Sebastian Pape, Hector Muñoz, Moritz Wiehe, Esteban Curras Rivera, Marcos Fernández-García, Michael Moll, Raúl Montero Santos, Rogelio Palomo, Cristian Quintana, Iván Vila Álvarez, Pere Pérez-Millán;* Applied Optics 61, 9386-9397 (2022); https://doi.org/10.1364/AO.470780
- **Characterisation of irradiated and non-irradiated silicon sensors with a table-top Two Photon Absorption TCT system**; *S. Pape, M. Fernández García, M.Moll, R. Montero, F.R. Palomo, I. Vila and M. Wiehe;* Journal of Instrumentation, C08011, 2022, volume 17, number 08; https://doi.org/10.1088/1748-0221/17/08/c08011
- **Plasma effects in silicon detectors and the Two Photon Absorption Transient Current Technique**; *F.R. Palomo, M. Moll, M. Fernández-García, R. Montero, I. Vila;* Proceedings of the 2021 21th European Conference on Radiation and Its Effects on Components and Systems (RADECS) https://doi.org/10.1109/RADECS53308.2021.9954488
- **Development of a Tabletop Setup for the Transient Current Technique Using Two Photon Absorption in Silicon Particle Detectors**; *Moritz Wiehe, Marcos Fernández García, Michael Moll, Raúl Montero, F.R.Palomo, Ivan Vila, Héctor Muñoz-Marco, Viorel Otgon, Pere Pérez-Millán;* IEEE TNS, Vol.68, Issue.2, Feb.2021, pages 220-228, https://doi.org/10.1109/TNS.2020.3044489
- **First observation of the charge carrier density related gain reduction mechanism in LGADs with the Two Photon Absorption – Transient Current Technique**; *S.Pape, E.Currás, M.Fernández García, M.Moll,R.Montero, F.R.Palomo, I.Vila, M.Wiehe, C.Quintana; July 2022;* Nuclear Instruments and Methods in Physics Research Section A Accelerators Spectrometers Detectors and Associated Equipment 1040:167190; https://doi.org/10.1016/j.nima.2022.167190