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

AIDAinnova 2nd annual meeting, 24-27. April 2023, CERN

Michael Moll (CERN)
on behalf of WP4.4.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101004761.

Outline

- Introduction to TCT and TPA-TCT
- TPA-TCT project & project partners
  - Status of TPA-TCT systems in AIDAinnova-community
  - Examples of recent TPA-TCT applications
- Towards a new – more compact - laser system with fiber output
- **Status:** Milestones and Deliverables
- Summary and Outlook

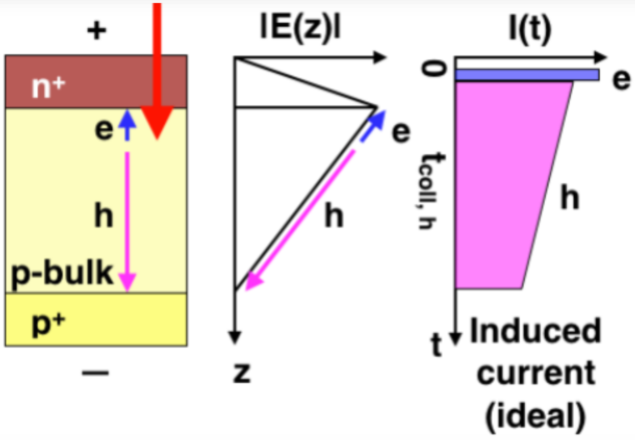
Transient Current Technique

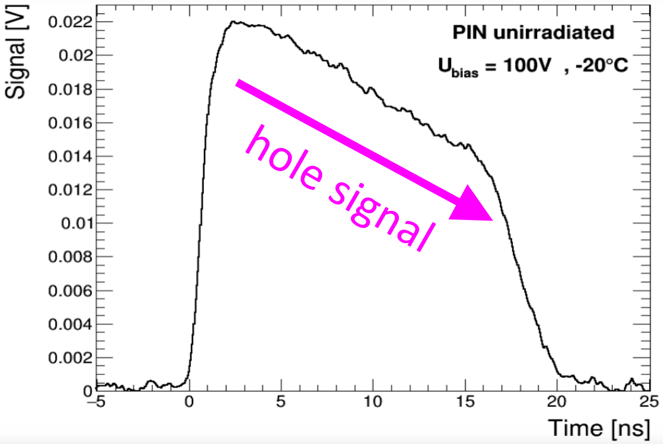
- **TCT working principle:** Characterization of a silicon sensor

(a) Illumination with laser light pulse (<1ns) **(b)** Recording of the resulting current transient

Example 1:
mode: “top TCT”

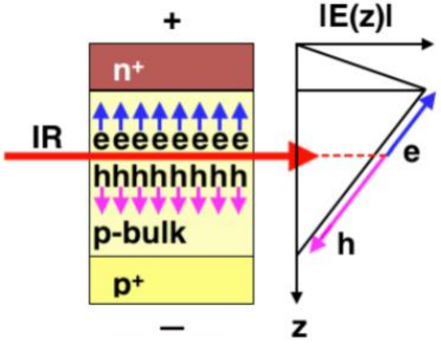
red laser
(e.g. 660 nm)

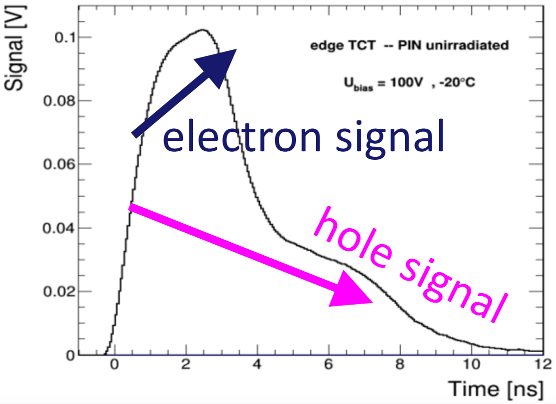




Example 2:
mode: “edge TCT”

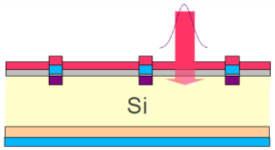
infrared laser
(e.g. 1060 nm)



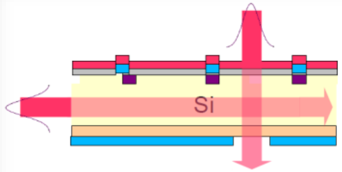


TCT: Transient Current Technique

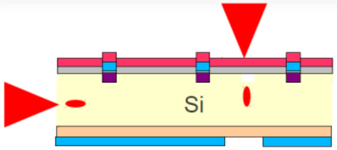
- **TCT:** Pulsed laser induced generation of charge carriers inside detector
  - Study of E-field in sensor, charge collection efficiency, homogeneity, ..
  - Benchmark simulation tools, e.g. signal formation,
  - Measure physics parameters e.g. mobility, impact ionization, ..



- **TCT (red laser)**
  - 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 laser)**
  - long penetration (1064nm = 1.17 eV)
  - similar to MIPs (though different dE/dx)
  - top and edge-TCT
  - 2D spatial resolution (5-10mm)



- **TPA-TCT (far infrared)**
  - No single photon absorption in silicon
  - 2 photons produce one electron-hole pair
  - Point-like energy deposition in focal point
  - **3D** spatial resolution (1.5 x 1.5 x 15 μm^3)

TCT “invented”: 1996

edge-TCT invented within RD50: 2010

TCT commercialized: 2013

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

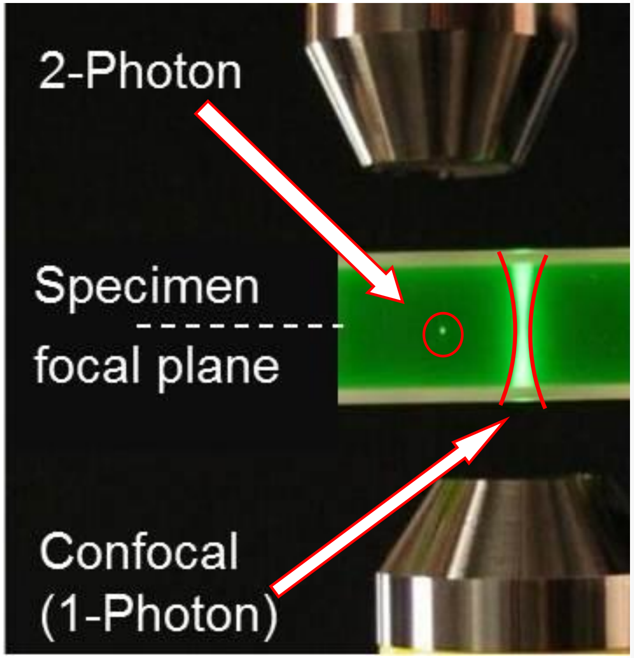
Table-top TPA-TCT laser commercialized: 2020/21

Table-top TPA-TCT system

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

TPA: Two Photon Absorption

- **Example:** Fluorescence → **TPA in silicon**



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

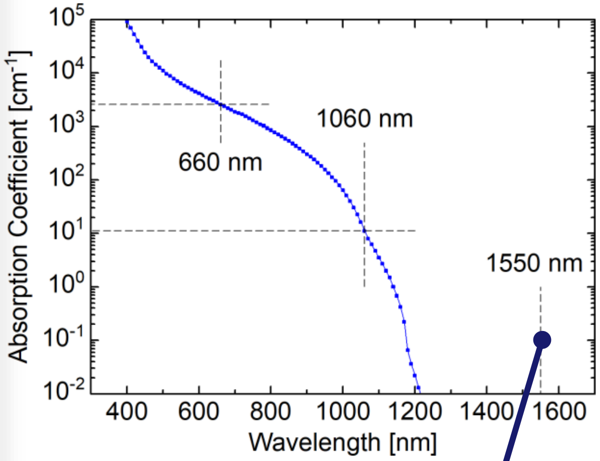
TPA – Two Photon Absorption

- Absorption only in focal point

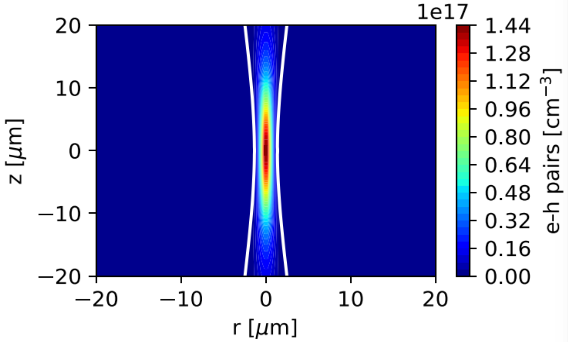
SPA – Single Photon Absorption

- Continuous absorption along beam

Si: SPA - Single Photon absorption



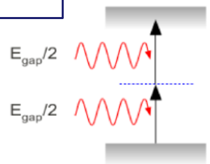
charge carrier density simulation $\lambda = 1550\ nm$

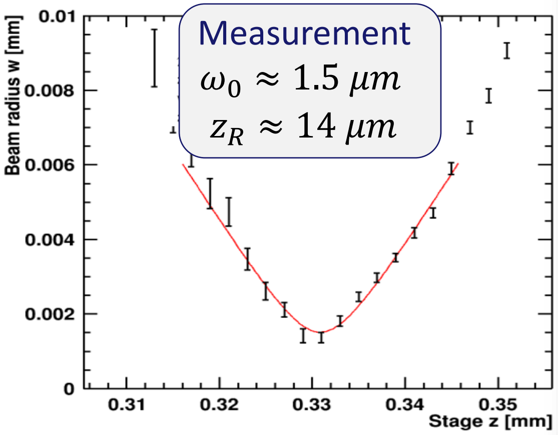


1550nm: no absorption unless two photons are absorbed at same time (i.e. within fs)

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

SPA TPA

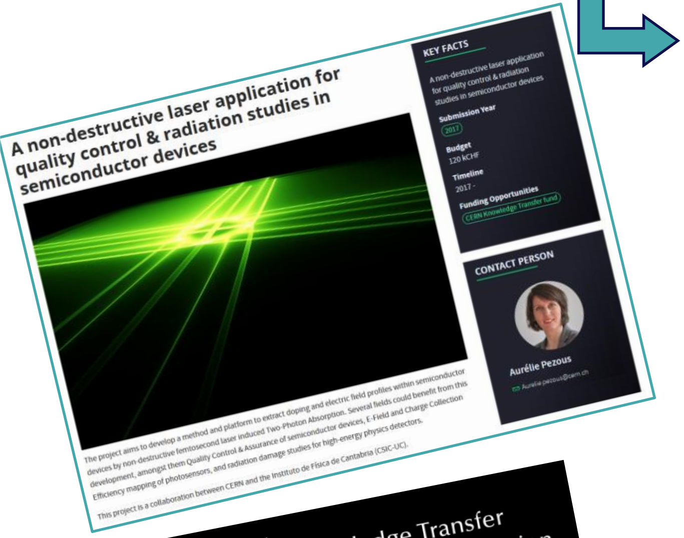




Measurement
$\omega_0 \approx 1.5\ \mu m$
$z_R \approx 14\ \mu m$

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, …..



A non-destructive laser application for quality control & radiation studies in semiconductor devices

The project aims to develop a method and platform to extract doping and electric field profiles within semiconductor devices by non-destructive femtosecond laser induced Two-Photon Absorption. Several fields could benefit from this development, amongst them Quality Control & Assurance of semiconductor devices, E-Field and Charge Collection Efficiency mapping of photosensors, and radiation damage studies for high-energy physics detectors.

This project is a collaboration between CERN and the Instituto de Física de Cantabria (CSIC-UC).

KEY FACTS

A non-destructive laser application for quality control & radiation studies in semiconductor devices

Submission Year
2017

Budget
120 kCHF

Timeline
2017 -

Funding Opportunities
CERN Knowledge Transfer fund

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CERN | Knowledge Transfer
Accelerating Innovation

- 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 replacement 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**

selection of company

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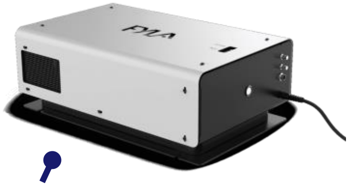
laser development



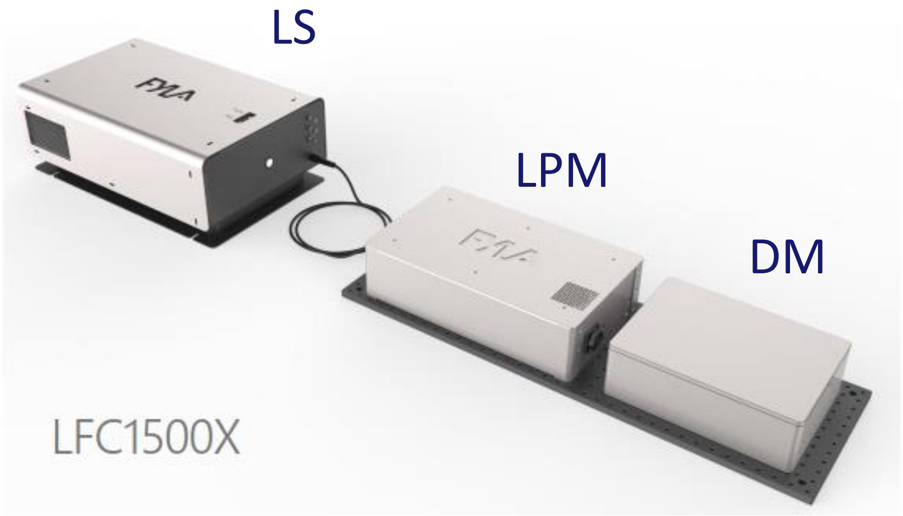
Fyla LFC1500X

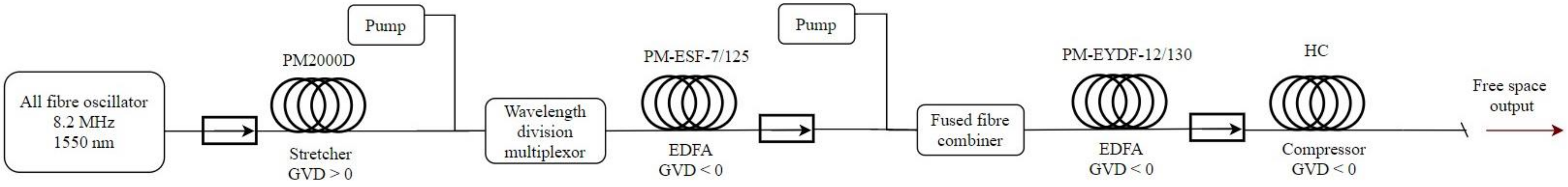
AIDAinnova WP4.4

further improvements & user community
system development & all fiber laser system

Laser system schematics

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



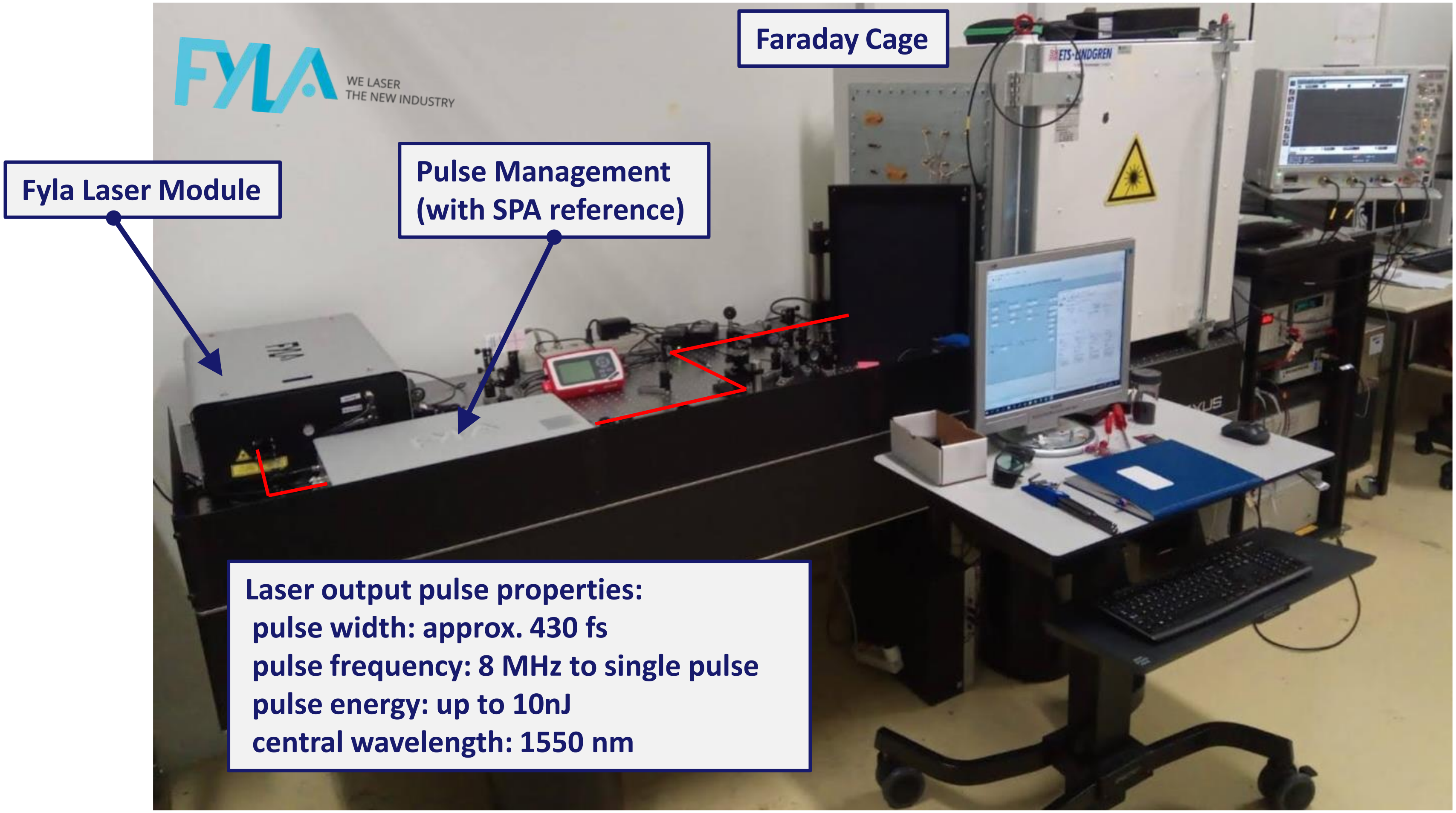


Details:

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

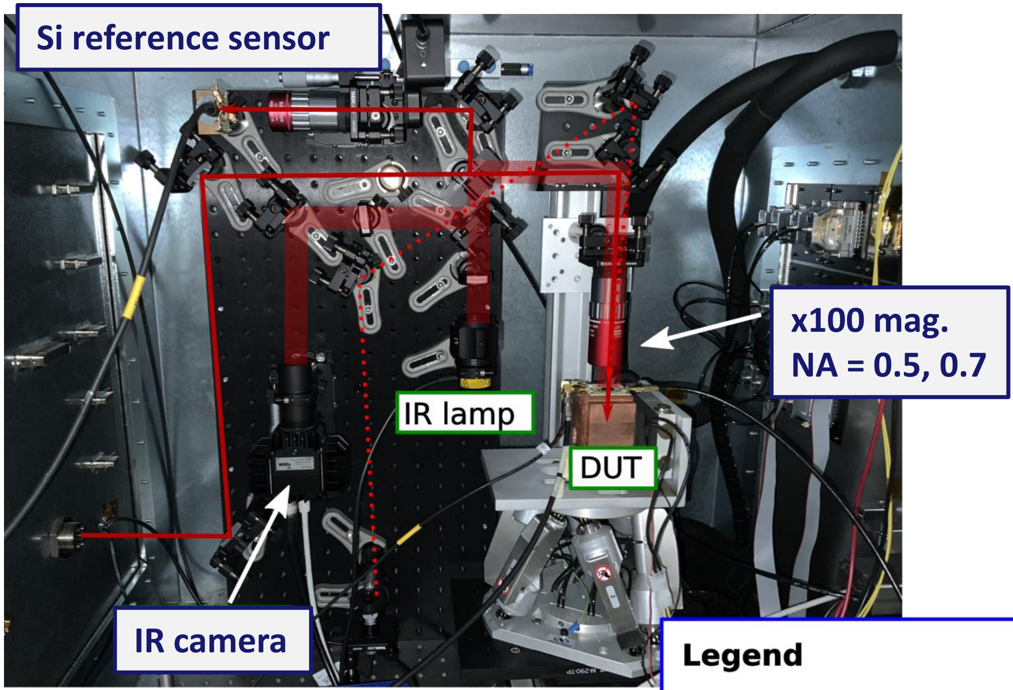


Laser output pulse properties:
pulse width: approx. 430 fs
pulse frequency: 8 MHz to single pulse
pulse energy: up to 10nJ
central wavelength: 1550 nm

[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]

Setup & Calibration (CERN)

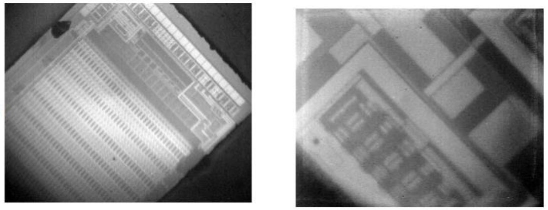
- **Inside the Faraday cage**



Legend

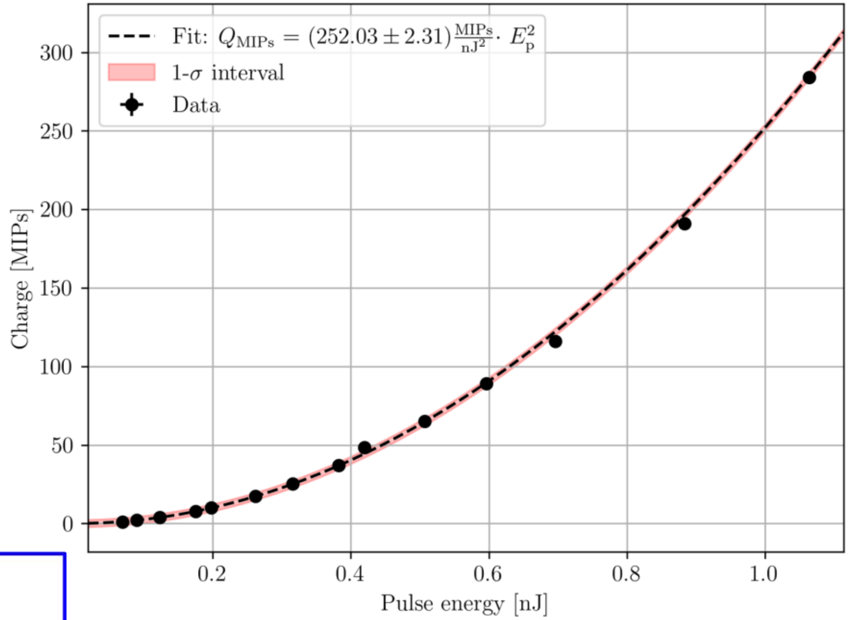
— Laser path
▬ IR microscope
⋯ Alignment laser

image from rear through bulk



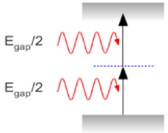
- **Calibration against MIP (^{90}Sr)**

Pulse energy against generated charge
(285 µm PIN; NA = 0.5 at 20°C and 0% humidity)



The pulse energy is measured with a S401C thermal power sensor from Thorlabs.

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



TPA-TCT systems

- TPA-TCT systems have been set up at several institutes with the LFC1500X laser

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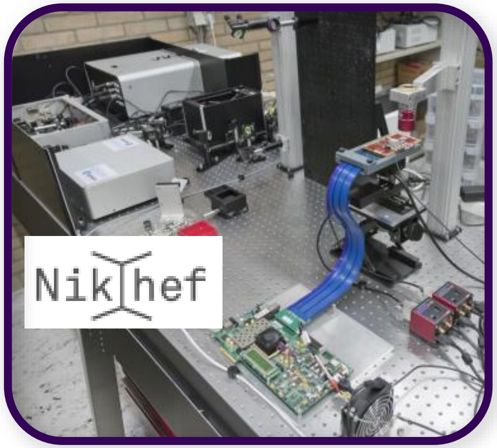
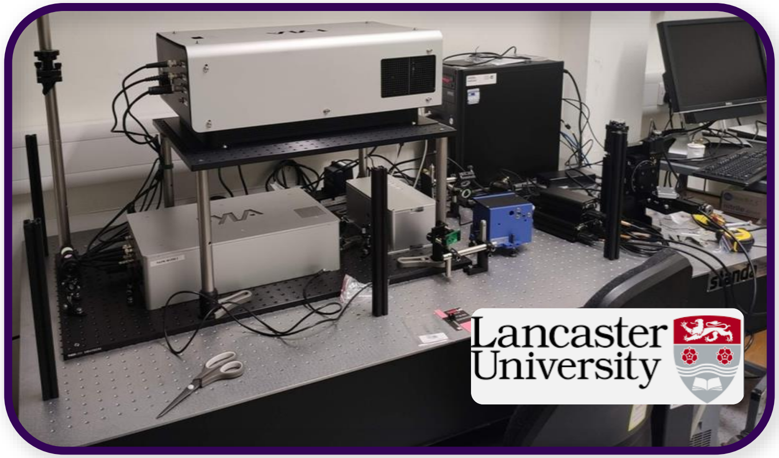
LFC1500X





Measurement technique improvements
&
Application examples

"The weighted prompt current method"

$\vec{v_d} = \mu_{e/h} \cdot \vec{E}$

- **Weighted prompt current method:**
  - mitigate the dependence on laser intensity, inhomogeneous charge generation

Prompt current

$$I_{pc} \approx Q\,\vec{E}_w(\mu_e+\mu_h)\,\vec{E}$$

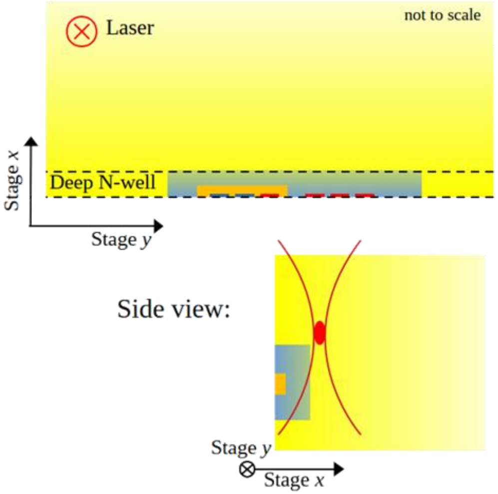
Generated charge

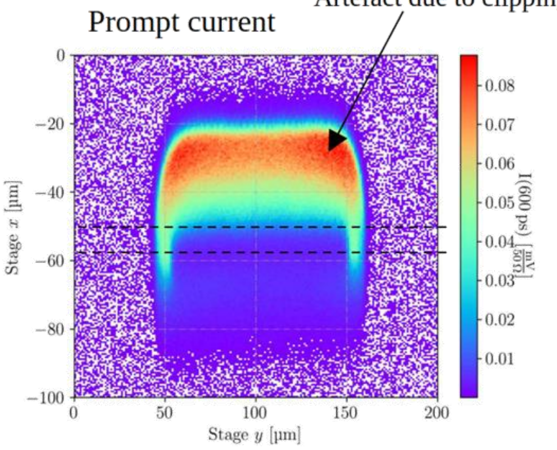
Weighted prompt current

$$\frac{I_{pc}}{Q_{coll}} \approx \vec{E}_w(\mu_e+\mu_h)\,\vec{E}$$

Collected charge

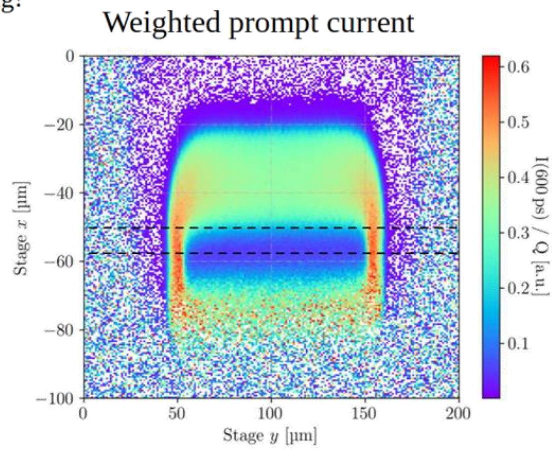
- **Example: HV-CMOS (CCPDv3)**




Prompt current

Artefact due to clipping!

Extensive clipping close to the surface and reflection at the Si-air interface


Weighted prompt current

Artefact not present in the weighted prompt current!

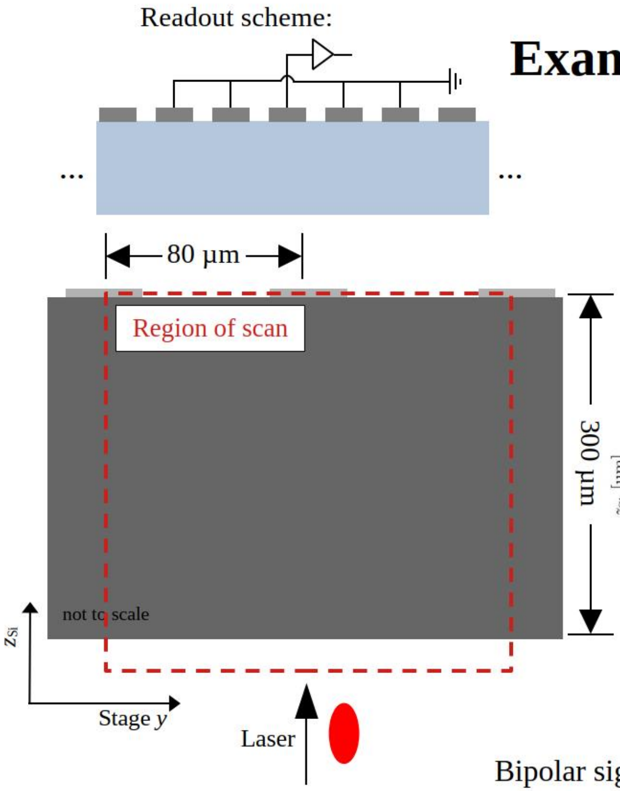
Highest $\vec{E}_w(\vec{v}_e+\vec{v}_h)$ found at the junction.

- **Comments on the weighted prompt current method:**
  - Weighting requires that all generated charge is collected (not applicable for significant charge trapping happens)
  - More sensitive towards SNR than prompt current method

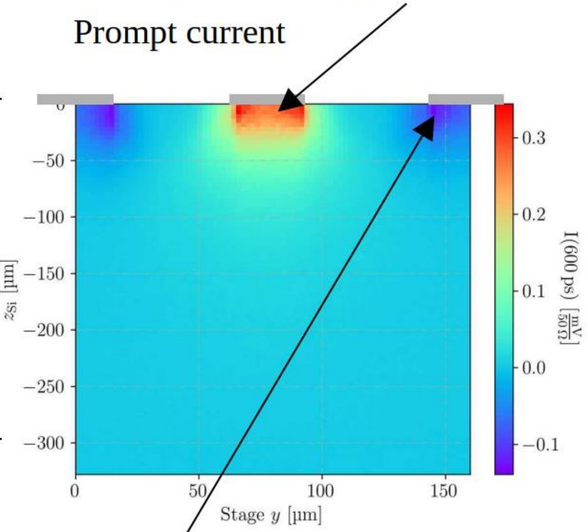
S.Pape et al. Sensors 2023, 23(2), 962; https://doi.org/10.3390/s23020962 , January **2023**

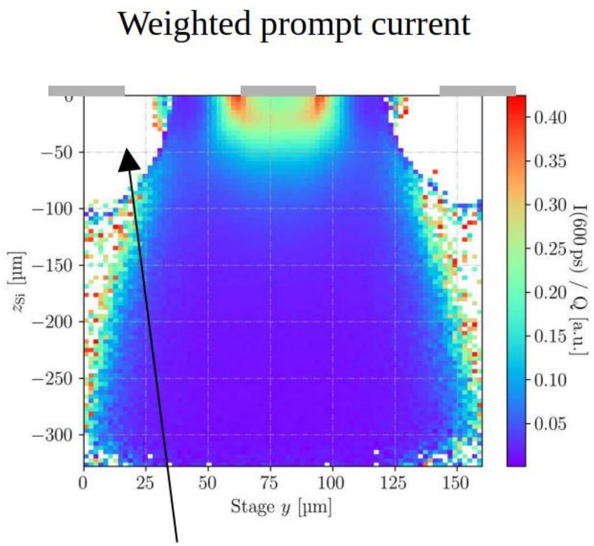
"The weighted prompt current method"

Example: Strip detector (FZ Micron)

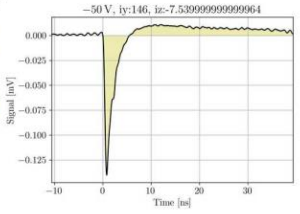


Reflection at top side metal increase the generated charge and lead to an artefact





Bipolar signals lead to a negative prompt current as the charge is collected by the neighboring strip

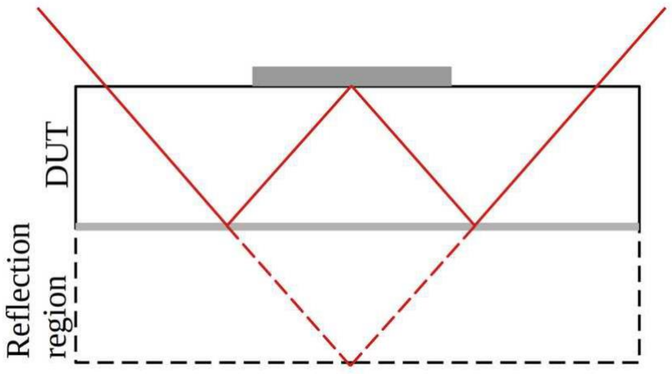


$Q_{\mathrm{coll}} \approx 0$ → leads to "-∞"

S.Pape et al. Sensors 2023, 23(2), 962; https://doi.org/10.3390/s23020962 , January **2023**

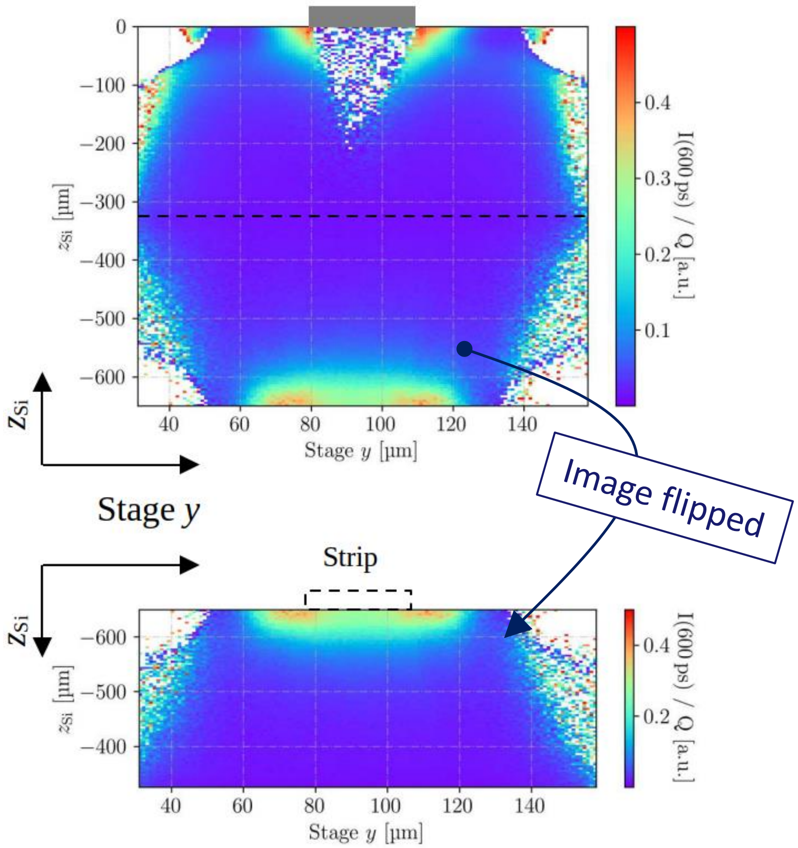
“The Mirror Technique”

- **The mirror technique**
  - Reflection at a metallized back side can be exploited to probe below the top side metallisation with illumination from the top



  - All intensity independent quantities can be probed in this way.
  - Requires a metallized back side
  - Enables a measurement below the top side metals
  - Note that beam clipping can reduce the numerical aperture and hence the special resolution.
- **This technique is only feasible with TPA-TCT as it requires 3D resolution!**

Standard strip detector as an example:

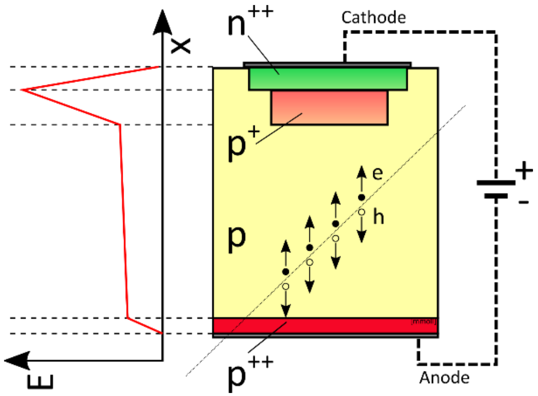


Details: S.Pape et al.: “**Techniques Techniques for the Investigation of Segmented Sensors Using the Two Photon Absorption-Transient Current Technique”, Sensors 2023, 23(2), 962; https://doi.org/10.3390/s23020962 , January 2023**

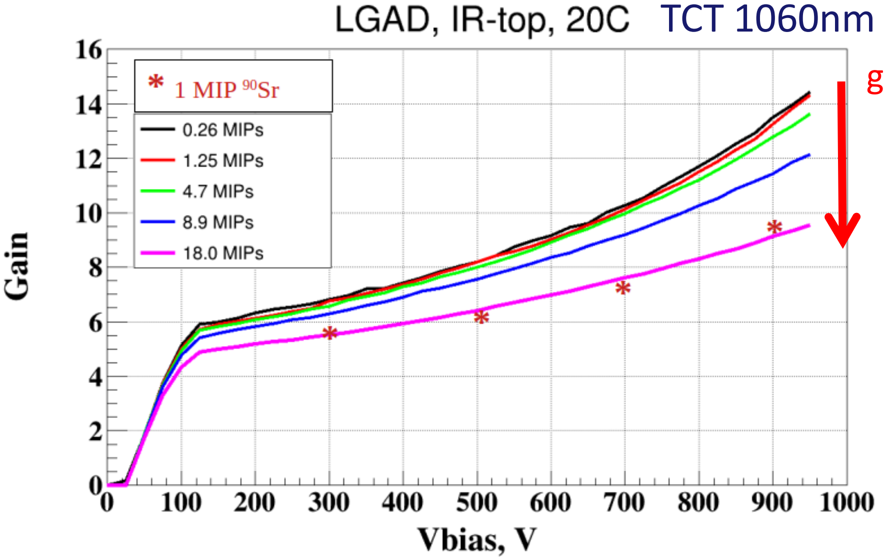
Application: Gain suppression in LGADs

- as studied with TPA-TCT -

- **Gain suppression in LGADs:**
  - The gain in Low Gain Avalanche Diodes (LGADs) depends on the charge density entering the gain layer
    Effect relevant for characterization and operation of LGADs for the HL-LHC ATLAS/CMS timing experiments
- **Example of a study employing standard TCT and ^{90}Sr source induced signals**
  - Sensors: LGAD and PIN from CNM 8622 batch (285 μm thick devices with/without a gain layer)



- LGAD schematics
- PIN (no p^+ , i.e. no gain layer)



TCT 1060nm top

gain reduction with increasing ionization density

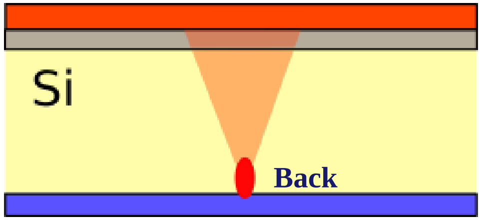
- Gain = Signal LGAD / Signal PIN

Data: E.Curras (CERN, SSD)

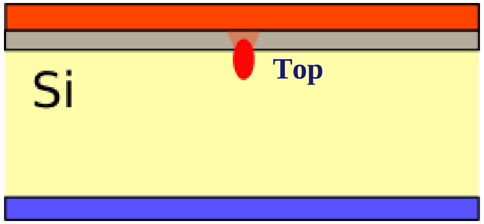
WP4.4. & 6.3. Gain suppression in LGADs

- as studied with TPA-TCT -

- **Characterization with TPA-TCT performed:**
  - [1.] Low charge density in the Gain Layer (GL) will lead to a higher gain: there will be a negligible gain suppression.
  - [2.] High charge density in the GL will lead to a reduction in the gain: drop in the GL E-field (less amplification).



Shaded red: *schematic evolution of the charge density inside the LGAD*

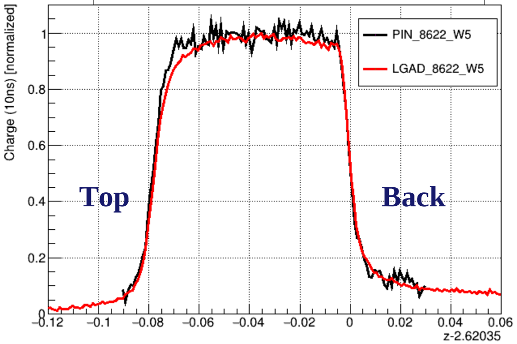


Gain suppression can be observed with TPA-TCT measurements:

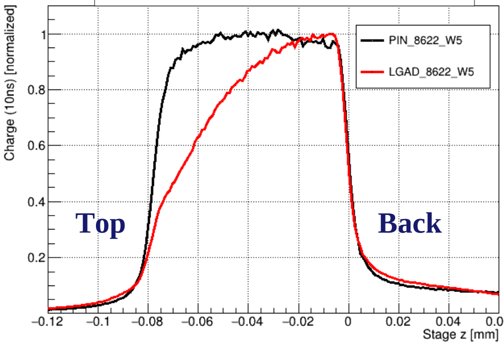
Color code in the plots:
Gain detector (LGAD)
PIN (standard sensor)

DUT information:
285µm p-type devices
Produced by CNM (8622_W5)

[1.] Low laser intensity



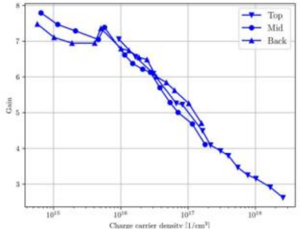
[2.] High laser intensity



Further detail can be found in:

E. Currás, M. Fernández and M. Moll:
Gain suppression mechanism observed in Low Gain Avalanche Detectors (2021)
S. Pape et al.:
First observation of the charge carrier density related gain reduction mechanism in LGADs with the Two Photon Absorption-Transient Current Technique (2022)

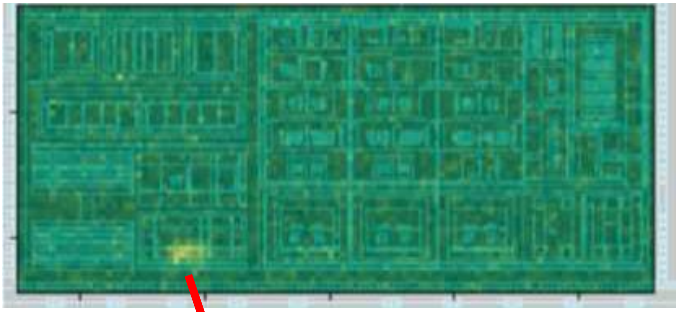
Gain reduction versus the charge carrier density:

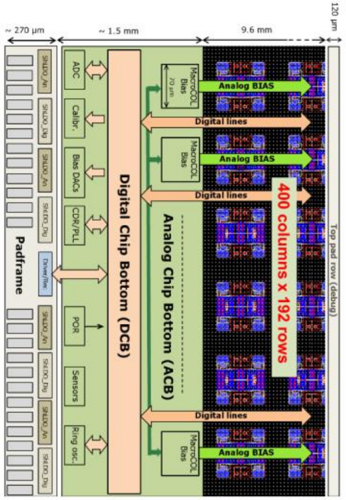


TPA-TCT SEE studies in a RD53B Chip

- SSD CERN (EP-DT): SEE tests on a RD53B chip in cooperation with CERN EP-ESE
- Two Photon Absorption – TCT employed
  → pulse energies of 1nJ and ≈1.3µm lateral resolution
- Scanned blocks in the digital chip bottom (DCB)
  → SEEs found in multiple blocks; measurements ongoing
  → Sensitivity maps show where the SEEs in the DCB occur

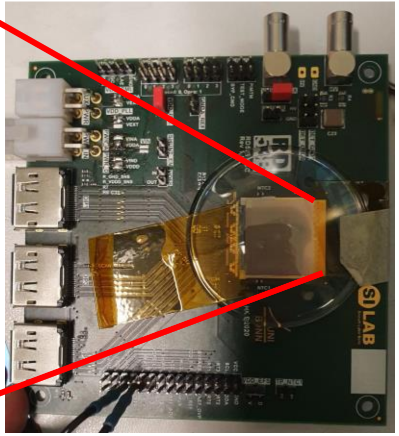
Example of sensitivity map (CDR core)

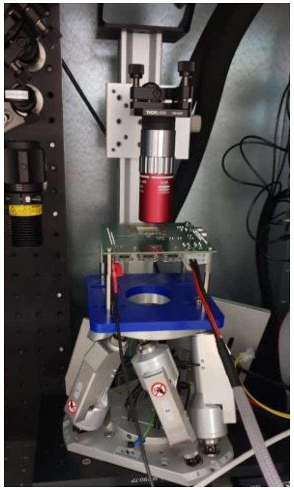




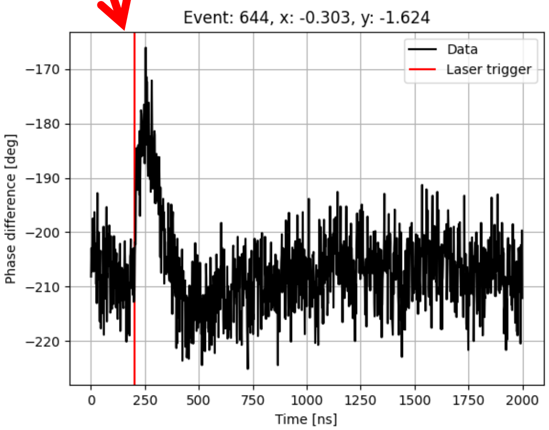
Sketch: RD53A Chip
(RD53B Chip has a comparable structure)

RD53B chip





DUT mounted in setup

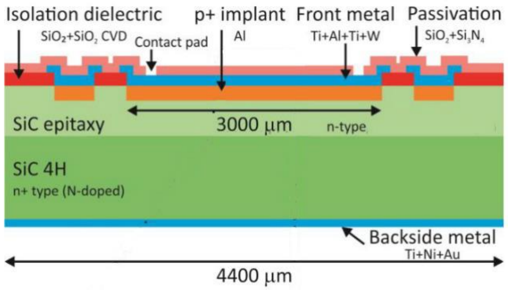


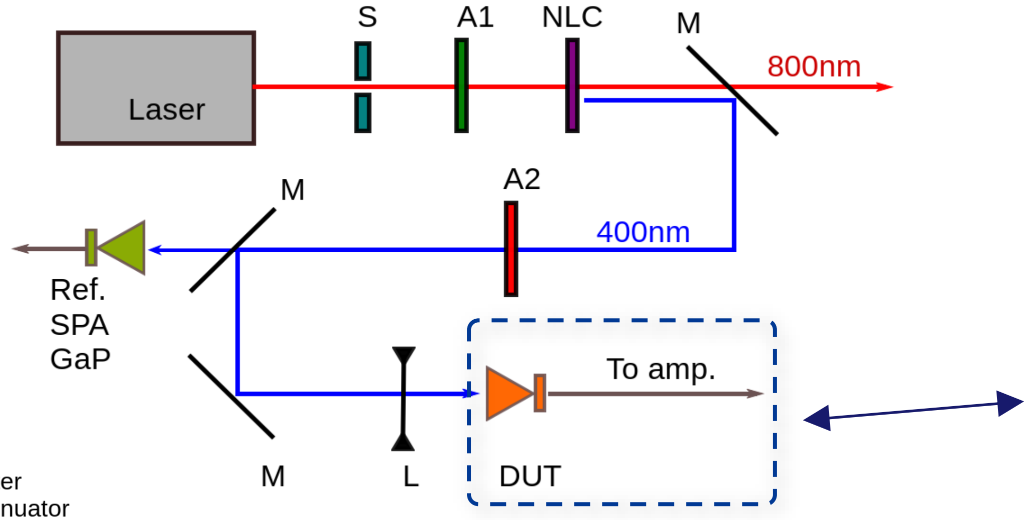
Example single event transient of the above shown block

Data: S.Pape, CERN SSD

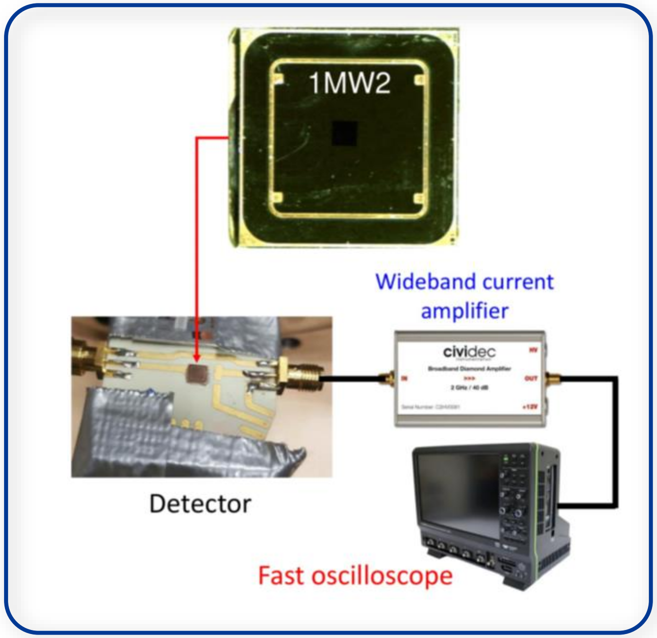
TPA-TCT: SiliconCarbide (SiC) sensors

- Extension of TPA-TCT to other semiconductors
  - Si (1.12 eV); **SiC (3.26 eV);** Diamond (5.46 eV)
- SiC sensor study at UPV/EHU laser facility in Bilbao
  - Sensor: CNM planar p-in-n SiC epitaxial (50um) sensor (Neff=1.5E14cm-3)



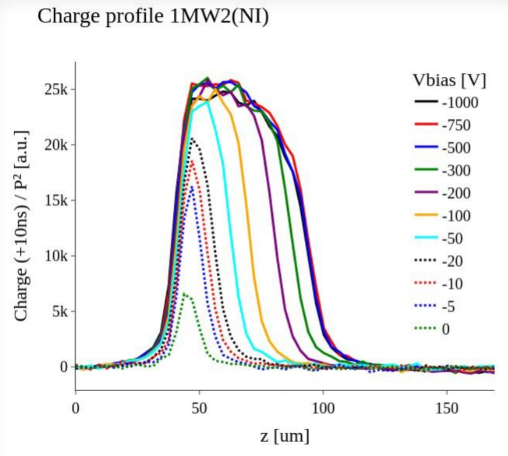


S: Shutter
A1: Attenuator
NLY: Non linear crystal
M: Mirrors
A2: Attenuator
Ref.: Laser power reference
L: focusing lens
DUT: Device under test

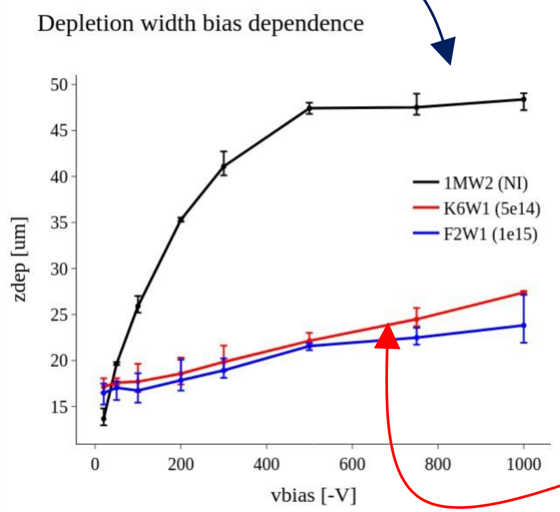


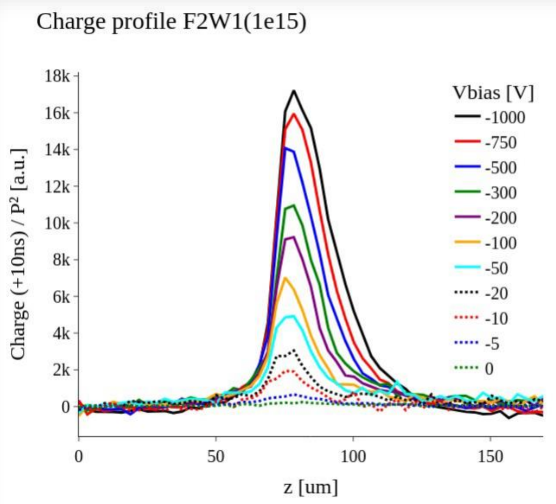
TPA-TCT: SiliconCarbide (SiC) sensors

- SiC sensor study at UPV/EHU laser facility in Bilbao
  - Sensor: CNM planar p-in-n SiC epitaxial (50um) sensor (Neff=1.5E14cm-3)


Charge profile 1MW2(NI)

before irradiation


Depletion width bias dependence


Charge profile F2W1(1e15)

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

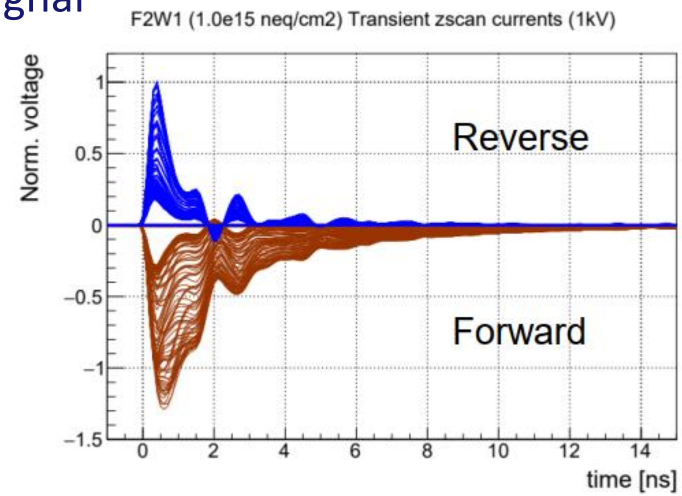
- Example: Measurement of charge profiles as function of applied reverse bias voltage before and after irradiation with neutrons

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

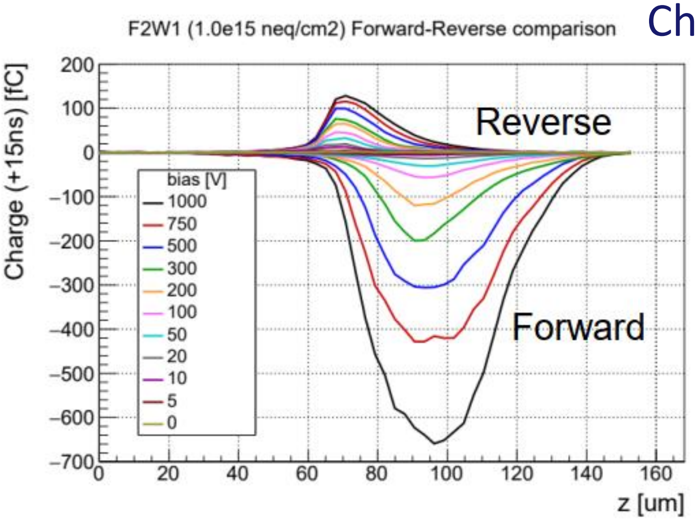
TPA-TCT: SiliconCarbide (SiC) sensors

- SiC sensor study at UPV/EHU laser facility in Bilbao
  - Sensor: CNM planar p-in-n SiC epitaxial (50um) sensor (Neff=1.5E14cm-3)

Signal



Charge profiles



- Interesting observation:
  Larger signal in irradiated sensor when operated with forward bias.

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

Ongoing Developments:

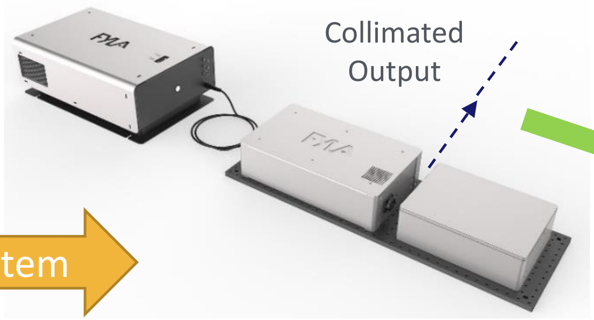
- A new compact TPA-TCT laser system
- Outlook: Smaller system improvements

Fiber based TPA-TCT System

Current TPA-TCT system

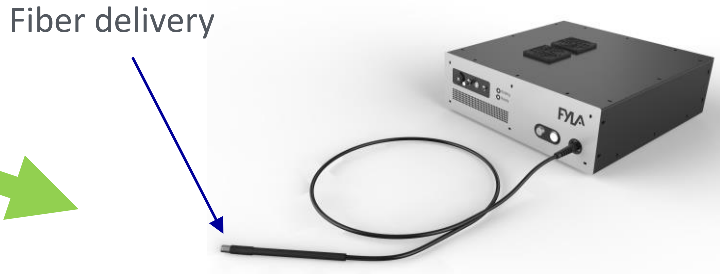
CURRENT

LFC1500X commercial model

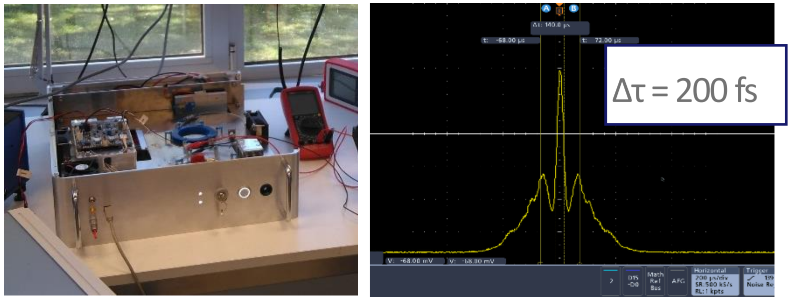


AIDA INNOVA

Single box fully all-fiber



- **LPS:** Laser Pulse Source
  - All-fiber CPA femtosecond pulses generation
  - Pulse rep rate selection. **Single shot to 8 MHz**
- **LPM**: Laser Pulse Management module
  - Pulse energy modulation: **<10 pJ to > 10 nJ**
  - Synchronized shutter**. rise/fall time < 1 us**



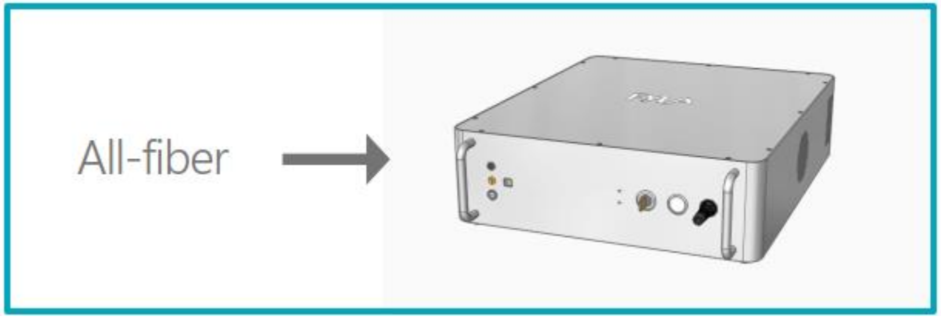
Prototype January 2022

Details on the new design: A.Almagro-Ruiz, Fyla “**Towards an All-Fiber Femtosecond Laser System as Excitation Source in the TPA – TCT**”, presented on 39th RD50 Workshop, November 2021, Valencia

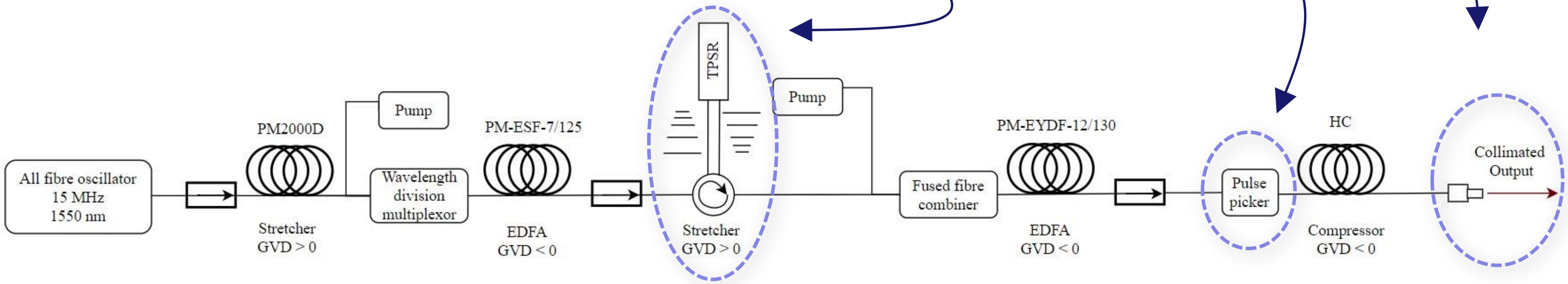
- **LPS + LPM + D-SCAN** in single box fully all-fiber
  - Pulse duration goal < 100 fs
  - Fiber-based tunable dispersion compensation: < 100 fs to 1 ps
  - Fiber-pigtailed AOM functionalites:
    - Energy modulation; Pulse rep rate selection; Sync shutter
  - Dispersion-less fiber output

All-fiber laser: system schematics

- All-Fiber Femtosecond Laser System
  - Less losses, higher efficiency
  - Better (and easier) alignment
  - Better dispersion matching



- Ambitious first development approach [2021 to 2022]
  - All fiber concept also within laser box
    - Fiber output delivery
    - Fiber-pigtailed pulse picker
    - Variable dispersion CFBG (chirped fiber Bragg grating)



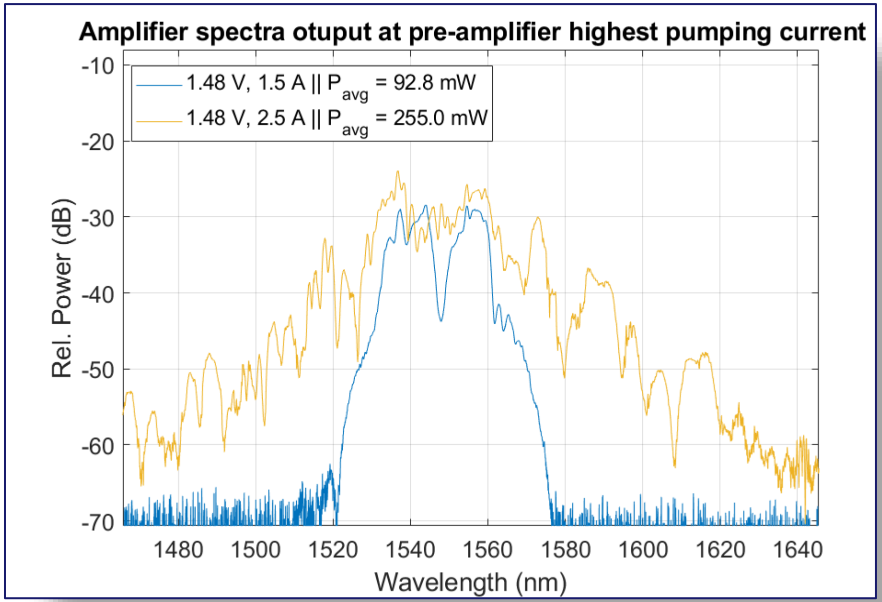
Details: A.Almagro-Ruiz, Fyla “**Towards an All-Fiber Femtosecond Laser System as Excitation Source in the TPA – TCT**”, presented on 39th RD50 Workshop, November 2021, Valencia

All-fiber laser: implementation difficulties

All-fiber laser system

- Implementation difficulties [2021-2022]
  - Variable dispersion CFBG (chirped fiber Bragg grating)
    - Pulses are not sufficiently stretched before amplification
  - Undesired non-linear effects at high currents
  - Low average output power at low currents

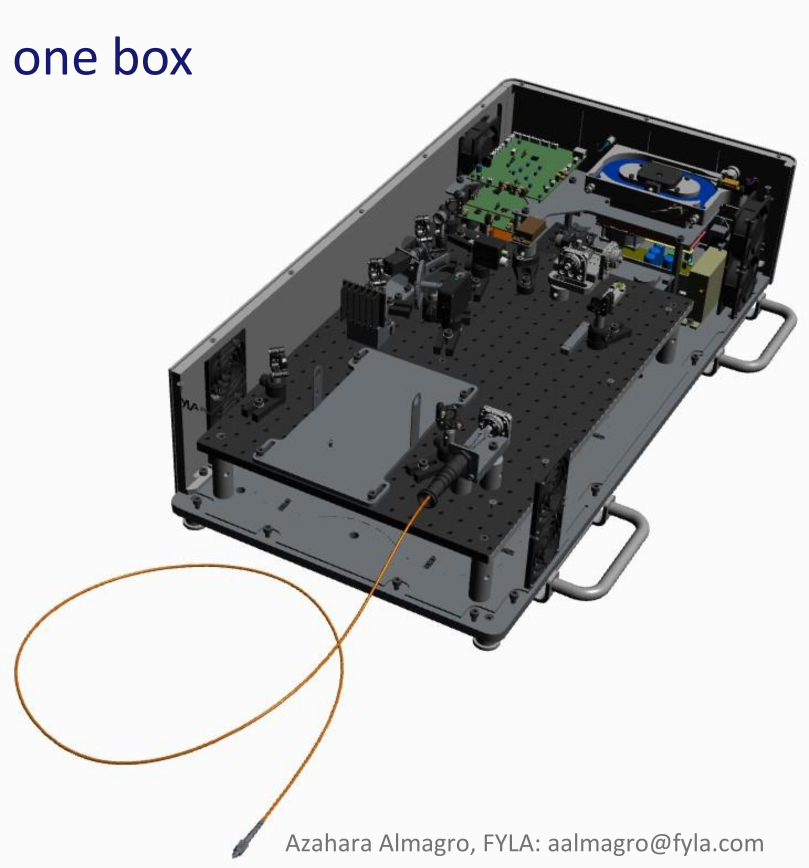
  - Conclusion [2022/23]
    - Look for another (and simpler) approach



“All-fiber laser”: New concept (2023)

New design: Compact laser system with fiber output

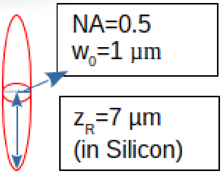
- **Compact** laser system: all modules in one box
- **Fiber output** delivery



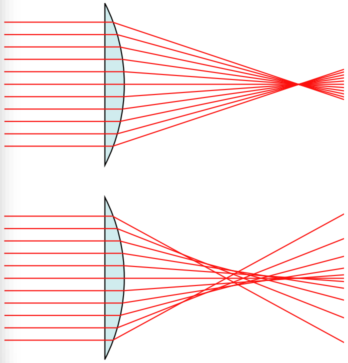
Azahara Almagro, FYLA: aalmagro@fyla.com

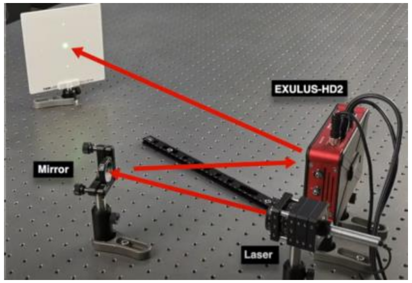
Outlook: Considered system improvements

sperical aberration correction



- Radiation hardness demands thin detectors (≲ 50 µm). Longitudinal resolution in TPA is improved using objectives with NA>0.5 (=TPA baseline) .
- In thick devices (> 70 µm), high NA (>0.5) leads to spherical aberration of the focus, degrading TPA measurement.

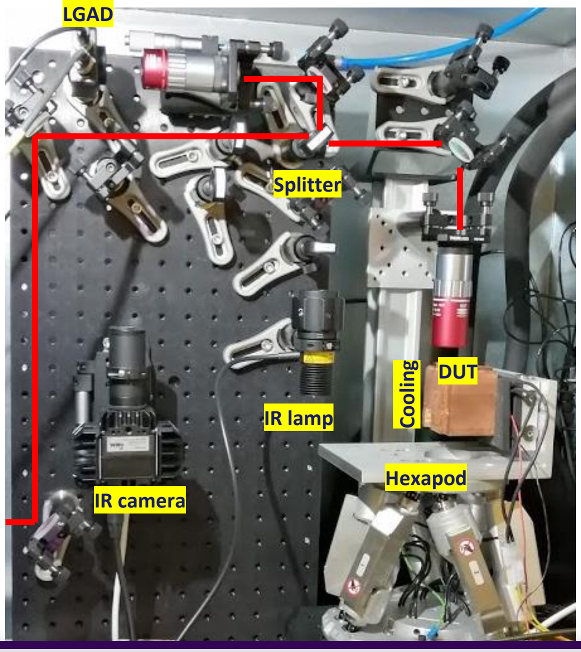




Idea: A Spatial Light Modulator (SLM) could compensate the effect.

timing measurements

- Timing measurements with TPA can be easily achieved splitting the beam before the objective. An LGAD placed on a monitoring branch can be used as time reference for jitter calculation.



More Details: M.Fernandez-Garcia "**Development of a new tool: Two Photon Absorption - TCT**", presented on Implementation of TF3 Solid State Detectors Workshop, March 2023

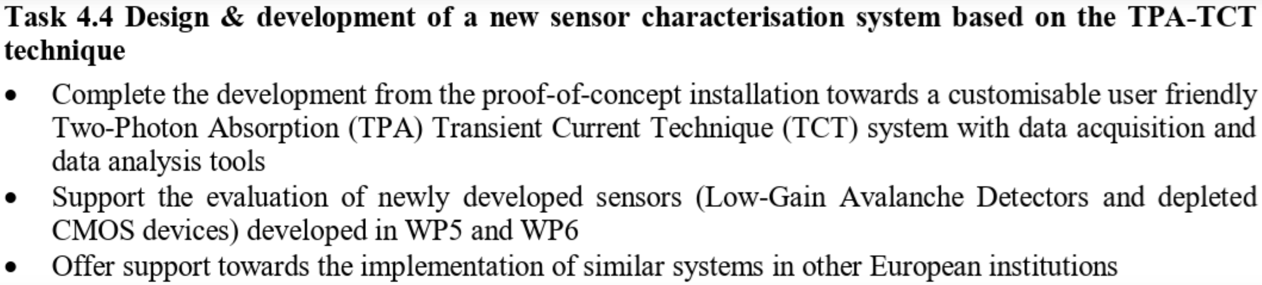
Summary: WP4.4 TPA-TCT development

- **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 test 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 [**o.k. MS report submitted**]
    - D4.4. (M46–January 2025) Publications & systems operational at several institutes [**well on track**]
  - **Status April 2023:**
    - **Laser system:**
    - Fyla free space laser systems at CERN, IFCA (Santander, ES), JSI Ljubljana(SI), NIKHEF(NL), Lancaster (UK)
      - **Work of last 12 months:** Systems operational and producing large amount of data (see given examples and list of publications)
      - **Goals for new compact laser and system developments re-defined**:
        (2021/22) evaluation of full-fiber based system studied and finally abandoned in end of 2022;
        second design approach produced in the course of 2022: 2023 work started at Fyla on this new design
    - **User community:**
      - TPA-TCT lasers have been delivered to 5 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.

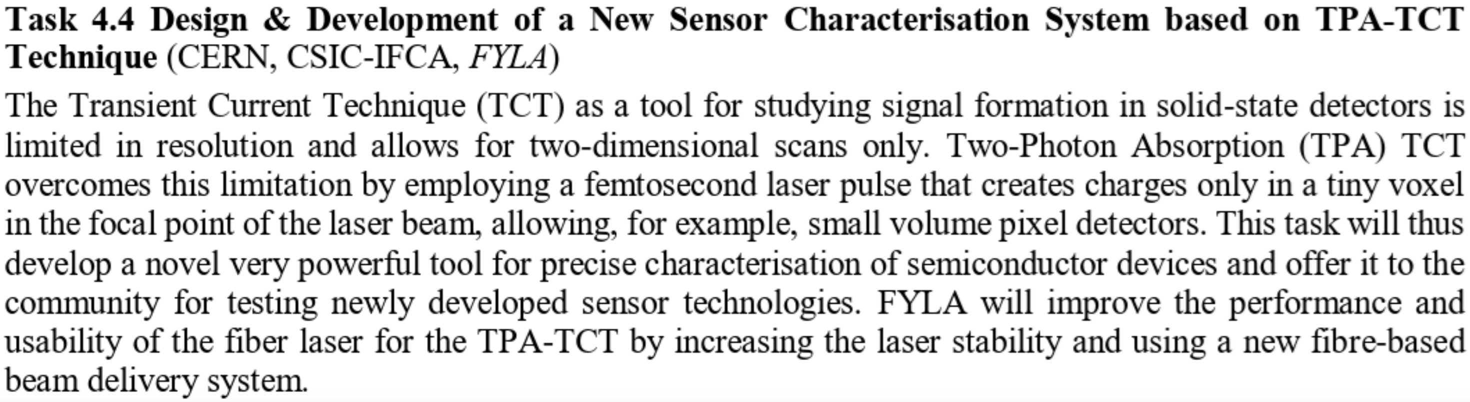
- Objectives:



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:



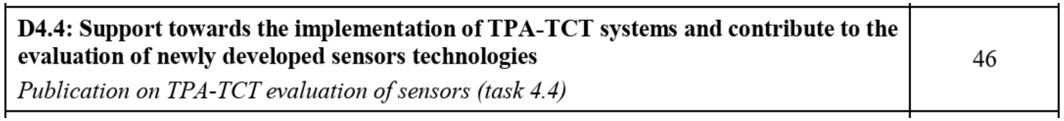
Task 4.4 Design & Development of a New Sensor Characterisation System based on TPA-TCT Technique (CERN, CSIC-IFCA, *FYLA*)

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