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Advancement and Innovation for Detectors at Accelerators
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MILESTONE REPORT

COMMISSIONING OF A COMPLETE TPA-TCT SYSTEM

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Abstract:

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, the characterization of small volume pixel detectors. The proof of concept for the TPA-TCT technique on silicon sensors was previously obtained in a complex laser facility and found to be very valuable for a large range of applications. This triggered the development, design and construction of a custom made bench-test system for TPA-TCT measurements. In this report we provide a summary on the final commissioning of this newly developed table top TPA-TCT system at CERN, Geneva, Switzerland and CSIC-IFCA, Santander, Spain.

AIDAinnova Consortium, 2023
For more information on AIDAinnova, its partners and contributors please see http://aidainnova.web.cern.ch/

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Executive summary

We report on the commissioning of two tabletop Two-Photon Absorption Transient Current Technique (TPA-TCT) systems that have been installed at CERN, Geneva, Switzerland and at CSIC-IFCA, Santander, Spain.

1. INTRODUCTION

The transient current technique (TCT) has been established as a standard tool for the characterization of unirradiated and irradiated silicon particle detectors over the last two decades [1]. In laser based TCT, laser light in the visible or near-infrared range is used to generate electron hole pairs inside the detector material. The drift current, resulting from the movement of the generated charge carriers in the biased silicon detector, is measured. The light can be injected from the top or bottom of the device under test (DUT), as well as from the edge (edge-TCT [2]). The wavelength of the light can be tuned such that charge is created only in a localized volume at the surface of the detector. In any case, conventional TCT, based on single-photon absorption (SPA), results in a 2-D spatial resolution, since the measurement is insensitive to a change of the position of the DUT along the beam axis. To achieve a fully 3-D characterization of silicon detectors, nonlinear absorption of light can be used.

The first description of two-photon absorption (TPA) was published in 1931 [3], while the first experimental confirmation of the process was only possible after the invention of the laser. For silicon detector testing, a wavelength of the light is chosen such that linear absorption is negligible. In this case, a single photon does not have enough energy to create an electron hole pair and the detector is transparent for the injected light. Only with a high enough intensity at the focal point of the laser, charge carriers can be created by the absorption of two photons. The focal point of the laser can be moved inside the silicon detector resulting in a 3-D resolution. In addition, due to the use of strong focusing optics, the beamwidth is significantly smaller than in current conventional TCT setups, resulting in an improved spatial resolution transverse to the beam propagation direction. This development is especially important, following the trend of ever thinner and higher granulated pixelated detectors.

TPA-TCT measurements performed at the Universidad del País Vasco (UPV)/Euskal Herriko Unibertzitatea (EHU) laser facility in Bilbao, Spain from 2013 onwards have demonstrated the feasibility and the potential of this new method for the silicon detector community [4, 5, 6]. This triggered the wish for a versatile and compact TPA-TCT setup. The corresponding development of the system started in 2018 with financial support from the CERN Technology Transfer Fund. A consortium of four scientific institutions and the laser company Fyla developed the first two table-top prototypes at CERN and CSIC-IFCA, Santander, Spain [7, 8], introduced a series of improvements to the method itself [9], produced a series of scientific results [10, 11] and brought the system, within the framework of AIDAinnova, to full operation. In this document, we report on the commissioning of the two TPA-TCT characterization systems: In section 2 we give a detailed description of the TCT and the TPA-TCT technique and highlight the advantages and drawbacks of the TPA against the standard approach. In section 3 we describe the custom-made TPA-TCT laser developed with the Fyla company and finally in sections 4 and 5 we report on the commissioning of the full systems and the most recent scientific results obtained.

2. THE TPA-TCT TECHNIQUE

The Two-Photon-Absorption Transient Current Technique is a new tool that mixes the Two Photon illumination techniques, already employed in radiation testing of microelectronics, with Transient Current Technique, for the characterization of the bulk of semiconductors detectors. It was first presented at the 25th RD50 workshop at CERN [12], and demonstrated at the SGIKER laser facility of the University of the Vasque Country (Spain) [4-6].

2.1. THE TCT TECHNIQUE

The Transient Current Technique (TCT) is an experimental method used to investigate the transport of charge carriers in semiconductors. In this technique, non-equilibrium charge carriers generated inside a semiconductor detector are separated using a reverse bias field. The current induced by the motion of these charges is then amplified by a transconductance amplifier and time-resolved using an oscilloscope. The magnitude and shape of the induced current provide information on the electric field inside the device. By analysing the shape of the curve, it is possible to determine the drift velocity of the carriers and discriminate between drift and diffusion regions.

Excess charge carriers can be generated using particles (such as alpha or beta sources) or using lasers. Laser-TCT can be further subdivided depending on the energy of the photons and illumination direction (see Figure 1).

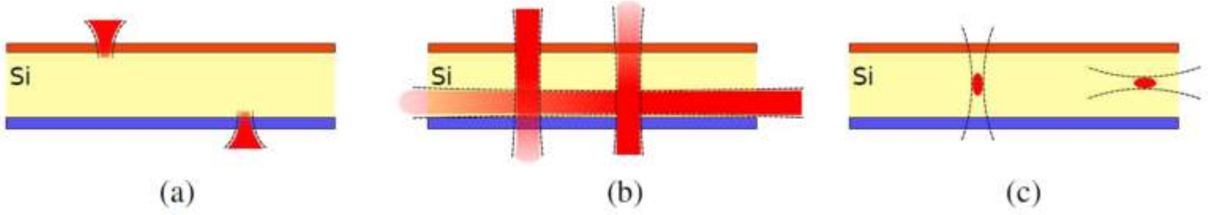


Figure 1: (a) Schematic of the usual illumination and charge generation in the red SPA-TCT. (b) Schematic of the near infrared SPA-TCT. Illumination from the top side, back side, and edge is usually performed. Charge is generated all along the beam propagation path. (c) Schematic of the TPA-TCT, showing the volume of excess charge carriers simplified as an ellipsoid. Illumination from the top side and back side is typically performed. Illumination from the edge is also possible, but often limited in depth by the high focusing.

2.2. THE TWO-PHOTON-ABSORPTION TRANSIENT CURRENT TECHNIQUE

If photons with energies above the band gap energy of the semiconductor are used, then a single photon is sufficient to generate an electron-hole (e-h) pair. This is known as Single Photon Absorption-TCT (SPA-TCT). In silicon, if the photon energy is in the visible range (such as red light), the penetration length of the photons will be very small, and the carriers will be produced very close to the surface as depicted in Figure 1 (a). Red light-TCT takes advantage of this effect to separate the contribution of each type of carrier to the signal formation independently. If the illumination is from the top, only one type of carrier will drift across the bulk. The drift of the complementary type can be obtained by bottom illumination. If the wavelength is in the infrared light range (but still above the bandgap), the absorption will be less pronounced and e-h pairs will be produced along the full beam path inside the detector, mimicking the passage of a minimum ionizing particle (MIP), as shown in Figure 1(b). Side illumination leads to so-called edge-TCT injection. The latter enables depth profiling of parameters such as the collected charge or the collection time of the carriers.

If the energy of the photons is below the bandgap, promotion of an electron from the valence to the conduction band is still possible via the simultaneous absorption of two photons. This process is called Two Photon Absorption-TCT (TPA-TCT). For simultaneous absorption to occur, the photons are focused using a high numerical aperture objective, which also improves the spatial resolution of the imaging. The increase in irradiance at the focus results in a non-linear absorption process, leading to a localized excitation volume. The dimensions of this charge carrier voxel depend on the numerical aperture of the objective and the schematic concept of the charge deposition is shown in Figure 1(c).

The required femtosecond laser pulses have tight specifications in terms of pulse length (60-400 fs), power (1-10 nJ/pulse), wavelength (1550 nm), stability (<5% power change in TPA signal which is related to the change in spectrum of the laser itself) and repetition rate (single pulse to kHz) to comply with the application.

3. THE LASER

The laser system is based in a chirped pulsed amplification architecture seeded by a solitonic passively mode-locked erbium doped fiber oscillator, where the properties of the output pulses from said architecture are configured arbitrarily by free space optics accessories. These accessories allow selection of pulse energy from < 10 pJ to > 10 nJ, pulse repetition rate from single shot to 8 MHz and pulse duration from 200 fs to 500 fs.

3.1. LASER USED FOR THE TPA-TCT SYSTEM COMMISSIONING

The laser system consists of three modules (see the block diagram in Figure 2). The laser pulse source (LPS) is the source of laser pulses, with a repetition rate of 8.2 MHz, central emission wavelength of 1550 nm, and pulse width below 300 fs. The laser pulse management (LPM) module is used to select the energy of the pulses (from <10 pJ to >10 nJ measured at the system output) and repetition rate of the pulsed signal (from 8.2 MHz to single shot) and to arbitrarily commute the laser emission at a response time of 1 ms. The dispersion-scan (D-scan) module comprises a pair of wedges, one of them motorized to select the temporal duration of the pulses in the range of 300 fs to 600 fs. Pulse characterization at the output of the system is performed preferably at the fundamental repetition rate of the pulses, 8.2 MHz. Once characterized, pulse energy, pulse repetition rate, and pulse duration are tuned independently by LPM and D-scan modules. The laser and all its components are described in very detail in reference [7].

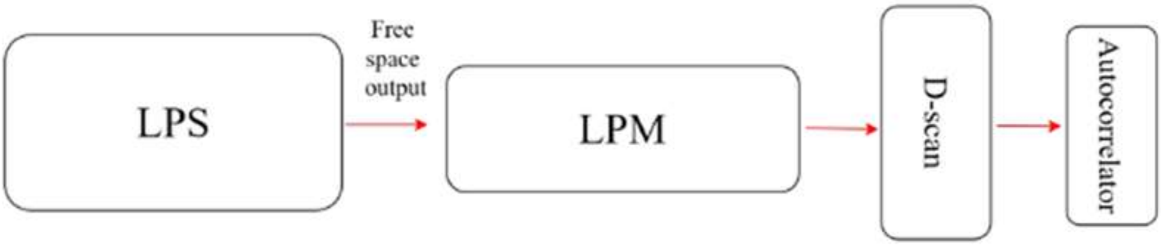


Figure 2: LPS, laser pulse source; LPM, laser pulse management module; D-scan, dispersion management module and characterization of the laser pulse by dispersion scanning.

3.2. OUTLOOK: NEW LASER UNDER DEVELOPMENT

Within AIDAINNOVA Task 4.4 we aim to build a robust and compact source that can deliver the output pulses through an optical fiber while maintaining the coherence and the required average power of the pulses. Therefore, as part of the AIDAinnova deliverable D4.4 planned for January 2025 and in parallel to the commissioning of the TPA-TCT systems at CERN and Santander with the laser described in the previous section, developments for a new compact fully fiber based laser have been performed. From M12 to M23, we have designed a new structure to compact all the modules of the system described in section 3.1 into a single one providing a fiber output delivery. Compared to free-space output, fiber output delivery will reduce the complexity of alignment between the system and the TPA-TCT measurement setup. The fiber used to deliver the output pulses must avoid nonlinear effects during the propagation and must maintain the spectral and temporal properties of the pulses. We have performed a test launching the LFC1500X output pulsed signal into a Kagome hollow core photonic crystal fiber. Kagome fiber has zero dispersion in the wavelength range from 1500 to 1600 nm and nonlinear effects are not generated because the air in the core has a low nonlinear index (~45e-21 m²/W), so the autocorrelation trace of the pulse remains the same.

In Figure 3, the preliminary design of the laser system can be observed. Additionally, figure 4 shows the comparison between the autocorrelated traces of input and output pulses through 3m of Kagome fiber.

Figure 3: New Pulsar design, compacting every module in a single box including a fiber.

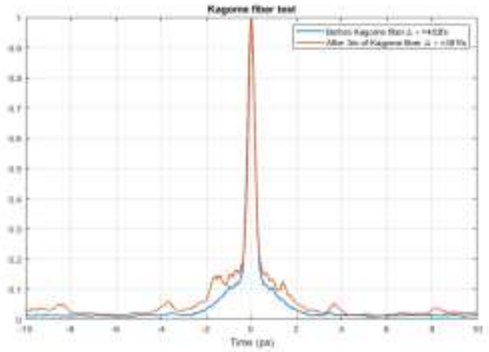


Figure 4: Blue: Autocorrelation trace of the LFC1500X output pulse. Orange: Autocorrelation trace of the LFC1500X output pulse after 3m of Kagome fiber.

4. COMMISSIONING OF THE TPA-TCT SYSTEM AT CERN

4.1. DESCRIPTION OF THE SYSTEM

A first compact TPA-TCT setup was developed at CERN and commissioned in 2021/2022. Technical details as well as a description of the method and first measurement results were published in [7]. The laser was described in detail in section 3.1. The laser source is mounted on an optical table together with a Faraday cage, containing the sample holder. The laser beam is transferred into the Faraday cage and to the sample using low dispersion mirrors and is focused with a 100x microscope objective (NA=0.5 or 0.7). The sample itself is mounted on a printed circuit board (PCB), which is used similarly for SPA-TCT. The PCB is fixed to a chuck, which can be cooled to -20°C using a Peltier element. For positioning of the sample and for performing spatial scans a Newport Hexapod is used.

To correct for fluctuations in the pulse energy or the spectral power distribution 50% of the beam is directed to a reference diode using a beam splitter. The charge is generated in the reference diode via two photon absorption to ensure a good correlation with the device under test. An alignment laser and an infrared microscope arrangement are used to position the sample and determine the location of charge generation.

For applying the bias voltage, a Keithley source meter is used. The transient current, resulting from the drift of the generated charges in the silicon sample, is amplified using a Cividec current amplifier and recorded by a digital oscilloscope. The recorded waveforms are transferred to a computer and stored for data analysis. A schematic view of the setup and a photograph of the optical table with the laser source and the Faraday cage can be seen in *Figure 5*.

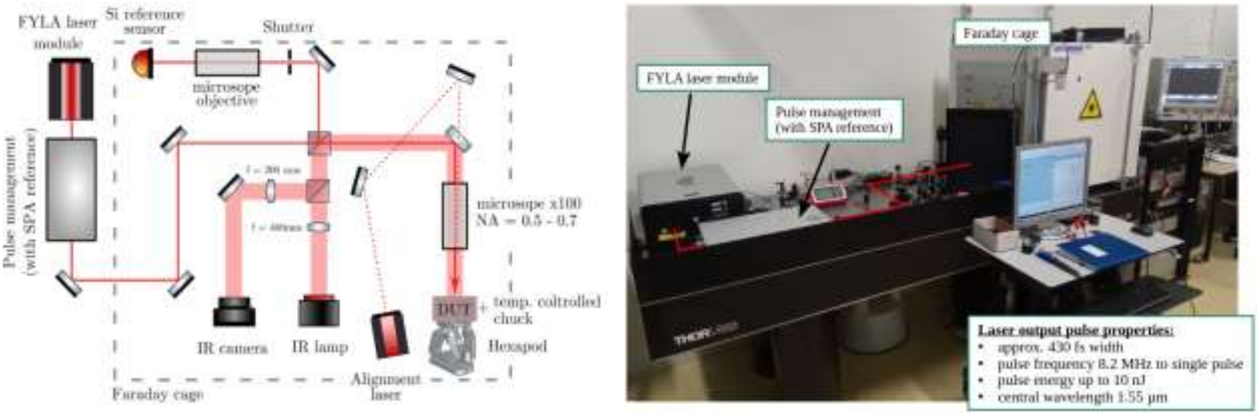


Figure 5: Schematic view (left) and photo of the implemented TPA-TCT setup installed at the SSD laboratory of the EP-DT group at CERN.

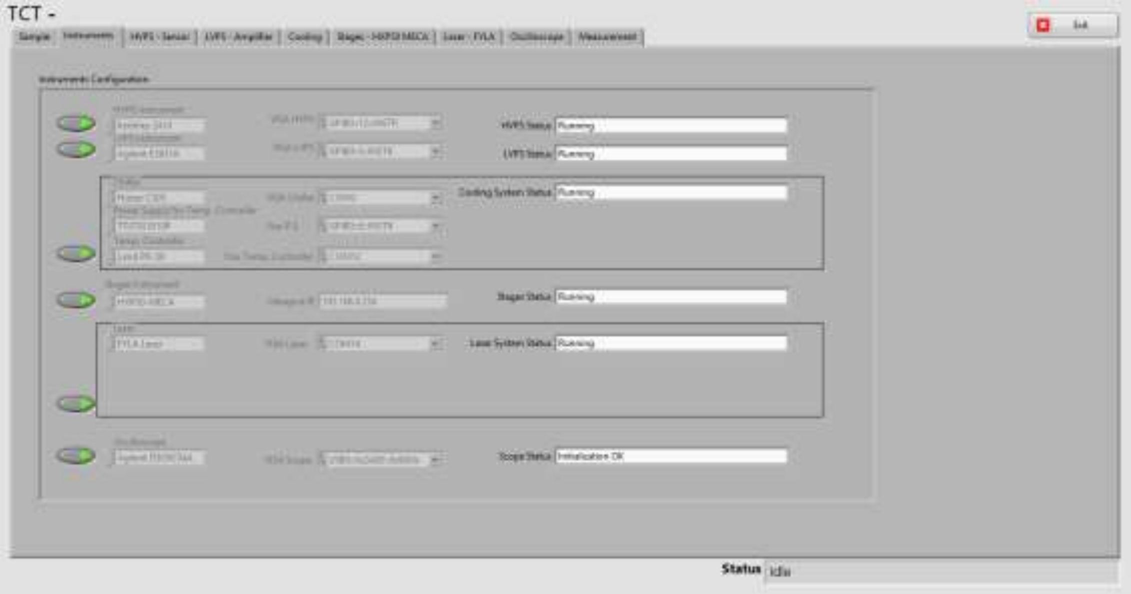
4.2. COMMISSIONING

The requirements to demonstrate the full commissioning of a TPA-TCT setup are driven by the following three objectives: full functionality of the data acquisition system, charge generation demonstrated to originate from the Two Photon Absorption mechanism and expected spatial resolution of the technique reached. In the following, we show the fulfilment of each of those objectives.

For the data acquisition a custom LabView program was developed that handles the measurement chain and the recording of the data. A screenshot of the DAQ program is shown in Figure 6. The program has multiple task windows to control different devices, e.g. the high voltage supply, the Hexapod stage etc., and it has a measurement window, where parameters for an automated measurement can be configured.

The two most important features of TPA measurements are 1) the quadratic dependence of the generated charge on the laser intensity and 2) the resolution, which can be obtained along the propagation direction of the beam.

Figure 7 shows the generated charge in silicon in units of minimum ionizing particle (MIP) equivalent for a 285µm thick sensor as a function of the pulse energy. The generated charge is measured by integration over the full transient current signal of the silicon sensor. The pulse energy was measured with a thermal power sensor. The measurement shows that the generated charge depends quadratically on the laser pulse energy, as is expected for a two photon absorption process.



HVPS Status: Running

LVPS Status: Running

Cooling System Status: Running

Stages Status: Running

Laser System Status: Running

Scope Status: Initialization OK

Status: Idle

Figure 6: Screenshot of the user interface of the LabVIEW based hardware control and data acquisition software.

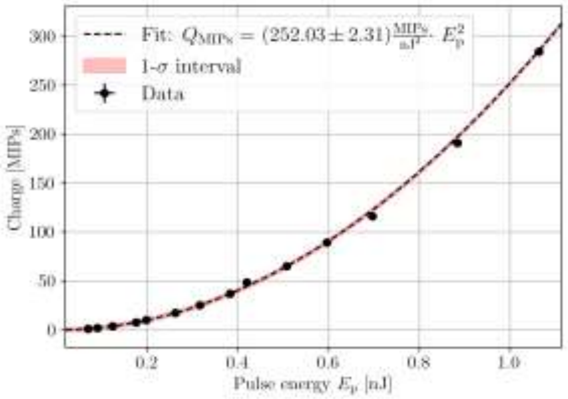


Figure 7: Generated charge in silicon in units of minimum ionizing particle (MIP) equivalent for a 285µm thick sensor as a function of the pulse energy.

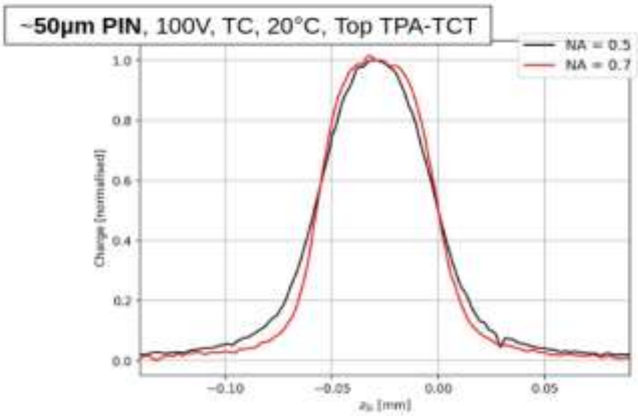


Figure 8: Charge generated in a 50µm thick silicon sensor as a function of the depth of the focal point in the sensor for two different numerical aperture objectives (NA=0.5 and 0.7).

The generated charge in a 50µm thick silicon sensor is shown in Figure 8 as a function of the depth of the focal point in the sensor. Two different microscope objectives were used (NA = 0.5 and 0.7). The measured charge generation profile is in agreement with the expectation from the beam parameters (beam waist w0 = 1.3µm / 0.9µm and Rayleigh length z0 = 12µm / 6µm for NA = 0.5 / 0.7). As expected, zero charge is created, if the focal point is sufficiently far away from the sensor while the light is still passing through it without leading to any measureable single (SPA) or two photon absorption (TPA).

As an example, for the whole measurement routine, an in-depth scan of a PIN detector with increasing bias voltages was performed. The device under test (DUT) is positioned so that the laser is injected in the optical window under normal incidence. The focal spot is moved through the active volume of the DUT and the generated signal is recorded for each position. Figure 9 shows the charge collected in 25 ns against the depth of the focal point inside the active volume of the DUT. It can be seen that the expected behaviour of a depleting PIN detector is measured; increasing bias voltages increase the active volume of the DUT until full depletion is reached. Such measurements are with SPA based methods only possible if illumination is applied from the edge.

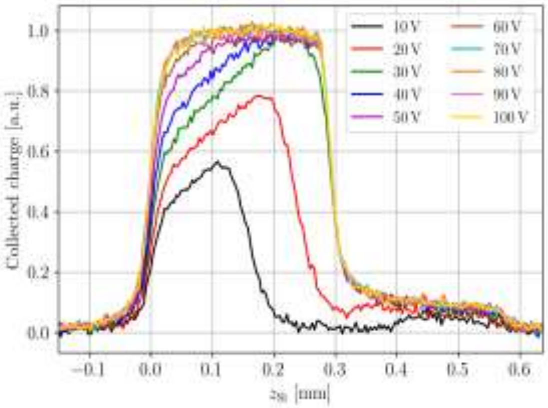


Figure 9: Charge collected within 25 ns after the laser pulse against the depth of the focal point inside the active volume of the DUT, a 300 µm thick silicon sensor.

4.3. IMPROVEMENTS OF CHARACTERIZATION TECHNIQUES

This chapter presents additional developments and applications that took place within the framework of the AIDAinnova project. First, techniques for the investigation of segmented devices are presented. Second, an outlook on additional applications is given, where the use of the setup for Single Event Effect (SEE) testing and the testing of optical links is shown.

The TPA-TCT achieves its great resolution using highly focusing optics that can employ opening angles ≥ 30°. Such high opening angles can lead to laser beam clipping if the laser dimensions exceed the geometry of the DUT. Clipping results in a position-dependent charge generation and hence introduces artefacts in the collected charge profile (see the cone-like structures in Figure 10).

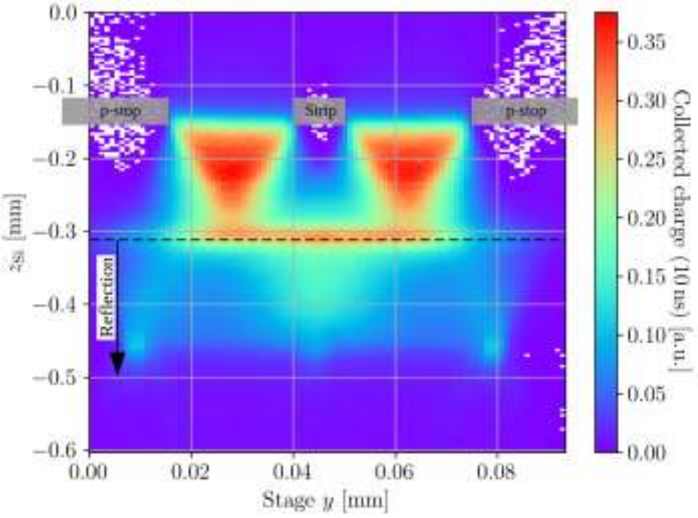


Figure 10: 2D charge collection profile of a strip detector. Light enters between the metallized strip and the p-stop implants into the sensor. Part of the beam is clipped when entering the silicon sensor bulk and in some areas, like directly underneath the strip metal no light arrives to the silicon bulk due to the reflection on the metallized surface on top. However, light reflected at the backside metal plane is reflected back into the bulk of the sensor and gives an image for focal spot positions beyond the physical size of the sensor (see lower part of the figure indicated with "Reflection").

Only quantities that are independent of the generated charge, i.e. laser intensity, are not affected by the varying charge carrier density, which would limit the application of the TPA-TCT to investigate the electric field of segmented devices. Therefore, the weighted prompt current method [9] was developed, which is an extension of the prompt current method [2]. The weighted prompt current method allows to investigate the electric field of a DUT even under the presence of a varying charge generation. Figure 11 shows a comparison between the prompt current method (left) and the weighted prompt current method (right) and it can be seen that the weighted prompt current method does mitigate the cone-like artefacts.

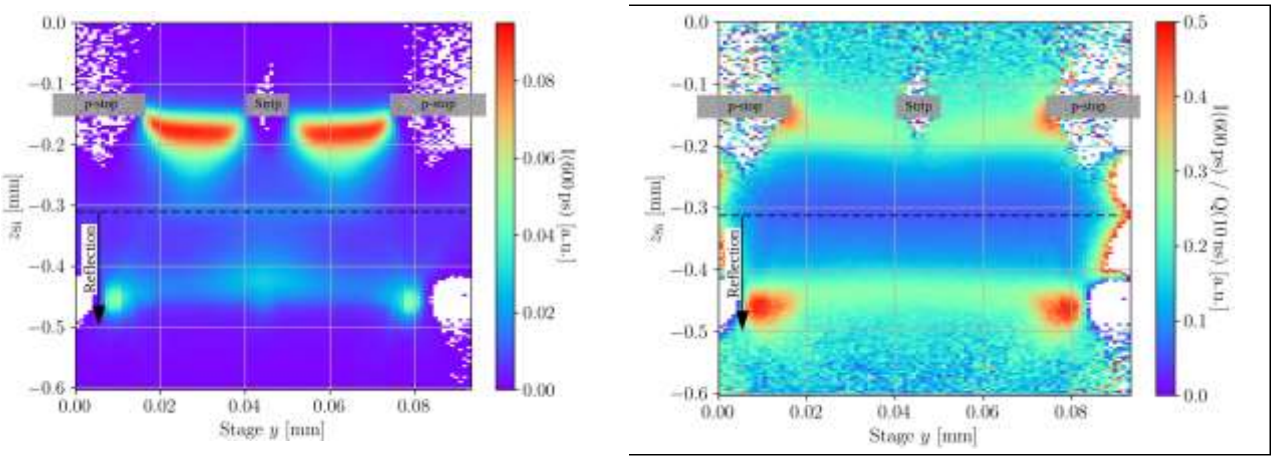


Figure 11: Comparison of measurements analysed with the prompt current method (left) and the weighted prompt current method (right). The plots are originating from the same measured data set. The new weighted prompt current method reduces the measurement artefacts originating from a geometrical inhomogeneous distribution of the laser induced charge generation.

4.4. OVERVIEW OF APPLICATIONS FOR THE TPA-TCT

Finally, some examples of further applications of the TPA-TCT setup are presented in this section including sensor characterisation and the testing of electrical and optical circuits.

The TPA-TCT can be used to measure below top side structures, e.g. the electrode metal, even if illumination is performed from the top side. This is done using the mirror technique that exploits a reflection at a rear side to measure below top side structures [9]. Figure 12 shows the weighted prompt current, measured in a 300µm thick p-type strip detector with a pitch of 80µm and the illumination is employed from the top side. The black dashed line indicates the rear side of the detector, which is metalised. The laser light is fully reflected at the metal and the reflection of the focal point is focused enough to provide an accurate image below the top side strip metal. The reflection allows to probe the DUT below the top side metal, even though the light is applied from the top side. This technique requires a three dimensional resolution and is therefore exclusively available for TPA-TCT.

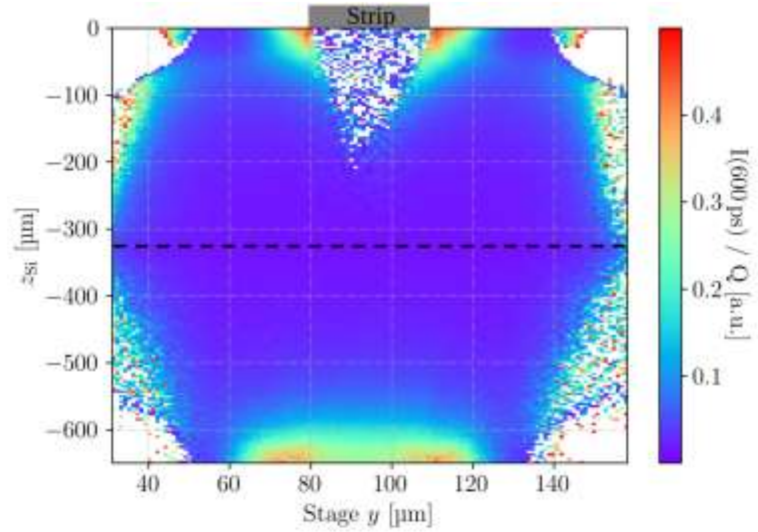


Figure 12: Weighted prompt current map of a 300µm thick p-type strip detector with a pitch of 80µm. The illumination is employed from the top side. The black dashed line indicates the rear side of the detector, which is metalised. All data below this line are originating from a laser beam that was reflected on the back plane. As can be seen, with the reflected beam even below the metal on the strip implantation at the top side.

The TPA technique is already widely used for the single event effect testing of electrical circuits [13]. The feasibility of such campaigns with the TPA-TCT setup at CERN was tested using the RD53B chip as an example. Figure 13 shows an electrical component (left) and a grid scan of this component (right). The yellow color indicates the presence of single event upsets.

Further, the TPA-TCT setup at CERN was used to investigate optical links that are based on silicon photonics. Therefore, absorption measurements were performed, whereby the excellent spatial resolution of the TPA-TCT is a necessity of the measurement. Figure 14 shows a time resolved absorption measurement in an optical fiber, where free charge carriers are generated inside the fiber that increase the absorptivity of the fiber until their recombination. The result is used to benchmark a simulation.

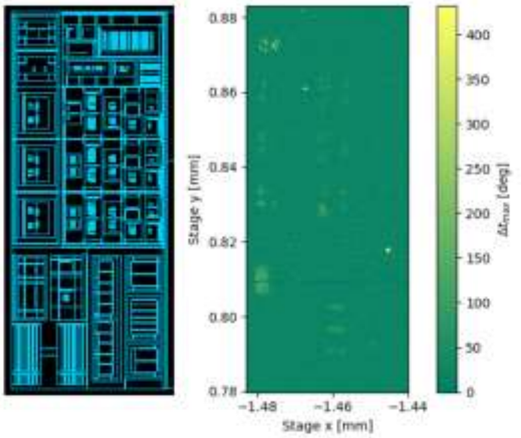


Figure 13: Sensitivity to SEE effects testing on the RD53b chip. Left: Electrical Circuit drawing. Right: Sensitivity map of the circuit to charge injection effects.

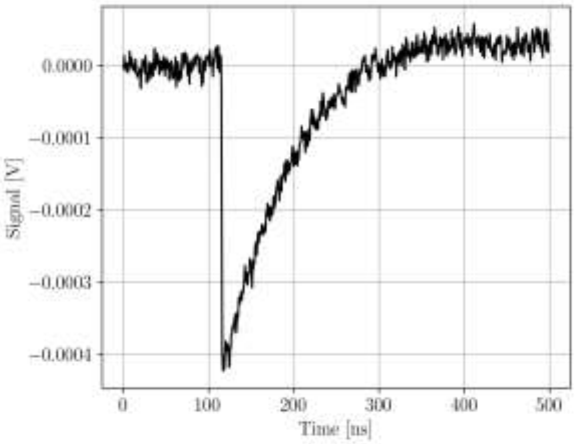


Figure 14: Laser induced signal in an optical fiber.

5. COMMISSIONING OF THE TPA-TCT SYSTEM AT CSIC-IFCA

5.1. DESCRIPTION OF THE SYSTEM

An experimental setup using a second laser from FYLA S.A. was established in IFCA's clean room, based on the architecture outlined in section 3.1 (see Figure 15). However, the D-scan dispersion management module was not incorporated in this particular implementation of the TPA-TCT arrangement.

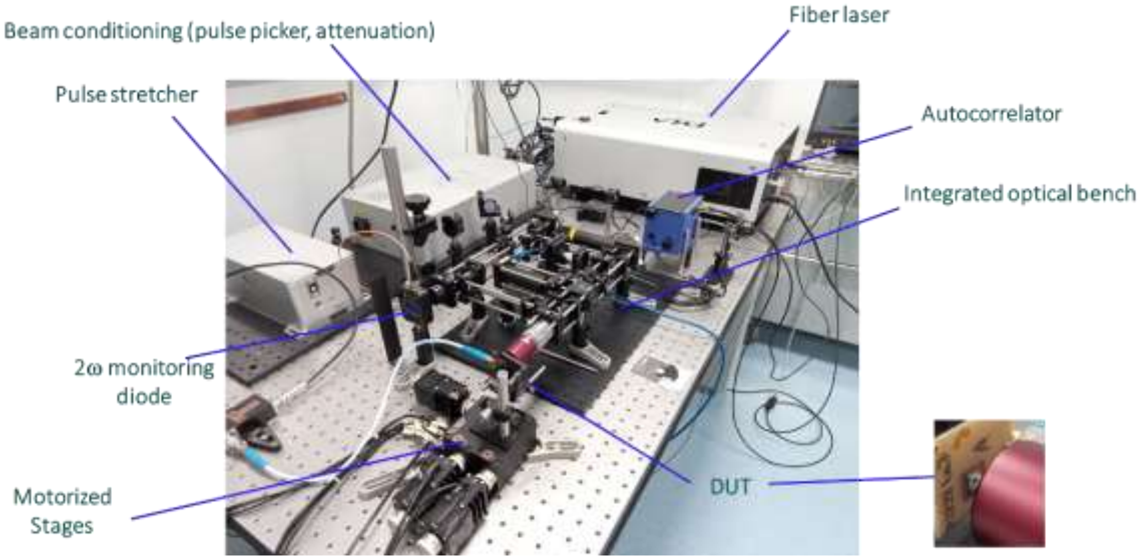


Figure 15 TPA-TCT setup at IFCA, Santander.

In addition to the laser modules, an optical bench, designed by the laser facility service of the University of the Basque Country (UPV-EHU), was installed. This optical bench integrates the optomechanical components required for the alignment and focusing of the laser beam onto the sample, imaging of the laser spot on the sample surface to determine its position and optimize the focusing, and the generation of the laser's second harmonic using a BGO crystal to monitor and correct the TPA signal fluctuations due to laser instability (see Figure 16). Finally, the DUT was mounted into a three axis piezoelectric stage for submicrometric precision displacement.

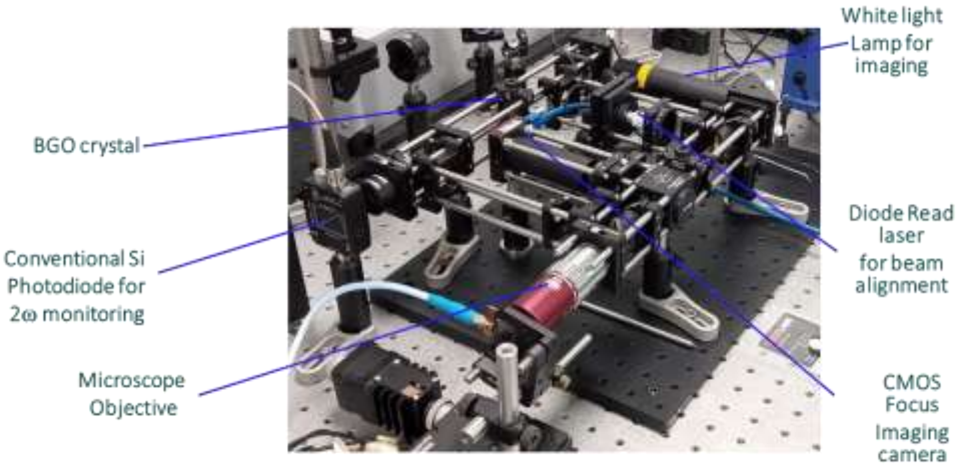


Figure 16 Optical bench showing the main components used for monitoring, focusing and alignment of the laser beam.

5.2. COMMISSIONING

To commission the TPA-TCT setup at IFCA, a z-scan was conducted on a reference 300 μm thick p-in-n diode. The initial study showed an impressive SPA stability below 1%. However, it also revealed significant excursions in the TPA signal amounting to more than 15% peak-to-peak, as depicted in Figure 17.

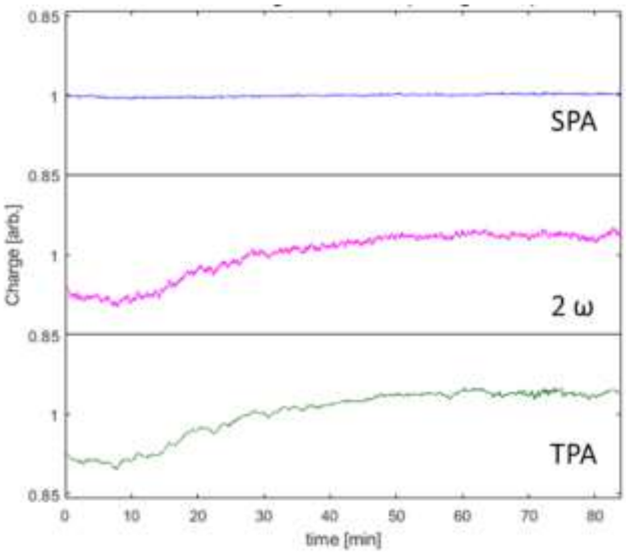


Figure 17 Relative variation of the SPA, 2w and TPA with time.

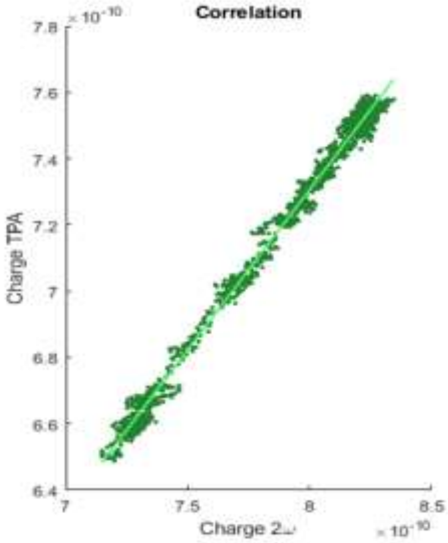


Figure 18 TPA signal vs 2w signal

The poor stability of the pulse temporal profile was probed using a dedicated long-range beam autocorrelation measurement. This temporal instability was identified as the reason behind the TPA signal's instability. As it was not possible to improve the laser's temporal profile stability, the second harmonic (2ω) signal was utilized to correct for the TPA signal fluctuations. Figure 18 shows a linear correlation between the 2ω signal and the TPA signal. The reproducibility of the z-scan profiles on the reference diode before and after the 2ω correction was applied, is illustrated in Figure 19. After applying the 2ω correction, the TPA signal stability was better than 1%.

Currently, the TPA-TCT setup is still waiting to be equipped with a light-tight interlocked enclosure required to comply with safety requirements of a 3b laser. The light-tight and a sample holder with cooling capability is still under design.

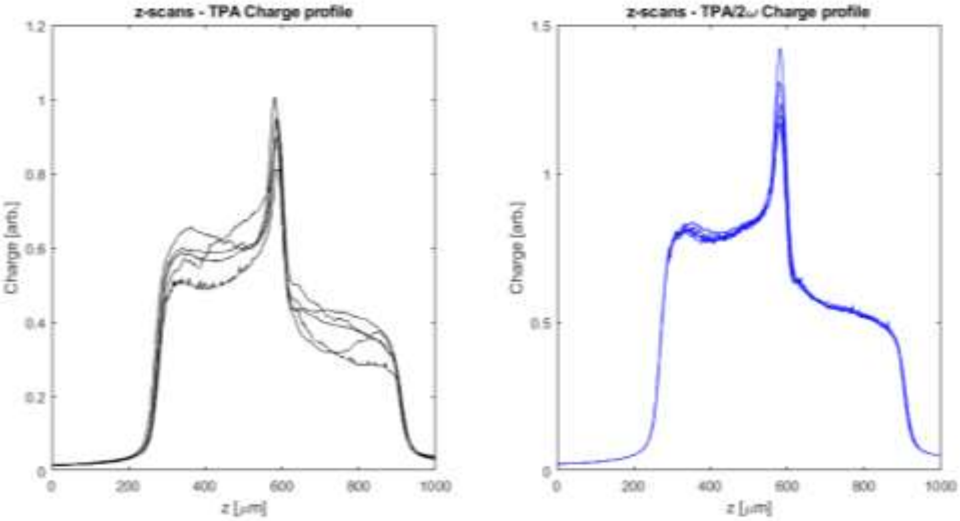


Figure 19 Z-scan profiles before (left) and after (right) 2ω correction. The Z-scan was carried out in a p-in-n diode with a thickness of 300 μm the peak of the profile is due to the metalized back side.

6. GLOSSARY

Acronym	**Definition**
DUT	Device Under Test
LPS	Laser Pulse Source
LPM	Laser Pulse Management
SEE	Single Event Effect
SPA	Single Photon Absorption
TCT	Transient Current Technique
TPA	Two Photon Absorption
TPA-TCT	Two Photon Absorption – Transient Current Technique

7. REFERENCES

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