MECOnet JOURNAL: WORKS in PROGRESS in EMBEDDED COMPUTING (WiPiEC), Volume 5, Issue 1, JUNE 2019

Research Enhanced Learning with Silicon Lab for Characterization of Silicon Detectors

Gordana Laštovička -Medin
University of Montenegro
Faculty of Natural Sciences and Mathematics
Dzordza Vashingtona bb, Podgorica, Montenegro
gordana.medin@gmail.com

Abstract—**In 2025, the Large Hadron Collider (LHC) will be upgraded to the High Luminosity (HL). This will challenge the CMS silicon-based detector performance with very high fluences and long operation time. Sensors have been designed to survive severe radiation damage and tools and methods are developed in order to predict and understand the long-term evolution of the sensor properties. Transient Current Technique (TCT) is one of the important methods to characterize silicon detectors and it is based on the time evolution of the charge carriers generated when a laser light is shone on it. University of Montenegro shows an interest in silicon detector R&D and has recently designed project in order to install first silicon laboratory with TCT setup and a probe station, on its own premises. In the meantime, initial TCT workshops promoting research enhanced learning were conducted. In this paper we share our experiences in relation to designing the lab and creation of outreach program for undergraduate students of physics.**

Keywords-research enhanced learning, silicon laboratory, CMS, TCT, probe station, LHC timing detector, LGAD

I. INTRODUCTION

Research enhanced learning and teaching (RELT) program within Learning Excellence and Development (LEAD) framework is a complex notion, and consequently is based on different understandings and practices across disciplines, institutions and countries [1-2]. There are two major aspects to RELT that we can look to for understanding. First is the way in which we as educators use research to inform our own teaching practice - that is, in the content of our lectures and other materials. Second is how regularly we use ideas and examples from our own research to enrich co-curricular program. In this view of RELT the research is not made explicit, but rather it is embedded within the resources that are presented to the students. However, what is required is a student-focused perspective where links between what is being taught and research are made explicit. The task of bringing research and teaching together potentially affects all the ways in which we think about the university as a site of scholarly practice.

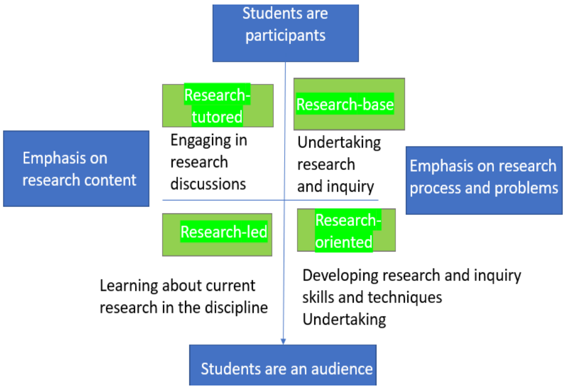

Figure 1. Types of research enhanced learning

There are some crucial guiding open questions: Are our students an audience for research, or are they engaged in research actively, or both? Is the teaching emphasis on the content of the research, the processes of research, or both? How accessible to students is the research carried out in Faculty for Natural Mathematics and Sciences Department? For example, do students know about publications in scholarly journals or other research? The question is also if students are taught only curriculum-based program or they are involved in extra-curricular, co-curricular program. For instance, if students are participants and emphasis in teaching is on research content then we come to *Research-tutored learning*; if students are participants and emphasis in teaching is on research process and problems then we arrive to so called *Research-based learning* where students are undertaking both research and inquiry (Figure 1). Importantly, teaching thus acts as a trigger by allowing those who are researchers and also teachers to think about the material differently and by serving as a catalyst for new research projects.

How to implement research enhanced learning at the BSc level at UoM? The objective of this papers is twofold. Paper presents 1) the program dedicated to developing a silicon laboratory; 2) along with setting up the laboratory, young researchers from the University of Montenegro (UM) will master semiconductor characterization techniques. These techniques will be used in studying state-of-the-art Low Gain Avalanche Detectors. The latter were developed within CERN-

RD50 collaboration ("Radiation hard semiconductor devices for very high luminosity colliders") and have since been identified as most promising detector technology for precise timing measurements and will be used in both large general-purpose experiments ATLAS and CMS after the upgrade of Large Hadron Collider (LHC) around 2026. As these sensors are considered as the main candidates for the future advanced beam monitors allowing detection of each proton delivered to the patient during the therapy, the knowledge gained in the framework of this project will have a much wider use.

II. SILICON LAB AS A LAB FOR RESEARCH ENHANCED LEARNING AND TEACHING

Why silicon lab? University of Montenegro has strong link to HEP community and from 2017, UoM is officially involved in CMS experiment. CMS is nowadays the world larges silicon detector (Figures 2 and 3). With a total surface area of 205 m^2, the CMS Silicon Strip Tracking Detector is by far the largest semiconductor silicon detector ever constructed. Its silicon sensors are patterned to provide a total of 10 million individual sensing strips, each of which is read out by one of 80,000 custom designed microelectronics chips. Furthermore, group of scientists from UoM joined MIP Timing Detector (MTD), which will play essential role during LHC-HL. The MTD detector [3] (Figure 4) includes a very advanced, state-of-the-art, silicon detector system that, when completed, will be the first high precision, large area, silicon timing detector. These state-of-the-art silicon detectors will be characterized in Si-lab and tests measurements will be based on TCT technique and probe station.

There are many more interesting opportunities in sensors testing, radiation hardness studies, and optimization of timing algorithms. This activity in CMS is strongly linked with the CERN-based Silicon R&D RD50. This will foster the integration of a new group from UoM into the Silicon sensors R&D community. One of the great benefits of the participation in RD50 is the access of many types of sensors, and excellent students training. CMS MIP endcaps (ETL) will be also based on the state-of-the-art: Low Gain Avalanche Diode (LGAD).

Reasons for the wide-spread use of silicon detectors in HEP, astrophysics, medicine is as follows: proportional response, good efficiency, good signal-to-noise ratio, segmentation technologically is easily achieved (strips, pixels) but radiation damage affects measurement precision due to worsening of S/N. However, there is limit with time resolution due to saturation of drift velocity. The solution to this problem is to improve silicon detector's performance by increasing the S/N with internal gain, and this gives birth to LGAD. Further optimization of timing performance of LGAD gives birth to UFSD (ultrafast silicon detector) – discovery enabling detector with huge potential to be exploited also for beam monitoring in particle therapy.

Thus, participating in development of radiation hardness detectors such as LGAD would allow us to expand our research not only in particle physics but also in the fields of biomedical engineering and hadron/heavy ion therapy.

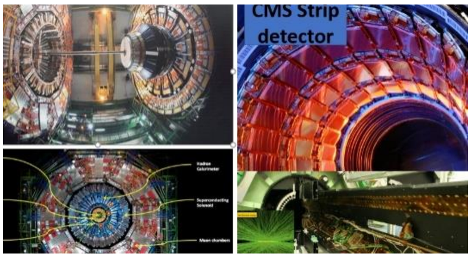

Figure 2. CMS detector; CMS silicon strip tracing and vertex silicon pixel detector

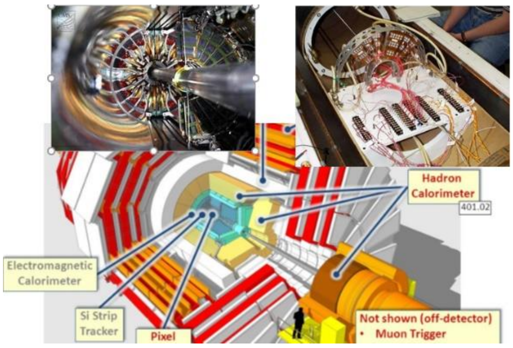

Figure 3. Design of CMS (pixel tracking system is magnified)

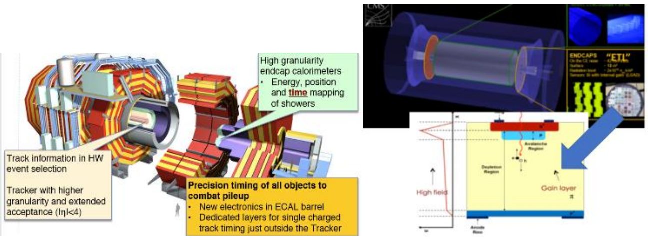

Figure 4. MIP Timing detector (to be integrated into CMS) – LHC Phase II (with increased luminosity); Endcap is based on LGAD sensor.

Thus, Silicon lab presents rich environing for fostering both, scientific research and technology enhanced learning.

III. SCIENTIFIC MOTIVATION

Besides a few indirect signals of new physics, particle physics today faces an extraordinary drought. Very little help in the direction of this path is coming from nature, the burden is on the accelerator and experimental physicists to provide the means for this crossing. Timing is one of the enabling technologies to cross the desert. The inclusion of track-timing in the event information has the capability of changing radically how we design experiments. For instance, timing at each point along the track leads to 4D tracking while timing at each point along the track at high rate leads to 5D tracking – all extremity innovative, and complex concepts.

Low Gain Avalanche Detectors [4] are, as already said, the current state of the art detectors for timing measurements of minimum ionizing particles [5] and will be used both in CMS and ATLAS collaboration [6] experiments. They can be segmented to cell sizes below 1 mm^2, i.e. position sensitive, and hence offer wide range of applications also outside high energy physics. They are based on silicon n^{++}-p^{+}-p-p^{++} structure where the so-called gain layer of 1-2 μm is sandwiched between the highly doped n^{++} implant and p bulk of the sensor. Electric field high enough for charge multiplication is established in highly doped p^{+} layer and results in initial gains of up to 100 (depending on the doping profile), thus allowing operation of very thin (i.e. fast) sensors. Special isolation techniques are used to allow multi-electrode design that prevents the cross-talk and early break down. Recently, a lot of studies have been triggered around the world after the original proposal in 2014 [4] (JSI were among them) with several major silicon detector foundries including Hamamatsu Photonics embarking on their development and production.

The major issue of LGAD is relatively fast degradation of performance with hadron irradiations [7]. After receiving around 10^{15} hadrons cm^{-2} the gain almost vanishes. At LHC experiments the most exposed sensors will receive around $6 \cdot 10^{15}$ hadrons cm^{-2}, which requires replacement of part of the detectors during the lifetime of the experiment [4]. The loss of gain is attributed to decrease of effective doping concentration in gain layer (effective acceptor removal) and consequently the electric field. This is a problem for experiments in high energy physics as well as for potential use in hadron/proton beam monitor for therapies where during patient treatments similar fluence is received in a year.

Understanding of radiation damage and consequences such as degradation gain, breakdown voltage, leakage current of the detectors and changes of their properties in relation to the operation conditions can be studied by employing the probe station and enabling this way CV-IV analyses and TCT (Transient Current Technique). With the help of the CV-IV setup one measures the change in capacitance by varying Voltage and the Change in Current with Voltage. From the I-V plot, for instance, we get information about leakage current and the breakdown voltage for the sensor and from the CV plot we get to know the value of end capacitance once the silicon bulk gets fully depleted. On plotting $1/C^2$ versus Voltage, the value of full depletion voltage is defined from the point of inflection in the curve. Furthermore, since most of the time we do one set of measurement per sensor keeping the varying parameters constant, we don’t know till what extent our measurements are true or consistent with the real values. Therefore, by repeating the measurements with different varying conditions, we can determine the systematic error of the set up. Systematic error (or systematic bias) refers to the consistent, repeatable error associated with an equipment or experimental design. The changing factors in an I-V measurement are temperature and in C-V measurement, the changing factor is temperature and frequency. Similarly, for TCT set up, the varying parameters are temperature and laser intensity which can be altered by changing the shutter opening for both red and Infra-red lasers.

Figure 5 shows image of the Probe station.

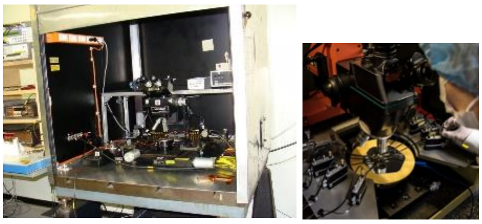

Figure 5. Image of probe station [http://ssd-rd.web.cern.ch/ssd-rd/labo28/default.htm]

Another key player of S-lab is the Scanning Transient Current Technique (Scanning-TCT), which is a powerful tool for probing electric field and carrier transport properties in various semiconductors structures. The Scanning-TCT system has the following feature: Wide band current amplifier; Bias-T; High voltage low pass filter; Laser diode (650 nm, 1064 nm); Programmable laser driver for sub-nanosecond laser pulses; Laser beam optics, beam spot 8 μm FWHM; XYZ moving stages for precise DUT positioning in the beam and focus tuning; Water cooled Peltier mounting block for DUT temperature control; Aluminum closure for light and RF shielding and atmosphere control; Dimensions: 80x40x40 cm’ Weight: 20 kg; Hardware control software (connection via USB); Data acquisition software; ROOT based package for data analysis. An image of fiber coupled laser with optics on translation stage is shown in Figure 6. It contains: Laser diode 660 nm or 1064 nm; Tunable pulse width 0.4 ns - 4 ns; Tunable pulse power equivalent to 10 MIP - 100 MIP in Si; Single pulse mode 50 Hz to 1 MHz, including 1024 bits deep pulse sequence, NIM logic trigger output, NIM external trigger

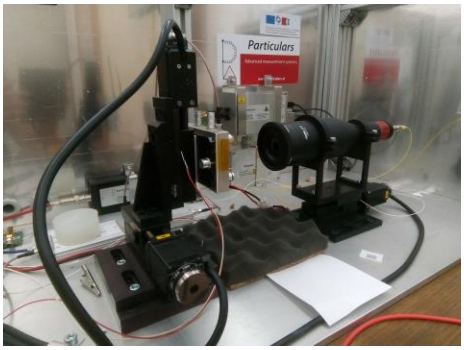

Figure 6. Advanced Scanning TCT system

Figure 6 shows Advanced (for research) Scanning TCT system, while simpler version for education is shown in Figure 7.

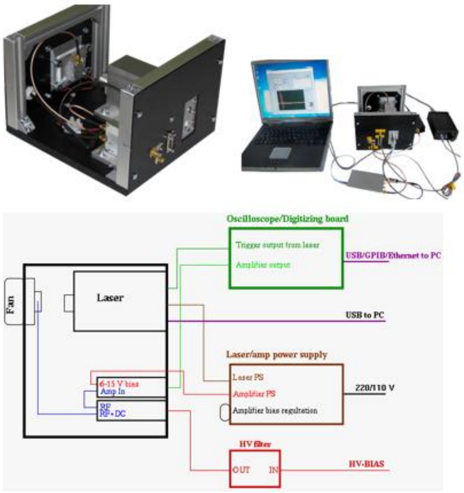

Figure 7. Educational TCT system

The scientific part of the Si-lab lab is characterization of Low Gain Avalanche Detectors after irradiations. Precise knowledge of the degradation of their performance and identified reasons for it will enable projection and better understanding of their use at ATLAS and CMS experiments after the LHC upgrade. The results will also broaden the knowledge of radiation damage in silicon in general.

A. *TCT Working principle*

Transient Current Technique (TCT) exploits the signal induced in electrodes by motion of non-equilibrium free charge carriers in a semiconductor structure. It is one of the important methods to characterize silicon detectors and is based on the time evolution of the charge carriers generated when a laser light is shone on it. The Transient Current Technique (TCT) is used to investigate the electric field profile and the collected charge of silicon detectors

The basic scheme of a TCT system is shown in the Fig. 8

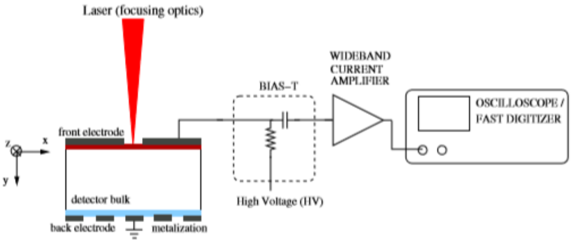

Figure 8. The basic scheme of a TCT system

The detector is connected to input of the transimpedance amplifier. Its output is fed to the oscilloscope. There are two ways of connecting the detector to the amplifier. Either back of the electrode of the detector is at high potential and the front of the electrode at ground or high potential is brought to the front side through so called bias-T which decouples detector bias voltage from the input to the amplifier (AC coupling).

Principles of operation are as follows: The Transient Current Technique is used to measure the current induced by motion of free carriers in a semiconductor device. Free carriers in a semiconductor can be thermally generated but can be also excited (from valence to conduction band) by laser light providing that the photon energy is larger than the band-gap of the semiconductor. Each photon creates therefore an electron and a hole – a so called e-h pair. Upon creation these free carriers: 1) drift if they enter/are generated in the region with electric field; 2) randomly move due to thermal energy (diffusion). The free carriers can be swept by collection electrodes: electrons by anode and holes by cathode. However, on their way to electrodes they can:1) recombine with oppositely charged carriers; 2) get trapped in the energy levels in the band gap of an imperfect semiconductor. They are eventually reemitted (de-trapped) or recombine.

If a reverse-biased detector is being illuminated from the front side, the measured signal originates from the charge carriers equal in sign to the majority carriers in the bulk as presented in Figure 9. The figure shows how the TCT signal in a p-type detector is caused by holes when illuminated from the front side. Illumination from the back-side results in a signal originating from electrons

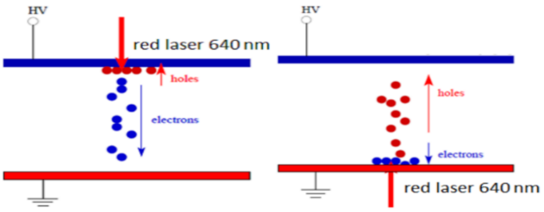

Figure 9. Schematic view of the charge creation process, Top-TCT: The back side of a diode is being illuminated, and the resulting TCT signal comes from electrons. b) Illumination of the front side of the same diode structure results in a TCT signal caused by holes.

The wavelength of the light determines the penetration depth in semiconductor, i.e. the pattern of generated e-h pairs in the semiconductor. For example, the red light generates carries only in first few microns at the surface of a silicon wafer, while infra-red light (1064 nm) generates e-h in few mm (exponential absorption).

The movement of the carries induces the current in the electrodes which is amplified and recorded in the oscilloscope. The current is given by a simple equation:

$$I(t) = e_0 N_{e-h} \exp\left(\frac{-t}{\tau_{eff,e,h}}\right) \cdot \frac{v(t)}{W}, \qquad (1)$$

where N_{e-h} is the number of e-h created at a given place in the detector e0 elementary charge W thickness of the sensor, $1/\tau_{eff,e,h}$ probability of carriers to be trapped and v(t) velocity of their travel, which is proportional to the electric field $v=\mu(E)\cdot E$. In a device where trapping is negligible (most silicon devices) the shape of electric field and mobility can be measured from the shape of the current. In order to be able to measure meaningful results the laser pulses have to short enough, few 100 ps.

IV. PROCUREMENTS AND SETTING THE LABORATORY

Procurements and setting the Laboratory is designed to follow a few steps:

- Procurement and setting up a Probe station for testing silicon sensors and Capacitance-Voltage and Current-Voltage measurements.
- carried out on selected samples to qualify and validate all the measurement techniques. This will include standard pad detectors as well as LGAD sensors
- Irradiation of prototype sensors: The sensors from ATLAS-CMS and RD50 prototype productions will be irradiated at Jožef Stefan Institute's research reactor. This is a reference facility for neutron irradiations in high energy physics with well-known neutron spectrum and dosimetry. One of the aims of the project will be to evaluate the impact of thermal neutrons to acceptor removal in gain layer. Around 20% of natural B which is used in gain layer doping is 10B, which has a large cross-section for capturing thermal neutrons although their displacement damage (NIEL) is very low. As thermal neutron component in both ATLAS and CMS will be different than at reactor it is important to establish the effect. Thus, samples will be irradiated in Cd envelopes to select only fast neutrons. A comparison of acceptor removal rates determined by CV and TCT with and without Cd will give the answer to that question. The dependence removal rate on fluence of fast and thermal neutrons will be evaluated for different gain layer doping. The values will be compared to the past measurements. Devices from different producers (FBK-Trento; Italy, CNM-Barcelona; Spain, HPK-Hamamatsu; Japan and Micron; UK) will be investigated. The annealing properties [8] of standard silicon detectors are well known. However, the annealing behavior of heavily doped p-type silicon is not well studied. We will concentrate on annealing studies of effective acceptor removal rate and at different temperatures in order to establish the temperature scaling. This will allow the prediction of detector operations at HL-LHC

V. FIRST WORKSHOP: TCT AND DEVICE CHARACTERIZATION

While developing strategies for Si-lab design, the first steps towards research enhanced teaching were taken on board. Full TCT (state of the art TCT setup for educational purposes) was brought by Gregor Kramberger from Jozef Stefan Institute to UoM. Figure 10 shows list of workshop's objectives. The data acquisition was fully controlled by a computer. The data taken were stored to disk and analyzed with custom written software SimKDet [9]. The samples were mounted into an aluminum box to assure radio frequency shielding and working principle of TCT were demonstrated using different samples: Float Zone (FZ) 15 kΩcm p-n diode (300 μm), LGAD n-p diode (300 μm) with with moderate gain and LGAD n-p diode (45 mm (SOI)) with very high gain.

The free charge carriers are generated in consequence of illuminating the detector by red laser light. If the front side implantation of the reverse-biased diode is illuminated, the charge carriers, that are collected from the front side, drift to the contact faster than the read-out electronics can respond. On the other hand, the carriers opposite in sign drift through the whole detector to the back side. This transient current is the measured signal. Additionally, TCT working principle were demonstrated when detector was illuminated from 1) back and 2) front side so students were able to spot the differences. If the back side of a n^+-p^--p^+ diode is being illuminated the resulting TCT signal comes from electrons. Oppositely, the illumination of the front side of the same diode structure results in a TCT signal caused by holes.

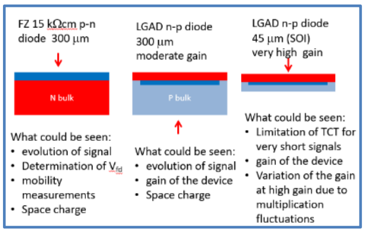

Figure 10. Objectives of TCT workshop at UoM.

Here are some of the parameter's students investigated:

- Depletion Voltage: To find the depletion voltage, the charge collected at certain position between strips for the deferent bias voltages has to be integrated. After reaching the depletion voltage charge stops to increase and becomes constant. Plotting the charge with square root of voltage, the dependency can be obtained, which has to be fitted with two lines - one fits the rising part, second one - the constant part, when all charge is collected (detector is fully depleted). The intersection of these curves gives the value of the full depletion voltage (see Figure 11).

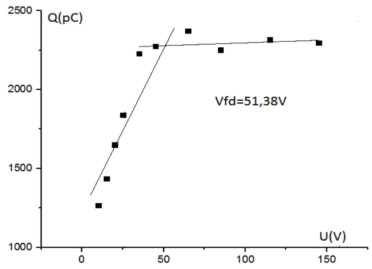

Figure 11. Depletion voltage search, Top-TCT

- Gain of LGAD as explained in Figure12. LGAD was n-p diode 300 mm with moderate gain. Students looked at the evolution of signal in order to recognize different regions of the signal and to determine the gain of depletion layer. They observed the space charge sign and estimated gain from the shape of the current.

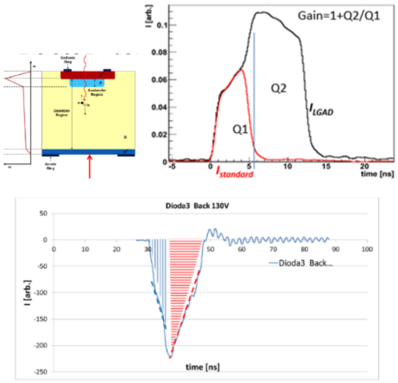

Figure 12. Determination of LGAD gain

- Mobility: The TCT is used to calculate the charge carrier mobility. The 80% of the red light is absorbed after 5 µm of silicon - this is used to measure the charge carrier mobility of deferent type. After applying positive voltage to the strips (p-type bulk sensor from Particulars) and negative to the back side, holes drifting to the back side and electrons to the strips. Shooting from the top side: electrons are collected immediately, and the transit time is the time of the hole drift. The average hole drift velocity through the sensor is given by $v_h = W/t_{transit}$, where $t_{transit}$ is the duration of the signal, W is the thickness of the sensor.

Some photos taken during workshop with TCT are shown in Figures 13-15.

Figure 13. Photos taken during TCT workshop at UoM: Gregor Kramberger demonstrates working principles of TCT.

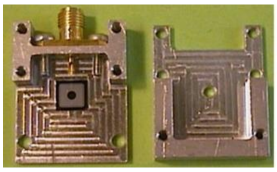

Figure 14. Photos taken during TCT workshop: The aluminum box providing the RF shielding. The sample can be seen on the left-hand side.

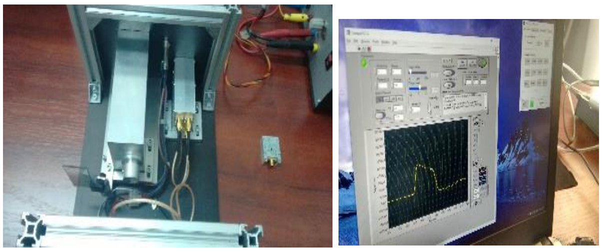

Figure 15. Photos taken during TCT workshop at the University of Montenegro.

VI. CONCLUSION

In this paper we present an approach of research enhanced teaching which we apply while setting up Silicon lab for development and characterization of silicon detectors which are designed for HEP discoveries under huge radiation environment. Here an excellent tracking of time and radiation hardness property of sensors will play crucial role towards enabling new discoveries.

ACKNOWLEDGMENT

We are very grateful to Gregor Kramberger from Josef Stefan Institute for his effort to bring UoM closer to the advanced R&D world of the radiation hardness silicon sensors and the TCT technique.

REFERENCES

[1] Homewood, Brendan Rigby, Angela Brew and Anna Rowe, Ed Glyn Mather, “Research Enhanced Learning and Teaching: Learning through scholarship”, ISBN 978-0-9805685-7-8, Macquarie University NSW 2109 Australia CRICOS Provider Code 000002J.

[2] S. Laursen et al., G. Melton (Eds.), “Undergraduate research in the sciences: Engaging students in real science”, New York: Jossey-Bass, 2010.

[3] MIP Timing (Technical Proposal): https://cds.cern.ch/record/2296612 . TDR Q1 2019.

[4] G. Pellegrini et al., “Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications”, Nucl. Instr. and Meth. A 765 (2014) 12.

[5] H.F-W. Sadrozinski, N. Cartiglia, A. Seiden, “4-Dimensional Tracking with Ultra-Fast Silicon Detectors”, Reports on Progress in Physics 81(2) · April 2017.

[6] Technical Proposal for a Mip Timing Detector in the CMS experiment Phase 2 Upgrade, CERN-LHCC-2017-027, LHCC-P-009.

[7] G. Kramberger et al., “Radiation effects in Low Gain Avalanche Detectors after hadron irradiations”, JINST Vol. 10 (2015) P07006.

[8] G. Kramberger, G. Medin et al., “Radiation hardness of thin low gain avalanche detectors”, NIM A 891, 2018, p. 68.

[9] M. Moll. Radiation damage in silicon particle detectors: microscopic defects and macroscopic properties. PhD thesis, Hamburg Univ., Hamburg, 1999.