Imaging In Space-Time And Tracking (INSTANT): Project Results and Perspectives after one year of activity.

Adriano Lai[1*], Maurizio Boscardin[2], Gian-Franco Dalla Betta[3], Cinzia Da Vià[4], Nicola Neri[5].

[1]INFN Sezione di Cagliari, SP per Sestu km 1.0 09042 Monserrato, Cagliari, Italia;
[2]Fondazione Bruno Kessler, Via Sommarive, 18, 38123 Povo, Trento, Italia;
[3]Università di Trento, Dipartimento di Ingegneria Industriale, Via Sommarive, 9, 38123 Povo, Trento, Italia;
[4]The University of Manchester, Department of Physics and Astronomy, Oxford Road, M13 9PL Manchester, UK;
[5]Università degli Studi di Milano, Dipartimento di Fisica, via Celoria 16, 20133 Milano, Italia.

*Corresponding author: adriano.lai@ca.infn.it

ABSTRACT

The INSTANT system is a video-camera for ionizing radiation having the capability of 100G frames per second, real-time reconstruction and very high radiation resistance. It is based on radiation-hard 3D sensors with trench electrodes and fast front end electronics. During Phase-1 it was demonstrated that a time resolution of 6.5ps is possible with a single channel readout. The key elements to design and demonstrate a full-size pixel system have been identified. They would allow scaling a single channel to pixelated sensor system of several square centimetres. Such a device can have a very wide number of applications ranging from Medicine, Biology, Neutron Imaging and Space science.

Keywords: 3D sensors, Timing detectors, precision physics, FPGA, Real Time Processing Algorithms.

1. INTRODUCTION

The conception of the INSTANT system takes origin from the study of the requirements posed by the High Energy Physics (HEP) experiments of the next decades. Such requirements concern simultaneous space-time precision respectively in the range of tens of micrometres and tens of picoseconds. They foresee the production of a huge data-stream produced at very high rate (1-10 tera-bits per second), to be processed in real-time, in such a way to reduce the amount of data to be stored. Moreover, such a system must operate in very harsh conditions, under high levels of radiation (> 10^{17} 1 MeV neutron equivalent per cm^2).

When exported out from the collider physics environment and assembled in a compact and more *easy-handling* package, such a high-precision system can be seen as a ultra-fast video-camera, capable of producing a high-rate sequence of event representations (images). We plan to develop the technology for:

1. a sensor space precision of ≈ 10 µm;
2. a sensor time precision of ≈ 10 ps;
3. adequately fast pixel read-out electronics;
4. a real-time processor for event reconstruction;

having all the above capable to operate in extremely high radiation fluences, so making the basic components of the INSTANT 100G fps video-camera available.

Such a starting concept uses the same technologies necessary for a precision tracker of the future, developed for detection of charged minimum ionising particles (MIPs). It has therefore a limited field of applications. However, suitable converting devices can be conceived, such to generate charged particles from different kinds of radiation and exploit the same sensing device for different regions of the radiation spectra.

When tracing the design specifications of the INSTANT video-camera, it is therefore necessary to list the requirements 1 to 4 above and then add two more key ingredients:

5. Development of radiation-converting stages;
6. Study of highly integrated packaging solutions.

In this first year, studies have been performed to address the main specifications of the core technology, that is items 1, 2 and 4. Concerning 3, single-channel high performance front-end stages have been designed and assembled.

The results are extremely encouraging:

- 20 ps system timing resolution obtained using 3D trench-electrodes sensors in a test beam experiment under MIPs.
- 6.5 ps system timing resolution obtained in the laboratory using the same sensors exposed to a calibrated laser beam.
- Successful implementation of FPGA-based real time image processing algorithms.

2. STATE OF THE ART

Silicon sensors are the only detectors able to provide excellent spatial resolution, fine pixel size and large area coverage in harsh radiation environments. Different technologies are in use and relevant progress has been achieved in the last decade to tackle the challenges discussed above. Several R&D studies are ongoing to improve the timing performances of silicon sensors towards the frontier of radiation-hard tracking systems with unprecedented space and time resolution. Small capacitance, high signal-to-noise ratio, speed and spatial response uniformity are key ingredients to be considered when designing a high-resolution timing detector. Ultra-Fast Silicon Detectors (UFSD), based on Low Gain Avalanche Diode (LGAD) technology, presently achieve 30 ps resolution up to fluences of 1-2x10^{15} neq/cm^2 [1]. Such devices are currently the baseline for the forward part of the ATLAS and CMS timing layers at HL-LHC [2, 3]. Sensors with three-dimensional electrodes (3D sensors) are also a valid alternative. Since their introduction in 1997 [4], this technology has consolidated: 3D detectors are presently used at the LHC experiments in regions very close to the beam (CMS-PPS [5], ATLAS-IBL [6]), are the adopted technology for the ATLAS Inner Tracker [7] and are good candidates for the LHCb Upgrade-II [8]. The sensors are characterised by cylindrical electrodes deeply penetrating the silicon bulk, perpendicularly to the surface. This unique structure, which decouples the charge carrier drift distance from the sensor thickness, exhibits very good radiation hardness, probed up to a fluence of 3x10^{16} neq/cm^2 [9]. The geometry of 3D sensors is also beneficial in terms of timing performance. Very short collection times can be achieved by choosing small inter-electrode spacing without reducing the substrate thickness, thus preserving the signal amplitude. The fact that the charge carriers are collected perpendicularly to the sensor thickness minimises time uncertainties due to nonuniform ionisation density (delta rays) and charge carrier diffusion.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

INSTANT is a complete detection and image processing system, aimed at the full real-time reconstruction of extremely complex images or events. INSTANT concurrently develops all the key elements of the system, from pixel sensors to data processing electronics, to achieve an outstanding performance far beyond the state-of-the art.

INSTANT is based on 3D silicon sensors, that are here optimized for high time resolution as never reached before. Full exploitation of the fast timing properties of such sensors requires the implementation of a complex pixel front-end, integrating the readout chain, from a fast amplifier to a Time-to-Digital-Converter in a very small area. This also has been never achieved in a particle tracking system. The usage of a new CMOS technology node (28-nm) is necessary to make effective the development of a sensor with superior space-time resolution. Developing an ultra-fast, ultra-small-pitch pixel implies also the production of a large amount of information to be read-out and processed. The traditional separation between front-end and back-end electronics is inadequate to such a complex system. Pre-processing of data, machine-learning real-time techniques for information analysis have to be integrated at the very early stages of the read-out chain. Each individual development pursued in the project is per se highly innovative, but the INSTANT ground philosophy and added value is to face the challenge at the system level.

As a result, the INSTANT is highly disruptive and will revolutionize the field of radiation imaging and tracking. It provides very high time (10 ps or better) and space (~10 μm) resolution per pixel, with embedded data processing for data compression and real-time reconstruction of extremely complex images or events at high rates. By construction, the device is extremely robust against radiation and suitable to be used in very harsh radiation environments (10^{17} 1 MeV neutron equivalent per cm^2 and some Grad). No other imaging and tracking device, either existing or under development, is capable of satisfying at the same time such requirements about space and time resolution, radiation hardness and complex data handling. INSTANT therefore candidates itself to be the core of a favoured option for future research programs in High Energy Physics (high luminosity, future circular colliders, muon colliders) that would otherwise be impossible. Moreover, the INSTANT system could be specialized, and its performance further enhanced for applications in many other fields calling for ultra-fast radiation imaging in harsh environments.

4. PROJECT RESULTS

As specified in the Introduction (section 1), our studies during this Phase-1 year have mainly concerned developments on space-time sensors and real-time processing. The obtained results are summarised in the present section.

4.1. Results on super-fast sensors

Besides an unmatched resistance to radiation fluences, in 3D silicon sensor technology have specific characteristics which make them very suitable for fast timing [10]. Our idea was to perform dedicated studies aiming at optimizing them in this direction. Dedicated simulations [11] indicated the 3D-trench geometry shown in fig. 1 as the most suitable one for such purpose, having the

sharpest distribution in terms of charge collection time of the charge carriers [11].
Encouraged by the outcome of such simulations, a test production batch of 3D-trench sensors was completed at Fondazione Bruno Kessler, partner of this initiative.
Sensors were characterized both in the laboratory, exposed to an infra-red laser beam, and at the πM1 accelerator facility of the PSI (Paul Scherrer Institute, Villigen, Switzerland), exposed to a beam of MIPs, that is charged positive pions at 270 MeV/c momentum.
The PSI setup is shown in fig. 2. Different geometries and read-out schemes were tested. The best result obtained is shown in fig. 3. In this case, at bias voltage $\boldsymbol{V_{bias} = -140}$ ***V***, the estimated intrinsic time resolution (sensor only) was about ***15 ps***. The measured time resolution, including the front-end electronics jitter contribution, was $\boldsymbol{\sigma_t = (20.6 \pm 0.4)}$ ***ps***. Details on the PSI tests can be found in [10].
Such high timing performance was confirmed in the laboratory by tests using an infra-red laser beam (wavelength $\lambda = 1030$ nm). A suitable configuration of the laser optics was adopted, such to obtain a laser waist of cylindrical shape. Inside the sensor bulk, the beam was a cylinder with radius $\boldsymbol{r \approx 5}$ ***μm***, mimicking the charge release profile of a MIP. Details on such experimental set-up can be found in [12]. A different and faster front-end electronics was used with respect to the PSI measurement. By impinging the laser beam in a single point of the pixel surface, the time fluctuations due to the sensor dis-uniformities were minimized and a time resolution of $\boldsymbol{\sigma_t = (6.56 \pm 0.34)}$ ***ps*** was obtained, as shown in fig.4.
All the reported results were obtained using fast custom-developed front-end boards, based on discrete-component bipolar Si-Ge stages. They were directly wire-bonded to single sensor channels. Although 3D-trench pixel matrices were produced in our test production batch, an integrated front-end for precision-timed readout of pixel matrices is still to be developed. Dedicated activities are ongoing within our collaboration team in this direction [13].

4.2. Real time processing

The idea of a ps-framed video-camera demands the capability of a super-fast processing of the huge amount of information generated by the front-end. This is a common problem concerning both tracking at high energy experiments and the envisaged INSTANT video-camera. In both cases the amount and rate of information produced is huge and the capability to store reconstructed objects (events or images) instead of raw data has a strong impact on system usage and operation.
Starting from physics event reconstruction techniques, we developed a fast algorithm, which uses precision timing information. Real-time reconstruction was demonstrated using simulated high-energy collision events up to 40 MHz input rate. A highly parallel algorithm [14] was implemented in FPGA and tested on a stream of data which emulates the output of a tracking system operating at high luminosity with about 1200 charged particles traversing the detector (see fig. 5). By using the timing information, assuming 30 ps time resolution, the processing device is capable to reconstruct event in real time at 40 MHz input rate and 1 μs latency. The reconstruction techniques is based on a massively parallel architecture and can be extended to different event topologies and applications [15].

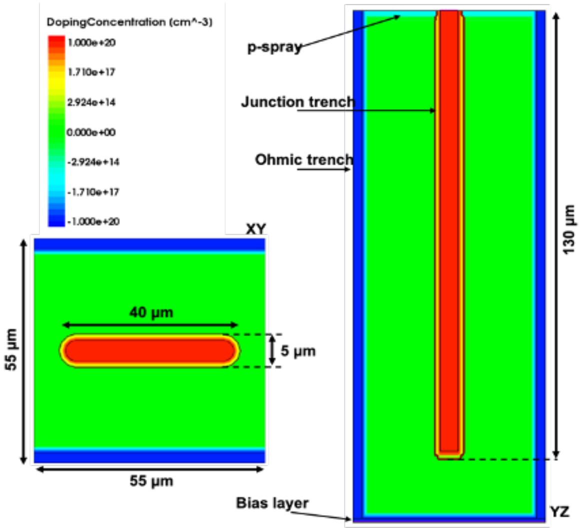

Fig. 1. Geometry of the 3D-trench pixel under tests. Left: transverse XY-cut. Right: Longitudinal YZ-cut.

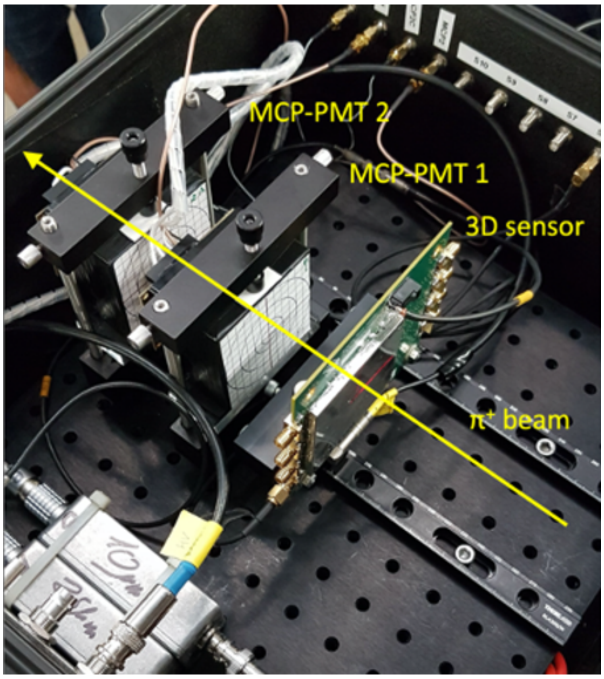

Fig. 2. PSI setup for tests of the 3D sensors exposed to a π+ beam. Two Micro-Channel-Plates (MCP-PMT 1 and 2) were used in coincidence as a time tagger with time resolution ≈ 15 ps.

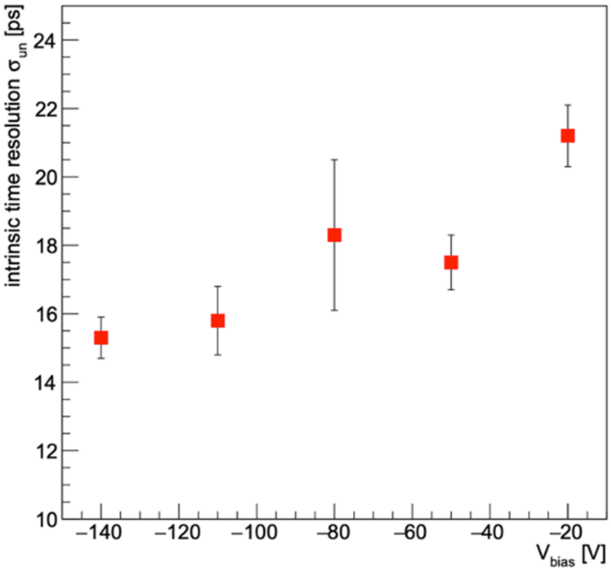

Fig. 3. Intrinsic sensor time resolution with respect to bias voltage.

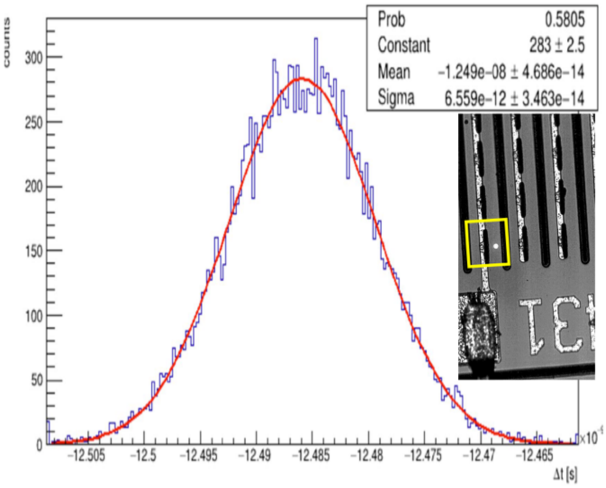

Fig. 4. Time distribution from sensor tests exposed to a infra-red laser beam. Inset: picture of the pixel surface with visible impinging laser spot**.**

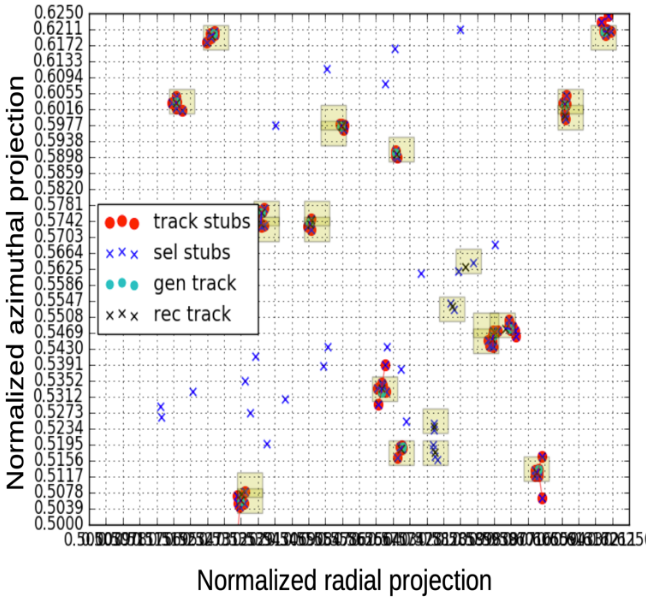

Fig. 5. Output of the real-time reconstruction algorithm, showing track projections in polar coordinates. A stub is a time coincidence between two adjacent planes. The matching between reconstructed and generated tracks is evident.

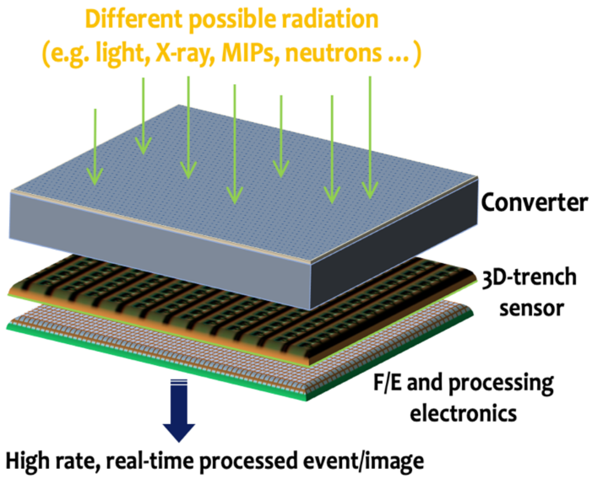

Fig. 6. A sketch of INSTANT2 device, separately showing the main components and stages.

5. FUTURE PROJECT VISION

INSTANT2 (the Phase-2 INSTANT device) is a compact and modular device of some dm^3 size, having an embedded high-performance timing sensor ($\sigma_t \approx 10$ ps) and fast front-end electronics with real-time image processing capabilities. It is extremely effective for a very wide area of applications. A sketch of the INSTANT2 concept is shown in fig. 6. The highlighted stages from the top include:

- The Converter, which would allow adapting the readout to the impinging radiation. Converting materials would include high Z semiconductor layers, efficient photocathodes in the visible and infrared, neutron and gamma converting materials. This stage could also include a static multiplication layer, if necessary.
- The 3D Si Sensor Core, where precision space-time sensors would convert the electrons generated by the Converter into ultra-fast electrical signals.
- F/E and processing electronics which would readout and pre-process the fast signals to

prepare them to be reconstructed in real-time and visualised.

5.1. Technology Scaling

The main steps required for scaling the Technology Readiness Levels (TRL) of INSTANT achieved in Phase-1 will mainly involve:

- design of a dedicated pixelated readout electronics,
- development of suitable Converter stages,
- packaging and integration.

The production of a demonstrator comprising the full system would allow reaching a TRL 5-7 after 3 years. Preliminary studies of a CMOS 28-nm readout electronics chip are encouraging [13]. Furthermore, integration and packaging fulfilling the requirements imposed by a fast readout have been implemented already in high speed photodetection [16].

5.2. Project Synergies and Outreach

Many applications of INSTANT2 satisfy benefits of the proposed research to health, demographic change and wellbeing societal challenge.
Collaboration studies on **fast gamma-detecting crystals** have boomed in recent years also thanks to developments on Positron Emission Tomography (PET) and their possible use “in-vivo” during cancer treatment at hadron beam lines. We would welcome collaborating with ATTRACT groups involved in crystal development and PET systems.
Neutron converting media have also undergone important developments thanks to projects like the European Spallation Source at Lund, Sweden. Members of the INSTANT consortium already have contacts with groups at Synchrotron Light Sources working in protein crystallography and material science.
The enlargement of the INSTANT consortium would **include expertise in converting media** to equip demonstrators capable of fast 2D imaging in the above-mentioned fields.
Another key step towards INSTANT2 is integration. **Collaborations with interconnection companies** who would study the best option to preserve the overall system bandwidth, while including modern options for cooling and packaging, are necessary.
Finally, **collaboration with end users in medicine and biology** to validate the system in real environments would also be important.
During Phase-2 we would enlarge the INSTANT consortium with 3 extra collaborators (converter developers, packaging developers, end users in medicine).
This project would require three years and production of 3D sensors (150kEuro), electronics (300kEuro), interconnectivity and packaging (200keuro), converting material deposition (200kEuro) and static electron multiplication (100kEuro), real-time processing device (150k). Funds would be needed for engineering work to design, simulate and test detectors and electronics (400kEuro). Finally, 300kEuro would be requested to support post-doc researchers, for travels, meetings, conferences and publications.

5.3. Technology application and demonstration cases

Precision Radiation Detectors are at the core of several scientific fields of research. In High Energy Physics, high precision in space and time have seen recently the first significant experimental evidence in the measurement of an ultra-rare decay by the SPS NA62 experiment at CERN [17]. This was possible thanks to a tracking system capable of 65ps precision [18]. Higher precision is necessary for the LHC experiments to disentangle the high multiplicity of events foreseen after the accelerator upgrade to high luminosity.
In biology, protein crystallography is being used to visualize protein structures after they have been crystallized at low temperature. To extract an image, the crystallized protein is exposed to a high intensity synchrotron x-ray beam. The process used allows one single exposure of the biological sample to the beam since its high intensity destroys it. Several medical conditions like Alzheimer and Parkinson seem to be related to a different folding of a particular protein. Only an ultra-fast detector would allow imaging the folding of the protein during beam exposure and understand the effect of possible drugs to the process [19].
In medicine the holy grail of fast imaging is Time-of-Flight PET with correlated 511 keV gamma pair detection time resolution of 10 ps [20], which can be achieved by INSTANT2.

5.4. Technology commercialization

Commercialization of this technology would be possible after the production and validation of a working prototype. The intention would be to start a company which would assemble the device and propose at the same time a software suit to analyse and visualize the obtained data. No concrete step has been initiated at the moment.

5.5. Envisioned risks

The risks associated with the INSTANT2 project are mainly associated with the fabrication and integration of the components forming the various stages of the system. They can be summarized as follows:
Risk1: Silicon 3D CORE fabrication failure or delay. Mitigation: Use an alternative fabrication facility.
Risk2: Fast Electronics chip errors. Mitigation: perform a thorough simulation of all the key components.
Risk3: Integration failures. Mitigation: proceed with at least 2 integration facilities.

5.6. Liaison with Student Teams and Socio-Economic Study

We intend to take the opportunity of liaising with MSc students with enthusiasm during Phase-2. Several members of the INSTANT consortium are from Universities and will participate actively in enabling this process with an involvement of students to the research, through seminars and lectures on the subject and experimental demonstrations in the lab.

The INSTANT consortium would be willing to participate to a socio-economic study of the ATTRACT initiative and ecosystem with interviews and by providing technology impact references.

6. Acknowledgement

The authors wish to thank all the members of the INFN TIMESPOT team, substantially contributing to the results reported in this document. This project has received funding from the ATTRACT project funded by the EC under Grant Agreement 777222.

7. References

[1] R. Arcidiacono et al., State-of-the-art and evolution of UFSD sensors design at FBK, Nuclear Inst. and Methods in Physics Research, A 978 (2020) 164375.

[2] ATLAS Collaboration, "Technical Proposal: A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade, CERN-LHCC-2018-023, LHCC-P-012, 2018.

[3] CMS Collaboration, "A MIP Timing Detector for the CMS Phase-2 Upgrade. Technical Design Report, CERN-LHCC-2019-003, CMS-TDR-020, 2019.

[4] S. Parker et al., 3D – a proposed new architecture for solid-state radiation detectors, NIMA395, 328-34 (1997).

[5] CMS Collaboration, The PPS tracking system: performance in LHC Run2 and prospects for LHC Run3, to appear in JINST (2019).

[6] B. Abbot et al., Production and integration of the ATLAS Insertable B-Layer, JINST 13 (2018) T05008.

[7] S. Terzo, The Phase-II ATLAS ITk pixel upgrade, Journal of Instrumentation 2017, vol 12 no. 7, C07023.

[8] LHCb collaboration, VELO Framework Technical Design Report for the LHCb Upgrade II, 2020, in preparation.

[9] J. Lange et al., Radiation hardness of small-pitch 3D pixel sensors up to a fluence of $3\times10^{16} n_{eq}/cm^2$, JINST 13 (2018) P09009.

[10] L. Anderlini et al., Intrinsic time resolution of 3D-trench silicon pixels for charged particle detection, published on JINST, temp. id. 82 (2020) P0420; arXiv:2004.10881.

[11] A. Loi, A. Contu, A. Lai, Analysis and timing Optimisation of 3D silicon sensors: the TCoDe Simulator, 2020, submitted to JINST; arXiv:2008.10730.

[12] A. Lai, Timing characterization of 3D-trench silicon sensors, published on JINST, temp. id. 136 (2020) P0420.

[13] L. Piccolo et al., The first ASIC prototype of a 28 nm time-space front-end electronics for real-time tracking, PoS TWEPP 2019 022, doi:10.22323/1.370.0022.

[14] N. Neri et al., 4D fast tracking for experiments at high luminosity LHC, 2016 JINST 11 C11040.

[15] M. Petruzzo et al., Progress toward a fast-tracking pixel detector, talk given at the CdT workshop, Princeton 2020, https://indico.cern.ch/event/831165/contributions/371710/

[16] GS Jeong, W Bae, DK Jeong. Review of CMOS Integrated Circuit Technologies for High-Speed Photo-Detection. *Sensors (Basel)*. 2017;17(9):1962. Published 2017 Aug 25. doi:10.3390/s17091962.

[17] NA62 Collaboration, An investigation of the very rare K+ → π+νν decay. arXiv:2007.08218.

[18] G. Aglieri Rinella et al, The NA62 GigaTracker: a low mass high intensity beam 4D tracker with 65 ps time resolution on tracks, 2019 JINST **14** P07010.

[19] S. Majid, JH Power, HJ Grantham, Neuronal response in Alzheimer's and Parkinson's disease: the effect of toxic proteins on intracellular pathways. *BMC Neurosci*. 2015; 16:69. Published 2015 Oct 23. doi:10.1186/s12868-015-0211-1.

[20] M. Conti, B. Bendriem, The new opportunities for high time resolution clinical TOF PET. *Clin Transl. Imaging* 7, 139–147 (2019). https://doi.org/10.1007/s40336-019-00316-5.