Ultra-fast infrared detector design and test for ground-based astronomy telescope

Alessandro Drago

The detection of the first gravitational wave in 2015 by the LIGO-VIRGO collaboration has opened a new era for the astronomy, that now can correlate even more types of signals from the space. After the classic and historical astronomy in the visible, after gamma rays and the other electromagnetic waves antennae, after neutrinos and cosmic ray detectors, it is now possible to consider the multi-messenger astronomy as a new approach to have a more complete and deeper vision of the universe. Goal of this philosophy is to evaluate how the synchronized arrival of quite different signals from the same astronomical source can give us a more detailed description of the events. If we consider the technologies implemented and analysing detectors and telescopes from the point of view of the location, the situation is very varied. Nowadays, observatories are placed both on the earth and in the space with different pros and cons. On the ground the preferred sites are on plateaus like Atacama or high mountains like Mauna Kea, or underground, like the Gran Sasso INFN Laboratory, or under the sea (KM3NeT), or even in the Antarctica for neutrinos. In addition, many artificial satellites, first the Hubble Space Telescope, are dedicated to astronomical observations.

Focusing on the photon detection, different approaches and technologies are used for observing remote sources in gamma or X rays, UV or visible, infrared, micro or radio waves. Considering in particular the infrared detection, some telescopes are for satellites, like JWST (James Webb Space Telescope) and WISE, a NASA IR telescope for long periods puts in hibernation, while others are ground based, like three infrared recent instruments: VIRCAM (the VISTA InfraRed Camera), MOONS (The Multi-Object Optical and Near-infrared Spectrograph) and ERIS-NIX, both by the European Southern Observatory (ESO)'s Very Large Telescope (VLT). For example, as comparison, the experiment MOONS uses the HAWAII-4RG detector by Teledyne Technologies (16,7 Megapixel of 15 square micron each). This detector can work up to 5 or 10 MHz. The launch of the JWST (budget 10G$), expected by the end of the year 2021, focuses the most current research on the infrared range which until now has perhaps received less attention than the other electromagnetic signals for many reasons, both astronomical and technological. MIRI, the Mid InfraRed Instrument, part of JWST, has four goals. The MIRI optics take full advantage of state-of-the-art large-format mid-infrared detector arrays. Three focal plane modules with 1024 X 1024 pixel Si:As detector interface to the Optical Module, with one array dedicated to imaging, coronagraphy, and low resolution spectroscopy, and the other two used in the medium resolution spectrometer. From MIRI specification (The Mid-Infrared Instrument for JWST, II: Design and Build, page 24), the detector frame read-out time is typically about 3 s. About the ground-based astronomy, it is well known that the terrestrial atmosphere shows a transmission window for the infrared. However, in the satellite, even if the radiation is not screened by the atmosphere, the infrared detection activity is often limited in time because the IR detectors usually need to be cooled by cryogenic system to maintain the noise to an extremely low level. This can be done by using material which, after some time, runs out. The IRAS telescope satellite worked only for 8 months. Ground-based observations do not have the time limits (for the cryogenic plant) and the atmospheric IR transmittance window can be used to make astronomic signal detection. In this scenario, a not very explored and interesting case, could be the fast and ultra-fast infrared detection, that is the goal of this thesis. Studies on astrophysical signals with fast transient seem more promising and interesting every day, as demonstrated for gamma ray bursts/flares or for the FRB (fast radio bursts). In the latter case, transients <1 ms have been observed.

In this research proposal, the author aims to design a low-cost detector based on HgCdTe semiconductor to be used for astronomical infrared fast transients, of the order of ns. The philosophy of the proposed detector consists in observing the IR signal longitudinally (which means recording time tracks) rather than transversely (which means taking pictures) as it is usually done by competitors. Time tracks of any length can be stored and analysed by using post-processing software tools. Recorded time tracks can be used, after cleaning the noise and applying Fourier transform, to frequency studies, too. Indeed, experiment done by the author in the past years at the IR beamline from DAFNE (INFN-Frascati) has shown the possibility of record the damping on/damping off instability of the longitudinal (synchrotron) frequency sideband. The proposed detector can potentially manage signals with rise time/fall time of the order of 1 ns [see ref. below]. The goal is to design and build a prototypal detector that shall be based on HgCdTe photovoltaic or photoconductor devices with most likely 0.1x0.1 mm2 area for each pixel. They could be placed on a small pcb (printed circuit board) with 19 single-pixel detectors arranged as a hexagon covering an area of about 5x4 cm. The device will have a single pixel connector (38 pins) output to evaluate the correct working of each single pixel and other three outputs adding all the pixel signals: I) DC-low frequency, amplified on the board, having low impedance out; II) DC-mid frequency, not amplified, for a high impedance out; III) AC RF output to be amplified externally in the RF range (0.001-1 GHz). The necessary tests can be done at a pulsed infrared beamline like SINBAD or 3+L, in the DAFNE circular accelerator. After the testing phase, the detector will be located close to the focus of a standard telescope for infrared observations in the range 2-11 micrometres. The small number of pixels is convenient to carry out a preliminary feasibility study and evaluation with reasonable budget requests. During the thesis work, sensibility, linearity, and noise level shall be evaluated both in DC and AC. More specifically, the sensibility needs to be carefully evaluated with reference to weak astronomical sources, acquiring DC signals to test the effective performance. Rise time and fall time of the detector, both foreseen <1ns, can be evaluated at the IR synchrotron beam lines. Even if not strictly necessary, a cooling system could be considered and designed to decrease the semiconductor noise level. The digital acquisition system can be standard (oscilloscope with very large memory) or custom.

Areas of application for this ultra-fast infrared telescope can be solar system science, stellar disk science, exoplanets, studies on our galaxy, on the bulge or areas close to SGR A*, nearby galaxies studies. The investigation for the SETI project could be very promising, too.

A. Drago, et al., "Bunch-by-bunch profile diagnostics in storage rings by infrared array detection". Meas. Sci. Technol. 26 (2015) 094003 (10pp). Published in Measur.Sci.Tech. 26 (2015) 094003. DOI: 10.1088/0957-0233/26/9/094003.

B. A.Bocci, Et al., "Fast infrared detectors for beam diagnostics with synchrotron radiation". Sep 2007. 4pp. Published in Nucl.Instrum.Meth.A580:190-193,2007.

C. A. Drago, et al., "Bunch-by-bunch profile diagnostics in storage rings by infrared array detection". Meas. Sci. Technol. 26 (2015) 094003 (10pp). Published in Measur.Sci.Tech. 26 (2015) 094003. DOI: 10.1088/0957-0233/26/9/094003

D. A. Bocci, et al., "Detection of the SR infrared emission of the electron bunches at DAΦNE", LNF-05-12 (NT), 15 September 2005.

E. A. Bocci, et al., "Detection of Pulsed Synchrotron Radiation Emission with Uncooled Infrared Detectors", LNF - 06 / 7 (P), 24 February 2006.

F. A. Bocci, et al. "Time resolved detection of infrared synchrotron radiation at DAFNE", Prepared for 9th International Conference on Synchrotron Radiation Instrumentation (SRI2006), Daegu, Korea, 28 May-2 Jun 2006. Published in AIP Conf.Proc.879:1246-1249,2007. Also in *Daegu 2006, Synchrotron radiation instrumentation* 1246-1249. DOI: 10.1063/1.2436290

G. A.Bocci, et al., "Bunch-by-Bunch Longitudinal Diagnostics at DAFNE by IR Light", presented at the 8th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators (DIPAC 2007), Venezia, May 2007. In the Conference Proceedings.

H. A. Bocci et al., "Fast infrared detectors for beam diagnostics with synchrotron radiation". Sep 2007. 4pp. Published in Nucl.Instrum.Meth.A580:190-193,2007.

I. A. Bocci et al., "Beam diagnostics at DAFNE with fast uncooled IR detectors". Jun 2008. 4pp. Proceedings of 13th Beam Instrumentation Workshop (BIW08), Lake Tahoe, California, 4-8 May 2008. Published in *Tahoe City 2008, Beam instrumentation Workshop 2008* 145-148. e-Print: arXiv:0806.1958 [physics.acc-ph]

J. A. Bocci et al., "Beam Diagnostics with IR Light Emitted by Positron at DAFNE". EPAC08-TUPC008, Jun 24, 2008. 3pp. Proc. of 11th European Particle Accelerator Conference (EPAC 08), Magazzini del Cotone, Genoa, Italy, 23-27 Jun 2008. Published in Conf.Proc. C0806233 (2008) TUPC008. EPAC08-TUPC008. ISBN 978-92-9083-315-4.

K. A. Bocci, et al., "Beam diagnostics at IR wavelengths at NSRL", PAC'09-TH5RFP056, 3pp. Presented at Particle Accelerator Conference (PAC 09), Vancouver, BC, Canada, 4-8 May 2009.

L. A. Bocci, et al., "Beam Diagnostics of the positron beam at DAΦNE by 3+L experiment", PAC'09-TH5RFP058, 3pp. Presented at Particle Accelerator Conference (PAC 09), Vancouver, BC, Canada, 4-8 May 2009.

M. A. Bocci, et al., "THE TIME RESOLVED POSITRON LIGHT EMISSION (3+L) EXPERIMENT: A NOVEL DIAGNOSTICS TOOL FOR THE DAΦNE POSITRON RING", LNF-09/15 (R), December 3, 2009.

N. A. Bocci et al.,"FAST IR ARRAY DETECTOR FOR TRANSVERSE BEAM DIAGNOSTICS AT DAΦNE". MOPD098. Proc. of IPAC'10, Kyoto, Japan. May 23-28, 2010. Published in Conf.Proc. C100523 (2010) MOPD098. IPAC-2010-MOPD098. ISBN 978-92-9083-352-9. Poster presented to Conference: C10-05-23. e-Print: arXiv:1006.2023.

O. A.Drago, et al., "Beam Diagnostics by Infrared Time Resolved Detectors". 20th IMEKO TC4 International Symposium, Benevento, Italy, Sept.15-17, 2014. Conf.Proc. 6 Pages. Oral presentation.

P. A.Drago; et al.., "Fast Rise Time IR Detectors for Lepton Colliders". Invited presentation at 4th ICFDT 2016, 31/3/2016. Published in JINST 11 (2016) no.07, C07004. DOI: 10.1088/1748-0221/11/07/C07004. Conference: C16-03-30.5 Proceedings. JOURNAL OF INSTRUMENTATION, vol. 11, pp. C07004-C07004, ISSN:1748-0221.