Milestones

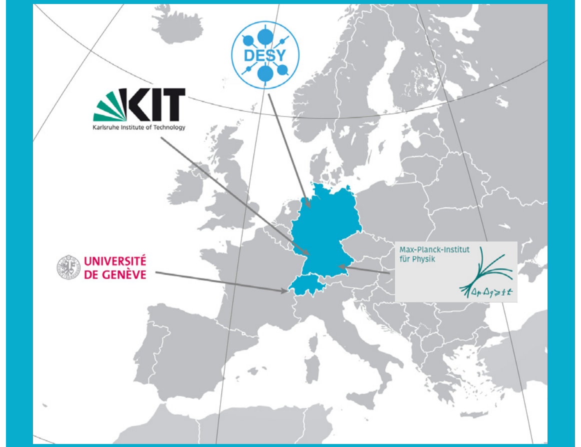
PMTs

- improve understanding of bulk properties of photo-cathode materials
- move towards engineering heterojunction photo-cathodes
- grow materials without grain boundaries
- pursue further improvements in transmisson dynodes

SiPMs

- understand potential for further improvements
- move towards "standard brick" SiPM
- move to fully integrated LEGO-brick trough 3D integration

Consortium:



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For more information and to download the Roadmap, please visit our website:
www.sense-pro.org

Ultimate Low Light-Level Sensor

A ROADMAP FOR DEVELOPMENT

Overview

The roadmap aims to define the R&D activities that SENSE intends to follow for the development of the **ultimate low light-level (LLL) sensor(s)**.

The Ultimate LLL Sensor

We focus on developments that are crucial for two photo-sensing technologies: **silicon photomultipliers (SiPMs)** and **photomultipliers (PMTs)**. We have identified three major sectors of development for each technology:

- performance of the sensors (which usually depends on the application)
- readout/control electronics
- integration of such electronics into the sensor.

This project received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 713171

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Executive Summary

The roadmap aims to define the R&D activities that SENSE intends to follow for the development of the ultimate low light-level (LLL) sensor(s), mainly for future astroparticle physics projects, but also for medical, automotive, biology, and safety applications. We focus on developments that are crucial for two photo-sensing technologies; silicon photomultipliers (SiPMs) and photomultipliers (PMTs). We have identified three major sectors of development for each technology: (1) the performance of the sensors (which usually depends on the application), (2) the readout/control electronics, and (3) the integration of such electronics into the sensor. For each sector, we point out the specifications required to address individual fields of application and which challenges must be overcome. In addition, the results of ongoing specific R&D activities, taking place in line with the SENSE roadmap, are presented in the document.

The State of the Art

All innovation with respect to LLL sensors is driven by the challenging demands by research projects and infrastructures. Currently, with about 600,000 PMTs/year, medical diagnostic instrumentation is the largest consumer of PMTs, where they are used in Positron Emission Tomography (PET), in gamma-ray cameras, and in many applications in life sciences. Besides specific applications of PMTs, e.g. in the oil drilling industry, large-scale experiments in basic research are consumers of several tens of thousands LLL sensors, albeit the net consumption varies from year to year.

The demand of astroparticle, particle, and nuclear physics experiments to reach an ever higher level precision in light detection, with broader dynamic range going from 1 to thousands of photons and with high efficiency is one of the main R&D drivers in the domain of the LLL detection.

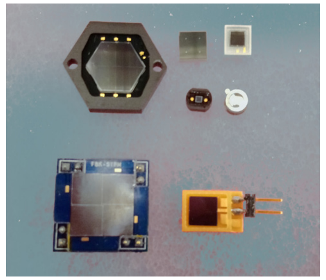
The market for LLL sensors in the context of future upgrades of astroparticle projects is huge. It was estimated in 2010 that about €0.5 Billion should be spent in the next decade on photosensors. SENSE is currently working to examine the photosensor developments for existing infrastructures, their major upgrades and upcoming projects. It is also examining products from industry and their performance.

Silicon Photomultipliers

SENSE identified a major scope for the case of application of SiPMs: the achievement of a sensor capable of providing the number of photons and their arrival times which should be scalable to any area. This aim can be achieved with associated electronics, which should also be scalable. Ultimately, a monolithic sensor with integrated electronics is an asset, which could offer maximum flexibility for different applications. We outline the necessary developments aimed at improving SiPM sensor performance for the future:

- the capability of having large-area surfaces instrumented with SiPMs without degradation of performance
- the achievement of picosecond-scale time resolutions for single photon (TOF-PET)
- the increase of Photon Detection Efficiency at:
  - infrared region (typically for car safety applications)
  - UV region (typically for Cherenkov light detection, fluorescence, etc.)
- the increase of radiation hardness (typically for High Energy Physics and radiation protection applications)
- the decrease of Dark Count Rate, crosstalk and afterpulses would lead to:
  - higher working voltage, therefore higher triggering probablity and Photon Detection Efficiency
  - possibility to reach single photon detection at room temprature without external trigger

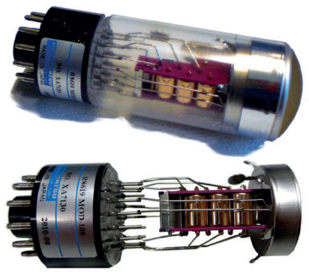
For the time being, we prioritize in this roadmap the large area development over the time resolution, which is especially useful in medical applications and in some particle-physics developments, though we consider the time resolution development extremely relevant for medical physics and some particle physics applications.



Photomultiplier Tubes

Currently the standard light sensors are the classical photomultiplier tubes (PMT). They are produced by companies in various sizes, from very small (order of 1 cm in size) to very large (up to 50 cm diamter). PMTs selected from Hamamatsu for the CTA project are now confirming the expected high quality performance of these devices. Measurements show substantially better performance of these devices than the requirements for parameters such as Quantum Efficiency, afterpulse rates, and Peak/Valley ratio of single photon counting set by the CTA collaboration. The primary developments to further improve PMT performance are:

- the significant enhancement of Quantum Efficiency (QE), a measure of a sensor's photon detection ability. The higher the QE, the higher is the probability to measure even a very low flux of photons at a high signal/noise ratio.
- improvement of Photoelection Collection Efficiency (ph.e.CE): Only a fraction of the ph.e.s from the photo cathode will have a chance to be collected by the 1st dynode and undergo multiplication process. The ph.e.CE on the 1st dynode is a function of the applied high voltage. Typically, the higher applied voltage between the photo cathode and the 1st dynode allow one collecting higher share of ph.e.s.
- the increase of Photon Detection Efficiency (PDE) which is the essential parameter of any given light sensor. PDE is the convolution of the wavelength dependent QE with the wavelength dependent ph.e.CE.
- reduce Afterpulsing mainly induced by ionization of the atoms of certain chemical elements as well as the light emission from the dynodes, which are bombarded by accelerated energetic electrons.
- the increase of Single Photoelectron Peak to Valley Ratio which describes how good a given PMT can detect single ph.e. events.



Summary

The roadmap represents not only a significant milestone, but also a benchmark for the future development of the ultimate low light-level sensor. While the creation of this plan required significant effort and commitment from many entities, it is only the beginning. Much work lies ahead to implement the strategies laid out in the document. Coordination and collaboration among SENSE, academia and industrial partners will be essential to moving the R&D forward. The strategies outlined in this roadmap will require immediate attention to ensure their ultimate success. If everything comes together in support of this plan, and its key elements are implemented, SENSE is confident the dream of an ultimate LLL sensor will become a reality.

SENSE

Discuss the roadmap in the SENSE forum and participate in the development of the ultimate LLL sensor(s):

www.sense.pro.org/forum

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