Ultimate Low Light-Level Sensor Development

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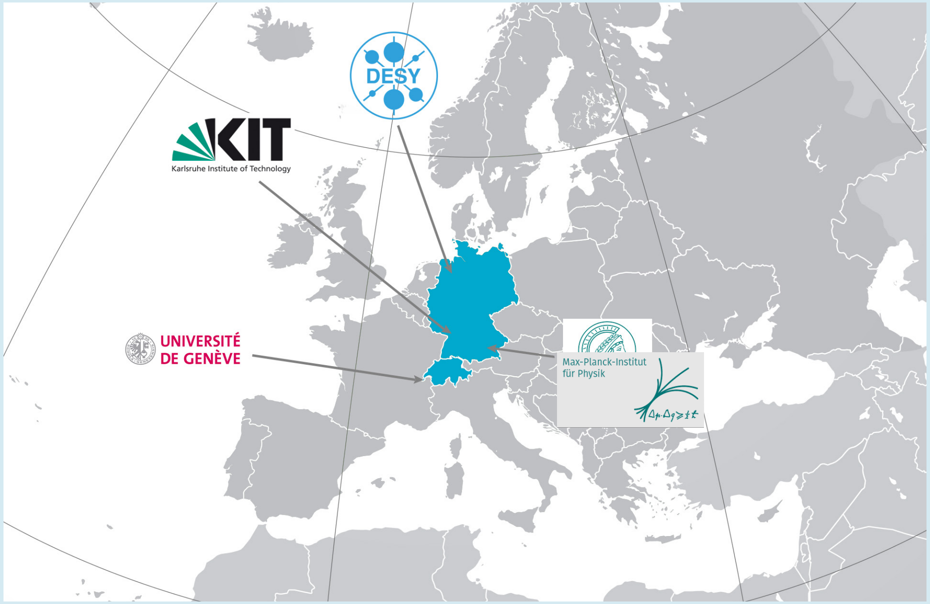
SENSE – Ultimate Low Light-



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Level Sensor Development

Objectives

- **to set up** an expert group and **facilitate** the development of a European R&D roadmap towards the ultimate low light-level (LLL) sensors,

- **to monitor** and **evaluate** the progress of the developments with respect to the roadmap,

- **to coordinate** the R&D efforts of research groups and industry in advancing LLL sensors,

- **to develop** a database of light sensor specifications and lab equipment, test stands and expertise available in the different institutions,

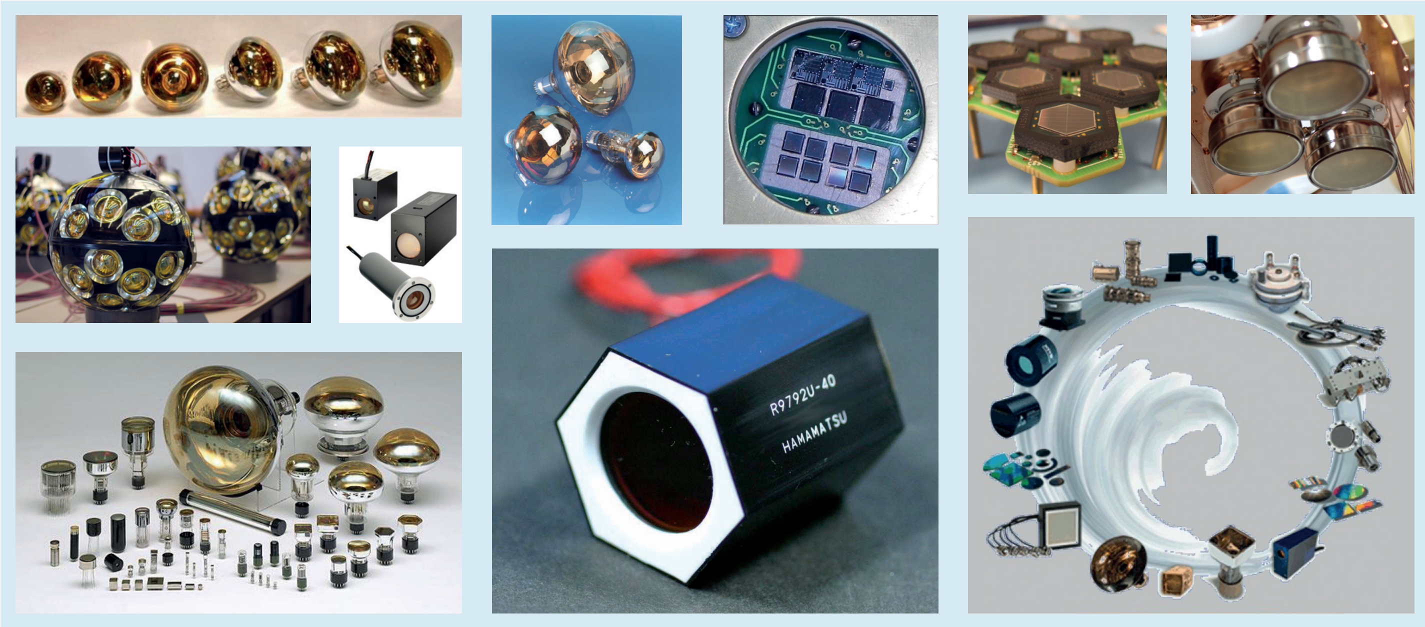
- **to liaise** with strategically important European initiatives and research groups and companies worldwide,

- **to create** the Technology Exchange Platform to enable an efficient exchange between researchers and developers being involved in SENSE,

- **to prepare** training events and teaching material especially towards young researchers,

- **to frame up** a technology training session that can be implemented in any existing summer school.

A diversity of low light-level sensors



of the ultimate low light-level sensors

Detection of light is one of the basic principles of measurements and diagnostics in science and many applications. With about 600000 PMTs/year medical diagnostic instrumentation is the largest consumer of PMTs; PMTs are used in Positron Emission Tomography (PET) scanners, Gamma cameras, and many applications in Life Sciences. Besides specific applications of PMTs, e.g., in oil drilling industry, large scale experiments in basic research are consumers of up to several 100000 low light-level sensors.

All innovation with respect to low light-level sensors is driven by the challenging demand by research projects and infrastructures. The demand of **reaching lower levels in light detection efficiency with the highest precision** in astroparticle, particle, and nuclear physics experiments is one of the main R&D drivers in the domain of low light-level detection.

Various European research groups have played and will play an important role in further advancing this technology. However, a **coordination and structuring** of these groups – especially in Europe – is currently missing; while competition is often speeding up developments especially in the prototyping together with industry, duplication in testing and evaluating available devices for research projects is a standard.

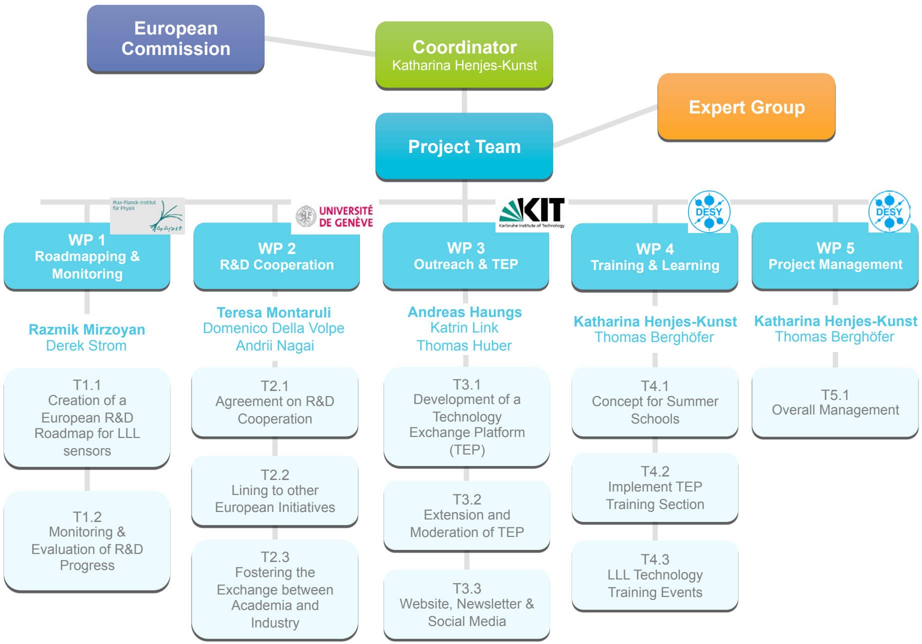
With SENSE R&D activities of European research groups, industry, and strategic partners worldwide shall be coordinated and supported with the clear goal to **develop the ultimate low light-level sensors**. Beyond current scientific collaborations, the involved groups from academia and industry will be guided in developing together a **roadmap** with the necessary technological steps and coordinating their synergetic work to maximize technological innovation. Of importance for SENSE is the attraction of **young academics** for this close-to-application R&D work, to ensure a long-term European perspective in this very innovation field with many new applications to be realized in the future.

The concept followed by SENSE is based on preparatory work and experiences made during the ERA-NETs ASPERA and ASPERA-2 funded by the European Commission during the Framework Programs 6 and 7. The technology fora dedicated to innovative technologies required in world class astroparticle projects have been continued within the frame of APPEC (Astroparticle Physics European Consortium). Furthermore, it integrates the experience made with the series of LIGHT conferences and a workshop series dedicated to advanced SiPMs.

Any improvement in the PMT technology evolving from science projects has allowed medical diagnostics industry to immediately come up with advanced products. Together with this immediate market there is a clear positive societal impact: a doubling of the light sensor's efficiency in a medical diagnostic instrument will allow to half the radiation doses for patients and thus **to reduce the possible negative consequences of irradiation**. PET scanners allow studies of the functional activity in vivo, which is important for cancer research, Alzheimer studies as well as drug tests. When replacing PMTs with SiPM devices it might be possible, for instance, to install PET inside the very strong magnetic field of MRI coils. Also, one will profit from ultra-fast time resolution of SiPM, for the so-called time-of-flight reduction of the background.

Silicon Photo Multipliers (SiPMs) are the future of PMT technology. SiPMs are robust and fea-

A coordinated approach towards the development



Experts Group

The Experts Group (EG) comprises first-rate developers in the field of low light-level sensors. They act as an advisory panel to the project.

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Stefan Schönert, Technische Universität München, Munich, Germany

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David Gascon, Institut de Ciències del Cosmos (ICCUB), Barcelona, Spain ture numerous advantages compared to PMTs, such as compactness, lightweight, mass producibility, insensitivity to magnetic fields, low bias, high photo-detection efficiency. Nonetheless, they are still so compact that instrumenting large area requires complicated readout electronics.

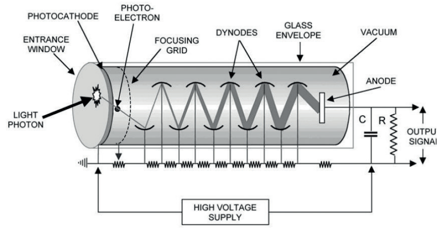
A first attempt in the ultimate sensor with immediate application has been made by Philips with a digital SiPM approach. This comes with an accompanying test set up which has still high costs. Moreover, the digital-SiPM cannot currently be employed in ns-timing applications because of its large dead time. Nevertheless, a breakthrough in the technology also addressing the SiPM noise issue is going to take place in the next years.

In addition to these two technologies, a complete proof-of-the-concept exists for a novel design of low light-level detectors, called Abalone, which has to be evaluated for its commercialization. Other novel ideas like the superconducting transition edge sensors (TES), the Neganov-Luke light devices, or new generation organic image sensors require further R&D before becoming a commercial product. The leading industrial partners confirmed that the **scientific and technological challenge of physics experiments** is the main driver for developments in the field of low light-level detector devices and electronics. For the industry alone – especially for SMEs – it is very difficult to improve the quality of low light-level sensors. The demands are very specific and if there is not enough market for the novel products, it is hard to justify the related development and investment costs.

For significant improvements it is necessary to produce test series of 10 to 100 sensors. However, it has been noted that the costs of such small series are difficult to transfer to the customers and from the physics experiments alone companies cannot make their living. Newly developed products must pay off, allowing the companies selling these in a wide market. For companies the time scale for a return of an investment is shorter than it is usual in the academic world.

Concerning the research projects, the challenge for industry is to develop and produce **the right technology at the right time**. To cope with the demand of several hundred thousands of PMTs within several years is not easy and new production capacities must be built up. To realize such a large production capacity a concrete commercial prospect is required. Furthermore, for such a high number of required units automation of the production processes and investments in extended production capacity are obviously needed.

Photomultiplier Tubes (PMT)



PMT is the technology state of the art. The operating principle is that – caused by the photoelectric effect – photons striking a photocathode at the entrance window of a PMT produce electrons, which are then accelerated by a high-voltage field and multiplied in number within a chain of dynodes by the process of secondary emission.

A continued R&D effort conducted by several European research institutes together with industry enabled the following milestones:

- The peak quantum efficiency of PMTs could be raised from about 25% (2005) to an order of 35-45% (2016).
- In the same time, the after-pulsing, one of the major problems in PMT technology, could be suppressed, for example, by a factor of about 40 down to a level of 0.01% for a preset threshold of ≥ 4 photo electrons (ph.e.).

Advanced R&D ideas for further substantial improvements do exist and are expected to use the potentialities for **doubling of the photo-detection efficiency** of the PMT technology. One major advantage of PMTs is that these can be produced in **different sizes**, starting from a few mm (as in multi-pixel PMTs) to half a meter in diameter (as those used in the Super-Kamiokande experiment).

One of the drawbacks of increasing the size of the PMT photocathode is the **deterioration of the time resolution**. KM3NeT, the future neutrino telescope in the Mediterranean sea, has adopted a multi-PMT solution, where multiplexed PMTs improve angular uniformity of the response, increase photocathode coverage while keeping the time resolution excellent.

For the time being, PMTs are the only viable solution when large detection areas are required (for instance for large volume neutrino detectors.

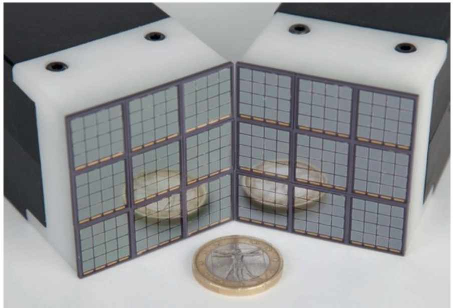
On the other hand, the use of PMTs in cryogenic detectors is inconvenient and requires dedicated optimization. Moreover, some applications require reduced level of radioactivity. Further R&D in this direction has to be carried out. For installations including thousands of PMTs in large vessels, a high pressure resistance is an important parameter to reach for minimizing the risk of catastrophic implosions. It is also important to advance the currently developed architecture of PMT-arrays with a common read-out electronic. These developments will definitely expand the scope of application and thus will become important for industry.

Silicon photomultipliers (SiPM)

SiPM are matrices of avalanche photo diodes with a common cathode that are operated in Geiger mode. Major steps have been taken towards a market available product. During the last two years almost all companies producing low light-level sensors have launched SiPM devices for various applications e.g. for gamma-ray cameras, PET scanners, X-Ray detection, calorimetry, neutrino detection, radiation monitoring. At present, the process of optimizing the sensor design and packaging tailored to the individual applications with their own set of critical parameters is fastly advancing.

Advantages of the SiPM technology are:

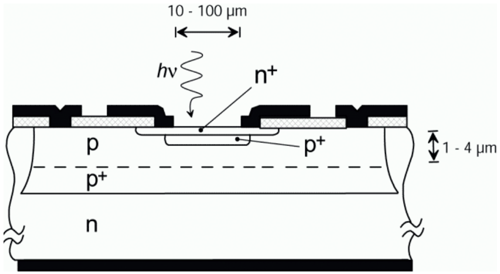
- it operates under a substantially **lower high voltage** than the PMT,
- it has **low power consumption**,
- it is **not affected by magnetic fields** like PMTs are,
- it is **robust**, since it is not affected by light as much as PMTs ,
- it has **negligible aging effects**, on the contrary to what happens to PMTs,
- SiPMs are **mass producible** and their **prize is fastly decreasing**.



Two major drawbacks of SiPMs at the moment are:

- the **cross-talk between neighboring photo-cells**,
- the **after-pulsing**.

They have been dramatically reduced in recent years thanks to the cooperative work of companies and scientists. A coordinated European R&D approach with major institutes and industrial partners is important for making progress towards the ultimate low light-level sensor, which shall be reached within the coming five years.



A third and very limiting drawback to overcome is the **limited effective detection area** of a SiPM. While it is technologically difficult to substantially increase the detection area of individual SiPMs (it is possible but at the expense of sacrificing their speed), a challenging but a possible way to follow is the development of optimized matrices of SiPMs with a fully-integrated readout chain. In case of a successful further development, one can place these matrices of SiPMs next to each other for assembling a coordinate-sensitive camera either as the imaging camera for a Cherenkov telescope or for a medical Gamma camera, similar to a CCD chip built in a mass-market digital photocamera.

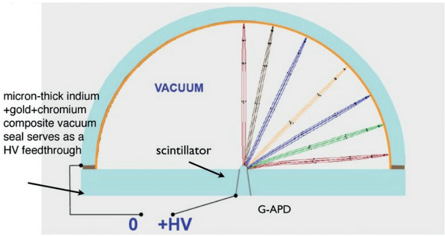
Superconducting transition edge sensors (TES)

A transition-edge sensor is a thermometer made from a superconducting film operated near its transition temperature. While in its transition from superconductor to normal metal, a very small change in temperature induced by absorption of photons causes a large change in resistance. Such devices are currently being employed in cosmic microwave background experiments, however, they may have a much broader application in the future. The challenge is to **build larger arrays** (tens of thousands of pixels) **while striving for an energy resolution** allowing for the detection of individual photons.

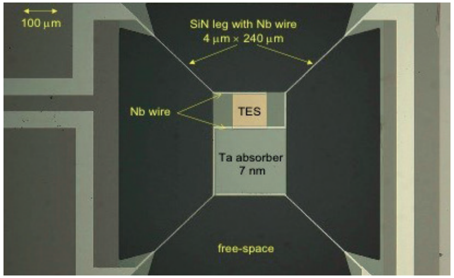
Abalone concept

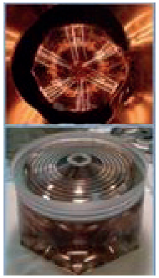
A full proof-of-concept for the novel low light-level Abalone photo-sensor has been carried out. It embodies only inexpensive scalable elements, namely a custom photodiode and readout, a vacuum seal, and a scintillator.

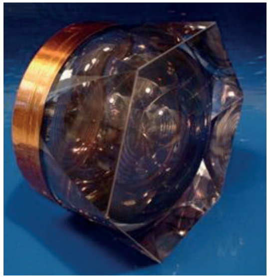
Prototype measurements demonstrate the **high potential** of this technology. However, building an Abalone device is a **complex process,** requiring a substantial effort under laboratory conditions. Companies' interest in this technology is currently unclear and the possibility of commercialization could be evaluated once manufacturing aspects result suitable to industry.

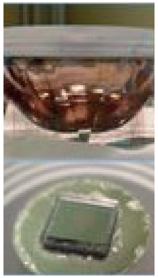


Abalone concept



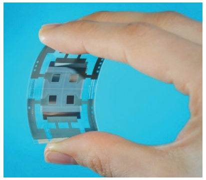






for low light-level detection

Organic sensors

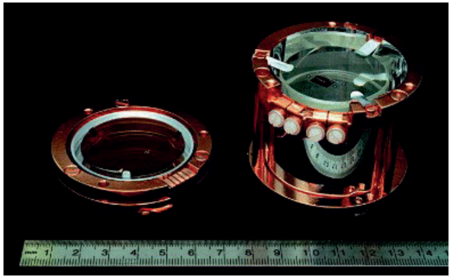


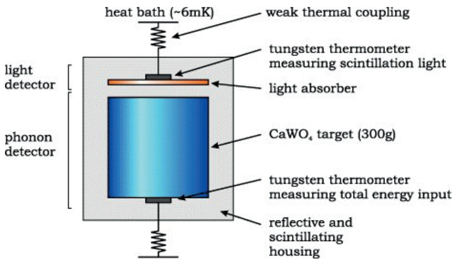
Quite recently a new generation of image sensors has been developed. These ultra-thin organic sensors – with carbon instead of silicon as material converting light into electrical signals – can be applied to CMOS chips over large and small surfaces, as well as to glass or flexible plastic films. These devices are **more sensitive to light** than the conventional silicon versions, with the advantage of **simple and cheap to produce**. Current laboratory tests show that the spectral sensitivity of the organic sensors varies with the chemical compounds used for the sensor. Experiments have been carried out so far to fine-tune the sensitivity in the optical and infrared spectral ranges. Nevertheless, for applications of organic sensors in the domain of low light-level, it is rather important to test their characteristics at low light-level and R&D is required to find a chemical compound that shifts the **sensitivity maximum to the ultraviolet part of the spectrum**.

Neganov-Luke light devices

For applications in low-temperature surroundings (e.g. detectors for direct dark-matter search) low light-level detector devices that make use of the Neganov-Luke amplification – **improving the threshold** of low-temperature light detectors based on semiconducting substrates by drifting the photon-induced electron-hole pairs in an applied electric field – have been developed.

A major drawback of Neganov-Luke light devices, the **decreasing amplification over time**, causing a detector response varying over time, can only be overcome by a new fabrication technique. So far such detectors have been built with $CaWO_4$ crystals. For further improvements new detector materials (e.g., $CaMoO_4$ or $Ti:Al_2O_3$ or YO_3) have to be selected and characterized. A commercialization of cryogenic low light-level detectors with applications beyond detecting dark-matter particles is promising.





SENSE – Impact

Structuring and fostering R&D efforts of academia and industry

A coordination of European research groups concerned with low light-level sensors is currently missing. On a technology forum on photo-sensors and auxiliary electronics organized in 2010 in the frame of the ERA-NET ASPERA-2, representatives from academia and industry pointed out that developments could be made faster when one or a small number of labs could take the lead of these activities and work in close collaboration with industry.

This advice is considered in SENSE. By formulating a **roadmap** incorporating all R&D activities necessary for the development of the ultimate low light-level sensors, the R&D efforts of European research groups, industry, and strategic partners worldwide will be efficiently aligned. This **coordination** shall reduce the redundancy of the efforts. The **competition** between groups shall be stimulated in those cases where developments can be made faster.

Engaging European leadership in emerging technology and support for new collaborations

The project aims at joining forces of European experts in developing the ultimate low light-level sensors and taking the leadership in these R&D activities. Following new and emerging technologies in detecting minimal quantities of light (single photons) is a challenge. However, the **close cooperation between industry and academia** in several research disciplines is defining an ideal partnership for developing substantially improved low light-level sensors that find immediate application in research projects and in commercial products.

Improved long-term innovation potential in Europe

European companies shall be supported in getting to know the latest developments during the technology fora and meetings with developers, experts, and young talented researchers with interested in technology development. This will help European companies to be competitive with first-class low light-level devices as well as with applications making use of the best low light-level sensors.

Given that many applications are in medical diagnostic instrumentation, the substantial improvement in low light-level sensor technology will have a **clear positive societal impact** when radiation doses for patients can be significantly reduced. The **innovation potential** is enormous when it comes to a replacement of PMTs by the new SiPM technology. PET scanners could then be integrated in MRIs and allow studying structure and functional activity in vivo, which is important for cancer research, Alzheimer studies as well as drug tests. With current state-of-the-art technology such a combined diagnostic cannot be realized. **Miniaturization** and **cheaper mass production** of low light-level sensors will definitely lead to a wealth of innovative products on the long-term.

Guide and support young researchers in taking up a technology-oriented research career

SENSE aims at attracting and supporting young researchers to get involved in forefront technology developments. This shall be realized by well-defined technology sessions at diverse summer schools. Videos, podcasts, tutorials, FAQs and other training material shall be disseminated via the **internet exchange platform** developed during the project. The platform shall also allow young researchers getting in touch with developers in academia and industry. The question on how to further involve young researchers in technology development – with special emphasis on young female researchers – shall be addressed in SENSE. Altogether the support of young researchers is seen as one of the key ingredients ensuring the long-term innovation potential in Europe.

Increase the quality of R&D research and generate opportunities by gender equality

Enhancing gender equality plays a major role to meet the objectives of SENSE. From the start on, special attention will be drawn to **diversity** e.g. mixed teams for the experts' group, project board and the involved R&D research groups. As one of the main targets is to attract and train young researchers, the project shall benefit from promoting **gender equality** by a wider pool of talents and an increase in the quality, objectivity and vitality to produce new ideas and knowledge. To ensure the promotion of gender equality, SENSE will liaise with the EU funded GENERA project, which is focussing on gender in physics. GENERA will function as a consultancy in gender related questions.

Altogether, SENSE will be well embedded and linked to all other relevant initiatives and the affiliation to APPEC shall ensure that all stakeholders from academia and industry participate in the project.

Dissemination and exploitation of results

The dissemination of the project results and the potential of advanced low light-level sensors for applications in other scientific communities – especially outside physics – and industries is substantial. The lead partner DESY is a world class research infrastructure in photon science. Synchrotrons and FELs at DESY are being used by an increasing number of scientific communities, e.g., from physics, chemistry, biology, medicine, and pharmacy. In this **interdisciplinary** working together at DESY, the task of low light-level detection is ubiquitous. Technology developers in these areas shall be reached in-house. The intense relation between the working group of Prof. T. Montaruli at UNIGE a and CERN, Dr. R. Mirzoyan at MPP and Dr. A. Haungs at KIT will further support.

The **web-based technology platform** constitutes the main tool for dissemination and exploitation of results to a broader public. It serves as a publicly accessible website that details the goals, status, and results of the project and shall allow accessing internal information and documents in a password-protected section. The task for the project is to first develop the platform, then fill and update the information and act as a moderator for the forum part of the platform.

A ROADMAP FOR DEVELOPMENT

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.

Photomultiplier Tubes (PMT)

We focus on developments that are crucial for two photo-sensing technologies; **silicon photomultipliers (SiPMs) and photomultipliers (PMTs)**.

- performance of the sensors (which usually depends on the application)
- readout/control electronics
- 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 long roadmap document, available on our website.

Milestones

SiPMs

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

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 transmission dynodes.

SENSE

Find out how you can participate on our Technology Exchange Platform
www.sense-pro.org/forum

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