This project has received funding from
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Ultimate Low Light-Level Sensor Development

Barcelona Meeting, July 9, 2019

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Max-Planck-Institut für Physik

SENSE ROADMAP

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- Introduction and review of the state of the art photo sensors (few slides by Razmik)
- Presentation of the SENSE Roadmap recommendations
- Summary

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One of the best known light sensors: the classical PMT

- The impinging photons kick out e- from the thin photo cathode (~25nm)
- e- are accelerated in a static electric field (~100V) and hit dynodes arranged in a sequential topology
- Every dynode enhances the number of e- by a factor 4-5
- The net gain of a PMT could be $10^5 – 10^7$
- That allows measuring single photons

Recent strong boost of QE → 45 %

HAMAMATSU
PHOTON IS OUR BUSINESS

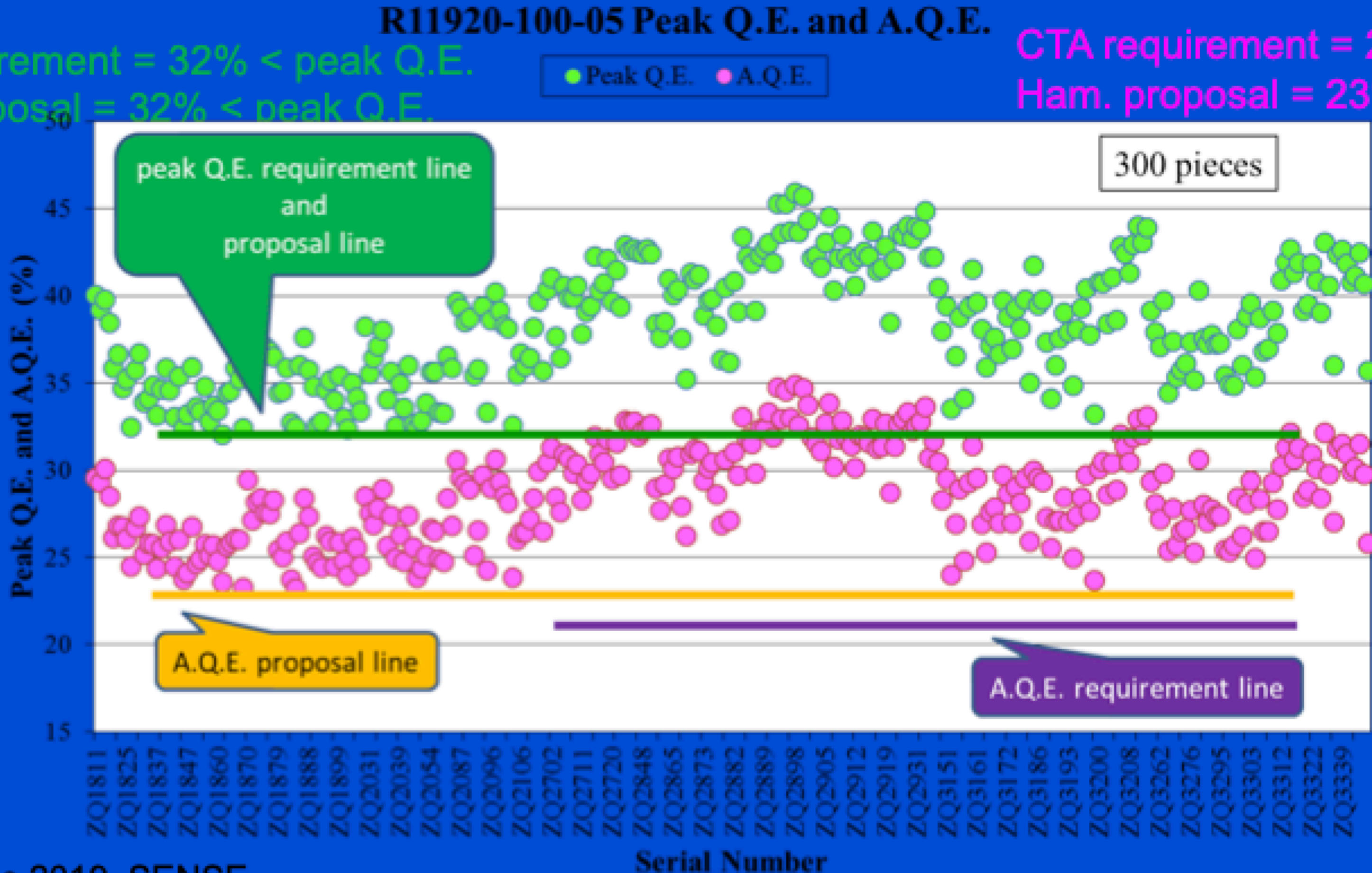
(See how the company met our request of a minimum 32% peak QE)

Peak Q.E.

Average QE over Cherenkov spectrum (290nm-600nm)

CTA requirement = 32% < peak Q.E.
Ham. proposal = 32% < peak Q.E.

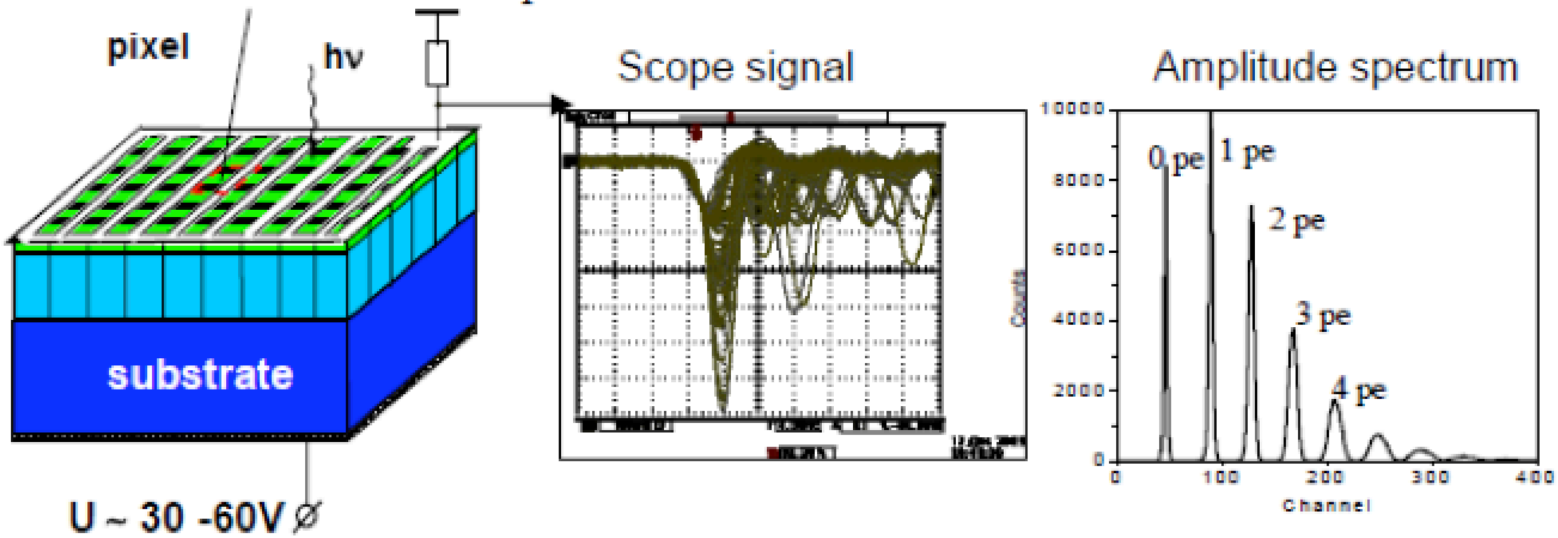
CTA requirement = 21% < A.Q.E.
Ham. proposal = 23% < A.Q.E.



Silicon Photomultiplier (SiPM)

The novel type of photon detector

Multipixel device with common readout



SiPM – main features:

- Each pixel – reverse biased above breakdown p-n-junction operated in selfquenching Geiger mode
- Sensitivity to single photons
- Pixel gain ~ 10^6-10^7
- Pixels number: ~ 100 - 10000/mm^2
- Pixel recovery time $R_{pixel}*C_{pixel}$~30ns ÷ 1 μs

Pixel signal - 0 or 1
But SiPM is analogue device

SiPM Essentials

- Photon Detection Efficiency (PDE):

$$PDE(\lambda) = QE_{internal} \times T(\lambda) \times A_{active\ area} \times G_{geiger\text{-}eff.}(\lambda)$$

$QE_{internal}$:	essentially 100 %
$T(\lambda)$:	strongly varies with λ, could reach 80-90 %
$A_{active\ area}$:	some number between 20-80 %
$G_{geiger\text{-}eff.}(\lambda)$:	strong function of applied $\Delta U/U$, for $\Delta U/U \geq 12\text{-}15$ % could become ≥ 95 %

Comparing PMTs and SiPMs

	2010	2015
PMT		
Peak Quantum Efficiency (QE)	28 – 34%	36 – 43%
Photoelectron Collection Efficiency on the 1st Dynode	60 – 80%	94 – 98%
Afterpulse Rate (for a set threshold $\geq$ 4 ph.e.s)	0.5%	$<$ 0.02%
SiPM		
Peak Photon Detection Efficiency (PDE)	20 – 30%	50 – 60%
Afterpulse Rate	30 – 40%	$<$ 2%
Dark Count Rate (DCR)	1 – 3 MHz/mm^2	50 – 100 kHz/mm^2
Crosstalk	$>$ 40 – 60%	5 – 10%

Table 1: Comparison of basic parameters characterizing PMTs and SiPMs available in 2010 and 2015 at room temperature.

What LLL sensor can we dream about ?

- Nearly 100 % QE and photon detection efficiency (PDE)
- Could be made in very large and in very small sizes
- Few ps fast (in air and in many materials the light speed is usually 20-30 cm/ns; in 5 ps it will make 1-1.5 mm)
- Signal amplification x10^6
- Noiseless amplification: F-factor - 1.001
- Few % amplitude resolution
- No fatigue, no degradation in lifetime
- Low power consumption
- Operation at ambient temperatures
- No danger to expose to light
- Insensitive to magnetic fields
- No vacuum, no HV, lightweight,...

Light Sensors for astro-particle physics

• Different types of advanced light sensors are used in Astro-particle and astro-physics experiments for measuring light
• Even the classical light sensors such as the photo-multiplier tubes, are continueing to strongly improve in performance
• The number and types of SiPM matrixes from different manufacturers is increasing, the parameters are steadily And really fast improving

• Sometime soon, in a time scale of 2-3 years, we should be able to buy Si-based matrixes from several manufacturers with complete readout. We could then assemble large coordinate-sensitive imaging cameras like a lego

SENSE ROADMAP: EXECUTIVE SUMMARY

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2 Executive Summary

This Roadmap aims to define the R&D activities that the SENSE Project is following towards the development of the ultimate low light-level (LLL) sensor(s), mainly for future astroparticle physics projects, but also medical, automotive, biology, and safety applications. In this document, 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 typically depends on the application), (2) the readout and control electronics, and (3) the integration of the electronics into the sensor. For each sector, we point out the specifications required to address individual fields of application and the challenges which must be overcome. In addition, the results of ongoing specific R&D activities, taking place in line with the SENSE Roadmap, are presented.

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SENSE ROADMAP: RECOMMENDATIONS

10 Recommendations

Here the SENSE Project makes its recommendations for areas to be actively developed in SiPM and PMT technologies to eventually lead to the ultimate LLL sensor(s).

SiPMs

- Understand the potential for further improvements to the major parameters of SiPMs as sensors and outline the possible developments and interactions with possible industrial partners;
- Give contours to a "standard brick" of the SiPM-based sensor of one or two-inch size;
- Move towards the SiPM "standard brick" with a "universal" fast readout scheme. This would be a first step towards the LEGO-brick principle for assembling imaging cameras of arbitrary size;
- Progress from semi-integrated standard brick to fully integrated LEGO-brick through the implementation of 3D integration.
- No coating significantly reduces optical cross-talk rate; Consider as an approach for CTA.
- Further reduce optical cross-talk by suppressing photons propagating through the backside of the device.

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SENSE ROADMAP: RECOMMENDATIONS

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PMTs

- Optimize light use - include reflecting surfaces when appropriate and use optical cavity properties of thin films (optical etalon) for some applications;
- Investigate new gain designs, such as active transmission dynodes; this is especially useful in applications where miniaturization is desirable;
- Improve the photocathode quantum efficiency, lifetime, and temporal response;
- Improve photocathode crystal quality and stochiometry through monitored coevaporation (slow growth), lattice matched substrate (epitaxy), and bulk material;
- Improve the understanding of the bulk properties of bialkali photocathode material as a semiconductor;
- Grow materials without grain boundaries – and potentially with complex material junctions to optimize for charge transport, also by considering ion implantation;
- Create photocathodes with internal fields via p/n doping and heterostructuring multiple antimonides, which requires control of film thickness and roughness;
- Improve surface termination to optimize electron affinity without damaging lattice structure;
- Investigate material purity when crystalline defects are under control.

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SENSE ROADMAP: RECOMMENDATIONS

Theoretical Modeling

- Extend TCAD to modeling of multiplication in geiger mode;
- Improve IV curve model; implement parameterization appoach of N. Otte, and theoretical models based on solid state physics (e.g.) by M. Biroth;
- Improve SiPM model as a signal source, and take into account light shape and nonlinearities;
- Pay more attention to avalanche timing within SER for ultimate time resolution (10 ps);
- Pay more attention to statistical grounds for SiPM characterization/metrology;
- Move forward in reward-renewal approach, i.e. include correlated effects and binomial nonlinearity;
- Aim for a nonlinear model of arbitrary waveform signal detection.

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Electronics

- Any decent electronics are sufficient for slow applications as long as slow shaping is used;
- Aim to maximize charge collection while minimizing impact of series noise;
- Optimize the amplifier to achieve good SNR in fast and large area applications;
- New hybrid (electronics embedded in the sensor) and 3D integration approaches should be developed to achieve the ultimate timing in large area detectors;
- Fast waveform sampling offers the ultimate performance;
- Custom ASIC with analogue shaping and dedicated ADC is the optimal solution for large systems.

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SENSE ROADMAP: RECOMMENDATIONS

Laboratory

- Reference detectors should be sent to NIST every 4-5 years for recalibration;
- NIST recalibrated detectors should be stored in a dry place and under vacuum if possible;
- Reference detectors used in laboratories should be recalibrated every 6 months to 1 year;
- Neutral density filters should be recalibrated every 6 months;

- Use calibrated SiPM as reference detectors to avoid the use of neutral density filters and the large differences in signal between the SiPM and the reference photodiode;
- Calibrated SiPM on-board a tile to simultaneously measure all other pixels may be useful for PDE measurements of SiPM tiles.

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11 Summary

This 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 and recommendations laid out in this document. Coordination and collaboration among SENSE partners, academia and industrial partners will be essential to moving the R&D forward. The strategies and recommendations 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.

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SENSE ROADMAP SUMMARY

- Roadmap document under preparation for ~3 years.
- Has gone through several review processes (both internal by SENSE community and external EU commission).
- Received input from SENSE experts group at both the TECH Forum and SENSE Experts Meeting in Vienna, and through private communications.
- Provides a thorough list of recommendations for advancing the field of LLL photosensors.
- Thank you to everyone involved in producing this valuable document.

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