CTAO and Hamamatsu Photonics collage

Behind the science

Many international research facilities rely on photonic technologies.

Hamamatsu Photonics has contributed to the success of numerous scientific research projects by providing advanced optical detectors and sensors. In this article, we reveal these key technologies behind two of the most exciting high-energy physics experiments, the Cherenkov Telescope Array Observatory CTAO and the High Luminosity Large Hadron Collider (HL-LHC) at CERN, which strive to uncover the deepest mysteries of our universe.

The glowing blue of our universe

Almost twenty years ago, visionary scientists devised a plan to push the technological boundaries of existing ground-based gamma-ray telescope detectors – HESS, Magic, and Veritas. These telescopes detect the particle showers released by gamma rays reaching our atmosphere. These ultrahigh energy particles create a blue flash of Cherenkov light, helping us to address some of the most perplexing questions in astrophysics. The researchers' desire was to create unprecedented technology in terms of sensitivity and accuracy. Thus, was born the idea of the next generation of telescopes: the Cherenkov Telescope Array Observatory (CTAO), surpassing its predecessors in terms of number, size, and technology.

Fast forward to today, the CTAO is now a multinational project that will become the world's largest and most sensitive observatory for gamma-ray astronomy, supported financially by a growing list of shareholders from more than ten countries and an intergovernmental organization. With more than sixty telescopes located in the northern and southern hemispheres, the CTAO will be up to ten times more sensitive than any current instrument and will explore the very high-energy universe within an unprecedented energy range (20 GeV – 300 TeV). The CTAO's unique capabilities will help to address some of the most perplexing questions in astrophysics. The Observatory will seek to understand the impact of high-energy particles in the evolution of cosmic systems, to gain insight into the most extreme sources in the universe, such as black holes, or to search for dark matter and deviations from Einstein's theory of relativity. Moreover, the CTAO will

◀ This rendering of CTAO South shows the three classes of telescopes that are required to cover the full CTAO energy range (20 GeV to 300 TeV)

be the first observatory of its kind to operate as an open, proposal-driven observatory providing public access to its high-level science data and software products.

The CTAO was promoted to a “Landmark” on the European Forum on Research Infrastructure (ESFRI) Roadmap 2018, and was ranked as the main priority among the new ground-based infrastructures in the Astronet Roadmap 2022 – 2035.

Succeeding in creating such a considerable feat demands innovative technology among many things. Many actors proposed ideas and prototypes over the years aiming to find solutions to overcome the various challenges posed by such an ambitious project. Hamamatsu Photonics, present from the very early scientific discussions, competed with its leading technology – the photomultiplier tube (PMT). This was only the start of a journey with many obstacles to face, starting with the customization of a product to exact specifications and trialing it until its success. Not to mention designing different and improved technologies such as Hamamatsu’s silicon photomultiplier (SiPM).

The key is blue

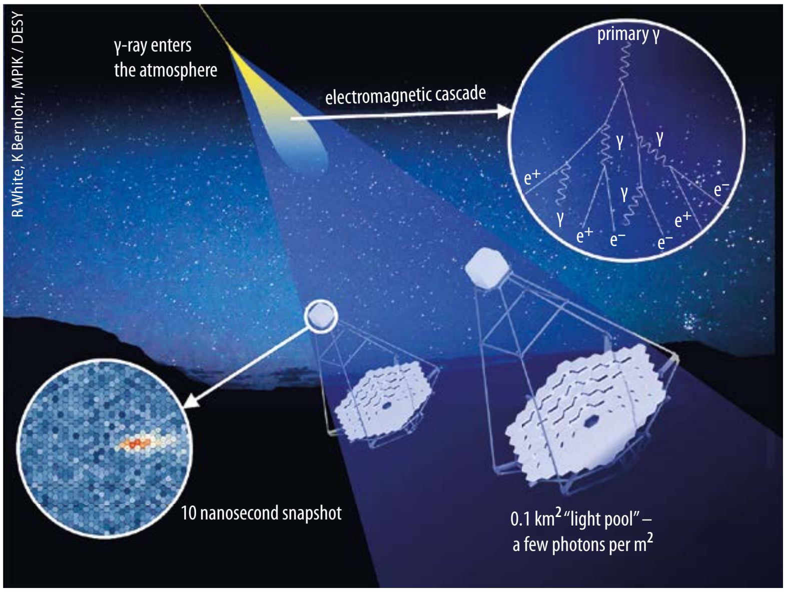
The particularity of the CTAO is its sensitivity to the highest-energy gamma rays. Gamma-ray bursts are powerful events generated from some of the most violent environments in our universe, such as supernova explosions. In fact, the gamma rays produced by these events are a trillion times more energetic than visible light. Identifying them is not an easy task, as they do not reach the Earth’s surface. However, when passing through the atmosphere, they produce subatomic particle cascades. As these particles descend into our atmosphere, they lose energy and emit Cherenkov radiation. The ultraviolet and finally visible (mostly blue) fraction caused by secondary particles can then be detected from the ground by the telescopes’ high-speed camera.

CTAO’s telescopes differ in size and in number to capture all the various energy spans. First, their large mirrors collect the glowing blue light, which is then detected by the high-speed PMT camera system. The light flashes are so faint and short (a few nanoseconds), it is not possible to see without this highly sophisticated technology. The PMTs detect the light flashes and amplify them in a compact, low noise, and wide dynamic range gain block. The information is then converted into a measurable electronic signal.

Early discussions projected the need for 200 000 PMTs to fulfill the whole range of telescopes. This required a colossal undertaking in terms of providing consistent quality to meet custom specifications. PMTs are mostly made by hand, and their assembly is an arduous task. Therefore, manufacturing and testing such a large number throughout each phase is both time-consuming and costly. One of the major pain points was achieving high sensitivity through high quantum efficiency in order to detect the faintest light signals. This challenge limited the maximum gain of the PMT. Timing, as mentioned, is also crucial; any signal delay means missing or providing distorted data. To maintain the time window low, PMTs need to be fast and small with a highly efficient photocathode.

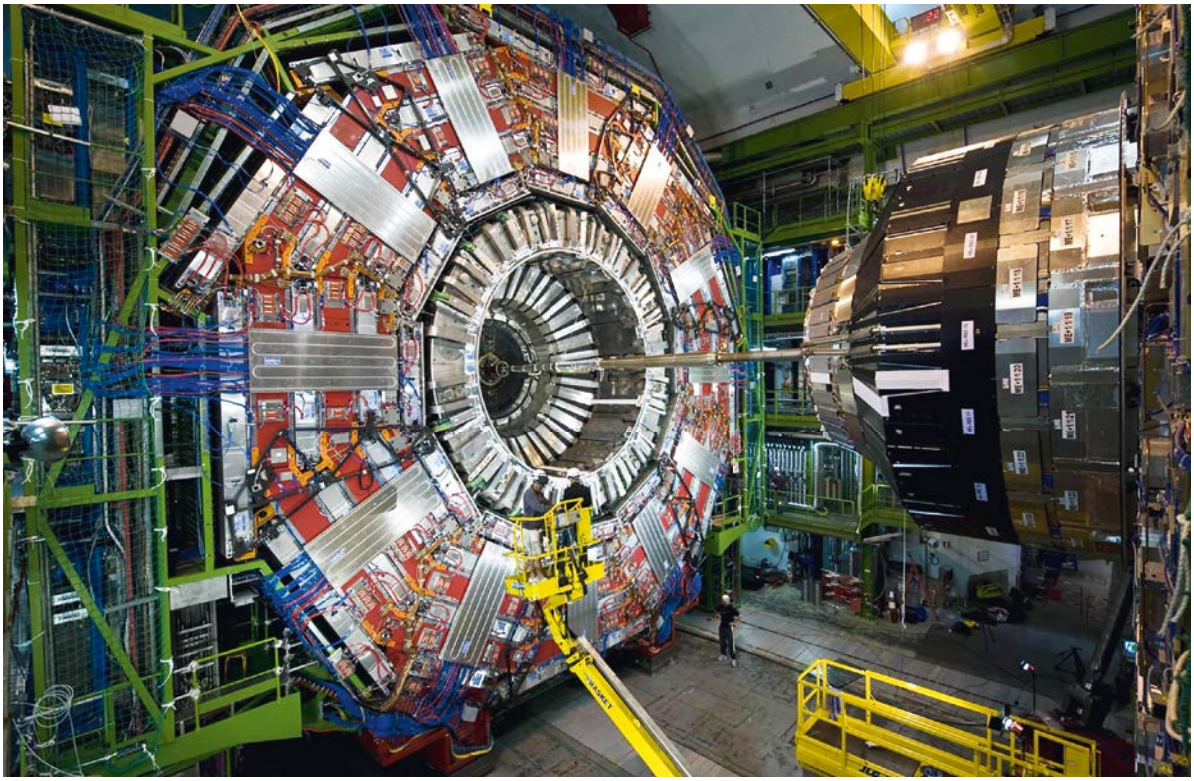
In addition, the after-pulse generated created a source of false signals that had to be minimized. Identifying the root of these challenges lead to a better understanding of materials and procedures in the manufacturing process.

Enabled by the EU FP7 program for the CTAO preparatory phase, many institutes, universities, and their laboratories, in collaboration with Hamamatsu, have been involved in improving these PMT properties. In parallel, given some of the technological challenges surrounding PMTs, the development



R White, K Bernlohr, MPIK / DESY

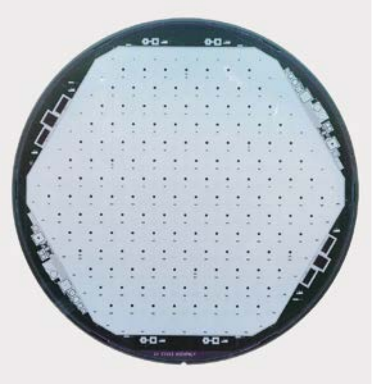
Fig. 1 A gamma ray’s particle shower in the atmosphere ultimately produces Cherenkov light that can be detected by special telescopes.



CERN, Maximilien Brice, 2008

Fig. 2 CMS is one of the Large Hadron Collider's main detectors.

of highly sensitive light detectors based on semiconductor technology, the SiPM was requested. The shape, dimensions, and microcell size of the SiPMs were evaluated from a fully customized hexagonal structure to a more typical square with 75 × 75 μm^2 cells. The technology required did not exist, yet scientists collaborating with Hamamatsu researchers worked together to find the optimal solution.



Hamamatsu Photonics

Fig. 3 8-inch pixel array detector

Improving technology over decades of collaboration

Over nearly twenty years of collaboration, scientists and Hamamatsu continue to push design ideas for both PMTs and SiPMs. The evaluation of the PMT design was reviewed and adjusted many times creating, for example, the SBA (super-bialkali) photocathode with increased quantum efficiency compared to common bialkali photocathodes. The idea was to replace the 1″ PMT with a newly developed one, which limited amplification while still maintaining the advantage of time speed. As there was less gain needed, one dynode was removed.

As the SiPM manufacturing process is quicker – using fewer parts, which can be mass-produced and lightweight materials – they have proven to be more cost-effective in large-scale production. Over the years, their technology improved drastically on many levels. One example is how Hamamatsu limited the crosstalk by adding trenches, effectively reducing the possibility of fake signals. Another is how the pulses improved over time.

Currently, as CTAO telescopes are in their advanced stages of development, thousands of PMTs and SiPMs are being produced and tested. The expected results obtained from the CTAO will provide insights into distant galaxies and extreme particle accelerators in space. Once completed, the hope is to accomplish a completely new view of the night sky and ultimately our universe.

Circular power revolutionizing physics

A ring 27 kilometers long of superconducting magnets with a number of accelerating structures currently resides 100 meters underground in the Franco-Swiss border near Geneva. Known for being the world's largest and most powerful particle accelerator, the Large Hadron Collider (LHC) remains the latest addition to CERN's accelerator complex.

Since 2010, when the accelerator became operational, inside it you will find two high-energy particle beams that travel in opposite directions at very close to the speed of light before they are made to collide, thus generating showers of particles which are investigated by the dedicated experiments around the accelerator ring. These powerful experiments have been the driving force behind several major discoveries in physics including the discovery of the Higgs boson in 2012. This major breakthrough has brought the scientific world one step closer to understanding our world and the origin of the universe.

Hamamatsu Photonics has been working with CERN on this project, and its planned upgrade, which aims to enhance the performance of the LHC for more potential discoveries beyond 2029. The upgrade named High Luminosity Large Hadron Collider (HL-LHC) aims to increase the integrated luminosity by a factor of five to seven beyond the LHC's design value. Hence, the technology used in those experiments must meet even stricter conditions and push the boundaries of current capabilities.

Increasing the demands

The upgrades of the HL-LHC and its related experiments are currently underway to achieve an even higher frequency of proton-to-proton collisions, in order to measure the Higgs boson properties more precisely and to search for dark matter of which little is known.

Although more data can be obtained by increasing the frequency of these collisions, this will generate higher radiation and impact the photodiode (PD) array. The PD array is used in the calorimeter of the CMS experiment, which measures the energy of the particles.

The challenge to solve is the fact that the PD arrays gradually lose their sensitivity while being exposed to radiation. One simple solution is to apply a higher voltage to the PD array to maintain high sensitivity even when exposed to radiation, however, this is only possible to a certain degree.

Additionally, CERN required an even larger-area PD array to reduce both the costs and the dead space of the entire detector system.

The final main challenge was the manufacturing of an even larger-area PD array – never done before – with quantities of about 27 000 pieces in a short timeframe. Therefore, Hamamatsu was faced with overcoming this while finding the right solution for higher sensitivity in its PD array.

The world's largest photodiode

To meet the high-tech needs of the HL-LHC experiments, Hamamatsu Photonics designed and developed the world's largest photodiode with the highest radiation resistance among PD detectors used in high-energy physics applications. Ideal for particle and radiation detection through the measurement of ionization energy deposits, it has both high resistance to radiation and a large area required for the HL-LHC project.

At first, Hamamatsu focused on the high resistance to radiation aspect. They successfully developed a large-area PD array prototype that can be made from a single 6-inch diameter wafer, is highly resistant to radiation, and operates at voltages as high as 800 V.

To utilize larger-diameter wafers as the material for a larger-area PD array, Hamamatsu installed new manufacturing equipment for an 8-inch diameter. The manufacturing process conditions were reviewed from scratch in order to improve the uniformity of the thin film thickness and impurity concentration formed on the wafers.

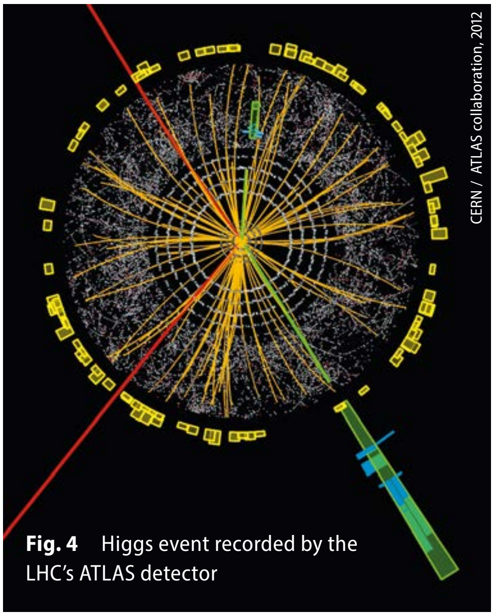


Fig. 4 Higgs event recorded by the LHC's ATLAS detector

CERN / ATLAS collaboration, 2012

By taking these steps, Hamamatsu managed to fabricate a PD array about twice the area of the previous one while maintaining the same high level of radiation resistance and performance characteristics.

Many other technological solutions have been and are currently being designed to support the demanding expansion of the world's most powerful particle accelerator. Each year as we get closer to its operational date, we also get a bit closer to finding out the true nature of our universe.

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Please visit Hamamatsu Photonics' Behind the Science page for more information:
https://hep.hamamatsu.com

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