High power lasers enable exploration of the far corners of the universe but also have more immediate applications, such as generating energy.

POWERFUL LASERS HERALD AGE OF NEW HUMAN ADVENTURES

HUGELY POWERFUL LASERS are shining light on the cosmos and can generate energy using the same process that occurs in the scorching interior of stars.

The ability to directly observe the extreme conditions in the hearts of stars and planets is still a way off. Using high-powered lasers, physicists in Japan are doing the next best thing — for the briefest of instants they are creating similar conditions in the lab.

The overall energy generated by those lasers is not especially impressive, but because it is highly compressed in time and space it creates mind-boggling power. These high-power laser pulses produce staggeringly high temperatures and pressures when they interact with matter.

"The energy of our lasers is usually less than a kilocalorie — roughly equivalent to the energy a 10-watt LED bulb emits over about 10 minutes," explains Ryosuke Kodama, director of the Institute of Laser Engineering at Osaka University.

"But because that energy is concentrated into an extremely short time and compressed into a tiny space, it's possible to produce pressures of around ten million atmospheres in solids and several hundred million atmospheres in plasmas, in a region measuring a few micrometers to several millimetres across," he adds.

ASTROPHYSICS IN THE LAB

These extreme conditions can be also tailored to mimic those encountered in astrophysics. For example, researchers at the institute are using the lasers to explore magnetic reconnection — the often-explosive conversion of pent-up magnetic energy into streams of energetic particles. This process drives several eruptive behaviours in astrophysics, such as supernova explosions and powerful solar flares, that can sometimes disrupt communications on Earth.

It is also possible to use the high pressures generated to explore what is going on inside planets. "Since the pressure at the centre of the Earth is about five million atmospheres, we can use high-powered lasers to simulate the interiors of various planets in the Solar System, as well as Super-Earths discovered in other planetary systems," says Kodama.

By generating even higher pressures, physicists can investigate more exotic astrophysical phenomena. "Recently, we have been using more intense laser light to create photon pressures that are so strong that they are close to those around a black hole," says Kodama. Such intense light interacts with the vacuum, which is thought to be empty. The pressure of the light also creates a strong acceleration field in plasmas. It is an acceleration field equivalent in magnitude to the gravitational field around the black hole where space-time is distorted, and photons are created.

Another way that high-powered lasers can advance research into fundamental physics is by investigating electromagnetic phenomena that occur at velocities approaching the speed of light, where Einstein's theory of special relativity holds sway. Researchers at the Institute of Laser Engineering have recently used their lasers to subject special relativity to a new stringent test — they showed that the distortion of the electric field around a beam of highly energetic electrons conforms with that predicted by the theory.

▲ Osaka University is focussing on high-power laser pulses and their many applications.

ADVANCING LASER FUSION

High-powered lasers also have more down-to-earth applications. The most ambitious is researching laser fusion — using lasers to generate energy by merging light nuclei.

This is the same process that powers stars such as the Sun, and, since it doesn't produce any pollutants or radioactive waste, it is extremely attractive as a potential energy source. It received fresh impetus recently with the announcement in December 2022 that researchers at the US National Ignition Facility (NIF) had achieved the major milestone of generating more energy from fusion than the laser energy used to drive it.

The high-power laser facility at Osaka University is one of about a dozen facilities in the world that is active in this area. In particular, researchers are seeking to use fusion heat energy to generate hydrogen, combining a pollution-free source of energy with a pollution-free fuel. In a proof-of-principle project, they are hoping to produce hydrogen from a miniature fusion power generation system by 2030.

While nuclear fusion offers immense promise, Kodama emphasizes it is vital to adopt a long-term view. Comparing the NIF fusion demonstration to the Wright's brothers first flight, he says that it would have been premature to talk about commercializing airflight at that point.

A DIFFERENT APPROACH

A unique emphasis at Osaka University is the pursuit of generating high-power laser pulses in short succession — in other words, lasers with high rates of repetition. Most large-scale high-power laser facilities have focused on realizing high peak powers, but this generally comes at the expense of repetition rate.

"Most experiments using large laser facilities are single-shot based. While increasing either the energy or the intensity of the laser light generates more extreme conditions, it's difficult to handle data of high accuracy because of the limited amount of data produced," explains Kodama. "But by using lasers with high repetition rates, you can collect a lot of data in a short time, increasing the accuracy of data analysis."

PHYSICISTS CAN INVESTIGATE MORE EXOTIC ASTROPHYSICAL PHENOMENA

Conventionally, Kodama notes, commercial applications of high-powered lasers use high repetition rates, whereas fundamental physics studies have used high peak powers. But he explains this distinction is less relevant now with the ability to analyse big data using machine learning. "The situation is changing a lot with the rising adoption of data science," says Kodama. "So lasers with high repetition rates are important even for fundamental studies."

To pursue this approach, the Institute of Laser Engineering is planning to construct a high-power laser facility, which will realize repetition rates that are up to 100,000 times higher than those of other facilities. They have already demonstrated a key underlying technology that produces up to 100 pulses per second. The facility will advance research in many different areas including quantum materials, laser fusion and quantum vacuum.

For Kodama, the real fascination lies in the potential of high-power lasers with high-repetition rates to open up new vistas on our Universe. "Quantum matter at ultrahigh pressures is the third quantum world, after the quantum world of the very small and the quantum world at extremely low temperatures," he says. "Until now, the world of high-power lasers has been the world of the classical physics, but now there is the possibility of opening a new world of quantum mechanics at high-energy densities, and I hope to explore this new world." ■

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