DOI: 10.24425/academiaPAS.2024.152343

Witold Zawadzki, PhD
works in the Photonics Department at the Institute of Physics, Jagiellonian University. His research focuses on plasma and ultrafast laser spectroscopy. His lab work, as he puts it, involves "shooting lasers at plasma." His interests include atomic optics, photonics, and laser technology. He is also dedicated to promoting physics through science lectures, nature workshops, and student competitions. He is a co-editor of the journals *Foton* and *Neutrino* and an active member of the Polish Physical Society.
witold.zawadzki@uj.edu.pl

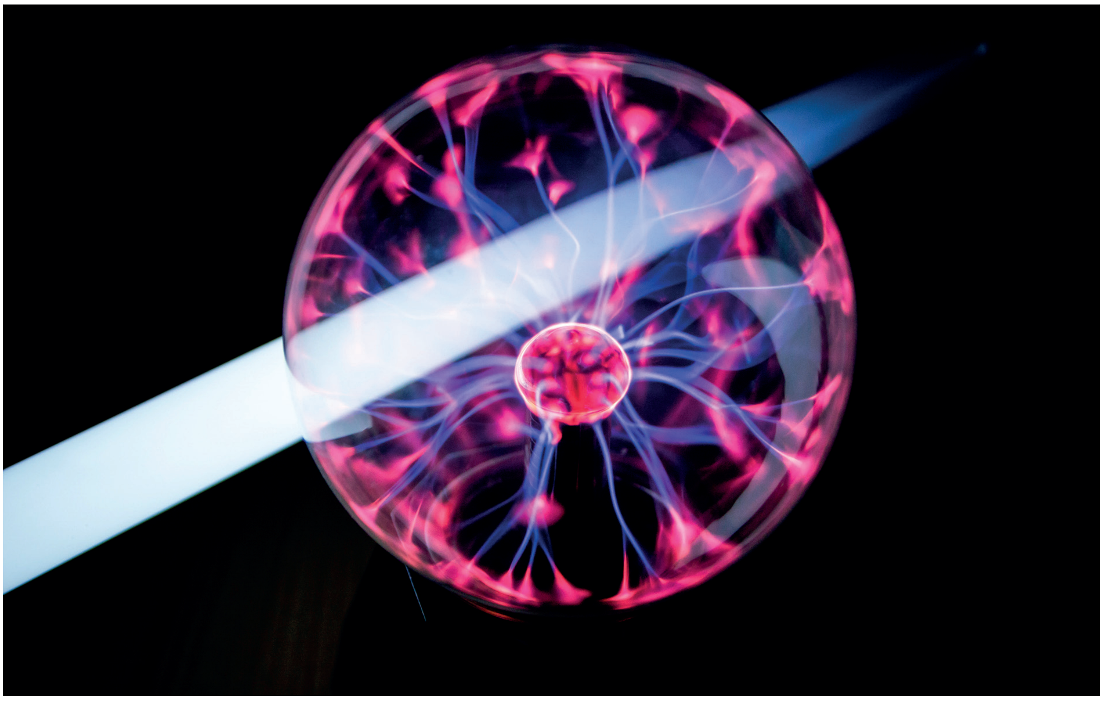
The First, Not Fourth

When we are out on an evening stroll, gazing up at the night sky dotted with thousands of stars, we often do not realize that these bright points are actually immense spheres of matter in a plasma state.

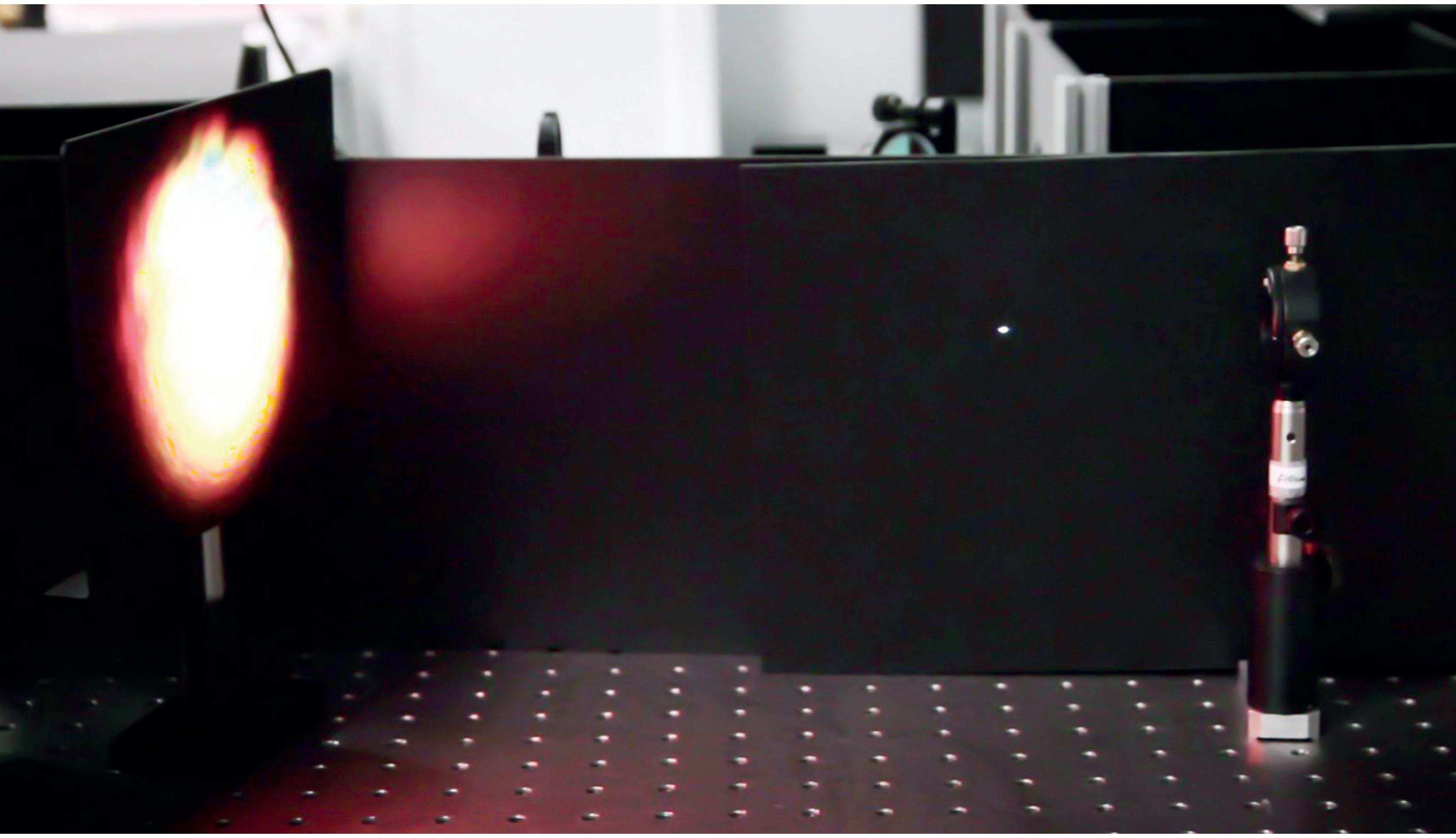
Witold Zawadzki

Department of Photonics, Institute of Physics, Jagiellonian University in Kraków

Plasma is widely known as *the fourth state of matter* because it is fundamentally different from the other three: the solid, liquid, and gaseous states. Plasma consists of charged particles, like ions and free electrons. Electrons separate from atoms when a gas is heated to high temperatures or subjected to a strong electric field. This presence of charged particles gives plasma properties that set it apart from gas. Unlike ordinary gas, plasma conducts electricity and is more chemically reactive. It is due to these unique features that plasma is classified as a distinct state of matter. However, some argue that plasma actually should be considered the *first* state of matter, given that most observable matter in the universe (an estimated 99%) exists in a plasma state. Additionally, plasma was the primary form of matter



A plasma globe is an example of an electric discharge at low gas pressure. A high-frequency alternating current flows through the gas, ionizing it. The resulting plasma forms thin filaments radiating from the central electrode. A fluorescent lamp placed near the globe lights up – the electric field of the globe also ionizes the gas within the lamp's tube



immediately following the Big Bang, regarded as the beginning of the universe.

Just a flash

Although plasma makes up most of the visible matter in the universe, it is relatively rare here on Earth – occurring, for instance, in flames, lightning, and electric sparks. Humanity has learned to harness the properties of plasma, whether from such natural occurrences or created with specially designed devices. Plasma plays a crucial role in understanding the processes within stars, including our Sun, and has wide-ranging applications in technology and science. Plasma research spans various scientific fields, with significant attention on medical uses, such as wound healing and sterilization. Plasma's applications continue to expand in semiconductor manufacturing, nanotechnology, and surface engineering. The greatest potential, however, lies in the quest to control plasma for nuclear fusion, aiming to generate clean energy. Projects like the International Thermonuclear Experimental Reactor (ITER) are exploring how to sustain stable plasma during fusion. Polish scientists, such as physicists from the University of Opole, are contributing to these efforts.

Polish researchers are not only active in international plasma research but also conduct their own studies in national institutes and universities. The main center for plasma research in Poland is the Institute of Plasma Physics and Laser Microfusion (IPPiLM) in Warsaw, specializing in thermonuclear fusion, plasma physics, and laser technology. In addition, the National Centre for Nuclear Research in Świerk conducts studies on plasma applications in nuclear physics and fusion energy technologies. Physicists at the University of Warsaw and Nicolaus Copernicus University in Toruń are engaged in plasma astrophysics, among other areas. Researchers at the Faculty of Physics and the Faculty of Power and Aeronautical Engineering at the Warsaw University of Technology are exploring industrial and energy applications of plasma technology. Plasma can also be generated in particle accelerators – research on this topic, along with plasma's role in nuclear physics, is done at the Institute of Nuclear Physics, Polish Academy of Sciences in Kraków.

At the Faculty of Physics, Astronomy and Applied Computer Science at the Jagiellonian University in Kraków, scientists study plasma in theoretical and experimental physics, astrophysics, nuclear fusion, and high-energy interactions. The Marian Smo-

Image of laser-generated plasma (the small, bright spot in the center-right of the image). A near-infrared laser beam enters from the right side and focuses through a lens. Plasma forms at the lens's focal point. On the left side, a phenomenon called supercontinuum light is visible – this laser radiation passes through the very hot plasma region and interacts with it, reducing the wavelength of the radiation. The white glow indicates the generation of light across the full range of the visible spectrum. This experiment was conducted with a laser producing pulses lasting 30 femtoseconds ($1 \text{ fs} = 10^{-15}$ s)

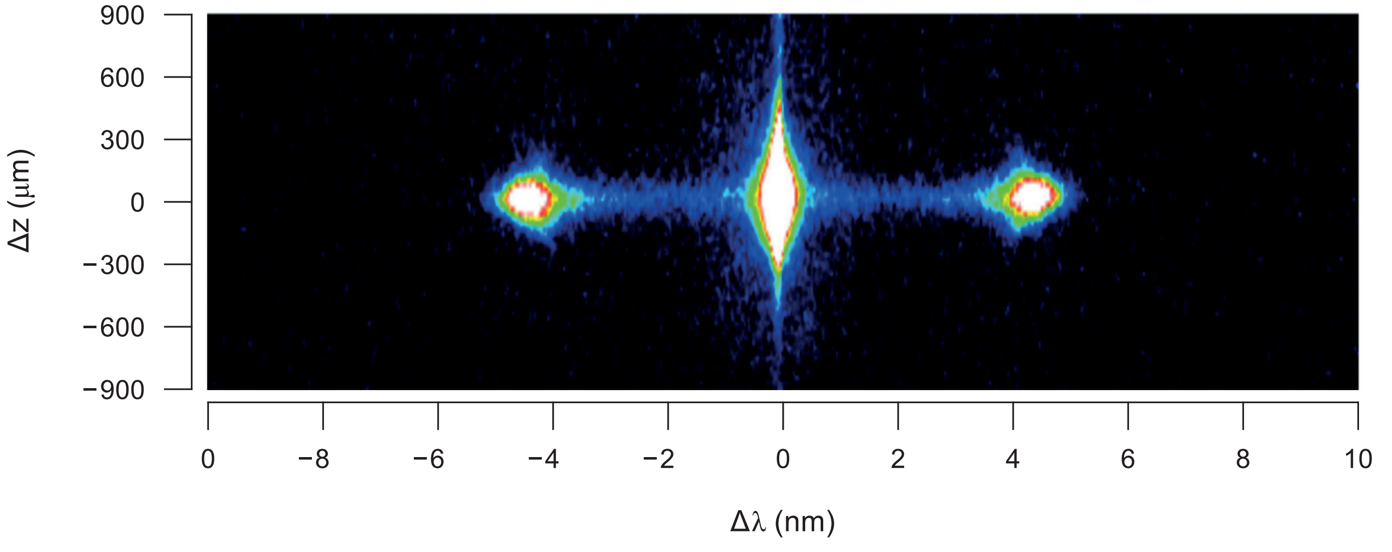


Image of Thomson scattering in arc plasma captured by a fast ICCD camera coupled with a spectrometer. The horizontal axis shows the wavelength shift Δλ of scattered light relative to the laser wavelength (532 nm), while the vertical axis represents the spatial dimension along the probing laser beam. Different colors correspond to various intensities of recorded light (white indicates the highest intensity). The bright, vertical line in the center corresponds to scattered laser light with an unchanged wavelength. The lighter horizontal band represents light scattered with a wavelength shift due to the Doppler effect. The two outer areas in white indicate high-intensity scattered light associated with the collective motion of free electrons in the plasma

luchowski Institute of Physics, particularly its Department of Photonics, does research seeking to deepen our understanding of plasma processes and develop plasma technology applications.

Plasma can be created by heating matter to high temperatures. This can be achieved with a laser, which focuses its beam on the sample's surface or within a gas. The laser beam's energy is absorbed by electrons in the material, which then eject atoms from the surface, forming a cloud of ionized gas. This plasma emits light, with a spectrum that depends on the sample's composition, among other factors. Analyzing the spectrum of glowing plasma allows for the identification of the material in the sample. Laser-induced breakdown spectroscopy (LIBS) is a versatile technique for analyzing the chemical composition of solids, liquids, and gases. A major advantage of this method is that it "vaporizes" only a small amount of material. The resulting crater in the sample is microscopic (on the order of tens of micrometers), making LIBS minimally destructive. LIBS has been successfully used by NASA's Curiosity rover to analyze the chemical composition of Martian rocks. This technique's clear advantages also make it useful on Earth – for example, in authenticating works of art.

Targeting plasma with lasers

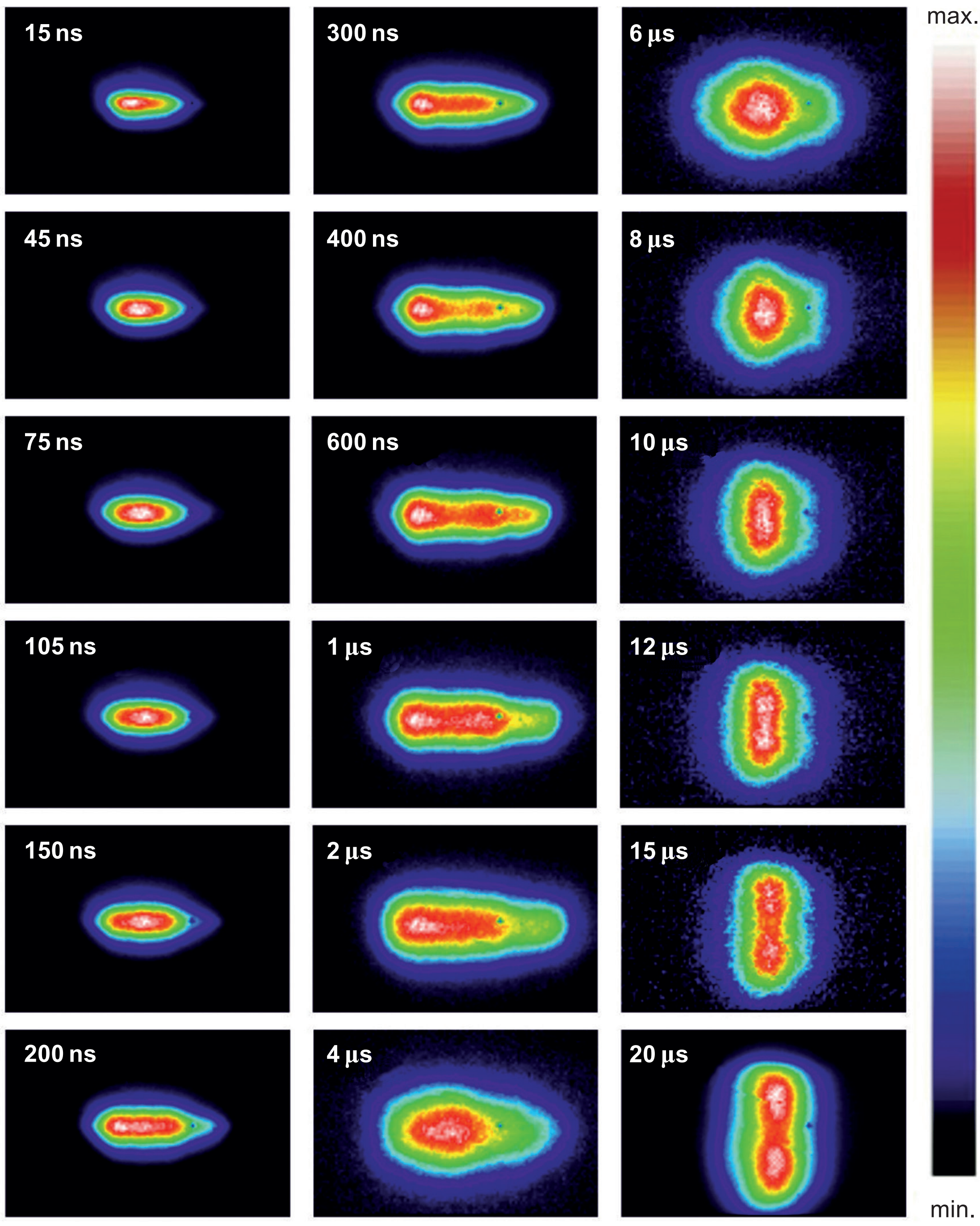
Research conducted by our team at the Department of Photonics, Jagiellonian University aims to understand the fundamental properties of laser-generated plasma. Knowledge of these properties is essential for its proper application in the future. Experiments are being conducted that combine multiple complementary plasma diagnostic methods to determine parameters like temperature and free electron concentration. Both spectroscopic and active scattering methods are used. The latter involves probing the plasma with a laser pulse and analyzing the spectrum of the scattered radiation.

One commonly used method for determining plasma parameters is called Thomson scattering. This technique is based on the scattering of laser light by plasma electrons. A focused beam from a secondary laser is directed at the plasma. The light waves (or more strictly speaking, the electric field of the wave) cause free electrons to oscillate rapidly, which makes the electrons emit radiation in all directions. This process is similar to how radio waves are generated by oscillating currents in a transmitting antenna.

However, due to the very fast movement of electrons in the plasma and the Doppler effect (the same effect that changes the pitch of a sound as a car passes by), the observed scattered radiation has a different wavelength than the laser light. Analyzing the spectrum of this scattered radiation allows scientists to determine the electron velocity distribution, which in turn enables the calculation of the plasma temperature.

A significant challenge with Thomson scattering is the disturbance of the plasma state by the probing laser pulse. To detect sufficient scattered light intensity, the light pulse must have enough energy, which additionally heats the plasma. Techniques must be applied to obtain reliable measurements of undisturbed plasma temperature, requiring an understanding of plasma behavior and the physical constants governing the processes involved.

It's important to keep in mind that plasma generated by light pulses is not static. It forms during the laser pulse (lasting from femtoseconds to nanoseconds) and can be further heated by the pulse itself as energy is supplied to it. The plasma emits radiation,



Sequence of recorded argon plasma emission, depending on delay relative to the plasma-generating pulse. Each frame represents a 3×2 mm area. The plasma was generated by light pulses lasting approximately 8 ns, with an energy density of 2 kJ/cm^2. Colors indicate different intensity levels of plasma radiation (relative scale on the right) (Mendys et al., 2011)

"releasing back energy" in the process, and evolves rapidly, on a nanosecond scale. Solving the energy balance problem is complex, as plasma is not spatially uniform – the center of the "cloud" has the highest temperature, and the farther from the center, the lower the temperature. Numerical calculations and various models assist by taking into account phenomena such as heat flow, radiation emission and absorption, electron and ion interactions, pressure, electric and magnetic fields, and other physical processes occurring in the plasma.

Overall, laser-generated plasma research is a fascinating area of physics that requires a combination of advanced laser technologies, precise diagnostic methods, and numerical modeling. These approaches enable researchers to closely monitor how plasma forms, evolves, and disperses. Gaining a better understanding these phenomena and processes is crucial for technologies like nuclear fusion and material processing. One area of work at Jagiellonian University involves implementing the LIBS method to study artworks, where a relatively non-invasive approach is required. ■

Further reading:

Buchanan E., *Introduction to Plasma Physics,* 2017.

Bolshakov A., "LIBS At Work On Mars," www.appliedspectra.com/mars-libs.html

Mendys A., Dzierżęga K., Grabiec M., Pellerin S., Pokrzywka B., Travaill. G., Bousquet B., Investigations of laser-induced plasma in argon by Thomson scattering, *Spectrochimica Acta Part B* 2011.