Laser technology for ultra-short laser pulses

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The shortest laser pulse ever produced lasted for 80 attoseconds. One attosecond is one thousand millionth of one thousand millionth of a second. This record was established in 2008 by a team led by Prof. Ferenc Krausz in the Laboratory for Attosecond Physics (LAP) at the Max Planck Institute for Quantum Optics. The physicists developed the technology at the Attosecond Beamline "AS1".

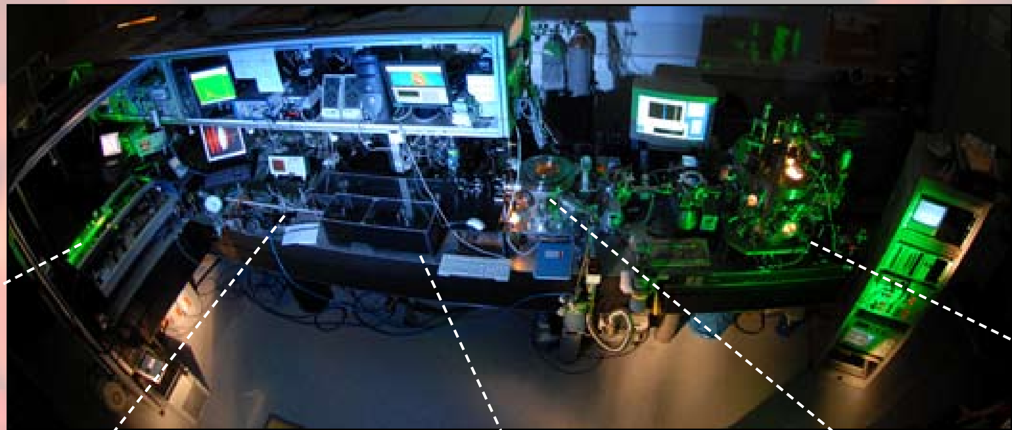
The name "beamline" comes from the elongated structure of the test track for the laser beam. The beamline is a technologically-advanced laser system paired with an experimental station. It is about 10 metres long and consists of several sections. The source of the laser pulses is a laser which delivers light pulses with durations of about 20 femtoseconds.

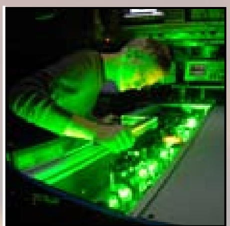
Laser pulses can be shorter if their spectrum is widened, i.e. if they comprise more "colours". For this reason, the light pulses from the laser are subsequently sent through a hollow fibre filled with a noble gas. In this fibre, the spectrum of the light is widened to the whole visible domain through the interaction of the femtosecond pulses with the gas atoms. Each colour of the light, from blue to red as well as an infrared portion, is included in the light pulses.

After leaving the hollow fibre, the light pulses are reflected by so-called "chirped mirrors". These mirrors have a multilayer structure, and the different optical wavelengths will penetrate to different depths until they are reflected out. By means of this difference in path lengths, the "earlier" and "delayed" wavelength components are superposed in time, and the duration of the light pulses is thereby compressed so that the latter finally last only about 3.5 femtoseconds.

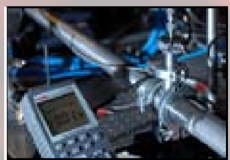
The femtosecond light pulses are then focused on a gas, such as neon or helium, in a small vacuum chamber. For each maximum of the electric field, electrons are extracted from the gas atoms. The electric field of the light accelerates the electrons away from the parent atom. As the field oscillates, the electrons are re-accelerated back and recombine with their parent atom. The kinetic energy gained by the electrons is then released as photons. The light has a wavelength in the X-ray domain or in the far ultraviolet domain (down to 13 nanometres). By filtering out a portion of this spectrum, light flashes with durations of less than 100 attoseconds are obtained.

Lastly, the attosecond light flashes are led into a large vacuum chamber in which the actual experiments take place. For example, how electrons behave in atoms, molecules, or solids is observed here. Since these processes occur within attoseconds, equally short light flashes are required in order to make the motions of the particles visible.





A commercial laser system produces light pulses of about 20femtoseconds. The pulsed light is amplified by a titanium-sapphire crystal. Pulses are produced in the laser by superposition of various light waves with different wavelengths, i.e. colours. In a femtosecond laser, several wave trains are coupled to a single pulse. The size of a femtosecond is almost unimaginably small: light with a velocity of almost 300,000 kilometres per second would circle the Earth 7.5 times within one second. In one femtosecond, it only covers a distance comparable to the thickness of one hair.

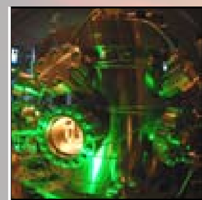


The bandwidth of the light is expanded in the hollow fibre filled with the noble gas. Before the light enters the hollow fibre, it has a wavelength spectrum from about 700 to 800 nanometres. After leaving the fibre, the light has wavelengths available from 400 nanometres up to 1,000 nanometres. So it ranges from visible blue down to infrared light. The wider spectrum is necessary to then produce pulses which are even shorter than 20 femtoseconds.

In order to control the light pulses, so-called "chirped mirrors" are applied. These mirrors are constructed of several layers. They reflect up to 99.99 percent of the light. They are moreover able to let different wavelengths penetrate to different depths. For example, blue light will penetrate the material less deeply than red light.

Red light has thus covered a longer path when it emerges again from the mirror after reflection. With this technique, physicists can temporally superpose wavelength components having different group delays. In this way, via "chirped mirrors", the light pulses are shortened from about 20 to 3.5 femtoseconds.

In a first vacuum chamber, the femtosecond laser pulses encounter a nozzle out of which flows the noble gas. The laser flashes then knock electrons out of the atoms of the noble gas and so produce ion cores. The electrons are then re-accelerated back to the ion cores. Upon impingement, the kinetic energy acquired by the electrons in the laser field is released as a photon. These pulses are in the X-ray or far UV light domain (XUV, wavelength of approx. 10 to 20 nanometres).



Another vacuum chamber at the end of the beamline is for experiments. The attosecond flashes are focused there on samples such as solids. The light flashes again excite electrons in the atoms of the sample.

The behaviour of these electrons is then investigated via a second, longer light pulse. The shorter the attosecond pulse, the more accurate are the observations which may be made of electrons in atoms and molecules.