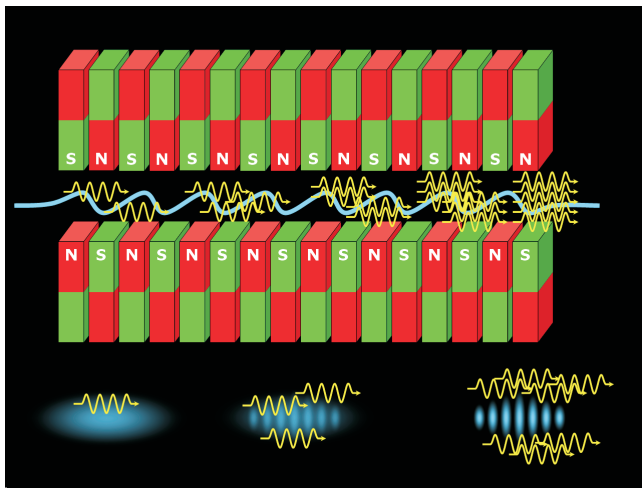




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Schematic drawing that illustrates the self-amplifying light emission from the electron packet (blue) in the undulator. Traversing the alternating magnetic structure, the electrons oscillate and thus emit light. By interaction with the light field, a density modulation is imposed on the electron packet (bottom), leading to an amplified coherent light emission.

Based on this working principle, the free-electron laser at DESY in Hamburg, FLASH, generates light pulses at wavelengths of only a few nanometres with pulse durations as short as 20 fs. The power of a single light pulse, of which up to thirty-thousand can be produced in a second, thereby exceeds one billion watts.

Using dedicated experiments, among them a reaction microscope permanently installed in the experimental hall of FLASH, we address fundamental questions for the interaction of this short-wavelength, super-intense radiation with matter: How do the building blocks of matter and life, i. e., atoms, molecules and ions, behave under such extreme conditions? How does a single atom or molecule absorb two, three or more photons within an extremely short time span? Is it possible to follow chemical reactions just like a movie at atomic resolution and in real time? This is only a short selection of actual research topics. It is anticipated that many other potential applications, in particular those unforeseen at present, will become possible with these laser-like, super-intense new “light machines”, the free-electron lasers (FELs).



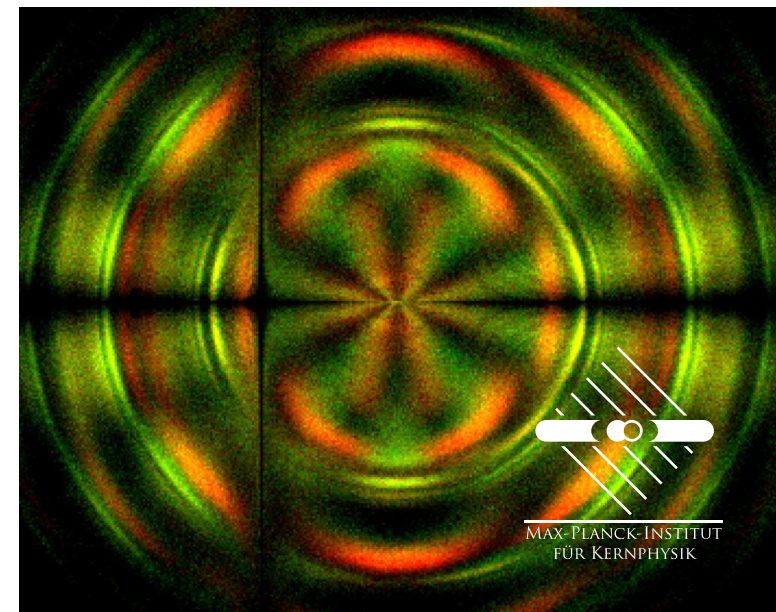
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Ultra-short Laser Pulses „Chemistry“ in Slow Motion



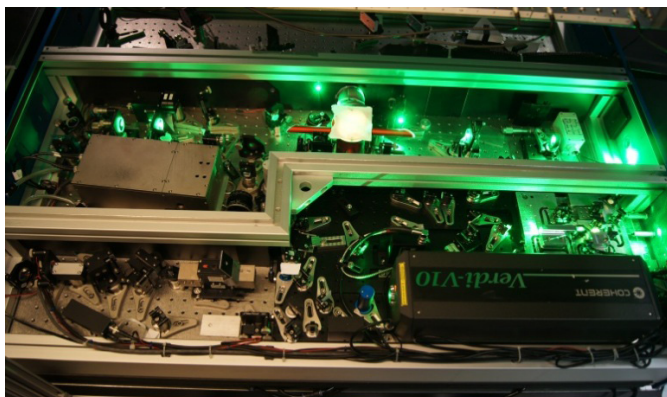
Ultra-short Laser Pulses

„Chemistry“ in Slow Motion

Unimaginably fast are the microscopic processes at the heart of chemical reactions: Atomic nuclei are vibrating around their equilibrium positions, the binding electrons are moving through a molecule, and its atomic constituents rearrange in space to form a new compound. All this happens within only a few femtoseconds (10^{-15} s) or even attoseconds (10^{-18} s) – fractions of a second which are so tiny compared to a whole second like a second compared to the age of our universe. The investigation of these processes in atoms and molecules provides a detailed understanding of the quantum mechanical rules that govern the material world around us. It is also a goal, however, to eventually modify or even control the outcome of chemical reactions. In order to reach this aim, we use intense, short-pulsed lasers in combination with cleverly devised detection systems called reaction microscopes to detect electrons, ions and photons.

Femtosecond Lasers

A frequently used procedure to observe ultra-fast processes are so-called pump-probe experiments. There, atoms or molecules are excited by a first laser pulse (“pump”) and subsequently measured by a second pulse (“probe”). The result of the measurement with the second light pulse depends on the time delay between pump and probe. In the case where the



A view inside a femtosecond laser.

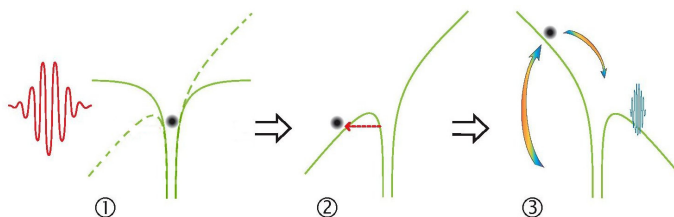
exciting pulse induces a vibrational motion of the molecule, a variation of the time delay between pump and probe produces something like a movie of the molecular motion: the motion of the atomic nuclei within the molecule can be reconstructed from many single such frames picture by picture.

The duration of the laser pulse in such a measurement plays essentially the same role as the exposure time in ordinary photography: The faster the object is moving in front of the camera, the shorter the exposure time has to be set in order to obtain a sharp image. Therefore, for the observation of the vibrations of the atomic nuclei within a molecule, light pulses of only a few femtoseconds (fs) duration are required. Using today's laser technology, it is possible to produce such short pulses with unimaginable high intensities.

Attosecond Light Pulses

For certain problems in present-day research, however, the temporal resolution which can be attained using femtosecond lasers, is no longer sufficient. For example, to observe the motion of electrons inside an atom or a molecule, one needs light pulses with durations shorter than only 100 attoseconds. Because light flashes must contain at least one complete oscillation cycle of the electrical field, this can be achieved only at much shorter wavelengths than those available with the presently prevailing femtosecond lasers.

A strategy towards shorter wavelengths is offered by the generation of high harmonics of the wavelength of a femtosecond laser. Using this technique, pulses with durations below 100 attoseconds can be produced in a wavelength region of only a few 10 nanometres. For the technical realization, the light of a femtosecond laser is focused into an atomic gas beam. The high electrical field strength in the focal point distorts the binding potential of the outermost electrons of the atoms (see the figure below). This creates a potential barrier, behind which no attract-



Scheme of the 3-step model: 1. Distortion of the atomic potential, 2. tunneling ionization, 3. recollision and emission of harmonic radiation at high photon energy (short wavelength).

ing but instead repulsive forces act on the electron. There is a non-vanishing probability that a bound electron may “tunnel” through the barrier and become free. This process is called tunnelling ionization. But the electromagnetic alternating field, to which the atoms are exposed, changes its direction about every 1.4 femtoseconds (this corresponds to a wavelength of about 800 nm). Therefore, directly after it escaped from the atom, the electron feels an electric field with exactly reversed polarity, which drives the electron back to the atomic core. There, it returns into a bound state, emitting the total excess energy (binding energy of the atom and the kinetic energy taken up from the electric field) in the form of an accordingly highly energetic photon.

Free-Electron Lasers: New „Light Machines“

Laser pulses with similarly short or even much shorter wavelengths but million times higher intensities can be generated at new accelerator-based light sources, so-called free-electron lasers (FEL). There, a packet of about one billion electrons with velocity close to the speed of light is sent through an arrangement of magnets with alternating field direction, a so-called undulator, which forces the electrons onto oscillating trajectories. As accelerated charges they emit light – the synchrotron radiation. This way it is possible to generate intense pulses of photons with energies up to the hard X-ray region.

Starting with an ultra-short bunch of electrons (blue illustrated cloud in the lower left corner of the figure on the following page) of length of a few hundred femtoseconds (1 femtosecond: 1 fs = 10^{-15} s) and allowing it to travel further and further through the undulator, the initially emitted light begins to interact with the electron packet in such a way that the electrons (center bottom) come increasingly in phase with the light: They move in synchrony and the emitted radiation becomes coherent, i. e., the wave maxima and minima of the light waves emitted by the individual electrons lie on top of each other. This has dramatic consequences: The intensity of the emitted light pulse is no more proportional to the number of electrons in the bunch (as in a normal, about 2 m long synchrotron undulator), but to that number squared, such that the emitted light intensity in the up to 200 m long FEL undulators increases by a factor of a billion!