Laser-Based Particle Acceleration

How table-top lasers can be used to efficiently accelerate particles

Using state-of-the-art high-power laser systems, we are able to routinely generate extreme energy densities and focused light intensities in a controlled laboratory environment. During the interaction of these laser pulses with matter a plasma is generated that can both sustain and support huge electric fields. These can be used as a novel type of accelerator structure for electrons and ions having properties favorable for a large number of future applications.

Even 50 years after the invention of the laser we still witness a rapid development of systems generating electromagnetic pulses with extreme parameters such as duration, wavelength, peak power, and focused intensity. The employment of solid-state laser materials such as titanium-doped sapphire (Ti^{3+}:Al_2O_3) that provide a broad amplification bandwidth allow the generation and subsequent amplification of light pulses as short as a few optical cycles only. When combined with the technique of chirped pulse amplification (CPA [1]) where the laser pulses are temporally stretched and recompressed before and after their amplification, respectively, using dispersive media or diffraction gratings, table-top laser systems reaching peak powers of several tens or hundreds of Terawatt (1 TW = 10^{12} W) can be realized. These systems easily fit into a university-scale laboratory. A few laser systems that are already operational or currently under construction are even able to deliver peak powers in excess of 1 Petawatt (1 PW = 10^{15} W). When laser pulses of such immense power are focused onto an area as small as a few μm² only, light intensities in excess of 10^{20} or 10^{21} W/cm² can be routinely generated in the laboratory. Such intensities are equivalent to the (fictitious) intensity that would be achieved when all light from the sun reaching the surface of the earth could be concentrated to a spot of ~100 μm diameter only.

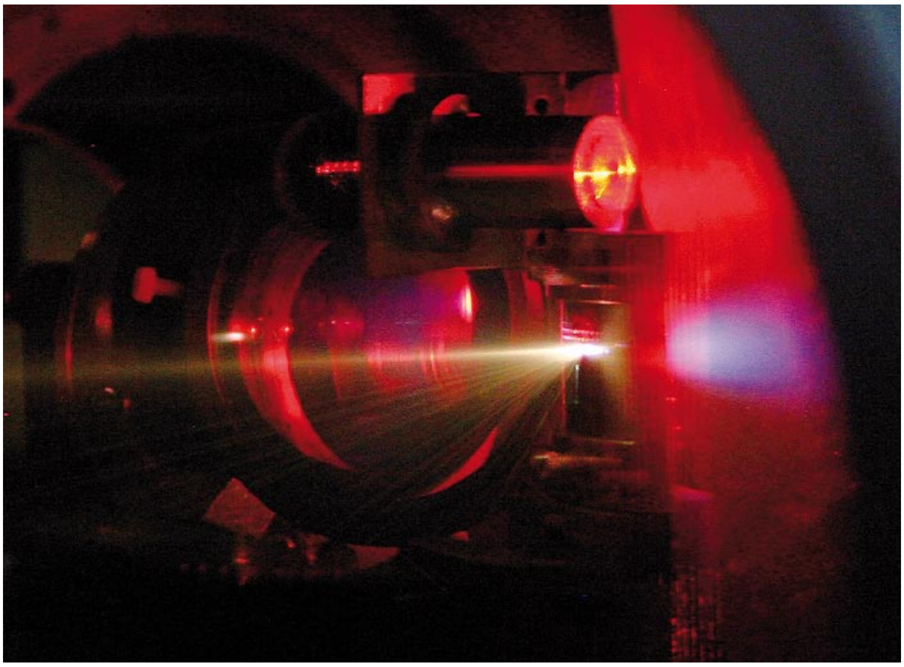

FIGURE 1: **The JETI laser pulses are focused onto a thin metal foil from the right, generating a plasma. Due to recombination at later times, the plasma radiates in the visible range. Starting from the metal foil, a jet of energetic ions is emitted to the left.**

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Malte Kaluza studied physics at the Technical University of Munich where he graduated with his diploma in physics in 2000. Here, he has been working theoretically on laser-matter interactions, which he continued experimentally at the Max-Planck-Institute of Quantum Optics. After receiving his Ph.D. in 2004 he joined Imperial College London as a research associate. In 2006 he joined the IOQ to become Junior Professor at the Friedrich-Schiller-University Jena. Since then he has been head of the POLARIS group. POLARIS is currently the only operating all-diode pumped laser system reaching peak powers in the range of several tens of TW.

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Formation of a Plasma

At such huge intensities, the rapidly oscillating electric field of the laser pulse reaches peak values exceeding the atomic fields binding the electrons to the positively charged nucleus by several orders of magnitude. It is due to this fact that all kinds of matter when exposed to laser light under such extreme conditions are almost instantaneously ionized and a plasma – sometimes called the "4th state of matter" – is formed. Note that the transition from one of the three other states of matter, i.e. solid, liquid or gas, to the plasma state is strictly speaking not a transition between two thermodynamic phases but a rather gradual transition where the ionization degree can be increased e.g. by increasing the light intensity. Within such a plasma, the interaction between the charged constituents mediated by the long-range Coulomb interaction governs the behavior of the plasma. This gives rise to a large magnitude of effects that makes the generation and application of plasmas a fascinating field of current research in physics. One of the most remarkable properties of plasmas is that they can both sustain but also supply electric and magnetic fields that are orders of magnitude larger than the fields that can be realized by any other means in a controlled laboratory environment. When generated by a high-intensity laser pulse, plasmas can – under certain experimental conditions or geometries – act to convert the rapidly oscillating electric field of the electromagnetic wave into a quasi-static field that then varies on the much longer time-scale of the laser pulse duration. This makes laser-generated plasmas a highly promising candidate for the next generation of particle accelerators. This is partly due to the fact that the electric fields generated within such a plasma can be larger by several orders of magnitude than the acceleration fields that can be applied in conventional accelerator structures. As a consequence, the acceleration length that is necessary to reach certain particle energies can be reduced by approximately the same factor. This considerably reduces the length and space requirements for laser-based particle accelerators compared to conventional devices. The laser-driven generation of a plasma on the surface of a thin metal foil using the high-power system JETI at the IOQ is shown in Figure 1. Here, the acceleration of particles to energies of many Megaelectronvolts (MeV) takes place over distances of a few micrometers only. The broad availability of high-power laser pulses in research laboratories all over the world has fuelled the race towards higher kinetic energies of the accelerated charged particles but also towards a higher degree of controllability and reproducibility of the parameters of the generated particle radiation. The latter turns out to be crucial for a number of applications. A few of them will be described in the following.

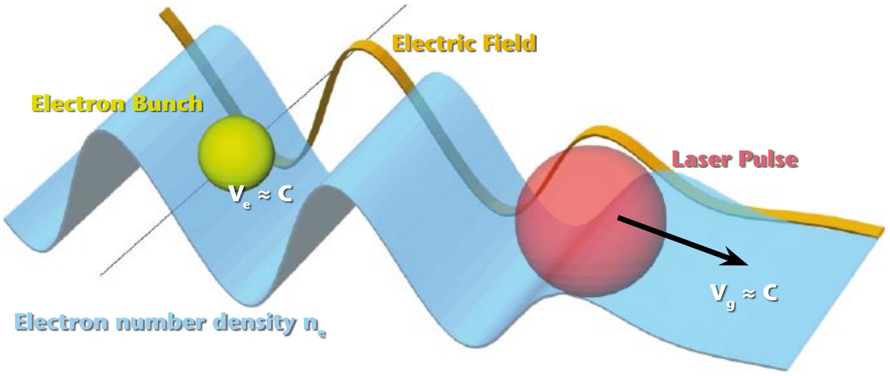

FIGURE 2: **Scheme of laser-driven electron acceleration. The laser pulse propagates to the right and generates a plasma wave in its wake. An electron bunch has been injected into the wave and is accelerated by the electric field pointing in the laser-forward direction.** (Courtesy of A. G. R Thomas, University of Michigan)

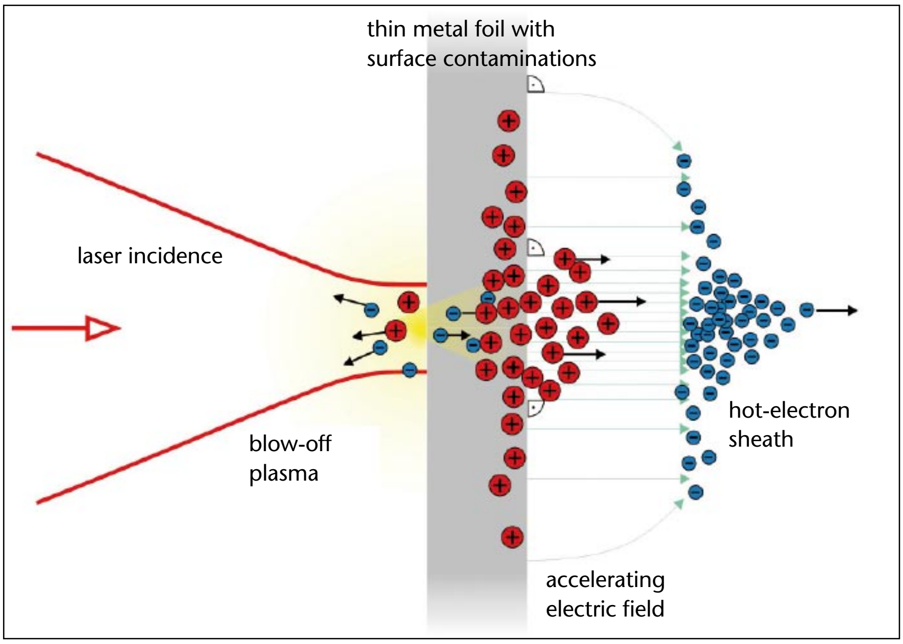

FIGURE 3: **Laser-driven ion acceleration. The laser pulse has generated a plasma on the left side of the metal foil, accelerating relativistic electrons to the right. After the first electrons have left the target it has charged up and atoms can be first ionized and then accelerated to high energies in this space charge field.**

Laser-driven Electron Acceleration

It has been shown that electrons can be accelerated to kinetic energies of the order of 1 Gigaelectronvolt (1 GeV) over an acceleration length of a few centimeters only [2]. In such experiments, the high-power laser pulse was interacting with an underdense plasma, i.e. a plasma where the electron density is sufficiently low to allow a propagation of the laser pulse. This plasma was either formed during the interaction of the laser pulse with a gas jet or within a pre-ionized plasma capillary. The latter formed a wave-guide-like structure counteracting effects due to natural diffraction that facilitates comparably long interaction lengths at high intensities. When the peak of the laser pulse interacts with this plasma, the severe disturbance of the plasma introduced by the ponderomotive force of the light pulse induces oscillations of the plasma electrons against the positive ion background. The ponderomotive force can be understood as a consequence of the light pressure induced by the high-intensity laser pulse acting on the plasma electrons. It tends to expel electrons from regions of high light intensity. As the light pulse further propagates through the plasma, the electron-density oscillations coherently add forming a so-called plasma wave. Due to the charge separation inherently connected to the plasma wave, it is associated with an electric field that has a strong component (up to several hundred GV/m) in the longitudinal direction. The periodic structure of the electric field is moving with the same speed as the plasma wave and the laser pulse which is slightly smaller than the vacuum speed of light. When electrons are injected into such a plasma wave, which can be accomplished, e.g., by the controlled breaking of the plasma wave, the longitudinal electric field can accelerate them to relativistic energies over distances of a few millimeters or centimeters only. This elec-

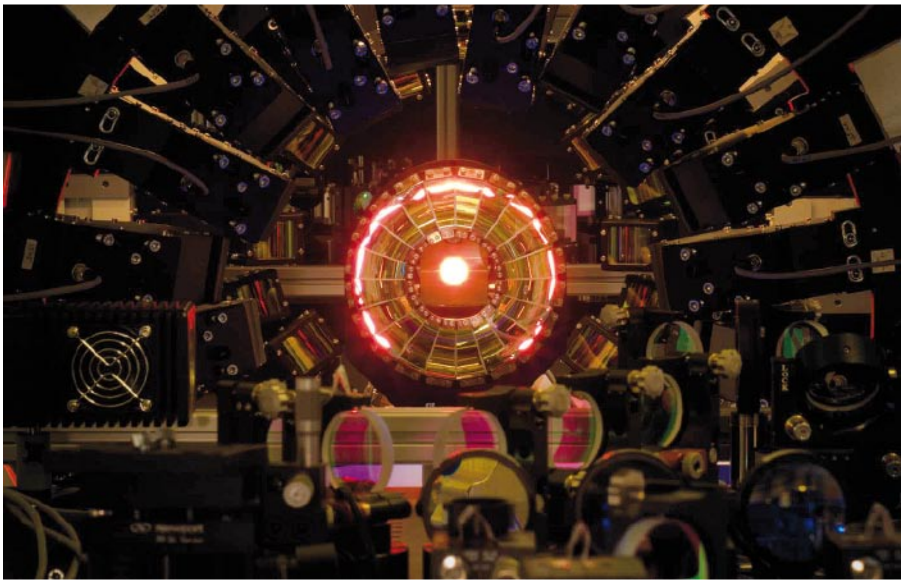

FIGURE 4: **View into the 4th power amplifier of the POLARIS system at the IOQ. The laser glass in the center is pumped by 40 laser-diode stacks arranged in two concentric rings around the glass. The POLARIS pulses pass several times through this laser glass and are amplified in energy during each pass.**

tron-acceleration process is called laser-wakefield acceleration and it is sketched in Figure 2.

One of the most remarkable properties of electron bunches generated by this process is that they exhibit narrow, quasi-monoenergetic features in their energy spectrum [3–5]. Furthermore, it has recently been shown experimentally that the electron bunches have a length that is even shorter than the duration of the driving laser pulse [6]. As a consequence, the application of such electron bunches for the generation of ultrashort and intense pulses of secondary electromagnetic radiation is one of the most exciting prospects for the future of small-scale laser-based particle accelerators. The generation of secondary radiation can be realized, e.g. by sending the electron pulses through external, periodic magnetic field structures such as undulators. In an experiment carried out at the IOQ, the feasibility of this approach and its future potential could be verified for the first time [7].

INFO

High-Power Laser Systems at IOQ

The IOQ operates two high-power laser systems, JETI and POLARIS. JETI is a conventional Ti:Sapphire system delivering 25-fs pulses containing up to 1 Joule of energy with peak powers of 40 TW with a repetition rate of 10 Hz. POLARIS is entirely based on diode pumping. This scheme allows for the generation of light pulses containing comparably high energies (in excess of 10 Joules) while maintaining a comparably short pulse duration (of the order of 150 fs) at a repetition rate of a few shots per minute. When taking into account each of these parameters alone a number of laser systems achieve similar or even higher performance values. However, the combination of these parameters and the prospect of increasing the pulse energy while increasing the repetition rate in the near future using advanced cooling schemes makes the POLARIS system unique. A view into the 4th power amplifier of POLARIS is shown in Figure 4.

Ion Acceleration with Lasers

Another direction of our research when studying the interaction of a high-power laser pulse with plasmas is the generation of proton and ion pulses with kinetic energies up to several tens of MeV. Here, the laser pulse is not interacting with underdense plasma over a comparably long distance, but it is focused onto the front surface of a thin metal foil, which is quickly transformed into a plasma, having a density that is so high that the laser pulse cannot enter. While a part of the laser pulse is reflected from this plasma, a considerable amount of energy is converted into relativistic electrons that are directed into the target. While the target material itself does not pose a significant obstacle for electrons having such high kinetic energies, the target gets positively charged up as soon as the fastest electrons have escaped it. As a consequence, a space-charge field is generated on the target rear surface that is sufficiently strong to decelerate and eventually pull back all subsequent electrons. This leads to the formation of a thin, quasistatic electron sheath at the rear side of the target that has not been disturbed by the high-intensity interaction taking place on the front surface. In this rear-surface electron sheath, huge electric fields as high as several Teravolt per meter (TV/m) are generated. While they tend to pull back the negatively charged electrons, the field strength is sufficiently high to field-ionize atoms sitting on the target rear surface. The positively charged ions can then be accelerated away from the target surface by the same electric field. As the electric field lines point away from the target surface under an angle of approximately 90 degrees, this ion acceleration mechanism is called target normal sheath acceleration (TNSA, [8], see Figure 3). It is worth noting, that even though we commonly use metal foils for ion acceleration experiments, the dominantly accelerated ion species is protons because their charge to mass ratio which determines the efficiency of the accelera-

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The Institute of Optics and Quantum Electronics (IOQ) is one of the physics institutes within the faculty of physics and astronomy at the Friedrich-Schiller-University Jena. The research profile of the IOQ comprises in addition to the development of high-power laser systems the interaction of intense ultrashort laser pulses with matter and X-ray physics and diagnostics. The entire range from nonperturbative but nonrelativistic strong-field laser physics to relativistic laser-plasma physics is covered. In 2009, the new Helmholtz-Institute Jena was founded. The IOQ – among the well-established Helmholtz centers GSI (Helmholtz Zentrum für Schwerionenforschung) and DESY (Deutsches Elektronen Synchrotron), the Fraunhofer Insitute of Applied Optics and Precision Engineering (IOF) and the Forschungszentrum Dresden (FZD) – is one of the central research establishments in this new institute.

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tion is highest for all ion species. Unless special arrangements to suppress protons are made, protons are present on all target surfaces due to water vapor or carbon hydrates e.g. from pump oil. Due to the fact that the acceleration of the ions or protons starts from the undisturbed and initially cold target rear side, the generated ion pulse exhibits a very low transverse temperature resulting in an almost perfect laminar flow of this ion beam away from the target. This predestines these proton beams for imaging techniques for dense but not too thick material samples and – as the ions are positively charged – electric and magnetic field distributions.

One of the drawbacks of laser-generated proton pulses, namely their broad energy distribution [9], was rectified in recent years. As the broad spectrum is partially caused by a nonuniform distribution of the acceleration field within the electron sheath on the rear surface, one solution was to spatially confine the source region of the ions to a small, homogeneous part of the field by using microstructured targets, a method which has been developed at the IOQ [10]. Here, a small (20 µm x 20 µm) dot of proton-rich material, e.g. polymethyl methacrylate (PMMA) is formed on the rear surface by micro-machining an initially unstructured thin film of PMMA using a kHz laser prior to the actual high-intensity interaction. Additionally, the mixture of different ion species (e.g. H$^+$ and C^{4+}) in the accelerated and subsequently expanding ion cloud eventually leads to the formation of monoenergetic peaks in the spectrum [11].

One of the envisaged applications of such monoenergetic proton pulses lies in medical radiation therapy of tumors. In this scheme, proton or carbon ion beams are planned to be used to treat deep-sited tumors. Here, the characteristic feature of energetic ions, namely the deposition of their kinetic energy in a well-defined depth of the tissue (described by the formation of the so-called Bragg peak) leads to an efficient treatment of the tumor. At the same time the damage inflicted on healthy and often sensitive tissue is reduced as compared to X-ray radiation therapy. This ion-based scheme for cancer treatment has already been studied at a number of large-scale accelerator facilities, but so far a widespread use of this treatment is still cost-prohibitive. Here, the use of small-scale laser-plasma based ion accelerators is highly promising and is the subject of a number of research projects. The IOQ, being part of the center for innovation competence (ZIK) "ultra optics" together with the Institute of Applied Physics (IAP), is currently investigating the potential of laser-based ion accelerators for this application. This is pursued within the project "onCOOPtics" together with the ZIK OncoRay in Dresden, the Fraunhofer Insitute of Applied Optics and Precision Engineering (IOF) in Jena and the Research Center Dresden Rossendorf (FZD).

Conclusion

So far, significant progress has been achieved within the field of laser-based particle accelerators. A large number of proof-of-principle experiments have impressively demonstrated the potential of this new and often complementary approach to conventional accelerator schemes. The future will show if it is possible to sufficiently increase the necessary kinetic energy of electrons and ions, while at the same time significantly enhance the controllability of the generated particle pulses with respect to their spectrum and their spatial distribution.

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