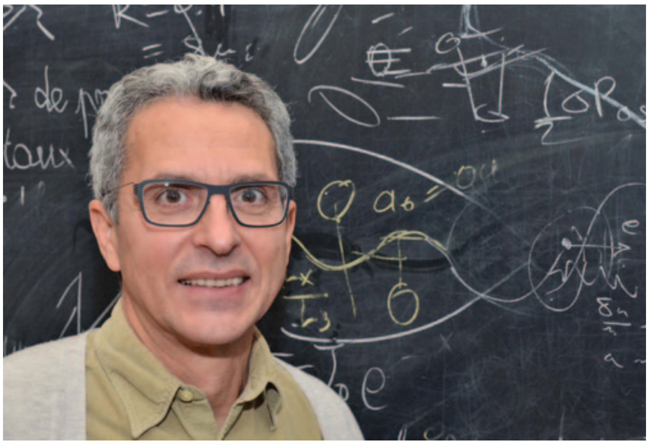
An ambitious exploration

Researchers from Laboratoire d'Optique Appliquée have made major breakthroughs in the quality and reliability of particle and radiation beams produced by lasers, and the applications of these breakthroughs are ambitiously being explored

The SPL (Laser produced Particle Sources) group at at LOA (CNRS/ENSTA/Ecole polytechnique) develops innovative approaches to produce compact accelerators with intense lasers. The related fundamental physics is the laser plasma interaction in the relativistic regime. By controlling the physics processes involved in such interaction, the group has made major breakthroughs in improving the quality and the reliability of particle and radiation beams produced by lasers. It also has the ambitious mission to explore the different applications expected for those beams. Medical application for cancer treatment (proton radiotherapy), cancer imaging and non-destructive material inspection for security are some examples of the applications that the group is exploring.

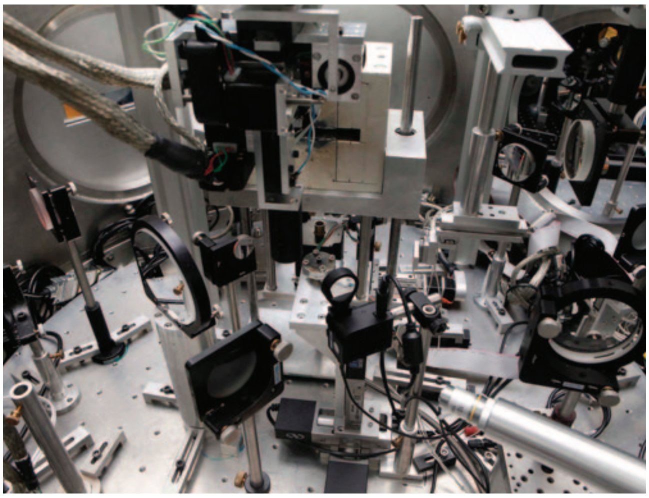


Victor Malka

Accelerators, science and society

With a market of more than €3bn per year, societal applications of accelerators cover many fields such as cancer therapy, ion implantation, electron cutting and melting, and non-destructive inspection to cite a few of them. The most energetic machines, that deliver particle beams with energies greater than 1GeV, were developed for fundamental research. They represent only 1% of the total number of accelerators.

Among these high-energy accelerators are synchrotrons and Free Electron Lasers devoted to the production of intense X-ray beams. Such beams of energetic radiation have many applications in the study of ultra-fast phenomena, for example in biology, to follow DNA structure evolution, or in material science to follow evolution of molecules or of crystal structures. Higher energy accelerators are crucial to answer important questions regarding the origins of the universe, of dark energy, of the number of space dimensions etc. The largest available one, the Large Hadron Collider has confirmed the existence of the Higgs boson. These machines, based on well-established and robust radio-frequency cavities, can deliver beams with extreme average (and peak) currents and extremely high qualities together with very large luminosities.



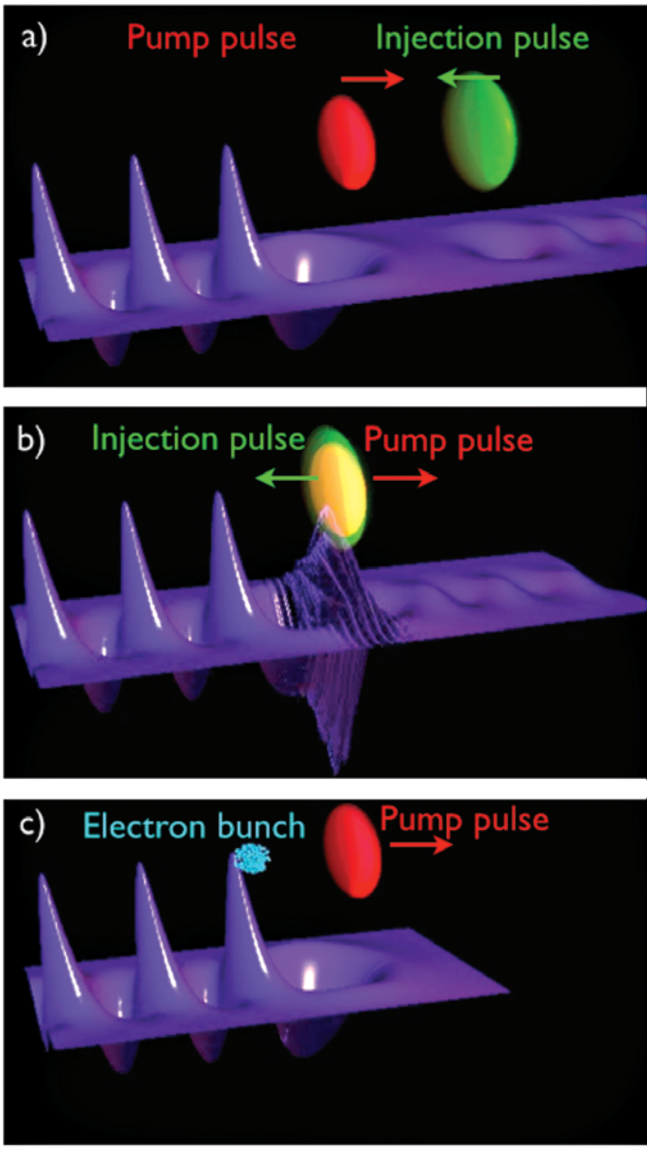
View of the interaction chamber

The limited value of the electric fields they can sustain without electric breakdown (below 200MV/m) implies that, to reach high particle energy, the accelerator length must be increased. In plasmas (ionised medium) such limitation doesn't exist, and fields up to TV/m can be reached.

A new paradigm

A new paradigm, based on the collective motion of electrons in plasmas, has been proposed and explored. The extreme electric field produced (few hundred of GV/m) opens the perspective of reducing the size and the cost of future accelerators. By manipulating electrons in such plasma mediums, physicists were able to produce a high quality electron beam with a record peak current in a reliable way by using a compact laser system in the tens of the TW power level.

In laser-plasma electron accelerators, a longitudinal accelerating electric field with an amplitude of several hundred GV/m is excited at the trail of the laser pulse. The ponderomotive force associated with the ultra-short and ultra-intense laser pushes the plasma electrons out of the laser beam path, thus creating an electric field by charge separation (ions, which are much heavier, remain at rest). Low density plasmas, with their plasma frequency being much lower than the laser frequency, are transparent and



Scheme of principle of the injection with colliding laser pulses: (a) the two laser pulses propagate in opposite direction, (b) during the collision, some electrons get enough longitudinal momentum to be trapped by the relativistic plasma wave driven by the pump beam, and (c) trapped electrons are then accelerated in the wake of the pump laser pulse

therefore the accelerating structure propagates along with the laser pulse at a velocity close to the speed of light. The characteristic scale length of the wakefield is the plasma wavelength, typically in the 10-30µm range.

Consequently, properly injecting electrons into a fraction of a single period of the wakefield will lead to ultra-short electron bunches, with a length shorter than the plasma wavelength. Electrons need to be injected into the wakefield with a sufficient initial energy so that they can be trapped and accelerated. Several injection mechanisms allowing the generation of high quality quasi-monoenergetic electron beams have been experimentally demonstrated. In the 'bubble regime', a single laser pulse is used to drive a wakefield strong enough to trap plasma electrons through transverse breaking of the plasma wave. The electrons will surf and then outrun the wake, forming a monoenergetic electron bunch. To date, laser facilities used in the experimental studies found in the literature have been unable to directly access this regime. Instead, the conditions for transverse wave breaking are eventually met as a result of the laser pulse evolution as it propagates in the plasma. Because of the non-linear nature of the laser propagation, and therefore of the self-injection, this scheme does not yet provide a reliable electron beam. With current laser technology, electron beams in the 100MeV range are currently produced over millimetre distances, with relative energy spreads of the order of 5-10% and a charge of hundreds of pC. With more powerful lasers in the PW class range of power, a few GeV electron beams have been produced.

The second mechanism uses two counter-propagative laser pulses. The first laser pulse, the 'pump' pulse, creates a wakefield whereas the second laser, the 'injection' pulse, is only used for injecting electrons in this wakefield. When laser pulses collide in the plasma, their interference creates an electromagnetic beatwave pattern, which pre-accelerates some electrons. A fraction of these has enough energy to be trapped in the wakefield driven by the pump pulse and further accelerated to relativistic energies. This scheme offers more flexibility: experiments have shown that the electron beam energy can be tuned continuously. The electron beam has a quasi-monoenergetic distribution with energy spread at the 1% level, with tunable charge in the 10-100pC range and with a much better stability. The electron bunch duration of a few fs with a peak current of a few kA make this approach very interesting for further applications.

European strategy effort

The co-ordinated work that has been pursued thanks to European projects such as CARE, EUCARD, EUCARD2, LaserLab 2 and 3, with the individual ERC grants (Paris, X-five, Coxinel) or ERC synergy grant (Axsis) show the dynamics of the European community in this emerging field of research.

The maturity of laser plasma accelerators, with an impressive list of groundbreaking results, reaches a level that allows thoughts of real application. This is now the direction that our community is facing. For Horizon 2020, a Design Study with several FET projects is in preparation to answer to these new challenges for societal applications.

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