

Principles and applications of compact laser–plasma accelerators

Rapid progress in the development of high-intensity laser systems has extended our ability to study light–matter interactions far into the relativistic domain, in which electrons are driven to velocities close to the speed of light. As well as being of fundamental interest in their own right, these interactions enable the generation of high-energy particle beams that are short, bright and have good spatial quality. Along with steady improvements in the size, cost and repetition rate of high-intensity lasers, the unique characteristics of laser-driven particle beams are expected to be useful for a wide range of contexts, including proton therapy for the treatment of cancers, materials characterization, radiation-driven chemistry, border security through the detection of explosives, narcotics and other dangerous substances, and of course high-energy particle physics. Here, we review progress that has been made towards realizing such possibilities and the principles that underlie them.

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The development of laser–plasma accelerators began in the early 1980s, inspired by the pioneering work of Tajima and Dawson¹. Key to their operation is the fact that unlike the superconducting radiofrequency cavities on which conventional accelerators are based, a plasma can support immense electric fields of 100 GV m⁻¹ and greater, which can be generated by separating the ion and electron charges with a high-intensity laser. Static fields of this order generated in a solid target can be used to accelerate protons and ions, whereas ‘travelling’ electric fields supported by the creation of electron plasma waves by a related process can be used to accelerate lighter particles such as electrons or positrons. And even more exotic processes arising from the generation of relativistic electrons within a target can be exploited to produce not just particle beams, but novel sources of X-ray radiation.

The purpose of this review article is to explain the physical processes involved in such laser–plasma accelerators, to underline the uniqueness of the resulting particle and radiation beams and to stress their relevance for fundamental and societal applications. We will restrict the scope of our article to the development of laser-driven plasma accelerators, leaving aside plasma accelerators driven by electron or positron beams^{2–3}. In the remainder of this article, we first describe the physical processes involved in the generation of high-quality electron, proton and X-ray beams. We then discuss the

most promising applications that have recently been demonstrated or identified and finally conclude with perspectives on beam developments. Previous review papers providing a broad coverage of the different theoretical processes involved in laser–plasma accelerators⁴ and of the development of experimental techniques and results in this domain^{5–7} can be used to gain a more thorough and in-depth view of this field and its recent developments.

ELECTRON BEAMS

In laser–plasma electron accelerators, a longitudinal accelerating electric field is generated by the ponderomotive force of an ultrashort and ultraintense laser. This force, proportional to the gradient of the laser intensity, pushes the plasma electrons out of the laser beam path, separating them from the ions. This creates a travelling longitudinal electric field, in the wake of the laser beam, with a phase velocity close to the speed of light, most suitable for accelerating particles to relativistic energies. This electric field can reach amplitudes of several hundred gigavolts per metre. In addition, the characteristic scale length of the wakefield is the plasma wavelength, 10–30 μm for electron densities $n_e = 10^{18}–10^{19}$ cm⁻³. Consequently, if we manage to inject and accelerate electrons into a single period of the wakefield, it will lead to ultrashort electron bunches, with 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. Experimentally, two injection mechanisms have recently demonstrated the generation of high-quality quasi-monoenergetic electron beams. In the first mechanism, a single laser pulse is used (Fig. 1a) to drive the wakefield to large enough amplitude such that electrons are injected into the rear of the first wake oscillation through transverse breaking of the plasma wave (Fig. 1a). The electrons then surf the wake and after outrunning the wave they form a monoenergetic electron bunch. This is

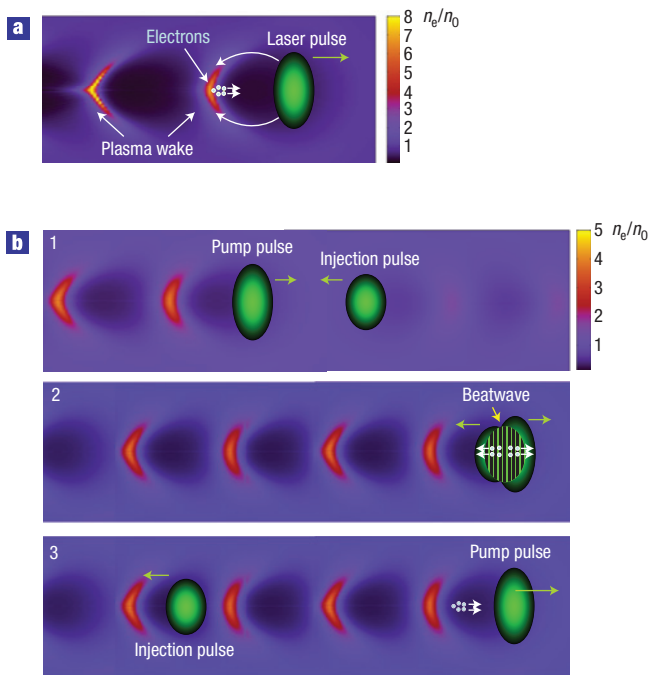


Figure 1 Injection schemes in laser–plasma accelerators. **a**, A schematic diagram of the self-injection mechanism in the bubble regime. The figure represents a plot of plasma electron density behind the laser pulse. The plasma wake is highly nonlinear with regions where electrons have been evacuated (black) and regions where electrons accumulate (yellow). The arrows show how electrons are deflected outward and then accumulate at the back of the wakefield, where some of them are trapped and accelerated. **b**, Schematic diagrams of the injection mechanism in the counterpropagating colliding pulse scheme. (1) The two laser pulses have not collided yet; the pump pulse drives a strong plasma wake, although less nonlinear than in the bubble regime case. (2) The pulses collide and their interference sets up a beatwave that preaccelerates electrons. (3) Some of the preaccelerated electrons are trapped and further accelerated in the wake.

referred to as the ‘bubble’ regime⁸. So far, laser parameters used in published experimental results have been unable to directly access this regime. Instead, the conditions for transverse wave breaking are eventually met as a result of laser pulse evolution as it propagates in the plasma. With current laser technology, electron beams in the 100 MeV range have been produced over millimetre distances^{9–11}, with relative energy spreads of the order of 5–10% and a charge of hundreds of picocoulombs. A 1 GeV electron beam has been reported in a recent experiment, where the laser pulse was guided and evolved over a few centimetres in a capillary plasma discharge¹². The second mechanism is based on the use of several laser pulses¹³. In its simplest form, the scheme uses two counterpropagating ultrashort pulses with the same wavelength and polarization (Fig. 1b). The first laser pulse, the ‘pump’ pulse, creates a wakefield, whereas the second laser, the ‘injection’ pulse, is only used for injecting electrons into this wakefield. The laser pulses collide in the plasma and their interference creates an electromagnetic beatwave pattern that preaccelerates some electrons. A fraction of these have enough energy to be trapped in the wakefield driven by the pump pulse and further accelerated to relativistic energies. Although this scheme is more complicated experimentally, it also offers more flexibility: experiments have shown that the electron beam energy can be tuned continuously from 10 to 250 MeV (ref. 14). The electron beam has a quasi-monoenergetic distribution with energy spread in the 5–10% range, charges in the 10–100 pC range and its

parameters are stable within 5–10%. This approach is promising for the control of the electron beam parameters, and might enable tuning of both the charge and the energy spread. For instance, increasing the beam energy to the giga-electronvolt range should decrease the relative energy spread to the 1% level. The electron bunch duration has never been measured experimentally with sufficient resolution, but simulations show that it might be shorter than 10 fs (ref. 15).

Although the experimental results obtained so far are impressive and useful beams have already been produced, there is still much room for improvement. In the ‘bubble regime’, scaling laws supported by three-dimensional particle-in-cell simulations have been derived. These laws predict that multi-giga-electronvolt electron beams with nanocoulomb charges might be attainable with the next laser generation^{16,17} without the need for a plasma channel, with a good transfer of energy from the laser to the electron beam (of the order of 10–20%), but still with an energy spread of a few per cent. For a pulse duration close to the plasma period, the beam energy should scale as $P_L^{1/3} n_e^{-2/3}$ and its charge as $P_L^{1/2}$, where P_L and n_e are respectively the laser power and electron plasma density. For example, a 200 TW, 30 fs laser can produce a 0.3 nC electron beam at 1.5 GeV over 1 cm length with a 3.8% energy spread and a 10 GeV, 1 nC beam can be obtained using a 2 PW, 100 fs laser over 15 cm length. Note that laser energy could be saved by using external guiding over a longer distance¹⁷. Transport and focusing of electron beams with large energy spreads can limit their applicability. The requirements are most stringent for free-electron lasers and high-energy accelerators, where a relative energy spread much below 1% is needed. Extending the acceleration length with external guiding in the colliding laser pulse regime is one solution. Two-stage laser–plasma accelerators, which require more laser energy for delivering the same electron energy, have also been considered recently in conceptual designs of compact accelerators delivering high-quality and ultrashort electron bunches at high energy with low energy spread. For example, a 170 TW, 60 fs laser pulse can provide after 18 cm propagation in homogeneous plasma a 1.2 GeV electron beam with 1% relative energy spread¹⁸, whereas a 9 J, 60 fs pulse can provide after 24 cm of propagation in a plasma channel a 3 GeV electron beam with 1% relative energy spread¹⁹.

PROTON BEAMS

In contrast to electrons, ions are best accelerated by a low-frequency (compared with the electron plasma wave frequency) or even a quasi-static electric field. Indeed, owing to their higher mass, the rapid field oscillations associated with an electron plasma wave average out to zero net acceleration for an ion. In experiments so far, the mechanisms of ion acceleration can be classified into two categories, on the basis of how the electric charge separation that produces the quasi-static field is generated: ponderomotive or thermal explosion acceleration.

In the ‘ponderomotive acceleration’ scenario, charge separation is generated by the ponderomotive force of the laser, which sets up a charge imbalance that accelerates ions in turn. It is indeed a low-frequency force, with the laser pulse duration as characteristic time. This mechanism includes forward ion acceleration at the surface of an irradiated solid target²⁰, and transverse ion acceleration associated with self-guided laser propagation inside a low-density plasma²¹. In the ‘thermal explosion’ type scenarios, illustrated in Fig. 2, charge imbalance is maintained by heating a fraction of the plasma electrons to very high temperature. The resulting electron thermal pressure drives an expansion of these hot electrons around the target, setting up a large-amplitude electrostatic field at the target–vacuum interfaces²². Field amplitudes greater than 1 TV m⁻¹ are produced, leading to efficient ion acceleration from the target

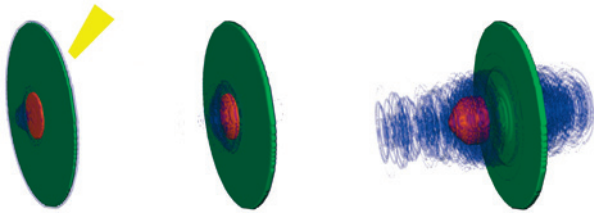


Figure 2 Three snapshots illustrating the dynamics of proton acceleration from the rear surface of a laser-irradiated thin target. A thin proton dot (red) is deposited onto a micron-thick heavier substrate (green). A short, intense laser pulse incident from the right (yellow) onto the hidden target surface accelerates electrons (blue) to relativistic energies at that surface (left panel). These electrons move through the target, emerge at the left surface and set up a quasi-static electrostatic field that accelerates the protons (middle panel). During acceleration, the proton layer expands and curves, as radial and longitudinal field non-uniformities translate into energy and position spread for the accelerated particles (right panel).

surfaces over very short distances. In these cases, ions will be accelerated out of the target, perpendicularly to its edges. To these ‘thermal explosions’ can be associated the accelerated ions detected behind thick targets²³ and the high-energy plasma plume emitted from the laser-irradiated surface²⁴. The relative importance of these various acceleration mechanisms has been largely debated over the past decade, with conflicting numerical and experimental evidence. Recent studies, however, show that both mechanisms can coexist, and that one can dominate over the other depending quite subtly on the interaction parameters^{25–27}.

Most experiments studying ion acceleration by high-intensity lasers report the detection of a large number of accelerated protons—even when using metallic targets. These protons can be traced back to hydrogenated contaminants deposited at the target surface. In the first experiments, the proton energy distribution was maxwellian-like with a sharp cutoff at high energy. For example, proton beams with energies up to 58 MeV have been measured at the Lawrence Livermore National Laboratory with the now-dismantled Nova petawatt laser²³. With smaller facilities, of the 1 J/30 fs class, distributions extending up to 10 MeV have been obtained²⁸. In some experiments, the target was heated before the interaction, to evaporate the hydrogenated layer. This enabled the detection of energetic ions with higher atomic numbers²⁹. Proton beams produced by rear-surface acceleration show good collimation, increasing at higher proton energy, and very low transverse emittance (below 10^{-2} mm mrad for protons above 10 MeV (ref. 30)). Several paths for beam optimization are now being actively pursued. The first is to operate with ultrathin targets, in the sub-100 nm range, which requires ultrahigh-contrast laser pulses. Improved acceleration with such targets has been reported recently^{31–33}. Another way to control the energy distribution is to engineer the target back surface to selectively accelerate ions in a given charge state or to a given energy^{34,35}. An alternative path for energy selection relies on laser-triggered microfocusing devices, the relevance of which for beam steering has been demonstrated experimentally³⁶.

X-RAYS

Despite one hundred years of history, the production and applications of X-ray radiation (with energy beyond 1 keV) remain extremely active in multidisciplinary fields. Spectacular increase in brightness and decrease in pulse duration of X-ray beams are now foreseen owing to the progress made in laser–plasma interactions.

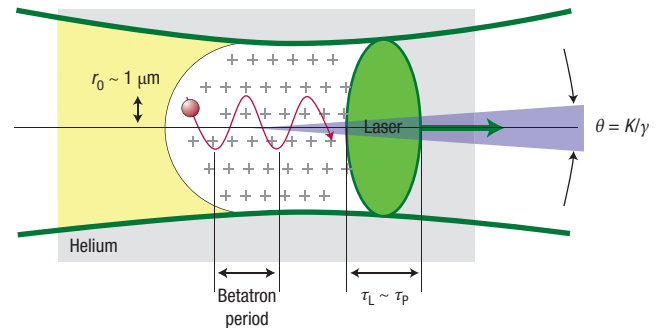


Figure 3 Principle of the betatron radiation produced in a wakefield cavity. The electron is accelerated to relativistic energies and wiggled in the cavity. As a result of this motion, an X-ray beam is emitted in the direction of the electron momentum.

At the frontier between plasmas and accelerators, novel ultrashort X-ray sources are produced using electrons accelerated in laser and electron beam wakefields. Based on radiation from moving charges, the most compact and promising schemes rely on the wiggling of relativistic electrons produced in laser–plasma accelerators, either within the plasma itself, in a counterpropagating laser beam or in a permanent magnet undulator. These novel sources, capable of combining femtosecond durations together with collimation, offer remarkable perspectives for countless applications.

PLASMA WIGGLER

The intense electromagnetic focusing fields of the plasma cavity driven in the wake of an ultrashort laser pulse act as an electron wiggler in addition to being an accelerator. As shown in Fig. 3, electrons trapped in the cavity are accelerated and wiggled at the so-called betatron frequency $\omega_b = \omega_p / (2\gamma)^{1/2}$, where ω_p is the plasma pulsation and γ is the Lorentz factor of the electron beam, producing X-ray radiation incoherently in the direction of their velocity. The number of photons increases linearly with the wiggler strength parameter of the plasma cavity, K ($K = \omega_b \gamma r_0 / c$), and the number of oscillations in the plasma cavity³⁷. The peak X-ray energy is given by E (eV) = $1.45 \times 10^{-21} \gamma^2 n_e$ (cm⁻³) r_0 (μ m) and the divergence is $\theta = K/\gamma$; here, r_0 is the amplitude of the betatron motion.

In current experiments, electrons are accelerated up to 200 MeV and oscillate in the ion cavity with a hundred micron wavelength and micrometre amplitude. Up to 10^6 photons/pulse/0.1% BW are now produced at 1 keV with a spectrum decreasing exponentially down to a few tens of kiloelectronvolts³⁸. The beam is collimated within a few tens of milliradians, has a duration of 20 fs (according to simulations) and an extremely small source size of 1 μ m (ref. 39). This source offers promising perspectives for improvement, as it will benefit from the expected progress of laser–plasma accelerators. Considering a 1 GeV electron beam, collimated within 1 mrad and with a 300 pC charge, up to 10^8 photons/pulse/0.1% BW at 10 keV could be produced within a milliradian beam⁴⁰.

LASER WIGGLER

The Thomson scattering source aims at producing higher-energy collimated X-rays. Here, the electrons beam is wiggled in a counterpropagating laser pulse. Owing to the Doppler shifts on the laser frequency seen by the electrons and on the radiation they emit, monochromatic X-rays at an energy $E = 4\gamma^2 E_l$ (where E_l is the photon laser energy) can be produced up to the megaelectronvolt range. In the linear regime for which the laser strength parameter $a_0 < 1$, the typical divergence of the produced X-ray beam is

of the order of $1/\gamma$. This process has been first demonstrated using a conventional accelerator⁴¹ and recently using a laser–plasma accelerator⁴². Because the X-ray energy scales with γ^2 , the X-ray photon energy can be tuned by adjusting the electron energy. Considering a picosecond, 1 J laser pulse scattering off a 200 MeV, 300 pC electron bunch that can currently be produced, a beam of X-rays with up to 10^9 photons at 1 MeV could be generated⁴³.

X-RAY FREE-ELECTRON LASERS

X-ray free-electron lasers (XFELs) generated using wakefield electrons could provide users with orders of magnitude brighter X-ray radiation (10^{12} photons/pulse/0.1% BW). In this scheme, the laser-accelerated electron beam is injected into permanent magnet undulators, shaped into microbunches separated by the resonance wavelength of the magnetic structure as it propagates into the undulator and produces a burst of bright X-rays from the coherent emission of all microbunches. Owing to the high electron beam peak current generated from laser-wakefield accelerators, saturation lengths for X-ray emission of a few metres can be obtained, offering the opportunity to develop very compact XFEL instruments. This is in contrast to the large-scale facilities being built worldwide based on radiofrequency technology acceleration, which require hundred-metre undulators and kilometre-long accelerating lines. Injection of electron beams into permanent magnet undulators is on the way, and the first signatures of synchrotron radiation (in the visible spectral range) have recently been observed⁴⁴. However, the very extreme electron beam properties required to produce an XFEL⁴⁵, or at least X-ray synchrotron light, are not available yet. Among them, a crucial parameter will be the charge contained in the 0.1% spectral bandwidth. 1 nC at 1 GeV will be required to produce an efficient XFEL.

APPLICATIONS

The spectacular increase in brightness and decrease in pulse duration of X-ray and particle beams will revolutionize the way researchers investigate matter. Fundamental events in biology, chemistry and solid-state physics can be recorded with ångström space resolution to capture electronic, atomic or molecular transient dynamics. The X-ray pulse requirements will depend on each experiment. Basic applications have been carried out with 10^3 photons/pulse/0.1% BW at 2 keV; 10^{10} photons/pulse/0.1% BW at a few tens of kiloelectronvolts are required to obtain a Laue diffraction pattern in complex molecules and in a single shot⁴⁶. Achievement of high X-ray intensities will extend nonlinear optics to the X-ray spectral range and enable the creation of new states of matter such as plasmas of astrophysical or geophysical interest. Source compactness, broad spectral range and perfect synchronization of particle and radiation bursts are unique properties that could extend the breadth of applications. As we have seen, the high peak current of laser–plasma electron beams could lead to compact XFEL facilities, on a size affordable by small-scale laboratories. High dissemination towards multidisciplinary users is then foreseen in fundamental science, but also in more societal fields. As an example, implementation in existing hospitals of phase-contrast imaging techniques developed at synchrotrons to provide high-resolution images with micrometre resolution could enable significant advancement in clinical diagnostics. Finally, time-resolved experiments, where the particle burst or the X-ray flash can act indifferently as a pump or a probe, would significantly extend the field of investigation in the dynamics of matter, compared with currently available techniques using a visible pump and X-ray or visible probes. Below, we discuss some of these novel application opportunities in medicine, radiation biology and physics.

MEDICINE

Up to now, X-rays with energies of a few megaelectronvolts represent the vast majority of ionizing radiations used for cancer radiotherapy of several million patients throughout the world. X-rays are commonly used because they are produced using flexible, compact and affordable machines. Higher quality, more energetic electron beams, such as those produced by laser–plasma accelerators, could be used for radiotherapy and provide better clinical results. It was shown that such beams are well suited for delivering a high dose peaked on the propagation axis, a sharp and narrow transverse penumbra, combined with a deep penetration. Comparison of dose deposition for 250 MeV laser-accelerated electrons with that of 6 MeV X-rays showed significant improvement for a clinically approved prostate treatment plan (T. Fuchs *et al.*, manuscript in preparation). Target coverage was computed to be the same or even slightly better for electrons, and dose sparing of sensitive structures was improved (up to 19%). These findings are consistent with previous results regarding very high-energy electrons as a treatment modality^{47–50}. The lack of compact and cost-efficient electron accelerators could be overcome by laser–plasma systems using existing commercial systems delivering tens of femtoseconds, 1 J laser pulses, and operating at 10 Hz repetition rate to deliver the required clinical electron beam dose in a few minutes.

With more than 30,000 patients worldwide with successful clinical results, proton and hadron therapies are still emerging, but represent promising methods for the specific treatment of deep tumours and radio-resistant cancers^{51–53}. However, although this treatment is expanding considerably (more than 20 new projects are under consideration worldwide), its use is still strongly limited owing to the size and cost of the infrastructure, which exceeds 100 M€. The infrastructure requirements, which include accelerator, beam lines, massive gantries of more than 100 tons and building, are not accessible to the majority of radiotherapy centres. With the outstanding progress in laser physics and fast development of high-power laser systems, several laser-based projects have emerged with the goal of reducing the cost of proton therapy treatment. These costs could be cut, not only by changing the accelerator itself (commercial accelerators that deliver stable and reliable 200 MeV protons beams cost about 10 M€), but mainly because the building footprint would be strongly reduced, and the gantry could be replaced by a smaller and lighter structure. Several severe conditions have to be met before considering such an approach for medical applications. It is necessary to (1) increase the proton energy up to 200 MeV, for which petawatt class lasers will probably be required^{54,55}, (2) have enough protons at this energy to treat patients in sessions of a few minutes, for which high repetition rates (10 Hz) could be needed, (3) have a reliable and stable laser–plasma accelerator. The dose requirement and dose profile could be achieved with particle selectors or structured targets. This promising application is also extremely challenging, as it requires the development of high-contrast, petawatt lasers operating at 10 Hz, as well as dedicated research activities in target design and high-intensity interaction. In a related field, lower-energy protons of several megaelectronvolts delivered with compact cyclotron machines of a few M€ are used to produce radioisotopes for medical diagnostics. A laser-based alternative has been considered⁵⁶, but does not seem economically competitive because higher repetition rate lasers would be required with a cost in excess of existing accelerators⁵⁷.

RADIATION BIOLOGY

Progress in conventional and conformational radiotherapies is highly dependent on innovative developments of radiation source quality, physics and engineering. Concerning radiation biology, a

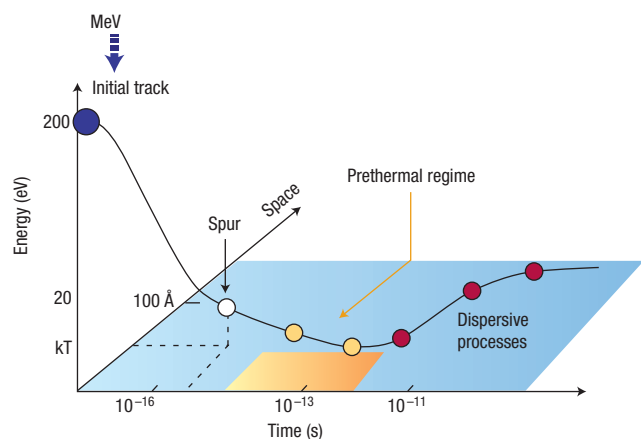


Figure 4 Time–space relationship characterizing energy deposition during the interaction of a relativistic electron beam (MeV) with liquid water. In less than 10^{-16} s, energy quanta of 200 and 20 eV are delivered in primary nanometric tracks and spurs, respectively. The early behaviour of secondary electrons produced in neoformed clusters of ionization events is dependent on the excess energy relaxation occurring in the temporal windows 10^{-14} – 10^{-12} s. Within this prethermal regime, a quantum excited state of the secondary electron (*p*-like excited state) follows a non-adiabatic transition towards an *s*-like ground state of the hydrated electron. Beyond 10^{-12} s, fully relaxed excess electrons in liquid water exhibit submicrometric dispersive diffusion processes.

crucial domain for cancer therapy, it is commonly admitted that the early spatial distribution of energy deposition following ionizing radiation interactions with biomolecular architectures is decisive for the prediction and control of damage at cellular and tissular levels. The complex link existing between radiation physics and biomedical applications concerns the complete understanding of spatio-temporal events triggered by an initial energy deposition in confined spaces called spurs. Microscopic radiation effects on integrated biological targets such as water, ‘the solvent of life’, nucleic acids or proteins cannot be satisfactorily described by an absorbed dose profile or a linear energy transfer. As primary radiation damage on biological targets is dependent on the survival probability of secondary electrons and radicals inside nanometric clusters of ionization, a thorough knowledge of these processes requires real-time probing of early events on the submicrometric scale. In the temporal range of 10^{-15} – 10^{-10} s, this domain concerns low- and high-energy radiation femtochemistry⁵⁸.

The course of ultrafast elementary ionizing events occurring in spurs is largely unknown because of the long duration of contemporary radiation sources used to probe it. In this context, laser–plasma accelerators providing shorter particle bunches open exciting opportunities for real-time probing of high-energy radiation physical chemistry and biology. Femtolysis experiments (from femtosecond radiolysis) of aqueous targets carried out with ultrashort, few-megaelectronvolt electron bunches produced by laser–plasma accelerators⁵⁸ have given new insights into the early behaviour of secondary electrons in the prethermal regime of nascent ionization clusters (Fig. 4). Pioneering femtolysis studies emphasized that the early hydrated electron yield at $t \sim 5$ ps is higher than predicted by calculations using classical stochastic modelling of irradiated water molecules⁵⁹, and underlined the pre-eminence of quantum effects during the ultrafast relaxation of secondary electrons.

As the early spatial distribution of ionization clusters is a major factor for the biological effectiveness of radiations,

spatio-temporal radiation biology would also benefit from the ability of laser–plasma accelerators to generate perfectly synchronized and jitter-free relativistic particle bunches. In the 2.5–15 MeV range, femtosecond electron beams may enable real-time observation of disulphide molecule reduction by quantum states of secondary electrons. Hence, the effective reaction radius of a molecule for a direct subpicosecond *p*-like electron attachment would be around 10 Å (ref. 60). Such data provide information on spatial radiation processes in track structures. The new domain of radiation femtochemistry would provide guidance for further developments in nanodosimetry⁶¹ for which a typical target areal mass of about 1×10^{-6} g cm⁻² corresponds to 100 Å at a density of 1 g cm⁻³.

The real-time investigation of relativistic particle interactions with biomolecular targets opens exciting opportunities for the sensitization of confined environments (aqueous groove of DNA, protein pockets) to ionizing radiation. However, compared with classical dose rate delivery in radiotherapy, ~ 1 Gy min⁻¹, the very high dose rate delivered with laser–plasma accelerators, $\sim 10^{13}$ Gys⁻¹, may challenge our understanding of biomolecular repair, as ultrafast radiation perturbations may be triggered on the timescale of molecular motions, ångström or sub-ångström displacements. With short relativistic particle bunches, high-energy radiation femtochemistry would foreshadow the development of new applications for spatio-temporal radiation biology, anticancer radiotherapy and radioprotection including multiple low-dose effects with nanometric spatial accuracy, predictive consequences of very high dose delivery in cellular environments and selective activation of prodrug in cancerous cells. Indeed, potential advances in cell biology are expected in the next decade, mixing the characteristics of pulsed monochromatic particle beams with those of X-ray generation: development of a charged particle micro-beam for irradiation of living targets, three-dimensional imaging of collective cellular responses (such as the so-called bystander effect) and *in vivo* X-ray microfluorescence of trace elements in living tissues subject to degenerative processes.

MATERIAL AND PLASMA SCIENCE

Fundamental phenomena of condensed matter and plasma dynamics can also be probed with these unique particle beams. Vigorous research is underway to use laser-accelerated beams to heat matter at solid density on a timescale shorter than that for hydrodynamic expansion⁶². Controlled production of plasmas in these ‘warm dense matter’ thermodynamic conditions is a key to progress in their theoretical description. Alternatively, energetic, low-emittance proton beams are a powerful probe for quasi-static magnetic and electric fields that develop in laser-produced plasmas^{63,64} and are also good candidates for injection into conventional accelerators. Proof-of-principle experiments⁶⁵ have also demonstrated the applicability of proton-based radiography to the probing of dense materials opaque to conventional photon sources, for shock measurement or inertial confinement fusion sciences. Key beam properties are put to use for these applications: short duration at the source, small virtual source size and ability to focus the beam down to micrometre spot size.

Electron beams produced in laser–plasma accelerators can be used to generate secondary radiation sources. The electron beam energy is efficiently converted into multi-megaelectronvolt Bremsstrahlung photons when it interacts with a solid target of high atomic number, providing a submillimetre pulsed γ -ray source that is significantly smaller⁶⁶ (450 μ m) and of shorter duration (in the picosecond range) than other sources available today. Ultrashort γ -ray sources are interesting for several applications, including imaging material compression to high density. A train of short laser pulses may enable recording of movies of dense objects

under fragmentation, or of the damage evolution of structures with a spatial resolution of 100 μm . Light and flexible devices for non-destructive material inspection would also be interesting, with potential applications in motor engineering, aircraft inspection and security.

The ultrashort duration of these particle and radiation beams will provide unprecedented time-resolved measurements down to the motion of electrons on atomic scales, and a zooming onto the two fundamental molecular building blocks, the electron and the atom. It will enable exposure of atoms and molecules to relativistic intensities before their disintegration. Coherent diffraction on single molecules will then become accessible, opening an entire new field of research. Time-resolved absorption spectroscopy and Thomson scattering of high-density plasmas require penetrating radiation such as X-rays and an ultrafast time resolution to reveal the properties of the warm dense matter produced in a laser-plasma experiment. Time-dependent measurements of plasma temperature and density will provide a valuable contribution to the understanding of degeneracy and coupling, as well as long- and short-range interactions between charged particles in dense plasmas. Finally, the simultaneous use of particles and radiation as probe or pump beams offers unique opportunities. As an example with societal issues, the study of the ultrafast kinetics following matter excitation by high-energy particles is a major subject in radiation physics and in nuclear technology, with implications on nuclear reactor lifetime. At present, the physical effects of intense particle energy deposition can only be accessed through modelling. There is a crucial need to look at vacancy dynamics that occur in the few-hundred-femtosecond timescale, by ultrafast X-ray or visible probing. Novel laser-based sources will provide the necessary tools.

OUTLOOK

Owing to this pioneering work and judging from the remarkable progress achieved over the past three years, the time is now ripe to exploit current understanding and technology in the design and construction of compact accelerators for practical applications. In parallel, fundamental and experimental research should be continued to optimize the proposed designs, to answer outstanding physics questions, to explore new regimes and to validate theories and numerical codes. The evolution of short-pulse laser technology, a field in rapid progress, will still improve the properties of laser-produced particle sources. For example, the development of diode-pumped lasers will enable the laser power efficiency to be increased by up to tens of per cent and will also lead to a significant reduction of the size of the laser systems. The rapid evolution of chirped pulse amplification laser technology⁶⁷, coupled to progress in laser-plasma interaction modelling, will soon result in improved performances, lower cost and still wider applicability of these compact particle sources⁶⁸. On a longer timescale, developments of these novel beam acceleration techniques should also prove of interest for high-energy physics experiments. Large projects such as the Extreme Light Infrastructure in Europe⁶⁹ will be instrumental in bringing together scientists from different communities to best develop and use these new particle and photon beams for scientific progress, but also to transfer the corresponding knowledge and technology to industrial and societal applications.

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