Multi-pulse laser wakefield acceleration: a new route to efficient, high-repetition-rate plasma accelerators and high flux radiation sources

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Multi-pulse laser wakefield acceleration: a new route to efficient, high-repetition-rate plasma accelerators and high flux radiation sources

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Abstract

Laser-driven plasma accelerators can generate accelerating gradients three orders of magnitude larger than radio-frequency accelerators and have achieved beam energies above 1 GeV in centimetre long stages. However, the pulse repetition rate and wall-plug efficiency of laser plasma accelerators is limited by the driving laser to less than approximately 1 Hz and 0.1% respectively. Here we investigate the prospects for exciting the plasma wave with trains of low-energy laser pulses rather than a single high-energy pulse. Resonantly exciting the wakefield in this way would enable the use of different technologies, such as fibre or thin-disc lasers, which are able to operate at multi-kilohertz pulse repetition rates and with wall-plug efficiencies two orders of magnitude higher than current laser systems. We outline the parameters of efficient, GeV-scale, 10 kHz plasma accelerators and show that they could drive compact x-ray sources with average photon fluxes comparable to those of third-generation light source but with significantly improved temporal resolution. Likewise free-electron laser (FEL) operation could be driven with comparable peak power but with significantly larger repetition rates than extant FELs.

Keywords: plasma accelerator, x-ray, radiation source, free-electron laser

(Some figures may appear in colour only in the online journal)
in the electron density from its mean value few centimetres long [2]
in synchrotrons and FELs [5]; and beyond 100 keV by harmonically-
lasers [6]; in the 10 keV range by betatron motion within the
radiation with photon energies: up to about 100 eV in undulator
bunches or a modulated particle colliders) is prevented by the low repetition rate \( f_{rep} \) (of order 1 Hz) and wall-plug efficiency (less than 0.1%) of the driving laser. In this paper we investigate the prospects for multi-pulse laser wakefield acceleration (MP-LWFA), in which the wake is excited by a train of low-energy laser pulses rather than by a single high-energy pulse. Moving the problem of energy storage from the laser medium to the plasma medium to the plasma would allow the use of novel laser technologies, such as fibre or thin-disc lasers, which can operate with \( f_{rep} \) in the multi-kilohertz range and with high wall-plug efficiency.

We note that MP-LWFA was studied theoretically [8–16] in the 1990s, but has yet to be demonstrated. Driving plasma wakefields with a train of particle bunches or a modulated particle bunch has also been investigated theoretically [17, 18], and generation of a wakefield of amplitude 22 MV m\(^{-1}\) by a train of seven electron bunches has been demonstrated experimentally [19].

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The purpose of the present paper is to re-examine the MP-LWFA concept and to evaluate its prospects in the light of developments in plasma accelerators and laser technologies. We build on our earlier work [20] and show that MP-LWFAs could drive: (i) compact incoherent x-ray sources with average photon fluxes comparable to that of time-resolved third-generation radiation facilities (and with significantly superior temporal resolution); and (ii) FELs with comparable peak power to existing machines, but with significantly higher repetition rates. We also consider some potential issues of the MP-LWFA approach and identify areas for future work.

1. MP-LWFA

In a laser wakefield accelerator (LWFA) a single laser pulse, with a peak intensity of order \( 10^{18} \text{ W cm}^{-2} \), propagates through a plasma and excites a density wave via the ponderomotive force, which acts to expel plasma electrons from the region of the laser pulse. As described in recent reviews [21, 22], the electric fields developed within the plasma wave are of the order of 100 GV m\(^{-1}\)—some three orders of magnitude greater than possible with a conventional accelerator.

In MP-LWFA a train of low-energy laser pulses, rather than a single high-energy pulse, is used to excite the plasma wave. The plasma wakefields excited by the pulses will add coherently—so that the amplitude of the wakefield increases with each additional pulse—if the pulses are spaced by the plasma period \( T_{pe} = 2\pi/\omega_{pe} \), where \( \omega_{pe} = (ne^2/m_ee^2)^{1/2} \) and \( n_e \) is the mean electron density. Particles can then be accelerated within a single period of the plasma wakefield trailing the driving train; usually this would be the ‘bucket’ immediately after the last pulse in the train. Excitation of a plasma
wakefield by single and multiple laser pulses is illustrated schematically in figure 1.

We note that driving a wakefield with a train of \( N \) pulses has several potential advantages over LWFA. First, the driving laser energy is spread over the duration of the pulse train, reducing by a factor of \( N \) the peak laser intensity to which the optical components are exposed. The reduced intensity could enable the use of an optic of smaller-diameter and shorter focal length to couple the pulse train into the plasma; this would considerably reduce the space required between plasma accelerator stages [23] and potentially avoid the need for plasma mirrors. Second, MP-LWFA offers scope for additional control by adjusting the spacing, centre frequency, energy, and duration of the pulses in the train; this flexibility is likely to be important for developing advanced plasma accelerators which are optimized for efficiency, which are stable against longitudinal variations of the plasma density [24] and/or which exploit longitudinal tapering to achieve acceleration beyond the dephasing length [25–27]. Third, it has been shown that large amplitude (nonlinear) wakefields can be excited more efficiently, and with reduced plasma instabilities, by a train of pulses than with a single pulse of the same total energy [9–13, 15].

1.1. Numerical modelling of a MP-LWFA

In order to develop a more quantitative understanding of the operation of a MP-LWFA we have investigated the plasma wave that could be driven by a pulse train with parameters similar to that produced by the state-of-the-art, high-repetition fibre laser system described below. Fluid calculations were performed using weakly relativistic equations [28] in 3D, assuming cylindrical symmetry. Particle-in-cell simulations were performed in 2D slab geometry using the code OSIRIS [29], with the laser electric field polarized out of the slab. The stationary PIC simulation grid comprised 12816 × 198 cells of dimensions \( \Delta x = 0.4a/2\pi \) and \( \Delta y = 0.4c/\omega_{pe} \), where the \( x \)-axis points along the direction of laser propagation, each cell contained eight electrons (and one ion when simulating the effects of ion motion). For both fluid and PIC simulations, each laser pulse in the train was assumed to have an energy of 10 mJ, a pulse duration of \( \tau_{FWHM} = 100 \) fs, and a centre wavelength of \( \lambda = 1 \) \( \mu \)m; the pulses were taken to be spaced by the plasma period and focused to a spot size of \( w_0 = 40 \) \( \mu \)m, corresponding to a peak normalized vector potential of \( a_0 = 0.052 \). Calculations were performed for a plasma density of \( n_e = 1.75 \times 10^{17} \) \( \text{cm}^{-3} \), which maximizes the electron energy gain produced by this pulse train.

Figure 2 shows the growth predicted by fluid simulations of the maximum axial accelerating field \( E_{\text{acc}}^{\text{max}} \) as a function of the number of pulses in the train; it can be seen that \( E_{\text{acc}}^{\text{max}} \) grows linearly. The amplitude of the plasma density wave (not shown) grows in similar way and reaches a relative value of \( \Delta n_e/n_e = 22\% \) on axis. This corresponds to only a mildly nonlinear wakefield and hence there was no need to adjust the spacing between laser pulses to counter relativistic detuning.

Our fluid simulations do not include ion motion, which is expected to be significant for pulse trains with a total duration

\[
\text{Figure 2. Calculated maximum accelerating field } E_{\text{acc}}^{\text{max}} \text{ within the plasma wave as a function of the number of pulses in the pulse train. The solid black line shows the results of fluid simulations, and the results of PIC simulations are shown for the case of stationary (blue) and mobile (red) Xe8+ ions, and for mobile hydrogen ions (grey). The parameters of the pulse train are described in the main text.}
\]

which is not short compared to the ion plasma period \( T_i = 2\pi/\Omega_{ri} \), where \( \Omega_{ri} = \sqrt{Z^2ne^2/(me_0)} \). The motion of the plasma ions arises from the fields of the plasma wakefield itself, and can be described by a nonlinear plasma wave ponderomotive force [30] which moves ions away from high gradients in the plasma electric field. Ion motion can reduce the amplitude of the plasma wave by decreasing the charge separation or by causing regions of low ion density, as has been analyzed for the case of self-modulated beam-driven plasma wakefields [30].

To understand the effect of ion motion we performed PIC simulations for neutral plasmas comprising electrons and: (i) pre-ionized hydrogen ions; (ii) immobile pre-ionized Xe8+ ions; and (iii) mobile pre-ionized Xe8+ ions. The PIC simulations of figure 2 show that using more massive ions increases the the total number of pulses which can usefully be used in a MP-LWFA. For the case of Xe8+ ions, for example, the maximum useful number of pulses is \( N \approx 120 \), at which point the plasma wave accelerating field has reached \( E_{\text{acc}}^{\text{max}} = 4.7 \text{ GV m}^{-1} \). For an accelerator with a length equal to half the dephasing length, \( L_{\text{acc}} = L_d/2 = 260 \) mm—corresponding to acceleration in the accelerating and focusing phases of the plasma wave—the energy gain is \( W_{\text{max}} = (2/\pi)E_{\text{acc}}^{\text{max}}L_{\text{acc}} = 0.75 \text{ GeV} \).

2. Lasers for MP-LWFA

State-of-the-art femtosecond solid-state lasers used for particle acceleration are joule-class titanium-sapphire chirped-pulse amplification (CPA) systems [2]. Lasers of this type can easily generate the high peak intensities required for driving plasma accelerators, but they can only operate at a relatively low average power due to their poor thermo-optical properties and low efficiency (typically much less than 0.1%). In contrast, innovative diode-pumped solid-state lasers such as slab, thin-disc and fibre lasers are able to provide ultra-short laser
pulses with average power \[31\] above 1 kW, but peak powers of only a few GW.

Recently, it has been proposed that the demanding requirements of LWFAs operating at high \( f_{\text{rep}} \) could be met by coherently combining the output of many lasers \[32\]. This approach involves spatially separated amplification of the pulses, which distributes the challenges imposed on the laser gain medium from one emitter to many and, in effect, operates as an amplifying interferometer. This scheme has been extensively investigated using optical fibres as the gain media, and performance beyond that possible from a single fibre amplifier has been demonstrated \[33\]. This idea can be further extended into the temporal domain by splitting each pulse into a short train, which is amplified and then temporally recombined into a single high-energy pulse—an approach known as divided-pulse-amplification (DPA) \[34\].

It is anticipated that a combination of spatial and temporal multiplexing will allow the production of joule-level pulses with \( f_{\text{rep}} \) in the kHz range.

Multi-pulse LWFAs could be driven by a related approach, but with the additional requirement of the generation of a train of approximately 100 pulses. Pulse trains can be generated using beam splitters and delay lines \[35\], or by employing spectral-shaping; however, these methods typically introduce losses exceeding 50%, or have challenging alignment requirements. Here we outline one method for generating a pulse train suitable for MP-LWFA based on interference of two spectrally-separated pulses in a variation of the well-known plasma beat-wave accelerator \[21, 36, 37\].

In this approach broadband pulses are amplified in two CPA systems and partially compressed to the duration required of the entire pulse train. If the pulses have a constant angular frequency difference \( \Delta \omega \), then the temporal profile of the combined pulses will be that of the stretched pulses modulated by a cosine-squared function of period \( \Delta T = 2\pi/\Delta \omega \).

We note that it may also be possible to generate a train of pulses with optimized parameters by phase-only filtering; this is compatible with CPA since it maintains a broad-band spectrum with minimal amplitude modulation \[38\].

Figure 3 shows a conceptual design of a table-top laser system suitable for driving a MP-LWFA. Pulses from a femtosecond oscillator are separated into two spectral branches with centre wavelengths of 1020 nm and 1035 nm. Each spectral branch is amplified as follows: the pulse is stretched to a few nanoseconds duration; the repetition rate is reduced to 10 kHz and the pulse is pre-amplified; the pulse is then amplified in a 16-amplifier DPA scheme in which the pulse is split into a train of eight replicas; following temporal recombination, the pulse is partially recompressed. The two spectral branches are then combined to form the MP-LWFA pulse train of \( N = 120 \), 10 mJ, 100 fs pulses at \( f_{\text{rep}} = 10 \) kHz.

An important feature of this approach is that it is possible to manipulate the spectral phases of the stretched pulses so that the two spectral branches, when partially compressed, have a non-constant angular frequency difference \( \Delta \omega(t) \). Combining these branches will then generate a pulse train with controllable, non-uniform pulse spacing. The additional control enabled by phase manipulation of two spectrally-broad spectral branches will allow resonance to be maintained for nonlinear plasma wake-fields, as discussed by previous authors \[39\]. It also offers scope for achieving auto-resonance by down-sweeping the beat frequency across the local plasma frequency, as discussed by Lindberg et al \[24\]; this could provide stability against variations in the local plasma density, or allow MP-LWFAs to achieve acceleration beyond the dephasing length by employing tapered plasmas \[25–27\].

3. Radiation sources driven by a kHz MP-LWFA

The high pulse repetition rate which could be achieved with MP-LWFAs would make them ideal drivers of femtosecond
radiation sources with high mean photon flux as well as exceptionally high peak brightness. Here we consider radiation generation in undulators and from the betatron motion of the transverse oscillation of the electrons as they accelerate in the plasma wakefield. We note that radiation generated by other methods, such as Thomson and Compton scattering [40, 41], would also benefit from the high values of $f_{\text{rep}}$ enabled by MP-LWFA. In the calculations below we assume parameters for the electron bunch which are close to the best values reported to date. This is an optimistic but reasonable prediction for the future performance of MP-LWFAs employing controlled electron injection, and is consistent with other recent calculations of radiation generation expected from LWFAs [42]. We assume the following parameters: an electron energy of 0.75 GeV; 1% relative energy spread [2, 43–46]; a bunch charge of 50 pC [2, 44, 47]; a normalized transverse emittance of 0.1$\mu$m [48]; and a Gaussian temporal profile of 5 fs FWHM [49].

### 3.1. Betatron radiation

The radiation generated by betatron motion within the MP-LWFA can be estimated using standard theory [52], noting that for the parameters we have considered the MP-LWFA will not operate in the ‘blow-out’ regime as is usually assumed. In our case the betatron oscillation wavelength is given by $\lambda_\beta = \frac{2\pi w_0}{\Phi_0}$, where $\Phi_0 = e\Phi_0/(m_e c^2)$ is the normalized maximum potential of the plasma wave. The number of photons emitted can be estimated to be $N_{\text{ph}} = (2\pi/3) r_e m_e c^2/2 k_\beta K N_\beta / E_e$, where $k_\beta = 2\pi/\lambda_\beta$ is the betatron wavenumber, $K = \gamma k_\beta r_\beta$ is the wiggler strength parameter for oscillation of amplitude $r_\beta$; $N_e$ is the number of electrons in the bunch; $N_\beta$ is the number of betatron oscillations and $E_e = \frac{\gamma^2}{2} K k_\beta c$ is the critical energy of the synchrotron-like spectrum of the radiation.

The betatron flux and photon energy both increase with increasing $\Phi_0$. Fluid simulations show that for a train of 10 mJ, 100 fs pulses, wakes of increasing $\Phi_0$ can be generated by reducing the focal spot size. However reducing the transverse size of the wake increases the transverse ponderomotive force of the plasma wave which contributes to the saturation of the wakefield amplitude by ion motion. For this reason, to demonstrate the potential for betatron radiation generation from MP-LWFAs we reduce the spot size from $w_0 = 40 \mu$m used in the simulations of figure 2 to $w_0 = 30 \mu$m; this produces an intermediate (but still quasi-linear) plasma wakefield. Figure 4(a) shows the calculated average flux of betatron radiation generated in this wakefield, assuming operation at $f_{\text{rep}} = 10$ kHz and a betatron oscillation amplitude of $r_\beta = 10 \mu$m. At a photon energy of 10 keV we find that the average flux is $\approx 2 \times 10^8$ photons s$^{-1}$ per 0.1% bandwidth. This average flux is greater than existing beam lines on 3rd generation synchrotron light sources used for sub-picosecond time resolved studies, and with a significantly improved temporal resolution (5 fs compared with ~1 ps). We note that optimizing the laser-plasma parameters for betatron emission will be the focus of further study.

![Figure 4](image-url)

**Figure 4.** (a) Average flux (photons per second per 0.1% BW) of radiation generated by a 10 kHz MP-LWFA compared to existing short pulse systems on 3rd generation light sources. Blue circles: 5 fs, 10 kHz, narrow-band pulses generated by a MP-LWFA-driven FEL employing a transverse gradient undulator. Blue diamonds: 5 fs, 10 kHz broadband betatron pulses generated within a MP-LWFA. Black line: 50 ps, 0.9 kHz broadband pulses generated on the ID9 beam line at ESRF [50]. Grey curves: 5 ps pulses generated at 530 kHz at Diamond operating in low alpha mode [51]. Grey squares: 200 fs, 40 kHz pulse generated on a slicing undulator at LLNL [50]. (b) Peak power of FEL radiation as a function of undulator length generated by a MP-LWFA beam in a standard (solid, green) and TGU (solid, blue) undulator.

### 3.2. Radiation from undulators

The MP-LWFA beam can be used to drive spontaneous undulator radiation with high average brightness and ultra short pulse duration. More interestingly, the MP-LWFA could be coupled with advanced accelerator transport techniques and undulator technology able to accommodate the relatively large energy spread generated by LWFAs. As suggested recently, these techniques include transverse gradient undulators (TGU) or bunch decompression [42, 53].

In a TGU the magnetic field of the undulator varies with transverse position. If the beam transport system is arranged so that each energy component of the electron beam enters the undulator at a different transverse point then it is possible to match the FEL resonance condition over the entire transverse dimension (and hence energy spectrum) of the electron beam by matching the dispersion function at the entrance of the undulator to the TGU field gradient.
has $2.5$ GV macc

The proposed FEL scheme holds the promise of generating femtosecond x-ray pulses of GW peak power at kHz pulse repetition rates, driven by—and therefore synchronized to—a compact femtosecond visible laser system.

### 4. Discussion

The advantages of MP-LWFA—such as the potential for high-repetition rate operation and the use of small diameter, short focal length optical components—have been highlighted above. Here we briefly discuss some potential issues arising from driving plasma accelerators with a train of laser pulses, before some concluding remarks.

A wakefield driven by a single (laser or particle) pulse can be subject to a deleterious transverse, or ‘hosing’, motion when the tail of the driver is not centred transversely in the wake driven by its head [57–60]. Similar behaviour could also occur in a MP-LWFA if the pulses in the train do not propagate along the same axis. We have developed an analytical model [61] of hosing in MP-LWFA which shows that, in the absence of a guiding structure, a single off-axis pulse trailling an on-axis pulse will oscillate transversely with an angular frequency $\omega_{\text{h}}$ which depends on the longitudinal separation of the two pulses and the strength of the wakefield driven by the leading pulse. The oscillation is found to be stable if the longitudinal pulse separation is $(1 - \alpha)\lambda_p$ with $0 < \alpha < \alpha_l \equiv [2(N - 1)]^{-1}$, i.e. if the pulses are separated by slightly less than $\lambda_p$. Further, the hosing can be stabilized for $\alpha > \alpha_l$ by channelling the laser pulses in a waveguide with $\omega_{\text{ch}} > \sqrt{(\pi/4)\omega_{\text{h}}}$, where $\omega_{\text{ch}}$ is the frequency that an off-axis pulse would oscillate in the waveguide in the absence of a plasma wave. These conclusions have been confirmed by numerical simulations, as will be reported elsewhere [61].

We envisage operating MP-LWFA in a linear or quasi-linear regime in which the laser pulses have a peak power below the critical power for relativistic self-focusing [21]. This regime has advantages in that the driving laser pulses propagate without self-focusing, and with reduced spectral shifting and self-steepening; however, it would be necessary to guide the laser pulses over the length of the accelerator. Guiding of pulses of peak intensity above $10^{17}$ W cm$^{-2}$ has been achieved over 8 cm (corresponding to 30 Rayleigh ranges $Z_R$) in gas-filled capillaries [62] and over 5 cm (40$Z_R$) in a capillary discharge waveguide [63]. For MP-LWFAs the peak intensity of the pulses in the train would be somewhat lower, of order $10^{16}$ W cm$^{-2}$, but the total energy in the train would be similar to that used in these earlier demonstrations. Further work will be required to develop waveguides tailored to MP-LWFAs, but the required parameters do not seem to be beyond reach.

In the quasi-linear regime the wake amplitude in a MP-LWFA would be below the threshold for self-trapping [21, 22]; this brings a significant advantage in that dark current is avoided, but also means that some method for injecting electrons into the wakefield would be necessary. Controlled injection would also be advantageous for LWFAs driven by single pulses and consequently this is an active area of research. To date many techniques have been studied, including the use of colliding laser pulses [64], density downramps [43, 44], and ionization injection [47, 65, 66]. Controlling injection into quasi-linear wakefields is more difficult than for the case of highly nonlinear wakes since the trapping potential is lower; however, schemes have been proposed [65], and it seems likely that suitable techniques will be developed.

We showed above that the onset of ion motion is likely to limit the number $N_{\text{max}}$ of laser pulses which can usefully be used in a MP-LWFA, but that this limiting number—and hence the acceleration gradient—could be increased by using a plasma of high-mass ions. As a first example we considered the case of a Xe$^{8+}$ plasma since the peak laser intensity required to ionize this species is an order of magnitude greater than that of the pulses in the driving train. Further work is required to identify the optimum species and generation scheme for the target plasma. However, we note that even for the case of a hydrogen plasma (which would be trivial to generate) our simulations show an acceleration gradient of $E_{\text{acc}} \approx 2.5$ GV m$^{-1}$ and a dephasing-limited energy gain of

### Table 1. Table of the parameters of the electron beam and undulator used in the calculations of FEL radiation driven by a MP-LWFA.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy</td>
<td>750 MeV</td>
</tr>
<tr>
<td>rms energy spread</td>
<td>1%</td>
</tr>
<tr>
<td>beam charge</td>
<td>50 pC</td>
</tr>
<tr>
<td>norm. transverse emittance</td>
<td>0.1 μm</td>
</tr>
<tr>
<td>peak current</td>
<td>10 kA</td>
</tr>
<tr>
<td>bunch duration</td>
<td>5 fs (FWHM)</td>
</tr>
<tr>
<td>bunch repetition rate</td>
<td>10 kHz</td>
</tr>
<tr>
<td>undulator type</td>
<td>Superconducting TGU</td>
</tr>
<tr>
<td>undulator period</td>
<td>10 mm</td>
</tr>
<tr>
<td>undulator length</td>
<td>4 m</td>
</tr>
<tr>
<td>undulator parameter $K$</td>
<td>2.0</td>
</tr>
<tr>
<td>Transverse gradient</td>
<td>150 m$^{-1}$</td>
</tr>
<tr>
<td>horizontal dispersion</td>
<td>1 cm</td>
</tr>
<tr>
<td>resonant wavelength</td>
<td>6.9 nm</td>
</tr>
</tbody>
</table>

Figure 4(b) shows the results of a full 3D time-dependent simulation with the code [54] GENESIS of the peak power of the FEL radiation generated by the MP-LWFA beam in a TGU with the undulator and electron beam parameters reported in table 1. These show that SASE saturation can be reached in the soft x-ray range ($\lambda_{\text{FEL}} = 6.9$ nm) within a 4 m long undulator, yielding a peak power exceeding 1 GW. This is a factor 20 larger than the power obtained from a planar undulator with the same electron beam. Harmonics of $\lambda_{\text{FEL}}$ can also be generated, albeit at significantly reduced power. We note that the assumed length of the electron bunch ($c\tau = 1.5$ μm) is long compared to wavelength of the generated radiation. As such the slowly-varying envelope approximation used in GENESIS will hold; for much shorter electron bunches, or generation of much longer wavelengths, non-averaged FEL codes would have to be employed [55, 56].

Further work will be required to develop waveguides tailored to MP-LWFAs, but the required parameters do not seem to be beyond reach.

In the quasi-linear regime the wake amplitude in a MP-LWFA would be below the threshold for self-trapping [21, 22]; this brings a significant advantage in that dark current is avoided, but also means that some method for injecting electrons into the wakefield would be necessary. Controlled injection would also be advantageous for LWFAs driven by single pulses and consequently this is an active area of research. To date many techniques have been studied, including the use of colliding laser pulses [64], density downramps [43, 44], and ionization injection [47, 65, 66]. Controlling injection into quasi-linear wakefields is more difficult than for the case of highly nonlinear wakes since the trapping potential is lower; however, schemes have been proposed [65], and it seems likely that suitable techniques will be developed.
approximately 0.4 GeV. A compact, high-repetition-rate accelerator providing this energy gain would already be a significant advance.

5. Conclusion

In conclusion MP-LWFA offers a route for enabling plasma accelerators operating at multi-kHz pulse repetition rates to be driven by tabletop laser systems with high wall-plug efficiency. Novel plasma accelerators of this type would be ideal for driving compact coherent and incoherent radiation sources providing ultrafast THz to x-ray pulses which are intrinsically synchronized to the driving laser system. The temporal resolution achieved by MP-LWFA-driven incoherent light sources would be at least three orders of magnitude better than possible with extant 3rd generation sources, yet with comparable average photon flux. Likewise MP-LWFAs could drive FELs with comparable peak power to FELs driven by conventional accelerators, but at a significantly higher repetition rate. Further developments—such as plasma accelerator staging—would allow generation of coherent radiation at shorter wavelengths than considered here. In the longer term the MP-LWFA could provide a stageable, efficient, and high-repetition rate structure capable of reaching beam energies of interest for particle colliders.

Several challenges remain, including the development of laser systems able to generate the required pulse train, development of long waveguides able to guide the trains over several centimetres of low-density plasma, and the development of techniques for controlling electron injection into quasi-linear wakefields. Further understanding of the physics of MP-LWFAs is also required, such as the effects of ion motion, pump depletion, and beam loading. In our view the very significant advantages brought by high-repetition-rate and efficient MP-LWFAs provide a strong incentive to further experimental and theoretical work on this approach.

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References

[22] Hooker S M 2013 Developments in laser-driven plasma accelerators Nat. Photonics 7 775–82