Monoenergetic Energy Doubling in a Hybrid Laser-Plasma Wakefield Accelerator

B. Hidding,[1] T. Königstein,[1] J. Osterholz,[1] S. Karsch,[2] O. Willi,[1] and G. Pretzler[1]
[1]Institut für Laser- und Plasmaphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany
[2]Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany
(Received 7 January 2010; published 14 May 2010)

An ultracompact laser-plasma-generated, fs-scale electron double bunch system can be injected into a high-density driver/witness-type plasma wakefield accelerator afterburner stage to boost the witness electrons monoenergetically to energies far beyond twice their initial energy on the GeV scale. The combination of conservation of monoenergetic phase-space structure and fs duration with radial electric plasma fields $E_r \sim 100$ GV/m leads to dramatic transversal witness compression and unprecedented charge densities. It seems feasible to upscale and implement the scheme to future accelerator systems.

DOI: 10.1103/PhysRevLett.104.195002 PACS numbers: 52.38.Kd, 41.75.Jv, 52.35.Mw, 52.65.Rr

New strategies are sought after to increase fundamentally the effectiveness of next-generation particle accelerators. It might be desirable to implement new acceleration schemes with accelerating fields orders of magnitude higher than the current limit of state-of-the art radio-frequency cavity-based accelerators of $\sim$100 MV/m. One concept is the use of high-density, longitudinal plasma waves which can provide accelerating electric fields $E_z \approx 100$ GV/m, the field scaling favorably with plasma density n_e as $E_z \propto n_e^{1/2}$. In the 1940s/50s, the particle accelerator community had already suggested exploiting the enormous collective fields in plasmas [1–4]. Today, two methods of how to excite and drive highly suitable plasma waves and wakefields are available which both have unique features: using high-intensity laser pulses [5,6] and using beams of charged particles themselves [7,8], Ref. [8] being a prime example of how rf-cavity accelerator technology is nowadays increasingly recoalescing with plasma-based techniques.

Laser drivers with pulse durations $\tau_L \lesssim 30$ fs allow for extremely high plasma densities n_e and wakefields E_z, and the accelerating bubblelike structures are in turn extraordinarily small. The laser pulse group velocity v_g in a plasma being slightly lower than the velocity of accelerated relativistic electrons $\approx c$ promotes monochromatization of electrons in the bubble wakefield, but on the other hand, this dephasing limits the energy gain. With relativistic electron beam drivers, in contrast, virtually no phase slippage occurs, and thus accelerating distances can be much longer. However, electron beams generated by rf-based accelerators are usually orders of magnitude longer (ps-range) than those obtainable by laser-plasma accelerators (few-fs-range), which limits plasma density, blowout size, and wakefield of a plasma post-accelerator.

To overcome this dilemma, we propose a hybrid acceleration scheme which combines the best of both worlds. In the first stage, ultrashort ($\tau_L \approx 3$ fs) quasimonoenergetic electron bunches are generated in a laser wakefield accelerator (LWFA) or a self-modulated LWFA, the latter leading to especially short bunches due to the maximized plasma densities involved. Both LWFA [9–11] and SMLWFA [12–15] are known to be able to generate even multiples of such bunches, which are accelerated in consecutive plasma wave buckets and therefore are separated by few tens of fs only. Using such ultrashort bunch durations and distances allows for a driver/witness-type plasma wakefield accelerator (PWFA) based on electron double bunches in the second stage of acceleration.

The paramount desirability of ultrashort electron bunches for plasma wakefield acceleration is well known and has given rise to complex setups designed to compress electron beams longitudinally. This enabled breakthroughs such as energy-doubling of a fraction of bunch electrons [8], where a single electron bunch extending over the whole blowout region was used so that the head of the pulse excites the wakefield and electrons at the tail are accelerated. Since this inherently leads to large energy spreads, instead trains [16] or pairs of electron bunches are desirable. Recently, for the first time, an electron double bunch with sub-ps distance (generated by splitting an rf-cavity based electron beam) was used for driver/witness acceleration, albeit here the energy gain was limited to ≈ 1 MeV [17] due to the bunch durations and distance

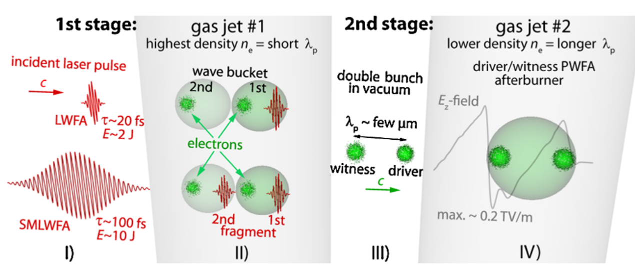

FIG. 1 (color online). Schematic of the hybrid accelerator scheme. (I) A focused high-power laser pulse generates quasi-monoenergetic, electron double bunches via LWFA or SMLWFA in a high-density gas jet (II), the witness/driver electron double bunch system leaves the gas jet (III), and the witness bunch is boosted by TV-scale electric fields in the afterburner (IV).

being orders of magnitude higher when compared to double bunches obtainable from laser-based accelerators.

State-of-the-art high-power laser systems can produce electron double bunches with distances of a few tens of fs and bunch durations down to 3 fs [11], energies up to 1.5 GeV, and charges up to 300 pC [9] via LWFA [9–11] or SMLWFA [12–14]. Here, we show by particle-in-cell (PIC) simulations how injection of such a double bunch into a mm-scale plasma wakefield acceleration stage can lead to dramatic energy gain of the witness bunch (in excess of energy doubling), while at the same time, the monoenergetic structure of the witness is conserved and the charge density can be massively increased.

Figure 1 shows a schematic of the proposed hybrid accelerator setup. In step I), a focused high-power laser pulse (e.g., with a laser pulse duration of $\tau \approx 20$ fs at an energy of $E \approx 2$ J in case of LWFA, or a pulse duration of $\tau \approx 100$ fs at an energy of $E \approx 10$ J in case of SMLWFA) is incident on a high-density gas jet with a plasma period of the order of $\tau_{p1} = [4\pi^2\epsilon_0 m^2/(n_e e^2)]^{1/2} \approx 40$ fs, corresponding to a plasma wavelength $\lambda_{p1} = \tau_{p1}c \approx 12\ \mu$m. The interaction of the laser pulse(s) with the gas jet (step II) leads to generation of electron double bunches via LWFA (where electrons are also self-injected and accelerated in the second plasma wave bucket although no laser pulse is present there as in [9–11]) or SMLWFA (where the laser pulse via self-modulation is split into pulse fragments which each drive a plasma wave bucket as in [12–14]). In both cases, the electron bunch distance is of the order of λ_{p1}. After leaving the first gas jet (step III), the first electron bunch acts as a driver in the second gas jet with a plasma wavelength λ_{p2} which is substantially longer than λ_{p1}. However, as the density in this second gas jet is still higher than in any previously considered plasma wakefield accelerator, the second electron bunch witnesses a very large accelerating wakefield E_{z2}.

Simulations of the PWFA stage were carried through with the particle-in-cell code OOPIC [18,19] in radialsymmetric 2d geometry, thus effectively being 3d. The results were retrieved from moving window runs with a window size of 84 μm $\times$ 30 μm, 15 particles per cell (background plasma), 32 particles per cell (electron bunches), a cell size of 0.3 μm $\times$ 0.3 μm and ionized hydrogen gas as the background medium. The input parameters were varied in a wide range, yielding essentially similar results, showing that the scheme is very robust. Here, we present exemplary results for moderate electron bunch energies of the driver/witness system of $E_{d/w} = 600/500$ MeV and charges of $Q_{d/w} = 100/10$ pC, respectively. The pancake-like (to take account for transversal bunch size increase during passage from stage I to stage II) Gaussian bunches were assigned diameters of $\sigma_d = 4\ \mu$m and lengths of $\sigma_z = 0.5\ \mu$m (rms) at a distance of $\lambda_{p1} = 12\ \mu$m. This choice of parameters of the driver/witness bunches is motivated by the fact that the witness, which is generated in the second bucket of the LWFA stage, is mostly significantly weaker in terms of charge and energy than the driver. This double bunch system was injected into the second, lower-density gas jet with an electron density of $n_{e2} = 3.8 \times 10^{18}$ cm^{-3}, corresponding to $\lambda_{p2} = [4\pi^2\epsilon_0 mc^2/(n_{e2}e^2)]^{1/2} \approx 17\ \mu$m ($\tau_{p2} = \lambda_{p2}/c \approx 56$ fs). The interaction of the driver bunch of density n_b with the gas jet of density n_{e2} ($n_b = Q_d/(2\pi)^{3/2}e\sigma_r^2\sigma_z \approx 5 \times 10^{21}$ cm$^{-3} > n_{e2} = 3.8 \times 10^{18}$ cm^{-3}) is overdense [20], and in addition, the optimum wakefield excitation condition $2\pi\sigma_z/\lambda_{p2} \approx \sqrt{2}$ is not met. Consequently, the linear theory result for optimum conditions $E_{\mathrm{acc}}[\mathrm{MV/m}] = 240(N_b/4 \times 10^{10})(600/\sigma_z[\mu\mathrm{m}])^2$ does not apply here [20]. Nevertheless, it is known from PIC simulations [21] that the $E_{\mathrm{acc}} \propto \sigma_z^{-2}$ scaling is valid also in the nonlinear regime and can be exploited here. The bunch duration is dramatically shorter, and the plasma density is substantially higher (due to the ultrashort driver/witness distance) than in any previously considered PWFA stage. Therefore, as shown in Fig. 2, a maximum accelerating field of $E_z > 200$ GV/m can be reached—an unprecedented value for a plasma wakefield accelerator.

At the same time, the ultrashort duration of the witness bunch allows for conservation of its low energy spread. This is shown via time-history snapshots of the bunches' position-energy phase space in Fig. 3. Energy is transferred from the driver to the witness via the longitudinal electric field of the background plasma. After an acceleration distance of $L_{\mathrm{acc}} \approx 6$ mm, the witness energy has more

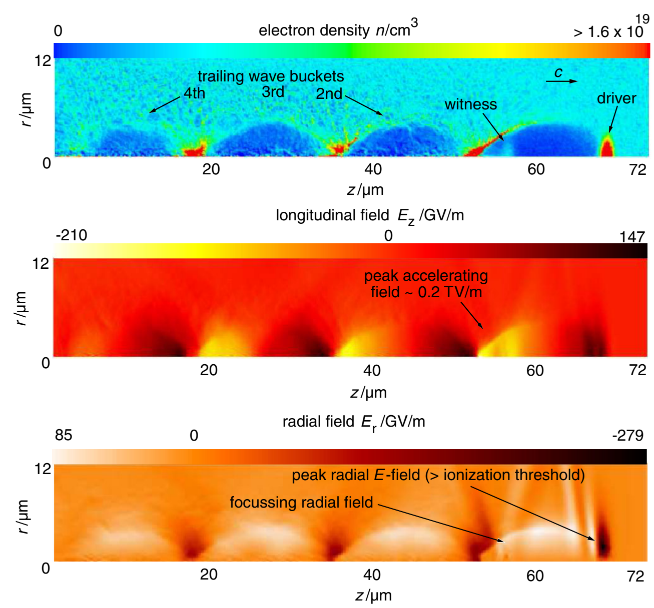

FIG. 2 (color online). Plasma plus bunch electron densities, and longitudinal and radial fields E_z and E_r obtained in the PIC simulation (bunches move from left to right). E_z which accelerates the witness peaks at $E_z > 200$ GV/m. The peak radial field is even higher and might allow for use of neutral background gases since the field ionization threshold is exceeded.

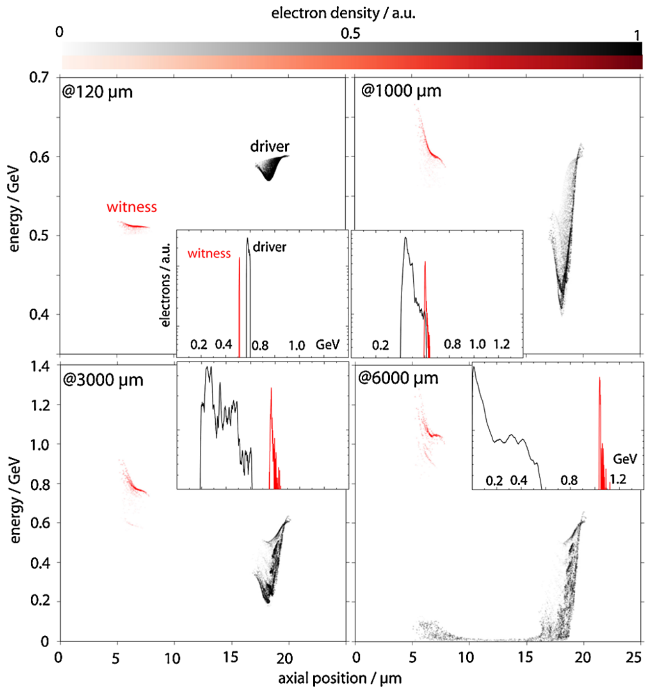

FIG. 3 (color online). Snapshots of driver/witness energy-position phase space during acceleration. The witness energy is boosted from 0.5 GeV to over 1 GeV in a distance of only $L_{acc} \approx 6$ mm due to the ultrahigh accelerating field set up by the driver ploughing through the plasma. The monochromaticity of the witness is maintained, as shown by the electron spectra (insets).

than doubled from 500 MeV to substantially >1 GeV, while the normalized transverse emittance has increased by about 2 mm mrad. This translates to an average accelerating field of $\bar{E}_{acc} \approx 0.1$ TV/m. While the driver erodes, the witness bunch remains quasimonoenergetic. This holds also for higher initial driver/witness energies which are in reach of upcoming laser systems, and which would allow for longer acceleration distances and larger energy gains. This is the first plasma wakefield acceleration scheme which (a) provides wakefields of $E_z > 100$ GV/m, and (b) at the same time opens up a route to monoenergetic witness acceleration.

The high density of the plasma wave produces enormous radial electric fields which allow extreme transverse witness bunch compression, dramatically increasing the charge and current density locally. Figure 4 visualizes the time history of this compression via the witness charge density, which rises from 3.5×10^{18} to $>1000 \times 10^{18}$ cm^{-3} in less than a picosecond, while the bunch density oscillates with a period length of ≈ 400 μm. In the inset in the last snapshot of Fig. 4, lineouts of the bunch diameters as calculated for each snapshot are given. This size reduction as well as the extreme acceleration with low energy spread are in the end all opened up by the small bunch distances and durations, now for the first time being accessible by laser-plasma acceleration.

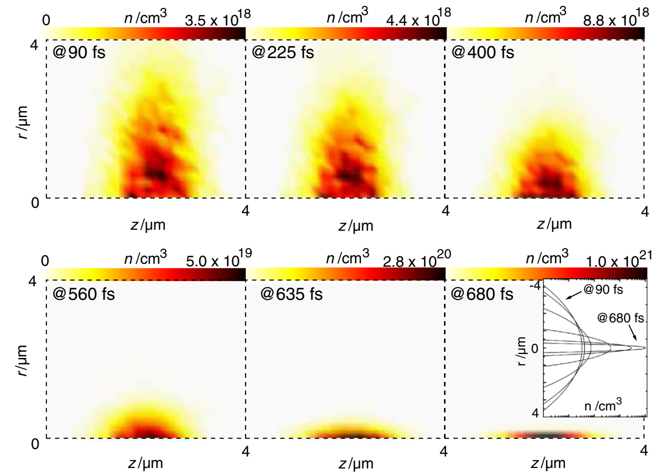

FIG. 4 (color online). Snapshots showing the radial witness bunch compression by over 3 orders of magnitude at the beginning of the plasma wakefield interaction in less than 700 fs of acceleration (corresponding to $L_{acc} \approx 200$ μm).

Some additional aspects shall be communicated. (i) The maximum radial electric self-fields of the ultrashort electron bunches, scaling favorably with beam size dimensions [22] as $E_r(r) = Ne/[(2\pi)^{3/2}\sigma_z\epsilon_0 r](1 - e^{-r^2/(2\sigma_r^2)})$ can approach the TV/m regime, which would be high enough to exceed the ionization threshold even of helium [23]. While ionization induced with such ultrashort, transient fields deserves special attention, in case of our scenario, it might enable a substantial simplification of the setup. Neutral gases could be used instead of preionized plasmas, which are complicated to generate especially when longer acceleration distances are considered. It shall be noted that in case of a very short distance between both gas jets of the order of a few Rayleigh lengths, there might be enough laser energy left to contribute significantly to ionization in the second gas jet. With longer distances, the laser pulse would be diffracted to intensities lower than the ionization threshold within millimeters, or could be blocked by a nm-scale thick foil in case a completely unperturbed second gas jet is desirable. (ii) Additional self-injection of background electrons into the accelerating field of the plasma blowout occurs, but does not spoil the witness' energy spread because the witness electrons' energy is always substantially higher. (iii) The presented scheme opens up strategies to increase laser-to-electron bunch energy transfer. It is known that a properly shaped train of multiple electron bunches can increase the energy transformer ratio R dramatically to $R \gg 2$ [24,25]. Since trains of electron bunches can be generated via laser-plasma interaction on the fs scale [10,13,15,26], it might therefore become possible to use PW-class lasers with longer pulse durations but much higher energies efficiently for electron acceleration via SMLWFA (although the charge of a single bunch and its self-field in such a scenario might be limited). (iv) Our simulations (see Fig. 5) show that the witness energy gain

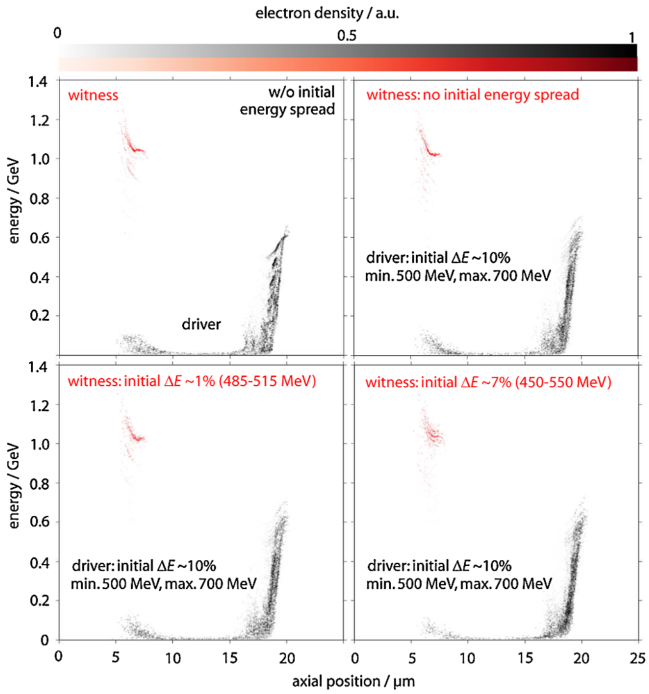

FIG. 5 (color online). Electron energy vs position after $L_{acc} \approx 6$ mm obtained with varying initial driver/witness energy spreads ΔE. Because all electrons are highly relativistic, there is no significant dephasing, and the driver energy spread can easily be $\Delta E \sim 10\%$ with no notable consequences for the witness.

and spectrum are rather insensitive to the initial driver energy spread. With the electrons all moving at highly relativistic velocities, there is no significant dephasing and the scheme works even when the driver has an initial energy spread of $\Delta E \approx 10\%$. A future scheme might gain attractiveness from this: provided sufficient synchronization can be reached with a conventional driver beam and a laser pulse, one could think of using a driver beam from a conventional accelerator, rotate it in phase space aiming at optimizing the duration, and instead accepting an energy spread of up to few tens of percent. This could strongly relax the requirements for future hybrid PWFA experiments, and still would enable to harvest the advantages of ultrashort LWFA-generated witness bunches.

The presented hybrid two-stage acceleration scheme paves the way for ultrastrong, monochromatic plasma wakefield acceleration. This is due to the ultrashort bunch durations and distances obtainable from laser wakefield experiments. In the approach introduced here, the monoenergetic structure of the witness is sustained, carrying this feature on to plasma wakefield acceleration and rendering it the first method which allows for monoenergetic plasma wakefield acceleration in the GeV range. As an additional benefit of the ultrashort time scales, the bunch electric radial fields can exceed the ionization threshold so that unionized gas might be used for the afterburner acceleration stage. The scheme also leads to extreme radial witness compression, which dramatically increases peak charge density and current. Although being experimentally challenging, the method is scalable to much higher energies and is thus effective as a peak energy doubler also with future advanced laser-plasma driven and rf-cavity accelerator systems.

We thank D. Bruhwiler and Tech-X for support with OOPIC. This work was supported by DFG SFB TR-18.

[1] V. Veksler, in *Coherent Principle of Acceleration of Charged Particles* (CERN, Geneva, 1956), Vol. I, p. 80.
[2] G. Budker, in *Relativistic Stabilized Electron Beam* (CERN, Geneva, 1956), Vol. I, p. 68.
[3] Y. B. Fainberg, in *The Use of Plasma Waveguides as Accelerating Structures in Linear Accelerators* (CERN, Geneva, 1956), Vol. I, p. 84.
[4] J. M. Dawson, Phys. Rev. **113**, 383 (1959).
[5] T. Tajima and J. M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).
[6] A. Pukhov and J. Meyer-ter Vehn, Appl. Phys. B **74**, 355 (2002).
[7] J. B. Rosenzweig *et al.*, Phys. Rev. A **44**, R6189 (1991).
[8] I. Blumenfeld *et al.*, Nature (London) **445**, 741 (2007).
[9] W. Lu *et al.*, Phys. Rev. ST Accel. Beams **10**, 061301 (2007).
[10] A. Oguchi *et al.*, Phys. Plasmas **15**, 043102 (2008).
[11] Y. Glinec *et al.*, Phys. Rev. Lett. **98**, 194801 (2007).
[12] B. Hidding *et al.*, Phys. Rev. Lett. **96**, 105004 (2006).
[13] M. Mori *et al.*, Phys. Lett. A **356**, 146 (2006).
[14] B. Hidding *et al.*, Phys. Plasmas **16**, 043105 (2009).
[15] S.-H. Yoo *et al.*, J. Opt. Soc. Korea **13**, 42 (2009).
[16] P. Chen *et al.*, Phys. Rev. Lett. **54**, 693 (1985).
[17] E. Kallos *et al.*, Phys. Rev. Lett. **100**, 074802 (2008).
[18] J. P. Verboncoeur *et al.*, Comput. Phys. Commun. **87**, 199 (1995).
[19] D. L. Bruhwiler *et al.*, Phys. Rev. ST Accel. Beams **4**, 101302 (2001).
[20] C. Joshi, and B. Blue *et al.*, Phys. Plasmas **9**, 1845 (2002).
[21] P. Muggli and M. J. Hogan, C.R. Physique **10**, 116 (2009).
[22] K. Wille, *The Physics of Particle Accelerators* (Oxford University Press, Oxford, 2000).
[23] D. L. Bruhwiler *et al.*, Phys. Plasmas **10**, 2022 (2003).
[24] J. Power *et al.*, *Proceedings of the 2001 Particle Accelerator Conference* (IEEE, Chicago, 2001), pp. 114–116.
[25] E. Kallos *et al.*, in *13th Advanced Accelerator Concepts Workshop*, AIP Conf. Proc. No. 1086 (AIP, New York, 2009), pp. 580–585.
[26] L. Veisz *et al.*, C.R. Physique **10**, 140 (2009).