Journal of Physics: Conference Series **78** (2007) 012021 doi:10.1088/1742-6596/78/1/012021

Laser wakefield simulations towards development of compact particle accelerators

C.G.R. Geddes[1], D. Bruhwiler[2], J.R. Cary[2,5], E. Cormier-Michel[4,1], E.Esarey[1,4] , C.B. Schroeder[1], W.A. Isaacs[1], N. Stinus[1,8], P. Messmer[2], A. Hakim[2], K. Nakamura[1,6] , A.J. Gonsalves[1], D. Panasenko[1], G.R. Plateau[1,7], Cs. Toth[1], B.Nagler[1], J. van Tilborg[1], T. Cowan[4], S. M. Hooker[9] and W.P. Leemans[1,3,4]

[1] Lawrence Berkeley National Lab, Berkeley CA 94720; http://loasis.lbl.gov
[2] Tech-X Corporation, Boulder CO 80303
[3] U. California Berkeley; [4] U. Nevada Reno; [5] U. Colorado Boulder; [6] U. Tokyo
[7] École Polytechnique, France; [8] U. Strasbourg, France; [9] Oxford University, UK

E-mail: cgrgeddes@lbl.gov

Abstract.
Laser driven wakefield accelerators produce accelerating fields thousands of times those achievable in conventional radio-frequency accelerators, offering compactness and ultrafast bunches to potentially extend the frontiers of high energy physics and enable laboratory scale ultrafast radiation sources. Realization of this potential requires understanding of accelerator physics to advance beam performance and stability, and particle simulations model the highly nonlinear, kinetic physics required. One-to-one simulations of experiments provide new insight for optimization and development of 100 MeV to GeV and beyond laser accelerator stages, and on production of reproducible and controllable low energy spread beams with improved emittance (focusability) and energy through control of injection.

1. Introduction

Laser driven plasma wakefield accelerators (LWFAs) [1, 2] sustain gradients up to several hundred GV/m, making them attractive as compact particle [3, 4] and radiation [5, 6, 7] sources. The ponderomotive, or radiation, pressure of an intense laser pulse drives a plasma density oscillation (wake), the longitudinal field of which can 'self-trap' and accelerate plasma electrons [1]. Recently, such experiments produced electron bunches with few MeV/c momentum spread near 100 MeV/c central momentum by extending the distance of propagation using a guiding channel [3] or large spot size [8, 9]. Channeled experiments also demonstrated bunches with tens of MeV/c momentum spread at 1 GeV/c and stable operation at 0.5 GeV/c [4, 10]. Initial controlled injection experiments demonstrated stable beams near 250 MeV/c, also with tens of MeV/c momentum spread [11] using the colliding pulse [12] method. In addition to scaling to 10 GeV energies and beyond, development of laser accelerators to facilitate applications now requires stabilization of performance and reduction of momentum spread (presently a few to ten's of MeV/c) and transverse momentum (presently order MeV/c, giving mrad divergence). Towards these goals, bunches at $\sim$1 MeV/c with 0.17 MeV/c momentum spread and stability over many run days have recently been demonstrated [13] using downramp trapping [14].

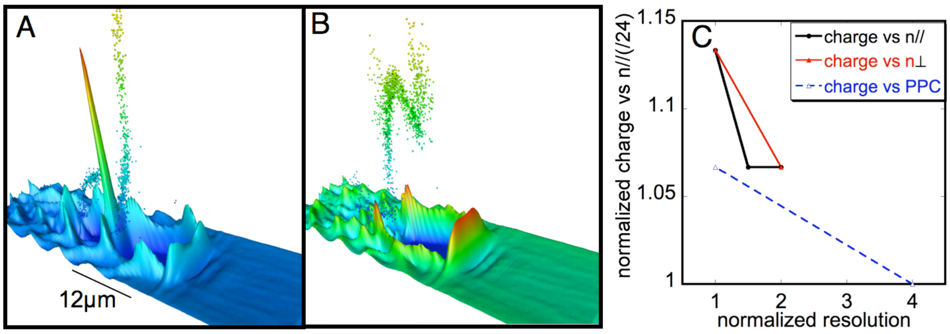

Figure 1. A 3D simulation of a 100 MeV LWFA stage shows electron density (surface; height and color=density) and particles (height and color = longitudinal momentum) showing trapping and acceleration of the bunch (A), and formation of a narrow energy spread bunch as the electrons dephase (B). For these parameters, chosen to be well above the trapping threshold, results vary only ~10 % in 2D scans of longitudinal and transverse resolution (n//, n⊥) and particles per cell (PPC) (C).

Here we describe simulations closely coupled to experiments at the LOASIS program of LBNL which reveal important physics behind recent experimental accomplishments, and guide development of next generation experiments. Simulations, benchmarked against experiments and theory, access internal dynamics of the accelerator not available to experimental diagnostics and conditions not tractable by analytic theory. The simulations are particle in cell models using the SciDAC code VORPAL [15], developed by Tech-X and University of Colorado. PSC [16], a second particle code, was used for development. The codes explicitly solve Maxwell's equations in the presence of charged particles (plasma), with resolution sufficient to resolve the laser wavelength (the shortest major scale in the problem). Modeling of 100 MeV [3, 17] stages and initial results on 1 GeV stages are described. In particular, the simulations have now been extended to three dimensions and high resolution under INCITE and SciDAC, and these MHour scale runs are providing more quantitative understanding of the experiments and methods for optimization. Results on controlled injection of electrons into the wake [13], numerical topics [18, 19], and details of the GeV bunches, are subject of upcoming publications and are briefly noted. Results have been detailed in [3, 20, 17, 21, 22, 23, 24, 25, 13, 26] among others. Related simulations by the OSIRIS/QuickPIC collaboration, and algorithmic developments, are summarized in these proceedings by [27].

2. Simulation

Simulations were conducted to evaluate the physics of recent experiments that demonstrated formation of narrow energy spread beams for the first time in LWFAs, and subsequent scaling of the bunch energy from 100 MeV to 1 GeV [3, 4, 10](related; [28, 27]). In the past year, these simulations were extended to high resolution and three dimensions allowing detailed convergence studies and evaluation of controlled parameter variation for optimization.

Experiments of 2004 produced high quality (low energy spread and divergence) beams for the first time in laser accelerators [3, 17, 23] by guiding 10 TW laser pulses in plasma channels with densities near $1.9 \times 10^{19} cm^{-3}$, extending laser propagation to > 10 Rayleigh ranges. Bunches with ±2% energy spread and ~300 pC charge were observed at 86 MeV, in contrast to previous experiments which displayed 100% energy spread. Simulations (Fig. 1) showed these experiments injected electrons by driving the plasma wave to an intensity sufficient for 'self trapping,' which occurs when the field of the wave is intense enough to accelerate electrons up to the phase velocity of the wave over a distance of $\sim$ one wave period. The low energy spread bunches were formed when trapped electrons damped the wake, suppressing further trapping. Because wake velocity is about the laser drive pulse velocity ($< c$ in the plasma), the electrons eventually outran the accelerating phase in the wake, and the leading electrons began to decelerate while the tail continued to accelerate [3, 17, 23]. Such 'dephasing', enabled by extension of the accelerating distance through channeling of the laser pulse, concentrated the electrons in energy, forming the high quality bunch observed. Detailed exploration of the physics of such stages has been enabled by an INCITE grant and ongoing NERSC and ATLAS grants, allowing detailed 2D simulations and a several 3D runs. Resolution of the laser wavelength over the wake volume of $\sim 100\mu\text{m}^3$ results in order 200 Mcells and $\sim$ 1 Gparticle, and over the propagation distance of mm-cm this requires $\sim$ 1 Mstep leading to 100khour simulations in 3D for 100 MeV stages, up to several Mhour for GeV stages. Good scaling has also been demonstrated to > 4000 processors even in the smaller simulations, making these simulations and scaling to future larger problems (higher energy accelerators, better numerical resolution) achievable.

Detailed 2D simulations are used to establish input parameters within the experimental uncertainties that produce the best match to experimental results, and are reasonably stable numerically, for subsequent large 3D runs. This is required because uncertainties in the experimental laser and plasma parameters are significant (at the $\sim 10\%$ level), and accelerator performance is highly sensitive. Because of trapping and laser focusing differences in 3D, small 3D simulations are conducted in interaction with the 2D simulations to verify the results. Full 3D simulations based on these studies have then provided quantitative comparison to the experiments, and these have produced agreement within 25% with experimental values of charge and energy. The simulations then show that laser pulse evolution and depletion are important to the dynamics, details not evident from the experiments. Energy spread and divergence are still above experimental values motivating work on higher order methods and smoothing to reduce noise [18, 19]; reduced models are also under development to increase compute speed [27].

With such simulations yielding quantitative comparison to experiments, evaluation of optimization is permitted because simulations allow controlled parameter variation. For example, increasing laser amplitude well above the threshold for trapping and accelerating electrons increases charge, and increases stability of the accelerator to small fluctuations in laser power because the trapping process is no longer on threshold. However, energy spread is degraded from few percent to 10% or more because increased beam loading is required to turn off trapping, resulting in a bunch that covers more of the wake phase. Similar behavior is observed with respect to plasma density, since increasing density decreases the trapping threshold by slowing the laser group velocity. Experiments also observe this behavior [10]. Simulations further indicate trapping of particles occurs due to transverse wakefields, increasing transverse emittance [28, 24]. These results motivate controlled injection to further stabilize and improve beam quality (below).

Because electron beam energy is limited by dephasing, increasing energy from hundred MeV to GeV class required reduced density and hence increased laser group velocity to extend the dephasing distance. Using 3cm capillary discharge waveguides at densities of $4.3 \times 10^{18} cm^{-3}$ driven by a 40 TW laser pulse, electron beams up to 1 GeV were produced with charge of $\simeq$30 pC, beam divergence of 1.6 mrad (rms), and energy spread of 2.4% [4, 10].

Simulations with parameters close to the GeV experiment closely reproduce electron beam performance, and show that the internal dynamics of laser pulse evolution, trapping, and dephasing-controlled beam formation is similar to the 2004 experiments (Fig. 2). Optimal matching of the experimental results in 2D was found for plasma density 20% above the nominal experimental value. The 40TW, 40 fs laser pulse steepens and self-modulates from its initial Gaussian profile through interaction with the wake, driving the wake to an intensity sufficient to trigger self-trapping after 0.25 cm propagation (A,B). The electron bunch then accelerates

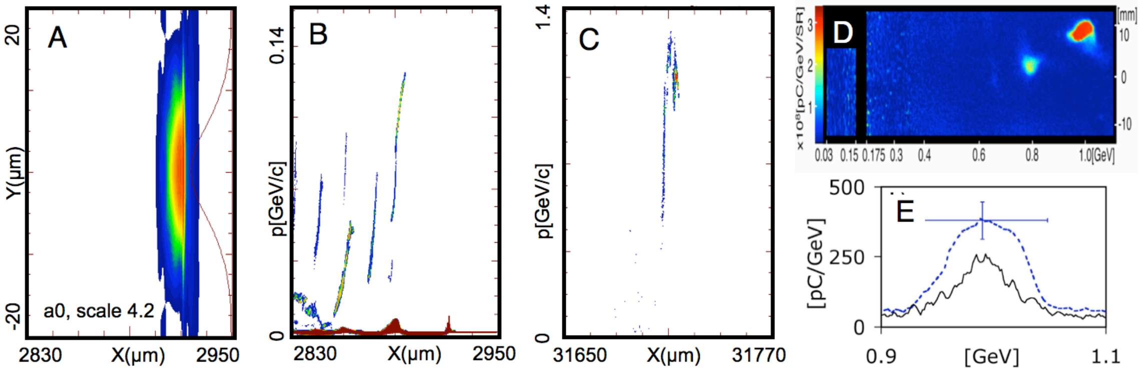

Figure 2. A 2D simulation of GeV experiments closely reproduces electron beam performance, revealing internal dynamics. The laser steepens and self focuses from its initial gaussian profile after 3 mm propagation (A), and electrons are trapped (density in longitudinal momentum phase space, B). The laser depletes and the wake decreases near 1 cm, and the bunch decelerates over the last 2 cm of the guide producing a final beam (C) with $\sim 25-65$ pC of charge in 4 % rms energy spread with 2.4 mrad divergence at 1 GeV. Experimental data (D) shows ∼30 pC charge, 2.5% (rms) energy spread, and 1.6 mrad (rms) divergence, similar to the simulation. The experimental (dotted) and simulated (solid, A.U.) spectra agree closely(E).

to 1.3GeV with 3% rms energy spread after $\sim$ 1 cm of propagation, at which point it begins to dephase. This bunch subsequently outruns the depleted laser pulse and drives its own wake in the plasma, causing the bunch to gradually decelerate over the last 2 cm of the guide. The final beam (C,E) has parameters close to the experimental result, with bunch energy 1.03GeV with 4% rms energy spread, 2.4 mrad divergence, and approximately 25-60 pC charge (the range corresponds to the uncertainty in inferring 3D charge from 2D data). 3D simulations of the first 0.7 cm at this density, which more accurately represent charge, show trapping and acceleration of an electron bunch with charge 60 pC, confirming the range given by the 2D simulations; 3D simulations at the experimental density are in progress to improve agreement with experiments. The spectrometer image of the experimental electron beam is shown in (D), with the space-integrated spectrum (dotted line) in (E). The simulations indicate low energy electrons are insufficiently stiff, and are defocused in the last 2 cm of the guide, leaving only the high energy beam, consistent with (D). The solid line in (E) represents the result of the 2D simulation (A.U.), which well matches the experimental spectrum. The close match of experimental parameters and results allows internal dynamics to be inferred. The prediction of early depletion and termination of acceleration is now being observed in experiments using shorter capillaries. The simulations also indicate that higher energies and reduced emittance (beam divergence) could be obtained by using controlled injection so that the plasma density in the acceleration channel could be lowered without turning off trapping, and such experiments are now in progress

Previous simulations predict that post acceleration of electron bunches in plasma channels can nearly preserve momentum spread and emittance [29], indicating that combination of a low energy spread injector and subsequent acceleration channel could lower energy spread. Injection experiments and simulations recently demonstrated production of fs electron bunches with momentum spreads as low as 170 keV/c, and a ten-fold reduction in inferred emittance, by using plasma density gradients to control injection. Such staging may enable greatly reduced relative momentum spread and emittance, potentially with hundred keV/c-class momentum spread and low transverse emittance at GeV and greater energies (present experiments have

Journal of Physics: Conference Series **78** (2007) 012021 doi:10.1088/1742-6596/78/1/012021

10's of MeV/c spread at a GeV). This data is the subject of an upcoming publication [13].

3. Conclusion

Large scale simulations revealed physics of 100 MeV experiments, scaling to 1 GeV, beam energy spread and emittance, and the scaling of beam quality with laser and plasma parameters. These one-to-one, first principles simulation of LWFA experiments (related work: [28, 27, 30]), with detailed comparison to experiments, point to the beginning of quantitative understanding and engineering of new accelerators. These simulations indicate that using controlled injection will allow higher beam energies and reduced emittance because the density of the acceleration channel could then be optimized for guiding and dephasing without the constraints imposed by self injection. Staged experiments and simulations are under way to evaluate this concept. If successful, this technology should be capable of providing 10 GeV class, reproducible beams using a PW-class laser system. Such modules are under development as stages for future HEP machines and light sources; modeling and optimizing these meter-scale plasmas will require petascale computing together with further development higher order and reduced models.

Work supported by the U.S. Dept. of Energy Office of Science, Office of High Energy Physics, contracts DE-AC02-05CH11231, DE-FG03-95ER40926, DE-FG02-01ER41178, DE-FG02-03ER83857, DOE SciDAC, INCITE7 2006, NERSC, and LLNL ATLAS programs, and NSF grants 0113907 and 0614001. We appreciate contributions from the members of the Vorpal team at Tech-X, and the LOASIS Program at LBNL.

References

[1] Tajima T. and Dawson J. M. , 1979 *Phys. Rev. Lett.* **43**, 267 .
[2] Esarey E. *et al.*, 1996 *IEEE Trans. Plasma Sci.* **24**, 252 .
[3] Geddes C. G. R. *et al.*, 2004 *Nature* **431**, 538 .
[4] Leemans W. P. *et al.*, 2006 *Nature Physics* **2**, 696 .
[5] Leemans W. P. *et al.*, 2005 *IEEE Trans. Plasma Sci.* **33**, 8 .
[6] Rousse A. *et al.*, 2004 *Phys. Rev. Lett.* **93**, 135005 .
[7] van Tilborg J. *et al.*, 2006 *Phys. Rev. Lett.* **96**, 014801 .
[8] Mangles S. P. D. *et al.*, 2004 *Nature* **431**, 535 .
[9] Faure J. *et al.*, 2004 *Nature* **431**, 541 .
[10] Nakamura K. *et al.*, 2007 *Phys. Plasmas* **14**, 056708 .
[11] Faure J. *et al.*, 2006 *Nature* **444**, 737 .
[12] Esarey E. *et al.*, 1997 *Phys. Rev. Lett.* **79**, 2682 .
[13] Geddes C. G. R. *et al.*, *submitted to Phys. Rev. Lett.*
[14] Bulanov S. *et al.*, 1998 *Phys. Rev. E* **58**, R5257 .
[15] Nieter C. and Cary J. , 2004 *J. Comp. Phys.* **196**, 448 .
[16] Ruhl H. , 2000 *Habilitationsschrift, Technische Universitt Darmstadt*
[17] Geddes C. G. R. *et al.*, 2005 *Phys. Plasmas* **12**, 056709 .
[18] Michel E. *et al.*, 2006 *Advanced Accelerator Concepts*, ed Conde M. and Eyberger C. (New York, Amer. Inst. Phys.), pp. 213–219.
[19] Esarey E. *et al.*, 2007 *Phys. Plasmas* **14**, 056707 .
[20] Cary J. R. *et al.*, 2005 *Physics of Plasmas* **12**, 056704 .
[21] Messmer P. *et al.*, 2005 *Proc. Particle Accel. Conf.* (Melville NY, AIP).
[22] Messmer P. and Bruhwiler D. L. , 2006 *Phys. Rev. ST Accel. Beams* **9**, 031302 .
[23] Geddes C. G. R. *et al.*, 2005 *Phys. Rev. Lett.* **95**, 145002 .
[24] Geddes C. G. R. , 2005 *Plasma Channel Guided Laser Wakefield Accelerator* (Berkeley CA, Ph.D. dissertation, University of California, Berkeley).
[25] Bruhwiler D. *et al.*, 2006 *J. Phys. Conf. Series* **46**, 215 .
[26] Dimitrov D. A. *et al.*, 2007 *Phys. Plasmas* **14**, 043105 .
[27] Tsung F. S. *et al.*, 2007 *these proceedings* (Philadelphia, IOP).
[28] Tsung F. S. *et al.*, 2004 *Phys. Rev. Lett.* **93**, 185002 .
[29] Shadwick B. A. *et al.*, 2005 *Bull. Am. Phys. Soc. Plasma Phys. Mtg. 47* (College Park MD, Am. Phys. Soc.), p. 213.
[30] Pukhov A. and Meyer-ter-Vehn J. , 2002 *Appl. Phys. B* **74**, 355 .