# Summary Report of Working Group 1: Laser-Plasma Acceleration

C.G.R. Geddes*, C. Clayton†, W. Lu† and A.G.R. Thomas**

*LOASIS program, Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, Berkeley CA 94720, USA
†Department of Electrical Engineering, University of California, Los Angeles, Westwood, CA 90024, USA
**Department of Nuclear Engineering and Radiological Sciences, University of Michigan, Ann Arbor, MI 48109, USA

**Abstract.** Advances in and physics of the acceleration of particles using underdense plasma structures driven by lasers were the topics of presentations and discussions in Working Group 1 of the 2010 Advanced Accelerator Concepts Workshop. Such accelerators have demonstrated gradients several orders beyond conventional machines, with quasi-monoenergetic beams at MeV-GeV energies, making them attractive candidates for next generation accelerators. Workshop discussions included advances in control over injection and laser propagation to further improve beam quality and stability, detailed diagnostics and physics models of the acceleration process, radiation generation as a source and diagnostic, and technological tools and upcoming facilities to extend the reach of laser-plasma accelerators.

**Keywords:** Laser Plasma Electron Acceleration
**PACS:** 52.38.Kd, 41.75.Jv

## INTRODUCTION

Working Group 1 (WG1) explored laser-driven acceleration of electrons and positrons in underdense plasmas, and the related topics of laser propagation and diagnostics. This includes laser wakefield acceleration [1], where acceleration by a plasma wave excited by the laser recently has been demonstrated to produce intense beams of electrons at MeV-GeV energies with percent energy spread and with gradients three orders of magnitude above conventional systems [2-9], and direct acceleration [10] where particles are directly accelerated by a laser pulse shaped by a plasma structure providing a linear mechanism with potential to harness low-energy laser systems [11]. With demonstration of high energies and gradients over the last several years, the focus of discussions was on control, detailed diagnostics and physics models, and technological tools to work towards the beam qualities required by applications. For high energy physics colliders at the TeV scale, this included how very low beam emittance can be obtained/preserved and staging/beam transport, and for novel and compact radiation sources, how these can be uniquely or advantageously driven by laser plasma accelerators.

The working group hosted eleven sessions, with thirty-nine oral presentations, including joint sessions on radiation generation and simulations and with the beam driven plasma group, and nine poster presentations supporting workshop discussions on recent experimental and simulation results, and on the physics mechanisms for continued improvement in beam quality and energy. These sessions were organized around discussions of the following questions:

- How should injection into the structure be controlled for reproducible beams with low emittance?
- How can laser propagation and accelerator structure be controlled for high beam quality and efficiency? How do we stage modules to reach high energies? (Joint with beam driven working group)
- How can laser-plasma accelerated beams generate unique radiation sources, and what insight does such radiation provide on the accelerator? (Joint with radiation working group)
- What diagnostic techniques allow us to understand the physics of beam production and acceleration, and laser evolution?
- How can simulations and theory address the required physics and design experiments, and where are improved diagnostics or methods needed? (Joint with computational working group)

In addition, techniques for controlling electron beam propagation were discussed as part of the radiation source session, which are also important to staging multiple modules to achieve high energies. Plans for new facilities designed to

CP1299, *Advanced Accelerator Concepts: 14th Workshop,* edited by S. H. Gold and G. S. Nusinovich
2010 American Institute of Physics 978-0-7354-0853-1/10/$30.00

push the energy frontier and to develop new techniques for control were also discussed. This summary paper presents highlights from each of these discussions, outlining the proceedings of the working group. In many cases, a paper presented results relevant to many of the topics, and may appear more than once in the following. Detailed results and references may be found in the respective papers in these proceedings.

## INJECTION CONTROL

The quality of the initial injected particle bunch, and control over the trapping process, are vital to obtaining high quality beams, and are a topic of intense research covered by the working group. This is because, in the absence of damping rings or other special techniques used in colliders, the accelerating structure at best preserves bunch emittance such that a low emittance injector is required. Similarly, the injector must be controlled to inject the appropriate longitudinal bunch shape at the correct phase in the structure such that acceleration, including beam loading and dephasing, will produce narrow energy spread. Progress was presented on controlling injection using a variety of techniques, including refinement of the controlled self trapping which first produced monoenergetic beams in such accelerators, and controlled trapping via colliding laser pulses, ionization, and shaping of plasma or applied magnetic fields.

Self trapping, which occurs when the wake reaches an amplitude sufficient to trap electrons from the plasma through which it propagates, has been used since early experiments, and refinement in understanding and control of this process continues. While broad energy spread beams were produced in early experiments ([12] and others) which drove the wake far above the trapping threshold and/or did not control acceleration length, it has been demonstrated that appropriate control of laser and plasma parameters (amplitude just above the trapping threshold, and extracting the bunch as it is momentum compressed by dephasing from the accelerating field) can generate bunches with few percent energy spread and mrad divergence [2, 3, 4, 13]. Stable operation at up to GeV energies has been observed [5, 8]. Several presentations addressed the theory of this injection process, including trapping threshold and beam quality. General trapping conditions for non-evolving wakes were presented by Wei Lu of UCLA, giving a physical picture of injection. Simulations were used for verification of the physical picture by utilizing non-evolving beam drivers. This method was then used to characterize the effects of driver shape and plasma channels. Analysis of the trapping condition in a bubble was also derived by Alec Thomas and presented by Stuart Mangles by analyzing trajectories in a comoving frame with the bubble, which is assumed non-evolving on the time scale of injection (though evolution of the laser up to the injection point is taken into account). Good agreement with experiments from Imperial and LLNL was shown. Two talks addressed the effects on injection of evolution in the bubble structure driven by intentional laser spot size variation, Sergei Kalmykov of U. Nebraska Lincoln and Vladimir Khudik of U. Texas Austin. Kalmykov presented simulations showing that an initially 'over focused' laser pulse diffracts to a stable self guided radius at which it then propagates. During diffraction, the bubble radius and length expand, trapping particles that would otherwise not be trapped (such an effect is also produced when the plasma density decreases [14, 7]). Simulations using the quasi-static code WAKE with add-on non-quasistatic 'test' electrons to simulate injection (preferred by some for noise reasons) gave reasonable agreement with full PIC under these conditions, neglecting beam loading of the structure which was not severe. Kalmykov and Khudik each presented a Hamiltonian model of trapping in such evolving bubbles. Khudik presented test-particle models of particle trajectories illustrating the role of expansion, and showing which particles are trapped. The difference between accelerated and trapped particles was analyzed. He found that the 'bump' in electron density caused by re-convergence of particles at the end of the bubble had a significant effect in lowering trapping threshold relative to idealized circular bubbles. The working group hosted discussion and comparison of each of these theories. While the first two talks found trapping criteria without laser evolution, the latter two found that bubble evolution was critical to injection, and this remains a topic of discussion as does the relative merit of quasistatic with add-on particles versus full explicit PIC (which self consistently handles injection) for these problems.

Improved understanding is facilitating control over self trapping. Results on production of stable 200 MeV electron bunches from self trapping using a gas cell were presented by Stefan Karsch of LMU/MPQ. A variable length gas cell was also used to characterize dephasing effects. A new laser system at MPQ is producing high power pulses at 8 fs, allowing resonant excitation of plasma wakes at high densities, and has demonstrated production of 25 MeV bunches with 3% energy spread using only 70 mJ, as presented by Laszlo Veisz. The self trapping threshold was characterized as a function of plasma density in experiments at LLNL presented by Bradley Pollock, and in a related plenary by Froula which also presented an overview of other experiments. Several other groups presented data on self trapping and its relation to laser spot evolution and symmetry, which are covered in the sections below.

To further improve bunch momentum spread and stability, the working group hosted discussions of significant advances in separate control over electron injection into a wake driven to an amplitude below the self trapping threshold, so that injection and wake structure can be tuned independently. This can be important to allow tuning of the wake structure into regimes that would not produce trapping, and may also reduce the transverse momentum spread that results in self trapping because particles are trapped from the transverse edges of the bubble. Colliding pulse injection uses the beat between two nearly counter-propagating laser pulses to give electrons a kick in phase and momentum into trapped orbits in the wake of the driver, and the charge and injected location of the injected electrons are controlled by the beat amplitude and location [15, 16, 6]. Experiments and simulations at LOA were presented by Victor Malka, demonstrating stable beams near 200 MeV with 5 % energy spread (limited by spectrometer resolution in this case, down to 1% having been shown in other cases) and energy tuning from 50 to 220 MeV using a small-angle collision and 32 TW drive power near $a_0$=1.5. Charge and energy spread were found to be correlated when tuning with collider strength or plasma density, and beam loading and injection phase space effects were characterized using simulation and experimental scans. Experiments at LBNL were presented by Guillaume Plateau, showing control over injection via beam timing, plasma density, and colliding pulse intensity, and demonstrating the use of computer controlled active beam pointing feedback to achieve reproducible injection over hours of operation. The experiments use a 10 TW driver with $a_0 > 2$ at a $19^o$ angle, investigating injection into nonlinear wakes, and guiding of the driver pulse has been demonstrated in preparation for guided colliding pulse experiments. VORPAL simulations used to design these experiments were presented by Estelle Cormier-Michel of Tech-X, and successfully predicted the plasma density and laser regimes for best injection observed in the experiments, as well as timing behavior. Effect of non-ideal laser modes and laser focal location and self-focusing in the plasma channel on the trapped bunch were evaluated. For optimized parameters, accessible to the experiment, a 20 pC electron beam can be accelerated to 300 MeV with percent level energy spread, twice the energy available from self-injected experiments on the same system.

The use of ionization to control injection into the wake [16-19] has been an area of intense research since the last AAC conference, and six presentations reviewed theory and experimental results. In this technique, a gas or gas mixture is used which has ionization states near the peak intensity of the wake drive laser for injection and ideally a large gap in intensity down to the next (bulk) group of states. In this case, the leading edge of the driver at low intensity ionizes the bulk states producing a plasma in which the wake is driven. The last state(s) are ionized near the peak of the laser pulse, injecting electrons at near-zero velocity into the wake at a phase where the bulk wake oscillation velocity is negative, and near the zero-crossing of the electric field. These electrons can hence be trapped more easily, at lower driver intensity, than the bulk plasma. Ionization trapping theory and VLPL simulations were presented by Min Chen of LBNL, showing the required wake amplitude for trapping of these electrons, and the behavior of injection and beam phase space was characterized with various gas mixtures and lengths. Optimum beam energy spread less than 0.5% is found for short mixed gas injector regions and few-percent mixtures of, for example, N, in H bulk gas followed by a pure H plasma for acceleration, and laser pulse skew was shown to further improve spread. Optimum emittance was found for intensities just above the ionization threshold. Theory showing the optimal injection phase and an analytical model for trapping and subsequent energy gain were presented along with experiments conducted at UCLA by Arthur Pak. The experiments showed 100 MeV electron energy gain with broad energy spectra for parameters where there is no self trapping and were analyzed through comparison with OSIRIS simulations. Bradley Pollock presented experiments from LLNL using He + $CO_2$ gas mixtures in which a broad energy spread with electrons up to 1.5 GeV was observed using a 200 TW laser in a plasma at $1.3x10^{18}$/cm$^3$ density [21]. Both of these experiments observed broad energy spread, with the highest beam intensity at low energy, attributed to continuous injection and acceleration over less than a dephasing length. Pollock also described designs of a two-stage gas cell, with a 500 $\mu$m mixed gas followed by a longer pure He region, and simulations showing that this design is anticipated to achieve narrow energy spread beams near 1.5 GeV. Experiments at Michigan characterized effects of variation in mixing concentration and species, as reported by Chris McGuffey. Ar and N doping into He gas resulted in increased charge and lowered divergence as well as reduced threshold density for injection. At 100 TW laser powers, quasi-monoenergetic beams were also observed near 200 MeV, though with broader energy spread than self trapping. Experiments at LBNL were described by Kei Nakamura, in which stable quasimonoenergetic beams at 13 MeV with shot-to-shot fluctuation of only 0.6 MeV over 1000 shots were generated in mm-scale gas jets with 1% N in He near $3x10^{18}$/cm$^3$ density using a 30 TW laser, and with minimal depletion of the drive laser pulse. These beams are suitable as an injector and tuning of injector charge and energy was demonstrated towards their use with capillary structures. JAEA results presented by Hideyuki Kotaki demonstrated improved pointing, divergence, stability and peak energy in Ar and N gas jets. Over 100 MeV energies were demonstrated from a 3 TW laser, and beam steering using the gas jet transverse position (and hence transverse plasma density gradients) was shown.

A variety of other injection methods were discussed, including further results on plasma density gradient trapping [14, 7]. A double gas nozzle incorporating a small and a large outlet, which produces a modulated density profile suitable for downramp trapping experiments, was presented by McGuffey. An asymmetrical supersonic jet exhibiting strong shocks was shown which may be applicable to density down-ramp trapping techniques was presented by Tomonao Hosokai of Osaka. Tailored capillaries incorporating gas jets, and use of Raman scattering to measure the resulting density modulation with benchmarking to gas flow simulations were presented by Karsch. Use of a sharp density transition produced by a shock in a gas jet, followed by a uniform plasma region, was shown to stabilize injection and reduce energy spread by Veisz, producing 27 MeV beams with 2.6% energy spread and 4 MeV energy stability.

## GUIDING AND ACCELERATOR STRUCTURE CONTROL

In a laser-plasma accelerator, the accelerator structure is formed by the self-consistent interaction of a laser propagating in a plasma. To preserve high bunch quality during acceleration, the laser and plasma profiles must be shaped such that the accelerator structure has the desired amplitude and shape, and to control evolution of the structure as the laser propagates. For wakefield accelerators the working group included discussions of the effects of non-ideal laser modes, of laser guiding using capillary discharge [22] and wall guiding [23] structures and relativistic 'self' guiding [24], of methods to structure the plasma density for injection control, and of advanced techniques for controlling the laser mode and plasma shape to increase performance. For high energy applications [25], staging of multiple modules in series is also beginning to be approached. In a direct laser acceleration scheme, lower laser powers are typical such that relativistic self guiding is not prominent, but the structure must be modulated to keep the laser field and particles correctly phased, and such structures were also addressed [11].

The effects of non-Gaussian laser modes and optical aberrations produced by high-power laser systems were a focus of discussion. While theoretical derivations of accelerator structure, and past simulations, have typically used the lowest-order Gaussian laser mode, experimental high-power lasers have high-order mode content which causes spot asymmetry and deviation from the Gaussian profile. The effects of laser mode quality on injection and acceleration in capillary waveguides at the Astra Gemini laser were presented by Simon Hooker (Oxford), showing that use of an iris reduced mode aberration producing a relatively clean mode with approximately half the energy. This reduced laser energy threshold for injection two-fold, indicating that the energy in the central spot controls injection. This was confirmed by simulations presented by Nicolas Bourgeouis (Oxford), which showed that the spot energy, not mode size, effect of the iris was dominant. In experiments at the Lund laser center presented by Stuart Mangles (Imperial), controlled aberrations were introduced resulting in an increase in beam divergence and injection of off-axis beams, demonstrating directly the importance of spot quality. Injection threshold density was then characterized as a function of laser power and focal spot quality, showing that energy in the central spot not total beam energy is the parameter controlling injection in agreement with the Oxford results. Pulse compression by the plasma wave was also characterized. Related work by the CNRS group is noted below. The effects of realistic modes are also being analyzed through simulation, and work by Estelle Cormier-Michel using the VORPAL code compared acceleration with realistic laser modes from LBNL experiments to ideal Gaussians for colliding pulse injection. This isolates the effect of laser mode on injection and structure, and showed that, even for high quality modes where $\sim 90$ % of the beam is in the central spot, the effect of aberrations can still be significant for both charge and beam energy, indicating that very high quality spots will be required to achieve optimal performance.

To achieve high energies, acceleration over distances much greater than the laser diffraction range $Z_R$ is required, which relies on laser guiding by preformed channels and relativistic self guiding, and their interactions. This was the focus of several talks. In self guiding the self-consistent modification of the plasma refractive index introduces a guiding effect for some parameter regimes. Preformed channels can further extend guiding regimes, and include discharge capillaries where striking a discharge in hydrogen gas creates a transverse density gradient by heat conduction which provides guiding, and wall guiding in capillaries without density shaping. Experiments by Oxford at Astra Gemini (S. Hooker) investigated the relative importance of channel and self guiding in discharge capillary plasmas by scanning the time of arrival of the laser pulse with respect to the discharge to vary the guiding profile. They found that at high densities trapping and acceleration could be achieved at any timing, consistent with stable self guiding as predicted by theory. At lower densities, the waveguide profile is required to achieve injection and acceleration, as expected, and it is in this regime that the highest quality and energy beams were observed. This was supported by WAKE simulations (Bourgeouis) showing that the channel contribution prevented diffraction and allowed stable propagation and was important even for cases where the laser spot was smaller than the channel matched spot size.

Discharge capillary experiments at LBNL showed that the transverse displacement of the laser spot at the channel exit, and its dependence on timing of the discharge and the input displacement, provides a precise diagnostic of the waveguide transverse plasma density profile. This improved channel profile data confirmed simulation predictions of channel profile and scalings with parameters, providing important data to design of future experiments. Discharge capillary guides using glass media (others use Sapphire) developed at Utsunomiya University, Japan were presented by Hiromitsu Terauchi. Plasma parameters were measured by an interferometer and a hydrogen plasma line spectrum, showing temperature of 3.3 eV and density near $10^{17}$/cm$^3$, and guiding was demonstrated using a low intensity laser pulse. Hydrogen filled wall-guiding capillary structures were investigated in the linear wake regime at CNRS France as presented by Brigitte Cros. Simulations were conducted showing that the laser mode must be centered in the capillary within 30% of its radius, in agreement with measurements, and that input angle and mode must also be controlled to achieve high quality guiding. Experiments at the Lund laser then implemented and evaluated methods for controlling beam pointing onto the capillary, showing that mechanical improvements and inhibiting shots during unstable parts of the 10 Hz cycle each gained $\sim$ 20%, and that active pointing with a pilot beam gained a further $\sim$ 15%. The focal spot was then controlled using a deformable mirror and wake amplitude in the capillary deduced from spectral shifts in the laser, and comparison of these results with simulations allowed inference of accelerating fields of 1-7 GV/m at densities of a few $10^{17}$/cm$^3$. Simulations demonstrating designs for multi-GeV experiments on the Texas Petawatt laser were presented by Xiaoming Wang of U. Texas.

Techniques to further control plasma shape and laser propagation include control of the pre-plasma created by the laser before the main interaction [26], and gas jets with shaped profiles [7]. Shaping of the pre-plasma using an applied axial magnetic field was discussed by Tomonao Hosokai of Osaka, showing that fields of $\sim 0.2T$ shaped the preplasma into a funnel shape. The prepulse level was adjusted by aligning the compressor, and combination of these techniques improved laser focusing and propagation distance through the subsequent plasma, producing quasi-monoenergetic beams at 100 MeV and improved stability versus exponential spectra at lower energies with uncontrolled prepulse. Related experiments on the role of coaxial magnetic field were presented by Will Schumaker of Michigan. Gas jets are targets for many laser plasma experiments, and are now being used within capillary plasmas to tailor the density profile along the laser propagation direction allowing a high density injector within a long low density structure. A fast valve is important for such applications to reduce gas loading and disruption to the capillary structure, and results on an electromagnetically driven valve were presented by Mahadevan Krishnan of Alameda Applied Sciences Corp. The valve, actuated by a flyer plate, opens in $\sim$100 $\mu s$, significantly faster than traditional valves at the required pressures. The mechanism provides scaling to 10's of microsecond opening times, and can operate larger apertures. A new version of the valve is under development to create shaped jets.

For high energy physics applications where TeV energies and beyond are desired, it has been envisioned that staging of multiple accelerators in series will provide the highest system gradient and also may be desirable for bunch charge considerations [25]. This is because, as single stage energy gain is increased, the accelerating gradient drops while bunch charge and laser energy increase so that a single - stage TeV accelerator would have lower gradient. To realize the benefits of staging, it is crucial to couple the stages as closely as possible to maximize geometric gradient. Experiments on plasma mirrors to achieve close coupling were presented by Thomas Sokollik of LBNL, showing that tape drive based mirrors can sustain high rep rate operation and provide 80% reflectivity, and that optimum compromise between mode quality and reflectivity is near $1x10^{16}$W/cm$^2$. Tape roughness, beam quality, and pointing stability were characterized.

Use of laser plasma accelerators for many applications demands improvements in both energy transfer from the laser to the beam, and in the emittance of the beam (in particular to meet the MW beam power and nm emittance requirements of future colliders), and advanced techniques to achieve these goals were discussed. Plasma density tapering [27] is a technique to compensate phase slippage of the accelerating particles when their velocity does not match the driver, and hence extend acceleration to laser depletion, improving efficiency. Simulations and theory demonstrating use of tapering to improve energy gain were presented by Antonio Ting of NRL including bucket jumping, where the density is suddenly shifted to switch the particles to a new wake period. This can further extend the acceleration distance if not limited by laser depletion, and in particular was applied to acceleration of moderate energy (9 GeV) protons where it is important for high gain because the particles are relatively low $\beta$. Other approaches for proton acceleration such as near-critical densities and beat waves to slow the wake were also characterized. To improve and control the transverse emittance of the beam, and to efficiently accelerate positrons, the focusing fields and their phase with respect to the accelerating fields must be controlled. Analytic theory showing this can be achieved in the linear regime by shaping the transverse laser mode, and VORPAL simulations demonstrating quasilinear operation and that the required high order modes propagate stably in plasma channels (from [28]) were presented by Cameron Geddes of LBNL. These simulations showed that the transverse fields can be reduced to allow acceleration of a very low emittance beam while keeping the beam size larger than in the Gaussian laser case, which was shown to be important to allow acceleration of high charge beams without inducing blow out of the wake. The phase of the accelerating and focusing fields can be controlled using mode ratio and delay which is the subject of ongoing work to compensate beam loading.

For direct laser acceleration the phase slippage length is much shorter than in wakefield acceleration since a particle experiences acceleration over a fraction of a laser wavelength, not a plasma period. Hence quasi phase matching where the density is modulated such that once the particle slips from accelerating phase, the wave is re-phased to put it back in accelerating phase of another period [11] - akin to bucket jumping - is crucial to achieve high energy gain, and techniques to achieve this were presented by Brian Layer of U. Maryland. Two techniques for making the required plasma channels which have both a transverse density gradient to provide guiding and an axial density modulation to allow quasi phase matching were developed. The first uses a ring grating to radially modulate the 100 ps channel forming laser pulse which is then focused by an axicon to a line focus where the radial modulation becomes an axial variation in intensity. Using such a beam to illuminate a cluster jet produced modulated guides with maxima at the maxima of laser intensity, and such structures were shown to guide a probe laser pulse. Alternatively, removing the ring grating, modulation was produced by placing a wire 'comb' across the cluster jet exit to create periodic regions free of clusters, allowing very fine longitudinal control. The 1D radial-like modes required for the guided laser to produce an accelerating field were generated by inserting a half pellicle into the beam, shifting half of it by $\pi$ phase, and an experiment to demonstrate acceleration is in progress.

## RADIATION JOINT SESSION

An important potential application of the electron beams produced by either laser or beam driven wakefield accelerators is in generating brilliant sources of radiation. In a joint session with Working Group 5, *Beam and radiation generation, monitoring and control*, a large number of groups reported on advances in radiation production, measurements and modeling from the oscillations of relativistic electron beams produced by laser wakefield accelerator. The radiation measurements that were reported were produced mainly in two ways, either by oscillations of the electrons in external magnetic undulators [29, 30] or by betatron oscillations in the transverse fields of the wakefield itself [31]. Another radiation generation mechanism, backscattering a laser-pulse from the relativistic electron beam [32], was also discussed – in particular by Ulrich Schramm relevant to a future upgrade of the FZD laboratory to enable such experiments – but no experimental results were reported.

The reported results show that considerable progress has been made, with many orders of magnitude increases in the brilliance and energy of the x-rays from the betatron source, in addition to technological steps being made towards a table-top free electron laser using an external undulator and new radiation diagnostics, both experimental and numerical. The LWFA betatron source has now been characterized by a number of groups and the radiation emission has been shown to achieve a peak brightness comparable to 3rd generation synchrotron light sources, although the average brightness is lower due to the currently low repetition rate. Radiation generation from a LWFA-produced beam in an external undulator has also been measured [30], which may potentially pave the way towards compact free-electron-laser light sources. The interesting aspect of the laser produced electron source, as opposed to a conventional accelerator, is the prospect for extremely short electron bunch durations. Hence, electron bunch duration measurements are of significant interest, as a short electron bunch enables short radiation pulse duration.

Stefan Kneip presented measurements of betatron x-ray properties from experiments by a collaboration of the Imperial College London and University of Michigan using the HERCULES laser system, demonstrating a 1-100 keV x-ray source with $1000\times$ greater peak brightness than previous laser driven betatron sources. This was principally due to the significantly higher electron beam energies compared with previous results. The source was also shown to have an appreciable degree of spatial coherence, which was inferred from modeling of Fresnel diffraction of the radiation from a cleaved crystal. This enabled phase-contrast x-ray images of biological material using photons with a $\sim$10 keV critical energy to be taken. Betatron x-ray emission measurements were also presented by Guillaume Plateau from LBNL, and used to measure the electron beam source size of a laser-plasma accelerator. Simultaneous measurements of electron beam spectra and divergence were taken with the single-shot CCD x-ray measurements and showed a correlation between x-ray and electron spectra.

Stuart Mangles introduced results from experiments by a collaboration of Imperial College London and the Lund Laser Center on increasing the amplitude of the betatron oscillations in the wakefield by deliberately inducing an asymmetry. This was done by adding the optical aberration coma to the laser spot [33]. This could find potential application in increasing the x-ray flux from a betatron source. A number of results from the ALPHA-X project were presented by Dino Jaroszinski of the University of Strathclyde. These included measurements of MeV photons from the betatron source, characterization of the electron beam transverse emittance using a 'pepper-pot' technique, and extremely short bunch durations, inferred from the coherent transition radiation spectrum (for related beam duration measurements by other groups see the diagnostics section below), which indicated that the laser produced beams would likely be suitable for driving a compact free electron laser.

Numerical advancements were also presented, including betatron calculations using a post-processing diagnostic and electron trajectories from the particle-in-cell code OSIRIS [34] presented by Luis O'Silva from the Instituto Superior Tècnico. This technique numerically calculated retarded potentials deposited on a 'virtual detector' in the far-field, giving an angularly resolved x-ray spectra and allowing the effects of realistic acceleration and beam dynamics on the x-ray source to be modeled. The diagnostic was used to numerically verify the results of Kneip, and also to predict the radiation from a 12 GeV laser wakefield accelerator.

Laser wakefield accelerator-produced electrons are also now being injected into conventional magnetic undulators to produce radiation of potentially narrow bandwidth, which is a step towards the development of compact free-electron lasers. Florian Grüner from Ludwig-Maximilians University presented the recent demonstration of a soft x-ray undulator source at 20 nm driven by the stable wakefield accelerator beam at 200 MeV presented by Karsch. He then discussed the steps towards a 'table-top' free electron laser using a laser wakefield accelerator, including the electron beam stability, tunability and undulator requirements towards a "minimal demonstration" of a free electron laser [30]. One important aspect of this, which is also relevant to staging of the laser wakefield accelerator, is beam transport between the wakefield accelerator and the undulator (or subsequent stages). Jens Osterhoff from LBNL and Raphael Weingartner from Ludwig-Maximilians University both demonstrated that miniature quadrupole permanent magnets could successfully mitigate pointing fluctuations and beam divergence issues. Undulator radiation measurements can also be used as an accurate diagnostic of the electron beam properties, as discussed by Michael Bakeman from LBNL. This is because the radiation peak energy, bandwidth and brightness depend on the electron beam charge, peak energy and energy spread, and provide diagnostics of longitudinally slice-resolved parameters in addition to the bulk beam properties.

Finally, Bernhard Hidding from Heinrich-Heine University presented a possible novel application for laser driven sources, in testing space components exposure to the sort of radiation fluxes that exist outside of the earth's magnetosheath. Since lasers routinely produce intense fluxes of ions, electrons and photons, and are relatively inexpensive and compact, they may prove to be an excellent test-bed for space electronic devices.

## BEAM PROPERTIES AND DIAGNOSTICS

The micron-scale accelerating structure of laser-plasma accelerators forms naturally ultrashort, intense electron bunches, and diagnostic techniques to analyze the wake structure, electron bunch, and the propagation and evolution of the laser pulse are advancing rapidly.

Measurement of the fs-scale electron bunch has been a focus of recent research. Coherent transition radiation measurements showing a 1.5 fs long electron bunch produced by colliding pulse experiments were presented by Victor Malka of LOA. Photon yield per electron was measured and indicated emission was coherent, and fitting to the spectrum was used to infer bunch length of 1.5 fs, which is close to that predicted by particle simulations for these parameters. Related data was presented by Jaroszinski, above, and in Fiorito and Lin's presentations in WG 5. Transverse oscillations of the electron beam attributed to the laser field were shown by Hideyuki Kotaki of JAEA, and analysis indicated the electron beam length was in the 4 fs range. THz diagnostics [35] were presented in a related plenary by Nicholas Matlis of LBNL. Measurement of beam charge for the intense ultrashort bunches has also been a subject of community discussion, and Kei Nakamura presented results of calibration between integrating charge transformers, LANEX phosphor screens, button type BPMs, and radionuclide activation measurements. It was shown that these techniques are in agreement for both RF accelerator and broad-band laser-plasma accelerator beams and for 0.1 - 1.5 GeV energies. Related calibrations were presented by Schramm from FZD. Pepper pot measurements of beam emittance at the $2\pi$ mm-mrad level were presented by Veisz, and use of calorimetery to measure GeV e-beams was discussed by Wang.

The transient plasma nature and small scale of the accelerator structure in laser-plasma accelerators present challenges to measurement, and until recently structure had been inferred from output electron and laser beam characteristics. New diagnostics were discussed which directly measure the plasma wake structure. An extension of the wake holography technique [36] was described by Zengyn Li of U. Texas, showing that by using multiple lines of sight, evolving wake structures can be recovered, which are those of greatest interest for acceleration since driver pulse evolution is often important. This was tested using a Kerr medium, demonstrating the recovery method, and is now ready for implementation to measure wakefields. The 'trapping' of a co-propagating probe by the plasma bubble was also measured by the U.T. group, presented by Peng Dong, and AM reconstruction of the optical phase was used to infer bubble structure and potential as an optical compressor. Polarograms in which polarization rotation of a probe laser pulse due to the magnetic field of the wake structure is measured, were shown by Malte Kaluza of Jena, and were used to measure the bubble structure. Beam hosing was also measured using a side scatter diagnostic. Wake structure was characterized using a cone of forward-directed 2-$\omega$ light in results presented by Dmitriy Kaganovich of NRL. Ring angle and thickness were correlated to experimental parameters and simulation results, providing a diagnostic of the bubble sheath parameters including cases in which the laser pulse overlaps two wake buckets. The relation of emission to electron injection and laser polarization was discussed.

Laser evolution and scattering was discussed in several talks. Forward Raman scattering in intense laser pulses longer than a plasma period, in the regime relevant to direct laser acceleration, was analyzed by John Palastro of U. Maryland. It was shown that while Raman growth would be problematic for such pulses in uniform plasmas, the introduction of modulated plasma densities as described by Layer for quasi-phase matching of the acceleration also detunes FRS preventing growth. Transmitted optical spectra were analyzed in the Oxford experiments and simulations, and it was shown that taking into account a relativistic shift in the Raman spectrum slowed dependence of the Raman shift with density and improved agreement with data, as presented by Bourgeouis and Hooker. McGuffey of Michigan presented results on relativistic effects on sidescatter. Guiding of the laser pulse through capillary structures and the effects of self and channel guiding were investigated using a wavefront sensor, in results presented by Satomi Shiraishi at LBNL. The use of such a sensor eliminates ambiguities in wavefront curvature present in spot-camera based analyses, allowing more precise analysis. Analysis of the interaction of plasma and electromagnetic waves towards diagnostics of beam emittance was presented by Arnesto Bowman of Florida A&M.

## UPCOMING FACILITIES

Many new facilities are planned to extend laser-plasma accelerator research in coming years. The FZD laboratory is combining a 150 TW laser with a superconducting electron linac to enable external injection of the linac beam into the wake as well as Thomson scattering experiments, as presented by Ulrich Schramm. Novel techniques for tilted phase fronts in line-focused laser beams were presented to increase Thomson yield. The CALA facility was outlined by Stefan Karsch of LMU and MPQ, and will include a compact sychrotron, 3 PW laser, and a 100 TW / 1 kHz laser for synchronized laser and beam sources. The BELLA facility at LBNL, which targets high-energy physics and light-source relevant stages at the 10 GeV level, was described in a related plenary talk by Wim Leemans.

## CONCLUSIONS

The presentations and discussions in the working group demonstrate the continued rapid progress of laser plasma accelerators in beam quality, stability, and in the physical understanding and diagnostics which underlay these. In particular, the past two years have seen widespread work on control of injection through both better understanding of self trapping by the wake, and separate control of injection via colliding laser pulses, density transitions and ionization, improving experimental control over and theoretical understanding of the beams. Controlled injection in turn allows tuning of the accelerator structure. To enable this, the effects of non-gaussian laser modes on the acceleration process, and the interaction of self and plasma channel guiding are being characterized. Simulations and theory are also beginning to provide predictive guidance to design experiments as well as increased fidelity in understanding and controlling the processes observed. New diagnostics access evolving wakes and resolve bunch and wake structure. These developments set the stage for new facilities and experiments to develop laser-plasma accelerators.

## ACKNOWLEDGMENTS

We thank the participants in the working group for contributing the material summarized here, and for productive workshop discussions exploring these topics. References and acknowledgments for the work described herein can be found in the respective papers in these proceedings.

# REFERENCES

1. T. Tajima, and J. M. Dawson, *Phys. Rev. Lett.* **43**, 267–70 (1979).
2. J. Faure, Y. Glinec, A. Pukhov, S. Kiselev, S. Gordienko, E. Lefebvre, J.-P. Rousseau, F. Burgy, and V. Malka, *Nature* **431**, 541–544 (2004).
3. C. G. R. Geddes, Cs. Tóth, J. van Tilborg, E. Esarey, C. B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary, and W. P. Leemans, *Nature* **431**, 538–541 (2004).
4. S. P. D. Mangles, C. Murphy, Z. Najmudin, A. Thomas, J. Collier, A. Dangor, E. Divali, P. Foster, J. Gallacher, C. Hooker, D. Jaroszynski, A. Langley, W. Mori, P. Norreys, F. Tsung, R. Viskup, B. Walton, and K. Krushelnick, *Nature* **431**, 535–538 (2004).
5. W. P. Leemans, B. Nagler, A. J. Gonsalves, C. Tóth, K. Nakamura, C. G. R. Geddes, E. Esarey, C. B. Schroeder, and S. M. Hooker, *Nat. Phys.* **2**, 696–699 (2006).
6. J. Faure, C. Rechatin, A. Norlin, A. Lifschitz, Y. Glinec, and V. Malka, *Nature* **444**, 737–739 (2006).
7. C. G. R. Geddes, K. Nakamura, G. R. Plateau, Cs. Tóth, E. Cormier-Michel, E. Esarey, C. B. Schroeder, J. Cary, and W. P. Leemans, *Phys. Rev. Lett.* **100**, 215004 (2008).
8. J. Osterhoff, A. Popp, Z. Major, B. Marx, T. P. Rowlands-Rees, M. Fuchs, M. Geissler, R. Horlein, B. Hidding, S. Becker, E. A. Peralta, U. Schramm, F. Gruner, D. Habs, F. Krausz, S. M. Hooker, , and S. Karsch, *Phys. Rev. Lett.* **101**, 085002 (2008).
9. D. H. Froula, C. E. Clayton, T. Döppner, K. A. Marsh, C. P. J. Barty, L. Divol, R. A. Fonseca, S. H. Glenzer, C. Joshi, W. Lu, S. F. Martins, P. Michel, W. B. Mori, J. P. Palastro, B. B. Pollock, A. Pak, J. E. Ralph, J. S. Ross, C. W. Siders, L. O. Silva, and T. Wang, *Phys. Rev. Lett.* **103**, 215006 (2009).
10. K. Shimoda, *Applied Optics* **1**, 1479–1484 (1962).
11. A. G. York, H. M. Milchberg, J. P. Palastro, and T. M. Antonsen, *Phys. Rev. Lett.* **100**, 195001 (2008).
12. A. Modena, Z. Najmudin, A. E. Dangor, C. E. Clayton, K. A. Marsh, C. Joshi, V. Malka, C. B. Darrow, C. Danson, D. Neely, and F. N. Walsh, *Nature* **377**, 606–608 (1995).
13. F. S. Tsung, R. Narang, W. B. Mori, C. Joshi, R. A. Fonseca, and L. O. Silva, *Phys. Rev. Lett.* **93**, 185002 (2004).
14. S. Bulanov, N. Naumova, F. Pegoraro, and J. Sakai, *Phys. Rev. E* **58**, R5257 (1998).
15. E. Esarey, R. F. Hubbard, W. P. Leemans, A. Ting, and P. Sprangle, *Phys. Rev. Lett.* **79**, 2682–2685 (1997).
16. G. Fubiani, E. Esarey, C. B. Schroeder, and W. P. Leemans, *Phys. Rev. E* **70**, 016402 (2004).
17. M. Chen, Z.-M. Sheng, Y.-Y. Ma, and J. Zhang, *Journal of Applied Physics* **99**, 056109 (2006).
18. T. P. Rowlands-Rees, C. Kamperidis, S. Kneip, A. J. Gonsalves, S. P. D. Mangles, J. G. Gallacher, E. Brunetti, T. Ibbotson, C. D. Murphy, P. S. Foster, M. J. V. Streeter, F. Budde, P. A. Norreys, D. A. Jaroszynski, K. Krushelnick, Z. Najmudin, and S. M. Hooker, *Phys. Rev. Lett.* **100**, 105005 (2008).
19. C. McGuffey, A. G. R. Thomas, W. Schumaker, T. Matsuoka, V. Chvykov, F. J. Dollar, G. Kalintchenko, V. Yanovsky, A. Maksimchuk, K. Krushelnick, V. Y. Bychenkov, I. V. Glazyrin, and A. V. Karpeev, *Phys. Rev. Lett.* **104**, 025004 (2010).
20. A. Pak, K. A. Marsh, S. F. Martins, W. Lu, W. B. Mori, and C. Joshi, *Phys. Rev. Lett.* **104**, 025003 (2010).
21. C. E. Clayton, J. E. Ralph, F. Albert, R. A. Fonseca, S. H. Glenzer, C. Joshi, W. Lu, K. A. Marsh, S. F. Martins, W. B. Mori, A. Pak, F. S. Tsung, B. B. Pollock, J. S. Ross, L. O. Silva, and D. H. Froula, *Phys. Rev. Lett.* **accepted** (2010).
22. D. J. Spence, and S. M. Hooker, *Phys. Rev. E* **63**, 015401(R) (2001).
23. B. Cros, C. Courtois, G. Matthieussent, A. D. Bernardo, D. Batani, N. Andreev, and S. Kuznetsov, *Phys. Rev. E* **65**, 026405 (2002).
24. E. Esarey, P. Sprangle, J. Krall, and A. Ting, *IEEE J. Quantum Electron.* **33**, 1879–914 (1997).
25. C. B. Schroeder, E. Esarey, C. G. R. Geddes, C. Toth, and W. P. Leemans, *Proc. Adv. Acc. Con. Wkshp.* pp. 208–214 (2008).
26. T. Hosokai, K. Kinoshita, A. Zhidkov, K. Nakamura, T. Watanabe, T. Ueda, H. Kotaki, M. Kando, K. Nakajima, and M. Uesaka, *Phys. Rev. E* **67**, 036407 (2003).
27. P. Sprangle, B. Hafizi, J. R. Peñano, R. F. Hubbard, A. Ting, C. I. Moore, D. F. Gordon, A. Zigler, D. Kaganovich, and T. M. Antonsen, Jr., *Phys. Rev. E.* **63**, 056405 (2001).
28. E. Cormier-Michel, E. E. andC. G. R. Geddes, C. B. Schroeder, and W. P. Leemans, *Phys. Rev. ST-AB* (submitted).
29. C.B.Schroeder, W.M.Fawley, F.Gruener, M.Bakeman, K.Nakamura, K.E.Robinson, Cs.Toth, E.Esarey, and W.P.Leemans, *Proc. Adv. Acc. Con. Wkshp.* pp. 637–42 (2008).
30. M. Fuchs, R. Weingartner, A. Popp, Z. Major, S. Becker, J. Osterhoff, I. Cortrie, B. Zeitler, R. Hoerlein, G. D. Tsakiris, U. Schramm, T. P. Rowlands-Rees, S. M. Hooker, D. Habs, F. Krausz, S. Karsch, and F. Gruener, *Nat. Phys.* **5**, 826 (2009).
31. A. Rousse, K. T. Phuoc, R. Shah, A. Pukhov, E. Lefebvre, V. Malka, S. Kiselev, F. Burgy, J.-P. Rousseau, D. Umstadter, and D. Hulin, *Phys. Rev. Lett.* **93**, 135005 (2004).
32. R. W. Schoenlein, W. P. Leemans, A. H. Chin, P. Volfbeyn, T. E. Glover, P. Balling, M. Zolotorev, K. J. Kim, S. Chattopadhyay, and C. V. Shank, *Science* **274**, 236–8 (1996).
33. S. P. D. Mangles, G. Genoud, S. Kneip, M. Burza, K. Cassou, B. Cros, N. P. Dover, C. Kamperidis, Z. Najmudin, A. Persson, J. Schreiber, F. Wojda, and C. G. Wahlstrom, *Appl. Phys. Lett.* **95** (2009), ISSN 0003-6951.
34. J. L. Martins, S. F. Martins, R. A. Fonseca, and L. O. Silva, “Radiation post-processing in PIC codes,” SPIE, 2009, vol. 7359, p. 73590V.
35. J. van Tilborg, C. B. Schroeder, C. V. Filip, Cs. Tóth, C. G. R. Geddes, G. Fubiani, R. Huber, R. A. Kaindl, E. Esarey, and W. P. Leemans, *Phys. Rev. Lett.* **96**, 014801 (2006).
36. N. H. Matlis, S. Reed, S. S. Bulanov, V. Chvykov, G. Kalintchenko, T. Matsuoka, P. Rousseau, V. Yanovsky, A. Maksimchuk, S. Kalmykov, G. Shvets, and M. C. Downer, *Nat. Phys.* **2**, 749–753 (2006).