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Summary Report: Working Group 2 on "Plasma Based Acceleration Concepts"

W.P. Leemans and E. Esarey

Accelerator and Fusion Research Division

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Presented at the
8th Workshop on Advanced Accelerator Concepts,
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Summary Report: Working Group 2 on "Plasma Based Acceleration Concepts"

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Abstract. A summary of the talks, papers and discussion sessions presented in the Working Group on Plasma Based Acceleration Concepts is given within the context of the progress towards a 1 GeV laser driven accelerator module. The topics covered within the Working Group were self-modulated laser wakefield acceleration, standard laser wakefield acceleration, plasma beatwave acceleration, laser guiding and wake excitation in plasma channels, plasma wakefield acceleration, plasma lenses and optical injection techniques for laser wakefield accelerators. An overview will be given of the present status of experimental and theoretical progress as well as an outlook towards the future physics and technological challenges for the development of an optimized accelerator module.

INTRODUCTION

The Working Group on "Plasma Based Acceleration Concepts" consisted primarily of presentations on experimental /theoretical progress on the following topics:

(1.) Laser wakefield acceleration (LWFA) including self-modulated regime (SMLWFA) and plasma beatwave acceleration (PBWA);
(2.) Laser guiding including relativistic self-guiding and plasma channel guiding;
(3.) Electron beam driven wake excitation including plasma wakefield acceleration (PWFA) and plasma lenses;
(4.) Plasma based radiation sources.

More than 45 papers were presented, 16 of them in poster format, during the Monday - Thursday sessions. On Friday, discussion groups were formed on the following subjects:

(1.) Laser guiding experiments: progress and challenges;
(2.) SMLWFA experiments: summary;

(3.) Particle trapping in SMLWFA: wavebreaking mechanisms, dephasing length and maximum energy gain;
(4.) LWFA experiments: summary;
(5.) Optimum wavelength choice for laser drivers.

Next, we present a brief summary of various papers presented in the Working Group as well as summaries of the discussion sessions. The emphasis is on highlighting new experimental/theoretical developments that address major issues as well as new challenges relevant to the development of a compact laser driven, plasma based accelerator structure.[1]

LASER GUIDING AND WAKEFIELD EXCITATION

Various groups presented experimental and theoretical progress on laser guiding in plasma channels.[2] Table 1 summarizes the present status of experiments on relativistic self-guiding of high power laser pulses at University of Michigan[3] and NRL;[4] and of experiments on laser guiding in preformed plasma channels at LBNL,[5] University of Maryland,[6] University of Texas at Austin,[7] and at Hebrew University/NRL.[8] The experiments using preformed channels rely on plasma channel formation through hydrodynamic shock expansion in a heated plasma column[5,6,7] or on a capillary discharge.[8]

The Michigan group (Umstadter et al.[3]) presented results on guiding of high power beams in relatively dense plasmas by relying on relativistic self-focusing. Waveguide profiles were obtained through interferometry.

The LBNL group (Leemans et al.[5]) presented results on laser guiding at vacuum intensities of up to $5x10^{17}$ W/cm^2 in plasma channels produced using a novel ignitor-heater scheme in a cylindrical gasjet, with a length of 1 mm. The ignitor pulse is a short intense pulse ($I > 10^{14}$ W/cm^2) that ionizes the gas and the heater pulse is an energetic (>200 mJ) relatively long (>150 ps) laser pulse that heats the plasma through inverse Brehmsstrahlung. This dual-pulse technique allows use of low Z gases which alleviates the concern of further ionization of the plasma by the intense pulse that is to be guided.

The Maryland group (Milchberg et al.[6]) presented results on guiding intense pulses (10^{17} W/cm^2) in 1-1.5 cm long plasma channels, produced in an Ar/N_2O slit gasjet which is ionized using a long pulse focused with an axicon lens. Results were presented of tunnel coupling of radiation into the fiber, a double heater pulse approach to improve control of the radial plasma profile, and fiber-end visualization using interferometry. The development of long gasjets is an important issue for extending the acceleration length in LWFA schemes.

An alternative approach for producing long plasma channels was presented by the University of Texas at Austin group (Downer et al.[7]). An initially low temperature plasma is generated using an electric discharge and a relatively long (100-400 ps), energetic (250-400 mJ) laser pulse is focused with an axicon to heat the plasma through inverse Brehmsstrahlung. Diagnostics based on frequency domain interferometry were also proposed to study the longitudinal wake excited in the channel.

The NRL group (Ting et al.), in collaboration with the Hebrew University (Zigler et al.), has been using a double capillary discharge scheme for guiding high intensity pulses.[8] The main capillary discharge is preceded by a small initial electric discharge to seed the main discharge in the CH_2 capillary. Guiding of intense pulses was reported ($<10^{17}$ W/cm^2). The lifetime of the capillaries is at the present time is limited to a few 100 shots.

TABLE 1: Summary of experiments on laser guiding presented at the Advanced Accelerator Concepts 1998 Workshop.

	U Mich	NRL	NRL	LBNL	Maryland	UT-Austin	Hebrew/NRL
1. Length [cm]	0.1	0.3	0.3	0.1	1.5	1-2	1,2,3,6
2. Diameter [μm]	10 (30)	5	10-20	16	variable	30	300
3. $n_e(r=0)$ [cm^{-3}]	$3x10^{19}$ ($3x10^{18}$)	$1\text{-}3x10^{19}$	$1.5x10^{19}$	$7x10^{18}$	$2x10^{18}$-$6x10^{19}$	$5x10^{18}$	$5\text{-}10x10^{18}$
4. Method	Relativistic	Relativistic	Relativistic	Hydro	Hydro	Hydro	Hydro
5. I_{max} [W/cm^2]	$2x10^{17}$	$5x10^{18}$	$3x10^{16}$	$2x10^{17}$	10^{17}	-	10^{16}-10^{17}
6. Gas/Target	He	H_2/He	He	N_2/H_2	Ar+N_2O	He	CH_2
7. Rep. Rate	7 min/shot	3 min/shot	3 min/shot	10 Hz	10 Hz	20 Hz	min/shot (few 100 shots/capill)
8. Gasjet/Backfill	Jet	Jet	jet	jet	jet	backfill	-
9. Transmission	60%	?	70%	25%	52%	-	15% (1cm) 50% (3 cm) 10% (6 cm)
10. Cost	$$	$$	$$	$$	$$	$$	$

The short term (next 2 years) goals for guiding experiments are:

(A.) guiding of laser pulses with $I>10^{18}$ W/cm^2
(B.) improvement of coupling and transmission efficiency
(C.) generation/ measurement of laser wakefields in channels

During the discussion session on guiding the following issues were raised:

(1.) Production of long channels: To achieve a 1 GeV net acceleration, few cm-long channels are needed. By extending current work, production of channels with lengths up to 10 cm seems achievable in the next few years. Some of the technology developed for z-pinches used in x-ray laser work have produced 10 - 20 cm long plasma columns (albeit in a different density parameter regime). This might be worth considering.

(2.) Efficient production of channels: There is a need for high efficiency in the channel production. Various schemes are currently being evaluated using laser ionization and heating (e.g., ignitor-heater) as well as electric discharge based methods. An open question remains on whether the laser beam can be re-used after producing a plasma channel, since only a small fraction of the laser energy is deposited in the channel.

(3.) Production of low on-axis density: There is a definite need to push $n_e(r=0)$ to lower values ($1\text{-}10\times10^{17}$ W/cm^2). As can be seen in Table 1, the on-axis density in all experiments reported at the Workshop was in the 0.2 - 6×10^{19} cm^{-3} range. To operate in the standard LWFA regime, such high densities would require laser pulses between 5 - 30 fs and would result in a linear dephasing length on the order of 13.8 mm (30 fs pulse) and 64 μm (5 fs pulse), where a laser wavelength of 1 μm is assumed. The maximum energy in GeV after such a dephasing length is then on the order of 0.336 P[TW] for a 30 fs pulse focused to a 10 μm radius spot size and 0.003 P[TW] for a 5 fs pulse, where P is the laser power in TW. From this argument it is clearly advantageous to keep the plasma density on axis as low as possible.

(4.) Plasma density profile control: There is a need for ideas/technology that would enable control of the radial plasma density profile (e.g., the production of hollow channels). It has been shown that a hollow channel supports an electromagnetic mode whereas a wide parabolic channel supports a predominantly electrostatic mode.[9] This implies that the electron beam phase space properties will be superior (i.e., lower emittance) for a hollow channel since the transverse focusing forces will be linear and nearly cancel. The effects of channel shape and uniformity on the wake amplitude and wake temporal decay will need to be examined in detail to help in assessing the laser–to-wake coupling efficiency for the laser driven accelerator schemes.

SELF-MODULATED LASER WAKEFIELD ACCELERATION

Experiments on self-modulated laser wakefield acceleration (SMLWFA) over the last several years have (I) shown acceleration to high energies, (II) provided a platform for the development of experimental techniques and diagnostics, and (III) allowed detailed comparison with analytic theory and simulations. In the SMLWFA regime, the initial laser pulse is many plasma periods long. As the laser pulse propagates through the plasma it gets temporally and spatial modulated at the plasma frequency via a self-modulation or Raman forward scattering instability and thereby efficiently excites a large amplitude plasma wave.[10] Self-trapping of plasma electrons in the wake can occur.

Table 2 summarizes the results presented at the Workshop by the Collaboration between Rutherford Appleton Laboratories, Imperial College and UCLA;[11] the NRL group;[12] and the Michigan group.[13] In all these experiments, electron acceleration to high energies (30 - 100 MeV) has been observed. The high power laser pulse (ranging from 2 - 20 TW) was observed to be self-guided by relativistic focusing in all experiments. Large numbers (up to 10^{10}) of electrons have been observed, most with energies around a few MeV with an exponential drop-off towards higher energies. The laser intensity in all these experiments was on the order of 3 ($\pm$ 1) x 10^{18} W/cm^2 and the wakefield amplitude $\Delta n/n$, measured using Thomson scattering, ranged from 0.3 - 1.0, i.e., approaching but still below the cold wavebreaking limit. Raman scattering spectra of the pump or probe beams, which are a measure of the plasma wave temporal structure, show significant broadening at laser powers above the onset of self-trapping. The NRL and Michigan groups reported observation of electron beams with a divergence less than the laser divergence. The Michigan group also performed measurements of spatial profiles versus laser power, obtaining electron beams with a divergence angle less than 1.5° from which a transverse geometric emittance less than 0.1 π mm-mrad was inferred.

In all these experiments, the accelerated electrons were self-trapped from the background plasma. Self-trapping limits the amplitude of a wakefield and thus the maximum acceleration field gradient which can be sustained by the structure. Aside from its basic plasma physics interest, this self-trapping or "uncontrolled" acceleration of background electrons is equivalent to production of "dark-current" in conventional structures, and is therefore a very relevant issue affecting the development of future laser driven accelerator modules. Several potential mechanisms have been proposed to explain the observations:

(1.) Trapping without pre-heating: Possible if the amplitude of the EPW was actually higher than inferred from Thomson scattering. The RAL/IC/UCLA group has proposed direct wavebreaking as the trapping mechanism.[11]

(2.) Trapping with pre-heating by Raman side- or backscattering (Esarey et al.[14]): Analytic modeling and simulations of the NRL experiments were presented showing reasonable agreement between theory and experiment.

(3.) Two-dimensional wavebreaking in the density channel associated with relativistic self-guiding, due to the curvature of the wavefronts of the plasma wave:[15] The Michigan group (J.K. Kim et al.[16]) reported analytic calculations of 2-D wavebreaking, identifying the transverse momentum as the key parameter and calculating the number of usable accelerating "buckets" behind the laser pulse front prior to the onset of wavebreaking. Results from fluid model calculations presented by Shadwick and Wurtele (Berkeley) indicate that phasefront curvature, which occurs also in parabolic channels, can be mitigated by the use of sufficiently steep channel walls, the limiting case being the hollow channel. The wake phasefront curvature that results from the radial dependence of the plasma wavelength (via the local density) in a parabolic channel, which leads to wavebreaking at relatively low amplitudes, can be avoided in hollow channels.

TABLE 2: Summary of results on self-modulated laser wakefield acceleration experiments as reported at the AAC98 meeting (B/FRS = backward/forward Raman scattering, TS = Thomson scattering, EMS = electromagnetic spectrometer). The wakefield amplitude is $\Delta n/n$, the dephasing length is λ_p^3/λ^2, and the accelerating field is $\Delta n/n\ (n_p)^{1/2}$.

	RAL/UCLA	NRL	U Michigan
Laser			
Wavelength [μm]	1.05	1.05	1.05
Pulse length [fs]	800	400	400
Peak power [TW]	20	2	4
Intensity [W/cm^2]	4x10^{18}	2.5x10^{18}	3x10^{18}
Rayleigh length [μm]	300	75	135
Rep. Rate	single shot	one/3 min	One/7 min
Plasma			
Source	gas jet	gas jet	gas jet
Plasma species	H, He	He	He
Plasma density [cm^{-3}]	5x10^{18} - 2x10^{19}	3x10^{19}	3x10^{19}
Plasma length [mm]	4	1	1
Laser guiding	self-guided	self-guided	Self-guided
P/P_{crit}	6-20	3	6
Wakefield			
Wavelength [μm]	7-8	6	6
Wakefield amplitude	0.5	≈ 1	0.3
Dephasing length [μm]	500	200	200
Acc. Field [GV/m]	160	500	160
Duration [ps]	not measured	5	2
Trapping Mechanism	self-trapped	2 stage acc w/BRS	Self-trapped
Accelerated electrons			
Max. gain [MeV]	96	120±50	70±20
Total # of el. Acc.	10^{10}	10^{8} (> 1 MeV)	10^{10}
Flux at ΔE_{max} [/MeV/sr]	10^{5}	10^{5}	3x10^{4}
S/N at ΔE_{max}	2	2	3
Divergence of acc. el.		less than laser divergence	1.5 degrees
Diagnostics			
Plasma	Stokes/Anti-S TS of Probe; TS of self-gen 2ω	0° FRS; 90° TS	Collective TS
Electrons	EMS	8 ch EMS; scintillating fiber/PMT	1 ch EMS; wire chamber detector

Another topic of discussion was on the maximum electron energies observed in SMLWFA experiments. In the RAL/IC/UCLA experiments, the observed energy of approximately 100 MeV exceeds the simple linear dephasing limit, $W_d = 2\gamma_p^2 \varepsilon mc^2$, where $\varepsilon = \Delta n / n$ is the wake amplitude and γ_p is the relativistic factor associated with the phase velocity of the wake ($\gamma_p = \omega / \omega_p$ in the linear limit). Likewise, in particle simulations performed at UCLA, the resulting maximum energies also exceeded W_d. The explanation proposed by the UCLA group[11] was that local wavebreaking near the front of the laser pulse led to the self-trapping and acceleration of a dense electron bunch. This bunch quickly reached velocities exceeding the wake phase velocity. When this occurs, a secondary wake produced by the trapped bunch itself is generated with a phase velocity greater than that of the initial wake. This secondary wake could then accelerate trailing bunches to energies exceeding W_d.

Esarey et al.[14] pointed out several nonlinear effects that could directly enhance W_d. They argued that in the self-modulated regime, the space charge force that results from electron self-channeling provides a radial force that is focusing for all wake phases. This can double the dephasing (and phase slippage) length resulting in a maximum energy gain of $W_{max} = 2W_d$. Furthermore, relativistic effects and self-channeling can substantially decrease the effective value of ω_p, which results in higher wake phase velocities and higher energy gains.

In summary, it is too early to say definitively what mechanisms are leading to self-trapping in SMLWFA experiments. There is a need for 2-D analytical theories[16] that can be compared with simulation and experiment. On the experimental side, wavebreaking and particle trapping might be most optimally studied by relying on wake excitation with resonantly driven LWFA, which, in principle, would allow better control and characterization of experiments. A parametric study of particle trapping versus λ/λ_p and γ_g, providing spatially and temporally resolved information on the electron distribution in the plasma and the plasma temperature, would allow direct comparison with theory.

LASER WAKEFIELD ACCELERATION

Two groups (Ecole Polytechnique, France[17] and KEK/JAERI, Japan[18]) presented experimental results on acceleration of externally injected electrons in a standard laser wakefield accelerator (LWFA). The experimental parameters are summarized in Table 3. Whereas the French group reported an absolute energy gain of 1.5 MeV, the Japanese group obtained an energy gain of approximately 300 MeV.

The French group reported results of an extensive study of their electron beam optics and spectrometer detection system. After careful measurement of contributions to the signal on the detectors from electron beam scattering in the plasma and wakefields, a detailed understanding was obtained of 3-D effects in electron trapping and acceleration. Good agreement between experiment and theoretical modeling was obtained.

The Japanese result is more than one order of magnitude larger than the expected value from linear LWFA theory. This was explained by the KEK/JAERI group by invoking channeling of the laser pulse over a distance of more than 1 cm. The low peak power and short pulse duration of the injected laser beam precludes relativistic guiding as being the guiding mechanism. Without the creation of a plasma channel, the laser beam would refract due to the presence of the plasma rather than being guided.[19] This anomalous channeling result is therefore not well understood although nonlinear effects in the neutral gas could provide a contribution to self-focusing at low intensity. The effect of electron scattering, as studied in the French experiment, could also contribute to the detected signal in the spectrometer and needs further evaluation.

TABLE 3: Summary of results on laser wakefield acceleration experiments with external electron injection as reported at the AAC98 meeting. (FRS = forward Raman scattering, TS = Thomson scattering, FDI = frequency domain interferometry). The wakefield amplitude is $\Delta n/n$, the dephasing length is λ_p^3/λ^2, and the accelerating field is $\Delta n/n\ (n_p)^{1/2}$.

	KEK/JAERI	Ecole Polytechnique
Laser		
Wavelength [μm]	0.79	1.057
Pulse length [fs]	90	400
Peak power [TW]	1.8	3.5
Intensity [W/cm^2]	$7x10^{17}$	$4x10^{17}$
Rayleigh length [μm]	670	2000
Rep. Rate	10 Hz	one/5 min
Plasma		
Source	Backfilled	Backfilled
Plasma species	He	He
Plasma density [cm^{-3}]	$1.4x10^{18}$	$2.2x10^{16}$
Plasma length [mm]	20	25
Laser guiding	Self-guided	no
P/P_{crit}	0.14	≈ 0
Wakefield		
Wavelength [μm]	29	226
Wakefield amplitude	0.11 (calculated)	0.1 (calculated)
Dephasing length [mm]	40	>>
Acc. Field [GV/m]	15 (calculated)	1.5
Wakefield duration	≈ 1 ps	≈ 1 ps
Injection		
Injector	3 GHz RF linac	VandeGraaff (CW)
Energy [MeV]	17	3
El./bunch	1 nC	300 _A (CW)
Phase occupied	360°	360°
Accelerated electrons		
Max. gain [MeV]	300	1.5
Total # of el. acc.	2x104 (>10 MeV)	200
Flux at ΔE_{max}[/MeV/sr]	250	6
S/N at ΔE_{max}	1	1
Divergence of acc el.	not reported	Not reported
Diagnostics		
Plasma	TS; FDI-wakefield	0° FRS; 90° TS
Electrons	Desmarques screen-spot size Cerenkov light-pulse length, timing 32 ch scintillator and magnet-energy	high acceptance 2-focus spectrometer/17 ch scintillating fiber/PMT at 0.15 MeV binning

Laser Injection. An issue of relevance to the standard LWFA is that of laser injection. The self-modulated LWFA demonstrated acceleration of electrons to high energies (near 100 MeV), however, since the electrons are self-trapped the resulting beam has 100% energy spread. To achieve acceleration in a standard LWFA with small energy spread requires the injection of an ultrashort electron bunch (short compared to the plasma wavelength) at the optimum phase location with respect to the wakefield. This cannot be achieved with present RF photoinjectors, since the duration of the wakefield bucket is typically <300 fs.

Umstadter et al.[20] suggested using a second laser pulse (the injection pulse), propagating transversely to the pulse driving the wake, to inject background plasma electrons into the wakefield. The transverse ponderomotive force of the tightly focused injection pulse would depart sufficient axial momentum to the background electrons such that they become trapped in the wake. Particle simulations of this scheme indicate the production of a 10 fs, 21 MeV electron bunch with a 6% energy spread. High intensities, however, are required in both the drive and injection pulses ($a \approx 2$).

The following schemes have been proposed for laser injection:

(1.) The transverse LILAC scheme originally proposed by Umstader et al.[20] (described above). Hemker et al.[21] also performed PIC simulations of this process, and pointed out the importance of the wake from the high intensity injection pulse.

(2.) The longitudinal LILAC scheme (Dodd et al.[22]). In this case the injection pulse propagates in the same direction as the drive pulse. The injection pulse is tightly focused with a much shorter Rayleigh range such that the wake produced by the injection pulse adds to that of the drive pulse to produce a local region of wavebreaking and hence trapping.

(3.) The colliding pulse scheme (Esarey et al.[23]). This concept uses two injection pulses, one propagating in the same direction and the other opposite to the drive pulse. When the two injection pulses collide some distance behind the drive pulse, they create a ponderomotive beat wave with a slow phase velocity. This slow beat wave can displace the plasma electrons in both phase and momentum such that they become trapped in the fast wake. Trapping can occur at low injection intensities ($a \approx 0.2$) and the colliding pulse geometry offers detailed control over the injection process via the phasing, duration, and amplitude of the injection pulses. Test particle simulations in 3D indicate the production of ultrashort (3 fs) bunches with low energy spread (1%) and emittance (1 mm-mrad).[24]

Experiments on laser injection are being pursued at Michigan, LBNL, and NRL.

LWFA SCALING LAWS

Working group discussions, initiated by presentations given by I. Pogorelsky,[25] commenced on the topic of the scaling of various wakefield quantities as a function of wavelength. In particular, how a 1 micron laser driver compares with a 10 micron laser driver. During his presentations, Dr. Pogorelsky gave examples in which a 10 micron laser driver may have advantages over a 1 micron driver. In this section, simple scaling laws for LWFA quantities are presented under idealized assumptions.

These idealized scaling laws assume the following:

(1.) A standard LWFA that is channel guided.
(2.) The mildly relativistic regime, $a^2 << 1$.
(3.) The acceleration length is limited by electron dephasing.
(4.) The plasma channel is sufficiently broad such that the formula describing wakefield generation in a uniform plasma apply.
(5.) The transverse size of the laser pulse is $2c/\omega_p$ and the transverse size of the electron bunch is c/ω_p.
(6.) The total electrons per bunch is the beam loading limit.

In the following, when equations are presented in practical form (with numerical coefficients), E_z is in V/m, n is in cm^{-3}, λ is in microns, I is in W/cm^2, W_L is in J, L_d is in m, ΔW is in GeV, Lum_s is in cm^{-2}, and a^2 is dimensionless.

In the mildly relativistic limit within a broad channel, the axial electric field of the wake can be written as $E_z = 0.38a^2 E_0$, where $E_0 = mc\omega_p/e = 96n^{1/2}$, i.e.,

$$E_z = 2.7\times10^{-17} I\lambda^2 n^{1/2}$$
$$= 3.4\times10^{-25} W_L \lambda^2 n^2$$

This assumes a linearly polarized laser pulse with Gaussian profiles in the radial and axial directions. This also assumes that the laser pulse length is optimized to maximize the wakefield amplitude, i.e., $L = \lambda_p/\sqrt{2\pi} = 0.4\lambda_p$, where the pulse length L is defined such that $W_L = (1/8\pi)A_L E_L^2 L$ is the pulse energy, $\lambda_p = 2\pi c/\omega_p$ is the plasma wavelength, E_L is the peak laser electric field, $A_L = \pi r_0^2/2$ is the cross-sectional area of the Gaussian pulse, and r_0 is the laser spot size. The laser spot size is assumed to be $r_0 = 2c/\omega_p$ in order to ensure high efficiency of energy transfer between the wake and the accelerated electrons,[26] since electrons loaded near the axis will absorb wake energy out to a radius of approximately c/ω_p. Furthermore,

$$a^2 = 9.4\times10^{-27} W_L \lambda^2 n^{3/2}$$

The acceleration length is assumed to be equal to the electron dephasing length $L_d = \lambda_p^3/\lambda^2$,

$$L_d = 3.7\times10^{25}\lambda^{-2} n^{-3/2}$$

The ideal maximum energy gain is given by $\Delta W = eE_z L_d$,

$$\Delta W = I/n$$
$$= 1.3\times10^{-8} W_L n^{1/2}$$

The number of electrons accelerated per bunch is assumed to be equal to the beam loading limit[26] $N_b = E_z A_b/4\pi e$, where A_b is the effective cross-sectional area of the beam which is assumed to be $A_b = \pi c^2/\omega_p^2$,

$$N_b = 1.7\times10^{-9} W_L \lambda^2 n$$

Another figure of merit is the luminousity $Lum = (k_b f_b/4\pi)N_b^2/\sigma_x\sigma_y$, where k_b is the number of bunches per linac, f_b is the linac rep rate, and $\sigma_{x,y}$ are the transverse rms bunch sizes, which are assumed to be equal to c/ω_p. For scaling purposes, it is convenient to define the "single bunch" luminousity as $Lum_s = N_b^2/\sigma_x\sigma_y$,

$$Lum_s = 9.9 \times 10^{-30} W_L^2 \lambda^4 n^3$$

Next, to determine scaling with wavelength, several examples are given. In all these examples, the laser pulse energy W_L is assumed constant.

(A.) Constant E_z: The axial electric field of the wake is held fixed (in addition to the pulse energy). This implies:
$n \propto \lambda^{-1}$, $L_d \propto \lambda^{-1/2}$, $\Delta W \propto \lambda^{-1/2}$, $N_b \propto \lambda$, $Lum_s \propto \lambda$

(B.) Constant L_d: The acceleration length is held fixed (in addition to the pulse energy). This implies:
$n \propto \lambda^{-4/3}$, $E_z \propto \lambda^{-2/3}$, $\Delta W \propto \lambda^{-2/3}$, $N_b \propto \lambda^{2/3}$, $Lum_s \propto const$

(C.) Constant ΔW: The electron energy gain is held fixed (in addition to the pulse energy). This implies:
$n \propto const$, $E_z \propto \lambda^2$, $L_d \propto \lambda^{-2}$, $N_b \propto \lambda^2$, $Lum_s \propto \lambda^4$

(D.) Constant N_b: The number of electrons per bunch is held fixed (in addition to the pulse energy). This implies:
$n \propto \lambda^{-2}$, $E_z \propto \lambda^{-2}$, $L_d \propto \lambda$, $\Delta W \propto \lambda^{-1}$, $Lum_s \propto \lambda^{-2}$

(E.) Constant Lum_s: The single bunch luminousity is held fixed (in addition to the pulse energy). This implies:
$n \propto \lambda^{-4/3}$, $E_z \propto \lambda^{-2/3}$, $L_d \propto const$, $\Delta W \propto \lambda^{-2/3}$, $N_b \propto \lambda^{2/3}$

In making comparisons between 1 and 10 micron drivers, care must be taken so as not to violate the above assumptions, in particular, $a^2 << 1$. Note that $a^2 \propto W_L \lambda^2 n^{2/3}$. Hence, when making comparisons at constant density and pulse energy, as in Case (C.), the assumption $a^2 << 1$ may be violated at long wavelengths. On the other hand, for short wavelengths, operation at high density is valid. A definitive conclusion regarding an optimum driver wavelength is problematic. For example, at sufficiently low density (such that $a^2 << 1$), a design for a fixed energy gain favors longer wavelengths, as implied by Case (C.). On the other hand, a design for a fixed number of electrons per bunch favors short wavelengths, as implied by Case (D.). Furthermore, a design for a fixed acceleration distance (and fixed luminosity) allows higher energies to be obtained for short wavelengths, however, a higher bunch number is obtained for long wavelengths. The above scaling laws all assume a fixed laser pulse energy. A rigorous study of a LWFA for various wavelength drivers must also include other properties of the driver, such as repetition rate, pulse stability, and average power. Since laser technology is rapidly progressing, a rigorous design study is premature. In terms of physics experiments, invaluable information can be obtained at both 1 and 10 micron.

WORKING GROUP PRESENTATIONS

On the topic of laser guiding in plasmas, the following presentations were given (titles and authors are approximate): Evolution of plasma waves and channels in self-guided laser pulse experiments (S.Y. Chen et al., Michigan); Experiments on two pulse laser channel formation (P. Volfbeyn et al., LBNL); Guiding in preformed plasma channel experiments (S.P. Nikitin et al., Maryland); Mode control in plasma waveguide experiments (H.M. Milchberg et al., Maryland); Generation and diagnosis of a preformed plasma channel in pure helium (E.W. Gaul et al., Texas); Laser guiding experiments at NRL/Hebrew U. (A. Ting et al.); Finite pulse effects on the stability of laser pulses (P. Sprangle et al., NRL); Long-wavelength laser hosing (K.C. Tzeng et al., UCLA); Ionization induced scattering of short laser pulses (T.M. Antonsen et al., Maryland); Electromagnetically-induced guiding of counter-propagating lasers in plasmas (G. Shvets et al., PPPL); Multimode analysis of the hollow plasma channel accelerator (C.B.Schroeder et al., LBNL); Simulations of pulse propagation in capillary discharge plasma channels (R.F. Hubbard et al., NRL); Plasma channels as accelerating structures (B.A. Shadwick, LBNL); Quasi-modes and continuum damping in plasma channels (G. Shvets et al., PPPL).

On the topics of LWFA, SMLWFA, and PBWA, the following presentations were given (titles and authors are approximate): Observation of LWFA of electrons (D. Bernard et al., Ecole Polytechnique); Laser wakefield acceleration of an injected electron beam (H. Dewa et al., JAERI); LWFA experiments at Imperial College (K. Krushelnick et al.); Status of the NRL LWFA experiment (A. Ting et al.); PBWA experiments at UCLA (C. Clayton et al.); High energy electrons from PW laser-solid interactions (T. Cowan et al., LLNL); Cold wavebreaking of 2D wakefields (J.K. Kim et al., Michigan); Suppression of electron blowout and self-focusing by Raman scattering and heating (W.B. Mori et al., UCLA); Optimal laser pulse shaping for LWFA (P. Chen et al., SLAC); LWFA with CO2 drivers (I. Pogorelsky et al., BNL); Experimental characterization of laser wakefields (R. Wagner et al., Michigan); Ultrafast optical diagnostics for LWFA (S.P. Le Blanc et al., Texas); Analysis of the electron spectrum in SMLWA (A. Charman et al., Berkeley); Electron beam characteristics from wavebreaking (W.B. Mori et al., UCLA); Particle dynamics map for LWFA (S. Cheshkov et al., Texas); Generation of ultrashort electron bunches by colliding laser pulses (C.B. Schroeder et al., LBNL).

On the topics of PWFA and plasma lens, the following presentations were given (titles and authors are approximate): PWFA experiments using the Neptune photoinjector (J. Rosenzweig et al., UCLA); Design for a 1 GeV PWFA at SLAC (R. Assmann et al.); Meter long plasma sources for advanced accelerators (P. Muggli et al., USC); Relativistic electron beam focusing by very overdense plasma lenses (R. Govil et al., LBNL); Underdense plasma lens experiment at UCLA (C.E. Clayton et al.); High energy plasma lens experiment at SLAC (P. Chen et al.); Acceleration in the blowout regime of the PWFA (N. Barov et al., ANL); Resonant excitation of plasma wakefields by multiple electron bunches (M. Conde et al., ANL); PWFA in the blowout regime with mobile ions (S. Lee et al., USC); Envelope equation for a magnetically self-focused beam in a plasma (K. Backhaus et al., Berkeley); Test results of the plasma source for underdense plasma lens experiments at UCLA (H. Suk et al.); Simulations of the SLAC E150 plasma lens experiment (S. Masudea et al.).

On the topic of plasma based radiation sources, the following presentations were given (titles and authors are approximate): Cerenkov radiation from electrostatic wakes in magnetized plasmas (P. Muggli et al., USC); Theory of laser-driven undulator radiation (G. Shvets et al.).

CONCLUSION

There has been tremendous progress over the last two years on experiments, analytic theory, simulations (fluid and PIC) for laser driven acceleration in plasmas as evidenced by the numerous publications in Science, Nature, Phys. Rev. Lett., Phys. Rev. E, Phys. Plasmas, etc. During this Workshop, various issues were discussed related to the development of a 100 MeV - 1 GeV compact, high brightness, plasma based laser driven accelerator module. The discussions were centered on a) laser guiding, b) self-modulated laser wakefield acceleration, c) standard laser wakefield acceleration, and d) power sources for wakefields in plasmas.

On power sources (laser systems), the topic of the scaling of various wakefield quantities as a function of wavelength was raised. There have been notable developments at BNL towards the generation of a picosecond, TW CO_2–based laser system. From simple scaling laws presented in this summary paper, the optimum choice of laser driver clearly depends on the quantity desired to be optimized. It therefore seems essential to maintain the complementarity in the area of parameter regimes that can be studied by the long and short wavelength laser drivers, to further enhance the field.

Several groups reported progress on channel guiding of intense laser pulses. The use of gasjets allowed an improved coupling of the laser beam into the plasma channel at high intensities. The intensity of guided pulses is now exceeding 10^{17} W/cm^2. Various methods of producing the plasma channels have been implemented: channels produced through hydrodynamic expansion and channels produced in capillary discharges. Multi-pulse laser schemes (e.g., ignitor-heater) are being studied to efficiently produce channels in gases with a high ionization potential. Discharge based techniques are being examined to produce channels at low cost. Optical diagnostics have been used to diagnose the spatial density profile of the channel, and are being designed and studied to measure the laser excited wakefields in the channel.

Various groups reported new results on self-modulated laser wakefield acceleration. These experiments are serving as a platform for development of experimental diagnostics and know-how, as well as a test-bed for theory/simulation tools. They have provided insight into the basic physics of wake excitation, laser beam propagation (self-guiding) and electron production. The measurements also indicate a further need to study the physics of wavebreaking and particle dephasing. Parametric measurements of maximum energy gain versus plasma and laser parameters will enable the evaluation of the maximum sustainable wakefield amplitude prior to electron self-trapping (the equivalent of dark current emission in RF structures) and the dephasing length. This in turn determines the length of the structure that needs to be produced for guiding the laser pulses and the energy gain per stage that can be expected.

Two groups reported results on standard laser wakefield acceleration of externally injected unbunched electrons. The experiments demonstrate the need for careful characterization of the experimental apparatus. The beam dynamics seemed to be well understood and modeled when including all 3-D effects. More experiments are needed to address some of the discrepancies that exist between some of the experimental results and theory.

Novel ideas on laser triggered injection of electrons were also discussed: the so-called LILAC and Colliding Pulse schemes. These schemes show great promise for producing high brightness ultrashort electron bunches. Results of proof-of-principle experiments are expected before the next Workshop.

Beam-driven plasma accelerators/devices are being pursued by several groups. Results were shown of a study of plasma lens focusing in the very overdense or return current cancellation regime where the plasma skin depth is comparable to the electron beam size.[27] Upcoming experiments on plasma lens focusing (SLAC E-150) and plasma wakefield acceleration (SLAC E-157) at SLAC with the 30 GeV electron beam were discussed. These experiments are expected to produce results in the summer of 1999.

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