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Summary Report Of Working Group 4: Electron Beam Driven Concepts

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Abstract. Although the title "Electron Beam Driven Concepts" can in principle cover a broad range of advanced accelerator schemes, in the context of this workshop and the various other working groups, working group 4 discussions centered primarily around the many active investigations of the electron or positron beam driven plasma wakefield accelerator. The past year has seen advances along three main fronts: experiment, simulation and theory. This paper will give a brief summary of the various talks presented to the group, summarize group discussions and conclude with a few comments on future directions.

INTRODUCTION

A particle beam driven plasma wakefield accelerator (PWFA) has two primary components – the beam and the plasma. A high-current drive beam displaces plasma electrons due to space charge forces. The displaced plasma electrons respond to a restoring force, provided by the space charge of the plasma ions, at the electron plasma frequency. The motion of the plasma electrons results in an electro-static wave or wakefield in the plasma propagating in phase with the drive beam. The transverse and longitudinal components of this wake can focus and accelerate particles with fields several orders of magnitude larger than conventional focusing and accelerating structures.

Experimental investigation is required to verify our understanding of the physics of the PWFA. Analytic models provide intuitive scalings which can be used to rate the relative merits of a given experiment or design. In some cases the fields generated in the beam-plasma interaction can be highly non-linear and thus not tractable with analytic techniques, and in this case computer simulations are required.

SUMMARY OF TALKS

The contributed talks, grouped according to experiment, simulation and theory, are listed in Table 1.

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TABLE 1. Summary of Presented Talks

Experiment	**Author**	**Title**
	Bruce Carlsten	Plasma Wakefield Experiment at Los Alamos
	Patrick Muggli	Energy Gain and Energy Loss in E-162
	Chris Clayton	E162: Positron Dynamics in a Long Plasma
	Brent Blue	Energy Loss of the Positron Drive Beam in the PWFA
Simulation	**Author**	**Title**
	Matt Thompson	Plasma Density Transition Trapping as a Possible High-Brightness Electron Beam Source
	Glenn Joyce	Simulation of PWFA in 3-D
	Tom Katsouleas	3-D Simulation of Plasma Wakefield Acceleration with Real (non-idealized) Plasmas and Beams
	Chengkun Huang	Modeling E-162 PWFA Experiment
	Wei Lu	2D Cylindrical PIC Simulation of Propose Experiment E-164
	David Bruhwiler	Ionization Effects in PWFA Simulations
Theory	**Author**	**Title**
	Tom Katsouleas	Analytic Estimate of Non-linear Positron Wakefields
	Jamie Rosenzweig	Energy Loss of Very High Charge Beams in Plasma
General	**Author**	**Title**
	Ken Marsh	Plasma Sources and Density Diagnostics

Experiments

The drive beam of a PWFA can be either a single bunch of particles or macro-pulse composed of several individual, discretely spaced in time, micro-bunches. The later case was studied by a Los Alamos group at the Short Pulse Accelerator (SPA) facility. The results of the Plasma Wakefield Experiment were presented by Carlsten. A train of typically 5 bunches, individually compressed via a magnetic chicane to a length of nominally 1ps, with 2 nC per bunch and 8 MeV in energy are produced via a photocathode rf gun. The bunch train is injected into a mach 5 xenon gas jet and then analyzed at an energy spectrometer. The secondary electrons produced via collisional ionization fully ionize the xenon gas by the time the third micro-bunch arrives. The measured energy loss of the third, fourth and fifth bunches is consistent with an energy loss gradient of 74 MeV/m. The narrow energy spread on the de-accelerated bunches is also consistent with PARMELA simulations indicating that the strong second order dispersion in the chicane leads to wedge shaped longitudinal distribution that has an adiabatic rising edge and a sharp drop off on the tailing edge.

The E-157/E-162 experiments conducted by a SLAC/UCLA/USC collaboration use a single bunch to drive the PWFA. The plasma acts as a head to tail energy transformer – particles in the head of the bunch drive the plasma wakefield (losing energy) and particles in the tail of the bunch sample the wakefield (gaining energy). Muggli gave a detailed discussion of the many techniques (and pitfalls) for measuring energy loss and gain in the E-162 experiment. Previous experience with the E-157 experiment indicated the strong transverse forces in the PWFA could deflect particles in the tail making initial estimates of energy gain and loss ambiguous. Experiment E-162 built an imaging magnetic energy spectrometer to isolate the changes to the beam energy spectrum. Preliminary analysis of the time integrated measurements indicates a peak energy loss in the center of the bunch of 170 MeV (120 MeV/m) at the highest plasma density (2.6×10^{14} e^{-}/cm^{3}) and a corresponding change in the beam energy centroid of 70 MeV or 50 MeV/m.. As the expected energy changes induced by the PWFA are smaller than the initial correlated energy spectrum, the most accurate measurements require an energy diagnostic with time discrimination. Preliminary analysis of measurements with a streak camera indicate de-accelerating and accelerating gradients on the order of 110 MeV/m. Systematics related to the streak camera measurement could result in both an overestimate of the energy loss and an underestimate of the energy gain.

Clayton presented a detailed discussion of the dynamics of a PWFA driven by a positron beam as opposed to an electron beam, with experimental data from a different E-162 run. Given the wide range of data presented at the previous AAC conference as well as in several of the invited talks, it was accepted that the transverse effects on electron beam drivers are well understood. For a positron drive beam the plasma electrons are sucked into the beam rather than being blown out as in the electron case. With an electron beam driver, once all the plasma electrons are blown out, the transverse force is dictated by the remaining ion column, which results in focusing forces that are constant along the bunch and linearly proportional to radius. For a positron beam driver, there is no blow-out regime and the focusing has large geometric aberrations – the forces vary along the entire bunch and are not linearly proportional to radius. Further, since a positron drive beam can draw in plasma electrons from up to one skin depth away, the focusing forces can be orders of magnitude larger than the electron beam case where the force is limited by the remaining ion column density. Despite the complicated nature of the forces at work on a positron drive beam, at low plasma densities ($< 1\times10^{12}$ e^{-}/cm^{3}) the net effect is an overall focus of the time integrated transverse beam profile. Experimental measurements with a streak camera showed a clear evolution of the focusing forces along the bunch in the region of the first pinch ($\sim1\times10^{12}$ e^{-}/cm^{3}). Continuous head to tail focusing as well as very strong focusing in the first few ps of the beam contrast sharply with the data for electron beam drivers. Finally, a simple model was presented that proves useful for predictions at low densities, but Particle In Cell (PIC) simulations are required for higher densities.

Blue presented preliminary estimates of the energy loss of a positron drive beam in a PWFA obtained from E-162. Although the dynamic nature of the positron beam-plasma interaction may make it unclear as to whether there will be significant energy loss or gain, PIC simulations indicate that indeed, particles in a positron drive beam will lose energy and gain energy in a manner similar to the case for electron beam drivers. The phase mixing resulting from the different arrival times of the plasma electrons will result in wakes more than twice as small as those created by an electron beam of similar conditions, unless the wake is optimized via a hollow channel. Preliminary measurements indicate a de-accelerating gradient on the order of 50 MeV/m, in agreement with predictions from the PIC code OSIRIS. Analysis of the energy loss and gain is ongoing.

Simulations

A variation on the PWFA scheme that uses a sharp density transition in the plasma to trap and accelerate background electrons is being pursued by several groups as a possible source of high-brightness electron bunches. Thompson from UCLA presented detailed MAGIC simulations of a planned proof of principle transition trapping experiment. Simulations indicate that a density transition from $2\text{x}10^{13}$ e^-/cm^3 to $5\text{x}10^{12}$ e^-/cm^3 can in principle lead to a trapped bunch of particles that is well defined, has substantial charge and isolated in energy from the drive beam – in this case 120 pC of charge in a 1 ps long bunch with an normalized emittance of 15 mm-mrad, a mean energy of 1.2 MeV and an 11% energy spread. The proof of principle experiment, using an argon pulse discharge plasma source and a porous screen to create the density transition is planned for the A0 facility at Fermilab within the next year.

The following four presentations were given in a joint session with the Computational Accelerator Physics working group. While code development for modeling laser- and particle-driven beam plasma interactions continues to be an area of active research, simulation codes from a different era, written for a different purpose, have found renewed relevance and application to today’s problems. Joyce presented simulations of the E-157 experiment and plasma afterburner parameters (as discussed during this working group during AAC2001) using the code Elba. Elba is a 3-D Particle in Cell (PIC) code for relativistic beam transport that models electromagnetic, relativistic particles. Some features peculiar to the Elba code are that fields are solved in cylindrical coordinates but the particles are pushed in Cartesian coordinates. The code also contains Monte-Carlo beam induced ionization. Elba simulations presented indicate acceleration in an electron beam driven PWFA is only slightly degraded by anisotropic emittance and small beam tilts, and although these conditions can lead to moderate growth of the electron-hose instability, the hose growth is not large enough to effect acceleration. Additional simulations predict that afterburner like parameters might require methods to control hose growth, such as plasma channels.

OSIRIS is a code from a UCLA/USC collaboration that has been used extensively to model an ongoing series of experiments being conducted at the Stanford Linear Accelerator Center (SLAC) – E-157/E-162/E-164. OSIRIS can be run in 2- or 3-D, is a parallelized, relativistic, electromagnetic PIC code that includes plasma return currents. Katsouleas discussed simulation results for three different cases relating to energy gain measurements in E-162: ideal beam and plasma, non-ideal beam and plasma, and non-ideal beam and plasma post-processed to simulate the effects of experimental diagnostics. For the non-ideal case a 20% density gradient was added to the plasma both longitudinally and transversely, and the beam was sent into the plasma with a 40% transverse tilt ($0.4\sigma_r$ per σ_z). The simulations indicated that the PWFA was remarkably robust against perturbations caused by non-ideal conditions, and for the above case the peak-accelerating gradient was only reduced by 25%. A far greater effect on the measured parameters comes from including diagnostic effects such a streak camera slits. A preliminary comparison of the non-ideal beam and plasma particles with and without diagnostic effects indicated that changes of up to the order of 2 can be expected.

In addition to OSIRIS, the UCLA/USC group has developed another code QuickPIC designed to allow for fast comparison of experiments and simulations. Where 3-D OSIRIS runs can take weeks or even a month to run on many processors, QuickPIC runs can be done on a stand alone desktop computer in less than a day. Huang summarized the status of the simulations of experiment E-162, concentrating on parametric studies using QuickPIC. Specifically, the first E-162 run looked at the transverse effects in a positron driven PWFA and these results are being actively compared to QuickPIC. The primary thread of the discussion related to understanding what role the properties of the incoming positron beam can play in determining the plasma density required to focus the beam at a diagnostic downstream of the plasma. Changes to the incoming positron beam size, divergence and tilt all can lead to a higher plasma density being required to produce a focus downstream, but even gross changes such as 1:1 beam tilts (one σ_r per σ_z) will only result in changes in the required plasma density of factors of 2-3. In analogy with the results presented earlier by Katsouleas, it was also discussed that including diagnostic related effects in the post-processing of simulation results can affect the quoted performance and should be done when at all possible. Finally, analysis of the plasma electron density in the simulation shows that the on-axis density of plasma electrons in the case of a positron beam driver can be 100 times the background plasma density, and that the peak density is on axis near the head of the drive bunch, but moves off axis towards the tail of the beam.

Lu presented a set of OSIRIS simulations that studied the dependence of the accelerating gradient on the plasma density for a fixed drive bunch length – in this case the 100 µm long electron bunch planned for experiment E-164. The simulations show the wakefield structure and amplitude depends on the plasma density, but this dependence is in itself dependent on where the field is measured. The on axis peak field, or spike, has a relatively broad dependence, changing by less than 40% when the plasma density is varied by a factor of 5. The peak of the de-acceleration showed a similar dependence. If the accelerating field is measured slightly closer to the core of the bunch at a feature defined as the “smooth peak”, the accelerating gradient changed by less than 15% for a factor of 5 change in plasma density. If the field is sampled at $3\sigma_z$ for each density, the accelerating gradient changes by more than 100% for the same factor of 5 change in density. The peak accelerating gradient expected in experiment E-164 was typically greater than 8 GeVm. For a positron beam with similar parameters, the peak accelerating gradient was simulated to be 1.2GeV/m with an unusual double-hump structure in the wakefiled at large plasma density.

A collaboration between Tech-X Corporation and the University of Colorado at Boulder and LBNL have modified the simulation code OOPIC to include ionization effects from both electron impact ionization and field induced tunneling ionization. Bruhwiler summarized how these effects might become important, or even dominant, in future PWFA designs involving high beam and plasma densities – like E-164 and the afterburner. Electron-impact ionization can result in secondary electrons being trapped in the plasma wake and accelerated to high energies. These trapped electrons could load down the plasma wake and such effects must be considered in afterburner type designs. Field induced tunneling ionization is very important for cases of high beam density, and correspondingly high electric fields from either the bunch itself or the plasma wake. If the wrong gas were chosen for an experiment, tunneling ionization could result in a time dependent plasma density evolving on the time scale of the drive beam, irrespective of other engineered techniques of controlling the plasma density. There were a total of three suggestions for dealing with tunnel ionization: choose a material with a threshold electric field higher than the peak fields generated by the beam fields and the plasma wakefields, fully ionize the plasma before the beam arrives since typically the threshold electric field for secondary ionization is much larger, or use tunnel ionization to create the plasma from a tube of neutral gas. Additional calculations of the fields required to ionize 0.1%, 1% and 10% of certain neutral gases within one plasma period were made in the working group and are summarized in Table 2.

TABLE 2. Electric field for which (10%) 1% (0.1%) of the neutral gas is ionized in one plasma period due to tunnel ionization.

	Afterburner **$n_0 = 1.4 \times 10^{16}$**	**E-164** **$n_0 = 5.6 \times 10^{15}$**	**E-157/E-162** **$n_0 = 1.5 \times 10^{14}$**
H	(21) 19 GeV/m (17) (10%) 1% (0.1%)	18 GeV/m	17 GeV/m (15) 1% (0.1%)
He	(57) 49 GeV/m (43)	48 GeV/m	43 GeV/m (39)
He^+	(160) 140 GeV/m (124)	140 GeV/m	125 GeV/m (113)
Li	(4.4) 3.9 GeV/m (3.5)	3.8 GeV/m	3.5 GeV/m (3.2)
Li^+	(273) 240 GeV/m (213)	230 GeV/m	210 GeV/m (192)

Theory

As mentioned earlier, individual simulations using relatively fast codes such as QuickPIC can take on the order of a day. This relatively long timescale makes it a tedious and time consuming process to numerically estimate the plasma response to changes in the initial conditions. While there exist theories and formulas to describe electron beam driven PWFA (within certain limits), no such formulas exist for the case of positron beam driven PWFA. Katsouleas presented initial attempts to make an analytic estimate of non-linear positron wakefields. The goal is to make an analytic expression for the transverse wakefield and then use the Panofsky-Wenzel Theorem to calculate the longitudinal wakefield. Although a positron beam can suck in plasma electrons from a distance of up to one skin-depth, for these electrons to contribute substantially to the portion of the wakefield that effects the drive bunch, they will have to travel to the axis on a timescale equivalent to the longitudinal bunch length. The time for individual plasma electrons to arrive on axis was estimated using a ring model developed by S. Lee. After estimating the number of electrons that arrive on axis during the passage of the drive beam, this new value for plasma electron density is used to estimate a transverse wakefield. Comparison with QuickPIC for one set of parameters showed the estimated wake to be a factor of three smaller than the simulation predicts. To determine if this factor of three was a constant/offset in the model or a factor that was different for every set of conditions, A. Ghalam made a heroic effort to try and compile a set of QuickPIC runs that could be checked against the new analytic model, but by the end of the workshop the calculations were still ongoing, so stay tuned.

A recent work by Lee *et al* compared the analytic estimates of longitudinal wakefield amplitude to 2- and 3-D OSIRIS predictions and found the surprising result that the linear scaling of the longitudinal wakefield $W_z \sim Q/\sigma_z^2$, where Q is the bunch charge and σ_z is the longitudinal bunch length, appeared to hold into very non-linear regimes where the equations were no longer valid. Rosenzweig presented a detailed analytic treatment of energy loss of very high charge beams in plasma. To set the stage for the discussion a dimensionless quantity $\tilde{Q}$ was introduced and defined as the ratio of the number of beam electrons to the number of plasma electron per cubic skin depth. $\tilde{Q}$ can be considered a measure of the non-linearity of the plasma response: $\tilde{Q} << 1$ is the linear regime and $\tilde{Q} > 1$ is the very non-linear regime. The amplitude of the field spike was also ruled out as a measure of the accelerating gradient for many reasons: the amplitude is sensitive to the mesh size used for the simulation, it corresponds to the longitudinal location where the good focal qualities of the blow-out regime fall apart, there is little stored energy in the spike and it will be eliminated if the wake is loaded down by an appreciable amount of charge. Energy loss calculations are not sensitive to these issues, can be easier to measure, so the theoretical estimates for energy loss were reviewed and re-derived with a novel approach. Theoretical estimates were compared to simulations with the codes MAGIC and OOPIC. The initial conclusion is that there is little field growth for values of $\tilde{Q} > 20$. Recent experiments E-157/E-162 and the FNAL/UCLA experiment have operated in a regime with $\tilde{Q} = 1.5\text{-}3.5$, but future experiments may reach into a regime of $\tilde{Q} \sim 100$. It was also noted that the peak field is still near the theoretical estimate for the upcoming E-164 experiment, but that a similar experiment with 10 µm long bunches should lose a factor of three or more when compared to the linear scaling and could provide an important first data point in the highly non-linear regime of $\tilde{Q} >> 1$.

General

As the field of PWFA matures, the trend in experiment is towards shorter bunches, correspondingly higher gradients, but necessitating higher plasma densities (shorter plasma wavelengths) to respond to these short bunches. Making and diagnosing plasma sources with density length products > 10^{17} e^{-}/cm^{2} is an area of important and active research, drawing on the expertise of the larger, non-accelerator research, plasma community. Marsh led a discussion of the limitations of the plasma sources used in current SLAC and FNAL based experiments. Pushing current sources much beyond 10^{17} e^{-}/cm^{2} will be problematic if not impossible. Alternate sources such as capillary discharges or field induced tunnel ionization plasmas deserve investigation. Many interesting and well understood techniques exist for measuring the neutral density (Hook method, white light absorption, thermo-couple measurements in the heat pipe oven case) and the plasma density (UV absorption, time gated hook method, time gated spectroscopy, and interferometry), but the promise of applying these techniques, especially time resolved on the ns time scale, has yet to be realized for extended plasma columns. This is an active area of research and development that is crucial for the next generation of PWFA experiments.

Plenary Session Talks

In addition to the talks given in this working group, there were also several plenary session PWFA talks which motivated some of the working group discussions. These included presentations on the SLAC and FNAL experiments, as well as a presentation by Mori which included electron-hose simulation results. These talks are summarized in the table below.

TABLE 3. Summary of Plenary Session Talks on PWFA

Author	Title
Mark Hogan	Acceleration and Focusing of Electrons and Positrons Using a 30 GeV Drive Beam
Caolionn O'Connell	Dynamic Focusing of the SLAC Electron Beam by a Plasma Column
Nikolai Barov	Plasma Wakefield Acceleration Experiments
Warren Mori	Advances in Computer Simulations of Plasma-Based Accelerators

PRESENT, NEAR TERM AND FUTURE DIRECTIONS

The field of beam driven plasma wakefield accelerators has much to be proud of. Experiments to date have led the working group to conclude that in the case of electron beam driven PWFA the focusing, energy gain and energy loss mechanisms are understood and have been born out by proof of principle experiments at ANL, FNAL, LANL and SLAC. More recently, aspects of positron focusing have been explored in experiments at SLAC (E-150, E-162), and again the conclusion of the working group is that the transverse dynamics for a positron beam driven PWFA are understood. Energy gain and loss for a positron beam has been explored by experiment E-162, but the data is in the first stages of analysis and not conclusive – although the "gut feeling" of the group was that the mechanisms will exist as expected. The near term horizon will be an exciting time for the PWFA. Experiment E-164 hopes to measure accelerating gradients > 1 GeV/m for an electron beam driver and add an extra data point to the linear scaling/$\tilde{Q}$ discussion.

Although there is much to be proud of, there is much still to be done. Demonstration of plasma focusing of electron and positron beams to below 1 µm in size must be done if plasmas hope to compete in the final focus of a future collider. Plasma source development efforts must produce plasmas with density length products reaching or even exceeding 10^{19} e^-/cm^2. Positron acceleration at gradients > 1 GeV/m must be demonstrated. Additional effects of large energy spread and polarization preservation must eventually be dealt with. The most urgent experiment that needs to be done however is related to beam loading. For the PWFA to move beyond the "gee-whiz" stage and into the realm of a practical accelerating module, it must show that a significant bunch of electrons (and positrons) can be accelerated with a large accelerating gradient and a narrow energy spread. Whether this is accomplished via a drive beam followed by a witness beam, or a single bunch shaped with substantial charge in the tail to load down the plasma wake, this should be considered one of the single most important goals of the PWFA community over the next couple years.

In addition to the plasma afterburner concept, where a traditional linac is augmented by a single plasma module acting as an energy booster, an additional approach to a plasma-based collider is to use a series of plasma stages driven by a common linac. Although staging has been demonstrated in the case of the IFEL, it remains a worthwhile goal to carry out a corresponding plasma-based experiment. A more realistic staged collider design would benefit from further work in the area of beam hosing, since it can cause beam steering and misalignments in subsequent stages. Such a design would also benefit from further advances in ultra-stable plasma production, and high average current linac technology.

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