Laser-Wakefield Electron Accelerators

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Abstract

In the late 1970's, Tajima and Dawson proposed a method of acceleration electron using the large electric field gradients that plasmas are capable of sustaining. They showed that when a large amplitude laser pulse is sent through an plasma, it is capable of creating a co-propogating longitudinal plasma wave that is capable of having an electric field gradient of multiple Gev/cm– orders of magnitude larger than that of conventional particle accelerators..

In this work, we review the state-of-the-art experimental progress being made in creating a fully functioning electron accelerator based on laser plasma acceleration (LPA) technology. We discuss how the energy in a transverse, oscillitory electric field of a high intensity pulsed laser can be converted into an electric field gradient that can be used to accelerate electrons, and we will briefly review the physics of its propogation.

Contents

1 Introduction

Laser plasma wakefield accelerators (LPWA) will be a revolutionary technology for scientists. The acceleration gradients that plasmas are capable of sustaining are many orders of magnitude larger than conventional particle accelerators. This allows technologies based on plasmas, such as LPWA, to be orders of magnitude smaller. Much like the introduction of the personal computer in the era of massive supercomputers, LPWA

[1] Multiple GeV's

will put the technology of electron acceleration to large[1] energies in the hands of many. The ability to accelerate particles to high energies is a cornerstone in many areas of science. Although the recent discovery of the Higgs boson[] at the LHC demonstrated the value of ion-accelerators capable of TeV energies, a more direct comparison to the regimes acheivable to LPWA technology would be to linacs– such as Stanford Linear Accelerator Center (SLAC), which can accelerate electrons to hundreds of GeVs[].

Although historically important to the development of particle physics[1], the most broad application of linacs such as SLAC is the use of accelerated electrons for an free-electron x-ray laser; the development of which has allowed investigation of structures from biology to solid state physics, as well as pioneering techniques in medical imaging.[]

[2] The famous cancellation of the Superconducting Super Collider in Texas due to budget problems in one dramatic example

But, much like the supercomputers of the 80's, the future of the field is limited by the size and expense of these facilities[2]. Laser plasma wakefield accelerators offer an option that is compact, and inexpensive by comparison. ALthough LPWA will never supplant linac's[2] they offer a complimentary approach at a fraction of the cost and real-estate. The prospect of a table-top free-electron laser has sparked intense interest in the field of laser plasma acceleration, and there is a dynamic field that is constantly improving the quality of the accelerated electron beam.

The quest to produce high-energy electrons has four main goals: getting high-energy electrons; having a narrow energy distribution; producing collumated beams; and having a large number of electrons produced.

[1] The experimental discoveries of the quark, and the tau lepton were made at SLAC

[2] This is because the beam produced by LPWA is not continuous; the nature of LPWA schemes means that the electrons beam produced will be an intense bunch, rather than a continuous beam like SLAC.

Need to add paragraph about why these are important

1.1 History

In the 1950's, Tajima and Dawson proposed shooting a high-intensity laser at a plasma. The laser would generate a wakefield very similiar to a boat moving through water. What Tajima and Dawson found was that under the right conditions, this wakefield could be used to accelerate electrons in a process analogous to surfing. Unfortunately, the lasers of the day were unable to get to the high-intensities required. N Plasma accelerator technology then moved in lockstep with improvements in lasers. Unfortunately, the electron bunches produced had large thermal distributions.

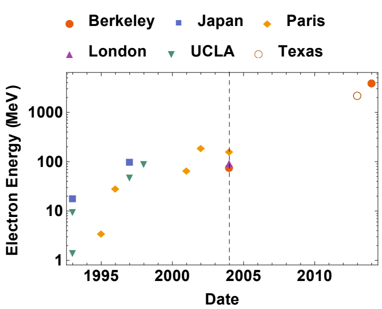

Figure 1: The progress of laser plasma wakefield acceleration by the total energy of the electrons. The dashed line shows the advent of quasi-monoenergetic electrons, until that point the electron bunches had large thermal tails. *This data was gathered from the web of science abstract list*

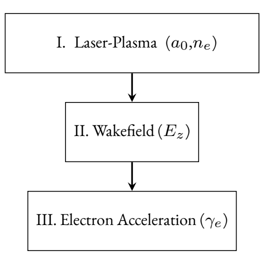

Figure 2: The LWFA process: first the intense laser (charaterized by the normalized field strength ($a_0 = eA/m_e c^2$) interacts with the plasma (characterized by the plasma density (n_e) producing a longitudinal density modulation; this gives rise to a longitudinal electric field (E_z); which will in turn accelerate the electrons to a relativistic energy γ_e.

In 2002, Pushkin predicted the bubble regime, which would solve many of the problems historyically faced by LPWA schemes.[] In 2004, three papers published simultaneously in Nature[], demonstrated quasi-monoenergetic electron bunches in the bubble regime. Their results were soon extended to obtain 1 GeV electron bunches.

Need to expand this more. Probably should read these papers

In 2013, a group at UT Austin produced a collumated, quasi-monoenergetic electron beam at 2.3 GeV[8], and in 2014 the Esarey group at UC Berkeley produced a 4 GeV[] beam.

2 The Physics of Laser-Plasma-Acceleration

The LPWA process can be divided into three main topics, as shown in Figure 2. This section will review each in turn: first the laser-plasma interaction will be discussed; then, the wakefield properties will be developed; and finally, the actual process of electron acceleration will be discussed.

Due to the complicated nature of the theory of LPWA in 3D relativistic fields, we will mainly discuss these topics in the linear regime, and show the numerical results of their extension into the 3D relativistic regime.

2.1 Laser-Plasma Interaction

As mentioned in Section ??, it was only the advent of CPA that allowed lasers to be amplified to the require intensities to see many of the effects of LPWA. In the non-relativistic regime, the interaction of these laser pulses with the plasma will be through the Lorentz force[?]. As the mass of the ions in the plasma is many orders of magnitude larger than the electrons, it is valid to approximate the behaviour of the plasma as a fluid of mobile electrons against a background of ions.

To first order, the movement of this fluid will be given by the electric force: $F = eE$, which will accelerate the electrons in the polarization plane. This is called the 'quiver' momentum[3]. This quiver momentum will not produce a net acceleration on the electrons.

[3] So named because the electron will undergo rapid oscillations while its time averaged acceleration will be zero, so it will appear to be quivering

If the Lorentz force law is expanded out to second order, a term will appear that is proportional to the intensity gradient, known as the ponderomotive force. This can be thought of as the radiation pressure of the laser pulse, and will act to push electrons away from the local space of the laser packet. It is this ponderomotive force that will be directly used to drive the density waves that all LPWA schemes use. This is analogous to the physical situation of shooting a cannonball underwater– it will excite a density wave that co-propogates with it.

Although tempting to imagine directly accelerating electrons using the ponderomotive force, it is worth noting that it scales inversely proporitional to gamma: at relativistic speeds it will be small. This is why the density wave is so important.

It is worth noting that modern LWFA schemes operate in the bubble regime, where the laser pulse is so intense that it completely expels the electrons from its local space. This regime are too complicated to solve analytically. This means that the majority of theoretical work currently being done is by using numerical methods. However, an intuition for the basic phenomena of LWFA can be developed by looking at simpler systems.

2.2 Wakefield Dynamics

As the electron fluid is perturbed by the ponderomotive force, there will be a large space-charge restoring force that acts upon them. In the simplest, one-dimensional case, this will give rise to a driven-oscillator type longitudinal density modulation that oscillates at the resonant frequency of the plasma (ω_p). This is analogous to the ringing sound produced by striking a metal block.

More formally, the equation that will govern the LPWA dynamics is:

$$\frac{\partial \mathrm{p}}{\partial t} + (\mathrm{v} \cdot \boldsymbol{\nabla})\mathrm{p} = \underbrace{\frac{e}{c}\frac{\partial A}{\partial t}}_{\text{fast time scales}} - \underbrace{m_e c^2 \boldsymbol{\nabla}^2 \bar{a_0}}_{\text{slow time scales}}, \tag{1}$$

In the regime where the normalized field strength is small ($a_0 \ll 1$) this can be linearalized, and are tractable to analytic techniques.

More generally, for the relativistic case where ($a_0/g1$), there will non-linear modifications. First, the ponderomotive force generalizes to $a_0 \rightarrow \bar{\gamma} = \left(1 + \frac{p^2}{m^2c^2} + \frac{a_0^2}{2}\right)^{\frac{1}{2}}$ Physically, these manifest as steepening phenomena, where the wave becomes steeper– very similarily to the process of wavebreaking of ocean waves.

The resonant frequency of the plasma will give an experimental constraint. As with all driven-oscillator type systems, to drive the oscillator at resonance, you need to force it at the natural frequency of the system. We want high-intensity waves, as their amplitude will ultimately determine the accelerating field E_z. In order to excite resonance then $\tau_{\text{laser}}\omega_p \approx \pi$. The resonance condition is further illustrated in Figure ??.

The numerical solutions to Eq. (1) are in Figure 3.

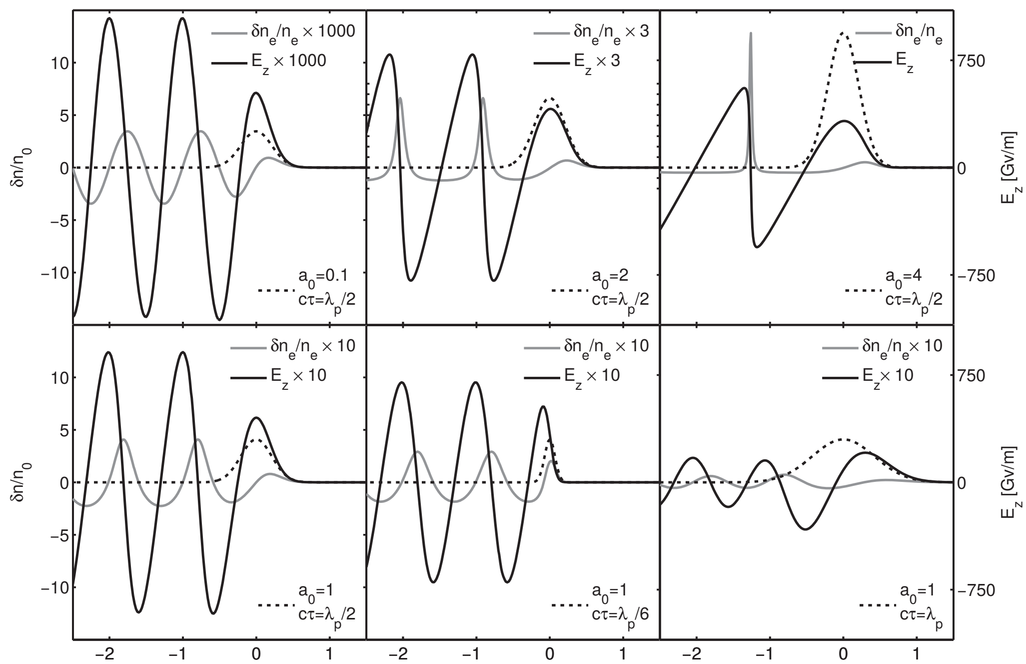

Figure 3: Showing plasmons generated with varying strengths of the peak amplitude of the laser pulse.[3] The laser pulse is the dashed line, the density perturbation is the grey line, and the longitudinal electric field E_z is the black curve. Different scenarios are shown: from left to right, the normalized field strength variable ($a_0 = e\mathrm{E}/m_e c^2$) is varied, and from top to bottom, the duration of the laser pulse is changed. *Figure courtesy of Guillaume Genoud, Lund Univeristy*

In summary, we have discussed the mechanism of acceleration (longitudinal electric field produced by the density wave), and we have discussed how we create this mechanism within the plasma (high-intensity laser pushes electrons with the ponderomotive force.) Now, we have to discuss how the electrons are actually accelerated. Much like water waves, plasmons cannot accelerate objects unless two conditions are met[5]: the object needs to meet some phase-matching requirements, and the plasmon needs to be non-linear.

2.3 Electron Trapping, Injection, and Acceleration

In order to be accelerated by the co-propogating electric field created by the plasmon, the electrons need to be travelling at some minimum speed. In the plasmon frame of reference, what an electron will see is, roughly, an ion-sphere. If we confine the electrons motion to 1D, then it can exhibit periodic motion about the centre of this sphere.

However, for this to work, the electron needs to have some minimum energy. Imagining a simple harmonic potential that is moving at some brisk speed $v_b > \sqrt{2V_{\text{heightofwell}}/m}$, we can see that an electron at rest will not be trapped: transforming to the potential's frame of reference, the electron will be moving at a large speed and will have too much energy to be trapped. This is quite similar to the case we are describing: however, we now have to consider that the electron's motion is going to be relativistic. The phase-space trajectories of various electrons are shown in Figure 4.

However, much like how the individual water particles do not gain a net acceleration in ocean waves, in the linear regime the electrons will not gain a net acceleration. For a very specific value of the accelerating electric field the background electrons that make up the density flucuations will actually meet the requirements to be trapped in this way. This gives rise to the phenomena of wavebreaking. In contrast to the perhaps more familiar example of water-wave's breaking, plasma wavebreaking is not a dispersion related phenomena. It is a non-linear effect, where the accelerating field created by the density flucuations of electrons in the plasma is strong enough to directly effect the density flucuations themselves.

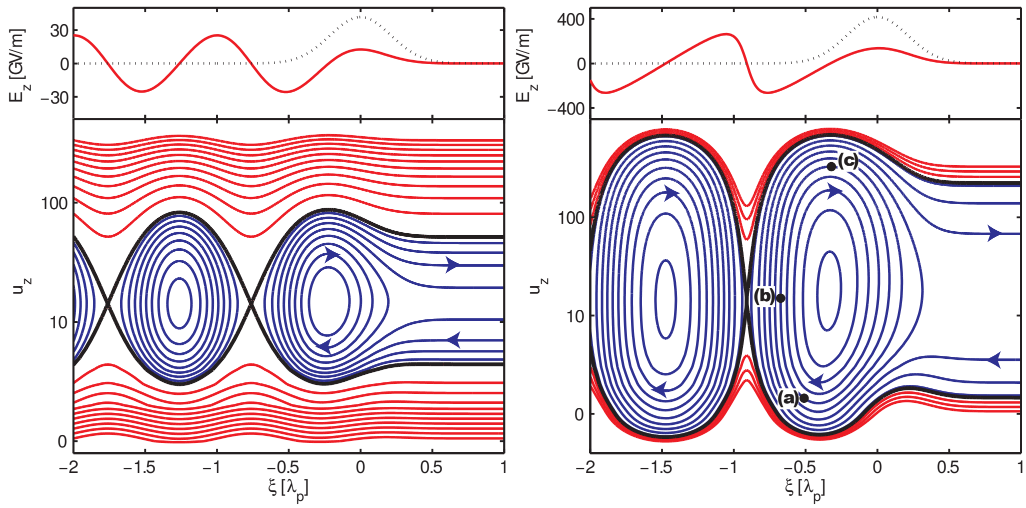

Figure 4: The various trajectories of electrons at different initial momentum ($u_z = p/m_ec^2$) in the reference frame of the laser pulse, which is moving at an relativisitc energy $\gamma = 13$ in the lab frame. For specific initial electron energies the electrons will be trapped and accelerated by the wakefield.

Wavebreaking is a useful phenomena for LWFA as it creates a larger field that can give more energy to the electrons. The phenomelogical differences between a linear plasmon and a wavebroken plasmon are show in Figure 3

2.4 Electron Acceleration

The plasma bubble will set up a very high GeV cm^{-1} acceleration field, however what will limit the total energy gain is how far the electron can be accelerated for. There are three main lengths involved with accelerating the electrons.

The first, $L_{\text{Dephasing}}$ is analogous to what happens when a surfer outruns the wave they are on; no longer being accelerated, they slow down as their energy is dissapated to the waves. Similarly, electrons can outrun the plasma bubble.

The second, $L_{\text{PulseDepletion}}$, occurs because the interaction with of the laser-plasma will dissipate the energy of the initial laser pulse. The energy in the initial laser will be transfered to the plasma wake, where it will ultimately be disappaited as heat.

The third length, $L_{\text{Diffraction}}$ is the most important, as it is the limiting length scale. This length scale is due to the inherent diffraction of lasers. In order to achieve the intense energies neccesary for the bubble regime, the lasers need to be focused down to a specific spot size. As soon as the minimum spot size is reached, the laser will begin to diffract, the length scale where the laser is approximately the spot size is the Rayleigh length. In a plasma this becomes more complicated, as the plasma can and will act like a lens. This leads to a feedback effect, where the intense laser pulse will change the plasma density, which in turn changes the intense laser pulse, and so on. The majority of effort in current wakefield accelerator programs is to overcome this issue.

In Figure 5, we can see the length scales multiplied by the accelerating electric field– giving the total energy possible if an electron was accelerated over that distance. Clearly, the limiting length scale is diffraction.

There are several strategies for extending the length of the laser-plasma interaction: two that we will mention are relativistic self-focusing, and external plasma-waveguide solutions. These are the two main solutions currently being pursued by the UT Texas group and the Berkeley group, respectively.

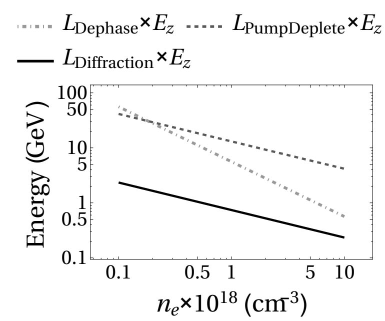

Figure 5: The three length scales involved with accelerating electrons: L_{Dephase} where the electron outruns the wave, self-limiting the total energy gained; $L_{\text{PumpDepletion}}$ where the incident energy in the laser pulse is completely transfered to the wakefield, and the laser can no longer sustain the bubble regime; and $L_{\text{Diffraction}}$ the inherent diffraction of the laser pulse. All lengths are scaled by an accelerating field using parameters from the Texas experiment[8], to show the total possible energy an electron could gain.

3 Experimental Set-Up and State-of-the-Art

In this review, we will focus on the experimental efforts of two groups, UT Austin Texas, and University of California Berkeley. Although there are many more groups doing interesting work in the field of LWFA, these two groups are the main ones actively pursuing the goal of high-energy electron accleration.

The Texas group uses very high-intensity laser pulses and exploits the phenomena of relativistic self-guiding to cancel out the inherent diffraction of the laser. The Berkeley group uses low-intensity laser pulses and plasma waveguide channels to overcome the diffraction issue. A more in depth review of each group and method is presented below.

3.1 Texas: Relativistic Focusing

In 2013, the Texas group reported a collumated beam of 2 GeV, which blew current records out of the water[8].

Their approach used the new petawatt laser facility at UT Austin. The large amplitudes that the laser was capable of generating placed them firmly in the relativisitic self-guiding regime.

3.1.1 Relativistic Self-Guiding

The group velocity of the laser pulse will be set by the index of refraction of the medium, which in turn is $eta = v_g/c = c^{-1}\frac{\mathrm{d}w}{\mathrm{d}k}$. The dispersion relation for a plasma is shown in Figure ??. Thus,

$$eta = \left(1 - \frac{\omega_p^2}{\omega^2}\right)^{1/2}. \tag{2}$$

If eta has a density distribution where it is larger on the optical axis, then a guiding plasma lens will be formed that can counteract the effects of diffraction. As we will discuss below, one can use relativistic effects to achieve this.

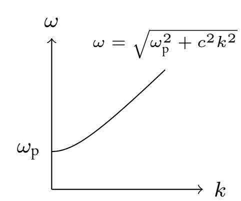

Figure 6: The plasma dispersion relation. We will be dealing with plasmas where $\omega_\mathrm{p}/\omega << 1$, so to first order the laser will be dispersionless.

Remembering back to Section ??, the first order effect of the high-intensity laser pulse will make the electrons quiver in the polarization plane.If the laser is intense enough, the electrons will be quivering relativistically, and will have maximum energy as they pass through the optical axis of the pulse. This means that their mass will be a maximum on the optical axis. This can be roughly seen to change the index of refraction, as:

$$\eta(m_e) \rightarrow \eta(\gamma m_e) \approx 1 - \frac{\omega_p^2}{2\omega^2}\frac{\delta n(r)}{\gamma} \tag{3}$$

where $\delta n(r)$is a density variation, and $gamma$ will be a maximum on axis.[?] This gives rise to the focusing behaviour discussed above.

This sets a very harsh experimental parameter, as the fields have to be relativistic enough to be able to counter the effects of diffraction. It can be shown that this limit is that the power in the field is P(GW) = 17.4 $(\omega/\omega_p)^2$[?].

In reality, the dynamics are much more complicated, and require detailed numerical simulations, one such example is shown in Figure 7[8]. This is partially due to the fact that the front and back of the waves will not satisfy the relativistic criterion, and diffract away– dynamically changing the pulse shape, which can have an effect.

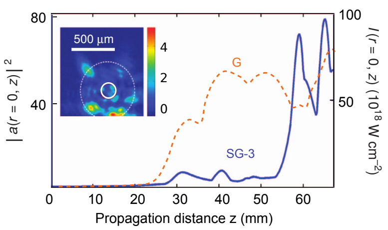

Figure 7: Simulations done by the Texas group using the WAKE code showing clear features of self-focusing.[8] As the normalized laser-intensity gets larger, the pulse is contracting– concentraing more of its energy over a smaller area. Interestingly, the self-focusing exhibits a periodic structure– going through two cycles of diffraction-focusing for the super-gaussian pulse.

3.1.2 Experimental Setup and Results

Shown in Figure 8 is the experimental setup for Texas. At its heart, it is a high-intensity laser that is hitting an ionized gas. The majority of the experiment is the diagnostics, which allow the team to determine the energy and spread of the electrons.

The Texas group is now hard at work trying to find a strategy to increase the energy

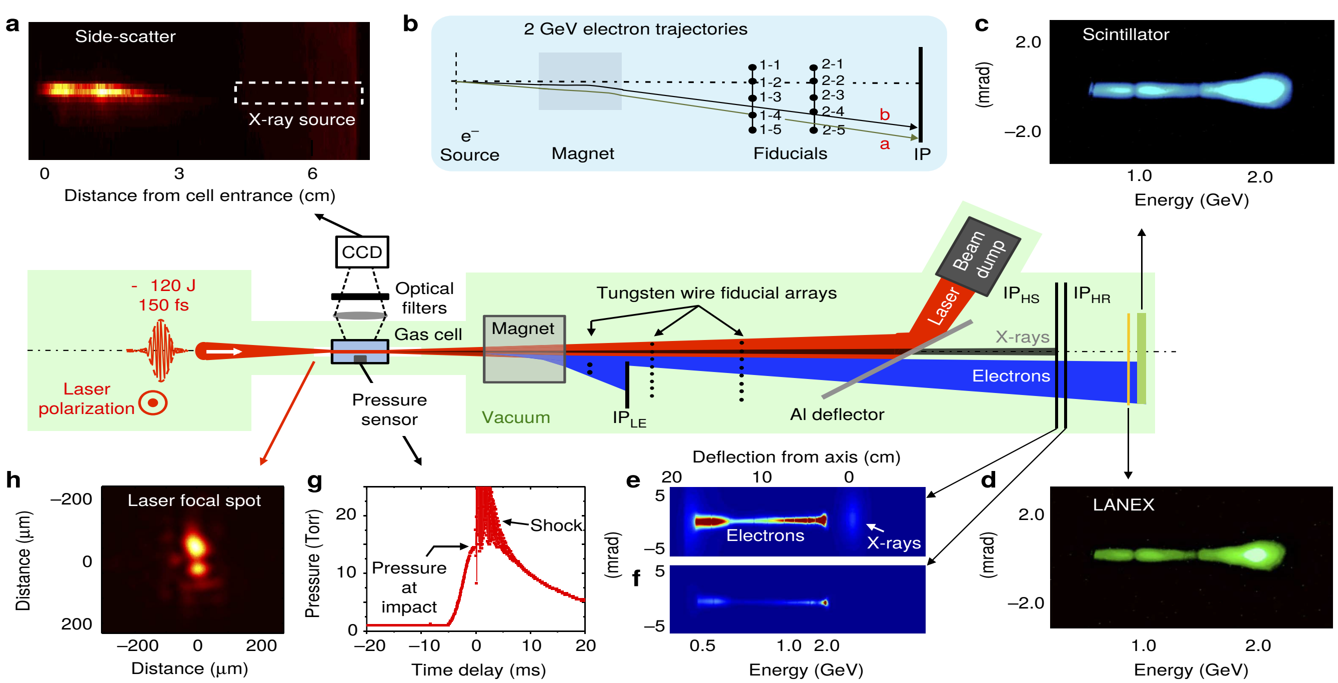

Figure 8: The experimental setup of the Texas group.[8] *This figure is reproduced from Nat. Commun. Vol. 4, 2013*

of the electrons. Although their initial result is very promising, there isn't a clear way forward. This is due to the very complicated dynamics of the highly non-linear laser-plasma interaction that leads to self-focusing. As shown in Figure 7, the behaviour of the self-focusing is very dependent on initial conditions (laser intensity, laser pulse shape, etc.). As no analytic model can fully encompass its behaviour, numerical simulation is required to understand the self-focusing behaviour required to produce acceleration lengths required for high energy electrons.

Their current work is focused on visualizing and understanding the propogation of high-intensity laser light through their plasma, and they have developed several novel techniques.

3.2 Low-Intensity, Quasi-Linear Plasmas with Waveguides

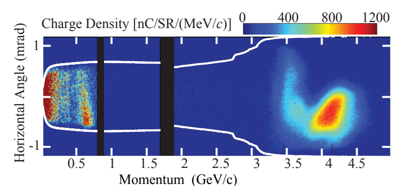

Figure 9: The energy spectrum for the recent Berkeley result.

In 2014, the Berkeley group reported a collumated electron beam with peak energy of 4.2 GeV.

The Berkeley has, for a while now, pursued the strategy of low-intensity laser pulses that are guided through channels. Their most current results use a capillary discharge channel. The physics of focusing remain the same: there is a radial density profile that has the same profile as a focusing lense. Instead of the density profile coming from relativistic effects, like the Texas group, the Berkeley group uses a plasma channel guide, which is a simple tube containing hydrogen gas, with a metal plate at each end. A voltage is applied across the length of the tube, ionizing the gas. The gas will cool down more rapidly along the edges of the tube, and this will give rise to an approximately parabolic density profile of the hydrogen gas[1, 6]. It is this parabolic density profile which will act as the focusing lens of the plasma wave. The evolution of a laser pulse in a plasma channel is shown in Figure ??.

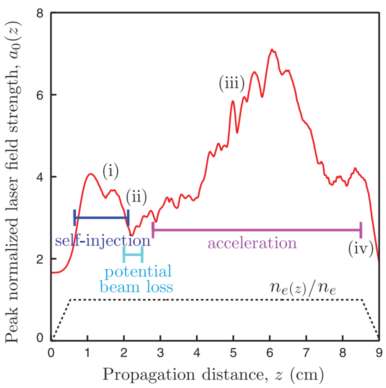

Figure 10: Evolution of the peak normalized intensity of the laser pulse, $(a_0(z)$ done using a particle-in-cell simulation for a top-hat laser pulse with energy 16 J, through a 9 cm plasma waveguide. *From Leemans et. al. 2014 [4]*

The benefits over the Texas strategy is that they gain signifigantly on energy conversion. Because they don't need to enter into the self-focusing regime, they can use much less powerful lasers, and compensate by accelerating the electrons over a larger distance. As well, there are some concerns in the field that the relativistic self-focusing process is too unstable to guide the beam over the necesariy distances[2], but some progress has been made to extend the distances that relativistic self-guiding can be used over[7].

4 Future Work and Outlook for the Field

5 Conclusion

$$\omega_{\mathrm{p}} = \sqrt{\frac{e^2 n_e}{m_e \epsilon_0}}. \tag{4}$$

Where m_e, n_e, and e are the mass, density and charge of the electron, respectively.

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