Plasma Wakefield Acceleration in its Youth

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Abstract

Acceleration is the key to reaching higher energy levels, which will enable physicists to better study the structures and interactions of leptons, quarks, gluons, and the forces that define elementary particle behavior. The Large Hadron Collider (LHC) should be operational in a few months. This collider will be able to collide opposing proton beams at an energy of 7 TeV per proton. This is an incredible amount of energy when the vast majority of colliders are still operating on a GeV or MeV scale. In order to study smaller particles such as quarks, we need even more energy to probe deep into protons and neutrons where these particles live. By advancing our methods of acceleration, scientists hope to reach even higher energy levels which could help describe the big bang, super novas, and other incomprehensible events. This author thinks plasma wakefields may usher in a new generation of accelerators.

1 Introduction

The term accelerator is sometimes used as a synonym for collider. There is a critical difference that needs to be pointed out. Generally, colliders consist of four subsystems: particle source, accelerator, storage system, and collision system (Tohreh 1996, 3). In this paper, the focus will only by the accelerator sections of colliders. Accelerators can be seperated into two catagories: Linear Particle Accelerators (Linacs), and Cyclic Accelerators. Now, the most basic way of increasing the attainable energy of an accelerator is to buy more space, better superconducting magnets, and more engineers. The inherint problem that we do not have infinite resources will force us to innovate. Some of these innovations inculde: improved RF cavities, laser acceleration, plasma wakefield acceleration, inverse free electron laser acceleration with a square wave wiggler, and there are still hundreds more! Given the time constraint of finals and the paper length restriction, this discussion will focus on obtaining a deep understanding of plasma wake-field acceleration.

2 Plasma Wake-Field Acceleration

These accelerators use plasmas as a medium to accelerate charged particle by inducing a special type of field... a wake-field! The correct abbreviation for this type of accelerator is PWFA. When discussing acceleration, one needs to be careful using this acronym because there are many types of PWFAs and this term is typically used synonymously. For example, there are key differences between a laser wakefield accelerator and a beam driven plasma wakefield accelerator, but both are commonly referred to as PWFAs. In the end of this discussion, we will bring many concepts together in an effort to understand a present day PWFA.

What is Plasma?

Plasma is a collection of free-moving electrons and ions that have been stripped of their electrons. It is commonly referred to as ionized gas. The requirement to create plasma is that energy must be used to strip electrons from ions (Wurtele 1994). There are numerous methods of maintaining plasma which are essential in accelerator design. Many plasma accelerators vary simply by the origin of this required energy: thermal, electrical, ultraviolet light, and high intensity lasers. When this energy source is removed, the plasma will simply recombine into neutral gas. Note that plasmas are considered a distinct state of matter, different from solids, liquids, and gases. Specific types of plasmas are characterized by their electron density and their temperature as shown below.

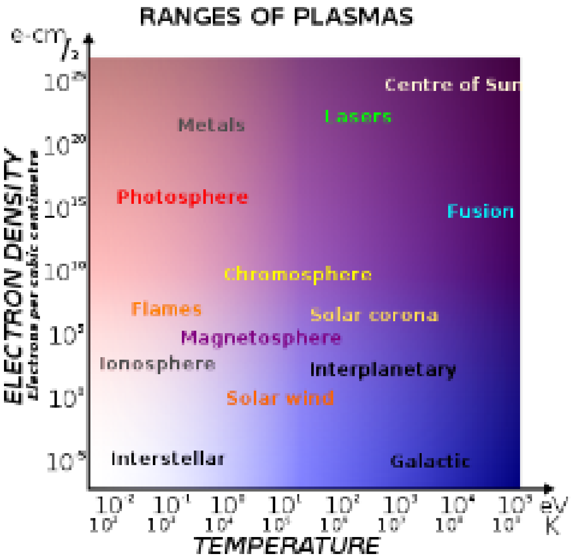

Figure 1: Range of Plasmas

Now that plasmas are no longer as mysterious, we can move on to the second component of this accelerator.

Wake-Field or Wakefield?

In all honesty, both of these spelling are just as popular, so we will alternate our spellings just like professional scientists. This type of field is appropriately named because it is generated in the wake of a moving bunch of charged particles. When a bunch of charged particles is accelerated through a plasma, there is an induced electric field which gives the bunch extra acceleration. Lets examine the figure below.

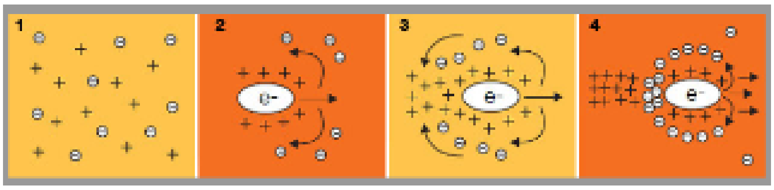

Figure 2: Wakefield in a Plasma

Note that the large electron in the diagram is actually an electron bunch which is being maintained by one of various sources: laser pulses, accelerated beam (usually via some linac), wiggler magnetic fields, etc. The moving electron bunch becomes surrounded by positive ions due to the EM interactions in the plasma. The key here is that an ion channel is created in the wake of the moving electron beam (Hooker 2006). With the electron bunch having passed, the displaced electrons are immediately attracted to the ion channel directly behind the moving electron bunch. The large groups of electrons that enter the ion channel create an electric field which helps to propel the moving electron bunch (Bruhwiler 2000). When considering an accelerator, we expect to have a beam of particle bunches moving through the plasma. This makes the choice in energy source critical in the efficiency of this type of accelerator. A common choice is a high intensity short pulse laser. Of course, the right choice is remains debatable.

The Scientific Truth

Up to now, we have been vague in describing the particle interaction with the electric fields present in the plasma. The beam which brings the electrons into the plasma generates an electric field in the path of the beam. As the electron bunch pushes through the plasma a few interesting things happen. First of all, the positive ion channel essentially neutralizes the electric field created by the beam. Here is the tricky part, the expelled electrons are typically propelled beyond a certain boundry called the charge neutralization radius, R_n. The electrons past R_n will oscillate at a frequency, ω, which is close to the electron plasma frequency, characteristic of the type of plasma and the radiation source maintaining the plasma state. The electrons oscillating near R_n will produce the electrostatic wakefield with components in the radial and axial directions. The axial field accelerates the electron bunch in the direction of the beam, which is what gives it a boost in energy. The radial field helps to compact the bunch by bring in the electrons around the perimeter. With this information, we can finally understand the more accurate illustration of a PWFA (Uhm 1989, 1).

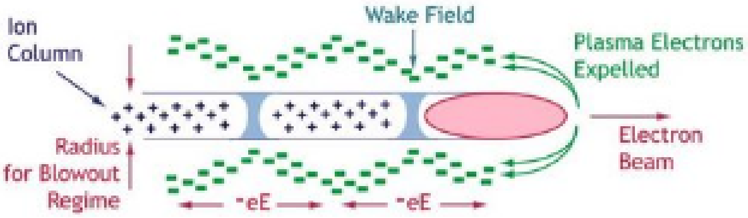

Figure 3: Ion Channel Behavior in a PWFA

The true nature of the wake field is shown above. Now that we have the theory for our accelerator, we can investigate the calculations involved in preparing this kind of accelerator.

Poisson to the Rescue

Before we leave the plasma regime for good, lets discuss why it works mathematically. The real issue is the correct plasmas and electric fields needed to induce a strong wakefield. When the plasma density is adjusted so that the plasma wavelengths match the seperation of our electron bunches, the electrostatic plasma waves become excited (similar to the effect of reaching the harmonic frequency of a material). The peak amplitude of the wave depends on the pulse length of the electron bunches, the peak density of the bunches compared to the plasma density, and the overall charge of the beam. The variables are as follows: n_e is the electron plasma density, n_i is the ion plasma density, n_b is the beam density, $\overrightarrow{v}$ is the velocity of the incoming electrons, $\overrightarrow{p}$ is the momentum of the incoming electrons, $\overrightarrow{E}$ is the total electric field in the plasma, and $\overrightarrow{B}$ is the total magnetic field in the plasma.

$$\begin{aligned} div\overrightarrow{E} &= -4\pi e(n_e - n_i + n_b) \\ \frac{\partial \overrightarrow{p}}{\partial t} + \overrightarrow{v}\nabla \cdot \overrightarrow{p} &= -e\overrightarrow{E} - e\frac{\overrightarrow{v}}{c} \times \overrightarrow{B} \\ \frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \overrightarrow{v}) = 0 & \end{aligned}$$

At this point the math becomes more difficult. We must reduce the above equation to 1 dimension (the beam direction) and then allow for relativistic corrections in the beam frame. Following this, we must approximate the system to a harmonic oscillator which is valid as long as $n_b << n_0$, where n_0 is the plasma density. The final solution is

$$\overrightarrow{E_z} = \frac{mc^2}{n_0 e}(2\frac{n_e}{n_0} - 1)^{-3/2}\frac{dn_e}{d\xi}$$

where $\xi = z - ct$ is the relativistic correction and $v_g \cong c$ is the group velocity of the bunch. Phew, since the mathematicians are pleased we can move on to a real world experiment using a PWFA (Kallos 2005).

E-157: 1 GeV Plasma Wakefield Accelerator

According to some scientists, it is clear that $100MeV/m$ is the close to the limit for metallic accelerating structures. They also claim, plasma based devices may be the only way to achieve $300MeV/m$ and higher. Lets see if this is really the case for this type of accelerator. This PWFA will accelerate parts of a $28.5GeV$ electron bunch from the SLAC linac and increase its energy up to $1GeV/m$. The $1m$ long plasma source will be created via a lithium ion heat-pipe oven. The Li vapor will be ionized by a uv laser pulse through a single photon absorption process. The bunch length of the incoming electrons is being shortened from $1.2mm$ to $.4mm$ to increase the plasma wakefield peak. The diagram below should make sense with the information presented in this paper.

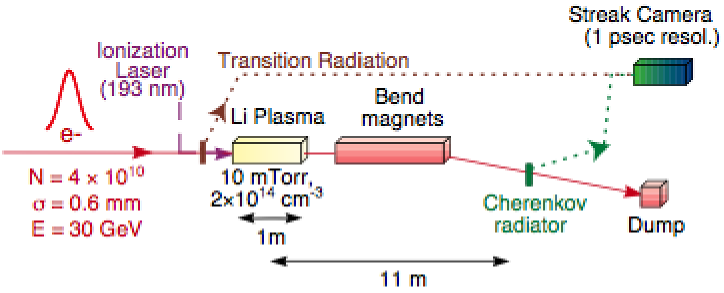

Figure 4: E-147 Plasma Wakefield Accelerator at SLAC

This experiment operates in the blow-out regime, which is where the number density of electron bunch is actually greater than the plasma density (Assmann 1999). This forces the electrons in the plasma away from the electron bunch. The movement of plasma electrons creates an electron plasma wave (EPW) which helps condense the electron bunch by accelerating the electrons in the tail end of the bunch. Let it be noted that a typical problem with this type of design is stablizing the EPW to avoid adverse effects in the wakefield (Assmann 1999). This accelerator is expected to produce the following beam diagnostics

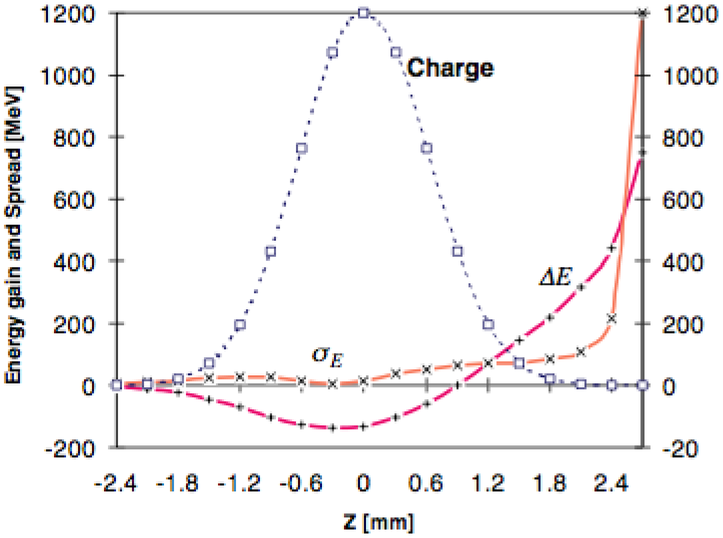

Figure 5: Beam Diagnostics for the E-147

In the figure, notice the tail of the drive bunch experiencing an acceleration of about $.5GeV$ over $1m$. This is due to the wakefield produced in the Li plasma. This is an exciting experiment that has actually achieved the highest (increase in energy / distance) in the realm of PWFA to this day.

3 Conclusions

The future of high energy physics depends on creating innovative and new accelerators that will reduce cost as well as size. There are many approaches to particle acceleration. The real trick is finding the right combination of experimental procedures that will yield a stable and high intensity acceleration field. This paper has enumerated some promising ideas, but the future of acceleration may lie in the hundreds of other different accelerator concepts. The use of plasmas and wake-fields are interesting in the very least. Whether or not these experiments will prove to be extremely successful, the physics behind the designs are both creative and compelling. It is time for someone to rise to the occasion and build the accelerator that will ”force” us to a new frontier.

4 References

1. David L. Bruhwiler et al., *Modeling Beam-Driven and Laser-Driven Plasma Wakefield Accelerators with XOOPIC* (Tech-X Corporation, 2000)

2. Parsa, Zohreh, *New Modes of Particle Acceleration: Techniques and Sources* (American Institute of Physics, 1997)

3. S. M. Hooker, D. A. Jaroszynski and K. Burnett, *Laser-Driven Plasma Accelerators: New Sources of Energetic Particles and Radiation* (CERN Courier, November 2006)

4. R. Assmann et al., *Progress Toward E-157: A 1-GeV Plasma Wakefield Accelerator* (IEEE Particle Accelerator Conference, 1999)

5. Jonathan S. Wurtele, *Advanced Acceleration Concepts* (Physics Today, July 1994)

6. Efthymios Kallos et al., *A Multibunch Plasma Wakefield Accelerator* (IEEE Xplore: Particle Accelerator Conference, 2005)

7. Han S. Uhm, *Theory of Wakefield Effects relativistic Electron Beams* (IEEE Xplore: Naval Surface Warfare Center, 1989)