Alysis of Laser-Plasma Based Electron-Positron Collider

Sheng Liu*

Department of Physics and Computer Science, University of California, Davis, California, US

* Corresponding Author Email: gggliu@ucdavis.edu

Abstract. Contemporarily, the collider plays a vital role in research and analysis for high energy physics, particle physics and astrophysics. However, conventional colliders usually need a large budget to operate as well as cover a large area for displacing the facility. With the rapid development of the laser techniques, the laser-plasma accelerator paves a path to accelerate particles in a compact way. On this basis, this paper will analyze the feasibility and recent progress for electron-positron collider realization via the concept of the laser-plasma acceleration. To be specific, the principles behind it will be analyzed initially. To be specific, an intense electromagnetic could make the plasma oscillated due to the pondermotive force, and the electron field created by the oscillation of the plasma could accelerate electrons to high energy. In addition, the possibility of applying laser plasma acceleration in to electron-positron collider is examined. These results shed light on guiding the further exploration of future electron-positron collider.

Keywords: Laser plasma acceleration; electron-positron collider; wakefield acceleration.

1. Introduction

The accelerator based on the radio-frequency cavities (RF) is the technology used in contemporary collider. Owing to the limited energy that could be sustain in the RF cavities, and the long length of the machine. It would be costly to build a collider in (TeV energy level) [1]. The Large Electron-Positron Collider (LEP) is one of the colliders in CERN. The LEP has the circumference of 27 kilometers. When LEP started operation in 1989, it accelerated the electron and positron in total energy of 45GeV and the LEP still holds the record of reaching the highest energy level. Since the accelerators are extremely large, the costs for operation as well as construction requires an extremely large budget.

In 1979, Tajima and Dawson developed the new concept of using laser plasma to accelerate the electron and positron [2]. It uses the wake field produced by the laser traverses through plasma to accelerate charge particles. The acceleration gradient could be 1000-10000 times larger comparing with the regular radio-frequency accelerator. In this case, the acceleration distance can be controlled into cm-m scale, which provided the potential of building ultra-small compact electron-positron collider with high energy [3-5].

In order to evaluate the feasibility of the approach, this paper discusses possibility of applying laser plasma accelerator in collider. The rest part of the paper is organized as follows. The Sec. 2 will talk about the principle of the laser plasma acceleration and the Sec. 3 will describe the concepts for realizing collider based on laser driven wakefield acceleration in detail. Subsequently, the Sec. 4 will discuss the challenges for applying laser plasma accelerator in electron-positron collider. Eventually, a brief summary will be given in Sec. 5.

2. Laser Plama Accelerators

When an intense laser pulse propagates through plasma (or ionized gas), the free electrons in the plasma would subject to the ponderomotive force and push away from the laser pulse. The positive ions would pull the free electrons back to its original position and cause the electron to oscillate around the initial position. The electron field caused by the separation of the electrons and ions due to the laser pulse is called the laser plasma wake field, which is like the lake wake forms by a moving boat [6]. The frequency of the oscillation of the plasma ω_p is given by

$$\omega_p = \left(\frac{n_e e^2}{m_e \epsilon_0}\right)^{\frac{1}{2}} \tag{1}$$

where n_e is the initial electron density, ϵ_0 is the Vacuum permittivity constant, m_e is the mass of electron and $-e$ is the charge of electron. If the oscillation of the electron and the laser wave are in phase, the wake field produced would be the strongest. Therefore, in order to get the strongest acceleration or the strongest wake field, the period of the laser pulse T should follow the formula $T = 2\pi/\omega_p$. The separation of the electron and positive ions in plasma forms a huge electron field which could accelerate the charged particles to relativistic energy.

The energy of the electron field theoretically can reach about several hundred GV per meter. When the electron moving through the wake field, the main force that the electrons experience is the ponderomotive force. The ponderomotive energy of the electrons is given by:

$$U_p = \frac{e^2 E_a^2}{4m\omega_0^2} \tag{2}$$

Expressing the formula in form of laser intensity I using $I = c\epsilon_0 E_a^2/2$, one gets:

$$U_p = \frac{e^2 I}{2c\epsilon_0 m\omega_0^2} = \frac{2e^2}{c\epsilon_0 m} \cdot \frac{I}{4\omega_0^2} \tag{3}$$

Where I is the laser intensity, ω_0 is the frequency of the laser carrier, e is the electron charge, m is the electron mass, and ϵ_0 is the Vacuum permittivity constant.

The laser intensity changes with space, and so does the ponderomotive energy and the ponderomotive force. The ponderomotive force $F_p = -\nabla U_p \propto -\nabla I$ could only push the electron away from the high gradients in laser intensity, and the particle could only obtain acceleration in a certain area. The distance that the charged particle could be accelerated is limited by the velocity of the plasma wave and the velocity of the lase pulse. In the linear regime, after accelerating for the distance of $L_d = \lambda_p^3/\lambda^2$, the particle would get into the deaccelerating area. The $\lambda_p \approx 2\pi c/\omega_p$ is the wave length of the plasma wave, and λ is the wave length of the laser. The defocusing of the laser and the depletion of the laser energy in the process of transforming energy into the plasma wave could also affect the acceleration distance. Because of $F_p \propto 1/\mathrm{m}$, the acceleration exerted on the proton is about 10^{-6} times of the acceleration exerted on the electrons. Therefore, the oscillation of the proton could be neglected in this process.

There are two main sources for the accelerated electrons. The electron does not have enough energy to break out from the oscillation in plasma with the low laser intensity. Therefore, in this circumstance of low laser intensity, to make sure the electrons could be captured by the laser, they have to must injected into the plasma with a relative high energy. To easily describe the electron in the laser field, this article introduced a normalized vector potential a_0:

$$a_0 = \frac{eE}{\omega m_e c} \tag{4}$$

When $a_0 > 1$, Electrons can be accelerated to the speed of light in one laser period, and the laser is said to be relativistic [7]. Which is the maximum velocity (eE/ω) divided by electron rest mass m_e and the speed of light c.

The motion of charged particle can be described as the Lorentz equation:

$$\frac{dp}{dt} = -e(E + v \times B) \tag{5}$$

Here, p is the electron momentum, $p = \gamma m_e v$, $\gamma = (1-\beta^2)^{-\frac{1}{2}}$ is the relativistic factor, and $\beta = v/c$ is the normalized velocity. Considering the non-relativistic situation, which $|B| = |E|/c$. The $v \times B$ term in the Lorentz equation could be neglected in the non-relativistic regime. It assumed that $E(z) = E_l \cos(k_0 z - \omega_0 t)\, e_x$. When $\beta \ll 1$ or saying that $\gamma \approx 1$, the Lorentz equation become:

$$\frac{dp}{dt} = m_e \frac{dv}{dt} = -eE \tag{6}$$

Therefore, the electron initially rest at z = 0, oscillates with the velocity of

$$\beta = \frac{v}{c} = -\frac{eE_l}{m_e c\omega_0}\sin(\omega_0 t) = -a_0 \sin(\omega_0 t) \tag{7}$$

For $a_0 > 1$ (in relativistic situation), the electron will oscillation velocity would reach c, and the $v \times B$ term could not be neglected form the Lorentz equation. The solution of the Lorentz equation in the relativistic regime be found. After changing the frame followed by Ref. [8], the solutions are:

$$u_x = \gamma\beta_x = a_0 \sin(k_0 \xi) \tag{8}$$

$$u_y = \gamma\beta_z = \frac{a_0^2}{2}\sin^2(k_0 \xi) \tag{9}$$

Since the electron is always positive in z direction, therefore the $v \times B$ force push the electron forward. The electron trajectory could be obtained by integrating u_x and u_y

$$x = -\frac{a_0}{k_0}\cos(k_0 \xi) \tag{10}$$

$$z = \frac{a_0^2}{8k_0}[2k_0\xi - \sin(2k_0\xi)] \tag{11}$$

In the situation of non-relativistic, the electron only traverses a little and does not obtain any energy from laser. This demonstrates the importance of operation in relativistic regime [8].

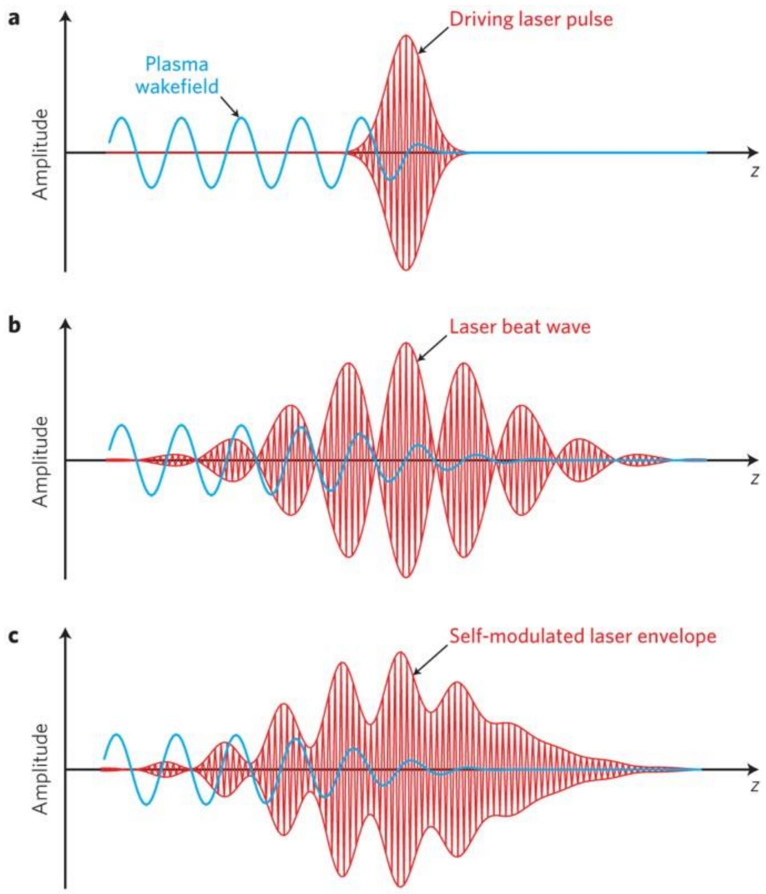

Fig. 1 Laser wakefield acceleraiton schemes. a. Single driven pulse (also named laser wake field accelerator, LWFA); b. Beats formed by two laser which have the difference of frequencies equals to the frequency of the plasma; c. Self-modulated laser envelope.

3. Realization Mechanims and Scenarios

3.1. Laser Wakefield Acceleration

The Fig. 1 shows few Laser-driven plasma acceleration schemes. In 1979, Tajima and Dawson publish a paper about laser wake field accelerator. Their methods was using one single intensive laser to excite plasma in relativistic circumstance. This accelerator is call laser wake field accelerator, or LWFA (seen in Fig. 1a) Tajima and Dawson start the exploration for using laser to accelerate particles. The laser wake field accelerator required the laser with pulse time which is slight shorter than the plasma period, which needs to be smaller than 100fs. This condition is hard to achieve using the glass laser at that time. Therefore, Tajima and Dawson give a alternative scheme: using two lasers which have the frequency difference equals to the plasma frequency. This scheme is call beat-wave accelerator, PBWA (in Fig. 1b). The beat-wave accelerator is first demonstrated by a group at UCLA by 70J, 300ps CO2 lasers. In the research, group of UCLA injected 2.1 MeV electrons and accelerate them to 9.1 MeV. However, one problem of PBWA is that when the relativistic increases the mass of electron, and hence reduces the frequency of the plasma. This would cause the beat wave cannot resonance with the plasma, and this instability prevent the development of PBWA. This problem is avoided by the self-modulated LWFA(seen in Fig. 1c).

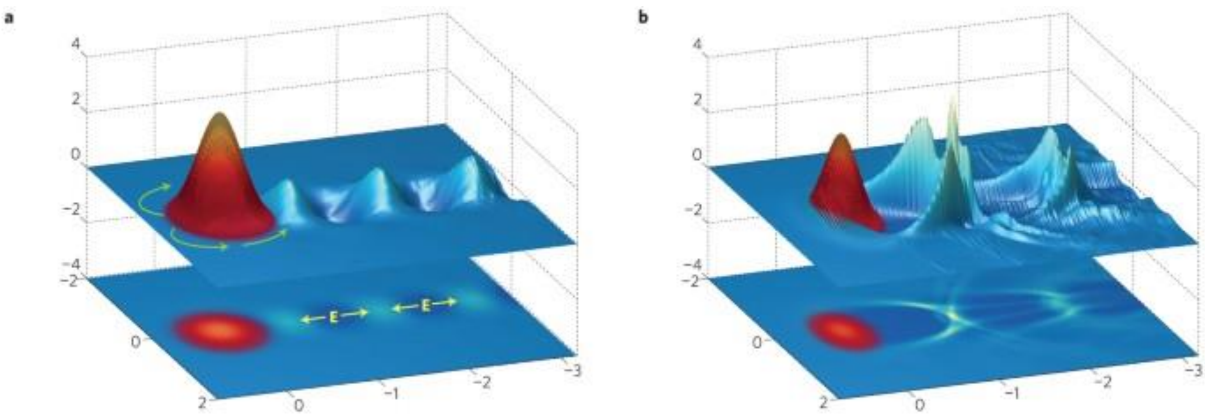

Fig. 2 Linear regime (left panel) and bubble regime (right panel)

3.2. Bubble Regime

Fig. 2 shows the laser pulse demonstrated in red traverses the plasma to drive the wakefield [6]. The plasma wave is shown in blue and green. In Figure a, the normalized vector potential for the laser $a_0 = 0.5$, which means the laser in Figure a is a linear regime(non-relativistic). The shape of the wake field wave is sinusoidal. In Figure b, the $a_0 = 4.0$, which means the laser in figure b is in a nearly bubble regime(relativistic). The vertical scale of Figure a is 10 times greater than the scale in Fig. 2 b. With the development of the high-power, short period laser, it is possible to drive the plasma wake field with only one single intensive laser with $a_0 \gg 1$. Rosenzweig etc found that some electrons would be blow out and leave a cavity in which is a idea field structure to accelerate electrons [6]. The bubble regime is very important because could produce high enough energy to let the electron in the plasma break from the oscillation and form high energy electron beam. The bubble provides a easy method to produce electron beam without injecting any electro

3.3. Electron-Positron Collider

In this subsection, the theoretical example of laser plasma based collider is operating in quasi-linear regime, and using a plasma channel to guide the intensive laser. The accelerator model works with the density $n = 10^{17}\ cm^{-3}$ and with the plasma channel which has radius of $22\mu m$. The laser of the accelerator is a 6.5J, 130fs FWHM laser, and it could excite the plasma with the peak accelerating field of 6 GV/m [9]. An proper particle beams of 0.19nC (3kA beams peak current) can be obtained energy above 5 GeV with the efficiency of 20% [9]. Energy recovery operations could be performs for the energy remain in the laser as well as the plasma. One possible methods of recovering energy is using the photovoltaic power. (see in Fig. 3). All the mechanism besides the acceleration parts is to be determined, including the beams generate, delivery system, cooling system etc.

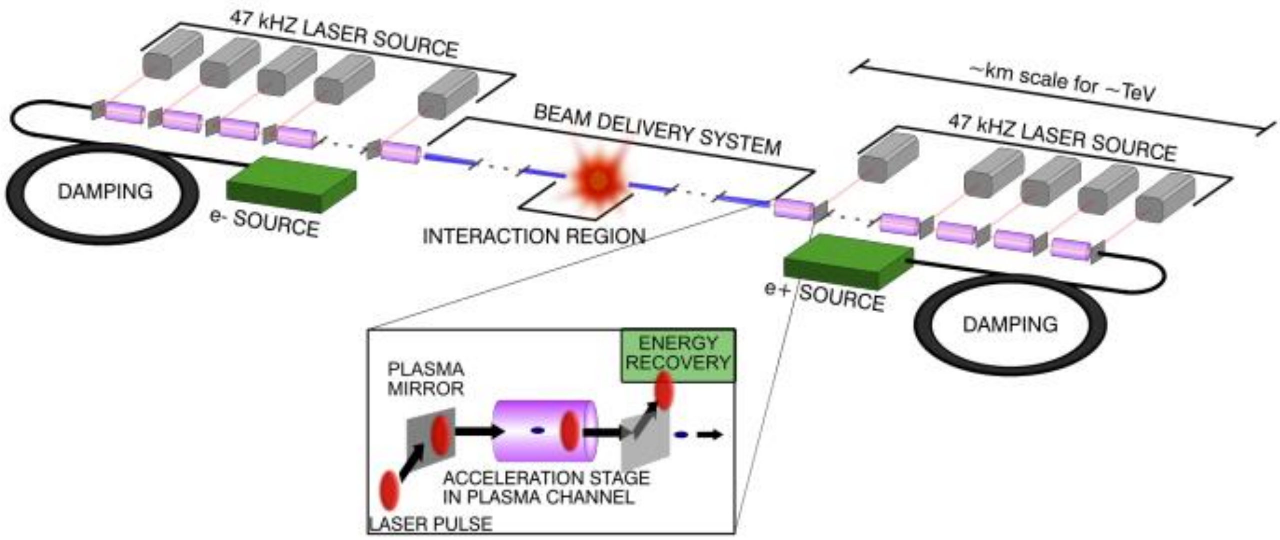

Fig. 3 Schematic of electron-positron collider.

4. Challenges

Transverse beam stability is considered as one of the critical challenges for realizing the laser plasma-based collider. With the emitting of the beams, the wake field of the beam may couple with the beam transverse position and causing the deviation of the center of the beam [10].

Another challenge for applying plasma accelerator into the electron-positron collider is that positron cannot be accelerated in bubble since they experienced and defocusing force [11]. the quality of the positron beam would be strongly reduced in the process of high-gradient plasma wake field acceleration for the positron beams, whatever method is used. This fact is demonstrated in both experiment and the theory. There have several new regimes of generate positron beam with both high-gradient and good quality, but none of them perform overall as good as the blow-out regime [11].

The geometric shape of the bubble in the bubble regime could also affect the quality of the electron beam [12]. When the ponderomotive force is not very strong, it is possible to have some electrons to get in the bubble. The charge of these charges of those electrons who accidentally get into the bubble would produce some electromagnet field, and the shape of the bubble may change due to the electromagnetic field. The experiment shows that the changing in geometric shape of the bubble resulted in obvious reduction in the traverse field, but the longitudinal field still have about half [12]. Although the longitudinal field does not change much, the acceleration distance of the electron has been greatly affected, and so does the quality of the electron beam generated.

5. Conclusion

In summary, this paper discusses possibility of applying laser plasma accelerator in electron-positron colliders. To be specific, the article introduces the principle of the laser plasma accelerator and use proposed data to simulate an electron-positron accelerator and analysis the challenges of applying laser plasma accelerator in electron-positron collider. According to the analysis, laser plasma accelerator could dramatically reduce the distance and the cost used to accelerate. Nevertheless, the bubble regime which is the most efficient method for laser plasma accelerator, may cause the loss of electron energy, and the geometric shape of the bubble may also harm the quality of the electron beam generated. In the future, with the development of accelerator, it would be possible to efficiently apply the laser plasma accelerator to collider. Overall, these results offer a guideline for how to dramatically reduce the cost and acceleration distance of electron-positron accelerator.

References

[1] Doche A, Beekman C, Corde S, et al. Acceleration of a trailing positron bunch in a plasma wakefield accelerator. Scientific reports, 2017, 7(1): 1-7..

[2] Tajima T, Dawson J M. Laser electron accelerator. Physical Review Letters, 1979, 43(4): 267.

[3] Thompson M C, Badakov H, Rosenzweig J B, et al. Ultra‐High Gradient Dielectric Wakefield Accelerator Experiments. AIP Conference Proceedings. American Institute of Physics, 2006, 877(1): 903-909.

[4] McGuffey C, Thomas A G R, Schumaker W, et al. Ionization induced trapping in a laser wakefield accelerator. Physical review letters, 2010, 104(2): 025004.

[5] Döpp A, Thaury C, Guillaume E, et al. Energy-chirp compensation in a laser wakefield accelerator. Physical Review Letters, 2018, 121(7): 074802.

[6] Hooker S M. Developments in laser-driven plasma accelerators. Nature Photonics, 2013, 7(10): 775-782.

[7] Umstadter D. Relativistic laser–plasma interactions. Journal of Physics D: Applied Physics, 2003, 36(8): R151.

[8] Cros B. Laser-driven plasma wakefield: propagation effects. arXiv preprint arXiv:1705.10566, 2017.

[9] Benedetti C, Bulanov S S, Esarey E, et al. Linear collider based on laser-plasma accelerators. arXiv preprint arXiv:2203.08366, 2022.

[10] Schroeder C B, Benedetti C, Bulanov S S, et al. Beam dynamics challenges in linear colliders based on laser-plasma accelerators. Journal of Instrumentation, 2022, 17(05): P05011.

[11] Adli E. Towards a PWFA linear collider—opportunities and challenges. Journal of Instrumentation, 2022, 17(05): T05006.

[12] Wu H C, Xie B S, Zhang S, et al. Bubble core field modification by residual electrons inside the bubble. Physics of Plasmas, 2010, 17(11): 113103.