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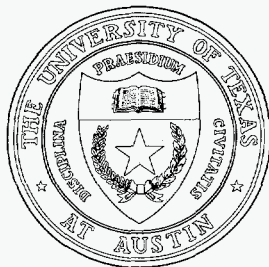and
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Abstract

An e^+e^- linear collider at energies beyond a TeV runs into a problem of severe beamsstrahlung, characterized by Υ on the order of unity (and beyond). In the regime of extremely high Υ the beamsstrahlung may be largely suppressed due to the quantum effect. In the design of an e^+e^- collider there are two ways to satisfy the collider physics constraints. One is to decrease the number of particles per bunch (and thus to increase the repetition rate) and the other is to decrease the longitudinal bunch length. The former approach can limit Υ, while the latter boosts it. (It may be useful to reevaluate the future collider parameters in view of this.) The laser wakefield driver for a collider in comparison with the microwave driver naturally offers a very short bunch length, which is appropriate for the latter collider option. We show that this choice of collider design with a short bunch length and high Υ has advantages and provide sample design parameters at 5 TeV. Such sample design parameters challenge us in a number of fronts, such as the preservation of high quality bunches, efficient high repetition rate lasers, etc. The collision point physics simulated by the CAIN code shows a surprisingly well preserved luminosity spectrum.

1 Introduction

In this article we report a recent work of a strawman's design based on the collaboration among the LBL, KEK, and The University of Texas at Austin and suggest where the laser-based accelerators in the future need further developments. The work was reported at the Advanced Acceleration Conference (Lake Tahoe, 1996) by M. Xie, T. Tajima, K. Yokoya, and S. Chattopadyay [1]. It is believed that a linear collider at around 1 TeV center of mass energy can be built more or less with existing technologies. But it is practically difficult to go much beyond that energy without employing a new, yet largely untested method of acceleration. However, apart from knowing the details of the future technologies, certain collider constraints on electron and positron beam parameters are general, and have to be satisfied, e.g. available wall plug power and the constraints imposed by collision processes: beamsstrahlung, disruption, backgrounds, etc. We have examined collider performance at the final interaction point (IP) of e^+e^- collider over a large space of beam parameters. It becomes increasingly necessary at higher energy to operate colliders in high Υ regime and use to our advantage the quantum effect to suppress beamsstrahlung. Here Υ is the ratio of the (classically calculated) beamsstrahlung photon energy to the beam electron (or positron) energy. Although the quantum suppression effect was known and studied before with simple models [2-5], it has not been checked with full-blown simulation at high Υ regime that have been considered in the paper by Xie *et al.* [1] (though several issues remain to be further checked). There are indeed several features revealed by this simulation, in particular in the differential luminosity spectrum, which is a crucial factor for collider detectors.

1.1 Collision Point Physics

An important collider performance parameter is the geometrical luminosity given by $\mathcal{L}_g = f_c N^2 / 4\pi\sigma_x\sigma_y$ where f_c is the collision frequency, N is the number of particles per bunch, σ_x

and σ_y are, respectively, the horizontal and vertical rms beam sizes at the IP. The real luminosity, however, depends on various dynamic processes at collision. Among them the most important ones are beamsstrahlung and disruption. These two processes are characterized by the beamsstrahlung parameter $\Upsilon = 5r_e^2 \gamma N/6\alpha\sigma_z(\sigma_x + \sigma_y)$, and the disruption parameter $D_y = 2r_e N\sigma_z/\gamma\sigma_y(\sigma_x + \sigma_y)$, where γ is the Lorentz factor, r_e the classical electron radius, α the fine structure constant, and σ_z the rms bunch length. Beamsstrahlung is in classical regime if $\Upsilon \ll 1$, and strong quantum regime if $\Upsilon \gg 1$. The physical effect of beamsstrahlung is not directly reflected in the magnitude of Υ, but rather it is more conveniently monitored through the average number of emitted photons per electron $n_\gamma = 2.54(\alpha\sigma_z\Upsilon/\lambda_c\gamma)U_0(\Upsilon)$ and relative electron energy loss $\delta_E = 1.24(\alpha\sigma_z\Upsilon/\lambda_c\gamma)\Upsilon U_1(\Upsilon)$, where $\lambda_c = \hbar/mc$ is the Compton wavelength, $U_0(\Upsilon) \approx 1/(1 + \Upsilon^{2/3})^{1/2}$, and $U_1(\Upsilon) \approx 1/(1 + (1.5\Upsilon)^{2/3})^2$.

The collider physics scaling laws may be epitomized [1] in two-dimensional parameter space $\{N, \sigma_z\}$ when $\{E_{\mathrm{cm}}, \mathcal{L}_g, P_b, R\}$ are considered fixed

$$f_c \sim 1/N, \quad \sigma_y \sim \sqrt{N}, \quad D_y \sim \sigma_z, \quad \Upsilon \sim \sqrt{N}/\sigma_z \tag{1}$$

$$n_\gamma \sim U_0(\Upsilon)\sqrt{N}, \quad \delta_E \sim \Upsilon U_1(\Upsilon)\sqrt{N}. \tag{2}$$

In the limit $\Upsilon \gg 1$, $U_0(\Upsilon) \to 1/\Upsilon^{1/3}$, $\Upsilon U_1(\Upsilon) \to 1/\Upsilon^{1/3}$. Equation (2) becomes [1]

$$n_\gamma \sim (N\sigma_z)^{1/3}, \qquad \delta_E \sim (N\sigma_z)^{1/3}. \tag{3}$$

We see from Eqs. (1) and (2) that once in the high Υ regime there are two approaches to reduce the effects of beamsstrahlung: either by reducing N or by reducing σ_z. The consequences on the collider design and the implied restrictions on the approaches, however, can be quite different. Reducing N requires f_c to be increased and σ_y decreased, thus the approach is limited by the constraints on f_c and σ_y. Reducing σ_z, on the other hand, is not directly restricted in this regard. Also the dependencies of Υ on the two approaches are quite the opposite. The second approach clearly demonstrates the case that beamsstrahlung

3

Table 1: One Example of Beam Parameters and Collider Physics Results of the 5 TeV Design [1]

P_b(MW)	$N(10^8)$	f_c(kHz)	ε_y(nm)	$\beta_y(\mu$m)	σ_y(nm)
2	0.5	50	2.2	22	0.1
$\sigma_z(\mu$m)	Υ	D_y	F_{Oide}	n_γ(theo)	δ_E(theo)
0.32	3485	0.93	0.89	0.72	0.2
n_p(theo)	$\mathcal{L}_g(10^{35}\,\text{cm}^{-2}\text{s}^{-1})$	n_γ(sim)	δ_E(sim)	σ_e/E_0	n_p(sim)
0.19	1	1.9	0.38	0.42	0.28
$\mathcal{L}/\mathcal{L}_g(W_{\text{cm}} \in 1\%)$	$\mathcal{L}/\mathcal{L}_g(W_{\text{cm}} \in 10\%)$				
0.83	1.1				

can indeed be suppressed by having larger Υ.

1.2 High Υ Physics with Short Bunches

Strong quantum beamsstrahlung physics with high Υ includes some important effects such as disruption and multiphoton processes [6]. A Monte-Carlo simulation code recently developed by Yokoya [7] was used to study QED processes at the IP for e^+e^- and $\gamma\gamma$ colliders [1]. Table 1 is the compilation of the design parameters [1] for a laser driven e^+e^- linear collider at 5 TeV, as well as consequential collider physics parameters. The differential e^+e^- luminosity for the parameter in Table 1 has been computed [1]. It is noted that the luminosity spectrum is characterized by an outstanding core at the full energy and a very broad, nearly flat halo. The outstanding core is more than two orders of magnitude above the halo. The sharpness and the high luminosity of the core is rather surprising but pleasantly so.

Another major deteriorating process at high Υ is coherent pair creation. The number of pairs created per primary electron, n_p, (Table 1) has been computed [1] based on formulas [6] and by simulations. According to the simulations the incoherent pair creation is 2 to 3 orders of magnitude smaller than that of the coherent pairs, thus negligible. Finally, we point out that such a differential luminosity spectrum should be rigorously assessed together with the

background of beamsstrahlung photons and coherent pairs from the point of view of particle physics and detector considerations. In particular, their angular distribution will critically determine the detector design.

In view of this quantum supression of beamsstrahlung it may be useful to evaluate the machine parameters and the detector technologies of future high energy colliders, incluing the next linear collider. However, in this little article we concentrate on an even shorter bunch scheme of laser accelerators.

2 Laser Driven Accelerator

As seen from Eq. (3), an effective way to suppress beamsstrahlung is to reduce σ_z, for which laser acceleration [8] has easy time to satisfy, as it offers much shorter acceleration wavelength than that of conventional microwaves. For laser wakefield acceleration, a typical wavelength of accelerating wakefield is $\sim 100\,\mu$m, which is in the right range for the required bunch length in Table 1. Laser wakefield acceleration [9,10] has been an active area of research in recent years primarily due to the major technological advance in short pulse TW lasers (T^3, or Table-Top Terawatt lasers) [10]. The most recent experiment at RAL has demonstrated an acceleration gradient of 100 GV/m and produced beam-like properties with 10^7 accelerated electrons at 40 MeV $\pm$ 10% and a normalized emittance of $\varepsilon < 5\pi$ mm-mrad [11].

For beam parameters similar to that in Table 1, we consider a laser wakefield accelerator system consisting of multiple stages with a gradient of 10 GeV/m. With a plasma density of 10^{17} cm^{-3}, such a gradient can be produced in the linear regime with more or less existing T^3 laser, giving a plasma dephasing length of about 1 m [12]. If we assume a plasma channel tens of μm in width can be formed at a length equals to the dephasing length, we would have a 10 GeV acceleration module with an active length of 1 m.

Although a state-of-the-art T^3 laser, capable of generating sub-ps pulses with 10s of TW peak power and a few Js of energy per pulse [10], could almost serve the need for the required

5

acceleration, the average power or the rep rate of a single unit is still quite low, and wall-plug efficiency inadequate. In addition, injection scheme and synchronization of laser and electron pulse from stage-to-stage to good accuracy have to be worked out. Yet another important consideration is how to generate and maintain the small beam emittance in the transverse focusing channel provided by plasma wakefield throughout the accelerator leading to the final focus. There are various sources causing emittance growth, multiple scattering [13], plasma fluctuations [14] and mismatching between stages, to name just a few. Should the issues of guiding, staging, controllability, emittance preservation, etc. be worked out, there is hope that wakefields excited in plasmas will have the necessary characteristics for particle acceleration to ultrahigh energies.

3   Accelerator Physics Issues of Laser Wakefield

We consider satisfying these collider requirements. As we have seen in Sec. 1, there are two important new guidelines for us to take. (a) The smaller the longitudinal size σ_z of a bunch of the electron (and positron) beams, the smaller the disruption parameter D_y, the amount of photons n_γ (and other secondary particle emissions), and the energy loss δ_E of the bunch due to the beamsstrahlung are, as seen in Eqs. (1) and (2). An alternative to make sure the last two numbers, i.e. n_γ and δ_E, are small, is to make the number of particles in a bunch N small. When we try to make N small in order to keep n_γ and δ_E small in accordance with Eq. (3), however, we have to make the frequency of bunch collisions f_c large and the size of the transverse beam size σ_y (and thus the beam emittance) small. The former requirement $f_c \propto N^{-1}$ (while n_γ, $\delta_E \propto N^{1/3}$) means that f_c has to be increased by a lot larger amount (K), when the N in Eq. (3) is reduced by a factor $1/K$. This sets a rather stringent constraint on accelerator considerations. The latter requirement also sets a rather stringent condition, as the emittance has to be reduced by a factor of $1/K$. A possible benefit of this strategy (reducing N) is to reduce the Υ parameter. (b) As we have seen in

6

Sec. 1, we ought not to set $\Upsilon < 1$. In fact, when we set $\Upsilon \gg 1$, a large amount of quantum suppression occurs, as seen in Eq. (2).

Combining the above two findings (a) and (b), we adopt the strategy to reduce σ_z to satisfy Eq. (3) in $\Upsilon \gg 1$. To adopt smallest possible σ_z means to adopt smallest possible driver wavelength λ. In the following we list some of the important physical constraints for the wakefield acceleration for collider considerations.

The mechanism of the wakefield excitation and acceleration of electrons by this mechanism have been demonstrated by a series of recent experiments ([9], for example). What this approach promises is: (i) short driver wavelength of typically $100\,\mu m$ (see below), at least two orders of magnitude shorter than the existing rf driver wavelength, and thus at least two orders of magnitude smaller σ_z than the competing linear collider equivalent (see, e.g. Wessenskow); (ii) the accelerating gradient far greater than any existing (or proposed) rf drivers by at least two orders of magnitude, thus leading to compactification of the accelerator at least by two orders of magnitude. The laser wakefield mechanism operates either in the linear regime or in the nonlinear regime. In the linear regime (as reviewed in [12]), the accelerating and focusing fields of the laser driven wakefields are

$$E_z = \mathcal{E}_0 \frac{\sqrt{\pi}}{2} a_0^2 e^{-r^2/\sigma_r^2} k_p\sigma_z \, e^{-k_p^2\sigma_z^2/4} \cos(k_p\zeta), \tag{4}$$

$$E_r = -\mathcal{E}_0 \sqrt{\pi} a_0^2 k_p\sigma_r \frac{r}{\sigma_r} e^{-r^2/\sigma_r^2} k_p\sigma_z \, e^{-k_p^2\sigma_z^2/4} \sin(k_p\zeta), \tag{5}$$

where $\zeta = z - ct$, $a_0 = eE_0/m\omega c$, E_0 is the laser electric field amplitude, and $\mathcal{E}_0 = m\omega_p c/e$. In the nonlinear regime stronger steepening (non-sinusoidal) wave profile as well as a higher wake amplitude is expected. In the linear regime the focused laser will diffract over the Rayleigh range $L_R = \pi w^2/\lambda_\ell$, where w is the focused waist size, λ_ℓ the laser wavelength. When there is a plasma fiber structure where the plasma density is depressed in the middle, the laser is expected to be contained much beyond the Rayleigh length [15], which has been demonstrated by Milchberg et al. [16]. When the laser is guided in such a plasma fiber, the

7

acceleration is expected to last over the length shorter of the two, the dephasing length L_{dep} and the pump depletion length L_{pd}, which are [8,12]

$$L_{\text{dep}} \approx 2\omega^2 c/\omega_p^3 \propto n_e^{-3/2}, \tag{6}$$

and

$$L_{pd} \approx L_{\text{dep}}/a_0^2. \tag{7}$$

In nonlinear regimes, however, the laser beam is expected to self-channel due to both the relativistic electron mass effect and the transverse wakefield space charge effect. The critical laser power above which this laser self-channeling takes place is theoretically given as

$$P > P_c = \frac{c}{4}\left(\frac{mc^2}{e}\right)^2\left(\frac{\omega}{\omega_p}\right)^2. \tag{8}$$

In recent years several experiments have demonstrated that self-channeling of laser happens above a certain threshold and in some experiments accompanying electron accelerations have been observed, though the mechanism and the threshold value are still in debate.

In the present collider design we take the laser wakefield excitation only in the linear regime with a (certain) external plasma channel formation (unspecified at this time). This is because we prefer a conservative, predictive, linear regime for collider operations. [On the other hand, for other applications of electron acceleration such as medical, a "carefree" nonlinear, self-channeling regime may be attractive.] The laser and plasma parameters we set for the laser wakefield accelerator operation are listed in Table 2.

The betatron oscillation length can be obtained from Eq. (5) through the focusing equation of motion as

$$y'' + \left(\frac{a_0^2 e \mathcal{E}_0 \sin(k_p \zeta)}{mc^2 \gamma k_p \sigma_r^2} k_p\right)\sigma_z y = 0, \tag{9}$$

where σ_r, σ_z is the transverse and longitudinal and longitudinal sizes of the wakefield, k_p the wakefield wavenumber (c/ω_p). From this the betatron wavelength λ_β is

$$\lambda_\beta = \left(\frac{mc^2 \gamma \sigma_r^2}{a_0^2 e \mathcal{E}_0 \sigma_z \sin \psi}\right)^{1/2}, \tag{10}$$

when $\cos\psi \equiv \cos k_p\zeta$, the phase factor of where the electron sits in the wakefield. We can show that the wakefield structure, Eqs. (4) and (5), has the quarter period of simultaneous focusing and acceleration, and at the same time this quarter period is the longitudinal focusing as well, a property distinct for laser wakefields and valuable for accelerator considerations. The associated electron (or position) beam size is given in terms of emittance ϵ as

$$\sigma_\perp = (\epsilon\lambda_\beta)^{1/2} = \left[\epsilon\sigma_r\left(\frac{\gamma mc^2}{a_0^2 e\mathcal{E}_0\sigma_z}\right)^{1/2}\right]^{1/2}. \tag{11}$$

It is instructive to check the interaction of beam electrons with the plasma particles. According to Montague and Schnell [13], the induced emittance growth due to the multiple scattering of electrons in a plasma is

$$\Delta\epsilon = \left(\sqrt{\gamma_f} - \sqrt{\gamma_i}\right) \cdot 4\pi r_e^2 \sigma_0 n \left(\frac{mc^2}{e\mathcal{E}_0\sin\psi}\right)^{3/2} \left(\frac{-\pi\tan\psi}{\lambda_p}\right)^{1/2} \ell n\left(\frac{\lambda_p}{R}\right), \tag{12}$$

where γ_f and γ_i are the final and initial energy, r_e the classical electron radius, λ_p the wavelength of the wakefield, σ_0 the standard deviation of the laser cross-section. ψ the accelerating phase angle and R the effective Coulomb radius of protons. Our design parameters allow this emittance growth well within control. We point out, however, that the emittance growth due to the plasma fluctuations and the nonideal wakefield structure is very crucial in evaluating the current collider design, which has to be a very important future theoretical investigation. The energy loss due to the synchrotron emission in wakefield is estimated [13] to be

$$U' = 5 \times 10^{-10} a^2 \left(\frac{\gamma}{\beta}\right)^4, \quad (\text{Vm}^{-1}), \tag{13}$$

where a is the betatron amplitude, while the particle cooling is

$$(U')_\sigma = 5 \times 10^{-10}\gamma\epsilon\left(\frac{\gamma}{\beta}\right)^3, \quad (\text{Vm}^{-1}) \tag{14}$$

which is neglibly small for our parameters.

9

We briefly discuss the issue of beam loading. When we load multiple bunches behind a single laser pulse which is exciting multiple periods of wakefields, the energy gain by the different bunchlets arises due to the energy absorption (beam loading effect) of the wakefield by the preceding bunchlets. Since we want to increase the coupling coefficient between the laser energy to the beam energy, the laser-induced wakefield energy should be exploited to a maximal possible extent. It turns out that the increased coupling efficiency and the minimum spread (i.e. longitudinal emittance) of energy gain conflict with each other. According to Katsouleas *et al.* [17], the spread in energy gain in the wakefield is

$$\frac{\Delta\gamma_{\max} - \Delta\gamma_{\min}}{\Delta\gamma_{\max}} = \frac{N}{N_0}, \tag{15}$$

where $\Delta\gamma_{\max}$ is the maximum energy gain of a bunch, while $\Delta\gamma_{\min}$ is the minimum of a bunch, while the beam loading efficiency η_b (the ratio of the energy gained by the beam to the energy in the wakefield) is given by

$$\eta_b = \frac{N}{N_0}\left(2 - \frac{N}{N_0}\right), \tag{16}$$

where N is the total number of particles in a bunch and N_0 is the total number of particles at the perfect beam loading. The perfect beam loading is given [17] as

$$N_0 = 5 \times 10^5 \frac{n_1}{n_0} \sqrt{n_0}\, A, \tag{17}$$

where n_1 is the density perturbation of the wakefield [which can be expressed as a function of a_0^2, see Eq. (4)], n_0 is the background electron density, and A the area (in cm) of the laser pulse (or wakefield). Because of this difficulty (though some optimization may be done with the shaping of the laser pulse), we adopt the strategy of having only one bunchlet per wakefield. Because of large Υ, significant quantum suppression takes place and n_γ and δ_E are independent of N in the extreme large Υ, we can put all particles in a single bunch (maximize N) to maximize the beam loading efficiency, without facing the consequence of

10

Eq. (15). Thus the beam loading efficiency can be as large as near 100% (though we probably choose it around $\frac{1}{2}$, for the internal bunch structure consideration).

Some additional comments are due for the preferred operating scenarios of [1], Scenario IA and Scenario IB. Scenario IA represents the design that is in the large Υ regime, where the condition Eq. (3) is respected, though it is at the edge of entering the extreme large Υ regime. Here the energy constraint for the beam energy gain per stage requires that the laser beam area A is of the order of $10^{-6}\,\text{cm}^2$, accelerating particles of $N \sim 10^8$. In this scenario, since the spot diameter of laser ($\sim 10\,\mu\text{m}$) is of the same order of the plasma collisionless skin depth, we recommend the use of the hollow plasma channel, in which (we do not specify how) the vacuum channel with width $\sim \mu\text{m}$ surrounded by a plasma of $n_0 \sim 10^{17}\,\text{cm}^{-3}$. Thus a small emittance requirement of Scenario IA might be met (though as we cautioned in the above, the plasma noise effects [14] need to be assessed). In this regime, required lasers are already available at the power etc., except for the high repetitive rate, although a gun barrel-like multiple lasers, for example, can be considered (see [10]).

An alternative scenario, Scenario IB, takes full advantage of the extreme high Υ regime. As we commented already, in this regime we need not respect Eq. (3) any more and once we choose σ_z and the related conditions in Eq. (15), we can arbitrarily set N as far as the collider considerations are concerned. As we metnioned in this section, we set N from the laser and plasma considerations and $N \sim 10^{10}$. In this scenario, Υ exceeds 10^4 and in a completely quantum regime. In such a high Υ regime we need further study of collision physics, however. The relatively large N allows relatively low laser repetition rate f_c, ($< 10^3\,\text{Hz}$) relatively large emittance ($\epsilon \sim 100\,\text{nm}$) at a relatively low power (2 MW).

Lastly, it might alarm some of us to know that a large number of instabilities [18] exist in a plasma. To our best knowledge, however, we fail to see these parameters of beam-plasma particles give rise to damaging beam-plasma instabilities. This is firstly because the bunch length is shorter than the typical wavelength of the instability $2\pi c/\omega_p$. Secondly, the rigidity

Table 2: Laser and Plasma Parameters for Case IA [1]

laser energy	$\frac{1}{3}$ J
pulse length	100 fs
plasma density	$10^{17}\,\mathrm{cm^{-1}}$
laser intensity	$10^{18.5}\,\mathrm{W/cm^2}$
spot size	$\sim 10\,\mu\mathrm{m}$
power	$10^{12}\,\mathrm{W}$
dephasing length	$10^2\,\mathrm{cm}$
pump depletion length	$10^2\,\mathrm{cm}$
E_{acc}	10 GeV/m
$\dfrac{dE_{\mathrm{acc}}}{dr}$	$10\,\mathrm{GeV/m}/(5\,\mu\mathrm{m})$
plasma channel	hollow channel of $\sim 10\,\mu\mathrm{m}$ diameter
rep rate	50 kHz

of beam at $\gamma \sim 10^6$ makes most of the plasma instability growth rate small.

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