LASER-PLASMA-ACCELERATOR-BASED $\gamma\gamma$ COLLIDERS*

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Abstract

Design considerations for a next-generation linear collider based on laser-plasma accelerators are discussed, and a laser-plasma accelerator gamma-gamma ($\gamma\gamma$) collider is considered. An example of the parameters for a 0.5 TeV laser-plasma accelerator $\gamma\gamma$ collider is presented.

INTRODUCTION

Advanced acceleration techniques are actively being pursued to expand the energy frontier of future colliders. Although the exact minimum energy of interest for the next lepton collider will be determined by the Large Hadron Collider experiments that are presently underway, it is anticipated that center-of-mass energies approaching 1 TeV will be required. This energy is already near the limit of what can be constructed using conventional accelerator technology, given space and cost restrictions [1].

Laser-plasma accelerators (LPA) [2] have demonstrated accelerating gradients on the order of 100 GV/m, some three orders of magnitude larger than conventional accelerators. Recent LPA experiments have demonstrated high-quality GeV electron beams at Lawrence Berkeley National Laboratory (LBNL) [3, 4]. LPA technology has the potential to significantly reduce the main linac length (and, therefore, the cost) of a future lepton collider. It is natural to consider a gamma-gamma ($\gamma\gamma$) collider since the same laser technology that drives the plasma wave to accelerate the electron beam may be used for Compton back-scatter, generating the gamma rays for collision.

LASER-PLASMA ACCELERATORS

The amplitude of the accelerating field of a plasma wave driven by a resonant laser (pulse duration on the order of the plasma period) is approximately $E_z \approx \left(\frac{\gamma_{\perp}^2 - 1}{\gamma_{\perp}}\right)E_0$. Here $\gamma_{\perp} = (1 + a^2/2)^{1/2}$ is the Lorentz factor associated with the quiver motion of the electrons in the linearly-polarized laser field, $a^2 = 7.3 \times 10^{-19}(\lambda[\mu m])^2 J_0[W/cm^2]$ the normalized laser intensity, and $E_0 = mc\omega_p/e \approx (96 V/m)(n[cm^{-3}])^{1/2}$ is the characteristic plasma wave accelerating field amplitude, with $\omega_p = k_p c = (4\pi me^2/m)^{1/2}$ the plasma frequency and $n$ the plasma number density. For additional control, the laser-plasma accelerator will operate in the quasi-linear regime ($a \sim 1$). The quasi-linear regime is accessible for parameters such that $a^2/\gamma_{\perp} < k_p^2 r_L^2$, where $r_L$ is the characteristic scale length of the transverse laser intensity. The transverse focusing force in the quasi-linear regime scales as $F_{\perp} \propto k_p^{-1} \nabla_{\perp} a^2$ and therefore by shaping the transverse profile of the laser, the transverse forces in the accelerator can be controlled. Control over the focusing forces enables control of the beam dynamics (e.g., the beam matching condition). This control is not available in the highly-nonlinear blow-out regime, where the transverse forces are determined solely by the plasma density.

In general, the energy gain in a single laser-plasma accelerator stage may be limited by laser diffraction effects, dephasing of the electrons with respect to the accelerating field, and laser energy depletion into the plasma wave. Laser diffraction effects can be mitigated by use of a plasma channel (transverse plasma density tailoring), guiding the laser over many Rayleigh ranges [5]. Dephasing can be mitigated by plasma density tapering (longitudinal density tailoring), which can maintain the position of the electron beam at a given phase of the plasma wave [6]. Hence the single-stage energy gain is ultimately determined by laser energy depletion [7]. The energy depletion length scales as $L_d \propto n^{-3/2}$, and, with $E_0 \propto n^{1/2}$, the energy gain in a single stage scales as $W_{\text{stage}} \propto n^{-1}$.

After a single laser-plasma accelerating stage, the laser energy is depleted and a fresh laser pulse must be coupled into the plasma for further acceleration. This coupling distance is critical to determining the overall accelerator length (average gradient of the main linac) and the optimal plasma density at which to operate. One advantage of laser drivers for plasma acceleration is the potential for a short coupling distance between stages, and, therefore, the possibility of a high average accelerating gradient and a relatively short main linac length. The overall linac length will be given by $L_{\text{total}} = L_{\text{stage}} + L_0/E_b/W_{\text{stage}}$, where $L_0$ is the required coupling distance for a new drive laser (and space for any required beam transport and diagnostics), $E_b$ is the beam energy before collision, and $L_{\text{stage}} \approx L_d$ is the single-stage plasma length. Figure 1 plots the main linac length versus plasma density for several coupling distances, with $E_b = 0.5$ TeV and $a_0 = 1.5$. Here the single-stage length and energy gain was calculated using a fluid code [8] to model the laser-plasma interaction. Plasma mirrors show great promise as optics to direct high-intensity laser pulses, potentially requiring only tens of cm to couple a drive laser into a plasma accelerator stage [9].

COLLIDER DESIGN CONSIDERATIONS

The rate of events in a collider is determined by the product of the collision cross section and luminosity. The geometric luminosity is $\mathcal{L} = \int dN^2/(4\pi\sigma_x\sigma_y)$

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a resonant laser pulse with Hydrogen plasma with a temperature of weakly-dependent on plasma density and that, assuming a ions) was examined. It was shown that the growth is onlytering of the beam electrons with the background plasma instabilities are absent.

Photon beams can be generated from the electron beams before the IP via Compton scattering. Here we will consider near backscatter (with small collision angle $\theta \ll 1$) of the electron beam with a circularly polarized laser (polarization of the counterpropagating laser opposite that of the electrons). Solving the energy-momentum conservation equations for the electron ($u_\mu$), laser ($k_L$), and scattered light ($k_s$), $mc u_\mu + h k_L = mc u'_\mu + h k_s$, yields the maximum photon energy $h \omega = E_0 c^2 (1 + x + a_L^2)$, where $a_L^2$ is the normalized laser intensity and $x = (4 E_0 h \omega_L / m^2 c^4) \cos^2(\theta/2)$. Maximizing scattered photon energy requires maximizing $x$.

Photons may be lost due to the creation of $e^+e^-$ pairs (with the associated background issues for the detector). To avoid $e^+e^-$ pair creation requires $(h k_\mu + h k_L)^2 = 4 h^2 k_\mu k_L \leq (2 m c^2)^2 (1 + a_L^2)$, or $x \leq 2 (1 + a_L^2) (1 + \sqrt{2}) \approx 4.83 (1 + a_L^2)$. For $x = 4.8$, $h \omega \approx 0.83 E_0$ assuming $a_L \ll 1$, and $\omega L E_b = (m c^2)^2 x/4 \approx 0.3$ (MeV)$^2$, or $\lambda_L [\mu m] \approx 4 E_0 [\mathrm{TeV}]$. For example, using a solid-state laser $\omega L = 1.2$ eV, and scattering off an electron beam with $E_e = 250$ GeV, yields $h \omega \approx 200$ GeV.

The luminosity of the photon beams is given by $\mathcal{L} = (N_\gamma / N_e)^2 \mathcal{L}_{e^+e^-}$, where $N_\gamma$ is the number of gamma-pulse. Comparable luminosity requires $N_\gamma \sim N_e$. The cross-section for single-photon Compton scattering ($x > 1$) is approximately $\sigma_C \approx 2 \times 10^{-25}$ cm$^2$ for $x = 4.8$. In the following we will assume $2 Z_R \approx l_L > l_b$ for efficient scattering in the linear regime, with $Z_R$ the Rayleigh range, $l_L$ the laser pulse length, and $l_b$ the electron beam length. To produce $N_\gamma \sim N_e$ requires $\sigma_C N_L / A_L \sim 1$, i.e., the thickness of the laser “target” is equal to one Compton scattering length. Here $N_L$ is the number of laser photons/pulse and $A_L \sim \lambda_L / Z_R / 2$. Setting $\sigma_C N_L / A_L = 1$, yields the required laser energy $U_L = N_1 h\omega_L = \pi \hbar c Z_R / \sigma_C$ or $U_L \approx 4 Z_R [\mathrm{mm}] \approx 2 l_L [\mu m]$. With this laser energy (i.e., one Compton scattering length), the conversion efficiency is $N_\gamma / N_e \approx 1 - e^{-1} \approx 0.65$. Using $U_L = \pi \hbar c z / \sigma_C$, the normalized intensity can be expressed as $a_L^2 l_L = (2 r_0^2 / \alpha \sigma_C) \lambda_L$ or $a_L^2 l_L [\mu m] \approx 0.4 E_0 [\mathrm{TeV}]$. The laser energy required is therefore $U_L [\mu m] \approx (0.8 a_L^2) E_0 [\mathrm{TeV}]$. The pulse duration must be long enough such that the intensity is sufficiently low to avoid nonlinear (multi-photon) scattering: $a_L^2 < 1$.

In addition the peak electric field of the laser in the rest frame of the beam must be less than the Schwinger critical field to minimize beamstrahlung. This condition can be expressed as $a_L < \lambda_L / (2 \lambda_C) = 2 / x \approx 0.4$. Setting $a_L^2 = 0.1$ yields $l_L [\mu m] \approx 4 E_0 [\mathrm{TeV}]$, and $U_L [\mu m] \approx 8 E_0 [\mathrm{TeV}]$.

For example, a beam with $E_b = 250$ GeV ($E_{\text{cm}} = 0.5$ TeV) requires a $1 \mu m$ wavelength, 2 J, 3 ps laser, with $Z_R = 0.5$ mm and $I = 2.7 \times 10^{13}$ W/cm$^2$. The gamma-ray energy peaks at $0.8 E_b = 200$ GeV, with luminosity $\mathcal{L}_{\gamma\gamma}/L_{e^+e^-} \approx (N_\gamma / N_e)^2 \approx 0.43$. Note that, although the interaction of the laser with the electron beam is at a point where the electron beam cross-section is approxi-

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mately that of the laser, the scattered light is along the direction of the electron beam (since $E_b \gg \hbar \omega_L$) and will converge at the IP. The interaction must be done sufficiently close to the IP such that the natural spreading of the gamma rays, with divergence $(1 + x + a_{\perp}^2)^{1/2}mc^2/E_b$, does not significantly reduce the collisions.

**Plasma Density Scalings**

The accelerating gradient scales with plasma density as $E_z \propto n^{1/2}$ and the single-stage length scales as $L_{\text{stage}} \propto n^{-3/2}$, yielding a single stage energy gain that scales as $W_{\text{stage}} \propto n^{-1}$. In general, for efficient coupling, the bunch number will scale with plasma density as $N \propto n^{-1/2}$. Therefore, for constant luminosity, and all other beam parameters fixed, the repetition rate scales as $f \propto n$, and the beam power will scale as $P_b = f NE_b \propto n^{1/2}$. The number of stages scales as $N_{\text{stage}} = E_b/W_{\text{stage}} \propto n$, so the average laser power per stage scales as $P_{\text{laser}} \propto n^{-1/2}$ and the total wall plug power for the acceleration scales as $P_{\text{wall}} \propto n^{1/2}$. Operational cost of future linear colliders limit the wall plug power to on the order of hundred MW.

Table 1 shows a 0.5 TeV $\gamma\gamma$ collider example using $n = 10^{17}$ cm$^{-3}$. Typical conversion efficiencies are ~50% for laser to plasma wave and ~30% for plasma wave to beam (shaped electron beams are assumed to avoid energy spread growth), such that the overall efficiency from laser to beam is ~15%. If we assume a wall-plug to laser efficiency of ~33%, then the efficiency from wall plug to beam is ~5%.

**CONCLUSIONS**

In this paper we have discussed several design considerations for future linear colliders based on LPAs. An example of collider parameters for 0.5 TeV center-of-mass energy using plasma density of $n = 10^{17}$ cm$^{-3}$ is summarized in Table 1. We have considered a gamma-gamma collider via Compton scattering of LPA electron beams. A gamma-gamma collider would eliminate the need for positron creation and accompanying damping rings. The scattering laser energy requirements for the 0.5 TeV gamma-gamma collider are near those required for driving the LPA (e.g., 1 $\mu$m wavelength with ~10 J of laser energy at the accelerator repetition rate). Significant laser technology advances are required to realize the next-generation linear collider. Although ~10 J, short pulse lasers are currently available, repetition rates of ~10 kHz and efficiencies of ~30% are presently beyond state-of-the-art laser technology. Diode-pump solid state lasers show promise to generate hundreds of kW with high efficiency in the next decade. In addition there is significant LPA R&D required before realization of a LPA-based linear collider is possible. In particular, these include demonstration of accelerator stage coupling, detailed control of beam injection, and maintaining high beam quality over the length of the accelerator. The next-generation linear collider is extremely challenging for any technology, but laser-plasma-based accelerators continue to show great promise as a solution to address the size of future linear colliders.

**REFERENCES**


