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High Energy Physics Applications**

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Terawatt Picosecond CO₂ Laser Technology for High Energy Physics Applications

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Abstract. Demonstration of ultra-high acceleration gradients in the SM LWFA experiments put a next objective for the laser accelerator development: to achieve a low-emittance monochromatic acceleration over extended interaction distances. The emerging picosecond terawatt (ps-TW) CO₂ laser technology helps to meet this strategic goal. Among the considered examples are: the staged electron laser accelerator (STELLA) experiment, which is being conducted at the Brookhaven ATF, and the plasma-channeled LWFA. The long-wavelength and high average power capabilities of CO₂ lasers may be utilized also for generation of intense x-ray and gamma radiation through Compton back-scattering of the laser beams off relativistic electrons. We discuss applications of ps-TW CO₂ lasers for a tentative γ - γ (or γ -lepton) collider and generation of polarized positron beams.

INTRODUCTION

The first ps-TW CO₂ laser is close to completion at the BNL ATF [1-3]. Benefits of using a long-wavelength laser driver for laser accelerators are two-fold. For processes based on electron quiver motion, like in the LWFA, the advantage of CO₂ lasers is primarily due to a gain of two orders of magnitude in the ponderomotive potential, W_{osc} , which is quadratically proportional to λ :

$$W_{osc} = e^2 E_L^2 / 2m\omega^2, \quad (1)$$

where E_L is the laser electric field amplitude. The ponderomotive strength of the CO₂ laser is the most easy to reveal in the self-modulated LWFA. In this case, it facilitates to attain the relativistic self-focusing condition,

$$P_L \geq 17(\lambda_p / \lambda)^2 [GW] \quad (2)$$

(where P_L is the laser peak power and λ_p is the plasma wavelength), and is ultimately responsible for the net energy gain scaling per the dephasing limited accelerator stage, $\gamma_{max} \propto \lambda \sqrt{P_L}$ [4].

It is acknowledged that after the successful experimental demonstration of the ultra-high gradient (up to 100 GeV/m) laser electron acceleration [5-7], the next goal in the laser accelerator development is to design and demonstrate extended quasi-monoenergetic acceleration of appreciably bulk electron charges (~ 0.1 nC).

Similar to a conventional RF accelerator, a high monochromaticity can be achieved in the laser driven accelerator when the electron bunch is a small fraction of the accelerating field period. Using the expansion of a sine function, it is easy to estimate that the electron beam energy spread, $\Delta E / E$ drops quadratically with the

reduction in the bunch length. For example, $\Delta E / E$ reaches 0.1% when the longitudinal and transverse dimensions of the quasi-relativistic electron bunch are equal to $\sim 2\%$ of the driving field period.

In the case of RF linacs, with their ~ 100 MHz accelerating fields, the required electron bunches are generated using photocathode RF guns driven by picosecond lasers. Orders of magnitude higher frequencies of the drive field in laser accelerators may require proportionally short electron bunches. Producing of sufficiently short, femtosecond bunches presents a serious technical problem. In addition, bunch shortening leads to reduction of the number of electrons per bunch (see below). Under these circumstances, a prudent selection of the laser driver wavelength is required.

In the present paper, we illustrate the importance of the wavelength optimization for both structure scaling and ponderomotive wake enhancement by two practical examples: a prospective plasma channelled LWFA and the far-field STELLA experiment which is ongoing at the ATF.

In Section 2, we start with a brief overview of the ATF, its ps-TW CO₂ laser project, and review some prospects of the ps-TW CO₂ laser technology.

In Section 3, we discuss the dependence of the LWFA performance upon the laser wavelength and apply our conclusions to optimization of the plasma-channel LWFA operating in a linear regime. In this case, the electron beam energy spread, emittance, and luminosity improve with longer λ_p which tends to be proportional to λ . This enables design of two-stage monochromatic GeV laser accelerators as well as future high-luminosity, multi-stage TeV electron linacs.

Electron bunch miniaturization is required for far-field laser accelerators based on direct electron acceleration in the laser beam. In this case, the electron bunch shall fit into a small fraction of λ . Such ultra-short periodical micro-bunches synchronized to the laser accelerating field can be produced by no means but energy modulation of the initial macro-bunch by the same laser source that drives the laser accelerator. A number of considerations point to the long-wavelength CO₂ laser as a practical choice for such an accelerator. In Section 4, we illustrate this approach by the example of STELLA experiment that is under way at the ATF.

The long-wavelength and large average power capabilities of CO₂ lasers may be utilized also for generation of intense x-ray and gamma radiation through Compton back-scattering of the laser beams off relativistic electrons. In Section 5, we discuss applications of TWps-CO₂ lasers for a tentative $\gamma\text{-}\gamma$ (or $\gamma\text{-lepton}$) collider and generation of polarized positron beams.

OVERVIEW OF THE ATF

The approach to the monochromatic laser acceleration discussed in this paper is based on using a combination of the emerging ps-TW CO₂ laser technology with conventional high-brightness picosecond and subpicosecond electron injectors. Both these ingredients become available at the ATF.

The ATF's electron linac delivers up to 3 nC, 10-0.3 ps, 50 MeV electron bunches with a peak current of 100-300 A, energy spread of 0.2%, and a normalized emittance $\epsilon_n=0.5$ mm.mrad. Note, that with the present 10-ps UV photocathode laser driver, the electron bunch compression to 370 fs is achieved by the proper electron phasing to the RF field in the gun [8]. A shorter, down to 100 fs electron bunch duration may be attained with the faster, ~ 1 ps, laser driver.

Upgrade of the presently operational at the ATF 100-ps 10-GW CO₂ laser to the terawatt level is close to completion. The power increase will be attained via both energy boost in the additional big-aperture laser amplifier and pulse shortening to 1-10 ps [1-3].

Shown in the floor plan in Fig.1, is the new CO₂ laser system called PITER I (1st Picosecond TERawatt). Positioning of the high-pressure laser amplifier in Room C1, and its 1-MV Marx generator behind the partition, helps to isolate these potential sources of the EM noise from the computer-interfaced control and diagnostics equipment located in Room C2. By means of in-vacuum laser beam transport tube, the control Nd:YAG laser located close to the linac front end is optically connected with the CO₂ laser system. The optical table in room C2 accommodates the oscillator, picosecond pulse slicer, and preamplifier.

The oscillator and semiconductor switch supply a seed pulse into the regenerative preamplifier with the active discharge volume of 1.2 liters (optical aperture 2×5 cm², discharge length 1.2 m). Extracted by a Pockels cell at several millijoules, the laser pulse is redirected for additional passes through the same discharge cell to acquire ~ 100 mJ energy. The preamplifier output is directed to the final high-pressure amplifier stage that is the main component of the ATF CO₂ laser upgrade.

In the 10-atm, x-ray preionized, transverse electric discharge amplifier, pressure broadening of the CO₂ gain spectrum into the 1 THz wide quasi-continuum permits direct amplification of picosecond terawatt laser pulses. For a $\tau_L=1$ ps pulse, the small-signal gain is 3-4%/cm, saturation fluence 500 mJ/cm², and the extractable specific energy ~ 20 mJ/cm³. Taking into account that the total discharge volume of the amplifier is 10 liters, the possibility of extracting of the order of 100 J of energy in a picosecond pulse looks possible. However, the limiting factor to the high energy extraction is the damage of the output window at the level of 0.5 J/cm². An optical window of the 80 cm² size permits ~ 30 TW peak power extraction at the 1-ps laser pulse duration.

The tests of the new laser system are close to completion. Fig.2 and 3 illustrate the last preparations of the amplifier high-pressure discharge cell to operation.

An alternative way to achieve gain smoothing is to reduce the spectrum modulation period using a CO₂ gas mixture with a combination of the isotopes O¹⁶ and O¹⁸. Due to the isotopic shifts, the combined spectrum has 4-times denser rotational line structure than with a regular CO₂ molecule. That permits to reach gain smoothing at a lower gas pressure. This approach will be used in the UV-preionized preamplifier that operates at the 5 atm gas pressure.

FIGURE 1. Fragment of the ATF floor plan showing CO₂ laser rooms and a portion of the experimental hall

However, 1 ps is still not the bottom limit for CO₂ laser pulse shortening. Taking a combination of all available isotopes O^(16,18) and C^(12,13,14) a continuum can be produced that extends over the spectral region of the 7 THz bandwidth [9]. Then amplification of as short as 100 fs pulse becomes possible. Another method of CO₂ laser pulse shortening uses ipulse chirping in a gas [9,10]. Physics of this process is rather straightforward. Intense laser pulse propagating in a gas produces ionization. As a result the refractive index is nonuniform across the pulse envelope, and the tail of the pulse propagates at a higher speed catching up the front. After a propagation over a certain distance in a gas, or in the dispersive medium, the pulse will shrink. This effect has been observed already by P. Corkum inside the laser amplifier [10]. The desired chirping may be organized in a more controlled fashion inside a gas-filled hollow fiber [11].

Because of the ease of the heat removal by fast gas exchange in the CO₂ amplifier, it is potentially capable to high repetition rates that are difficult to attain with massive glass or crystal active elements. This is important for future advanced applications.

A review of potential capabilities of the TWps-CO₂ laser technology implies that relatively moderate efforts may lead to development of CO₂ lasers with ~10 kW of average power, ~10 J per pulse, as short as 100 fs pulse duration, with the resulting peak power of ~100 TW [2,3]. This set of parameters looks even more attractive if to take into account additional advantages of the CO₂ lasers due to their longer wavelength.

OPTIMUM LASER DRIVER FOR HIGH BRIGHTNESS MONO-ENERGETIC LWFA

Due to a relatively high stability and regularity of the produced wake field, the linear LWFA scheme [12] is considered as the most promising candidate for the

FIGURE 2. At the amplifier output window

FIGURE 3. Alignment of the ground mesh electrode inside the amplifier discharge cell

prospective laser-driven accelerator in the GeV energy range. For this scheme, the laser pulse duration and plasma wavelength satisfy the resonance condition $\tau_L \approx \lambda_p/2c$.

The amplitude of the accelerating field is

$$E_{a0}[V/cm] = 0.4 \frac{a^2}{\sqrt{1+a^2/2}} \sqrt{n_e} [cm^{-3}], \quad (3)$$

where a is the normalized vector-potential

$$a = eE_L/m\omega \quad (4)$$

and

$$n_e [cm^{-3}] = \frac{\pi m c^2}{e^2 \lambda_p^2} = 10^{19} / \lambda_p^2 [\mu m] \quad (5)$$

is the plasma density. By definition of the linear regime, $a < 1$.

The net acceleration attainable over the dephasing distance

$$L_{ph} = \lambda_p \left(\frac{\lambda_p}{\lambda} \right)^2 \quad (6)$$

is

$$\Delta W [MeV] = \int_0^{L_{ph}} E_a dz \approx \frac{E_a L_{ph}}{2} = 0.6 \frac{a^2}{\sqrt{1+a^2/2}} \left(\frac{\lambda_p}{\lambda} \right)^2. \quad (7)$$

In the uniform plasma, the acceleration distance within the laser focus waist is defined by the Rayleigh length, $z_0 = \pi r_L^2 / \lambda$. To extend the acceleration over several Rayleigh distances, some form of laser channeling needs to be used. As long as the relativistic self-focusing regime is not allowed for the standard LWFA scheme, we assume that a plasma channel is pre-formed and has a density step at the "wall" to satisfy the waveguide condition

$$\Delta n_e [cm^{-3}] = 1.13 \times 10^{20} / r_L^2 [\mu m]. \quad (8)$$

Assuming an evacuated channel "drilled" in the uniform plasma with λ_p defined by Eq.(5) we come to the conclusion that the radius of the vacuum channel is equal to $\lambda_p/3$. If we assume just a partially rarefied plasma channel with the 10% stepped-down density, $\Delta n_e = 0.1 n_e$, then $r_L \approx \lambda_p$. These estimates define pragmatic limits for r_L .

Using Eqs. (3)-(7), we make a quick estimate for the maximum net gain. We assume $a=1$, the length of the channel $L_{ch} \approx L_{ph}$ and $\lambda_p/r_L \approx 2$. Then,

$$\Delta W^{\max} [GeV] \approx 0.06 P_L [TW]. \quad (9)$$

Another scaling law follows from the resonance condition and Eq. (7):

$$\tau_L^{\min} [\lambda] \approx 20 \sqrt{\Delta W} [GeV]. \quad (10)$$

For example, the 3 GeV LWFA requires $P_L \approx 50$ TW and $\tau_L \geq 1$ ps at $\lambda = 10 \mu m$. The length of the accelerating channel, $L_{ch} \approx 1$ m. Such compact accelerator is attractive as

a stand-alone device or as a construction block for a future staged linac of the TeV energy range.

For any application, such an accelerator shall provide a reasonable monochromaticity ($\Delta E / E \leq 1\%$) and an appreciably high charge ($N_e \geq 10^9$ electrons/bunch). The maximum number of the electrons per bunch is defined by the condition that the self-field of the bunch does not alter the plasma wakefield structure,

$$N_e \leq n_e \left(c / \omega_p \right)^3 = 4 \times 10^6 \lambda_p [\mu m]. \quad (11)$$

That means that the $N_e^{\max}$ scales proportionally to λ_p reaching 10^9 at $\lambda_p \approx 250 \mu m$. A similar conclusion may be driven from the energy conservation condition. Indeed, as follows from Eqs.(9) and (10), with the increase of λ_p the proportionally higher laser pulse energy is required to drive the LWFA in the linear regime. A higher laser energy permits to accelerate the proportionally bigger electron bunch charge.

We know that another important condition for the small energy spread requires the electron bunch to be much shorter than the plasma wake period, $\tau_b \ll \lambda_p / c$. This again favors bigger λ_p . At the other hand, there is an apparent downside to the λ_p increase: drop in the acceleration gradient that, according to Eqs.(3) and (5), is

$$E_a^{\max} [GV / m] \approx 10^3 / \lambda_p [\mu m]. \quad (12)$$

Thus, we see a certain tradeoff between two trends (λ_p increase for better $\Delta E / E$ and N_e but its reduction for higher E_a) that has to be resolved depending upon the accelerator design goals.

The main cumulative performance characteristic of the collider is a luminosity,

$$\Lambda = \frac{N_e^2 f}{4\pi\sigma_{\perp}^2}, \quad (13)$$

where f is the repetition rate of electron bunches (laser pulses), and $\sigma_{\perp}$ is the e-beam radius at the interaction point. The luminosity-targeted optimization of the 2 GeV LWFA design for two possible types of lasers is attempted in Table 1 that shows the proportionality between N_e and λ under the optimum conditions. According to Eq.(13), λ -proportional increase in N_e allows λ^2 -proportional reduction in f . Then, the average laser power calculated from

$$P_{av} = P_L \tau_L f \quad (14)$$

scales as $P_{av} \sim 1/\lambda$. For example, to meet the extremely luminosity requirements for the future e^-e^+ collider, $\Lambda = 10^{35} \text{ s}^{-1}\text{cm}^{-2}$ [13], the picosecond CO_2 laser of the 10 kW average power may be required. The equivalent 1- μm laser driver must be of the 100 kW power! Thus, CO_2 laser appears to be the only possible choice to drive the high-luminosity LWFA.

This statement is illustrated by the examples in columns 1 and 2 of Table 1. These examples, together with the generic analytical approach elaborated in this paper, show

TABLE 1. Prospective comparative characteristics for multi-stage LWFA driven with 1- μm and 10- μm lasers

PARAMETERS	Column number			
	1	2	3	4
Wavelength, λ [μm]	10	1	10	1
Pulse Energy [J]	50	5	1.5	15
Pulse length, τ_L [ps]	1	0.1	0.3	0.3
Peak power, P_L [TW]	50	50	5	50
Focal spot radius, r_L [μm]	360	36	120	120
Peak intensity, I [W/cm^2]	10^{16}	10^{18}	10^{16}	10^{17}
Laser field, E_L [TV/m]	0.33	3.3	0.33	1
Dimensionless laser strength, a	1	1	1	0.3
Plasma density, n_e [cm^{-3}]	3×10^{15}	3×10^{17}	3×10^{16}	3×10^{16}
Plasma wavelength, λ_p [μm]	600	60	200	200
Critical laser power, P_{cr} [TW]	60	60	6	600
Acceleration gradient, E_a [GeV/m]	2	20	6	0.8
Free space interaction length, πz_0 [cm]	10	1	1	10
Phase detuning length, L_{ph} [cm]	220	22	7	700
Assumed channel length, L_{ch} [cm]	125	12.5	5.5	125
Energy gain (with channeling), ΔW_{ch} [GeV]	2	2	0.2	0.8
Electrons/bunch, N_e	3×10^9	3×10^8	10^9	10^9

that the ponderomotively strong long-wavelength laser tends to improve the LWFA performance (within the selected spectral range). To abate any concerns regarding the “arbitrary” choice of the input laser parameters, we evaluate two extra cases (columns 3 and 4). These examples illustrate that deviations from the optimum laser driver parameters result in deterioration of the accelerator performance.

For example, in column 3 we estimate the impact of the laser pulse reduction below the minimum calculated by Eq.(10). We see that in order to stay in the linear regime we need to reduce the laser peak power in proportion $P_L \sim \tau_L^2$. Because of the higher plasma density, the acceleration gradient improves inversely proportional to τ_L . However, due to the significant reduction in L_{th} , the net gain per stage drops dramatically. Together with the reduction in N_e , this leads to less attractive accelerator performance (consider the seven times higher number of stages and two times higher total plug-in power consumption by the laser system).

In other example, illustrated by column 4, we increase the laser pulse duration above the calculated optimum (minimum) value. However, due to the recognized solid state laser technology limitations, we can not keep up with the τ_L increase by upscaling $P_L \sim \tau_L^2$ that is required to maintain the acceleration gradient at the same

level. In spite of the longer interaction length, the net acceleration per stage is also down. The number of the acceleration stages and the total accelerator length is up. The requirements to the average laser power will be relaxed, but still beyond any realistic expectations for the solid state laser technology.

Returning to discussion on the electron monochromaticity attainable with the CO₂ laser driven LWFA, we address recent simulations for electron bunch acceleration by plasma wake excited in the matched parabolic plasma channel [14]. The following input parameters have been used in simulations: CO₂ laser with $\tau_L=1$ ps, $P_L=50$ TW, $a=0.71$; plasma channel parameters $k_p r_L=3.8$, $k_p R_{ch}=14.3$, $\lambda_p=800$ μm , where λ_p and k_p are defined at the axis of the plasma channel that has the profile $n_e(r) = n_e^0 \left(1 + \left(r/R_{ch}\right)^2\right)$. The injected electron bunch has the initial energy 50 MeV,

energy spread 0.2%, geometric emittance 3 mm.mrad, the 30 μm (100 fs) length, and 80-160 μm radius at the entrance to the plasma channel. These conditions can be practically realized using a combination of the prospective ps-TW CO₂ laser, linac with the photocathode RF gun, and a plasma channel produced by the high-current capillary discharge in vacuum.

Simulations [14] revealed a need for further reduction in τ_b in order to maintain the electron energy spread below 10%. Accordingly, a feasible monoenergetic LWFA scheme (see Fig.4) includes: the LWFA bunch compressor to 20-15 fs and the energy gain stage. Result of 3D test particle simulations for these stages are shown correspondingly in Fig.5 and 6. In this configuration, 1.7 GeV energy gain with 2% of the energy spread is predicted.

STELLA - FAR-FIELD STAGED ELECTRON LASER ACCELERATOR EXPERIMENT

The problem of the monoenergetic electron acceleration looks even more demanding for far-field accelerator schemes driven directly by the laser electromagnetic field with the wavelength 10-100 times shorter than the plasma wake wavelength. The important step towards a solution of this problem is the STELLA experiment at the ATF. In STELLA, the inverse free electron laser (IFEL) accelerator serves as a prebuncher and inverse Cherenkov accelerator (ICA) provides the main energy gain, similar to the two-stage LWFA discussed in Section 3.

IFEL is based on the accelerating action of a linearly polarized laser beam onto electrons having an oscillating trajectory inside the wiggler [15]. Transverse laser field has an electrical component along the local direction of the e-beam propagation. Electrical field produces an additional kick to the electrons in the direction of propagation if the laser field is in phase with wiggling. Electrons injected in the form of a long bunch will experience both acceleration and deceleration, however, in a very regular way as is shown in Fig. 7 [16].

FIGURE 4. Principle diagram of the two-stage monochromatic LWFA

FIGURE 5. Energy modulation and bunch compression in the LWFA bunching stage; initial bunch length $\tau_{b0}=100$ fs; black boxes - $r_b=50 \mu\text{m}$, $\varepsilon_\theta=0.6 \text{ mm.mrad}$; open circles - $r_b=100 \mu\text{m}$, $\varepsilon_\theta=0.3 \text{ mm.mrad}$

FIGURE 6. Net acceleration (filled boxes) and energy spread (open boxes) in the LWFA acceleration stage after prebuncher; initial electron bunch parameters: $\tau_{b0}=100$ fs; $r_{b0}=50 \mu\text{m}$, $\varepsilon_\theta=0.6 \text{ mm.mrad}$ [14]

FIGURE 7. Simulations of electron beam bunching at $\Delta E/E=1.2\%$ energy modulation in IFEL wiggler: a) initial uniform energy distribution; b) energy modulation at the wiggler exit; c) energy distribution at the entrance to the ICA cell; d) longitudinal density distribution in which 50% of the electrons are bunched into $\text{FWHM}=0.63 \mu\text{m}$. [16]

Being allowed to propagate in a free space, faster electrons will catch up with slower electrons thus developing periodical micro-bunches exactly at the laser wavelength spacing (Fig.7 c-d). This micro-bunch train is injected into the inverse Cherenkov accelerator stage.

In the ICA scheme we start with a radially polarized laser beam [17,18]. Using an axicon, the laser beam is converged to the e-beam axis. Because of the wave front inclination, a longitudinal accelerating component of the electric field is developed. The length of the interaction region depends upon the axicon angle and the input beam diameter. The interaction cell is filled with gas to satisfy the Cherenkov phase matching condition,

$$\beta n \cos \theta = 1. \quad (15)$$

In the separate ATF ICA experiment, the used 10 ps e-bunch uniformly covered 300 CO_2 laser periods. As a result a diffuse electron energy modulation was observed on the spectrometer [19]. In order to make acceleration monochromatic, the electrons need to be injected precisely at the maxima of the accelerating field. That is what the IFEL prebuncher is for.

The principle diagram in Fig.8 illustrates the layout of the STELLA experiment [16]. The CO₂ laser beam is split into two beams. A relatively small amount of the laser power is sent into the IFEL in order to modulate the energy just enough so that the peak bunching occurs at the end of the 190 cm long drift region at the entrance to the ICA stage.

FIGURE 8. Principle diagram of STELLA experiment [17]

Another portion of the split CO₂ laser beam, after passing through a radial polarization converter, is introduced into the ICA gas cell and focused by an axicon mirror along the e-beam axis. To satisfy the phase matching Cherenkov condition, the ICA cell is filled with ~1.7 atm of hydrogen gas. The interaction cell is separated from the vacuum beamline by the 1- μ m thick diamond windows transparent for the electron beam.

Let us reveal how the laser driver wavelength affects the STELLA performance. Self-interference of the axicon-focused radially polarized laser beam results in the J_0 Bessel distribution for the longitudinal (accelerating) field and J_1 distribution for the radial (focusing) component of the electric field. The amplitude of the accelerating field, $E_0(z)$, at the axicon axis is

$$E_0(z) = 2\pi\theta \sqrt{\frac{2zI(R)}{\epsilon_0 c \lambda}} \quad (16)$$

where $z = R/\theta$ and $I(R)$ is the laser intensity distribution at the axicon surface. The radial position of the first minimum of the J_0 Bessel distribution is observed at

$$r_{\min} = 0.38\lambda / \theta. \quad (17)$$

To ensure monochromatic acceleration, $r_{\min}$ shall be set much bigger than the realistic size of the e-beam. The results of Monte-Carlo computer simulations for the realistic low-emittance bunched ATF e-beam acceleration in the ICA cell induced by the 1 TW CO₂ laser pulse (see Fig.9) demonstrate the importance of the condition $r_{\min} > r_b$.

FIGURE 9. Simulations for electron bunch acceleration over 19.4-cm ICA interaction length at $P_L=1$ TW: a) e-beam spot size at axicon; b) e-beam spot size exiting ICA interaction cell; c) radial energy distribution; d) electron spectrum

Electrons farther away from the axis do not experience the peak laser field and, therefore, do not gain the maximum possible amount of energy. However, Fig. 9(c) shows that, due to the initially small electron beam radius and focusing in the laser field, most of the accelerated electrons are confined within the central portion of the beam. As a result, most of the electrons gain up to 125 MeV energy. The FWHM of the electron spectrum shown in Fig. 9(d) is 6 MeV and contains ~50% of all the electrons.

From Eq.(17) we see that the longer λ permits to maintain the proper $r_{\min}$ at the proportionally bigger angle θ . Combining this condition with Eq.(16), we come to the conclusion that $E_{\text{max}} \sim \lambda^{1/2}$. Thus, the acceleration gradient achievable with the CO₂ laser is three times higher than with the solid state laser, due to stronger inclination of the laser wavefront to the e-beam propagation.

Another advantage of using the relatively long-wavelength CO₂ laser radiation for STELLA is due to the favorable proportion of the longitudinal microbunch dimension

to the laser wavelength. Simulations show that the finite electron beam emittance and energy spread, together with the difference in the drift distance of the axial and off-axis electrons between the IFEL and ICA stages results in the microbunch smearing to the minimum 0.63 μm size (see Fig.7). Due to a jitter of the optical components in the laser beam transport to the IFEL and ICA, it is not conceivable to ensure phase synchronization between the microbunches and the accelerating laser field in the ICA stage to the accuracy better than 0.5 μm . All these and similar considerations add to the conclusion that the long-wavelength CO_2 laser is the only practical choice for the staged far-field laser accelerator, such as STELLA.

GAMMA AND POSITRON SOURCES BY COMPTON SCATTERING OF CO_2 LASER BEAMS

By Compton backscattering of the laser photons from the relativistic electron beam, a high brightness x-ray and gamma photon beams can be created. By this process, e^-e^+ collider can be reconfigured into the lepton-gamma collider. It opens an opportunity to study a variety of interaction processes by colliding e^- , e^+ and γ beams in any combination and at independently controlled polarization.

The expression for the maximum gamma photon energy for linear (single photon) Compton backscattering is

$$\hbar\omega_\gamma = \frac{x}{x+1} E_e, \quad (18)$$

where E_e is the electron energy, and $x = 4E_e\hbar\omega/m^2c^4$. At $x \gg 1$, the Compton photon energy approaches the electron energy, $\hbar\omega_\gamma \approx E_e$. For CO_2 laser, $x=1$ at $E_e=0.5$ TeV.

Another strong requirement to the laser wavelength is set by rescattering of gamma photons on the laser beam into pairs through the reaction $\gamma + \lambda \Rightarrow e^- + e^+$. This occurs when $\omega\omega_\gamma > m^2c^4/\hbar^2$. Based on this condition and using Eq.(18), the optimum laser wavelength is derived:

$$\lambda[\mu\text{m}] = 4.2E_e[\text{TeV}]. \quad (19)$$

Then, for the 2.5 TeV collider the laser with $\lambda=10.5$ μm is the right choice.

For $\tau_L=1$ ps, probability of the $e^\pm \Rightarrow \gamma$ conversion,

$$\chi = \sigma_C E_L / \hbar \tau_L c^2, \quad (20)$$

where $\sigma_C=1.9 \times 10^{-25}$ cm^2 is the Compton scattering cross-section, reaches unity at the laser pulse energy $E_L \approx 1$ J.

The polarization of electrons and positrons in the future linear colliders will play an important role for experimental verification of the standard model and for a search of new phenomena beyond the standard model. A prospective high-intensity polarized positron source [20] is based on production of the electron-positron pairs when Compton scattered gamma-quanta are stopped at the foil target. Polarization of the

produced particles is easily controlled by the input laser beam. The recent observation of the first polarized positrons produced by this method proves the viability of this approach [21]. Capable of high average power and delivering ten times more photons than solid state lasers of the similar energy, picosecond CO₂ lasers become the optimum choice for this application as well. The requirements for the high peak flux and short pulse duration of the polarized gamma rays specify the high-brightness electron accelerator and the picosecond subterawatt CO₂ laser as essential components of the projected Compton source for the Japan Linear Collider (JLC). A preliminary proof-of-principle Compton scattering experiment using a ps-TW CO₂ laser is initiated at the BNL ATF.

The JLC project requires up to 1 kHz repetition rate of the delivered positron bunches. To obtain such a cumulative repetition rate, the plan is to deliver the electron and laser pulses in trains of 85 pulses with the 1.4 ns separation between the pulses and 0.1 s intervals between the trains. It will employ 40 CO₂ lasers of 10 ps pulse duration and ~ 1 kW of average power. This project may become the most massive application of CO₂ lasers in fundamental science, to date.

CONCLUSIONS

In the previous sections, by examples of two laser accelerator schemes, STELLA and LWFA, we demonstrate potential advantages of the picosecond CO₂ lasers for high gradient monochromatic laser accelerators. This advantage is primarily due to the favorable scaling of the characteristic accelerator structures (e.g., the accelerating field period) with the laser wavelength, or the quadratic increase in the ponderomotive potential (important for LWFA).

Similarly, big amplitude of electron oscillation in the low-frequency CO₂ laser beam results in the λ -proportional intensity of the Compton (Thomson) scattered radiation. This feature will be utilized in the prospective polarized positron source for JLC.

The proposed schemes can be practically realized using a combination of the conventional electron beam injectors and the emerging ps-TW CO₂ laser technology. The first laser of this kind will be operational at the Brookhaven ATF in 1999.

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