laser collimation

Compton scatter particles in beam halo on high-power laser beam

scattered particles are off energy
- intercepted on downstream absorbers

collimator ('spoiler') cannot be destroyed
  \Rightarrow \text{small } B \text{ functions}
  \Rightarrow \text{short length}

- collimation efficiency
- laser parameters / beam parameters
- chicane for energy collimation
Cross section for Compton scattering

$E_0 = 500 \text{ GeV}, \theta_0 = 10 \mu\text{m} \rightarrow x \approx 0.9$

$\sigma = 2.5 \times 10^{-25} \text{ cm}^2$

Thomson cross section

$x = \frac{E_0}{\theta_0} \frac{E_0}{\text{TeV}} \frac{\text{eV}}{\text{eV}}$

$pairs$
$\frac{d\sigma}{d\Omega}$

\[ y_{\text{max}} = \frac{x}{x+1} \]

\[ y = \frac{xu}{E_0} \quad \text{relative energy of scattered } y \]
use $\text{TEM}_{1,0}$ mode $k=1, m=0$

conversion efficiency: $K_c = 1 - e^{-k_c}$

Gaussian laser modes:

$|E_{l,m}(x,y,z)| = E_0 \frac{w_0}{w(z)} H_0\left(\sqrt{\frac{x^2}{w(z)}}\right) H_m\left(\sqrt{\frac{y^2}{w(z)}}\right) e^{-\frac{x^2+y^2}{w^2(z)}}$

$w^2(z) = w_0^2\left(1 + \frac{z}{z_0}\right)$; $w_0 = \left(\frac{2\alpha^2}{\pi}\right)^{1/2}$; Rayleigh length $z_0 = \frac{\lambda z_0^2}{w_0^2}$
\[ k_c = \frac{c}{\frac{dN_T^2}{d\omega d\theta}} = \frac{c}{\frac{E_0 \cdot |E|^2}{\lambda \omega}} \]

\[ = \frac{A_{\text{laser}}}{\lambda \omega \, w^2 \, \pi} \left( \frac{|E|^2}{E_0^2} \right) \]

Factor 2 or not? (circular vs. linear polarization)

\[ I \, T_L \geq \frac{\lambda \omega}{e} \sim 10^5 \, \frac{W \, s}{cm^2} \quad \text{for reasonable efficiency} \]

want to stay away from nonlinear Compton scattering

\[ \xi \leq 1 \quad \text{or} \quad I \leq 10^{16} - 10^{17} \, \frac{W}{cm^2} \]

\[ \left( \xi = \frac{eE_0}{\hbar \omega \, c} \right) \]

for \( \xi \geq 1 \): electrons become heavy
cross section shrinks
multi photon processes occur

\[ s + g \rightarrow g' + h' \]

\[ \xi = \frac{eE_0}{m \, c \, \gamma} \quad \text{(note: } \gamma = \frac{e}{m \, c^2} E_p \text{)} \]
combine limit on
\[ \frac{I}{1} \text{ and } I \cdot \tau_2 \]

\[ \tau_2 \geq 2 \text{ ps} \]

this approximately fixes Rayleigh length and transverse size

larger \( a \) (e.g., \( a \approx 10 \mu m \)) easier

because cross section is higher

same number of \( \gamma \) for smaller pulse energy
<table>
<thead>
<tr>
<th>parameter</th>
<th>symbol</th>
<th>NLC (1 TeV cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy</td>
<td>$E_b$</td>
<td>500 GeV</td>
</tr>
<tr>
<td>hor. emittance</td>
<td>$\gamma z$</td>
<td>$5 \times 10^{-6}$ m</td>
</tr>
<tr>
<td>vert. emittance</td>
<td>$\gamma z$</td>
<td>$5 \times 10^{-8}$ m</td>
</tr>
<tr>
<td>rms hor. beam size at coll.</td>
<td>$\sigma_z$</td>
<td>2.3 $\mu$m</td>
</tr>
<tr>
<td>rms vert. beam size at coll.</td>
<td>$\sigma_y$</td>
<td>500 nm</td>
</tr>
<tr>
<td>hor. beta function at coll.</td>
<td>$\beta_z$</td>
<td>1.1 m</td>
</tr>
<tr>
<td>vert. beta function at coll.</td>
<td>$\beta_y$</td>
<td>5.0 m</td>
</tr>
<tr>
<td>rms bunch length</td>
<td>$\sigma_z$</td>
<td>125 $\mu$m</td>
</tr>
<tr>
<td>repetition rate</td>
<td>$f_{rep}$</td>
<td>120 Hz</td>
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<tr>
<td>no. bunches per train</td>
<td>$n_b$</td>
<td>90</td>
</tr>
<tr>
<td>time separation of bunches in a train</td>
<td>$t_{sep}$</td>
<td>2.8 ns</td>
</tr>
<tr>
<td>laser energy / bunch</td>
<td>$E_{laser}$</td>
<td>5 J</td>
</tr>
<tr>
<td>laser wavelength</td>
<td>$\lambda$</td>
<td>10 $\mu$m</td>
</tr>
<tr>
<td>laser pulse length</td>
<td>$\tau_l$</td>
<td>2 ps</td>
</tr>
<tr>
<td>Compton sc. parameter</td>
<td>$z$</td>
<td>0.9</td>
</tr>
<tr>
<td>laser parameter</td>
<td>$w_0$</td>
<td>60 $\mu$m</td>
</tr>
<tr>
<td>Rayleigh length</td>
<td>$z_0$</td>
<td>1 mm</td>
</tr>
<tr>
<td>f number</td>
<td>$f$</td>
<td>10</td>
</tr>
<tr>
<td>optical focal length</td>
<td>$F$</td>
<td>33 cm</td>
</tr>
<tr>
<td>number of photons / pulse</td>
<td>$N_\gamma$</td>
<td>$2.7 \times 10^{20}$</td>
</tr>
<tr>
<td>laser intensity</td>
<td>$I$</td>
<td>$4 \times 10^{16}$ W/cm$^2$</td>
</tr>
<tr>
<td>hor. collimation depth</td>
<td>$n_x$</td>
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<td>hor. collimation limit</td>
<td>$n_{x_{max}}$</td>
<td>29</td>
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<tr>
<td>fraction of 'core' scattered (x coll.)</td>
<td>$\Delta N_c/N_c$</td>
<td>1%</td>
</tr>
<tr>
<td>vert. collimation depth</td>
<td>$n_y$</td>
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<td>vert. collimation limit</td>
<td>$n_{y_{max}}$</td>
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<tr>
<td>fraction of 'core' scattered (y coll.)</td>
<td>$\Delta N_c/N_c$</td>
<td>&lt;0.1%</td>
</tr>
</tbody>
</table>

Table 1: Sample parameters for laser collimation at the 1-TeV NLC [4].
50 Hz to 100 Hz within reach!
1 kHz to 10 kHz need 5 T

TERAWATT PICOSECOND CO2 LASER TECHNOLOGY FOR FUTURE TeV COLLIDERS

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Abstract. The first terawatt picosecond (TWps) CO2 laser is under construction at the BNL Accelerator Test Facility (ATF). TWps-CO2 lasers, having an order of magnitude longer wavelength than the well known table-top terawatt (10^11 W) picosecond solid state lasers, offer new opportunities for strong-field physics research. Laser wakefield accelerators (LWFA) serve as an example where the advantage of the new class of lasers is due to a quadratic dependence of the energy acquired by the electron oscillating in the electromagnetic field upon the period of oscillation. This intensifies such LWFA-essential effects as gas ionization, plasma wave excitation, and relativistic self-focusing. The anticipated progress of TWps-CO2 laser technology towards multi-terawatt high repetition rate devices will open prospects for relatively economical and compact linear accelerators of the TeV energy required to enable advances in high-energy physics research. We show how TWps-CO2 laser technology may help in designing the LWFA stages for the projected TeV electron-positron (e^-e^+) linear colliders.

By Compton backscattering of IR laser photons from the relativistic electron beam, high brightness gamma radiation can be produced. This offers an opportunity to study a variety of interaction processes by colliding e^- e^+ and gamma (γ) beams in any combination and at independently controlled polarizations. We consider the requirements of the e^-γ converter and show that the CO2 laser appears to be a practical choice to drive a e^-γ converter for the 5-TeV e^+e^- collider.

I. INTRODUCTION

Progress in the exploration of particle interactions relies to a great extent upon the development of a new-generation of accelerators on a TeV energy scale. One of the prospective approaches is a linear e^-e^+ collider. The proposal for the next generation 0.5-1.0 TeV Stanford Linear Collider is based on conventional RF accelerating structures (Snowmass 1996). At the typical accelerating field of 50-100 MV/m, this design will require a 20 km long linac.

Another, unconventional approach to the TeV collider is based on high-gradient laser accelerators (AAC 1996). The enthusiasm that drives research in this area is based on ultra-high electric fields, up to 10^11 V/cm, attainable upon the tight focusing of terawatt laser beams. Being used for particle acceleration, such fields may permit reduction of accelerator dimensions by orders of magnitude.

*Work performed under the auspices of the U.S. Dept. of Energy.
absorber for off energy particles

\[ \frac{N_e}{\sigma_x \sigma_y} \leq \frac{n_{\text{limit}}}{\delta} \mu \text{m}^{-1} \]

\[ n_{\text{limit}} = N_e \times 10^{12}, \quad \gamma = 10^6 \]

\[ \sigma_x \approx \gamma \delta_c = l_0 \theta \delta_c \quad | \quad \text{beam size at center of chicane} \]

\[ \sigma_y = \theta \frac{2l_0}{\gamma} \approx 2 \frac{l_0}{\gamma} \]

\[ \gamma = l_0 \theta \]

\[ \delta_c = 0.1 \]

\[ l_0 \geq \left( C_\delta \frac{\varepsilon^2 \gamma^2}{\gamma^2} \right)^{1/5} \]

\[ C_\delta = 55 r_c \frac{r}{(12.5)^2} \approx 2.3 \times 10^{-24} \text{ m}^2 \]

Survivability:

\[ l_0^2 \theta \geq \frac{\gamma^2 N_e}{2 n_{\text{limit}} \delta_c} \]
Combine (w) and (w+): 

\[ 4l_0 \geq 4 \left( \frac{\varphi^2 N_e^3}{(2 \pi \hbar n_{\text{he}} \delta_c)^3 \Theta g^2} \right)^{1/8} \]

Use \( \varphi \approx 25000 \), \( N_e = 10^{12} \), \( \gamma = 10^6 \)

\[ \rightarrow 4l_0 \geq 250 \text{ m} \quad \text{not bad} \]

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Laser system

divergence \( \Theta_{\text{d}} \approx \frac{2}{\pi F w_0} \)

damage threshold for mirror \( \sim 1 \frac{\text{W}}{\text{cm}^2} \)

\[ \frac{A_{\text{beam}}}{2 \pi (F w_0)^2} \sim 1 \frac{\text{W}}{\text{cm}^2} \quad F \text{ is distance, mirror focal point} \]

\( F \geq \sqrt{A_{\text{beam}} F w_0 / (2 \pi)^2 / 17 / \text{cm}^2} \approx 17 \text{ cm} \)

\( w_0 = 0.62 \varphi^* \rightarrow \varphi^* = 10 \quad \text{easy} \)
example map: octupoles of alternating sign + rotation

\[ H = 2 \Delta \phi \overline{I} - \frac{1}{12 \pi} I^2 \beta^2 k_0 \cos 2\Phi \]

\[ \left( \frac{\partial \hat{H}}{\partial I} \right)_{I_{\text{max}}} = 0 \rightarrow I \approx \frac{12 \pi |\Delta \phi|}{\beta^2 k_0} \]

estimate for dynamic aperture
Phase advance $\phi_x = 90^\circ$

$k_3 = 4000 \text{ m}^{-3}$, linac à la Yuni, emittance growth
loss distribution 13 σ oscillation

13 sigma oscillation
50 $\sigma$ oscillation

Quite narrow distribution now...
puzzles

(1) final doublet & octupole
    estimated $k_3$ ? huge discrepancy?
    $k_3$ required by MAD
    is formula wrong?
    some problem with MAD?

(2) tracking option $T_X = 6$
    seems inconsistent with explicit
    value for $x_1$, $p_x$

who can help?