IP for the photon collider

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The photon collider at ILC, special requirements

In order to have the photon collider in future it should be planned from the very beginning; its specific requirements should be taken into account in designs of practically all LC systems and one of detectors.

“...two collision points could allow the optimization of the detectors for different studies. For example, the conditions around the $\gamma \gamma$ collision point are different than those at the $e^+e^-$ interaction region and suggest differences in detectors.”

“Understanding matter: ...the case for the Linear Collider” signed by 2695 LC supporters.
Special requirements for photon colliders:

- for removal of the disrupted beams the crossing angle at one of the interaction regions should be about 25-30 mrad (the exact number depends on the final quad design);

- the $\gamma\gamma$ luminosity is almost proportional to the geometric $ee$ luminosity, therefore the product of horizontal and vertical emittances should be as small as possible (requirements to damping rings and beam transport lines);

- the final focus system should provide a spot size at the interaction point as small as possible (the horizontal $\beta$-functions can be smaller by one order of magnitude than that in the $e^+e^-$ case);
• the beam dump should withstand absorption of the narrow photon beams and which follow a straight line from the interaction point (deflection is not possible); used electron beams have a wide energy spread and large disruption angles.

• the detector design should allow replacement of elements in the forward region ($\leq 100$ mrad), including the vacuum pipe and the vertex detector;

• A key element of the photon collider is a state-of-art laser system; it needs a space in and around the detector and housing.
After the collision the beams have a large energy spread: 

\[ E \sim (0.02 - 1)E_0 \]

and disruption angles \( \theta_d \sim 10 \text{ mrad} \) (the background from particles with \( \theta > 10 \text{ mrad} \) is less than from unavoidable backgrounds).

The removal of disrupted beams need large crab-crossing angle:

\[ \alpha_c \sim \frac{R_{\text{quad}}}{L^*} + \theta_d \]

\[ \sim \frac{6}{400} + 0.01 \equiv 25 \text{ mrad} \]
The angle between tunnels, bending angle

The crab-crossing angle for $e^+e^-$ (IP1) is about $\alpha_{c,1} = 0$-$20$ mrad, smaller than for $\gamma\gamma$ (IP2) which is $\alpha_{c,2} \sim 25$ mrad.

Scheme a), the angle between tunnels $\alpha_t = 0$, the simplest configuration. The only problem: for maximum beam energies the bending length $L_b$ required for a small beam emittance dilution may be too long.

Scheme b) bending angles are minimum, but the disrupted beams from IP1 cross the beamlines of the IP2.

Scheme c) there is no problem with the beam dump. It is optimum for both IP in the case when bending angles for IP1 and IP2 are equal (smallest $L_b$), i.e. the angle between tunnels $\alpha_t = (\alpha_{c,1} - \alpha_{c,2})/2$. If the corresponding $L_b$ is too large, then only one IP is optimized for achieving maximum beam energies.
Increase of the horizontal beam emittance due to SR in the big bend

\[ \Delta \epsilon_{nx} \propto \frac{E^6 \alpha_b^5}{L_b^4}. \]

Taking the coefficient from the NLC ZDR one gets

\[ \Delta \epsilon_{nx} = 1.8 \times 10^{-10} \left( \frac{2E_0}{\text{TeV}} \right)^6 \left( \frac{\text{km}}{L_b} \right)^4 \left( \frac{\alpha_b}{10 \text{ mrad}} \right)^5 \text{ m} \]

For \( \epsilon_{nx} = 2 \times 10^{-6} \text{ m}, \alpha_b = 10 \text{ mrad}, \)
\( \Delta \epsilon_{nx}/\epsilon_{nx} = 0.05 \) at

<table>
<thead>
<tr>
<th>( \frac{2E_0}{\text{TeV}} \text{ km} )</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_b ) km</td>
<td>0.2</td>
<td>0.57</td>
<td>1.04</td>
<td>2.25</td>
</tr>
</tbody>
</table>

The choice of the scheme depends on the assumed maximum energy of the collider in this tunnel. The total cost of the collider will be somewhat cheaper when only one IP reaches the maximum energy (without the luminosity degradation), the scheme c) with \( \alpha_t \sim \alpha_{c,1} \).

From user’s point of view, both IP should have similar energy reach. In the latter case, and \( \alpha_{c,1} = 20 \text{ mrad} \) and \( \alpha_{c,2} = 25 \text{ mrad} \) the optimum angle between tunnels in the scheme c) \( \alpha_t = (25 - 20)/2 = 2.5 \text{ mrad} \) (not too much gain compared with zero angle).
Optimization of the luminosity

Collision effects:

- Coherent pair creation
- Beamstrahlung
- Beam-beam repulsion.

On the right: dependence of $\gamma\gamma$ and $\gamma e$ luminosities in the high energy peak on the horizontal beam size:

For $\epsilon_{nx} = 2.5 \times 10^{-6}$ m, $\beta_x = 1.5$ mm, $\sigma_x \sim 90$ nm at $2E_0 = 500$, that is factor of 5 smaller than in $e^+e^-$ collisions. Having beams with smaller emittances one could have by one order higher $\gamma\gamma$ luminosity.

$\gamma e$ luminosity in the high energy peak is limited due to the beam repulsion and beamstrahlung.

Resume: in $\gamma\gamma$ collisions the collisions effects are not important (for $2E_0 < 1$ TeV), $\epsilon_{nx}$ and $\beta_x$ should be as small as possible.
Chromo-geometric aberrations in the FF system
Dependence of the geometric $e^-e^-$ luminosity for TESLA on the horizontal $\beta$-function (A. Seryi, Dec. 2000).

We see, $\beta_x \sim 1.5$ mm seems feasible. More careful optimization is needed. Small $\beta_x$ needs small $\epsilon_{nx}$, otherwise SR may hit the vertex detector.

Resume: the final focusing system for the photon collider should allow $\beta_x$ much smaller than that for $e^+e^-$ collisions.
Energy and luminosity of $\gamma\gamma, e$ collider

$\lambda_{laser} = 1.06 \ \mu m.$

<table>
<thead>
<tr>
<th>$2E_0$ (GeV)</th>
<th>200</th>
<th>500</th>
<th>800</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{geom}, 10^{34}$</td>
<td>4.8</td>
<td>12.0</td>
<td>19.1</td>
</tr>
<tr>
<td>$W_{\gamma\gamma, max}$ (GeV)</td>
<td>122</td>
<td>390</td>
<td>670</td>
</tr>
<tr>
<td>$L_{\gamma\gamma}(z &gt; 0.8z_m, \gamma\gamma), 10^{34}$</td>
<td>0.43</td>
<td>1.1</td>
<td>1.7</td>
</tr>
<tr>
<td>$W_{\gamma e, max}$ (GeV)</td>
<td>156</td>
<td>440</td>
<td>732</td>
</tr>
<tr>
<td>$L_{e\gamma}(z &gt; 0.8z_m, \gamma e), 10^{34}$</td>
<td>0.36</td>
<td>0.94</td>
<td>1.3</td>
</tr>
<tr>
<td>$L_{e^+ e^-}, 10^{34}$</td>
<td>1.3</td>
<td>3.4</td>
<td>5.8</td>
</tr>
</tbody>
</table>

$L_{\gamma\gamma}(z > 0.8z_m) \sim \frac{1}{3} L_{e^+ e^-}$

where $z = W_{\gamma\gamma}/2E_0$. 

$L(W > 0.8W_{max})$

$W_{max} \sim 0.8 \times 2E_0$ in $\gamma\gamma$

($W_{max} \sim 0.9 \times 2E_0$ in $e\gamma$)
## $\gamma\gamma$ and $\gamma e$ luminosities

<table>
<thead>
<tr>
<th>$2E_0$ GeV</th>
<th>200</th>
<th>500</th>
<th>800</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_L$ [$\mu$m]/$x$</td>
<td>1.06/1.8</td>
<td>1.06/4.5</td>
<td>1.06/7.2</td>
</tr>
<tr>
<td>$t_L$ [$\lambda_{\text{scat}}$]</td>
<td>1.35</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$N/10^{10}$</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$\sigma_z$ [mm]</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>$f_{\text{rep}} \times n_b$ [kHz]</td>
<td>14.1</td>
<td>14.1</td>
<td>14.1</td>
</tr>
<tr>
<td>$\gamma_{x/y}/10^{-6}$ [m·rad]</td>
<td>2.5/0.03</td>
<td>2.5/0.03</td>
<td>2.5/0.03</td>
</tr>
<tr>
<td>$\beta_{x/y}$ [mm] at IP</td>
<td>1.5/0.3</td>
<td>1.5/0.3</td>
<td>1.5/0.3</td>
</tr>
<tr>
<td>$\sigma_{x/y}$ [nm]</td>
<td>140/6.8</td>
<td>88/4.3</td>
<td>69/3.4</td>
</tr>
<tr>
<td>$b$ [mm]</td>
<td>2.6</td>
<td>2.1</td>
<td>2.7</td>
</tr>
<tr>
<td>$L_{ee}(\text{geom})$ [$10^{34}$]</td>
<td>4.8</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>$L_{\gamma\gamma}(z &gt; 0.8z_m,\gamma\gamma)$ [$10^{34}$]</td>
<td>0.43</td>
<td>1.1</td>
<td>1.7</td>
</tr>
<tr>
<td>$L_{\gamma e}(z &gt; 0.8z_m,\gamma e)$ [$10^{34}$]</td>
<td>0.36</td>
<td>0.94</td>
<td>1.3</td>
</tr>
<tr>
<td>$L_{ee}(z &gt; 0.65)$ [$10^{34}$]</td>
<td>0.03</td>
<td>0.07</td>
<td>0.095</td>
</tr>
</tbody>
</table>

For the same energy

$$L_{\gamma\gamma}(z > 0.8z_m) \approx \frac{1}{3}L_{e^+e^-}$$

(cross sections in $\gamma\gamma$ collisions are typically larger than in $e^+e^-$ by one order of magnitude)

More universal relation (for $k^2 = 0.4$)

$$L_{\gamma\gamma}(z > 0.8z_m) \approx 0.1L_{ee}(\text{geom})$$
The beam dump at LC

The beam dump at the linear collider TESLA suggested for the $e^+e^-$ interaction region consists of the deflecting magnets (deflect bunches inside one train) and the water vessel at the distance 250 m from the interaction point. However it does not suit for the photon collider because the photon beam is neutral.

Characteristic beam parameters: $N = 2 \cdot 10^{10}$, the number of bunches in one train 2820, $\Delta t = 337$ nsec, $\nu = 5$ Hz, the angular divergence $\sigma_{\theta_x} \sim 3 \cdot 10^{-5}$, $\sigma_{\theta_y} \sim 10^{-5}$. The beam is mixed, about half of the energy is carried by electrons and half by photons.
The deflecting magnets rotate the electron beam \((R=0.5-1\,\text{cm} \text{ at } 100\,\text{m from the IP})\) in order to reduce local temperature at the entrance window. The energy deposition by photons in the entrance window is small.

A gas volume \((\text{Ar at } P=3-5\,\text{atm})\) of \(4-5\,X_0\) rad. length thickness serves for conversion of photons and broadening of the shower before the water dump.
Simulation results

Maximum local $\Delta T$ in the water dump after passage of the train from 250 GeV photons is 75, 50, 25° at 3, 4, 5 atm Ar, respectively and by a factor of 2 lower from electrons.

Maximum local $\Delta T$ at the exit Be-Ar (may be other material) window is small, $\sim 10^\circ$.

The maximum $\Delta T$ at the entrance Be-Al window is about 40° for $\sigma_{\theta x} = 3 \times 10^{-5}, \sigma_{\theta y} = 10^{-5}$ and R=0.5 cm (sweeping radius). For the removal of the heat the thermal conductivity is sufficient (gas cooling can be added if necessary).

Note, the problem of the stress in solid materials in cold-LC beam dump is not important because the train duration is much longer than the decay time of local stress ($r/v_{sound} \sim 1 \mu s$). It is more serious for warm-LC with short train.
Neutron background at the IP

For $10^5$ incident 250 GeV electrons and $P_{Ar} = 4$ atm there are 6 neutrons at the IP plane $z = 0$ with the radial coordinates $r = 1.5, 2.5, 4.5, 14.5, 18.5, 21.5$ m. Due to the collimation by the Fe tube we do not expect the uniform density, the density per cm$^2$ should be larger near the axis. Assuming the uniform density for three neutrons closest to the axis we find the flux $5 \cdot 10^{-11}$ n/cm$^2$ per incident electron or about $1.5 \cdot 10^{11}$ n/cm$^2$ for $10^7$ sec run time.

For comparison just the water dump at the distance 100 m gives $3 \times 10^{11}$ n/cm$^2$ for the same time (quite similar).

It is remarkable that after the replacement of the first 20 m of Ar by $H_2$ at the same pressure there is only one neutron at $r = 1.5$ m for $8 \cdot 10^5$ incident electrons. With account of collimation by the tube it means the decrease of the neutron flux at least by a factor of ten!
Conclusion

The photon collider will add significant extra physics value to the LC programme for small additional cost on the scale of the whole project. It is important to make design decisions in the baseline project which are not prohibitive or unnecessarily difficult for the photon collider, allow to reach its ultimate performance and rather easy transition between modes.

Taking into account organization aspects and cost optimization it would be rational to develop the photon collider as an inherent part of the whole LC project (not as some future option)