A Photon Collider at TESLA

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-Zeuthen

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- Laser system
- Luminosity optimisation
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Introduction

Physics Motivation:
Want to study $\gamma \gamma \rightarrow H \rightarrow b\bar{b}$, $\gamma \gamma \rightarrow W^+W^-$, $\gamma \gamma \rightarrow$ SUSY
$\Rightarrow$ need $\sqrt{s} = 120\text{GeV}$ – maximum possible with high luminosity.

TESLA bunch structure: bunch trains with 2800 bunches/train and 337 ns bunch crossing time

Laser completely driven by time structure, study only partially valid for warm technology

Detector design:

- Large disruption angle requires crab crossing with $\alpha \approx 35\text{mrad}$
- forward part of detector completely driven by laser and crossing angle
- outer part kept identical to $e^+e^-$ TDR-detector
# Beam parameters for $\sqrt{s_{ee}} = 500$ GeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$e^+e^-$</th>
<th>$\gamma\gamma$</th>
<th>$\gamma\gamma$ (optimistic)</th>
</tr>
</thead>
<tbody>
<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>pulses/train</td>
<td>2820</td>
<td>2820</td>
<td>2820</td>
</tr>
<tr>
<td>Repetition rate [Hz]</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$\gamma\epsilon_{x/y}/10^{-6}$ [m⋅rad]</td>
<td>10./0.03</td>
<td>3./0.03</td>
<td>2.5/0.03</td>
</tr>
<tr>
<td>$\beta_{x/y}$ [mm] at IP</td>
<td>15/0.4</td>
<td>4/0.4</td>
<td>1.5/0.3</td>
</tr>
<tr>
<td>$\sigma_{x/y}$ [nm]</td>
<td>553/5</td>
<td>157/5</td>
<td>88/4.3</td>
</tr>
<tr>
<td>$\mathcal{L}(z &gt; 0.8z_m)$</td>
<td>3.4</td>
<td>0.6</td>
<td>1.1</td>
</tr>
<tr>
<td>$[10^{34}\text{cm}^{-2}\text{s}^{-1}]$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Wavelength of powerful solid state lasers is in the 1μm range, e.g. Nd:YAG
\[ \lambda = 1.06 \mu m \]

\((x = 4.5 \text{ for } \sqrt{s} = 500 \text{ GeV})\)

(If really needed can double or triple frequency)

Laser focusing in diffraction limited region:

\[
\sigma_{L,r}(z) = \sigma_{L,r}(0)\sqrt{1 + \frac{z^2}{Z_R^2}} \quad \sigma_{L,r}(0) = \sqrt{\frac{\lambda Z_R}{2\pi}}
\]

\(Z_R:\) Rayleigh length

→ cannot vary length and diameter of laser spot simultaneously

Optimum around \(Z_R \approx \sigma_z \Rightarrow \text{half opening angle of } \mathcal{O}(1^\circ)\)
Fraction of converted electrons:

\[ k = \frac{N_{\gamma}}{N_e} \approx 1 - \exp\left(-\frac{A}{A_0}\right) \]

A: pulse energy of laser

For \( Z_R \approx \sigma_z \) and head on laser-beam collisions:

\[ A_0 \approx \frac{\pi \hbar c \sigma_z}{\sigma_c} \approx 1.5J \]

\[ \Rightarrow \text{need } A \approx 2J \text{ (corresponds to } \xi^2 \approx 0.2) \]

(for head on \( e^- \)-laser collisions)

\[ \Rightarrow \text{total laser power of } \sim 2 \times 30 \text{ kW needed} \]

\[ \Rightarrow \sim 60 \text{ Mercury lasers from the Livermore fusion program} \]
TESLA solution: recycle photons in resonant ring cavity:

- total length:  
  \( \sim 100 \, \text{m} \)
- mounted around the detector
- all mirrors outside detector
**Principles of a cavity**

- cavity with \( N \) mirrors with reflectivity \( R_i \)
- loss per round trip \( V = R_2 \cdot R_3 \ldots \cdot R_N \cdot L \) (\( L = \) other losses)
- power enhancement of cavity \( A = \frac{1-R_1}{(1-\sqrt{R_1 V})^2} \) (\( R_1 = \) coupling mirror)
- maximal for \( R_1 = V \)

Power enhancement \( > 100 \) possible for realistic reflectivities
• To have highly efficient mirrors need crossing angle beam-laser
crossing angle results in smaller conversion probability
• laser divergence and therefore mirror size depends on Rayleigh length
• finite mirrors result in diffraction losses and broadening of the focus
• have to find optimum crossing angle/Rayleigh length
⇒ even higher laser power needed
Diffraction losses are small even for small mirrors.
However diffraction broadening is serious

**telescopic cavity, magnification sqrt(3)**

![Graph showing aperture at final focus vs. a/w (in respect to gaussian). The graph includes multiple lines for different waist sizes: 100 μm waist, 80 μm waist, 70 μm waist, 60 μm waist, 50 μm waist, 46 μm waist, 40 μm waist, and 30 μm waist.](Overview_loss_HH_Zeuthen_meeting.OPJ)
Optimum for relatively small mirrors

Laser energy 8.55 J, pulse duration 1.5 ps
Optimum parameters

<table>
<thead>
<tr>
<th>Laser parameters</th>
<th>TDR pt. VI</th>
<th>This study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rayleigh length $Z_R$</td>
<td>0.35 mm</td>
<td>0.63 mm</td>
</tr>
<tr>
<td>Collision angle $\alpha_0$</td>
<td></td>
<td>55.1 mrad</td>
</tr>
<tr>
<td>Laser energy $A$</td>
<td>5 J</td>
<td>9.0 J</td>
</tr>
<tr>
<td>Pulse duration $\sigma_{L,z}$</td>
<td>1.5 ps</td>
<td>1.5 ps</td>
</tr>
<tr>
<td>Nonlinearity parameter $\xi^2$</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>Total Luminosity $[10^{34} \text{cm}^{-2}\text{s}^{-1}]$</td>
<td>1.10</td>
<td>1.05</td>
</tr>
</tbody>
</table>

TDR parameters can be reproduced

However larger laser pulse-power needed
Alignment tolerances

Total length of cavity: $\Delta L \sim 0.3$nm

Correction procedure understood e.g. from gravitational wave antennas

Misalignment of focusing telescope:

Need precision of $\sim 100$nm
Filling of the cavity

- Eigenmode in cavity is non-Gaussian due to diffraction broadening
- However filling of cavity with Gaussian mode works reasonably well
- Need $\sim 1000$ pulses for $A = 215$

![Graph showing number of roundtrips vs. $A_{\text{max}} = 215$.]

- $R_1 = 99\%$
- $a/w = 0.75$
- Gaussian seed, $w_0 = 40 \, \mu\text{m}$
- 500 roundtrips
- 1000 roundtrips
Design of the laser resonator in the hall
Detector and backgrounds

Background in the detector driven by

- large disruption angle
- angle between outgoing beam and B-field

- direct background from pair production smaller than in $e^+e^-$ due to anti-pinched effect
- large potential background from backscattering at detector exit
Background can be suppressed by masks and choice of material

- Backgrounds are similar to $e^+e^-$ and should thus be manageable
- However detector is dead for $\theta < 7.5^\circ$
Low energy $q\bar{q}$ background

- Large luminosity and large cross section $\gamma\gamma \rightarrow q\bar{q}$ at low $\sqrt{s}$
- $\mathcal{O}(1)$ event/bx overlaid to physics events (pileup)

- Due to large boost pileup tracks are forward peaked
- Can be largely rejected if physics in not forward peaked (like $\gamma\gamma \rightarrow W^+W^-$)
- Additional help/complication: beamspot length $\sim 200\mu m$

$\Rightarrow$ signal and pileup separated in $z$

- microvertex detector can help to separate
- can screw up b-tagging, e.g. in Higgs analysis

Integrated Impact Parameter distribution for signal and pileup
Pileup gives also non negligible background in detector
Pileup affects seriously some analyses

Conclusions pileup

- Pileup is a serious issue at a $\gamma\gamma$-collider
- Very good time stamping is a must (no problem at TESLA)
- the long bunches at TESLA help additionally
Conclusions

- no showstoppers found so far

- the laser-cavity seems difficult but possible

- backgrounds are under control

- however the price to pay is a dead detector below 7.5°

- if you want the photon collider to become a reality you have to work on the technical issues