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A LASER CAVITY FOR A FUTURE PHOTON COLLIDER AT ILC*

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Within a future photon-collider based on the infrastructure of ILC the energy of near-infrared laser photons will be boosted by Compton backscattering on a high energy electron beam to well above 100 GeV. By reason of luminosity, an extremely powerful lasersystem is required that will exceed today's state-of-the-art capabilities. An auxiliary cavity for resonantly enhancing the optical peak-power can relax demands on the power output of the laser. In this paper a possible design and the static aspects of a passive cavity are discussed.

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1. Introduction

The purpose of a photon collider has already been discussed elsewhere [1,2]. Contrary to a storage ring, in an e^+e^-linear collider the beams collide only once. It should thus be possible to convert the electrons into high energy photons by scattering them on a high power laser a few mm in front of the interaction point [3]. If the laser wavelength is chosen correctly photon energies up to 80 % of the electron beam energy can be achieved.

The detailed layout of a photon collider depends on the principles of the linear accelerator. Especially the time structure of the beam influences heavily the layout of the laser system. In this paper the layout of the TESLA machine will be used [4]. The setup of the ILC is not yet finalized, but the time structure will be very similar to the one studied for TESLA [5]. A principle layout of a photon collider at TESLA as presented in [1] imposes several technical challenges [6]. The most important one is certainly the

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laser system. In order to reach high conversion factors a laser power of $\mathcal{O}(5\,\mathrm{J/pulse})$ and a spot size of $\mathcal{O}(10\,\mu\mathrm{m})$ is needed. The generation of such laser pulses that have a 3 MHz repetition rate within 5 trains per second of a few 1000 bunches each, is very difficult if not impossible by today's standards. On the other hand from the more than 10^{19} photons in a laser pulse only $\mathcal{O}(10^{10})$ are scattered per beam-laser interaction. This makes it natural to store a laser pulse in an optical ring resonator and reuse it many times [7–9]. Due to the interaction with the laser the electron beam gets significantly disrupted. This requires a large crossing angle between the beams.

2. Power enhancement within a passive optical cavity

Inside an optical ring resonator the circulating electric field just after passage of the input coupling mirror c is given by a superposition of the transmitted incoming electric field from the laser and a scaled replica of the circulating field that emerged from this coupling mirror at the previous round-trip. On resonance the power enhancement factor A reflects a monotonous increase of power with the number q of stored pulses:

$$A = (1 - R_c) \left[\frac{1 - \sqrt{R_c V}^{\,q}}{1 - \sqrt{R_c V}} \right]^2 . \qquad (1)$$

R_c represents the intensity reflectivity of the coupling mirror and V the power loss factor for one round-trip. If the reflectivity of the coupling mirror equals the loss factor V of the cavity, the maximum possible steady-state power enhancement factor of $1/(1-V)$ is obtained and all light is absorbed by the resonant cavity. This is known as impedance matching.

3. Proposed design for an optical cavity

For a sufficient high γ flux density and hence a luminosity of around $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, the cavity must generate a focus at the Compton conversion point (CP). At the inevitable high power level within the cavity optical windows would imply the risk of distortion of the circulating ps-pulse as a result of the non-vanishing B-integral [10, 11]. The Compton-interaction requires therefore operation of the cavity in the vacuum of the accelerator.

The particle detector for the $\gamma\gamma$-option is expected to be almost identical to the one for e^+e^--physics located at the leptonic IP. Due to shortage of space any optics for the optical cavity should preferably be positioned outside the environment of the particle detector.

Compton conversion at each of the counter-propagating electron beams requires two cavities as exemplified by Fig. 1. They are interlaced without mutual interference.

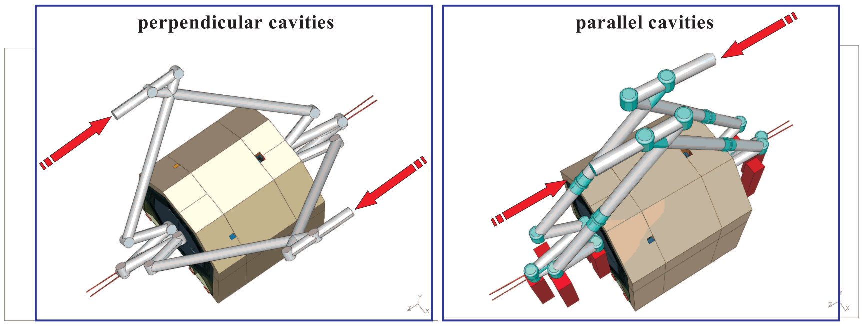

Fig. 1. Top view (schematic) onto two possible configurations of both optical cavities with counter-propagating beam directions. They are folded around the particle detector which extends 14.8 m along the electron beam path. The thin lines traversing the detector represent the latter. A slight mutual vertical tilt between the cavities permits free passage of the particle beams. The laser beams are coupled into the cavity at positions marked by the arrows. The optical beam path is contained within the sketched pipes that preserve the vacuum. The high power lasers itself will be located in a separate hall above the detector (not shown).

Their optical paths are enclosed within the associated optical beam pipes which are needed for maintaining the vacuum. Fig. 2 shows the optical configuration of an individual cavity. At least one adaptive mirror seems to be essential for reducing residual aberrations that tend to deteriorate the optical photon flux at the focus. The focusing is accomplished by means of a reflective beam expander and a second, identical telescope is used for re-collimation. This also introduces a moderate beam magnification of $\sqrt{3}$ for reduction of the beam size within the nearly collimated region of the cavity outside the detector. For details see [6]. The focal spot size at CP and the influence of finite diameter of the mirrors were calculated numerically. Total correction of the aberrations introduced by the telescope mirrors was thereby assumed. Especially the diameter of the final focusing concave mirrors determine the minimal collision angle α_0 between laser and electron beam. They should be kept small for high yield of γ. The major effect in reducing the size of the mirrors turned out to be a diffractive broadening of the focal spot size rather than increased loss due to radiative energy that spills over the boundaries of the mirrors.

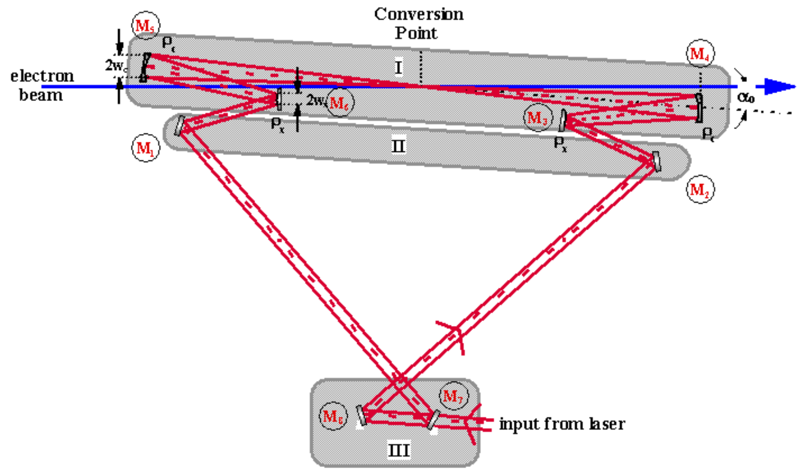

Fig. 2. Geometry (to scale) of one of the identical plane cavity, comprising a beam magnification $\mu = w_c/w_x = \sqrt{3}$. CP: Compton conversion point. I: aberration compensated telescopic focusing, II: optional adaptive mirrors III: folding mirrors and laser pulse coupling.

4. Laser-electron crossing angle

Diffractive broadening was taken into account in calculation of α_0 and specification of the laser beam size w_{CP} at CP. In respect to a high yield of γ, crossing angle α_0, diameter of mirrors M_4, M_5, waist size w_{CP}, laser pulse energy E_{pulse}, as well as laser pulse duration τ_{pulse} are all interdependent parameters. Their respective values were determined by a numerical optimization process using the CAIN Monte Carlo code [12]. The results are compiled in Table I. An estimation based on the known properties of laser induced damage, the suggested size of the mirrors provides still some reserve

TABLE I

Optical parameters resulting from an optimization of the $\gamma\gamma$ luminosity. $(1/e^2)$ designates the radius that is defined by a drop of the intensity to $1/e^2 \approx 13.5\,\%$ of its maximum value at the beam center.

laser pulse energy E_{pulse}	≈ 9.0 J
pulse duration τ_{pulse}	3.53 ps FWHM ($\sigma = 1.5$ ps)
beam waist w_{CP}	$\approx 14.3\,\mu$m $(1/e^2)(\sigma = 7.15\,\mu\mathrm{m})$
laser-electron crossing-angle α_0	≈ 56 mrad
diameter of mirrors M_4, M_5	120 cm
laser wavelength λ	1.064 μm
total luminosity $L_{\gamma\gamma}$	$1.05 \cdot 10^{34}$ cm^{-2}s^{-1}

before the energy fluence of the circulating optical pulse reaches the damage threshold. For a final judgement of the upper limit, an experimental study with a representative of the special ILC bunch structure is required.

5. Enhancement capability of the cavity

According to the results obtained in [6] all mirrors could have a diameter of about 120 cm. In this case cutoff occurs at approx. 75 % of the hypothetical Gaussian beam radius at the final focusing mirror which represents the dominant aperture at which diffraction will occur. This leaves sufficient room for the wings of the electric field distribution as can be inferred from a plot of the round-trip diffraction loss factor in the left of Fig. 3. Diffraction loss declines towards smaller foci within the cavity. $LF_{\mathrm{diff}} = 1$ denotes no power loss due to diffraction. The total loss factor V of the cavity is the product of the individual contributions by all loss mechanisms: intra-cavity absorption, diffraction and scattering as well as the finite reflectivity R of all cavity mirrors with exception of the coupling mirror. As an example, the build-up of power obtained from the numerical propagation of an optical pulse under Gaussian seed-conditions through many revolutions is shown in the right of Fig. 3. The stationary enhancement of 353 after ≈ 1000 circulations of the pulse reflects a 92 % coupling of the injected Gaussian mode into the cavity mode. The number of laser pre-pulses for reaching an approximate steady-state declines as the impedance matching condition is

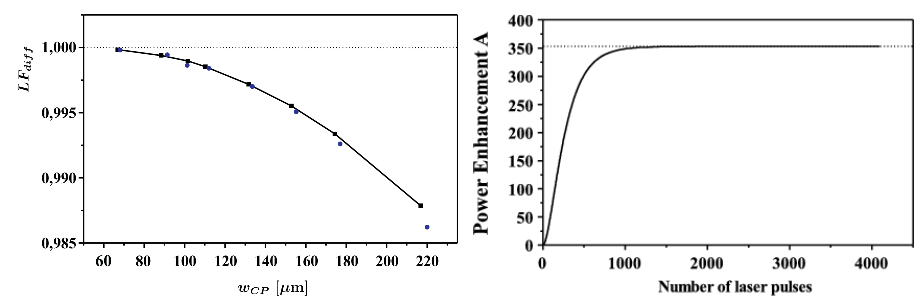

Fig. 3. **Left:** Comparison of numerically obtained diffraction loss factor LF_{diff} for a sequence of cavities with finite apertures of its mirrors and varying focal spot sizes w_{CP} at the Compton conversion point. Circles: Finite apertures of all mirrors; squares: Just finite concave mirrors and cutoff at 75 % of the Gaussian beam radius at the final focusing mirror. There is no significant difference. **Right:** Numerical example for power build up, assuming a total loss factor $V = 0.9998$ and a reflectivity of $R_c = 99.0$ % for the coupling mirror. This demands the accumulation of at least 1034 pre-pulses for reaching an enhancement within 99 % of the steady-state.

violated. An estimated fractional power loss due to diffraction of roughly $LF_{\rm diff} \geq 0.9998$ per round trip and a reflectivity of between $R_{HR} = 99.99\,\%$ and $99.95\,\%$ for presently available standard mirror coatings would permit a steady-state impedance matched power enhancement between 1100 and 270, for otherwise perfect conditions. The larger the amount of A, the more sensitive the enhancement against any impedance mismatch.

Maintaining the power enhancement factor *e.g.* above $90\,\%$ of its optimum value demands sub-nm precision for controlling the circumference. While this in principal appears to be manageable, major R&D effort will be required.

6. Conclusions

The greatest technical challenge of a photon collider appears to be the laser system. A conceptual design for a resonant optical cavity has been shown which probably could reach a power enhancement factor around 100 and thus reduce the required laser power to an acceptable level. The actual enhancement factor of the cavity results from the cumulative effect of many small contributions affecting the total loss factor. Residual aberrations tend to enlarge the focused beam at the Compton conversion point. Both are difficult to predict in advance. However, for the proposed cavity the influence of diffraction loss is almost negligible.

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