



Prospects of high energy photon colliders

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Abstract

Photon colliders ($\gamma\gamma$, γe) have been considered a natural addition to e^+e^- linear-collider projects for more than 30 years [1, 2]. It was a common opinion that such linear collider with four types of colliding beams (plus e^-e^-) would be the best instrument for the study of particles physics at energies from 100 GeV to several TeV where a lot of new physics was expected, including the dark matter. Following the discovery of the Higgs boson at LHC (and nothing else), the physics community has been actively considering various approaches to building a Higgs factories for precision measurement of the Higgs properties, among them there are several proposals of photon colliders (PC). In this paper, following a brief discussion of general situation in particles physics and the place of the photon collider among candidates for future colliders, I give an overview of photon colliders based on linear colliders ILC and CLIC and of more recently proposed photon-collider Higgs factories (with no e^+e^- collision option) based on recirculation linacs in ring tunnels.

Keywords: Photon collider, linear collider, gamma collider, photon electron, Compton scattering

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1. Introduction

In the middle of 2012, two detectors at the LHC announced the discovery of a new particle with the mass of about $126 \text{ GeV}/c^2$, with properties consistent with those predicted for the Standard Model Higgs boson. Physicists around the world had been waiting for many years for the first round of LHC discoveries in order to decide what the next HEP projects should be.

Since 1990-th the HEP community was unanimous that the next large HEP project should be a linear collider (LC) with the energy $2E_0=500\text{--}1000 \text{ GeV}$. Up to now, the LHC has found only the Higgs boson—and nothing else below approximately one TeV/c^2 : no supersymmetry, no dark matter particles, not a hint of anything else. It is not excluded that new physics will yet be found at LHC as higher statistics are accumulated and as LHC ramps up to its full design energy of 14 TeV.

This means that the LC decision could be made no earlier than 2018. The physics motivation for an energy-frontier LC is no longer as strong as before because we know that the energy region below 1 TeV is not nearly as rich as had been expected. Are there any other strategies HEP could follow?

At the end on 2011, A. Blondel and F. Zimmermann [3] proposed e^+e^- ring collider in the LHC tunnel to study the Higgs boson with the energy $2E_0 = 240 \text{ GeV}$, which is only somewhat larger than it was at LEP-2 (209 GeV). Soon thereafter, it became clear that it would be preferable to build a ring collider with a radius several times as large as LEP-2's because: a) for a fixed synchrotron radiation power, the luminosity is proportional to the ring's radius, b) in the future, one can place in the same tunnel a $\sim 100 \text{ GeV}$ pp collider. The e^+e^- luminosity of such a ring collider could be several times larger than that at the ILC. This clearly sounds like a serious long-term HEP strategy which is now seriously considered at CERN (FCC-ee [4, 5, 6]) and China (CEPC [7]).

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Such colliders in ~ 100 km ring can cover the $t\bar{t}$ threshold energy $2E_0 = 350$ GeV. So, such scenario assumes building a low-energy facility for the detailed study of the Higgs boson while leaving the energy frontier to the LHC, the high-luminosity HL-LHC, and to some future, even more high-energy pp or muon collider.

Nevertheless, linear colliders are still not forgotten, though appearance of circular collider projects and absence of new physics signals other than the Higgs, certainly, weakens LC position. At present, there two linear collider projects: ILC ($2E_0=250\text{--}1000$ GeV) [8] and CLIC ($2E_0=350\text{--}3000$ GeV) [9]. The ILC team has published a Technical Design Report and waiting for approval in Japan, possibly after the LHC 2015-16 run at full energy. The CLIC team issued a Conceptual Design, with a Technical Design to be ready a few years later. The situation with linear colliders is really not clear. Correspondingly, photon colliders based on linear colliders have similar probability and additionally shifted by 15–20 years. There are also suggestions for a ring-type photon collider Higgs factory without e^+e^- based on recirculating linacs [10, 11, 12], their prospects will be discussed below.

Another option is a muon-collider Higgs factory [13]. The technology is not ready yet, but the development of muon colliders is needed in any case for access to the highest energies. Various approaches to Higgs factories were discussed at HF2012 [14, 15].

Below we consider photon colliders, their physics motivations, possible schemes and some technical aspects.

2. Photon colliders, basic features and physics motivation

Photon colliders ($\gamma\gamma, \gamma e$) based on one-pass linear colliders (PLCs) have been in development since 1981 [1, 2]. A detailed description of the PLC can be found in Ref. [16]. After undergoing Compton scattering at a distance $b \sim 1$ mm from the IP (Fig. 1), the photons have an energy close to that of the initial electrons and follow the electrons' original direction toward the IP with a small additional angular spread of the order of $1/\gamma$. Using a modern laser with a flash energy of 5–10 joules, one can “convert” most of electrons to high-energy photons. The maximum energy of the scattered photons is

$$\omega_m = \frac{x}{x+1+\xi^2} E_0; \quad x = \frac{4E_0\omega_0}{m^2c^4} \simeq 19 \left[\frac{E_0}{\text{TeV}} \right] \left[\frac{\mu\text{m}}{\lambda} \right],$$

where ξ^2 is the the parameter characterizing nonlinear effects in Compton scattering. Tighter focusing of a

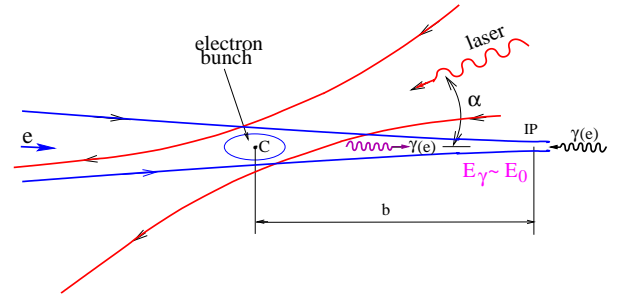


Figure 1: Scheme of $\gamma\gamma, \gamma e$ collider

laser is profitable for reduction of the flash energy, but leads to decrease of the maximum energy of scattered photons. It should be 0.15–0.3 is order to have the energy shift less than 5% for typical values $x=2\text{--}5$. The maximum value of x is about 5 due to e^+e^- pair creation in the conversion region. So, the maximum collision energy is about 80% for $\gamma\gamma$ and 90% for γe collisions. For example: $E_0 = 250$ GeV, $\omega_0 = 1.17$ eV ($\lambda = 1.06$ μm) (for the most powerful solid-state lasers) $\Rightarrow x = 4.5$ and $\omega_m/E_0 = 0.82$.

If laser photons are 100% circularly polarized the backscattered photons at highest photon energy have also 100% circular polarization. A high degree of the photon circular polarization is essential for the study of many physics processes, for example, for suppression of QED background in the study of the Higgs boson. Using linear polarized laser photon one can obtain linear polarized backscattered photons, there polarization degree at ω_m varies between 0.6–0.3 for $x=2\text{--}5$, respectively.

The luminosity in the high-energy part of the spectrum $L_{\gamma\gamma} \sim 0.1L_{\text{geom}}$ [16], where L_{geom} in present ILC design with damping rings could be about 1.5 times larger than $L_{e^+e^-}$ due to tighter focusing in horizontal direction [17], so $L_{\gamma\gamma}$ (in peak) is about 15% of $L_{e^+e^-}$. Due to absence of collision effects in $\gamma\gamma$ collisions for energies below one TeV the $\gamma\gamma$ luminosity is limited only by available beam emittances.

Let me enumerate briefly main arguments for photon colliders.

- the energy is lower than in e^+e^- collisions only by 10–20%;
- the number of interesting events is similar (this is valid both for charged pair and Higgs boson production);
- access to higher particle masses: single resonances H, A , etc., in $\gamma\gamma$ (while $H+A$ in e^+e^-); heavy charged and light neutral (SUSY, etc.) in γe (while two charge in e^+e^-);

- in some SUSY scenarios, heavy H/A -bosons will be seen only in $\gamma\gamma$, but not in e^+e^- (not enough energy to produce $H+A$) or LHC [18]
- higher precisions for some important phenomena (for example the Higgs $\gamma\gamma$ width) or $\tan\beta$ in SUSY via $\gamma\gamma \rightarrow \tau\tau H$ [19];
- different types of reactions (for example: in e^+e^- collisions charged pairs are produced via γ and Z while in $\gamma\gamma$ only QED);
- polarized photons allows to measure the Higgs CP properties;
- the relative incremental cost is small;
- there are no technical stoppers; the risk is small because because a collider is constructed first of all for e^+e^- .

The physics program of photon colliders was considered in [16, 20, 21, 23, 24, 25, 26, 27] and other papers.

3. Higgs physics

Prospects of various approaches for precision studies of Higgs properties are considered elsewhere [14, 15, 28], below we consider only what can add the photon collider to e^+e^- in the Higgs study.

3.1. Higgs physics at e^+e^- colliders

The total cross section at the 240 GeV e^+e^- Higgs factory is about 300 fb (200 fb for unpolarized beams), (see diagrams and cross sections in [15].) Typical luminosity of e^+e^- LC colliders is about 10^{34} $\text{cm}^{-2}\text{s}^{-1}$, therefore, the total number of produced Higgs bosons per one year (10^7 sec) is about 20000-30000, or about 300000 for life of the experiment. Large circular e^+e^- colliders like FCC-ee CEPC can have luminosities several times greater, especially in the case of several interaction points; therefore, the number of produced Higgs bosons could be over 1 million. A unique feature of e^+e^- colliders is the reaction $e^+e^- \rightarrow ZH$. By detecting the leptonic decays of the Z , one can measure directly all branching ratios and see even invisible Higgs boson decays via the recoil mass. Measurements of the cross section cross of this process and branching to ZZ gives the total Higgs width. Similar possibilities provides the reaction $e^+e^- \rightarrow H\nu\bar{\nu}$.

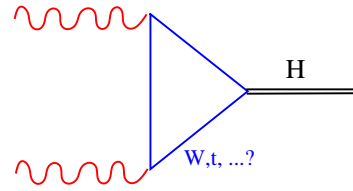


Figure 2: The diagram for Higgs production in $\gamma\gamma$ collisions.

3.2. Higgs physics at photon colliders

In $\gamma\gamma$ collisions, the Higgs boson is produced as a single resonance via the loop diagram (Fig. 2) where the leading contributions come from the heaviest charged particles in the loop: t , W , b . The measurement of this reaction's cross section can reveal the existence of yet-unknown heavy charged particles that cannot be directly produced at colliders due to their high masses. For monochromatic photons, the cross section would be huge, about 700 pb. Unfortunately, at realistic photon colliders based on Compton backscattering the energy spread of the high-energy peak is about 15% at half maximum. Even with such an energy spread, the Higgs rate at the photon collider is comparable to that in e^+e^- collisions. The Higgs boson at photon colliders can be observed in the bb , $\gamma\gamma$, WW , ZZ , WW , $\gamma\gamma$ decay modes. The Higgs $\gamma\gamma$ width $\Gamma_{\gamma\gamma}$ can be measured better than at other collider types. However, this requires the knowledge of $\text{BR}(H \rightarrow b\bar{b})$, which can be measured with sufficient accuracy only at e^+e^- colliders. Using variable photon polarizations, one can measure the Higgs boson's CP properties. Although the photon collider can produce similar numbers of Higgs bosons as an e^+e^- collider, due to the irreducible QED backgrounds one cannot detect the Higgs in the cc , $\tau\tau$, $\mu\mu$, gg modes, measure directly the branchings, and see the invisible decays. Therefore, an e^+e^- collider would be much more powerful for the Higgs study, and the photon collider will be useful only for a number of specific additional measurements—first and foremost, $\Gamma_{\gamma\gamma}$, which, in fact, could be the most interesting in the Higgs study.

The Higgs boson rate in $\gamma\gamma$ collisions [16]

$$\begin{aligned} \dot{N}_H &= L_{ee} \times \frac{dL_{0,\gamma\gamma}}{dW_{\gamma\gamma} L_{ee}} \frac{4\pi^2 \Gamma_{\gamma\gamma}}{M_H^2} (1 + \lambda_1 \lambda_2 + CP * l_1 l_2 \cos 2\varphi) \\ &= L_{ee} \sigma, \end{aligned}$$

$$\sigma = \frac{0.98 \cdot 10^{-35}}{2E_0[\text{GeV}]} \frac{dL_{0,\gamma\gamma}}{dz L_{ee}} (1 + \lambda_1 \lambda_2 + CP * l_1 l_2 \cos 2\varphi), \text{ cm}^2,$$

where L_{ee} is the geometric ee luminosity, $L_{0,\gamma\gamma}$ is the $\gamma\gamma$ luminosity at total helicity zero, $z = W_{\gamma\gamma}/2E_0$, $\lambda_{1,2}$ and

$l_{1,2}$ are the helicities and linear polarizations of the high-energy photons, φ is the angle between the directions of linear polarizations, and CP is the CP parity of the Higgs boson.

The most reasonable choice of photon collider energy and the laser wavelength for the Higgs study is $E_0 = 110$ GeV and $\lambda \sim 1.05 \mu\text{m}$ (most powerful lasers available); the corresponding parameter $x = 4E_0\omega_0/m^2c^4 \approx 2$. For the measurement of $\Gamma_{\gamma\gamma}$ one should use circular polarization of photon beams, while for CP measurement linear polarization is needed. The effective cross sections (corresponding to L_{ee}) are 75 fb and 28.5 fb (see details in [28]), which should be compared with 290 fb for the process $e^+e^- \rightarrow ZH$.

Assuming the geometric ee luminosity in the case of the photon collider to be 1.5 times higher than e^+e^- luminosity the Higgs production rate at the photon collider is approximately 2.5 times lower than in e^+e^- collisions.

The photon collider measures $\Gamma_{\gamma\gamma}$ by detecting the decay mode $H \rightarrow bb$ ($\sim 57\%$ of the total number of Higgs decays). In e^+e^- collisions, the Higgs' $\gamma\gamma$ width is measured in the $H \rightarrow \gamma\gamma$ decay, which has a branching fraction of 0.24%. This means that at the photon collider the statistics for the measurement of $\Gamma(H \rightarrow \gamma\gamma)$ is higher by a factor of $0.57/0.0024/2.5 = 95$. This is the main motivation for the photon collider. The photon collider at the upgraded ILC with the expected $L_{ee} \approx 4.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ will produce about 30000 Higgs bosons per year (10^7 sec), which would enable the determination of $\Gamma(H \rightarrow \gamma\gamma) \times Br(H \rightarrow bb)$ with an accuracy better than 2% [23, 21, 27].

The photon collider can be used also for the measurement of the Higgs boson's CP properties using linearly polarized high-energy photons. For this measurement one should collide linearly polarized γ beams at various angles between their polarization planes. The effect is proportional to the product of linear polarizations l_1l_2 . The degree of linear polarization at the maximum energies is 60% for $x = 2$ and 34.5% at $x = 4.6$. This means that the effect in the latter case will be 3 times smaller, and so in order to get the same accuracy one would have to run the experiment 9 times longer. This is one of strongest argument in favor of low parameter $x \approx 2$ for the photon collider Higgs factory. The case of $x = 1.9$ was simulated in ref. [21] and it was found that the CP parameter can be measured with a 10% accuracy given an integrated geometric ee luminosity of $3 \cdot 10^{34} \times 10^7 = 300 \text{ fb}^{-1}$.

4. Photon colliders at the ILC and CLIC

The photon collider for TESLA (on which ILC is based) was considered in detail at the conceptual level [16, 17]. The expected e^+e^- luminosity of the updated ILC design at $2E_0 = 250$ GeV is $3 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The geometric ee luminosity at the $\gamma\gamma$ collider could be similar. To increase the luminosity further, I have proposed [29] to combine many (about 50-100) low-charge, low-emittance bunches from an RF photogun into a single bunch in the longitudinal phase space using a small differential in beam energies. Using this approach, it may be possible to increase the luminosity by a factor of 10 compared to that with damping rings. To achieve this, we need low-emittance polarized RF guns, which have appeared only recently and are yet to reach their ultimate performance. The idea of beam combining is highly promising and needs a more careful consideration.

The TESLA TDR, published in 2001, dedicated a 98-page chapter to the photon collider. The recently published ILC TDR, on the other hand, includes only a brief mention of the photon collider, as an option. The focus of the present ILC TDR was the minimization of cost while attempting to preserve ILC's primary performance characteristics. This has resulted in cuts in all places possible. In particular, only one IP remains in the design, instead of two, with two pull-push detectors. In the ILC TDR, the IP was designed for a beam crossing angle of 14 mrad, while the photon collider requires a crossing angle of 25 mrad. It is not too late to reoptimize the ILC IP and make it compatible with the photon collider.

5. Photon colliders based on recirculating linacs

Two year ago, F. Zimmermann et al. [10] proposed to use the 60 GeV recirculating electron linac developed for ep collisions with LHC protons (LHeC) as a photon collider (project SAPPHiRE). The ring contains two 11 GeV superconducting linacs and six arcs, each designed for its own beam energy. An injected electron would make three turns to reach the energy of 60 GeV required for LHeC. To obtain the 80 GeV required for the photon collider, the authors propose adding two additional arcs. One must also double the number of arcs to accommodate the second electron beam traveling in the opposite direction. It was proposed to use polarized electron beams with no damping rings; the required photoguns are still under development.

The idea is interesting because 2x80 GeV electron beams are obtained with only 22 GeV's worth of linac.

The radius of arcs is 1 km, and the total circumference is 9 km. On the other hand, the total length of all arcs is 72 km! In addition, such a design would be impractical due to the unacceptable increase of horizontal emittance in the bending arcs per turn is proportional to E^6/R^4 . This proposal assumes 80 GeV electron beams and the $1/3 \mu\text{m}$ laser wavelength ($x = 4.6$). This choice of parameters makes it very difficult to remove the disrupted electron beams from the detector (too low energies of outgoing disrupted particles) and, as it was mentioned above, leads to low sensitivity in the measurement of the CP properties of the Higgs boson. The energy $E_0 = 110$ GeV is needed which is impossible in this scheme.

The idea behind SAPHIRE has become very popular and has been cloned for all existing tunnels at major HEP laboratories. In particular, it has been proposed to build a photon collider in the Tevatron ring at FNAL (6 km circumference), Higgs Factory in Tevatron Tunnel (HFITT) [11]. This collider would contain 8 linac sections providing a total energy gain of 10 GeV per turn. In order to reach the energy of 80 GeV, the electron beams would make 8 turns. The total number of beamlines in the tunnel will be 16, with the total length of approximately 96 km. This proposal contains just a desired set of numbers without any attempt at justification. Simple estimates show that such a collider will not work due to the strong emittance dilution both in the horizontal and vertical directions. The eight arcs would be stacked one on top another, so electrons will jump up and down, by up to 1.5 m, 16 times per turn, 128 times in total. The vertical emittance is assumed to be same as in the ILC damping ring; it will be certainly destroyed on such “mountains”.

The most interesting feature of the HFITT proposal is a novel laser system based on fiber lasers, see Sect. 6.

There is also a proposal [12] to build a photon collider based on the existing SLAC linac. Electrons would acquire 40 GeV traveling in the linac in one direction, then make one round turn in a small ring, get another 40 GeV traveling in the same linac in the opposing direction, and then the two beams would collide in $R = 1$ km arcs, similar to the SLC. It is a nice proposal; however, for the Higgs factory it is desirable to have $E_0 = 110$ GeV, as explained above. Reaching 110 GeV would require either a higher acceleration gradient (or an additional 30 GeV injector) and arcs with a larger radius.

6. Laser systems for photon colliders

The requirements on the laser system for the PLC are as follows: flash energy about 10 J, duration ~ 1 ps, the wavelength $\lambda \sim 1 \mu\text{m}$, and the pulse structure similar to

that for the electron beams [17]. In the case of single use of laser pulses, the average energy of each of the two lasers should be of the order of 100 kW, both for ILC and CLIC. At the ILC, the distance between the bunches is large, about 100–150 m, which makes possible the use of an external optical cavity [30, 31, 17, 25], which, in turn, can reduce the required laser power by a factor of $Q \sim 100$. At CLIC, the distance between the bunches is only 15 cm, and so having an optical cavity is not possible—one needs a very powerful one-pass laser.

Such a laser system, while certainly feasible, would not be easy to build and would require a great deal of R&D and prototyping. The optical-cavity technology, proposed for the photon collider in 1999, has been developed very actively for many applications based on Compton scattering; however, its present status is still far from what is needed for the photon collider.

New hopes came from LLNL’s laser-fusion project LIFE [32], which is based on the diode-pumping technology. LIFE’s laser system will consist of about 300 lasers, each operating at a repetition rate of 16 Hz and delivering 8.4 kJ per flash. The photon collider at the ILC would require a laser that produces 1 ms trains of 2600 pulses, 5–10 J per pulse, with a repetition rate of 5–10 Hz. The volume of one LIFE laser is 31m^3 . It can be modified for the production of the required pulse trains with further chirped pulse compression. The advancement of this technique has been enabled by the significant reduction of the cost of pumping diodes, currently estimated at \$0.10 per watt, which translates to \$3 million per laser (the ILC-based photon collider would require ~ 6 such lasers). If so, one can use such a laser both for ILC and CLIC without any enhancement in optical cavities.

Naturally, it is very attractive to simply buy a few \$3M lasers and use them in one-pass mode rather than venturing to construct a 100 m optical cavity and stabilize its geometry with an accuracy of several nanometers. For the CLIC-based photon collider, the optical-cavity approach would not work at all due to CLIC’s very short trains; a LIFE-type laser is therefore the only viable option.

Another very promising laser system for photon colliders was suggested for the HFITT photon collider project [11] discussed above. Only recently have laser physicists succeeded in coherently combining the light from thousands of fibers. A diode-pumped fiber laser is capable of producing 5–10 J pulses with a repetition rate of 47.7 kHz as required by HFITT. In this project electron bunches follow with constant repetition rate that is very convenient for such laser system because pumping diodes work continuously that reduce their total pulse

power.

It would have been very attractive to use such a fiber laser for the photon collider at the ILC as its total power would be larger than needed. Unfortunately, the pulse structure at the ILC would be very bad for a such laser, as the ILC needs $2600 \times 10 \text{ J} = 26 \text{ kJ}$ per 1 ms, which translates to a 55 times greater (peak) power of the diode system. Correspondingly, the diode cost would be greater by the same factor.

7. Conclusion

The photon collider based on ILC (or CLIC) is a most realistic project. However, if the e^+e^- program occupies all the experiment's time, the photon collider will not become reality for least 40 years from now, which is unattractive for the present generation of physicists. More attractive would be a collider with two interaction regions.

A laser system based on the project LIFE lasers is the most attractive choice at this time; fiber lasers can also reach the desired parameters at some point in future. Development of low-emittance polarized electron beams can increase the photon collider luminosity by a further order of magnitude. The photon collider would be very useful for the precise measurement of the Higgs' $\gamma\gamma$ partial width and its CP properties.

The idea of a photon-collider Higgs factory based on recirculating linacs looks interesting as it can use shorter linacs. Unfortunately, the problem of emittance dilution is very serious and the total length of the arcs is very large. Most importantly, a photon collider with no e^+e^- does not make much sense for the study of the Higgs boson.

At this time, the ILC is the best place for the photon collider. It will be useful for any new physics study. Unfortunately, future of linear colliders remain uncertain already several decades.

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