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Issues with current designs for e^+e^- and $\gamma\gamma$ colliders

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This talk at PHOTON2013 covers two hot topics of the last year, both triggered by the discovery of the Higgs boson:
1) Limitation on the luminosity of e^+e^- storage rings due to beamstrahlung;
2) Photon collider Higgs factories.

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1. Introduction

The most important event after the last PHOTON conference was the discovery at the LHC the long-sought Higgs boson with the mass $M \approx 126\,\mathrm{GeV}/c^2$. The precision study of the Higgs boson's properties would require the construction of an energy- and luminosity-frontier Higgs factory, that could be a e^+e^- collider or (and) photon and muon colliders.

Linear e^+e^- colliders (LC), which have been in development for over 40 years, are perfectly suited for such studies. Two LC projects are in advanced stages of development: the $2E_0 = 500\,\mathrm{GeV}$ ILC [1] and the $2E_0 = 500$–$3000\,\mathrm{GeV}$ CLIC [2]. Linear colliders were always considered as the best machines for search and study new physics in the above energy region. Unfortunately, by now only the Higgs boson has been found in the region below one TeV. The observed low mass Higgs boson can be reached also with storage ring e^+e^- colliders (SRC). Several proposals [3, 4, 5, 6, 7, 8, 9] for a $2E_0 = 240\,\mathrm{GeV}$ SRC for the study of the Higgs boson in $e^+e^- \to HZ$ have recently been put forward. Lower cost and reliance on firmly established technologies and higher luminosity are cited as these projects' advantages over an LC. The required energy is only 10% higher than that obtained at the LEP storage ring which was considered for many years as the last circular e^+e^- collider due to synchrotron-radiation (SR) energy losses, which are proportional to E_0^4/R. The excessive power of SR is a well known limitation on the energy of storage ring e^+e^- colliders. Below I discuss another limitation on the luminosity at high energy SRC due to beamstrahlung [10]. *Beamstrahlung*, i.e., synchrotron radiation in the electromagnetic field of the opposing beam, in high-energy e^+e^- SRCs determines the beam lifetime through the emission of single photons in the tail of the beamstrahlung spectra, thus severely limiting the luminosity. This effect is most dramatic for a crab-waist scheme of collisions and, in fact, close this approach. Beamstrahlung reduces the luminosity for head-on collisions several times as well. Nevertheless, the luminosity of such ring colliders (with $C \sim 100$ km) at 2E=240 GeV could be larger than at linear colliders.

The second part of the paper is devoted to photon colliders, more exactly, to photon collider Higgs factories. The $\gamma\gamma$, γe photon colliders have been considered for more than 30 years [13, 14] as a natural addition to e^+e^- linear-collider projects. The measurement of the Higgs two-photon decay width was always considered as a primary task for the photon collider. Following the recent discovery of the Higgs boson, the physics community has been actively considering various approaches to building a Higgs factory, a photon collider (with or without e^+e^-) being one of them. In this paper, following a brief discuss of photon colliders based on ILC and CLIC, I give a critical overview of the recently proposed photon-collider Higgs factories with no e^+e^- collision option based mostly on recirculating electron linac where the electron bunches make several turns in a ring to reach the energy of 80 GeV required for the Higgs production in $\gamma\gamma \to H$. For example, there is project of such photon collider in the Tevatron tunnel (as well as in the HERA tunnel and others). Such projects of photon colliders based on recirculating linac looks attractive only on first sight. As explained below, for removal of highly disrupted beams from the detector and for obtaining sufficiently high linear polarization of high energy scattered photons, the electron energy for the $\gamma\gamma$ Higgs factory should be about 110 GeV, which is absolutely impossible due to beam emittance dilution (both in horizontal and vertical directions).

2. Beam lifetime due to beamstrahlung, restriction on beam parameters, resulting luminosities [10]

At storage rings the particles that lose a certain fraction of their energy in a beam collision leave the beam and strike the vacuum chamber's walls; this fraction η is typically around 0.01 (0.012 at LEP) and is known as the ring's energy acceptance. To achieve a reasonable beam lifetime, one must make small the number of beamstrahlung photons with energies greater than the threshold energy $E_{\rm th} = \eta E_0$ that causes the electron to leave the beam. These photons belong to the high-energy tail of the beamstrahlung spectrum and have energies much greater than the critical energy. As was clearly shown in [10] the beam lifetime is determined by such single high-energy beamstrahlung photons, not by the energy spread due to the emission of multiple low-energy photons. The critical energy for synchrotron radiation

$$E_{\rm c} = \hbar\omega_{\rm c} = \hbar\frac{3\gamma^3 c}{2\rho}, \tag{2.1}$$

where ρ is the bending radius and $\gamma = E_0/mc^2$. The spectrum of photons per unit length with energy well above the critical energy

$$\frac{dn}{dx} = \sqrt{\frac{3\pi}{2}}\frac{\alpha\gamma}{2\pi\rho}\frac{e^{-y}}{\sqrt{y}}\left[1+\frac{55}{72y}...\right]dy, \tag{2.2}$$

where $y = E_\gamma/E_{\rm c}$, $\alpha = e^2/\hbar c$. Integration was done numerically assuming flat Gaussian beam and precalculated values of the field inside such beam. After integration we obtain the number of photons emitted by one electron during one beam collisions energy $E_\gamma \geq \eta E_0$:

$$n_\gamma(E_\gamma \geq \eta E_0) \approx \frac{\alpha^2\eta\sigma_z}{\sqrt{6\pi}r_e\gamma}F(u); \quad u = \frac{\eta E_0}{E_{\rm c}}. \tag{2.3}$$

Here $E_{\rm c}$ corresponds already to the maximum beam field and the function

$$F(u) = \frac{0.167e^{-1.225u}}{u^{3/2}} \approx 0.057e^{-1.475u}. \tag{2.4}$$

The result of calculations and these functions are shown in Fig.1. Also the approximation of the ref.[10] is shown, where it was just assumed that the electron is affected by the maximum field with the probability 1/20. As we will see below typical values of u are 4–8, so the agreement between the rough estimate and the exact calculation is rather good. The beam lifetime

$$\tau = n_\gamma\frac{2\pi R}{c} = \frac{2\pi R}{c}\frac{\sqrt{6\pi}r_e\gamma\cdot e^{1.475u}}{\alpha^2\eta\sigma_z\cdot 0.057} \tag{2.5}$$

From this formula one obtains u for a given lifetime τ and collider parameters

$$u = \frac{\eta E_0}{E_{\rm c}} = 0.68\cdot ln\frac{\eta\sigma_z c\tau}{2\pi R r_e\gamma} - 9.25 \tag{2.6}$$

For typical values $E_0 = 120$ GeV, $\sigma_z = 0.1$ cm, $\eta = 0.01$, $2\pi R = 80$ km we get $u = 8$, 5.2 and 2.9 for $\tau = 30$ min, 30 s and 1 s, respectively. The accuracy of the approximation (2.4) for the beam

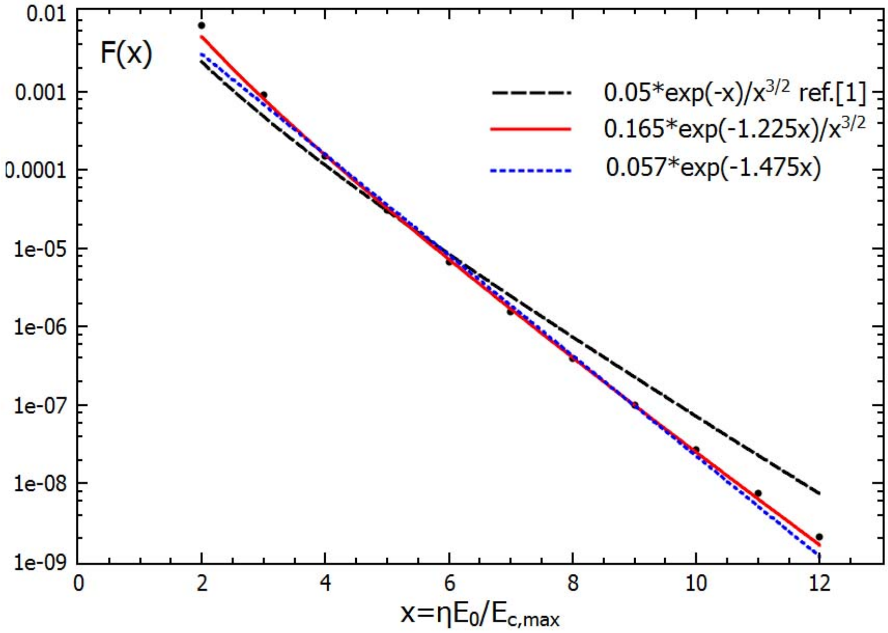

Figure 1: The function F(x) in Eq.(2.3)

lifetime is about 15% in the range of u between 3 and 10. The values of u depend logarithmically on the lifetime, therefore the accuracy of u is about 1-2%. The critical energy is related to the beam parameters as follows:

$$\frac{E_{\rm c}}{E_0} = \frac{3\gamma {r_e}^2 N}{\alpha\sigma_x\sigma_z}, \tag{2.7}$$

Combined with Eq. 2.6, this imposes a restriction on the beam parameters,

$$\frac{N}{\sigma_x\sigma_z} < \frac{\eta}{u}\frac{\alpha}{3\gamma {r_e}^2}, \tag{2.8}$$

where N is the number of particles in the beam, $\alpha = e^2/\hbar c \approx 1/137$, and σ_x and σ_z are the rms horizontal and longitudinal beam sizes, respectively. *This new constraint on beam parameters should be taken into account in luminosity optimization.*

Performing calculations we assumed that the beam lifetime is determined solely by the tail of the synchrotron radiation spectrum and stated that the accuracy of the lifetime is better than 15%. This is not completely true due to the beam energy spread. It is caused both by SR in rings and by beamstrahlung. Though it was shown in [10] that the lifetime is always determined by the radiation of hard SR photons, but the energy spread can increase somewhat this probability (because the photon is emitted by the electron which already has the energy deviation from the equilibrium energy). Let σ_E is the r.m.s. energy spread. According to the above consideration the spectrum can be approximated as $F(E_\gamma) \propto exp(-bE_\gamma/E_{\rm c})$ with $b \approx 1.48$. Overlap of this spectra with the Gaussian energy spread mathematically means the convolution of the two spectra. It is easy to show that the resulting deviation for the electron energy after emition of the hard SR photon remains proportional to $exp(-bE_\gamma/E_{\rm c})$ but the spectrum increases by the factor $exp(b^2\sigma_E^2/2E_{\rm c}^2) \approx$

$exp(\sigma_E^2/E_c^2)$. As it was shown $E_c \approx \eta E_0/u$ with $u \sim$ 5–8. The energy spread σ_E could be, in principle, $\sim (0.1-0.15)\eta E_0$ (for which the beam lifetime is still not affected). For such numbers the argument in the exponent is of the order of one, that means the drop of the beam lifetime by a factor of about 3. According to (2.6) the drop of the beam lifetime by a factor of 3 can be compensated by the increase of u approximately on 0.7. As result, we should take (for safety) $u \approx 8.7 \sim 9$ and $5.9 \sim 6$ for desired lifetimes 30 min and 30 s, respectively. In [10] the very similar number was obtained: $u = 8.5$ for $\tau = 30$ min which was rounded up to $u = 10$ for practical applications.

Taking into the additional constraint (2.8) one can obtain the following expression for the luminosity of the collider (see the derivation in [10])

$$\mathscr{L} \approx h \frac{(\eta\alpha/u)^{2/3} PR}{32\pi^2\gamma^{13/3} r_e^3} \left(\frac{R_b}{R}\right) \left(\frac{6\pi\xi_y r_e}{\varepsilon_y}\right)^{1/3}, \tag{2.9}$$

where h is the hourglass loss factor, ξ_y is the vertical beam-beam strength parameter, ε_y is the vertical beam emittance, P is the power of SR in rings, R_b and R are the average bending radius and the geometric collider radius, η is the energy acceptance and u is the parameter discussed above. In practical units,

$$\frac{\mathscr{L}}{10^{34}\,\mathrm{cm^{-2}s^{-1}}} \approx \frac{100h\eta^{2/3}(10/u)^{2/3}\xi_y^{1/3}}{(E_0/100\,\mathrm{GeV})^{13/3}(\varepsilon_y/\,\mathrm{nm})^{1/3}} \left(\frac{P}{100\,\mathrm{MW}}\right) \left(\frac{2\pi R}{100\,\mathrm{km}}\right) \frac{R_b}{R}. \tag{2.10}$$

Note, the decrease of the beam lifetime from 30 min down to 30 s increases the luminosity only by a factor of $\sim (8.7/5.9)^{2/3} \approx 1.3$.

As was shown in [10] the beamstrahlung suppresses the luminosities of high-energy e^+e^- storage rings as $1/E_0^{4/3}$ at beam energies $E_0 \gtrsim 70\,\mathrm{GeV}$ for head-on collisions and $E_0 \gtrsim 20\,\mathrm{GeV}$ for crab-waist collisions. Very importantly, beamstrahlung makes the luminosities attainable in head-on and crab-waist collisions approximately equal above these threshold energies.

At present, CERN considers very seriously a strategy based on very large ring collider with the circumference 80 km. It will accommodate the e^+e^- collider TLEP [5, 11] on the energy $2E = 90-350$ GeV and the pp collider on the energy 100 TeV. The expected luminosity of TLEP at the Higgs energy $2E = 240$ GeV is $5\cdot10^{34}$ cm^{-2}s^{-1} per one IP (four is possible). At the linear collider ILC the corresponding luminosity (in TDR) is $0.75\cdot10^{34}$ [1], the upgrade to $L = 3\cdot10^{34}$ is foreseen [12].

3. Physics motivation of the photon collider

In short, the photon collider can study New Physics at energies and statistics similar to those in e^+e^-collisions—but in different reactions. In some cases, the photon collider provides access to higher masses or allows the study of some phenomena with higher precision than.

Let us compare the strengths of e^+e^- and $\gamma\gamma$ colliders in the study of the Higgs boson. The photon collider can measure $\Gamma(H\to\gamma\gamma)\times Br(H\to bb, ZZ, WW, \gamma\gamma)$ and, using linearly polarized photons, the Higgs' CP properties. In order to extract $\Gamma(H\to\gamma\gamma)$, one needs the value of $Br(H\to bb)$ from an e^+e^- collider. In e^+e^- collisions, one can measure $Br(H\to bb, cc, gg, WW, ZZ, \mu\mu,$ invisible), Γ_{tot}. The process $e^+e^-\to ZH$ with Z tagging allows the measurement of the absolute values of branching fractions, including Higgs decays to $\tau\tau, \mu\mu, cc$, which are not accessible in $\gamma\gamma$ collisions due to a large QED background.

The rate of Higgs boson production in $\gamma\gamma$ collisons [15]

$$\dot{N}_H = L_{ee} \times \frac{dL_{0,\gamma\gamma}}{dW\gamma\gamma L_{ee}} \frac{4\pi^2\Gamma\gamma\gamma}{M_H^2}(1+\lambda_1\lambda_2 + CP * l_1 l_2 cos2\varphi) = L_{ee}\sigma \tag{3.1}$$

$$\sigma = \frac{0.98 \cdot 10^{-35}}{2E_0[\text{GeV}]} \frac{dL_{0,\gamma\gamma}}{dzL_{ee}}(1+\lambda_1\lambda_2 + CP * l_1 l_2 cos2\varphi), \text{ cm}$$

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 $\lambda \sim 1.05$ μm (most powerful lasers available); the corresponding parameter $x = 4E_0\omega_0/m^2c^4 \approx 2$.

Let us consider the two most important sets of parameters: 1) for the measurement of $\Gamma\gamma\gamma$, 2) for the measurement of CP. In both cases, it is preferable to use longitudinally polarized electrons, $2\lambda_e = -0.85$ is possible. For case 1, the laser polarization should be $P_c = 1$ and $2P_c\lambda_e \sim -0.85$ (to enhance the number of high-energy photons); then, the resulting polarization of the scattered photons $\lambda_{1,2} \approx 1$, $l_{1,2} = 0$. For case 2, one should take $P_l = 1$, then $\lambda_{1,2} = 0.68$, $l_{1,2} = 0.6$. Simulation has been perfomed for a laser target thickness of 1.35 (in units of the Compton scattering length) and the CP-IP distance $b = \gamma\sigma_y$; it gave $dL_{0,\gamma\gamma}/dz/L_{ee} = 0.84$ and 0.35 for cases 1 and 2, respectively. The corresponding effective cross sections are 75 fb and 28.5 fb, which should be compared with 290 fb for the process $e^+e^- \to ZH$.

The geometric *ee* luminosity in the case of the photon collider is approximately equal to the e^+e^- luminosity (the pinch factor in e^+e^- collisions is compensated by a tighter focusing in $\gamma\gamma$ collisions). This means that for the same beam parameters the Higgs production rate at the photon collider is approximately four times lower than in e^+e^- collisions.

The photon collider can measure better only $\Gamma\gamma\gamma$, which determines the Higgs production rate in $\gamma\gamma$ collisions and can be measured by detecting the decay mode $H \to bb$ ($\sim 57\%$ of the total number of Higgs decays). In e^+e^- collisions, the Higgs' $\gamma\gamma$ width is measured in the $H \to \gamma\gamma$ decay, which has a branching fraction of 0.24%. This means that at the photon collider the statistics for the measurement of $\Gamma(H \to \gamma\gamma)$ is higher by a factor of $0.57/0.0024/4 \approx 60$ (or even larger if a lower-emittance electron source becomes available). This is the main motivation for the photon collider. The study of the $H\gamma\gamma$ coupling is arguably the most interesting area of Higgs physics because it procedes via a loop and therefore is the most sensitive to New Physics. The photon collider at the ILC with the expected $L_{ee} \approx 3 \times 10^{34}$ will produce about 22500 Higgs bosons per year (10^7 sec), which would enable the determination of $\Gamma(H \to \gamma\gamma) \times Br(H \to bb)$ with an accuracy of 2% [16, 17, 18].

The photon collider can also be used also for the measurement of the Higgs boson's CP properties using lineary polarized high-energy photons (details are provided below).

As one can see, while e^+e^- collisions are more powerful overall for the study of Higgs properties, a $\gamma\gamma$ collider would add very significantly in some areas. The relative incremental cost of adding a photon collider to an e^+e^- linear collider is very low. Therefore, the best solution would be to build an e^+e^- linear collider combined with a photon collider; the latter would come almost for free.

3.1 The collider energy for the $\gamma\gamma$ Higgs factory

The preferable electron beam energy and laser wavelength for the $\gamma\gamma$ Higgs factory are $E_0 \approx 110$ GeV and $\lambda \approx 1\,\mu$m, corresponding to the parameter $x \approx 2$ (this includes the spectrum shift due to nonlinear effects in Compton scattering). Note that all photon-collider projects that appeared in the last year assumed $E_0 = 80$ GeV (85 GeV would be more correct) and $\lambda = 1/3$ μm ($x = 4.6$). This choice was driven by the simple desire to have the lowest possible collider energy. However, life is not so simple, there are other important factors that must be considered:

1. As proposed, these projects would suffer from the very serious problem of the removal of used electron beams. That is because the minimum energy of electrons after multiple Compton scattering in the conversion region will be a factor of 4.5 lower [15], and these electrons will be deflected at unacceptably large angles by the opposing beam as well as by the solenoid field (the latter due to the use of the crab-crossing collision scheme).

2. For the measurement of the Higgs' *CP* properties one should collide linearly polarized γ beams at various angles between their polarization planes. The effect is proportional to the product of linear polarizations $l_1 l_2$. 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. The case of $x = 1.9$ was simulated, with backgrounds taken into account, in ref. [17]; it was found that the *CP* parameter (a value between 1 and -1) can be measured with a 10% accuracy given an integrated geometric *ee* luminosity of $3 \cdot 10^{34} \times 10^7$ = 300 fb^{-1}.

Both of these facts strongly favor a photon collider with $E_0 = 110$ GeV and $\lambda \approx 1$ μm.

4. Photon colliders at ILC and CLIC

The future of these collider projects is quite unclear due to their high cost, complexity, and (as of yet) absence of new physics in their energy region (other than the Higgs boson). If ILC in Japan is approved, there is a very high probability that it will include the photon collider.

The photon collider for TESLA (on which ILC is based) was considered in detail at the conceptual level [15, 19]. The next major step must be R&D for its laser system. Until a year ago, the most promising solution for the laser system was an external optical cavity, which would reduce the required laser power by a factor of 100. 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.

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New hopes arise from LLNL's laser-fusion project LIFE, which is based on the diode-pumping technology. LIFE's laser system will consist of about 200 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. LLNL experts say that the LIFE laser 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).

Naturally, it is very attractive to simply buy a few $3M lasers and use them in one-pass mode rather then 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.

The expected e^+e^- luminosity of the updated ILC design at $2E_0 = 250$ GeV is $3 \cdot 10^{34}$ cm^{-2}s^{-1}. The geometric ee luminosity at the $\gamma\gamma$ collider could be similar. To further increase the $\gamma\gamma$ luminosity, one needs new ideas on the production of low-emittance polarized electron beams. ILC damping rings are already close to their ultimate performance. To increase the luminosity further, I have proposed [20] 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. In the past, only DC polarized photoguns were available, which produce beams that require further cooling with damping rings. 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 scope document on linear colliders, developed and supported by the physics community, states that the ILC design should be compatible with the photon collider. 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. The choice of a crossing angle incompatible with the photon collider was made simply because all attention in the TDR effort was focused on the baseline e^+e^- collider, not because someone was against the photon collider (no one was). It is not too late to reoptimize the ILC IP and make it compatible with the photon collider. Two IPs would be the best solution.

5. Photon colliders based on recirculating linacs

About one year ago, F. Zimmermann et al. [21] 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, see Fig. 2. One must also double the number of arcs to accomodate 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.

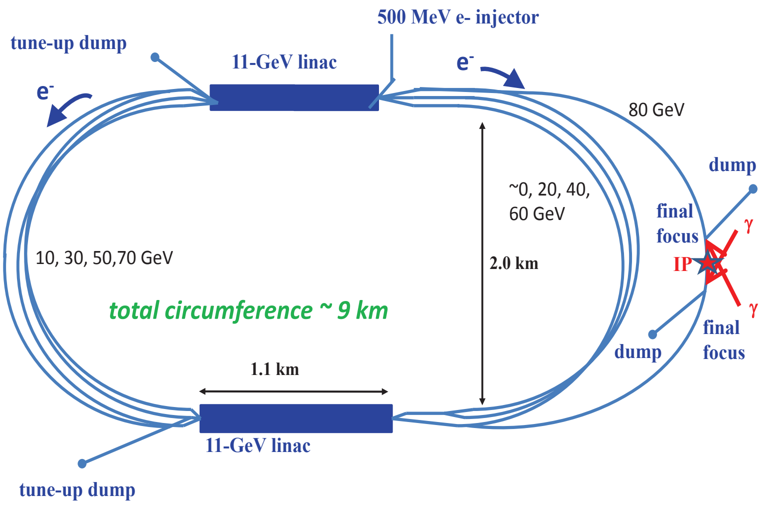

Figure 2: The SAPPHiRE Higgs factory

In any case, the idea is interesting because two 80 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 fact, about 15 years ago I considered a substantially similar approach for a photon collider in the HERA ring at DESY (recall that the HERA ring has four straight sections). My conculsion was that such a design would be impractical due to the unacceptable increase of horizontal emittance in the bending arcs. The increase of the normalized emittance per turn is proportional to E^6/R^4. To solve this problem, the authors of SAPPHiRE have proposed to use $\times 4$ shorter arc structures, which would lead to $\times 64$ smaller emittance dilution. This might be possible but would require $\times 16$ stronger quadrupole magnets.

Another weak point of this proposal is the use of 80 GeV electron beams and the 1/3 μm laser wavelength. As mentioned above, this choice of parameters makes it very difficult to remove the disrupted electron beams from the detector and leads to low sensitivity in the measurement of the *CP* properties of the Higgs boson.

It is highly unlikely that the LHeC project (and, correspondingly, SAPPHiRE) will be approved. However, the idea behind SAPPHiRE 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) [22]. 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".

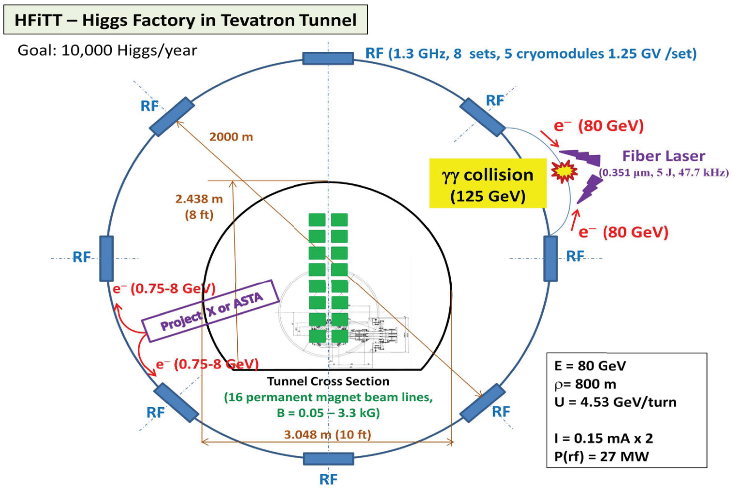

Figure 3: The HFiTT Higgs factory

The most interesting feature of the HFiTT proposal is a novel laser system based on fiber lasers. 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. 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 2600×10 J $= 26$ 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.

There is also a proposal [23] 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. Conclusion on photon colliders

The photon collider based on ILC (or CLIC) is a highly 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. The best solution for this problem is to build 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. A very high-luminosity photon collider at the energy $2E_0 = 400$ GeV can help measure the Higgs' self coupling. The photon collider based on ILC (CLIC) can work with the 1 μm laser wavelength up to $2E_0 \sim 700$ GeV; for higher energies, one should use a greater laser wavelength.

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. The pulse structure of such colliders (equal distance between collisions) is very well suited for fiber lasers. Such a recirculating collider with a desirable E_0 (≈ 110 GeV) can possibly work in large rings such as LEP/LHC or UNK, but then the total length of arcs will be several hundred km and the cost would exceed that for linear colliders with similar energy (that could be, for example, a warm linear collider with the 4 km length). 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.

In conclusion, the discovery of the Higgs boson has led to the revival of high energy e^+e^- storage rings which have a very high potential for Higgs study as well as for Z and $t\bar{t}$. It is interesting that one of fundamental limitation for such colliders, beamstrahlung, was discovered only recently. Photon colliders is very interesting and cost effective option when it is based on some linear collider. Unfortunately, future of linear colliders remain uncertain already several decades.

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