An X-ray FEL-based $\gamma\gamma$ Collider Higgs Factory

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1 Introduction

The conversion of a linear e^+e^- collider into a $\gamma\gamma$ collider through the scattering of laser light off the e^+e^- beams has been considered for some time [1, 2, 3], as has the use of such a collider as a Higgs factory [4, 5]. Interest in a $\gamma\gamma$ collider Higgs factory has waned, however, as studies have demonstrated that e^+e^- colliders such as the ILC, FCC-ee and CEPC would produce better Higgs physics [6].

Existing studies of $\gamma\gamma$ collider Higgs factories have been confined to optical wavelength lasers. The center-of-mass energy of the electron–photon system is usually constrained to $x < 4.82$, where $x = 4E_e\omega_0/m_e^2$, m_e is the electron mass, and E_e (ω_0) is the electron (laser photon) energy. Larger x values are problematic due to the thresholds of $x = 4.82$ ($x = 8.0$) for the processes $\gamma\gamma_0 \to e^+e^-$ ($e^-\gamma_0 \to e^-e^+e^-$), where γ and γ_0 refer to the Compton-scattered and laser photon, respectively. Larger x values, however, also carry advantages. As x is increased the $\gamma\gamma$ differential luminosity distribution with respect to center-of-mass energy becomes more sharply peaked near the maximum center-of-mass energy value. Such a distribution increases the production rate of a narrow resonance relative to $\gamma\gamma$ background processes when the peak is tuned to the resonance mass.

This study will explore the design of a $\gamma\gamma$ Higgs factory with $x = 1000$, in which 63 GeV electron beams collide with 1 keV X-ray free electron laser (XFEL) beams. The $\gamma\gamma$ differential luminosity distribution with respect to center-of-mass energy has a single asymmetric peak at the Higgs boson mass with widths of 2.8 GeV (0.4 GeV) on the low (high) side of the peak, and no other structure. In contrast, the distribution for an $x = 4.82$ collider would have a peak at the Higgs boson mass with widths of 15.8 GeV (4.3 GeV) on the low (high) side plus additional structure at lower $\gamma\gamma$ center-of-mass energies, and would therefore produce a much greater $\gamma\gamma$ background to the Higgs signal. The Higgs boson production rate for the collider considered here is 30,000 Higgs bosons per (10^7 second) year, roughly the same as the ILC Higgs rate. With such a unique experimental environment the Higgs physics output of an XFEL $\gamma\gamma$ Higgs factory could be greater than that of optical wavelength $\gamma\gamma$ colliders.

2 System Configuration and Machine Parameters

2.1 Higgs Factory Configuration

The $\gamma\gamma$ collider consists of two 62.8 GeV electron accelerators which feed the final focus lines and two 31 GeV electron accelerators which feed the XFEL lines, all using Cool Copper Collider (C^3) technology [7]. The final focus and XFEL lines make small angles with respect to each other, aligned so that the X-ray laser beams collide with the 62.8 GeV electron beams 100 microns upstream of the e^-e^- collision point. The RF gun for the 62.8 GeV accelerator provides 90% polarized electrons with 0.62×10^{10} electrons per bunch and 75 bunches per train at a repetition rate of 120 Hz. The normalized horizontal and vertical emittances out of the gun are 0.12 microns each, eliminating the need for damping rings. The r.m.s. bunch length is 30 μm. With an interaction point beta function of 30 microns the geometric horizontal and vertical spot sizes are 5.4 nm and 18.8 nm at the e^-e^- interaction point and Compton collision point, respectively. The e^-e^- geometic luminosity with this configuration is $9.7 \times 10^{34}\mathrm{cm}^2\ \mathrm{s}^{-1}$.

The X-ray laser pulse energy is 0.7 Joules. The horizontal and vertical r.m.s. beam sizes at the Compton collision point are each 37.7 nm, and the Rayleigh length is 7.5 μm for a total laser pulse length of 15 μm. The non-linear QED parameter is $\xi^2 = 0.16$, so that non-linear QED effects should be limited. The electron and laser photon helicities are given the same sign, which leads to collision lengths of 34, 25, and 95 μm for the Compton process $e^-\gamma_0 \to e^-\gamma$, the trident process $e^-\gamma_0 \to e^-e^+e^-$, and the $\gamma\gamma_0$ annihilation process $\gamma\gamma_0 \to e^+e^-$, respectively. The $\gamma\gamma_0$ annihilation collision length is 3× longer than it would have been if the electron and laser beams were unpolarized, and 5× longer than the collision length if the electron and laser beams had been given opposite helicities. With a collision length of 6.3 times the total laser pulse length, the $\gamma\gamma_0$ annihilation process is a nonissue. The total conversion efficiency of electrons to primary first generation photons is 18%. The fractions of primary photons from electrons that have undergone 0, 1, and 2 or more trident scatters are 83%, 15%, and 2%, respectively, so that the trident process scales the peak in the $\gamma\gamma$ differential luminosity by a factor of $(0.83)^2$=70%.

As calculated by the CAIN Monte Carlo program [8] the luminosities for $\gamma\gamma$, $e^-\gamma$, and e^-e^- collisions are 1.9, 7.7, and 3.9×10^{33} cm^{-2} s^{-1}, respectively. Despite the nearly 10^{35} cm^{-2} s^{-1} geometric luminosity and the loss of only 18% of the electrons to Compton scattering, the e^-e^- luminosity is remarkably low, due to the anti-pinch beam-beam interaction. At 1.9×10^{33} cm^{-2} s^{-1} the $\gamma\gamma$ luminosity is ten times smaller than the ILC e^+e^- luminosity, and yet the two machines would produce the same number of Higgs bosons.

Given these luminosities one could say that the XFEL-based $\gamma\gamma$ collider Higgs factory is mostly a $\sqrt{s} = 125$ GeV e^-e^- and $e^-\gamma$ collider, with just enough $\gamma\gamma$ luminosity to produce 30,000 Higgs bosons per year. The e^-e^- and $e^-\gamma$ backgrounds for both the detector and physics need to be studied. Consider, for example, the physics background for hadronic decays of the Higgs boson. The event rate for processes such as $e^-e^- \to e^-e^-q\bar{q}$ and $e^-\gamma \to e^-q\bar{q}$ is much higher [9] than the $\gamma\gamma$ Higgs production rate. But the hadronic systems in these background events are highly boosted along the beam axis with masses below a few tens of GeV, and so should not present a major problem. The one exception is on-shell production of the Z boson, $e^-\gamma \to e^-Z$ with $Z \to q\bar{q}$. Although most of the Z bosons are boosted along the beam axis, enough are produced centrally to potentially cause trouble. However, in this case the small angles that the vector Z boson decay products make with the beam axis can be used to discriminate against the isotropic decays of the scalar Higgs. The large detector background from very low energy electrons and photons following multiple Compton scatters is a major concern, and will be studied using the CAIN Monte Carlo.

2.2 Electron Accelerator Configuration

The C^3 technology represents a new methodology for dramatically reducing the cost of high gradient accelerators, while increasing their capabilities in terms of gradient and efficiency. After two decades of exploring the high gradient phenomena observed in room-temperature accelerator structures, we have been able to deduce the underlying physics models related to these phenomena. This knowledge led us to create a new paradigm for the design of accelerator structures, which includes: a new topology for the structure geometry [10, 11] operating at cryogenic temperature [12], the use of doped copper in the construction of these structures [13], and a new methodology for the selection of operating frequency bands [13]. In particular, for science discovery machines, optimization exercises have revealed that the optimal frequency should be around 6–8 GHz for operation with a gradient well above 100 MV/m while maintaining exquisite beam parameters. That explains why both UCLA and LANL are trying very hard to build their infrastructure at C-band (5.721 GHz), a frequency band that is close enough to the optimal point, but with some industrial support behind it.

Furthermore, the so-called "distributed-coupling structure" [10] and its operation at cryogenic temperature represent a breakthrough for the e$^-$ source. Electron guns can be designed around this concept with an unprecedented brightness [14]. Using this technology can result in an extremely economical system for this γ-γ collider. The 4 linacs required for both e$^-$e$^-$ portion and for the XFEL portion could be made extremely compact due to the high gradient capabilities of the C^3 technology and the limited energy reach required of 62.5 GeV. With the bright electron beam sources, we could also eliminate the damping rings. An example parameter set is discussed below.

2.3 X-ray FEL Configuration

The two identical X-ray FEL lines, which provide the necessary circularly-polarized 1.2 nm (1 keV) photons, can be constructed using a long helical undulator. Due to the high magnetic field and high electron energy considered here, the quantum diffusion energy spread in such an undulator must be taken into account and properly included in design calculations. As the main linac can accelerate electrons to 62.5 GeV, we take the electron energy for the XFEL line to be around 31 GeV, with normalized emittance of 120 nm, bunch charge of 1 nC and relative RMS slice energy spread of $\langle \Delta\gamma/\gamma \rangle$ of 0.05%.

Using a permanent-magnet undulator, with peak magnetic field slightly above 1 Tesla, undulator period around 9 cm and an average β-function of 12 m, we can produce 1 keV X-ray pulse energy $\sim$ 0.07 J at FEL saturation length of roughly 60 m and with negligible quantum diffusion effects [15, 16]. As we know from a decade of X-ray FEL studies, if we can produce a seeded FEL (such as through self-seeding or other similar processes) and taper the undulator's K parameter after saturation, we can continue to extract X-ray pulse energy with an order-of-magnitude improvement in efficiency [17]. Then we can reach the targeted pulse energy of 0.7 J at 1 keV photon energy, which is about 2.3% of the electron beam energy. The overall length of the undulators is estimated to be within 200 m. This is just an example parameter set (summarized in Table 1 below). Detailed optimization and simulation studies will be reported elsewhere.

Table 1: Summary of approximate design parameters.

Accelerator parameters	Approx. value	XFEL parameters	Approx. value
Electron energy	62.8 GeV	Electron energy	31 GeV
β_x/β_y	0.03/0.03 mm	normalized emittance	120 nm
$\gamma\epsilon_x/\gamma\epsilon_y$	120/120 nm	RMS energy spread $\langle\Delta\gamma/\gamma\rangle$	0.05%
σ_x/σ_y at e^-e^- IP	5.4/5.4 nm	bunch charge	1 nC
σ_z	30 μm	Undulator B field	$\gtrsim$ 1 T
bunch charge	1 nC	Undulator period λ_u	9 cm
Rep. Rate	120×75 Hz	Average β function	12 m
σ_x/σ_y at Compton IP	18.8/18.8 nm	x-ray λ (energy)	1.2 nm (1 keV)
$\mathrm{L}_{\mathrm{geometric}}$	9.7×10^{34} cm^2 s^{-1}	x-ray pulse energy	0.7 J

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