DESIGN CONCEPT OF A γ-γ HIGGS FACTORY DRIVEN BY THIN LASER TARGETS AND ENERGY RECOVERY LINACS*

Y.H Zhang#, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

Abstract

A γ-γ collider has long been considered an option for a Higgs Factory. Such colliders usually rely on Compton back-scattering for generating γ photons. The present designs all choose a thick laser target for scattering. In this paper, we present a new approach for a γ-γ collider utilizing a thin laser target, thus leading to a low electron to γ photon conversion rate. This new concept eliminates useless soft γ photons from multiple Compton scattering. It also relaxes the requirement of the high peak power of the laser. A high luminosity of such a γ-γ collider can be achieved through an increase of the bunch repetition rates and currents of the electron beams. Further, multi-pass recirculating linac could greatly reduce the linac cost and energy recovery is required to reduce the RF power.

INTRODUCTION

Since the recent discovery of Higgs bosons at the LHC, there is renewed interest in constructing a Higgs Factory (HF) [1]. One option is a γ-γ collider [2,3] which was proposed initially as the 2nd interaction point (IP) in various linear collider proposals [4-9]. Recently, a stand-alone γ-γ collider driven by recirculating linacs has been proposed for a HF [10, 11].

The standard mechanism of γ photon generation for γ-γ colliders is Compton back-scattering of laser photons by ultra-relativistic electrons. The conventional approach is to employ a thick laser target, i.e., high laser intensity, for harvesting a large number of γ photons in order to achieve a high luminosity. Such an approach has several disadvantages including a very large number of low energy soft γ photons generated by multiple scatterings, in addition to requiring a very high peak laser power. These soft γ photons don't contribute to generation of Higgs bosons but do increase the detector background.

A new concept proposed recently [12] is based on a thin laser target for Compton scattering. It utilizes a low laser photon density such that only a small fraction of electrons are scattered by the laser photons, resulting a much lower electron to γ photon (e-→γ) conversion. This ensures the elimination of nearly all the useless soft γ photons from multiple scatterings, thus improving the detector background. Other advantages are requiring a lower peak laser power and eliminating the nonlinear effects (including multi-photon scatterings) of strong laser fields.

To achieve a high luminosity of γ-γ collisions with a thin target, one increases the electron beam current to generate a high flux of γ photons. A higher current electron beam requires a higher RF power for acceleration, nevertheless, much of the beam power can be recovered since a high percentage of electrons are not scattered at all. Thus, the net RF power consumed in this new scheme is similar to that of the thick target designs.

THE THICK LASER TARGET DESIGN

The mechanism for generating γ photons through Compton back-scatterings has been extensively studied; a good review can be found in [3]. The γ photons have a broad spectrum with a cut-off at the high energy end [3]

$$\frac{E_{\gamma,max}}{E_e} = \frac{x}{1+x} \quad \text{and} \quad x = \frac{4E_e\hbar\omega_0}{(m_e c^2)^2} \approx 15.3\left[\frac{E_e}{\text{TeV}}\right]\left[\frac{\hbar\omega_0}{\text{eV}}\right] \qquad (1)$$

where E_e and $\hbar\omega_0$ are energies of the electrons and laser photons. The optimized value of x is 4.8, resulting a highest γ photon energy $E_{\gamma,\max} \approx 0.83E_e$.

The number of γ photons generated from Compton back-scattering of an electron bunch depends on the laser photon density. The e-→γ conversion rate in the regime of low laser photon density, assuming no multiple scattering, is given by

$$k = \frac{N_\gamma}{N_e} \sim 1 - e^{-\frac{A}{A_0}} \approx \frac{A}{A_0} \qquad (2)$$

where A is the energy of a laser flash. A_0 is a parameter depending on the length and profile of the laser pulse and Compton cross-section [3].

A thick laser target is achieved by pushing up the laser flash energy. A typical γ-γ collider design calls for $A \approx A_0$, thus the e-→γ conversion rate is about 63%. There are proposals with even higher laser flash energies such that the e-→γ conversion rate is 2.4 for CLICHÉ [8] and 1.2 to SAPPHiRE [10].

There are several issues associated to the thick laser target approach. The first issue is a high number of multiple Compton scatterings of an electron, generating a large amount of soft γ photons, as shown in Figure 1. It can be seen that more than half of γ photons are generated by multiple scatterings when $A=A_0$. When $A=2A_0$, over 80% of γ photons are soft ones.

The second issue is ultra high peak laser power required to support a saturated photon density. A thick laser target demands $A \geq A_0$, and a typical value of A_0 is 1 J. With a nominal 0.1 mm RMS bunch length for an electron beam from a linac, the peak laser power is on the order of 1 TW. The average laser power, on the other hand, is fairly modest, up to several tens of kW, for either a pulsed beam or an CW beams of a low to modest bunch repetition rate.

The third issue is the influence of an ultra strong EM field of the laser on the e-→γ conversion. When the laser photon density is very high, the multi-photon effects become non-negligible. Such nonlinear effects are characterized by the following parameter [3]

$$\xi^2 = \left[\frac{4F\hbar}{m_e\omega_0 c}\right]^2 \approx \frac{2}{\pi a}\frac{\sigma_c}{\sigma_0}\frac{\lambda}{l_\gamma}k \qquad (5)$$

where F represents the E or B field of the laser , $k=N_\gamma/N_e$, l_γ is the laser pulse length, a is the electron beam spot

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*Supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC05-06OR23177. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.

yzhang@jlabl.org

ISBN 978-3-95450-122-9

size, σ_c and σ_0 are Compton cross-sections associated to x=0 (non-relativistic) and $x \neq 0$ respectively. σ_c/σ_0~0.75 for x=4.8. When $\xi^2 \ll 1$, the nonlinear effect is negligible. Otherwise, two or more laser photons can be scattered at the same time. There are several bad effects of the nonlinear fields, one of them is the reduction of the maximum energy of γ photons.

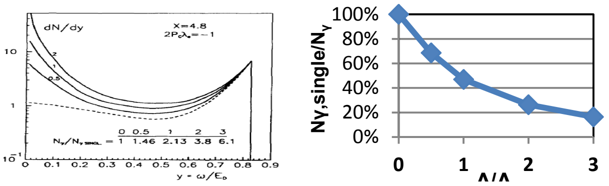

Figure 1: (Left) Normalized γ photon spectra for different laser targets (the solid curves), dashed curve is photon spectra without secondary scatterings [3]; (Right) Ratio of the γ photons from single Compton scatterings over the total γ photons.

THE NEW DESIGN CONCEPT

The new concept aims to address the above issues associated with the thick laser target approach. Its key feature is a thin laser target, $A/A_0 \ll 1$, therefore, it could

- eliminate effectively all the soft γ photons generated by multiple Compton scatterings;
- lower the peak laser power;
- reduce nonlinear effect of the high intensity laser

Reduction of the laser target thickness leads to less γ photons from scatterings, thus affecting the luminosity. However, one could increase the electron beam current through higher bunch repetition rate and higher bunch charge to compensate for the luminosity loss. Specifically, assuming the same electron beam parameters

$$\frac{L_{b,thin}}{L_{b,thick}} = \frac{f_{thin}}{f_{thick}} \left[\frac{N_{e,thin}}{N_{e,thick}}\right]^2 \left[\frac{k_{thin}}{k_{,thick}}\right]^2 \qquad (3)$$

where $L_{b,thin}$ $L_{b,thick}$, f_{thin}, f_{thick}, $N_{e,thin}$, $N_{e,thick}$, $k_{e,thin}$ and $k_{e,thick}$ are the broadband luminosities, bunch repetition rates, electrons per bunch and the e→γ conversion rates for the thin and thick targets respectively. It is possible to archive $L_{b,thin}/L_{b,thick}$~1, for an example, letting f_{thin}/f_{thick}~5, $N_{e,thin}/N_{e,thick}$~2, $k_{e,thin}/k_{e,thick}$~0.14/0.63~0.22. Though the bunch charge is doubled in this example, the laser density is nevertheless reduced by a factor of 1/0.15≈6.7, therefore, the required laser photons per flash is reduced by a factor of 3.3 for the thin target design.

DESIGN PARAMETERS

Table 1 lists the main parameters of a γ-γ HF with a thin laser target. The laser flash energy is chosen empirically such that A/A_0=0.15, thus the e→γ conversion rate is about 14%. As a comparison, we also list SAPPHiRE parameters [11].

Table 1: The Design Parameters for a γ-γ Collider Based Higgs Factory

		SAPPHiRE*	Thin-Target
Electron energy and polarization	GeV / -	80 / 80%	80 / 80%
Electron beam current / bunch charge / Electrons per bunch	mA / nC / 10^{10}	0.32 / 1.6 / 1	2.4 / 2.4 / 1.5
Bunch repetition rate / RMS bunch length / crab crossing angle	MHz / μm / mrad	0.2 / 30 / 20	1 / 100 / 20
Normalized emittance, horizontal & vertical	mm	5 / 0.5	5 / 0.5
Beta function at IP, horizontal & vertical	mm	5 / 0.1	5 / 0.1
Electron beam RMS spot size at IP, horizontal & vertical	nm	400 & 18	400 & 18
e^-e^- geometric luminosity	10^{34} cm^{-2}s^{-1}	2.2	25
Distance between IP & CP / Electron hori. & vert. RMS size at CP	mm / nm / nm	1 / 154 / 131	2 / 431 / 355
Electron to γ photon conversion rate ($k=N_\gamma/N_e$) / Parameter x and ξ^2		1.2 / 4.3 / -	0.14 / 4.8 / 0.04
Number of γ photons per electron bunch (N_γ)	10^{10}	1.2	0.21
γ-γ luminosity (broadband)	10^{33} cm^{-2}s^{-1}		4.8
Reduction factor k' for $E_\gamma > 0.6E_0$ per beam			~0.5
γ-γ luminosity ($E_\gamma > 0.6E_0$)	10^{33} cm^{-2}s^{-1}	3.6	1.2

The broadband luminosity in Table 1 is obtained from $L_{\gamma\gamma}=k^2L_{e\text{-}e\text{-}}$ where $L_{e\text{-}e\text{-}}$ is the luminosity for e^-e^- collisions and k is the e→γ conversion rate. The luminosity for γ photon energy above 60% of the electron energy (i.e., E_γ>60%E_e) can be estimated by multiplying k'^2, where k' is the percentage of the hard γ photons. It is estimated, using Fig. 4 of [3], k'~0.5. This result is consistent with the estimation using the spectrum luminosity plot (Fig. 7 of [3]). Also as shown in Table 1, the thin laser target reduces the parameter ξ^2 to 0.04, ensuring there is no nonlinear effect of the laser.

Table 2 summarizes the laser parameters for both the new thin target design and SAPPHiRE [11]. It can be seen that the peak laser power is reduced significantly for the thin laser target design.

RECIRCULATING LINAC AND ENERGY RECOVERY

For the above thin target design, it needs 384 MW RF power to accelerate two 2.4 mA beams to 80 GeV. Table 3 shows the RF power budgets. Fortunately, much of the beam energy can be recovered since 86% of electrons are never scattered by laser photons. We divide an electron beam to two parts: a used beam of 0.334 mA and unused beam of 2.066 mA, according to whether the electrons have been scattered by laser photons or not. We propose to recover the energy of the unused beam, thus saving about 330.5 MW RF power, while the used beam is simply dumped as in all other γ-γ collider proposals. With energy recovery (ER), the net RF power consumption for the thin target design should be comparable to that of the conventional thick target designs.

Table 2: Laser Parameters for a γ-γ Higgs Factory

		SAPPHiRE	Thin-Target
Wavelength (λ)	µm	0.351	0.317
Photon energy ($\hbar\omega$)	eV	3.53	3.92
Target (A_0)	J		0.707
Flash energy (A)	J		0.106
Pulse length (l_γ)	mm		0.1
Peak power	GW		112.5
Peak intensity, 10^{20}	W/cm^2	2.96	0.73
Photons per flash	10^{17}		1.7
Photons per electron	10^{7}		1.13
Peak photon density	ph./cm^2/s	$1.1\cdot10^{40}$	$1.1\cdot10^{36}$
Repetition rate	MHz	0.2	1
Average power	MW		0.106

Table 3: The RF Power Budgets for a γ-γ Collider

		SAPPHiRE	Thin-Target
Electron energy	GeV	80	100
Electron current	mA	0.32	2.4
$e^- \rightarrow \gamma$ conversion rate		120%	14%
Used beam	mA	0.32	0.334
Unused beam	mA	0	2.066
Total beam power	MW	51.2	384
Used beam power	MW	51.2	53.5
Unused beam power	MW	0	330.5

The simplest ER scheme is the "push-pull" (P-P) concept [13,14] shown in Figure 2, in which each of the two beams is accelerated in one linac, then passes through the convention point (CP) and IP, then goes straight to the other linac to have its energy recovered.

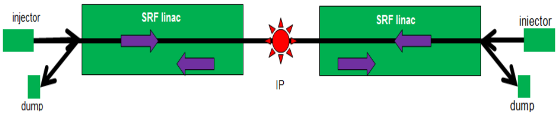

Figure 2: A "push-pull" ER scheme for a γ-γ HF.

Recirculating linacs have also been considered for γ-γ collider designs [10,11]. Below we use a simple scheme shown in Figure 3 to complete our study. It is basically a linear collider with a recirculating pass consisting of two 180° arcs and a straight beam-line. Table 4 shows the parameters for up to four passes of the two linacs and also the synchrotron radiation (SR) loss in arcs for both accelerating and deceleration (for the unused beam only, assuming the used beam is deflected and sent to a dump). The calculations are performed assuming a 1 km bending radius for the recirculation ring of 1.5 km arc radius.

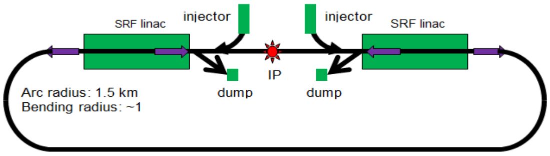

Figure 3: A recirculating linac scheme for a γ-γ collider.

For the case of high electron current required for the thin target design, the SR loss is significant. Beam quality preservation is also an important issue in selecting a baseline since high energy electron beams experience serious emittance degradation due to SR in the recirculating arcs. A detailed study of this issue can be found in [15].

Table 4: Recirculating Linacs for a γ-γ Collider

Recirculating	pass	P-P	1	2	3	4
Single linac	GeV	80	40	20	13.3	10
Total linac	GeV	160	80	40	26.6	20
Linac reduction	%		50	75	83	87.5
SR loss (up or down)	GeV	0	0.23	1.16	2.75	2.75
SR power (up, 2.4 mA)	MW	0	0.54	2.80	4.75	6.61
SR power (down, 2.1 mA)	MW	0	0.47	2.40	4.09	5.69
SR power (ERL=up+down)	MW	0	1.01	5.19	8.83	12.3
for two beam	MW	0	2.03	10.4	17.7	24.6
Total RF (SR loss + γ photon)	MW	53.5	55.5	63.9	71.2	78.1

SUMMARY AND DISCUSSIONS

The new γ-γ HF concept should be validated with further studies. Several issues not addressed in this paper must be included in such studies. One issue is the impact on the detector background. While the concept greatly reduces soft γ photons generated by multiple Compton scattering, it is expected the beamstrahlung becomes much stronger due to the higher electron beam current. This effect on the detector background must be examined. Another issue is energy recovery. Though it is expected the technology should work in the range of energy and current of interest to a γ-γ HF, further studies must focus on efficient recovery of energies of the unused (un-scattered) electron beam which has a very large energy spread due to very strong beamstrahlung [16].

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