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Review

Application of fiber laser for a Higgs factory

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Abstract. This paper proposes a medium size ($\sim 6\,\text{km}$) circular Higgs factory based on a photon collider. The recent breakthrough in fiber laser technology by means of a coherent amplifier network makes such a collider feasible and probably also affordable.

1 Introduction

The world's first linear accelerator was built by Rolf Wideröe in an 88-cm long glass tube in Aachen, Germany in 1924. Since then, particle accelerators have evolved enormously in the past 90 years. A series of important inventions – Van de Graaff generator, cyclotron, Cockcroft-Walton accelerator, klystron, betatron, synchrotron, drift tube linac, electron linac, induction linac, FFAG, phase stability, strong focusing, RFQ, FEL, stochastic cooling, superconducting magnet, superconducting radio-frequency, storage ring, circular e^+e^- collider, linear e^+e^- collider, proton-proton collider, proton-antiproton collider, heavy ion collider, *ep* collider, etc. – have brought particle accelerators to the human being's knowledge frontier and fundamentally changed the way we live, think and work. It is seen that each milestone in the evolution of accelerators was accompanied by a major technology breakthrough.

Recently, another breakthrough introduced by a collaboration between the accelerator community and laser community appears to take place. Namely, the invention of coherent amplifier network (CAN) of fiber laser makes it possible to collide a high-energy electron beam with a high-intensity laser beam to produce high-energy gamma rays for a Higgs factory. [1]

The discovery of Higgs particle at the LHC at CERN was ranked the No. 1 scientific achievement in 2012 by the journal *Science*. Immediately after the discovery, a number of proposals for building a Higgs factory were put forward in order to study in great detail the properties of this nicknamed "*God Particle*," for example, a superconducting linear e^+e^- collider (ILC), a two-beam linear e^+e^- collider (CLIC), an x-band klystron-based linear e^+e^- collider, various large size circular e^+e^- colliders (LEP3, TLEP, SuperTRISTAN, CEPC, Fermilab site-filler, VLLC), a muon collider and several types of photon collider. [2] Among these options, a photon collider has the distinct advantage of the lowest energy requirement for an electron beam. This advantage is especially important for a circular Higgs factory, in which the synchrotron radiation power increases to the fourth power of the electron energy. For an e^+e^- collider, the minimum required energy per beam is 120 GeV, while for a photon collider

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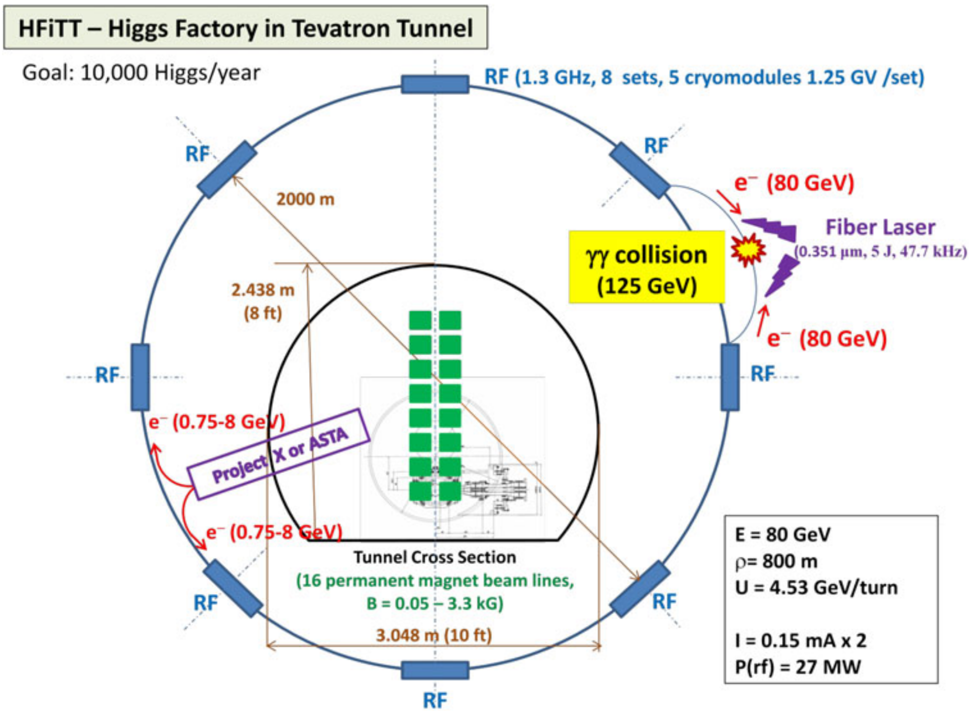

Fig. 1. Layout of HFiTT.

it is 80 GeV. The corresponding ratio of synchrotron radiation power is 5 to 1. This makes it possible to consider building a photon collider in a medium size ring, such as the 6-km Tevatron tunnel at Fermilab. In this paper, we will call such a photon collider HFiTT, or *Higgs Factory in Tevatron Tunnel*. The layout is shown in Fig. 1.

A photon collider is based on Inverse Compton Scattering (ICS) by shooting a low energy (~ 3.5 eV) laser beam into a high energy (10 s of GeV) electron beam to generate a back-scattered high energy (10 s of GeV) photon beam for collision. The cross section for $\gamma\gamma \to H$ is large and comparable to $e^+e^- \to ZH(\sim 200\,\text{fb})$. Since this is an s-channel resonance, the required photon energy is low (63 GeV), corresponding to 80 GeV for an electron beam. The design goal is 10,000 Higgs per year.

If we look to the far future of electron collider technology, very high gradient acceleration techniques such as plasma wakefield acceleration are asymmetric between electrons and positrons. It is therefore important to develop a technology that will allow physicists to accelerate electrons only and still access annihilation reactions with precisely understood point-like interactions. The photon collider fills this need. This project will not only carry out important measurements of the Higgs boson properties but will also demonstrate the unique technologies needed to construct photon collider experiments at higher energies.

2 Higgs physics of a photon collider

There have been several publications on the physics of a photon collider.[3–6] The strength of a Higgs factory based on a photon collider is its ability to study CP admixture and violation of the Higgs to better than 1%. This cannot be done by any other machine. Such a study can be carried out by using either circularly or linearly polarized photon beams. The unique attribute of a photon collider is the initial coupling to a pair of photons. Higgs can be observed in, e.g. the $\overline{b}b$ final state, following which, using the $\overline{b}b$ partial width measured at another machine, the $H \to \gamma\gamma$ partial width can be extracted to a precision of 1%. This quantity is of particular interest because this decay proceeds through an inclusive loop that can potentially reveal heavier charged particles into which the Higgs cannot decay directly. A photon collider also has the ability of measuring precisely the rates for several additional processes, such as $\gamma\gamma \to H \to WW^*, ZZ^*$ and perhaps $\tau^+\tau^-$ and gg. It can also study non-standard Higgs decays. These contributions – high precision measurement of couplings to SM particles and measurement of non-standard Higgs decays – go beyond the LHC.

3 Accelerator of a photon collider

The design of HFiTT is similar to a recirculating electron linac. As illustrated in Fig. 1, there are eight RF stations. Each station consists of five ILC-type cryomodules. Each module has nine ILC-type SRF cavities. Each station occupies a straight section of 70 meters and provides 1.25 GV acceleration voltage. The total RF is 10 GV. The required RF power is 27 MW (24 MW for beams and 2.3 MW for synchrotron radiation), which leads to 75 kW per coupler. The dynamic heat load at 2°K is $\sim$ 850 W per cryomodule for CW operation. The wall power for cryogenics is about 25 MW.

There are eight recirculating beam lines for each electron beam. These beam lines are made of Recycler-type permanent magnets. Each section has different field strength, which is determined by the beam energy in that section. The maximum bending field is 3.3 kG. If a scanning of a few GeV around the peak collision energy is desired, the magnets in the final arcs can use powered ones to provide variable field strength.

The Tevatron tunnel has a radius of 1,000 m and a circumference of 6,283 m. The tunnel size is 3.048 m (10 feet) wide and 2.438 m (8 feet) high. The Tevatron used 53.2 m long straight sections. But these straight sections can be readily extended to 70 m or longer.

Two electron beams will be injected in opposite directions. Each beam will circulate eight times and be accelerated to 80 GeV before they are directed to the experimental hall. This hall has a large detector and also a fiber laser system. Two laser beams will collide with the two electron beams at the conversion point (CP) respectively and generate two high energy ($\sim$ 64 GeV) photon beams for head-on collision at the interaction point (IP) in the center of the detector. The spent electrons need to be dumped before the IP. The dumping scheme is a major R&D for a photon collider.

The main accelerator and beam parameters are listed in Table 1. Many of the electron beam parameters are similar to those of an ILC-based photon collider. But the collision frequency is 47.7 kHz, which is about a factor 3 higher than an ILC-based photon collider. The electron beam intensity is 2×10^{10} per bunch. For each circulating beam, the current is 0.15 mA for each line or 1.22 mA for 8 lines.

The injection requires a low emittance, highly polarized (80%) electron gun. The polarization must be controlled carefully to go around a bend and end up in the right state in the ring. We can also envision that the injection beam comes from ASTA or Project X if their beams are available for HFiTT.

4 Laser of a photon collider

A major challenge for HFiTT is the required laser beam, which must have high repetition rate (47.7 kHz) and high average power (240 kW). A recent breakthrough in fiber laser technology demonstrates that such a laser system is indeed within reach.

Table 1. HFiTT accelerator and beam parameters.

Top level parameters		
Collision energy (center of mass)	GeV	126
Luminosity (per IP)	$10^{34}\,cm^{-2}\,s^{-1}$	0.5
definition of luminosity		$\gamma\gamma > 125\,GeV$
Luminosity for e-e-	$10^{34}\,cm^{-2}\,s^{-1}$	3.2
No. of IP		1
No. of Higgs per year (per IP)		10,000
Circumference	km	6.28
P(wall)	MW	80
Polarization e-		80%
Polarization γ		90% (lum. peak)
Accelerator parameters		
Machine radius	m	1000
Revolution frequency	kHz	47.7
Bending radius	m	800
Bending field	kG	0.05 –3.3
RF voltage	GV	10
RF power (total)	MW	26.7
RF power (per coupler)	kW	75
No. of recirculating arcs		8
Electron beam parameters		
Beam energy	GeV	80
Energy loss per turn (at 80 GeV)	GeV	4.53
Number of electrons per bunch	10^{10}	2
Number of bunches		1
Collision frequency	kHz	47.7
Circulating beam current	mA	1.22×2
Collision beam current	mA	0.15×2
Beam power	MW	12.2×2
Synchrotron radiation power	MW	2.3
ε x,n	mm-mrad	10
ε y,n	mm-mrad	0.03
beta_ x CP	mm	4.5
beta_ y CP	mm	5.3
σx, CP	nm	535
σy, CP	nm	32
σz, CP	mm	0.35
sigma_ E IP	%	0.22
Laser beam parameters		
Wavelength	μm	0.351
Pulse energy	J	5
Repetition rate	kHz	47.7
Peak power	TW	1.5
Average power	kW	240
Rayleigh length	mm	0.63
σ x, CP	nm	4200
σ y, CP	nm	4200
σ z, CP	mm	0.45
IP $<->$ CP distance	mm	1.4
Laser-beam crossing angle	mrad	
γ **beam parameters**		
n_ gamma	10^{10}	1 (primary)
σx, IP	nm	480
σy, IP	nm	10

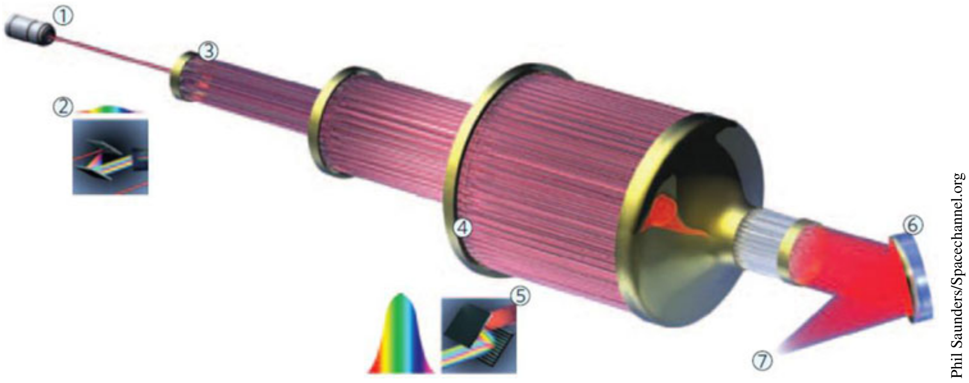

Fig. 2. Principle of a coherent amplifier network (CAN) based on fiber laser technology. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of $\sim 1\,\text{mJ}$ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of 10 kHz (7). [7]

Reference [7] shows that thousands of fiber channels can be combined coherently to produce a pulse with an energy of $> 10\,\text{J}$ at a repetition rate of $\sim 10\,\text{kHz}$ (Fig. 2). Such a system would meet our needs. There are, of course, several challenging issues that have to be addressed before one can claim the required laser technology is in hand, for instance, protection of the optical components near the CP, cooling of thousands of high power fibers, interface between the fiber and diode pumps, etc. There is an active R&D program in the IZEST collaboration that aims to address these issues.

5 Detector of a photon collider

After the completion of the Tevatron experiment, the DZero detector is in "frozen" state. [8] A number of its sub-systems could be resurrected and reused. A new tracker and precision vertex system will be needed.

6 Cost consideration

It is impossible and even inappropriate to have an estimate of the cost for this proposal that is still under development. However, it will be useful to provide cost references for several major systems based on the ILC study [9] and Recycler experience.

- 40 cryomodules. Cost – \$2-3 million each according to the ILC cost estimate. (As a comparison, the ILC would need $\sim 1,700$ cryomodules.)
- 27 MW of RF power. Assuming 50% efficiency, one needs 54 MW of wall power for RF. Cost – \$5 million per MW according to the ILC cost estimate.
- 25 MW of wall power for cryogenics. Cost – about 2/3 of the ILC cryogenics.
- 16 permanent magnet beam lines. Cost reference – the Recycler permanent magnet total cost was \$3.2 million.
- $2 \times 240\,\text{kW}$ laser system. Assuming wall plug efficiency of 30%, compressor efficiency of 50%, diode price of €5/W and the rule of thumb that "3 times the diode cost equals the cost of the full system," the laser system will cost $\sim$ €50 M, or \$65 million.

– Civil – the Tevatron tunnel, CDF and DZero experimental halls, service buildings and utilities can be reused to minimize the civil cost.

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