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$\gamma\gamma$ Collider – A Brief History and Recent Developments

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Abstract
There is renewed interest in constructing a $\gamma\gamma$ collider following the discovery of the Higgs boson and the formation of an ICFA (*International Committee for Future Accelerators*) – ICUIL (*International Committee on Ultrahigh Intensity Lasers*) collaboration. ICUIL brings state-of-the-art laser technology to build new types of accelerators such as a $\gamma\gamma$ collider. A recent ICFA mini-workshop on $\gamma\gamma$ colliders investigated the possibility and physics value of a low energy $\gamma\gamma$ collider. This paper uses a 1 MeV (c.m.) $\gamma\gamma$ collider currently under design at IHEP as an example to discuss various aspects of this collider, including the physics case, requirements on the laser beam, the electron beam, the accelerator and detector.

Keywords
photon, collider, γ-ray, light-by-light scattering, pair production

1 A Brief History

$\gamma\gamma$ colliders were first suggested in the early 1980s as a possible extension of two proposed linear colliders: VLEPP and SLC [1,2]. BINP played an important role in the early development of fundamental accelerator physics of $\gamma\gamma$ colliders [3,4]. In the 1990s, there were a number of high-energy linear collider (LC) proposals including the NLC from SLAC, the JLC from KEK and TESLA from DESY. In each of these three LC design reports, there was an appendix on a $\gamma\gamma$ collider as a potential add-on. In the 2000s, under the leadership of ICFA, the world HEP community activities towards building a linear collider converged to a single effort – the International Linear Collider Global Design Effort (ILC GDE) led by B. Barish. In 2007 the GDE released an initial ILC cost estimate (US$ 6.74 billion plus 24 million person-hours), which exceeded the previous TESLA cost estimate for a similar machine by a factor of two. This figure was further inflated by the US accounting system and the US Department of Energy quickly withdrew from bidding for hosting the ILC in the United States. Another potential host country, Japan, also expressed serious concern about the high cost. To lower the upfront cost, H. Sugawara in 2008 proposed to the ICFA to build a pair of 90 GeV e^- linacs and use them as a $\gamma\gamma$ collider as an initial phase towards an eventual full-scale 250×250 GeV ILC. ICFA commissioned a working group headed by M. Peskin to study this proposal. However, at a meeting in February 2009, ICFA decided to reject this proposal for three reasons: (1) the physics of a $\gamma\gamma$ collider was not as strong as that from an e^+e^- collider; (2) the cost saving (US$ 3 billion and 11 million person-hours) was insufficient; (3) it would require a major laser R&D program, which ICFA was not prepared to initiate. After this decision, the $\gamma\gamma$ collider activity stalled.

A change came in 2012 when the Higgs boson was discovered at the LHC. Because the Higgs mass is low (125 GeV), there are many options for a Higgs factory as documented in a report from the 2012 ICFA workshop on "*Accelerators for a Higgs Factory: Linear vs. Circular*" [5], which included the option of a $\gamma\gamma$ collider. The advantage of a $\gamma\gamma$ collider is that the cross section for $\gamma\gamma \rightarrow H$ is large and comparable to $e^+e^- \rightarrow ZH$ (~200 fb) but the required energy is much lower (63 GeV for a photon beam, corresponding to 80 GeV for an electron beam, compared to 120 GeV per electron beam in an e^+e^- collider). This makes a $\gamma\gamma$ collider an attractive option for either a low energy linear collider (80

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GeV per electron beam) or a low energy circular collider (80 GeV per beam). Furthermore, for a $\gamma\gamma$ collider there is no need for positrons and only one damping ring is required.

In the meantime, another important event gave new momentum to the $\gamma\gamma$ collider, namely, the formation of an ICFA-ICUIL collaboration. ICFA is the leading body of the world HEP community, whereas ICUIL the leading body of the world laser community. The “marriage” between the two has had a profound impact on both communities. A White Paper of the ICFA-ICUIL Joint Task Force was published in December 2011 [6], in which there was detailed discussion about applying high power laser technology to a $\gamma\gamma$ collider.

In addition to an add-on to a linear collider such as ILC and CLIC, a $\gamma\gamma$ collider for a Higgs factory can also be an add-on to a circular collider such as FCC-ee and CEPC, or a dedicated recirculating linac such as SAPPHiRE and HFiTT, as reported at the 2017 ICFA mini-workshop on $\gamma\gamma$ colliders [7]. There is also a recent review article discussing various aspects of $\gamma\gamma$ colliders [8].

2 Low Energy $\gamma\gamma$ Colliders

Among the many $\gamma\gamma$ collider proposals listed above, a common feature is that they all will explore the energy frontier, i.e., at the energy scale of a Higgs factory or higher. However, construction of such a high energy $\gamma\gamma$ collider would require at least 20 years. Therefore, an important topic at the ICFA mini-workshop was to identify the shortest path for designing and constructing a low energy $\gamma\gamma$ collider.

Several low energy $\gamma\gamma$ colliders were proposed. V. Telnov suggested using the European XFEL (17.5 GeV) as the linac for a $\gamma\gamma$ collider to study the physics in the c-quark and b-quark energy region of 3-12 GeV. M. Velasco proposed a $\gamma\gamma$ collider at the $\tau\tau$ threshold (3.6-8 GeV) to study τ physics including τ(g-2). In these energy ranges, one can contemplate using existing electron linacs instead of waiting for the construction of major new linacs (ILC or CLIC).

Further discussions revealed that even a $\gamma\gamma$ collider at 1 MeV can provide important physics such as light-by-light scattering and Breit-Wheeler pair production. Both processes were predicted in the 1930s but have never been observed or measured in the laboratory [9-13]. This opened an avenue to explore the feasibility of designing and constructing a $\gamma\gamma$ collider in the near future because low energy electron linacs are widely available.

In the following we will use the BEPC linac at the IHEP, China as an example for a low energy $\gamma\gamma$ collider.

3 $\gamma\gamma$ Collider Study at IHEP

The BEPC linac is the injector to the e^+e^- collider at IHEP, which serves as a tau-charm factory. The maximum energy of the linac is 2.6 GeV; it is continuously tunable down to ~200 MeV. The linac has the capability of generating two consecutive electron bunches in each pulse. The spacing between the two bunches can vary from 7 ns to 4 μs. The pulse rate is 50 Hz. Currently it uses a thermionic gun, which gives rise to large beam emittance (2 μm at 2 nC, unnormalized). To use the linac for a $\gamma\gamma$ collider, the gun must be replaced by a photo-injector. In order to minimize the disruption to collider operation, the plan is to add a photo-injector to the last 200 MeV section of the linac.

Figure 1 shows the layout of a $\gamma\gamma$ collider with a center-of-mass energy around 1 MeV for direct observation of $\gamma\gamma \to \gamma\gamma$ scattering and $\gamma\gamma \to e^+e^-$ pair production [9,10]. The size of the building is based on an existing experimental hall, which is a candidate site to host this $\gamma\gamma$ collider.

Two consecutive electron bunches, spaced by tens of ns (several meters), come from the BEPC linac, each of 200 MeV and 2 nC. A kicker gives a kick on the second bunch and sends the two bunches to two separate transport lines. Each bunch passes through a final focusing system (FFS) and is focused to a few μm in the transverse dimension. An intense laser beam hits each of the electron bunches at the conversion point (CP) and generates a back-scattered high energy (~1 MeV) γ-ray. The two γ-rays then collide at the interaction point (IP). The used electrons remain at about 200 MeV and go downstream to a beam dump near the bending magnet. There is also a dump for the used laser beam (not shown in Fig. 1). The FFS is a permanent magnet quadrupole (PMQ) triplet chosen due to the requirements of high gradient and small size. The details of the interaction region (IR) including the triplet and laser path are under design. Table 1 lists a preliminary set of parameters.

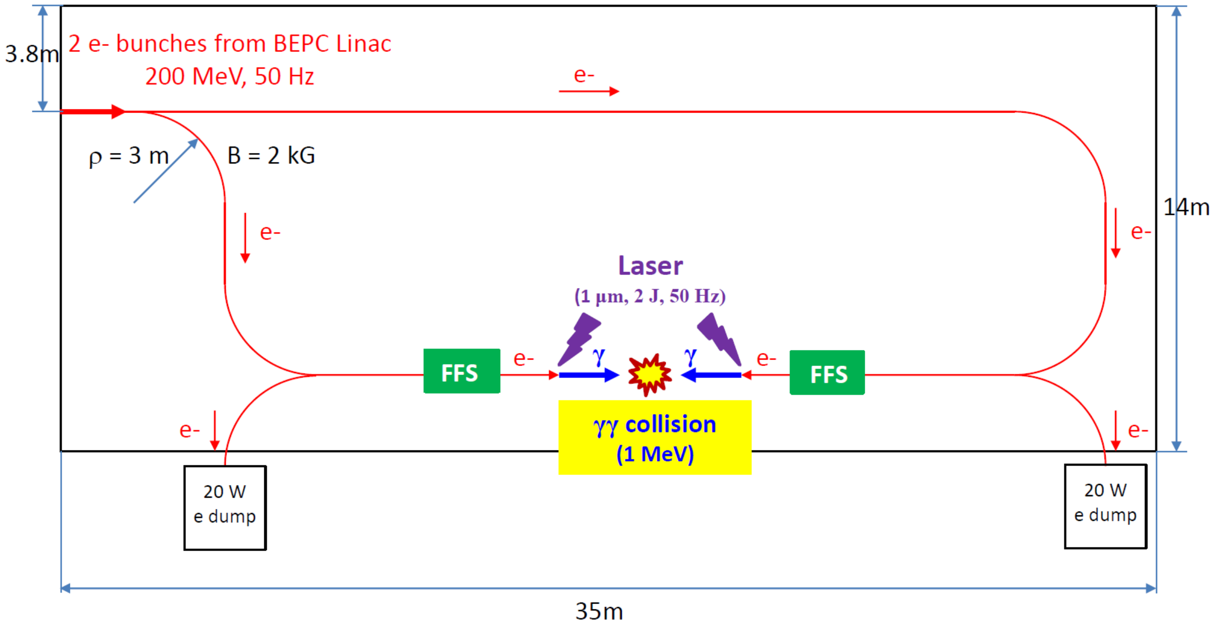

Fig. 1: Layout of a 1 MeV $\gamma\gamma$ collider in an experimental hall at IHEP.

Table 1: Preliminary parameters of a 1 MeV (c.m.) $\gamma\gamma$ collider

Laser beam		**Electron beam**	
Wavelength	1.064 μm	Energy	200 MeV
Waist size (RMS)	5 μm	Bunch charge	2 nC
Rayleigh range	298 μm	Size at CP (RMS)	2 μm
Pulse energy	2 J	Emittance	6.4E–3 μm
Pulse length	0.33 ps	β*	626 μm
Repetition rate	50 Hz	Bunch length (RMS)	2 ps
Cross angle	167 mrad	Repetition rate	50 Hz
IP – CP distance	313 μm	Crossing angle	0
Nonlinear parameter a_0	0.45	Geometric luminosity of e^-e^-	1.6E28

Based on the parameters in Table 1, CAIN simulation gives a $\gamma\gamma$ collision luminosity of 3.3×10^{27} cm^{-2}s^{-1} for all energies and 1.1×10^{27} cm^{-2}s^{-1} for energies above 0.9 MeV, as shown in Figure 2 [14]. At 1 MeV, the cross section of $\gamma\gamma \to \gamma\gamma$ is peaked at about 3 μb, $\gamma\gamma \to e^+e^-$ about 100 mb. So, the expected event rate is, respectively, several per hour for light-by-light scattering and ~100 per second for pair production. (It is interesting to note the light-by-light scattering event rate is comparable to the Higgs event rate from the CEPC, in which the luminosity is higher by 7 orders of magnitude but the cross section for $e^+e^- \to ZH$ is smaller by the same order of magnitude [15].)

The required laser (2 J, 50 Hz, 100 W, 0.33 ps) is challenging but achievable according to several laser experts and vendors. It is a TW system at 50 Hz. Compared to HAPLS, a PW/10 Hz laser made for ELI-Beamlines, it should be simpler, easier and less expensive. The synchronization between the two laser pulses and between the laser and electron is critical. Modern technology can give a time jitter at 100 fs or less, which should be adequate for our purpose [16].

The detector is another challenge because of large background from e^-e^- and $e^-\gamma$ collisions in addition to background from the environment and cosmic rays. A preliminary design uses a multilayer cylinder consisting of plastic scintillators, CsI crystals and photo multiplier tubes (PMT). Physics simulations using CAIN, PYTHIA and other generators and detector simulations using Geant4 are underway.

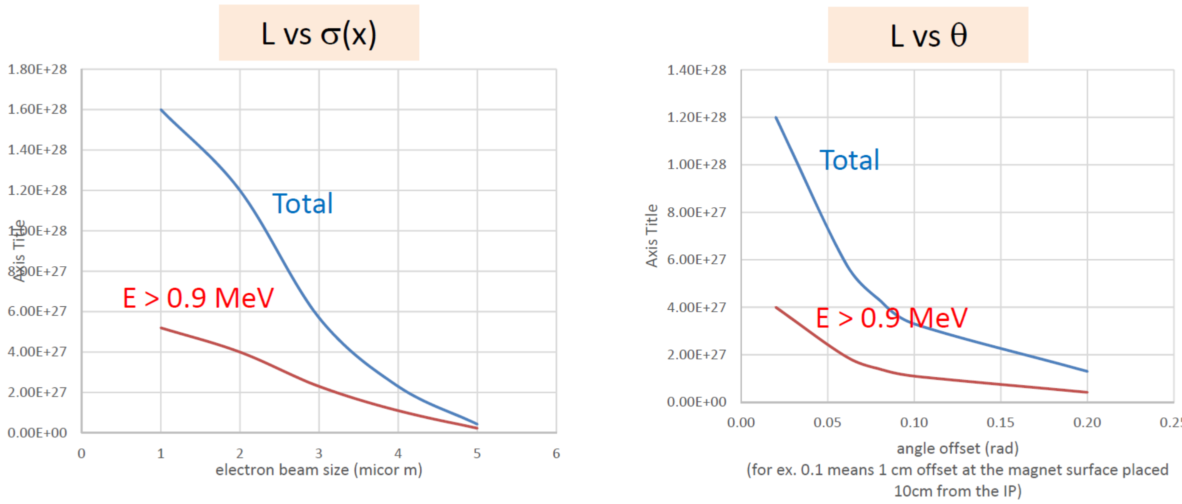

Fig. 2: Left: luminosity vs. bunch length. Right: luminosity vs. laser crossing angle. (courtesy T. Takahashi)

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