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The Use of a Prototype Next Linear Collider for $\gamma\gamma$ and $e\gamma$ Collisions*

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Abstract

It is likely that a prototype linear accelerator with a beam energy of a few GeV will be built sometime in the next decade to provide a testbed for development of a high energy Next Linear Collider. We consider the possibility that, by employing high-power, free electron lasers and Compton backscattering, one can obtain useful $e\gamma$ and $\gamma\gamma$ collision rates at a few GeV linear collider. Given expected luminosities of order 10^{31} cm^{-2} s^{-1}, such a collider could give tens of thousands of events from the two-photon production of charmonium C = +1 states. Resonances in the mass region 1.5-3 GeV could be thoroughly explored, with reasonable expectations for identifying exotic states. Tests of explicit QCD predictions for the rates of $\gamma\gamma \rightarrow$ meson pairs in the 3-4 GeV mass range should also be possible. Perhaps of greatest interest would be the study of $e\gamma$ collisions, where the structure of the photon in the transition region between vector dominance and QCD could be thoroughly explored with event rates which cannot be achieved at other accelerators. We explore the accelerator, laser and final focus requirements of such a collider, calculate some $\gamma\gamma$ event rates and conclude with some speculative thoughts about costs and prospects for such a machine.

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I. Introduction

The future of e^+e^- physics requires the further development of single-pass linear colliders, the only machines capable of reaching center-of-mass energies significantly greater than that of LEP-200 at reasonable cost. SLC has successfully demonstrated the concept of producing and colliding low-emittance beams, and substantial research and development of the components necessary to construct a 500 GeV collider is already underway.[1] A very important step on the road to such a machine may be to build a prototype collider at low energy (perhaps a few GeV), both to demonstrate that a high-luminosity linear collider can be built, and to serve as a testbed for linear collider technology development. It would be extremely attractive if, in addition to serving as a research and development tool, such a collider also had a legitimate particle physics program attached to it. Unfortunately, any such low-energy e^+e^- physics program, such as that proposed for B-, τ/charm- or Φ-factories, requires a luminosity of at least 10^{33} cm^{-2} s^{-1}, which is not yet practical for linear colliders.

Such a low-energy machine could, however, provide a rich experimental program if it were operated not in e^+e^- mode, but as an $e\gamma/\gamma\gamma$ collider, utilizing Compton backscattering of light from powerful lasers to convert the electrons to photons of comparable energies in one or both beams just prior to collision.[2] Although two-photon physics has been very successfully pursued at e^+e^- storage rings over the last decade, the limitation of virtual photon fluxes which decline rapidly with energy have restricted the accessible mass range to less than about 2 GeV. Many interesting subjects remain to be explored fully, including the two-photon widths of C = +1 charmonium, the search for and study of exotic QCD resonances in the 1.5–3.0 GeV mass region, deep-inelastic scattering in $e\gamma$ collisions in the transition region between hadron-like and point-like interactions, and inclusive hadron production at high enough masses to test explicit QCD predictions.[3] We believe that all of these topics can be studied with equivalent e^+e^- luminosities of about 10^{31} cm^{-2} s^{-1}, well within the capabilities of a low-energy linear collider. In addition, the relatively high photon energies available at a low energy linear collider allow the production of final states whose center-of-mass is nearly at rest in the laboratory frame, as opposed to the highly boosted $\gamma\gamma$ system available at storage rings.

In this note, we first make a very preliminary examination of the physics potential of a low-energy linear collider outfitted for $e\gamma/\gamma\gamma$ collisions. Following that, we discuss some of the required linear collider and laser parameters. For several choices of machine parameters, we then give some examples of event rates to be expected and compare them to those expected at other future facilities. Finally we conclude with some thoughts on costs and prospects for such a machine.

II. Physics Motivation

Charmonium and Bottomonium Physics

The C = +1 charmonium spectrum (whose lowest-lying members are η_c and the χ_c states) is of considerable theoretical interest, with predictions for two-photon decay widths from potential models and QCD sum rules which vary by factors of five.[3] Present $\Gamma\gamma\gamma$ measurements come from the observation of only a small number of events and do not provide significant discrimination between the models. Also, the decay branching ratios of these states are still not well known and the excited state spectrum is poorly determined. Given the known exclusive decay channels with branching ratios of the order of a few per cent, one would need to produce 10's of thousands of events from each resonance to really study the spectrum properly. As we shall see later, this appears possible at a $\gamma\gamma$ collider with beam energies of 3–5 GeV and luminosity of order 10^{31} cm^{-2} s^{-1}.

Although the bottomonium spectrum is just as interesting as that for charmonium (and much more poorly measured), there is a conspiracy between the low production rates from $\gamma\gamma$ interactions ($\propto e_q{}^4$) and unknown (probably small) branching ratios to readily-measurable individual final states. Luminosities of order 10^{33} cm^{-2} s^{-1} will be required to overcome this, well beyond what can be obtained at a low energy linear collider. The two-photon study of bottomonium will likely have to wait for a high energy NLC. However, the experience gained on a low energy 'prototype' linear collider may be needed to allow the higher energy machines to reach such luminosities.

QCD Resonances of Mass 1.5-3.0 GeV

The search for exotic QCD resonances such as four-quark states, hybrid mesons composed of $q\bar{q}g$, or glueballs has become the main focus of resonance studies in many reactions, including $\gamma\gamma$[3]. Theoretical predictions are that such resonances should begin appearing at masses as low as 1.5 GeV but that a very rich spectrum should be evident in the 2–3 GeV mass region which has not yet been explored in $\gamma\gamma$ reactions. Predictions for the two-photon widths of such resonances range from 0.1–1 keV for four-quark and hybrid states to 1-10 eV for glueballs, which do not couple to two-photons at lowest order. Unfortunately, for most J^{PC} values, these exotic states will mix with standard $q\bar{q}$ mesons, making it difficult to disentangle the spectra. For the special case of spin-1 states, which cannot couple to two real photons, one can distinguish them from even-spin resonances by comparing the mass spectra from $e\gamma$ production (really $\gamma^*\gamma$) with those from real $\gamma\gamma$ production for the same final states. This may then allow the use of simple angular distributions to separate 1^{++} axial vector mesons from 1^{-+} states which must be exotic. However, in general, detailed partial wave analyses will be needed to understand the mix of states, and this will require large numbers of events and excellent detector solid-angle coverage, with good calorimetry and particle identification, so as to preserve high detection efficiency for the final-state hadrons. These goals should be easier to obtain at a low-energy $e\gamma/\gamma\gamma$ collider than at storage ring two-photon experiments due to the extended photon flux at high energies and the ability to produce final states with relatively little boost. Again, it appears that luminosities of order 10^{31} cm^{-2} s^{-1} will allow very substantial progress to be made.

Hadron Pair Production - Higher Twist QCD

The processes $\gamma\gamma \rightarrow \pi\pi, \rho\rho, KK, \ldots$ all provide definitive tests of QCD, but only at masses well above the resonance region, where the predictions of perturbative QCD are reliable.[4] The present cross section measurements, restricted to masses below about 2 GeV, appear to approach the QCD predictions in the $\pi\pi$ and KK channels, but there is a large excess of $\rho^o\rho^o$ as compared to $\rho^+\rho^-$. Also, the study of many interesting channels such as $D\overline{D}$ will require much larger statistics and better detectors. A low energy $\gamma\gamma$ collider could provide high luminosity out to masses of at least 4 GeV, allowing detailed study of such processes. A low energy $e\gamma$ collider would allow the measurement of the production form factors (Q^2 dependence), which are also predicted by QCD.

Deep Inelastic Scattering

Deep inelastic scattering of virtual photons from nearly-real photon targets has been a focus of effort at storage ring two-photon experiments.[3] The probing virtual photon can be thought of as behaving like a hadron (vector meson) at low 'masses' (i.e. Q^2) and is resolved into its point like components at higher 'masses.' The transition region between Vector Meson Dominance and the quark-parton picture of the photon occurs in the $Q^2 = 0.5\text{-}3.0$ GeV^2 region, which has been studied at storage rings only by experiments with very low angle tagging capability.[5] A low energy $e\gamma$ collider would provide a superb environment for the further study of the photon structure function in the region $0.5 < Q^2 < 10$ GeV^2 and $1 < W_{\gamma\gamma} < 4$ GeV, since it supplies a flux of real (target) photons as much as 100 times greater than that available at storage ring machines for the same e^+e^- luminosity. The $\gamma\gamma^*$ cross section in this region is of the order of nanobarns, so 100's of thousands of events per year can be expected at a low energy $e\gamma$ collider.

III. Machine Requirements

Linear Collider

Clearly the definition of the prototype linear collider will be made mostly on the basis of accelerator issues which provide its *raison d'être*. Since there are many different approaches to a possible next linear collider, we note here only some general principles and the impact of the $e\gamma/\gamma\gamma$ physics on such a machine.

The first and most striking impact is that positrons would not be required! This could have significant monetary and technical advantages if the accelerator physics goals are mostly in the area of preserving small emittance in lots of bunches with large currents. Although a machine with only electrons and photons has much smaller beam-beam effects than an e^+e^- collider, the computer codes for calculating these processes could still be tested. The lack of significant beamstrahlung in $e\gamma/\gamma\gamma$ interactions allows one to consider much less flattened beam shapes at the interaction region than in e^+e^- collisions, although it is actually easier to focus flat beams. If we assume round gaussian beams for simplicity, the beam spot size radius and collider luminosity are given by

$$\sigma = \sqrt{\frac{\varepsilon_n \beta^* m_e}{E_b}} \qquad L = \frac{N^2 f E_b}{4\pi\varepsilon_n \beta^* m_e} \tag{1}$$

where E_b is the beam energy, ε_n the invariant emittance of the beam, N the number of particles per bunch, f the collision frequency, and β^* the beta-function at the interaction point. Written this way the linear dependence on beam energy is clear (none of the other quantities being explicitly energy dependent). Assuming conservative values of

$$\begin{aligned} &N = 10^{10} && \varepsilon_n = 4\times10^{-6}\ \text{m - rad} \\ &\beta^* = 1\ \text{mm} && f = 12\ \text{kHz (100 bunches / pulsetrain @ 120 pulsetrains / sec)}, \end{aligned} \tag{2}$$

all of which should be obtainable in a 'first-generation' linear collider,[6] we obtain

$$\sigma \approx \frac{1.43\ \mu\text{m}}{\sqrt{E_b}} \qquad L \approx \frac{E_b}{2.14}\times10^{31}\ \text{cm}^{-2}\ \text{s}^{-1}, \tag{3}$$

with E_b in GeV. So for an electron beam of energy a few GeV, sub-micron spot sizes and luminosities greater than 10^{31} cm^{-2} s^{-1} are possible. Although some of the above assumptions may be too conservative, it appears that luminosities of order 10^{33} cm^{-2} s^{-1} can be obtained only with beam energies in excess of 200 GeV!

Free Electron Laser

To get photons with energies, ω, of 1–3 GeV using electron beam energies, E_b, of 3-5 GeV, laser photon energies, ω_o, in the range of 10–50 eV (wavelengths in the 25–125 nm range) are necessary since the maximum backscattered photon energy is $\omega_{max} = E_b \frac{x}{x+1}$, where

$$x = \frac{4E_b\omega_o}{m_e^2} = .0153\left(\frac{E_b}{\text{GeV}}\right)\left(\frac{\omega_o}{\text{eV}}\right). \tag{4}$$

Additionally, the lasers must be capable of high power (~3 Joules/pulse), short pulses (~3 psecs), and high repetition rate (~10 kHz) so as to convert fully the electron beams into high energy photon beams.[2] Only free electron lasers (FEL's) are capable of satisfying all of these requirements, although even they have yet to reach them all simultaneously.[7]

In an FEL, an electron beam passes through an undulator, a series of magnetic fields with the transverse field orientation of each section along the beam axis rotated with respect to its neighbors by 90° for a helical undulator or 180° for a linear undulator. The electrons follow either a helical or sinusoidal path, respectively, emitting quasi-monochromatic coherent radiation which is circularly (linearly) polarized for a helical (linear) undulator. The radiation field must stay synchronized to the field of the electron beam in order to extract energy from it efficiently. The FEL photon wavelength is given by

$$\lambda = \frac{\lambda_u}{2\gamma^2}(1+\xi K^2) \qquad \left(K = \frac{eB\lambda_u}{2\pi m_e}\right) \tag{5}$$

where λ_u is the spatial period of the undulator, γ is E/m_e of the electron beam, B is the on-axis peak magnetic field and $\xi = 1$ (0.5) for helical (linear) undulators. Although, in principle, the whole of the electromagnetic spectrum is accessible with an FEL, only wavelengths in the 10 nm – 1cm range have been achieved in practice.[7]

The necessary pulse length and repetition rate is easy to achieve with an FEL, as the time structure of the driving electron beam is imparted to the FEL light. Assuming that we can get the required single-pass gain, all that is needed for an optimal match to the colliding beams (the beams which get Compton-converted to photons) is an FEL drive beam with the same bunch length and time structure as the colliding beams.

The high laser power needed is the most difficult of the requirements to satisfy. Typical extraction efficiencies for FEL's (the amount of e^- beam energy which is converted to FEL light) are of order 1% and this decreases as one gets into the soft x-ray range where highly-reflecting mirrors are increasingly difficult to make. An electron bunch of 10^{10} particles at 1 GeV has total energy 1.6 Joules, so such a beam used as a driver can only provide FEL pulses with energy of order 16 mJ, two orders of magnitude below our power requirements. At wavelengths where highly-reflective mirrors are available (over most of our range of interest), it would be possible to store the FEL light in a resonator surrounding the region where high energy electrons are to be converted to photons; then the FEL can replenish the stored energy lost by the resonator by operating as an oscillator. However, it would still be complicated to use the colliding beams simultaneously as drive beams for the FEL and so it is likely that a separate linac or storage ring with higher currents (ie. a larger number of bunches or frequency) will have to be used for this purpose.

It should be noted that the PEP storage ring at SLAC has been outfitted with an x-ray (2.5-16 keV) undulator for synchrotron light studies and has been run in a low emittance mode with beam currents up to 33 mA at a beam energy of 7 GeV;[8] this constitutes a total stored energy of 1700

Joules! Since PEP has a large RF capture bucket (> 2%), one could extract energy at the few tenths of a percent level and use the RF to replenish the energy without significant loss of electrons or positrons. Unfortunately, we want ~ 100 times smaller laser photon energies and, since undulator photon energies scale as

$$\omega\,(\text{keV}) = \frac{0.95\,\text{E}_b^2\,(\text{GeV})}{\lambda_u\,(\text{cm})}, \tag{6}$$

this would require a beam energy ~ 0.7 GeV. Although modifications to PEP would be required to run at such low energies and high currents, these might be cheaper than building an FEL from scratch. Alternatively, the effective repetition rate of 0.136 MHz for low emittance bunches of 10^{12} electrons and positrons in the energy range of interest makes the use of PEP to supply the *primary* beams to be converted to high energy photons an intriguing possibility.

Finally, we should point out that high extraction efficiencies (34%) and high peak power (1 GW in 30 ns pulses) have been achieved in single-pass FEL's using tapered wigglers [9], although at smaller photon energies (~ 0.02 eV) and lower repetition rate (~ 1 Hz) than we need here.

Linear Collider + Free Electron Laser = Low Energy Compton Collider

Figure 1 shows a conceptual scheme for the low energy $\gamma\gamma$ collider (the $e\gamma$ mode simply omits one of the lasers). A few millimeters prior to collision, the electrons from the linac pass through a pulse of FEL light and Compton scatter, giving up a fair fraction of their momentum to the laser photons. The result is a high energy, highly-collimated beam of photons incident on the interaction point. Figure 2 shows typical backscattered photon energies.

In the Compton collision, the resulting high energy photons scatter at small but finite angles, correlated with photon energy:

$$\theta(\omega) = \theta_o\sqrt{\frac{\omega_{\max}}{\omega} - 1} \qquad \left(\theta_o = \frac{m_e}{E_b}\sqrt{x+1} \approx \frac{511\ \mu\text{rad}}{E_b\,/\,\text{GeV}}\sqrt{x+1}\right) \tag{7}$$

so that the lowest energy photons scatter at the highest angles. In the collision of two high energy photon beams, the resulting luminosity spectrum depends on the luminosity parameter η:

$$\eta = \frac{z\theta_o}{\sigma} \approx 0.5\left(\frac{z}{\text{mm}}\right)\left(\frac{E_b}{\text{GeV}}\right)^{-1}\left(\frac{\sigma}{\mu\text{m}}\right)^{-1}\sqrt{x+1} \tag{8}$$

with z the distance from the conversion point—where the laser intersects the electron beam—to the interaction point, and σ the electron beam spot size radius. At $\eta < 1$, the high energy photons collide with as small a spot size as the electrons would have, so the total *ee* luminosity is preserved.

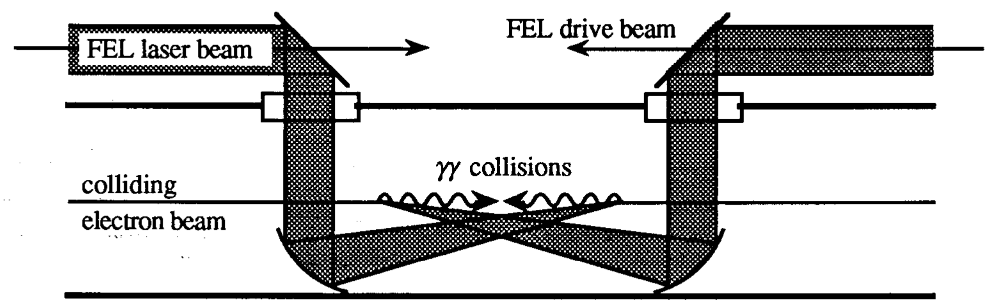


Figure 1 Conceptual scheme of a low-energy $\gamma\gamma$ linear collider (not to scale)

At $\eta > 1$, the photon spot size is greater than the electron spot size and the luminosity is correspondingly decreased. The low energy photons scatter at the highest angles, so as η grows their contribution to the luminosity is reduced the most and the luminosity spectrum skews toward the higher invariant masses.

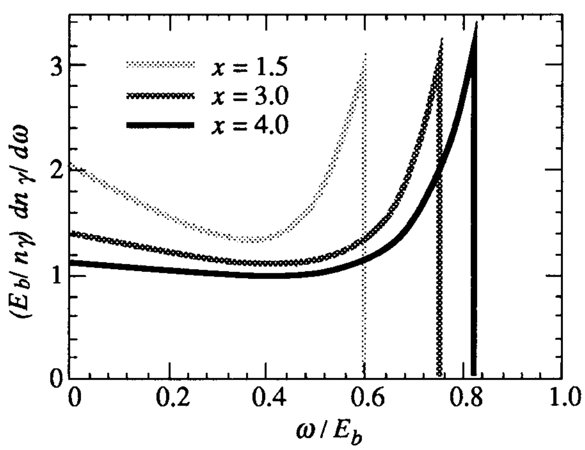
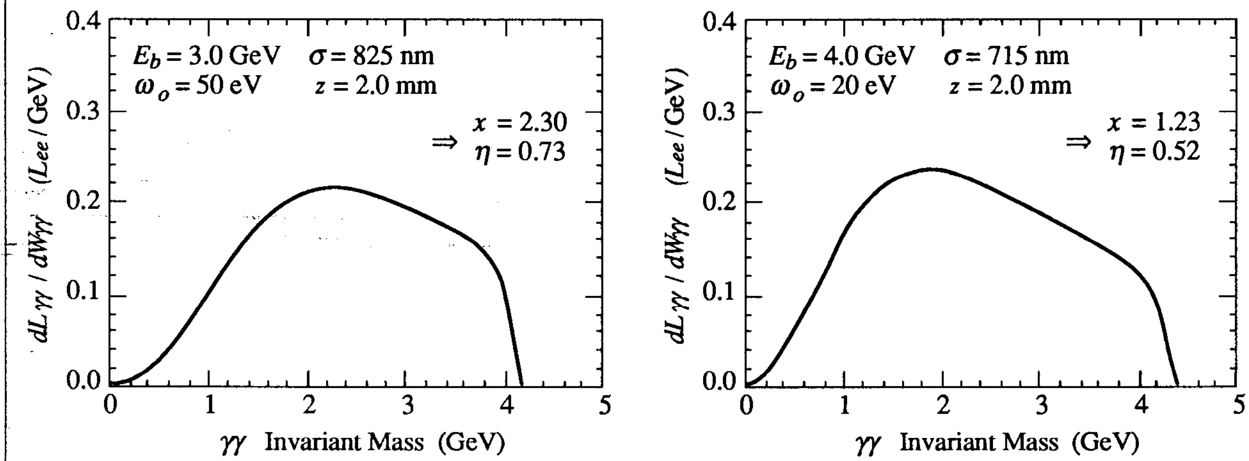


Figure 2 Backscattered photon spectrum for various values of the x parameter.

For two-photon physics a luminosity spectrum which covers the whole range from 1.5–4.0 GeV is desired. Given electron beam energies of a few GeV and spot sizes of order 1 μm, conversion distances (z) of a few millimeters will be necessary to keep η well below 1. An even more stringent bound on conversion distances is supplied by the requirement that the electron beam's transverse size must be smaller than that of the laser pulse when they meet. Together with the requirement that conversion distances be larger than electron bunch lengths (~ 1 mm), this sets a lower limit on the electron beam energy of about 3 GeV.

Figure 3 shows the luminosity spectrum resulting from a low energy Compton collider with *ee* center-of-mass energy of 6, 8, and 10 GeV, where the laser wavelength has been chosen in each case to tailor the photon spectrum to the 1.0–4.0 GeV mass region. In each case the beam spot size is assumed to come from relation (3) and a conversion distance of 2 mm is assumed. Also in each case it is assumed that each electron has scattered exactly once in the laser pulse; the effect of unscattered electrons will be included later when we consider production rates. Notice that at higher e^- beam energies the η parameter is smaller so that the low mass luminosity is greater, and that the necessary FEL wavelength is longer so that the laser requirements are easier to meet. Also, by (3),



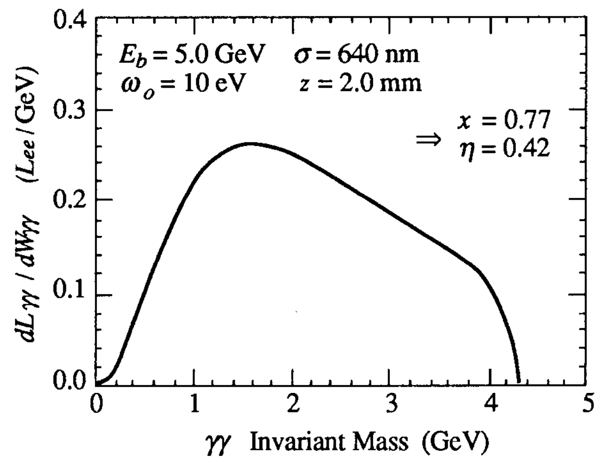


Figure 3. The two-photon luminosity distribution for a $\sqrt{s}$ = 6, 8, and 10 GeV collider. In each case the laser wavelength has been chosen to tailor the photon spectrum to the 1.0–4.0 GeV mass region, and the beam spot size is assumed to come from relation (3). At the higher e^- beam energies the η parameter is smaller, resulting in larger luminosity at low invariant mass. Also note that at higher beam energies the required FEL photon frequency is reduced.

the total luminosity attainable is greater for the higher energy machines. On the basis of only these considerations, the higher energy machines seem preferable.

The cost, however, will be significantly larger for a 5 + 5 GeV collider than for a 3 + 3 GeV collider. We expect the bulk of the cost of a low energy Compton collider to be in the accelerating structures themselves, so financial considerations argue for the lowest energy design which will preserve the physics.

IV. Expected Event Rates

To get 'ballpark' estimates for the $\gamma\gamma$ physics potential of such a machine, we make several simplifying assumptions. First, we consider only produced event rates, ignoring both branching ratios and detector efficiency (while the latter assumption would be fatal for storage ring two-photon processes, it is not so bad here where the events are not severely boosted). Secondly, we assume that the accelerator energy and FEL wavelengths can be tuned over a wide range; in practice, it will likely be difficult to justify the cost of prototype linear collider beam energies of more than a few GeV and difficult to obtain FEL frequencies larger than about 10 eV. These estimates are only intended to give a feeling for whether there could be a viable physics program at such a facility.

For the $\gamma\gamma$ production of a spin J resonance, the number of events per 'Snowmass year' (10^7 sec) is given by:

$$N = 1.54 \times 10^6 (2J+1) \left(\frac{L}{10^{31}\ \text{cm}^{-2}\ \text{s}^{-1}} \right) \left(\frac{\Gamma_{\gamma\gamma}}{\text{keV}} \right) \left(\frac{M}{\text{GeV}} \right)^{-2} \left(\frac{dL_{\gamma\gamma}/dW_{\gamma\gamma}}{L_{ee}/\text{GeV}} \right) \kappa^2 \tag{9}$$

where κ is the *conversion coefficient*—the fraction of electrons in each bunch that are converted to photons. We assume a conversion coefficient of 0.5 (i.e. the laser pulse is 0.7 interaction lengths long); this is the conversion coefficient one can expect for a 3.5 Joule, 3 psec laser pulse focused on a 1 mm long electron bunch. We consider the production of two typical resonances: the pseudo-scalar η_c with a two-photon width of 5 keV and mass of 3 GeV, and a fictitious, spin-zero, R(2000), a resonance with two-photon width of 1 keV and mass of 2 GeV. The latter state is a reasonable guess at values for $q\bar{q}$ excited states, as well as four-quark states and some hybrids, although $\Gamma\gamma\gamma$ values which are 10 times lower would not be particularly surprising. A glueball state would likely have a two-photon width of 1–10 eV. Given the three designs shown in Figure 2, and total luminosities given by (3), the expected production rates are given in Table 1. With reasonable detector efficiencies, and assuming the total branching ratios into states which are relatively easy to reconstruct are of order 10%, one is still left with rates of thousands of events per year, which far

Table 1 Expected event rates for various collider designs.

E_b (GeV)	ω_o (eV)	σ (nm)	z (mm)	x	η	L (10^{31} cm^{-2} s^{-1})	N_{η_c} (year^{-1})	$N_{R(2000)}$ (year^{-1})
3.0	50	825	2.0	2.30	0.73	1.4	58,400	28,300
4.0	20	715	2.0	1.23	0.52	1.9	74,700	42,900
5.0	10	640	2.0	0.77	0.42	2.3	90,000	55,600

exceed the present samples of ten's of events for η_c. One should be able to do a very thorough job of mapping the meson spectrum from 1.5–3 GeV as well, separating out exotic from normal states. Glueballs will be difficult to observe, but the very low limits which would be obtained on their $\gamma\gamma$ production, in comparison to significant rates from radiative J/ψ decays, should easily confirm such states.

The main competition for the $\gamma\gamma$ physics described above will be from CLEO-II at Cornell and the proposed B Factory facilities planned for the late 1990's. Studies[10] have shown that much larger event samples at low mass, and comparable numbers of events in the 3-4 GeV mass range, would be produced at a 10^{34} cm^{-2} s^{-1} B Factory. However, trigger and detection efficiencies may be considerably better for the low energy Compton collider. LEP200 will not be competitive for this physics, although it will likely produce detectable event rates at higher two-photon masses ($W \sim$ 5 GeV) and at higher Q^2 (10-2000 GeV^2). The $e\gamma$ measurements of the photon structure function at low Q^2 would be unique to this low energy Compton collider.

V. Cost and Prospects

Only rough guesses have been ventured about the costs involved with design and construction of a low energy linear collider. Each linear accelerator could be expected to cost in the neighborhood of 5-10 M$ / GeV, especially since they would be prototypes. Added to this would be the FEL costs (probably of order 5-10M$ each) and the intricate final focus system, which could easily be of order 1M$. Appropriation of such large sums of money seems unlikely unless: a) a prototype linear collider in this energy range is a *required* next step toward a high energy linear collider and b) there is enough interest in the low energy $e\gamma/\gamma\gamma$ physics we have outlined. It should be noted that serious consideration is being given to implementing Compton backscattering at the higher energy NLC's, where there are rich prospects for physics at the weak mass scale.[2] Early development of lasers and final focus schemes appropriate for such a facility at a low energy collider may be crucial to this effort.

There has been some study of implementing a prototype linear collider linac with energy up to 10 GeV within one of the PEP straight sections.[8] Similar ideas could be entertained for the use of PETRA or TRISTAN. Such a linac could inject electrons into the storage ring which would either drive FEL's or supply the colliding beams with FEL photons produced from the linac itself and stored in a resonator. Together with one of the presently-idle detectors at these mothballed storage rings, this would supply all of the components for a low energy Compton collider. Of course, the competing uses for all of these machines make it difficult to determine the likelihood of using them in the manner we have outlined. If there is sufficient interest in the community, the next step in the process of defining a low energy $e\gamma/\gamma\gamma$ collider would involve a better determination of the physics potential and more realistic estimates of the accelerator and laser parameters which would be needed.

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