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Photon-Photon Colliders

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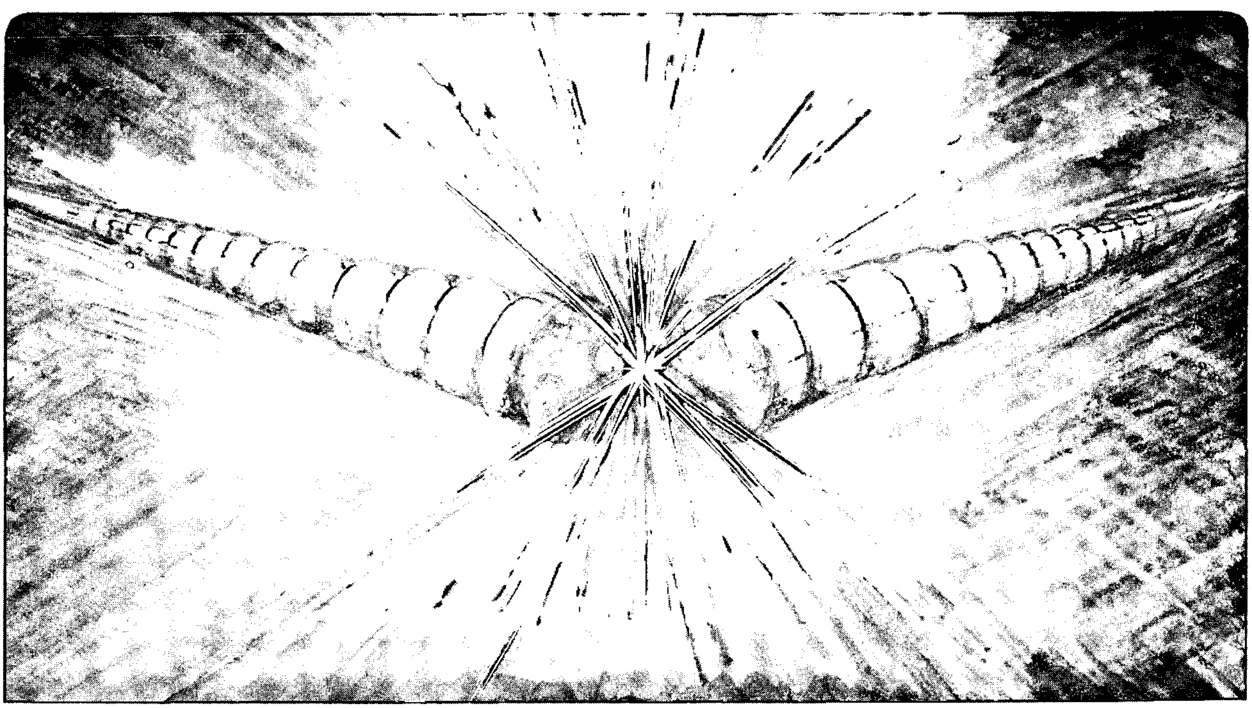

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"Photon-Photon Colliders"

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PHOTON-PHOTON COLLIDERS*

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Since the seminal work by Ginsburg, *et al.*, the subject of giving the Next Linear Collider photon-photon capability, as well as electron-positron capability, has drawn much attention [1]. A 1990 article by V.I. Telnov describes the situation at that time [2]. In March 1994, the first workshop on this subject was held [3]. This report briefly reviews the physics that can be achieved through the photon-photon channel and then focuses on the means of achieving such a collider. Also reviewed is the spectrum of backscattered Compton photons—the best way of obtaining photons. We emphasize the spectrum actually obtained in a collider with both polarized electrons and photons (peaked at high energy and very different from a Compton spectrum). Luminosity is estimated for the presently considered colliders, and interaction and conversion-point geometries are described. Also specified are laser requirements (such as wavelength, peak power, and average power) and the lasers that might be employed. These include conventional and free-electron lasers. Finally, we describe the R&D necessary to make either of these approaches viable and explore the use of the SLC as a test bed for a photon-photon collider of very high energy.

I. INTRODUCTION

From earliest times, man has known that light does not affect light. In modern terms, if you shine one flashlight on a wall, and direct the beam of a second flashlight through the beam of the first flashlight, shaking the second beam up and down, no matter how violently, will not affect the first beam. Maxwell formalized this in his famous electrodynamic equations, from whose linearity we would quickly deduce the above-described phenomenon. Of course, none of this is true in quantum mechanics, and the scattering of light upon light (Delbruck scattering), a quantum electrodynamic effect (QED), was first proposed in 1933 [4]. This phenomenon was first observed in 1954, and an experiment is now under way to carefully study this and other nonlinear QED effects [5].

As the energy of the light increases, not only do QED phenomena occur, but particle physics begins to play a role, so that in the light-light scattering, diverse pairs of particles are produced. In photon-photon colliders, the intensity of the light is so strong and the energy so high, that the collider becomes interesting for elementary particle physics.

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In this report, we discuss the elementary particle physics and experimental detectors (Section II), the kinematics, cross sections, and geometrical constraints of gamma-ray production and collision (Section III), conventional lasers (Section IV), free-electron lasers (Section V), and an R&D program (including the possible conversion of the SLC to a photon-photon collider) (Section VI).

II. ELEMENTARY PARTICLE PHYSICS AND EXPERIMENTAL DETECTORS†

The structure functions of the photon, probed by deep inelastic scattering from a photon target, are a fundamental and largely unresolved area of investigation in quantum chromodynamics (QCD). Clearly, the electron-photon collision option would provide the paramount facility for these studies. In another important area of QCD, photon-photon collisions would allow studies of the top quark threshold region that would complement studies performed in electron-positron collisions. Here some unique measurements are possible by using polarized photon beams. Large circular polarization allows direct observation of p-wave toponium, not possible in electron-positron collisions, while linear polarization may make possible very sensitive measurements of the strong coupling constant.

Studies of W boson pair production in photon-photon collisions provide the most sensitive tests for quartic anomalous interactions of the electroweak gauge bosons. The photon-photon option also provides unique advantages for Higgs boson studies. The two-photon width of a Higgs boson is most directly measured; the width is a fundamental probe both of (1) the electroweak theory and (2) electrically charged, ultraheavy quanta (which would affect the two-photon rate if their mass is generated by the Higgs boson). The search for supersymmetric Higgs bosons is also enhanced by the photon-photon option. In electron-positron collisions, the heavy scalar and pseudoscalar of the minimal supersymmetric model must be produced together in the same event, requiring energy greater than the sum of their masses, but in photon-photon collisions, they can be produced and observed individually. The circular polarization of the photon beams is an important asset in these studies, both enhancing the signal and suppressing the background. Linear photon polarization may also be useful, since it would allow direct measurement of the parities of the Higgs bosons, which might not be directly measured in any other way.

III. GAMMA RAY PRODUCTION AND COLLISION

Photons of high energy, equivalently gamma rays, may most readily be obtained by Compton backscattering. The general scheme of a photon-photon collider, with the Compton collision occurring at the "conversion point" (different from the collision point) is shown in Fig. 1.

1. The Conversion and Collision

The scattered photon differential cross section is:

$$\frac{1}{\sigma_c}\frac{d\sigma_c}{dy} \equiv f(x,y) =$$

$$\frac{2\sigma_0}{x\sigma_c}\left[\frac{1}{1-y}+1-y-4r(1-r)+2\lambda P_c rx(1-2r)(2-y)\right]$$

$$\sigma_0 = \pi\left(\frac{e^2}{mc^2}\right)^2 = 2.5\times10^{-25}\mathrm{cm}^2$$

where λ = electron helicity, P_c = photon circular polarization,

$$r=\frac{y}{x(1-y)} \quad , \quad y=\frac{\omega}{E_0} \quad ,$$

$$\omega=\frac{\omega_m}{1+\left(\frac{\theta}{\theta_0}\right)^2} \quad , \text{ and } \quad x=\frac{4E_0\omega_0}{m^2c^4} \quad .$$

The total Compton cross section is:

$$\sigma_c = \sigma_c^{np} + 2\lambda P_c \sigma_1 \quad ,$$

$$\sigma_c^{np} = \frac{2\sigma_0}{x}\left[\left(1-\frac{4}{x}-\frac{8}{x^2}\right)\ell n(x+1)+\frac{1}{2}+\frac{8}{x}-\frac{1}{2(x+1)^2}\right]$$

$$\sigma_1 = \frac{2\sigma_0}{x}\left[\left(1-\frac{2}{x}\right)\ell n(x+1)-\frac{5}{2}+\frac{1}{x-1}-\frac{1}{2(x+1)^2}\right] \quad .$$

σ_c is hardly affected by $2\lambda P_c = 1$ or $2\lambda P_c = 0$, but the spectrum very much depends upon $2\lambda P_c$.

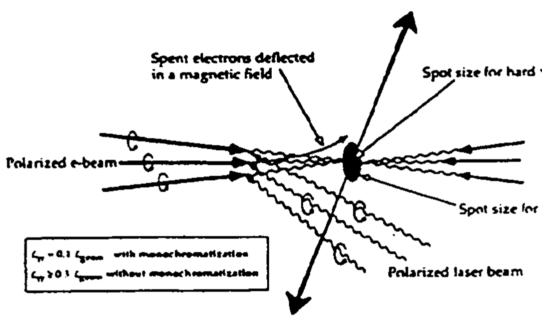


Figure 1: A schematic drawing indicating the conversion point from infra-red photons to gamma rays and the collision point or the gamma rays.

The geometry of conversion and collision produces a significant hardening of the spectrum. If we let ℓ be the distance between the conversion and collision point, and introduce the parameter ρ by $\rho = \ell / \gamma a_e$, where a_e is the radius of electron beam, then the luminosity spectrum strongly depends on beam parameters, but only through the parameter ρ.

If we introduce the geometrical luminosity $L_{ee} \equiv N^2 f / 2\pi a_e^2$, the resulting spectral luminosities are shown in Fig. 2.

It can be seen that laser photon polarization and electron helicity have a large effect upon the specific luminosity. This feature is important for experiments. Employing this analysis, we arrive at Table 1.

2. Laser Characteristics

In determining laser parameters, there are several considerations. The first is wavelength. Incident photons, ω_0, cannot be too energetic. If they are, then pairs are produced. The condition is

$$x \equiv \frac{4E_0\omega_0}{m^2c^4} > 2(1+\sqrt{2}) \approx 4.8$$

The best is to choose x close to 4.8 or $\lambda = 4.2E_0\,(\mathrm{TeV})$ μm.

The pulse length of the laser should equal that of the electron bunch (and its pulse structure should match that of the electrons). The amount of energy in one pulse or, equivalently, the laser peak power is given by the desire

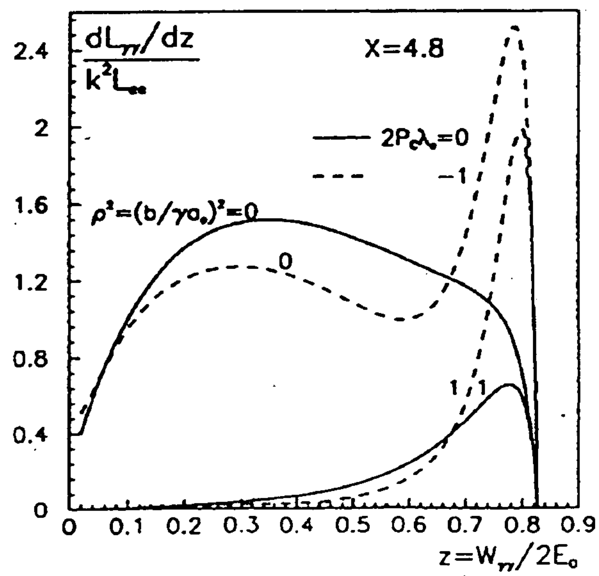


Figure 2: The spectral luminosity of γ–γ collisions. The curves represent unpolarized electrons or photons and fully polarized photons on helicity unity electrons. Two different distances between the conversion point and the collision point are considered. [From V. Telnov, Nucl. Instrum. Methods **A355**, 3 (1995)].

Table 1. Luminosity for various collider projects at 250 GeV × 250 GeV. Direct conversion to a photon-photon collider is given in the first column; the second assumes only the final focus is modified; while the third column gives the luminosity if, further, the electron beam emittance is reduced by the factors given in the last two columns. (The table was developed by V. Telnor, K.-J. Kim, P. Pielini, and the author.)

Machine	Direct Operation	Modified FF	Reduced Emittance	Emittance Reduction Factor	
TESLA	2.59E+32	9.20E+32	1.84E+33	1.00	4.00
SBLC	2.23E+32	4.12E+32	1.43E+33	3.00	4.00
JLC	5.47E+32	9.48E+32	1.90E+33	2.00	2.00
NLC	5.32E+32	1.11E+33	1.93E+33	2.00	1.50
CLIC	1.89E+32	4.33E+32	1.06E+33	2.00	3.00
VLEPP	4.93E+32	1.97E+33	1.97E+33	1.00	1.00

to have one γ-ray per electron. Then $N_{ph} = \pi w^2 / \sigma_c$. The energy in the laser pulse is $W = N_{ph} \cdot \hbar\omega_0$. The photon Rayleigh length should be the length of the electron bunch, that is $\ell_e = \pi w^2 / \lambda$. Combining $N_{ph} = \lambda \ell_e / \sigma_c$, independent of electron bunch radial size (provided $a_e < w$). More careful treatment puts a π upstairs. The pulse energy W is $hc\ell_e / \sigma_c$ or $W \sim 25 l_e$ (cm) J. For various projects W ~ 1 to 4 J, $\tau \equiv (l_e/c) \sim 1$ to 5 ps.

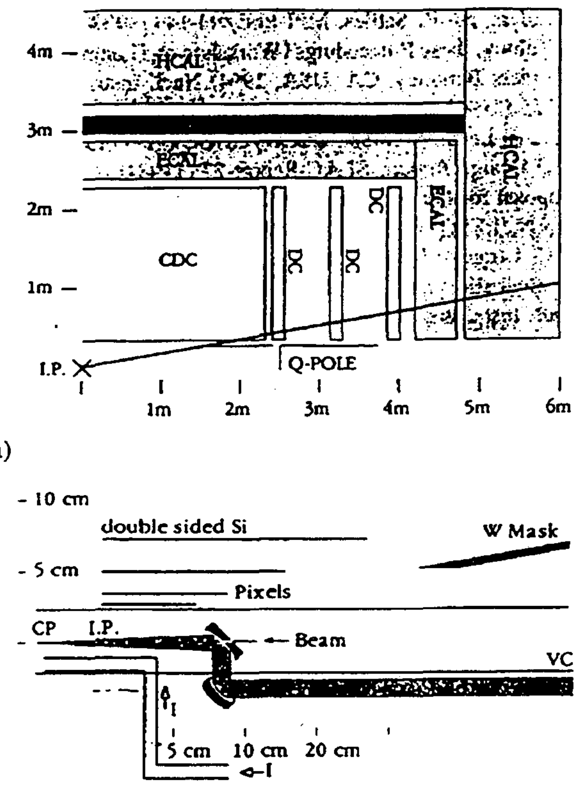
Finally, we recall that the laser should be able to vary the polarization of the output beam.

3. Detector Configurations

So far, only minimal thought has been given, and much more work is needed, on the detector aspects of a photon-photon collider. A first consideration is presented in Fig. 3.

It is not necessary, but highly desirable, to separate the used electrons from the γ-rays. Since the distance between these two points is, at best, a few centimeters, very high magnetic fields (within the detector!) are needed. Figure 4 shows some possible ways to generate such fields while minimizing the external fields.

Alternatively, a plasma lens (over-focusing the electrons and, therefore, greatly reducing spurious collisions) might be ideal, as it has no external magnetic field. Getting in the gas (for the plasma), and then removing it may, however, introduce too much mass into the detector.



(a)

(b)

Figure 3: (a) A schematic layout of the IP in a photon collider, with drift chambers and electromagnetic calorimeter. (b) Details of the region around the IP. [From F. Richard, Nucl. Instrum. Methods **A355**, 92 (1995)].

IV. SOLID-STATE LASERS

Several laser possibilities can meet the requirements for a photon-photon collider. Recall that backwards Compton scattering requires an input laser with the following properties: wavelength for electron energy of E_0 (TeV) ($\lambda = 4.2\ E_0\ \mu$m), laser power (P > 1 TW), pulse length ($\tau = 1$ ps), helical polarization, and pulse structure of about 100 pulses with a rep rate of about 200 Hz or 20 kW of average power.

Solid-state lasers can easily satisfy the first four requirements. But they cannot yet satisfy the average (as contrasted with the peak) power requirements. On the other hand, solid-state lasers without chirped pulse compression have produced an average power of 500 W.

Thus it is necessary to marry these two technologies, perhaps by having diode pumping of a Nd glass laser that is then used to drive a (wide band) Ti sapphire laser with a compressible pulse.

Possible schemes are shown in Fig. 6, but this subject requires much work.

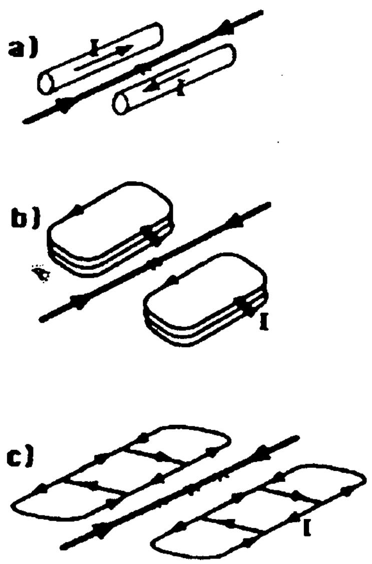


Figure 4: Possible setups for generating the strong transverse magnetic fields required to separate the electrons from the photons. [From D. Miller, Nucl. Instrum. Methods A355, 101 (1995)].

Generation of the pulse structure required for a collider can readily be accomplished. A possible scheme is shown in Fig. 5.

Getting the laser light to the electron beam, so as to have Compton backscattering, deep inside a detector is one of the major challenges of a photon-photon collider.

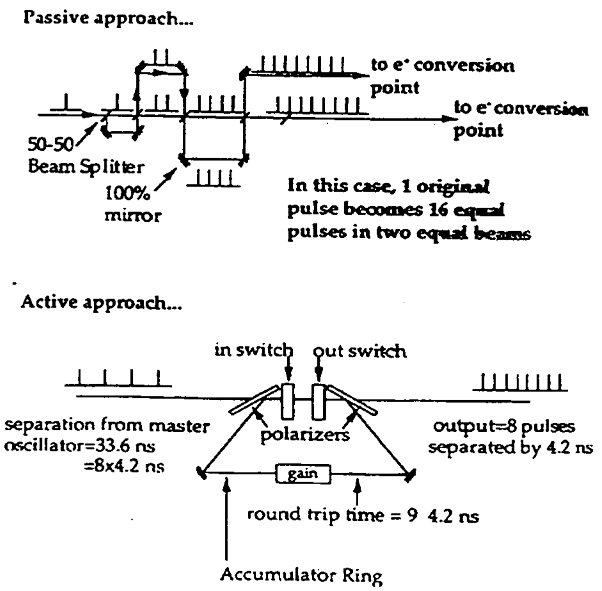


Figure 5: Two possible schemes for generating the train of laser pulses needed for a collider [From C.E. Clayton *et al.*, Nucl. Instrum. Methods A355, 121 (1995)].

V. FREE-ELECTRON LASERS

Free-electron lasers (FELs) are a possibility for a photon-photon collider; however, it is true that FELs have neither achieved the requisite peak power nor average power. Various possibilities have been considered [6] such as:

1. 10 FELs each driven by 3–4-kA, 150-MeV, induction-accelerated e-beam.
2. MOPA with amplifier driven by 1-GeV, 2.5-kA, induction-accelerated e-beam.
3. Photon compression of a ~100-ns induction-accelerated e-beam of 100 MeV and 1 kA.
4. Oscillator, with rf-accelerated e-beam and with high-power output switching.

The first possibility is the most extensive (and the most expensive) but the most likely to be successful. On the other hand, the last approach, an oscillator, is least expensive but requires the most R&D (to learn how to

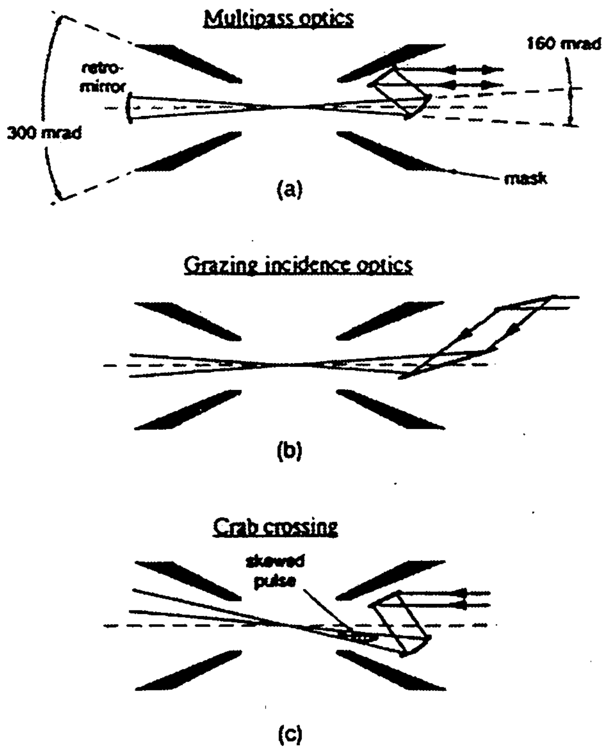


Figure 6: Three possible arrangements of the laser-focusing optics within the vertex detector: (a) an optical arrangement that uses the same laser pulse at both conversion points, (b) grazing-incidence optics that reduce the effect of collision debris upon the mirrors, (c) a crab-crossing geometry that even further reduces the effect of debris. [From C.E. Clayton *et al.*, Nucl. Instrum. Methods A355, 121 (1995)].

Table 2. Parameters for an FEL Pulse Compression Scheme.

Beam	
	$I = 1$ kA
	$E = 100$ MeV
	$\Delta E/E = 10^{-3}$
	$\varepsilon_N = 50 \times 10^{-6}$ πm – r
	$\lambda_\beta = 11.3$ m
Conventional Tapered Planar Wiggler	
	$\lambda_w = 4.0$ cm
	$K = 1.4$
	$L_{sat} = 16$ m
	$L_W = 25$ m
Output	
	$P_{out} = 1.6$ GW
	$E_{out}(1.4$ ns$) = 2.24$ J

circulate MW of power in contrast with the present achievement of only 1 W).

A pulse-compression scheme, very similar to that done with solid-state lasers, would seem to be a good way to take advantage of the fine average power capability of an FEL (without pressing it excessively on peak power) [7]. The scheme has the parameters shown in Table 2.

It is easy to show that the pulse-compression scheme, for light of wavelength λ (~1 μm), compressed from pulse length T (~1 ns) to pulse length τ (~1 ps), requires fluctuations in frequency limited by a number of relations, the most restrictive being $\Delta\omega / \omega < \lambda / 4\pi c T$. This requires $\Delta\omega / \omega < 2 \times 10^{-7}$

For an FEL, it is easy to show that variation in input beam energy (measured by γ) or current (I) will lead to an error in frequency (at the output) of

$$\frac{\Delta\omega}{\omega} = -\left(\frac{\lambda}{Tc}\right)\left(\frac{Lw}{\lambda_w}\right)\phi\rho\left[\frac{1}{3}\frac{\Delta I}{I} - \frac{\Delta\gamma}{\gamma}\right] ,$$

where L_W is the length of the wiggler, λ_W is the wiggler wavelength, φ is the phase change due to the FEL, and ρ is the FEL parameter. For our example,

$$\frac{\Delta\omega}{\omega} \sim 10^{-5}\left[\frac{1}{3}\frac{\Delta I}{I} - \frac{\Delta\gamma}{\gamma}\right] ,$$

and thus with a 1% tolerance on beam characteristics, pulse compression can be accomplished.

VI. AN R&D PROGRAM

The relevant R&D has both immediate and long-term aspects. It should consist of work on:

1. Detectors and masking
2. High-power lasers including FELs
3. Special final-focus components
4. Bright sources of polarized electrons
5. High-power, low-loss optical components.

The SLC can provide a realistic test bed for a higher energy γ-γ collider and, furthermore, would provide interesting new particle physics. Many of the problems faced by developing detectors, the final focus geometry, and high-power lasers for SLC-II are almost the same as those for a higher-energy collider. The cost-effective upgrade of the SLC to allow for e^+–e^-, e-γ, and γ-γ collisions will provide an opportunity to the international HEP community that we cannot afford to miss.

In sum, then, the R&D program consists of work on solid-state lasers and free-electron lasers, experiments in the FFTB, development of a low rep-rate collider at SLC, and finally implementation of the high rep-rate, high-luminosity γ-γ collider at SLC.

VII. CONCLUSIONS

To the HEP community, the basic question is, "How seriously do you take the γ-γ, γ-e, and e-e capability"? There are many possible answers and consequences:

1. "Not at all." Then you don't need to build and instrument a second interaction region.
2. "As an add-on." Then the luminosity $L_{\gamma\text{-}\gamma} = (1/10)$ $L_{e^+\text{-}e^-}$ (and is probably not very interesting). If you change the final focus, then $L_{\gamma\text{-}\gamma}$ = (1/4 to 1/5) $L_{e^+\text{-}e^-}$.
3. "Very seriously." Then one designs rather different damping rings and, as a consequence, can achieve $L_{\gamma\text{-}\gamma} = (1/2)\, L_{e^+\text{-}e^-}$.

If the answer, A, is such that $2 \leq A \leq 3$, then an R&D program should be initiated now.

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