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Test of QED Using a Laser at the SLAC Final Focus Test Beam*

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ABSTRACT

Experiment #144 at SLAC has three parts: the search for low-mass states excited in $\gamma\gamma$ collisions and observed in pair decay, the study of nonlinear, nonperturbative QED in γe and $\gamma\gamma$ collisions, and its possible applications to general purpose linear colliders. Such colliders could produce the full range of $J^{PC}_{q\cdot\cdot q}$ states, leptoquarks $J^{PC}_{l\cdot\cdot\bar{q}}$, the particles of supersymmetry, the top quark or Higgs. However, to realize them a number of technical problems need resolution that are addressed in E144 together with interesting possibilities for highly polarized, high brightness $\vec{\gamma}$ and $\vec{e}^{\,\pm}$ beams that are needed for electroweak studies.

1. Introduction

This Experiment is a collaboration between Princeton, Rochester and SLAC[1] to collide high-power laser beams (1 TW) with high-energy electrons (50 GeV) to explore critical field effects [Sauter (1931), Heisenberg & Euler (1936) & Schwinger (1954)[2]]

$$\Upsilon \equiv \frac{E^*}{E_c} = \frac{\gamma(1+\beta)E_{Lab}}{E_c} \rightarrow 1 \quad \text{with} \quad E_c \equiv \frac{(mc^2)^2}{e\hbar c} = 1.32 \cdot 10^{18}\ \frac{V}{m} \ .$$

$E^* \approx 2\gamma E_{Lab}$ is the boosted laser field seen in the average rest frame of the electrons. For high enough electron energy or laser power density[3] one expects strong vacuum polarization effects. While these haven't been observed in such a direct way and are interesting for QED they could also provide new ways to search for and study particles with different quantum numbers J^{PC}. Quarks and quarkonium states are examples and since quarks are elementary fermions without asymptotic states and noninteger charge, it is also reasonable to consider lepton-quark, boson and hybrid combinations. The question is how to excite them and study their characteristics along with questions on symmetry, confinement and cosmologic missing mass.

The answer is a natural extension of the SLAC facility i.e. a general linear collider that provides $\vec{e}^{\,\pm}\vec{e}^{\,\pm}$, $\vec{\gamma}\vec{e}^{\,\pm}$ and $\vec{\gamma}\vec{\gamma}$ incident channels. This is discussed relative to E144 which introduces γe and $\gamma\gamma$ interaction points (IPs) into the FFTB line. These allow us to study the nonperturbative, multiphoton Compton and Breit-Wheeler processes, to measure the corresponding e^+e^- mass spectrum e.g. to study the e^+ production in heavy-ion and electron colliders as well as to study other practical questions on a general linear collider (GLC) by necessarily confronting the production, timing and stability problems associated with strong fields and independent, micron-size beams.

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2. SLAC and a GLC

In a sense, the SLAC linac was built to provide highly space-like photons for deep inelastic experiments on few-nucleon systems. Such experiments showed the basic underlying parton structure of the nucleon. In contrast, the subsequent development of SPEAR provided highly time-like photons via the e^+e^- annihilation process that led to the resonant production of charmed quark pairs $q_c\bar{q}_c$ and the tau lepton.

With the higher energies from PEP, higher-order processes were important with space-like, two-photon ($\gamma^*\gamma^*$) production being dominant. This is the main channel for C-even particles but since the photons are virtual, it lacks the simplicity of the resonant annihilation process dominant at lower energies and uses the available center-of-mass energy s less efficiently. Thus, while the SLC is a natural extension of electron colliders such as PEP, TRISTAN and LEP, it still has some of SPEAR's limitations such as a strong emphasis on 1^{--} states.

To solve this dilemma, a GLC needs real, polarized photons that are on the light cone or light-like. Figure 1 shows half of a possible system. Milburn & Arutyunian et al. (1963) predicted and Ballam et al. (1969) verified that Compton backscattering of polarized laser beams could produce quasi-monochromatic beams of high energy, polarized photons. It has also been suggested (1991) that a subsequent laser-photon interaction of the Breit-Wheeler type, with laser photons of the same helicity as in the laser-electron interaction, could produce highly polarized $\vec{e}^{\,\pm}$ beams (dependent on v/c in the pair rest frame[4]). With target-free conversion, such beams would have much higher brightness than those from the corresponding conventional process[5].

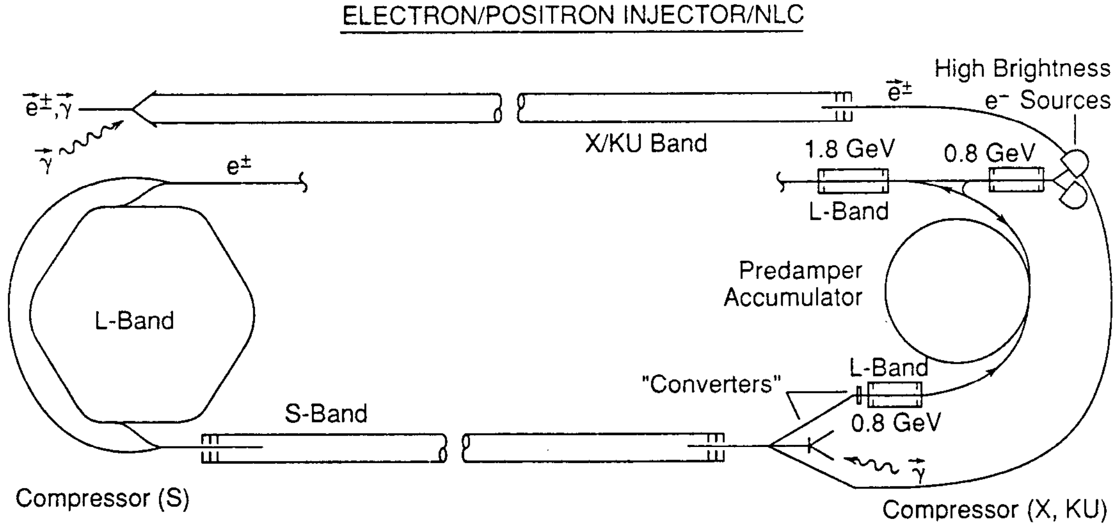

Figure 1: A versatile, high-brightness, stable source that allows any combination of $\vec{\gamma}$ and $\vec{e}^{\,\pm}$ experiments. The semi-circular, bunch-length compressors at either side allow causal feedforward before final launch into the X/KU band linac. Significant micro and macro bunch rate and current variations are possible that allow us to avoid using the damping rings. The lasers and/or FELs for the $\vec{\gamma}s$ are not shown. Notice that the high-brightness source (RF gun) doesn't need to be polarized.

3. Breakdown of Low-Order Perturbation Theory

The Compton and Breit-Wheeler processes are cross-channel reactions that are more efficient than Bethe-Heitler for the same reasons we want real photons. They are two-body processes whose incident energies and angles can be well defined (field free). For low laser[3] and electron[6] densities, two independent, kinematic invariants[7] are then needed to specify the exit channels (also asymptotically free) e.g. the energy of the outgoing Compton photon (ω_2) depends only on its scattering angle (θ_2) relative to the incoming particle and its energy ($\epsilon_1 = \gamma m$) and that of the laser photon (ω_1):

$$\frac{\omega_2}{\omega_1} = \frac{1-\beta\cos\theta_1}{1-\beta\cos\theta_2 + \frac{\omega_1}{\epsilon_1}[1-cos(\theta_1-\theta_2)]} \simeq \frac{4\gamma^2}{1+(\gamma\theta_2)^2+4(\epsilon_1\omega_1/m^2)} \ .$$

For lasers ($\omega_1 \approx 1$ eV), the mass is important (10% level) for $\epsilon_1 = m^2/(40\,\omega_1) \gtrsim 6$ GeV. Below this $y \approx x \ll 1$ while for $y_{max} \to 1$, $(d\sigma^C/\sigma^T) \to (d\Omega_2/4\pi)(4\gamma^2/x) \gg 1$. With increasing laser intensity, multiple photons (n) may be absorbed coherently giving the electron an average quasi-momentum $q_\mu q^\mu = m_*^2$ in the field determined by one more invariant Υ or η (next section) relating the particle and field. In terms of n and m_* we have:

$$\left(\frac{\omega_2}{n\omega_1}\right)_{max} = \frac{4\gamma^2}{1+4\epsilon_1 n\omega_1/m_*^2} \ ; \quad \left(y \equiv \frac{\omega_2}{\epsilon_1}\right)_{max} = \frac{4(\epsilon_1 n\omega_1/m_*^2)}{1+4(\epsilon_1 n\omega_1/m_*^2)} = \frac{nx_*}{1+nx_*} \ .$$

Table I gives the peak photon energy from leading-order conversion together with the number of photons (n) required to convert $\geq$ 80% of the electron's energy when $\Upsilon = 1$. At 250 GeV, lasers can convert a maximum of 75% with one photon but the conversion probability $P_C = \rho_\gamma c\tau\sigma_1^C \gg 1$ for **all** incident electron energies (σ_1^C grows with decreasing energy) so that multistep processes in the initial and final states as well as damping of the lowest-order perturbative result by multiphoton conversion and pair production have to be considered[8]. In succeeding sections we discuss n, m_* and σ_n^C etc.

Table I: $(y = \omega_2/\epsilon_1)_{max}$ in lowest-order, 'conventional' Compton scattering. The number of photons n required to convert $y \geq 80\%$ of ϵ_1 in critical field scattering ($\Upsilon \equiv 1$) is in parentheses ($n \propto x^{-3}$). Lasers apply for 1 eV but only FELs for $\omega_1 \gtrsim 10$ eV. For our purposes NLC and TLC can be considered to be equivalent to a GLC.

ϵ_1(GeV)	2	10	50	250	500
ω_1	SPEAR	PEP	SLC	NLC	TLC
1 eV	0.030 ($6 \cdot 10^5$)	0.133 ($5 \cdot 10^3$)	0.434 (41)	0.793 (2)	0.885
10 eV	0.235 (569)	0.605 (7)	0.885 (1)	0.975	0.987
100 eV	0.754 (2)	0.939 (1)	0.987	0.997	0.999
1 keV	0.968 (1)	0.994	0.999	1.000	1.000

4. Classical and Quantal Strong-Field Invariants as Experimental Knobs

Beyond the standard, two-body channel invariants and products of 4-momenta[7] there are the related, dimensionless invariants Υ involving a particle's Compton wavelength and η involving the photon's wavelength:

$$\eta = \frac{e}{m}\Big[-\frac{(F_{\mu\nu}p_1^\nu)^2}{(p_1k_1)^2}\Big]^{\frac{1}{2}} \rightarrow \frac{eE_{Lab}}{mc^2}\lambda\!\!\!^{-} = \Upsilon\frac{(mc^2)^2}{2\omega_1\epsilon_1} = \frac{2\Upsilon}{x}$$

where $\eta = 1$ is an energy gain of one electron mass in one wavelength while $\eta\rightarrow\infty$, $\omega\rightarrow 0$ is the static field limit. The minus sign comes from our choice of metric[7] e.g. $F_\mu = (\vec{E}\cdot\vec{p},\ i(\epsilon\vec{E}+\vec{p}\times\vec{B}))$. Although one writes the fields as if they were constant, their variation within the beams provide measurable 'ponderomotive' effects and their overall variations via laser intensity or wavelength provide our lowest-order knobs for the experiment. When the E and B fields are equal and orthogonal e.g. in a plane wave, the pure field invariants like ${F_{\mu\nu}}^2$=E^2-B^2 don't give us knobs but normalizing them provides a measure of 'strongness' e.g. E^* compared to m^2/e in Eq. 1 tells us when the pair channel couples strongly whereas eF_μ/m^2 is the dimensionless 4-vector that couples the particle and field in the Lorentz-Dirac equation for the 4-velocity.

An important distinction between IP1 & 2 in Fig. 2, for an NLC, is that one wants to be near threshold ($\sim 2m_*$) at IP1 but well above[4] for IP2 since IP1 produces the high energy photons by Compton upshifting the laser and IP2 collides the laser with the photons from IP1. For circularly polarized light on an electron in its average rest frame, one easily finds an 'invariant' mass m_* for the particle in the field:

$$m_* = m\sqrt{1+\eta^2} \quad\Rightarrow\quad n = \frac{m^2\eta^2}{2p_1k_1} \rightarrow \frac{\eta^2}{x}$$

using $q=p_1+nk_1$. For the conditions in Fig. 3, n=0.2 and the expected range for the experiment is $0<n<10$ corresponding to $0<\Upsilon\lesssim 1$. For the NLC, we want $\eta\lesssim 1$ and $x\gg\eta^2$.

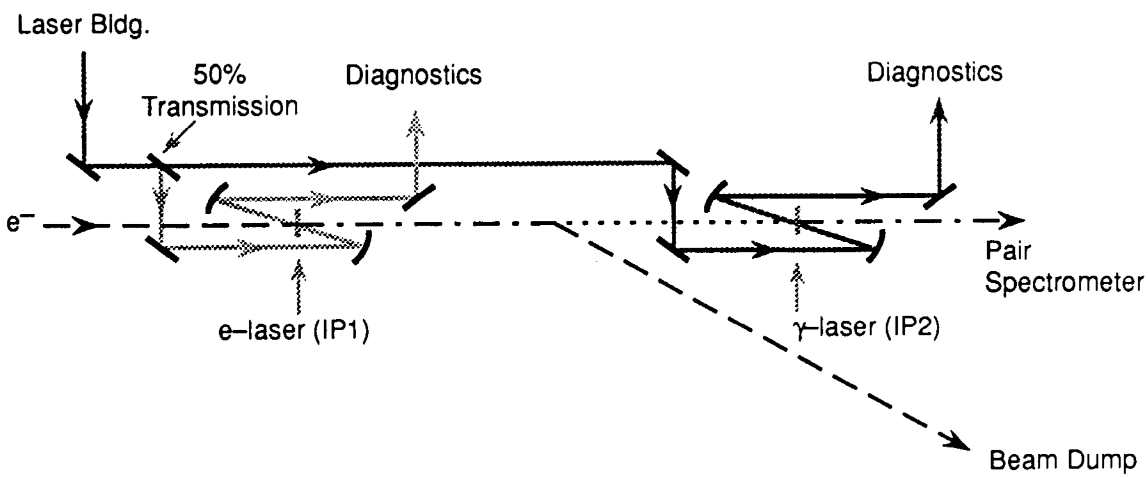

Figure 2: Schematic of E144 downstream of the final focus in the FFTB. The e-beam is dashed.

5. Multiphoton Compton Effects $\left[n\omega_1 + e \rightarrow \omega_2 + e'\right]$

This part of E144 occurs at IP1 in two phases. First, we want to measure the photon spectrum $N(\omega_2)$ using a very parallel e-beam and then collide the high energy photons with the split laser pulse as shown in Fig. 2 for $n\omega_1 + \omega_2 \rightarrow e^+e^-$.

Lowest-order, perturbative Compton scattering by free electrons is described by Klein-Nishina (1929) and for moving electrons by Feenberg and Primakoff (1948) with higher order processes depending on the intensity of the incident photon beam by Narozhnyi, Nikishov and Ritus (1964). The multiphoton cross section can be expressed in terms of the normalized, dimensionless variables[7] u, x, y & z:

$$\frac{d\sigma_n^C}{dy} = \frac{\sigma_o}{x}\left\{-\frac{4}{\eta^2}J_n^2(z) + \left(2 + \frac{u^2}{1+u}\right)\left[J_{n-1}^2(z) + J_{n+1}^2(z) - 2J_n^2(z)\right]\right\}$$

$$u \approx \frac{y}{1-y}\,, \quad y_{max} = \frac{nx}{1+\eta^2+nx}\,, \quad z = \eta\sqrt{1+\eta^2}\frac{2}{x}\sqrt{u\left(\frac{nx}{1+\eta^2} - u\right)}$$

where $\sigma_o \equiv 2\pi r_e^2 = \frac{1}{2}$ barn with the total C-M energy $s/m^2 = 1 + x$. Figure 3 shows $d\sigma_n^C$ for the 1 eV laser photons of Table I and 50 GeV electrons. Note that $z \rightarrow 0$ for $\eta \rightarrow 0$ and at the endpoints of $y(= 0, y_{max})$.

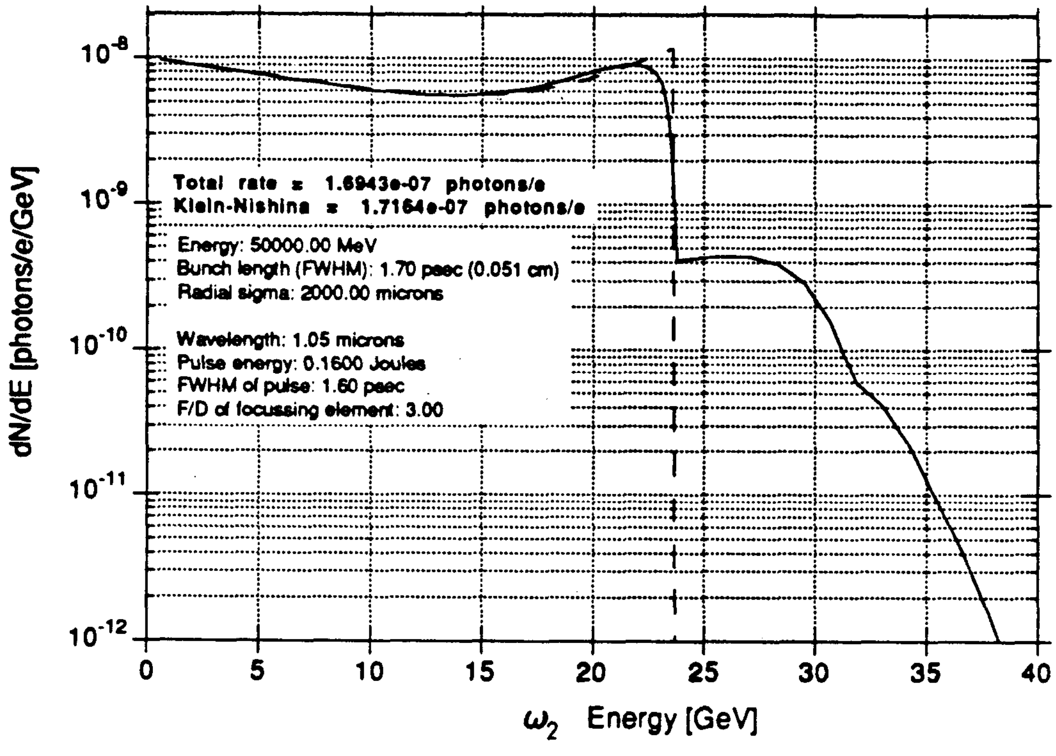

Figure 3: Comparison of the conventional, one-photon process with $\eta \rightarrow 0$, shown as the dashed line, with that for $\eta = 0.4$ which shows observable multiphoton effects up to $n \leq 3$ photons. The laser intensity[3] is $I_L = 4 \cdot 10^{17}$ W/cm^2 with $E_{Lab} = 6$ GV/cm that is still adequate for strong field emission.

6. Multiphoton Breit-Wheeler $\left[n\omega_1 + \omega_2 \to e^+e^-\right]$

Lowest-order, Breit-Wheeler pair production (1934) is cross-channel to Compton. Here the motivation is to study and look for possible resonance effects in the pair channel. However, doing this successfully also verifies the practicality of providing more than one interaction region (e^+, e^-) i.e. it allows the possibility of **polarized** $(e^\pm, e^\pm)$, $(e^\pm, \gamma)$, and (γ, γ) incident channels[9] for the first time.

$$\frac{d\sigma_n^{BW}}{dy} = \frac{\sigma_o}{x}\left\{\frac{4}{\eta^2}J_n(z) + (u-2)\left[J_{n-1}^2(z) + J_{n+1}^2(z) - 2J_n^2(z)\right]\right\}$$

$$x = \frac{4\omega_o\omega}{m^2}, \quad y = \frac{E_e}{\omega}, \quad y_{max,min} = \frac{1}{2} \pm \sqrt{\frac{1}{4} - \frac{1+\eta^2}{nx}}, \quad u = \frac{1}{y(1-y)}.$$

Tradeoffs between energy, intensity and background determine the optimum values of $\omega_1, \epsilon_1, x, \eta, etc.$ under differing constraints. This will be discussed in a SLAC-PUB.

7. Conclusions

I have tried to show that strong field effects become increasingly important for the NLC but impose no insurmountable problems and may even provide advantages. One doesn't want just a $\gamma\gamma$ collider but the γe and ee options for the different physics they provide but also because of the way the γs are produced. Similarly, it appears that by producing the γ-beams we have a better way to obtain polarized $\vec{e}^\pm$ beams. However, one problem with γs of concern for the SLC was the loss of C-M energy when using lasers to Compton convert the particle's energy. While lasers could be made to convert the electron beam with good efficiency, one would lose too much C-M energy to produce the intermediate vector bosons. Likewise, while free electron lasers could provide energy variability they might not provide enough intensity. Ten years later, with the SLC having demonstrated the practicality of the e^+e^- channel, E144 at the FFTB is an ideal demonstration test of a GLC by using the laser to do fundamental, multiphoton QED physics e.g. to try to create a 'little-bang'; to simulate the missing positron beam for beam-beam studies at high fields; or to produce the required high-energy, polarized photon and electron beams.

Such beams would be useful for fixed target channels (e-A & γ-A scattering and reactions) as well as for synchrotron radiation users because the required FELs still haven't been demonstrated. While high power lasers are needed for GLCs, for $\epsilon_1 \lesssim 100$ GeV they are inefficient. For Compton photons we want $x_{max} \lesssim 4.8(1+\eta^2)$ which is higher than previously suggested (Telnov 1990) with 4.8 a purely kinematical factor[4] coming from the threshold for cross-channel damping when n=1, β=0 and $\eta \to 0$. This gives the important constraint $y_{max} \leq 0.83$. For Breit-Wheeler production of *polarized* particle beams we still want n=1 but η & x are otherwise unconstrained whereas for unpolarized beams n is also unconstrained – all of which favors FELs over lasers.

8. Acknowledgements

I would like to thank my colleagues on the experiment and at SLAC for their help and contributions to the experiment which is difficult but compelling. Special thanks go to Kirk McDonald, Adrian Melissinos and Paul Tsai.

9. References/Footnotes

1. J.G. Heinrich, C. Lu, K.T. McDonald (Princeton U.), C.Bamber, A.C. Melissinos, D. Meyerhofer, Y. Semertzidis (Rochester U.), P. Chen, J.E. Spencer (SLAC), R.B. Palmer (SLAC & BNL), *Proposal for a Study of QED at Critical Field Strength in Intense Laser High-Energy Electron Collisions at the Stanford Linear Accelerator*, SLAC Proposal E144, Oct. 1991. Additional members of the collaboration at SLAC include D. Burke, T. Barklow, C. Field, J. Frisch, K. Jobe, A. Odian and D. Walz.

2. Most of the references are in Ref. 1 or in the references therein so they aren't repeated here. Notice that E_c gives an energy gain of one m over one Compton wavelength i.e. $\bar{\lambda}_m$ or $\bar{\lambda}_e$.

3. The laser intensity for a critical field of Υ=1 is: $I_L = E_{Lab}^2/377\Omega \approx E_c^2/(4\gamma^2 \cdot 377)$. For 50 GeV electrons $I_L = 1.2 \cdot 10^{19}$ W/ cm^2 and for 1 eV photons we have $\rho_\gamma = 2.5 \cdot 10^{27} \gamma\text{s/cm}^3 \gg 6 \cdot 10^{23} \rho/A$. This corresponds to a 1.5 TW laser (1.5 J in 1 ps) focused to a spot size with a 2 μ radius. In this example, a high intensity laser is one having a density $\rho_\gamma \gg 1/\bar{\lambda}^3 \approx 4 \cdot 10^{15}$.

4. From Footnote 7 we have $2\epsilon = \sqrt{t}$ so the velocity in the pair rest frame is $\beta = \sqrt{1 - m_*^2/\omega_1\omega_2}$. From Table I and Fig.1, this indicates FELs for both polarization and the efficient use of ϵ_1.

5. Conventional pair production implies Bethe-Heitler bremsstrahlung and pair production on nuclei which are also cross-channel processes similar to Compton and Breit-Wheeler. However, this is not a typical operating condition because it implies a target thickness $L_R/10^3$. One should then consider external Compton and Bethe-Heitler pair production in various forms e.g. low-emittance, circularly-polarized photons incident on a channeling crystal when Breit-Wheeler dominates as well as the corresponding strong-field, multiphoton case when the pair gain is more important than polarization. Measurement of the pair spectrum and polarization with laser intensity is then an interesting extension of E144.

6. Classically, the electrostatic self-energy of an electron reaches E_C at the geometric mean of r_e and $\bar{\lambda}_e$. Quantum effects enter at the scale of $\bar{\lambda}_e$ and total breakdown of the classical at r_e. A typical momentum transfer to the electron in E144 is less than these scales. The field intensities of the particle beams are also relevant. At SLC with $5 \cdot 10^{10}$ particles and a 1.5μ radius one approaches E_c for a bunch length $\lesssim$2 mm. On FFTB, the bunches are only 10^{10} and the worst transverse dimension is comparable (or much larger for E144).

7. If $p \equiv (\epsilon, i\vec{p})$ and $\hbar = c = 1$, the C-M energy squared for Breit-Wheeler is $(\omega_1 + \omega_2)^2 - (\vec{k}_1 + \vec{k}_2)^2 = 4\omega_1\omega_2$ for collinear γs. This is the t-channel for Compton scattering where $s \equiv (1+x)m^2$ with $x = 2p_1k_1/(p_1p_1) \rightarrow 4\epsilon_1\omega_1/m^2 = 0.0153\epsilon_1(GeV)\omega_1(eV)$; $u = k_1k_2/(k_1p_2)$; $y = \omega_2/\epsilon_1$ and $\epsilon_i = \gamma_i m$.

8. The conditions for applicability of the first Born approximation were relevant to Sauter's understanding of Klein's paradox or when the voltage drop over a wavelength approaches the rest energy of an electron. At small enough distances or impact parameters ($\bar{\lambda}_e$), the matrix element for pair production can violate unitarity bounds. In the present context, the laser creates a potential that can act in a variety of ways. However, the ponderomotive effect on the $e^\pm$ motion is only important for low energies. Finally, competitive processes such as double Compton or radiative corrections are higher order (Jauch and Rohrlich 1955) so it is valid to infer that only thick target effects need to be considered even for strong fields.

9. One expects significant depolarization effects for strong fields and/or low velocities for a variety of reasons. It is hard to control or limit the strong field harmonics because the fields are neither static nor spatially uniform across the beams. Nevertheless, because η increases threshold, it takes more photons n to produce pairs and this naturally limits the process from below and constrains harmonics but with reduced polarization compared to single harmonic production. There are also strong field dynamical effects that reduce polarization e.g. due to lack of cancellation of Lorentz components for lower velocities from conventional sources.