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Breeding New Light Into Old Machines (and New)*

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Abstract

Photons produced by lasers or wigglers backscattered on high energy electron or proton beams can provide high energy, high luminosity photon-electron, photon-photon or photon-proton collisions. This allows the study of short-distance QCD processes such as high transverse momentum photon-photon and photo-production reactions, deep inelastic Compton scattering, the photon structure function, direct photon reactions, or searches for pseudo-Goldstone bosons and supersymmetry particles like the photino or goldstino. The relative reaction rates should be quite high since (1) photo-production cross sections are significantly larger than the corresponding electro-production cross sections and (2) absence of the conventional beam-beam interaction allows significantly higher currents and smaller interaction areas. It thus seems possible to have photon luminosities much larger than for electrons. Examples are given using the PEP storage ring with the SLAC linac beam.

Introduction

In a sense, the SLAC linac was built to provide highly space-like photons[1] for deep inelastic scattering experiments on few-nucleon systems. These experiments demonstrated the underlying parton structure of the nucleon. The subsequent development of SPEAR provided highly time-like photons via the (e^+, e^-) annihilation process shown in Fig. 1b which led to the first observations of resonant production of quark pairs $(q_c, \bar{q}_c)$ and the heavy, electron-like particle called tau.

With the higher energies available at PEP, higher-order processes become important with the space-like processes of Fig. 1c being dominant. This is the main production channel for C-even particles, with the physics of interest at the internal vertices in diagrams like Fig. 1f where $X \equiv f\bar{f}$. Because there are two virtual photons, such processes lack the simplicity of the annihilation diagram but are richer because of the experiments they provide depending on whether the photons are almost real or far off the mass shell. The situation again simplifies when Fig.'s 1f or 1g become the incident channel producing η_b's, $A2_b$'s, $A3_b$'s ...

The present proposal considers using real photons that are on the light-cone or light-like such as shown in Figures d-h. The basic idea resulted from a study related to the SLC more than five years ago[3] where the motivation was to provide more than the one (e^+, e^-) interaction region by allowing for (e^-, e^-), (e^-, γ), (e^+, γ) and (γ, γ) channels. One problem of concern in the SLC study was the loss of C-M energy when using lasers to Compton convert the particle beam to photons. While lasers could probably convert the electrons with good efficiency, one would lose too much C-M energy to make intermediate vector bosons[3]. This is not relevant for PEP using a higher energy, lower emittance linac beam to double Compton produce high energy photon beams from a PEP FEL arrangement.

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Luminosity Limitations

The incoherent beam-beam interaction between colliding bunches produces strong, nonlinear forces on the bunches which limit the operation of present rings. The leading-order, linear focusing force for head-on $e^\pm$ collisions, expressed as a tune perturbation per crossing, is[4]

$$\Delta\nu_{x,y} = \frac{r_e N_e \beta^*_{x,y}}{2\pi\gamma\sigma_{x,y}(\sigma_x + \sigma_y)}$$

where σ is the rms bunch size, N_e is the number of particles per bunch and β^* is the beta function at the crossing point. Although this expression can be identified with the *average*, small amplitude tune shift for gaussian bunches it is best thought of as the tune *spread* in the core of the bunch. At some limiting value $(\Delta\nu^*)$ or bunch current (N_e^*), the bunch cross-section increases, luminosity stops increasing and the lifetime may even decrease. If this limit is made the same in both transverse directions by making $\beta^*_y/\beta^*_x \simeq K(\equiv \epsilon_y/\epsilon_x$, the tune independent, x-y coupling in the machine), one expects the maximum achievable luminosity for $\sigma_x \gg \sigma_y$ to be:

$$\mathcal{L}_{max} = \frac{(N_e^*)^2}{4\pi\sigma_x^*\sigma_y^*} fn = (\Delta\nu^*)^2 (\frac{\gamma}{r_e})^2 \frac{\epsilon_x}{\beta_y^*} fn$$

where $\epsilon_x = \pi\sigma_x^2/\beta_x$, f is the revolution frequency and n is the number of bunches per beam.

Increasing the frequency via superconducting magnets, or the number of bunches or the energy i.e. stiffening the beam are all expected to improve luminosity. However, increasing the number of bunches (and duty factor) produces multi-bunch instabilities and other problems when the total number of bunches exceeds the number of IR's. Thus, one seldom sees a linear increase in luminosity with n unless $\Delta\nu \ll \Delta\nu^*$. Decreasing either β^*_y or increasing the horizontal emittance ϵ_x reduces the beam-beam force but is difficult because this increases the sensitivity to transverse instabilities. Decreasing β^*_y also implies shorter bunches which increases sensitivity to synchrobetatron resonances.

Evidence from many rings has shown[5] that $\Delta\nu^* \lesssim 0.05$ and that it is difficult to keep this matched in both directions with increasing beam currents. Nevertheless, this number can presumably be increased in a variety of ways e.g. by increasing damping by going to higher bend fields (and thus also increasing f) or by incorporating more wigglers. While the magnitude of $\Delta\nu^*$ seems small it is quite large compared to tune spreads allowed for individual power supply ripple. Because the multipole expansion of the beam-beam interaction goes to high order the linear description is clearly not adequate but it is not clear how to study this problem in a self-consistent way.

I will not go into the many attempts to compensate or cancel $\Delta\nu$ except to mention the charge-neutralization scheme of the Orsay Group[6] using 4 beams and double rings. This approach was supposed to improve $\mathcal{L}_{max}$ of two-orders of magnitude but so far has not been made to work. The Stanford single-pass collider (SLC) represents the opposite extreme where it hopes to *maximize* $\Delta\nu^*$ with high bunch current and

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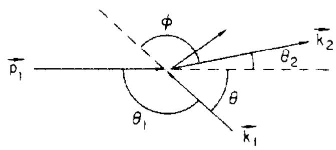
low emittance to enhance luminosity through a pinch effect. The attitude we have taken is to *avoid* the beam-beam problem through conversion of the charged particles into photons.

Compton Characteristics and Applications

Since this is a two-body process with incident energies and angles narrowly definable, the energy of the outgoing photon(ω_2) depends only on its laboratory scattering angle relative to the incoming particle beam (θ_2) and the energies of both incident particle ($\epsilon_1 \equiv \gamma m_1$) and incident photon ($\omega_1$):

$$\frac{\omega_2}{\omega_1} = \frac{1 - \beta\cos\theta_1}{1 - \beta\cos\theta_2 + \frac{\omega_1}{\epsilon_1}(1 - cos\phi)};$$



$$\frac{\omega_2}{\omega_1} \simeq 4\gamma^2 \frac{[1 - (\theta/2)^2]}{1 + (\gamma\theta_2)^2 + 4\gamma\frac{\omega_1}{m_1}[1 - (\theta/2 + \theta_2/2)^2]} \simeq \frac{4\gamma^2}{1 + (\theta_2\gamma)^2 + 4\gamma(\frac{\omega_1}{m_1})}$$

$$(\frac{\omega_2}{\omega_1})_{max} = \frac{4\gamma^2}{1 + 4\gamma(\omega_1/m_1)}\ ;\ x \equiv (\frac{\omega_2}{\epsilon_1})_{max} = \frac{4\gamma(\omega_1/m_1)}{1 + 4\gamma(\omega_1/m_1)} \equiv \frac{z}{1+z}.$$

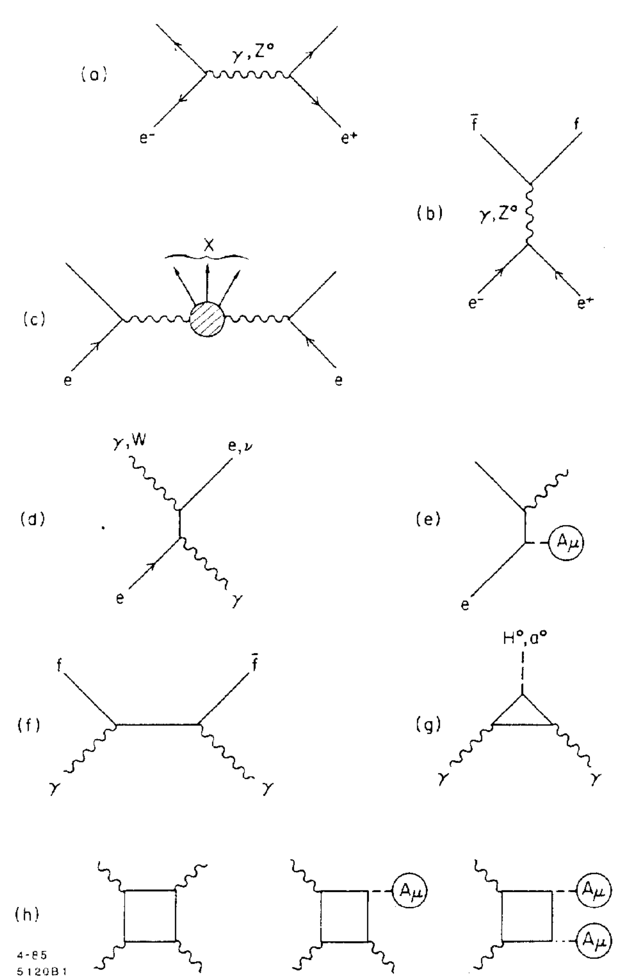


Fig. 1: Low order diagrams in the standard model for: (a,b) elastic, electroweak scattering; (b) electron-positron annihilation into elementary fermions $f = e, \mu, \tau \ldots q_u, q_d, q_s \ldots \nu_{e,\mu,\tau \ldots}$ as well as elementary bosons ($W^\pm, Z^o H^o, H^\pm$?); (c) two-boson, electro-weak production; (d) Compton scattering or conversion ($\gamma \to W^\pm$); (e) potential bremsstrahlung; (f) two-photon annihilation to fermions; (g) two-photon annihilation to bosons; and (h) photon-photon scattering, inverse photon bremsstrahlung (harmonic production) and Delbrück scattering.

The variation in the energy of the outgoing photons varies primarily with θ_2 but only weakly with incident photon direction, θ. Maximum energy transfer occurs when both $\theta = \theta_2 = 0$.

Spectral and differential cross sections for both outgoing photons and electrons are calculated and plotted elsewhere[7]. Here we only comment that the scattering cross sections are very strongly peaked in the forward direction where the momentum transfer falls quadratically with θ_2 so the photons are naturally collimated. Similarly, the electrons are predominantly scattered in the very forward direction e.g. for laser photons on SLAC beams they remain in the beam until magnetically separated. Nevertheless, backgrounds require detailed calculations of a number of processes, just as for electrons. Compton scattering of synchrotron radiation by stored beams can be a serious cause of lifetime loss as well as detector noise so most rings take careful precautions to guard against it through detailed simulations of additional elements such as masks and low field bends. In this sense, the addition of wigglers and chicanes in the IR is not atypical.

Applications of the Compton effect often depend on whether there is a relative energy gain or loss by ω_2:

$\theta_1 = 0°$	$\theta_2 = 0°$	$\omega_2/\omega_1 = 1$	Coherent Bunching
	$\theta_2 = 90°$	$\omega_2/\omega_1 = 1/2\gamma^2$	Inverse Accelerator
$\theta_1 = 90°$	$\theta_2 = 0°$	$\omega_2/\omega_1 = 2\gamma^2$	Undulator Condition
	$\theta_2 = 90°$	$\omega_2/\omega_1 = 1$	Mirror Detector
$\theta_1 = 180°$	$\theta_2 = 0°$	$\omega_2/\omega_1 = 4\gamma^2$	Photon acceleration
	$\theta_2 = 90°$	$\omega_2/\omega_1 = 2$	Energy doubling

It is interesting that Compton setups have been used at many rings for diagnostic purposes and presumably could be used in many other ways – just like the storage rings themselves[7].

Photons, Electrons or Both?

Another reason for converting electrons to photons is based on the equivalent photon approximation of Weizsacker and Williams or the fact that the spectral distribution of the electron's field is equivalent to a field of virtual photons with the same energy distribution. In this sense, the electron has been called photon-like and so one might reasonably ask under what conditions the effective luminosity can be improved by using real photons. Using only a storage ring, this may seem absurd because it would destroy the lifetime but this isn't necessarily so as we show below. The equivalent number of virtual photons per electron[8,9] or $e\gamma$ vertex in the range dx of scaled photon energy ($x = \frac{\omega_2}{\epsilon_1}$) is:

$$\frac{dN_\gamma(\epsilon_1, x)}{dx} \simeq (\frac{\alpha}{\pi})\ln(\frac{2\epsilon_1}{m_e})[\frac{1 + (1-x)^2}{x}].$$

This expression is based on integrating over the full angular range of the electrons whose energy $\gamma_1 \gg (1-x)/2x$. The number in the interval from full energy to $x\epsilon_1$ is:

$$\int_1^x dx\,\frac{dN_\gamma}{dx} = (\frac{2\alpha}{\pi})\ln(\frac{2\epsilon_1}{m_e})G(x)$$

where $G(x) = x + \frac{1}{2}(1 - x^2) - \ln x$. For $\epsilon_1 \lesssim 10$ GeV and $x = 0.9$ in the deep inelastic region, there are less than 5×10^{-3} photons per electron and for $x \geq 0.1$ there are still less than 0.09 $\gamma's/e$. Because this expression overestimates the number of photons theoretically and since the experiments have both limited angular acceptance and efficiency it provides a very conservative upper bound on the relative gain to be expected from using real photons.

The reaction rate (and ideally the counting rate) for a process such as shown in Fig. 1f or 1g, when using real photons, can be obtained from

$$\frac{dN_X}{dt} = \mathcal{L}_{\gamma\gamma}\sigma_{\gamma\gamma\to X}(s_{\gamma\gamma}) \equiv \frac{N_{\gamma_1}N_{\gamma_2}}{4\pi\sigma_x^*\sigma_y^*} f\sigma_{\gamma\gamma\to X},$$

where $s_{\gamma\gamma} = 4\omega_1\omega_2$. The corresponding rate, with one real photon and one electron in the incident channel will be

$$\frac{dN_X}{dt} = \mathcal{L}_{e\gamma}\sigma_{e\gamma\to X}(s_{e\gamma} = 4\omega_1\epsilon_1) \equiv \int dz \frac{dL_{e\gamma}}{dz}\sigma_{\gamma\gamma\to X}(z)$$

with $\sigma_{\gamma\gamma}$ the spectral cross section for head-on collisions and $z = s_{\gamma\gamma}/4\omega_1\epsilon_1 \approx \omega_2/\epsilon_1 = x$. The equivalent photon, differential luminosity function is defined as:

$$\frac{dL_{e\gamma}}{dz} = \mathcal{L}_{e\gamma}(\frac{2\alpha}{\pi})\ln(\frac{2\epsilon_1}{m_e})\frac{1}{z}G(z).$$

Finally, the same reaction channel in the conventional, two-photon reaction with two incident electrons is:

$$\frac{dN_X}{dt} = \mathcal{L}_{ee}\sigma_{ee\to X}(s_{ee} = 4\epsilon_1^2) \equiv \int dz \frac{dL_{ee}}{dz}\sigma_{\gamma\gamma\to X}(z)$$

where $z = s_{\gamma\gamma}/4\epsilon_1^2 \simeq \omega_1\omega_2/\epsilon_1^2 = x_1x_2$ for nearly real photons and an equivalent photon luminosity function:

$$\frac{dL_{ee}}{dz} = \mathcal{L}_{ee}[(\frac{2\alpha}{\pi})\ln(\frac{2\epsilon_1}{m_e})]^2\frac{1}{z}F(z).$$

with $F(z) = -\frac{1}{2}(2+z)^2\ln z - (1-z)(3+z)$ the same function derived by Low[8].

The effective luminosity decreases by successive powers of $(\frac{2\alpha}{\pi})\ln(2\epsilon_1/m_e) \sim 1/20$ for $\epsilon \sim 10$ GeV for a perfect, 4π detector with *neither* noise nor channel competition from other diagrams such as Bhabha scattering. At higher momentum transfers, the rate falls drastically from the G and F factors while at lower momentum transfers, angular cutoffs and momentum thresholds become significant e.g. Low's original proposal for the pion where $X \equiv \pi^o$ still hasn't been done accurately even though this is quite important.[10] Furthermore, where higher mass particles are involved, such as η_b, $A2_b$, ... etc., it appears there is very little possibility of observing these in the conventional 2-photon reaction at PEP or elsewhere unless one pushes the energy considerably higher than is likely *and* keeps $\mathcal{L}_{ee}$ from falling much faster than $\ln^2(2\epsilon_1/m_e)$. This seems highly unlikely based on conventional methods.

Example I: Linac Photons on PEP Positrons

One way to increase C-M energy with existing storage rings is to collide them with upgraded linac beams.[11] At SLAC, the SLC upgrade of the linac provides an ideal example of such a scheme which was revived[12] to search for the top quark via annihilation to $q_t\bar{q}_t$ at higher energies before the "truth" of the matter put it above the ceiling of PEP, PETRA or TRISTAN. Perhaps the most important point to be made here is that this again illustrates the dominant importance of the critical current because this approach is again limited below optimum luminosity ($\mathcal{L}_{max}$) by the critical current of the linac bunch N_L^*.[12] An alternative is to convert the linac beam into photons and collide these with the PEP stored beam. This provides a simple example of the basic idea.

The benchmark, invariant emittance for SLC is, without the usual factor of π, $\epsilon_L \equiv \gamma\sigma\sigma' = 5\times10^{-5}$ rad·m for $N_L = 5\times10^{10}$. The emittance decreases with increasing energy from the linac while it increases proportional to $(E(GeV)/15)^2$ in PEP. Assuming a fully coupled beam in PEP ($K = 1$) it is possible, according to Rees and Wiedemann[12], to obtain an emittance $\epsilon_P = 1.2\times10^{-8}$ rad·m at 15 GeV. This reduces to $\epsilon_P = 5.3\times10^{-9}$ rad·m at 10 GeV compared to $\epsilon_L = 8.5\times10^{-10}$ at $\epsilon_1 = 30$ GeV i.e. $\epsilon_P/\epsilon_L \sim 6$. Assuming we can nearly convert the linac electrons into quasi-monochromatic photons using an $\omega_1 \simeq 1$ eV laser or PEP FEL then gives:

$$\mathcal{L}_{\epsilon\gamma} = \frac{N_PN_L}{4\pi\beta^*\epsilon_P}f_L = \frac{7\times10^{30}}{\beta^*(cm)}[\frac{I_P}{100mA}][\frac{10}{E(GeV)}]^2\ cm^{-2}s^{-1},$$

for a linac rep rate of $f_L = 180/s$. A low-β^* of $\lesssim 1$ cm should be possible in a way that doesn't increase emittance due to high-order aberrations just as for SLC.[13] A 30 GeV beam with $\omega_1 \sim 1$ eV photons gives $\omega_2 \sim 10$ GeV photons i.e. $\sqrt{s} = E_{cm} \sim 20$ GeV – the same as for conventional 10 GeV colliding beams.

If $\mathcal{L}_{ee} \sim 2\times10^{31}$ at 15 GeV and scales as E^2, then the effective $\mathcal{L}_{e\gamma}$ achieved in $\mathcal{L}_{ee}$ must necessarily be less than that for real photons while deep inelastic contributions will be down by several orders of magnitude. Although the photon emittance (ϵ_γ) increases as the square of the distance from the $e\gamma$ interaction point, the variable energy of the linac beam and its lower emittance allow ϵ_γ to be matched to ϵ_P with natural energy collimation. The number of incident laser photons is $N_\gamma^L = A_L/\sigma_c \sim 10^{19}$ at $f_L = 180/s$ and pulse length 10 ps.

Conclusions

When one realizes that all non-hadronic processes in Fig.1 decrease[7] inversely with s while $\mathcal{L}_{ee}$ barely stays constant, it is clear that a different approach is needed. So far, only the Russian group[3] has taken such ideas seriously but what is needed are actual experiments at existing rings such as PEP.

References

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