

SUMMARY of the ECFA LINEAR COLLIDER WORKING GROUP on BEAMSTRAHLUNG and PHOTON-PHOTON INTERACTIONS

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1 Introduction

This paper presents a concise summary of the developments achieved in the context of the “Photons” Working Group of the 1991 ECFA Workshop on Physics with Linear Colliders. After reviewing, in Section 2, the current knowledge on the beam-beam interaction and its main physics implications, we calculate in Section 3 effective photon and electron luminosity spectra. Section 4 discusses background issues associated with photon-photon processes. Finally, we briefly survey, in Section 5, recent updates on the principle issues and the physics potential of the so-called “Compton Collider”.

2 Implications of the Beam-Beam Interaction

Beamstrahlung, or the synchrotron radiation emitted, at the interaction point (IP) of an e^+e^- Linear Collider, by one of the colliding bunches in the field of the opposing one, is a largely unavoidable consequence of the quest for luminosities three orders of magnitude above those currently achieved. As intense electron and positron beams are squeezed to minute transverse dimensions of a few to a few hundred nanometers, individual electron (or positron) trajectories are deflected by the coherent electromagnetic field of the oncoming positron (or electron) bunch. This field, typically of the order of hundreds of MGauss, causes the deflected particles to radiate photons, the energy of which spans a range, depending on the accelerator design, that extends from a few per mille to several tens of percent of the initial beam energy. Therefore, and in contrast to what happens in storage rings, the e^+e^- center-of-mass (c.m.)

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energy is no longer confined within a very narrow “spike”, but instead is spread over a relatively wide distribution.

This degradation of the effective c.m. energy is probably the most commonly known manifestation of the beam-beam interaction in Linear Colliders; but it is far from being its only significant aspect. Deflection of individual particle trajectories by the coherent field of the opposing bunch also manifests itself by a macroscopic deformation of the whole bunch, called disruption, which results, in some cases, in a substantial increase of the luminosity due to the “pinching” of one bunch by the focusing field of the other. But disruption is also responsible for a substantial widening, during the collision, of the angular divergence of the spent beam, thereby imposing severe constraints on the geometrical layout of the interaction region. This is also true of the long-range beam-beam interaction in most designs, where the threshold on the multibunch kink instability forces a non-zero crossing angle and a minimum separation between consecutive bunches.

Another consequence of the beam-beam interaction is the abundant production of e^+e^- pairs by the beamstrahlung photons. Limiting the pair production rate to levels manageable from the background viewpoint impacts, in a major way, the overall choice of accelerator parameters, as well as the design of the interaction region. In addition, two-photon-induced hadronic final states might also contribute a new, intense source of dangerous backgrounds. This particular topic, which triggered much interest during the workshop, is currently the subject of intense investigation.

A detailed discussion of the beamstrahlung process, and of its companion phenomena - disruption, luminosity pinch enhancement, and pair creation - lies beyond the scope of the present workshop. Instead, we refer the reader to two excellent recent reviews [1, 2], which provide both a pedagogical introduction to the subject, and an extensive bibliography. The results documented there supply the foundation for most of the studies reported in the following sections.

3 Effective e^+e^- and $\gamma\gamma$ Luminosity Spectra

Realistic simulation of high energy e^+e^- or $\gamma\gamma$ scattering processes whose cross-section or kinematics are energy dependent, mandates an accurate description of the differential luminosity as a function of the effective c.m. energy. The “broad brush” discussion presented here is based on the results of Barklow *et.al.* [3] and Frary *et.al.* [4].

The beamstrahlung spectrum is determined once the number N of electrons (and positrons) per bunch, the normalized beam energy γ , and the three r.m.s. beam radii σ_x , σ_y , σ_z are specified. It is normally characterized [1] by a dimensionless “beamstrahlung parameter” Υ , proportional to the average magnetic field inside the bunch, and given by

$$\Upsilon = (5 r_e^2/6) \gamma N / [\alpha \sigma_z (\sigma_x + \sigma_y)]$$

(here r_e is the classical electron radius and α the fine structure constant). At SLC, where $\Upsilon \ll 1$, classical synchrotron radiation theory applies. But the combination of luminosity requirements, beam dynamics, technological constraints, and down-to-earth economics, in most

cases [5] brings beamstrahlung at future Linear Colliders in the transition to the quantum regime ($\Upsilon \approx 0.1 - 0.5$).

Beamstrahlung spectra are typically calculated analytically in the one-photon approximation (see [1] and references therein), or by time-consuming computer simulations in order to properly handle multistep radiation. Recently however, Chen has proposed an analytically concise approximation [6] to the full formulas for multiphoton beamstrahlung, which describes both the beamstrahlung photon spectrum and the resulting electron and positron energy spectra, and exhibits satisfactory agreement with numerical models in the regime of interest. This formalism was incorporated [3] into a set of Monte-Carlo programs, that also take into account the intrinsic momentum spread of the Linac beam, as well as initial state radiation (in the Weizsaecker-Williams sense). Given a set of Linear Collider IP parameters, this code supplies the user with the differential luminosity as a function of the e^+e^- or $\gamma\gamma$ effective c.m. energy.

The Working Group examined five typical Linear Collider designs, which hopefully span a representative range of technologies: X-band, room-temperature RF Linacs [7] with intense (Palmer G) or moderate (Palmer F) beamstrahlung [5]; S-band designs [8], either optimized for high luminosity (Desy-Darmstadt, Wide-Band) [9] or sharp energy resolution (Desy-Darmstadt, Narrow-Band) [10]; and superconducting RF technology (TESLA, Narrow-Band) [11, 12]. The highest total luminosity is obtained at the cost of intense beamstrahlung. It provides, for new particle searches, a possibly useful self-scanning feature, but makes this design (Palmer G) unsuitable for analyses that rely on a precise beam energy constraint, and in particular for top quark physics near threshold [13]. This last remark, interestingly enough, also applies to the Desy-Darmstadt Wide Band design, where the large Linac momentum spread (2.5% full width) badly dilutes narrow energy structures. The two Narrow-Band, low-frequency designs, radiate in the form of beamstrahlung a similar, low fraction (0.5%) of the initial electron beam energy.

Even if the beamstrahlung calculations were totally reliable, the luminosity spectrum is exceedingly sensitive to machine conditions: continuous monitoring of both its magnitude and its shape is therefore mandatory. A first study [4] concludes that, as long as the Linacs themselves deliver sufficiently narrow momentum spread, it should be possible to use the acollinearity distribution of Bhabha scattering events to monitor the luminosity spectrum with sufficient statistical and systematic accuracy so as to resolve structures as fine as the $t\bar{t}$ threshold. Away from threshold, where very fine resolution in $E_{c.m.}$ is not essential, other channels such as WW production should also be useful for luminosity measurement, though high statistics and ease of measurement makes Bhabha scattering the best luminosity monitor in all circumstances.

Let us now turn to the photon-photon luminosity spectra of e^+e^- Linear Colliders. The average $\gamma\gamma$ c.m. energy (from beamstrahlung photons only) varies by almost an order of magnitude between the five designs, with a very large fractional spread; and the $\gamma\gamma$ luminosity enhancement due to multiphoton emission is substantial only for the highest- Υ X-band design. However, for most of the cases considered, initial state radiation dominates the shape of the $\gamma\gamma$ effective c.m. energy distribution [3], except at small photon energies. Only for the high- Υ (Palmer G) design does beamstrahlung extend the potential for two-photon physics beyond the kinematic reach naturally accessible to photons from initial state radiation. But this may be at the cost of intolerable detector backgrounds, as we now proceed to discuss.

4 Photon-induced Backgrounds

$\gamma\gamma$ -related backgrounds in Linear Colliders arise from two broad classes of interactions. Firstly, the large beamstrahlung flux (which amounts to a few photons per incident electron or positron) gives rise to e^+e^- pair production by the beamstrahlung photons, both coherently [14] off the electromagnetic field of the opposing bunch, and incoherently [1] through the Breit-Wheeler and Bethe-Heitler processes (to which one must add a significant contribution of e^+e^- -induced pair production through the Landau-Lifshitz process). Because of their soft momentum spectrum, the reaction products are much more sensitive than the primary beam electrons, to focussing or (for the same-sign member of the pair) defocussing disruption effects. They produce an intense flux of electromagnetic debris, that scatter or shower off nearby accelerator components, thereby requiring careful masking of the detector against low energy electrons and photons [15, 16].

Next, Drees and Godbole point out that high-energy photon-photon scattering into hadronic final states might contribute another form of background. The cross-sections for both the simplest hard two-photon process, $e^+e^- \rightarrow e^+e^- q\bar{q}$, and for events where partons “inside” the photon, rather than the photon itself, undergo hard scattering, grow with increasing $\gamma\gamma$ c.m. energy. Taking the production of two central high p_T jets as the benchmark for hard $\gamma\gamma$ backgrounds, the authors argue [17] that not only will the hard two-photon events outnumber, at high enough e^+e^- c.m. energy, the annihilation events; but the cross-section for semi-hard (“minijet”) and soft $\gamma\gamma$ processes could become so large that one should observe up to several such events per machine pulse. This would then lead to the presence of “underlying events”, as in high luminosity hadron colliders, that could not only mimic interesting physics processes, but also affect the trigger or the pattern recognition of the experiment.

From the viewpoint of accelerator and detector builders, it should be pointed out that the relevant quantity is the detectable $\gamma\gamma \rightarrow \text{hadrons}$ rate per resolving time of the detector. The $\gamma\gamma$ minijet background can therefore be reduced in several ways: either by reducing the beamstrahlung flux per pulse (lower Υ); by spacing bunches within a train by a delay longer than the memory time of the detector (as is done in the TESLA design for unrelated reasons, viz. on the basis of wakefield and RF considerations); or by time-correlating raw detector data with each bunch within a train [18], thereby effectively shortening the memory time.

So far, the analysis of Ref. [17] can only be confronted with recently reported evidence for hard scattering of hadronic constituents in $\gamma\gamma$ collisions at TRISTAN [19]: the agreement between theory and observation appears satisfactory. In the near future, measurements of the $\gamma\gamma$ cross-section at LEP, and of the γp cross-section at HERA, should help constrain the models further. The topic is also the subject of theoretical debate [20].

5 The “Compton” Collider

An intriguing extension of an e^+e^- Linear Collider is the so-called photon-photon, or “Compton”, Collider. Here, intense laser pulses are back-scattered off the e^+e^- beams just upstream of their focal point, and thereby converted to tightly focussed, colliding photon beams with a $\gamma\gamma$ c.m. energy of up to 80% of the original e^+e^- c.m. energy.

This possibility was originally raised by Akerlof [21], and by Ginzburg *et.al.* [22]. In the last few years, several authors [23, 24] have re-examined the physics potential and the feasibility of such a collider. Most recently, Telnov updated [25] his broad review of $\gamma\gamma$ and $e\text{-}\gamma$ collider issues with more realistic accelerator and laser [26] scenarios. QCD background rates were evaluated in Ref. [17]. The benchmark reaction $\gamma\gamma \rightarrow H^0$, which probes, through radiative corrections, a kinematical domain beyond that accessible to direct production of new heavy objects, was simulated in detail by Richard [27], and by Borden *et.al.* who also performed a detailed optimization of “scanning strategies” for this and other interesting processes [28].

The picture that emerges from the above-mentioned reports is that the physics potential of $\gamma\gamma$ and $e\text{-}\gamma$ collisions is by now well established, and that the basic principles of producing the high-energy back-scattered photon beams have been studied in abundant detail. But three broad categories of issues offer a major challenge to laser experts, accelerator builders, and experimenters alike. Firstly, while there already exists lasers capable of delivering either the necessary power per pulse, or the necessary repetition rate, these requirements cannot yet be achieved simultaneously. Extensive research and development is needed to bridge the gap of two to three orders of magnitude in usable laser power [26]. Next, the optimum design parameters of a linear collider are different for e^+e^- and $\gamma\gamma$ collisions. Accelerator technology and e^+e^- physics considerations favor flat beams, low bunch currents and many bunches per train to achieve high luminosity with acceptably low beamstrahlung. In contrast, in the $\gamma\gamma$ mode, technological limitations favor round beams, high bunch currents, and short bunch trains to make optimal use of diffraction-, intensity- and duty-cycle-limited laser operation; but if QCD-induced two-photon backgrounds become as severe as suggested in Ref. [17], this again argues for many bunches spread over a very long train. A concerted effort by accelerator designers and laser experts is thus required to converge on a linear collider design that lends itself to the “Compton Collider” mode of operation, without putting unrealistic demands on either the light source, or on the beam dynamics and power consumption of the Linac. Finally, there are formidable problems to be solved in designing a realistic interaction region : piping of the light towards the conversion point, sweeping away of the low energy electrons and of their unscattered companions, disposal of the high power levels carried by the charged and neutral spent beams, shielding against machine-induced backgrounds, all of this a few cm from an interaction point in the middle of a particle detector...This is an area where effort is urgently needed to transform this elegant idea into a pragmatic proposal.

6 Conclusion

“Beamstrahlung.
Photons mediate,
But electrons radiate:
The loss of counting rate
Makes people fulminate.”

Will this quote from “The Ubiquitous Photon” [29] prove true ? Hopefully the creativity of the Linear Collider community shall turn the curse into a blessing...

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