Background in future linear e^+e^- colliders

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Abstract

General machine backgrounds relevant for linear colliders are described: Off momentum particles from beam-gas and Compton scattering on black body radiation, beam-tails, muons and synchrotron radiation. The discussion of these conventional machine backgrounds is largely based on experience with LEP. [*]

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1   Introduction

High energies are easier to reach with proton collisions. The LHC will very likely be in operation before any new high energy linear collider. The advantage of e^+e^- machines used to be:

- low background
- well defined initial state (quantum numbers and energy)

It will be challenging to maintain these advantages at high energy. Beamstrahlung will become very strong, producing both significant backgrounds and a large energy spread.

With the exception of the SLC, e^+e^- colliders so far have always been circular machines. In the largest one built, the LEP machine at CERN, the loss in synchrotron radiation is enormous: for a beam energy of $100\,\mathrm{GeV}$ (as used in 1999), each circulating particle loses about $3\,\mathrm{GeV}$ per turn (nearly $20\,\mathrm{MW}$ power loss in total). The quantum nature of the synchrotron radiation also implies a spread in the collision energies (about 10^{-3} in LEP).

Ideally, linear colliders could be extremely clean machines: no synchrotron light from main bending magnets and very little energy spread.

For high energy linear colliders, this will be difficult to achieve in practice. The need for high luminosity implies very small beams and strong focusing (very low β functions, high local chromaticity) at the interaction point. Bending magnets are still needed to produce dispersion for the chromatic correction of the final focus and for momentum collimation. Conventional beam delivery systems (BDS) will become very long and expensive to build [1, 2].

Even in rather clean machines there is often a trade-off between performance and background at some level. In LEP1 ($2 \cdot 45.6\,\mathrm{GeV}$, Z-production) for instance, the maximum useful luminosity has in fact been limited by background [3, 4].

General features of the main conventional background processes that have been important in LEP will now be analyzed in view of future high energy linear colliders.

Before that, one remark on the background and energy spread caused by the beam-beam interaction with beamstrahlung and disruption which is expected to become a serious limitation in very high energy linacs. There are in principle ways to avoid these new high energy beam-beam backgrounds: the strong coherent fields can be compensated or neutralized – for example using symmetric $e^+e^- \leftrightarrow e^+e^-$ collisions (or other schemes, see [5, 6, 7, 8]). Such schemes are certainly rather challenging but also have the potential to allow clean collisions even at very high energy.

2   Off momentum

Off momentum particles are produced by scattering processes. The relevant process for high energy electron machines are bremsstrahlung in beam-gas scattering and Compton scattering off thermal photons. The scattering angles are of the order of

$1/\gamma$ or rather negligible for high energy electrons. Ideally, the probability for an off-momentum particle hitting directly the detector should be small like about 1 % per bunch crossing. The forward calorimeters could then be used to veto background and help to identify events with missing energy in searches for new particles. To achieve this, one should aim for a vacuum level of about 1 ntorr (mainly in the region from the last off-momentum collimator to the experiment). At this level, the off-momentum background originating in beam-gas and Compton scattering off thermal photons are about equal.

In some more detail: According to Tsai [9], the photon (= energy loss) spectrum in bremsstrahlung is rather broad and can be approximately written as:

$$\frac{d\sigma}{dk} = \frac{A}{N_A X_0} \frac{1}{k} \left(\frac{4}{3} - \frac{4}{3}k + k^2 \right) \quad , \tag{1}$$

where k is the photon energy in units of the beam energy, N_A the Avogadro constant and X_0 the radiation length of the material. The cross section scales roughly with the nucleus charge Z^2. For N_2 ($\approx CO$) $A/(N_A X_0) = 1.224$ barn and the integrated cross section for at least 1 % energy loss $\sigma = 6.5$ barn (4.7 barn for 3 %, 2.9 barn for 10 % energy loss). For 1 ntorr of N_2 or CO gas at room temperature there are $\rho = 3.26 \cdot 10^{13}$ molecules/m^3, resulting in a probability for scattering with ≥ 1 % energy loss of $\rho\sigma = 2.1 \cdot 10^{-14}$ /m. For 10^{10} particles per bunch and a length of 1000 m this results in a 20 % probability for an off momentum particle. How many of these eventually hit the detector can be determined by tracking through the lattice. Based on work for LEP and an estimate for the NLC [10] one would roughly expect a 4 % probability per bunch to have an off-momentum particle hitting the beam-pipe within 200 m from the interaction point and about 0.5 % probability to directly hit the detector.

Now a rough estimate for the background from thermal photons (a program for a detailed estimate is described in [11]). The total cross section is close to the Thomson cross section $\sigma = 8\pi/3r_e^2 = 0.665$ barn. At room temperature, the density of black body photons in the beam pipe is $\rho_\gamma = 5.32 \cdot 10^{14}/m^3$ and the scattering probability $\rho\sigma = 3.5 \cdot 10^{-14}$/m. The mean relative energy loss increases about linearly with beam energy and reaches 5.3% for a beam energy of 250 GeV. With 10^{10} particles per bunch the probability for a scattering in 1000 m is 35 % which is quite comparable to the beam-gas scattering probability of 20 % for 1 ntorr, particularly when the actual spectra as shown in Fig. 1 are taken into account.

3 Synchrotron Radiation

The background from synchrotron radiation seen by the experiments will strongly depend on details of the BDS design and collimation. Here just some remarks.

The typical layout of a straight section in LEP [4] with collimators is shown in Fig. 2. The geometry is such that only scattered synchrotron light reaches the detector. The last dipoles have 10 % of the full strength. It is important to stop the strong, main
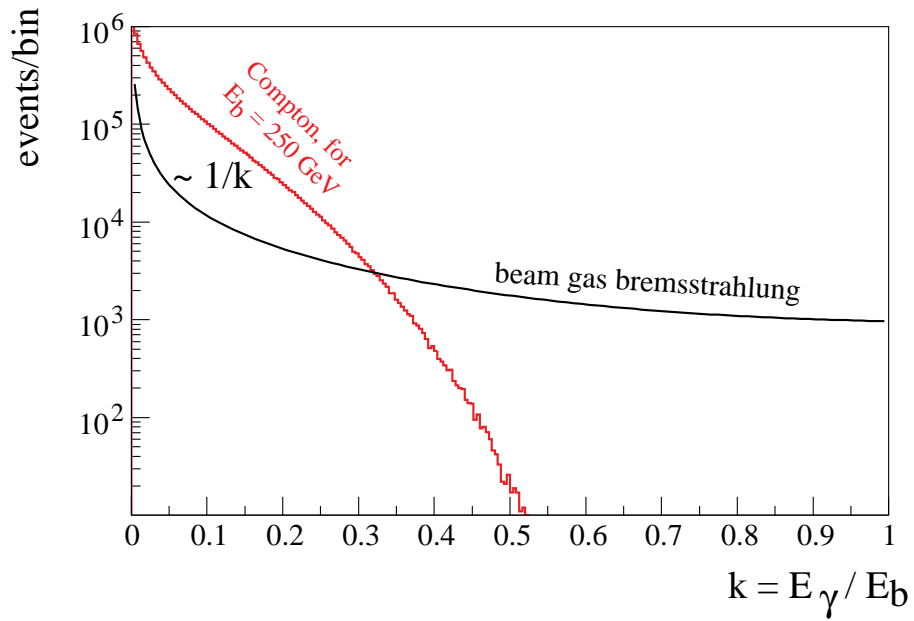
Figure 1: Comparison of the relative photon energy or energy loss spectra in beam-gas scattering and Compton scattering for a beam energy of 250 GeV.
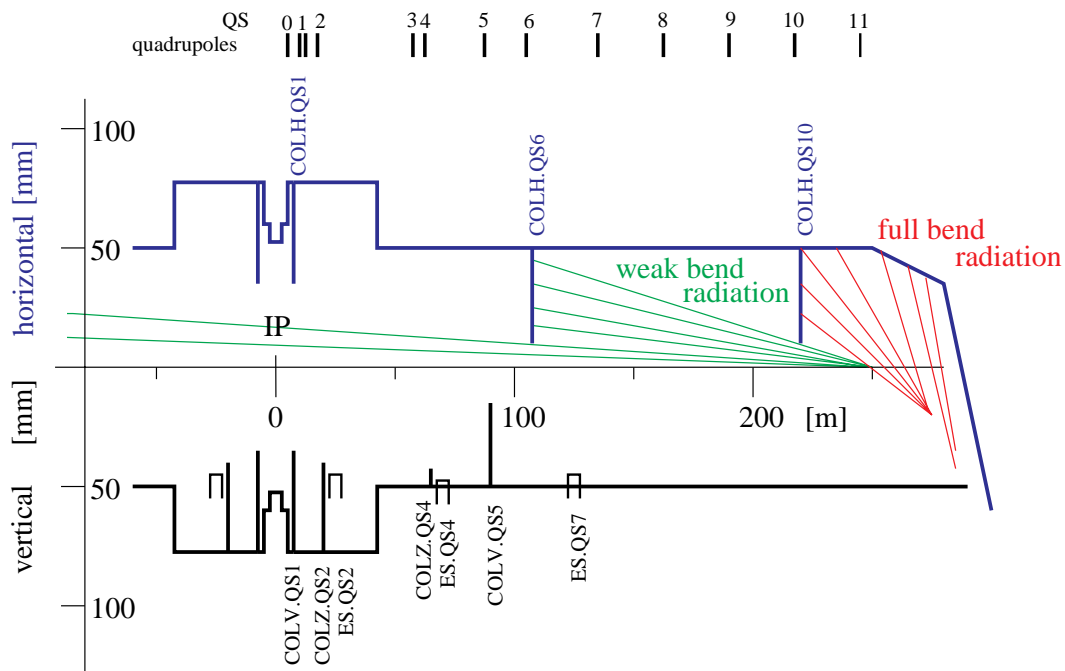

Figure 2: Schematic layout of a straight section at an interaction point (IP) of LEP in the horizontal (top) and vertical (bottom) planes. Shown are the locations of the quadrupoles (QS), electrostatic separators (ES) and collimators (COLH, COLV, COLZ). The solid lines mark the inner vacuum chamber radii.

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dipole radiation close to the arcs, far away from the experiment. In LEP2, the critical energy for the main bend radiation is 630 MeV. The synchrotron radiation spectrum is very broad and rather soft photons down to about 20 keV can leave the beam pipe and should be considered. The lower energy X-ray radiation can undergo (multiple) specular reflection [12].

Local masks about 2.4 m from the interaction points were introduced to better shield the experiments from the increased synchrotron radiation at LEP2. Details in the design of collimators and masks can be quite important. Collimators and masks close to the interaction point designed to intercept background will at the same time also act as source of scattered background particles [4]. The surface material and surface angles of the masks installed in LEP were chosen such that the scattering towards the experiment is minimized. The masks are made of tungsten. To reduce fluorescence photons, the surface is coated with silver and copper layers.

The background photons observed in the detector originate mainly from synchrotron radiation in the last quadrupoles – backscattered into the experiment from local collimators. The bunch crossing rate in LEP is about 45 kHz and typically only a few background photons were recorded per bunch crossing in the large wire chambers of the LEP detectors. There was no problem with occupancy, but the currents drawn in the gas-chambers (typically 50 nA per sector) were reported to be not too far from the tolerable limit.

Without collisions, the level of non-Gaussian tails is very low and well understood [13, 14]. Substantial non-gaussian beam tails were observed at high currents and beam-beam tune shifts. Particles at large amplitude can produce hard synchrotron radiation in the quadrupoles around the interaction points and background showers, if they are lost locally.

The increased occurrence of background spikes and storms actually limited the maximum useful currents at LEP1 (45.6 GeV) energies. The background spikes are attributed to resonance excitation in the beam-beam collisions and small shifts in the betatron tunes.

A lot of superconducting cavities were added in LEP to allow for the increase in energy from LEP1 to LEP2 (from 45.6 GeV to about 100 GeV) and to compensate for the energy loss of 3 GeV per turn. The superconducting cavities are operated at relatively high gradient (about 7 MV/m at 352 MHz) and can produce substantial radiation levels, even in the absence of beams. There is no evidence for any beam halo or background spikes originating in the cavities in LEP. While the overall background level increased as expected with the synchrotron radiation, the probability for background spikes rather decreased and much higher currents could be collided at LEP2 (100 GeV) energies.

4 Muons

Whenever a high energy beam particle hits an obstacle and produces an electromagnetic shower, there is a small probability for muon production, of the order of $4 \cdot 10^{-4}$ per primary electron. The muon flux from collimation of halo particles can be substantial. Collimation of a fraction of 10^{-3} halo particles in 10^{10} electrons per bunch implies $4000\,\mu$'s per bunch. Many of these may hit the detector, unless particular precautions are taken like: doing the halo collimation very far from the experiment, use of magnetic fields (toroids) to sweep away the muons.

The muon background in LEP is negligible. As argued before, there was no evidence for halo production in the high gradient superconducting acceleration section and the only fundamental source of a beam halo was scattering processes. For a vacuum level of 1 ntorr (CO equivalent), the scattering probability to produce a halo particle is $2.1 \cdot 10^{-14}$/m. In a $10\,\mathrm{km}$ linac with 10^{10} particles per bunch this amounts to only 2 halo particles per bunch.

Unfortunately there seems to be little information on the origin of the halo observed in the SLC. For future machines it appears to be a good investment to aim for good vacuum conditions in the whole system and to foresee monitoring and if necessary collimation of halo particles in all stages (including damping rings and compressors).

5 Summary and conclusion

To be complementary to proton colliders, future high energy e^+e^- colliders should still be comparatively clean machines. With beamstrahlung and disruption this will be more difficult to achieve and should be considered as one of the main challenges and design constraints for future machines.

Good vacuum conditions and a careful design of collimators and masks should allow to keep conventional backgrounds at a low level.

With reference to LEP one can argue that there is no fundamental reason for a substantial amount of halo particles and muon background.

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