6 Collimation

Particles at large betatron amplitudes or with a large momentum error constitute what is generally referred to as a *beam halo*. Such particles are undesirable since they produce a background in the particle-physics detector. The background arises either when the halo particles are lost at aperture restrictions in the vicinity of the detector, producing electro-magentic shower or muons, or when they emit synchrotron radiation that is not shielded and may hit sensitive detector components. In superconducting hadron storage rings, a further concern is localized particle loss near one of the superconducting magnets, which may result in the *quench* of the magnet, i.e., in its transition to the normalconducting state.

In order to remove the unwanted halo particles, multi-stage collimation systems are frequently employed. Aside from the collimation efficiency, the collimators must also serve to protect the accelerator from damage due to a mis-steered beam. Especially for linear colliders, the collimator survival for different (linac) failure modes is of interest.

In this chapter we discuss a few sources of beam halo and then discuss several collimation issues, first for linear colliders and then for storage rings.

6.1 Linear Collider

In general, the beam entering the beam delivery system of a linear collider is not of the ideal shape, but it can have a significant halo extending to large amplitudes, both in the transverse and in the longitudinal direction. There are many sources of beam halo:

- beam-gas Coulomb scattering,
- beam-gas bremsstrahlung,
- Compton scattering off thermal photons [1],
- linac wakefields,
- the source or the damping ring.

The halo generation due to beam-gas Coulomb scattering can be reduced by using a higher accelerating gradient, while the halo formation due to beam-gas bremsstrahlung and thermal-photon scattering scales with the length of the

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accelerator. The contributions of linac wake fields and of the injector complex to the size of the halo depend on many parameters; as a rough approximation, if measured as a fraction of the bunch population, such contributions could be considered as constant, independent of energy. A Monte-Carlo simulation study of beam loss in the next linear collider (NLC) beam-delivery system due to the first three processes given above and the positive effect of additional collimators is described in reference [2].

If the halo particles once generated strike the beam pipe or magnet apertures close to the interaction point, or if they traverse the final quadrupole magnets at a large transverse amplitude, they may cause unacceptable background. This background can be due to muons, electromagnetic showers, or synchrotron radiation. In particular, muons, with a large mean free path length, are difficult to prevent from penetrating into the physics detector. The muon generation occurs by a variety of mechanisms, the most important one being the Bethe–Heitler pair production [3]: $\gamma Z \to Z\mu^+\mu^-$. On average about one muon is produced for every 2500 lost electrons. Differential cross sections for muon production were derived by Tsai [4], and are used in simulations of the background induced by muons [3, 5]. In the Stanford Large Detector (SLD) at the Stanford Linear Collider (SLC) 1 muon per pulse entering the detector corresponded to a marginally acceptable background. Muons are produced when electrons and positrons impinge on apertures.

At the SLC, collimation upstream of the final focus was found to be essential for smooth operation and for obtaining clean physics events. In addition, large magnetized toroids had to be placed between the location of the collimators and the collision point to reduce the number of muons reaching the detector. When a muon passes through such a toroid it scatters, loses energy, and its trajectory is bent. A complex collimation system and muon toroids, whose length scales at least linearly with energy [6], will also be indispensable for future linear colliders [7, 8].

A conventional collimation system proposed for future linear colliders consists of a series of spoilers and absorbers. This collimation system serves two different functions: removing particles from the beam halo to reduce the background in the detector, and also protecting downstream beamline elements against missteered or off-energy beam pulses. The spoilers increase the angular divergence of an incident beam so that the absorbers located downstream can withstand the thermal loading of an entire bunch train [7]. A schematic is shown in Fig. 6.1.

Collimator shape (surface angle) and material should be chosen to minimize the fraction of re-scattered particles [9]. A further design criterion concerns wake fields generated by the collimators themselves [10]. An important criterion, which has influence on the length of the collimations system, requires that the collimators survive the impact of an entire bunch train. This implies that the collimators are located at positions where the β function is large. The correspondingly large area of the beam should ensure that the col-

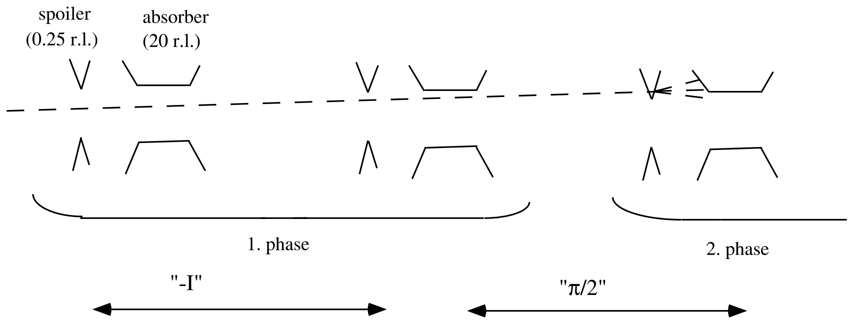

Fig. 6.1. Schematic of a conventional collimation system, consisting of a series of spoilers and absorbers. The lengths of the spoilers and absorbers are approximately 1/4 and 20 radiation lengths (r.l.), respectively

limator surface does not fracture or melt somewhere inside its volume in case it is hit by a mis-steered beam. For the NLC parameters, fracture and melting conditions give rise to about the same beam density limit (roughly 10^5 e^- per μm^2 for a copper absorber at 500 GeV [7]). While the surface fracture does not depend on the beam energy, the melting limit does, since the energy of an electromagnetic shower deposited per unit length increases in proportion to the beam energy. Therefore, for energies above a few hundred GeV, the beam area at the absorbers must increase linearly with energy. Since, in addition, the emittances decrease inversely proportional to the energy, the beta functions must increase not linearly but quadratically. Assuming that the system length l scales in proportion to the maximum beta function at the absorbers, this results in a quadratic dependence of the system length on energy: $l \propto \gamma^2$. Including both sides of the interaction point, the NLC collimation system is 5 km long. At 5 TeV the length of a conventional collimation system could approach 50 km.

Therefore, ideas for shorter and indestructible collimation schemes have been pursued, such as nonlinear collimation [11], laser collimation [12], plasma collimation [13], or nonlinear resonant collimation [14].

6.2 Storage Rings

Also the performance of storage rings can be limited by beam halo. At electron or positron rings the halo arises from beam-gas Coulomb scattering, beam-gas bremsstrahlung, beam-beam resonances, small tune drifts, and at high energies also from Compton scattering off thermal photons. In the case of proton or ion rings, halo may be caused by space-charge forces, injection errors, intrabeam scattering (multiple collisions of beam particles with each other), Touschek effect (single collision of particles within a bunch), diffusion driven by magnet nonlinearities or by the beam-beam interaction.

A collimation system proved invaluable at the HERA proton ring [15], and an advanced two-stage collimation system is contemplated for the LHC [16]. Here, the collimation also protects the superconducting magnets against local particle losses. The halo normally extends in both transverse and in the longitudinal direction, and collimation may be needed in all three planes.

The performance of LEP1 at 45.6 GeV (Z production) was limited by unstable transverse tails generated by the beam-beam interaction. Associated with these tails were a drop in the beam lifetime and background spikes (involving electromagnetic showers and hard synchrotron radiation from low-β quadrupoles), which frequently tripped the experiments. The partial cure consisted in changing the betatron tunes and the chromaticity, increasing the emittance (via a shift in the rf frequency), and opening the collimators. A lesson learned was that scraping into the beam halo close to the experiments had to be avoided.

For the higher energies and shorter damping times at LEP2 (80–100 GeV), background spikes were no longer observed. Stationary tails due to beam-gas scattering and thermal-photon scattering however were still present. Figure 6.2 compares a measurement of the beam tails in LEP using movable scrapers and the result of a Monte-Carlo simulation.

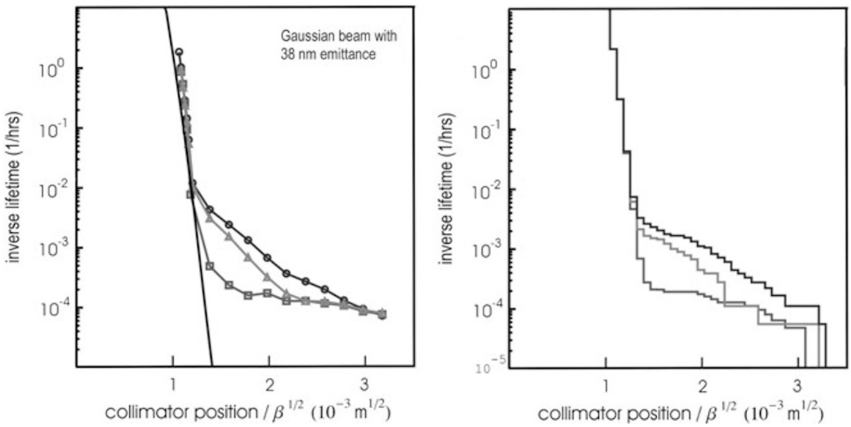

Fig. 6.2. Beam tails in LEP2 at 80.5 GeV: (*left*) measurement with collimation retracted (*circles*) and using movable scrapers at dispersive (*squares*) and nondispersive (*triangles*) locations, and (*right*) result of Monte-Carlo simulation [17, 18] (Courtesy H. Burkhardt, 1999)

An important scattering process for electron beams is beam-gas bremsstrahlung. The differential cross section for this process is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}k} = \frac{A}{N_A X_0}\frac{1}{k}\left(\frac{4}{3} - \frac{4}{3}k + k^2\right), \tag{6.1}$$

where k denotes the ratio of the energy of the emitted photon and the beam energy: $k = E_\gamma/E_b$, X_0 is the radiation length ($X_0 \propto A/(Z(Z+1))$ or roughly $\sigma \propto Z^2$). For carbon monoxide molecules: $A/(N_A X_0) = 1.22$ barn, and the total cross section for an energy loss larger than 1% amounts to 6.5 barn (2.9% barn for an energy loss larger than 10%) [9]. For a gas pressure of 1 nTorr at a temperature of 300 K, the scattering probability is 2×10^{-14} m^{-1}.

The effect of elastic Coulomb collisions can also be significant. Here, the incident particles can scatter off residual nuclei or atomic electrons. In the first case, the energy change of the incident particle is relatively small and the primary effect is an angular deflection that may cause the particle to exceed the beam-pipe aperture. On the other hand, the energy change can be comparatively more important when scattering off the atomic electrons. The differential cross-section for Coulomb scattering off atomic nuclei can be written:

$$\frac{\mathrm{d}\sigma_{en}}{\mathrm{d}\Omega} = \frac{4F^2(q)Z^2r_e^2}{\gamma^2}\frac{1}{(\theta^2+\theta^2_{\mathrm{min}})^2}\,, \tag{6.2}$$

where θ_{min} is a function of the screening due to the atomic electrons, equal to $\theta_{\mathrm{min}} \approx (\hbar/pa)$ where p is the incident particle momentum and a is the atomic radius: $a \approx 1.4\lambda\!\!\!^{-}_e/\alpha Z^{1/3}$. In addition, $F(q)$ is the nuclear form factor which for relatively small scattering angles can be approximated by 1 and we have neglected the recoil of the nucleus; both of these later effects reduces the large angle scattering thus causing a slight overestimate of the scattering effect.

The second type of Coulomb collision is the elastic scattering off the atomic electrons. Here, the angular deflection can be roughly accounted for by replacing Z^2 with $Z(Z+1)$ in (6.2); again this will over-estimate the scattering, but the correction is small. In this case, however, the recoil of the electron cannot be neglected as it can result in a significant change in the energy of the incident particle. The differential cross-section for a relative energy change of δ is [19]:

$$\frac{\mathrm{d}\sigma_{ee}}{\mathrm{d}\delta} = \frac{2\pi Z r_e^2}{\gamma}\frac{1}{\delta^2} \tag{6.3}$$

and the cross section for scattering beyond a limiting energy aperture δ_{min} is:

$$\sigma_{\delta_{\mathrm{min}}} = \frac{2\pi Z r_e^2}{\gamma}\frac{1}{\delta_{\mathrm{min}}}\,. \tag{6.4}$$

At energies higher than a few 10s of GeV, also the Compton scattering off thermal photons becomes significant [1, 20]. The photon density from Planck black-body radiation is

$$\rho_\gamma = \frac{2.4(k_BT)^3}{\pi^2(c\hbar)^3} \approx 20.2\left[\frac{T}{\mathrm{K}}\right]^3\frac{1}{\mathrm{cm}^3}\,, \tag{6.5}$$

or, at room temperature,

$$\rho_\gamma(T = 300\mathrm{K}) \approx 5 \times 10^{14}\ \mathrm{m}^{-3}\,. \tag{6.6}$$

The scattering cross section is of the order of the Thomson cross section, $\sigma_T \approx 0.67$ barn. If all scattered particles are lost, the beam lifetime would be

$$\tau_{\mathrm{beam}} \approx \frac{1}{\rho_\gamma c \sigma_T}\,. \tag{6.7}$$

Another important source of backgrounds is synchrotron radiation generated in the focusing optics near the interaction point in lepton accelerators. At both LEP and the SLC the synchrotron radiation was minimized by weakening the last bending magnets closest to the interaction point by a factor ~10, which reduced the critical energy of the emitted photons as well as the number of photons emitted per unit length. In addition, radiation masks were installed to absorb the synchrotron radiation from the weak bend and from the upstream strong bending magnets. The layout of bends and synchrotron masks for LEP is illustrated in Fig. 6.3.

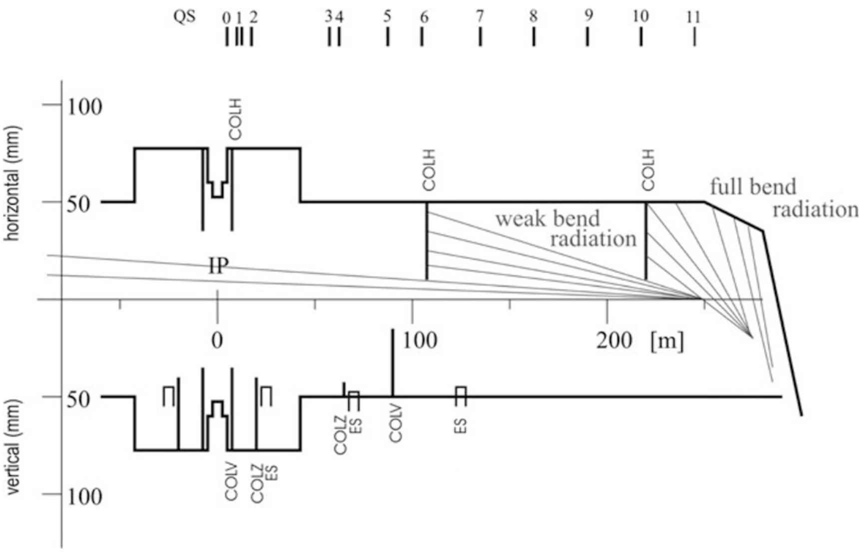

Fig. 6.3. Layout of the straight section around IP4 or IP8 in the horizontal and vertical planes. Shown are the quadrupoles (QS), electrostatic separators (ES), and collimators/masks (COLH, COLV, COLZ). The solid lines mark the inner vacuum chamber radii for the LEP1 layout [9, 21] (Courtesy H. Burkhardt, 1999)

Radiation collimators and masks around each LEP experiment provided complete shielding against direct photons and also against singly scattered synchrotron radiation, as illustrated in Fig. 6.4. For this reason, residual background at LEP arose mainly from multiply scattered radiation. Specular

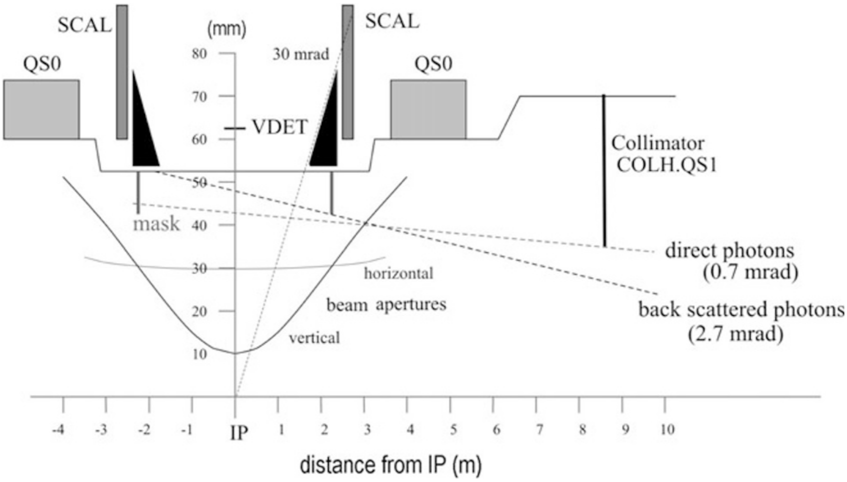

Fig. 6.4. Schematic of the synchrotron radiation masks around a LEP IP, indicating the constraints for mask solutions: (1) to stay outside the required LEP aperture (*solid lines*), (2) to cast a shadow over the entire unshielded IP beampipe length for small angle backscattered photons (*dashed*), (3) to stay outside of the very intense beam of direct photons collimated by the (8.5 m) synchrotron radiation collimator, when closed to 12 σ of the transverse beam distribution [9, 21] (Courtesy H. Burkhardt, 1999)

reflection of soft X rays is close to 100% at angles of incidence smaller than a so-called critical angle θ_c, where the angle is measured between the photon direction and the plane of impact. The critical angle is roughly

$$\theta_c \approx 30 \text{ mrad } \frac{\text{keV}}{E_\gamma} . \tag{6.8}$$

For a photon energy of 30 keV it is equal to about 1 mrad. Photons of this energy would still have a 95% chance of penetrating through a 1-mm Be layer. Multiple photon reflection can be reduced by coating or roughening of the vacuum chamber surface. In the LHC arcs, photon reflection will be reduced by impressing a sawtooth pattern on the beam screen which is installed inside the cold magnets [22].

Exercises

6.1 Scattering off Thermal Photons

Estimate the beam lifetime due to scattering off thermal photons:

a) in LEP at $T = 300\,\text{K}$, and

b) for a storage ring with a vacuum chamber cooled to 4 K.

c) Consider an NLC-like beam with 10^{12} electrons per bunch train. How many particles per train are scattered on thermal photons ($T = 300\,\text{K}$) over a linac length of 10 km?