HALO AND TAIL SIMULATIONS WITH APPLICATION TO THE CLIC DRIVE BEAM

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Abstract

We report about generic halo and tail simulations and estimates. Previous studies were mainly focused on very high energies as relevant for the beam delivery systems of linear colliders. We have now studied, applied and extended these simulations to lower energies as relevant for the CLIC drive beam.

INTRODUCTION

Halo and Tail Generation

Halo particles can be a major source of beam losses and radiation and can therefore lead to performance limitations of future accelerators. If the amplitude of a core particle increases significantly, it becomes a halo particle. The increase of the amplitude can be caused by the following particle processes:

- Beam gas scattering: elastic scattering (Mott scattering), inelastic scattering (Bremsstrahlung), multiple scattering
- Scattering of thermal photons (Compton scattering)
- Touschek effect
- Intrabeam scattering
- Electron and Ion cloud effects
- Space charge effects
- Synchrotron radiation

The most relevant processes for halo generation are usually beam gas scattering and multiple scattering, which can be simulated with the halo and tail generation package HTGEN [1]. In addition to the scattering processes, optics related effects like mismatch, coupling, dispersion and nonlinearities can enlarge the halo. These as well as the effect of synchrotron radiation are fully included in the tracking code PLACET [2], which can be used in combination with HTGEN. Previous studies using PLACET-HTGEN were done for high energy beams like the 250 GeV beam of the ILC [3]. In the following we will describe the extension of PLACET-HTGEN to low energy beams with high intensity like the CLIC drive beam decelerator.

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CLIC Drive Beam Decelerator

The CLIC Drive Beam decelerator will extract X-band RF power from a 100 A Drive Beam. The focussing and alignment systems must ensure transport of particles of all energies through the decelerator sectors, ensuring minimal losses. A short summary of relevant beam parameters is given in Table 1 and a more detailed description can be found in [4].

Table 1: CLIC drive beam decelerator parameters

Parameter	Unit	Value
Drive beam sector length	m	1053
numb. of part. per bunch	10^9	52.5
numb. of bunches per train		2928
mean initial beam energy	GeV	2.40
mean final beam energy	GeV	0.40
$\epsilon_{N,y,initial}$	μm	150
$\epsilon_{N,y,final}$	μm	334

THEORY

Elastic Scattering

The electron is deflected by the Coulomb potential of the particles in the residual gas. Taking the spin of the electron into account the differential cross section is given by [5]:

$$\frac{d\sigma}{d\Omega} = \left(\frac{Zr_e}{2\gamma\beta^2}\right)^2 \frac{1-\beta^2 \sin^2\frac{\theta}{2}}{\sin^4\frac{\theta}{2}} \tag{1}$$

where Z is the charge of the nucleus, r_e the classical electron radius, γ the Lorentz factor E/mc^2 of the electron and β the velocity of the electron in units of the speed of light. Relevant for halo production are only scattering angles exceeding the beam divergence, so roughly:

$$\theta > \theta_{\min} = \sqrt{\epsilon_{N,y}/(\gamma\beta_y)} \tag{2}$$

where $\epsilon_{N,y}$ is the normalized emittance and β_y the local vertical beta function. Integration over the solid angle yields the total cross section:

$$\sigma = \pi \left(\frac{Z r_e}{\gamma \beta^2} \right)^2 \left(\frac{1+\cos\theta_{\min}}{1-\cos\theta_{\min}} + \beta^2 \ln\left(\frac{1-\cos\theta_{\min}}{2} \right) \right) \quad (3)$$

In the relativistic limit $\beta \approx 1$ and for small scattering angles $\theta_{\min} < 0.1$ the terms except $(1+\cos\theta_{\min})/(1-\cos\theta_{\min})$ can be neglected.

$$\sigma = 2\pi \left(\frac{Z r_e}{\gamma} \right)^2 \left(\frac{1}{1-\cos\theta_{\min}} \right) \quad (4)$$

This is used in HTGEN. Because the electron mass is very small, $\beta \approx 1$ also for low energies, so Eq. 4 is still valid for low energy electron beams. Assuming a constant normalized emittance, the cross section scales with the inverse of the beam energy, hence Mott scattering becomes more relevant for low energies.

Inelastic Scattering

In the Bremsstrahlung process the electron interacts with the field of the residual gas nucleus and radiates photons. At high energies the cross section can be approximated in the "complete screening case" [6] by:

$$\frac{d\sigma}{dk} = \frac{A}{N_A X_0} \frac{1}{k} \left(\frac{4}{3} - \frac{4}{3}k + k^2 \right) \quad (5)$$

where k is the photon energy in units of the beam energy, N_A the Avogadro constant and X_0 the radiation length. A compact fit of the radiation length after Dahl of Tsai's formula gives values better than 2.5% accuracy for all elements except Helium, where the result is 5% to low [7]:

$$X_0 = \frac{A}{4\alpha r_e^2 N_A Z(Z+1) \ln(287/\sqrt{Z})} \quad (6)$$

Integration of (5) over k from $k = k_{\min}$ to $k = 1$ yields the total cross section:

$$\sigma = \frac{A}{N_A X_0} \left(-\frac{4}{3} \ln k_{\min} - \frac{5}{6} + \frac{4}{3} k_{\min} - \frac{k_{\min}^2}{2} \right) \quad (7)$$

A good value for $k_{\min}$ is 0.01. Note that the cross section is energy independent. A more accurate approximation of the Bremsstrahlung cross section is given by GEANT4. For energies lower than 1 GeV GEANT4 uses a fit to the EEDL data set [8] and above 1 GeV the exact Tsai formula. The error of the parameterisation is estimated to be smaller than 5 % for energies bigger than 1 MeV [9].

SIMULATION TECHNIQUE

With $\sim 10^{10}$ particles per bunch the CLIC drive beam is a rather high intensity beam and therefore a sliced beam model is used in the simulation. The halo generation requires a particle beam model, because the simulation is done by scattering of individual particles. We have extended interface and tracking routines of PLACET-HTGEN, so that a sliced beam model can be used for the beam and a particle beam model for the halo. Due to the high particle density of the CLIC drive beam collective effects like wake fields become important. To get a realistic halo tracking we have implemented the effect of transverse wake fields of the beam on the halo.

DISCUSSION FOR THE CLIC DECELERATOR

Analytical Estimates

We expect to have the largest halo generation in the longest decelerator, for which we performed the simulations. For the analytical estimates of beam gas scattering and Compton scattering we assumed a residual gas constitution of 40% H_2O, 40% H_2 and the remaining 20% shared among CO, N_2, CO_2, a total pressure of 10 nTorr and a temperature of 300 K. As minimal scattering angle $\theta_{\min}$ we used the beam divergence and as minimal photon energy with respect to the beam energy $k_{\min} = 0.01$. The beam divergence and the beam energy were calculated from the simulation results. We based our calculations for Compton scattering on [10]. The results are presented in Table 2. Elastic scattering is the dominant process and increases along the beamline. The energy spread caused by Compton scattering stays below 0.25% and is negligible compared to the energy spread due to the deceleration of the beam. The total scattering probability integrated over the whole decelerator is $7.69 \cdot 10^{-9}$. Therefore we expect a very small halo generation due to beam gas and Compton scattering. The cross sections for beam gas scattering change slightly, when the effect of ionization of the residual gas is taken into account. Our analytical estimates show, that the ionization level stays below 3%, so no extension of our model is required.

Table 2: Analytical estimates for beam-gas scattering and Compton scattering. ρ is the molecule density in the case of beam gas scattering and the photon density in the case of Compton scattering, P_{init} and P_{final} the initial and final scattering probability

Process	ρ [m^{-3}]	P_{init} [m^{-1}]	P_{final} [m^{-1}]
Mott	$3.22 \cdot 10^{14}$	$7.96 \cdot 10^{-12}$	$4.21 \cdot 10^{-11}$
Brems.	$3.22 \cdot 10^{14}$	$1.11 \cdot 10^{-13}$	$1.11 \cdot 10^{-13}$
Comp.	$5.45 \cdot 10^{14}$	$3.63 \cdot 10^{-14}$	$3.63 \cdot 10^{-14}$

The total number of intra-beam-scattering events per unit time scales with $1/\beta^4$ [11], where β is the velocity in units of speed of light, and increases with the particle density, which shows that intrabeam scattering as well as Touschek effect become more relevant for low energy beams with a small beamsize. In the CLIC decelerator the Touschek ef-

fect could be more important than in comparable linear accelerators without decelerating sections, because beam particles, which have performed Touschek scattering and lost longitudinal momentum, could lose almost all their longitudinal momentum during the deceleration and get lost.
As the drive beam is a negatively charged beam, only ion cloud effects are important. Ion cloud effects are known from ring accelerators, but also in linear accelerators an instability can occur - the fast ion instability. We have performed analogous analytical studies for the decelerator as for the CLIC long transfer lines [12]. To ensure the stability of the beam, the number of rise-times should stay below one. Taking the inital beam parameters it lies between 1.9 and 5.7 and taking the final beam parameters between 0.5 and 1.6, which might indicate an eventual appearance of the fast ion instability.

Simulation Results

In the simulations we used a sliced beam model with a reduced number of bunches per train. We included alignment errors as well as an initial beam offset in the vertical and horizontal plane. For simplicity we performed the simulation with a gas equivalent consisting of pure nitrogen. Our tracking results are shown in Fig. 1 and Fig. 2. If the amplitude of a particle exceeds the aperture of the element it is considered as lost.
We find that only a very small fraction of particles of 10^{-7} is lost. Most of these are low energy particles with large scattering angles, which are lost at the end of the beamline.

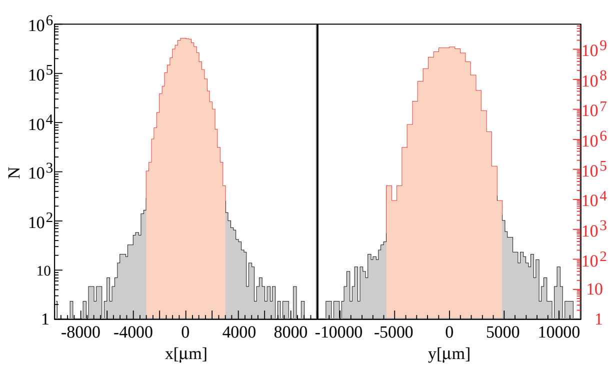

Figure 1: Transverse Beam profiles at the exit of the CLIC decelerator

SUMMARY AND OUTLOOK

We have extended the simulation capabilities of PLACET-HTGEN to low energy, high intensity beams, performed simulations for the CLIC drive beam decelerator and presented the results together with analytical estimates. We have started to apply PLACET-HTGEN to the Test Beam Line drivebeam [4] and intend to perform simulations for other low energy linear accelerators like for example TBONE [13]. To provide an even more complete simulation of low energy beams, we consider to include also a simple model of the Touschek effect. An extension of the fast-ion simulation code FASTION [14] for the CLIC drive beam is in progress.

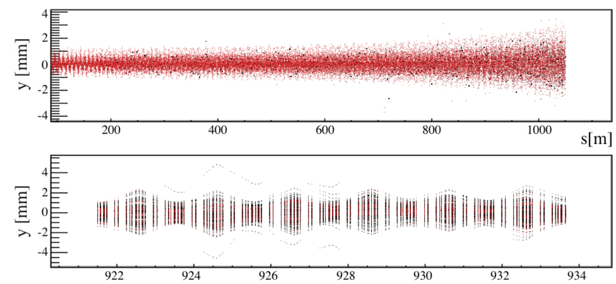

Figure 2: Vertical beam position along the complete CLIC decelerator and along an extract. Halo particles are shown in black, beam particles in red

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