MONTE CARLO SIMULATIONS OF BEAM LOSSES IN THE TEST BEAM LINE OF CTF3

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Abstract

The Test Beam Line (TBL) of the CLIC Test Facility 3 (CTF3) aims to validate the drive beam deceleration concept of CLIC, in which the RF power requested to boost particles to multi-TeV energies is obtained via deceleration of a high current and low energy drive beam (DB). Despite a TBL beam energy (150-80 MeV) significantly lower than the minimum nominal energy of the CLIC DB (250 MeV), the pulse time structure of the TBL provides the opportunity to measure beam losses with CLIC-like DB timing conditions. In this contribution, a simulation study on the detection of beam losses along the TBL for the commissioning of the recently installed beam loss monitoring system is presented. The most likely loss locations during stable beam conditions are studied by considering the beam envelope defined by the FODO lattice as well as the emittance growth due to the deceleration process. Moreover, the optimization of potential detector locations is discussed. Several factors are considered, namely: the distance to the beam, the shielding provided by the different elements of the line, the detector sensitivity and possible saturation effects of both the radiation detectors and electronics.

INTRODUCTION

The Compact LInear Collider (CLIC) project [1] investigates the feasibility of a future electron-positron collider optimized for a center of mass energy of 3 TeV. The required accelerating gradient (100 MV/m) is produced by a novel two-beam acceleration method, in which a low energy (up to 2.4 GeV), high current (100 A) drive beam is decelerated and the extracted power is transferred to a high energy (up to 3 TeV), low current (1.2 A) main beam. The CLIC Test Facility (CTF3) aims at demonstrating this novel acceleration scheme. On the Test Beam Line (TBL) [2], in particular, the power extraction and the stability of the DB under the resulting deceleration is investigated. The TBL comprises eight FODO cells. Each half cell features a quadrupole, a Beam Position Monitor (BPM) and a Power Extraction and Transfer Structure (PETS), seen from right to left on Figure 1. The key nominal parameters of the CTF3 TBL and the CLIC drive beam are displayed in Table 1. The 16 BPMs installed at the TBL [3] provide beam current measurements along with the reconstruction of the beam centroids. The sensitivity of the BPMs to measure beam current is on the order of 0.5 A. Destructive beam losses can be measured with the BPMs, but subtle beam losses during stable beam transport are not observed. This problem is overcome with the installation of a beam loss monitoring (BLM) system based on detection of secondary showers [4], as particle detectors for BLM systems are chosen to have both high sensitivity and large dynamic range. In this document, several factors affecting the estimation of the BLM signals are studied.

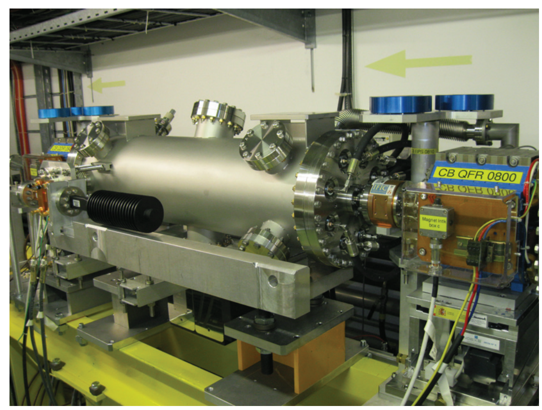

Figure 1: View of a half FODO cell in the TBL.

Table 1: Key Nominal Parameters of the TBL and CLIC Drive Beam.

Parameter	TBL	CLIC DB
N_{PETS}	16	1492
Current (A)	28	101
Pulse Length (ns)	140	240
Initial energy, E_{ini}(MeV)	150	2400
Final energy, E_{end}(MeV)	80	240
Norm. Emittance $\epsilon_{x,y}(\mu m\, rad)$	150	150
Beam Pipe radius, r_0(mm)	11.5	11.5

BEAM LOSS ESTIMATION

In order to commission the BLM system on the TBL, a general understanding of the beam losses is required. A simple model that aims for a qualitative description is based on the assumption of a two dimensional Gaussian beam. The Gaussian means, $\mu_{x,y}$, are obtained via linear interpolation of the beam centroids measured by the BPMs. The

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estimation of $\sigma_{x,y}$ is based on a MAD-X simulation [5]. The Twiss parameters measured on the diagnostic section before the TBL are used to calculate a matching of the incoming beam to the FODO lattice [2]. The simulated beta function is an input for the calculation of the beam size as $\sigma_{x,y} = \sqrt{\beta_{x,y}\epsilon_{x,y}/\gamma\beta}$. The relativistic factor $\gamma\beta$ is inferred from the expected initial and final energies. The energy deceleration is assumed equal in each PETS, linear along its lenght and of value $\Delta = (E_{ini} - E_{end})/N_{PETS}$. Figure 2 presents the energy, beta function $(\beta_{x,y})$ and beam envelope (3σ) along the line assuming a round beam with nominal values for $\epsilon_{x,y}$, E_{ini}, E_{end} and N_{PETS}. Towards the end of the line, more than half of the beam pipe is expected do be filled.

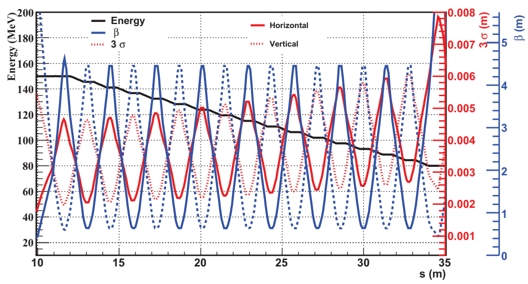

Figure 2: Energy, $\beta_{x,y}$ and beam envelopes vs s.

The amount of beam loss is calculated as the Gaussian integral outside of the radius defined by the beam pipe:

$$P_{LOSS}(s) = \int_{\phi=\phi_i}^{\phi=\phi_e} \int_{r=r_0}^{\infty} f(s,r,\phi) \cdot r \cdot dr \cdot d\phi \qquad (1)$$

where $f(s,r,\phi)$ represents the Gaussian profile and the angular limits provide a way to estimate the direction of the beam losses in the transverse plane. For the subsequent study, four azimuthal regions corresponding to (ϕ_i, ϕ_e) pairs of $(-45^o, 45^o)$ (right), $(45^o, 135^o)$ (top), $(135^o, 225^o)$ (left) and $(225^o, 315^o)$ (bottom) are defined. Figure 3(a) presents the calculation of beam losses for a centered beam. A periodic structure is observed with the losses peaking at the quadrupole locations, where the beta function is maximum. A minimum is observed equidistantly from the two nearest maxima, corresponding to a longitudinal position 30 cm after the beginning of the next PETS. Losses in the top and bottom regions are identical and they follow the vertical beta function, while the same is true for the left/right regions and the horizontal beta function. For the total beam loss, there is a variation from peak to minimum that ranges from 11 orders of magnitude at the first quadrupole to 5 at the last one. Figure 3(b) presents the same estimation for a beam heavily misaligned. The periodic structure is still visible but strongly distorted by the beam positions, which are presented in figure 3(c). The peak to minimum variation ranges from 1 to 10 orders of magnitude. Finally, Figure 3(d) compares the total fraction of beam losses for a centered and misaligned beam. The two largest peaks are observed at those positions where the measured centroids are closer to the beam pipe, in the direction of maximum beta function. Note that the fraction of beam lost is calculated with respect to a normalized Gaussian at each position s, i.e, beam losses happening upstream of the considered point are not taken into account. This is a good aproximation as measurements of beam current in the TBL indicate that the total beam losses along the full line are below the 1% level.

MONTE CARLO SIMULATIONS

A Monte Carlo model for beam losses in the TBL is discussed here, with a description of the geometry, a systematic analysis of particle shower composition and an estimation of BLM signals.

Geometry, Magnetic Field and Physics Settings

A geometric model of the TBL was implemented in FLUKA [6]. The main part features sixteen 1.4 m long modules composed of a quadrupole, a BPM and a PETS. The metallic support of the line is also implemented. The recreations of the quadrupoles are built of an iron yoke and pole and copper coils. The beam pipe is modelled as a cylindrical tube of stainless steel, with an inner and outer radius of 1.2 and 1.35 cm respectively. In the magnet areas, where the field has an influence on the propagation of the shower, a Poisson simulation field map is provided. The BPMs are 7 cm long cylinders with the inner radius defined by the beam pipe and an outer radius of 2.5 cm. The material composition is 50% copper and 50% iron. The PETS were constructed as copper hollow cylindrical tubes with inner and outer radii 13.5 and 48 mm respectively. The PETS tank is defined as a 3 mm thick iron cylindrical tube with inner radius 12.5 cm. Note that no electromagnetic fields are present at the PETS in the simulation. The production and transport thresholds for electrons, positrons and gammas was set to 100 keV. Photo-nuclear and muon-photon interactions were also simulated.

Dedicated Simulations

A systematic analysis [7] was carried out to estimate the energy deposition in the surroundings of the line and particle fluences at four potential detector locations. To make this study irrespective of the detector technology choice, virtual detectors are defined in the simulation as air filled 1 cm long cylinders with radius 2.5 cm and their axis parallel to the beam direction. Longitudinally, the detectors are placed 1.3 cm downstream of each quadrupole. Horizontally they are situated at 10 cm from the beam pipe center and vertically at 0, - 10, - 20 and - 30 cm. These detector locations (referred in the text as locations A, B, C and D) were choosen where the TBL still has room available for the installation of instrumentation. Various simulations were analyzed in order to study the effect of the energy of the primary particle, its incident angle on the beam pipe and the location of the loss. For beam losses originating at quadrupoles, roughly 80% of the energy was absorbed in

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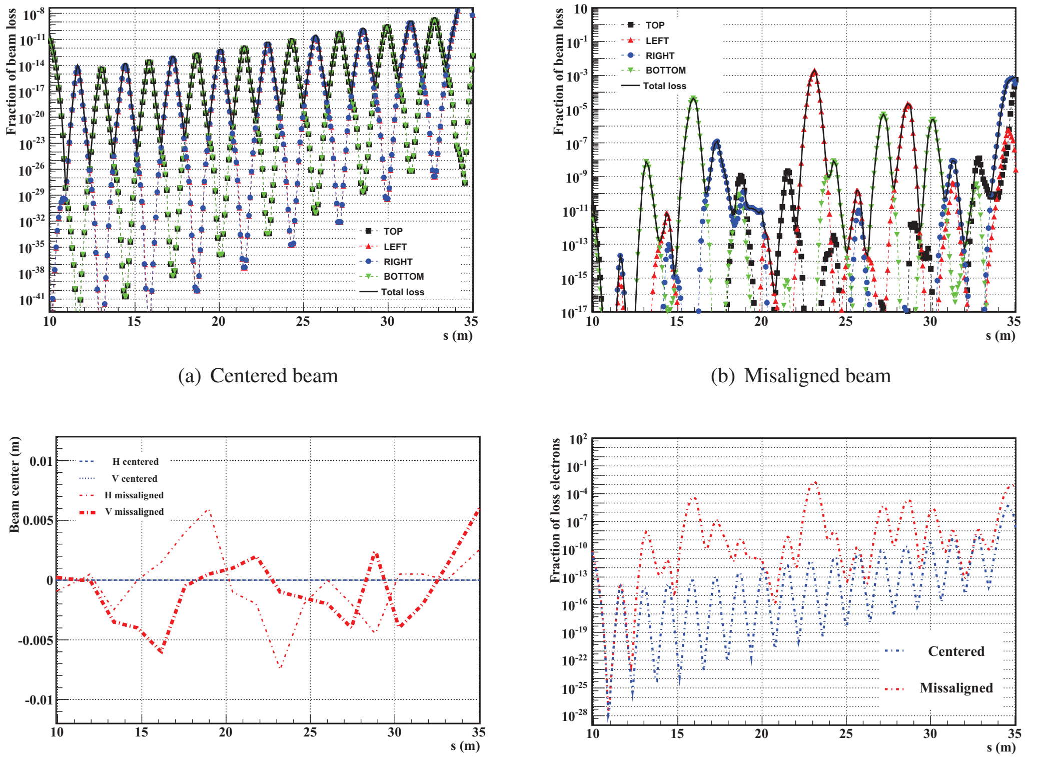

(a) Centered beam (b) Misaligned beam

(c) Beam positions (d) Comparison of beam loss for aligned/misaligned beam

Figure 3: Beam loss fraction and beam position vs longitudinal coordinate.

the beam pipe, magnetic coils and yoke. The propagating fraction of the shower outside of the quadrupole was composed of electrons (64%), photons (28%), positrons (3.1%) and neutrons (4.9%). No significant differences were found for primary particles with energies ranging from 85 to 150 MeV. The incident angle of the particles on the beam pipe was found to have a much stronger effect on the particle fluences at potential detector locations. In the following, only electron fluences are considered for two main reasons, namely: electrons account for the largest fraction of the shower and the detectors installed on the TBL [4] are mostly sensitive to electrons. Impact angles of 0, 1, 5 and 10 degrees were simulated to find that the electron fluences, at location A, increase by up to a factor 2 from 0 to 10 degrees. This is due to the fact that the maximum energy density is more directed towards the detector location for the case of a 10 degree angle. For horizontal losses generated at the longitudinal center of the quadrupoles and pointing towards the detector locations, the electron fluences were observed to decrease by up to a factor 20-30 when moving vertically from location A to location D. This indicates that detectors located near the beam line may be suitable for the detection of very subtle beam losses but saturation effect will likely be observed for stronger losses. Moreover, four different loss scenarios were simulated to investigate their effect on the expected signals at detector locations, namely: point-like loss, distributed loss over the focusing/defocussing plane and homogeneously distributed losses around the circle of the beam pipe. Taking the point-like loss as a reference, the electron fluences at detector locations vary by 30-70% depending on the loss scenario. Finally, several other loss locations were investigated (losses at BPMs and PETS) to find that the expected detector signals are at least one order of magnitude lower than those observed for losses generated at quadrupoles. For losses at PETS, only when the loss location is towards the end of the structure, immediately upstream of a quadrupole, do the observed signals in downstream detector reach values on the same order of magnitude. Considering also the drop on beam losses when moving away from the local maxima, as shown in figure 3(d), it is a good approximation to assume that all the losses will be generated at the quadrupoles.

BLM Signal Estimation

The signal observed in a BLM depends on many factors: detector type, detector location and loss scenario among others. In this model, we simplified the BLM signal as:

$$S_{BLM} = \sum_{i=1}^{4} a_i \times s_i \tag{2}$$

where a_i represents the number of lost electrons and is estimated via equation (1) for s values corresponding to the center of the quadrupoles. The sum runs over the four azimuthal regions defined in the previous section. The value of s_i is estimated via FLUKA as the electron fluence ob-

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tained at detector locations for losses simulated longitudinally at the center of the quadrupole and transversaly distributed over the left, top, right and bottom of the beam pipe circle. Two virtual detectors per quadrupole are defined as air filled cylinders with centers in the transversal plane at (0, -5) cm and (10, -15) cm (locations E and F). The obtained electron fluences at detectors downstream of a focussing and defocussing quadrupole are shown in Table 2. The maximum (minimum) fluence occurs for particles lost in the bottom (top) azimuth region of the beam pipe. For particles lost in left and right, similar fluences are obtained in detector location E but the differences are more than a factor two for location F. Differences on the order of 10% between detectors downstream of focussing/defocussing quadrupoles are attributed to the redistribution of the charged component of the shower due to the magnetic field. Note that the particle fluences show a reduction of more than a factor 300 from location E to F. Moreover, a significantly larger statistical error is observed for the same amount of simulated events, as fewer particles reach a detector farther away.

Table 2: Electron Fluences (cm^{-2}) per Primary for Detectors (Locations E and F) Downstream of a Focussing/Defocussing Quadrupole.

Azi/loc	**Focussing**	**Defocussing**
Right E	$(4.36 \pm 0.18) \cdot 10^{-3}$	$(3.78 \pm 0.18) \cdot 10^{-3}$
Top E	$(2.55 \pm 0.08) \cdot 10^{-3}$	$(2.89 \pm 0.12) \cdot 10^{-3}$
Left E	$(4.95 \pm 0.12) \cdot 10^{-3}$	$(4.01 \pm 0.12) \cdot 10^{-3}$
Bottom E	$(3.08 \pm 0.03) \cdot 10^{-2}$	$(2.81 \pm 0.03) \cdot 10^{-2}$
Right F	$(7.89 \pm 3.04) \cdot 10^{-5}$	$(6.10 \pm 1.92) \cdot 10^{-5}$
Top F	$(4.49 \pm 2.46) \cdot 10^{-5}$	$(4.51 \pm 1.55) \cdot 10^{-5}$
Left F	$(3.39 \pm 1.03) \cdot 10^{-5}$	$(3.30 \pm 1.45) \cdot 10^{-5}$
Bottom F	$(1.01 \pm 0.26) \cdot 10^{-4}$	$(8.44 \pm 2.65) \cdot 10^{-5}$

The BLM signals estimated for a centered and a misaligned beam are shown in Figure 4. A 16 A beam with a pulse length of 150 ns is assumed for subsequent comparison with data. For a centered beam, an increase is observed as the beam size grows along the line. The periodicity is attributed to two factors: the effect of the magnetic field on the charged component of the shower and the growth of the beam size in the other plane on consecutive quadrupoles. For the misaligned beam the distance from the beam centroid to the beam pipe dominates the observed signals where the beam is both misaligned and defoccused on the same plane. The simulation is compared with data taken during May 15th. No detailed comparison can be made, since position measurements were not stored for offline analysis. The data points show a flat behaviour which may indicate a larger contribution of a beam halo as well as non Gaussian beam profiles as observed in the TBL after full recombination.

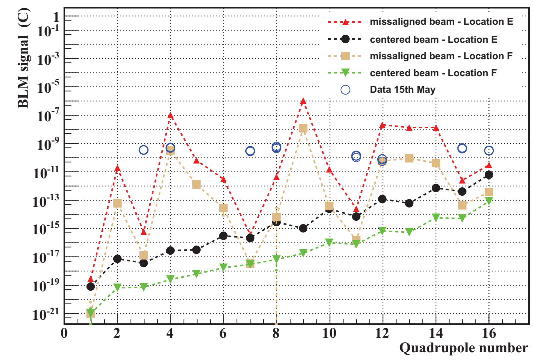

Figure 4: BLM signals for detector located at quadrupoles.

CONCLUSIONS

A Monte Carlo study of beam losses on the TBL has been performed to help with the commissioning of the BLM system. A simple model for the estimation of beam losses has been produced and is based on the numerical integration of gaussian beams. Following this approach, the misalignment of the beam shows bigger impact than the growth in its size throughout the TBL. Several Monte Carlo simulations have been performed to study the effect of detector location, impact angle, beam energy and loss scenario on the energy depositions and particle fluences at detector locations. The uncertainties found range between 10% and 70%, the detector location and the impact angle being the most relevant. Finally, the electron fluences at detector locations are used as an estimator for the BLM signals. The fraction of losses and the electron fluences expected at a detector for particles lost on a given azimuthal region on the beam pipe are combined to produce a realistic estimation of the BLM signals. Despite the relatively large differences of the expected BLM signals for the different azimuthal cases, the BLM signals are dominated by the total fraction of beam loss irrespective of the direction of the loss in the transverse plane.

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