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CLIC DECELERATOR – MACHINE PROTECTION

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Abstract

The Compact Linear Collider CLIC is based on a four beam scheme, two colliding beams (main beams) and two drive beams, which are used to accelerate the main beams. The intended drive beam parameters exceed the "safe beam" threshold by two orders of magnitude. Hence, in case of a beam impact serious structural damages of the accelerator equipment are expected. In order to avoid structural damages caused by the drive beam, detailed studies of its beam dynamics are on-going. In this paper the major characteristics of the drive-beam beam-dynamics and preliminary machine protection results are summarised.

INTRODUCTION

The four beam scheme of CLIC is composed of two drive beam and two main beam complexes, Figure 1.

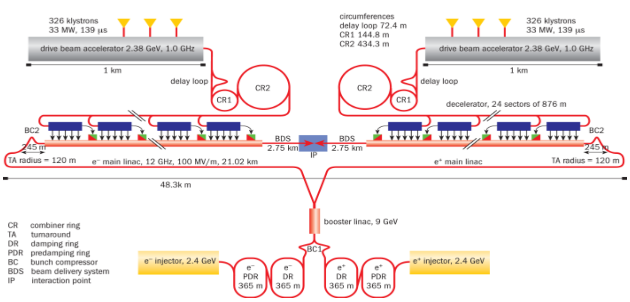

Figure 1: CLIC complex.

A set of 24 bunch trains of 2928 bunches each with particle energies of 2.4 GeV provide the required RF power for one main beam. Due to the increasing particle energy along the Main Linac the optics of the 24 decelerator units are slightly different. At higher energies "Power Extraction and Transfer Structure" (PETS) [1] are spared out for sake of quadrupole magnets in the Main Linac. Hence, the length of the decelerator units varies from 800 m to 1050 m. For investigations in terms of machine protection the decelerator #11 with a length of 880 m was chosen.

DAMAGE LIMITS

In case of machine failures the beam can scrape the aperture. The damage limit is based on the yield temperature. The yield temperature defines the limit of an instantaneous temperature rise that causes structural damage. This temperature rise will be caused by the energy deposition of electrons in matter $\frac{dE}{dx \cdot \rho}$ by e.g. Bremsstrahlung and ionisation. In combination with the specific heat capacity damage limits in terms of maximum charge density are defined, Table 1. The lowest limit of the charge density of $3.94 \cdot 10^{-4}$ nC/µm² is given for copper.

Table 1: Damage Limits

	Be	C	Cu	W
Yield Temp. [K]	370	14207	201	670
Limit [nC/µm²]	$3.02 \cdot 10^{-2}$	$4.01 \cdot 10^{-2}$	$3.94 \cdot 10^{-4}$	$5.60 \cdot 10^{-4}$

As a first approach the beam intensity at the aperture surface is used. Em. shower processes enhance the charge densities inside the material. Hence, lower beam intensity limits might be required. Therefore, detailed Fluka [2] simulations are ongoing.

INTENSITY RAMPING

The initial parameters of the drive beam are given by a transverse emittance of $\varepsilon_x = \varepsilon_y = 150$ µm and a bunch charge of 8.4 nC. Depending on the Twiss parameters, peak charge densities of $8.8 \cdot 10^{-2}$ nC/µm² to $3.9 \cdot 10^{-3}$ nC/µm² can be expected. Since the peak charge density exceeds the damage threshold by two orders of magnitude, an intensity ramping for operation and commissioning is envisaged to minimise the possibility of causing structural damage. To lower the beam intensity a reduction of the number of bunches is foreseen. As a safe beam limit a bunch train of 30 bunches (pilot beam) with a bunch frequency of 500 MHz is defined [1]. During the intensity ramping the length of the bunch train will be successively increased to 121 bunches followed by a piecewise increase of the bunch frequency using the beam combination schemes of CLIC [1].

BEAM DYNAMICS

The essence of the four beam collider scheme is that the kinetic energy of the drive beam particles is converted into RF power and used to accelerate the main beam particles. The drive beam generates wake fields in the PETS, which act back on the beam causing a self-amplification effect of the wake fields. Since the longitudinal dimensions of the drive beam bunches of $\sigma_z = 1$ mm are in the order of the 12 GHz RF wave length, a significant energy spread of approximately 40% at the end of the decelerator is expected, Figure 2.

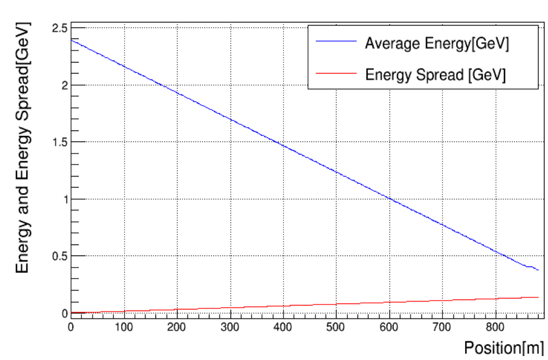

Figure 2: Energy and energy spread.

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The initial and final beam parameters of a perfectly aligned machine are summarised in Table 2.

Table 2: Drive Beam Parameters

	Initial Beam	Final Beam
ε_x [10^{-6} m]	150	192
ε_y [10^{-6} m]	150	192
σ_z [mm]	1.0	1.0
$\Delta E/E$ [-]	1%	40%

The focusing structure is based on the FODO cell with a phase advance of 90° for the lowest-energetic particles. A consequence of the rising energy spread is an increase of the phase advance spread, Figure 3.

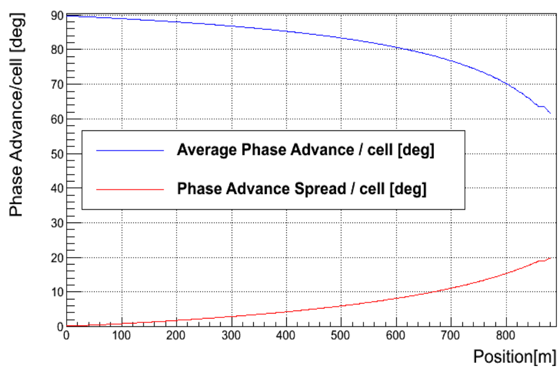

Figure 3: Phase advance and spread.

The energy spread determines the filamentation velocity. This defines a coherence length, over which several alignment errors and RF-kicks can be summed up. An illustration of the filamentation speed along the decelerator is given in Figure 4, simulated with Placet [3].

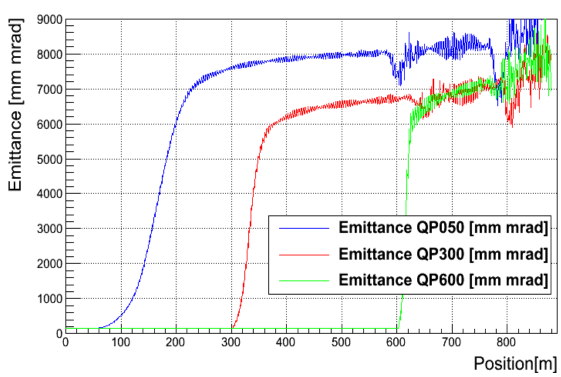

Figure 4: Emittance development.

At a perfectly aligned machine, transverse kicks at 50 m, 300 m and 600 m are applied to demonstrate the filamentation speeds. The development of the transverse emittances in these three scenarios shows that the filamentation of the beam is extended over a longer distance, if the phase advance spread is rather small.

SINGLE KICKS

In a first approach the single kick limits are determined. These limits serve to define safe maximum step sizes for beam feed-back systems and to estimate the importance of fast, non-correctable errors such as RF break-downs. In the single kick studies a single quadrupole is gradually displaced on a perfectly aligned machine until structural damage occurs. The maximum quadrupole offsets converted into kick strengths in units of keV are shown in Figure 5.

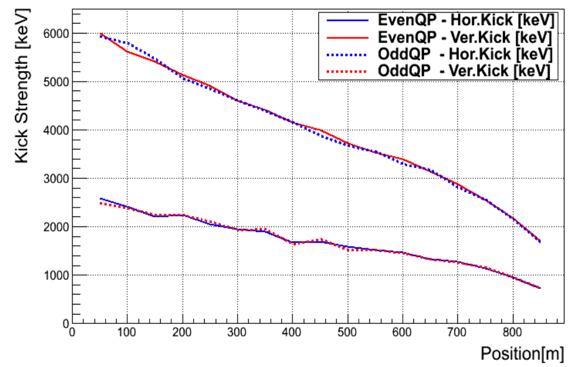

Figure 5: Kick strength limits.

Horizontal focusing and defocusing quadrupoles are displaced in horizontal and vertical direction. To cause structural damage higher kick strength are needed, when the following quadrupole is focusing in the plane of the applied kick. Also the kick strength limit is decreasing along the decelerator based on the decreasing particle energy. The determined kicks strengths are in the order of several hundreds of keV. Measurements at the CLIC Test Facility CFT3 have shown RF break-down kicks limited to tens of keV [4].

MULTIPLE KICKS

In first studies of multiple kick scenarios the impact of quadrupole misalignments, BPM misalignments, PETS misalignments and randomly distributed RF break-down kicks on the beam emittance is examined. The alignment errors for quadrupoles, BPMs and PETS correspond to the specifications of an uncorrected decelerator given in [1]. By means of 1500 runs the average development of the transverse emittance is estimated, Figure 6.

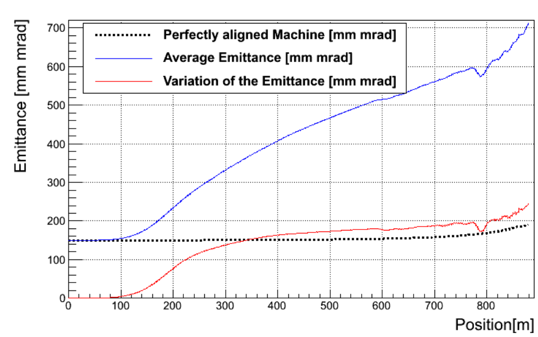

Figure 6: Development of the emittance.

The development of the average emittance and its variation indicates the presence of three different regimes along the decelerator. Due to the small energy spread in the first 100 m the filamentation speed is very low. Hence dipole kicks caused by e.g. misaligned quadrupoles do not

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lead to an instantaneous emittance growth. The dipole kicks are partly compensating each other leading to a conservation of the transverse emittance upstream position 100 m independent of the applied quadrupole alignment errors. Downstream position 300 m the energy spread strongly limits the compensation of beam kicks. Each misaligned quadrupole contributes to the emittance growth, whereby the beam emittance continuously raises while the variation of the emittance becomes flat. In between position 100 m and 300 m partly compensation of the transverse kicks is possible, however, a residual emittance growth is expected depending on the spatial distribution of the alignment errors.

DAMAGE ESTIMATION

In case of an uncorrected decelerator an increased beam envelope is expected, which most likely exceeds the aperture constraints of r=11.5 mm. In Figure 7 the maximum beam emittance and beam envelope of 1500 uncorrected decelerator cases is shown.

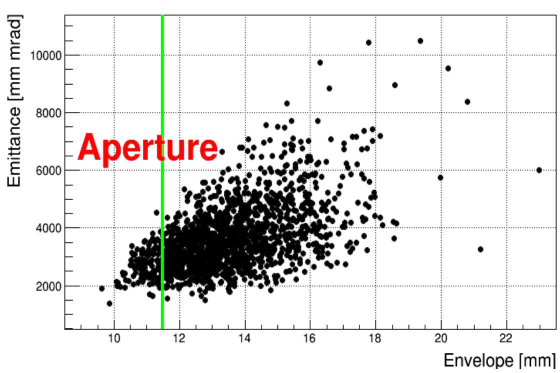

Figure 7: Maximum emittances and envelopes.

Most of the simulated machines the beam envelope exceeds the aperture constraints. Several of these scenarios are characterised by very high maximum envelope values. For these scenarios the maximum charge densities at the aperture surface are estimated, Figure 8.

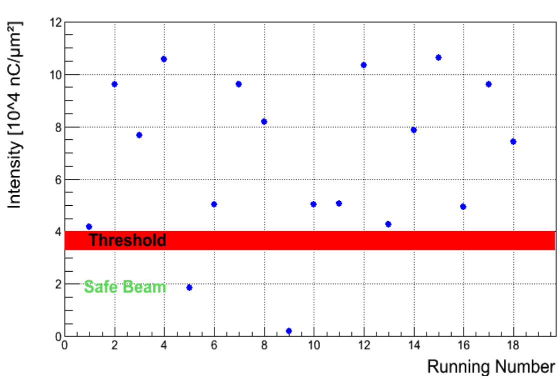

Figure 8: Deposited charge intensities.

The maximum charge density for bunch trains of 3000 bunches is in the order of $1.1 \cdot 10^{-3}$ nC/µm², i.e. approximately 2.5 times above the damage threshold. But since the damage threshold is exceeded only by a factor of 2.5, longer pilot bunch trains for commissioning and operation might be possible depending on the FLUKA simulation results. During commissioning and operation beam-based alignment-procedures are foreseen. The first correction scheme is the 1-to-1 correction [5]. It was applied to several scenarios with damage potential. During commissioning pilot beams, characterised by reduced numbers of bunches, will be used for steering. Steering impact on the development of the beam envelope is shown in Figure 9.

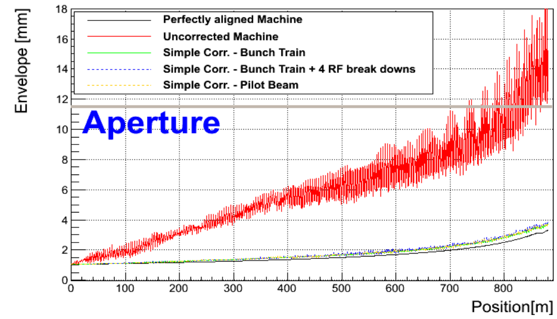

Figure 9: Envelope development.

This figure shows the development of the beam envelope for a perfectly aligned machine(black), for an uncorrected machine(red), for a corrected machine using pilot beams for steering(yellow) and for a corrected machine using an entire bunch train for steering(green, blue). For the steering effects on the BPM signal such as signal noise is not included. The impact of RF break-downs on the envelope of the corrected machines seems negligible. Due to the significant reduction of the beam envelope using the 1-to-1 correction scheme no particle losses by aperture constraints are expected. Another source of particle losses is residual gas scattering. In order to avoid beam instabilities by ion trapping a pressure limit is determined [5]. The operational beam losses, based on these pressure limits, will be evaluated.

LOSS PATTERNS

In case of uncorrected machines the losses are mainly located downstream of 650 m. Due to the deceleration of the particles and in particular due to the alignment errors of the lattice elements the beam exceeds the aperture constraints. Major parts of the emittance growth can be mitigated using beam-based alignment-schemes. In terms of operational losses due to residual gas scattering etc. further studies are ongoing.

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