FAILURE STUDIES AT THE COMPACT LINEAR COLLIDER: MAIN LINAC AND BEAM DELIVERY SYSTEM

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Abstract

The proposed Compact Linear Collider (CLIC) is based on a two-beam acceleration scheme. The energy of two high-intensity, low-energy drive beams is extracted and transferred to two low-intensity, high-energy main beams. The CERN Technology Department - Machine protection and electrical integrity group has the mission to develop and maintain the systems to protect machine components from damage caused by ill controlled conditions. Various failure scenarios were studied and the potential damage these failures could cause to the machine structures was estimated. In this paper, first results of the beam response to kick induced failures in the main LINAC and in the beam delivery system (BDS) sections are presented together with possible collimator damage *s*cenarios.

CLIC AND THE TWO-BEAM CONCEPT

The Compact Linear Collider (CLIC) is a 50 km long high energy e^-/e^+ accelerator concept working with 12 Ghz (X-band) room temperature radiofrequency cavities. To accomplish the desired 3 TeV collision energy, an accelerating gradient of 100 MV/m will be used. Using the two-beam accelerating concept, a high current electron beam (drive beam) runs parallel to the main beam line. The drive beam is decelerated in power extraction and transfer structures (PETS) which generate the RF power for the lower current high energy main beam.

The two main LINACs, one for positrons and one for electrons, accelerate the beams from an initial energy of 9 GeV to the final value of 1.5 TeV over a length of ~21 km. The main LINAC optics consists of twelve FODO lattice sectors with a phase advance of 72 degrees per cell throughout the main LINACs. There are four different types of quadrupole magnets of different length (0.35 m, 0.85 m, 1.35 and 1.85 m), same aperture (0.004 m beam pipe) and same field gradient (200 T/m) [1]. A layout of the two-beam module is presented in Fig. 1. The quadrupole spacing is constant in any particular sector but varies from sector to sector [1]. Other main LINAC specifications can be found on Table 1.

The Beam Delivery Systems (BDS) start at the exit of the Main LINACs. Each BDS consists of 206 dipoles, 70 quadrupoles and 18 sextupoles (while higher order n-pole magnets are considered) [1]. The BDS is responsible for transporting the beams, protecting the beam line and detector against mis-steered beams, removing the beam halo, focusing them to the required sizes (σ_x = 45 nm, σ_y = 1 nm) and bringing them into collision. The BDS can be divided in three regions, named: the diagnostics region, the energy and betatron collimation region and the final focus region. The BDS layout can be seen in Fig. 2.

Table 1: Main LINAC Specifications

Parameter	Symbol	Value
Energy at injection	E_{inj}	9 GeV
Energy at extraction	$E_{ext,linac}$	1.5 TeV
Particles/bunch	N	3.72 10^9
Bunch length	σ_{inj}	44 μm
Bunches/train	N_b	312
Train length	τ_{train}	156 ns
Repetition rate	f_{rate}	50 Hz
RF frequency	f_{rf}	11.994 GHz
Beam power/beam	P_b	14 MW
Energy spread	$\Delta E/E_{inj}$	1.3 %

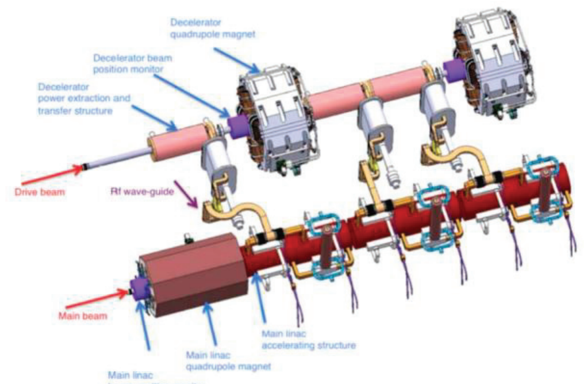

Figure 1: CLIC 12 GHz two-beam module highlighting the power extraction and transfer principle. One module contains up to 4 *power extraction and transfer structures* (PETS), where each PETS feeds 2 accelerating structures. RF waveguides transfer the RF power generated from the PETS into the accelerating structures. Quadrupoles are used for strong focusing. [1]

KICK STUDIES AND BEAM DAMAGE

Due to the wide variety of failures, from real-time failures (RF breakdowns, kicker misfiring), to slow equipment failures, beam instabilities caused by temperature drifts or slow ground motions and others, the strategy was to study the response of a kick to the beam and to track and understand the effect -and possible damage- that different kicks could have in different accelerator structures regardless of its origin [2].

The beam transport through the main LINAC and the BDS was simulated using the particle tracking code PLACET [3] and its results analysed using various tools. Linear tracking simulations, including wakefield effects and synchrotron radiation emission, were performed using 150000 macroparticles with a 1% energy spread. Because the destructive capacity of the beam is primarily given by its charge density, we calculated the charge density limits for different materials [4] obtaining for Cu: 0.4 10^{-3} nC μm^{-2}, for Be: 3.0 10^{-3} nC μm^{-2} and for Ti-alloy: 4.5 10^{-3} nC μm^{-2}.

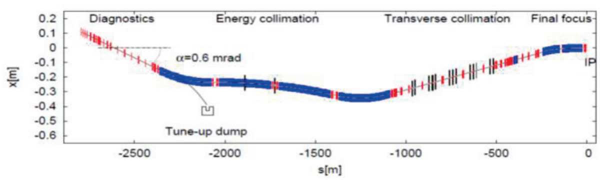

Figure 2: CLIC BDS layout showing the diagnostics, collimation and final focusing regions. Dipoles, quadrupoles and collimators are shown in blue, red and black respectively. (*Picture: CLIC study).*

Main Beam LINAC

If different kicks are applied to one location at a time, the beam starts to grow and to become unstable due to the effect of intra-beam (head-tail) transverse wakefields and chromatic effects. Although the beam tends to blow up, its charge density is still too large to be ignored. Figure 3 shows beam blow up as a function of kick strength for different kicks applied at the 9th quadrupole position. Similar effects can be seen for other quadrupoles along the LINAC. In figure 4, the charge density and its damage capability for the unperturbed and perturbed beam are shown. The beam profile for kicks on quadrupoles separated by a phase advance of 2π*n rads (n: integer) have similar charge density distribution as long as the kick is not applied at a location near the LINAC exit (for which the beam does not have time to evolve similarly).

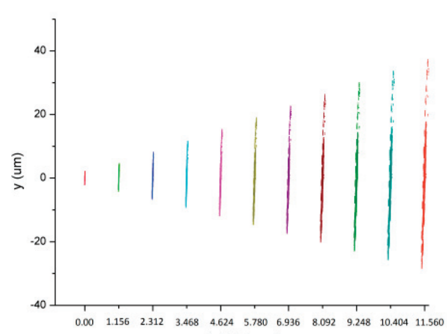

Figure 3: Beam blow up as a function of kick, simulated by a quadrupole displacement using the PLACET code. Shown is the y-y' phase space at the LINAC end for various kick strengths at the 9th quadrupole.

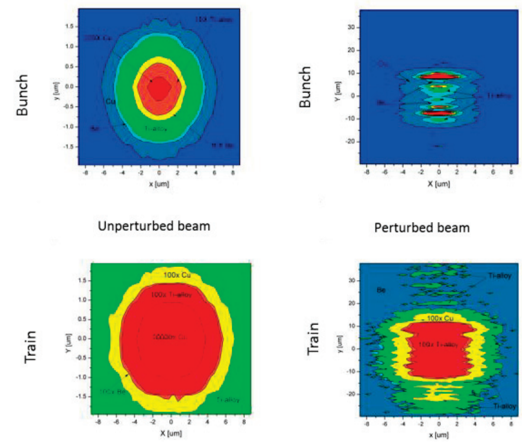

Figure 4: Charge density at the LINAC end for 11.56 µrad kick at the 9th quadrupole. Deep blue: safe for Cu. Grey blue: destroys Cu, safe for Be, Ti. Light blue destroys Cu, Be, safe for Ti. Green and above, unsafe for Cu, Be, Ti.

Beam Delivery System. Collimators

The CLIC collimation section fulfils 2 critical functions: removal of the beam halo and protection of the down-stream beam line and detector against mis-steered beams from the main LINAC. As such, it constitutes a passive protection system.

There are two different types of collimators: energy collimators and betatron (transverse) collimators. The former protects against energy errors caused by drive beam failures, RF phase errors or intensity errors. The latter protects against betatron errors, such as quadrupole related failures or kicks that lead to off orbit particles. The energy collimators are designed to withstand the impact of a full beam train while the betatron collimators are sacrificial. Figure 5 shows the beam profile and its charge density distribution at the collimators.

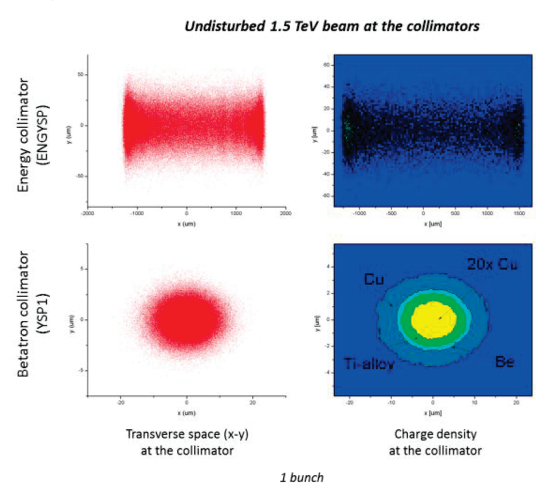

Figure 5: Beam profile and charge density distribution at the collimators for an unperturbed beam bunch. Pockets of higher charge density able to destroy Cu and Be are found at the energy collimators distribution. The damage potential at the betatron collimators is unambiguous.

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When different kicks are applied to the main LINAC quadrupoles, the bunch charge density can only damage surface made of Cu but not Be neither Ti-alloy, as shown in Fig. 6. But when a full train is considered then the beam has the capability to damage Cu, Be and Ti-alloy. For any kick over 16 μrad the beam train will impact and hence damage the transverse collimators.

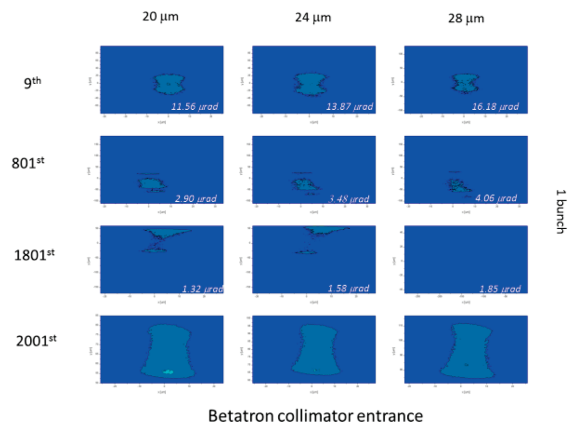

Figure 6: Bunch charge density distribution at the betatron collimators for different kicks on the main LINAC quadrupoles. Gray blue colour: Cu is damaged.

Pilot Beam

At a 'cold' start-up, when the machine is completely unknown, only a pilot beam, i.e. a beam of reduced intensity that cannot cause structural damage to the accelerator components is safe. Once the machine is probed by such a pilot beam, the intensity can be increased in steps by the beam control system. A bunch with 30% intensity that is kicked at the main LINAC will likely end up with a diluted charge density unable to damage the collimators, Fig. 7.

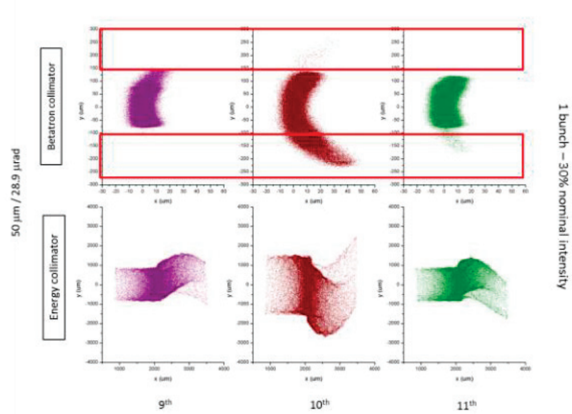

Figure 7: Beam profile for a 30% intensity bunch at the collimators for a 29 μrad kick on the LINAC. The charge density is too diluted to damage the collimators (red).

Injection (Intensity) Errors

A beam with an injection intensity error may be more sensitive to transverse perturbations as in this case the BNS damping applied in the main LINAC [1] does not properly compensate the transverse wakefields induced by a perturbed beam. To evaluate the significance of this effect, we studied beam trains of different intensities that were kicked with critical strength (i.e. causing the nominal beam to fill the betatron collimators aperture). Figure 8 compares beam and charge density profiles at the betatron collimators for a nominal beam with the profiles for beams with a 5% intensity error. This comparison shows no substantial change in the beam profiles. This can be understood as the BNS mechanism compensates intra bunch head-tail wakefields, while the blow up of a full beam is by large caused by inter bunch effects.

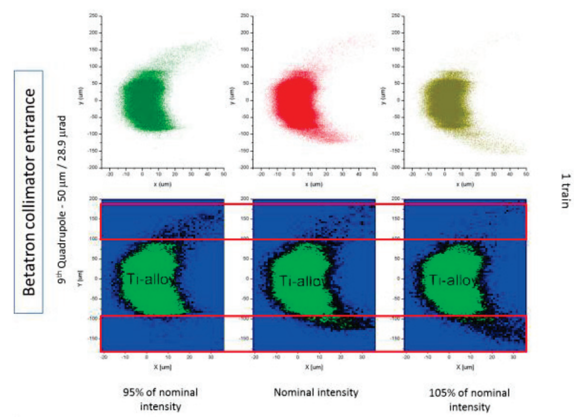

Figure 8: Beam profile (top) and charge density distribution (bottom) for a ±5% intensity error for a 29 μrad kick at the main LINAC. The betatron collimator positions are outlined by the red square.

CONCLUSIONS

Various failure scenarios were studied and the potential damage these failures could cause to the accelerator structures was estimated with main emphasis on the damage the charge density could cause on the betatron collimators. The analysis of the large data set allowed us to understand the beam dynamics, the interaction that high brilliant beams with materials may have, and to estimate dangerous conditions. Furthermore it will help to develop methods and diagnostics for machine protection control systems and to improve the mechanical design of collimators. Future studies will allow evaluation of more complex failure scenarios and it will include the effect of induced current on metallic structures with the aim to set operational constraints and to further improve methods and procedures already foreseen.

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