EFFECTS OF THE EXTERNAL WAKEFIELD FROM THE CLIC PETS

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Abstract

The Compact Linear Collider (CLIC) main linac accelerating structures will be powered by the Power Extraction and Transfer Structures (PETS) located in the drive beam decelerators. Misalignments of the PETS and drive beam injection jitter will excite dipolar modes in the couplers of the main linac structures that will kick the beam leading to beam quality degradation. In this paper, the impact of such dipolar kicks is studied, and tolerances based on analytical estimations, both in the single- and multi-bunch regimes, are derived. Numerical simulations obtained using the tracking code PLACET confirm the analytical estimates.

INTRODUCTION

The External Wakefield from the PETS

In CLIC, the accelerating structures of main linac are powered by the Power Extraction and Transfer Structures (PETS) of the decelerator. When the drive beam traverses the PETS with an offset, wakefields are induced in the PETS extractor. These wakefields can slip into the accelerating structures of the main linac (see Fig. 1 and [5]). Due to the symmetry of the RF structures [1], these wakefields deflect the beam mainly through horizontal dipole modes. These modes are mainly at 17 GHz [1] and in the main linac, see Fig. 2, because of the heavy damping of the High-Order-Modes (HOM) in the accelerating cells [4], they get trapped in the couplers of the accelerating structures, where they kick the beam with high Q factors.

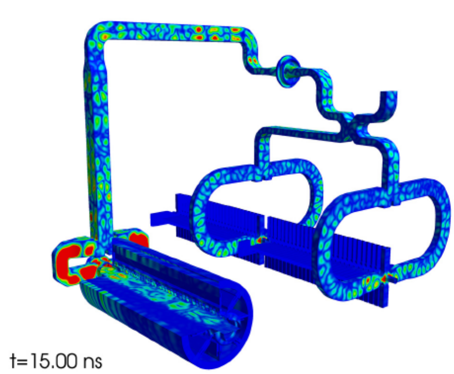


Figure 1: Pictorial representation of the RF network connecting the PETS with the main linac accelerating structures. The picture shows a transient electric fields for the "single dipole X" case.

One can represent the external dipole mode induced by a single drive beam with the following formula:

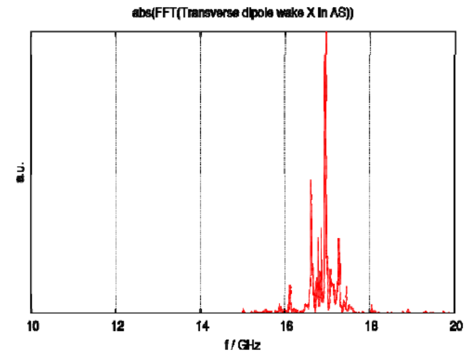


Figure 2: The external horizontal dipole modes in the frequency domain.

$$U = W_x \, x_{\mathrm{PETS}} \, \sin(\frac{2\pi}{\lambda} z + \varphi_0) \exp(-\frac{\pi}{\lambda Q} z), \quad (1)$$

where: $W_x \simeq 275 \ \mathrm{V/bunch_{PETS}/mm_{offset\ in\ PETS}/2AS}$ is the amplitude of the wakefield generated by a single drive-beam bunch on two accelerating structures (2AS): in fact, as illustrated in Fig. 1, every PETS feeds two consecutive accelerating structures. In Eq. 1, λ is the wavelength at 17 GHz, $0.15 \ \mathrm{m}/8.5$ expressed in units of main-linac bunch spacing: that is 6 RF-buckets at 12 GHz; $Q = 1500$ is the quality factor [1]; φ_0 is the phase seen by the first bunch on the main beam; z is the position in the main beam train, and x_{PETS} is the beam offset in the PETS.

External Wakefield Induced by a Consecutive Drive Beam

By "consecutive drive beam" we mean a train of drive beam without the empty bunches otherwise utilized for compensating the beam-loading in the main linac [6]. In such a drive beam, the bunch offsets tend to the same value typically after 10 bunches. The wakefield of this steady state is about half the one from a single bunch: $W_x \simeq 138 \ \mathrm{V/bunch_{PETS}/mm_{offset\ in\ PETS}/2AS}$. In the following, when we will talk about wakefields from consecutive drive beams, we always refer to the steady state.

Drive Beam for Beam-Loading Compensation

To limit luminosity losses to less than 1%, the rms bunch-to-bunch relative energy spread in the main beam must be below 0.03% (see [3] for details). A special pulse shape in the drive beam is used to compensate this energy spread effect induced by the transient beam-loading in the main linac [2, 6]. Empty RF bunches in a drive-beam train, can induce additional kicks on the main beam. To study these additional kicks, we first consider the kick from a drive beam with a single bunch in a train.

In the following, two sources of external wakefields are considered: misaligned PETS and drive beam injection jitter. The dipole kick from the PETS to the main linac will lead to a beam offset or jitter and emittance growth at the exit of main linac, thus will lead to a luminosity loss. For the case of misaligned PETS, we will study the additional kicks from a single drive beam, and the kicks from a consecutive drive beam as well. For the case of drive beam injection jitter, we only present the kicks from a consecutive drive beam. The study on the additional kicks is ongoing.

IMPACT OF MISALIGNED PETS

A realistic configuration of the beam positions in the PETS should in principle be obtained through accurate simulation of a reaslitic decelerator drive-beam; anyway, in first approximation, useful conclusions can be obtained also considering the simplified case of a point-like drive-beam bunch traversing the PETS with an offset. We rewrite Eq. 1 as

$$U = A\,\sin(\frac{2\pi}{\lambda}z + \varphi_0)\exp(-\frac{\pi}{\lambda Q}z), \tag{2}$$

where $A = W_y\sigma_{y,\mathrm{PETS}}$ [V/m] is the average kick. The impact on horizontal axis scales with the vertical results.

Single-Bunch Effects in the Main Beam

We study the case with $Q = \infty$ and $\varphi_0 = \pi/2$, which represents the worst possible scenario. We analyze analytically, and then simulate, the beam offset for a single bunch of main beam under the effect of the PETS-induced kick. The relative vertical beam offset at the exit of the main linac for a point-like bunch is:

$$\frac{\left\langle y_f^2\right\rangle}{\sigma_{y_f}^2} = \frac{LA^2e^2}{\varepsilon_y mc^2}\sum_{i=1}^{N_{\mathrm{PETS}}}\frac{\beta_i L}{2E_i}, \tag{3}$$

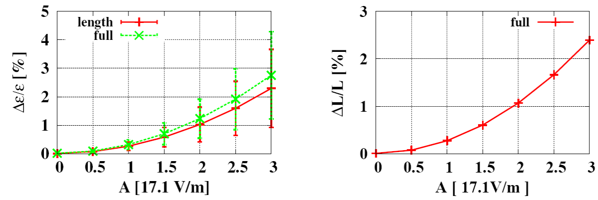
where L, β_i, and E_i are the length, the beta function, and the beam energy in an accelerating structure powered by the i-th PETS. For CLIC at 3 TeV in the center of mass,

$$\frac{\sqrt{\left\langle y_f^2\right\rangle}}{\sigma_{y_f}} = 5.85\cdot 10^{-3}A\,[\mathrm{V/m}] \tag{4}$$

To limit the relative vertical beam offset to less then 0.1 σ_y, one obtains that $A \leq 17.1$ V/m. The impact on the horizontal axis is diluted by a factor $\sqrt{\frac{\varepsilon_x}{\varepsilon_y}} = \sqrt{60}$. The luminosity loss can be estimated as

$$\frac{\Delta L}{L} \simeq \frac{1}{2}\frac{\Delta\varepsilon_y}{\varepsilon_y} + \frac{1}{4}(\frac{\Delta y}{\sigma_y})^2 \simeq \frac{1}{2}\frac{\Delta\varepsilon_y}{\varepsilon_y} + \frac{1}{2}(\frac{y_{\mathrm{rms}}}{\sigma_y})^2.$$

The plots in Fig. 3 show these results. We conclude that, to limit the relative luminosity reduction due to beam offset and emittance growth to less than 1%, the amplitude of the dipole kick should be less than 32.5 V/m. The impact on the horizontal axis is diluted by a factor $\frac{\varepsilon_x}{\varepsilon_y} = 60$.



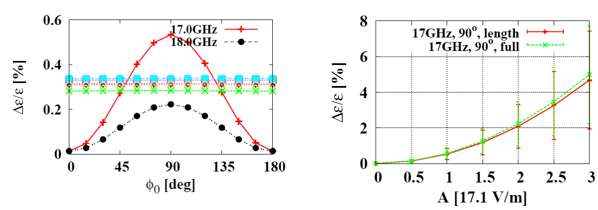
(a) (b)

Figure 3: Single-bunch simulations: (a) relative emittance growth at the main linac exit; (b) luminosity reduction as a function of the kick amplitude. The labels: length and full mean, respectively, full-length bunch with $\Delta E/E = 0$ and fully-featured bunch.

Multi-Bunch Effects in the Main Beam

Again, we study the worst case: $Q = \infty$. We concentrated on the multi-bunch emittance growth because the offset of a train can in principle be correct at the exit of main linac. The impact of phase and frequency of the dipole kick on the emittance growth is studied.

The phase dependence of Eq. 1 is such that the kicks for $(A, -\varphi_0, f)$ and $(A, \pi - \varphi_0, f)$ are the same, therefore it is enough to simulate φ_0 from 0 to 180 degrees. Similarly, it is enough to simulate the frequency in the range 17 to 18 GHz, since $(A, \varphi_0, 17 - \Delta)$ is equivalent to $(A, \pi - \varphi_0, 17 + \Delta)$. We studied several cases around $A = 17.1$ V/m. Figure 4 shows that the amplitude must be less than 31 V/m to keep the relative luminosity loss due to beam offset and emittance growth to less than 1%. The impact on the horizontal axis is diluted by a factor $\frac{\varepsilon_x}{\varepsilon_y} = 60$.



(a) (b)

Figure 4: Multi-bunch simulations: (a) estimated relative emittance growth at slightly different frequencies in the vicinity of 17 GHz; (b) dipole mode at 17 GHz as a function of A. In (a), the bump at $\varphi_0 = 90$ degrees for $f = 17$ GHz: the bunch spacing is such that the every bunch in the train experiences a dipole kick with opposite sign.

Effect of Wakefields from a Consecutive Drive Beam

We study the effects of wakefield from a consecutive drive beam. We apply the steady wakefield from a consecutive drive beam: $W_x \simeq 138$ $\mathrm{V/bunch_{PETS}/mm_{offset\ in\ PETS}/2AS}$. The procedures is the same as the single drive beam case. We found that the luminosity reduction is negligible, less than 0.06%.

DRIVE BEAM INJECTION JITTER

When the drive beam has an initial pulse-to-pulse position or angle jitter, the 24 decelerators behave like 48 independent jittering components. The drive beam jitter amplitude has been estimated as $\sigma_{x_0} = 135\ \mu$m, $\sigma_{x_0'} = 237\ \mu$rad. For drive beam injection jitter, consider a consecutive drive beam. We concentrate on the multi-pulse emittance (the overlying projected emittance of subsequent pulses), because the CLIC pulse is so short that applying an intra-train feedback at the end of the main linac is impossible.

Single-Bunch Effects in the Main Beam

Analysis of position jitter at the exit of main linac: the local kick in the accelerating structures powered by the i-th PETS of the m-th decelerator is :

$$\Delta x'_{mi} = \frac{W_x \tilde{x}_{mi} L e}{E_{mi}}$$

The drive beam offset in the PETS $\tilde{x}_{mi}$ can be obtained by linearly combining the offsets due to the injection position jitter or angle jitter:

$$\tilde{x}_{mi} = A_{x_0 m}\, \tilde{x}_{mi}(x_0) + A_{x_0' m}\, \tilde{x}'_{mi}(x_0')$$

where $\tilde{x}_{mi}(x_0)$ and $\tilde{x}'_{mi}(x_0')$ are the drive-beam offsets in the PETS due to the injection position jitter x_0 and angle jitter x_0'. They are taken from a realistic drive beam simulation [7]. $A_{x_0 m}$ and $A_{x_0' m}$ are the scales. In our simulation we set $x_0 = 1\ \mu$m, $x_0' = 1\ \mu$rad and considering one sigma jitter the scale should be:

$$\left\langle A^2_{x_0 m} \right\rangle = \sigma^2_{x_0},\ \left\langle A^2_{x_0' m} \right\rangle = \sigma^2_{x_0'}.$$

The final position jitter is:

$$x_f = \sum_{m=1}^{N_{DEC}} \sum_{i=1}^{N_{\mathrm{PETS},m}} \sqrt{\frac{\beta_f}{\gamma_f}} \cdot$$

$$\cdot \sin(\varphi_f - \varphi_{mi}) \sqrt{\beta_{mi}\gamma_{mi}} \Delta x'_{mi},$$

where N_{DEC}, $N_{\mathrm{PETS},m}$, φ_f, φ_{mi}, β_{mi}, γ_{mi} are the numbers of decelerators, numbers of PETS in m-th decelerator, lattice phase at the exit of main linac, lattice phase, beta function and lorenz factor at the accelerating structures.

Then we estimate the final beam jitter using the analytic formula considering the steady wakefield from a consecutive drive beam : $\frac{x_{rms}}{\sigma_x} \simeq 0.006$. The emittance growth for the "length" and the "full" cases contain the growth from chromatic filamentation due to mismatch between different sector lattices of main linac. See Fig. 5. The "point" refers to point like bunch simulation.

Multi-Bunch Effects In the Main Beam

The procedure is the same as single-bunch effects. We get almost the same results as the multi-bunch wakefield is negligible. The luminosity loss for a multi-pulse emittance growth can be estimated with $\frac{\Delta L}{L} \simeq \frac{1}{2}\frac{\Delta\varepsilon_x}{\varepsilon_x}$. For the

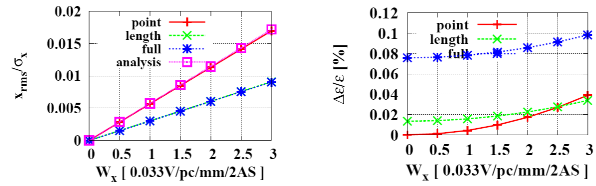


Figure 5: Multi-pulse emittance growth of a main linac single bunch in case of drive-beam injection jitter.

external wakefield from a consecutive drive beam due to injection jitter, the final beam jitter and multi-pulse emittance growth are negligible so as it is the luminosity reduction. A simulation using a realistic drive beam pulse is still ongoing.

CONCLUSIONS

The degradation of main beam quality and its consequent impact on the luminosity due to the kick induced by the PETS to the main linac accelerating structures has been derived analytically, then verified in simulation. Two cases have been studied: a drive beam with statically misaligned PETS, and a drive beam in the presence of dynamic injection jitter. The impact of the kick on both a single-bunch and on an entire train have been studied. In both cases the kick from a consecutive drive beam lead to negligible degradation of main beam and luminosity reduction.

In the case of a drive beam with statically misaligned PETS, we studied the additional kicks from the empty RF bunches, in a drive-beam train used for beam-loading compensation.The tolerances on the kick have been derived analytically, then verified in simulation. In this case, to keep the luminosity loss below 1%, the amplitude of the dipole kick should be less than 31 V/m. The authors are working on evaluating the additional kicks from the gaps in a drive beam with a realistic pulse.

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