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PLACET3: 6D TRACKING THROUGH PETS' AND ACCELERATING STRUCTURES' WAKEFIELDS

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Abstract

We present the latest updates to the PLACET3 tracking package, which focus on the impact of both transverse and longitudinal wakefields on a beam travelling through accelerating and decelerating structures. The main focus of this update was the first implementation of 6D tracking through Power Extraction and Transfer Structures (PETS) for the Compact Linear Collider (CLIC), which is described through short and long-range longitudinal wakefields. Additionally, we present the impact of different numerical schemes on the computation of wakefields in accelerating structures.

INTRODUCTION

In recent years, the design specifications of state-of-the-art accelerator facilities have become increasingly strict, which has created a demand for increasingly complex and accurate simulation tools. `PLACET` [1] was developed to track low emittance electron bunches through the Compact Linear Collider (CLIC) and the International Linear Collider (ILC), as well as the high-intensity beams of the CLIC Drive-Beam. `PLACET2` [2] was developed as the primary simulation tool for accelerators with a re-circulating topology such as CLIC Test Facility 3, CLIC's Drive-Beam recombination complex, and Energy Recovery Linacs such as the Large Hadron-electron Collider (LHeC) and the Powerful Energy Recovery Linac Experiment (PERLE). `PLACET3`, here presented, consolidates the functionalities of its two predecessors while expanding its scope to include non-electron species in anticipation of the needs of future muon collider designs.

One of the most impactful higher-order effects on the dynamics of linear accelerators is that of wakefields in RF structures. This phenomenon is traditionally detrimental to accelerator operation, but some novel designs, such as CLIC, take advantage of it to efficiently transfer power out of the beam. Either way, the accurate simulation of wakefields is paramount for accelerator design, characterization, and optimization. Specifically, regarding power extraction, `PLACET` is currently the only tracking package with a dedicated element for Power Extraction and Transfer Structures (PETS). This paper will discuss the newest update to `PLACET3`'s wakefield modelling, benchmark it, and demonstrate it by tracking CLIC's Drive-Beam through its decelerator section.

MODELLING WAKEFIELDS

Wakefields can broadly be understood as the electric field generated by the interaction between a travelling particle and changes in the beampipe geometry. The vacuum-chamber geometry establishes a wake function, $\omega(t)$, characterizing how the field evolves and dampens with time. For `PLACET3` users, $\omega(t)$ can be defined as an interpolation table or a list of cosine modes. For the purpose of tracking, it is necessary to know, for a given longitudinal bunch slice which passes a given location at time τ, what is the wakefield potential $W(\tau)$ due to all preceding charges. This is computed by convoluting $\omega(t)$ with the charge distribution. Assuming a cylindrically symmetric wake function, the wakefield potential seen by a slice can be separated into its longitudinal component

$$W_L(\tau) = \int_0^\infty \omega_L(t)\lambda(\tau - t)dt \tag{1}$$

and its transverse component

$$W_T(\tau) = \int_0^\infty \omega_T(t)\mu(\tau - t)\lambda(\tau - t)dt\,, \tag{2}$$

where $\lambda(t)$ is the longitudinal charge distribution and $\mu(t)$ is the average transverse offset at τ. In addition to the transverse-longitudinal separation, our implementation distinguishes between short-range (intra-bunch) and long-range (bunch-to-bunch) interactions.

The effect of short-range wakefields while a bunch travels through an element is computed by slicing said element into two or more sections and applying the wakefield on the bunch. At the same time as the bunch traverses the computational node between those sections. Computation limitations require us to model the bunch as a discrete longitudinal mesh of charged slices to calculate Eqs. 1 and/or 2, which is one of the bunch models supported by `PLACET1`. This model, however, does not account for changes in the longitudinal charge distribution that may occur due to momentum spread

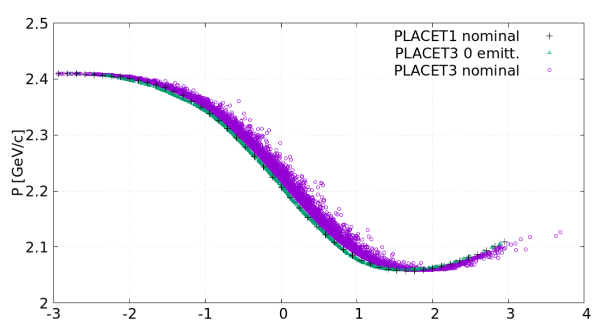

Figure 1: Single-bunch tracking of the third stage CLIC decelerator. PLACET1's results obtained from [3].

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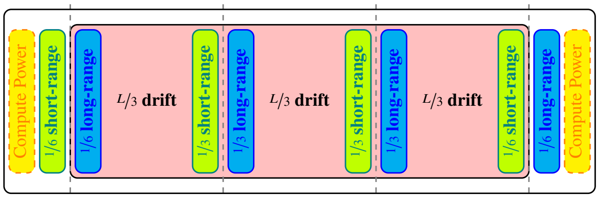

Figure 2: Schematic representation of a PETS element.

and/or betatron oscillation (PLACET1 does offer a full 6D bunch model alternative, but not with an option to compute wakefields). For PLACET3, which offers only the 6D model, we opted for an intermediate solution: using a Fast Fourier transform at the site of each wakefield computation, we generate a longitudinal charge mesh and perform the required convolution with the wake function to generate a wakefield potential mesh. This mesh is then interpolated to apply a transverse momentum kick for each macro-particle in our continuous distribution. The most notable difference between this model and PLACET1'a is that, in between wakefield estimations, these macro-particles are allowed to drift longitudinally, altering the charge distribution before the next mesh computation.

As an example of the effect of a short-range longitudinal wakefield, Fig. 1 presents the tracking results of a Drive-Beam bunch through the third-stage CLIC decelerator. In the figure, we can see that a bunch with nominal transverse emittance (150 µm) is both lengthened by ~1.2% and delayed by ~0.13 mm ≡ 0.42 ps as it travels along the decelerator. These results would surpass the requirements established in [4] but can be mitigated by adjusting the initial bunch length for the former and the longitudinal PETS position for the latter. This result is further discussed in [5]. For benchmarking purposes, the tracking of a 0-emittance bunch that suffers no longitudinal drift driven by betatron oscillations and the results of a PLACET1 simulation is also shown. The two latter results agree as expected.

Regarding long-range wakefields, even though their underlying physics is similar to their short-range counterpart, the distance between the bunch generating the wakefield and the bunch witnessing it allow for the treatment of the former as a point source rather than a longitudinal mesh. For this reason, when tracking through elements that play a major role, such as the PETS, the element implementation separates the two effects and applies them sequentially, as shown in Fig. 2. Additionally, one must consider the group velocity of the travelling field to determine how delayed a following bunch can be from the driver to interact with its wakefield before the latter reaches the end of the structure. This effectively limits the number of preceding bunches affected by any given bunch. Using the CLIC Drive-Beam decelerator as an example, this limits the number of generating bunches to the previous 10 in the pulse, after which the pulse is said to reach its steady state.

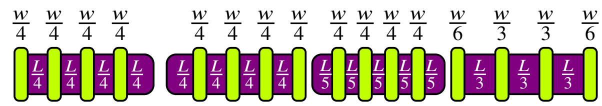

Figure 3: From left to right: upstream, downstream, mid-element and leapfrog integration schemes using four nodes.

ELEMENT SLICING METHODS

In tracking simulations, estimating the impact of the wakefield on the beam as it travels through a given element of length L is done in a discrete position of that element, even though the momentum or transverse kick resulting from the wakefield-beam interaction (w) happens continuously. To increase computing accuracy (at the expense of computing time), one relies on slicing the element in multiple sections and applying a fraction of the total kick w in the nodes placed on the border of these slices. The degree of accuracy of this technique depends on the number of nodes n and the spacing between the nodes. Figure 3 shows four slicing methods which we will compare in this section. Though, for $n \to \infty$, all these slicing schemes converge, this section aims at selecting which of the four converges faster, given a fixed number of computing nodes ($n = 4$ in the figure).

The most straightforward approach is simply alternate between applying w/n and transporting the beam through L/n, leaving us with the choice of whether to start with the wakefield node and finish with a travel slice (upstream integration) or vice-versa (downstream integration). Alternatively, to avoid potential systematic over or under-estimations, we can slice the element in $n+1$ slices and only apply the wakefield node to the interior borders between slices. Finally, we have tested a method commonly referred to as "drift-kick-drift", which is inspired by leapfrog integration. With it, we slice the element in $n-1$ slices and place nodes of impact $w/(n-1)$ in the interior slice borders, and we add one node to each element end-cap with half the impact of the interior nodes. This last method is slightly more complex to implement, but it requires one less travel slice computation.

We studied short-range transverse wakefields during intra-element transport to compare the four slicing methods. Both their direct effect is on transverse divergence (x') and their

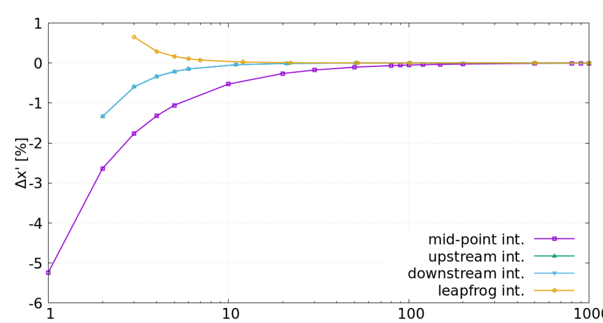

Figure 4: Short-range transverse wakefield convergence benchmark: x' error for the different slicing methods.

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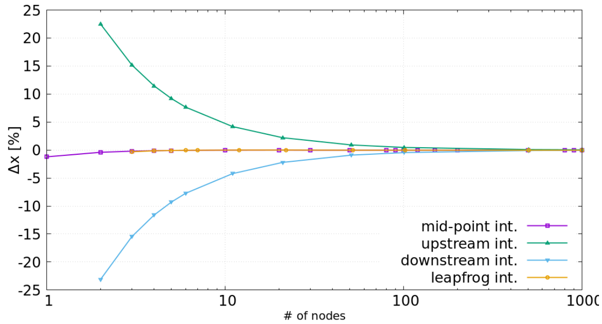

Figure 5: Short-range transverse wakefield convergence benchmark: x error for the different slicing methods.

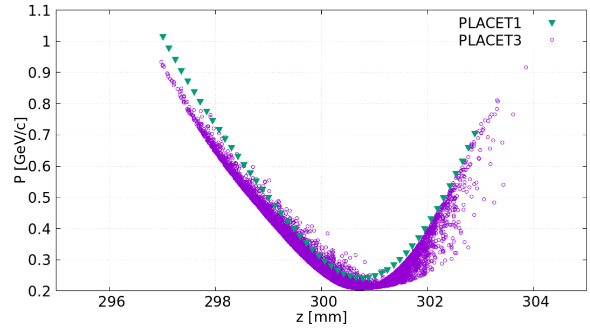

Figure 7: Longitudinal profile of a steady-state Drive-Beam bunch after deceleration.

indirect effect is on transverse offset (x). We tracked a zero-emittance bunch with a 1 mm horizontal offset through an accelerating structure with an increasing number of nodes and with all four methods. As shown in Fig. 4, when checking only the effect on the directly affected coordinate (x'), the mid-point integration underperforms when compared with the other three methods, which present almost identical convergence rates, albeit the leapfrog method overestimates the effect for a low number of nodes. In contrast, the upstream and downstream methods underestimate it. However, the results of Fig. 5 clearly show that for properties whose dynamics depend on the indirect interaction between nodes and slices (such as x in our test case), the upstream and downstream methods are inferior up to a fairly high n, thus not advisable for this kind of application. Overall this leads us to conclude that, in scenarios where $n \geq 3$, the leapfrog method is the most advisable. We expect the results to be generalizable to most higher-order effects that require element slicing.

CLIC DECELERATOR

The third-stage CLIC Drive-Beam decelerator is a useful case study to test PLACET3's newest capabilities. This 878-meter-long sector extracts up to 90% of the energy form the 8.4 nC, 2.4 GeV Drive-Beam in order to power the CLIC Main-Linac. The energy extraction is performed in 1492 PETS with 21 cm of length, a fundamental longitudinal mode at 12 GHz (same as the beam frequency) and

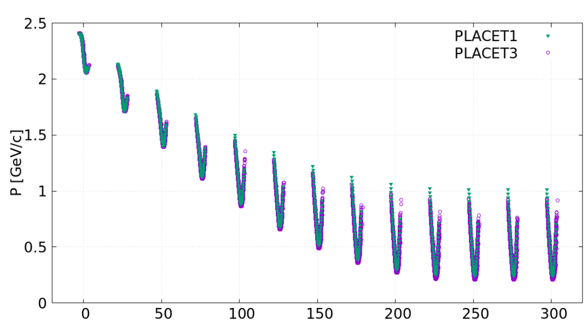

Figure 6: Longitudinal profile of the Drive-Beam train after deceleration, from the start of the pulse until steady-state.

a group velocity of $\beta_g = 0.45$. The high charge and short distance between bunches allow for both short-range and long-range wakefields to play a major role in the dynamic of this beamline.

Using PLACET3, we generated and tracked the Drive-Beam pulse to compare with the results from [3]. Figure 6 shows the cumulative longitudinal wakefield effect along the pulse momentum from the first bunch up to the steady state. A comparison with the previous PLACET1 results validates the macro-scale dynamics of the decelerator. Figure 7, zooms in on a single steady-state bunch and demonstrates the consequences of the modelling difference from one tracking code to the other. In it we can see how the betatron-driven longitudinal drift alters the shape, length and centroid of a well behaved bunch, to which one must add the effects of dynamic jitter studied in [6]. A future study is necessary to evaluate the effect of both effects on the most recent decelerator lattice.

Though this study was made with relatively well behaved bunches to allow for the comparison with [3], PLACET3 allows for the generation and tracking of any number of bunches from the 2928-bunches-long Drive-Beam pulse, inserting any number of charge, position or shape errors to any individual bunch within the pulse. Making use of these capabilities, a more exhaustive study of the first-stage CLIC decelerator lattice design and characterization is being presented in [5].

CONCLUSION

Wakefields can play a decisive role in the beam dynamics while the bunch is travelling through RF accelerating structures or PETS. In this paper, we present and benchmark our new 6D implementation of this effect in PLACET3 and a comparison between element slicing methods in the form of a convergence study. We conclude that the "leapfrog-inspired" method is preferable for our purposes. Furthermore, we made use of this new tracking code to simulate the third-stage CLIC decelerator lattice, revealing that betatron-driven longitudinal dynamics play a significant role in the dynamics of the CLIC decelerator and that the capabilities of PLACET3 are required to characterize said effect and optimize the beamline design to mitigate it.

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