Single and Multi-bunch Wakefields Effects in the TESLA Linac

Alban Mosnier, Armen Zakharian†
CEA, DSM/DAPNIA/Service d'Etudes d'Accélérateurs
CE-SACLAY,F-91191 Gif/Yvette Cedex, France

Abstract

Once the tolerable emittance growth of a beam accelerated in the main linac of a linear collider, departing from a perfect transport line, is fixed, all the tolerances on the various errors, like injection jitter, magnets and structures misalignment, can be in principle determined. The maximum allowable magnitudes of the errors however are closely related to the correction schemes considered in the machine. Furthermore, one correction method, which is favourable for single bunch effects, may be disastrous for multi-bunch effects, and vice versa. This observation led us to develope a tracking code named DILEM, which combines simultaneously single and multi-bunch effects[1] and includes numerous correction techniques, from orbit steering to wakefields compensation methods. Thus, we are able to evaluate the emittance dilution reduction not only for the first bunch but also for the entire bunch train. After a brief description of the code, results of simulations applied on the TESLA linac parameters are presented. In addition to the beam orbit corrections, like "one-to-one", "Dispersion Free" or "Wake Free" [1], further correction methods of emittance dilution, like non dispersive bumps or fast kickers [2] are also tested. The discrepancies in the results depending on wether the short- and long range effects are separately or simultaneously taken into account, are then discussed.

1. TRACKING CODE DILEM DESCRIPTION

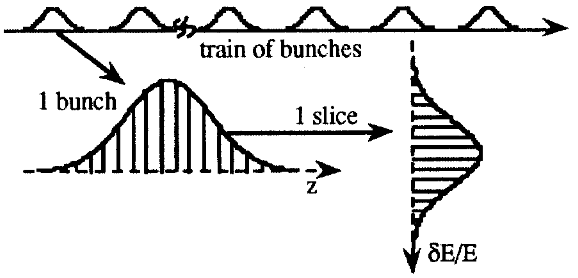

Figure 1 : The train is split into bunches, slices and subslices

Each bunch of the train (figure 1), as usual, is divided into N slices, typically 41, along the z-axis, with a gaussian charge distribution truncated at a couple of rms bunch lengths, in such a way that a slice in a bunch experiences the wakes induced by all the previous slices of this bunch but also by all the previous bunches of the train. Each slice itself is again divided into n subslices along the energy-axis, in order to take into account the chromatic effects of uncorrelated energy spread, which can be important at the beginning of the linac for injected beams of non-vanishing energy spread. All these macro-particles, defined by three indexes (bunch, slice, subslice) and associated to a charge, an energy, a centroid and a beam matrix, are tracked successively down the discrete focusing and accelerating elements forming the linac. The overall rms emittance and energy spread of the entire bunch train are computed along the machine and at the exit by a triple summation on the bunches, the slices and the subslices. For example, the kick angle imparted by a structure to a macroparticle i and belonging to the bunch m is given by

$$\Delta x_i' = \frac{e}{E_i}\left\{\sum_{j<i}^{N} Q_j x_j W_\perp^{s.r.}(z_j - z_i) + \sum_{k<m}^{M} Q_b x_k W_\perp^{l.r.}(z_k - z_m)\right\}$$

where $W_\perp^{s.r.}$, $W_\perp^{l.r.}$ are the short- and long-range point-like wakes; x_k, x_j are the bunch and slice (averaged on the subslices) offsets; Q_b, Q_j are the bunch and slice charges.

All the errors (quad, cavity and BPM offsets, cavity tilts, gradient-spread, frequency-spread of the dipole modes,...) are generated for the whole machine at the beginning of every new run and stored in scratch files. The accelerating field error, which induces the bunch-to-bunch energy spread, depends on the structure type and hence is read from a separate input file. For the TESLA cavity, the amplitude and phase errors during the beam pulse are caused mainly by the Lorentz forces. The net energy gain of the slice i belonging to bunch n is then

$$\Delta E_{i,n} = \Delta E_n \cos(\phi_n^{rf} + \delta\phi_i) + e w_i$$

where ΔE_n and ϕ_n^{rf} are the peak energy gain and phase for the bunch n, including the amplitude and phase errors, $\delta\phi_i$ is the phase of slice i with respect to the bunch center and w_i is the z-dependant longitudinal bunch wake.

The three orbit correction techniques, i.e. one-to-one, Dispersion Free (DF) and Wake Free (WF) [1], with the possibility of using multiple trajectories [2], are identical to the ones previously implemented in the distinct single-bunch (SB) and multi-bunch (MB) codes, except the bunch index, for which the trajectories are read by the BPMs, must be specified. In addition to these beam orbit corrections, further methods of correcting the emittance dilution heve been implemented, like the multiple non dispersive bumps [3] or the use of fast kickers [2] installed at a few judicious locations along the linac. The bumps are normally used to compensate globally the short-range wakefields induced in particular by cavity alignment errors. Once the bumps locations and the number of oscillations have been chosen by the user, the code looks for the amplitudes for each bumps pair, which

---

† On leave from Erevan Physics Institute, Armenia

[1] The first tracking code combining single and multi-bunch effects for emittance growth computation in linacs was presented by K. Kubo at the Fifth Intern. Workshop on Next-Generation Linear Colliders, SLAC, Oct 13-21, 1993.

minimize the beam emittance just before the next downstream bumps pair. Fast kickers are used for the re-alignment of multiple bunches, scattered by the long-range wakefields (beam breakup). In the same way, once the locations of fast kickers pairs have been chosen, the code adjusts the kick amplitudes imparted to each bunch of the train, to zero the measurement of the 90° phase-shifted, downstream BPM, except for a BPM error plus a kick error (figure 2).

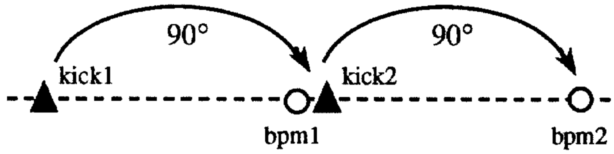

Figure 2 : Bunch re-alignment by fast kickers

2. TESLA LINAC

Since the s.c. cavities have low rf frequency and large iris aperture, short-range and long-range transverse wakefields effects and chromatic effects due to correlated bunch energy spread are low in the TESLA linac. The resulting tolerances were evaluated previously, see for example [4], by computing the emittance growth for SB and MB separately with the help of two distinct tracking codes. Table 1 shows the cavity, quadrupole and BPM alignment tolerances (assuming gaussian distributions truncated at ± 2 σ), which give a mean emittance growth lower than 10% among 50 different simulations, by using the optimal constant beta lattice (β=66m) and the classic one-to-one orbit correction.

cavity scatter	500 μm
quadrupole scatter	100 μm
BPM scatter	100 μm
BPM resolution	10 μm

Table 1 : Tolerances for the TESLA linac

More sophisticated correction algorithms, like DF or WF were also tested but without providing spectacular improvement because of the wakefield effects induced by the large cavity random offsets. When applying the orbit corrections for MB simulations, a first side-effect however was discovered [4], as soon as some bunch-to-bunch energy spread was introduced. This forced us into changing the correction method, which was only effective for the SB case. In fact, the trajectories of the different bunches in the train are strongly displaced from axis, leading to multi-bunch filamentation. Since the steady-state however is rapidly achieved, most of the bunches follow the same trajectory and this problem was solved by applying the static correction on the trailing instead of the leading bunches of the train.

3. ORBIT CORRECTIONS ALONE

The single-bunch rms energy spread can be reduced to 5.4 10^{-4} by running properly the bunch off the crest of the accelerating wave, while the rms bunch-to-bunch energy spread amounts to 2 10^{-4} in taking realistic fluctuations of cavity phase and amplitude during the beam pulse [5]. This results in an overall rms energy spread of about 6.9 10^{-4} for the entire bunch train. The orbit corrections gave the best results when the trajectory measurements are chosen for a bunch index larger than 150, when the steady-state is practically reached. The MB emittance growth is then much smaller than the SB emittance growth (more than 10 times), even in the presence of bunch-to-bunch energy spread. Therefore, we expect no big differences between pure SB simulations and combined simulations in TESLA. This was confirmed by DILEM, which gave emittance growths (average on 20 simulations) of 9.6 % with combined effects instead of 8.1 % with SB effects alone, by taking the simple "one-to-one" correction algorithm and the tolerances of table 1. Figure 3 shows an example of emittance dilution along the linac for MB alone (dashed line), SB alone (dotted line) and combined effects (solid line). The cavity, quadrupole and BPM errors are identical in the 3 simulations.

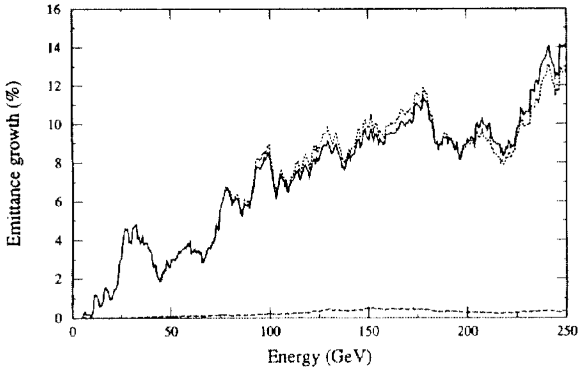

Figure 3 : Emittance growth for MB alone (dashed line), SB alone (dotted line) and combined effects (solid line) in the TESLA linac

Conversely, a linac with SB and MB emittance dilutions of the same order of magnitude, would have a net emittance dilution much larger than each of them. As an illustration, we assume that the damping of the dipole modes in TESLA are 10 times worse than the actual ones. Simulations of this fictitious linac show emittance growths of about 10% for SM or MB alone, but 3 times more (30%) with combined effects (see figure 4).

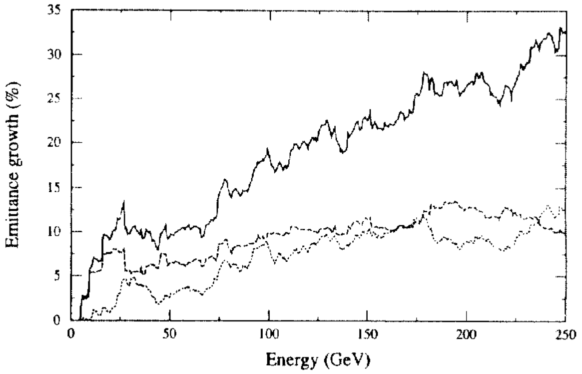

Figure 4 : Emittance growth for MB alone (dashed line), SB alone (dotted line) and combined effects (solid line) in a fictituous linac

4. ADDITIONAL ND BUMPS

In order to still more loosen the tolerances in TESLA, a global correction like non dispersive bumps [3] could be used. They might cancel the dilutions due to wakefields excited in particular in misaligned structures, where the other techniques fail. Three pairs of bumps, each with 3 oscillations, were distributed along the linac, at the beginning, at the middle and at 75%. The amplitudes of the bumps were first optimized by DILEM on a single bunch run. The largest emittance growth (30%) found among 20 different SB simulations was reduced by a factor of 6 (5%). The combined SB and MB simulation with the optimal bumps values gave about the same improvement (see figure 5).

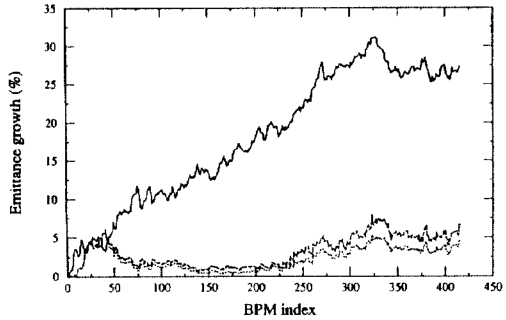

Figure 5 : Emittance growth in TESLA w/o bumps (solid line), with ND bumps for a single bunch (dotted line) and for a train of bunches (dashed line)

If we consider a linac with MB effects as strong as SB ones, this nice result cannot be repeated with simulations involving simultaneous SB and MB effects, because the bunches of the train have much larger trajectory differences. Degrading again the damping of the dipole modes in TESLA by a factor of 10, the overall emittance of the bunch train could be hardly improved (see figure 6).

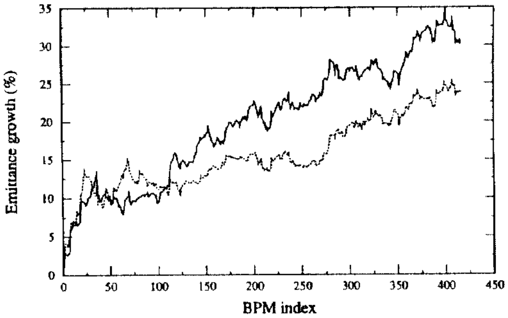

Figure 6 : Overall emittance growth with stronger MB effects w/o bumps (solid line), with ND bumps (dotted line)

5. ADDITIONAL FAST KICKERS

In a linac with a strong multibunch Beam Breakup, we could imagine to correct the individual orbits of the different bunches by means of fast kickers placed all along the linac [3]. Assuming a static orbit correction described in paragraph 2, based on the BPM readings of the last bunches, this dynamic bunch correction will not be very useful in TESLA because of the low MB dilution. The method was nevertheless tested by starting from the largest dilution caused by MB effects alone, among 20 simulations. Figure 7-a shows the reduction of the MB dilution after the adjustment by DILEM of the amplitudes of 2 kickers pairs located at the 100th and 300th half-cells. This improvement, however (7-b), disappears when the SB effects are added, as expected. If we now increase the MB effects, by lowering again the damping of the dipole modes, the efficiency of the method is evident even for 3 kickers pairs. Figure 7-c show the dilution reduction for MB alone (top-right) and combined simulations (7-d).

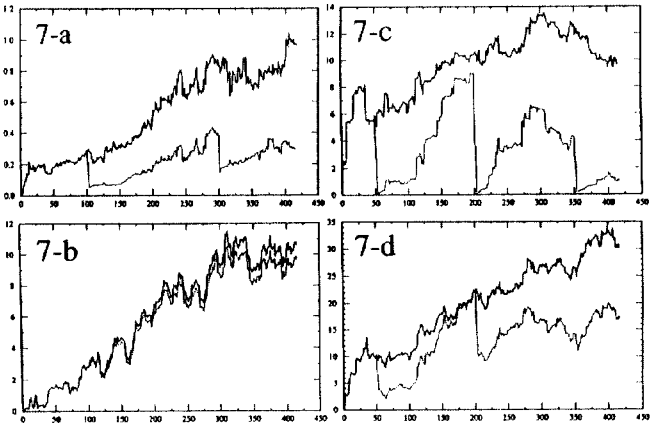

Figure 7 : Emittance growth with fast kickers correction before correction (solid line) and with kickers (dotted line)

6. CONCLUSION

A combined single and multi-bunch tracking code DILEM has been developed in merging two previous separate codes. The new correction techniques [3], like multi-trajectory DF and WF, non dispersive bumps for wakefields compensation or fast kickers for multiple bunches re-alignment have been implemented. The simulations demonstrate the necessity to take simultaneously into account the short- and long-range effects in the emittance growth evaluation, when both effects are of the same order of magnitude. Concerning the TESLA linac, since the multi-bunch dilution is much lower, the tolerances of table 1 given previously [4] are still valid and the use of a few bumps pairs would still more reduce the emittance growth (mean value of 10%).

7. REFERENCES

[1] T. Raubenheimer, "A new technique of correcting emittance dilutions in linear colliders", *Nucl. Inst. and Methods* , A306, 1991

[2] T. Raubenheimer in *Proc. of the Fith Intern. Workshop on Next-Generation Linear Colliders*, SLAC-436, 1993

[3] T. Raubenheimer, "The Generation and Acceleration of Low Emittance Flat Beams for Future Linear Colliders", SLAC-387, 1991

[4] A. Mosnier, "Beam Instabilities Related to Different Focusing Schemes in TESLA", *Proc. Part. Acc. Conf.*, Washington, 1993

[5] A. Mosnier and J.M. Tessier, "Field Stabilization in a Superconducting Cavity Powered in Pulsed Mode", these proceedings