Beam Instabilities Related to Different Focusing Schemes in TESLA

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Abstract

The preservation of beam emittances during the transport through the main linac is essential to achieve maximum luminosity. An increase of the beam area in transverse phase space occurs when beam trajectories are displaced from the accelerator axis : Chromatic effects due to the finite energy spread are generated by the focusing magnets while beam instabilities due to the excitation of wakefields are induced by the accelerating structures. The major sources of emittance growth of a beam accelerated in the TESLA main linac are studied for different focusing schemes, including the constant β and the energy dependent β lattices. Since the accelerating structures have a low rf frequency and a large iris aperture, very weak or even no BNS damping is necessary to cure the single bunch instability from coherent betatron oscillations. In addition, different orbit correction techniques have been tested and the resulting emittance dilutions are compared. However, the choice of the steering method will be determined mainly by the effects of the wakefields, both short-range and long-range, induced by the randomly displaced cavities, which are allowed to have a large scatter in their misalignments.

INTRODUCTION

An increase of the beam area in tranverse phase space arises from a variety of errors and is mainly driven by 3 phenomena : the short-range and long-range dipole wakefields and the dispersion resulting from the finite beam energy spread. The errors of main concern are quadrupole and cavity static misalignments, injection jitter, and quadrupole jitter due to ground motion. The effects of the major errors can be reduced in some cases thanks to various techniques (BNS damping, steering algorithms, de-Q'ing ...) and their maximum allowed magnitudes are then fixed once a limit on the emittance growth has been prescribed. A typical set of machine parameters for TESLA 500 with the high charge option [1] is listed below and have been used throughout this study.

Energy / Linac (GeV)	250
Injection energy (GeV)	3
Bunch population	$5\ 10^{10}$
Bunch length σ (mm)	1
Number of bunches	800
Bunch separation (µS)	1.
Eacc (MV/m)	25
Tot number of cavities	10000

Two focusing schemes have been considered : the FODO lattice with a constant focusing strength all along the linac (focal length and beta function); and the $E^{1/2}$ beta scaling suggested in [2] because it provides a BNS damping criterion [3] independent of energy. Since eight cavities per cryomodule are assumed, the modules are grouped in sections with matching cells in between such that the beta function best fits the $E^{1/2}$ law. The resulting beta function at the focusing quadrupoles and the exact scaling are shown in figure 1 for starting cells filled with one module. We should emphasize that the matching cells were assumed ideal and their quadrupoles perfectly aligned for the simulations.

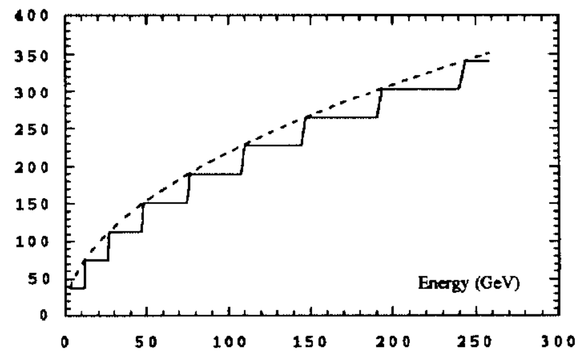

Figure 1 : Beta function for the actual scaling (full line) and for the exact scaling law (dashed line) at the focusing quads.

SINGLE BUNCH INSTABILITY

Injection jitter

When a beam is injected off-axis, the tail particles are driven on resonance by the wakefield of the head particles and oscillations will grow along the linac. Figure 2 shows the development of the emittance growth along the linac assuming a beam offset of 28.5 µm (half the beam size) for the constant (β = 66m) and energy dependent (starting β = 22m) beta lattices

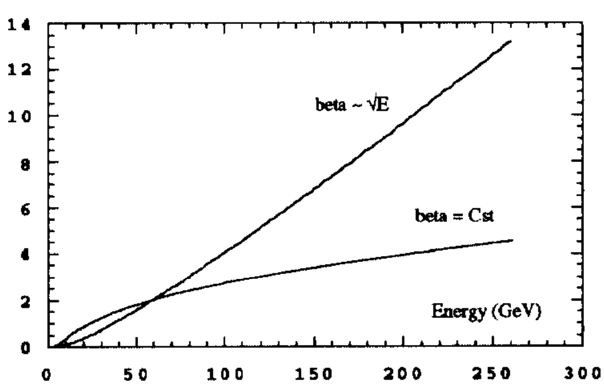

Figure 2 : Vertical emittance growth for both focusing lattices (beam offset = 28.5 µm).

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The instability driven by the short-range wakefields could be controlled by means of BNS damping by simply shifting the rf phase in such a way that the tail is more focussed. Although the damping is more efficient for the √E beta scaling, the damping conditions are barely achieved for the whole bunch. After optimization of the rf phase, the same dilution of about 1 % is found for both focusing lattices but the energy spread has been multiplied by a factor of 4, increasing the chromatic effects induced by the alignment errors. We conclude that BNS damping is not necessary for the constant β case since the final dilution is small (4 %) while keeping the energy spread to the minimal value of $5.5\ 10^{-4}$.

Alignment errors

In order to prevent a continually growing trajectory in the presence of quadrupole errors, the beam must be steered all along the linac. Different correction techniques have been tested on the TESLA linac and are recalled below.

1) The "one to one" correction : the BPM readings are zeroed such a way the beam is steered to the center of the quadrupoles. Chromatic dilution arises because the actual orbit follows the BPM errors, however.

2) The Dispersion Free correction [4] : the dispersive errors are cancelled by measuring the difference of 2 trajectories with effective different energies. The difference orbit and the original trajectory are then simultaneously corrected. The measurement of the difference orbit is then independent of the BPM errors but some errrors remain due to the finite BPM resolution.

3) The Wake Free correction [5] : two difference orbits must be minimized to correct both the dispersive errors and the wakefields effects (one by varying only the QF's and one by varying only the QD's).

These 3 correction algorithms were first tested on the TESLA linac (constant β = 66m) with a final energy spread of $1.5\ 10^{-3}$ assuming only quadrupole and BPM errors, and without any cavity errors. Figure 3 shows the beam slice centroids emerging from the linac as well as the beam ellipses of the first and last slices. This points out the benefit of the DF and WF algorithms (beam slices nearly superimposed) compared to the one to one algorithm (beam slices strongly diluted) where the dispersive errors are not corrected.

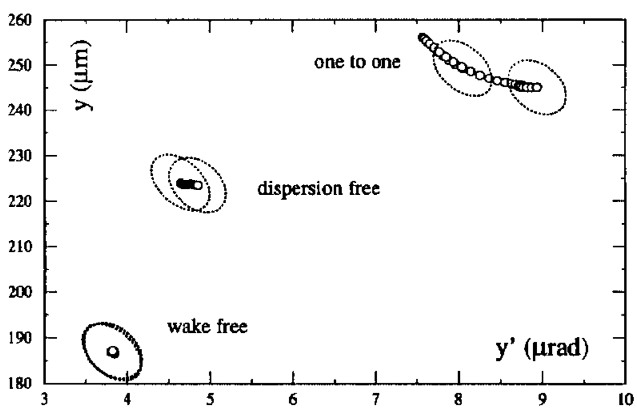

Figure 3 : Beam slice centroids and beam ellipses of the first and last slices at the linac exit in transverse phase espace.

The WF correction cancels the wakefields effects for a corrected trajectory but not the wakefields effects induced by the random errors of cavity misalignments. A less spectacular improvement is hence expected when using these non dispersive corrections in case of large cavity random offsets. Figure 4 gives the emittance growth for 10 sets of random errors for the constant beta lattice with different beta values for the 3 corrections. The √E beta scaling lattice with a starting beta of 22m gives about the same results than the constant β=66m lattice. The linac is corrected section by section, with each section containing 20 cells. The rms values of the errors chosen for these computations are :

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

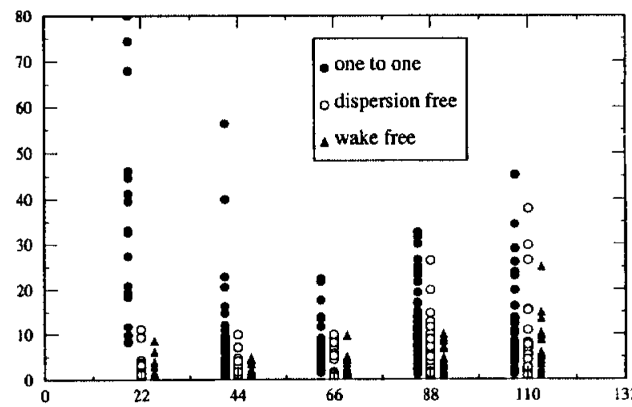

Figure 4 : Vertical emittance growths (%) for the 3 correction algorithms vs. beta (m) for the constant beta lattice

We note that the dilution has clearly decreased when using the DF or WF corrections, especially in the region of stronger focussing (higher number of cavities / half cell), as expected. The maximal emittance dilution is lowered by a factor of 2 to 4 with respect to the "one to one" correction used with the optimal lattice (β=66m). This improvement has however to be balanced by the fact that the simple "one to one" algorithm allows for a fast correction and then a feedback within the bunch train (bunch repetition frequency = 1 MHz).

MULTIBUNCH INSTABILITY

The growth of the transverse motion of the bunches due to the long-range wakefields are controlled in TESLA both by damping of the modes and by the frequency spread of each mode which spoils the coherence. We assume a mode frequency spread due to fabrication tolerances of 1 MHz and Q values of around or below 10^5 for the highest R/Q modes, in agreement with the measurements [6].

Injection jitter

When the beam is launched off-axis, both lattices (always with a starting beta value of 22 m for the √E scaling and 66m for the constant beta) give about the same results : a multibunch emittance of only 0.6 % of the single bunch emittance design value for a beam offset of 1 mm at the entrance of the linac when the dispersive errors are neglected. But if some bunch to bunch energy spread is introduced, the emittance dilution arises mainly from the partial filamentation due to the chromatic phase advance. The emittance growth is then 2 % of the design value for an injection jitter of 28.5 μm and an energy spread of 10^{-3}.

Alignment errors

Finally, we study the effects of cavities randomly misaligned with an rms value of 1 mm and neglecting any energy spread. The emittance at the exit would be only a few percent higher than the design bunch emittance for the constant β lattice with a mean beta of 66 m [7], while the emittance was found to be about 3 times higher for the energy dependent lattice with a starting beta of 22 m.

However, if a bunch to bunch energy spread is introduced, due, for example, to a systematic fluctuation of the cavity fields, the emittance becomes 10 times more, e.g. 0.4 10^{-6}, for an energy spread of 10^{-3}. Figure 5 shows the 800 bunches emerging from the linac in transverse phase space both with and without energy spread.

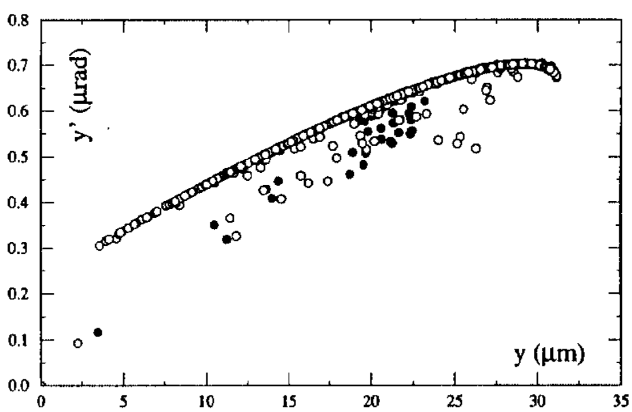

Figure 5 : Coordinates in phase space of the 800 bunches without (full circles) and with energy spread (empty circles).

For vanishing energy spread (full circles) the first bunches are slightly scattered but the others bunches form a dense core. For the energy spread of only 10^{-3} (empty circles), the plot reveals a large chromatic effect. In fact, the steady state regime is rapidly achieved in TESLA because of the strong mode damping, and after approximately 150 bunches, the next bunches follow the same trajectory, resulting in a small rms emittance if no energy spread is present. However, the beam is strongly displaced from the accelerator centerline as we can see in figure 6, where the trajectory of the last bunch is plotted along the linac exhibiting a betatron oscillation of final amplitude 20 μm. If the filamentation was complete, occuring at $\sigma_E/E = 5.10^{-3}$, the emittance would be 6.10^{-6} instead of 0.03 10^{-6} without dispersive errors.

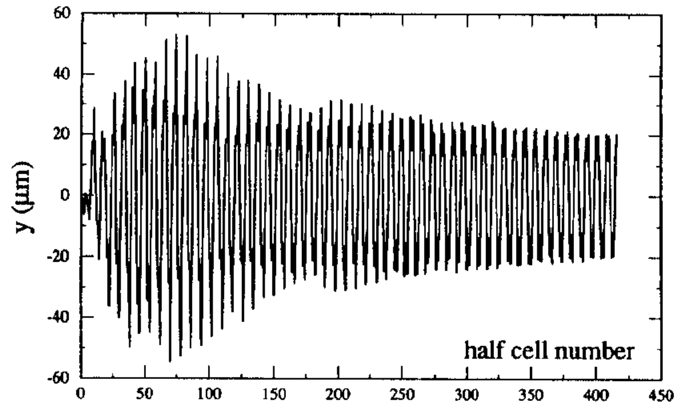

Figure 6 : Trajectory of the last bunch (steady state regime) for an energy spread of 10^{-3}.

In order to get rid of this wakefield-chromatic combined effect, which demands a stringent tolerance on the bunch to bunch energy spread (a few 10^{-4}), we could imagine a correction scheme which measures the trajectory once the steady state is achieved. This method was successfully applied by using the one to one correction where the wakefields effects can be easily taken into account with BPM readings on the last bunch. The initial emittance growth of a few percent obtained without energy spread was fully recovered with 10^{-3} energy spread assuming the BPMs perfectly aligned. Some computations were carried out with BPM and quadrupole alignment errors: the emittance becomes 0.13 10^{-6} with a rms BPM error of 100 μm; and 0.22 10^{-6} if an additional rms quadrupole error of 100 μm is added.

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