Higher Order Mode Effects and Multi-Bunch Orbit Stability in the TESLA Main Linac

N. Baboi and R. Brinkmann
DESY, Hamburg

October 27, 2000

Abstract

We investigate the stability of the multi-bunch orbit deviations caused by higher order modes (HOMs for short) in the accelerating structures of the TESLA linear collider. It is shown that the beam break-up (BBU) orbit pattern over the length of the bunch train is essentially static, i.e. invariant over long periods of operation time. The BBU effect can therefore be removed by a fast orbit feed-forward, which is part of the fast intra-pulse orbit correction system foreseen in the TESLA design.

1 Introduction

In the TESLA linear collider, multi-bunch beam break-up (BBU) due to HOMs can be kept at a tolerable level with very moderate assumptions on the HOM detuning and damping. The reasons are the very small wakefields in the low-frequency (1.3 GHz) structures and the large spacing between bunches (337 ns). It is nevertheless useful to investigate methods for further reduction of BBU, with respect to the following considerations:

- The variation of individual bunch offsets driven by HOMs affects only a small fraction of the entire bunch train, because due to HOM damping a steady state is reached after about one tenth of the beam pulse length (see below). Should the HOM quality factors exceed the presently expected values, the offset variations extend over a larger fraction of the beam pulse and the multi-bunch emittance growth increases.

- When operating with short beam pulses, the steady state may not be reached at all. This is undesirable for commissioning of the collider and it can also be a potential problem with certain modes of operation for the TESLA Free Electron Laser, for which relatively short "bursts" of bunches with large gaps in between instead of a continuous train are accelerated.

The large bunch spacing makes it easy to correct the individual offsets with a kicker system of a few MHz bandwidth. Such a system is foreseen at the end of the TESLA linac to remove pulse-to-pulse orbit jitter [1]. This fast digital feedback system also includes an adaptive feed-forward option, suitable to correct orbit errors on a bunch-to-bunch basis, which are reproducible from pulse to pulse. A prototype of the system was recently successfully tested at the TTF linac [2]. To which extend the BBU effect can actually be corrected with the feed-forward system depends on the variation of the multi-bunch orbit pattern from pulse to pulse. In the study presented here we have investigated this issue with computer simulations, taking into account orbit drift induced by ground motion, injection orbit jitter and bunch charge fluctuations.

2 Computer Simulations of the HOM-driven Beam Break-Up

In the present technical design, the main linac of TESLA consists of about 900 16 m long accelerator modules. For the arrangement of superconducting cavities in the modules, different possibilities are still under discussion. In a most conservative approach, each module houses 12 one meter long 9-cell cavities (similar to the TTF linac module layout, but with somewhat reduced inter-cavity spacing). In the so-called superstructure approach several cavities are grouped together and fed with RF-power by a single input coupler. We have studied here specifically the version with 4×7-cell superstructures [3], but the results are essentially also applicable to other superstructure versions or to the TTF-like linac layout.

Concerning beam optics, the main linac is divided in two sections: from the 5 GeV injection energy to 125 GeV, 4 modules and 2 quadrupoles form a FODO cell; from 125 to 250 GeV, each FODO cell contains 6 modules. The phase advance per cell is 60°. The accelerating gradient for 250 GeV final beam energy is 22 MV/m. For the simulation of the multi-bunch beam dynamics we use the tracking code L [4, 5]. The frequencies and loss factors of the dipole modes are obtained from numerical calculations [6] and the quality factors from measurements performed with a copper model of the superstructure (see table 1). We take into account a random variation of the mode frequencies by 0.1% (rms). The beam parameters, shown in table 2, are the present TESLA design values. In order to save computation time, only 500 bunches in the train are used for the tracking (the design value is n_b=2820). This is sufficient for our analysis, because the steady state regime of the bunch train is of little concern here. The random alignment error for the accelerating structures is 0.5 mm (rms).

2.1 Influence of Ground Motion

We start the simulation procedure with the parameters as defined above for a linac with misaligned accelerating structures, no quadrupole offsets and no injection orbit error.

	Frequency [GHz]	Loss factor [V/pC m^2]	Quality factor
TE-like modes	1.4377	26.7	164000
	1.4367	26.7	81600
	1.437	26.7	131200
	1.6547	12.9	204300
	1.6839	13.1	30300
	1.6871	19.9	56700
	1.6926	80.0	11100
	1.6941	31.1	17600
	1.7182	405.9	1300
	1.7226	943.8	55600
	1.7267	127.6	16300
	1.7281	168.5	95700
	1.7613	112.4	1300
	1.7638	512.4	7900
TM-like modes	1.8491	41.0	18700
	1.8521	146.2	2400
	1.854	72.7	4000
	1.8649	119.0	7800
	1.8664	208.3	8100
	1.8734	37.7	28900
	1.8745	309.1	21900
	1.8749	290.3	208800
	1.8758	20.7	27700
	1.8803	9.5	81700
	1.8806	28.4	72200
	1.9042	28.7	52100
	1.9028	28.7	500200
	1.9043	28.7	33500
TE-like modes	2.5751	977.3	14400
	2.5762	116.5	16600
	2.5758	1009.9	13200

Table 1: *Dipole modes used for the simulations*

The resulting orbit for the 500 bunches at the end of the linac shows an rms-offset with respect to the average orbit of $1.0\,\mu m$. The orbit pattern for a single random seed of structure misalignments is shown in fig. 1. This variation corresponds to one third of the vertical beam size and translates into a 15% dilution of the multi-bunch emittance (the variation in orbit angle is also about one third of the beam angular spread). With respect to the full length of the bunch train, the emittance dilution is only 3%, confirming that with our assumptions on the HOM properties the BBU has litte effect on the beam quality [7].

Diffusive ground motion is simulated by randomly moving the quadrupoles and

Bunch charge	[nC]	3.2
Bunch spacing	[ns]	337
Beam current	[mA]	9.5
Number of bunches		500
Repetition rate	[Hz]	5
norm. emittance at injection ϵ_y	[m]	$2 \cdot 10^{-8}$
injection energy	[GeV]	5
accelerating gradient	[MV/m]	22
final energy	[GeV]	250
beam size at injection	[μm]	18
beam size at end of linac	[μm]	3.2

Table 2: *Bunch train parameters used for the simulations*

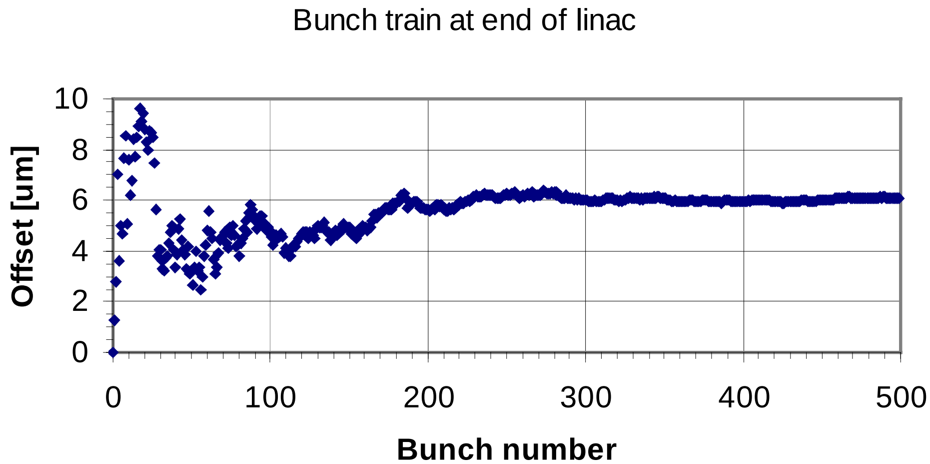

Figure 1: *Offset of the first 500 bunches at the end of the TESLA linac for one random seed of cavity misalignments. Initial structure misalignments are 0.5 mm rms, no quadrupole misaligments.*

accelerating structures according to the ATL law:

$$< \Delta y^2 >= A \cdot T \cdot L, \qquad (1)$$

where Δy is the relative vertical displacement of two points separated by the distance L, after a time T. A is a coefficient depending on the geological conditions. We have assumed here the value derived from measurements at HERA [8]: $A = 4 \cdot 10^{-6}\ \mu\mathrm{m}^2/\mathrm{m\,s}$. The rms-position error of the quadrupoles in the linac as a function of time is shown for one random seed example in fig. 2. The obvious effect of the time-varying quadrupole misalignment is a drift of the average orbit, shown for example at the end of the linac in fig. 3. Note that the average orbit at t=0 is not zero, which reflects the steady state orbit shift caused by the HOMs. The orbit drift as well as the slight change of the cavity misalignments, which are also subject to ground motion, also causes the beam-induced dipole mode fields to change. This effect, however is found to be very small: as shown in fig. 4, the orbit pattern after one minute of simulated beam time looks practically identical to the one at t=0, except for the shift in the average value. After subtracting this average shift, the residual rms offset difference (fig. 5) for the 500 bunches amounts to only a few nm, 0.1% of the beam size. Thus from the point of view of ground motion, there is no problem to remove the bunch-to-bunch orbit variation with an adaptive feed-forward system.

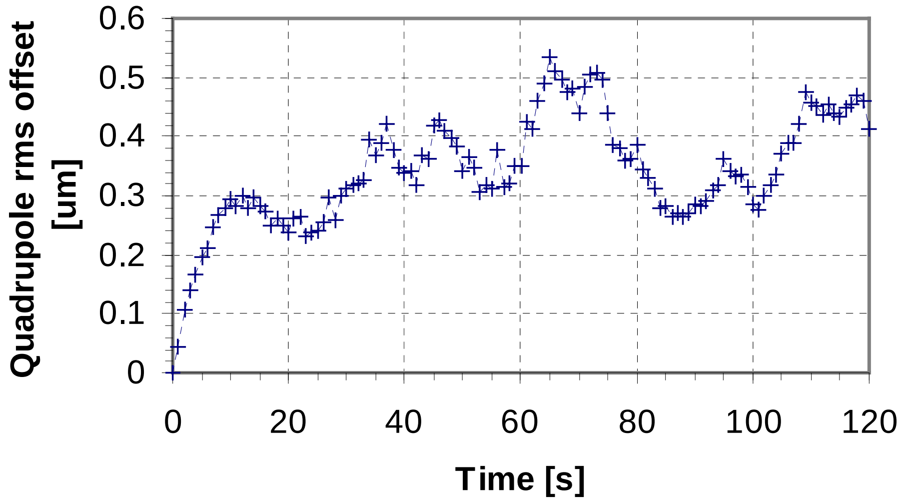

Figure 2: *Rms-offset of the quadrupoles versus time for one random seed of ATL-like ground motion.*

2.2 Injection Orbit Jitter and Charge Fluctuations

A non-zero displacement (or angle) of the orbit at the linac entrance causes a betatron oscillation with amplitude $\hat{y}(s) = \hat{y}(0) \cdot \sqrt{\beta(s)\gamma(0)/\beta(0)\gamma(s)}$ along the linac. The beam induced HOMs also change in this case, which, similarly as for the orbit drift due to ground motion, causes a slight change in the individual bunch offsets (with respect to the average) at the end of the linac. For a one beam sigma injection error (fig. 6), and after subtracting the average orbit change, we find an rms variation of the bunch positions of 17 nm, which is uncritical. Finally, we have studied the effect of a random bunch-to-bunch charge fluctuation of 1% (fig. 7). Again, the induced variation of the individual bunch offsets is very small compared to the beam size and does not present any problem for the feed-forward correction.

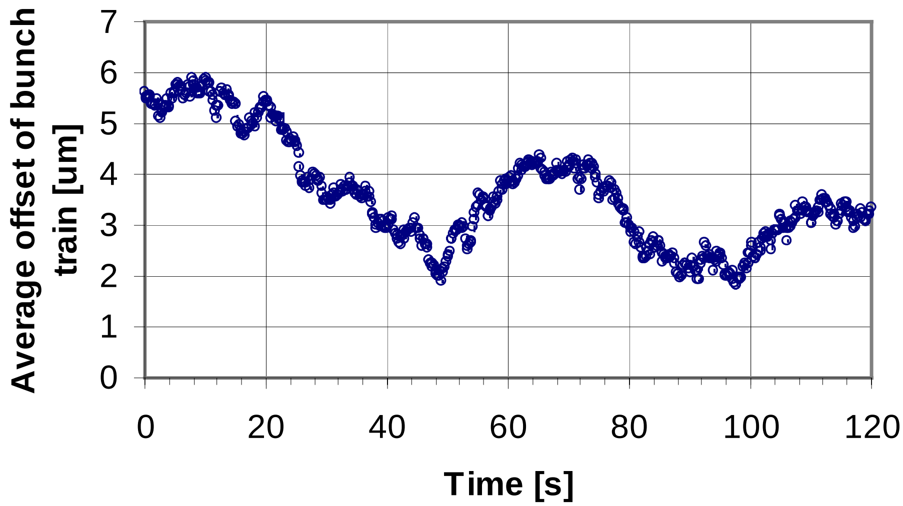

Figure 3: *Average offset of the first 500 bunches at the end of the TESLA linac as a function of time under the influence of ATL-like ground motion.*

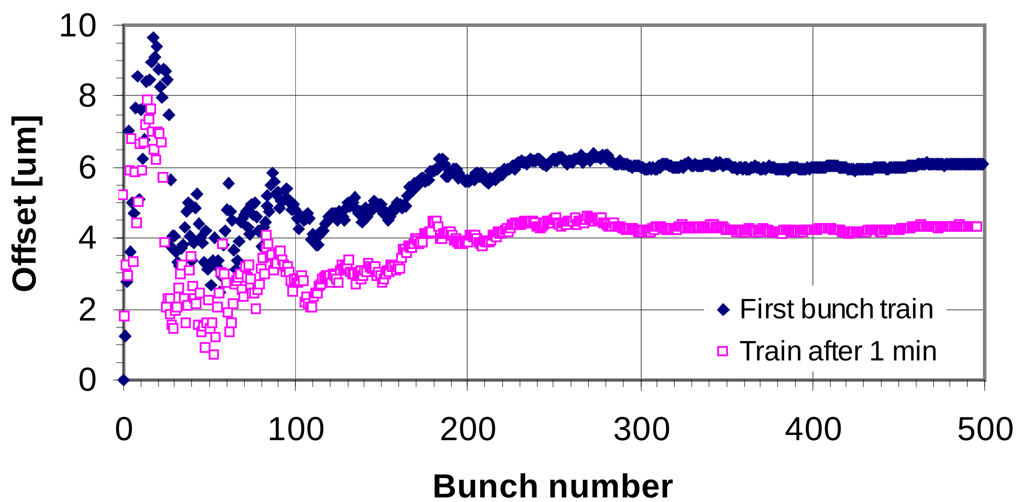

Figure 4: *Offset of the first 500 bunches at the end of the TESLA linac for one random seed of cavity misalignments. The upper curve (diamonds) shows the initial pattern (same as in fig. 1), the lower curve (squares) the one after applying ATL-like ground motion with T=1 min. (see text). Initial structure misalignments are 0.5 mm rms.*

3 Conclusions

We have shown that the multi-bunch orbit pattern caused by HOMs in the accelerating structures is practically static under ground motion, injection error and charge jitter

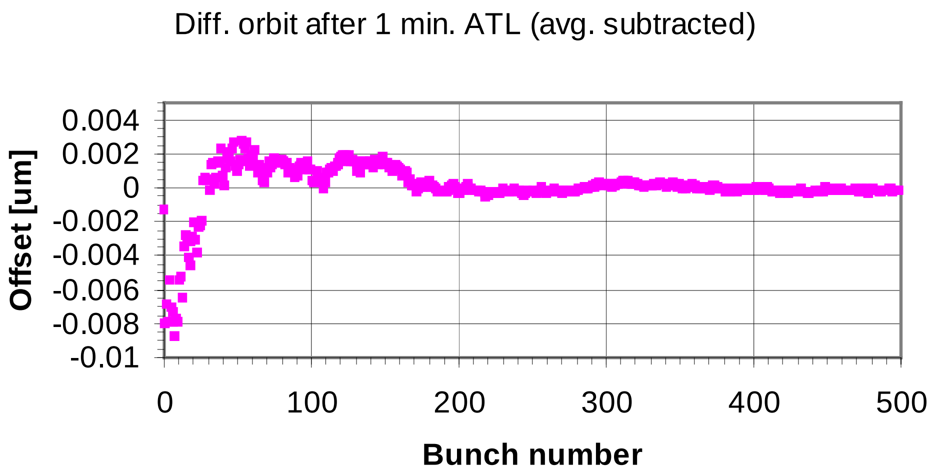

Figure 5: *Relative change of the individual bunch offsets at the end of the linac caused by one min. of ATL-like ground motion, after subtracting the average orbit shift.*

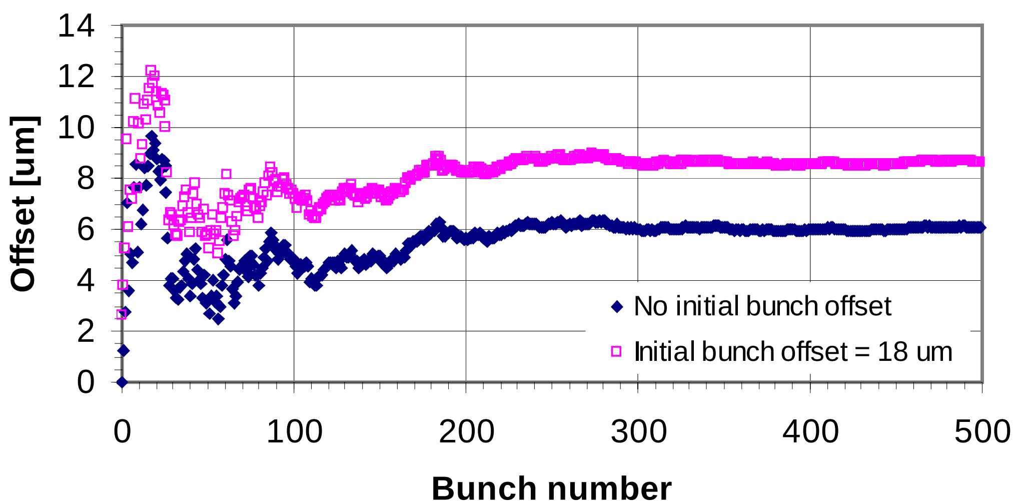

Figure 6: *Offset of the first 500 bunches at the end of the TESLA linac for for perfect on-axis injection (lower curve, diamonds) and with 18 μm (one σ_y) initial offset (upper curve, squares). Structure misalignments are 0.5 mm rms, no quad misalignments.*

effects of realistic magnitude. There are, however additional effects which have not been taken into account.

First, the RF-regulation against Lorentz-force detuning and microphonics will not be perfect and leave a residual energy spread over the bunch train of the order of a few 10^{-4} rms [9]. A non-zero spurious dispersion function, which we expect to be of the order of 2 mm at the end of the linac after applying beam-based alignment techniques,

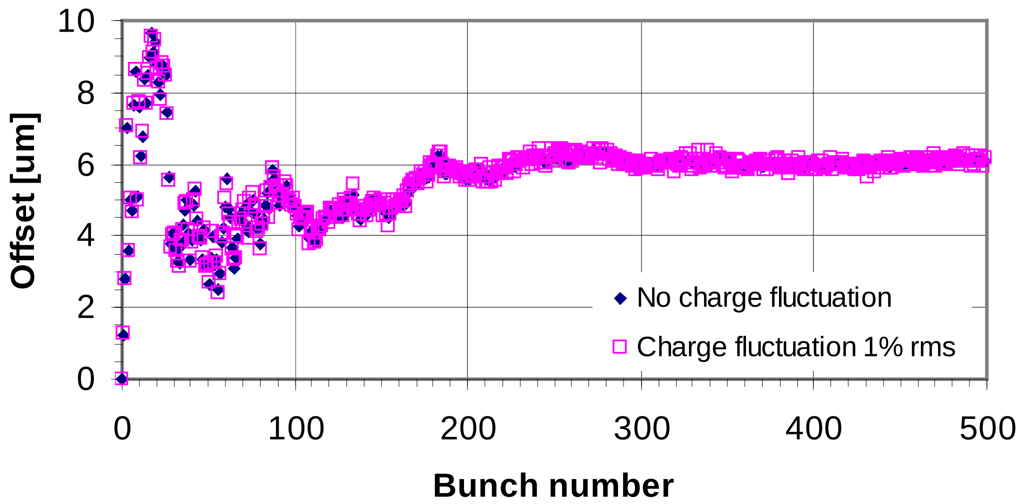

Figure 7: *Offset of the first 500 bunches at the end of the TESLA linac for nominal bunch charge (diamonds) and with 1% (rms) random bunch-to-bunch charge fluctuation (squares). Structure misalignments are 0.5 mm rms, no quad misalignments. The rms difference between the two curves is 10 nm.*

then leads to a variation of the orbit over the bunch train. This effect is slow compared to the fast feedback response time and can therefore be corrected.

Second, single bunch effects also need to be taken into account. Even if all bunches are put back on the same orbit after the linac, they have experienced different short-range wakefields due to their different orbits along the linac. For the orbit amplitude typical for the bunches in the first part of the train before the steady state regime (about one sigma at the linac end), we estimate a single bunch emittance growth of a few percent, which seems to be tolerable.

References

[1] R.-D. Kohaupt and I. Reyzl, "*Fast Feedback Systems for Orbit Correction in the TESLA Linear Collider*", Proc. Particle Accelerator Conference, New York 1999.

[2] H.-Th. Duhme et al., talk given at the HERA/TTF Seminar, Grömitz September 2000, to be published.

[3] J. Sekutowicz, M. Ferrario and Ch. Tang, "*Superconducting Superstructure for the TESLA Collider*", Phys. Rev. ST Accel. Beams, vol. 2, No. 6, 1999.

[4] M. Drevlak, "*On the Preservation of Single and Multi-Bunch Emittance in Linear Accelerators*", PhD Thesis, TU-Darmstadt 1995.

[5] M. Drevlak, M. Timm and T. Weiland, "*Simulation of Linac Operation Using the Tracking Code L*", Proc. XVIIIthInt. Linear Accelerator Conf., Geneva 1996, Vol. I, p. 246.

[6] H. Chen, Private communication.

[7] N. Baboi et al., "*HOM Damping Requirements for the TESLA Superstructures*", Proc. VIIth European Particle Accelerator Conference, Vienna 2000.

[8] R, Brinkmann and J. Roßbach, "*Observation of Orbit Motion in HERA Covering Eight Decades in Frequency*", Nucl. Instr. Meth. A **350**, p. 8, 1994.

[9] A. Mosnier and J. M. Tessier, "*Energy Spread Sources in TESLA and TTF*, DESY-TESLA-95-05, 1995.