MULTI-BUNCH BEAM DYNAMICS STUDIES FOR THE EUROPEAN XFEL

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Abstract

In the X-ray free electron laser (XFEL) planned to be built at DESY the acceleration of the electron bunches will be made by 9-cell superconducting cavities. These cavities have been initially developed within the TESLA (TeV Energy Superconducting Linear Accelerator) linear collider study. The impact of the higher order modes (HOM) has been shown to be within the acceptable beam dynamics limits for the collider. For the XFEL the dynamics is relaxed from the point of view of multi-bunch effects (e.g. lower bunch charge, higher bunch emittance). However the lower energy and different time structure of the beam make the study of the HOM effects in the XFEL linac desirable. Multi-bunch beam dynamics simulations have been made. The results of the HOM measurements at the TESLA Test Facility are used. Several options for the beam structure and energy are studied.

INTRODUCTION

In the European XFEL [1, 2, 3] a beam of up to 400 electron bunches with 10 to 20 GeV energy will generate ultrashort, high-intensity, coherent X-rays in long undulators. The design is based on the superconducting technology developed for the TESLA linear collider study [1, 4]. For the SASE FEL process, a good alignment, low emittance and small energy spread of the beam are essential. The main cause of degradation of the multi-bunch beam dynamics is the long-range wakefields generated by each bunch in the accelerating cavities. These may lead to accumulating deflections of the subsequent bunches, so that the multi-bunch emittance increases. The study of the wakefield effects is therefore important.

No dedicated multi-bunch beam dynamics simulations have been made so far for the XFEL. However many estimations could already be made based on the extensive studies made for TESLA [1, 5]. In the linear collider two beams, one of electrons and one of positrons, would be accelerated against each other to an energy of 500 GeV c.m. in an initial stage, and later up to 800 GeV c.m. The emittance preservation in the XFEL is less critical than in the case of TESLA due to the lower bunch charge and length and the higher design emittance (see Table 1). Therefore smaller wakefield effects are expected. However one should take into account some major differences, such as the lower energy, where the wakefield kicks are stronger and the different pulse structure. Therefore a series of simulations have been made of the multi-bunch emittance dilution along the XFEL linac. The results are discussed hereafter.

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Table 1: Comparative parameters for XFEL and TESLA

	XFEL	TESLA
bunch length (fs)	80	1000
bunch spacing (ns)	min. 200	337
bunch train length (μs)	max. 800	950
bunch charge (nC)	1	3.2
beam energy (GeV)	max. 20	250
normalized emittance (m·rad)	$1.4 \cdot 10^{-6}$	$3 \cdot 10^{-8}$

MULTI-BUNCH DYNAMICS SIMULATIONS

Linac layout For the multi-bunch tracking, we have considered the linac design previously used in simulations of single-bunch effects [6]. The layout has been recently slightly changed, to two bunch compression stages in order to increase jitter tolerances [3, 7]. These changes should not affect the multi-bunch effects. A photo-injector produces electrons bunches of 1 nC which are immediately accelerated by four cryo-modules. Each cryo-module contains eight 1 m long 1.3 GHz accelerating cavities (TESLA cavities). Fig. 1 shows the beta function along the linac starting with the last cavity of the first module, where our simulations begin. The linac elements are also schematically shown.

After the first TESLA modules, the bunches pass through a cryo-module with eight cavities working at 3.9 GHz, used to compensate for non-linear distortions of the longitudinal phase space. Two subsequent bunch com-

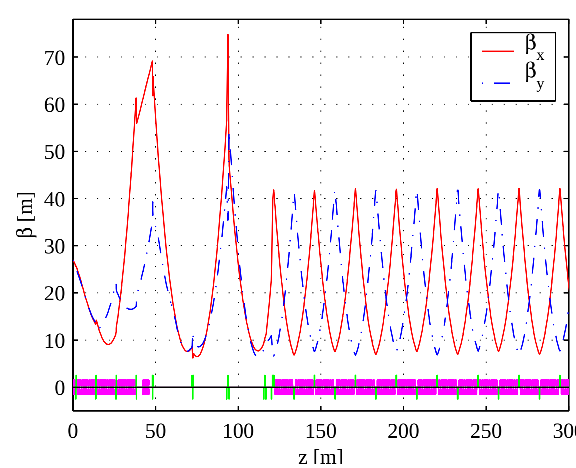


Figure 1: Beta function along the linac. The cryo-modules and quadrupoles are also sketched. The 3.9 GHz module is situated at z ≈ 45 m. Two bunch compressors are placed between about 50 and 120 m.

pressors reduce the bunch length to 80 μs. Then 57 FODO cells containing each 2 cryo-modules and 2 quadrupoles bring the electrons to a maximum energy of 20 GeV. The figure shows only the first few FODO cells, which repeat themselves up to a total length of about 1.5 km. From here the bunch train is directed into the undulators where the FEL beam is produced.

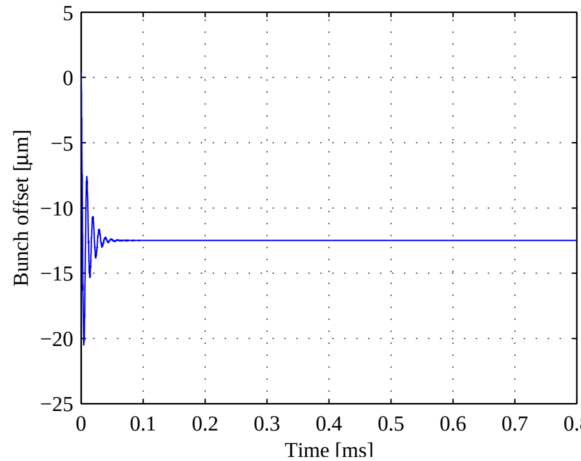
HOMs in the TESLA cavities The long-range wakefield, excited by each bunch at the passage through an accelerating cavity, are given by the sum of many individual resonances, the higher order modes (HOM). The main effect on the beam is given by dipole modes.

The frequencies and quality factors of the modes from the first 2 dipole bands have been measured in a single cavity test setup in most cavities built for the TESLA Test Facility (TTF) [8]. It has been found that in most cavities all modes are well damped by the special couplers mounted at each side of the cavities. For the simulations the average frequencies resulted from these measurements are considered. For the quality factors (Q) higher quantities than the most likely values are assumed. For the simulations we take into account all modes from the first 2 bands and 3 modes with highest loss factor in the 3rd band. However there are only few modes with a large loss factor, i.e. with a strong interaction between the mode and the beam [9].

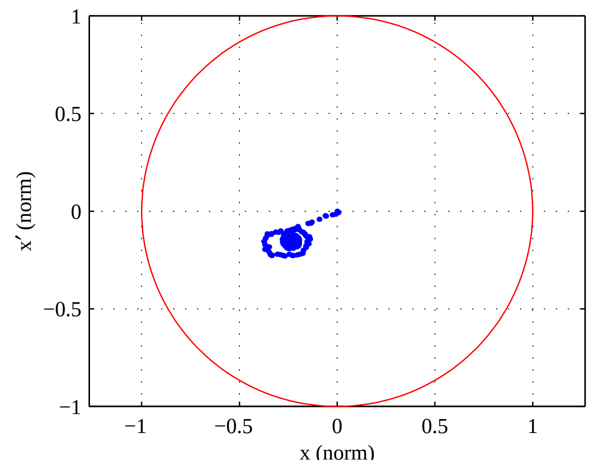
Simulation assumptions For the simulations we have used the MAFIA-L code [10]. The beam is injected on-axis with an energy of 117 MeV into the last cavity of the first cryo-module, where the simulation is started. In the first four cryo-modules and the 3.9 GHz cavities the acceleration is made off crest, for bunch compression. The electrons are accelerated here up to about 730 MeV. The phase in the cavities of the FODO cells is adjusted for maximum acceleration. The gradient is 20.65 MV/m. The beam reaches a final energy of approximately 20 GeV. All the modes from the first 2 dipole passbands as well as 3 modes from the 3rd passband are considered, although only about 5 dipole modes will effectively contribute to emittance dilution. The wakefields in the 3.9 GHz cavities has been neglected. The cavities have a misalignment of 500 μm rms. The HOM frequencies have a spread among the cavities of 0.1% rms. The bunch spacing is 200 ns, and the maximum number of bunches is 4000. Other bunch distances, train lengths and final energies have been considered as well. 100 random machines have been calculated in each case.

Results

Reference bunch train We consider first the case of 200 ns bunch spacing and 800 μs pulse length (4000 bunches). Fig. 2(a) shows typical offsets of the bunches at the end of the linac, while in Fig. 2(b) the bunch train is displayed in the phase space. The rms of the bunch positions is in this case 0.7 μm (5.7%). While the maximum oscillation of the bunch offsets of 20 μm may be a problem for the FEL process, it is important to note that the variations are concentrated in the first less than 50 μs. This part could be deflected towards a dump and only the high quality tail of the beam be used in many experiments. On the other hand, the deflections in subsequent beam pulses are almost identical, as it was shown for TESLA [11]. Therefore the unwanted offset (and angle) variations along the trains can be corrected with a feedback system.



(a) bunch offsets



(b) phase space

Figure 2: Typical bunch train at the linac end for 4000 bunches spaced by 200 ns. The energy is 20 GeV.

Fig. 3 shows the emittance dilution along the linac. The average over all machines has been made. The emittance growth relative to the design slice emittance $\Delta\varepsilon/\varepsilon$ is $0.02 \pm 0.02\%$, which is negligible.

Various pulse length and bunch spacings If the pulse length is shortened as compared to the reference case above, the steady state is not reached (see first part of the beam in Fig. 2(a)). The emittance increases significantly. In particular for a train length of 20 μs a multi-bunch emittance growth of $0.62 \pm 0.69\%$ is reached. In many situations one can accelerate a pulse longer than the desired

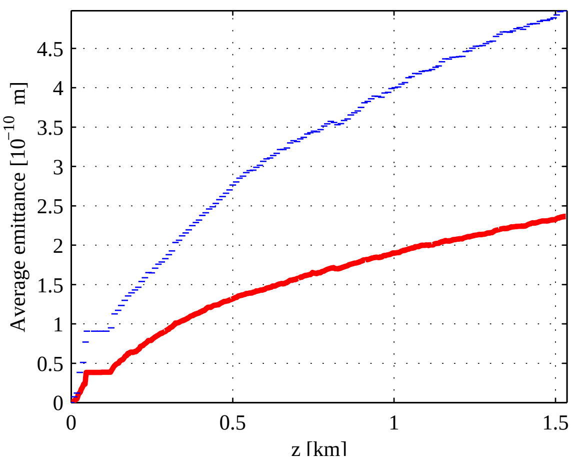


Figure 3: The emittance growth along the linac for 4000 bunches spaced by 200 ns. The energy is 20 GeV. The emittance is averaged over 100 random machines. The upper lines represent the limit of standard deviation bars.

length and then retain only the steady state part. However the question remains about the unconventional pulse structures needed by various experiments, e.g. with mini-train within each bunch train. In this case the steady state is not reached. This will be the object of future studies.

For larger bunch spacings, multiple of 200 ns the situation can only improve. This is shown in Table 2 in terms of emittance growth, in comparison to the reference case. The double of the smallest spacing is considered. Although not planned to be used, the results for a distance of 337 ns, which is the design spacing for TESLA, are also displayed. It is remarkable that the latest case gives much smaller values than for 400 ns. This is due to a concurrent relationship between the bunch spacing and the mode frequencies.

Table 2: Emittance growth $\Delta\varepsilon/\varepsilon$ (in %) for various beams. Each number is the average over 100 linacs. The standard deviation is of the same order of magnitude.

Spacing [ns]	**Bunch train length** [μs]		
	800	120	20
200	0.017	0.11	0.62
400	0.003	0.022	0.11
337	0.0005	0.003	0.016

Lower beam energy The results mentioned above are for the maximum energy needed in the linac. For lower bunch energies the HOM kicks on the beam are stronger and therefore the beam quality is deteriorating. Indeed, simulations show an emittance growth of $0.86 \pm 0.95\%$ for a beam of 20 ns, with 200 ns spacing, and a final energy of 15 GeV (gradient in the FODO cells of 15.34 MV/m). For the 10 GeV case (gradient 10.05 MV/m), the same beam has an emittance growth of $1.5 \pm 1.6\%$. As mentioned above, the relative bunch offsets can be compensated with the feedback system.

Energy spread The three strongest longitudinal monopole HOMs, which are situated in the second monopole band of the TESLA cavities, have also been included in the calculations. The rms energy spread is 5.15 MeV for a pulse length of 20 ns. For a full bunch train (800 μs) the rms spread is 0.88 MeV. A final peak-to-peak energy spread of 17 MeV has been obtained. For a 20 GeV beam this represents 0.085%, while for 10 GeV it is 0.17%.

As for the bunch offsets, the energy variation occurs in the first part of the bunch train. For short pulses this should be compensated by the RF system.

SUMMARY

The simulations we present in this paper show a somewhat large effect of the wakefields on the bunch offsets within the train for short bunch trains and low beam energies. However, on one hand the negative effects are concentrated in the first part of the beam, which gives us the option to dump this part of the beam and send to the undulator only the high quality tail. On the other, the multibunch excitation is quasi-static, which makes easy the compensation of the bunch offsets by a feedback system. The energy spread may require compensation by the RF system for short trains. Unconventional pulse configurations remains to be studied.

Last but not least, we would like to mention that the possibility to align the beam in the cryo-modules based on the HOM signals is under study at TTF2 [12]. This is important particularly at low energy and would further contribute to the improvement of the beam quality.

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