SINGLE BUNCH EMITTANCE PRESERVATION IN XFEL LINAC

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Abstract

The single bunch emittance preservation in booster and main linacs of European XFEL project is presented. The wakefield and chromatic dilution of the beam emittance caused by free betatron oscillations, cavity and modules offset misalignments and random tilts are evaluated. The effects of cavities misalignments correlation along the linac are discussed. The effects of quadrupole misalignments and the corresponding trajectory steering based on one-to-one correction technique are given. The residual chromatic emittance dilution of the corrected trajectory is evaluated.

INTRODUCTION

A single bunch emittance preservation in the linear accelerator for single pass FEL operation is one of the main requirements to match the electron beam with angular and transverse phase-space characteristics of the radiation emitted by an electron in undulator [1]. Due to imperfections of the linac components and the beam parameters the design beam emittance is diluted due to chromatic and transverse wakefield effects in linear accelerator [2].

In European XFEL project [3], the acceleration of the electron beam with normalized emittance of 1.4 mm-mrad to the design energy of 20 GeV is performed in the booster linac (0.5-2 GeV) and the main linac (2-20 GeV). They are separated by the bunch compression system. The main parameters of the beam at the entrance of each linac are summarized in Table 1.

Table 1: Beam parameters at the entrance of linacs

Beam parameters	**Linac 1**	**Linac 2**
Initial energy (GeV)	0.5	2
Accel. Grad. (MV/m)	16	20.8
Bunch length (μm)	121	24
Init. corr. energy spread (%)	1.75	0.4
Init. uncorr. energy spread (%)	0.1	0.125

The main linac downstream from the 2nd bunch compression consists of 100 accelerator modules with one quadrupole each forming a FODO cell with 24 m length and a phase advance of 60 deg. One horizontal or vertical steering magnet per module is foreseen. The booster linac contains 6 standard FODO cells with average gradient in cavities of about 16 MV/m.

The single bunch emittance dilution in linacs is determined by chromatic and transverse wakefield effects.

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In the booster linac these effects are negligible due to high relative energy gain of the particles with respect to their initial energy. The single bunch emittance dilution in the main linac is mainly caused by the coherent oscillations of the beam due to transverse injection jitter, random cavity tilts and quadrupole misalignments. Cavity and module random misalignments are additional sources of correlated emittance grow due to transverse wakefields exited by off-axis beam trajectory in the accelerating sections. In Table 2 the rms tolerances to the main linac component misalignments are given.

Table 2: Assumed rms misalignment tolerances

Injection transverse jitter		1 σ
Cavity misalignments	Mm	0.5
Modules Misalignments	Mm	0.5
Correlated 4 modules misalign.	Mm	0.5
Cavity tilts	Mrad	0.25
Quadrupoles misalignments	Mm	0.5
BPM misalignments	Mm	0.2

CORRELATED ENERGY SPREAD

The RF accelerating field and the short range longitudinal wakefield lead to an extra negative correlated energy spread (tail particles have lower energy than the head) with rms value of $5\cdot10^{-4}$ at the end of the main linac. However, the electron bunch at the entrance to main linac has an initial positive correlated energy spread of 0.4% required for the bunch compression system [4]. This initial energy spread partially cancels the induced correlated energy spread in the main linac thus providing a rms relative correlated energy spread at the linac exit of about $1.2\cdot10^{-4}$ or absolute rms energy spread of 2.4 MeV.

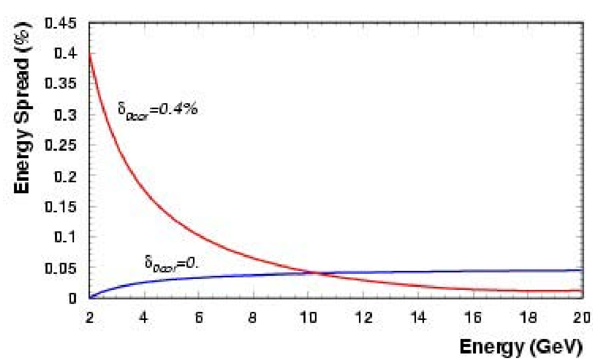

Figure 1: RMS correlated energy spread evaluation along the main linac with (red) and without (blue) initial positive correlated energy spread.

CAVITY , MODULES MISALIGNMENT

In the linac with misaligned cavities and modules, the tail particles of the bunch experience the transverse kick caused by the transverse wakefield induced by the heading particles. However, the point wake potentials in 1.3 GHz TESLA cavities [5] are so weak that lead to negligible relative emittance growth for XFEL beam for the cavity and modules rms random mislaignment of 0.5 mm. Fig. 2 presents the transverse wakefield caused correlated relative emittance growth along the linac for cavity and module misalignments. The results are averaged over 25 random seeds of misalignments.

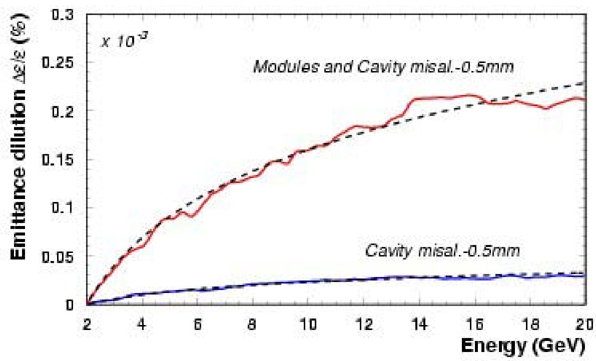

Figure 2: Wakefield caused emittance dilution along the main linac for cavity and modules random misalignments

The effect of cavity misalignment correlation to emittance growth along the linac has been evaluated. Fig.3 presents the emittance dilution at the end of the main linac for correlated misalignments of 0.5 mm vs the phase advance per correlation length. Dashed line shows the analytical prediction averaged over the betatron wavelength and cavity misalignments [6]. The emittance growth caused by correlated cavity misalignment along the linac reaches the maximum for the betatron phase advance of 130 degrees per correlation length (about 4 modules). For longer correlation length the effect is damped due to betatron oscillations of the bunch tail particles. Concluding this section, the single bunch relative emittance growth in XFEL main linac caused by the cavity, modules and correlated rms misalignments of 0.5 mm is less than $1.5 \cdot 10^{-5}$.

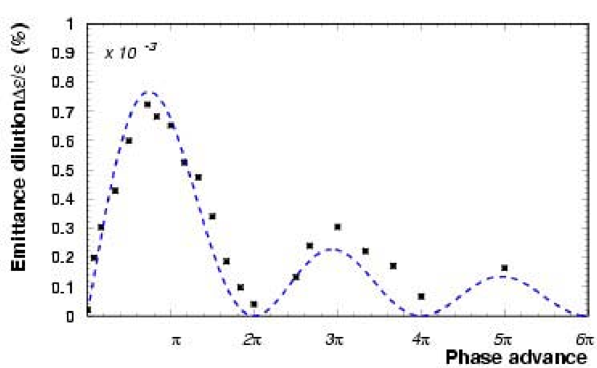

Figure 3: Emittance dilution at the end of the main linac vs phase advance per misalignment correlation length.

BEAM COHERENT OSCILATIONS

Due to injection jitter, cavity random tilts and quadrupole misalignment, the beam performs coherent oscillations down to the main linac leading to chromatic and wakefield emittance dilution.

Fig.4 presents uncorrelated and correlated emitttance dilution of the beam along the linac when the beam performs free betatron oscillations with initial one sigma offset. Very small uncorrelated chromatic emittance dilution is caused by initial small uncorrelated energy spread (0.125%) and a weak focusing lattice of the linac. The correlated emittance dilution is also dominated by the chromatic effects as the effect of transverse wakefield is negligibly small.

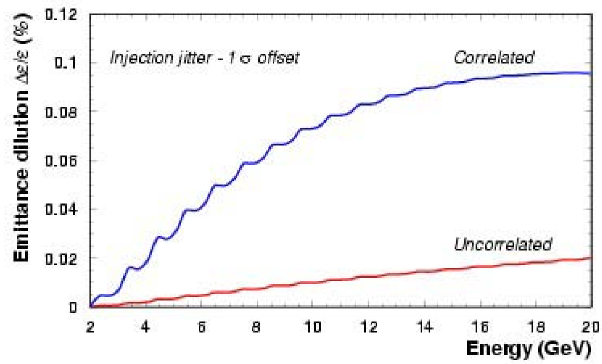

Figure 4: Uncorrelated and correlated emittance dilution in the main linac caused by free coherent oscillation.

In the case of cavity random tilts the particles experience the transverse Lorenz force of the accelerating RF field and the beam performs coherent oscillations. Fig. 5 presents the correlated and uncorrelated chromatic emittance dilution along the linac for the rms cavity tilts of 0.25mrad.

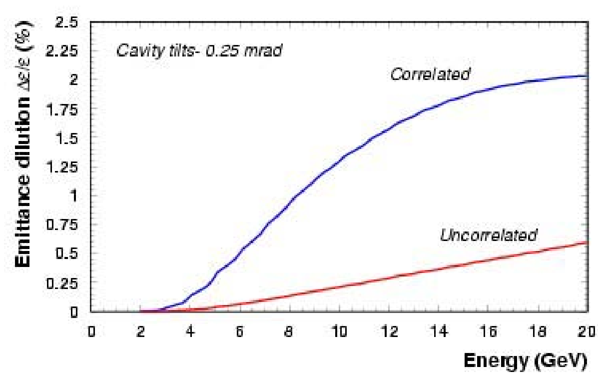

Figure 5: Correlated and uncorrelated beam emittance dilution along the main linac for cavity random tilts.

The chromatic effects cause the main contribution to the emittance dilution in the linac for beam coherent oscillations caused by injection jitter and cavity tilts. Therefore, the emittance dilution is significantly reduced with increasing the number of the modules per FODO lattice that can be one of the options during the main linac commissioning.

QUADRUPOLE MISALIGNMENTS

The strongest impact of the chromatic effect is observed for a disturbed central trajectory caused by quadrupole misalignments. The steering of the central trajectory is supposed to use one-to-one correction algorithm: the beam trajectory is corrected in each focusing quadrupole to its geometrical axis based on the beam position monitors (BPM) reading by correction dipole coils incorporated in the previous quadrupole. Fig.6 presents the disturbed central trajectory of the beam in the main linac for a single random seed of quadrupole misalignment and the corrected trajectory (top) and the resulting uncorrelated and correlated chromatic emittance dilution of the beam (bottom).

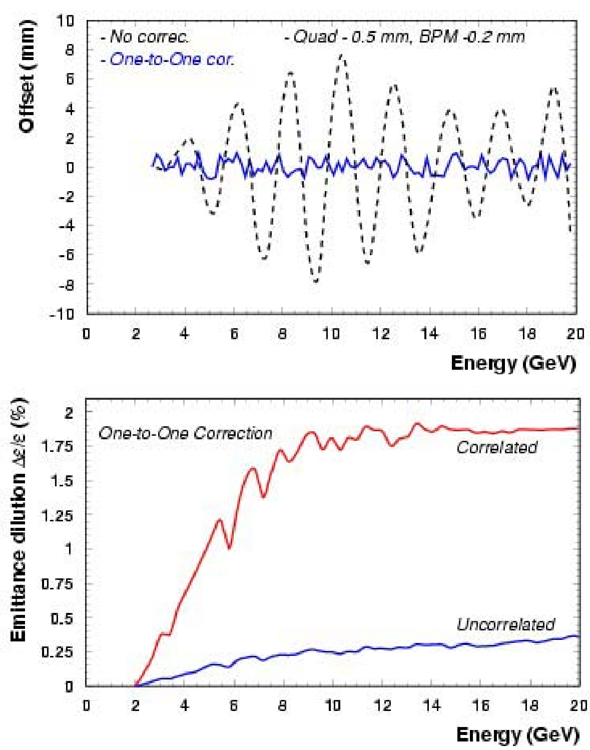

Figure 6: Coherent betatron oscillation of the beam in the main linac with misaligned quadrupoles and steered trajectory by one-to-one correction algorithm (top). Correlated and uncorrelated emittance dilution along the linac after trajectory steering (right).

SUMMARY

The study of the single bunch emittance preservation in XFEL linear accelerators shows that the chromatic effect fully dominates the beam emittance dilution. The strongest impact is observed for a disturbed central trajectory caused by quadrupole misalignments. However, the relatively high required normalized emittance of the beam and low chromaticity of the focusing lattice in XFEL linac allow by application of one-to-one trajectory correction algorithm to preserve the design emittance at the level of 2%.

Table 3 presents the summary of the emittance dilution in the booster and main linacs. The total emittance dilution is below 3% and 5% for the booster and the main linacs respectively.

Table 3: Summary of the emittance dilution in booster and linacs

Beam parameters	Booster linac	Main linac
Coherent oscillations Uncorrelated Correlated	 $6{\cdot}10^{-6}$ $2{\cdot}10^{-3}$	 $2{\cdot}10^{-4}$ $1.2{\cdot}10^{-3}$
Cavity misalignments	$5{\cdot}10^{-6}$	$3{\cdot}10^{-7}$
Modules misalign.	$4{\cdot}10^{-5}$	$2.5{\cdot}10^{-6}$
Correlated misalign. (4 modules)	-	$7{\cdot}10^{-6}$
Cavity tilt Uncorrelated Correlated	 $5.8{\cdot}10^{-5}$ 0.6%	 0.6% 1.9%
One-to-One Correc. Uncorrelated Correlated	 $6.3{\cdot}10^{-5}$ 1.7%	 0.4% 2%
Total	<3%	<5%

As emittance dilution is dominates by chromatic effects, the further reduction of the emittance dilution is predicted for the main linac operation with the switched off quadrupoles providing 6 accelerating modules per one FODO focusing lattice.

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