# CHROMATIC AND WAKEFIELD EFFECTS IN PSI-XFEL LINAC

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*Abstract*

Detailed knowledge about the wakefield and chromatic effects on electron beam emittance is an important issue to preserve the natural emittance of the beam in linear accelerators for FEL. The study of these effects for beam and accelerator components imperfections in PSI-XFEL S-Band linear accelerator is presented. Emittance dilution caused by the beam coherent oscillations, accelerating section and quadrupole misalignments is analysed. The residual chromatic emittance dilution of the corrected trajectory is evaluated.

## INTRODUCTION

Linac driven XFEL project under study at PSI [1] is aimed to achieve the radiation wavelength down to 0.1 nm with reduced electron beam energy, peak current and undulator length in comparison with RF photo-cathode gun based options [2,3]. This approach implies an order of magnitude lower beam emittance from the electron gun that is supposed to be achieved using the field-emitter technology [4].

The current performance of PSI-XFEL project is based on 6 GeV energy electron beam with normalized emittance $\varepsilon_N$ of 0.2 mm-mrad and bunch charge $Q$ of 0.2 nC. A 250 MeV electron beam from injector is compressed in BC1 and accelerated in two S-Band linear accelerators spaced by the second bunch compressor BC2. Three extraction lines at different energies provide the FEL radiation at different wavelengths (Fig. 1).

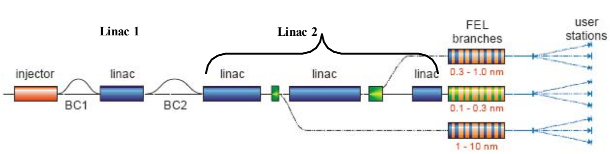


Figure 1: The schematic layout of PSI-XFEL project.

The preservation of the beam emittance along the accelerator is an important issue to achieve design XFEL performance. In a real imperfect machine the beam emittance is diluted due to chromatic and wakefield effects. In this paper the emittance dilution is evaluated by particle tracking simulation for beam energy range of 0.25-1.5 GeV (linac 1) and 1.5-6 GeV (linac 2). The focusing system of the linac is composed of symmetric FODO lattices that contain two 4 m long S-Band accelerating sections per cell. The nominal accelerating voltage is 24 MV/m. We consider the effects caused by beam injection jitter, accelerating sections misalignments, quadrupole errors and the orbit steering. The point wake functions for S-Band structure [5] are used to evaluate the wakefield effects. The main parameters of the beam are given in Table 1.

Table 1: Electron Beam Parameters

| Parameter | | Linac 1 | Linac 2 |
|---|---|---|---|
| Beam energy | [ GeV ] | 0.25 – 1.5 | 1.5 – 6.0 |
| Slice energy spread | [ % ] | 1.46 – 0.5 | 0.5 – 0.01 |
| Peak current | [ kA ] | 0.35 | 1.5 |
| Bunch length rms | [μm ] | 170 | 40 |
| Number of FODO cells | | 11 | 23 |

## CORRELATED ENERGY SPREAD

Along with the beam emittance the limitation to particle relative energy spread at the level of 0.01 % is an important requirement to drive the SASE XFEL process. As the beam is accelerated in the linac the correlated energy spread within the bunch is induced, caused by the interaction of the particles with the external RF field and the longitudinal wakefield.

For particle acceleration on RF crest the rms value of induced negative energy spread (tail particles have lower energy than the head) at the end of the linac 2 is about 0.025 % (Fig. 2, dashed line). However, at the entrance to linac 2 the bunch has positive correlated energy spread of 0.5 % (tail particles have higher energy than the head) required for BC2 to compress the bunch by a factor of about 4. This initial positive energy spread is partially cancelled by the induced negative energy spread in the linac down to 0.1 %. Further reduction of the energy spread at the end of the linac can be achieved by acceleration of the beam at the negative phase behind the RF crest. Fig. 2 shows the energy spread along the linac 2 for the accelerating phases of –15 and –30 degrees that provide the rms correlated energy spread of 0.05 % and 0.01 % at the end of the linac respectively.

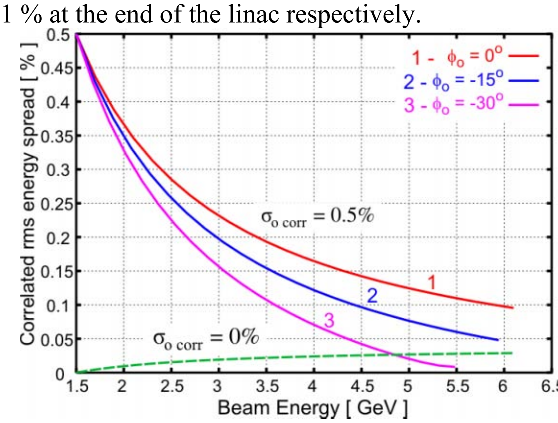


Figure 2: RMS correlated energy spread in Linac 2.

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## BEAM COHERENT OSCILLATIONS

Due to injection transverse jitter, the beam performs coherent betatron oscillations down to the linac leading to the chromatic and wakefield emittance dilution. The chromatic emittance dilution in turn is conditioned by residual uncorrelated energy spread after the bunch compressor and correlated energy spread. Longitudinal wakefields modify the correlated energy spread, while the transverse wakefields induced by off-axis beam motion disturb the transverse shape of the bunch. As a result, the particles of the bunch are diluted in a single slice (uncorrelated, chromatic) and within the bunch (correlated, chromatic and wakefield).

The residual uncorrelated energy spread after BC1 and BC2 is assumed at the level of 0.1 %. Fig. 3 presents the uncorrelated chromatic emittance dilution for linac 2 for one sigma initial offset of the beam (~30 µm).

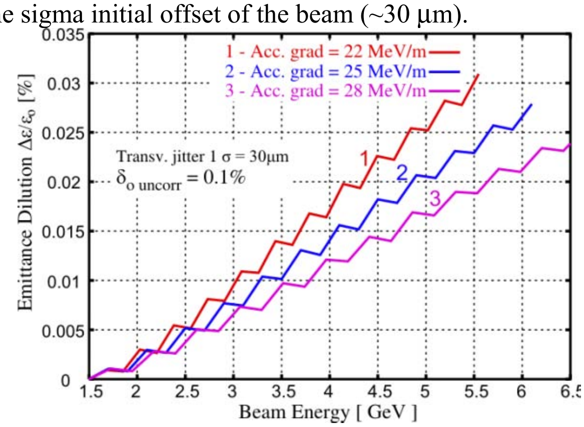


Figure 3: Uncorrelated emittance dilution in linac2.

The correlated emittance dilution is conditioned by both chromatic and wakefield effects. The off-axis beam produces longitudinal and transverse wakefields in accelerating sections. Fig. 4 presents the correlated emittance dilution along the linac 2 for beam coherent oscillations with one sigma initial offset. The accelerating phase is –30 degree that provides the energy spread at the end of the linac at the level of 0.01 % (Fig. 2).

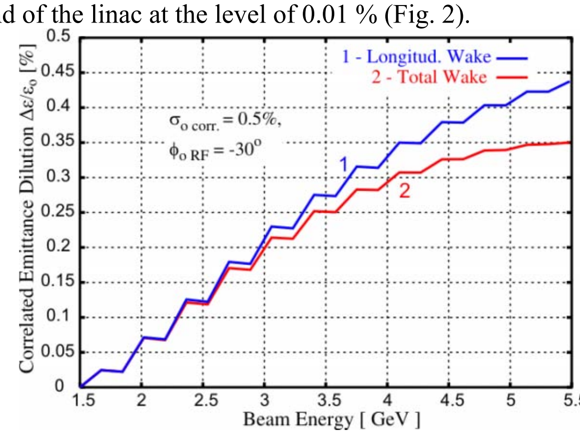


Figure 4: Total (red) and longitudinal (blue) wakefield contribution to emittance dilution for linac 2.

The total emittance dilution is at the level of 0.5 % and is dominated by the chromatic effect.

## ACCELERATOR SECTION MISALIGNMENT

In the linac with randomly misaligned accelerating sections, the tail particles of the bunch are deflected by transverse wakefield induced by the heading particles. For small emittance dilution ($\Delta\varepsilon/\varepsilon < 1$) a good analytical approximation can be obtained in two-particle model of the beam. In this model the bunch of charge $Q$ is modelled by two macroparticles spaced by a distance of $\Delta z=2\cdot\sigma_z$, where $\sigma_z$ is the bunch rms length. The tail particle experiences the deflecting dipole wake potential $W_D$ excited by the heading particle in misaligned section. The resulting emittance dilution along the linac is then given by [6]

$$\frac{\Delta\varepsilon}{\varepsilon} = \frac{\sigma_A^2}{32\varepsilon_N}\left(\frac{QW_D}{G}\right)^2 \frac{L_c^2}{\sin\mu}\frac{G}{E_r}\ln\frac{E}{E_0} \quad (1)$$

where $\sigma_A$ is the rms offset of accelerating sections, $L_c$ , $\mu$ are the FODO cell length and phase advance per cell, $E_o$, $E$ are the initial and actual design energies, $G$ is the accelerating gradient, $E_r$ is the electron rest energy.

Fig. 5 presents the results of particle tracking simulation for the linac 2 with 0.5 mm rms randomly misaligned accelerating sections. Shown is the emittance dilution for two random seeds and averaged over 40 random seeds. The rms value of the emittance dilution is at the level of 0.02 %, which is basically caused by the low bunch charge in PSI-XFEL project.

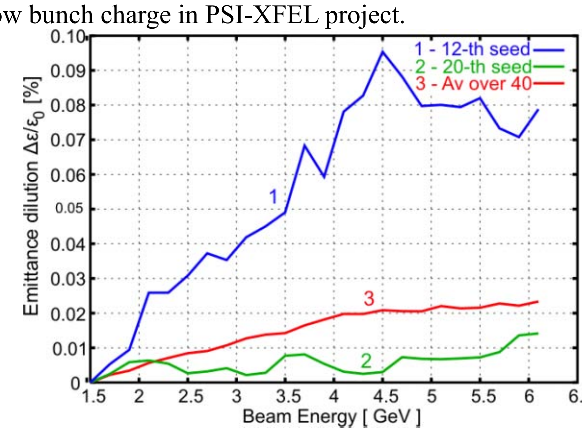


Figure 5: Emittance dilution due to accelerating section misalignments.

## QUADRUPOLE MISALIGNMENTS AND ORBIT CORRECTION

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 by correction dipoles based on the beam position monitors (BPM). Fig. 6 presents the disturbed central trajectory of the beam in linac 2 for a single random seed of quadrupole misalignment before and after trajectory steering. The rms quadrupole misalignment $\sigma_q$ and BPM $\sigma_b$ misalignment are 0.5 mm and 0.1 mm respectively; the BPM resolution $\sigma_r$ is 20 μm.

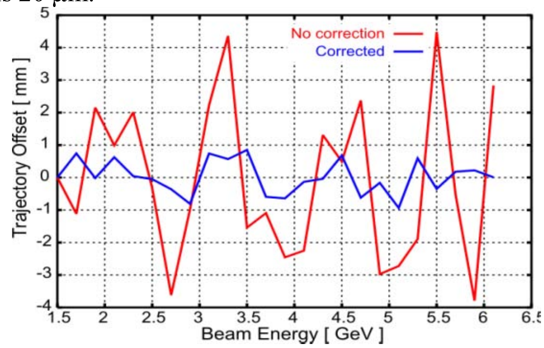


Figure 6: Coherent betatron oscillation of the beam in the main linac with misaligned quadrupoles and the steered trajectory by one-to-one correction algorithm

For the small degree of beam filamentation, the uncorrelated emittance dilution of corrected trajectory can be evaluated in two-particle model as [6]:

$$\frac{\Delta\varepsilon}{\varepsilon} = 8\delta_0^2 \frac{\sigma_c^2 \tan\mu/2}{\varepsilon_N L_{cell}} \frac{E_0^2}{E_r \Delta E} \ln\frac{E}{E_0} , \quad (2)$$

where $\delta_o$ is the initial rms uncorrelated energy spread, $\sigma_c$ is the rms offset of the beam central trajectory in quadrupoles given by $\sigma_c^2 = \sigma_q^2 + \sigma_b^2 + \sigma_r^2$. Figure 7 presents chromatic uncorrelated emittance dilution of the beam after orbit correction in linac 2 for initial uncorrelated energy spread of 0.1 %. The emittance dilution for one random seed of quadrupoles and BPM misalignments, the averaged over 25 seeds and the analytical prediction are shown.

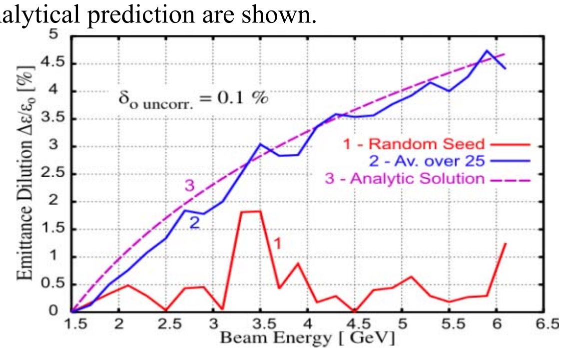


Figure 7: Uncorrelated emittance dilution after orbit correction.

The results for correlated emittance dilution in linac 2 for quadrupoles rms misalignments of 0.5 mm and 0.1 mm averaged over 25 random seeds are presented in Fig. 8. As is seen to keep the emittance dilution below 5 %, the quadrupoles in lattices should be aligned with rms offset of 0.1 mm.

In summary, Table 2 presents the contributions to the emittance dilution for linac 1 and linac 2 of: a) one sigma injection jitter, b) 0.5 mm rms accelerating sections misalignments, c) corrected trajectory for quadrupoles with rms BPM misalignments of 0.1 mm and a BPM resolution of 20 μm.

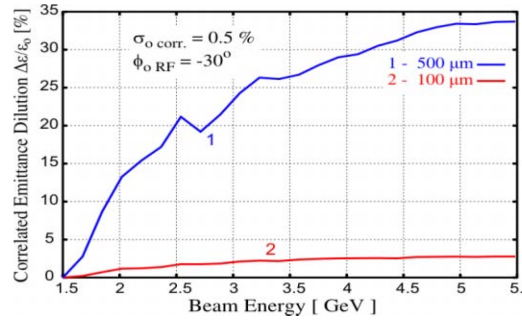


Figure 8: Correlated emittance dilution along the linac 2 after trajectory steering

Table 2. Emittance dilution for PSI-XFEL linac.

| Effect | Linac 1 | Linac 2 |
|---|---|---|
| One sigma injection jitter | | |
| uncorrelated | < 0.001 % | 0.04 % |
| correlated | 0.4 % | 0.45 % |
| Accel. section misalign. | 0.007 % | 0.02 % |
| Corrected trajectory | | |
| uncorrelated | 0.2 % | 0.6 % |
| correlated | < 1.5 % | 3 % |
| Total | <3 % | <5 % |

## CONCLUSION

The particle tracking simulation study is performed to evaluate the emittance preservation in S-Band linear accelerator for PSI-XFEL project. The total emittance dilution does not exceed 5 % for realistic alignment of the accelerator components. Due to low bunch charge the wakefield contribution to emittance growth along the linac is negligibly small. The dominant contribution is caused by the correlated chromatic effect, therefore the reduction of both the number of FODO cell in linac and the phase advance per cell can be considered as the next iteration of the accelerator performance. In the near future we will re-investigate chromatic and wakefield effects with a realistic beam distribution, which is obtained from start-to-end simulations.

## REFERENCES

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