DESIGN STUDY OF THE LINAC OF THE SHANGHAI SOFT X-RAY FREE ELECTRON LASER FACILITY

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Abstract

Shanghai soft X-ray Free Electron Laser (SXFEL) will be the first X-ray FEL facility in China. In this article, physical study in the design process of the linear accelerator (LINAC) will be given. The study is about how to improve the performance of the LINAC to gain stable operation and control over the possible instabilities such as the microbunching instability [1], which are critical to the success of the FEL facility.

INTRODUCTION

The recent approved Shanghai soft X-ray FEL facility is planned to be built in a few years. It is proposed to be a cascading HGHG FEL facility which will be working at 9 nm soft X-ray band. The main beam parameters at the exit of the LINAC are shown in table 1.

Table 1: Main beam parameters of SXFEL LINAC

Parameter	Value
Electron energy (MeV)	0.84
rms energy spread (%)	0.10 - 0.15
rms normalized emittance (mm-mrad)	2.0 - 2.5
Bunch length (ps, FWHM)	~0.8
Bunch charge (nC)	0.5
Peak current (A)	600
Rep. rate	1 - 10

In order to reach the desired beam quality and match the engineering requirements, the LINAC lattice was designed and optimized. The layout of the LINAC is illustrated in Figure 1. The working parameters of each LINAC components are determined, the jitter analysis and transverse trajectory error correction are given. The mechanism of microbunching instability in SXFEL is also studied.

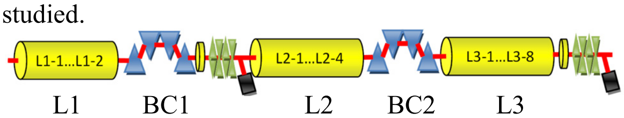

Figure 1 (color): layout of SXFEL linear accelerator (LINAC).

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BASIC DESIGN

As shown in Figure 1, the SXFEL LINAC mainly consists of 3 accelerating sections, 2 compressors and 2 diagnostic sections. The 2 bunch compressors (BC1, BC2) provide 10-fold compression rate in total to increase the peak current from ~60 A after the injector to ~ 600 A at the LINAC exit; the 3 accelerating sections includes 2 S-band structures (L1, L2) and a C-band structure (L3). The C-band structure is more compact and able to provide stronger wake field, which is very important to reduce the total size of the LINAC and compensate the beam energy spread after the 2nd bunch compressor. The total length of the LINAC is about 135 m. The longitudinal phase spaces and current profiles at various locations are shown in Figure 2 for comparison.

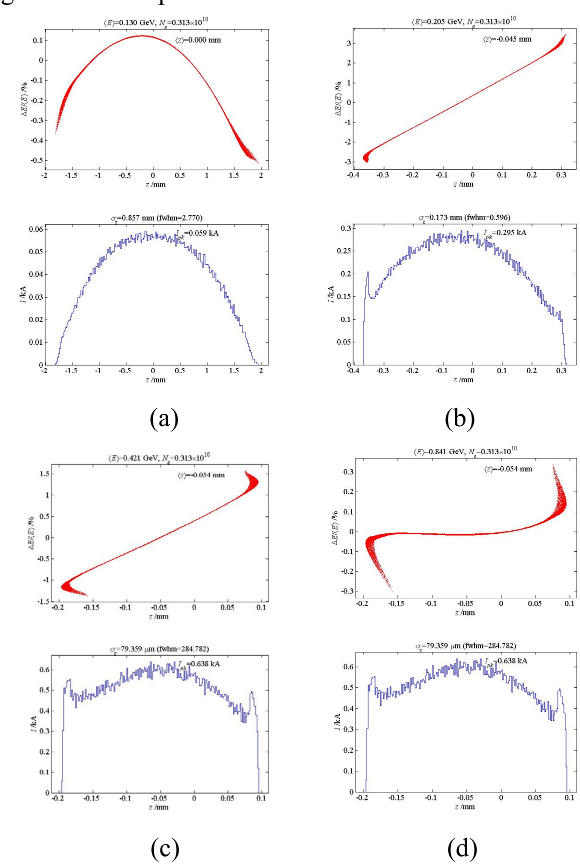

Figure 2 (color): longitudinal phase space (red) and current profile along the bunch (blue) at (a): entry of injector; (b)exit of injector; (c)exit of BC2; (d) exit of L3.

The FODO focusing structures are used at the exit of BC1 and L3 to make the transverse emittance measurement and beam tomography. A number of quadruple magnets are also used in between each section to do transverse matching. The betatron functions and the transverse beam

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envelope are computed by Elegant [2], which are illustrated in Figure 3:

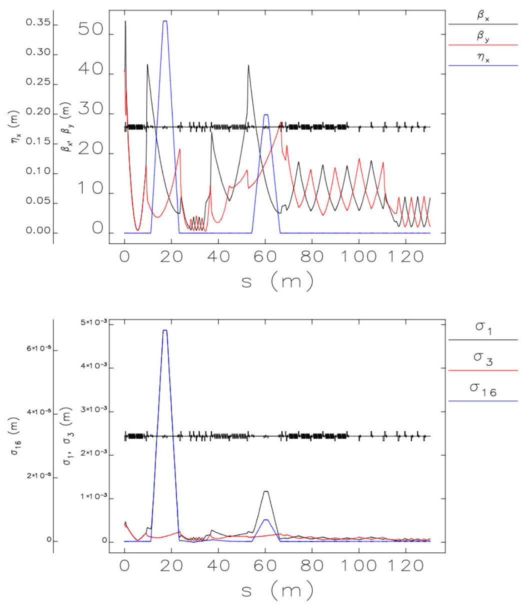

Figure 3 (color): upper: betatron functions: βx (black); βy (red) and ηx (blue) along the LINAC; Lower: beam envelope functions: σ_1 (black), σ_3 (red), σ_{16} (blue).

BEAM STABILITY CONTROL

In general, the instrumental errors are the major factors to disturb the beam parameters. If the errors are not well-controlled, the beam quality will be impaired and the trajectory error will also be significant. In the following, the details will be discussed separately in longitudinal and transverse direction.

Longitudinal Jitter Analysis

The longitudinal stability control usually includes energy, current and arrival time. As introduced before, SXFEL is a cascaded HGHG FEL facility, which has very high demands on the electron beam quality. For example, since SXFEL adopts fresh bunching technology, it requires that the pulse length of the seed laser to be much less than that of the electron pulse, meanwhile, the jitter between seed laser and beam bunch shall be much less than the electron pulse length. In summary, the variation of the beam parameters are mainly produced by errors of bunch charge, arrival time, accelerating phase and amplitude, and the magnetic field of the bending magnet, etc. The basic jitters of different kind in SXFEL are shown in table 2.

Table 2: Basic jitters of SXFEL

Jitter source	Value	Unit
Central energy	< 0.1	%
Peak current	< 10	%
Arrival time	< 100	fs

Because of the diversity of the errors, we need to reasonably assign the errors to each part. In our study, the total compression rate keeps constant, the compression rates and R56s of BC1 and BC2 are then adjusted separately to find different working points, and the errors at each working point are analyzed at last to obtain the best working condition.

The results indicate that as the R56 of BC1 falls in between -50 mm and -45 mm, and the R56 of BC2 falls in between -16 mm and -14 mm, the working point is optimized in terms of the jitter introduced by the instrumental errors. Moreover, we observed that the change of the jitters of peak current and arrival time are in the same direction of the change of the compression rate assignment, whereas that of central beam energy is opposite to the change of the compression rate assignment. As shown in Figure 4. As a result, we choose the compression rate of BC1 to be -48 mm and that of BC2 to be -15 mm.

Transverse Orbit Correction

Because of the mechanic errors during manufacture and installation, the beam will not always be on the ideal trajectory, which introduces nonlinear effects and results in bad beam quality. If those errors are not well-controlled, serious beam loss will happen and the whole machine will not work properly. Therefore, precise orbit control and correction are needed to guarantee the working condition of machine.

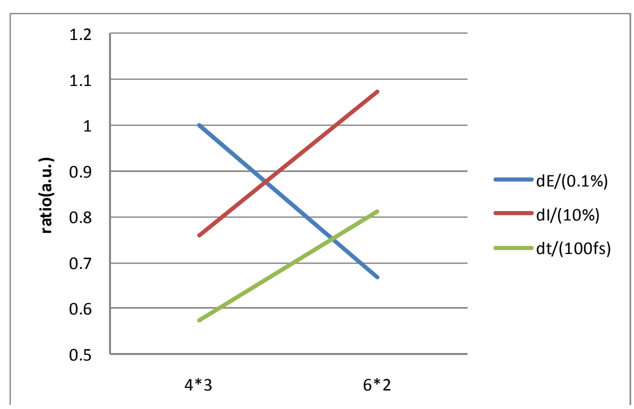

Figure 4 (color): comparison of jitters at different compression rate assignments (BC1*BC2).

In the study, we used the method of BBA [3] (Beam-Based Alignment) to solve this problem including one to one, global and dispersion-free algorithms. The initial errors used in this study are in table 3. The beam trajectories before and after correction are shown in Figure 5 and Figure 6, respectively. In the figures, we can see that the deviation of the beam trajectory due to initial errors can be corrected effectively, e.g., the order of amplitude is reduced from mms to microns.

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Table 3: Initial errors to start correction

Error source	Δx,Δy (μm)	Δθ (mrad)	ΔK/K, ΔB/B (%)
dipole	150	1	0.01
quadruple	150	1	0.1
BPM	150	N/A	N/A
Accelerating tube	150	N/A	N/A

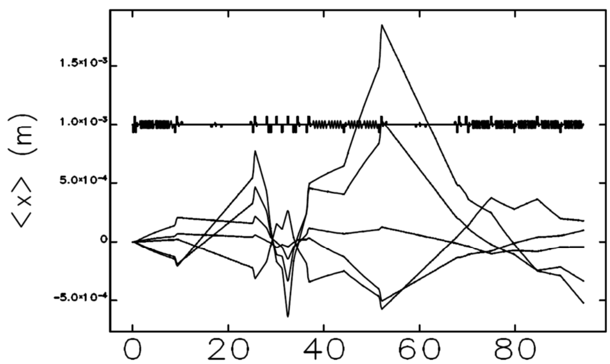

Figure 5: SXFEL beam trajectory before correction: 5 particles, 30 BPMs.

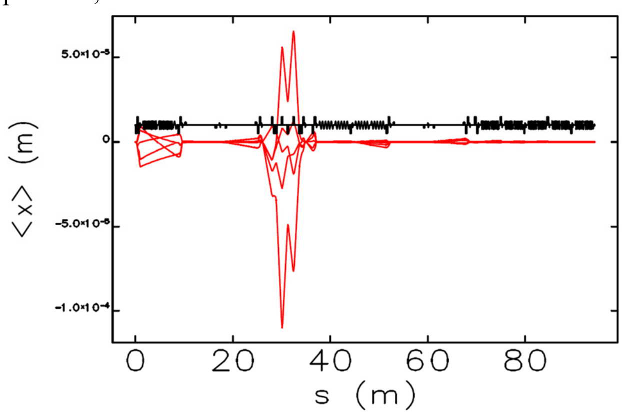

Figure 6: SXFEL beam trajectory after correction: 5 particles, 30 BPMs.

MICROBUNCHING INSTABILITY

Microbunching instability (μBI) is an important issue in the LINAC of a FEL facility. If the gain of the instability is too large, the quality of the electron beam will be destroyed and is harmful to the whole FEL device.

Both the analytical computation and numerical simulation show that the microbunching instability in SXFEL is not negligible, and the LSC impedance induced growth is much larger than that driven by the CSR impedance. Moreover, the gain is sensitive to some critical beam and lattice parameters such as the beam size, uncorrelated energy spread and the R56 in the chicanes, etc.

As a matter of fact, a laser heater is needed to suppress the instability. Further study is on the way to optimize and properly implement the laser heater into the SXFEL lattice. The gain curves of μBI computed by different methods are shown in Figure 7. The result by Elegant seems to have higher peak gain and it may be due to numerical noise with the default settings of digital filter. The gain curves by Elegant with laser heater on with various laser spot sizes are in Figure 8. We can see that the gain is suppressed dramatically with Laser heater, especially when the laser spot size matches the transverse size of the beam.

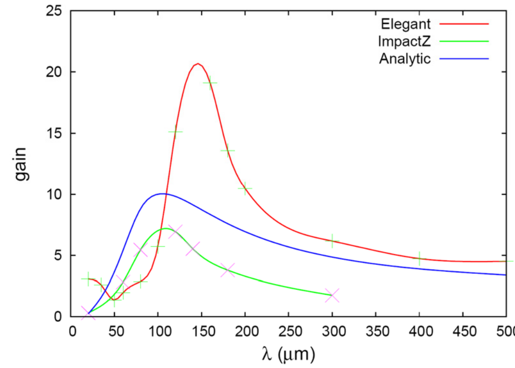

Figure 7 (color): μBI gain in SXFEL computed by different methods: Elegant (red), ImpactZ (green) and Analytic (blue).

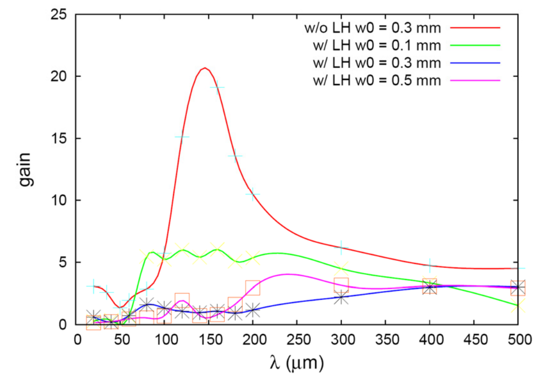

Figure 8 (color): μBI gain in SXFEL computed by Elegant with various laser waist sizes: without laser heater & waist = 0.3 mm (red), with laser heater & waist = 0.1 mm (green), with laser heater & waist = 0.3 mm (blue), with laser heater & waist = 0.5 mm.

CONCLUSIONS

The study of physial design for the LINAC of SXFEL has started. The beam and machine parameters are being optimized to gain the best performance. The basic structure is determined, the beam dynamics in both direcctions is analyzed, the longitudinal jitter study is done, the orbit correction analysis has been carried out and the microbunching instability study is ongoing. The work is continuing to be detailed and is expected to turn into a real machine.

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