BEAM STABILITY MODELLING AND JITTER CONTROL FOR SXFEL LINAC*

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Abstract

FEL operations foresee stringent requirements for the stability of the global linac output parameters and this requirement is particularly stringent for the successful operation of an externally seeded FEL. In order to understand the sensitivity of these parameters to jitters of various error sources along the SXFEL linac, studies have been performed based on analytical methods and tracking code simulations. Using the tolerance budget as guidance, beam jitter control techniques are discussed on the view of the beam dynamics.

INTRODUCTION

The Shanghai Soft-X ray FEL (SXFEL) is a seeded FEL facility based on the high brightness beams generated from a compact linac, which consists of S-band photocathode injector and C-band main linac [1]. Two-stage chicanes are adopted to longitudinally compress the beam in combination with off-crest RF phases setting of the upstream accelerating structures. While earlier studies show 840MeV beam energy can get the desired output laser pulse at 8.8nm, after adding extra 4 sets of RF units at the reserved space, 1.5GeV electron beam can be accomplished and SXFEL can be upgraded to a user facility working at water window regime [2]. In this paper, beam jitter performances are analysed based on this upgraded configurations and Fig.1 shows the overall layout. Four sets of S band RF units are adopted before the first stage bunch compressor to ease the effect of transverse wakefields and nonlinearity from S band RF structures. Then, ten sets of C band RF unit, which nominal operating at 40MV/m, consist of the main linac to upgrade the beam to the desired energy.

To generate stable FEL pulses, a stringent tolerance budget is required for the LINAC output parameters, such as the mean beam energy stability, electron bunch arrival time jitter, peak current variation and the transverse beam position offset. This stability requirement is even more demanding for the cascaded HGHG scheme adopted by SXFEL. Non-invasive detector based feedback loops are only effective at low frequencies. Meanwhile, pulse-to-pulse jitter should be guaranteed effectively by hardware tolerances, which is too fast to be corrected. In order to understand the jitter sensitivity of these parameters to various error sources along the LINAC, an elaborate study should be performed to give the tolerance budget for hardware specifications.

In this paper, jitter studies are done using un-correlated summed method, both for beam in longitudinal and transverse direction. The jitter mechanisms associated with linacs are introduced briefly and the un-correlated summed method is explained. Then, tolerance budget for longitudinal beam jitter is obtained and control techniques are explored on the context of beam dynamics. For transverse beam jitter, we deal with the tolerance budget separately depending on different jitter mechanisms. In the last, a brief summary is given for the beam performance at the exit of linac.

BEAM JITTER AND TOLERANCE BUDGET

In general, beam stability can be treated independently as the phase space planes are only weekly coupled. In the longitudinal plane, electric fields accelerate the bunch and compress the bunch length by magnetic chicane. Jitter from amplitude and phase of the accelerating fields should be controlled properly to control the longitudinal beam jitter, which usually includes beam energy, beam arrival time and bunch length stability. Compared with one stage bunch compression, although it has been optimized, the two-stage compressor system is still sensitive to various jitter sources to beam jitter [3]. Take beam arrival time as example, this jitter is defined as the time-of-flight variation of the center-of-mass relative to the time-of-flight of a reference particle and described by [4],

$$dt = \frac{1}{c}\left(d(R_{56}\delta) - \frac{1}{2}dR_{56}\right) \quad (1)$$

The first term of the equation associated with the bunch compression factor and last term comes from the magnetic field of the dipole.

Considering all jitter sources as independent perturbations, the electron bunch arrival time jitter after the one-stage chicane is obtained and the resultant jitter comes magnetic field jitter of the dipole, and the amplitude jitter and phase jitter of the accelerating field before the chicane.

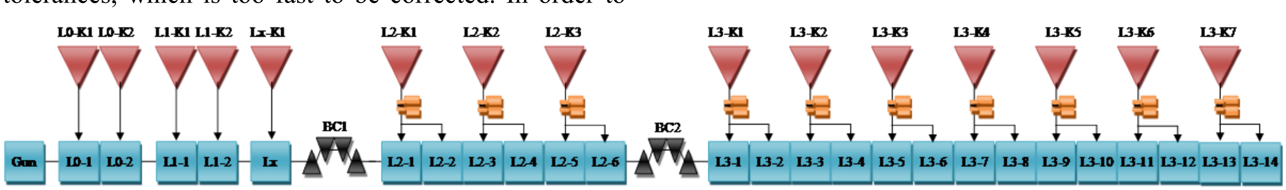

Figure 1: Overall layout for SXFEL linac.

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$$dt^2 = \left(\frac{dt_0}{CF}\right)^2 + \left(\frac{dB}{B}\right)^2 \left(\frac{R_{56}}{c}\right)^2 + \left(\frac{dV}{V}\right)^2 \left(\frac{R_{56}}{cE}\right)^2 (eV \sin\varphi)^2 + (d\varphi)^2 \left(\frac{R_{56}}{cE}\right)^2 (eV\cos\varphi)^2 \quad (2)$$

In traverse plane, pulse-to-pulse trajectory instability can be caused by various sources either, including mechanical vibration, poor power supply regulations. Additionally, the linac can amplify pulse-to-pulse centroid motion that coupled with bunch longitudinal motion. For SXFEL, both the jitter in longitudinal direction between pulses and the transverse stability prohibit the maximum performance of both the FEL itself and the possible experiences that can be performed. The requirements of the beam stability, which deduced from the FEL lasing process, are listed in Table 1.

Table 1: Beam Stability Requirement for SXFEL Linac

	Value	Unit
Mean beam energy	0.1	%
Beam current	10	%
Beam arrival time	200	fs
Transverse beam jitter/Beam size	10	%

To generate a tolerance budget for various jitter systems, formula (3) is adopted based on summing random, uncorrelated effects:

$$\sqrt{\sum_{i=1}^{N} \left(\frac{p_{tol}}{p_{sen}}\right)_i^2} < 1 \quad (3)$$

The sensitivities psen are weighting values for the summation and defined as the value when only one jitter source corresponding to the desired jitter performance. If the tolerances are chosen such that, ptol < psen for all i, then a budget is formed.

LONGITUDINAL JITTER CONTROL

For two stage bunch compression scheme, much more variables should be included in the formula (2). For beam energy and bunch length jitter, the situation is more complex when the wakefield effects should be taken into consideration for beam dynamics modelling. In reality, we analyses the longitudinal jitter effect through numerical method.

Tolerance Budget

Each sensitivities for longitudinal beam jitter is obtained using 1D fast tracking code LiTrack [5] and the tolerance budget for SXFEL linac are formed as Table 2.

The tolerances are quite tight for many of the parameters, especially those systems driven by a single klystron (e.g., L1). Actually, L1 section, which is associated with beam chirp generated, is the most sensitive components. Although the multiple-klystron linacs such as L2 and L3 could have looser requirements than the tolerance listed, specifications which comparable with L1 section are indicated to improve beam stability performance.

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Table 2: Longitudinal Tolerance Budget for SXFEL Linac

	Value	Unit
Driving laser arrival time	0.25	ps
Charge jitter	5	%
L0-L1 phase jitter (S band)	0.1	deg
L0-L1 amplitude jitter	0.1	%
Lx phase jitter (X band)	0.3	deg
Lx amplitude jitter	0.25	%
L2-L3 phase jitter (C band)	0.1	deg
L2-L3 amplitude jitter	0.1	%
relative R56 error (BC1&BC2)	0.05	%

Jitter Dependence on Compression Ratio Distribution

Because of the diversity of the errors, we need to reasonably assign the errors to each component. By a careful choice of the linac acceleration and compression parameters, the longitudinal beam jitter can be minimized. In our study, the total compression rate keeps constant and then adjusted the ratio distributions between two chicanes. For different working points with same output beam parameters, the jitters are analysed as shown in Fig. 2.

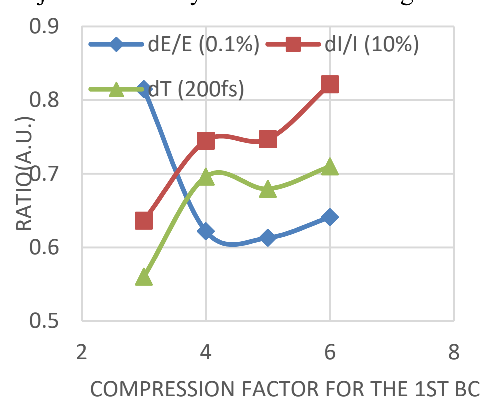

Figure 2: Normalized longitudinal beam jitter depending on different BC ratio distributions.

BEAM TRAJECTORY STABILITY

In linear accelerators, the transverse beam orbit jitter is induced by the current regulations for steering correctors and misaligned quadrupoles. Collective effect, which comes from CSR effect during bunch compression and transverse wake when the beam passing through the misaligned accelerating structures, also related to the transverse beam jitter. Usually as longitudinal beam jitter, such beam orbit estimation can be performed using tracking

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simulations, with many different sets of beamline elements, which tend to take a long time. Instead, introducing the dimensionless normalized trajectory amplitude, Ax,y, a much faster method of quantitative estimation of beam jitter can be adopted [6].

$$A_x \stackrel{\text{def}}{=} \sqrt{\frac{x^2+(x\alpha+x'\beta)^2}{\varepsilon\beta}} \quad (4)$$

Here x and x′ are the horizontal trajectory centroid offsets at any point along the accelerator, and β, α, and ε are the Twiss parameters and geometric transverse emittance at that same point. This normalized amplitude is constant along the accelerator and can be summed up to get the final trajectory amplitude at the exit of the linac. So a total jitter budget can be formed by the sensitivity results as described in sec. 2.

Vibration Measurements of Key Components at SXFEL

Vibration measurements were carried out at the SXFEL tunnel. We used a DHDAS5927 data acquisition system and DH610 seismometers from Donghua Testing Technology Co., LTD, China. The measurement points at SXFEL are shown in Fig. 3 as P1-P6 and the RMS values of vibration from 1-100Hz are listed in Table 3.

Table 3: RMS Values of Vibration (μm) (1-100Hz)

Location	Vertical	Horizontal
P1	0.0970	0.2075
P2	0.0895	0.1996
P3	0.0962	0.1970
P4	0.0966	0.1923
P5	0.0991	0.1948
P6	0.0932	0.1777

Transverse Beam Orbit Jitter

Using equation (4), we calculate the sensitivity for current regulations of each steering coil and the quadrupole magnet in SXFEL linac. Vibrations induced orbit kick also included and the summarized results are shown in Table 4 and the sensitivity for steering coil along the beamline is shown in Fig.4.

Table 4: Trajectory Jitter at the Linac Exit

	sensitivity	Kick expression	Ax
Steering coil regulations (0.002G-m)		$e\int \lvert B\rvert dl/p$	6%
Quadrupole vibrations (250nm)	$x'_s = \sqrt{\varepsilon/\beta}/10$	$\sigma_{\Delta x}/\lvert f\rvert$	5%
Quadrupole regulations (0.1%)		$(\sigma_I/I)\lvert\Delta x\rvert/\lvert f\rvert$	5%

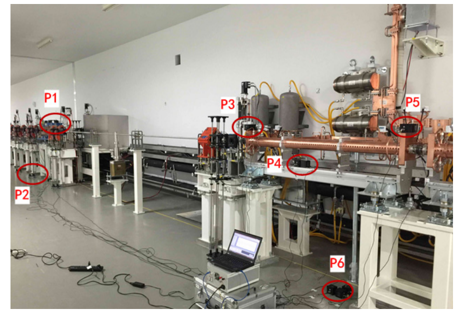

Figure 3: Test site at SXFEL. Point P1 locates on the top of magnet, P2 on the floor of magnet support, P3 on the upper of accelerating structure, P4 on the middle of support for accelerating structure, P5 on the lower of accelerating structure and P6 on the ground of accelerating structure assembly.

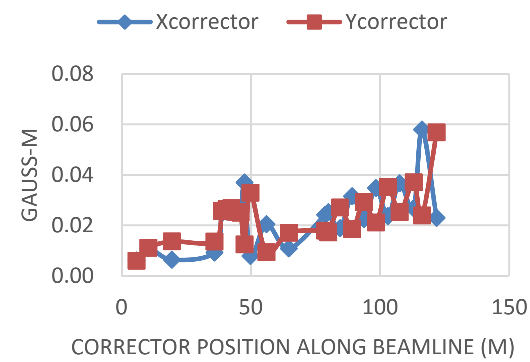

Figure 4: Sensitivity for steering coil along SXFEL linac.

Orbit Jitter from Beam Collective Effect

Collective effects also relate to the beam jitter in transverse plane. Numerical calculations are performed by tracking method, and the coefficient is given with the beam parameter as variable.

$$A_x \approx 2(\Delta\sigma_z/\sigma_{z0})$$

SUMMARY AND DISCUSSION

The sensitivity of beam parameters to jitters of various error sources along the SXFEL-UF linac has been performed and tolerance budget to be used as guidance in the design of the linac are constructed based on tracking studies and analytical formula.

Control techniques on view of beam dynamics are discussed for 6D beam phase space. Different working point conditions are compared to get the optimized performance. According to the knowledge from longitudinal tolerance budget, working points can be tuned flexibly according to the FEL lasing condition. For transverse plane, the 10% beam size jitter is not an easy target and contributions from CSR jitter should be controlled properly. On the view of this point, the phase stability of the RF system should be maintained to get the better performance for bunch length stability.

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