BEAM OPTICS AND PARAMETER DESIGN OF THE XFEL/SPRING-8

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Abstract

The transverse optics of the XFEL/SPring-8 is designed using newly introduced linear formulation of the beam envelope including acceleration effects. The beam optics of the main linac and undulator section is based on a FODO-like lattice. To avoid the FEL gain reduction due to a longitudinal kink in the bunch, the horizontal beta function is set small at bending magnets to minimize the CSR effect. Since the accelerator of XFEL/SPring-8 uses a thermionic gun with an 1 A initial beam current, the total bunch compression ratio reaches about 3000, which is one order higher than a photocathode system. For nonlinearity compensation in the bunch compression, two correction cavities are installed, which are operated at the same frequency as the linac and not at its harmonic. In this paper, the XFEL/SPring-8 accelerator layout and its expected beam parameters are shown to achieve the 0.1 nm x-ray FEL.

INTRODUCTION

The XFEL/SPring-8 facility is designed based on a compact FEL concept [1]. By using short-period undulators (λ_u=18 mm), 0.1 nm FEL can be achieved with a relatively low beam energy of 8 GeV [2]. Also high-gradient C-band accelerators (35 MV/m) reduce the length of the accelerator less than 400 m [3].

In this paper, the component layout and basic parameters of the XFEL/SPring-8 accelerator are shown to obtain the required beam current of 3 kA with a normalized slice emittance of 1 πmm-mrad.

ACCELERATOR LAYOUT

The layout of the XFEL/SPring-8 accelerator is illustrated in Fig. 1.

The injector section is essentially the same as that of the SCSS test accelerator, which has been successfully operated as a VUV FEL since 2006 [4]. An 1 ns electron bunch is sliced out of 2 μs-1.2 A cathode emission using a deflector and a circular slit installed just after the 500 kV gun. An energy chirp is given to the bunch by a 238 MHz cavity for velocity bunching, and then the beam energy is boosted up to 1 MeV by a 476 MHz cavity to ease the space charge effect. The final accelerator of the injector section is L-band APS accelerators. The frequency of the final accelerator is lowered, which was S-band in the SCSS test accelerator, to increase capture efficiency and reduce the energy loss in a C-band correction cavity. After the injector section, the electron bunch is accelerated to 8 GeV by the following S-band and C-band accelerators.

In order to check the final bunch distribution and slice parameters, a deflector cavity is installed downstream of the third bunch compressor (BC-3). The frequency of the deflector cavity is chosen to be C-band to share the common RF system of the main accelerator. The structure of the deflector cavity is newly designed and optimized for C-band, which is named RAIDEN [5]. In order to analyze the bunch structure after the bunch compression in BC-1 and BC-2, straight bypass lines are installed in BC-2 and BC-3.

High-gradient operation of the C-band accelerator produces a nonnegligible dark current, which may cause a serious problem of demagnetization for in-vacuum undulators [6]. Although most of the dark current is lost in an energy-mismatched focusing system, the energy slits are installed at the three BCs and two chicanes to completely eliminate the surviving electrons [7].

At the end of the accelerator, a switching dipole magnet distributes the electron beam to five undulator beamlines (BL1~5) and an injection line to the SPring-8 8 GeV storage ring (XSBT). In the initial phase of the XFEL commissioning, 18 undulators are installed in BL3, and BL1 is used as a bypass line.

In the undulator section, straightness of the electron beam orbit is the most important issue. To avoid the FEL gain degradation, the electron orbit deviation in the undulator section should be suppressed within ±4 μm [8]. In order to achieve this requirement, we use x-ray radiation from an alignment undulator, which is installed upstream of the switching magnet, as a reference line of BL3. Although a visible laser can be an alternative, shorter wavelengths are desirable to minimize diffraction along the 100 m-long undulators. In order to align the BPMs and quadrupole magnets (Q-mags) on the reference light, a pinhole is inserted to the center of each BPM to check and adjust its position by observing the diffraction image downstream. Then the electron beam based alignment is applied to achieve the required orbit straightness.

TRANSVERSE OPTICS

There are several possible sources to degrade beam emittance, such as space charge, CSR, wake fields and residual dispersion. Except for the nonlinear space charge effect, the slice emittance is hardly affected unless there is longitudinal mixture of the bunch due to over-bunching. However, those sources may change the transverse center of each slice and cause a kink of the electron bunch. Once the electron bunch is kinked, it not only increases the projected emittance, but also starts to oscillate with respect to the reference orbit like head-tail instability. Since the electron orbit in the undulator section should be

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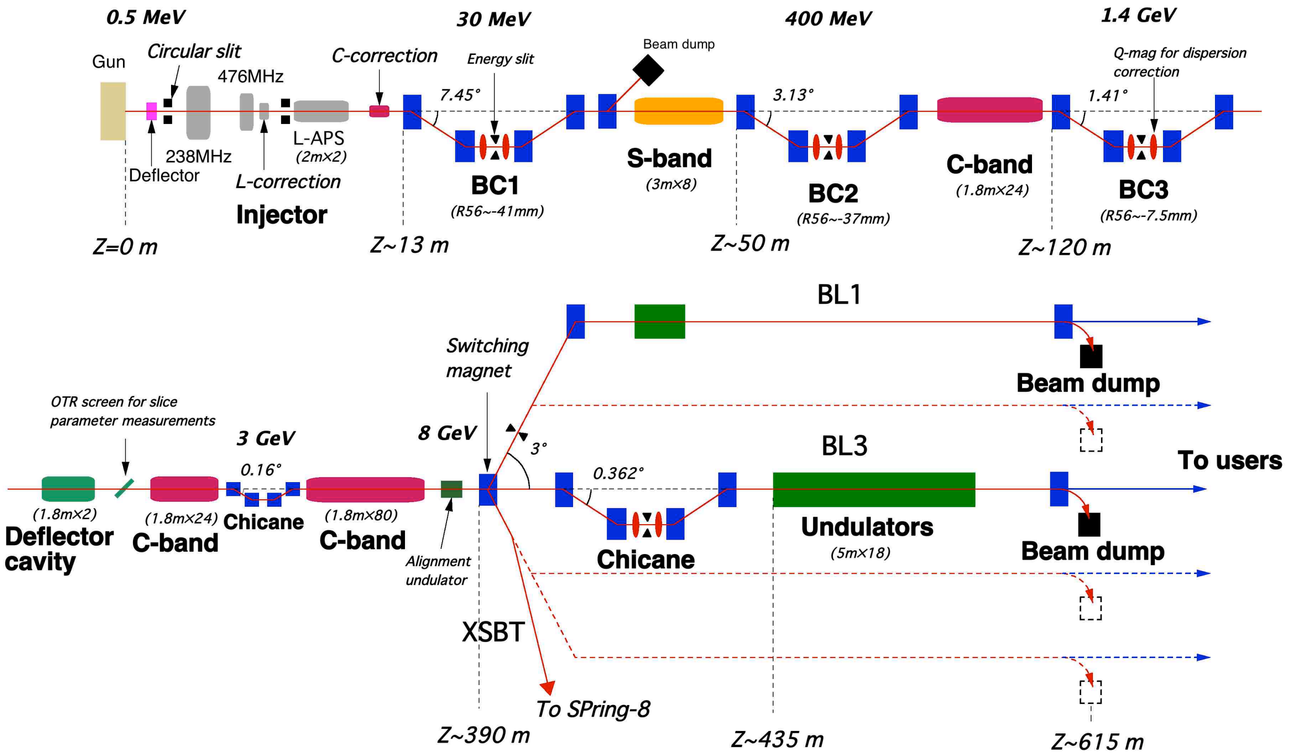

Figure 1: Layout of the XFEL/SPring-8 accelerator and beamlines.

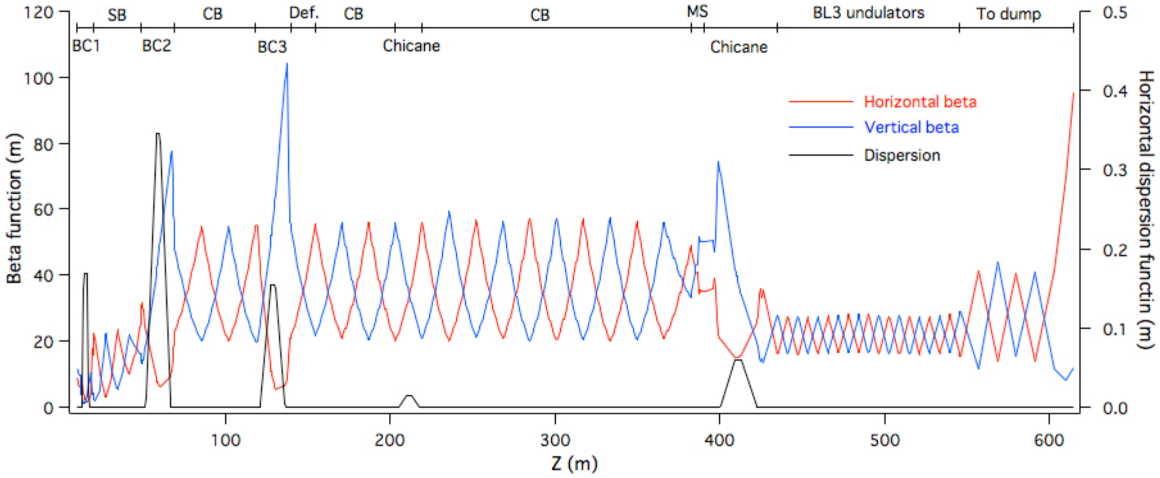

Figure 2: Beta functions and horizontal dispersion of the XFEL/SPring-8.

accurately straight, the kink of the bunch may result in FEL gain reduction. Therefore it should be avoided.

The other aspect required for the XFEL/SPring-8 optics is compactness. In order to save space, the lattice of the XFEL/SPring-8 is based on FODO. In a FODO lattice, the electron beam has an asymmetric transverse cross-section and excites multipole wake fields particularly in accelerator structures. However the emittance of the XFEL/SPring-8 is small enough to neglect them.

In the injector, a CeB_6 cathode of the electron gun emits a uniform beam with 0.6 πmm-mrad emittance of the beam core [9]. This transverse uniformity of the electron beam density is important at low energies to avoid the slice emittance growth due to the nonlinear space charge fields. In addition, the edge of the gun emission is removed by a circular slit installed after the deflector (Fig. 1).

The transverse focusing system of the injector section consists of magnetic lenses with an iron yoke. By eliminating a long solenoid conventionally covering an accelerator, various components, such as monitors and steering magnets, can be freely arranged in the injector. The focusing strength of the magnetic lens is set to compensate the linear space charge force of the uniform beam, and the beam radius is kept almost the same to realize a laminar flow before the L-band APS accelerators.

When we consider and design beam optics, a transverse beam envelope is transferred along an accelerator. The beam envelope is generally expressed with Twiss parameters, which defines the electron distribution in an x-x' phase space as

$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = \varepsilon\,, \qquad (1)$$

where α, β, γ are Twiss parameters, ε is an emittance, and x and x' are the position and divergence of electrons. In case of a storage ring, the transfer of the beam envelope is easily calculated using a symplectic transfer matrix. However this procedure can not be applied to a linac, since the emittance changes due to acceleration and it is no more an invariant. Therefore, the transverse beam envelope is conventionally calculated in an x-p_x phase space for a linac, where p_x is the transverse momentum of electrons. Although Twiss parameters can be obtained indirectly from the beam envelope in the x-p_x phase space, it is not convenient for rapid estimation and feedback correction of the lattice. Considering also that the phase space volume of a photon is defined in the x-x' phase space, the formulation of the envelope transfer in the x-x' phase space is preferable for a light source accelerator.

In order to calculate and design the transverse beam envelope of the linac, the formulation in an energy-normalized phase space (X-X') is newly introduced, where X and X' are defined as

$$X = \sqrt{\bar{\beta}\bar{\gamma}}\,x$$
$$X' = \sqrt{\bar{\beta}\bar{\gamma}}\,x'. \qquad (2)$$

$\bar{\beta}$ and $\bar{\gamma}$ are the electron velocity and energy in units of the light velocity and the electron's rest mass respectively. In this X-X' phase space, the electron distribution can be expressed by using the same Twiss parameters in Eq. 1 as

$$\gamma X^2 + 2\alpha X X' + \beta X'^2 = \frac{\varepsilon}{\bar{\beta}\bar{\gamma}} = \varepsilon_n. \qquad (3)$$

Since the right-hand side of Eq. 3 is a normalized emittance (ε_n), it is an invariant for acceleration. Therefore the transformation of Twiss parameters can be directly obtained using a symplectic matrix in the X-X' phase space, as in a storage ring [10,11].

The lattice of the XFEL/SPring-8 is calculated with this newly introduced formulation in the X-X' phase space. The beta function after BC-1 to the BL3 beam dump is shown in Fig. 2. Due to a relatively large energy chirp and chromatic aberration of the focusing system in the injector section, the projected normalized emittance of the XFEL/SPring-8 reaches typically 2 πmm-mrad, while the slice value is around 0.8 πmm-mrad. Since there is only one diagnostics of the slice parameters in the XFEL/SPring-8, which is the deflector cavity located after BC-3, the transverse optics is designed for the projected parameters.

The lattice of the S-band and C-band accelerators is FODO-like, but with acceleration in between the Q-mags. The lattice period of the C-band section is 16 m to reduce the number of the Q-mags. Considering the transverse wake fields, all accelerator structures are aligned within ±0.3 mm to avoid the projected emittance growth and the kink of the bunch.

The horizontal beta function at the BCs and chicane is set small to minimize the CSR effect as in Fig. 2. In order to correct leakage of the dispersion function, a pair of small Q-mags is installed at the center of each BC and chicane.

Since no significant difference in the FEL gain was found between singlet, doublet and triplet Q-mag arrangements, a simple FODO lattice is applied to the undulator section. The beta function is set so that the FEL gain length becomes minimum.

Table 1: RF Parameters of XFEL/SPring-8, 0 Degree Phase Corresponds to Crest Acceleration

	Amplitude	**Phase**
238 MHz	0.198 MV	-119 deg.
476 MHz	0.8 MV	-12 deg.
L-band correction	0.14 MV	-180 deg.
L-band APS1	9.2 MV/m	-22deg.
L-band APS2	9.2 MV/m	-28 deg.
C-band correction	8.8 MV/m	-193 deg.
S-band	16.7 MV/m	-20 deg.
C-band (between BC2 and BC3)	32.2 MV/m	-44 deg.
C-band (after BC3)	35.3 MV/m	0 deg.

BUNCH COMPRESSION

Since the XFEL/SPring-8 uses a thermionic gun, the total compression factor reaches 3000. 1 A emission from the gun is first compressed to 25 A in the injector section by velocity bunching. Then the electron bunch is gradually compressed by three BCs and the final beam current is 3 kA. As in Fig. 3, the bunch is successfully compressed without serious emittance degradation in numerical simulations. In the calculation of Fig. 3, PARMELA is used for the injector section including the space charge effects, and ELEGANT is used for the rest of the accelerator including the CSR and wake fields [12]. The parameters of the BCs and RF fields of the XFEL/SPring-8 are given in Fig. 1 and Table 1.

In order to achieve the compression factor of 3000, linearization of the bunch compression process is indispensable. A harmonic correction cavity is conventionally used to compensate nonlinear terms of the main accelerator RF fields and the BCs, but the XFEL/SPring-8 employs a simpler solution [13,14]. When the electron bunch goes through a correction cavity, the energy modulation is given to the bunch at the frequency of the correction cavity. For nonlinearity compensation, this frequency should be higher than that of the main accelerator. By installing the correction cavity before the BC, however, the frequency of the energy modulation given by the correction cavity is effectively increased by a factor of the bunch compression ratio. Although the initial energy chirp for the first bunch compression should be given by a lower RF frequency, the correction cavity can be operated at the same frequency as the main accelerator.

There are two nonlinear correction cavities installed in the XFEL/SPring-8, an L-band cavity in the injector section and a C-band cavity upstream of BC-1. The L-band correction cavity mainly linearizes the velocity bunching in the injector, and the C-band correction cavity compensates the three-stage bunch compression.

Although the initial bunch charge after the deflector is 1 nC, the charge being successfully compressed and accelerated to the undulators is expected to be 0.3 nC. By using the slits of the BCs and chicanes, unnecessary part of the bunch is removed at the energies as low as possible to decrease radiation dose.

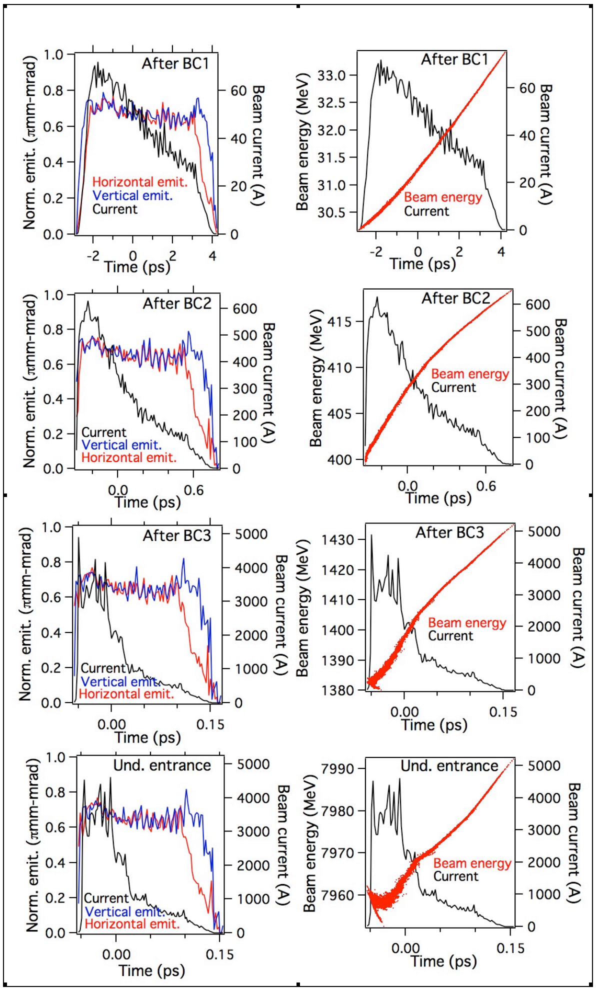

Figure 3: Electron bunch distribution after each BC and at the undulator entrance. Normalized slice emittance and current distribution are shown on the left. Energy and current distributions are shown on the right.

SUMMARY

The basic layout and parameter design of the XFEL/SPring-8 are shown. In the SCSS test accelerator, the electron beam performance of 0.7 πmm-mrad with 300 A has been already confirmed at the energy of 250 MeV [4]. Also most of the important hardware components, such as the injector, the C-band accelerator and the cavity-type BPM, have been tested and improved at the test accelerator. For the beam commissioning scheduled in the spring of 2011, we are currently preparing software tools, including a beam envelope feedback system using the newly developed formulae, to realize the design parameters in a real machine.

REFERENCES

[1] T. Shintake et al., Nature Photonics 2, p.555 (2008).

[2] T. Tanaka, T. Seike and H. Kitamura, "Measurement of SPring-8 XFEL Undulator Prototype with the SAFARI System", FEL'08, Gyeongju, August 2008, TUPPH053, p. 371 (2008); http://www.JACoW.org.

[3] T. Inagaki, T. Hasegawa, H. Maesaka, T. Oshima, Y. Otake, T. Shintake, C. Kondo, T. Sakurai and K. Shirasawa, "Construction of 8 GeV C-band Accelerator for XFEL/SPring-8", FEL'10, Malmö, August 2010, WEOC3, in these proceedings.

[4] Tsumoru Shintake et al., Phys. Rev. ST Accel. Beams 12 (2009) 070701.

[5] Hiroyasu Ego and Yuji Otake, "Design of the Transverse C-band Deflecting Structure for Measurement of Bunch Length in X-FEL", EPAC'08, Genoa, July 2008, TUPC023, p. 1098 (2008); http://www.JACoW.org.

[6] T. Sakurai, T. Inagaki, K. Shirasawa, C. Kondo, S. Suzuki and T. Shintake, "High-power RF Test on the Mass-produced C-band RF Components for XFEL/SPring-8", IPAC'10, Kyoto, May 2010, THPEA010, p. 3694 (2010); http://www.JACoW.org.

[7] H. Tanaka, K. Togawa, T. Hara, H. Kitamura and N. Kumagai, "Dark Current Suppression at XFEL/SPring-8 by Using the Chromatic Aberration", PAC'09, Vancouver, May 2009, WE5RFP051, (2009).

[8] T. Shintake and T. Tanaka (eds), SCSS X-FEL Conceptual Design Report, RIKEN Harima Institute Hyogo (2005); http://www.riken.jp/XFEL/eng /index.html.

[9] K. Togawa, T. Shintake, T. Inagaki, K. Onoe and T. Tanaka, Phys. Rev. ST Accel. Beams 10 (2007) 020703.

[10] D.R. Douglas and J. Kewisch, "Betatron Function Parameterization of Beam Optics Including Acceleration", LINAC'88, Proc. of Linac Conference p. 328 (1988).

[11] Toru Hara, Kazuaki Togawa and Hitoshi Tanaka, submitted for publication.

[12] M. Borland, Phys. Rev. ST Accel. Beams 4 (2001) 070701.

[13] Kazuaki Togawa, Toru Hara and Hitoshi Tanaka, Phys. Rev. ST Accel. Beams 12 (2009) 080706.

[14] Toru Hara, Kazuaki Togawa and Hitoshi Tanaka, "Electron Bunch Compression with Dynamical Non-linearity Correction for a Compact FEL", FEL'09, Liverpool, August 2009, TUOA02, p. 215 (2009); http://www.JACoW.org.