BEAM COMMISSIONING OF THE SACLA ACCELERATOR

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Abstract

The beam commissioning of the X-ray FEL facility at SPring-8, which is named SACLA (SPring-8 Angstrom Compact free-electron LAser), has been started since February 2011. During the beam commissioning, a beam diagnostic system and a control system are also tested and improved to enable fine tuning of the machine. The position and energy of the electron beam show excellent stability and the fault rate of an RF system is currently decreased to one per a half-hour. Since coherent OTR prevents beam profile measurements after full bunch compression, several OTR screens are changed to YAG screens with a mask to remove coherent OTR. The beam tuning was started from an injector, and then proceeded to bunch compression and beam envelope matching. After the orbit alignment at undulators, the first lasing was obtained in June 2011 at the wavelength of 0.12 nm. The commissioning status of the SACLA accelerator is reported.

INTRODUCTION

The layout of the SACLA accelerator is shown in Fig. 1. Considering stability and ease of maintenance, a 500 kV pulsed gun with a thermal cathode is used as an electron source [1]. The facility size is considerably reduced by the use of high-gradient C-band accelerators (35 MV/m) and short-period in-vacuum undulators (λ_u=18 mm), which reduce the beam energy required for X-ray FEL operation.

Since the beam current from the thermionic gun is about 1 A, the bunch compression factor of SACLA reaches 3000, which is roughly one order higher than that of a photo-cathode system. The electron bunch is first compressed by velocity bunching in the injector, and then by three bunch compressors (BC1-3). The length of the compressed bunch is measured and confirmed by an RF deflector installed downstream of BC3. There are straight bypass lines installed in BC2 and BC3 to enable the bunch length measurements after each compression stage.

The requirements for undulator field errors in X-ray FELs are much more strict than those in synchrotron radiation sources. According to the results of demagnetization tests of the undulators, the beam loss of the undulator section should be less than 10^{-6} of the bunch charge [2]. To achieve this, the electron halo and dark current from the C-band accelerators are removed by two additional chicanes installed in the middle and downstream of the accelerator. To monitor the beam loss in the undulators, beam loss monitors and a diamond halo monitor are installed [3].

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 storage ring (XSBT). 18 undulators are currently installed in BL3 and BL1 is used as a bypass line for the beam commissioning.

INJECTOR COMMISSIONING

The RF system of the SACLA injector consists of a 238 MHz buncher, a 476 MHz booster and two L-band APS accelerators. Magnetic lenses with a steel yoke are used to give transverse focusing. The injector components and layout are essentially the same as those of the SCSS test accelerator, which has been successfully operated as a VUV FEL since 2006, except for several improvements [4]. The frequency of the APS accelerators is lowered from S-band to L-band to increase electron capture efficiency and an L-band correction cavity is introduced to linearize velocity bunching. In order to reduce the deflection of the beam orbit, 7 m-long coils cover the low energy part of the injector to cancel the earth magnetic field. With this earth field correction, strengths of steering magnets are decreased to 1/3 in comparison to the SCSS test accelerator.

After adjusting the beam orbit to pass through the center of each injector component, the beam emittance of the gun is measured by slit scan. The initial emittance is confirmed to be 1.1 mm-mrad, which is a design value, and 20-30 % of the outer part of the beam is removed by a circular aperture for the FEL operation [1].

The RF phases of the injector cavities are determined by detecting the phase of self-induced electro-magnetic fields of the electron beam. The condition of the velocity bunching is checked by measuring the power of coherent radiation from a screen and its dependence on RF phases.

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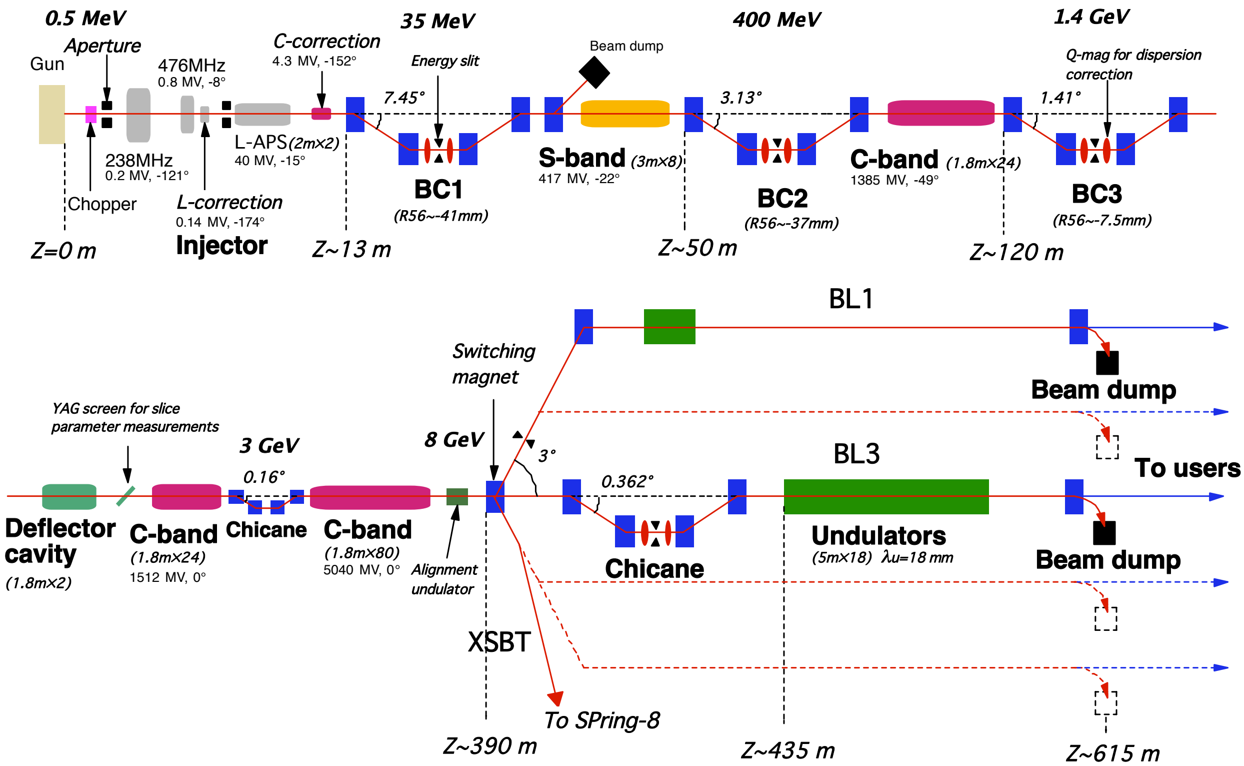

Figure 1: Schematic of the SACLA accelerator.

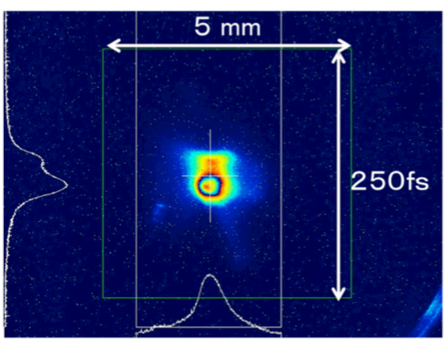

Figure 2: Temporal profile of the compressed bunch with 40 μJ FEL output.

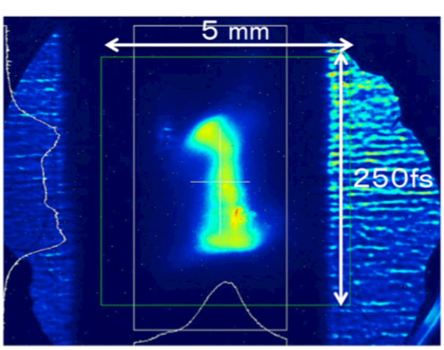

Figure 3: Temporal profile of the compressed bunch with design RF parameters (1 μJ FEL output).

BUNCH COMPRESSION

The initial bunch length of the SACLA accelerator is 1 ns, which is determined by a fast chopper of the injector. The bunch of 1A is first compressed to 20 A by velocity bunching, and then it is gradually compressed to 3 kA in three BCs. For non-linearity compensation, two correction cavities (L-band and C-band) are installed upstream of BC1. Since the bunch length is still long at these correction cavities, the frequency of energy chirp given by these cavities are effectively increased downstream due to the bunch compression [5]. By using this frequency up-conversion, the correction cavity can be operated at the same frequency as the main accelerator. After the beam orbit correction, R56 of the BCs and the RF parameters are set at their design values.

The RF deflector of SACLA is newly designed and developed, which is named RAIDEN [6]. It has racetrack-shaped coupling irises and its cavity structure is deferent from a LOLA type cavity. Two RAIDEN accelerating tubes are installed to project a temporal bunch distribution into a vertical spatial distribution with 50 fs/mm. Since the operation frequency of RAIDEN is C-band, the same RF system as the C-band main accelerator is also used for the RF deflector.

Figure 2 is the measured temporal distribution of the compressed bunch after BC3, with which the FEL output power of 40 μJ is obtained. The RF parameters, however, are slightly different from the design values. The bunch

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charge of 0.1 nC is also lower than the design due to a small energy aperture of the BC1 slit.

When the design parameters are set, the electron bunch of 0.4 nC is successfully compressed to 120 fs as shown in Fig. 3. Nevertheless, the FEL output in this case decreases to 1 μJ. The reason for this low FEL output power is not clear yet, but possibly due to a large emittance.

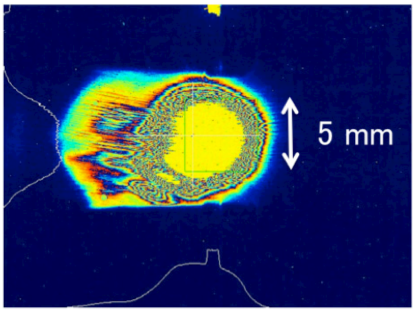

Figure 4: Coherent OTR observed on a BC3 OTR screen.

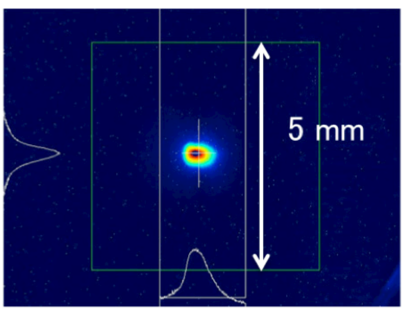

Figure 5: Beam profile observed on a YAG screen with a mask after BC3.

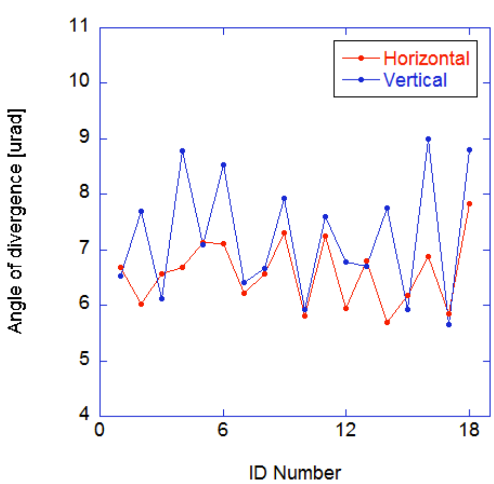

Figure 6: Divergence of spontaneous radiation from 18 undulators.

TRANSVERSE BEAM ENVELOPE

After fixing the RF parameters, the beam envelope is adjusted along the accelerator to match the FODO lattice of the undulator section.

The beam envelope of the SACLA accelerator is calculated using a linear accelerator model based on a normalized emittance [7]. In this model, a symplectic matrix of the acceleration is defined in an x-x' phase space (not in an x-p_x coordinate) to transfer the beam envelope. Therefore, the beam envelope of the linear accelerator can be directly calculated and controlled as in a storage ring.

The beam profile monitors used in SACLA are OTR screens except for the injector and beam dump. Although coherent OTR (COTR) was not observed in the SCSS test accelerator, it causes a problem in the SACLA accelerator. As shown in Fig. 4, intense radiation due to COTR covers the whole screen and a beam profile or position can not be measured after the bunch compression in BC3. In order to resolve this problem, two OTR screens were changed to YAG screens and a mask was inserted on its optical path. By covering the divergent angle of OTR with a mask, COTR can be removed and only the fluorescence of YAG is focused on a CCD. Figure 5 is a beam profile observed downstream of BC3 using a YAG screen with the mask.

Since the number of available screens is limited, the beam envelope is measured on one screen with changing the parameters of various quadrupole magnets (Q-mags) of the accelerator. In the undulator section, the beam profile is estimated from the divergence of spontaneous radiation from each undulator. Figure 6 is obtained radiation divergence of 18 undulators. Although the envelope matching is still not perfect and fine adjustment is necessary, the uniformity of the beam size along 18 undulators is within an acceptable range.

BEAM ORBIT IN UNDULATORS

The electron beam orbit of the undulator section should be straight in order to overlap the radiation and the electron bunch and avoid destruction of the density modulation developed inside the bunch.

In SACLA, 18 undulators are installed in BL3 for the XFEL, and the target accuracy of orbit straightness is ±4 μm. The length of each undulator is 5 m and the total length of the undulator section is about 110 m. Between undulators, steering magnets, a Q-mag and a beam position monitor (BPM) are installed as shown in Fig. 7. The BPM used in the undulator section is a cavity type BPM and an iris can be inserted at its electrical center position [8]. The Q-mag, BPM and iris are fixed on the same granite stage, and their positions on the stage are aligned and measured before installation in the undulator section.

The beam orbit alignment of the undulator section is implemented in two steps. The first step is to place the BPMs on a straight guide line. Since diffraction of a conventional visible laser over a 100 m-long distance makes the alignment difficult, x-ray radiation from an alignment undulator is used as a straight guide line. After inserting two irises at most up and downstream, which determine the guide line, all irises are inserted one by one. The position of each iris is adjusted so that the x-ray

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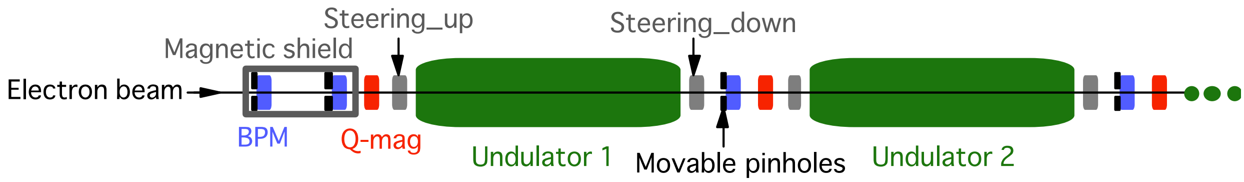

Figure 7: Schematic of the SACLA undulator section.

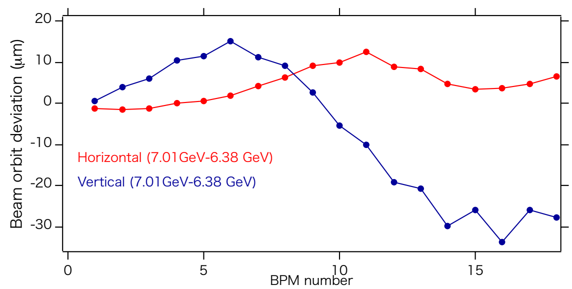

Figure 8: The difference of beam orbits between 7 GeV and 6.4 GeV in the undulator section.

passes through the iris by observing the x-ray profile and intensity at the beamline. As a result, 20 irises of the undulator section are placed on the straight guide line within a ±30 μm accuracy. Although the position of the iris and the BPM center were pre-aligned within a few 10 μm, the BPM center seem to have ±100 μm disagreement with respect to the position obtained in a beam based alignment (BBA). Since the pre-alignment was done in the air, the relative position between the iris and the BPM may be changed in a vacuum.

The second step of the beam orbit alignment is the BBA. To make the orbit straight, the position and angle errors of each undulator, namely first and second integrals of magnetic fields, should be corrected by two steering magnets. In the BBA, the beam position and angle are measured for different beam energies using the BPM and focusing scan of the Q-mag. Then the parameters of the steering magnets are determined so that a dispersion function and its slope become zero at each undulator. The difference of the beam orbits between 4 and 7 GeV is supressed within ±5 μm after the BBA, however, the radiation axes of 18 undulators are revealed to have intolerable errors of 5 μrad on a CCD of the beamline. This inconsistency might come from the dependence of the BPM signal on a beam profile at different energies.

Currently the beam orbit alignment of SACLA is performed so that the radiation axes of 18 undualtors overlap on the beamline CCD. In this condition, only the angle is corrected at each undulator, but there remains the beam position error. Figure 8 is the difference of the beam orbits between 6.4 and 7 GeV. The straightness of the beam orbit at the undulator section should be improved in the upcoming beam tuning schedule.

SUMMARY

The SACLA accelerator commissioning has been started since February 2011, and the first X-ray FEL was successfully obtained in June. The stability and reliability of the accelerator is good enough to perform the beam tuning. However, the FEL gain of the last half of the undulator section is currently smaller than that of the first half, and a small bunch charge limits the FEL output power. The beam tuning should be still continued to resolve these problems and get full FEL performance of SACLA. In March 2012, SACLA will be open to public users.

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