BEAM PARAMETERS OF THE SCSS PROTOTYPE ACCELERATOR DESIGNED BY PARMELA AND COMPARISON WITH THE MEASURED VALUES

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Abstract

The 250 MeV prototype facility of the X-FEL project at SPring-8 was constructed in Octorber 2005 and the machine commissioning was started in May 2006. One month later, we have succeeded in confirming the amplification of synchrotron radiation. The electron beam parameters, such as peak currents and emittances, have been designed and estimated using PARMELA. In contrast to other X-FEL projects, the SCSS injector uses a thermionic pulsed electron gun. Compared with RF photocathode guns, a thermionic gun is stable and easy to handle. Its peak current, however, is smaller and compression of an electron bunch is necessary at the early stage of a low beam energy injector. In this report, we compare the simulation and the measured beam parameters, such as the bunch length and the projected emittance, on the SCSS prototype accelerator. The measured values, after the bunch compression process and the emittance degradation due to space charge, show fairly good agreement with the simulation.

INTRODUCTION

The SPring-8 Compact SASE Source (SCSS) prototype facility was constructed in 2005 as a test bench of the X-FEL project aiming at the lasing wavelength less than 0.1 nm [1]. One of the unique features of the project is the use of a thermionic pulsed electron gun instead of a laser photo-cathod RF gun. In order to reduce the initial beam emittance, a single crystal CeB_6 (ϕ 3 mm) is used as a cathode and a high pulsed voltage of 500 kV is applied to the anode to extract the electron beam [2]. The thermionic gun has clear advantages such as stable operation and easy maintenance, however, its peak current is smaller compared with that of photo-cathode guns. As a result, electron bunch compression is necessary at the low beam energy section ($\leq$ 1 MeV) of the accelerator.

Fig. 1 shows a schematic layout of the SCSS prototype accelerator. A fast deflector is installed just after the electron gun, and an 1 ns electron bunch is sliced out from a μsec electron beam of 1 A from the gun cathode. At the same time, the periphery of the electron beam, which is emitted from the cathode edge, is removed by a pinhole (ϕ 5 mm). Then the 1 ns electron bunch is compressed by a velocity bunching scheme using a 238 MHz, 476 MHz and S-band APS cavities. The peak current is reached about 80 A after the S-band traveling wave tube with the beam energy of 40 MeV. At this point, the beam parameters are similar to those of the RF photocathode guns. Then the electron bunch is further compressed in a magnetic bunch compressor (BC), and accelerated up to the 250 MeV nominal energy using C-band accelerators.

Since the slice emittance and the peak current, which are the most important parameters for the FEL operation, does not change significantly in the C-band main accelerator, the key of the parameter design is how to obtain a large peak current without degrading the gun emittance at the BC end.

BEAM PARAMETER DESIGN WITH PARMELA

Initial Conditions

Since PARMELA can not treat a DC electron gun, 500 keV energy is immediately given to the electrons at the start, and no DC acceleration process between the cathode and anode is considered in the simulation. The bunch length and normalized emittance at the gun cathode are assumed to be 1 ns and 0.5 π mm-mrad respectively. In order to focus the electron beam, magnetic lens are used in the prototype accelerator for the beam energy below 1 MeV. The initial beam size and divergence at the cathode are determined so that the simulation reproduces the measured sizes at three locations of the injector section ((a), (b) and (c) in Fig. 1) as a function of the focusing strength. Fig. 2 shows the simulated and measured beam sizes at these locations as a function of the magnetic lens current.

Bunch Compression

The emittance degradation of the SCSS prototype accelerator is mainly due to the space charge effect at the low energy injector section. The focusing strength and the RF parameters should be chosen so as to keep the uniform transverse electron beam profile from the gun cathode during the velocity bunching process. In other words, the nonlinear divergence coming from the space charge effect should be minimized to avoid the slice emittance degradation. The optimized beam energies and peak currents along the accelerator are shown in Fig. 1.

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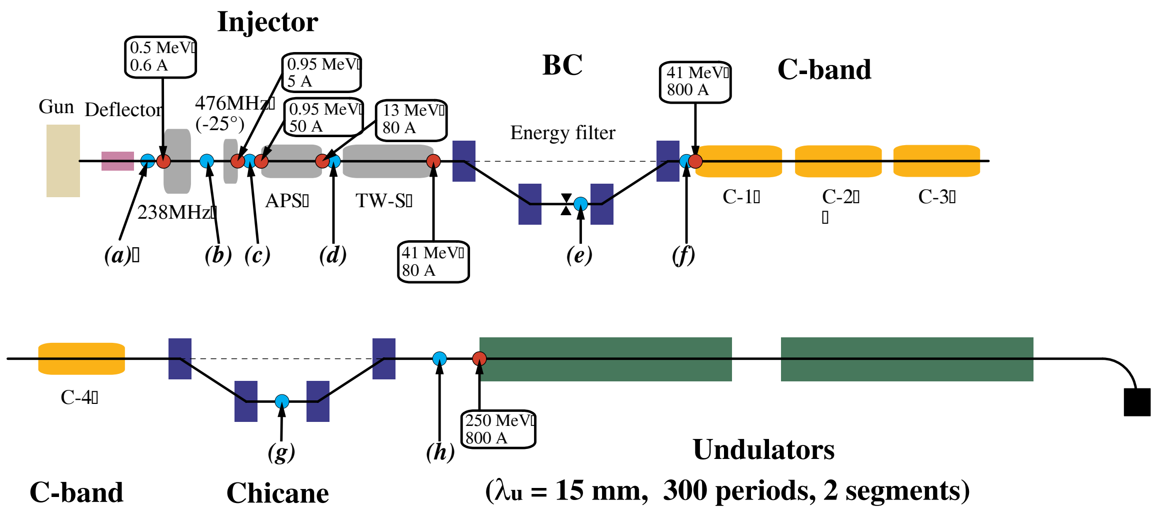

Figure 1: Layout of the SCSS prototype accelerator.

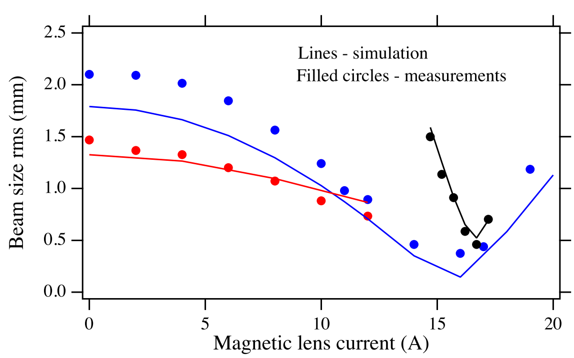

Figure 2: Comparison of the beam sizes between the measurements (filled circles) and the simulation (lines). The figure shows the beam sizes at three locations (a)-black, (b)-blue and (c)-red in Fig. 1 as a function of the focusing strength of neighboring magnetic lens.

In order to verify the velocity bunching process, a microwave spectrometer was used to estimate the bunch length [3]. The microwave spectrometer measures coherent radiation power of specific spectral regions generated from the electron bunch passing through a fluorescent screen. Since the coherent radiation power is increased for a shorter bunch length and a higher peak current, the RF phase of the maximum compression at the observation point, where the bunch length becomes the minimum, can be found. Beyond the RF phase of the maximum compression, the bunch length increases again, so called overbunching.

Fig. 3 is the measured variation of the bunch length at two different locations ((c) and (d) in Fig. 1) as a function of the 476 MHz cavity RF phase. The S-band APS cavity was switched off at the time of measurement. By comparing the RF phases of the maximum bunch compression between the measurements and simulation in Fig. 3, it is confirmed that the electron bunch is compressed as expected. For the FEL operation, the phase of 476 MHz cavity is set at $-25°$ corresponding to the maximum bunching point in the S-band APS tube, and the velocity bunching is stopped before overbunching due to the beam acceleration in the APS.

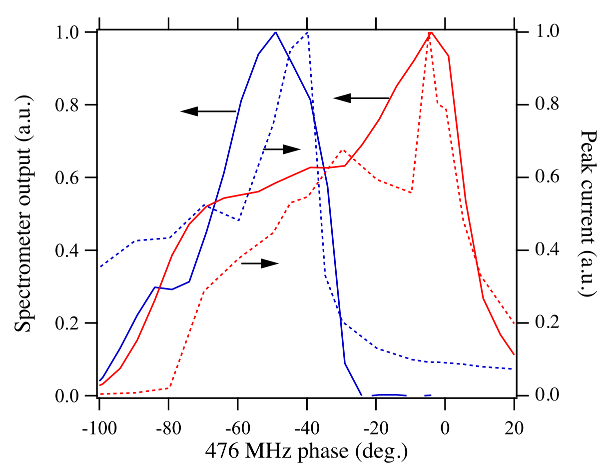

Figure 3: Relative change of the bunch length measured by a microwave spectrometer (solid lines) and the peak current calculated with PARMELA (dotted lines) as a function of the RF phase of the 476 MHz cavity. Left peaks (blue lines) corresponds to the location just before the S-band APS ((c) in Fig. 1), and right peaks (red lines) after the APS ((d) in Fig. 1). 0° is the crest phase of the 476 MHz RF (maximum acceleration).

The final bunch length after the BC is measured using dispersion of the chicane and energy chirp given by the last two C-band tubes. When putting the electron bunch at zero-cross phase of the C-band RF, the amount of energy chirp inside the bunch is roughly proportional to the bunch length. This energy chirp is converted into the increase of the horizontal beam size at the middle of the chicane ((g) in Fig. 1), where the dispersion is not zero. From this, the bunch length can be roughly estimated. The result of the measurement was about 1.1 ps (full width) and it is slightly longer than the simulated value 0.7 ps (full width).

We also tried to measure the bunch length with a streak camera using OTR (Optical Transition Radiation) from a gold mirror. The obtained value was about 2 ps (RMS). The discrepancy thought to be the chromatic aberration of the transport line between the OTR screen and the streak camera, which is about 8 m.

Emittance and Beam Size

The transverse electron beam profiles were measured at various locations along the accelerator using fluorescent and OTR screens. Fig. 4 is an example of the beam sizes measured and simulated at the middle of the BC ((e) in Fig. 1). The measured beam size is slightly larger due to the thickness of the fluorescent screen (1 mm).

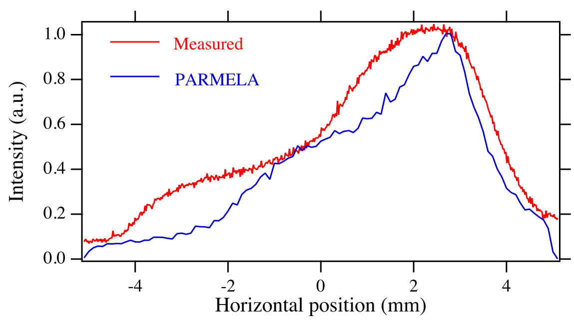

Figure 4: The horizontal beam profiles measured (red) and simulated (blue) at the middle of the BC ((e) in Fig. 1).

Table 1: Comparison of the projected emittances between the Q-magnet scan measurements and the PARMELA simulation

Location	Measurement (mm-mrad)	Simulation (mm-mrad)
End of BC (f) in Fig. 1	$\varepsilon_x \approx 3\pi$ $\varepsilon_y \approx 3\pi$	$\varepsilon_x = 2.8\pi$ $\varepsilon_y = 2.6\pi$
Before undulator (h) in Fig. 1	$\varepsilon_x \approx 4\pi$ $\varepsilon_y \approx 2\pi$	$\varepsilon_x = 2.3\pi$ $\varepsilon_x = 2.3\pi$

Since the slice emittance can not be directly measured at the moment, the projected emittance was measured using a Q-magnet scan method. Table 1 compares the measured and simulated projected emittances at two locations of the accelerator, the end of the BC ((f) in Fig. 1) and just before the undulator ((h) in Fig. 1). Considering the measurement errors, the measurement and the simulation are in good agreement.

Fig. 5 is the slice emittance and longitudinal profile of the electron bunch just before the undulator obtained from the simulation. The measured brightness of the electron beam, which was estimated from the FEL gain dependence on the bunch charge and the undulator K parameter, is between $240 \sim 310A/\pi^2 mm^2 mrad^2$, and the design value ($200A/\pi^2 mm^2 mrad^2$) is expected to be achieved in the prototype accelerator [4].

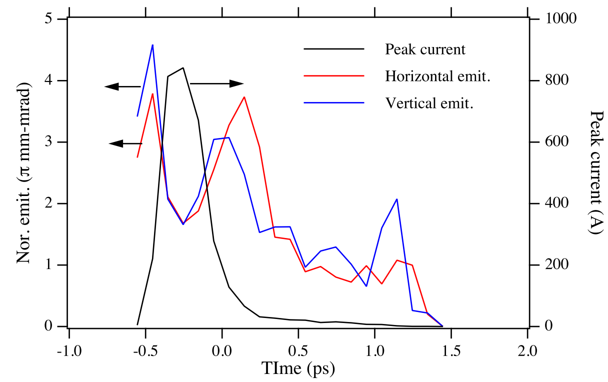

Figure 5: Longitudinal electron bunch profile and slice emittances just before the undulator ((h) in Fig. 1) expected by the PARMELA simulation.

SUMMARY

Though the electron beam simulation carried out using PARMELA does not include Coherent Synchrotron Radiation (CSR) effect at the bending magnets, the results of the simulation reproduce well the measured beam parameters. Particularly, the measurement and the simulation show a fairly good agreement in the bunch compression process and the space charge effect at the low energy section. It is an important step toward the construction of the XFEL facility that the design parameters of the electron beam were achieved in the prototype accelerator.

REFERENCES

[1] http://www-xfel.spring8.or.jp

[2] K. Togawa, et al., "Emittance Measurement on the CeB6 Electron Gun for the SPring-8 Compact SASE Source", Proceedings of the FEL Conference 2004, pp. 351-354, URL: http://www.JACoW.org.

[3] H. Maesaka, et al., "Development of the Microwave Spectrometer for the Bunch Length Measurement Using Coherent Synchrotron Radiation at the SCSS Prototype Accelerator", Proceedings of the 3rd Annual Meeting of Particle Accelerator Society of Japan, August 2006, Sendai, Japan, pp. 328-330.

[4] Hitoshi Tanaka, et al., "Low Emittance Injector at SCSS", Proceedings of the FEL Conference 2006, Berlin, Germany, pp. 769-776.