Current Status of Short X-ray Pulse Generation with a Vertical Kicker in the SPring-8 Storage Ring

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Abstract. From 2008, we have developed a scheme of short X-ray pulse generation by head-tail oscillation with a vertical kicker in SPring-8 storage ring in order to fulfill the demand of shorter pulse undulator radiation for the time resolved experiment. The developed system generates a vertical kick of 0.143 mrad and pulse width as short as 2.4 μs with 200 Hz repetition. With this system we successfully observed a bunch profile which tilted 362 mrad by visible light streak camera measurement for bending magnet light source. The expected tilt angle on the undulator position is 163 mrad, whose tilt angle has a capability of generating the 630 fs (RMS) without the beam spread effect after 50 μm slitting. As a preliminary test, we observed the reduction of the X-ray pulse duration as a function of the tilt angle by X-ray streak camera for the undulator radiation. From this result, we observed the saturation of the minimum short pulse duration at 4.5±2.1 ps (RMS) by 50 μm slitting, which almost corresponds to the detection limit of the X-ray streak camera, in the tilt angle region larger than 40 mrad.

1. Introduction
The X-ray Free Electron Laser facility SACLA which was constructed in the SPring-8 site in 2011 is a most promised light source for generating a short X-ray pulse from 20 to 30 fs [1]. However, a linac-based synchrotron light source does not have a large capability to fulfill many user demands consistently at the same time, and there is a large time resolution gap between current undulator radiation of about 40 ps (FWHM) and the future light source by the XFEL. There are many complex schemes to generate shorter pulse X-ray in storage ring [2]. Our vertical-kick scheme [3, 4] using small vertical beam size of 18 μm (RMS) in the SPring-8 storage ring has the advantages the system is simple which means we just need installation of a fast and high power vertical kicker to small free space and that handling is easy which means just give a vertical kick to stored beam. There are following two key technical issues to obtain a short X-ray pulse: 1) the development of a fast and strong kicker to obtain a large tilted electron bunch and 2) the understanding the correlation between ring accelerator parameters as vertical chromaticity and betatron tune and beam tilt to obtain a reproducible large tilted electron bunch. For the first issue, we continuously developed the fast and high power pulsed kicker to the following strategies: a) the large tilt angle generation and to check feasibility of hybrid operation both for multi-bunch users and for short X-ray pulse users and b) the high repetition for laser pump probe experiment and for covering the less photon flux due to slitting effect. The target kick angle, pulse width, and repetition are more than 0.15 mrad to induce the beam oscillation amplitude more than 4 mm (RMS), less than 2.4 μs as a half of the revolution time, and more than 200 Hz.
to realize the laser-pump probe experiment, respectively. For the second issue, we continuously studied about the following accelerator parameter dependencies: a) the dependence of the beam tilt angle on the oscillation amplitude and the vertical chromaticity and b) the reproducibility of the beam tilt angle and the optimum turn number which generates a large beam tilt.

2. Current status of the power supply development

We aimed at the fast, high power, and compact pulsed power supply system to install the kicker system anywhere in a 30 cm free space [5]. In this design concept, the power MOSFET is the key electrical device to realize the compact driving power supply system. The power supply specification has been improved with the progress of the MOSFET technology. Recently, we succeeded in achieving the output current of 641 A/0.29 m-coil-length corresponding to a pulse width of 2.4 μs and the 200 Hz repetitions. Using this power supply system, the beam oscillation examination was carried out. The beam energy is 8.0 GeV and a single bunch of 1.0 mA beam current was stored. The accelerator parameters such as a vertical chromaticity ϵy and a vertical tune νy (nominal: 18.35) were set to a precision of 0.1 and 0.01 respectively for all studies. The beam oscillation as a function of the high-voltage supplied to the power supply system was measured by using 14 single-pass beam position monitors arranged uniformly in the storage ring as shown in fig. 2 (left). We achieved the enough beam oscillation amplitude of 4.2 mm (RMS) corresponding to a 0.15 mrad kick angle. The fluctuation of the oscillation amplitude was well suppressed to a value smaller than 2% for different experiment period and less than 1% for a day by reproducing the vertical chromaticity and kick power. This power supply specifications fulfill the early technical target values and are enough to solve the first technical issue.

3. Beam tilt development and optimum beam tilt

We performed beam tilt development studies with the developed power supply system to solve the second technical issues. First of all, the beam tilt angle dependence on the chromaticity was studied. The beam profile was measured by observing the visible-light radiation from the bending magnet light source (BM) with the visible-light streak camera (VSC) [6] whose readings are converted from pixel size data to position vs longitudinal duration data to estimate the beam tilt quantitatively. From the data, the beam tilt angle, the vertical shift of the beam center position, and the linearity of the longitudinal beam shape are calculated. The quantitative comparison of the beam profile data for the vertical chromaticity ϵy of 2, 6, and 10 indicates the following two important technical knowledges. First, for the chromaticity of more than 6, the linearly tilted shape is induced at an early turn number of around 20 against the expected optimum turn number of 50 which is a half synchrotron oscillation period, and the induced maximum tilt angle is smaller than that for the lower chromaticity of 2. Second, for the chromaticity value of 2 the induced beam tilt angle at around 50-turn has a good linearity against the S-like beam tilt for the chromaticity of 6 and 10. These results indicate that the linear and large beam tilt needs to be slowly excited under the lower chromaticity condition of around 2. For this reason, most of our beam tilt development studies have been done with

![Figure 1. Left: The tilt angle (solid) and vertical shift (dashed) progresses for the turn number after kick. Center: The tilt angle (solid) and R-value (dashed) progresses for the turn number. Right: The tilt angle distribution for the R-value. Circles show all experimental data.](image)
the chromaticity of 2. Fig. 1 shows the turn by turn progress of the beam tilt angle, beam vertical position, and beam shape linearity expressed by using a correlation coefficient between the longitudinal position and the vertical position of the beam profile (R-value: it distributes from 0 to 1), and the tilt angle distribution for R-value (black, square and triangle plots shows vertical shift less than 1.0, 0.5 and 0.25 mm respectively) with the kick power of 900 V. The turn by turn progress shows the 3 turn structure due to vertical tune value. The tilt angle ramps up turn by turn up to half synchrotron period of around 55 turns and R-value also grows turn by turn. In the result of R-value vs tilt angle (Fig. 1, right), the beams which have large tilt angles have R-values of more than 0.9. There are some optimum beam tilt and turn number which fulfill a good condition for slitting: a high R-value, small vertical position shift and large tilt angle. The optimum beam tilt is selected by filtering the vertical position shift of less than 0.5 mm, which is the resolution of the visible-light streak camera, and R-value of more than 0.9.

4. X-ray pulse duration for a tilted beam
The fig. 2 (center) shows the induced maximum tilt angle and the optimum tilt angle which fulfills the good tilt conditions as a function of the kick power for two experimental periods in 2011 and 2012. The induced beam tilt angle increased linearly for the excited oscillation amplitude, and the maximum tilt angle at the BM reached 460 mrad. The optimum tilt angles are smaller than maximum tilt angles. If the useful beam tilt for slitting is defined to fulfill the good tilt conditions, the available beam tilt angle is 362 mrad at the kick power of 900 V. In the region over the oscillation amplitude of 4.0 mm, the beam tilt angle starts decreasing due to the beam instability, which is caused by tune shift induced in the non-linear field region of sextupole magnet. An evidence of the tune shift is shown in fig 2 (right). It is understood that the turn number where an optimum tilt appears shifts with the oscillation amplitude, though for small oscillation amplitudes, the maximum and optimum beam tilt appears at around 50 and 48 turns at the BM and undulator (ID) light source respectively. The difference between the observed tilt angle at the BM and the expected tilt angle at the ID is due to a β-function difference by a factor 0.45. The expected shortest longitudinal duration at the ID light source position is estimated to be 630 fs (RMS: a longitudinal duration value is calculated by root-mean-square in what follows as long as not mentioned specially) by the simple geometrical calculation without beam spread effect by using the beam tilt of 163 mrad as shown in fig. 3 (left) at the 50 μm slit aperture. The turn by turn slitting X-ray radiation is observed by the X-ray streak camera (XSC) in the ID [6]. The results of X-ray longitudinal pulse duration is combined with the beam tilt profile observed by the VSC in the BM beam line considering the phase difference between the two source points. After filtering of the good tilt selection, the X-ray longitudinal pulse durations are plotted in fig. 3 (center) with statistical errors as a function of the beam tilt angle.
at the ID. The solid line is a fitting result obtained by using a simple geometrical calculation for the slitting with 50 μm aperture. The obtained X-ray pulse duration seems to be saturated in the kick angle region over 40 mrad. The observed shortest longitudinal duration is 6.5±2.0 ps from the fitting result. By the geometrical calculation for slitting, the 2.6 ps is expected as a longitudinal duration without beam size spread effect at the 40 mrad tilt angle. The detector resolution is estimated to be 4.7±0.5 ps which involves a single photo-electron imaging spread at the photon energy of 10 keV, a slit imaging spread at the the slit aperture of 50 μm, and a timing jitter. After subtracting the detector resolution, we obtained the value of 4.5±2.1 ps as the actually achieved X-ray pulse duration. The observed longitudinal duration is saturated at the almost same level as the detection limit within the statistical error. However, we need to confirm whether this saturation is due to the beam size spread effect or the detection limit. In the beam dynamics simulation, the beam size spread effect due to the vertical tune shift dependent on the oscillation amplitude appears compared with the nominal vertical beam size. We are now considering about details. In fig. 3 (right), the expected X-ray longitudinal pulse duration from the fitting result is shown together with the geometrical calculation result for slitting with 50 μm aperture. The dashed line shows the function extended from the fitting result without the saturating effect and the solid line is a geometrical calculation result. The fitting results match to the calculation results within 32%. Thus, if the beam spread effect is negligible, we can expect to achieve the shorter X-ray pulse less than 1.0 ps.

Figure 3. Left: The expected longitudinal duration for each slit aperture by simple geometrical calculation assuming vertical beam size of 6 μm at the ID. Center: The observed shortened X-ray by slitting with 50 μm aperture after filtering of the optimum tilt selection. Right: The fitting function for the observed X-ray pulse (dashed) and the expected longitudinal duration as a function of the tilt angle (solid).

5. Future perspectives
As a next step, we need to overcome the following technical issues. First one is the confirmation whether the beam size spread effect is negligible or not. Then, if the beam size spread effect is dominant comparing with the beam slitting effect, we need to develop the suppression scheme of the beam size spread by suppressing the tune shift dependent on the oscillation amplitude with the sextuple magnet tuning. Second one is establishing the reverse kick scheme after 100 turns to give a next kick in order to reduce the oscillation damping time. By this scheme, we can achieve the 1 kHz kick repetition to realize the flux integration to compensate the low photon flux. Third one is achieving the 400 ns fast pulse kick to treat multiple filling modes.

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