HIGH-PRECISION PATTERN POWER SUPPLY OF KICKER MAGNET FOR MULTI-BEAMLINE OPERATION AT SACLA

Chikara Kondo†, Toru Fukui, Toru Hara, Takahiro Inagaki, Yuji Otake, Hitoshi Tanaka
RIKEN SPring-8 Center, Sayo, JAPAN
Kenji Fukami, JASRI/SPring-8, Sayo, JAPAN
Yusuke Kawaguchi, Hideaki Kawaguchi, Nichicon (Kusatsu) Corp., Kusatsu, JAPAN
Shingo Nakazawa, SPring-8 Service Corp., Ltd, Sayo, JAPAN

Abstract

At the Japanese XFEL facility SACLA, two XFEL beamlines (BL2 and BL3) has been switched by a kicker magnet. However, CSR effects at a dogleg beam transport to BL2 with a deflecting angle of 3 degrees limited the peak current of the electron beam. In order to cancel out the CSR effect, new beam optics is introduced for the dogleg. Here, a deflecting angle of the first kicker magnet is increased to 1.5 degree, which is three times larger than that of the previous one. To drive the kicker magnet, a high-power pattern power supply, which outputs the maximum power of 0.3 MW (299 A and 1 kV) with a stability of 10 ppm (peak-to-peak), has been developed using SiC MOSFETs as switching elements. This power supply can generate bipolar trapezoidal current waveforms at 60 Hz, and the amplitude and polarity of each waveform are controllable from pulse to pulse depending on a beam energy and a destination. Beam commissioning of the new beam switching system was started in February 2017. Through beam tunnig over one month we succeeded in the stable pulse-by-pulse operation of XFEL multi-beamlines with a nominal peak current of about 10 kA.

INTRODUCTION

At the SPring-8 Angstrom Compact Laser (SACLA) facility, an X-ray Free Electron Laser (XFEL) has been used for many advanced scientific experiments [1]. Because SACLA is a linac based light source, like other XFEL facilities, user experiments are performed at only one beamline. To improve the efficiency of user experiments, multi-beamline operation is important.

In SACLA, the second XFEL beamline (BL2) was installed and has been operated since 2014 [2]. But, the laser intensity of BL2 was limited compared to that of the first central beamline, BL3. The reason of the intensity reduction was projected emittance growth caused by the coherent synchrotron radiation (CSR) effect at a dogleg like beam transport from the linac end to BL2, which forced the peak current to be less than 3 kA for the BL2 laser operation.

To suppress the CSR effect, we rearranged the beam transport based on a double bending achromat (DBA) structure [3]. In the new optics, the CSR effect is cancelled out between symmetric four bending magnets. Since the bending angles of four magnets should be the same as 1.5 degree, the bending angle of a kicker magnet is required to be 3 times larger compared to that of the previous kicker magnet (0.5 degree). Due to larger inductance of the new kicker magnet, the high output power is required for a pattern power supply to implement pulse-by-pulse deflecting operations at 60 Hz.

†ckondo@spring8.or.jp

CONCEPT AND DESIGN OF BEAM TRANSPORT TO BL2

Beam Optics

Figure 1 shows a schematic layout of a new transport from the linac section to BL2 with a twin DBA structure of a dogleg. The transport line is composed of four identical bending magnets and thirteen quadrupole magnets symmetrically placed with respect to the centre of the dogleg. In each bending magnet, the electron beam is deflected by 1.5 degrees and the horizontal phase advance between the two DBA cells is set to π. By changing the horizontal beam orbit at the two quadrupole magnets of the DBA cells, R56 of the dogleg can be adjusted to suppress a bunch length change.

In the new optics, the kicker magnet switches the electron beam orbit for three beam transport lines from pulse to pulse, i.e., BL2, BL3, and a transport line to the SPring-8 storage ring (named XSBT). A large deflecting angle of 1.5 degrees leads to a severe field stability of 10 ppm (peak-to-peak) of the kicker magnet for the stable XFEL operations.

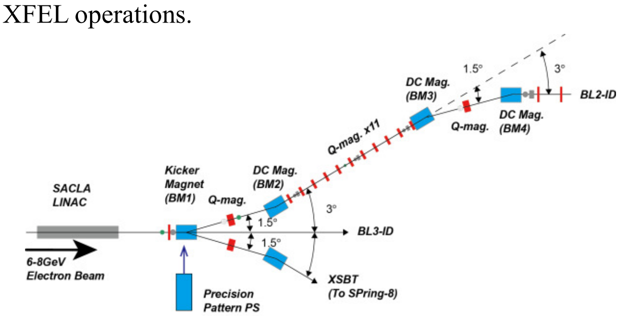

Figure 1: Schematic layout of beam transport from linac to BL2.

Design of Pattern Power Supply

The new pattern power supply drives the kicker magnet, whose inductance is 16 mH, with a bipolar and trapezoidal current waveform. A time-response from 0 to ± 299 A is less than 6 ms and the target stability is set at 10 ppm (peak-to-peak) at a beam timing, which is about 10.4 ms after the start of the trapezoidal waveform.

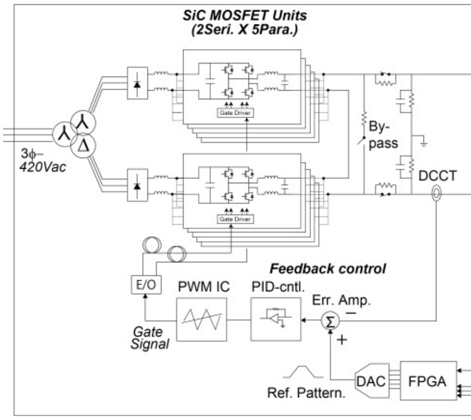

Figure 2: Block diagram of the pattern power supply of the kicker magnet.

Table 1: Major Specifications of Kicker Magnet and Power Supply

Kicker magnet	
Magnetic field	0.893 T @ 299A
Pole length and width	950 mm and 75 mm
Inductance	16 mH @ 1kHz
Total resistance	25 m Ohm
Pattern power supply	
Input	3-phase 420Vac
Output current	+/- 299 A max.
Pattern profile	Trapezoidal
Current stability at beam timing (pulse by pulse)	< 30 ppm
Output voltage	+/- 1000V max.
Repetition rate	60 Hz max.
Chassis size (W, D, H)	3m x 1m x 2.7m

Figure 2 shows a block diagram of the high precision pattern power supply. To achieve the fast rise time and high current stability, an output voltage of 1 kV and a high switching frequency are required for a power switching module. We employ SiC MOSFET switching devices, which can operate at high voltage and large current with a fast switching speed [4], resulting in reducing the power supply size and making the system simple.

The switching circuit is composed of ten full-bridge units connected in five parallel and two series to provide the required voltage and current. The effective switching frequency is about 100 kHz by adopting a phase shift switching method. The output current is controlled by the pulse width modulation (PWM) with the proportional-integral-differential (PID) feedback.

A reference trapezoidal pattern is generated pulse-by-pulse using FPGA and DAC operated in synchronisation with trigger signals from the SACLA timing system. The output current is varied and stabilized according to the reference trapezoidal pattern by the feedback control. After the flat top, the current decreases, and then the stored energy in the magnet is regenerated to bank capacitors.

In addition to the large current operations, the power supply should also provide small current operations ranging from 0.3 to several amperes for hysteresis cancellation when the beam is sent to BL3. For the small output current, a long turn-off time of the MOSFET device makes the current regulation unstable. To avoid this instability, we stop eight full-bridge modules and decrease the number of operating modules from ten to two for the small current operation. In addition, a bypass circuit is introduced to increase the effective current for the switching device for the small current operation. By these design considerations, the power supply can control the output current in a wide range from 0.3 to 299 A with the required stability.

OPERATION OF POWER SUPPLY

Before beam commissioning, the power supply was connected to the kicker magnet and the current waveforms were measured by DCCT (HITEC TOPACC-B600). Figure 3 shows the current and voltage waveforms. An output current was raised from 0 to 240 A within 6 ms. The inset in Figure 3 shows the current stability at the beam timing. The current jitter at the beam timing was 27 ppm (peak-to-peak) at this measurement.

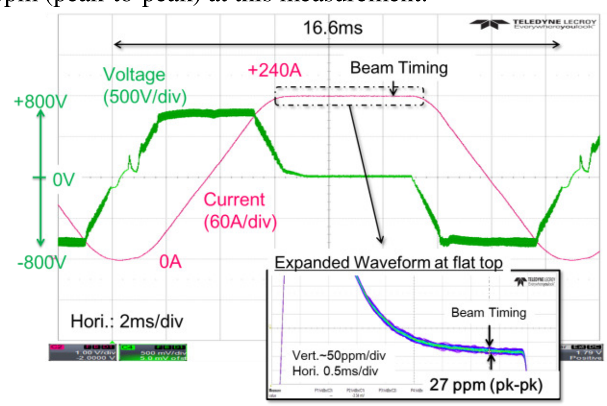

Figure 3: Measured waveforms of the output current (red) and voltage (green). An output current is 240 A and a repetition rate is 60 Hz. In the lower window, the flat-top of the trapezoidal pattern is expanded.

The magnetic field of the kicker magnet was checked by a gated nuclear magnetic resonance (NMR) detector. The gated NMR detector measures the magnetic field during 0.6 ms in synchronization with an external gate

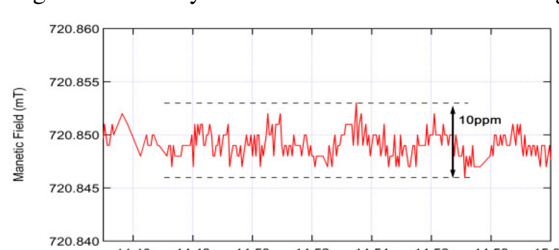

Figure 4: Trend graph of the kicker magnetic field at the beam timing measured by a gated NMR detector. The power supply was operated at 60 Hz with a peak current of 240 A.

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signal. Figure 4 shows the measured magnetic field stability. The pulse-by-pulse field fluctuation is estimated to be 10 ppm (peak-to-peak) over a few minutes. The change of the magnetic field by 10 ppm corresponds to the electron beam orbit error of 0.26 μrad. This is small enough compared to the horizontal orbit stability of SACLA, which is typically 1 μrad. The slow field drift due to the temperature changes of the magnet yoke and the cooling water can be compensated by a beam orbit feedback system.

BEAM OPERATION

Stability of the Electron Beam

We investigated the suppression of the CSR effect in the new optics at the dogleg transport. The beam parameters were first optimized for BL3 and the peak current was around 10 kA as shown by the red line in Figure 5 (upper). Then, we switched from the BL3 solo operation to the BL2/BL3 multi-beamline operation with a repetition rate of 15 Hz at each BL. Figure 5 (lower) shows a horizontal orbit fluctuation measured at BL2 with the new optics (left) and the previous optics (right). The area in the phase space is 1.7 pm-rad (rms), which is an order of magnitude smaller than that in the previous optics. The orbit fluctuation due to the CSR effect is drastically suppressed in the new optics.

Multi-beamline XFEL Operation

Multi-beamline XFEL operation was demonstrated under the following conditions: Beam energy and a repetition are 7.9 GeV and 30 Hz, and an undulator K-value is 2.1 for both beamlines, respectively. Figure 6 shows XFEL intensity variations of BL2 and BL3 over 10 min. XFEL intensities were about 300-500 μJ at both beamlines, which are sufficient for user experiments.

To verify the duration of the XFEL pulses of BL2, we measured (1) the single-pulse spectral spikes at the BL2 and BL3 beamlines and (2) XFEL pulse duration of BL3 by auto-correlation measurement. The pulse duration is in

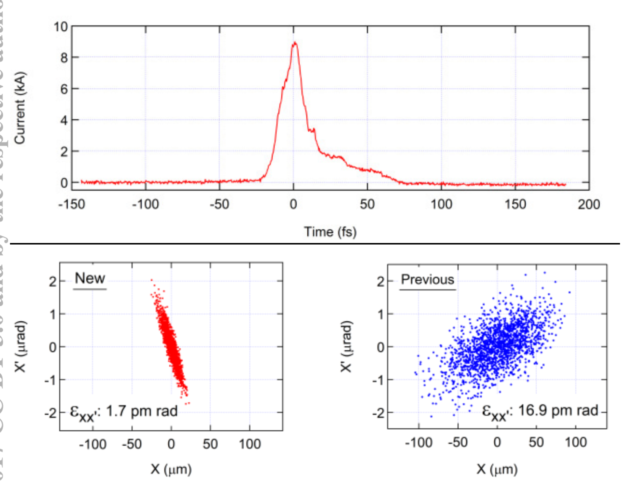

Figure 5: A beam current profile measured by TCAV (upper) and comparison of the horizontal orbit fluctuation measured before the BL2 undulator (lower).

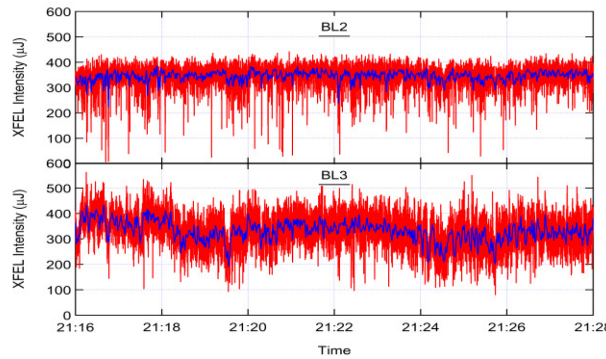

Figure 6: Trend graphs of XFEL pulse intensities measured at BL2 (upper), and BL3 (lower). A photon energy is 10 keV at both beamlines.

general correlated with the spectral width of spikes [5]. Figure 7 shows the measured XFEL spectra at BL2 and BL3 and no significant difference are observed between the two spectral widths. On the other hand, the auto correlation measurement shows that the XFEL pulse duration at BL3 is shorter than 10 fs (FWHM). These experimental results suggest us that the multi-beamline XFEL operation gives almost the same pulse duration as obtained in the usual BL3 solo operation.

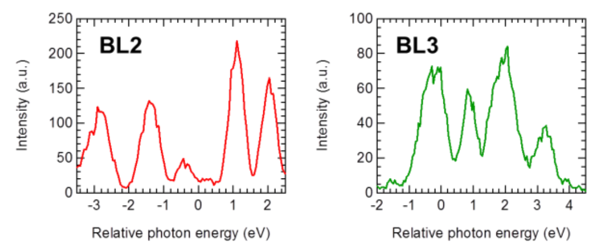

Figure 7: Typical single-pulse spike spectra of XFEL at BL2 (left) and BL3 (right) in the multi-beamline operation. The central photon energy is 10keV.

SUMMARY AND OUTLOOK

A beam switching system including a beam transport to BL2 has been reconstructed to suppress emittance growth by the CSR effect employing the twin DBA optics. For this purpose, we have developed a kicker magnet and a 0.3 MW pattern power supply. The beam commissioning of the new beam switching system was successfully completed and we achieved the full-performance pulse-by-pulse multi-beamline XFEL operation for the first time, conserving the short pulse characteristics of SACLA. In the future, we will build an innovative beam delivery system by using the developed beam switching system, in which the electron beam driver of XFELs also works as an injector for the upgraded SPring-8 storage ring.

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