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DEVELOPMENT OF A PROTOTYPE PULSED POWER SUPPLY USING SiC-MOSFETS FOR A FAST KICKER SYSTEM IN KEK-PF

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Abstract

In the KEK-PF 2.5 GeV storage ring, the filling pattern of the hybrid mode consists of a multi-bunch train and an isolated single-bunch stored in the same orbit. To separate the orbit, we have a plan to use a camshaft bunch kicker system in KEK-PF. The system requires a fast pulsed power supply whose target specifications are a pulse width of 100 ns, a repetition rate of 1 MHz, a peak current of 500 A within a 1 % uncertainty, a timing jitter of less than 300 ps, and a voltage rating of 15 kV. To achieve the requirements, we have newly started the development of a pulsed power supply using SiC-MOSFETs. We succeeded in developing the first prototype, whose voltage rating was close to the required value. We evaluated the stability of the output-peak current and timing. We confirmed that the stabilities satisfied the requirements even after two months of operation.

INTRODUCTION

In the KEK Photon Factory (PF) 2.5 GeV storage ring, the filling pattern of the hybrid mode consists of a 400-mA multi-bunch train and an isolated 50-mA single-bunch. The revolution frequency of the ring is 1.6 MHz, and the single-bunch synchrotron radiation is provided every 620 ns. In the hybrid filling mode, both types of bunches are stored in the same orbit, and the multi-bunch synchrotron radiation can reach the single-bunch user. To separate the orbit of the single bunch periodically, we have a plan to use a camshaft bunch kicker system [1, 2] in KEK-PF. In this system, a kick-and-cancel scheme is required; a single-bunch is first displaced to a different orbit and then kicked back to the original orbit by a single fast kicker within a few revolutions. To use this system in KEK-PF, we need a fast kicker to control the single-bunch every two revolutions of 800 kHz. For such a high repetition rate, it is difficult to drive the kicker using a conventional switch device such as a thyratron. We have newly started to develop a pulsed power supply using SiC-MOSFETs, especially for the high repletion drive.

In this paper, we first introduce the requirements of the power supply. We then show the detailed design and composition of a prototype model using SiC-MOSFETs. We finally report on the stability evaluations of the output-peak current and timing for the prototype model.

REQUIREMENTS OF THE PULSED POWER SUPPLY

Table 1 shows the requirements for the pulsed power supply. To kick only the single-bunch, the pulse width of 100 ns is required, which is narrower enough than the time interval between the single-bunch and multi-bunch of 360 ns. The target repetition rate is 1 MHz so as to include the revolution frequencies of two turns. The pulsed current is provided to a newly developed air-core type pulsed magnet that suppresses eddy current, named Ceramics Chamber with integrated Pulsed Magnet (CCiPM) [3, 4]. The inductance of the CCiPM is 1 μH, and the supplied peak current of 500 A within a 1% uncertainty is required to change the beam orbit. To generate a short pulsed current using the CCiPM, we adopt a resonant circuit with a capacitor, as shown in Fig. 1. In this scheme, the output waveform is a half sinusoidal wave. When the output timing varies shot by shot (timing jitter), the current value at the kick timing varies. The timing jitter is required to be less than 300 ps to obtain the required current stability of 1%. To output 500 A peak current, the supplied voltage is required to be 15 kV. To reduce the impedance of the power supply, the power supply should be located near the accelerator ring. Considering the installation location in KEK-PF, radiation endurance against the synchrotron radiation is required.

Table 1: Requirements of the Pulsed Power Supply

Contents	Requirements
Pulse Width	100 ns
Repetition Rate	1 MHz
Peak Current	500 A (±1%)
Timing Jitter	300 ps
Voltage	15 kV

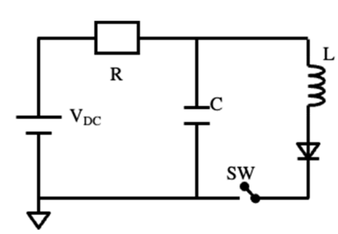

Figure 1: Schematic view of the circuit to generate a half sinusoidal wave pulse. “L” indicates the load of the kicker coil, and “SW” indicates the switch.

PROTOTYPE DEVELOPMENT

The first target of the development is to secure the voltage rating of the power supply. The power SiC-MOSFET semiconductors can switch at over 1 MHz, but the voltage rating is generally less than a few kilovolts. To secure a sufficient voltage rating of the power supply, SiC-MOSFETs are needed to be connected in series. In such a connection, the size of the circuit tends to increase, and the total stray inductance of the circuits will increase. It is

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necessary to ensure the voltage rating while suppressing stray inductance.

Figure 2 shows the first assembled prototype using SiC-MOSFETs based on the circuit shown in Fig. 1. The power supply mainly consisted of a switching module, capacitors, and rectifiers. The switching module consisted of 16 SiC-MOSFETs of 1.2 kV rated voltage connected in series. To ensure isolation between the switching module and the gate driver for driving the switches, wireless power transmission was adopted. The gate signal to turn on/off MOSFETs supplied from a pulse generator was converted to the optical signal once to ensure isolation. As for the capacitors used for charging/discharging, four film capacitors were connected in series, and their total capacitance was 1 nF. As for the rectifiers used to shape the pulse, we adopted DSEP15-12CR, whose reverse recovery time was small at 15 ns. To reduce the stray inductance of the capacitor and rectifier circuit board, the area of the current path was reduced, and the inductance of each board was kept as much as small by the level of several tens of nH. Each component was connected using 20 kV silicon cables, which were easily twisted to reduce the inductance of cables.

One feature of the prototype was that each component, such as the switch, capacitor, and rectifier, was modularized to improve each component separately. The switching module was specially developed by NexFi Technology Inc. [5, 6].

Table 2 shows the voltage rating of the main components in the prototype. The switching module had a high voltage rating of 14 kV in spite of its small size ($12 \times 12 \times 14$ cm^3) and could switch with 200 kHz. The voltage rating of the prototype had already reached close to the target voltage rating of 15 kV.

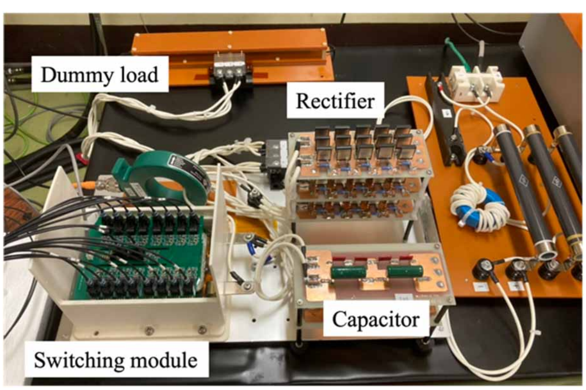

Figure 2: Test system of the prototype SiC-MOSFET switching module with LC resonance circuit.

Table 2: Voltage Rating of Main Components in the Prototype

Component	Voltage Rating
SiC-MOSFET Switch	14 kV
Capacitors	16 kV
Rectifiers	18 kV

PERFORMANCE OF THE PROTOTYPE

Figure 3 shows the waveform of the output current when the DC voltage of 10 kV was supplied to the prototype. In the measurement, a coil of 1.1 μH simulating the CCiPM was connected to the prototype. Output current was measured by using a CT (Pearson, Model 110) and the oscilloscope whose vertical resolution was 12-bit at the sampling interval of 80 ps. The gate signal was supplied by a pulse generator whose timing jitter was less than 25 ps. Figure 4 shows the dependency of output current for the supplied voltage. Each point in Fig. 4 was obtained by averaging 100 waveforms. We confirmed that the peak current values were proportional to the supplied voltage up to 10 kV.

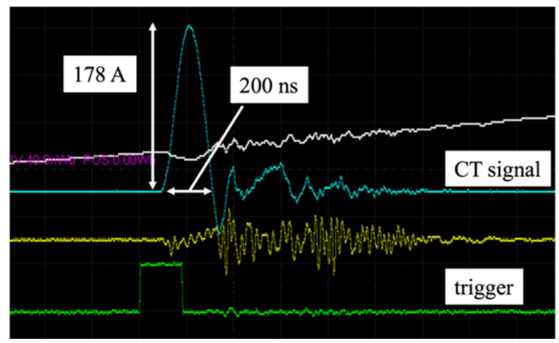

Figure 3: Waveform of the output current to the coil measured with a CT. In the measurement, the supplied voltage was 10 kV, and the switching repetition rate was 10 Hz.

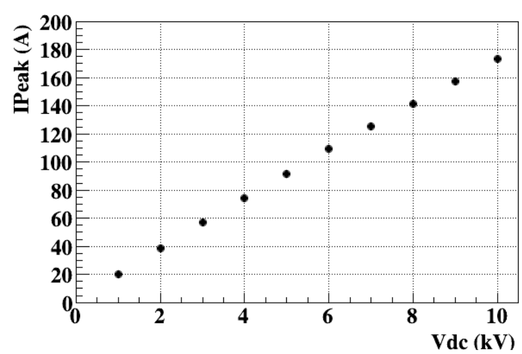

Figure 4: Peak current as a function of the supplied voltage. The switching repetition rate was 10 Hz.

In the measurement, two issues were found. One was the stray inductance which decreased the output current by 37% compared with the case of the ideal circuit. The other was a ringing continued after the half-sine wave that could cause an unexpected turn-on the MOSFETs. The source of the stray inductance was silicon cables, and its inductance was estimated to be 2 μH. It was difficult to precisely control the inductance for the soft cables which had the advantage of making them twisted. To reduce the stray inductance, we are planning to use a solid material instead of a soft cable.

The ringing was caused by the incompetence of reverse recovery of the rectifiers. The ringing noise may couple the gate signal line through the parasitic capacitance of

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MOSFETs. It is necessary to suppress the ringing to construct a reliable power supply in future.

Figure 5 on the left and right axes shows the stability of the output current and the timing jitter for each supplied voltage, respectively. The output current stability was defined as the variance of the peak current. The timing jitter was defined as the fluctuation of the point where the pulse height exceeded half of the pulse peak. At the supplied voltage of 10 kV, the output current stability and timing jitter was measured to be 0.2% and 280 ps, respectively. We found that both stabilities were limited by the offset noise of the oscilloscope. The actual output current stability and timing jitter was expected to be much better.

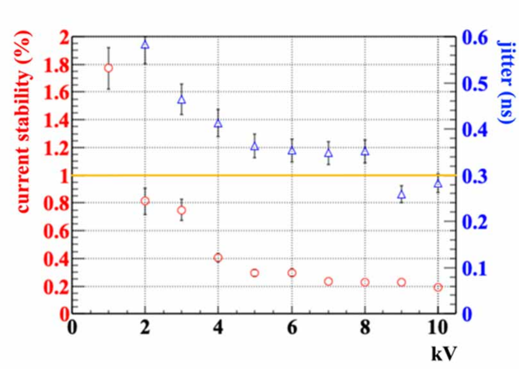

Figure 5: Peak current stability in the left axis (red circle) and timing jitter on the right axis (blue triangle) as a function of the supplied voltage. The repetition rate was 10 Hz in each measurement. The orange line represents the target value for the development.

To test long-term operation, the prototype was installed in the accelerator tunnel, as shown in Figure 6. To reduce radiation damage, the prototype was put in a box consisting of a 1.0-mm-thickness lead plate sandwiched by 1.5-mm-thickness aluminum plates. We operated the prototype with the supplied voltage of 10 kV and the repetition rate of 10 Hz for two months without any severe failure. The variance of the peak current was estimated to be 0.57% during the two months.

Although the supplied voltage and the repetition rate was still below the development target, we had successfully constructed a power supply with a high-current, short-pulse, and high stability of output current.

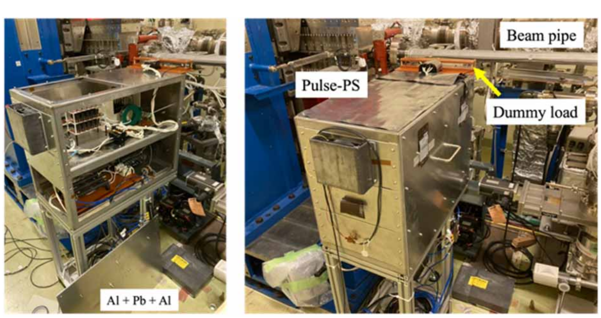

Figure 6: Test system of the prototype put near the accelerator ring before and after housing the pulsed power supply in the left and right figure, respectively.

SUMMARY AND PROSPECTS

In KEK-PF, we have newly started developing a pulsed power supply using SiC-MOSFETs for a camshaft bunch kicker system. The requirements for the power supply are as follows: 100 ns pulse width, 1 MHz repetition rate, 500 A (< ± 1%) peak current, 300 ps timing jitter, and 15 kV voltage rating. We succeeded in making the first prototype, which could generate a half-sine pulse with high stability that satisfied the requirements. In the prototype, we found two issues to be solved. One was the stray inductance of the silicon cables. To control the stray inductance, we are considering using a stripline to connect each component of the pulsed power supply. The other was the ringing after the main pulse. To suppress the ringing, we plan to add RC snubbers to the rectifiers circuit. The next target of the development is to achieve a high repetition rate. For this purpose, we are considering using vacuum capacitors as the charging/discharging capacitors, which could be operated at over 1 MHz with a peak current of 500 A. We are also investigating the possibility of introducing an energy recovery circuit to reduce the heat generated by the resistors. Based on the knowledge obtained from the prototype, we are constructing a power supply capable of 500 A peak, 400 kHz repetition rate, and 150 ns pulse width output in 2023. We aim to construct a pulsed power supply that achieves the development target using SiC-MOSFETs by FY2024.

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