SOLID-STATE COMPACT KICKER PULSAR USING STRIP-LINE TYPE BLUMLEIN WITH SiC-MOSFET IN SPRING-8

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Abstract

In the case of handling an electron beam by bunch-by-bunch and turn-by-turn with a kicker at the SPring-8, the performances required to a pulsar are short pulse width (<40 ns) and high repetitions (208 kHz). For this purpose, we developed the prototype Blumlein pulsar as an experimental attempt. The prototype was composed of the solid state switch of SiC power MOSFET and 6 series Blumlein pulse forming networks (BPFNs) made by stripline of 2 m. By connecting the pulsar to coil inductance of 2.5 μH, the 2.0 MW power pulse of 158 ns pulse width was obtained without any failure by supplying 2 kV high voltage. At 120 pps burst repetitions under natural air-cooling condition, the high current stability of 0.14 % and high amplified voltage of 14.0 kV was achieved.

INTRODUCTION

SPring-8 storage ring has no enough space to install the additional kicker system due to the many non-linear optics correction magnets. The averaged remaining drift space is about less than 30 cm length. There are two subjects in our kicker pulsar development. Firstly, pulsar must satisfy requirements of both compact size and high power output to compensate the shortness of the magnet length to install small space anywhere. Secondary, pulsar must be able to generate a pulse with high repetition and short pulse width when it is used as beam control of turn-by-turn and bunch-by-bunch.

For first requirements, our kicker system is separated into magnet coil, pulsar(=driving circuit), and DC high voltage and control power source. By separating the kicker system into three functions, separated compact pulsar can be set up near to the load so that the lead-line inductance from the pulsar to a magnet is reduced as small as possible. In our system, the compactness of the pulsar is one of the important feature.

One of the solution realizing the second requirements is using solid-state power MOSFET instead of the thylatron, because power MOSFET prepares merits of low switching power loss, fast switching speed and small discrete package. But, in order to increase the voltage resistance of the pulsar, the highly technological development to stack the serial and parallel jointed MOSFET is needed so that the disadvantage of its small breakdown voltage is compensated.

In the SPring-8, compact pulsar using Si MOSFET is operated in the storage ring for fast correction kicker [1]. This pulsar is composed of single switching module which use 2 serial (2s) and 6 parallel (6p) jointed Si MOSFETs whose breakdown voltage is 1.2 kV each [2]. Therefore, this module has the withstanding voltage of 2.4 kV. To increase output voltage of the pulsar and to achieve a shorter pulse by using this switching module, Blumlein amplifying method is proposed. Because Blumlein length is in proportion to the generated short pulse width, it is suitable to make a pulsar compact for short pulse generation. As a result, an amplified high power output, short pulse and compactness which are our development purposes are accomplished by Blumlein circuit with MOSFET switch.

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PROTOTYPE BLUMLEIN CIRCUITS

SiC Solid-state Switcher

Initial targeted values of output pulse width, high voltage, current and burst repetition rate were 100 ns, 12 kV, 200 A and 1 kHz respectively for an inductance load. In order to realize these parameters, 6 series BPFNs was designed to amplify the supplied 2.0 kV high voltage by a factor of 6. In this development, our already developed 2.4 kV switching module was modified for two technical elements. First one is that SiC power MOSFET (Rohm:SCH2080KE) which has smaller ON resistance and faster switching speed was introduced to our switching module instead of Si power MOSFET (IXYS:IXFB30N120P) for the first time. The gate driver circuit was also improved to fit to the SiC gate characteristics. Second one is that MOSFET arrangement on the board of

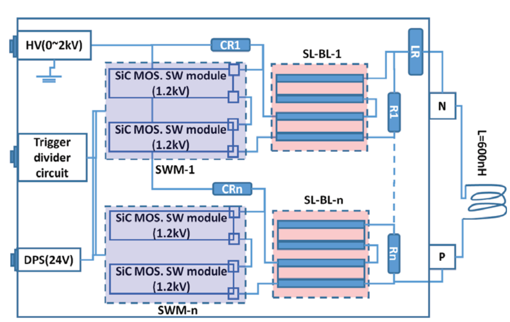

Figure 1: Schematic view of *n* series BPFNs circuit.

our module was changed. Whereas 2s x 6p jointed MOSFET were arranged in round circle shape to reduce the stray impedance to output terminal in utilization as single module, 1s x 6p jointed MOSFET were re-arranged in arc shape to the BPFN terminal. By this way, the impedance from 6 parallel MOSFETs on the single module to single line of BPFN was

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reduced. Finally, one BPFN circuit jointed to two series 1.2 kV switching modules had 2.4 kV withstanding voltage.

Table 1: Design Parameter of Single Line for 3 and 6 BPFNs.

Parameter/single line	6 series	3 series
W_{Cu} (mm)	30	16
W_p (mm)	40	40
Line length (m)	2.0	4.0
L (nH)	25	94
C (nF)	5.8	6.2
Z (Ω)	2.0	3.9
Transmission vel. (m/s)	1.65×10^8	
Resonance freq. (MHz)	262.8	
Pulse width for R=40Ω (ns)	24	48
Pulse width for L=600nH (ns)	130	189
Output current for R=40Ω (A)	317	159
Output current for L=600nH (A)	139	112

Figure 1 shows the schematic view of the pulsar. The pulsar is connected to the high voltage and controller power source and trigger generator out of the accelerator tunnel with 30 m cable in ground floating. In the schematic view, except for the inductance load, the pulsar totally consists of twelve 1.2 kV switching modules (SW), six stripline (SL) BPFNs and trigger and controller power source distributors. The current charged in the 99 kΩ resistor (CR shown in the figure) is released at the external trigger (DG645) timing. Another 1.5 kΩ resistor (R) is also used as impedance matching resistance for BPFN capacity. The resistor (LR) between output terminal and BPFNs is composed of parallel jointed RC snuber, 200 Ω limiting resistor and super fast diode (IXYS, DSEP30-12CR) bank which suppress the undershoot of the output pulse.

Stripline Type Blumlein

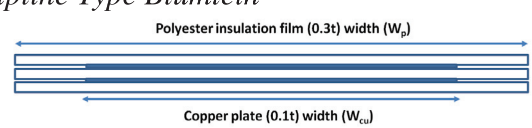

Figure 2: The cross-sectional structure of the stripline type Blumlein. Copper plate lines are sandwiched by the films.

If the pulsar is used as a driver of kicker magnet, it is an important subject to achieve a high current. The stripline Blumlein was proposed to our pulsar from a point of view of impedance reduction. Additionally, the downsizing effect of BPFN circuit volume was also expected due to the its thin plate structure. Figure 2 shows the stripline structure. Film thickness was determined assuming the insulation withstanding voltage of 30 kV. Firstly, 3 series BPFNs was constructed as the proof of principle. Based on this experiences, prototype pulsar prepared 6 series BPFNs was constructed in order to generate larger current and shorter pulse. To connect multi-BPFN in series, plate bakelite holder of 340(W)× 5(t)×200(D) mm was used for 6 series BPFNs. Striplines were folded inserting it between bakelites. 6 pairs of folded single Blumlein lines were stacked to face to face in vertical direction to decrease the distance to output terminal as shown in the left side picture of the Figure 3. Table 1 shows the design parameter assuming the inductance load (L=600 nH) and a pulse generation of pulse width of 50 ns.

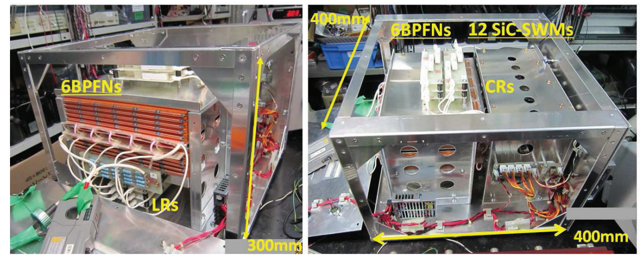

Figure 3: The prototype pulsar with 6 series BPFNs.

OPERATION PERFORMANCES

Characteristics of Serial Multi-jointed BPFNs

The completed prototype pulsar with 6 series BPFNs is shown in Figure 3. The power flows from right side to left side straightforwardly in the right side picture to prevent unnecessary impedance from generating. As a result, the compact pulsar was achieved. Figure 4 shows the achieved

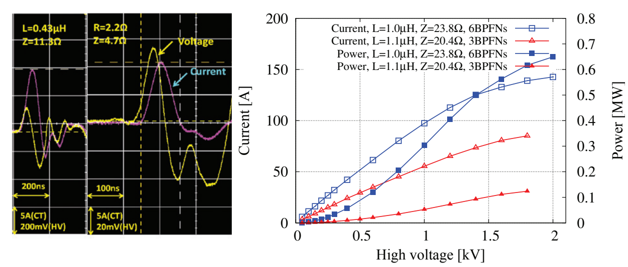

Figure 4: Achieved shortest pulsed current for R-load and L-load. The plots show the high voltage dependency of the output current and power for 3 and 6 series BPFNs.

shortest pulses for load impedances less than the designed impedance of BPFNs in supplied 100 V high voltage. Measured pulse widths for pure resistance (R) and inductance (L) load were 108 ns and 120 ns which was smaller than pulse width of 160 ns achieved by 3 series BPFNs on the same condition. The pulse width for L-load was almost the same as the designed value. But it for R-load was different from the expectation, because MOSFET switching speed and the LCR resonance frequency including the BPFNs was dominant factor of increasing the pulse width compared with single line length. The undershoot wave looked remarkable in these pulse width regions because undershoot wave frequency was over the suppressing diode switching speed.

The right side plots of Figure 4 show a high voltage dependency of the output current and power at using typical coil inductance whose impedance matched to designed it by using 6 series and 3 series BPFNs. The current and power saturation's appeared more than 1.0 kV for both pulsar. These saturation's are thought to be caused by the capacitance and inductance which stripline BPFNs circuit has. Due to this saturation, the measured current was almost the same as the estimation for L-load (L=600 nH).

Figure 5 shows the impedance dependency of the output power and gain efficiency (Eff.=$V_{output}/6_{or}3\times V_{supply}\times 100$.) for the BPFNs series number at the 100 V high voltage supply. The matching impedance was indicated at about 45 Ω for L and R load. Although the BPFN designed impedance of 24 Ω was not consistent with measured results due to underestimating the blumlein capacitance, the impedance of multi-stacking BPFNs circuit was kept low as expected by using stripline BPFN. It was confirmed that the output power for R-load was exactly increased by a factor of 2 by increasing series number of BPFN from 3 to 6. Then, as noteworthy result, the high gain-efficiency of 80% was obtained for L-load.

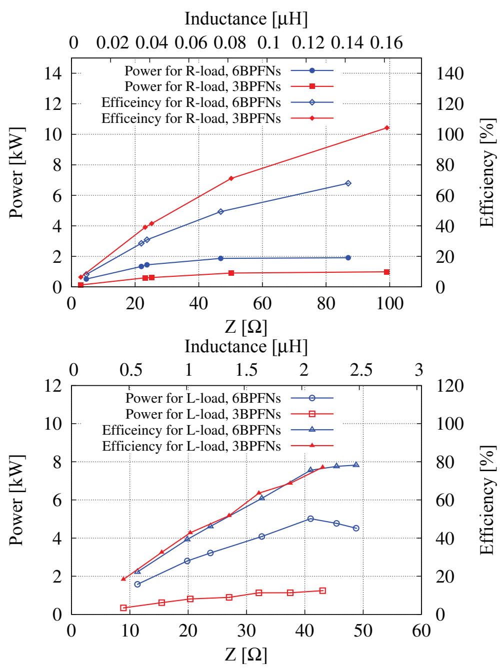

Figure 5: The R and L load impedance dependency of the output power and gain efficiency for the number of BPFNs.

Jitter of Multi-stacked SiC Switches

Table 2: Jitters for Pulse Width and Fire Timing

Burst repetition	1 pps	100 pps
Firing jitter (ps) at 100 V	186.6±10.6	180.5±7.9
Firing jitter (ps) at 1 kV	120.1±15.0	119.9±6.1
Pulse width jitter (ps)	86.5±4.6	89.4±2.2

Table 2 shows the timing jitter for firing and pulse width at 300 V high voltage supply. In the measurement of firing jitter, the jitter of about 30 ps which trigger generator has was included. Although our pulsar must drives whole 72 switching elements simultaneously, the jitter level was kept low enough to satisfy the requirement of beam operation. There was a tendency that the jitter was slightly increased in supplying high voltage of less than 300 V in this measurement. It is thought to be caused due to the SiC solid state characteristics. Figure 6 shows current stability for the burst repetitions in the high power operation test. From 1 pps to 1 kpps, it was also kept <0.1%.

FIRST HIGH POWER OPERATION TEST

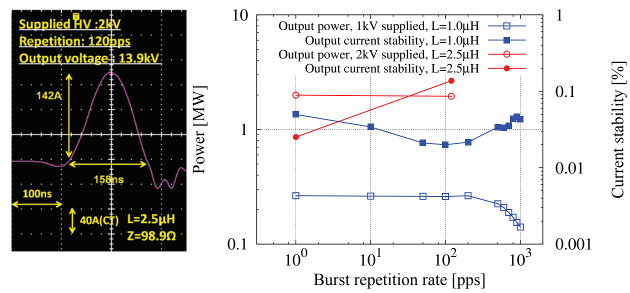

Figure 6: The pulse shape at 120 pps high power test and the plots show the power and current stability for repetitions.

First of all, the low power and 1 kpps burst repetition test was tried under the condition which the pulsar was connected 1.0 μH inductance coil and the 1.0 kV high voltage was supplied. Maximum power was 0.27 MW.As shown in Figure 6, the output power and current stability tended to decrease in the burst repetition of more than 200 pps. At this test, the surface temperature of charging resistor, switching module, and blumlein circuit increased by 60, 2, and 7 °C under natural air-cooling condition. The resistances in the circuit were changed by the heat generation whereas SiC MOSFET had little heating loss for high repetitions. The highest power output of 2.0 MW and amplified voltage of 14.0 kV was achieved for the inductance load (L=2.5 μH). The measured output current is shown in Figure 6. On this condition, the 120 pps burst repetition was succeeded under natural air-cooling. The burst repetition rate was limited by the temperature of the charging register in this test.

CONCLUSION

The prototype pulsar must be improved for the temperature increasing of the resistor and blumlein circuit by using fan or water cooling system for higher burst repetition test. However, the combination of the stripline BPFN and SiC solid-state switch showed the high capability in the point of the stability, high burst repetition, and high power output for L-load. And, it also demonstrated to achieve the downsizing of the pulsar volume even for high power output.

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