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New SiC Kicker Power Supply for J-PARC

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NEW SiC KICKER POWER SUPPLY FOR J-PARC

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Abstract. A new kicker power supply using silicon carbide metal–oxide semiconductor field-effect transistors (SiC-MOSFETs) is under development at the Japan Proton Accelerator Research Complex (J-PARC). SiC-MOSFETs fabricate compact high-speed pulse power supplies to replace the thyratron switch power supply. The base circuit of the new power supply uses the linear transformer driver (LTD) system, and the semi-conductor module circuit comprises a radial symmetry type that achieves low noise. The three main components of the current kicker power supply, i.e., the thyratron, pulse-forming network (PFN) circuit, and end clipper, can be assembled on a single board as the new module circuit board. The new power supply contains a 1.25 kV/2 kA main board that forms a trapezoidal pulse and a 0.1 kV/2 kA correction board, compensating for the flat section droop. The 32 main boards and 20 correction boards are hierarchically connected in series to achieve the waveform specifications required for the J-PARC rapid cycling synchrotron (RCS) kicker power supply: output voltage of 40 kV, output current of 2 kA, and pulse width of 1.2 µs. Furthermore, a 25 % power saving has been confirmed and an insulating cylinder for the conductor has been developed to suppress corona discharge and withstand continuous operation for a long time.

1. Introduction

Silicon carbide (SiC) power semiconductors, which have superior performance regarding high breakdown voltage, low loss, and high-speed operation compared to silicon (Si) semiconductors, are expanding their market by taking advantage of their high-current high-speed switching characteristics [1-4]. The Japan Proton Accelerator Research Complex (J-PARC) [5] is developing SiC semiconductor- pulsed power supplies to replace the rapid cycling synchrotron (RCS) kicker power supplies using discharge tube thyratrons. As a kicker power supply, a module circuit board combining silicon carbide metal–oxide semiconductor field-effect transistors (SiC-MOSFETs) and a linear transformer driver (LTD) system [6] was developed [7-10]. The required specifications were achieved after repeated testing on prototype machines with a rated output of 40 kV/2 kA per unit, a pulse width of 1.2 µs, a repetition frequency of 25 Hz, and a flat top flatness within ±1.0 %. Furthermore, stable continuous energization for 8 h under reflected wave conditions was achieved using coaxial cables equivalent to those used in the actual equipment, confirming a 25 % power saving. However, copper rust due to corona discharge was observed in the transmission conductor; therefore, a new cylindrical insulator was developed to suppress corona discharge.

2. Performance of new power supplies

2.1. Development of New Types of Power Supplies

Table 1 shows the power supply specifications of the current [11, 12] and new models. All SiC-MOSFETs in the switch circuit operate stably with a jitter of less than a few nanoseconds relative to the operating trig-ger. For rated voltage can be halved for new power supplies without pulse-forming network (PFN) circuits.

Development started in 2017 with an output of 3.8 kV/2 kA and by 2021 a rated output of 40 kV/2 kA was achieved withs a simulated load. Then, in 2022, the same 130 m coaxial cable as the actual equipment was used, and tests were conducted at the same level as the actual equipment with reflected waves. Figures 1 and 2 show the pictures and measurements of this test. Forced air cooling is not equipped at this point. The charging voltage is 1.32 kV for the main boards and 10 V for the correction boards. The results confirm that the requirement specification replacing RCS kicker power supplies using thyratrons.

Table 1: Power Supply Specifications

Item	Current model	New model
Switch Circuit	Thyratron	SiC Semiconductor
Power Supply Structure	Twin-type (1 with 2 circuits)	Parallel units (1 with 4 units)
Rated Voltage	80 kV	40 kV
Current Per Power Supply	4.0 kA	2.0 kA
Rise Time	0.08 μs	0.20 μs
Flat Time	0.90 μs	1.20 μs

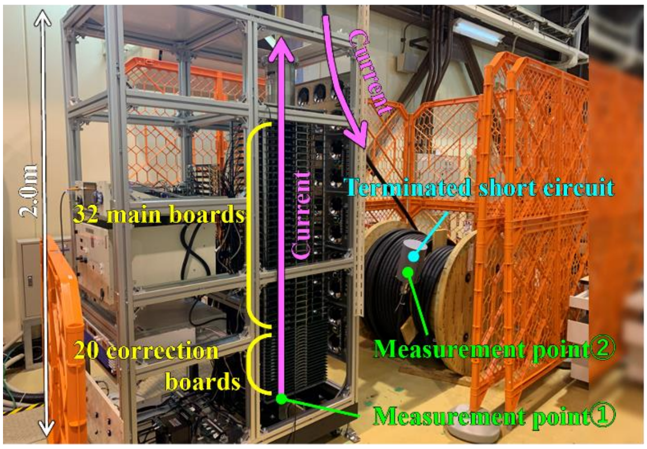

Figure 1: Picture of the experiment in progress**.**

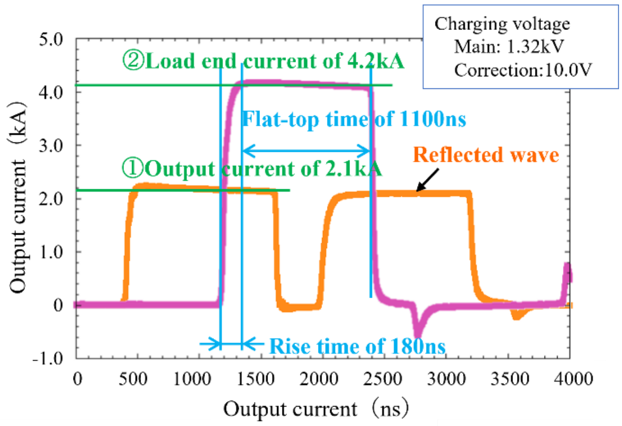

Figure 2: Waveform measurement results from load tests on coaxial cables. The results satisfy the required specifications.

2.2. Issues for Long-term Stable Operations

Continuous operation for 8 h was achieved without malfunctions or stoppages due to breakdowns. In this test, a forced-air cooling fan was operated. However, the effect of the forced air cooling was negligible, and the temperature of the resistor for absorbing reflected waves on the board increased by ΔT=120 °C. The results show that adding a cooling duct in the control cabinet should be considered.

Besides, copper rust was observed inside the outer conductor rings for the power transmission after three sets of 8 h continuous energization. Figure 3 shows a longitudinal section of the power transmission section and a photograph of the oil-soaked inner conductor. Moreover, Figure 4 shows a picture of the copper rust area.

The power transmission section of this circuit board, which uses the LTD system, is a coaxial structure combining an outer conductor with a superimposed induced voltage and an inner conductor through which the output current flows [6-10]. The maximum output voltage is applied between the inner and outer conductors, depending on the number of circuit boards hierarchically connected in series. Early measures against electrical discharges were a combination of liquid insulation with the inner conductor immersed in insulating oil and air insulation with a space between it and the outer conductor, which did not cause problems when energizing up to 20 kV. However, when energized up to 40 kV, copper rust occurred on the inner surface of the outer conductor contacting the air layer, indicating corona discharge.

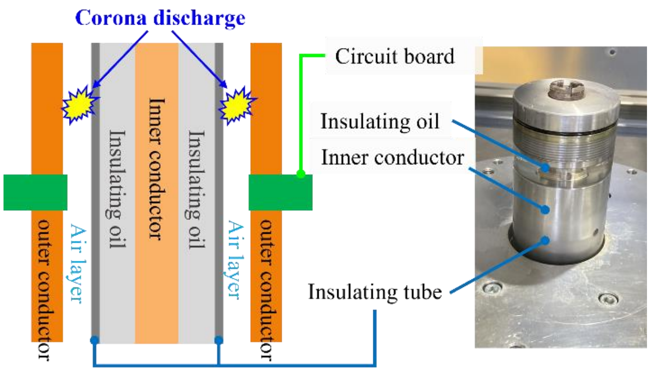

Figure 3: Longitudinal schematic of the power transmission section and photograph of the oil-immersed section.

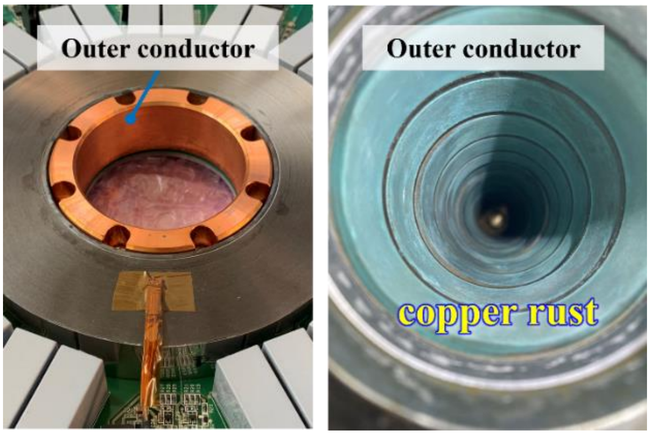

Figure 4: Picture of the outer conductor and a copper rust.

3. Development of a potential fixing insulating cylinder

3.1. Structure of the New Insulating Cylinder

The insulating cylinder developed for the test is a cylindrical structure covering the inner conductor fabricated using a three-dimensional (3D) printer. The inner and outer surfaces of the cylinder were plated. A metal contactor was used to bring the outer surface of the cylinder in the contact with the outer conductor. The inner surface of the cylinder and the inner conductor were brought in the contact with a flat metal plate, ensuring that the inner and outer plated parts of the cylinder were at the same potential as the inner and outer conductors, respectively. This structure is not air-insulated but individually insulated with the electrodes sandwiched between insulators without gaps. Figure 5 shows the old and new cross-sections of the transmission line conductors.

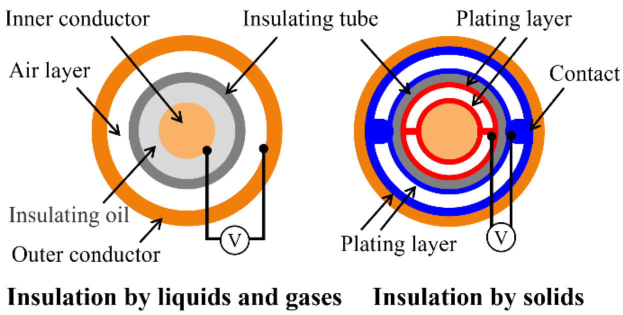

Figure 5: Comparison of cross-sectional views of transmission conductors. Left: Old type, right: new type.

3.2. Test Results and Practical Issues

Figure 6 shows a picture of the fabricated insulating. The plating was applied by hand with conductive paint. The plated area is aligned with the 30 mm height of the copper ring of the outer conductor. The distance between the upper and lower plated areas is 5 mm, equal to the circuit board thickness to accommodate the creepage distance of the insulation with a potential difference of up to 1250 V on the hierarchical board. The insulating cylinder is 150 mm is high, the fabrication limit of the 3D printer.

A power-on test with an output of 3.2 kV was con-ducted using four LTD main boards (M19 type) to evaluate the new insulating cylinder. No difference occurred between the circuit impedance and the pulse output waveform with and without the insulating cylinder, and no discharge appeared when using the insulating cylinder. The new insulating cylinder can sup-press corona discharges and does not affect the waveform. Figures 7 and 8 show the measurement results. The actual machine has an output voltage of 40 kV, and the circuit boards are connected hierarchically and are 1.6 m high. To accommodate this long length, an insulating cylinder must be joined. Furthermore, it is necessary to establish a joint structure for the insulating cylinder that does not cause insulation breakdown due to creepage discharge or penetration against the application of 40 kV.

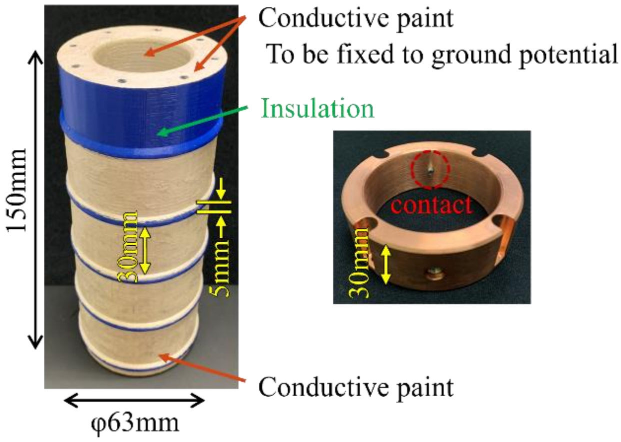

Figure 6: Picture of a fabricated insulating cylinder.

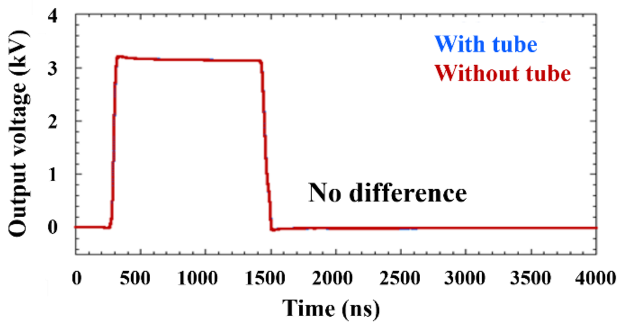

Figure 7: Circuit impedance measurement results.

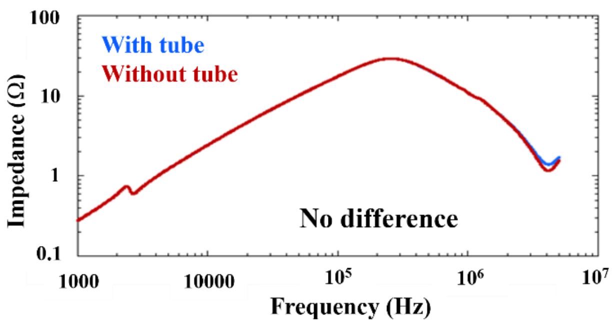

Figure 8: Measurement results of the pulse output waveform.

4. Power savings

The new kicker power supply with SiC-MOSFETs saves power. The power usage of the new kicker power supply and the current kicker power supply were com-pared when operating at 60 kV/3 kA/25

Hz. Connecting four units of the new kicker power supply in parallel is equivalent to one current kicker power supply (twin type). Since only one of the new kicker power supplies has been manufactured yet, the measured power of one unit is multiplied by four to compare with the current kicker power supply.

The current kicker power supply has a power consumption of 9.87 kW, and the new kicker power supply has a power consumption of 7.43 kW. Therefore, re-placing the current power supply with the new kicker power supply can save 25 % of electricity. Further-more, the new kicker power supply is forced-air-cooled, meaning that no cooling-water equipment is required. Moreover, the cost of purchasing spare parts for thyratrons, which must be replaced periodically, is also reduced.

5. Conclusion

The development of a pulsed power supply using next-generation semiconductors was initiated to re-place the current thyratron-based kicker power supply.

A new kicker power supply with an LTD circuit that satisfies the rated specifications was developed. By using the characteristics of next-generation semiconductors, it can save power. Now, we develop a potential-fixing long insulating cylinder to achieve long-term stable operation with reduced corona discharge.

6. Acknowledgements

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