UPGRADE OF THE KLYSTRON MODULATOR OF THE L-BAND ELECTRON LINAC AT OSAKA UNIVERSITY FOR HIGHER STABILITY

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Abstract

The klystron modulator for the L-band linac is upgraded for higher stability. The two-step charging system for the pulse forming network (PFN) is upgraded by adding a high impedance resonant charging line in parallel with the main line. The charging step of the PFN voltage is reduced considerably near the setting value by switching the main resonance line off so that the charging current flows only through the high impedance line. The second model of the solid-state switch is developed using 60 static-induction thyristors, ten of which are connected in series with six such series connected in parallel to meet maximum specifications of 25 kV and 6 kA. The air-cooling capacity is reinforced so that repetition rate is increased from 10 pps for the first model to 60 pps. The fluctuation and accuracy of the klystron voltage are measured to be 7.8×10^{-6} or 7.8 ppm for the upgraded klystron modulator using a differential amplifier with much higher sensitivity than one used in the previous measurement.

INTRODUCTION

The 40 MeV L-band electron linac is one of the main facilities of the Research Laboratory for Quantum Beam Science, the Institute of Scientific and Industrial Research, Osaka University. It is used mainly for pulse radiolysis in the time range from nanoseconds down to sub-picoseconds and the development and applications of a terahertz (THz) free electron laser (FEL). To generate a highly intense and stable FEL beam, a highly stable electron beam in terms of energy is required. The energy stability of the electron beam accelerated with the linac is dependent on stability of high power RF pulses generated with a klystron. Both the amplitude and the phase of the RF power depend on the voltage applied to the klystron, which is generated using a klystron modulator, so that flatness of high-voltage pulses needs to be high and small fluctuations of the peak voltage are indispensable to generating a highly stable multi-bunch electron beam for FEL.

Figure 1 shows the circuit diagram of the klystron modulator. Electric charge accumulated in the pulse-forming-network (PFN) to a high voltage is discharged using a high-speed switch, and the generated pulse is supplied to the klystron via a step-up transformer, and then a high power RF pulse is generated for accelerating the electron beam in the linac. To obtain the highly stable RF power, the charging voltage of PFN must be accurate and precise, and stable operation of the switch are required.

The switching frequency of the inverter power supply shown in Fig. 1 is 21.75 kHz but the charging frequency is doubled due to the full-wave rectifier, 43.5 kHz. The accuracy of the charging voltage is inversely proportional to the number of pulses sent to PFN, provided that charge per pulse is constant, whereas the charging time is given by the number of pulses divided by the charging frequency, so that a longer time is required for attaining higher accuracy. However, the charging time restricts the maximum repetition frequency of output pulses. Because the repetition frequency of the klystron modulator is 60 pps, the number of charging pulses would be limited to 725 and accordingly the accuracy of the charging voltage would be 0.13 %. To improve the charging accuracy to the order of 10^{-4}, the pulse width was reduced when the charging voltage approached the target value, which solved the contradicting requirements. As for the switch, the thyratron was used for the klystron modulator, which is a discharge tube filled with hydrogen or deuterium and widely used as a high speed and high current switch.

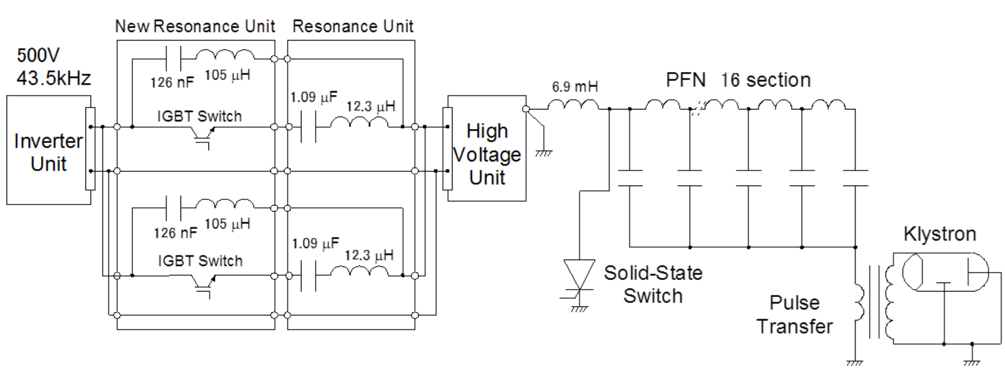

Figure 1: Circuit diagram of the klystron modulator.

In spite of their superior performance, however, thyratron has some drawbacks; they generate strong electric noises, the gas pressure must be regularly adjusted, and the accuracy of timing and turn-on resistance is not very high owing to inherent instability of discharge phenomena. It turned out that the accuracy and precision of the klystron voltage were not sufficiently high for stable operation of the FEL, so that the charging system to PFN was upgraded and the thyratron was replaced with a solid state switch for higher stability of the linac and the FEL [1]. The maximum repetition frequency of the solid state switch was 20 pps, which was limited by air-cooling capacity, and the fluctuation of the klystron voltage was too small to precisely measure with a differential amplifier used in the measurement. In this report, we will briefly describe the new charging system and the second model of the solid-state switch, which can be operated at 60 pps owing to reinforced cooling capacity, as well as accurate measurements of the klystron voltage and its stability using a differential amplifier with higher sensitivity.

CHARGING SYSTEM

The charging system consists of the inverter unit, the high voltage unit, and the resonant unit connecting the other two units for resonantly transfer electric pulses to the high voltage unit. The resonance unit is a series resonance circuit made up of a inductor L and a capacitor C and the resonance frequency is tuned to the operation frequency of the inverter unit, f = 43.5 kHz. The current I and the frequency f of the resonance unit are respectively given by $I = \sqrt{(C/L)}V \equiv V/Z_0$ and $f = 1/\left(2\pi\sqrt{LC}\right)$, respectively, where Z_0 is the characteristic impedance given by $Z_0 = \sqrt{L/C}$. To reduce the charging current quickly and appreciably during the charging process, we installed another series resonance circuit, in parallel with the main circuit, with the impedance Z_0 higher than that of the main circuit but with the same resonance frequency. In the fast charging mode with the lower impedance, the IGBT switch in the main circuit is turned on and a higher current flows through both the low impedance and the high impedance lines to the high voltage unit and the PFN voltage rises rapidly. When the voltage approaches the setting value, the switch is turned off and the current flows only through the high impedance line, so that charge per pulse is reduced for setting the PFN voltage with higher resolution sin a short period.

More specifically, capacitance and inductance are C = 1.09 μF and L = 12.3 μH in a series resonance circuit of the main line, and they are C = 0.126 μF and L = 105 μH in that of the sub line. Because there are two parallel resonance circuits in the main and the sub lines, impedance of the main line is calculated as Z_0 = 1.68 Ω and that in the sub line is Z_0 = 14.4 Ω, and therefore the combined impedance of the main and the sub lines is 1.50 Ω. As the output voltage of the inverter unit is 500 V, the current in the fast charging mode with both the lines is 332 A and that in the fine mode with the high impedance line is 34.7 A.

Figure 2 shows a photograph of the new resonance unit. A pair of reactors and capacitors for two series resonance circuits are installed on the upper plate. The reactors are coils wounded around magnetic cores with an air gap, and the number of turns and the gap were adjusted to tune the resonance frequency for twelve 10 nF capacitors connected in parallel. On the lower plate, two IGBTs for the switch are fixed on right and left faces of the forced-air-cooled heat sink, and circuit boards for driving IGBTs by trigger signals received via optical links are installed at both end of the plate.

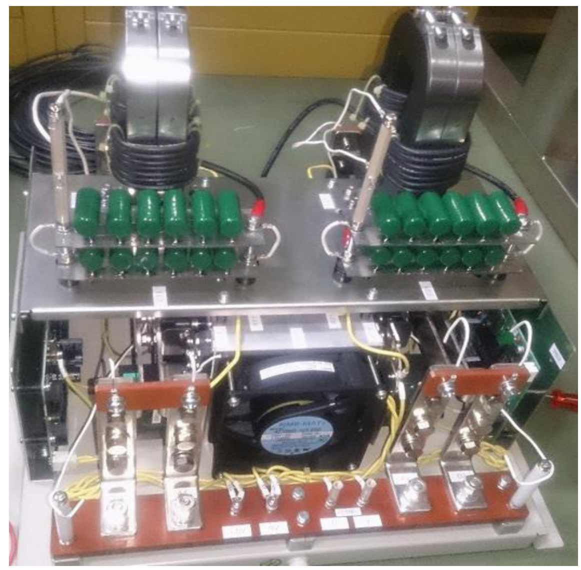

Figure 2: New resonance unit.

SOLID-STATE SWITCH

The maximum blocking voltage and the maximum current of the switch for the klystron modulator are 25 kV and 6 kA, respectively, for 60 pulses per second (pps) with a 5 μs duration or 30 pps with a 10 μs duration. We used static-induction thyristors (SI-thyristors) for the solid-state switch replaced with the thyratron. Specifications of the SI-thyristor show that the maximum blocking voltage is 3.2 kV and the average maximum current is 50 A in DC operation. However, it can conduct much higher current for such short pulses as those used in the klystron modulator of the L-band linac. Our test experiment conducted with 10 μs pulses shows a current up to 1 kA can flow whereas the leak current increases rapidly above 2.6 kV, which is appreciably lower than the specified maximum voltage, 3.2 kV. Therefore, we set maximum operational conditions of the SI-thyristor to be 2.5 kV and 1 kA. The solid-state switch is configured to be ten series of SI-thyristors for the maximum blocking voltage of 25 kV and six parallel such circuits for the maximum current of 6 kA.

Figure 3 shows the outline drawing and the photograph of the second model of the solid-state switch. It consists of ten aluminium-alloy frames, which are

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vertically stacked with insulator frames in between, and a base box. Two sets of three thyristors are installed on each long side face of the aluminium-alloy frames with many slits for cooling, and a control circuit board including the trigger circuits for gate and error detection circuits is attached over each thyristor set. Isolated DC-DC converters operating at 100 kHz supply the electricity of 5 V to control circuits on ten isolated units, and the trigger signals are sent to them via optical links. Two fans are installed in the base box and air is send upward thorough the 10 frames for cooling. By changing wiring from 6 parallel circuits of 10 series of tyristors to 3 parallel circuit of 20 series of thyristors, the solid-state switch can be also operated at 50 kV and 3 kA, which meet specifications for most of the klystron modulators for S-band linacs.

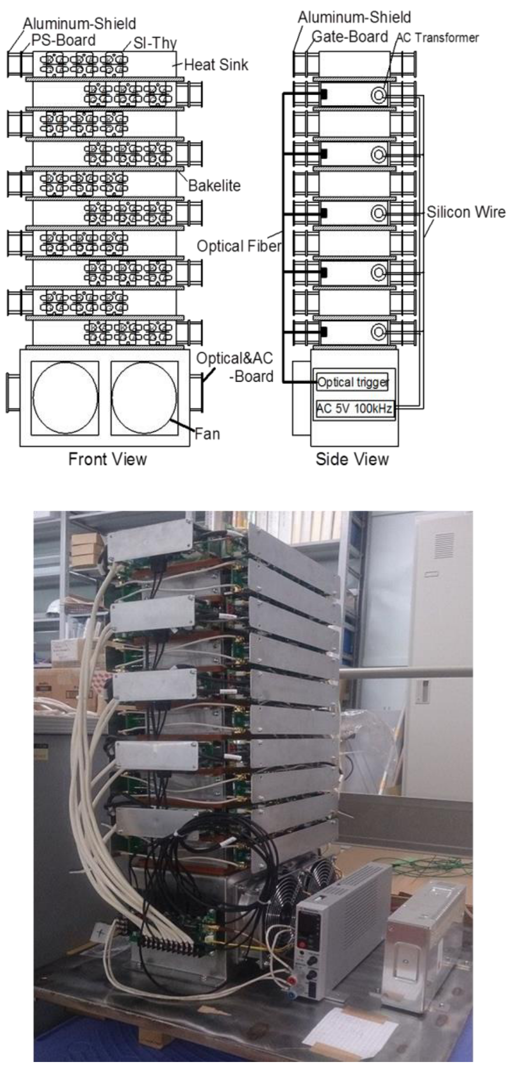

Figure 3: Solid-state switch using SI thyristors.

MEASUREMENT

To evaluate the performance of the solid-state switch and the charging system, we measured stability of the voltage applied to the klystron using a differential amplifier (DA1855A, Teledyne Lecroy), which has a low input noise level and hence high sensitivity enough to measure small fluctuations. The voltage and the current of the klystron were measured for the klystron modulator operated at the charging voltage of 20 kV and 10 pulses per second. Figure 4 shows voltage and current waveforms of klystron and solid-state switch (upper panel), and the expansion waveform of klystron voltage (lower panel), where 532 waveforms are overlaid. The standard deviation of the fractional voltage fluctuation is 7.8×10^{-6} or 7.8 ppm.

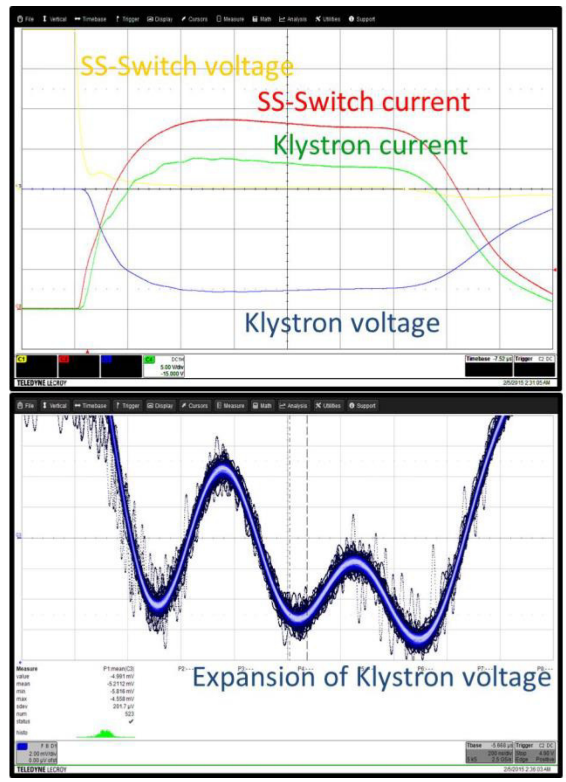

Figure 4: Voltage and current waveforms of klystron and solid-state switch and expansion of the klystron voltage.

CONCLUSION

We upgraded the charging system and developed the solid-state switch for higher stability of the klystron modulator of the L-band linac. The new charging system uses a two-step charging scheme for finer charging steps near the setting value with the single inverter power supply. The second model of the solid state using 60 SI thyristors was developed, that can be operated up to 25 kV and 6 kA at the maximum repetition frequency of 60 pps in the short pulse mode. The accuracy and precision of the klystron voltage were measured to be 7.8 ppm, and it is used without any serious problems in the regular operation of the linac.

REFERENCES

[1] A. Tokuchi, F. Kamitsukasa, K. Furukawa, K. Kawase, R. Kato, A. Irizawa, M. Fujimoto, H. Osumi, S. Funakoshi, R. Tsutsumi, S. Suemine, Y. Honda, G. Isoyama, Nucl. Instrum. Methods **A769** (2015) 73.