SOLID-STATE SWITCH FOR A KLYSTRON MODULATOR FOR STABLE OPERATION OF A THZ- FEL

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Abstract

A solid-state switch using static induction (SI) thyristors has been developed for a klystron modulator of the L-band electron linac at Osaka University to enhance stability of a THz-FEL based on the linac. The switch meets the maximum specifications such that the holding voltage is 25 kV with the switching time of 270 ns, that the current is 6 kA for a pulse duration of 10 μs, and that the repetition frequency is 10 Hz. The fluctuations of the klystron voltage are considerably reduced compared to those with a thyratron. The FEL is operated with the solid-state switch and the macropluse energy of the FEL at a wavelength of ~70 μm are measured with an energy meter for infrared lasers. The fractional variation of the macropulse energy measured in successive 500 pulses is 2.4 % for the solid-state switch (standard deviation), which is much smaller than 5.4 % for the thyratron.

INTRODUCTION

We are conducting basic studies on the THz-FEL and its applications using the L-band electron linac at the Institute of Scientific and Industrial Research (ISIR), Osaka University. The FEL has been operated in the wavelength range from 25 to 150 μm (2~12 THz). Performance of the FEL depends strongly on the accelerator providing the electron beam for the FEL. One of the crucial factors affecting such studies is stability of the FEL macrpoulse energy. To obtain a highly intense and stable FEL beam, the energy and the intensity of the electron beam must be constant in an electron pulse of a several microsecond duration, and pulse-to-pulse intensity fluctuations are required to be small. To enhance the stability of the electron beam, the klystron modulator was upgraded, in such a way that the fluctuations of the charging voltage of the PFN are reduced to 0.008% (peak-to-peak). Nevertheless, pulse-to-pulse fluctuations of the height of the high voltage pulse applied to the klystron are measured to be almost ten times larger than those of the charging voltage. Because the source of the instability is considered to be the thyratron, which is a fast high voltage and high current switch for a PFN in the klystron modulator, we have developed a solid-state switch that is expected to be more stable.

The first klystron modulator with a solid state switch for an electron linac was developed, to our knowledge, in the early 1990s at the FOM Institute for Plasma Physics for the FEL facility, FELIX [1]. The switch is made of 32 thyristors that are connected in a series to operate at the maximum voltage of 40 kV and the maximum current of 2.6 kA. The following activities to develop solid-state switches and to use them began increasing at approximately 2000 in Europe, America, and Japan using semiconductor devices, including thyristors, IGBTs, and MOS-FETs. These devices, however, have both advantages and disadvantages for meeting the specifications and requirements for various klystron modulators.

Another candidate for a semiconductor device that is suitable for the solid state switch is the Static Induction Thyristor (SI-thyristor) because it has fast switching characteristics as well as a high holding voltage and a high current [2]. Two types of solid state switches with different types of SI thyristors were developed for the JLC project and were successfully tested at KEK. These switches, however, have not been used in operation of linacs.

In this paper, we will describe the development of the solid-state switch using SI thyristors and the evaluation of its performance in terms of the stability of the klystron voltage, the RF power and phase, and energy of the FEL macrpulses. More detailed report on the solid-state switch will be published elsewhere.

STATIC INDUCTION THYRISTOR

The SI thyristor is a type of PIN diode that is equipped with the gate. The characteristics that are measured from a test sample for pulsed-power applications are reported to be as follows: the hold-on voltage is 5.5 kV, and the turn-on time is 35 ns, with di/dt = 95 kA/μs [2]. Because these values are sufficient for our purpose, we decided to develop a solid-state switch using SI thyristors. Although they are not available on the market, we obtain SI thyristors by courtesy of Shindengen Electric Manufacturing Co., Ltd., which is developing such devices. Figure 1 shows an SI thyristor manufactured by the company.

Two important specifications of the SI thyristors that we use are the maximum blocking voltage of 3.2 kV and the maximum average current of 50 A (root-mean-square), although the details are not available yet from the manufacturer. It is, however, expected that a much higher current can flow if the pulse duration is short and the repetition rate is not so high that the average power consumption in the SI thyristor does not exceed the value in the slow operation. Characteristics of a SI thyristor measured with square pulses of 2 kV, 1 kA, and a 2 μs duration are the switching time of 360 ns (90%-to-10% change) and the turn-on resistance of 0.12 Ω. To evaluate

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the holding voltage of the SI thyristor, the leak current is measured as a function of the applied voltage at several temperatures of the thyristor from 20 up to 80 ºC because the leak current increases as the temperature becomes higher. The measurement shows that the leak current increases gradually with increasing temperature at lower voltages, whereas it increases sharply above 2.6 kV at any of the temperatures. Although the maximum value of the holding voltage written in the manufacturer's specifications is 3.2 kV, we assume that the maximum holding voltage of the SI thyristors is 2.5 kV for this purpose.

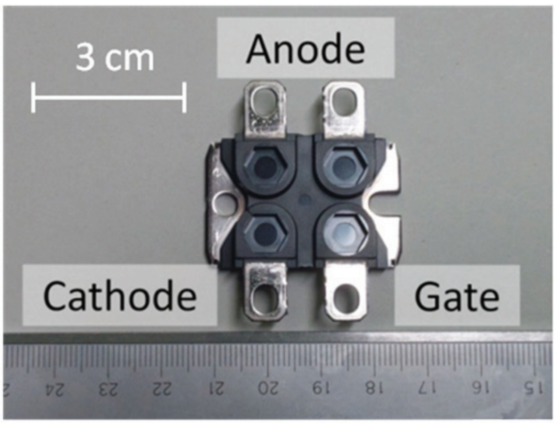

Figure 1: Static induction (SI) thyristor.

SOLID-STATE SWITCH

The modulator currently provides square pulses of 218 kV and 186 A, with a duration of 10 µs, or those of 236 kV and 210 A with a 5 µs duration to a klystron (Thales, TV2022D) at a repetition rate of 10 Hz using a 1:24 step-up transformer. Because the charging voltage of the PFN is shared almost equally by the PFN and the klystron when it is on, the switch is operated at 20 kV and 4.5 kA in the long-pulse mode or at 22 kV and 5.0 kA in the short-pulse mode. To fulfill the conditions for the voltage and the current with sufficient margins, the specifications of the switch are determined to be the maximum holding voltage of 25 kV and the maximum current of 6 kA; as a result, ten thyristors are connected in series, and six such series are connected in parallel for the solid-state switch using 60 SI thyristors with the measured characteristics of 2.5 kV and 1 kA at the maximum. Figure 2 shows the external views of the solid-state switch. The main frame consists of five 8-cm thick aluminum-alloy frames with a parallel lattice for air cooling. They are vertically stacked with bakelite frames in between for insulation. Three sets of two serially connected thyristors are installed directly on each longer side of each frame, and a control board with six trigger circuits for gates, a set of error detection circuits, and a power supply are installed on each shorter side, which means that six sets of two serially connected thyristors with peripheral circuits are on each frame. Thus, five such frames comprise a solid state switch with six parallel circuits of ten serially connected SI thyristors. These frames are placed on a base box, which has two fans installed that send air upward through the five frames, a trigger circuit that sends trigger signals to the ten control boards via optical links, and a 5 V, 100 kHz insulated DC-DC converter that sends power to the boards. The dimensions of the solid-state switch are approximately 0.35 m wide, 0.25 m deep and 0.54 m high, which can be replaced with a thyratron switch in the klystron modulator.

The switching time of the solid-state switch was measured to be 270 ns at a PFN charging voltage of 20 kV using a dummy load.

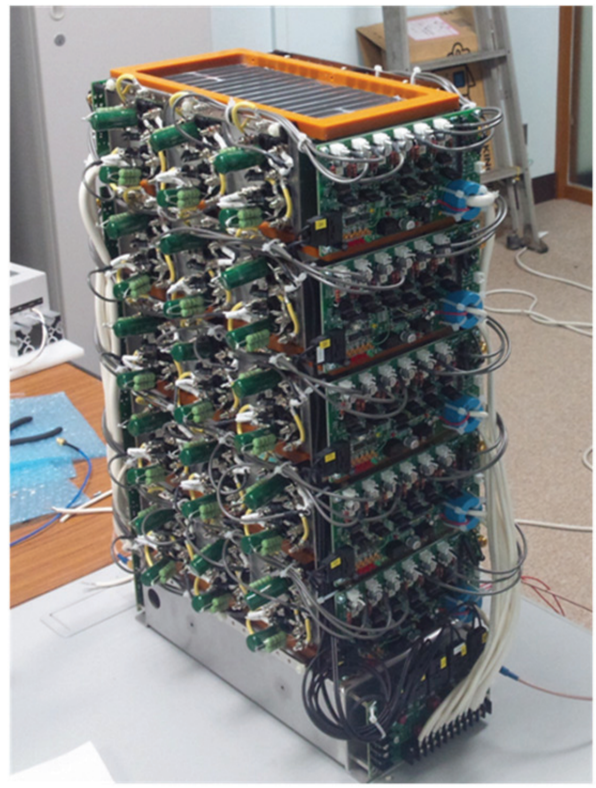

Figure 2: Solid-state switch using the SI thyristors.

OPERATION TEST

In the next step, an operations test of the solid-state switch was conducted to generate high power RF pulses using the klystron modulator at a charging voltage of 20 kV and a repetition rate of 10 Hz in the long pulse mode. The pulse height with the solid-state switch is slightly lower than that measured with a thyratron (L3 Communications, L-4888B) for comparison, because the turn-on resistance of the solid-state switch is slightly higher. Pulse-to-pulse fluctuations of the klystron voltage are obtained by measuring plateaus of 100 pulses using a differential amplifier (Tektronix, ADA400A) and a digital oscilloscope. The voltage fluctuation with the solid-state switch is constant in the pulse duration of ~8 µs and it is $\delta V_k/V_k$ = 1.45 (±0.12)×10^{-4}, which is very close to the noise level of 1.27 (±0.09)×10^{-4}. If the noise contribution is subtracted from the measured value, the true value of

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the fluctuation is estimated to be 7.0 (±3.0)×10^{-5}. The fluctuation with the thyratron is similar in the front of the pulses but it increases toward the rear part up to ~3.2×10^{-4}. The variation in the RF power with the solid-state switch is similarly measured using a diode detector to be δP/P = 1.52 (±0.11)×10^{-3} and is constant over the pulse, which should be compared to the noise level of 1.42 (±0.07)×10^{-3}, and the true value of the power fluctuation is estimated to be (5.4±3.6)×10^{-4}, whereas the variation with the thyratron is also the same as that with the solid-state switch in the front part, but it increases in the latter half to ~3×10^{-3}, which is similar to the behavior of the klystron voltage. The phase variation with the solid-state switch is δϕ = 0.102±0.008 degrees over the pulse, and the true value is estimated to be 0.056±0.017 degrees using the noise level of 0.085±0.006 degrees. The phase variation with the thyratron varies slowly over the range from 0.13 to 0.18 degrees in the pulse and is larger than that with the solid-state switch.

The FEL was operated with the solid-state switch to measure the energy of the FEL macrouplse using an energy meter for infrared lasers. The operating conditions of the FEL are such that the electron energy is 15 MeV, that the gap of the wiggler is 36 mm, which yields the maximum macropulse energy and the FEL wavelength of ~70 μm or 4.3 THz, and that the detuning of the optical cavity is close to zero. Figure 3 shows such measurements of 500 successive pulses with the solid-state switch (a) and with the thyratron (b). The red lines show mean values of the FEL energy and the broken lines indicate ranges of standard deviations of the variations. The fractional variation for the solid state switch is 2.4 % whereas that for the thyratron is 5.4 %, indicating that the solid state switch can significantly reduce the pulse-to-pulse fluctuations of the FEL intensity, though these variations are neither the best ones nor the worst ones.

The results of these measurement are summarized in Table 1.

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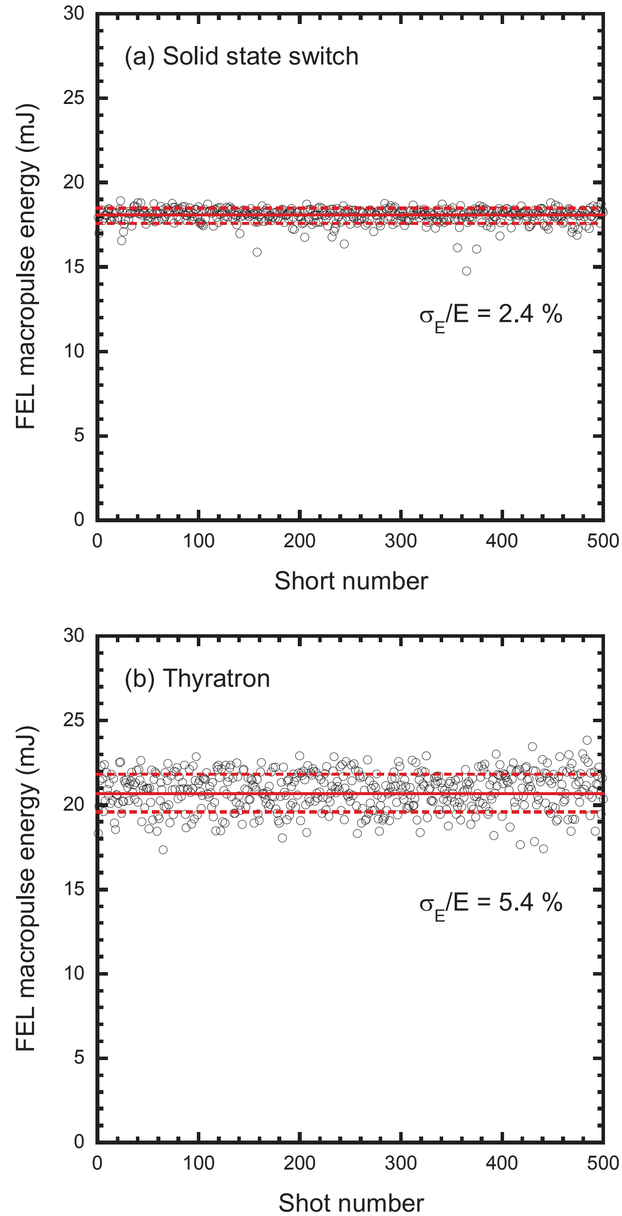

Figure 3: Fluctuations of macropulse energy measured with an energy meters. The red lines show mean values and the broken line indicate standard deviations.

Table 1. Summary of the Measured Variations

	Thyratron	Solid-state switch		
	measured	measured	noise	noise-subtracted
		Fractional variations (×10^{-4})		
Klystron Voltage	~3.2	1.45 ± 0.12	1.27 ± 0.09	0.70 ± 0.30
RF power	~30	15.2 ± 1.1	14.2 ± 0.7	5.4 ± 3.6
		Variations (×10^{-2} degs.)		
RF phase	~18	10.2 ± 0.8	8.5 ± 0.6	5.6 ± 1.7
		Fractional variations (%)		
FEL macropulse	5.4	2.4	-	-

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