24-MW, 24-μs PULSE RF POWER SUPPLY FOR LINAC-BASED FELs

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SUMMARY

Two infrared free electron lasers (FELs) of the FELI are operating using S-band 80-MeV linac with a thermionic gun and a 165-MeV linac and UV-FEL facility are under construction. Since an RF system for linac-based FELs is required of long pulse duration and high quality, a improved pulse klystrons (Toshiba E3729) has been operated in 24-MW, 24-μs pulse mode for the FELI linac. Our klystron modulator developed by the FELI and NISSIN Electric Corp. has a PFN consisted of 4 parallel networks of 24 capacitors and 24 variable reactors. The line switch is consisted of 30 light triggered thyristors (Toshiba SL1500GX22). A saturable reactor is used in series to protect 30 thyristors from overvoltage caused by a delay of thyristor's turn-on time. The flatness of modulator pulses is $0.08\%_{p-p}$ at 20-MW, 24-μs pulse operation. The 24-μs stable RF pulses can increase a conversion efficiency from electron beam power to FEL power at short wavelength FELs. Saturated FEL outputs have been observed for 18-μs at 5.5-μm FEL oscillation and for 12-μs at 1.88-μm FEL oscillation, respectively.

INTRODUCTION

The FELI is now operating two IR-FELs using an 80-MeV linac with a thermionic gun and is constructing a 165-MeV linac and a UV-FEL facility. It is essentially necessary for linac-based FELs using pulsed rf sources to get a stable and long rf pulse from a klystron. A stable and long rf pulse sources enables to yield a stable and saturated FEL pulse source. The FELIX group has succeeded in keeping a pulsed rf source stable to accelerate a 22.5-MeV, 10-μs beam with an energy spread of 0.5%[1]. For this purpose, we have developed a 24-MW, 24-μs pulse power modulator for an S-band klystron (Toshiba E3729) at three operation modes shown in Tab. 1. Mode 1 and Mode 2 are for FEL generation and Mode 3 is for injection to a storage ring.

Table 1 Parameters of Klystron Modulator

Mode	Mode 1	Mode 2	Mode 3
Output voltage(kV)	285	304	390
Output current(A)	280	305	477
Pulse width(μs)	24	12.5	0.5
Flat-top$_{(p-p)}$(%)	0.08	0.08	1.5
Stability(%)	0.08	0.08	1.5
Repetition(pps)	10	10	10
Rise time(μs)	2	2	2
Fall time(μs)	3	3	3.5

*Rise and fall time is measured from 10-90% of the output pulse.

KLYSTRON MODULATOR

Fig. 1 shows the circuit diagram of the klystron modulator. This modulator is consisted of the charging section using converter-inverter, the pulse forming network(PFN) section with 4 parallel L-C circuit, the main switch section using light triggered thyristors, and the mounting tank for the klystron to supply high voltage by a pulse transformer. The output voltage is measured at the secondary side of the pulse transformer by a capacitive divider. Details of these sections are as follows.

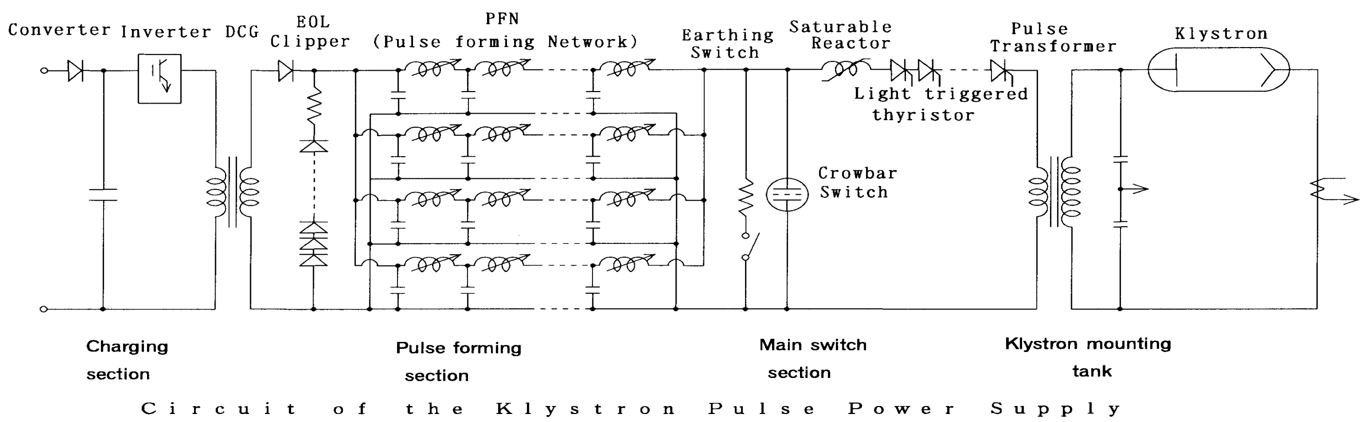

Fig. 1 Circuit Diagram of Klystron Modulator

(1) Charging Section

We use a converter-inverter charging circuit instead of IVR~De-Qing one, because De-Qing one has the following problems.

i) A charging voltage of the PFN involves about 0.2% fluctuation due to an input voltage.

ii) Pulse repetition rate is low (10pps). Therefore, the scale of charging section becomes bigger due to a large time constant at resonant charging.

Therefore, our inverter is consisted of 5 cascades at 15kHz and we have achieved a high stability within $\pm 1 \times 10^{-4}$ of charging voltage.

(2) Pulse Forming Section

The PFN is consisted of 4 parallel networks and the output pulse width are 24μs, 12.5μs and 0.5μs at mode 1, 2 and 3, respectively. Because of the 4 parallel PFNs, an inductance of each variable reactors can be designed to be larger than that of the single PFN. Therefore, effects of the wiring inductance to the modulator pulse waveform is small. Each reactor of the PFN is adjustable by means of a remote control system using a motor driving plunger. The minimum adjustable amount of the PFN reactor is 0.005% and the maximum adjustable span is 45%. Therefore, the adjustment of output waveform has been easily performed, and a 0.08% flat-top of output pulse waveform has been achieved. If the klystron has break down during a high voltage is applied, the PFN capacitors suffer from large reverse voltage. To reduce this damage, an EOL (End of line) clipper circuit is set and the reliability of the modulator becomes high.

(3) Main Switch Section

We have used the light triggered thyristor (Toshiba SL1500GX22, 30series) stack as the main switch for keeping the output voltage stable. Generally speaking, a thyratron is suitable for switching of high voltage and large current. But in this case, the thyratron is not suitable because a change of its resistance is large ($\geq$0.1%) during the conduction time.

However, in order to use the light triggered thyristors, we have solved the following problems.

i) The value of dI/dt is more ten times (~3000A/μs) than the thyristor's specification.

ii) It is necessary to trigger 30 thyristors simultaneously as a switch.

Before adopting light triggered thyristor, we have tested dI/dt of the same device. The result was that the thyristor was breaked down at about 1700A/μs. Therefore, we have set a saturable reactor in series with the light triggered thyristors to keep a counter-measure to a delay of each thyristor's turn-on and a suitable conduction space at the switching time. The use of the saturable reactor enables us its running under a hard condition of dI/dt ~3000A/μs. On the other hand, the use of the light triggered thyristors makes it easy to insulate the gate drive circuit and to withstand to a high reverse voltage.

PERFORMANCE

1. Light Triggered Thyristors

Fig. 2 shows the time response of the resistance of light triggered thyristors at the mode 1. After the main current reaches the peak, the resistance is about 0.6-0.3Ω/30devices, that is, 20mΩ-10mΩ/1 device. The resistance at the whole conduction is about 0.5mΩ (at current is 4kA). Therefore, the conduction space of this thyristor is about 1/40-1/20 of the whole conduction at the mode 1. Though we have already tried 3×10^7 shots under this condition, there are no any troubles at all.

It is easily understood from Fig. 2 that the resistance of the light triggered thyristor decreases in micro-second order, so we can adjust the waveform so as to cancel this effect.

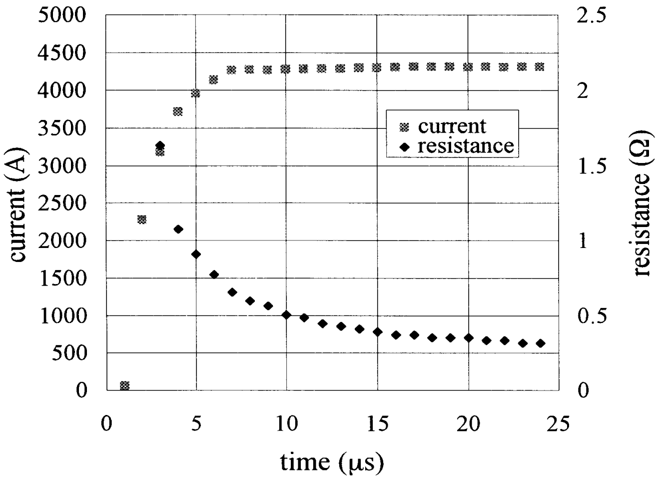

Fig. 2 Time Dependence of the Resistance of Light Triggered Thyristor

2. Klystron Modulator and Klystron

Table 2 shows the characteristics of the output at three modes and Figs. 3 and 4 show the waveforms of the output voltage at the mode 1.

Table 2 Performance of Klystron Modulator and Kystron E3729

Mode	Mode 1	Mode 2	Mode 3
Output voltage(kV)	285	304	390
Output current(A)	280	305	477
Pulse width(μs)	23.2	12.0	0.5
Flat-top$_{(p-p)}$(%)	0.08	0.08	0.3
Stability(%)	0.07	0.06	0.15
Repetition(pps)	10	10	10
Rise time(μs)	2.0	2.5	2.0
Fall time(μs)	4.5	6.5	6.4
RF output(MW) from E3729	24	34	70

*Rise and fall time is measured from 10-90% of the output pulse.

The rise time of the output is about 2-3μs. This shows that the light triggered thyristors can withstand for the rise time of micro-second order due to the effect of the saturable reactor. Fig. 4 shows the flatness of the modulator pulses is kept within $0.08\%_{p-p}$ at 24-MW, 24-μs pulse operation.

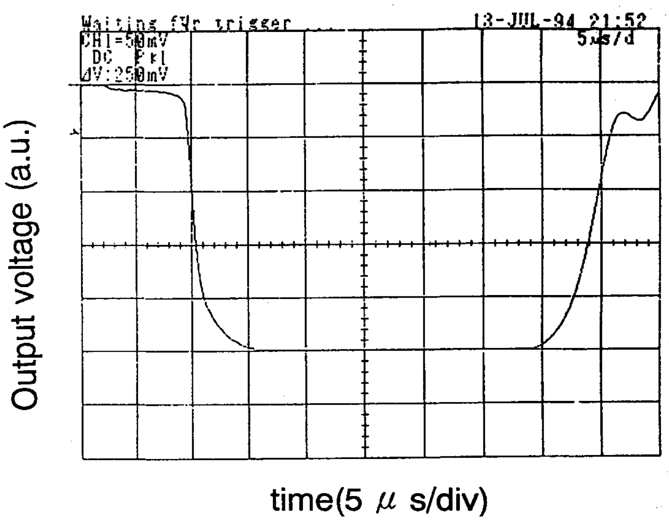

Fig. 3 Waveform of Output Voltage at the Mode 1

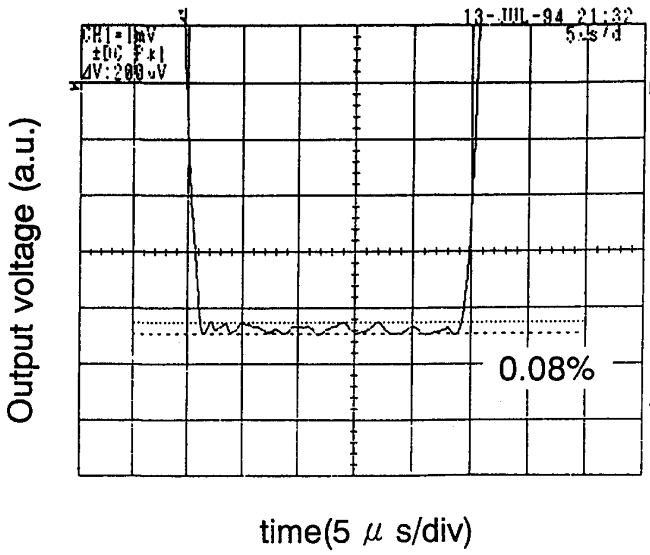

Fig. 4 Expanded View of Top Part of the Waveform shown in Fig. 3

3. *Modulator Pulse and 24-μs rf Pulse*

Fig. 5 shows the waveforms of the modulator current pulse and 24-μs rf pulse. Tiny ripples seen on the waveforms are due to white noise of the sampling oscilloscope (TDS460-Tecktronics).

4. *24-μs rf Pulse and 5.5-μs FEL Macropulse*

Fig. 6 well demonstrates a saturated 5.5-μs FEL macropulse continues for a duration of 18-μs at the 24-μs rf pulse operation[2]. This is a good example to show that a stable and long rf pulses can improve a conversion efficiency from electron beam power to FEL power.

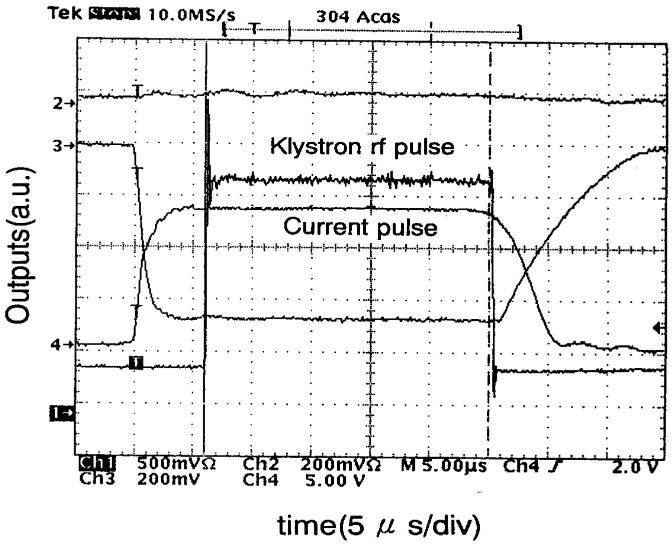

Fig. 5 Modulator Pulse and 24-μs rf Pulse

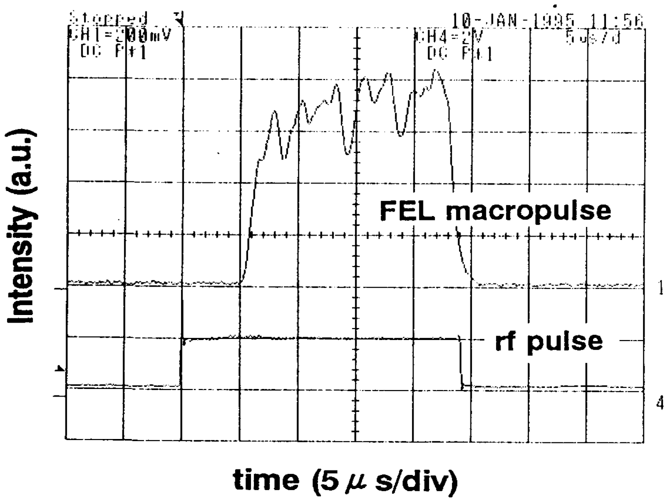

Fig. 6 24-μs rf Pulse and 5.5-μs FEL Macropulse

CONCLUSION

A 24-MW, 24-μs pulse rf power supply has been developed for linac-based FELs. The flatness of the klystron modulator pulses is kept within 0.08% at 24-MW, 24-μs pulse operation by using the light triggered thyristors and remote control systems for variable reactors of the PFNs. Experimental data on FEL oscillations at 5.5μm have demonstrated that stable and long rf pulses can yield saturated and long FEL macropulses can improve a conversion efficiency from electron beam power to FEL power at short wavelength FELs.

REFERENCES

[1] D. A. Jaroszynski, et al., Nucl. Instr. Meth., A331, 52 (1993)

[2] T. Tomimasu, et al., in this Proceedings