DEVELOPMENT OF AN X-BAND KLYSTRON MODULATOR WITH A PULSE-FORMING LINE AND MAGNETIC SWITCH

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Abstract

A new type of klystron modulator has been developed for the Japan Linear Collider. It consists of a pulse-forming line (PFL), a pulse transformer and a magnetic switch. In order to realize a compact modulator, a triplate strip transmission line using deionized water as a dielectric was adapted for the PFL. An Fe amorphous core was used for the magnetic switch and the pulse transformer to reduce the size and cost. A preliminary test has shown that an output pulse with a peak voltage of 550 kV, a pulse length (flat-top) of 440 ns and a rise time of 165 ns can be generated for a dummy load with an impedance of 412 Ω. It was also experimentally confirmed that the power efficiency of the modulator is approximately 83%.

Introduction

In the rf system of the Japan Linear Collider (JLC), X-band klystrons with a peak rf power of 100 MW-class and a pulse width of 400 ns, and their modulators are necessary to obtain the designed accelerating gradient of 100 MV/m [1]. Since the pulse width for the X-band is particularly short, short rise and fall times are required for the modulator in order to obtain high efficiency. Moreover, a high-reliability modulator of compact size is necessary, since JLC is a large-scale accelerator system with ~ 3,600 klystrons. For this X-band klystron, a conventional modulator using a thyratron and a pulse-forming network (PFN) has already been developed [2]. However, it is difficult for this PFN-type modulator to realize these requirements. Especially, the lifetime of the thyratron is a serious problem for stable operation of JLC.

An all-solid-state modulator using magnetic-pulse-compression techniques, consisting of only passive components, such as saturable inductors and capacitors, is suitable for the X-band klystron modulator, because of its short rise-time capability and high reliability. We have designed and carried out performance tests concerning a simple modulator using a pulse-forming line (PFL), a pulse transformer and a magnetic switch. In this paper, the design, specifications and results of performance tests of the discharge unit of the modulator are described.

System Design and Modulator Specifications

Table 1 gives the specifications of the X-band klystron modulator.

TABLE 1
Specifications of the X-band klystron modulator

Output pulse voltage	600 kV
Output pulse current	1200 A
Output impedance	500 Ω ± 15%
Pulse rise time	150 ns
Pulse length(flat-top)	400 ns
Pulse height deviation from flatness	< ±1.0%
Pulse repetition rate	50 pps

The output impedance of the modulator depends on the micro-perveance of the klystron. Although the impedance of the prototype X-band klystron is on the range of 1~2.5 kΩ, the impedance of the modulator was designed to be 500 Ω, considering the following points: (1) The modulator system of a single modulator provides power to more than two klystrons is one of the suitable methods to reduce both the cost and size. (2) A low output impedance is preferable for short rise and fall times.

The X-band klystron requires a 600 kV pulsed-beam voltage with a 400 ns flat top. In this pulse-width range, both PFN- and PFL-type modulators can be constructed. However, we have chosen a simple PFL-type modulator system using a magnetic switch and a pulse transformer because the passive components are physically suitable for the high-voltage system and, therefore, a very compact system is possible. The main design features of the modulator are summarized as follows:

(1) A triplate strip transmission line was chosen to be the PFL because of its simple structure and easy fabrication.

(2) Deionized water is to be used as a dielectric in order to reduce the length of the PFL.

(3) An output pulse transformer with a step-up ratio of 1:15 is to be used to obtain the low-voltage PFL as well as matching between the PFL impedance and the load impedance.

(4) An Fe amorphous has been chosen as the core material of the pulse transformer and magnetic switch in order to reduce both the size and cost.

(5) Passive components are to be used for all components of the modulator in order to obtain a long lifetime.

A simplified diagram of the all-solid-state X-band klystron modulator is shown in Figure 1. This system consists of a 10 kV dc power supply controlled by SCRs, a capacitor bank, a two-stage saturable reactor, a water-filled PFL and a pulse transformer. A pulse triggered by the GTO switch is transferred from C1 to the PFL by increasing the voltage through the 1:8 pulse transformer. The pulse is finally transferred from the PFL to a klystron load through the 1:15 pulse transformer.
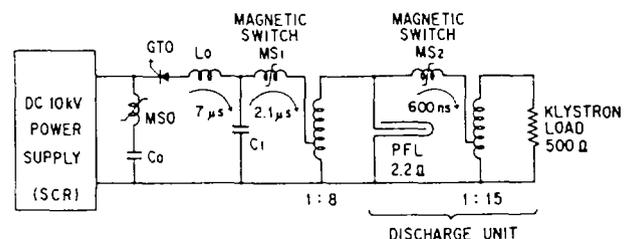

Figure 1. Simplified diagram of the all-solid-state X-band klystron modulator.

Discharge Unit of the Modulator

Figure 2 shows a discharge unit of the X-band klystron modulator. This unit is divided into two parts, a cylindrical tank and a PFL box. The pulse transformer

and the magnetic switch are housed in the same oil tank made of stainless steel (SUS 304); a water dummy load is also set on the top of the tank. The tank is connected to the PFL box through a short coaxial line. The high-voltage input socket under the tank is used to supply a high-voltage to the unit. Details are described in the following subsections. A photograph of the discharge unit is shown in Figure 3.
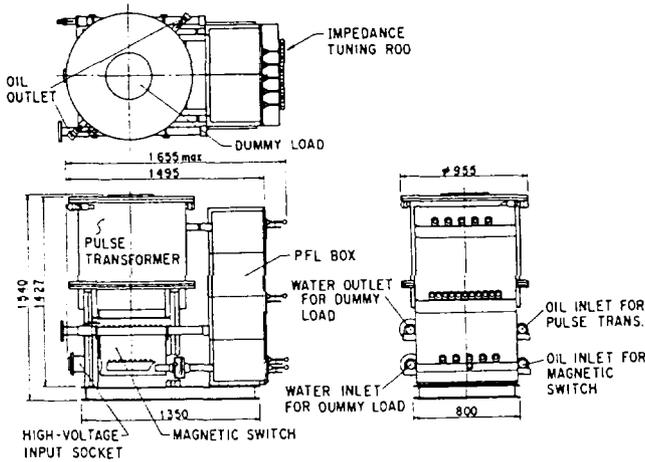
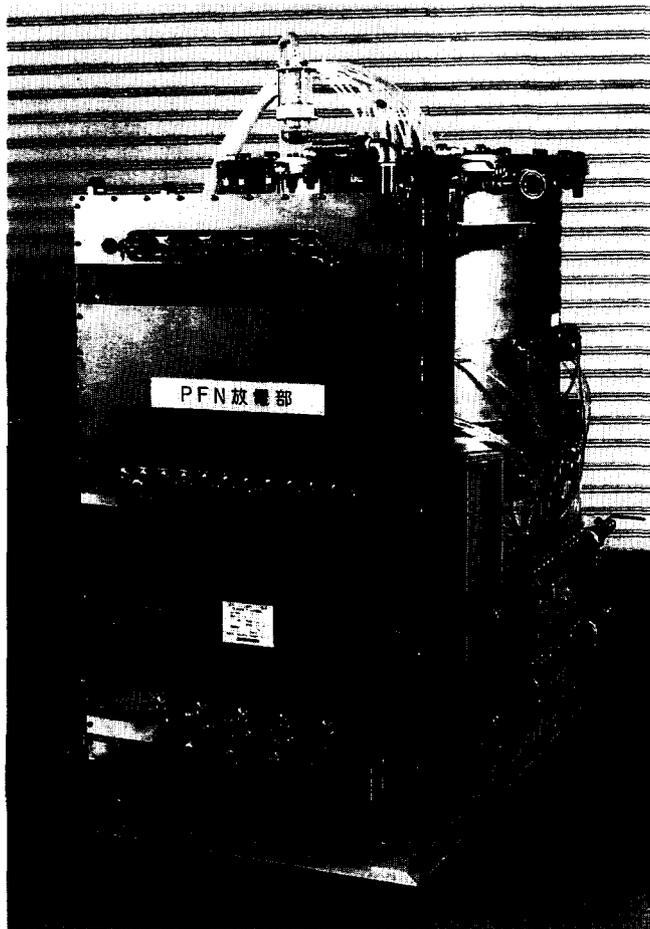Figure 2. Discharge unit of the X-band klystron modulator.

Figure 3. Photograph of the discharge unit.

Pulse-forming line

Figure 4 shows the structure of the PFL. It has one high-voltage electrode between two ground electrodes. These electrodes are made of stainless steel. The length of the PFL was determined to be 12.1 m by considering its pulse length as well as the dielectric constant of water. In order to realize a compact PFL, the line is bent eleven times. Moreover, plastic plates are inserted between the high-voltage and ground electrodes in each of straight and bend lines, making it possible to adjust the impedance. This mechanism enables us to adjust the impedance of the PFL as well as the flattop of the output waveform.

(1) High-voltage electrode
(2) Two ground electrodes
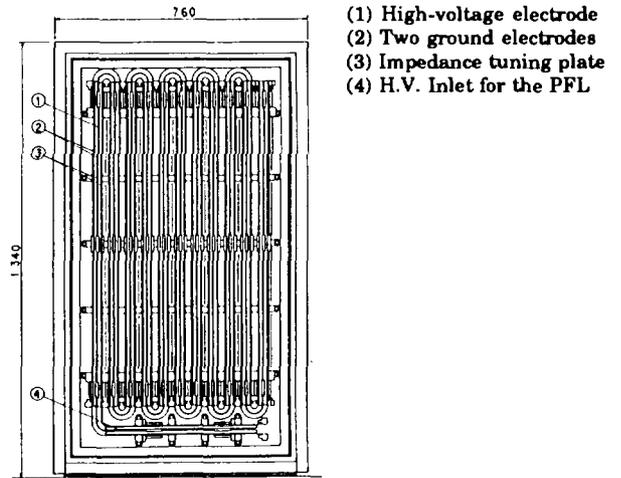(3) Impedance tuning plate
(4) H.V. Inlet for the PFL

Figure 4. Structure of the PFL.

The PFL is mounted on a stainless-steel base plate. This assembly is housed in a 660 mm wide x 390 mm deep x 1260 mm high water-filled box. The parameters of the PFL are summarized in Table 2.

TABLE 2
Parameters of the PFL

Line length	12.1 m
Characteristic impedance	2.2 $\Omega \pm$ 15%
Pulse length	720 ns
Width of the high-voltage electrode	140 mm
Width of the ground electrode	200 mm
Thickness of the high-voltage electrode	6 mm
Gap between the high-voltage and the ground electrodes	12 mm

Magnetic switch

An Fe amorphous AC 10 (TDK Ltd. Co.) was chosen as the core material of the magnetic switch owing to its high magnetic flux density swing (2.1 T) and low cost. The relative unsaturated and saturated permeabilities of the core are 2.0 and 2000, respectively. The parameters of the magnetic switch are summarized in Table 3.

TABLE 3
Parameters of the magnetic switch

Number of turns	1
Outer radius of the magnetic core	230 mm
Inner radius of the magnetic core	130 mm
Axial height of the core in the magnetic switch (eight cores used with h=48 mm)	384 mm

Since the power loss of Fe amorphous core is 15-times larger than Co amorphous, the temperature rise caused by the magnetic core losses is a key problem at a higher repetition rate. The core comprises 8 smaller subcores. In order to remove heat from the core, each subcore is wound from a 22 µm thick, 48 mm wide amorphous ribbon and a 4 µm thick, 52 mm wide PET film with a heat-transfer coefficient of 200 W/m^{2}K. The saturated switch inductance was estimated to be 110 nH.

Pulse transformer

To generate a square-wave pulse, we must design a pulse transformer with a low stray capacitance and leakage inductance. The core comprises 3 subcores, which is the same core used in the magnetic switch. The primary and secondary windings of the pulse transformer comprise one turn and fifteen turns, respectively. The leakage inductance and stray capacitance that were referred to regarding the high-voltage side were estimated to be 17.5 mH and 134 pF, respectively.

Performance Test

A preliminary test of the discharge unit was performed in order to confirm the performance of this modulator. Figure 5 shows the test circuit. The impedance of the dummy load was set at 412 Ω.
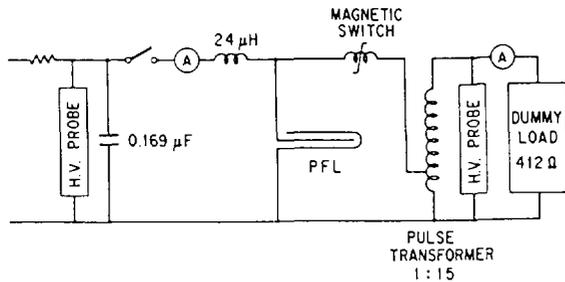

Figure 5. Test circuit.

Output waveform

After the primary capacitor was charged to 81 kV, a gap switch for an initial switch was triggered to charge the PFL. The input and output voltage waveforms were measured by high-voltage dividers. Figure 6 shows the output voltage waveform.
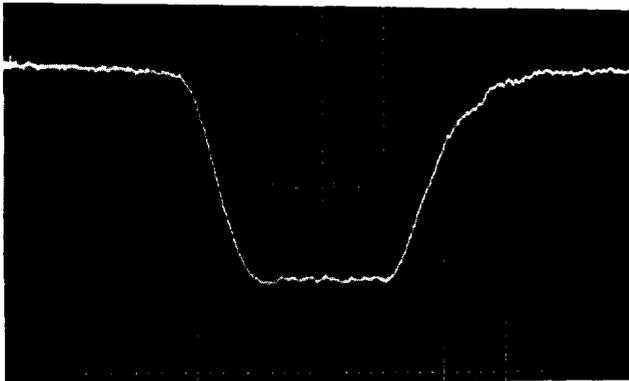

Figure 6. Output pulse voltage at the dummy load.
(V: 160 kV/div., H: 200 ns/div., peak ~ 550 kV)

A pulse with a peak voltage of 550 kV and a width of 714 ns was successfully generated. Although a 440 ns flat-top with ± 0.9% satisfies the requirement, a rise time (10-90%) of 165 ns is slightly longer than the expected value. Further investigations are necessary to obtain a shorter rise time.

Power efficiency and losses

The power efficiency of the modulator is very important for the application of a large-scale modulator system. The power efficiency of the modulator in this experiment was estimated form the input power at the primary capacitor and output power at the dummy load. The result was 83%. The power losses of the modulator were mainly due to magnetic core losses, as well as resistive and Joule losses of the PFL. These losses under this condition could be calculated, and are summarized in Figure 7. The calculated power efficiency was 84% from an initial stored energy of 1/2CV^2= 554 Joules; there was good agreement between the calculation and the experiment.
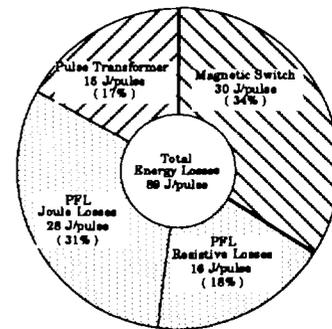

Figure 7. Energy losses of the modulator.

Conclusions

We have developed a compact X-band klystron modulator for the JLC using a PFL, a pulse transformer and a magnetic switch. From performance tests, this modulator should enable us to generate an output pulse with a peak voltage of 550 kV, a pulse length (flat-top) of 440 ns and a rise time of 165 ns for a dummy load with an impedance of 412 Ω. We also found that the power efficiency of the modulator is approximately 83%.

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References

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