High-Power Klystron Modulator Using a Pulse-Forming Line and Magnetic Switch

Mitsuo Akemoto and Seishi Takeda
KEK, National Laboratory for High Energy Physics
Oho 1-1, Tsukuba, Ibaraki 305, Japan

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. A preliminary test has shown that an output pulse with a peak voltage of 600 kV, a pulse length (flat-top) of 460 ns and a rise time of 153 ns can be generated for a dummy load with an impedance of 500 Ω.

I. 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 X-band klystrons of the JLC [2], a conventional modulator using a thyratron and a pulse-forming network (PFN) has been developed [3]. 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. The modulator using all-solid-state components provides the nearly endless lifetime. An all-solid-state modulator prototype has been designed, and a discharge unit has been constructed. In this paper, the design, specifications and results of performance tests of the discharge unit are described.

II. DESIGN

A. Specification

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

Table 1
Specifications of the X-band klystron modulator

Output pulse voltage	600 kV
Output pulse current	1200 A
Output impedance	500 Ω ± 16%
Pulse rise time	150 ns
Pulse length(flat-top)	400 ns
Pulse height deviation from flatness	< ±1.0%
Pulse repetition rate	50 pps

A simplified diagram of the whole modulator system 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.

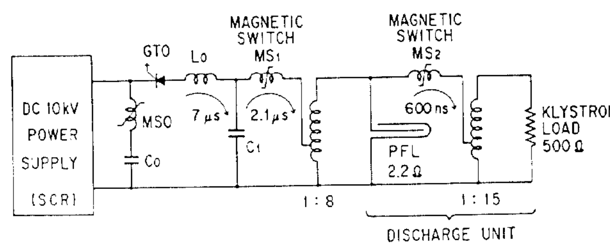

Figure 1. Simplified diagram of the all-solid-state klystron modulator.

B. Pulse-Forming Line

A triplate strip transmission line, which is a simple structure and can be made easily, was adapted for the PFL, and deionized water was used as a dielectric. Figure 2 shows the cross section of the PFL. The impedance Z of this PFL is given by

$$Z = \frac{377}{2\sqrt{\varepsilon_r}} \frac{d}{w}$$

where ε_r is the dielectric constant, d is the spacing between lines and w is the width. The spacing d was determined to be 12 mm by assuming that the limitation of the electric field strength is 12 kV/mm in deionized water. The width w was

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determined to be 140 mm by giving d=12 mm, ε_r=76.8(at 30°C) and Z=1.848 Ω. The line length L of the PFL was determined by

$$L = \frac{\tau \cdot c}{2\sqrt{\varepsilon_r}}$$

where τ is the pulse length of the PFL and c is the speed of light in vacuum. The line length L was determined to be 12 m by giving τ=700 ns and c=3.0x10^8 m/s.

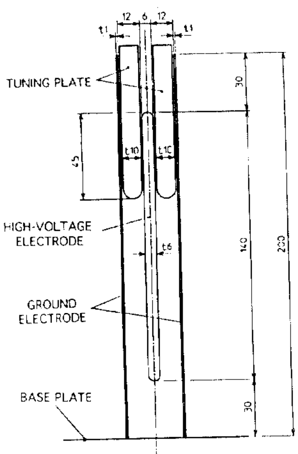

Figure 2. Cross section of the PFL.

The structure of the PFL has one high-voltage electrode between two ground electrodes as shown in Figure 2. These electrodes are made of stainless steel. 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 lines. This mechanism enables us to adjust the impedance of the PFL as well as the flat-top of the output waveform. Two ground electrodes are mounted on a stainless steel base plate. This assembly is housed in 1260 mm wide x 660 mm deep x 390 mm high water box made of stainless steel. The parameters of the PFL are summarized in Table 2.

Table 2
Parameters of the PFL

Line length	12 m
Characteristic impedance	2.2 Ω ± 16%
Pulse length	700 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

C. Magnetic Switch

The magnetic switch was designed by setting the allowable range for the switch volt-seconds production and the saturated inductance. From the charging voltage waveform of the PFL, the volt-seconds production for the switch must be 0.084 v-s. To achieve the required output rise time, the saturated inductance of the switch should be less than 120nH. The core size of the switch was calculated by the following equation:

$$v - s = N \cdot \Delta B \cdot A$$

$$L_{sat} = \frac{\mu_{sat} \cdot N^2 \cdot h}{2\pi} \ln\left(\frac{r_o}{r_i}\right)$$

where

v-s	=	volt-seconds production for the switch
N	=	number of turns around the core
A	=	cross-sectional area of the magnetic core
ΔB	=	total magnetic flux density swing of the magnetic core
L_{sat}	=	saturated switch inductance
μ_{sat}	=	permeability of free space multiplied by the relative permeability of the core when saturated
h	=	axial length of the core in magnetic switch
r_o	=	outer radius of magnetic core
r_i	=	inner radius of magnetic core.

For the core material of the magnetic switch, a Fe amorphous AC 10 (TDK Ltd Co.), which has a high magnetic flux density swing of 2.1 T was chosen to reduce the size of the magnetic switch. The relative unsaturated and saturated permeabilities of the core are 2.0 and 2000, respectively. The core comprises 8 smaller subcores. 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. 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

D. 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 μH and 134 pF, respectively.

III. PERFORMANCE TEST

A preliminary test of the discharge unit was performed in order to confirm the performance of this modulator. Figure 3 shows the test circuit. The impedance of the dummy load was set at 500 Ω.

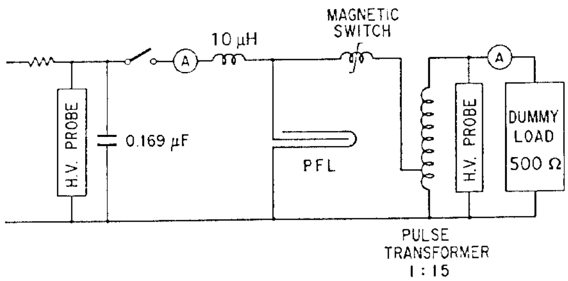

Figure 3. Test circuit.

A. Output Pulse Waveform

After the primary capacitor was charged to 82 kV, a gap switch for an initial switch was triggered to charge the PFL. The input and output voltage waveforms were measured by low inductance high-voltage dividers, and the current was measured by a Rogowski coil. Figure 4 shows the output pulse waveforms.

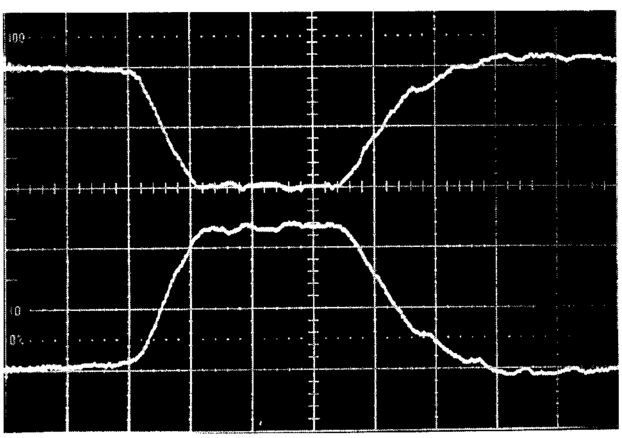

Figure 4. Output pulse waveforms at the dummy load.
H: 200 ns/div
Upper trace: Output pulse voltage (300kV/div)
Lower trace: Output pulse current (520A/div)

A pulse with a peak voltage of 600 kV and a width of 730 ns was successfully generated. Although a rise time (10-90%) of 153 ns and a flat-top of 460 ns satisfy the requirement, a flatness of ± 3.7% is fairly larger than the expected value ± 1%.

B. Power Efficiency and Loss Analysis

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 82%.

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 Table 4. The calculated power efficiency was 82% from an initial stored energy of $1/2CV^2$= 563 Joules; there was good agreement between the calculation and the experiment.

Table 4
Energy losses of the modulator

Components	J/pulse	%
Magnetic Switch	30	29
PFL resistive losses	42	41
joules losses	19	18
Pulse Transformer	12	12
Total energy losses	103	100

IV. SUMMARY

A compact klystron modulator using a PFL, a pulse transformer and a magnetic switch has been developed for the JLC. From performance tests, this modulator should enable us to generate an output pulse with a peak voltage of 600 kV, a pulse length (flat-top) of 460 ns and a rise time of 153 ns for a dummy load with an impedance of 500 Ω. The improvements of the pulse transformer are now under way to obtain a good flatness.

V. ACKNOWLEDGMENTS

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VI. REFERENCES

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