DESIGN STUDY OF AN X-BAND KLYSTRON MODULATOR USING MAGNETIC-PULSE-COMPRESSION TECHNIQUES

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Abstract

The design considerations of an X-band klystron modulator for the future JLC (Japan Linear Collider) project are presented. This modulator is designed to produce 200-ns wide, 600-kV voltage and 1200-A peak current pulses; it is based on magnetic-pulse-compression techniques with a very high peak-power capability and a repetition rate exceeding 200 Hz.

Introduction

An e^+e^- linear collider in the TeV region has been proposed to reach energies beyond that of LEP.[1,2] Fig. 1 shows a conceptual drawing of the Japan Linear Collider (JLC), which comprises two linear accelerators, one for e^+ and the other for e^-, with a collision point in the middle. It requires an accelerating gradient on the order of at least 100 MV/m in order for the facility be of reasonable scale. To realize this high field gradient, high-power microwave sources are required with a peak output power of about 100 MW/m and with a frequency between 10 and 30 GHz.[3] Since such a high peak power is much beyond the level which can be easily achieved with conventional technology, R&D is being undertaken at various laboratories (SLAC,[4] CERN,[5] KEK[6,7] etc.).

At KEK, along with studies of a two-beam accelerator scheme (TBA) using a free-electron laser as a high-power microwave source,[6] the development of high power X-band klystrons using conventional technology is being undertaken.[7] The TBA technology may be of use in the very distant future, while X-band klystrons may be of use during the first phase of the JLC. For the prototype tube, a maximum output power of 30 MW is expected at the maximum design voltage of 450 kV. The diode model of this prototype tube was high-voltage conditioned using one of the modulators[8] of the SLAC 5045 klystrons at the KEK test accelerator facility (TAF), which was established in 1987 to pursue R&D technology for linear colliders.[9] Although processing with 2.5-μs, 2-Hz pulses has successfully increased to a voltage of 365 kV,[7] a specially designed modulator, which is capable of producing very short (~200 ns) pulses with high peak power, is necessary for any realistic test of X-band klystrons, since the required pulse flat-top is on the order of 100 ns.[2] This paper describes the design studies of this X-band klystron modulator.

Modulator specifications

Specifications of the X-band klystron modulator are listed in Table 1. The output impedance of the modulator is strongly dependent on the micro-perveance of the klystron. Although, the prototype tube has a rather small micro-perveance of 0.56, we expect to have X-band klystrons with a micro-perveance of 1.5 ~ 2.0 for our modulator design. The reason for requiring a micro-perveance of 1.5 ~ 2.0 is as follows. If we use X-band klystrons with a micro-perveance of 0.56, an output voltage of 950 kV with an output inpedance of 1.8 kΩ is necessary

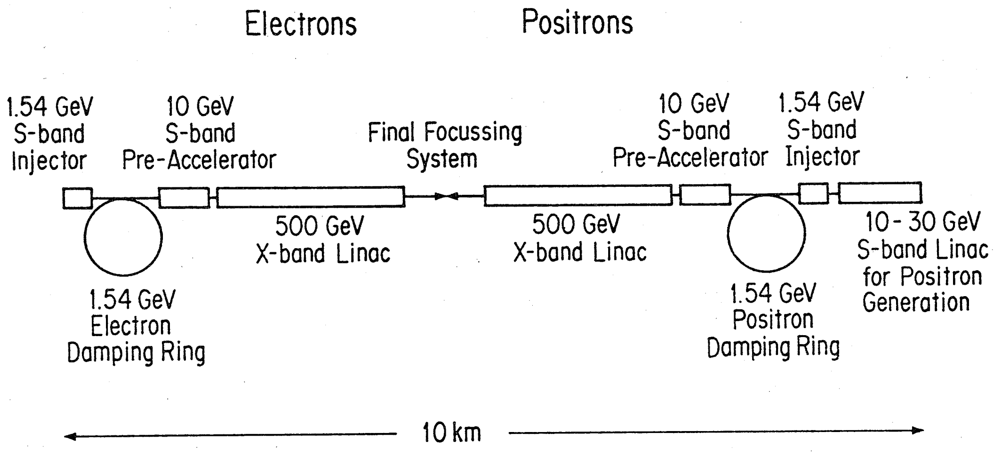

Fig. 1 Conceptual drawing of the Japan Linear Collider (JLC).

Table 1

Specifications of the X-band klystron modulator

Output pulse voltage range	400 ~ 600 kV
Output pulse current (max.)	1200 A
Output impedance	500 Ω
Rise time	< 100 ns
Pulse length (flat top)	> 100 ns
Pulse high deviation from flatness	<± 1 %
Pulse amplitude drift	<2 %
Jitter	<5 ns
Pulse repetition rate	200 pps

to achieve 200 MW of microwave power, assuming a 40% efficiency from beam power to microwave power. This rather high impedance of 1.8 kΩ results in a longer rise time (more than 500 ns) due to the estimated stray capacitance of ~150 pF around the klystron socket and output transformer. It is not practical to generate pulses with a rise time of more than 500 ns for pulses of 100-ns duration. Therefore, a lower impedance is preferable (higher micro-perveance). On the other hand, a higher micro-perveance requires heavy cathode loading, which limits the cathode lifetime.

The limits to pulse amplitude drift and pulse hight deviation come from the requirement of acceptable phase modulation (~2°) of the microwave source. Although, the microwave circuit design has not yet been completed, a relativistic accelerating voltage of ~ 600 kV lessens the requirements on pulse-top flatness and amplitude stability.

Circuits of the X-band klystron modulator

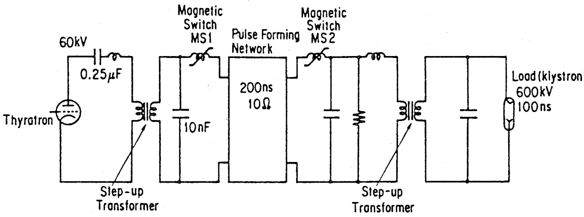

Fig. 2a A simplified diagram of the X-band klystron modulator using PFN, pulse transformer and magnetic switches.

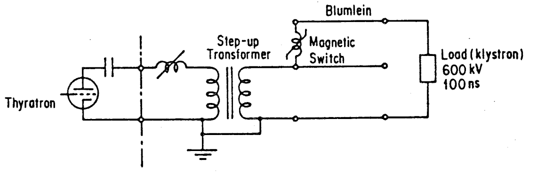

Fig. 2b A simplified diagram of the blumlein-type modulator.

Among the many different types of modulator designs, two types (see Fig. 2) using magnetic pulse compression techniques are considered because of their high reliability consisting of only passive components, such as saturable inductors and capacitors.[10] Since the impedance of the Blumlein is half of the klystron load, a Blumlein-type modulator (Fig. 2b) seems to have some advantage. On the other hand, semi-conventional type modulators (Fig. 2a: a combination of pulse forming network, pulse transformer and magnetic switches) has also been intensively studied because of its ease in adjusting pulse-top flatness.

The equivalent circuit diagram of the simulated klystron modulator is shown in Fig. 3.[11] The stored energy of capacitor C_0 is transferred into another capacitor (C_1) through the thyratron. Although a sufficiently long lifetime of the thyratron is not expected at 200 Hz continuous operation, we adopt thyratrons as a switching device for our prototype modulator, due to the lack of another good device. The energy is successively transferred from C_1 to the pulse-forming network (PFN) capacitors by increasing the voltage through the 1 : 15 step-up transformer. The energy is finally transferred from the PFN capacitors to a klystron load through the 1 : 4 step-up transformer. The compression factor of each stage is 1/4.

For the saturable inductor core, we are planning to use a low-loss Co amorphous core. Since the required pulse repetition rate is 200 Hz, the use of an Fe amorphous core is not practical because of a temperature increase caused by power loss at the inductor core.

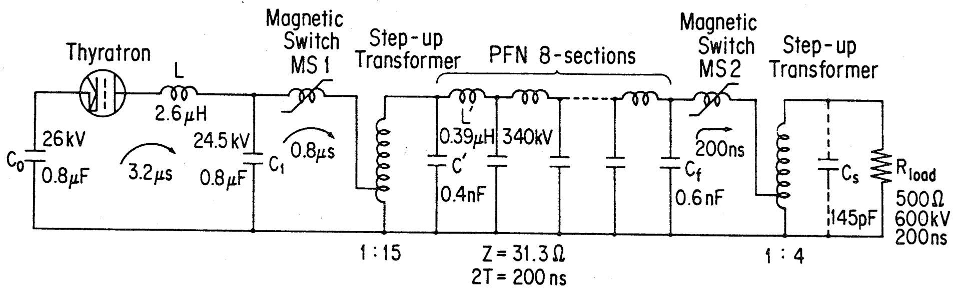

Fig. 3 Equivalent circuit diagram of the simulated klystron modulator.

The stray capacitance at the secondary circuit of the final step-up transformer is estimated to be on the order of 150 pF.

The simulated output voltage of this circuit is shown in Fig. 4. A rise time of ~ 90 ns is expected with more than 120 ns of pulse flat-top duration. The result of the simulation is very encouraging for the use of X-band klystron modulators.

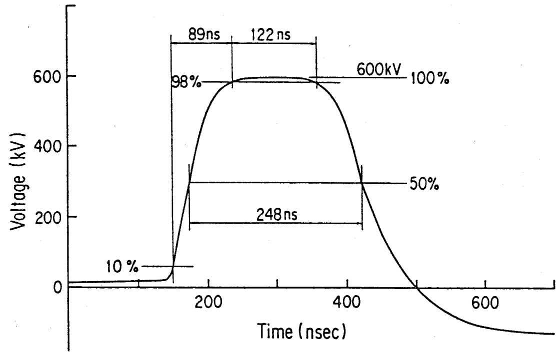

Fig. 4 Simulated output voltage of the X-band klystron modulator.

R&D items

Although the simulated result is very hopeful, there are several R&D items required in order to realize this type of modulator for future linear collider use.

Amorphous Core

The Co amorphous core is sufficient for our modulator use from a technical point of view. The problem is the price. The cost of Co amorphous cores amounts to almost half of the modulator price. Since more than 10,000 X-band klystron modulators are used in JLC, R&D on a low-cost amorphous core sutiable for our use is inevitable.

Switch device

The lifetime of thyratrons is, roughly speaking, on the order of 10^8 shots. If we operate our modulator at a pulse repetition rate of 200 Hz, this lifetime becomes 150 hours. Since more than 10,000 modulators are operated in JLC, we must replace failed thyratrons every one minute. Therefore, R&D on a switching device with a longer lifetime is a key point in realizing the JLC project. Solid-state devices such as thyristors, GTO (Gate Turn Off) thyristors and IGBT (Insulated Gate Bipolar Transistor) are good candidates.[12] We will soon start R&D on solid-state switching devices capable of large $\frac{di}{dt}$ (5,000 ~ 10,000 A/μs).

Output transformer

R&D on an output transformer with very low stray capacitance (less than 100 pF) is quite important for minimizing the pulse rise time. We are planning to make several real models and to test them while comparing the results with the simulation.

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