PLA-90-60

90/08/31

1 GeV リニアック検討資料
1 GEV LINAC DESIGN NOTE

題目(TITLE) A Long-Pulse Thyristor-Switched Modulator for the JHP Proton Linac

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概要(ABSTRACT)

A long-pulse, high-duty klystron modulator, which was fabricated as a prototype for the JHP 1-GeV proton linac, has been operated at 15 MW peak power with a 400 μs pulse width and a 50 Hz repetition rate. This modulator is of the line type, which has a pulse-forming network switched by two thyratrons in parallel. From the viewpoint of reliable operation and long lifetime it seems that thyratrons are unsuitable in terms of our requirement for long-pulse, high-average currents (now, 15 A at 400 μs pulse width and, final, 23 A at 600 μs); we must therefore develop the use of SCR or GTO thyristors to replace the thyratrons. Prior to the construction of a full-rate thyristor switch, SCR- and GTO-stack modules with a 10 kV hold-off voltage were built and tested in the modulator with a klystron load through a pulse transformer. The design considerations and the test results are reported.

KEY WORDS: Ion Source, RFQ, DTL, Magnet, Monitor, Beam Dynamics, Transport, Vacuum, Cooling, Klystron, Low Level RF, High Power RF, Modulator, Control, Operation, Radiation, Others

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KEK Preprint 90-151
November 1990
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*Submitted to the 1990 Linear Accelerator Conference,
Albuquerque, NM, U.S.A., September 10-14, 1990.*

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A LONG-PULSE THYRISTOR-SWITCHED MODULATOR FOR THE JHP PROTON LINAC

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Abstract

A long-pulse, high-duty klystron modulator, which was fabricated as a prototype for the JHP 1-GeV proton linac, has been operated at 15 MW peak power with a 400 μs pulse width and a 50 Hz repetition rate.[1-3] This modulator is of the line type, which has a pulse-forming network switched by two thyratrons in parallel. From the viewpoint of reliable operation and long lifetime it seems that thyratrons are unsuitable in terms of our requirement for long-pulse, high-average currents (now, 15 A at 400 μs pulse width and, final, 23 A at 600 μs); we must therefore develop the use of SCR or GTO thyristors to replace the thyratrons. Prior to the construction of a full-rate thyristor switch, SCR- and GTO-stack modules with a 10 kV hold-off voltage were built and tested in the modulator with a klystron load through a pulse transformer. The design considerations and the test results are reported.

Introduction

The 1-GeV proton linac for the Japanese Hadron Project, which is now under development at KEK, requires 36 L-band klystrons and modulators in its high-ß section. Although the klystrons will be operated at an rf output power of 4 MW at the unsaturated level, the power capability is required to be about 6 MW in order to achieve reliable operation; the first-fabricated prototype modulator, which is needed for testing developed klystrons, must produce maximum 15 MW pulses.

The performance of modulators is a key point for successful operation of the rf system. We had decided to adopt a line type for the prototype from the standpoint of our great experience in their operation. The main switch used for discharging a pulse-forming network (pfn) is the most important device of a line-type modulator. For its operational reliability and maintainability, it is apparent that solid state devices, such as SCR and GTO, are more suitable than thyratrons for extremely high-duty factor, long-pulse operation.

Prototype Modulator

A 6-MW klystron requires a modulator with 15 MW pulsed power and a 140 kV anode voltage, where the rf conversion efficiency and the perveance are estimated to be 40 % and 2×10^{-6} A/V$^{3/2}$, respectively.[2] Taking account of the characteristics of thyratrons, which are tentatively used as switching devices, we determined the modulator output voltage to be 20 kV; this means a pfn charging voltage of 40 kV, so that the step-up ratio of the pulse transformer is 1:7.[3] When the pulse width is 600 μs and repetition rate 50 Hz, the average output power becomes 450 kW.[1]

The design values required for the prototype modulator are summarized in table 1. Widening the pulse width increases the pfn size as well as cost, and a very high duty factor makes it difficult to perform stable operation. Thus, at the time of the first construction we decreased the pfn pulse width to 200 μs, and then, after various test operations, we increased it up to 400 μs. This prototype modulator was designed so that the output pulse width can easily be increased up to the 600 μs by only adding a pfn section.

A circuit diagram of the fabricated and upgraded modulator is shown in Fig. 1. The output voltage is continuously variable from 20 % to 100 % by rotating the

TABLE 1
Basic Parameters of the Prototype Modulator

Peak Power	15 MW
Average Power	300 kW (* 450 kW)
Pulse Voltage	20 kV
Pulse Current	750 A
Pulse Width	400 μs (* 600 μs)
Pulse Rise Time	< 20 μs
Pulse Repetition Rate	50 Hz

(Symbol * indicates the final objective)

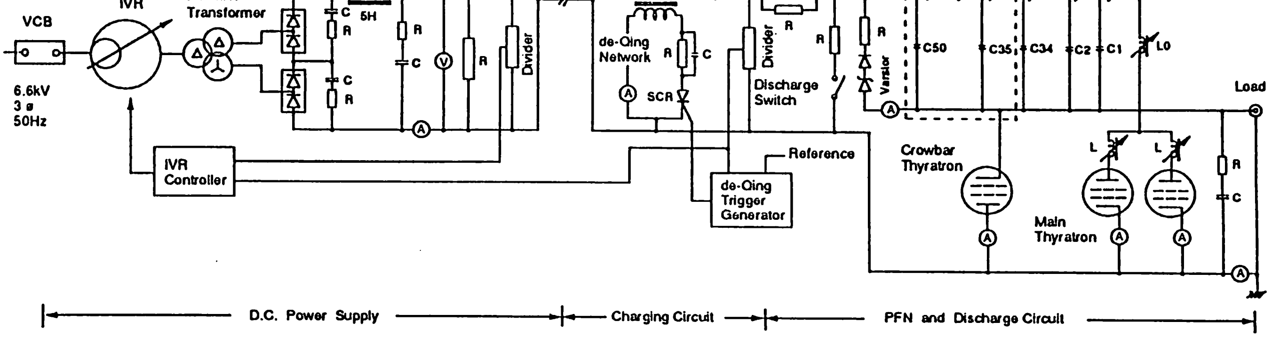


Fig.1 Circuit diagram of the prototype modulator. A dashed box indicates pfn components added at final phase.

rectifier transformer taps and the IVR; it is regulated by a de-Q'ing circuit. A short-circuit current in the event of a main thyratron fault or HV circuit arcing is limited to no more than 10 times the normal full load current by a 10 % inductance of the IVR and the transformer.

At first, though, we used two ITT F-175 thyratrons in parallel as the main switch for 200 μs pulse-width operation, it was found that they could not withstand a charging voltage greater than 30 kV under our operation conditions. Immediately after that, we replaced two F-175's with one F-259, which had been recently developed by ITT for very high-duty use (50 kV, 10 kA peak and 25 A average). When increasing the pulse width up to 400 μs one more tube was added in parallel in order to be ready for 600 μs operation.

Turn-off of Switches

In very high-duty line-type modulators it becomes impossible to turn off the main switch, because the time necessary to recover after conduction is insufficient. The following methods can be considered to overcome this problem:

1. Short-circuiting the output for producing negative pulses.
2. Triggered charging (command charging) for delaying the charging of the pfn.
3. Using GTO thyristors for turning off the anode current.

The output short-circuiting method is adopted into our prototype modulator, in which a crowbar thyratron clips or short-circuits part of the first pulse tail or the positive mismatched pulse to ground by proper timing of its firing. However, since the reverse-voltage pulse does not appear at the anode until the shorted pulse transmits between the pfn front and end, the charging current from the dc power supply is bypassed by the main thyratrons during more than one pulse output, resulting in a lowering of the circuit efficiency.

Command charging is the most conventional and useful method. By replacing a charging diode with some device which can be triggered, it becomes possible to control the charging start and, therefore, to even use such SCR's with long recovery times as main switches.

SCR Switch

High hold-off voltage SCR's generally have a high current handling capability as well as high critical rate of rise of the anode current (di/dt). However, information about the allowable value of di/dt for repetitive operation is not opened to users by device suppliers. If the initial rate of the anode current exceeds a certain value, the SCR may be either destroyed or permanently damaged owing to excessive localized overheating.

In order to obtain the di/dt capability and to predict the lifetime under our required operating conditions, we tested general-use type of SCR's (Hitachi CSP300AG35; 300 A, 3.5 kV). As a result of the test it was found that the di/dt value allowable for long-term use was estimated to be 100 A/μs during repetitive pulse operation with a 750 A peak current, a 600 μs pulse width and a 50 Hz repetition rate.

A circuit diagram of the SCR switch designed for the prototype modulator is shown in Fig. 2. The SCR switch comprises the 5 SCR-stack modules connected in series through each anode inductor for suppressing the rapid di/dt. As shown in Fig. 2, one SCR module comprises a 6-SCR stack with the circuits of RC snubbers and balance resistors, a gate-drive circuit and transformer, as well as an insulating transformer for supplying ac power. The characteristics of each SCR, turn-on time, off-state leak current and turn-off stored charge, could be made to range within certain values by

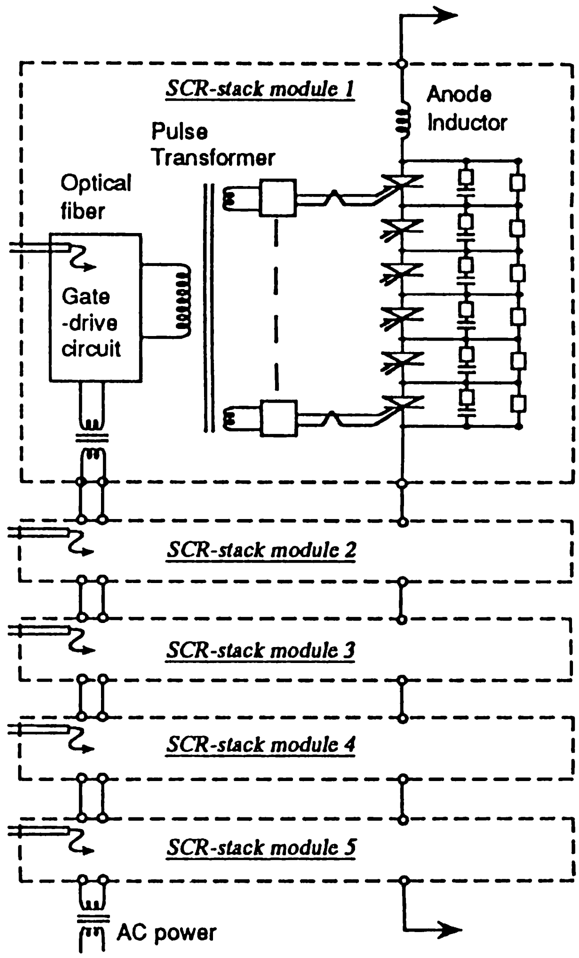


Fig. 2 Circuit diagram of the SCR switch designed for the prototype modulator (45 kV max. forward voltage, 750 A peak current).

selection. The circuit parameters were determined according to the conventional technology established in the industrial field of high-voltage electric power. These SCR modules will be operated at a maximum forward voltage of 9 kV, which means an applied voltage of 1.5 kV per SCR, corresponding to 43 % of the maximum allowable device voltage. The entire circuit is now being constructed and the first test will be carried out without any command charging circuit.

Test of SCR Stack Module

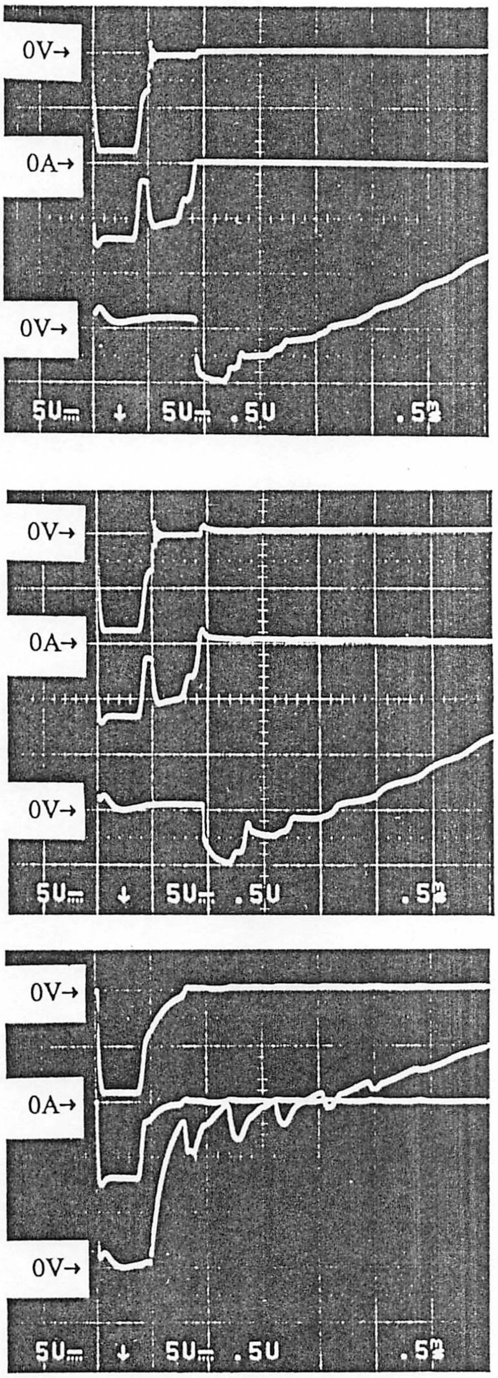
The 6-SCR stack module was fabricated and tested to make sure of the switching performance at an actual high-power level. The SCR module incorporated into the prototype modulator was operated at a pfn charging voltage of 10 kV, and produced output pulses with a 6.3 kV peak voltage and a 130 A peak current. The modulator output was terminated with a klystron load through a step-up transformer. The observed waveforms are shown in Fig. 3(b), together with those obtained by the thyratron switch for a comparison (Fig. 3(a)). In these waveformes, though there is no difference between output pulses obtained by the SCR and the thyratron, there are slight differences in the anode currents and voltages:

the appearance of a slight reverse current and a lower forward voltage drop of the SCR.

GTO Switch and its Test

As mentioned above regarding high duty, it comes to be an advantage that GTO thyristors capable of self-turning off are used, even for line-type modulators; however, it is dangerous to turn off any high current flowing through circuit components with residual or lumped inductances. Since high-power GTO's generally have a very high, but uncontrollable, rate of fall of the anode current (~1000 A/μs), which result in inducing very high voltage at the falling time, very careful considerations must be given to the circuit design as well as the gate timing control.

A GTO stack switch was also tested in the prototype modulator to observe the turn-off transient. The GTO used has the following characteristics: 8kV repetitive off-state voltage, 1000 A controllable on-state current, 300 A/μs critical rate of rise of on-state current and 300 A turn-off gate current (MEIDENSHA G10D80YNH). A circuit diagram of the tested GTO switch is shown in Fig. 4. Resistor and diode series circuits, called a flywheel circuit, were equipped in parallel with the first pfn inductor and the filter inductor for absorbing and suppressing overvoltages induced during rapid current falling. The observed waveforms are shown in Fig. 3(c). The test conditions were the same as those of the SCR module: 10 kV charging voltage and turn-off triggered at the same timing as the crowbar trigger.



(a) Thyratron

(b) SCR

(c) GTO

Fig. 3 Waveforms. Upper traces are klystron cathode voltage (25 kV/div), middle traces device cathode current (100 A/div) and lower traces device anode voltage (1 kV/div): Horizontal scales 0.5 ms/div.

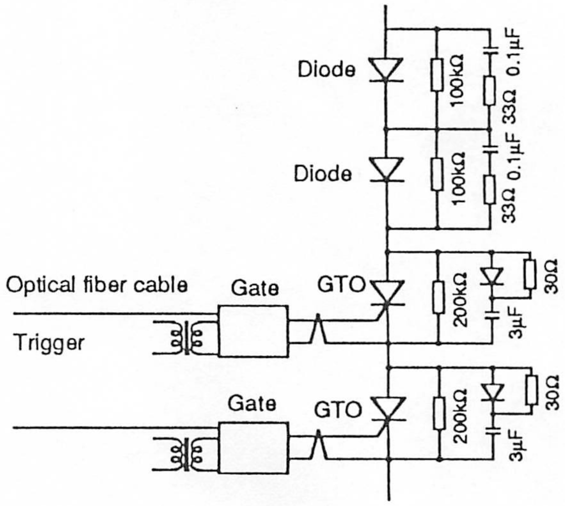


Fig.4 Circuit diagram of the GTO stack module.

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