# Design of 200MW Pulse Modulator for PLS 2.0 GeV Electron Linac*

M.H. Cho, S.H. Nam, J.S. Oh, and W. Namkung
Pohang Accelerator Laboratory, POSTECH,
P.O. Box 125, Pohang, Korea 790-600

## *Abstract*

The fabrication of 200 MW pulse modulator is underway to drive 80 MW S-band klystron tubes which are the highest power output requirement used in a linac design. Typical specifications of the modulator unit are 200 MW peak power, 400 kV peak beam voltage, 60 pps pulse repetition rate, and 4.4 $\mu s$ flat-top pulse width with 800 $\Omega$ load impedance. This paper presents the circuit design of the 200 MW modulator and the test results of the prototype 150 MW modulator together with the PLS 2-GeV linac rf power budget.

## 1 INTRODUCTION

The layout design of the 2.0 GeV electron linac for PLS has been finalized to have 11 sets of high power S-band klystron and modulator units [1], 10 SLAC type energy doublers (SLED), and 42 sets of accelerating columns. This layout design is based on the selection of the klystron tube which can produce more than 60 MW peak rf power output with at least 4 $\mu s$ pulse width. The pulse width is chosen to have better than 1.5 beam energy gain from the SLED. Table 1 shows the characteristic parameters of SLAC-5045 and E-3712(Toshiba) klystron tubes which meet our design requirement and available in the world. The base formula for the estimation of the electron beam energy is as follow [2]: $E = 20 \times N\sqrt{P}\eta$, where, $E$ is the electron beam energy in GeV, $N$ is the number of total klystron units, $P$ is the peak rf power output of one klystron unit in MW, and $\eta$ is the e-beam energy gain of the SLED. If we count only 10 units of the klystron tubes, that is excluding 1st unit which serves as a power driving unit as well as powering the preinjector linac which has two accelerating columns, and also assuming $\eta = 1.3$, the peak rf power output, P, to assure 2.0 GeV e-beam energy, must be greater than 64 MW. This estimation assumes approximately 90% achievement from the design goal of the linac high power rf system. This condition will leave us the rf system without any standby unit or no reserved rf power for the final beam adjustment. This forced us to design the high voltage pulse modulator with maximum power capacity, enough to drive the highest power klystron tube shown in Table 1. More power from the klystron will give us relaxed energy budget, which will make the entire machine operation more stable for maintaining the target beam conditions. As shown in Table 1, the highest power available from the existing klystron tube is 80 MW at 4 $\mu s$ pulse width, and this unit requires 200 MW level high voltage pulse modulator.

Table 1: Main parameters of high power klystron tubes.

| Description | Toshiba E3712 | SLAC 5045 |
|---|---|---|
| Operating Freq (MHz) | 2,856 | 2,856 |
| Peak Power (MW) | 80 | 64 |
| Average Power (kW) | 18 | 42 |
| Pulse Length ($\mu s$) | 4.0 | 3.5 |
| Max. Rep. Rate | 60 | 180 |
| Beam Voltage (kV) | 400 | 350 |
| Beam Current (A) | 500 | 415 |
| Gain (dB) | 52 - 53 | 53 |
| Efficiency (%) | 42 | 45 |
| Microperveance | 2 | 2 |

## 2 MODULATOR SPECIFICATIONS

Among several different types of modulator design the line type modulator was chosen because of the reliability that has been proved by the SLAC's almost 30 years of operation of the 2-mile long accelerator [2]. The main high voltage level in the modulator up to the primary input of the pulse transformer was chosen to be less than 50 kV mainly due to the insulation rating of the air cooled high voltage switching tube, which allows easier maintenance and less severe humidity control of the klystron gallery. Since the 80 MW klystron tube requires 400 kV (nominal value) on its cathode, a pulse transformer with turn ratio of 1:17 was selected to step up and match the impedance between the modulator and klystron load. For the nominal ratings, therefore the modulator is required to generate pulses with 23.5 kV peak voltage, 8500 A peak current. This peak voltage will be doubled, 47 kV, at the pulse forming network (PFN). This value seems rather high, however, the pulse transformer turn ratio of 1:17 is upper maximum for the ~ 4 $\mu s$ flat top, and the SLAC's long term operation experience showed no critical problems involved with the voltage rating. For the better margin of the switching current ITT F303 thyratron tube is selected.

The Table 2 lists the main specifications of the 200 MW modulator. Approximately 5% positive mismatch is chosen at the full voltage for the proper operation of the thyratron. The load impedance is about 5% higher than the output impedance of the modulator. The stringent

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specifications of the flatness of the pulse flat-top and the amplitude stability are required to prevent rf phase modulation and amplitude variation during each pulse as well as between pulses.

Table 2: Main specifications of the modulator.

| | |
|---|---|
| Peak Power | 200 MW |
| Average Power | 85 kW |
| Peak Beam Voltage | 400 kV |
| Peak Beam Current | 500 A |
| Pulse Repetition Rate | 60 Hz |
| Pulse Width (Flat Top) | 4.4 $\mu s$ |
| Pulse Flatness | ± 0.5 % |
| PFN Impedance | 2.8 $\Omega$ |
| Pulse Risetime | 0.8 – 1.0 $\mu s$ |
| Pulse Falltime | 1.5 – 2.0 $\mu s$ |
| Pulse Transformer Turn Ratio | 1 : 17 |

## 3 MODULATOR CIRCUITS

The basic circuit design of the modulator is schematically shown in Fig. 1. There are few points worth mentioning: the primary voltage control for the DC high voltage generation will use phase controlled SCR regulator (Semikron), ITT F-303 thyratron tube (see Table 3 for the main parameters) is selected for the high power switching of the PFN, and the pulse transformer turn ratio is selected to be 1:17.

Table 3: Main specifications of the ITT F303 thyratron. (The value in parenthesis: max. operating parameter for the 200 MW modulator)

| | |
|---|---|
| Heater Voltage (V, AC) | 6.0 - 6.6 |
| Heater Current (A) | 80 Max. |
| Reservoir Voltage (V) | 2.5 - 6.0 |
| Reservoir Current (A) | 20 |
| Max. Peak Anode V, Forward (kV) | 50 (47) |
| Max. Peak Anode V, Inverse (kV) | 50 |
| Min. DC Anode Supply V (kV) | 2.0 |
| Max. Peak Anode Current (kA) | 15 (9.5) |
| Max. Avg. Anode Current (A, DC) | 8 (2.6) |
| Max. RMS Anode Current (A, AC) | 200 (160) |
| Max. Heating Factor | 300(27) × $10^9$ |
| Max. Anode Delay Time ($\mu s$) | 0.3 |
| Max. Time Jitter (ns) | 2 |

The power supply used in this modulator is a conventional, 3-phase full wave rectifying bridge, with filtering chalk, and tank capacitors. The dry type rectifier transformer has ratings of 440 V input (delta) and 19 kV(rms) ouput (Y). Six stacks of rectifying diode arrays are also mounted in the cabinet without oil tank.

The PFN capacitors (50 nF each, 12 stacks and 2 rows in parallel) are resonantly charged using the charging inductor (2 Hy) to approximately twice the DC high voltage. Since the resonant charging frequency is determined by the inductance of the charging transformer ($L_c$=2 Hy) and total capacitance of the PFN ($C_t$=1.2 $\mu F$), the charging time (T) is calculated from $T = \pi\sqrt{L_c C_t}$. This leads to 1.56 msec, which is rather short, however, the prototype modulator (150MW power level) circuit performance test showed the voltage droop less than 0.1% at 60 Hz operation or 1% droop at 10 Hz operation.

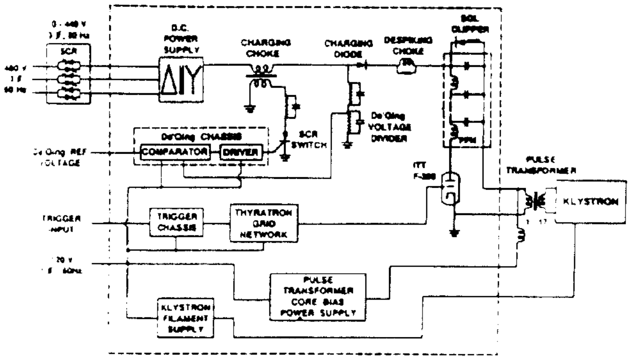

Figure 1: The schematic circuit diagram of the 200 MW modulator

Once the hydrogen thyratron is triggered, the PFN capacitors discharge through the PFN inductors, the switch tube (ITT F303), and the primary windings of the pulse transformer. To prevent reverse arcing and over-voltage on the PFN capacitors and the thyratron tube during the next charging cycle an end of line clipper (EOLC) circuit is adapted. The reverse reflected power from the klystron load or other malfunctioning points is absorbed in this circuit and the thyratron tube does not see the voltage. The EOLC tested in the prototype modulator (150MW) consists of diode stacks, resistors (3.3 $\Omega$), and thyrite stacks. Some concerns were reported [3], such as limited lifetime of the varistor(same function as thyrite) and necessity for the current transformer to work at high voltage. As our operating experience accumulates we will explore further on this problems.

The individual PFN inductor has maximum 4 ± 1 $\mu$Hy (total 12 in series, 2 rows in parallel) made out of 1 cm diameter copper tube wounded 10 turns in cylindrical shape with 10 cm inner diameter and 18 cm long, and has copper slug for the fine variable tuning. The high voltage pulse is transmitted through two oil impregnated triaxial pulse cables in parallel. Since the impedance of the klystron load into the pulse transformer is approximately matched with the impedance of the PFN, half of the charged voltage on the PFN capacitors appears across the pulse transformer. Output pulse voltage regulation is accomplished by the de-Q'ing circuit which consists of RC network in series with a SCR switch device. Fig. 2 is a typical oscilloscope traces of De-Q'ing voltage from the prototype modulator with R = 3 $\Omega$ and C=100 $\mu F$. The circuit design is based on the 5% regulation by the De-Q'ing.

The voltage regulation by the electric company is guaranteed within 2%, however we expect approximately 3% fluctuation by the operation of the other facility in site. The De-Q'ing connections are made to the secondary

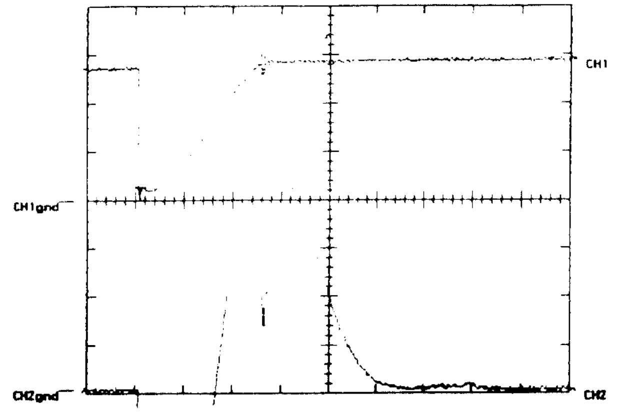

Figure 2: Oscilloscope trace of 5% De-Q'ing voltage. Upper: PFN charging voltage, lower: De-Q'ing voltage. V:500 V/div. H:1ms/div.

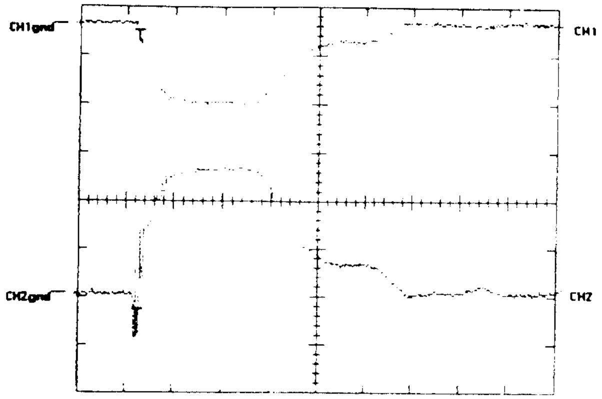

Figure 3: The primary (500A/div:Lower), secondary (50A/div:Upper) current waveform of the pulse transformer. H:2 μs/div.

transformer in the charging inductor which has 25:1 turn ratio. The switching device has one SCR with 1.2 kV PIV and 800 A ratings. The SCR turns on with 3 V, 150 mA trigger signal and stops firing when the current reaches bellow 300 mA. The time jitter and delay of the de-Q'ing trigger which generates the pulse to fire the SCR are very important for the charging voltage regulation, and it is also very important to prevent the malfunction due to the large noise spikes generated from the main thyratron fire. The careful design and test with the noise suppression circuit has been made through the prototype assembling and testing.

SCR based fast switching circuit is currently used in the prototype modulator for the generation of the 2 kV trigger pulse with 0.1 μs rise time, 2 μs pulse width, 50 Ω output impedance, and less than 5 nsec time jitter. We plan to build trigger circuit with IGBT (Insulation Gate Bipolar Transistor) for the thyratron trigger in the main modulator.

## 4 CONCLUDING REMARKS

The 150 MW prototype modulator has been as a circuit components test unit for the 200 MW main modulator, such as De- Q'ing, EOLC, SCR controller, interlock circuit boards, fault counting circuits, PFN impedance matching, EMI suppression, and so on. This first prototype of 150 MW modulator has 3.5 μs flat-top pulse width with secondary pulse output ratings of 365 kV, 410 A. Due to the insulation limitations of the temporary water load and pulse cable the charging voltage has been tested only up to 10 kV and pulse transformer secondary voltage up to 150 kV using this prototype modulator. Fig. 3 shows the current wave form traces at the primary side of the pulse transformer. The hump in the tail part is due to the load impedance mismatch.

The machine protection circuits built into the modulator are fault counting circuits, number of meter relays for the over and/or under voltages and currents, contact limiter switch type interlocks for the cabinet doors and ground sticks, the emergency stop button, and so on.

For the suppression of noises and interferences during the operation, surge killer devices and bypass capacitors are installed, and especially, the cabinet compartments are manufactured as a single body with seam welding joints and all the door contact lines have rf shielding strips, and the cables between the compartments are laid through metallic conduit pipes.

The grounding of the pulse circuit also designed very carefully to have single contact point to the ground. The special earth grounding network provides less than 0.5 Ω ground resistance.

## 5 ACKNOWLEDGEMENT

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