EFFICIENCY ANALYSIS OF THE FIRST 111-MW C-BAND KLYSTRON-MODULATOR FOR LINEAR COLLIDER

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Abstract

The first modulator (111 MW peak-power) driving a 50 MW klystron (C-band 5,712 MHz) has been constructed for an e+e- linear collider. An initial design value of the wall plug power for the whole RF system is 150 MW with 2.5 μsec RF pulse width and 100 Hz pulse repetition rate. Test results of the first system are analyzed and compared with design values. The power distribution of the system is examined to estimate net RF system efficiency. This analysis shows the pulsing efficiency of 56.4 %, and the RF system efficiency of 18.9 %. So the wall plug power of 270 MW is necessary to operate all 4080 units.

1 INTRODUCTION

An e+e- linear collider at 500 GeV C.M. energy requires 4080 units of klystrons (50 MW peak) and modulators (111MW peak) in the C-band scheme [1]. At first, high reliability and availability must be considered to realize feasible operation for this kind of large-scale machine. Reasonable power efficiency is important to reduce operational cost. There are also many requirements such as low construction cost, simple and easy maintenance, flexible operation, etc. A smart modulator is designed and fabricated for the C-band linear collider. The system characteristics and the optimum efficiency of the smart modulator are described in the previous paper [2]. This paper presents the test results including the measured power consumption and the analyzed efficiency of the first 111-MW C-band klystron-modulator.

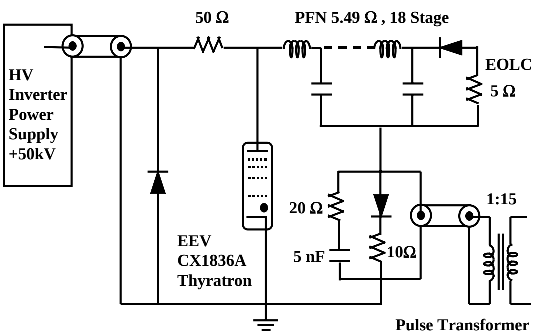

Figure 1. Circuit diagram of the C-band modulator

2 SYSTEM PERFORMANCE

Figure 1 is the circuit diagram of the first klystron-modulator. The HV inverter power supply can charge a PFN (Pulse Forming Network) up to +50 kV with less than 0.5 % regulation without additional de-Qing module. Figure 2 displays the voltage trace of the PFN under the pulse repetition rate of 50 Hz. The inverter power supply is a constant current source so that the PFN voltage is linearly increasing during active charging time. It takes 13.5 msec to charge the PFN up to 48 kV using an EMI 303 model of which the maximum charging speed is 37.5 kJ/s. The command charging function provides sufficient recovery time for a thyratron switch. The single bucket that comes out from the resonant switching circuit in the inverter power supply can charge PFN with 62 V step as shown in figure 3, the expanded view of figure 2.

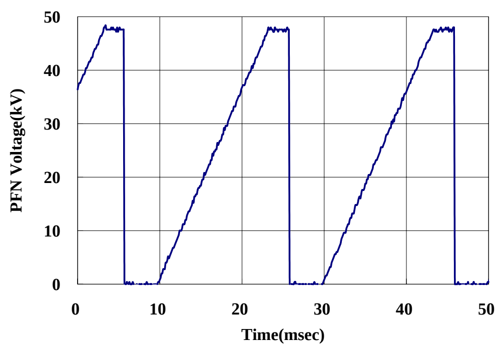

Figure 2. Charging waveform of the PFN.

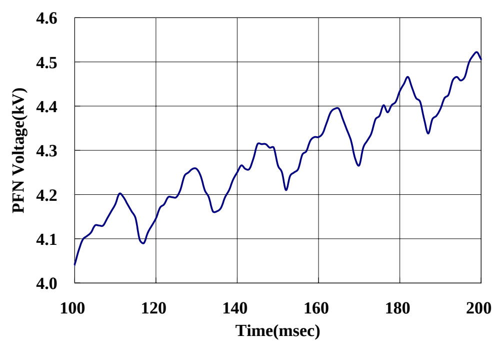

Figure 3. Expanded view of figure 2.

This is the minimum controllable magnitude using the inverter power supply. The stability of beam voltage is directly affected by this fluctuation which is 0.39 % under the charging level of 48 kV. The measured stability of beam voltage is 0.35 % at the beam voltage of 348 kV. So the fluctuation estimation by a single bucket agrees well with measured output stability. Corresponding phase variation of the klystron RF output is about 2.0°.

Figure 4 is the output waveform of klystron beam voltage. The solid line in the figure is the simulated curve using PSPICE code. The klystron is a first tube of C-band (Toshiba E3746) with peak power of 50 MW designed for linear collider [3]. The rise time of 0.96 µsec is two times larger than the optimized design value of 0.47 µsec given in the previous paper [2]. The present system is temporarily using the existing pulse transformer for SLAC-5045 tube. And the anode choke of about 2 µH is added to limit the peak value of primary voltage spike under the safe level. There is more inductive component due to the wiring distance between the PFN and the center conductor of the triaxial cable. So the stage number of the PFN is increased from 16 to 18 to guarantee the flat top width of 2.5 µsec.

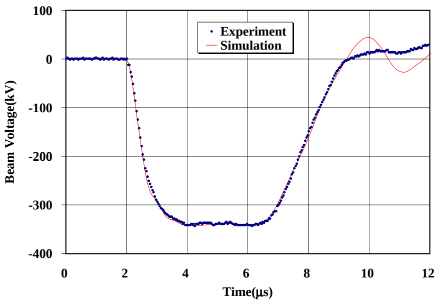

Figure 4. Pulse waveform of klystron beam voltage.

Table 1 summarizes test results of the first modulator. Design parameters are compared with measured values. The modulator delivers 103 MW peak power with 4.35 µsec (ESW, Equivalent Square Wave) pulse width to the klystron. The flat top portion of 2.5 µsec with ripple less than 1% is obtained by the tuning of the PFN inductors. The repetition rate of 50 pps is limited by the average charging capacity of 30 kW of inverter power supply. Parallel operation of two EMI 303 is required to run the system with repetition rate of 100 pps. HV pulse length and PFN inductance have been adjusted to slightly higher values after PFN tuning. So the PFN is tuned with negative mismatch of 4.7 %.

Pulse-to-pulse jitter should be kept low for the phase modulation in the C-band system [4]. Moreover, the rising portion of the beam voltage may be utilized to generate RF power by feedback control of drive phase in the case of small jitter. Figure 5 shows the time jitter distribution of output pulses. Double peak distribution caused by the fluctuation of the thyratron heater voltage is originated from unstable AC line. The time jitter of 9.4 nsec is decreased to 7.1 nsec with single peak distribution of AC line. It is expected that the jitter of less than 5 nsec can be obtained by stabilized AC power for the thyratron heater circuit. The jitter of 5 nsec is equivalent to 1.75 kV variation of the beam voltage at the rising portion, which gives phase shift of 2.84° of the klystron RF output.

Table 1. Test result of the first C-band RF system.

Parameter	Design	Test
Peak output power (MW)	111	103
Beam voltage (kV)	350	348
Beam current (A)	317	296
RF pulse length (µsec)	2.5	2.5
HV pulse length (µsec, ESW)	3.94	4.35
Repetition rate (pps)	100	50
Average output power (kW)	44.6	22.8
PFN charging voltage (kV)	47.2	48
PFN impedance (Ω)	4.91	5.49
Stored energy in PFN (J)	446	456
PFN stage number	16	18
Output stability (%)	1.0	0.35

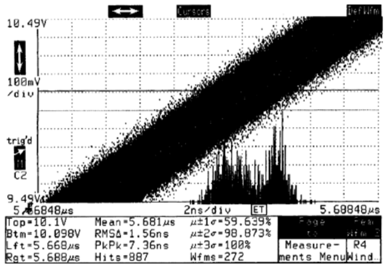

Figure 5. Jitter distribution of the beam pulse.

3 RISE TIME ANALYSIS

The rise time can be roughly determined by following equation [2].

$$T_r = f(\sigma)\,(\,(L_W + L_L)\,(C_D + C_L)\,)^{0.5} = 1.1\ \mu\text{sec}$$

$R_L = 5.23\ \Omega$, $R_G = 5.49\ \Omega$,

$m = R_L / R_G = 0.95$,

$L_L = 2.4\ \mu H$, $L_W = 4.0\ \mu H$, $C_D = 11.3$ nF, $C_L = 23.6$ nF

$Z_T = (\,(L_T + L_W) / (C_D + C_L)\,)^{0.5} = 13.5$

$\gamma = Z_T / R_L = 2.58$

$\sigma = (\gamma m + 1/\gamma) / (\,2\,(m\,(m+1)\,)^{0.5}\,) = 0.995$

$f(\sigma) = 2\pi\sigma\,(m/(m+1))^{0.5}\,(\,0.255 - 0.256\,\sigma + 0.537\,\sigma^2\,)$
$= 2.32$

$f(\sigma)$ is a fitting function to give the rise time from 10 % to 90 % of maximum pulse height. L_L is the leakage inductance of a pulse transformer and L_W is the wiring inductance of the system. C_D is the distributed capacitance of the pulse transformer between primary and secondary coil and C_L is the distributed load capacitance of the system including the klystron. R_L is the klystron load impedance and R_G is the PFN generator impedance. The optimum value of $f(\sigma)$ generating good waveforms is 1.74 with σ of 0.78, γ of 1.58, and m of 1.05 [2]. It is important to keep the optimum γ, and minimize distributed capacitance and leakage inductance to get the fast rise time with small overshoot. Total series inductance of 6.4 μH and parallel capacitance of 34.9 nF gives somewhat larger values than the optimum values of γ and σ.

More correct value of σ can be determined by using measured pulse shape. Figure 6 shows the rising portion of the measured beam pulse (filled circle) and analytic rising curves (solid lines) for different σ from 0.6 (top trace) to 1.0 (bottom trace). The value of σ is changing from 0.6 to 0.9 through the rising transition due to the dynamic variation of klystron load impedance. Effective value of σ is 0.9 for the rise time evaluation.

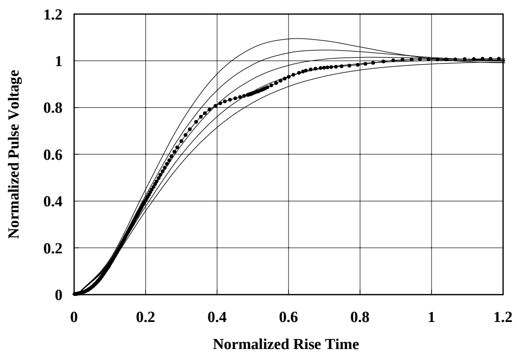

Figure 6. Analytic rising curves and beam voltage trace.

4 POWER DISTRIBUTION

The power distribution of the 111-MW C-band klystron-modulator system is summarized in table 2. Total average power of 66.1 kW is required to generate average RF power of 12.5 kW for 100 Hz operation. The beam power of 15.3 kW is dumped to the collector of the klystron within the flat top, which is caused by the conversion inefficiency of the klystron tube. The wasted pulse power of 21.5 kW includes all the losses that are not contributed to the flat top of the pulse energy generated from the stored energy of the PFN. The switching loss of the IGBT and the core loss of the transformer in the inverter power supply make the charging loss of 8.7 kW. The solenoid coil power of the klystron magnet is 6.5 kW that takes main part of the auxiliary power.

5 EFFICIENCY

Table 3 shows the efficiencies of the each sub-system. The pulse efficiency of 56.4 % is mainly limited by large series inductance between the PFN and the pulse transformer. A net RF system efficiency is 18.9 % so total AC wall-plug power of 270 MW will be consumed to generate the total RF power of 51 MW using 4080 units of a klystron-modulator system.

Table 2. Power Distribution of a C-band system.

Parameter	Design	Test
RF Power (kW)	12.5	12.5
Wasted Beam Power (kW)	15.3	15.3
Wasted Pulse Power (kW)	12.1	21.5
Charging Loss (kW)	7.1	8.7
Aux. Power (kW)	4.5	8.1
Total Power (kW)	**51.4**	**66.1**

Table 3. Efficiencies of the C-band system.

Parameter	Design	Test
Charging Efficiency (%)	85.0	85.0
Pulse Efficiency (%)	69.8	56.4
Klystron Efficiency (%)	45.0	45.0
Modulator Efficiency (%)	59.3	47.9
K-M Efficiency (%)	26.7	21.6
RF System Efficiency (%)	24.4	18.9

6 CONCLUSIONS

The RF efficiency of the present C-band system is 18.9 % and this requires total AC wall-plug power of 270 MW for linear collider. The pulse efficiency of 56.4 % is not optimized. If the PM-AM modulation method of the C-band system [4] allows the 2-3 % tolerance of the flat top ripple, it can be increased up to 75 %. The klystron efficiency of 45 % could be raised up to 60 %. Then it is expected to get a net RF efficiency of 30.6 % and total AC wall-plug power can be decreased to 167 MW.

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