EFFICIENCY ISSUE IN C-BAND KLYSTRON-MODULATOR SYSTEM FOR LINEAR COLLIDER

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Abstract

A C-band (5,712MHz) RF system for an e+e- linear collider at 500 GeV center-of-mass energy requires total 4,080 units of 50 MW pulse klystrons and matching 111 MW peak-power modulators for two main linacs. An initial design value of the wall plug power for the entire RF system is 150 MW with 2.5 μsec RF pulse width and 100 Hz pulse repetition rate. A detailed circuit analysis shows that it is possible to get the overall RF system efficiency of approximately 24 %, or equivalent to 210 MW wall plug power. This includes 85 % DC high voltage charging efficiency using compact inverter power supplies, and 70 % pulse efficiency using 3.5 μsec pulse length (ESW) with less than 1 % flat top ripple, and auxiliary powers for thyratron heater, klystron heater, focusing magnet, pulse transformer reset, and etc.

1 INTRODUCTION

An e+e- linear collider at 500 GeV C.M. energy is a very large scale machine of which total length is around 20 km. There are many general requirements for this system such as high reliability and availability, reasonable power efficiency, lower construction cost, simple and easy maintenance, easy and flexible operation.

This paper analyzes the power consumption and efficiency of a C-band RF system for an e+e- linear collider at 500 GeV C.M. energy. This system has total 4,080 units of klystrons (50 MW peak) and modulators (111MW peak) for two main linacs[1].

2 SYSTEM DESCRIPTION

Table 1 shows specifications of a C-band RF system including a klystron and a modulator. A modulator produces 3.5 μsec (ESW, Equivalent Square Wave) pulse with 111 MW peak power. The flat-top portion of 2.5 μsec with ripple less than 1% is utilized to generate 50 MW RF power by a klystron with 45 % conversion efficiency. Fig. 1 is a simplified circuit diagram of the modulator. The HV inverter power supply provides DC high voltage generation with 0.5% fine regulation of PFN charging voltage without de-Qing system. It also has a feature of command charging. This makes the system simple, modular, and reliable. A PFN is a 16-stage Guillemin E-type LC network. There is no thyrite to present the low inverse voltage required for the thyratron deionization in the EOLC circuit due to the command charging scheme of the inverter power supply.

Table 1: Specifications of a C-band RF system.

Klystron (E3746)		
Operating frequency	5712	MHz
Peak output power	50	MW
Repetition rate	100	pps
Efficiency	45	%
Perveance	1.53	$\mu A/V^{1.5}$
Gun voltage	350	kV
Beam current	317	A
RF pulse length	2.50	μsec
Modulator		
Peak output power	111	MW
Average output power	38.9	kW
HV pulse length	3.50	μsec (ESW)
Peak switching current	4758	A
PFN charging voltage	46.7	kV
PFN impedance	4.91	Ω
Stored energy in PFN	389	Joule
PFN cell number	16	

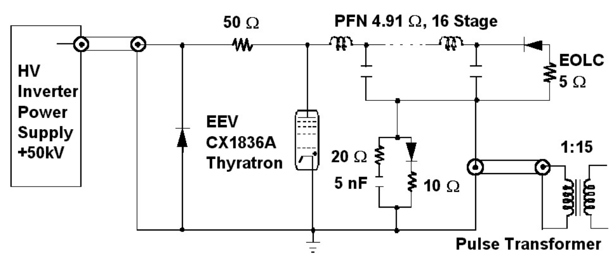

Figure 1: Circuit schematic of a C-band modulator.

3 DEFINITION OF EFFICIENCY

Fig. 2 is a block diagram of power flow for a pulsed RF system. It shows the power conversion flow and corresponding efficiencies of each sub-system. A charging system with P_{AC}, input power supplies P_{DC}, charging power to PFN of a pulsing system. A pulsing system produces P_{PULSE}, pulse power which is the flat-top portion of a pulse. Then a klystron utilizes it to generate RF power, P_{RF}. A P_{AUX}, auxiliary power includes the solenoid coil power for klystron magnet, heater powers for thyratron and klystron, a core reset power for a pulse transformer, a cooling fan power, and so on. η_C, η_P, and η_K represent efficiencies of each sub-system. Table 2

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is the list of essential efficiencies.

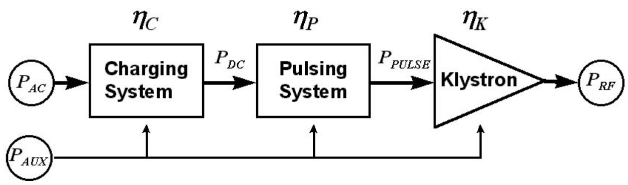

Figure 2: Power flow and efficiencies of an RF system.

Table 2: Definition of efficiencies.

η_C	$= P_{DC} / P_{AC}$	; Charging Efficiency
η_P	$= P_{PULSE} / P_{DC}$	; Pulsing Efficiency
η_K	$= P_{RF} / P_{PULSE}$	; Klystron Efficiency
η_M	$= P_{PULSE} / P_{AC}$	; Modulator Efficiency
η_{KM}	$= P_{RF} / P_{AC}$	; Klystron-Modulator Efficiency
η_{RF}	$= P_{RF} / (P_{AC} + P_{AUX})$	; RF System Efficiency

4 RISE TIME ANALYSIS

A charging system has an efficiency of 85 % specified by the vendor of the inverter power supply. The efficiency of a klystron is given by the design value of 45 %. A pulse efficiency depends on the detail design parameters of the pulsing system including a pulse transformer and a klystron. The rise time of a pulsing system including a pulse transformer and a klystron load for a matched PFN can be described by following equations;

$$\boldsymbol{T_r = f(\sigma)\,((L_W + L_L)(C_D + C_L))^{0.5}}$$

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

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

$$m = R_L / R_G$$

$$\gamma = Z_T / R_L$$

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

where $f(\sigma)$ 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, L_W is the wiring inductance of a system, C_D is the distributed capacitance of a pulse transformer between primary and secondary coils, C_L is the distributed load capacitance of a system including the klystron, R_L is the klystron load impedance, R_G is the PFN generator impedance. Z_T is the transformation impedance of the pulse transformer including L_W and C_L, and m is the matching parameter between the PFN and the klystron. γ is the impedance matching parameter between the transformation system and the klystron.

For a lumped PFN modulator with given total distributed capacitance and total leakage inductance, the optimum value of $f(\sigma)$ for generating good waveforms is 1.74 with σ of 0.78, γ of 1.58, and m of 1.05. A good waveform means that it has a minimum rise time with less than 2 % overshoot. A larger γ gives a slow rise time and a smaller γ makes the large overshoot with ringing. It is important to keep the optimum γ, and minimize distributed capacitance and leakage inductance to get the minimum rise time with good waveforms. A wiring inductance of 1 μH of the pulsing system at the primary side with 15 step-up ratio of the transformer gives 225 μH inductance at the secondary side. This inductance corresponds to the minimum rise time of 0.22 μs with γ of 1.58. Fig. 3 is the analyzed result of distributed capacitances using DENKAI in the pulse tank including the klystron assembly. The right-half of the figure shows potential lines in the region of the klystron tube and between the coils of the pulse transformer in the tank. The calculated values of capacitance are presented at the left-half of the figure. Total distributed capacitance in the tank except the capacitance between the coils is 115 pF. If the capacitances between the corona ring and other structures not included in this estimation is added to the result, it becomes approximately 120 pF. This capacitance corresponds to the minimum rise time of 0.39 μs with γ of 1.58. So the large distributed capacitance in the pulse tank is more limiting parameter for the pulse rise time in the case of the C-band RF system.

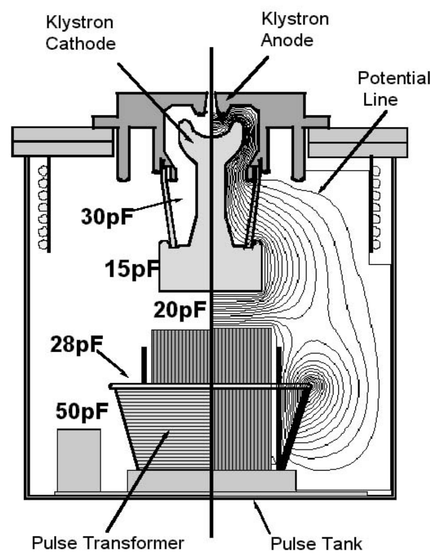

Figure 3: Distributed capacitance and potential lines in the pulse tank with E3746 klystron.

Table 3: Parameters of the C-band pulse transformer.

Turn Ratio	15
Primary turns	3
Leakage inductance (μH)	1.60
Stray capacitance (nF)	6.33
Shunt Inductance (mH)	0.36
Core Resistance (Ω)	411
Droop (%)	2.39
Overshoot (%)	1.96

The primary consideration of the transformer design is to keep the capacitance low between primary and secondary coils, for example under 30 pF to make the rise time of less than 0.5 μs and guarantee the flat-top width of 2.5 μs. Typical parameters of the pulse transformer at the primary side are summarized in Table 3. Total inductance and capacitance including transformer parameters are 499 μH and 164 pF which give the rise time of 0.47 μs.

5 POWER DISTRIBUTION ANALYSIS

The simulated klystron voltage waveform with its expanded view using PSPICE is shown in Fig. 4. The expanded view shows 2.5 μs flat-top with ripples less than 1 % which results the phase shift of 5.68° of the klystron RF output. Analyzed power distribution of a C-band klystron-modulator system is described in Table 4. Total 51.4 kW is required to generate 12.5 kW RF power with 100 Hz operating condition. The beam power of 15.3 kW is dumped to a collector of a klystron within the portion of flat-top. This loss caused by the conversion inefficiency of the klystron is 30 % of the total power. Wasted pulse power includes all the losses which are not contributed to make RF power from the stored energy of the PFN. The loss during rise and fall time is 10 kW which includes stored energies in the leakage inductance and the distributed capacitance, and electron beam power delivered to the collector during this time interval. This is the main loss in the pulse modulator, which is 19.5 % of the total power. The magnetizing loss of 0.9 kW means the stored energy in the shunt inductance of the pulse transformer which is finally dissipated at the tail clipper. The solenoid coil power of the klystron magnet is assumed just as 3 kW but it still takes main part of the auxiliary power.

Table 4: Power distribution of a C-band system.

Total Power = 51,371 W		
1. RF Power	12,488	(24.3%)
2. Wasted Beam Power	15,263	(29.7%)
3. Wasted Pulse Power	12,071	(23.5%)
4. Charging Loss	7,072	(13.8%)
5. Aux. Power	4,477	(8.7%)
Wasted Pulse Power		
a. Rise/Fall Time Loss	9,991	(19.45%)
b. Magnetizing Loss	929	(1.81%)
c. Thyratron Loss	416	(0.81%)
d. Eddy Current Loss	463	(0.90%)
e. RC Snubber Loss	272	(0.53%)
Aux. Power		
a. Klystron Magnet	3,000	(5.84%)
b. Thyratron Heater	567	(1.10%)
c. Cooling Fan	450	(0.88%)
d. Klystron Heater	316	(0.62%)
e. Core Bias	100	(0.19%)
f. Thyratron Reservoir	44	(0.09%)

6 EFFICIENCY

Table 5 shows the efficiencies of the each sub-system of the C-band klystron-modulators. The pulse efficiency of 70 % is mainly limited by distributed capacitance in the oil-filled pulse tank. It is difficult to improve the pulse efficiency using the standard method. Since a net RF system efficiency is 24 %, the total AC wall-plug power of 210 MW will be consumed to generate the total RF power of 51 MW using 4,080 units of a klystron-modulator system.

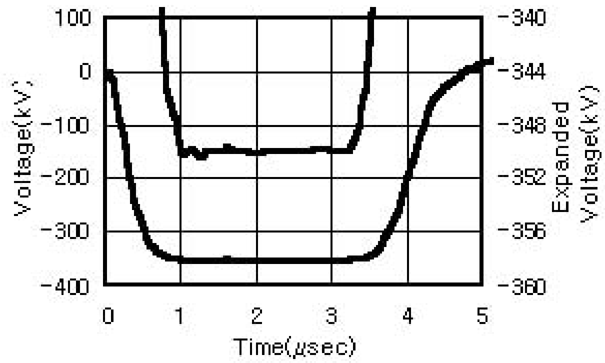

Figure 4: Simulated klystron voltage waveform.

Table 5: Efficiencies of the C-band system.

Charging Efficiency	85.0	%
Pulse Efficiency	69.8	%
Klystron Efficiency	45.0	%
Modulator Efficiency	59.3	%
K-M Efficiency	26.7	%
RF System Efficiency	24.4	%

7 CONCLUSIONS

A net RF efficiency of the C-band system is estimated to be 24 %, and this requires total AC wall-plug power of 210 MW. The charging efficiency of 85 % can be improved up to 90 % through the trade-off design of the inverter power supply. The pulse efficiency of 70 % is almost optimized. If the PM-AM modulation method of the C-band system[2] allows the 2-3 % tolerance of the flat-top ripple, it can be improved up to 75 %. The klystron efficiency of 45 % is the most flexible parameter in the RF sub-systems. It could be raised up to 60 %. Then it is expected to get a net RF efficiency of 35.4 %, and total AC wall-plug power demand can be lowered to 144 MW.

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