Criteria for Comparing the Suitability of Microwave Amplifiers for Driving TeV Linear Colliders

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I. INTRODUCTION

Many types of microwave amplifiers are being considered at various institutions as candidate sources for driving future linear colliders. The choice of operating frequency ranges from 2.85 GHz to 35 GHz. Peak microwave output power and pulse duration also vary widely. In this paper, we propose three criteria for evaluating and comparing amplifier options. These are as follows: 1) N_t, the number of amplifiers required to drive an accelerator with a given final energy and a given accelerating gradient; 2) V, the voltage required to operate the microwave amplifier; and 3) η_T, the overall efficiency including the output efficiency of the amplifier, the efficiency of the pulse compression circuit if any is used, and the high voltage modulator pulse-shape efficiency. All of these criteria will affect the cost of a linear collider system. The cost of the microwave amplifiers will, of course, equal the cost of each amplifier (with its associated power supplies, magnets, and pulse compression circuit) multiplied by the number of amplifiers, N_t. The cost of each amplifier and its power supply/modulator will increase with the voltage, V. In fact, we have chosen to restrict our consideration of specific amplifiers to those in which $V < 1$ MV; at voltages above 1 MV very large insulators and more exotic pulsed power supplies such as induction linacs would be required and these might be excessively costly. Overall efficiency will, of course, influence average power consumption as well as the size and cost of power supplies.

II. THE NUMBER OF AMPLIFIERS REQUIRED TO DRIVE A COLLIDER

First, consider the relationship between peak microwave power required per unit accelerator length, p, the accelerator gradient, E_a, and the microwave wavelength, λ. Perry Wilson has recently presented[1] the result that for an accelerator structure consisting of a chain of pillbox TM_{010} resonators, the microwave power per unit length is given by

$$p \approx 1.2 \times 10^{-7} E_a^2 \lambda^{1/2} \tag{1}$$

(throughout this paper mks units are used unless otherwise noted), while the structure fill-time is given by

$$t_f \approx 2.3 \times 10^{-5} \lambda^{3/2}. \tag{2}$$

Thus, the required microwave pulse energy per unit length is

$$u = pt_f \approx 2.8 \times 10^{-12} E_a^2 \lambda^2. \tag{3}$$

Then, a single microwave amplifier with peak output power, P_p, and pulse duration $\tau_p \geq t_f$ would be able to drive a length of accelerator structure

$$\ell_1 = \frac{P_p \tau_p \eta_c}{u} \approx 3.6 \times 10^{11} \frac{P_p \tau_p \eta_c}{E_a^2 \lambda^2}, \tag{4}$$

where we have used Eq. (3), and η_c is the efficiency of any pulse compression circuit that is used. If we estimate that each factor of 2 in pulse compression can be achieved with 90% efficiency,[2] then

$$\eta_c = 0.9 \exp\left[\log_2(\tau_p/t_f)\right]. \tag{5}$$

The required overall length of an accelerator with final energy, U_f, is

$$L = U_f / eE_a \tag{6}$$

while the total number of microwave tubes required is obtained from Eqs. (4) and (6) as

$$N_t = \frac{L}{\ell_1} \approx 1.7 \times 10^7 \frac{U_f E_a \lambda^2}{P_p \tau_p \eta_c}. \tag{7}$$

Accelerator cost will increase both with the length of the required tunnel, L, and with the number of microwave tubes, N_t. However, since $L \sim E_a^{-1}$ and $N_t \sim E_a$, the choice of an optimum E_a is not obvious, and involves a complicated analysis of such factors as tunnel cost versus microwave tube cost.

Once U_f and E_a are chosen for a collider, Eq. (6) together with Eqs. (5) and (2) may be used to evaluate N_t. It may be seen from Eq. (6) that N_t could be decreased by choosing a higher microwave frequency if $P_p \tau_p$ decreased less rapidly than λ^2. In addition,

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high frequency has the advantages of increased limiting values of E_a as determined by rf breakdown[3] and increased pulse repetition frequency[4] which diminishes problems caused by ground jitter. However, there is a practical upper limit on frequency that is currently estimated to be in the neighborhood of 35 GHz. At higher frequency, fabricating and aligning the smaller accelerator structures becomes increasingly difficult; this might be alleviated however by using higher order transverse modes in the accelerator cavities which would not substantially affect the values of ℓ_1 or N_t.

III. OVERALL MICROWAVE AMPLIFIER SYSTEM EFFICIENCY

A typical microwave amplifier system consists of the microwave tube, the pulse compression circuit, and the high voltage modulator (plus other elements which will not be considered in this first-cut analysis). Accordingly, the total system efficiency may be defined as

$$\eta_T = \eta_a \eta_c \eta_v \tag{8}$$

where η_a is the output efficiency of the microwave amplifier (i.e. microwave output power divided by the power of the electron beam in the amplifier), η_c is defined in Eq. (5), and η_v is the pulse-shape efficiency of the high voltage modulator.

In contrast to the behavior of pulse compression efficiency, the high voltage modulator pulse-shape efficiency, η_v, decreases as pulse duration τ_p becomes shorter due to the increasing fraction of unused energy in the rise and fall of regions of the modulator pulse. The efficiency η_v is thought[1] to have the form

$$\eta_v = \frac{\tau_p}{\tau_p + \sqrt{\alpha \tau_p}} \tag{9}$$

where we estimate empirically that the constant $\alpha = 0.25 \times 10^{-6}$ sec.

IV. COMPARISON OF EXPERIMENTAL MICROWAVE AMPLIFIERS

The performance parameters of a number of leading microwave amplifier experiments are displayed in Table 1 together with the calculated values of η_T and N_t. The various experimental studies are in different stages of maturity and so the tabulated data indicates only what has been demonstrated by the beginning of 1993 and not ultimate potential. For purposes of comparison the performance characteristics of the S-band SLC klystron is tabulated on the first line.

It will be noted that both the X-band klystron and the two gyroklystron experiments show significant progress in reducing the value of N_t from the SLC klystron value. The free electron laser, extended interaction klystron and traveling wave tube would have lower values of N_t if they could be made to operate with longer pulses. An acceptable value of N_t might be 1000-2000 and thus new higher power experiments are of interest. For example, a 17.4 GHz amplifier operating with an output pulse of $P_p = 100$ MW and $\tau_p = 1\mu$s would have $N_t \approx 1300$.

It will also be noted that none of the higher frequency amplifier experiments have yet equalled the SLC klystron in efficiency and improvement in η_T is emphatically called for. Perhaps energy recovery schemes such as depressed collectors should be seriously studied.

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Table 1. Demonstrated amplifier performance ($V \leq 800$ kV); N_t is the total number of amplifiers required to drive a 1 TeV accelerator with E_a = 100 MV/m.

Type of Amplifier	Research Institution	f (GHz)	P_p (MW)	τ_p (μs)	η_a (%)	V (kV)	N_t	η_T (%)
SLC klystron	SLAC	2.856	65	3.5	45	350	17 k	28
X-band klystron[5]	SLAC	11.4	50	1.0	22	447	5.6 k	10
X-band gyroklystron[6,7]	U. Md.	9.85	27	1.4	32	425	10 k	15
K-band gyroklystron[8,**]	U. Md.	19.7	30	0.8	27	440	4.2 k	11
Free electron laser[9]	MIT	33	61	0.02	27	750	19 k	6
Extended interaction klystron[10]	SRL*	11.4	100	0.05	43	440	42 k	13
Traveling wave tube[11]	Cornell	8.76	200	0.1	24	800	16 k	9

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**In the K-band gyroklystron the output cavity operates at twice the input frequency.