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

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1. 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) $\eta_t$, 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, $V$.

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, $\lambda$. Perry Wilson has recently presented 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

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

(1)

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

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

(2)

Thus, the required microwave pulse energy per unit length is

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

(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

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

(4)

where we have used Eq. (3), and $\eta_c$ 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, then

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

(5)

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

$$ L = U_f/eE_a $$

(6)

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

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

(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 $L \approx E_a^{-1}$ and $N_t \approx E_a$, 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 $\lambda^2$. In addition,
high frequency has the advantages of increased limiting values of $E_0$ as determined by rf breakdown and increased pulse repetition frequency 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 $\ell_1$ 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

$$\eta_T = \eta_0 \eta_c \eta_v$$

where $\eta_0$ is the output efficiency of the microwave amplifier (i.e. microwave output power divided by the power of the electron beam in the amplifier), $\eta_c$ is defined in Eq. (5), and $\eta_v$ 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, $\eta_v$, decreases as pulse duration $\tau_p$ becomes shorter due to the increasing fraction of unused energy in the rise and fall of regions of the modulator pulse. The efficiency $\eta_v$ is thought\(^{1}\) to have the form

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

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 $\eta_T$ 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 $\eta_T$ is emphatically called for. Perhaps energy recovery schemes such as depressed collectors should be seriously studied.

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V. REFERENCES


5. G. Caryotakis, private discussions.


8. J. Calame, et al., these proceedings.


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 $E_0 = 100$ MV/m.

<table>
<thead>
<tr>
<th>Type of Amplifier</th>
<th>Research Institution</th>
<th>$f$ (GHz)</th>
<th>$P_p$ (MW)</th>
<th>$\tau_p$ (µs)</th>
<th>$\eta_p$ (%)</th>
<th>$V$ (kV)</th>
<th>$N_t$</th>
<th>$\eta_T$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLC klystron</td>
<td>SLAC</td>
<td>2.856</td>
<td>65</td>
<td>3.5</td>
<td>45</td>
<td>350</td>
<td>17 k</td>
<td>28</td>
</tr>
<tr>
<td>X-band klystron$^5$</td>
<td>SLAC</td>
<td>11.4</td>
<td>50</td>
<td>1.0</td>
<td>22</td>
<td>447</td>
<td>5.6 k</td>
<td>10</td>
</tr>
<tr>
<td>X-band gyroklystron$^6,7$</td>
<td>U. Md.</td>
<td>9.85</td>
<td>27</td>
<td>1.4</td>
<td>32</td>
<td>425</td>
<td>10 k</td>
<td>15</td>
</tr>
<tr>
<td>K-band gyroklystron$^8,\text{**}$</td>
<td>U. Md.</td>
<td>19.7</td>
<td>30</td>
<td>0.8</td>
<td>27</td>
<td>440</td>
<td>4.2 k</td>
<td>11</td>
</tr>
<tr>
<td>Free electron laser$^9$</td>
<td>MIT</td>
<td>33</td>
<td>61</td>
<td>0.02</td>
<td>27</td>
<td>750</td>
<td>19 k</td>
<td>6</td>
</tr>
<tr>
<td>Extended interaction klystron$^{10}$</td>
<td>SRL$^*$</td>
<td>11.4</td>
<td>100</td>
<td>0.05</td>
<td>43</td>
<td>440</td>
<td>42 k</td>
<td>13</td>
</tr>
<tr>
<td>Traveling wave tube$^{11}$</td>
<td>Cornell</td>
<td>8.76</td>
<td>200</td>
<td>0.1</td>
<td>24</td>
<td>800</td>
<td>16 k</td>
<td>9</td>
</tr>
</tbody>
</table>

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$^{**}$In the K-band gyroklystron the output cavity operates at twice the input frequency.