# 1. INTRODUCTION

Detailed designs exist for linear colliders in the 0.5 - 1.0 TeV center-of-mass (c.m.) energy range (see, for example, the recent report of the International Linear Collider Technical Review Committee, (1)). The rf operating frequencies for these machines range from 1.3 GHz (TESLA) to 30 GHz (CLIC), and for the 0.5 TeV c.m. designs the beam-loaded accelerating gradients range from 25 MV/m (TESLA) to 90 MV/m (VLEPP). Four of these machines propose upgrades to 1.0 TeV c.m. energy by simply doubling the active accelerator length (TESLA, JLC-X, VLEPP and CLIC). Three designs also propose an increase in accelerating gradient: the DESY S-band design (SBLC), the KEK C-band design (JLC-C) and the SLAC X-band design (NLC). In these upgrade designs, the accelerating gradient is strongly correlated with the rf operating frequency. Except for CLIC (which is a two-beam accelerator), the unloaded gradients vary roughly as the square root of the rf frequency. There is, of course, a simple physical reason for this correlation between gradient and frequency: the energy stored per meter of accelerating structure varies approximately as $(G_0\lambda)^2$, where $G_0$ is the unloaded gradient and $\lambda$ is the rf wavelength. Thus, for a linac which is pulsed at a fixed repetition rate, a higher operating frequency makes it possible to achieve a given final energy with both a shorter accelerator length and a lower ac "wall plug" power.

In this report we look at the possibility of a leap in linear collider energy into the 5-15 TeV energy range. If we are to keep the active accelerator length and ac power within reasonable bounds ($L_{active} \sim 30$ km, $P_{ac} \sim$ 200-300 MW), the preceding argument suggests that this will be possible only if the rf frequency is increased in rough proportion to the desired c.m. energy. The starting point for this scaling-with-frequency exercise will be a 1 TeV linear collider design at 11.4 GHz, as described in the next section. Following that, the principles of scaling to higher gradient at higher frequencies are discussed in more detail, and rough rf parameters given for c.m. energies of 5, 10 and 15 TeV.

Because the peak power of discrete rf sources such as klystrons is limited and tends to decrease with increasing rf frequency, and because the peak power per meter of accelerating structure will tend to increase with frequency if the accelerating gradient is also increased, there will be some cross-over frequency (not sharply defined) above which rf pulse compression is required to enhance the peak power available from practical microwave tubes. From the designs as proposed in the Technical Review Committee Report (1), the frequency at which pulse compression is required seems to be at about C-band (5 GHz) and above. Rough designs for high gain, high efficiency pulse compression systems for 11.4 GHz and 34 GHz are given in the fourth section of this report.

Standard round-beam klystrons, which are adequate to power an X-band collider to 500 GeV c.m. energy, have been designed and tested. At SLAC, a PPM-focused klystron has achieved a peak power of over 50 MW at a pulse length of 1.5 microseconds with an efficiency greater than 60%. Such a klystron, however, will not provide adequate power if scaled up in frequency by a significant factor. In Section 5 of this report, some considerations on the frequency scaling of round beam and sheet beam klystrons are presented, along with example parameters for devices which can deliver adequate power at 34 GHz.

## 2. BASE DESIGN AT 11.4 GHz

As a base design for scaling to higher frequencies and gradients, we start with the NLC 11.4 GHz accelerating structure operating at an unloaded gradient of 100 MV/m. Details of the NLC rf system design for a collider with a c.m. energy of 500 GeV (unloaded gradient = 50 MV/m) are given in the NLC Zeroth-Order Design Report, or ZDR (2). A rough outline for upgrading the rf system to achieve 1 TeV c.m. energy is given in Sec. 8.1.2 of the ZDR. The upgrade requires four 75 MW klystrons per rf module. An rf module consists of one SLED-II pulse compression unit feeding four 1.8 m long accelerator sections operating at an unloaded gradient of 85 MV/m. The rf system efficiencies for the 1 TeV design are: klystron, 60%; modulators, 75%; pulse compression and power transmission, 87%; net rf system efficiency, 39%. The high pulse compression system efficiency is achieved assuming the use of a binary pulse compression system (BPC) (3) with a compression ratio of 4. A BPC compression system has an intrinsic efficiency of 100% in the absence of copper losses and losses due to mode conversion and imperfections.

For our base design we assume a BPC system with a larger compression ratio (factor of 8) and an efficiency of 80% including power transmission, giving a net power gain of 6.4. Some details as to how such a compression system might be built using discrete cavities to reduce delay line lengths are given in Sec. 4. The NLC accelerating structure requires 200 MW/m to reach a gradient of 100 MV/m. Again assuming $4 \times 1.8$ m = 7.2 m of accelerating structure per BPC system, the required power for each of two klystrons is (200 MW/m $\times$ 7.2 m)/($2 \times 6.4$) = 112 MW/klystron. As in the NLC 1 TeV design, four 61 MW klystrons could be used per BPC system, although this is less desireable because it doubles the number of klystrons.

It will be difficult to produce 112 MW in a conventional round-beam klystron, especially since we will also require an efficiency on the order of 70%. Klystron simulations at SLAC indicate that this efficiency can only be achieved if the microperveance is dropped to about 0.35. Assuming a beam voltage of 500 kV, such a klystron would produce an output power of about 40 MW. To achieve a power output 112 MW at 70% efficiency, a multiple-beam or sheet-beam klystron would be required. These option are briefly discussed in Sec. 5.

A major assumption in the rf system base design is that klystron beam is pulsed on and off by means of a grid or mod-anode, thus eliminating the need for a conventional pulse modulator. It is assumed that the grid modulation can be carried out with an efficiency of 90% (wall plug power to energy in the flat-top portion of the klystron beam). The overall rf system efficiency is therefore: 0.70 (klystron) $\times$ 0.90 (modulator) $\times$ 0.80 (pulse compression) $\approx$ 0.50.

As in the NLC design, we assume that the beam-loaded gradient is about 75% of the unloaded gradient. An overhead factor is also required to take account of the fact that the bunch is run off-crest for BNS damping. Overhead will also be needed for feedback, and to allow for rf stations which are temporarily off-line for klystron and modulator maintenance. Following the NLC 1 TeV design, we take the total overhead factor to be 1.14. Including the factor of 1.33 is needed to take account of beam loading, the active length of accelerator structure which is required is

$$L_A \;\approx\; 1.5\; E_{c.m.}/G_0 \tag{1}$$

where $G_0$ is the unloaded gradient. For a 1 TeV collider at $G_0 = 100$ MV/m, $L_A = 15$ km.

We compute the ac wall plug power assuming a constant repetition rate of 120 Hz:

$$P_{ac} = 120\hat{P}_m\; T_p L_A/\eta_{rf} \quad . \tag{2}$$

Here $\hat{P}_m$ is the peak power per meter at the structure input, $T_p$ is the pulse length at the structure and $\eta_{rf}$ is the net rf system efficiency. In the present calculation we do not take into account auxiliary power due to klystron and thyratron heater power supplies etc. Such auxiliary power sources typically increase the total ac power requirement by about 5% (1).

For the 1 TeV NLC design at 100 MV/m, $\hat{P}_m = 200$ MW/m and $T_p =$ 240 ns. Thus for $\eta_{\rm rf} = 50\%$ as described above, $P_{\rm AC} \approx 175$ MW. Scaled to 1.5 TeV, this collider would have an active length of 22.5 km and would require an

AC power of 260 MW. In the NLC design the physical linac length (allowing for quadrupoles and beam-line instrumentation) is 8% longer.

## 3. SCALING TO HIGHER FREQUENCIES

Several factors must be taken into account in scaling the rf system of a linear collider to a higher frequency. One of the most important is the threshold capture of an electron at rest by a traveling wave with a phase velocity equal to the velocity of light. This "dark current" capture threshold is given by

$$G_{th} = \pi mc^2/e\lambda_{rf} = 1.605 \text{ MV}/\lambda_{rf} \quad . \tag{3}$$

Many linear collider designs involve gradients that exceed this threshold by a modest factor (30% or so). However, it would be unwise to plan on a gradient which is considerably in excess of $G_{th}$ without strong experimental support from measurements at a test facility showing that the dark current level is acceptable.

Other considerations suggest that it may be best to scale gradient with frequency slightly less than linearly. For example, assuming the pulse length varies as $\omega^{-3/2}$ (proportional to the structure filling time), some evidence suggests that the rf breakdown threshold scales as $\omega^{1/2}/T_p^{1/4} = \omega^{7/8}$. A slower variation with frequency also reduces the ac power consumption, the required peak klystron power, and the pulse temperature rise in the structure. To work out some specific scaling relations, we choose $G_0 \sim \omega^{5/6}$. The active accelerator length then scales as $L_A \sim E_{c.m.}\lambda^{5/6}$.

We will also want to increase the iris opening $a/\lambda$, and hence the group velocity $v_g/c$, with $\omega$ to reduce wakefield effects and to make the structure length somewhat longer at higher frequencies. The elastance (defined as $s \equiv G_0^2/u$ where $u$ is the stored energy per unit length) and the group velocity vary with iris opening approximately as $s \sim \omega^2 s_n(a/\lambda)$, $s_n \approx (a/\lambda)^{-1}$ and $v_g/c \approx (a/\lambda)^3$. We choose $a/\lambda \sim \omega^{1/6}$. Then $s_n \sim \omega^{-1/6}$ and $v_g/c \sim \omega^{1/2}$. The energy stored per unit length varies as $u \sim G_0^2\lambda^2/s_n \sim G_0^2\lambda^{11/6} \sim \lambda^{1/6}$. The ac power then varies at $P_{ac} \sim uL_A f_r \sim E_{c.m.} f_r \lambda$.

We consider collider frequencies at 11.4 GHz (4 times SLC), 34.4 GHz (12 times SLC) and 91.4 GHz (32 times SLC). Assuming a constant structure attention parameter $\tau \approx 0.5$ and a pulse length equal to 2.5 times the structure filling time, we obtain the structure parameters shown in Table 1. In this table an elastance variation $s_n \sim \lambda^{1/6}$ has been assumed. The other structure parameters, however, are obtained from computer calculations and not from the rough scaling relations discussed previously. In the table, $T_0 = 2Q/\omega$ is the decrement time, $T_F = \tau T_0$ is the structure filling time, $L_s$ is the structure length, $\hat{E}_s/G$ is the ratio of the peak surface field to the local accelerating gradient and $T_{0n} \sim T_0/f_n^{3/2}$ is the normalized decrement time. For a constant gradient structure, $v_g$ is an average group velocity given by $L_s/T_F$.

The peak power per meter required at the input to the accelerating structure is given by

$$P_m = \frac{G_0^2}{\eta_s(\tau) s T_f} \tag{4}$$

**TABLE 1. Accelerating Structure Parameters at three Frequencies**

| Frequency (GHz) | $a/\lambda$ | $s_n$ $(\sim \lambda^{1/6})$ | $v_g/c$ | $T_0$ (ns) | $L_s$ (m) | $T_F/T_p$ (ns) | $\hat{E}_s/G$ |
|---|---|---|---|---|---|---|---|
| 11.4 $(f_n \equiv 1)$ | 0.52 $(a_n \equiv 1)$ | 1.0 | .06 | 198 $(T_{0n} \equiv 1)$ | 1.8 | 100/250 | 2.4 |
| 33.4 $(f_n = 3)$ | 0.63 $(a_n = 1.19)$ | 0.83 | .10 | 40 $(T_{0n} = 1.03)$ | 0.60 | 20/50 | 2.6 |
| 91.6 $(f_n = 8)$ | 0.70 $(a_n = 1.33)$ | 0.71 | .13 | 9 $(T_{0n} = 1.05)$ | 0.20 | 5/12 | 2.8 |

where $\eta_s$ is the structure efficiency. For a constant gradient structure, $\eta_s = (1 - e^{-2\tau})/2\tau$. For the NLC structure at $\tau = 0.52$, $\eta_s = 0.62$ and the effective elastance is 815 $\Omega$/ps/m. Using scalings $G_0 \sim \omega^{5/6}$ and $s \sim \omega^{11/6}$, then $P_m \sim \omega^{4/3}$.

In addition to the obvious limitation on accelerating gradient imposed by the intense electric fields on the copper surface near the iris, there may also be a problem due to pulse heating by the magnetic fields at the cell walls. The temperature rise at the end of a pulse of duration $T_p$ is

$$\Delta T = \frac{R_s}{K} \left( \frac{D T_p}{\pi} \right)^{1/2} \left( \frac{G}{Z_H} \right)^2 \quad . \tag{5}$$

Here $R_s$ is the surface resistance, $K$ is the thermal conductivity and $D$ is the thermal diffusivity, given by $D = K/C_s\rho$ where $C_s$ is the specific heat and $\rho$ the density. $Z_H$ is an impedance defined as $Z_H \equiv G/\hat{H}_s$ where $\hat{H}_s$ is the peak surface magnetic field. For the NLC structure, the minimum value of $Z_H$

is 307 ohms. Using $D = 1.15$ cm$^2$/sec and $K = 3.95$W/cm/ $^\circ C$ for copper, Eq. (5) gives a temperature rise of 23°C for the NLC structure at $G_0 = 100$ MV/m and $T_p = 250$ ns. Assuming that the gradient is scaled as $\omega^{5/6}$ and $T_p \sim \omega^{-3/2}$, the temperature rise scales as $\Delta T \sim \omega^{1.42}$. The temperature rise would then reach the melting point of copper at a frequency of 170 GHz and a gradient of 830 MV/m.

Based on the preceding discussion, Table 2 gives some basic parameters for linear collider in the 1-15 TeV energy range. The first row in the table gives parameters for the present 1 TeV NLC design based on an rf system with an efficiency of 40%. A repetition rate of 120 Hz is assumed in all designs.

**Table 2. Linear Collider Designs Scaled in Frequency and Energy**

| $E_{c.m.}$ (TeV) | Frequency (GHz) | $G_0$ (MV/m) | $G_0/G_{th}$ | $\hat{P}_m$ (MW/m) | $P_{ac}$ (MW) | $L_A$ (km) | Max$\Delta T$ ($^\circ C$) |
|---|---|---|---|---|---|---|---|
| 1.0 | 11.4 | 85 | 1.39 | 145 | 180 | 17.7 | 16 |
| 1.5 | 11.4 | 100 | 1.64 | 200 | 270 | 22.5 | 23 |
| 5.0 | 34.3 | 250 | 1.37 | 825 | 300 | 30 | 112 |
| 10 | 91.4 | 500 | 1.02 | 2200 | 190 | 30 | 355 |
| 15 | 91.4 | 600 | 1.23 | 3150 | 350 | 37.5 | 515 |

## 4. PULSE COMPRESSION AT 11 AND 34 GHZ

All SLED pulse compression schemes suffer from a loss in efficiency due to unavoidable reflected power from the coupling iris during the energy storage period. For a SLED-II system with a compression ratio of five, for example, this reflected power amounts to 16.5% of the energy in the incident pulse. In addition, 3% of the energy remains in the delay lines at the end of the pulse, giving a net intrinsic efficiency of 80.5%. For a 0.5 TeV collider such as the NLC with a wall-plug power on the order of 100 MW, this loss in efficiency is acceptable in view of the simplicity and demonstrated performance of a SLED-II compression system. However, for a 1 TeV collider with a wall-plug power of about 200 MW, this 20% hit in intrinsic efficiency converts to an unacceptable of power loss on the order of 40 MW.

Two basic methods are under consideration for improving the compression efficiency over that of a SLED-II system. First, Tantawi *et al.* (4) have proposed using an active switch (a silicon wafer illuminated by a laser) to change the reflection coefficient of the coupling iris at the entrance to the SLED-II delay lines. By switching twice during the rf pulse, the efficiency can be increased to 99% for a compression ratio of five and to 96% for a compression ratio of eight (assuming losseless delay lines and waveguide components). The switch is under active development at SLAC at present time; high power limitations, however, have yet to be determined.

The second method for increasing compression efficiency is to go to a binary pulse compression system which, as mentioned previously, has an intrinsic efficiency of 100%. A major disadvantage of a BPC system is the length of the delay lines. The total time-length of these lines is equal to $R$-1 times the output pulse length, where $R$ is the compression ratio. This length can be cut in half by using a variation of the BPC scheme, the Delay Line Distribution System (DLDS) as proposed at KEK. In this scheme, the rf is sent toward accelerating structures upstream (toward the gun) for one-half of the delay period; the returning beam then provides the other half of the delay.

In this note we consider the possibility of loading the delay lines to achieve a length reduction factor which is much larger than two. However, any loading scheme which reduces delay line length must not lead to an unacceptable decrease in transmission efficiency, either by enhanced copper losses or through a distortion of the pulse shape (rise-time degradation and ripple). The simplest approach would use a disk-loaded structure operating in the $TE_{01}$ mode as a delay line. However, we will show that in such a structure there is too much loss in the loading disks, unless they are spaced so far apart that there are only a dozen or so disks in the entire line. In that case it is better to think of the structure as a relatively small number $N$ of coupled resonant cavities, where $N \sim$ 5-15. The exact number needed will depend on the acceptable peak-to-peak ripple (a few percent) and rise-time degradation. This can be worked out using an equivalent circuit model with adjustable tuning and coupling for each cavity (this work is now in progress).

The $Q$ of a $TE_{01n}$ cavity of length $L$ and radius $\underline{a}$ (ignoring the effect of the coupling hole) is

$$Q_0 = \frac{p_{11} Z_0}{2R_s} \left[ y^3 + \frac{p_{11}\lambda}{\pi L} \left(1 - y^2\right) \right]^{-1} \qquad (6)$$

$$y \equiv \lambda/\lambda_c = \lambda p_{11}/2\pi a \ \ ,$$

where $p_{11} = 3.83$, $Z_0 = 377\ \Omega$ and $L = n\lambda_g/2 = n(\lambda/2)(1-y^2)^{-1/2}$. As an example, take $a = 12$ cm and $L = 1.5$ m. Using $R_s = 0.028\ \Omega$ at 11.4 GHz, Eq. (6) given $Q_0 = 1.1 \times 10^6$ and $T_0 = 2Q_0/\omega = 31\mu$s. Note that 90% of the loss is in the cavity end walls, even though they are more than six cavity diameters apart. The external $Q$ of the cavity is given by $Q_e = \omega U/2P_F$, where $P_F$ is the power flowing on the line. In turn, $P_F = NU/T_p$. Thus $Q_e \approx Q_L = \omega T_p/2N$. Delay line parameters for a $\times 8$ BPC system at 11.4 GHz with $N = 8$ are given in Table 3. Here $T_p = 250$ ns is the output pulse length, $T_k = 8T_P = 2.0$ $\mu$s is the klystron pulse length, and $\eta = \exp(-2T_D/T_0)$ with is the transmission efficiency (copper losses only) for a delay $T_D$, with $T_0 = 31$ $\mu$s as calculated above. The net efficiency is 89.5%. If we add an additional 2% per stage for losses in other waveguide components, and assume a power transmission

**Table 3. A 3-Stage BPC System at 11.4 GHz**

| Stage | Delay ($\mu$s) | $Q_L$ | $\eta$ |
|---|---|---|---|
| 1 | 1.00 | 4500 | 0.94 |
| 2 | 0.50 | 2200 | 0.97 |
| 3 | 0.25 | 1100 | 0.985 |
| net | 1.75 | — | 0.895 |

efficiency of 95%, then the net compression efficiency is 80%, and the power gain is 6.4. This may be optimistic, since there is no allowance for rise-time degradation or pulse-top ripple. However, a 25 ns switching-time allowance is included in the 250 ns output pulse length, which may cover the rise-time degradation. A peak-to-peak ripple of 5% would reduce the compression efficiency to 0.78, and the power gain to 6.25.

The total delay line length (per stage) is $8 \times 1.5$ m = 12 m, plus an allowance for the spacing between cavities. If folded into an out-bend-return configuration, the line would fit easily in the $\approx 8$ m length available for an NLC rf module.

These concepts can be extended to a four-stage BPC system at 34 GHz. For an output pulse length of 50 ns (see Table 1), the klystron pulse length would be 0.8 $\mu$s. Since there are now four stages of compression, we must double the cavity $Q$ to maintain a net compression efficiency of 80% to give a power gain of 12.8. This can be done by doubling $L/\lambda$ for each cavity, giving a cavity length of 1.0 m at 34 GHz. If four 0.6 m structure are fed from each BPC unit the required klystron power is (825 MW/m $\times$ 2.4 m)/(2 $\times$ 12. 8) = 78 MW/klystron. The rf module length will be about 2.6 m, while the folded delay line length will be about 4.5 m. Thus the delay system for one module will need to overlap with that of the next module. It would be desireable to increase the klystron power output to 155 MW to double the rf module length and cut the number of klystrons in half.

## 5. RF POWER GENERATION FOR 34 GHz

There are two basic limitations on the power that can be generated by a conventional round-beam klystron. First of all, it is well known that the electronic efficiency of a klystron depends on the microperveance, defined as $K_\mu \equiv (I_b/V_b^{3/2}) \times 10^6$. The perveance sets the scale for space charge forces, which in turn limit the compactness of the electron bunches and hence the rf component of the beam current. An expression which fits recent simulations on X-band klystrons at SLAC is: $\eta \approx 0.77 — 0.20\ K_\mu$. To achieve the desired efficiency of 70%, $K_\mu \approx 0.35$. At a beam voltage of 500 kV, the output power would be $P_k = \eta K_\mu V_b^{5/2} \approx 45$ MW. This limitation is independent of rf frequency.

A second limitation on klystron output power has its origin in the finite beam area, which does depend on wavelength. To achieve good coupling to the longitudinal rf fields in the gap, the radius of the beam should not be larger than about $\lambda/8$. If the beam radius exceeds this, then electrons on the beam axis and electrons at the edge of the beam will see substantially different rf voltages, and efficiency will suffer. The beam area at the cathode will be larger than the beam area in the drift region by a factor $C_A$, where $C_A$ is the area compression ratio. This ratio is limited by aberrations in the gun optics, transverse emittance, alignment tolerances, etc. The limit on the compression ratio is not a sharp one, but $C_A \approx 200$ is pushing current technology. Finally, the beam current is limited by the current per unit area that can be drawn from the cathode. Again, the limit on cathode loading is not a sharp one, but current technology indicates that for good cathode lifetime $I_A$ should be less than about 10 A/cm$^2$. Putting these factors together for $V_b = 500$ kV and $\eta$ = 70%,

$$\begin{aligned} P_k &\approx \eta V_b I_A C_A \pi(\lambda/8)^2 \\ &\approx 35(\lambda/cm)^2 \quad . \end{aligned} \tag{7}$$

This gives $P_k \approx 25$ MW at 34 GHz. The cross-over frequency at which the limit imposed by Eq.(7) is equal to the perveance/efficiency limit of 45 MW lies at about 30 GHz.

Several methods have been proposed for beating the $\lambda^2$ limit imposed on a round-beam klystron by Eq.(7). H. Bohlem (5) has proposed an annular-beam klystron in which the beam interacts with a higher $TM_{0n0}$ radial mode of a cylindrical cavity. Sheet-beam klystrons have also been studied fairly extensively (see, for example, Ref. (6)). In such a klystron, space charge forces are reduced by, essentially, putting a number of square beams in parallel. The measure of space charge forces is then the perveance per square, equivalent to $\pi/2$ times the perveance of a round beam carrying the same current. Thus for good efficiency ($\approx 70\%$), the perveance per square should not exceed $K_\square \approx 0.20$. The power limit per centimeter of beam width at $V_b = 500$ kV is then $P_k/cm \approx 150MW/\lambda(cm) \sim \omega$.

There is also a beam area limit for a sheet beam klystron, analogous to Eq.(7), given by

$$\begin{aligned} P_k/cm &\approx \eta V_b I_A C_L (\lambda/6) \\ &\approx 9\lambda(cm)MW/cm \end{aligned} \tag{8}$$

at $V_b = 500$ kV, $\eta = 0.7$ and $I_A = 10A/cm^2$. Here $C_L$ is the linear compression ratio in beam thickness, taken to be 15. Again, this is not a sharply defined limit. The cross-over frequency at which the limit imposed by Eq. (8) is equal to the perveance-efficiency limit of 150 MW/$\lambda$ is about 7 GHz. At 34 GHz, $P_k$/cm $\approx$ 8 MW/cm. Thus to meet the 78 MW power requirement calculated in the previous section a beam about 10 cm wide by 1.5 mm thick will be needed. Note that $K_\square \approx 0.01$. Thus space charge forces are truly negligible in such a device.

Multiple beam klystrons have been proposed in which several beams are packaged together in a common vacuum envelope. They would share rf cavities, but would probably have separate stacks of PPM focusing magnets for each beam. At 34 GHz, in the frequency regime covered by Eq.(7), a single round-beam klystron can produce 15-25 MW at 400-500 kV with good efficiency ($\approx 70\%$ at $K_\mu \approx 0.35$). It would take 3-5 such beams to produce the desired 78 MW, or 6-10 beams to produce 155 MW.

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## ADDENDUM TO SLAC-PUB-7256

After this paper was submitted for publication in the conference proceedings, it was pointed out by R. M. Phillips (SLAC) that the maximum area compression ratio that can be achieved in a gun design is a strong function of perveance. Very crudely, $C_A \approx 150/K_\mu^2$ within a factor of two or so for microperveance values in the range 0.2 to 2.0. For $I_A = 10A/cm^2$ and $V_b = 500kV$, the microperveance at the maximum area compression ratio is given by $K_\mu \approx 0.6(\lambda/cm)^{2/3}$. If a microperveance of 0.35 is chosen for good efficiency, the klystron power output will be limited by area compression and cathode loading considerations only above a frequency on the order of 65 GHz. Alternatively, at 34 GHz the klystron output power will be limited by these considerations for $K_\mu \geq 0.55$.