Scaling Linear Colliders to 5 TeV and Above*

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Abstract. Detailed designs exist at present for linear colliders in the 0.5–1.0 TeV center-of-mass energy range. For linear colliders driven by discrete rf sources (klystrons), the rf operating frequencies range from 1.3 GHz to 14 GHz, and the unloaded accelerating gradients from 21 MV/m to 100 MV/m. Except for the collider design at 1.3 GHz (TESLA) which uses superconducting accelerating structures, the accelerating gradients vary roughly linearly with the rf frequency. This correlation between gradient and frequency follows from the necessity to keep the ac "wall plug" power within reasonable bounds. For linear colliders at energies of 5 TeV and above, even higher accelerating gradients and rf operating frequencies will be required if both the total machine length and ac power are to be kept within reasonable limits. An rf system for a 5 TeV collider operating at 34 GHz is outlined, and it is shown that there are reasonable candidates for microwave tube sources which, together with rf pulse compression, are capable of supplying the required rf power. Some possibilities for a 15 TeV collider at 91GHz are briefly discussed.

1. INTRODUCTION

Detailed design parameters have been developed for linear colliders in the 0.5–1.0 TeV center-of-mass energy range (see, for example, the report of the International Linear Collider Technical Review Committee (1)). Some basic rf-related parameters for these machines at the 1 TeV design energy are given in Table 1. The designs listed are the SBLC (S-band Linear Collider) at DESY; the JLC (Japan Linear Collider) C-band and X-band designs developed at KEK, Japan; the NLC (Next Linear Collider) at SLAC; and the VLEPP (Russian acronym for colliding linear electron positron beams) at the Branch Institute for Nuclear Physics, Protvino. Parameters for the first (and as yet the only) operating linear collider, the 0.1 TeV SLC machine at SLAC, are shown for comparison. All the machines shown in the table use copper accelerating structures. Not shown is the TESLA linear collider at DESY, which is based on superconducting rf technology. Operating at a frequency of 1.3 GHz and a gradient of 25 MV/m, the TESLA technology is difficult to scale to a higher gradients and energy. Also not shown in Table I are two proposed linear colliders which are based on the two-beam accelerator approach: CLIC at CERN and the Two-Beam NLC proposed by LBNL, Berkeley, and LLNL, Livermore. Although the drive beam of a two-beam accelerator is capable of producing copious amounts of rf power at good efficiency, for the purpose of scaling linear colliders with frequency we consider here only colliders powered by discrete rf sources.

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Table 1
Linear Collider RF Parameters at 1 TeV Center-of-Mass Energy

	SBLC (DESY)	JLC-C (KEK)	JLC-X (KEK)	NLC (SLAC)	VLEPP (BINP)	SLC (SLAC)
RF Frequency GHz	3.0	5.7	11.4	11.4	14.0	2.856
Accelerating Gradient Unloaded/Loaded (MV/m)	42/36	58/47	73/58	77/64	100/91	21
Dark Current Capture Gradient (MV/m)	16	31	61	61	75	15
Peak Power per Meter at Structure Input (MV/m)	49	97	100	96	120	12
Klystron Peak Power (MW)	150	100	67	75	150	65
Klystron Pulse Length (μs)	2.8	2.4	0.75	1.44	0.5	3.5
Repetition Rate (Hz)	50	50	150	120	300	120
Pulse Compression Type	SLED	SLED	DLDS	BPC	VPM	SLED
Compression Ratio	≈3.5	5.0	3.0	4.0	4.6	4.2
Compression Power Gain	2.0	3.5	2.9	3.5	3.3	2.6
Compression Efficiency (%)	≈60	70	97	87	73	62
RF System Efficiency (%)	23	26	31	40	40	14
Number of Klystrons	4900	6200	9200	6500	2800	240
Active Length (km)	29	22	18	18	12	2 × 2.85
Wall Plug Power (MW)	285	200	220	180	115	25

The Technical Review Committee report is primarily concerned with the design of linear colliders at 500 GeV c.m. energy; upgrade paths to 1 TeV are only briefly considered. However, we have selected the 1 TeV parameters because particle physicists strongly urge that collider designs should include the potential to reach this energy. Also, it is more likely that the higher-energy designs push the limitations of rf sources at each frequency. If the unloaded accelerating gradients listed in Table 1 are plotted as a function of rf frequency, it will be seen that the gradients vary approximately as $G_0 \sim \omega_{rf}^{0.55}$. For the more detailed designs at 0.5 TeV, it is found that the unloaded gradients vary approximately linearly with rf frequency. There is, of course, a simple physical reason for this correlation with frequency; the stored energy per meter of accelerating structure varies approximately as $(G_0\lambda)^2$, where λ 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 power. Further details on frequency scaling are given in the following section.

Starting with the NLC 1.0 TeV parameters as a base design, and following (at least approximately) the scaling relations developed in Section 2, rough rf parameters for linear collider designs at 5, 10 and 15 TeV are presented in Section 3. It will be found that the peak rf power per meter of structure varies roughly as $\omega_{rf}^{3/2}$. Because the peak power that can be obtained from discrete rf sources such as klystrons is limited and tends to decrease with increasing rf frequency, there will be some cross-over frequency (not sharply defined) above which rf pulse compression is required to enhance the 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. Some background on pulse compression methods is given in Section 4, along with a rough design for a 34 GHz pulse compression system for a 5 TeV collider.

Even with the peak power enhancement provided by pulse compression, the power required from a 34 GHz rf source will be in the 100–150 MW range. In Section 5 some limitations are given on the power that can be reached by round-beam klystrons, and how this maximum power output scales with frequency. It will be found that a conventional round-beam klystron operating at a reasonable beam voltage cannot provide 100 MW of power at 34 GHz. Other possible microwave power sources which can provide power at this frequency and this power level are discussed.

The conclusion of Section 5 is that there is a reasonable expectation that, together with rf pulse compression, a microwave tube source can be built which can provide adequate peak power for driving a 34 GHz linear collider at a gradient on the order of 200 MV/m. However, it does not seem reasonable that discrete rf sources can provide the 2400 MW/m required to drive a 91 GHz, 15 TeV collider at 600 MV/m, unless a new scheme for pulse compression or active power switching is developed. Perhaps at this frequency and gradient the two-beam accelerator approach is the best route to rf power production. A possible two-beam, 91 GHz scheme, due to H. Henke (2), is outlined in Section 6. Finally, we note that this paper is concerned with scaling rf parameters in order to obtain higher gradients and hence a higher energy in a reasonable linac length. How the beam parameters must be scaled in order to reach the 5–15 TeV energy range is another story. A number of papers have been written which provide parameter lists for these, and even higher, collider energies. A set of beam parameters specific to the 34 GHz, 5 TeV collider described here is given in (3).

2. SCALING WITH FREQUENCY

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 for the 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 gradient is given by

$$G_{th} = \pi \, mc^2/e\lambda = 1.605 \text{ MV}/\lambda .$$ (1)

Some linear colliders are designed at gradients that exceed this threshold by a modest factor (30% or so for the 0.5 TeV c.m. designs in the Technical Review Committee report. However, it would be unwise to plan on an operational 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.

The peak power required per meter of structure is given by the energy stored per unit length, $u \sim G_0^2 \, \lambda^2$, divided by the filling time, $T_f = \tau T_0$, where τ is the attenuation parameter and T_0 is the decrement time, $T_0 = 2Q/\omega \sim \lambda^{3/2}$:

$$P_m \sim G_0^2 \lambda^2 / T_f \sim G_0^2 \lambda^{1/2} \quad . \tag{2}$$

The above scaling assumes a constant group velocity and iris aperture, a/λ, relative to the wavelength. If the normalized aperture varies, the above expression should be multiplied by a function $F(a/\lambda)$, where F is approximately proportional to $(v_g/c)^{1/3}$
in the group velocity range of interest for linear colliders, $v_g/c \approx .03$ to 0.10.

Ignoring dark current considerations, the accelerating gradient will eventually be limited by rf breakdown. Some evidence indicates (this is a long story) that the breakdown gradient scales as $\omega^{1/2}/(T_p)^{1/4}$, where T_p is the rf pulse length. Since the pulse length tends to scale in proportion to the structure filling time, $T_p \sim \omega^{-3/2}$, then $G_{br} \sim \omega^{7/8}$. Loew and Wang[4] obtained a breakdown threshold for the peak surface field of 330 Mv/m at 2.856 GHz for a pulse length of several times a typical structure filling time. Using this as a calibration point, the breakdown field limit becomes

$$G_b(Mv/m) \approx 130 \ [f(GHz)]^{7/8} \quad . \tag{3}$$

Using the fact that the peak surface field is on the order of 2.3 times the average accelerating gradient in a typical accelerating structure, the breakdown threshold accelerating gradient will be about 140 MV/m at 2.856 GHz. This is about 9 times the dark current capture gradient. At 91 GHz this ratio is about 6. Thus for any projected linear collider rf frequency, the accelerator will always operate well below the breakdown threshold and operation will be limited to effects related to dark current capture and rf processing.

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

$$\Delta T = (R_s/K) \ (DT_p/\pi)^{1/2} (G/Z_H)^2 \tag{4}$$

Here R_s is the surface resistance, K is the thermal conductivity and D is the thermal diffusivity, given by $D = K/C_v$ where C_v is the specific heat per unit volume. Z_H is an impedance defined as $Z_H \equiv G/H_s$ where H_s is the maximum surface magnetic field anywhere in the structure for a given average (not local) accelerating gradient. For the NLC structure, the minimum value of Z_H is 307 ohms (the maximum value is about 400 ohms). Using $D = 1.15 \ cm^2/sec$ and $K = 3.95 \ W/cm/°C$ for copper,

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Eq. (5) gives a temperature rise of 16^0C for the current 1 TeV NLC parameters (G_0 = 77 MV/m and T_p = 360 ns). Assuming the pulse length scales as $\omega^{-3/2}$, the temperature rise scales as $\Delta T \sim \lambda^{1/4} G^2$.

There is considerable controversy over the detailed mechanism for surface damage due to pulsed heating, and the resultant effect on structure Q. Rough estimates indicate that the yield strength in copper is exceeded at a pulse temperature rise on the order of 40^0 C, resulting in surface roughening and fatigue cracks (5). However, the extent to which this surface damage might degrade the rf surface resistance is not clear. To help answer these questions, an experiment is underway at SLAC in which a pulse temperature rise of several hundred degrees is applied to a demountable surface in an X-band cavity (6). After measuring possible changes in surface resistance through changes in cavity Q, the test surface can be removed for microscopic inspection of surface damage.

Finally, we consider the effects of these frequency scaling relations on accelerator length and an ac wall plug power. In the next section, we take some linear collider examples in which the accelerating gradient is scaled in proportion to the dark current capture threshold. The active structure length then scales as $L_A \sim E_{c.m.}\lambda$. In scaling the ac power, we consider a rf pulse repetition rate which is fixed at 120 Hz. The ac power (and luminosity) can always be decreased by lowering the repetition rate. However, as the repetition rate decreases, pulse-to-pulse feedback against the effects of the high frequency component of ground motion becomes more difficult. For a fixed repetition rate, the ac power scales as

$$P_{ac} \sim G\lambda^2 E_{c.m.}/\eta_{rf}, \tag{5a}$$

where η_{rf} is the efficiency for conversion of power from the ac line to the structure input. Again, if the iris aperture is opened up at shorter wave lengths to reduce wakefields and to increase the length of the individual accelerating structures, the above expression must be multiplied by $F(a/\lambda) \sim (v_g/c)^{1/3}$. In the next section we will consider a collider scaling which follows approximately $v_g/c \sim \omega^{1/3}$ and $G \sim \omega$. In this case,

$$P_{ac} \sim \lambda^{8/9} E_{c.m.}/\eta_{rf} \tag{5b}$$

3. COLLIDER DESIGNS AT THREE FREQUENCIES

Table 2 shows some linear collider designs scaled in frequency and energy, based on the 1 TeV NLC design shown in the first row. In this design the parameters of

the NLC damped, detuned structure are assumed: $v_g/c = 0.05$, structure length = 1.8 m, $T_f = 120$ ns, $T_0 = 220$ ns, $\tau = 0.545$ and an effective shunt impedance per

Table 2. Linear Collider Designs Scaled in Frequency and Energy

$E_{c.m}$ (TEV)	Frequency (GHz)	G_0 (MV/m)	G_0/G_{th}	P_m (MW/m)	P_{ac} (MW)	L_A (km)	Max ΔT (^{0}C)
1.0	11.4	77	1.26	96	180	17.7	16
1.5	11.4	100	1.64	160	260	20.6	27
5.0	34.3	225	1.23	530	280	30.4	112
10	91.4	500	1.02	1700	160	27.4	405
15	91.4	600	1.23	2400	290	34.3	585

unit length of 94 MΩ/m. Effective shunt impedance means that, using this value in the standard expression for acceleration in a constant gradient (CG) structure, an unloaded gradient of 77.4 MV/m is obtained in the actual NLC structure (which differs somewhat from a true CG design because of the Gaussian detuning) for a peak power per meter of 96 MW. A beam loading gradient of 13.6 MV/m is obtained for bunches with 1.1×10^{10} electrons spaced 2.8 ns (32λ) apart (an effective shunt impedance of 96.5 MΩ/m must be used in standard CG expression to obtain the beam loading gradient for the actual NLC detuned structure). The loaded gradient is then 63.8 MV/m. Assuming an overhead factor of 1.15 (to account for off-crest operation for BNS damping, feedback overhead etc.), and allowing for an injection energy of 10 GeV per linac, the total active structure length is 17.7 km. The rf pulse length of 360 ns allows for a train of 81 bunches (225 ns), the structure filling time (120 ns) and a switching and rise time allowance of 15 ns.

The beam size at the IP is 5 nm × 250 nm with a pinch enhancement factor of 1.4, giving a luminosity of 1.0×10^{34}/cm^2/sec. More complete beam parameters are given in the NLC ZDR Design Report (7). The required klystron power is obtained assuming a binary pulse compression system with a factor of 4 compression ratio and an efficiency of 0.875 (power gain = 3.5). Assuming four klystrons and six 1.8 m accelerating structure per BPC system, the klystron power is (96 MW/m)(10.8m)/(4)(3.5) = 74 MW. The ac power assumes an rf system efficiency of 40%: klystron efficiency = 61%, modulator efficiency = 75%, pulse compression and rf power transmission efficiency = 87.5%. The rf energy per pulse at the structure input is (360 ns)(96 MW/m) = 34.5 J/m. Multiplying this by the active length and repetition rate, and dividing by the rf efficiency gives $P_{ac} = 183$ MW. The number of pulse compression systems is 17.66 km/10.8 m = 1635. The number of klystrons is four times this or about 6500.

The next row in Table 2 shows how the 11.4 GHz, 1 TeV collider might be scaled to 1.5 TeV with only a modest increase in length by employing a higher power, higher efficiency rf system. The unloaded gradient is increased to 100 MW/m by increasing the klystron power to 124 MW. This implies an extended beam or multiple beam device (see Sec. 5), or the use of two 62 MW tubes in place of each 74 MW klystron. The ac power is computed on the assumption that the klystron efficiency has been raised to 66% (efficiencies of this order are already being obtained in simulations). Also, it is assumed that the modulator has been

eliminated and that the klystron beam is switched by a grid from a dc supply with a switching efficiency of 95%. The net rf system efficiency is then 55%.

In the third row parameters are given for a 5 TeV collider with a frequency and unloaded gradient which are both three times the 1 TeV X-band values. The group velocity has been increased to .072c, giving a structure length and filling time of 0.5 m and 23 ns. The decrement time scales to $T_0 = 220/3^{3/2} = 42$ ns, giving $\tau = 0.54$. Taking into account the larger iris aperture, the shunt impedance scales to 144 MΩ/m. This gives a peak power per meter of 530 MW/m for an unloaded gradient of 225 MV/m. The beam loading gradient is based on a charge of 2.4×10^9 electrons per bunch and a bunch spacing of $12\lambda = 0.350$ ns. The loaded gradient then works out to be 188.5 MV/m, and the active length to 30.4 km, assuming again a 15% overhead in length. The rf pulse length of 80 ns is based on a train of 150 bunches (52 ns), plus the 23 ns filling time, plus a 5 ns allowance for phase switching and rise time. The ac power then works out to be 280 MW. Assuming a transverse beam size of 0.3×30 nm at the IP, a luminosity of 1.5×10^{35}/cm^2/sec is obtained with a pinch enhancement factor of 1.7. More detailed beam parameters are given in (3). To calculate the required klystron power a pulse compression system design must be assumed. This is described in Sec. 4.

The 91 GHz (8 × 11.42 4 GHz) parameters listed in Table 2 are obtained assuming a group velocity of 0.10c and a structure length 0.18 m, with $T_f = 6$ ns, $T_0 = 10$ ns, and $\tau = 0.60$. The beam loaded gradient is assumed to be 84% of the unloaded gradient, as in the 5 TeV example, giving a total active structure length of about 34 km. An rf pulse length of 16 ns is chosen, allowing for a train of 100 bunches spaced 8λ apart. For the assumed beam loading gradient, the bunch charge is about 1×10^9 electrons. The beam cross section will have to be incredibly small (on the order of $.04 \times 4.0$ nm) to achieve a luminosity of 1×10^{36}/cm^2/sec.

The pulse heating is marginally high, but within the realm of possibility for the 5 TeV collider. Perhaps same sort of surface treatment or surface coating can ameliorate the effects of a pulse temperature rise of this magnitude. However, it does not seem reasonable that pulse temeprature rises of 400–600^{0}C can be tolerated. Also, even with pulse compression, a very large number of very high power rf sources will be needed for the 91 GHz machines because of the high peak power per unit length. It is also questionable whether the required peak power flow can be accommodated without breakdown in the power transmission components. For these reasons, a 5 TeV, 34 GHz linear collider may be the end of the line for a machine based on conventional rf technology.

4. RF PULSE COMPRESSION

An rf pulse compression system can enhance the peak power output from a microwave tube by trading increased peak power for reduced pulsewidth. The power gain is given by the compression ratio in pulsewidth, R, times a compression efficiency which takes into account intrinsic losses (e.g., reflected

power in a SLED pulse compression system), resistive copper losses, and the efficiency reduction due to a non-flat output pulse. Pulse compression reduces the burden on the rf power source and helps to match the modulator pulse length to the accelerating structure filling time. This is especially important at higher frequencies where the filling time is short and the production of peak power is more difficult. A pulse compression system always involves an energy storage element to delay or transfer energy from the early portion of the rf pulse into the compression output pulse.

The first large-scale pulse compression system for an accelerator application was the SLED scheme, implemented on the SLAC linac in the late 1970's. Using a pair of TE_{015} cylindrical cavities ($Q_0 \approx 1 \times 10^5$) as energy storage elements, SLED produces a power gain of about 2.7 with a compression efficiency of 62% (R = 4.4). A characteristic feature of the SLED compression method is a 180^0 phase reversal in the klystron drive, which triggers the release of the energy stored in the high Q cavities. Two cavities and a 3 db coupler are used so that the energy reflected and emitted from the cavities will not return to the klystron but will be directed into the transmission line to the accelerator.

Because the SLED output pulse has a shape which is dominated by the exponential decay of energy in the storage cavities, it is poorly adapted for powering a linear collider with long bunch trains. The pulse shape problem can be solved by replacing the two storage cavities with shorted delay lines. In this scheme, called SLED-II, the delay line length (in travel time) is equal to one-half the desired output pulse length. The power gain is optimized by adjusting the reflection coefficient of an iris at the entrance to the delay lines. Assuming lossless components, the power gains (and intrinsic efficiencies) for a SLED-II system with compression ratios of 4, 5 and 6 are 3.44 (86%), 4.0 (80%) and 4.5 (75%). The 0.5 TeV NLC design uses a SLED-II pulse compression (PC) system with R = 5. Losses in the delay lines and other components reduce the efficiency from 80% to 76%. Power transmission losses from the klystron to the PC system and from the PC system to the accelerator are usually included in calculating the PC system efficiency and power gain. Including transmission losses, the net efficiency of the NLC system falls to 72% and the power gain to 3.6.

If the 0.5 TeV NLC design is scaled to 1 TeV, the power loss due to the intrinsic inefficiency of the SLED-II system translates to an intolerable 30–40 MW increase in ac power. There are several schemes for pulse compression which eliminate or reduce this loss. In the so-called Binary Pulse Compression (BPC) scheme, the input rf pulse is divided into 2^n time bins, where n is the number of compression stages and $R = 2^n$ is the net compression ratio. At the input to the first stage, the power from two klystrons is combined by a 3–db directional coupler (hybrid). The phase relation between the waves at the input ports of the hybrid is such that, during the first half of the pulse, the power from both klystrons is directed into a delay line with a time length equal to half the pulse length. Half way through the pulse the relative phase at the input ports of the hybrid is switched by 180^0 (by reversing the drive phase of one of the klystrons), causing the combined klystron power to come out of the second output port of the hybrid, in time coincidence with the power emerging from the delay line. A clever phase switching pattern devised by Z. D. Farkas allows compression stages to be chained in series,

the peak power being doubled and the pulse width cut in half at each stage. The total length of delay line needed for a BPC system is $(R-1)T_p$, where T_p is the output pulse width. For the NLC 1 TeV design, a two-stage BPC system is envisional with an efficiency (due mostly to copper losses) of 0.875 and a power gain of 3.5. The total delay length is 3×360 ns = 1.08 μs.

If cylindrical pipe is used to achieve this delay, the total length of pipe would need to be about 300 m. In principle, the pipe can be replaced by a sequence of high Q TE_{01n}-mode cylindrical cavities having a much shorter total length. An analysis using an equivalent circuit model (a chain of inductively-coupled resonant circuits) has shown that a relatively small number of coupled cavities can produce a reasonably flat output pulse. The transmission efficiency of such a system can be quite high. For example, a cavity 20 cm in diameter and 2.5 m long would have a Q of 1.5×10^6 and a decrement time of 42 μs at 11.4 GHz. A two stage BPC system employing such cavities would have a transmission efficiency of 95% (neglecting pulse shape effects) for an output pulse length of 360 ns.

This concept for pulse compression can be applied to produce the 530 MW/m required by the 5 TeV, 34 GHz linear collider example listed in Table 2. Assume eight 0.5 m accelerating structures per 3-stage BPC system. A TE_{01n}-mode cavity 1 m long by 10 cm in diameter would have a Q of 1.25×10^6 and a decrement time of 11.7 μs. For an output pulse length of 80 ns the transmission efficiency due to cavity losses would be 91% (there would be an additional efficiency loss due to pulse-top ripple and rise time degradation). Assuming additional losses of 6.5%, the net compression efficiency would be 85% and the power gain would be 6.8. The required klystron power is (530 MW/m)(4.0 m)/(2)(6.8) = 155 MW. In the next section, we discuss how this source power might be achieved at 34 GHz. Note also that the peak power flow at the output of the BPC system is about 1100 MW. It will be difficult to design the hybrid and other waveguide components to accommodate this power flow without breakdown, but carefully designed oversized components could do the job.

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:

$$\eta \approx 0.75 - 0.17 \, K_\mu. \qquad (6)$$

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To achieve the desired efficiency of 68%, $K_\mu \approx 0.41$. At a beam voltage of 500 kV, the output power would be $P_k = \eta K V_b^{5/2} \approx 50$ MW. This limitation is independent of rf frequency.

A second limitation on klystron power is related to the area of the electron beam, which does depend on wavelength. To achieve good coupling to the longitudinal rf fields in the output gap, the radius of the beam should not be larger than about $\lambda/8$. If the beam radius exceed this, then electrons on the beam axis and electrons at the edge of the beam will see a substantially different rf gap voltage, and efficiency will suffer. Next, the beam area at the cathode can be larger than the beam area in the drift region by a factor A_c, the area convergence ratio. This ratio is limited by aberrations in the gun optics, transverse emittance, alignment tolerances, etc. A good measure of these effects is the convergence half-angle, which is related to the f ratio of conventional optics. In practice, it is found that the convergence half-angle is limited to about 40^0, corresponding roughly to f 0.6. Because of the dynamics of space-charge-limited electron flow in the gun region, the gun focal length and hence the area convergence ratio depends on the perveance (8). By plotting A_c vs. K_μ for a variety of gun designs with a convergence half angles of 35^0–40^0, the points can be crudely fit (within a factor of two or so) by

$$A_c \approx 150/K_\mu^2 \; . \tag{7}$$

A further limitation is the acceptable cathode loading current per square centimeter, I_A. Putting these factors together, the maximum output power is

$$P_k \approx \eta \, V_b \, I_A A_c \pi \, (\lambda/8)^2 \; , \tag{8}$$

where both η and I_A are functions of perveance. If Eq. (7) is equated to $P_k = \eta K v_b^{5/2}$, an expression is obtained for the maximum perveance allowable which is consistent with the limitations imposed by Eq. (7):

$$K_\mu = 194 \, I_A^{1/3} \, \lambda^{2/3}/V_b^{1/2} \; . \tag{9}$$

Taking $I_A = 10\text{A/cm}^2$ and $V_b = 500$ kV, Eq. (9) gives K_μ (max) = 0.54, $\eta = 0.66$ and $P_k = 63$ MW at 34 GHz. A lower perveance can, of course, be chosen for better efficiency at lower output power.

The bottom line is that it should be possible to build a klystron at 34 GHz which has good efficiency (65–70%) and an output power on the order of 50 MW. To obtain the 150 MW desired to drive the 34 GHz pulse compression system described in the previous section, there are several possibilities. For example, three

or four 40–50 MW beams can be packaged together in the same vacuum envelope. Such a multibeam klystron having common rf cavities but separate PPM-focused beams has indeed been proposed (8). Klystrons using a sheet beam, which is essentially equivalent to many round beams in parallel, are also capable (in simulations) of producing 150 MW at 34 GHz with good efficiency (9). It is well known that gyroklystrons are also capable of producing high power at high frequency. At the University of Maryland, a coaxial-circuit gyroklystron frequency doubled from 17 to 34 GHz has been designed which produces an output power of 150 MW at a simulated efficiency of 42% (10). A single-stage depressed collector can increase the efficiency to 56%.

Another annular-beam device capable of delivering high power output at high frequencies is the Ubitron (FEL) proposed by McDermott et. al (11). Using a TE_{01}-mode coaxial cavity and a PPM wiggler, it produce a simulated output power of 250 MW at 11.4 GHz with an efficiency of 50%. It should be capable of producing a high output power when scaled to 34 GHz.

6. TWO-BEAM 15 TeV COLLIDER CONCEPT

As shown in Table 2, a high gradient, 91 GHz collider runs into trouble from pulse heating, in spite of a very short rf pulse length of 16 ns. As a possible way around this difficulty, H. Henke (2) has proposed a two-beam accelerator scheme which uses a beat-wave transformer to extract rf power from the drive beam in extremely short bursts. Very briefly, the transformer consists of two 91 GHz side-by-side coupled cavities with an aperture for the drive beam in one cavity and an aperture for the main accelerated beam in the other. The coupling is adjusted to produce a beat frequency period which is equal to on-half of the period of the rf for the drive beam re-acceleration cavities. A drive beam bunch, which has a bunch length of about $\lambda/2$ so that higher modes are not significantly excited, deposits energy in the fundamental mode in the first cavity. This energy then passes into the accelerating cavity in a time given by one-half the beat frequency period. At this time the bunch (or short train of bunches) to be accelerated passes through the second cavity, removing a fraction of the stored energy. The remaining energy now couples back into the first cavity during the second half of the beat frequency cycle. At this time a scavenger bunch, riding at the decelerating phase of the drive beam rf, passes through the first cavity and removes a major portion of the unused energy and returns it to the drive beam.

As an example, assume that the 1.3 GHz TESLA superconducting accelerator provides the drive beam. The beat frequency period would then be $(2.6\ \text{GHz})^{-1}$ = 385 ps. The effective time the energy spreads in the accelerating cavity is about a fourth of this, or about 100 ps. The temperature rise at a gradient of 600 MV/m is then only 45^0C.

Finally, we note that, even with efficient pulse compression by a factor of eight, a 15 TeV accelerator powered by conventional rf sources would require five 70 MW tubes per meter of active length. The two-beam accelerator scheme outlined above seems to be a much cleaner and efficient way to provide the rf power. It could be viewed at as a 15 TeV upgrade to the TESLA machine.

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