SLAC-PUB-4706
September 1988
(A)

A CLUSTER KLYSTRON*

ROBERT B. PALMER and ROGER MILLER

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

ABSTRACT

We consider a honeycomb-like array of 126 individual klystrinos all fed from a single high-voltage source and all focused by a single axial magnetic field. It is argued that such a device may be a practical and economic power source for a TeV Linear Collider. It could be used either as a source of $\frac{1}{2}$ μsec rf pulses to be binary pulse compressed or, with a grid cathode and oil line energy storage, as a direct source of power.

1. INTRODUCTION

For a .5 on .5 TeV Linear Collider we need (for example)[1]

wavelength $\lambda = 17.5$ mm
power/length $P \approx 600$ MW/m
length/feed $\ell_{\text{feed}} = 1.6$ m
power/feed $P_{\text{feed}} = 930$ MW
no feeds $n_{\text{feed}} = 3.6$ K
pulse length $\tau = 60$ nsec
energy/length $J = 36$ Joules/m
total length $\ell_{\text{cavity}} \approx 6$ Km
total energy $J_{\text{TOTAL}} \approx 200{,}000$ Joules
total power $P_{\text{TOTAL}} \approx 3.4$ TWatts

If we consider the use of "conventional" klystrons operating at a voltage of the order of 400 KV then space-charge considerations (perveance ≤ 2) limit the current to 500 amps and the power output (at 50% beam-to-rf efficiency) per tube to 100 MW. And even this would be hard to achieve at 17 GHz. With 100 MW/tube, 34,000 tubes would be required. To avoid this two approaches are possible: either raise the voltage thus allowing higher currents; or use sheet or multiple beams so as to provide the very large number of "tubes" required without excessive cost.

The objections to raising the voltage are now becoming clear:

A) Higher voltage implies intense X-ray production, requiring significant shielding, and probably forcing the location of such klystrons in the accelerator tunnel rather than in a gallery.

B) Very high voltages are best obtained with Induction Linacs rather than a simple gun. Such Linacs are excessively expensive unless the drive current is relatively high (e.g., ~ 10K amps). But such high currents require even higher beam energies with corresponding problems and development time.

C) The power supplies (e.g., magnetic compressors) to drive the required Induction Linacs with short pulses are also expensive.

For these reasons it is worth considering the other alternatives.

A) The Sheet-beam klystron has been studied by R. Miller et al.[2] Several problems were revealed: The efficiency was relatively low; there is a problem with maintaining the phase stability in the cavities, and there is a danger of feedback from the output to the input cavity of transversely polarized rf.

B) These problems are, of course, absent in a multi-klystrino approach as proposed by G. Loew.[3]

The present note represents an alternative packaging of Greg's basic idea.

2. PARAMETERS OF AN INDIVIDUAL KLYSTRON

We will consider two cases: 1) with a cathode of 8 amps/cm^2 and 2) with 32 amps/cm^2 and compare these

---

*Work supported by the Department of Energy, contract numbers DE-AC02-76CH00016 and DE-AC03-76SF00515.

Invited talk at the DPF Summer Study Snowmass '88, High Energy Physics in the 1990's, Snowmass, Colorado, June 27–July 15, 1988 with a conceptual design[4] of a 100 MW 12 GHz tube (refer to the table on the following page).

It is seen that the parameters of examples (1) are universally conservative, and of example (2) conservative in everything but the cathode current. Let me assume that we adopt example (1) for phase I of our TLC (i.e., 250 + 250 GeV) and hope that the higher current will become available for the full TLC (500 + 500 GeV). Then the number of tubes required is:

		Klystrino	
	Ref Design	Expl(1)	Expl(2)
f gH_z	12	17	
j_{cathode} A/cm^2 [1]	8	8	(32)
diam (cathod) mm	90	18	
I amps	500	20	(80)
V kVolts	400	400	
Perveance [2]	$2\ 10^{-6}$	$.08\ 10^{-6}$	$(.32\ 10^{-6})$
efficiency [3]	50	75	(70)
P_{out} MWatts	100	6	(24)
B Tesla [4]	0.5	0.15	(0.3)
diam (drift tubes) mm	9	6	
$R = \frac{\text{cathode diam}}{\text{drift tube diam}}$ [5]	10	3	
J_{in} for 62 nsec		5	(20)
J_{in} for 75 nsec		6	(24)
J_{in} for 520 nsec		42	(166)

Notes:

[1] 8 amps/cm^2 is standard SLAC 5045 performance and thus very conservative. 32 amps/cm^2 is claimed to be now available from Varian, although its vacuum requirements and lifetime seem uncertain; it represents a less conservative but not unreasonable goal.

[2] Perveance is defined by

$$Pv = \frac{I(\text{amps})}{V^{\frac{3}{2}}(\text{Volts}^{\frac{3}{2}})}$$

and is a measure of the severity of space-charge effects.

[3] The efficiency of converting beam power to rf power could, if there were no space-charge effects, approach 100%. In practice the efficiency obtainable falls as the perveance rises (fig. 1),[6] and the assumed efficiencies used have reflected this empirical observation.

[4] The field required to balance the space-charge forces in the beam is given by:

$$B \propto \frac{1}{\lambda}\left(\frac{I}{\beta\gamma}\right)^{\frac{1}{2}} .$$

In these examples I have scaled from the 17 GHz 100 MW design.[4]

[5] The ratio of cathode to drift tube diameters is a measure of the precision with which the gun must be designed and built. There may be no theoretical limit to this ratio but in practice ratios larger than about 7 are hard to achieve without beam loss.

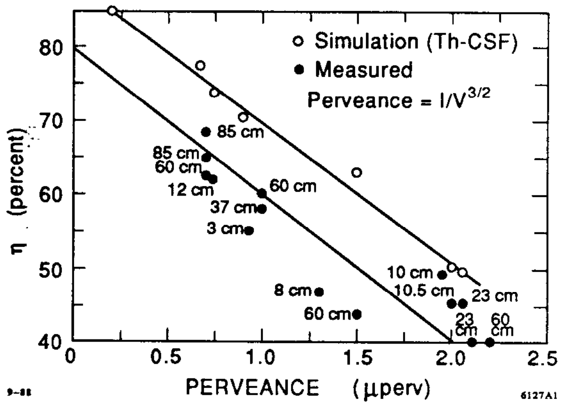


Fig. 1. Klystron efficiences plotted as a function of perveance. The wavelengths of examples are given by each measured point. The lines represent an approximate fit to the simulated and measured values.

a) With 8× pulse compression at 85% efficiency[5]

$$n = \frac{3.4\ 10\ 12\ \text{Watts}}{.85 \times 24\ 10\ 6\ \text{Watts}} \times \frac{1}{8} = 29,000 \quad ;$$

b) with no pulse compression

$$n = \frac{3.4\ 10\ 12}{24\ 10\ 6} = 140,000 \quad .$$

These are formidable numbers. How can one build them at reasonable cost?

3. THE HONEYCOMB CONCEPT

It is proposed here to build the klystrons into honeycomb-like structures. Each structure containing 126 individual klystrons. The number of such structures is now

a) with 8× pulse compression at 85% efficiency

$$w_s = \frac{18,000}{.85 \times 126} \approx 170 \quad (1 \text{ per } 35 \text{ m}) \quad ,$$

b) with no pulse compression

$$n_s = \frac{140,000}{126} = 1140 \quad (1 \text{ per } 6 \text{ m}) \quad .$$

Both of which seem reasonable. Indeed, if such clusters can be built for a reasonable cost, and if a method to power the tube for ≈ 60 nsec can be provided, then pulse compression would seem unnecessary.

It is proposed here to group the klystrons into clusters of 18 (see fig. 2a). Each cluster would have its own input and output wave guide. Within a cluster the cavities of all 18 tubes would be strongly coupled and thus locked in phase and amplitude. Each cluster of tubes would act as a single klystron, with the only difference that the current is broken up into sub beams, and, as a result the space charge forces greatly reduce.[7] Seven of these clusters would form a single structure with 126 individual tubes (see fig. 3a).

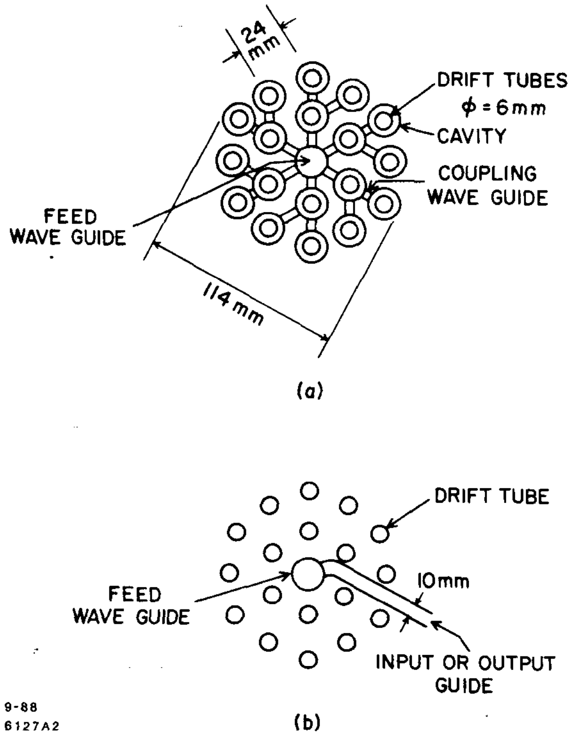


Fig. 2. A single cluster of 18 klystrinos; a) showing the cavities with rf feed at center; b) showing drift tubes between cavities with input or output guide to the feed.

The waveguides to feed, damp or extract power from a cluster of cavities could consist of short longitudinal mode guides at the center of each cluster. In the case of the output cavities these longitudinal guides could continue out through the beam dump. For the input guides they would extend just into the space before the next cavity, and there convert to conventional guides passing between the drift tubes (fig 3b). They could then couple again into longitudinal guides outside the honeycomb and pass thus out through the beam dump.

The object in this design is to minimize the number of parts. The input, output, or intermediate cavities, of all 126 tubes would be machined into discs of Copper, as would the feed waveguides (fig. 4). Though each disc would involve complex machining, the number of such discs would be no more than the number of parts in a single klystron.

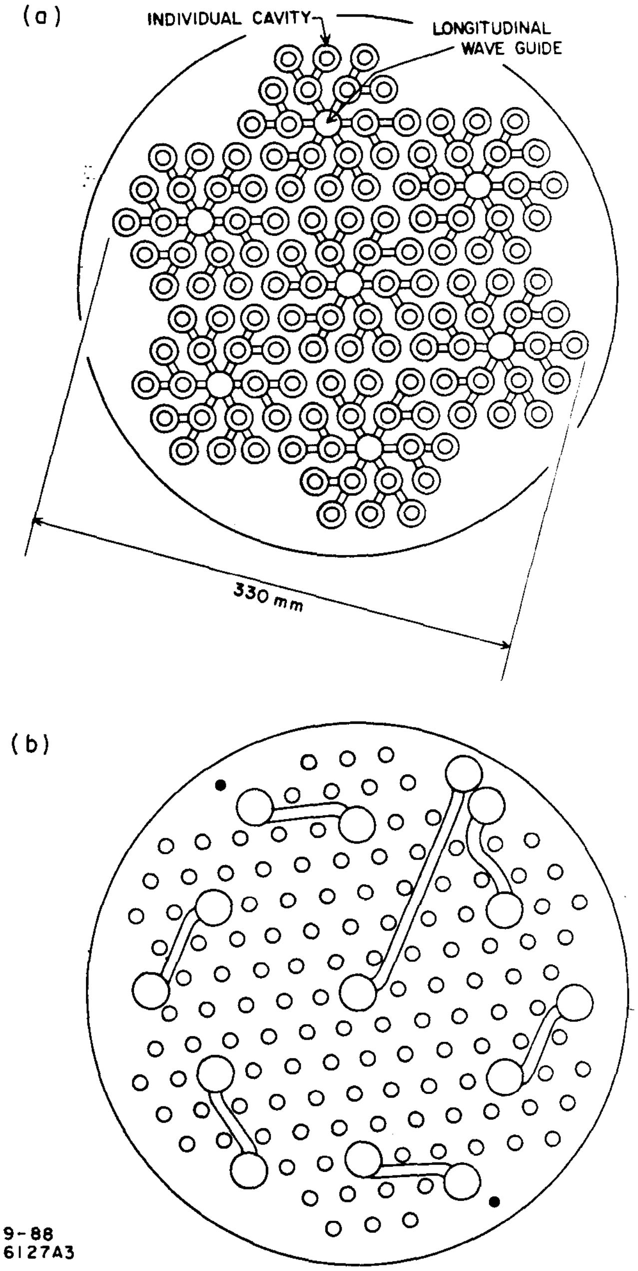


Fig. 3. Seven clusters in a single copper block; a) showing cavities; b) showing guides joining cluster feeds to external axial wave guides.

4. GUN DESIGN

Focusing within the honeycomb of klystrons can be provided by a uniform axial magnetic field. In order to keep the beams within the drift tubes the transverse fields must be small and the field quality requirement for the 275 mm diameter area should be of the order of:

$$\frac{\Delta B}{B} \leq 2 \times 10^{-3} \quad .$$

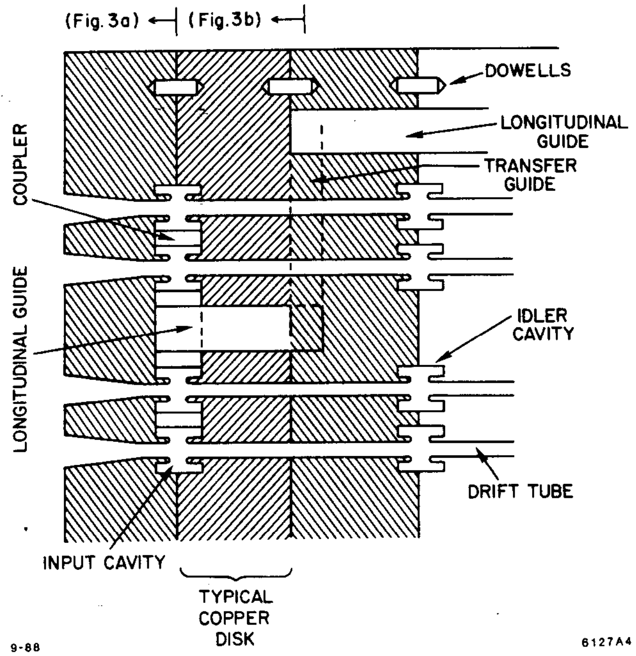


Fig. 4. Section showing construction.

At the cathode end the situation is more complicated. The field must be reduced in order to allow the current to converge from the larger cathode area into the smaller drift tubes. The method proposed is to use an iron end plate with holes in it to effectively end the axial fields (fig. 5).

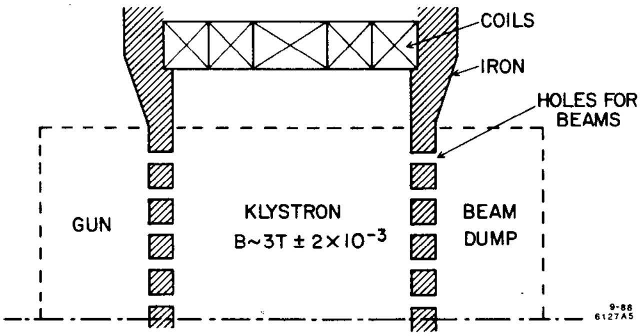


Fig. 5. Magnet with perforated iron end plates to restrict field to the klystron region.

The required thickness t of the iron plate depends on the focusing field B_k, the allowed field in the iron B_{Fe}, the hole radii r, the hole spacing s and the total honeycomb radius R

$$t = \frac{R}{2}\frac{B_k}{B_{Fe}}\frac{s}{s-r} \quad .$$

For the high j_c example: $B_k = 0.3$ Tesla, $B_{Fe} = 1$ Tesla R $= 140$ mm, r $= 10$ mm and s $= 24$ mm. Then, $t = 43$ mm (or 22 m for the lower current density).

Outside the iron plate the gun geometry would be relatively conventional (fig. 6). The design is complicated by the relatively late application of the magnetic field, but is eased by the low reduction ratio from the cathode to drift tube (3×).

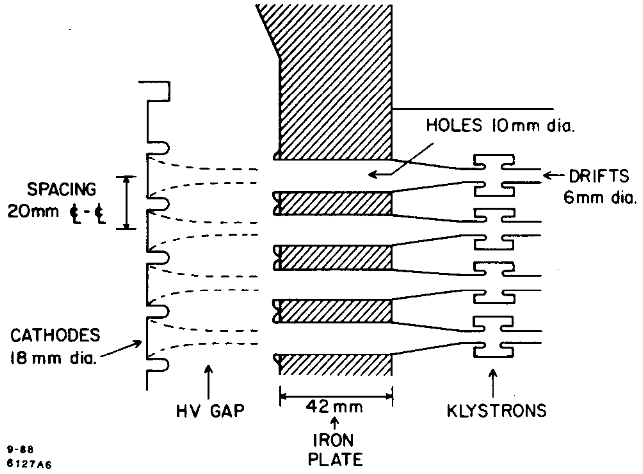


Fig. 6. Conceptual view of gun.

5. POWER SUPPLIES AND EFFICIENCY

A. Binary Pulse Compression

If used with 8× pulse compression then an initial pulse of 520 nsec would be required (60 nsec output pulses with 6 nsec between pulses to allow time for the phase to change). A 400 KV 520 nsec modulator could presumably be designed along more or less conventional lines. If the rise and fall times of such a modulator were ≈ 100 nsec, and the power supply efficiency were 90% than the overall efficiency would be:

$$\eta_a = \underset{\substack{\uparrow\\ \text{Power}\\ \text{Supply}}}{\cdot 9} \times \underset{\substack{\uparrow\\ \text{Rise \&}\\ \text{Fall}}}{\cdot 8} \times \underset{\substack{\uparrow\\ \text{Klystron}}}{\cdot 7} \times \underset{\substack{\uparrow\\ \text{Time to}\\ \text{Change}\\ \text{Phase}}}{\cdot 9} \times \underset{\substack{\uparrow\\ \text{Pulse}\\ \text{Compression}}}{\cdot 85} = \cdot 38$$

It would be reasonable to put a separate pulse compressor on each pair of clusters. For the 32 amp per square cm case, the output power is 432 MW per cluster of 18 tubes (18 * 24). Using two such clusters as input to an eight-fold compressor, the output (at 85% efficiency) would be 2.8 G watts emerging from each of two waveguides. These would have to be divided into three to give the required .9 G watt per feed. There would then be:

1 klystron/21 feeds, (1 klystron/35 m)
1 compressor/6 feeds, (1 compressor/10 m)
Total: 3.6 K feeds
600 compressors
171 klystrons

B. Magnetic-Pulse Compressor

If no pulse compression were used then a power supply is needed that can give 400 KV for a 60 nsec pulse. Magnetic compressors could do this. The rise and fall time would be of the order of 15 nsec leading to an overall efficiency:

$$\begin{array}{ccccccccc} \eta_b = & \cdot 9 & \times & \cdot 9 & \times & \cdot 75 & \times & \cdot 7 & = \cdot 42 \\ & \uparrow & & \uparrow & & \uparrow & & \uparrow & \\ & \text{Power} & & \text{Magnetic} & & \text{Rise \&} & & \text{Klystron} & \\ & \text{Supply} & & \text{Compressor} & & \text{Fall} & & & \end{array}$$

C. Grid-Controlled Cathode

Another way to obtain the required 60 nsec pulse of 10,000 Amps would be to leave essentially full voltage on the gap but switch the current with a grid placed close to the cathode. The gun gap would be connected to a suitable oil delay line (fig. 7a), recharged by a power supply between pulses. The voltage wave from the gap would be as shown in fig. 7b; and the maximum gap voltage V_0 will be given by:

$$V_0 = V_k \frac{1 + Z_0}{R_k} \quad ,$$

where V_k = klystron voltage = 400 KV, R_K = klystron impedance = $\frac{400\text{KV}}{10{,}000\text{A}}$ = 40 Ω 's (160 Ω 's for the lower current density) and Z_0 = impedance of the line.

The energy stored in the line U_0 is given by:

$$U_0 = U_K \frac{R_K}{4Z_0}\left(1 + \frac{Z_0}{R_K}\right)^2 \quad ,$$

where U_K is the energy required by the klystron.

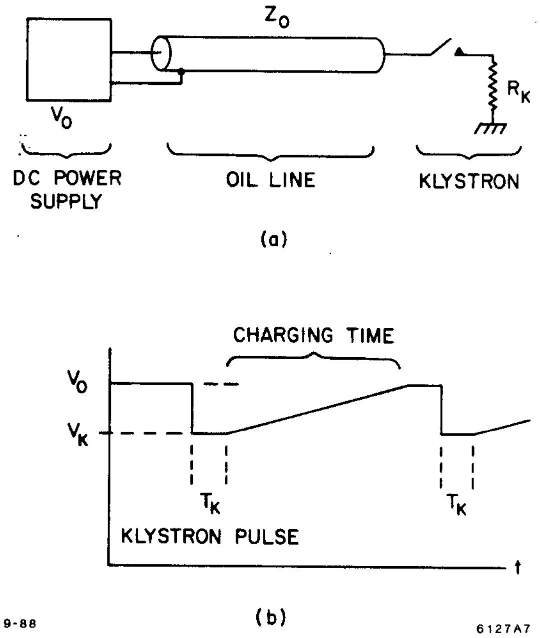
$$Z_0 = 10\Omega (40\Omega \text{ for the lower current density})$$

and the energy stored in the line is

$$U_0 = 1.56\ U_K \quad .$$

It is not unreasonable to expect a rise time for the grid voltage, and thus currents, of the order of 2 nsec—significantly faster than that for the magnetic compressor. We will assume a 6 nsec rise time for the klystron. The efficiency of the oil line will be near 100%. Assuming a 90% efficiency for the power supply then the overall efficiency would be:

$$\begin{array}{ccccccc} \eta_c = & \cdot 9 & \times & \cdot 9 & \times & \cdot 7 & = \cdot 57 \\ & \uparrow & & \uparrow & & \uparrow & \\ & \text{Power} & & \text{Rise \&} & & \text{Klystron} & \\ & \text{Supply} & & \text{Fall} & & & \end{array}$$



9-88 6127A7

Fig. 7. Power supply for a grid controlled klystron a) schematic; b) voltage at end of oil line as a function of time.

Although the grid-controlled cathode and oil lines require significant R&D the higher efficiency that could be obtained would be well worthwhile.

6. COST ESTIMATES

It is clearly very hard to estimate costs at this time. We do it only to see if there is any hope of the costs being significantly lower than other methods.

In the case using binary pulse compression the modulator can be scaled from SLAC at about .5 $/Joule input. For the pulse compressor we use 100K$ per unit which is twice P. Wilson's estimate (physicists are usually a factor of 2 low).

For the magnetic compressor we have used prices from W. Barletta at Livermore of .7 $/Joule input including the power supply. Bayless' estimates are similar.

For the oil line and power supply we took .4 $/Joule, a little less than the SLAC Modulator cost. This is a very unreliable guess.

For the klystron itself we have guessed a figure of 200K$ per unit. This is four times the SLAC 5045 cost, and is based on the observation that the cluster klystron is likely

Table 1.

	Units	K$/Unit	M
A. With Binary Pulse Compression ($\epsilon \approx 38\%$) and Conventional Modulators			
	Units	K$/Unit	M
Modulators	170	1000 (250)	180 (50)
Klystrons	170	200	30
Binary Compressors	600	100	60
Total rf Source			270 (140)
B. With Magnetic Compression and no BPC ($\epsilon \approx 42\%$)			
	Units	K$/Unit	M
Magnetic Compressor + PS	1100	200 (50)	200 (60)
Klystrons	1100	200	220
Total rf Source			440 (280)
C. With Grid Cathode and no BPC ($\epsilon \approx 57\%$)			
	Units	K$/Unit	M
PS + Oil Line	1100	100 (25)	110 (30)
Klystrons	1100	200	220
Total rf Source			330 (250)

to weigh about four times more!

Using these assumptions, we estimate costs in Table 1. The parenthesized numbers in the table are for the lower current Phase I.

From Table 1 we conclude:

1) These costs are low and efficiencies higher, compared with those obtained for current moderate energy ($\leq$ 2 MeV) relativistic klystron designs.

2) There seems no advantage in using the magnetic compression example (B).

3) If 32 amps/cm^2 cathodes are okay then there is little significant cost difference between the approaches (A) and (C). The grid cathode and oil line (example C) is then preferred for its higher efficiency and pulse flatness.

4) If the cathodes only operate at 8 amps/cm^2 then there is probably a cost advantage in using binary pulse compression (example A).

But these conclusions may change when more is known. Note that other combinations such as grid control plus some Binary pulse compressions were not considered but may be a good compromise.

7. WORK TO BE DONE

1. See if the gun design is possible. Note that it may *not* be possible. Multiple Iron plates might be needed to raise the field more gently. Intermediate potential electrodes may be needed between cathode and anode to shape the fields and or shield space-charge effects.
2. Make a better cost estimate of the klystron. What will a 1.5 or 3 Kg magnet with 10^{-3} field quality cost? What are the machining costs? Can the iron be a brazed part of the klystron?
3. Design the Klystrino itself. Emphasis should be given to achieving the high efficiency that the low perveance should make possible. Double output cavities are essential and R. Ruth's phase-space swirling should be studied.
4. Get information on performance and cost of oil lines and 500KV DC supplies. It is important to gain order of magnitude cost estimates early to avoid wasted effort if they are too high.
5. Get better engineering, including installation cost estimates for binary pulse compression as a function of the number of stages.
6. Get more information on 32 amp/cm^2 cathodes, including information from LBL on LaB_6 thermionic cathodes.
7. Build a single cluster gun with a *single* klystrino on the central cathode. Tuning and variable damping should be available for all cavities to fix these parameters prior to #8.
8. Build a full single-cluster klystron with 18 tubes giving 108 MWatts.
9. Start R&D Program on high current cathodes.
10. Start R&D Program on grid-controlled cathodes (conditional on #4).

REFERENCES

1. Palmer, R.B., *The Interdependence of Parameters for TeV Linear Colliders*, SLAC–PUB–4295 (1987) and *Proceedings of the Workshop on New Developments in Particle Acceleration Techniques*, June 29–July 1987, Orsay, France; CERN 87-11; ECFA 87-110. R. B. Palmer, *Linear Collider Energy Scaling*, SLAC–PUB–4707 (1988) and *Proceedings of the DPF Workshop*, June 27, 1988, Snowmass, Colorado.
2. Eppley, K. R., W. B. Hermansfeldt and R. H. Miller, *Proceedings of the 1987 IEEE Particle Physics Conference*, March 16–19 1987, Washington D.C.
3. Loew, G., *Considerations of r.f. Frequency and Power Generation in Linear Colliders Using Conventional Technology*, SLAC Internal Report AAS #22.
4. Eppley, K. R., private communication.
5. Farkas, Z. D., *Binary Peak Power Multiplier and Its Application to Linear Accelerator Design*, SLAC–PUB–3694 and IEEE Trans. on Microwave Theory and Techniques, MTT–34, No. 10, p. 1036 (1986).
6. Simulation data is from Thompson–CSF, private communication.
7. The use of multiple channels to suppress space charge effects has been proposed for light ion acceleration by A. W. Maschke, Brookhaven National Laboratory Report, BNL 51209 (1979).