LINEAR COLLIDER RESEARCH AND DEVELOPMENT

R. H. Siemann*
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA

Introduction

The parameters of linear colliders with E_{CM} = 0.5 TeV based on a compilation made by G. Loew at the LC-93 Conference is given in Table 1.[1] These colliders are:

TESLA which is based on superconducting RF. All the others would use room temperature RF.

SBLC which uses S-band (3 GHz) RF where there is extensive operating experience.

NLC which uses higher frequency X-band (11.4 GHz) RF in a modulator-klystron-accelerator configuration similar to S-band linacs.

JLC-I which has three frequency options, S-band, C-band (5.7 GHz), and X-band. Multiple bunches are accelerated in each RF pulse as they are in TESLA, SBLC, and NLC.

VLEPP which employs a single high intensity bunch rather than multiple bunches.

CLIC which is a "two-beam" accelerator with klystrons replaced by an RF power source based on a high-current, low-energy beam traveling parallel to the high energy beam..

This paper will cover some of the same material as in other survey papers[2,3,4] with an emphasis on recent progress.

Beam Power and Spot Size

The luminosity is given by

$$L = \frac{1}{4\pi}\frac{N^2 f_c}{\sigma_{x0}\sigma_{y0}} H_D = \frac{1}{4\pi}\frac{N^2 f_c}{\sigma_x \sigma_y} \tag{1}$$

where N is the number of particles/bunch and f_c is the collision frequency. Focusing during the collision, disruption, can be accounted for by an enhancement factor, H_D, in the left- hand expression where the beams sizes without disruption $(\sigma_{x0}, \sigma_{y0})$ are used or by using the disrupted beam sizes (σ_x, σ_y) as in the right-hand expression.

The electromagnetic fields at the collision point are parametrized by

$$Y = \frac{5 r_e^2}{6\alpha}\frac{\gamma N}{\sigma_L(\sigma_x + \sigma_y)} \tag{2}$$

where field enhancement is approximately accounted for by using the disrupted sizes. The energy in units of mc^2 is denoted by γ, and σ_L is the bunch length. The mean beamstrahlung energy loss, $\delta_B \propto Y^2$, and backgrounds from beamstrahlung, e^+e^- pairs, and hadronic events depend on Y. When $Y \ll 1$ and $\sigma_x \gg \sigma_y$, the mean number of beamstrahlung photons per incident particle is[5]

$$n_\gamma \approx \frac{5\alpha\sigma_L}{2 r_e \gamma} Y \approx \frac{2\alpha r_e N}{\sigma_x}; \tag{3}$$

n_γ serves as an approximate measure of backgrounds.

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

The luminosity can be rewritten in terms of four parameters: γ, n_γ, σ_y, and the beam power, $P_B = N f_c \gamma m c^2$

$$L \approx \frac{1}{8\pi\alpha r_e m c^2}\frac{P_B n_\gamma}{\gamma \sigma_y}. \tag{4}$$

Detector backgrounds fix n_γ, and the center-of-mass energy determines γ. The trade-off is between beam power and spot size. Roughly speaking, TESLA and SBLC would have high beam powers and large spots while the others would have small beam powers and small spots. "Large" and "small" are relative to each other; all of these colliders have large beam powers and small spots compared to present day practice at the SLC.

The Final Focus Test Beam

Emittance, pulse-to-pulse jitter, and final focus optics all contribute to the spot size. The most impressive progress this year has been the experimental work by the Final Focus Test Beam (FFTB) Collaboration that has demonstrated final focus optics similar to that required for a next generation linear collider.[6]

This experiment was performed by a large, international collaboration in the straight-ahead beam from the SLC. The goal was to focus a 47 GeV beam with a vertical emittance $\gamma\varepsilon_y = 2.5 \times 10^{-6}$m and an energy spread to ±0.3% to σ_y = 60 nm. This would be a demagnification of the beam at the end of the linac by a factor of 380 which is to be compared with the demagnifications of roughly 300 in many next generation designs. Third order optical and geometric aberrations must be corrected to do this.

The beam was commissioned this Spring and during the last three hours of the first extended run they achieved the results shown in Figure 1. The laser spot size monitor had an rms length of 60 μm and β^* = 100 μm for these measurements. The spot size is reduced to 70 nm when a depth-of-field correction is made. The histogram also shows that the size was stable and reproducible over several hours.

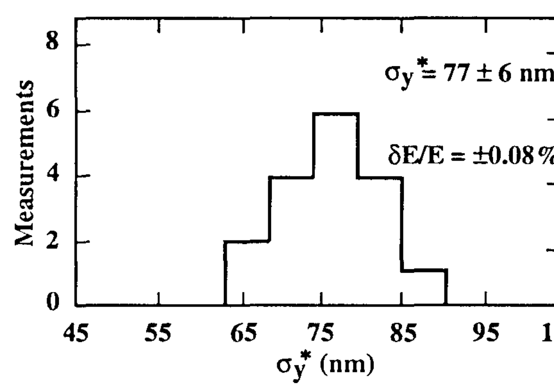

Fig.1 Histogram of spot size measurements. These are raw data, and when corrected the mean is σ_y = 70 nm.[6]

TABLE 1
Selected Linear Collider Parameters for E_{CM} = 0.5 TeV (G. Loew, Linear Collider 93)[1]

Parameter	TESLA	SBLC	JLC-I (S)	JLC-I (C)	JLC-I (X)	NLC	VLEPP	CLIC
L $(10^{33}cm^{-2}s^{-1})$	7	4	4	7	6	8	15	2 - 9
RF Freq (GHz)	1.3	3.0	2.8	5.7	11.4	11.4	14	30
Rep Rate (Hz)	10	50	50	100	150	180	300	1700
Bunches per RF pulse	800	125	55	72	90	90	1	1 - 4
N (10^{10})	5.15	2.9	1.30	1.0	0.63	0.65	20.	0.6
BPM Precision (μm)[a]	10.	10.	NA	NA	1.	1.	0.1	0.1
$\gamma\varepsilon_x/\gamma\varepsilon_y$ $(10^{-8}m)$	2000/100	1000/50	330/4.5	330/4.5	330/4.5	500/5	2000/7.5	180/20
β_x^*/β_y^* (mm)	25/2	22/0.8	10/0.1	10/0.1	10/0.1	10/0.1	100/0.1	2.2/.16
σ_{x0}/σ_{y0} (nm)	1000/64	670/28	300/3	260/3	260/3	300/3	2000/4	90/8
σ_L (μm)	1000	500	80	80	67	100	750	170
IP Crossing Angle (mrad)	0	3	7.3	8	7.2	3	–	1
Y	0.029	0.055	0.24	0.21	0.16	0.096	0.074	0.35
Disruptions, D_x/D_y	0.54/8.5	0.36/8.5	0.13/13	0.13/11.7	0.07/6	0.08/8.2	0.4/215[b]	1.3/15
H_D	2.3	1.6	1.6	1.5	1.7	1.4	1.3	3.3
δ_B	0.03	0.03	0.10	0.08	0.05	0.03	0.13	0.36
n_γ	2.7	2.0	1.6	1.4	1.0	0.9	5.0	4.7
Unloaded Gradient (Mv/m)	25	21	22	40	40	50	108	80
Loaded Gradient (MV/m)[c]	25	17	19	33	31	38	96	78 - 73
Active Linac Length (km)	20	29.4	28	16.7	17.7	14	6.4	6.6
Section Length (m)	1.04	6	3.6	2	1.3	1.8	1.01	0.273
Number of Sections	19232	4900	7776	8360	13600	7778	5200	24000
Number of Klystrons	1202	2450	1944	4180	3400	1945	1300	2
Klystron Peak Power (MW)	3.25	150	85	45	70	94	150	700
Klystron Pulse Length (μs)	1300	2.8	4.5	3.6	0.84	1.5	0.7	0.011
Pulse Length to Section (μs)	1300	2.8	1.2	0.6	0.21	0.25	0.11	0.011
Pulse Compression Gain	–	–	2.4	4.2	3.2	4	4.22	–
a/λ (input/output cavity)	0.15	.15/.11	0.13	.16/.12	.24/.14	.22/.15	.14	.2
P_B (MW)	16.5	7.3	1.4	2.9	3.4	4.2	2.4	.4 - 1.6
AC Power (MW)[d]	137	114	106	193	86	141	91	175
$2P_B/P_{AC}$	0.24	0.13	0.03	0.04	0.09	0.06	0.05	0.02

a) from T. Raubenheimer, Proc of 1993 Part Accel Conf, 11 (1993).
b) VLEPP employs a "traveling focus".
c) Before applying further reductions for off-crest running, BNS damping, etc. (VLEPP excluded)
d) Linac power only (damping ring, detector, utility power, etc. not included). SBLC bases its number on a combined klystron-modulator efficiency of 45%. JLC and NLC have assumed this number to be closer to 35%. In addition, SLED-I (used for JLC-I(S)) and SLED-II (used for JLC-I(C), JLC-I(X), NLC, and VLEPP) are assumed to be 65% efficient. Power for klystron focusing is not included.

The next FFTB run is scheduled for September, 1994. The plans are to complete development of the diagnostics, to correct the remaining aberrations, and to measure the performance with a wider energy spread. They will also study the long term stability of the system.

Multiple Bunches

All but CLIC and VLEPP use multiple bunches to achieve good energy efficiency. The cost of filling the accelerator structure with RF energy is amortized over a large number of bunches rather than a single bunch. Using multiple bunches has implications for both the fundamental and higher modes. Each bunch needs roughly the same energy profile down the linac to avoid emittance blow-up from dispersive effects, and they need to have the same energy in the final focus to minimize chromatic aberrations. Bunch train lengths and accelerator structure filling times are comparable, and the accelerator must be prefilled and the RF amplitude ramped so that each bunch gains the same energy.[7]

The long-range transverse wakefields from higher modes can cause emittance blow-up that is in addition to that from short range wakefields. The higher modes must be

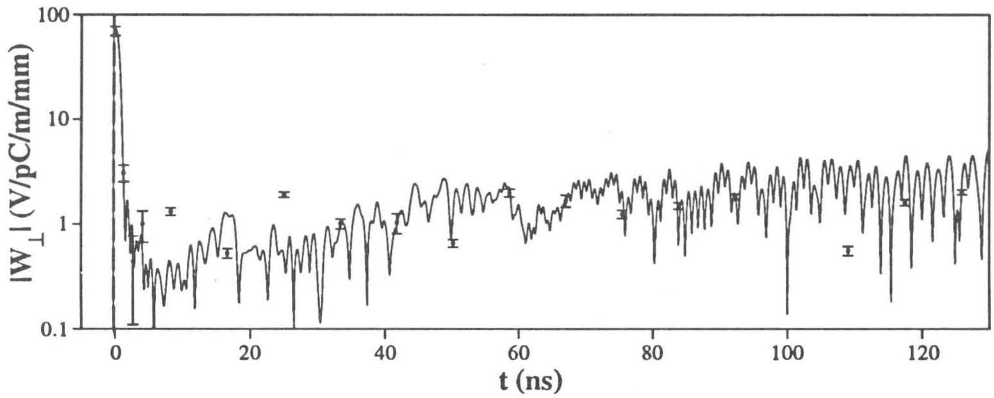

Fig. 2 The amplitude of the dipole wakefield given by the data points is compared with a prediction that assumes that the cells had an rms fractional frequency error of 1.5×10^{-4} in addition to the design frequency spread.[8]

damped or "detuned",[9] spread out in frequency, to reduce these wakefields to acceptable levels.

A striking demonstration of long range wakefield reduction with a detuned structure has recently been performed in the ASSET facility at SLAC.[10] There a 1.8 m long detuned X-band structure was probed in a drive-witness bunch configuration inspired by the Argonne Advanced Accelerator Test Facility.[11] The individual cells making up the structure had a Gaussian distribution (truncated at $\pm 2\sigma$) with an rms fractional width of 2.5% for the first dipole mode frequency. Wakefield data are shown in Figure 2 together with the wakefield calculated assuming a reasonable random error in the cell frequencies.[8] The rapid fall-off at early times is in good agreement, and the long time behavior agrees qualitatively with work in progress to understand the results more quantitatively.

The dominant multibunch effect in TESLA is associated with chromatic effects from the bunch-to-bunch energy spread.[12] A systematic spread could be caused by effects such as Lorentz detuning where the cavity dimensions change during the pulse due to the pressure from the stored electromagnetic energy. With a bunch-to-bunch energy spread of 10^{-3} the emittance increase is a factor of ten. This results in a tight tolerance of a few times 10^{-4} on the energy spread.[12]

Two of the designs, VLEPP and CLIC, are not designed for multiple bunches. VLEPP has a large, single bunch, and there are stringent tolerances on the linac for emittance preservation and a novel final focus that employs a "traveling focus" is needed. The possibility of using up to four bunches in CLIC is still under study with the issues being energy compensation and control of intrabunch transverse wakefields.

RF Power

Most of the colliders in Table 1 require a large number of high peak power klystrons. S-band klystrons delivering 80 MW peak power for 4.5 µsec are in operation at the KEK Accelerator Test Facility. This is essentially the performance assumed for JLC-I (S). The gun for the S-band klystron under development by DESY and SLAC for the SBLC has reached the required performance in a diode test, but there haven't been any RF tests yet. X-band klystrons have operated at KEK with the latest tube reaching an output power of 70 MW in 50 nsec pulses and having 35% efficiency. At SLAC an X-band klystron has reached a power of 51 MW with an output pulse duration of 1.5 µsec and an efficiency of 35%.

The efficiency for transforming AC wall plug power to RF power is one of the major factors determining the economics of linear colliders. This efficiency has two major contributors, the modulator and the klystron. The need to improve modulator efficiency has led to a number of ideas including a Blumlein configuration for the pulse-forming network that has been successfully tested at KEK and the use of a high voltage switch tube rather than a pulse transformer being pursued for SBLC. That has proven to be more difficult than anticipated, and switch tubes are now a backup to conventional modulators in the SBLC test linac.

It is impractical to directly generate the short RF pulses needed for the high frequency colliders. A substantial fraction of modulator inefficiency comes from the rise- and fall-times of the pulse transformer that steps-up the output voltage. Pulse compression[13] matches a long klystron pulse at a reduced peak power to the short bunch trains and accelerator structures that are appropriate for high frequency RF. SLED-II pulse compression has been tested with 32 MW, ~1 µsec input pulses, and power gains of 3.6 to 4.1 with efficiencies of 58-60% have been demonstrated.[14] The intrinsic efficiency of this design is 70-75%, and with improved components it is expected to reach a power gain of 4.2 to 4.6 with 66-70% efficiency.

For the colliders based on room temperature RF and a large number of individual power supplies, extension to higher energies is crucially dependent on improvements in the AC to RF efficiency. The operating costs become prohibitive without such improvements. The VLEPP design uses a girded klystron gun and a DC power supply to avoid a modulator and its inefficiency. Fifty megawatts of output power in a 700 nsec pulse have been reported although the tube has high beam interception and tends to oscillate due to having a high gain. The cluster klystron is another idea for improving efficiency by using multiple beams and a mod anode to control the RF.[15]

TESLA has unique power source requirements. The high Q cavities and long pulse length reduce the peak power to 3.25 MW, but the modulator must be capable of delivering that power for over a millisecond.

The two-beam accelerator, personified by CLIC in Table 1, avoids the complexity of thousands of individual RF power sources by replacing them with a high current, low energy drive beam. This low energy beam has a time structure appropriate for generating 30 GHz RF. It is accelerated by a 350 MHz superconducting RF system, and energy is extracted with transfer structures spaced roughly 1.5 m apart. Drive beam generation is under study at the CLIC Test Facility. There single, 8 bunch, and 24 bunch pulse trains have been produced,[16] and using a CLIC section as the transfer structure 56 MW of RF power has been generated. This corresponds to a peak decelerating field in the last cell of 107 MV/m. When this power was transferred to the accelerating section an average accelerating field of 71 MV/m was seen with no signs of breakdown.[17]

Accelerator Structures

Room temperature accelerators are performing with gradients close to those listed in Table 1. Precision machining is being used for tight fabrication tolerances and for the surface qualities needed for high gradients. Structures are being made at KEK and CERN using direct copper-to-copper diffusion bonding of precision machined cells. A CERN made 11 GHz structure has been tested at KEK and exceeded 100MV/m accelerating field after a reasonable amount of conditioning. Its performance was limited by the available RF power. The NLC section tested at ASSET had reached over 55 MV/m in a high power test, and, as mentioned above, a 30 GHz CLIC structure has shown excellent performance. Costs for mass fabrication are not excessive.[4]

High power pulsed processing is having continuing success in raising the gradient of superconducting cavities with a gradient of 25 MV/m being reached in a 5 cell, 1.3 GHz cavity.[18] Performance before and after high power pulsed processing is shown in Figure 3. Demonstrating this type of behavior in a larger scale linac together with reducing costs are major goals of the TESLA Test Facility under construction at DESY.

Emittance Preservation

The vertical invariant emittances, $\gamma\varepsilon_y$, are small, and emittance preservation during acceleration is a central consideration. Emittance growth caused by the combination of injection jitter and wakefields must be controlled by tight tolerances on injection elements and BNS damping.[19] Those tolerances are about 1 µm for NLC and JLC-I(X) to about 10 µm for the S-band accelerators and TESLA.[20]

Misalignments of the accelerator sections, quadrupoles, and beam position monitors in the main linac cause emittance growth through wakefields and dispersion different central trajectories for different energies. Beam

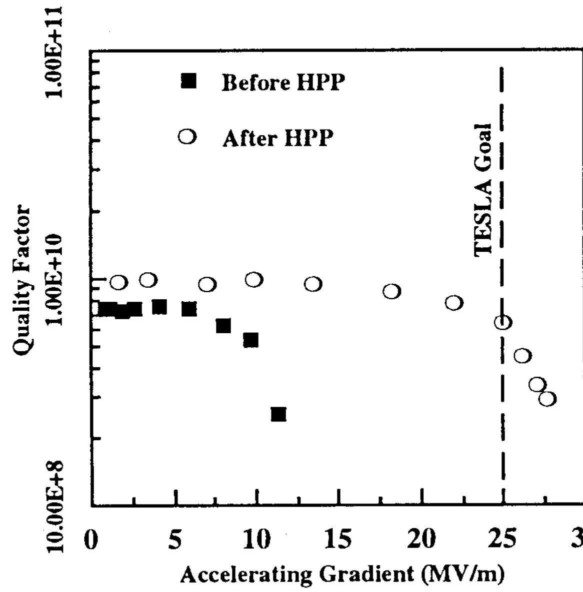

Fig. 3 Results of high power pulsed processing (HPP) of a 5 cell, 1.3 GHz superconducting cavity. Processing was performed with a peak field of 90 MV/m.[18]

based orbit correction procedures, where optical elements are varied and orbit changes measured, have become almost universally adopted as the way to loosen alignment tolerances.[20] The strengths of all the quadrupoles are increased, or decreased, in dispersion free (DF) steering to measure momentum dependence of the central trajectory; then, the orbit is corrected to minimize the dispersion. The strengths of focusing quadrupoles are reduced while those of defocusing quadrupoles are raised to approximate the defocusing effect of wakefields in wakefield free (WF) steering. These procedures depend on measuring orbit changes, and the beam position monitors must be precise. Estimates of the required precisions are included in Table 1 and range from 0.1 µm for CLIC and VLEPP to 10 µm for SBLC and TESLA.

A recent simulation study of emittance growth reached the conclusion that the situation is different in TESLA due to the low RF frequency and large iris apertures.[12] First, emittance dilution from injection errors is 4% even without BNS damping. There is less emittance growth with DF and WF steering than with straight one-to-one steering, but with the expected random errors of 500 µm in cavity alignment the improvement is not as large as is usual. For example, with the optimum focusing along the linac, the vertical emittance blow-up with one-to-one steering is ~20% vs ~10% with WF and DF steering.

$E_{CM} \geq 1$ TeV

The discussion above has concentrated on $E_{CM} = 0.5$ TeV, but there is substantial interest in higher center-of-mass energies. Ideally the luminosity would increase as E_{CM}^2 to reflect the decrease in the cross section for production of point-like particles. Table 2 gives recent parameters for upgrades of TESLA, SBLC, and NLC to 1 TeV.

TABLE 2
Comparison of Parameters for E_{CM} = 0.5, 1.0 TeV [a]

Parameter	TESLA [b]		SBLC [b]		NLC [c]	
E_{CM}	0.5	1.0	0.5	1.0	0.5	1.0
L	7	10	4	6	8	20
Rep Rate	10	5	50	50	180	120
Bunches/pulse	800	4180	125	50	90	75
N	5.15	0.91	2.9	2.9	0.65	1.3
$\gamma\varepsilon_x/\gamma\varepsilon_y$	2000/ 100	500/ 6.3	1000/ 50	500/ 5	500/ 5	500/ 5
σ_{x0}/σ_{y0}	1000/ 64	325/ 8	670/ 28	742/ 6.3	300/ 3	425/ 2
σ_L	1000	500	500	500	100	100
δ_B	0.03	0.03	0.03	0. 04	0.03	0.08
Load Grad.	25	25	17	34	38	74
Linac Length	20	40	29.4	29.4	14	14
Klystr's	1202	2404	2450	4900	1945	3850
Klystr Pk Pwr	3.25	3.25	150	150	94	105
Pulse Compr	–	–	–	2	4	6.6
P_B	16.5	15.3	7.3	5.8	4.2	9.4
P_{AC}	137	153	114	230	141	144
$2P_B/P_{AC}$	0.24	0.20	0.13	0.05	0.06	0.13

a) 0.5 TeV parameters from Table 1. All units as in Table 1
b) 1 TeV parameters from references [3] &[21]
c) 1 TeV parameters from reference [22]

The two ways to reach 1 TeV are to double the length or to double the gradient by quadrupling the peak power by a combination of increasing the number of klystrons, the klystron peak power, and the pulse compression gain. The former is used in TESLA since 50 MV/m would be near the fundamental gradient limit of superconducting RF in Nb. The latter is used in SBLC and NLC. The threshold for RF capture of dark current is about 20 MV/m at 3 GHz and about 80 MV/m at 11.4 GHz. The SBLC gradient is well above that threshold, but can be reached with appropriate attention to surface preparation and with RF processing. The NLC gradient is below the dark current limit and has been easily exceeded in the tested mentioned above.

A straightforward application of either way of doubling the energy would lead to unacceptable AC power consumption, so the parameters have changed to reflect this. First, the luminosity has not been scaled as E^2_{CM}. Second, the trade-off between high beam power and small spots (eq. 4) is no longer the central theme that it has been in the 0.5 TeV discussion. All of the parameter lists have evolved in the direction of small spots with nearly identical invariant emittances. The underlying assumption for TESLA and SBLC are that after gaining experience with correction and optimization procedures the vertical emittance can be reduced by an order of magnitude.[3] This is possible if the accelerator complex has been designed and constructed with the goal of producing small emittances.

The 1 TeV NLC parameters show a third approach to the problem of AC power consumption. They are based on improved efficiency. Some of that improvement has come from evaluating the modulator, klystron and pulse compression efficiencies for the E_{CM} = 0.5 TeV collider. The current estimate is that the AC power for the linac would be 92 MW versus the 141 MW at LC-93.[22] Additional efficiency improvements are counted on for 1 TeV. These include elimination of modulators through using a grided klystron or a cluster klystron.

The potential for energy increases is an important consideration in the development of high energy linear colliders. In all cases research and development beyond that being done for 0.5 TeV is required, and the simplicity of a two-beam approach becomes more attractive.

References

[1] G. Loew, Proc Fifth International Workshop on Next Generation Linear Colliders, p. 431 (1993).
[2] R. Siemann, Proc of the 1993 Part Accel Conf 532 (1993).
[3] R. Brinkmann, "Low Frequency Linear Colliders", 1994 European Particle Accelerator Conference.
[4] W. Schnell, "High Frequency Linear Colliders", 1994 European Particle Accelerator Conference.
[5] Pisin Chen, *Photon-Photon Collisions*, p. 418 (1992).
[6] D. L. Burke *et al*, 1994 European Particle Accelerator Conference.
[7] K. A. Thompson and R. D. Ruth, Proc of the 1993 Part Accel Conf, 3693(1993).
[8] C. Adolphsen *et al*, Proc of the 1994 Meeting of DPF.
[9] H. Deruyter *et al*, "Damped and Detuned Accelerator Structures", Proc Linear Accel Conf, (1990).
[10] C. Adolphsen *et al*, SLAC-PUB-5941 (1992).
[11] J. Simpson *et al*, ANL-HEP-CP-86-46.
[12] A. Mosnier, "Beam Instabilities Related to Different Focusing Schemes in TESLA", 1994 European Particle Accelerator Conference.
[13] P. B. Wilson, Z. D. Farkas and R. D. Ruth, SLAC AP-78 (1990).
[14] T. Lavine, private communication.
[15] R. Palmer, private communication.
[16[R. Bossart *et al*, CLIC Note 231, 1994 European Particle Accelerator Conference.
[17] I. Wilson, private communication.
[18] T. Hays *et al*, "Achieving the TESLA Gradient of 25 MV/m in Multicell Structures at 1.3 GHz", 1994 European Particle Accelerator Conference.
[19] V. Balakin, A. Novokhatski and V. Smirnov, Proc of 12th Int Conf on High Energy Accel, p. 119 (1983).
[20] T. Raubenheimer, Proc of 1993 Part Accel Conf, 11 (1993).
[21] B. H. Wiik, Proc Fifth International Workshop on Next Generation Linear Colliders, p. 463 (1993).
[22] R. Ruth, private communication.