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REVIEW OF STUDIES ON CONVENTIONAL LINEAR COLLIDERS IN THE S- AND X-BAND REGIME*

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ABSTRACT

This paper gives a status report on the conventional approaches to linear colliders at DESY, KEK, SLAC and INP-Protvino in the S- and X-Band regime. Critical topics are reviewed and a discussion of global issues such as future R&D requirements is included.

1 INTRODUCTION

At the time of this conference, we find ourselves at a very interesting juncture in the technical development of $e^{\pm}$ linear colliders. The first such machine, the SLC, in the arduous process of overcoming some major technical obstacles, has given birth to a large number of accelerator innovations and is now producing 20 Z's/hour with polarized electrons. Encouraged by these results, the HEP community would like to see the inception of a linear collider in the 300 GeV to 1.5 TeV center-of-mass energy range in the next decade or so. However, in contrast to earlier machines such as the AGS, the SLAC linac, the Fermilab main ring, the SPS, LEP and the SSC, where the starting technology of choice was not in dispute, there are today four distinct approaches to the design of the next $e^{\pm}$ linear collider: the conventional S-Band approach, the conventional X-Band approach, the TESLA superconducting L-Band approach, and the CLIC approach. These four approaches all have advantages and disadvantages and it is too early to tell which one will prevail. However, it is not too early to make serious comparisons and indicate the work that must yet be done to facilitate an enlightened choice among these candidates. The object of this paper is to review the status of the first two approaches, the S-Band approach spearheaded by DESY and the X-Band approach put forward by KEK, SLAC and INP.

2 COMPARISON OF OVERALL PARAMETERS OF MAJOR LINEAR COLLIDER CANDIDATES

In order to put the various studies in perspective, it is useful to start out with a comparison of the major linear collider parameters. These are shown in Tables I and II for the four linear collider candidates: DLC (DESY), JLC (KEK), NLC (SLAC) and VLEPP (INP). All four machines start from an initial center-of-mass energy of 500 GeV (Stage I) with a luminosity between 10^{33} and 10^{34} $cm^{-2}sec^{-1}$. All four machines are meant to be expandable in energy through the addition of RF power and/or extra length. The differences between the four machines are highlighted below.

The S-Band DLC has a long train of bunches (172) spaced 32 λ apart with two choices of peak current (100 mA and 300 mA), the first being ~ 8% beam loaded, the second 19% beam loaded [1]. The average beam powers are 2.4 and 7.2 MW per beam, respectively. With a loaded gradient of 17 MV/m, the total two-linac RF length is ~ 30 km. The final focus properties per bunch are fairly similar to those of the JLC and NLC except that for the 300 mA case, σ_y^* is ten times larger (similar to the FFTB design at SLAC), thus more forgiving. The machine requires new 150 MW klystrons with 2.8 μsec pulse length and 6-meter long structures with the appropriate beam breakup detuning. Altogether, it is roughly equal to 10 SLACs. The AC power for the two linacs is calculated to be 112 or 145 MW (as compared to 200 MW AC for the generation of RF for 10 SLACs at 120 Hz). This is achieved by avoiding the inefficiency of pulse compression (SLED) and limiting the repetition rate of the DLC to 50 Hz.

The X-Band JLC [2] and NLC, although they are close cousins, are presently somewhat different from each other because the JLC starts with a total two-linac RF length of 19 km as compared to 14 km for the NLC. Both machines are heavily beam loaded (over 30%): the number of bunches per pulse for the JLC is 20 as compared to 90 for the NLC while the charge per bunch for the JLC is twice that for the NLC. The JLC is assumed to run at 150 Hz and the NLC at 180 Hz. The resulting beam powers are 1.56 MW and 4.2 MW respectively. Both machines use high peak power klystrons (150 and 94 MW feeding 8 and 4 sections respectively) but the shorter RF pulse for the JLC (100 vs. 250 ns for the NLC) requires a shorter klystron pulse and less pulse compression (a factor of 4 vs. 6 for the NLC) and ultimately less total AC power for the

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Table I

Overall Parameters of Conventional Linear Colliders

	DLC	**JLC**	**NLC**	**VLEPP**
Initial energy (c. of m.)	500	500	500	500
Luminosity (10^{33}cm^{-2}sec^{-1})	4.1/2.2	2.4	6	12
RF-frequency of main linac (GHz)	3	11.4	11.4	14
Linac repetition rate (Hz)	50	150	180	300
Number of particles/bunch (10^{10})	.7/2.2	1.3	0.65	20
Peak beam current (mA)	100/300	1480	742	–
Number of bunches/pulse	172	20	90	1
Bunch train length (nsec)	2000	28	126	–
Bunch spacing (nsec)	10.66	1.4	1.4	–
Bunch spacing (λ)	32	16	16	–
Unloaded gradient (MV/m)	18.4/21	40	50	108
Loaded gradient (MV/m)	17/17	25.3	37.6	96
Total two-linac RF length (km)	30	19	14	6.4
Total two-linac AC power (MW)	112/145	54.6	152.3	91
Damping ring energy (GeV)	3.15	1.98	1.8	3.0
Final Focus:				
$\gamma\varepsilon_x$ (m-rad x 10^{-8})	410/1000	550	500	2000
$\gamma\varepsilon_y$ (m-rad x 10^{-8})	4/100	7.5	5	7.5
β_x* (mm)	3/5	10	10	100
β_y*(mm)	0.3/0.8	0.13	0.1	0.15
σ_x* (nm)	169/316	335	300	2000
σ_y* (nm)	5.5/40	4.5	3	4
σ_z* (μm)	200/500	150	100	750
Upsilon (beamstrahlung parameter)	.05/.09	0.11	0.1	0.06
D_y (vertical disruption)	17/8.5	15	8	150
δ_B (average $\delta p/p$ from beamstrahlung)	.05/.05	0.06	0.03	0.09

RF production for the two linacs (54.6 MW vs. 152.3 for the NLC). The final focus properties of the two machines are very similar.

VLEPP distinguishes itself from all the other designs in that it uses a single long bunch (σ_z = 750 μm) of 2 x 10^{11} e$^\pm$ per RF pulse [3]. This feature does away with multibunch effects (longitudinal as well as transverse) but requires all the refinements of BNS damping, "autophasing", traveling-wave final focus, etc. proposed by the INP-Protvino group. The relatively high gradient (96 MV/m) results in a shorter two-linac length (6.4 km). The repetition rate is 300 Hz and the beam power is relatively low (2.4 MW per beam). In the final focus, the emittance yields a relatively wide σ_x* (1μm) and a σ_y* of 4 nm, on the same order as the JLC and NLC.

We will now examine the work on RF power and modulators, accelerator structures, e± sources, beam dynamics and systems tests in progress at the various laboratories in the world toward the realizability of these four different machines. Damping rings, bunch compressors, final bends and foci are not considered here for lack of space and because it is assumed, somewhat arbitrarily, that the problems related to these systems can be solved independently.

3 RF POWER AND MODULATORS

An overview of all the pulsed RF power sources can be found in Ref. [4]. The DLC high-current design is based on a 150 MW peak, 21 kW average, 2.8 μsec, 50 Hz, S-Band klystron. Such a klystron does not presently exist but SLAC with Japanese collaborators built a 150 MW, 1 μsec flat top, 60 Hz prototype in the early 1980s [5] and may agree to develop such an upgraded tube with DESY support. The modulator will need a voltage of about 450 kV, and assuming 45% klystron efficiency and 80%

Table II

Main Linacs RF and Associated Parameters

	DLC	JLC	NLC	VLEPP
Linac repetition rate (Hz)	50	150	180	300
Peak beam current (mA)	100/300	1480	742	–
Total two-linac RF length (km)	30	19	14	6.4
RF wavelength (cm)	10	2.625	2.625	2.143
Unloaded gradient (MV/m)	18.4/21	40	50	108
Loaded gradient (MV/m)	17	25.3	37.6	96
Number of accelerator sections	4902	15600	7778	5200
Length of sections (m)	6	1.22	1.8	1.01
Type of section	C.G.	~ C.G.	~ C.G.	C.I.
(a/λ) range	.154-.108	.24–.12.	.210–.147	.140
Attenuation (nepers)	0.57	0.40	0.51	0.68
Average shunt impedance (Megohms/m)	53.6	71	81	124
Section filling time (nsec)	825	75	100	107
RF pulse length (nsec)	2800	100	250	110
Peak power into section (MW)	56/72.5	50	87	142
Pulse compression ratio	–	4	6	6.5
Pulse compression gain	–	3.2	4	4.22
Pulse compression efficiency (%)	–	80	67	66.5
Number of klystrons	2451	1950	1945	1300
Number of sections/klystron	2	8	4	4
Peak RF power from klystron (MW)*	118/152	140	94	150
Average RF power from klystron (kW)	16.5/21	8.4	25.4	31.5
Klystron RF pulse length (nsec)	2800	400	1500	700
Klystron efficiency (%)	45	40	45	50
Number of modulators	2451	1950	1945	---
Modulator voltage (kV)	400	550	600	1000**
Modulator efficiency (%)	80	75	72	> 90
Total peak RF power (GW)	289/373	874	731	822
Total P_{pk} x L (GW x km)	8497/10970	16606	10236	5267
Total average RF klystron power (MW)	40.5/52.1	16.4	49.4	41
Single beam energy/RF pulse (kJ)	48.2/144.5	10.4	23.4	8
Single beam power (MW)	2.4/7.22	1.56	4.2	2.4
Klystron RF→beam efficiency (%)	8.5/27.6	19	17	11
Total two-linac AC power (MW)***	112/145	54.6	152.3	91
AC→beam efficiency (%)	4.3/10	5.7	5.5	5

* Allows for power dissipation in waveguide feeds
** No modulator, DC voltage on HV line
*** Does not include klystron focusing power nor any other linac power

modulator efficiency, an energy storage per pulse of 1180 joules (almost twice the value of 640 joules for the 5045 klystron at SLAC). DESY is presently seeking help from VARIAN to build a hard-tube pulser for this application to increase the efficiency of the modulator. One might guess that the completion of a successful klystron and modulator prototype will realistically require three years. The DLC design has the advantage of not needing pulse compression for the 500 GeV stage.

The JLC is based on a 140 MW peak, 8.4 kW average, 0.4 µsec, 150 Hz, 40% efficiency, X-Band klystron followed by a 4-to-1 SLED-II pulse compression with 80% efficiency [2]. This klystron does not exist either at the present time. The current collaborative program between KEK and Toshiba consists of 30 MW and 120 MW designs (XB50K and XB72K) with respective modulator voltages of 400 and 550 kV respectively. The maximum peak powers respectively obtained have been 18 MW at 100 nsec, 32%

efficiency, and 24 MW, 100 nsec, 15% efficiency. The present limitations have been window and gun ceramic failure respectively. Modulator research is proceeding on conventional models with energy storage up to 485 joules/pulse and 15:1 transformer ratio, and Blumlein models charging up to 80 kV and 7:1 step-up. The efficiency goal for these advanced modulators is 75% but it is too early to tell whether this goal is achievable for 400 nsec flat-top pulses.

The NLC is based on a 94 MW peak (or two 50 MW), 25.4 kW average, 1.5 μsec, 180 Hz, 45% efficiency, X-Band klystron followed by a 6-to-1 SLED-II pulse compression. Development of this klystron is advancing on several fronts: XC models with 1.8 μperveance, XL models with 1.2 μperveance, and various traveling-and standing-wave outputs and window designs. So far, the best XC model with TW output has produced 50 MW peak with 1 μsec pulse at 60 Hz with 20% efficiency at 445 kV. The limiting factors for the SW output designs have so far been beam interception and breakdown in the output cavity, and window fractures. A conventional 450 kV modulator is being used for these tests but a more advanced 3-PFN design with a net output voltage of 100 kV stepped-up to 600 kV by a 6:1 transformer is now being constructed. The hope is that 75-80% efficiency might be reachable with such a modulator. The 6-to-1 SLED-II pulse compression system is under active development. Presently, effort is being concentrated on a 3-db hybrid using circular overmoded waveguide, a compact mode converter from TE_{10} rectangular to TE_{01} circular guide and techniques to bend circular guides by 90 degrees without producing mode conversion. A complete high-power SLED-II prototype is expected to be ready for test by Autumn 1992.

One problem common to the DLC, JLC and NLC klystrons is beam focusing. Particularly for the X-Band tubes with high current density and small bore (.95 cm diameter), solenoidal fields of 5 to 6.5 kG are needed, which require very power hungry power supplies (~ 20 kW typically) unless one uses superconducting solenoids (which may be quite costly). For this reason, there is an extra incentive to move to beams with lower perveance and higher voltage which result in longer plasma wavelengths, and open the possibility of periodic permanent magnet focusing. This technique, which for these very high power tubes has only been tried at INP-Protvino (see below) has an enormous pay-off because at the present time, the power required by the room temperature solenoid for the X-Band tube exceeds the power consumption required to produce the RF.

The VLEPP design is based on a 150 MW peak, 31.5 kW average, 700 nsec, 300 Hz, 50% efficiency, 0.2 μperveance, 14 GHz klystron [3]. These tubes will be connected to a 1 MV line and use a gridded triode gun with an oxide cathode consisting of 37 micro-cathodes (2-6A/cm^2) which face the holes in the grid to minimize interception. So far the tubes have been limited to about 50 MW peak by an HEM_{11}-type oscillation at 18 GHz. Periodic permanent magnets imbedded in the copper body of the tube have been used successfully. The INP-Protvino group has also developed an RF pulse compression system called VPM which uses an open toroidal cavity in the form of a "whispering gallery" with a maximum demonstrated efficiency of 40%. The plan now is to achieve a 6.5 compression ratio (from 700 to 107 nsec) with an efficiency of 66.5%.

4 ACCELERATOR STRUCTURES

The DLC linac module is based on two 6 m-long constant-gradient sections fed by one klystron. These sections are very similar to the existing SLAC sections except that they are twice as long. To obtain the same filling time as SLAC (t_F = 0.825 μsec), the normalized group velocity must go from 0.041 to 0.013, corresponding to an a/λ range of 0.154 to 0.108 and an average shunt impedance of 53.6 megohms/meter [6]. (Also see Refs. [7] and [8]). Two main challenges are being faced in the design and fabrication of these sections: multibunch "beam breakup" suppression and inexpensive mass production. The beam breakup problem is being attacked in two ways: a) HOM loading of two cavities at the front-end of the sections by means of two lossy rectangular waveguide stubs each, two vertical and two horizontal, and b) detuning of the HEM_{11} mode into twenty distinct families of sections with a frequency spread with a σ of 2.4 MHz. The combined effect of these two remedies is calculated to keep multibunch emittance under control. As for cavity fabrication, work is in progress at DESY to build cavity models in the form of self-jigging nested cups with good copper-to-copper contact. The cups have one 10 mm radius rounded corner and one 90 degree corner, and are thus asymmetrical. Tolerances on cup and iris diameter are ± 10 μm, and surface finish is 50 nm. The assumption is that the sections will need final tuning like at SLAC.

The JLC linac module consists of eight 1.22 m-long sections fed by one klystron. Both detuning and damping techniques are being studied for multibunch beam loading and emittance growth control [9]. Precision fabrication studies include copper machining techniques via lathe (down to ± .5 μm) or mill (down to ± 1 μm), electroforming, and bonding studies include conventional silver brazing ($\Delta f/f \sim 3 \times 10^{-4}$), gold-assisted diffusion bonding ($\Delta f/f \sim 3 \times 10^{-5}$) and direct diffusion bonding (requiring surface flatness ~1 nm).

The NLC linac module is based on four 1.8 m-long sections fed by one klystron. The damping technique for multibunch emittance growth control has been temporarily set aside and HOM detuning is presently receiving primary attention [10]. The detuning that is being proposed takes the 206 cavities (204 + 2 couplers) in each section and spreads their dipole mode (HEM_{11}) frequency in a Gaussian distribution with a σ_f of 2.5% and with a full width of 10% (truncated) while preserving the $2\pi/3$ phase advance per cavity for the fundamental mode. This is done by varying the iris diameter and thickness, and results in a quasi-constant gradient with a maximum unloaded field variation of 10% along the section. Calculations show that 1.4 nsec after the passage of a bunch, the dipole wakefield is attenuated to less than 1% when the next bunch comes along. A first-order test done with an approximate 50-cavity prototype at the ATF at Argonne National Laboratory confirmed this result [11]. Further wakefield suppression will be achieved by building four different families of sections which will be displaced with respect to each other at the center by $\Delta f/f$ of 7.5×10^{-5}. The mechanical tolerance is assumed to be $\Delta f/f \sim 10^{-4}$. A variety of mechanical fabrication techniques are being considered, all based on individual cups to be brazed together, but differing in the extent to which water cooling, pumping and tuning channels are integrated into the walls of the cups or attached externally. In any case, the present approach assumes that over a 1.8 m section, pumping takes place through the end-couplers (two symmetrical feed waveguides at both ends) and three other equally spaced cavities along the structure where radial pumping slots are machined into the cup walls and communicate with an external manifold.

The VLEPP linac module is based on four 1.01 m-long constant-impedance (uniform) sections fed by one klystron. The sections are all alike, have a relatively small iris diameter (6 mm) and must sustain a high gradient (~ 100 MV/m). Their alignment is based on a dynamic feedback system which minimizes transverse beam displacements by detecting these via a position monitor which is coaxially attached to the structure, and by moving the section accordingly with a magnetic mover. A sensor capable of resolving 1 nm is used to keep track of the position of the section.

Two problems which are of common concern in all these accelerator structures are breakdown and dark current. In the last year since LC91, experiments in traveling-wave structures have been carried out at S-Band [12] and X-Band [9] at KEK and at SLAC. At KEK, a 22-cavity uniform X-Band structure (with an iris diameter of 6 mm) has recently reached a maximum of 80 MV/m in the first cell for a short pulse (50 nsec at ~ 10 Hz) after about 500 hours of processing. At SLAC, a 30-cavity X-Band uniform structure (with a double coupler input and an iris diameter of 7.5 mm) recently exceeded 85 MV/m in the first cell with a 60 nsec RF pulse, after about 80 hours of processing. The total dark current pulse had the same length as the RF pulse, and was about 2 mA peak at 85 MV/m vs. 10 μA peak (i.e. 2 orders of magnitude lower) at 50 MV/m. It was found, however, that during the rise time of the pulse, the frequency modulation causes the average accelerating frequency to be higher and the phase velocity to be lower, thus making electron capture easier. By adjusting the rise time, it was possible to change the net frequency and greatly increase the dark current during roughly the first filling time, in this case 26 nsec. After this, the current subsided to a lower steady-state value. This effect probably explains the large dark currents observed during the filling time, as reported by Orsay and KEK at LC91. Another point that should be considered regarding dark current is the fact that there is a qualitative difference between field emitted electrons which simply rattle around in cavities and eventually produce an "electron gas", and electrons which get captured by the RF wave and are cumulatively accelerated. The former parasitically absorb some RF energy, produce X-rays and outgassing, and possibly wakefields. The latter, in addition, can produce a cumulatively accelerated beam which will cause additional radiation and, if not deflected by the FODO array, backgrounds if it or its debris is allowed to reach the final focus. It can be shown that an electron at rest will be captured by a velocity-of-light traveling wave if the peak accelerating field in MV/m reaches $1.6/\lambda$. Thus, a 3 GHz linac will capture field-emitted electrons at 16 MV/m while an 11.4 GHz linac will not capture them until it reaches 61 MV/m. Of course, it must be remembered that field emission varies exponentially with surface field and therefore is much more severe in the higher gradient machines.

5 ELECTRON AND POSITRON SOURCES

While the RF frequency of the main linacs in the colliders discussed in this review goes from 3 GHz to 14 GHz, it is generally agreed that the initial linac to the damping rings and perhaps up to 10 GeV will be at S-Band. Thus, when one thinks about $e^{\pm}$ sources for such a linac, the SLC experience is entirely applicable. The CID injector has already produced trains of two bunches with charge in excess of 10^{11} electrons (unpolarized) per bunch, spaced 60 nsec apart. There is no reason why a similar injector could not be designed to satisfy the injector requirements of any of the four machines shown in Table I, although admittedly, the VLEPP injector may require some extra work. Conventional thermionic or laser-driven cathode guns are already being developed in conjunction with integral or separate RF cavities [13] and possibly grid pulsers [14] to produce these bunch trains. As for polarized electrons, the SLC experience [15] indicates that in order to extract trains of 10 mA peak, 2 nsec polarized electron bunches from a laser-driven cathode, several problems must still be overcome: high voltage gun breakdown (above 120 kV), charge limitation (which scales with the quantum efficiency and depends on the doping of the GaAs in the cathode), cathode lifetime, and above 50% polarization, development of new superlattice cathodes [16] and strained-lattice cathodes which can yield 90% polarization [17] but which have not yet been tested at high voltage, high quantum efficiency and high current. For an entirely different approach, the reader is referred to a proposal by a group from Kharkov [18].

Regarding positrons, the SLC source can produce 4 x 10^{10} e^+ per RF pulse and 5 x 10^{12} e^+/sec but the NLC will require 10^{14} e^+/second and the DLC up to 2 x 10^{14} e^+/sec (in the 300 mA current case). Clearly, a combination of existing techniques will be needed, or a new approach altogether. The former is being proposed by a Japanese collaboration [19] in a system combining a 10 GeV e^- linac, an e^+ target, an adiabatic phase-space transformer, a 1.98 GeV e^+ linac and a 1.98 GeV pre-damping ring. A new approach based on an idea by V. E. Balakin and A. A. Mikhailichenko [20] uses circularly polarized gammas produced by electrons traversing a helical undulator and impinging on a low-Z and thin enough target to avoid depolarization [21,22].

6 BEAM DYNAMICS

A comprehensive discussion of linac beam dynamics and tolerance issues is beyond the scope of this report and is covered elsewhere at this conference [23]. The ultimate challenge for all the machines considered here is to produce colliding beams capable of yielding the desired luminosity without undesirable backgrounds (e± pairs, minijet events, etc.). Both $e^\pm$ beams must have the required charge contained within the desired six-dimensional phase space. The design goal of the linacs, assuming that the damping rings and bunch compressors can produce this phase space, is to transmit it without growth. The two most difficult problems are beam loading compensation (single and multibunch) and transverse emittance growth control. For single bunch beam loading, the remedy (imperfect) is to place the bunch at an angle ahead of the crest (in space) so that the rising slope of the sine wave compensates (as well as possible) for the wakefield. If BNS damping is needed, this angle has to be an average over the length of the linac. The compensation can be improved by proper shaping of the bunch. For multibunch beam loading, it is possible to inject the train of bunches before the accelerator sections are fully filled and to stagger the onset of the various klystron triggers so that the integrated field is constant to less than 0.5%. The degree of staggering must be adjusted as a function of current. Alternately, it is possible to shape the RF pulse amplitude and phase (by means of the klystron drive) so as to compensate for beam loading. Transverse emittance control is probably the most challenging problem, particularly in the vertical phase space where the final emittance requirement is the most stringent. Clearly here, the S-Band linac is more forgiving than the X-Band ones because of its larger iris aperture, but the DLC linac is twice as long as the NLC and five times longer than VLEPP, and has a lower gradient. How these effects compensate each other and affect alignment and stability tolerances as well as the cost to achieve these is not yet clear.

7 SYSTEMS TESTS AND CONCLUSIONS

During the next three or four years, DESY, KEK, SLAC and INP will all become involved in various important prototype and systems tests. The first such test, starting in Spring of 1993, will be the checkout of the FFTB at SLAC. The major milestone will be the production and measurement of flat beams with a σ_y^* hopefully as small as 60 nm. During this period, SLAC will also initiate the construction of the 600 MeV, 4 klystron NLC Test Accelerator [24], a test-bed for the entire X-Band RF chain including an injector, multibunch beam and spectrometer, which should take about three years to complete. On a smaller scale, SLAC will also mount an experiment in Sector 2 of the linac, called ASSET, to measure wakefields in X-Band structures. Meanwhile, at KEK, the 1.54 GeV S-Band linac [25] will be completed, and installation of the ATF Damping Ring [26] will begin in 1993 with beam operation starting in 1995. Also in 1993, DESY will begin design and construction of its 450 MeV, 2 klystron multibunch S-Band Test Facility to be completed by 1996. This facility will test the entire S-Band chain as well as structures with HOM couplers, position monitors, section alignment down to 15 μm and quadrupole position tolerances down to 0.1 μm. INP-Protvino meanwhile will be developing its 100 m, 20 klystron, multi-GeV, 14 GHz linac with its single bunch beam and its dynamic alignment system. As a result of these parallel and somewhat interwoven programs, the international community will find itself toward the end of 1996 with a great wealth of knowledge on many of the major components of the so-called conventional linear colliders. Estimating that the integrated cost of these R&D programs is well under $40M/year, the world HEP community will have spent about $150M from 1992 through 1996 for the effort described in this report. If one adds the cost of the TESLA and CLIC R&D programs, the total world cost will then be approximately $200M over the same period of time. While this sum is not small, it is not unreasonable if one accepts the fact that the linear collider to be ultimately selected from this study will no doubt be a multi-national, multi-billion project. Without solid R&D and engineering up front of at least this magnitude, such a project could not be built responsibly.

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