

# REVIEW OF ELECTRON-POSITRON LINEAR COLLIDERS

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## Abstract

This paper reviews the work performed by the International Linear Collider Technical Review Committee to examine and compare the designs and R&D status of the various  $e^+e^-$  linear colliders currently under study in the world. The paper summarizes the highlights of the report issued in December 1995 and, where applicable, indicates some of the changes that have occurred since its publication.

## Introduction

In June 1994 at EPAC 94 in London, the International Council of the Interlaboratory Collaboration of R&D Towards TeV-scale Electron-Positron Linear Colliders created an International Technical Review Committee (TRC) consisting of close to sixty scientists, and charged it with producing a report bringing together in one document all the  $e^+e^-$  linear collider designs and technologies in the world. The machines to be studied and compared were to start at c.m. energies of 500 GeV and have expansion capability to 1 TeV and above. The report [1] was completed in December 1995. The author of this paper was Chair of the TRC, T. Weiland represented the Secretariat, and E. Mitchell at SLAC was in charge of production. The TRC report is 186 pages long and only some of the highlights can be summarized here.

The particle physics community has been greatly interested in such an accelerator for some years, and, if anything, this interest has grown with the decision to proceed with the LHC. Indeed, these two machines are highly complementary in what they can contribute to the field. The linear collider will be a precision tool to study  $t\bar{t}$  production at threshold and above. If the Higgs and/or supersymmetric particles exist, the linear collider will be instrumental in discovering and/or studying them. If none of these particles exist, the machine will make it possible to explore other mechanisms to explain electroweak symmetry breaking. These are some of the most burning issues to be elucidated in the next few years. The  $e^+e^-$  linear collider also has the potential of producing exciting physics from  $e^-e^-$ ,  $e^-e^+$  and  $\gamma\gamma$  collisions, and of involving other applications such as FEL's and other technologies.

The TRC report consists of six chapters. The first chapter is a description of six machines at 500 GeV c.m. energy: TESLA, SBLC, JLC (S-, C- and X-band), NLC, VLEPP and CLIC. The second chapter includes the reports of six working groups respectively describing and comparing Injection Systems, Damping Ring and Compression Systems, Linac Technology, Beam Dynamics, Beam Delivery and Experimentation for the various machines. The third chapter describes methods proposed for each machine to upgrade their c.m. energies to 1 TeV and to obtain  $e^-e^-$ ,  $e^-e^+$  and  $\gamma\gamma$  collisions. Chapter 4 describes on-going experiments and test facilities, Chapter 5 discusses present and future areas of collaboration, and Chapter 6 presents conclusions. Given that

this conference is devoted primarily to linacs, the emphasis in this paper is focused on this subject.

## Machine Parameters and Designs

Overall and final focus parameters for all the machines are shown in Table 1 and those for pre-linacs, damping rings and main linacs are given in Table 2. For each machine, there are two columns: the first one gives the numbers listed in the TRC report of December 1995, the second one shows new numbers where an update has taken place as of August 1996. As can be seen, all the machine designs have now reached luminosities above  $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$  which with the exception of VLEPP, are obtained by using many bunches per rf pulse. The main linacs which operate at the lower rf frequencies have the lowest gradients and are therefore the longest. For all machines, the ultimate and most challenging specification is the  $\sigma_y^*$  at the IP which ranges between 19 and 3 nm. For reference, the FFTB at SLAC at 50 GeV has so far reached a  $\sigma_y$  of 70 nm. Let us now characterize the various machines by dividing them into four groups in order of ascending rf frequency: 1) TESLA, 2) SBLC, JLC(S), JLC(C), 3) JLC(X), NLC (with its future TBNLC option), VLEPP, and 4) CLIC. The building blocks of the various main linac "power units" for these machines are shown in Fig. 1. The design, engineering, mass production and cost of these "power units" are crucial to the success of whichever linear collider ultimately gets selected and built because of the large quantities of identical components involved.

### TESLA (Group 1)

This machine is in a category by itself because it is the only one that uses superconducting accelerator sections for the main linacs. The rf frequency is the lowest (1.3 GHz) and the beam aperture is the largest ( $2a = 7 \text{ cm}$ ). All the characteristics of TESLA result from these basic features. The advantages are that the rf pulse is long, the bunch spacing is wide (708 ns), the transverse wakefields [which for single bunches vary roughly as  $\lambda^{-3}(a/\lambda)^{-2.2}$ ] are weakest, and corresponding alignment tolerances are loosest (by at least a factor of 5 for multibunches). As a result, emittance growth will be easiest to control. Ground motion effects may be compensated by fast feedback controls and by bunch-to-bunch steering at the end of each linac. Note, however, that the decision to reduce the repetition rate from 10 to 5 Hz has forced  $\sigma_y^*$  down from 64 to 19 nm to conserve luminosity. The biggest challenge for TESLA is to perfect the rf superconducting technology to the point where accelerating gradients of 25 MV/m can be attained reliably with  $Q_0$ 's of at least  $5 \times 10^9$ , and that costs can be made affordable. The main linacs consist of 616 power units, each involving a pulsed modulator supplying an 8 MW peak power klystron which in turn drives 32 one-meter long superconducting structures in four long cryostats, incorporating HOM couplers and quadrupoles. Related

	TESLA		SBLC		JLC(S)		JLC(C)		JLC(X)		NLC		VLEPP		CLIC	
	TRC	Updated* 8/96	TRC	Updated* 12/95	TRC	Updated* 8/96	TRC	Updated* 12/95	TRC	Updated* 8/96	TRC	Updated* 12/95	TRC	Updated* 8/96	TRC	Updated* 8/96
Initial energy (c. of .m.) (GeV)	500		500		500		500		500		500		500		500	
RF frequency of main linac (GHz)	1.3		3		2.8		5.7		11.4		11.4		14		30	
Nominal Luminosity ( $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ ) <sup>†</sup>	2.6	3.69	2.2	3.16	5.2	5.29	7.3	4.19	5.1	5.49	5.3	3.9	12.3	11.9	0.7-3.4	5.27
Actual Luminosity ( $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ ) <sup>†</sup>	6.1	6	3.75	5.3	4.3	4.6	6.1	6.3	5.2	5.1	7.1	5.5	9.3	9.7	1.07-4.8	6.4
Linac repetition rate (Hz)	10	5	50		50		100		150		180		300		2530-1210	700
No. of particles/bunch at IP ( $10^{10}$ )	5.15	3.63	2.9	1.1	1.44		1		.63		.65		20		.8	
No. of bunches/pulse	800	1130	125	333	50		72		85		90		1		1-10	20
Bunch separation (nsec)	1000	708	16	6	5.6		2.8		1.4		1.4		--		.67	1
Beam power/beam (MW)	16.5	8.2	7.26	7.25	1.3		2.9		3.2		4.2		2.4		.8-3.9	4.5
Damping ring energy (GeV)	4	3.2	3.15		2		2		1.98		2		3		2.15	
Unloaded/loaded gradient (MV/m) <sup>††</sup>	25/25				31/--		40/32		73/58		50/37		100/91		80/78	100/95
Total two-linac length (km)	29		33		22.1		18.8		10.4		15.6		7		8.8	7.5
Total beam delivery length (km)	3		3		3.6		3.6		3.6		4.4		3		2.4	
$\gamma\epsilon_x/\epsilon_y$ (m-rad $\times 10^{-5}$ )	20/1	14/25	10/5	5/25	3.3/05		3.3/05		3.3/05		5/05		20/08		3/15	3.4/1
$\beta_x/\beta_y$ (mm)	25/2	25/7	22/8	11/45	10/1		10/1		15/2		10/1		100/1		10/18	10/13
$\sigma_x^*/\sigma_y^*$ (mm) before pinch	1000/64	845/19	670/28	335/15.1	260/3		260/3		318/4.3		320/3.2		2000/4		247/7.4	264/5.1
$\sigma_z$ (Hm)	1000	700	500	300	120		120		200		100		750		200	160
Crossing Angle at IP (mrad)	0		3	6	6.4		6		8		20		6		1	20
Disruptions $D_x/D_y$	.56/8.7	.28/17	.36/8.5	.32/7.1	.29/25		.20/18		.225/16.7		.098/8.38		.4/2.15		.29/9.8	.21/10.6
$H_D$	2.3	1.63	1.8	1.68	1.6		1.4		1.5		1.34		2		1.42	1.2
Upsilon sub-zero	.02		.037		.2		.14		.079		.12		.09		.07	
$\delta_B$ (%)	3.3	2.5	3.2	2.8	12.7		6.5		3.4		3.5		3.2		3.6	3.6
$n_\gamma$ (no. of $\gamma$ 's per e)	2.7	2.0	1.9	1.4	2.2		1.5		1.3		1.4		1.1		4.7	1.3
$N_{pairs}$ ( $p_T^{min}=20 \text{ MeV}/c, \theta_{min}=0.15$ )	19.	31	8.8	7.1	31.6		10.3		15.8		2.9		7		1700	1219
$N_{hadrons}/crossing$	.17	.13	.1	.04	.98		.23		.1		.05		.05		45.9	11
$N_{jet} \times 10^{-2}$ ( $p_T^{min}=3.2 \text{ GeV}/c$ )	.16	3	.14	.1	3.4		.66		.27		.14		.14		56.4	28

<sup>†</sup> For the sake of uniformity, the nominal luminosity is simply defined as  $N^2/4\pi \sigma_x^* \sigma_y^*$  times the number of crossings per second, and in all cases assumes head-on collisions, no hour-glass effect and no pinch. The actual luminosity incorporates all these effects, including crossing angle where applicable. NLC calculations assume crab-crossing. The TRC background calculations were made by P. Chen of SLAC. The updated ones were made by D. Schulte of DESY.

<sup>††</sup> The main linac loaded gradient includes the effect of single-bunch (all modes) and multibunch beam loading, assuming that the bunches ride on crest. Beam loading is based on bunch charges in the linacs, which are slightly higher than at the IP.

\* If a number does not appear in the updated column, this means that the number in the TRC column still holds.

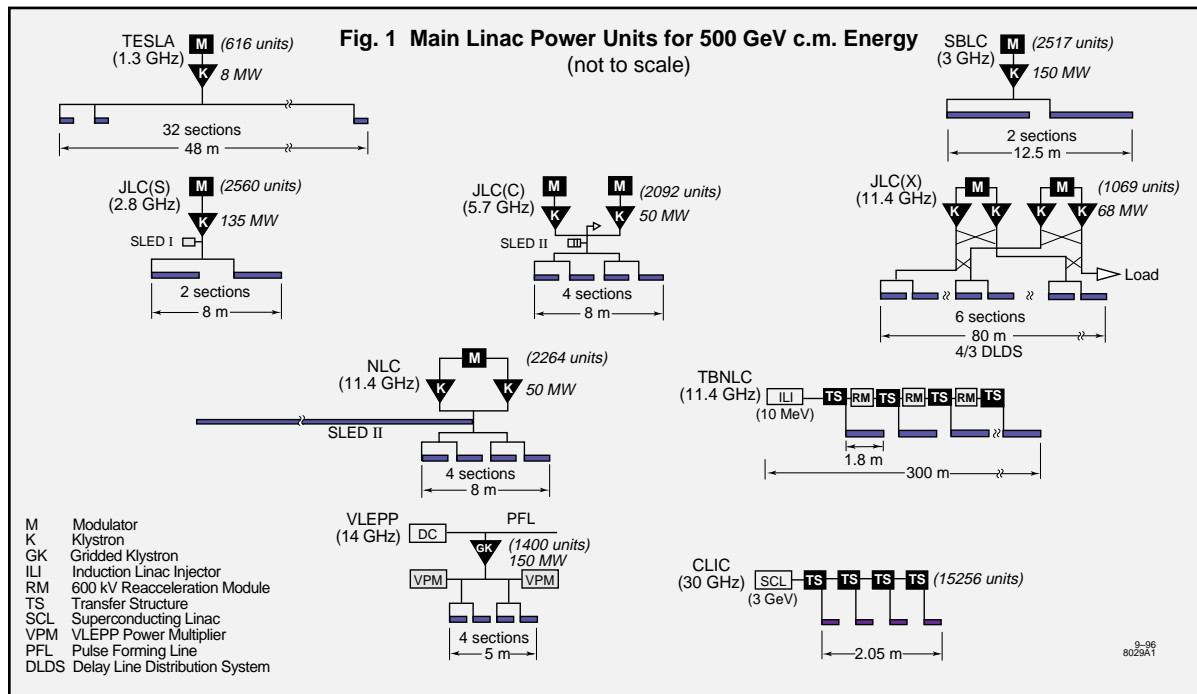
Table 1. Linear Colliders: Overall and Final Focus Parameters—500 GeV c.m. Energy

	TESLA		SBLC		JLC(S)		JLC(C)		JLC(X)		NLC		VLEPP		CLJC	
	TRC	Updated* 7/96	TRC	Updated* 7/96	TRC	Updated* 7/96	TRC	Updated* 7/96	TRC	Updated* 7/96	TRC	Updated* 7/96	TRC	Updated* 7/96	TRC	Updated* 7/96
<b>Pre-linacs</b>																
First stage e <sup>±</sup> energy (GeV)	4	3.15		1.98	1.98	1.98	1.98	1.98	1.98	1.98	2	1.98	3		2.15	
Second stage e <sup>±</sup> energy (GeV)	-	-		-	10	10	10	10	10-20	20	10	10	-		9	
Beam energy to make e <sup>±</sup> (GeV)	250	250		10	10	10	10	10	10	10	3-6	150	150		2.15	
<b>Damping Rings</b>																
e <sup>±</sup> pre-damping ring energy (GeV)	-	-		1.98	1.98	1.98	1.98	1.98	1.98	1.98	2	1.98	-		2.15	
e <sup>±</sup> damping ring energy (GeV)	4	3.15		1.98	1.98	1.98	1.98	1.98	1.98	1.98	2	1.98	3		2.15	
Ring circumference (m)	20,000	650		321	277	321	277	321	277	277	223	160	160		283	
Damping times (ms) (τ <sub>x</sub> , τ <sub>y</sub> )	20/20	3.8/3.8		6.1/8	3.5/4.3	6.1/8	3.5/4.3	6.1/8	3.5/4.3	4.0/5.2	4.1/4.6	1.8/2.9	1.8/2.9		10.5/10.5	
Number of bunches per ring	800	125		100	288	100	288	100	340	340	360	3	3		48x10	
Bunch length (mm)	10	3.6		4.8	5	4.8	5	4.8	5	5	4.1	9.8	9.8		1.8	
Extr. beam emittance, (γ <sub>e</sub> /γ <sub>p</sub> , 10 <sup>-6</sup> )	20/1	10/5		3.3/0.5	3.3/0.5	3.3/0.5	3.3/0.5	3.3/0.5	3.3/0.5	3.3/0.5	2.5/0.3	3/0.3	45.5/4.5		2.5/0.4	
<b>Main Linacs</b>																
RF frequency (GHz)	1.3	3		2.8	5.7	2.8	5.7	2.8	11.4	11.4	11.4	14	14		30	
Unloaded/loaded gradient (MV/m)**	25/25	21/17		31/-	40/32	31/-	40/32	31/-	73/58	73/58	50/37	50/35	100/91		80/78	100/95
Active two-linac length (km)	20	30.2		19.8	15.7	19.8	15.1	15.1	8.7	8.4	14.2	16.3	5.8		6.3	4.9
Total two-linac length (km)	29	33		22.1	18.8	22.1	18.8	18.8	10.4	10.5	15.6	17.6	7		8.8	7.5
Total number of klystrons	604	2517		2560	43561	2560	4184	43561	3320	4276	3936	4528	1400		NA	10
Total number of modulators	604	2517		2560	2178	2560	2092	2178	3320	2138	1970	2264	140		NA	10
Klystron peak power (MW)	8	150		135	48	135	50.3	48	135	68	50	150	150		NA	700
Klystron repetition rate (Hz)	10	50		50	100	50	100	100	150	150	180	300	300		2530/1210	0.413
Klystron pulse length (μsec)	1315	2.8		4.5	2.4	4.5	2.4	2.4	5	7	1.2	5	5		.0116/.00176	.0413
Pulse compression ratio	-	-		3.75	5	3.75	5	5	2	3	5	3.2	4.55		3.2	
Pulse compression gain	-	-		~2	3.5	~2	3.35	3.35	1.96	2.9	3.83	3.6	3.2		-	-
RF pulse length at linac (μsec)	1315	2.8		1.2	48	1.2	48	48	23	24	24	11	11		.0116/.00176	.0413
Number of sections	19328	5034		5120	8712	5120	8368	8712	6640	6414	7872	9056	5600		22466	15256
Section length (m)	1.04	6		3.6	1.8	3.6	1.31	1.8	1.31	1.8	1.8	1.4	1		.280	.323
a/λ (range if applicable)	15	.16/.11		.14/.1	.16/.12	.14/.1	.173/.125	.16/.12	.20/.14	.20/.14	.22/.15	1.4	1.4		2	
Total AC power to make rf (MW)	164	139		118	139	118	153	139	114	99	103	121	57		100	96
Wall plug → beam efficiency (%)	20	10.7		3.0	4.6	3.0	4	4.6	5.6	6.8	8.2	7.9	8.4		1.6/7.8	9.3

\*\* The main linac loaded gradient includes the effect of single-bunch (all modes) and multibunch beam loading, assuming that the bunches ride on crest. Beam loading is based on bunch charges in the linacs, which are slightly higher than at the IP.

\* If a number does not appear in the updated column, this means that the number in the TRC column still holds.

Table 2. Pre-linacs, Damping Rings and Main Linac Parameters—500 GeV c.m. Energy



requirements are the compensation of the mechanical cavity detuning due to the Lorentz force, the absolute need to suppress field emission to avoid heat losses and captured dark current, the construction of a variable coupler, and alignment of components within the cryostats. The electron bunch train can be produced from a laser-driven gun but the positron bunch train is too intense for a conventional target to survive. Hence, the intent is to shoot the spent  $e^-$  beam after the IP through an undulator to produce  $\gamma$ 's which then produce positrons in a thin rotating target. The 3.2 GeV damping rings (often called dog-bones because of their shape) must be designed to accept and damp each long train of bunches (240 km) in a "compressed" circumference (17 km). Finally, since the main linacs are already very long (32 km), the expandability to 1 TeV c.m. energy will preferably be achieved, at least in part, by an increase in gradient (say 40 MV/m). Such a gradient will require an additional 25% increase in length to 40 km. The desired luminosity at 1 TeV can be reached with a  $\sigma_y^*$  of 6.5 nm and a  $\delta_B$  of 2.5%.

### SBLC, JLC(S) and JLC(C) (Group 2)

SBLC and its close cousin, JLC(S), benefit from the most widespread and proven technology developed at SLC and elsewhere for many years. Roughly speaking, their main linacs are equivalent to 7–10 SLAC linacs. SBLC has the next-to-largest  $\sigma_y^*$  (15 nm) after TESLA and gets its luminosity at 50 Hz repetition rate with 333 bunches per pulse spaced 6 ns apart and  $1.1 \times 10^{10}$  particles per bunch. JLC(S) gets its luminosity with a  $\sigma_y^*$  of 3 nm, 50 Hz, 50 bunches spaced 5.6 ns apart and  $1.44 \times 10^{10}$  particles per bunch. For the 500 GeV c.m. case, SBLC does not use pulse compression whereas JLC(S) uses SLED I. The respective power units are shown in Fig. 1. Because of multibunch operation, the accelerator structures are designed to detune and damp transverse wakefields. SBLC has tested 6 m-long sections with

two sets of higher-order mode couplers along their length, which can also be used as pick-ups to align the sections by minimizing beam induced fields. Sputtering of a 20  $\mu\text{m}$ -thick low conductivity material onto the disk edges is also being used to differentially reduce the Q of undesirable modes by a factor of 5 without affecting the fundamental mode Q by more than 5%. Initial alignment tolerances are on the order of 100  $\mu\text{m}$  and sections must be mounted on girders to within a tolerance of about 30  $\mu\text{m}$  rms. JLC(S) uses 3.6 m-long sections similar to the SLC. The electron and positron sources for SBLC are similar to TESLA's, those for JLC(S) resemble those of the SLC but have not yet been designed in detail. The energies of the damping rings are respectively 3.15 and 1.98 GeV. Extension to 1 TeV c.m. for SBLC is envisaged by doubling the number of klystrons and adding pulse compressors to double the gradient within the original machine length. No upgrade option to 1 TeV has been offered for JLC(S).

JLC(C) was not considered in any detail in the TRC report because experimental work at C-band had not yet started at KEK at the time. Since then, an active R&D program has been launched on the rf components, including a 50 MW peak power klystron, a choke-mode type, 1.8 m-long accelerator structure and a multicell coupled cavity system for a short SLED II pulse compressor. The choke-mode structure eliminates the multibunch wakefield problem and has an alignment tolerance of 30  $\mu\text{m}$ . The beam characteristics are similar to those of the X-band design, except for a longer bunch length. Extension to 1 TeV c.m. energy would be obtained by doubling the klystron output power to 100 MW and increasing the length of the main linacs by 40%.

### JLC(X), NLC and VLEPP (Group 3)

Although VLEPP is designed for 14 GHz while JLC(X) and NLC use 11.4 GHz for their main linacs, these three

machines can be described in a single group because of their technological similarities. JLC(X) and NLC have similar luminosities, repetition rates, numbers of bunches per pulse and charges per bunch. The  $\sigma_y^*$  at the IP for JLC(X) is 3 nm whereas that for NLC is about 6 nm, but this difference does not arise from any fundamental differences in design. There is also a slight difference in  $\sigma_z^*$ , and crab-crossing at the IP is proposed for NLC whereas it may not be needed for JLC(X). The main difference between the two machines appears in their main linac gradients (57 MV/m for JLC(X) vs. 35 MV/m for NLC) and results from the differences in their power unit designs (see Fig. 1). JLC(X) proposes to use the delay line distribution system (DLDS) whereas NLC uses SLED II, possibly to be replaced by the more efficient binary pulse compression (BPC) at a later date. The NLC klystron is planned to be a 50 MW tube (later to be upgraded to 75 MW) with periodic permanent magnet (PPM) focusing, which is currently being tested successfully at SLAC. The JLC klystron will probably be similar. R&D toward efficient and simplified modulators is crucial for eventual economy of electric power and manufacturing costs. For accelerator structures, NLC will use sections in which transverse deflecting modes are both detuned (within a Gaussian distribution) and damped to a Q of about 1000 (by coupling to four external parallel rectangular matched manifolds). First tests of this so-called DDS structure indicate that its fabrication can be achieved successfully by diffusion bonding of cups with cell-to-cell alignment better than 4  $\mu$ m. It is likely that JLC(X) will use very similar sections, albeit 1.3 m long. The electron bunch trains for both machines will be produced by laser-driven photocathode guns, and the positrons by improved SLC-type sources, in combination with various L-band and/or S-band pre-accelerators. The pre-damping and damping ring energies are all at about 2 GeV.

VLEPP is based on a design with a single bunch per rf pulse which does away with the multibunch wakefield problem. This design must get its luminosity from a much greater charge per bunch ( $2 \times 10^{11}$  particles) which unfortunately leads to very high backgrounds. The VLEPP rf power unit can also be seen in Fig. 1. In theory, it leads to a loaded gradient of 91 MV/m. For extension to 1 TeV c.m., JLC(X) and VLEPP would be doubled in length whereas NLC would get there by a 20% increase in length (built-in from the beginning), a doubling in the number of klystrons and an increase in their power from 50 to 75 MW. Alternatively, if the TBNLC (two-beam) technology based on drive beams accelerated by induction linacs were to become successful in the future, the NLC could have its array of klystrons, modulators and rf pulse compressors replaced by 64 sequential drivers, each 300 m-long (see Fig. 1) with reacceleration modules and transfer structures to supply the individual linac structures with the desired rf pulses.

#### CLIC (Group 4)

CLIC occupies a unique position in parameter space. The IP spots are similar to those in Group 3. The machine is characterized by the highest linac rf frequency, highest dark current capture field and potentially highest gradient. It requires

many innovations, has the strongest wakefields, and therefore the tightest fabrication and alignment tolerances. The rf power is generated by an intense drive beam, accelerated by LEP-type superconducting structures, which induces the power in special transfer structures. The problem of producing thousands of klystrons, modulators and rf pulse compressors is replaced by having to create two high-current drive beams with a bunch time structure capable of generating rectangular rf pulses at 30 GHz. The problem of producing these drive beams and then conserving their phase space qualities along the full length of the linacs is a major challenge. An advantage of the CLIC two-beam scheme is that it allows all the components to be housed in one tunnel. The front end of the main  $e^+e^-$  beam generation is analogous to the front end of the SLC. A number of design features of these drive and main beams remain to be elucidated, particularly for 20 bunches/pulse operation which has recently been chosen to bring up the luminosity within the range of the other machines. For 1 TeV c.m. energy, both the drive and main linacs would be doubled in length.

#### Conclusions

Because of lack of space, there are many topics in the TRC report that cannot be reviewed in this paper. Fortunately, many other papers at this conference deal with recent important linear collider developments. Worldwide investment in this field is spawning a vast amount of new knowledge and technologies. The SLC at SLAC and the new test facilities at DESY, KEK, SLAC, BINP, CERN and LBNL are contributing to an explosion of R&D. New laser-driven photocathode electron sources with 80% polarization have become a reality, and new positron sources and pre-linacs are undergoing design. The very small emittances that must be created by the damping rings and preserved through the bunch compressors, main linacs, beam delivery systems and final foci are giving rise to new ideas about instrumentation, alignment, stability, collimation and beam containment. New insights are being gained into beam dynamics (dispersion-free and wakefield-free steering, transient beam loading) and into the important field of ground vibrations over a wide range of frequencies ( $10^{-2}$  to  $10^{+2}$  Hz) and coherence lengths. Finally, a whole new approach towards design for manufacturing (DFM) to decrease mass production costs while preserving tolerances, cleanliness to avoid field emission and dark current, high vacuum conditions, and above all, reliability of operation, is being introduced into the field of accelerator fabrication and pricing.

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#### References

- [1] "International Linear Collider Technical Review Committee Report," SLAC-R-95-471, (1995).