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Review of Linear Colliders in the Framework of Future World Accelerators

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The HEP communities in three major regions, Asia, Europe and North America, have recently agreed that experimental particle physics in the next twenty years will be greatly enriched if an e^+e^- linear collider were to be available in the TeV c.m. energy range to supplement the opportunities offered by the LHC. This abridged paper of a longer oral presentation at ICHEP 2002 outlines several current design options for such an e^+e^- linear collider, which are presently under intense study by the International Linear Collider Technical Review Committee (ILC-TRC).

1. Introduction

This paper is a condensed version of a much longer oral report given by the author at ICHEP 2002. The review of linear colliders, which was the main subject of that oral presentation [url to come], is currently the subject of a major international study requested by ICFA at its February 8/9, 2001 meeting at DESY. The results of the study will be published in early 2003 in the Second International Linear Collider Technical Review (ILC-TRC) report. The report will contain descriptions of TESLA, JLC(C), JLC(X)/NLC and CLIC at 500 GeV c.m., their upgrade potentials to higher energies, their test facilities, assessments of their various technologies and the R&D work that the ILC-TRC has identified as necessary before one of these machines can be selected and constructed. Table 1 is a list of present and future HEP accelerators, the framework within which such a linear collider would be built and made available for particle research complementary to the LHC.

Table 1
Present and Future HEP Accelerators

In Operation:
DAΦNE
VEPP4
BEPC I
SLAC LINAC
CESR, KEK B, PEP II
JINR NUCLOTRON
10 GeV ITEP PS
70 GeV SERPUKHOV PS
YEREVAN SYNCHROTRON
CERN PS and SPS
PETRA, HERA
AGS, RHIC
TEVATRON
Under Construction:
VEPP 2000 (2003)
LHC (2007)
Under Proposal, Design or Study:
CESR-c
BEPC II
TESLA, JLC/NLC, CLIC
SUPER *B* FACTORIES
MUON RING NEUTRINO FACTORIES
VLHC, VLLC
EIC, HIP
FUTURE TECHNOLOGIES

2. The Four Linear Collider Options

Among future HEP machine options (almost all lepton or hadron colliders), the international community has now converged on an e^+e^- linear collider. While the technology for such a col-

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lider still remains to be determined, the machine should start with an energy of 500 GeV c.m., later expandable to higher energies. The colliders reviewed here are not all in the same state of readiness. TESLA and JLC(X)/NLC have fairly mature designs, based on significantly advanced system tests. JLC(C) consists only of a 400 GeV c.m. rf design based on technology being developed for a linac-based FEL at SPRING-8 in Japan. CLIC follows a much more futuristic approach based on a two-beam system which, if successful, could eventually reach 3 TeV c.m.

TESLA's main characteristics are illustrated in Figs. 1, 2, and 3. The site is 33 km long, the main linacs are based on 1.3 GHz superconducting 9-cell niobium structures, 17 km perimeter "dog-bone" shaped damping rings, 337 ns bunch spacing and a bootstrap positron generation system which uses gamma rays produced by the primary electron beam passing through an undulator and impinging on a thin titanium target. All main linac systems are located in single tunnels.

The JLC(X)/NLC (essentially a unified design, except for the repetition rate) is shown in Figs. 4 and 5. It has independent injectors and damping rings, main linacs operating at 11.4 GHz using room-temperature damped-detuned copper structures powered by 75 MW PPM klystrons and SLED-II rf pulse compression systems located in separate tunnels. Peak input rf power is 450 MW with 400 ns pulse length and 1.4 ns bunch spacing. The total site length, including space for a 1 TeV upgrade, is 30 km.

The JLC(C) rf design is not shown here for lack of space. It uses main linacs running at 5.7 GHz with PPM klystrons, three-cavity SLED-III rf pulse compressors and "choke-mode" cavities. The layout is very similar to the present 3-km-long SLAC linac, with injector designs identical to those for JLC(X)/NLC. The C-band portion of the linacs is 17 km long and assumes that any energy upgrade would use X-band extensions. Bunch spacing is 1.4 ns.

CLIC is shown in Figs. 6 and 7: it uses two drive-beam linacs followed by three-stage bunch combiners to generate 30 GHz rf power in transfer structures (decelerators) which feed the main linac accelerator structures. The number of drive-beam decelerators and total linac lengths scale directly with the ultimate beam energy desired. The injector designs, not shown in Fig. 6, are not yet entirely completed but they are more or less conventional. Bunch spacing is 0.67 ns.

3. Technical Challenges

The major technical challenges posed by the above machines fall into two categories:

1. Luminosity expectations based on extremely high beam powers with very tight emittance generation and preservation, and
2. Energies based on electric field gradients which for each machine stretch the state-of-the-art.

The examination and assessment of how these challenges are to be met constitute the main subjects of the ILC-TRC's effort which will be spelled out in great detail in its final report. As mentioned earlier, the ILC-TRC will also list and discuss in great detail a large number of R&D tasks which in its judgment still remain to be done before any of the machines can begin construction.

The challenges in Category 1 are summarized in Table 2, which shows the normalized emittances out of the damping rings and at the IP, the beam sizes and power, and the luminosities. As seen, the conditions necessary to attain the design luminosities put very stringent tolerances on the designs of the damping rings and the allowable emittance dilutions in the linacs and beam delivery sections (with their collimators) all the way to the IP. For TESLA, the allowable vertical dilution is only 50%, and for JLC(X)/NLC it is a factor of 2 (i.e., 100%). Neither one of these tolerances is easy to meet and requires extremely sophisticated static and dynamic computer tuning simulations as well as effective feedback systems which are much too elaborate to be discussed here.

The challenges in Category 2 are summarized in Table 3 which shows the unloaded and loaded main linac gradients required for the 500 GeV c.m. and upgrade energies. Note that TESLA must increase its gradient from 23.4 to 35 MV/m to reach 800 GeV c.m. whereas JLC(X)/NLC

Table 2
Luminosity, Emittance Generation and Preservation

LC 500 GeV	TESLA	JLC/NLC	CLIC
DR Extraction			
$\gamma \in_x^* / \gamma \in_y^*$ ($\times$ 10^{-6} m.rad)	8/0.02	3/0.02	1.6/0.005
IP			
$\gamma \in_x^* / \gamma \in_y^*$ ($\times$ 10^{-6} m.rad)	10/0.03	3.6/0.04	2/0.02
β_x^*/β_y^* (mm)	15/0.4	8/0.11	10/0.15
σ_x^*/σ_y^* (nm) at IP	554/5.0	243/3.0	202/2.5
$P/Beam$ (MW)	11.3	8.7/6.9	4.9
H_D	2.1	1.5	1.8
L (10^{33} cm^{-2} s^{-1})	34	25/20	14.1

Table 3
RF Parameters and Upgrade Strategies.

LC	TESLA		JLC(C)	JLC(X)/NLC		CLIC	
GeV	500	800	500	500	1000	500	3000
Unloaded/Loaded Gradient (MV/m)	23.4/23.4	35/35	41.8/31.5	65/50		172/150	
Total Two-Linac Length (km)	30	30	17.1	13.4	27.6	5	28

must reach at least 65 MV/m unloaded and 50 MV/m loaded from the beginning. The 1 TeV c.m. energy for JLC(X)/NLC is attained by simply doubling the length of the main linacs. JLC(C) at 400 or 500 GeV c.m. has intermediate unloaded and loaded gradients of 41.8 and 31.5 MV/m respectively. Finally, CLIC is based on an extremely high unloaded gradient of 172 MV/m and a loaded gradient of 150 MV/m. These gradients are not only difficult to sustain, given the current understanding of copper structure breakdown and damage limits, but also hard to generate, given that klystron designers are hard-pressed to produce peak powers in excess of 75 MW peak at any frequency, and peak powers of, for example, 150 MW at X-Band are needed to establish the above electric fields. Very sophisticated and efficient rf pulse compression or beam combiner systems must be designed to reach these very high pulsed peak powers.

Finally, it has become very clear from the ILC-TRC studies that the complexity of any of these linear colliders will require great attention to reliability, availability and operability of all the constituent systems, all the way from the beam sources to the IP, including the design of the beam dumps. Indeed, these machines are very vulnerable to vibrations, ground motion, poor tuning algorithms and single point failures. It is essential that the designs be robust enough so that commissioning can be achieved fairly rapidly and that both expected peak luminosity and integrated luminosity be attained routinely in a year or so after commissioning.

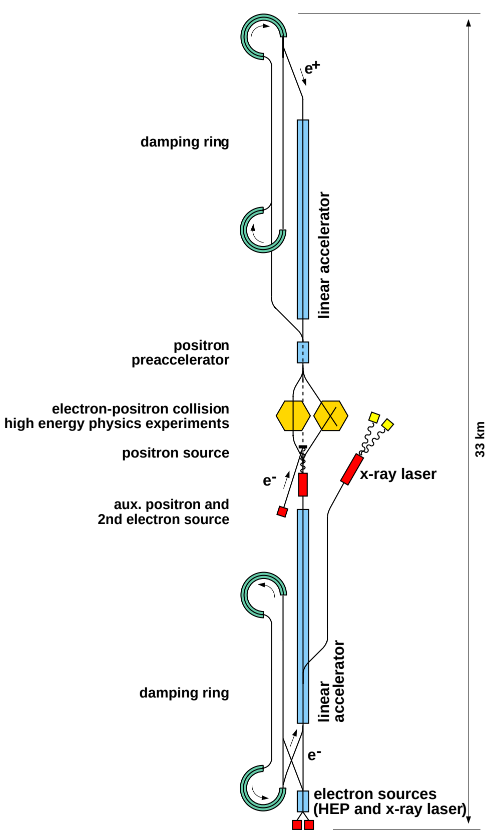

Figure 1. TESLA layout

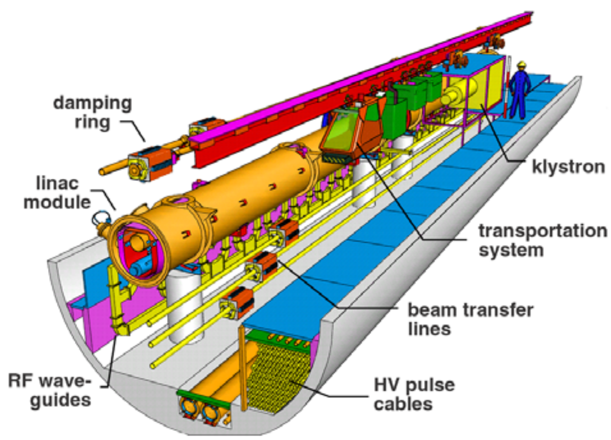

Figure 2. Sketch of the 5 m diameter TESLA linac tunnel.

Figure 3. The 9-cell niobium cavity for TESLA.

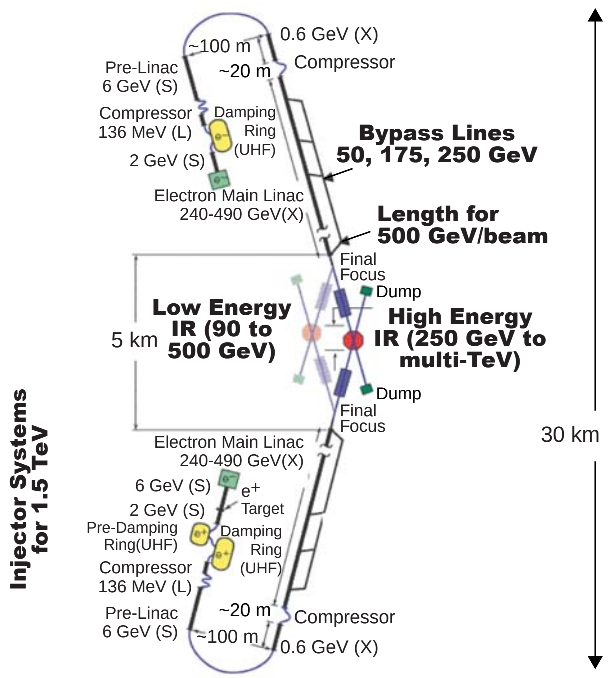

Figure 4. JLC(X)/NLC layout

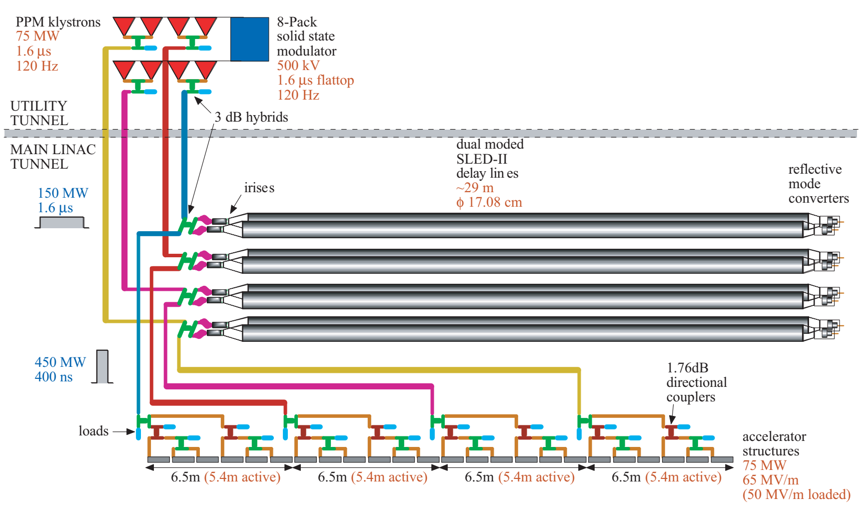

Figure 5. Schematic of a JLC(X)/NLC linac RF unit (one of 254 per linac); the SLED-II delay lines could be located in either the linac or utility tunnels.

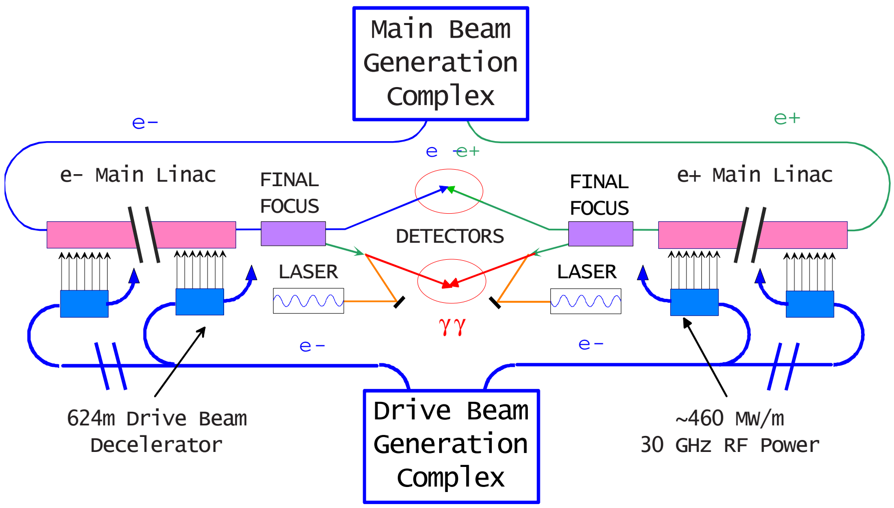

Figure 6. CLIC layout

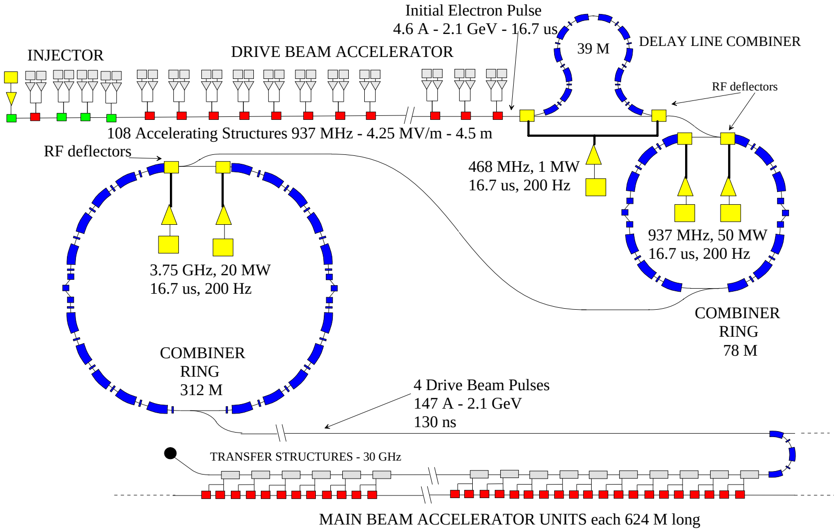

Figure 7. Drive-beam klystron-modulators and bunch combiners for one rf generation complex.