M3 Snowmass Working Group on Linear Colliders
Executive Summary

The M3 Snowmass Working Group on Linear Colliders (LC) consisted of roughly 40 people who met during the three weeks of the Snowmass2001 meeting. The working group examined many of the fundamental issues regarding the design of these facilities including the rf systems necessary to attain the desired beam energy, and the luminosity performance that might be expected. In the following, the primary issues will be reviewed and then some suggestions for R&D to be completed before construction are listed. Finally, it should be noted that many of these issues were covered in more depth in the T1 (Interaction Region), T2 (Magnet design), T3 (Rf systems), T4 (Particle sources), T5 (Beam dynamics), T6 (Environmental Control and stability), and T9 (Instrumentation) working groups and further discussion can be found there.

The center-of-mass (cms) energy at a next generation LC is 10 times higher than that achieved in the Stanford Linear Collider (SLC) and the luminosity 10,000 times higher than that attained by the SLC. The working group primarily discussed the NLC/JLC X-band designs, which are based on normal conducting rf at 11.4 GHz, the TESLA design which is based on superconducting cavities operating at 1.3 GHz, and, briefly, the JLC C-band 5.7 GHz option. These designs aim for an initial energy of 500 GeV in the cms and have upgrade paths to energies of roughly 1 TeV. The group also considered many of the issues relevant to higher energy LC concepts, including the two-beam CLIC design, which is based on normal conducting 30 GHz rf and a relativistic drive beam as the rf power source.

The NLC/JLC-X and TESLA designs and technology are sufficiently developed and either could be used to build a 500 GeV collider. The performance limitations are well understood and the measures which must be taken to achieve the design performance at a high level of confidence are precisely defined. The R&D on the X-band will take another 3 to 4 years, i.e. 2004, before being ready for large scale industrial production. Similarly, TESLA will be ready in 2 to 3 years, i.e. 2003. In both cases, final engineering R&D should be performed in the framework of a funded project.

Beam Energy and Rf Systems

The rf components (modulators, klystrons, rf distribution, and accelerator cavities) of the NLC/JLC-X and the TESLA LC have been developed over the last decade. Integrated systems with prototype components have been in operation since 1997 at the NLC Test Accelerator at SLAC and the TESLA Test Facility at DESY. These test facilities have accelerated beams with loaded gradients of 40 MV/m and 23 MV/m, respectively, and with parameters (acc. gradient, beam intensity, pulse length and energy stability) sufficient for a 500 GeV linear collider. The ongoing R&D programs, described below, aim at the higher loaded gradients, 55 MV/m and 35 MV/m, required for 1 TeV/800 GeV operation, and at an optimization of rf systems with respect to cost and power efficiency.

Linear colliders with cms energy above 1 TeV are primarily envisaged using high-gradient, high-frequency acceleration with the rf energy supplied by an auxiliary drive beam (Two-Beam-Acceleration). The CLIC R&D program (30 GHz) presented designs which extend from 0.5 TeV up to 5 TeV, with the primary emphasis on the 3 TeV design. Energy upgrades to the NLC/JLC using high-gradient X-Band acceleration (1.7 TeV) and 22.8 GHz acceleration (2.5 TeV) were also presented, with both designs using by Two-Beam Acceleration.

Luminosity

All of the key topics relevant to the luminosity performance of the colliders were discussed: (1) sources & damping rings (DRs), (2) linacs, (3) beam delivery systems (BDS), (4) stabilization and ground motion issues, and (5) operational issues such as commissioning and machine protection strategies.

Sources & Damping rings: The particle sources for the NLC/JLC design are based on extrapolations from the SLC. The TESLA electron source is similar and the positron source uses photons produced by the high energy electron beam in a wiggler. Although the requirements for the beam quality in the damping rings (emittance, energy spread) are similar, the NLC/JLC and TESLA designs are significantly different because of the different bunch train structure. The 300-m circumference rings for the X-band LC are moderate extrapolations of the ATF ring at KEK and currently operating synchrotron radiation facilities. The TESLA damping ring is much larger (17 km) to store all of the 3000 bunches in the train.

In both cases, one of the most difficult challenges will be achieving and maintaining the very small vertical emittances. The ATF ring has demonstrated emittances within a factor of 2 ~ 5 of the DR design. Many other operating rings have achieved similar emittance *ratios* (0.1 ~ 0.5%) but not the same *absolute* emittance. Another issue that distinguishes the damping rings from presently operating rings is the large damping decrement provided by special wiggler magnets. The NLC/JLC ring has 45-m of high field wiggler, similar to ATF, while the TESLA ring has 400-m. Issues regarding the wiggler non-linearity will be addressed by simulations and by experiments at ATF and at the planned CESR-c.

Finally, the ring designs will have to address several collective effects that could be detrimental, including intra-beam scattering, space charge forces, ions, electron cloud and wakefields. It is felt that most individual collective effects can be well described in simulation. Experience with the current generation of high luminosity factories provides confidence in these beam simulations.

Linac Beam Dynamics: The linac beam dynamics is one of the topics that has been studied most extensively. In the normal and superconducting designs, it is important to damp the higher-order modes (HOM) of the cavities to prevent multi-bunch beam breakup instability. At this time, both the TESLA and NLC/JLC projects have demonstrated control of these HOM sufficient to prevent multi-bunch beam breakup. In the normal conducting design, four damped detuned cavities have been measured. In all cases, the transverse wakefield was decreased to the required level; however, in each case, identified construction errors prevented meeting the ideal values. In the TESLA superconducting cavities, the HOM are damped with external loads. One important mode was not adequately damped with this system and a slight modification of the HOM couplers has been proposed. Very high frequency modes must be absorbed by suitable material that will be inserted into the beam pipe between the cryo-modules to avoid additional heat load into the Helium at 2K. In both the NLC/JLC and TESLA, these solutions have been applied to prototype components and there is confidence that these methods can be implemented successfully in the final designs.

Another issue for single bunch dynamics is the component alignment. In the normal conducting designs the typical alignment is 2 to 10µm. To attain these values, beam-based alignment (BBA) techniques must be used and to this end measurement and position controllers are included on all components. These techniques and technologies have been studied and used at the SLC, the Final Focus Test Beam and the ASSET facilities at SLAC. Experiments at the FFTB demonstrated the ability to align components to within a factor of 4 of the NLC/JLC specifications. Improvements in instrumentation, optimization of the optics design for implementation of BBA, and application of other demonstrated techniques assure the needed alignment capability. In the TESLA design, the individual component alignment tolerances are between 100 and 500µm. These alignment tolerances have been obtained within 8-cavity cryo-modules. The systematic (correlated) alignment tolerance on the cryo-modules is tighter than for individual cavities, ranging between 100 and 40µm. If this tolerance is not met during installation, the increased emittance dilution can be mitigated using the techniques developed for the NLC/JLC such as emittance correction orbit bumps.

Beam Delivery Systems: The beam delivery systems of all the designs have very similar requirements. The discussions covered optics designs, spot size tuning, stabilization and jitter issues, beam collimation, and beam-beam effects. In general, the optics designs are far advanced and a number of recent improvements are applicable to all of the designs. The tolerances on collision stability and spot size dilution are comparable in all of the designs but are achieved differently because of the different repetition rates. In the TESLA design, the collision jitter can be effectively removed using the intra-train feedback. However, the tolerances on the spot size increase can be exceeded at a noisy site, in which case active stabilization of some of the components is also required. In the NLC/JLC design, the beam jitter must be stabilized by choosing a sufficiently quiet site and by adding additional active stabilization to magnets which do not meet the tolerances. A very high frequency intra-train feedback might also ease these jitter tolerances. Regarding spot size stabilization, the higher beam pulse rate for NLC/JLC (and CLIC) is advantageous due to the decrease of ground motion amplitude with frequency.

Two primary beam-beam issues were considered: high disruption effects and high-energy limitations. In the high disruption regime, the luminosity becomes sensitive to the single bunch kink instability. As the disruption parameter increases, there is a rapid luminosity decrease due to beam offsets and correlated emittance dilutions. With the present TESLA beam parameters, the sensitivity to a correlated emittance dilution of 1% leads to a ~30% decrease in luminosity, about half of which is recovered by the IP feedback. In the NLC design, the disruption is half as large and preliminary calculations indicate that this reduces the sensitivity significantly. If this sensitivity to disruption is confirmed, the TESLA design parameters can be adjusted to decrease the disruption at the expense of higher beamstrahlung energy loss. At higher energy, multi-TeV designs where $\Upsilon \gg 1$, a 20 mrad IP crossing angle is required.

Operational Issues: Three operational issues were discussed: machine protection, commissioning strategies, and the complexity of the beam-based alignment procedure. A fundamental difficulty for each design is that a single errant bunch with the nominal charge density is capable of damaging whatever it strikes. A fully integrated machine protection system is required to deal with the high potential for damage. This also imposes constraints on the speed with which full luminosity can be achieved because an extensive period of running with reduced charge densities and pulse repetition rates will be necessary. This period provides time to safely align and test the machine components, ensure that all control and protection systems are operating properly, and to validate real-time operating procedures such as the beam-based alignment. At present it is felt that these operational issues are consistent with a 2-year ramp up to full luminosity. Such a schedule assumes that initial beam operations of some subsystems can commence before the formal end of construction; this capability is specifically included in both designs.

R&D Programs

The R&D required before construction can be divided into two areas: that on the rf systems and that to ensure the luminosity performance. For the X-band system at present, much attention is given to the damage in accelerator structures arising from the rf breakdown which occurred at gradients below the 1 TeV NLC/JLC design value. Recent tests with shorter structures and lower group velocities have reached the unloaded design gradient of 70MV/m but have not yet shown sufficient overhead to assure the 1 TeV specifications. Should these tests, continuing through 2001, be concluded successfully, a structure with low group velocity and sufficiently small short-range wakefields (larger iris, higher phase advance) will be tested in early 2002. Following this, it is expected that a final version of structure with full control of the short- and long-range wakefields, suitable for the NLC/JLC linac, will be available by beginning of 2003. In parallel, the rf power sources development will be completed. The NLC collaboration is aiming at a full test of the 1 TeV rf system, including the modulator, klystrons, DLDS pulse compression system, and high gradient structures, to be performed by the end of 2003.

For TESLA, the main R&D focus is on higher gradients. Gradients up to 43MV/m have been obtained in single-cell resonators and 33 MV/m has been achieved in a standard 9-cell cavity by applying an electro-polishing treatment to the Niobium surface. The reproducibility of these results must be proven in the integrated system test to ensure the upgrade capability of TESLA to the foreseen cms energy of 800 GeV at a gradient of 35MV/m. A second issue is the test of the superstructure concept where pairs of 9-cell cavities are powered by one coupler. This increases the linac packing factor by 6% and saves cost by reducing the number of rf-couplers by 50%. These R&D programs should have conclusive results by the end of 2003. In parallel, operation of the TTF linac with parameters close to those of the 500 TeV TESLA design is planned to provide additional operational experience over extended periods of time.

After first successful demonstration of the two-beam concept at CTF-2, the R&D program for CLIC will focus on the rf breakdown problem at high gradients and on the construction of a drive beam generation prototype in the framework of the CTF-3. CTF-3 is aimed at two-beam acceleration at a gradient of 150 MV/m and its construction is to be completed by 2005.

There are a number of R&D items that must be directed at the luminosity performance. First, continued studies at the KEK ATF and other existing rings are necessary to understand all of the beam dynamics issues in the damping rings. In parallel, simulation studies must be performed to address many of the collective effects that may limit the ring performance. These studies are needed for both the NLC/JLC rings as well as the less conventional TESLA damping rings. Second, continued R&D is needed to complete the ground motion and vibration studies and to accurately model the stability of the beam optics systems with all of the tuning and beam-based alignment techniques. In addition, more detailed models of the commissioning and the machine protection strategies are clearly needed. Finally, the feedback systems, the active stabilization techniques, and the diagnostic development must be continued. The LINX interaction region facility at SLAC, which will use the modified SLC final focus to perform engineering studies in the interaction region, could test these technologies and techniques.

Snowmass, CO, July 18
M3 Group