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TECHNOLOGY OPTIONS FOR LINEAR COLLIDERS

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Abstract

A worldwide consensus has developed in the international high-energy physics community that an electron-positron linear collider, with an initial center-of-mass energy of around 500 GeV, should be the next energy frontier accelerator. This paper will review the technical highlights of options for the machine's realization, and discuss the advantages and disadvantages of each.

LINEAR COLLIDER MOTIVATIONS AND REQUIREMENTS

The international high-energy physics community has concluded that a high-energy, high-luminosity, electron-positron linear collider, operating concurrently with the Large Hadron Collider, is necessary to explore and understand electroweak unification and related physics at the TeV energy scale. The underlying science indicates the need for initial operation at a center-of-mass energy of 500 GeV, with capability for upgrade to roughly 1 TeV. An average luminosity of roughly 100-150 fb^{-1}/yr is required, corresponding to a peak luminosity of at least 2×10^{34}cm^{-2}s^{-1}.

To achieve the required luminosity, beams with very high transverse density must be brought into collision. The strong electromagnetic fields of these dense beams cause them to radiate copiously (producing "beamstralung") during the collision. To limit this radiation, which increases the effective energy spread of the beams and produces background, "flat" beams, with a small vertical-to-horizontal aspect ratio, are used. For flat beams, the peak luminosity of the linear collider is given by

$$\mathcal{L}\left[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}\right] \cong 121 N_\gamma H_D \frac{P_b\,[\mathrm{MW}]}{E_b\,[\mathrm{GeV}]\,\sigma_y\,[\mathrm{nm}]}$$

in which E_b is the beam energy, P_b is the beam power, σ_y is the vertical beam size at the collision point, N_γ is the number of beamstralung photons per electron, and H_D is the luminosity enhancement due to beam-beam focusing at the collision point. To limit beamstralung, N_γ must be kept in the range <2, for which $H_D \sim 1.5$.

This relation illustrates the need to collide beams with the highest feasible beam power, and the smallest feasible vertical spot size. These criteria drive much of the design of the linear collider.

LINEAR COLLIDER ACCELERATOR SYSTEMS

The accelerator systems required for a linear collider include electron and positron sources in which the beams are created, damping rings[1] in which the beams are cooled to low emittance, main linacs in which the acceleration takes place, and beam delivery systems which bring the beams into collision. In the following sections, the options being considered for these accelerator systems will be described, the advantages and disadvantages noted, and the outstanding technical challenges outlined. A detailed presentation of the leading issues can be found in the recent report of the International Linear Collider Technical Review Committee[1].

MAIN LINACS

The dominant technical systems in the linear collider are the main linacs, and the choice of technology for the main linac accelerating structures is the fundamental design decision for the machine.

Options

Over the past two decades, an enormous amount of accelerator R&D has been done to develop technologies for the main linacs which can realize the demanding requirements at an affordable cost. The fruits of this R&D are the following options for the main linac accelerating structures:

- superconducting standing-wave cavities, operating at L-band (1.3 GHz), developed by the TESLA collaboration[2] at DESY;
- normal-conducting traveling-wave cavities, operating at X-band (11.4 GHz), developed by the JLC/NLC collaboration[3, 4] at SLAC and KEK[2];
- very high gradient normal-conducting traveling-wave cavities, operating at 30 GHz, potentially capable of reaching beam energies up to 1.5 TeV, being developed by the CLIC collaboration[5] at CERN.

The basic features of the three options are displayed in Table 1, for the baseline beam energy of 250 GeV, and for the upgrade energy.

TESLA utilizes 104 cm long 9-cell pure niobium standing-wave cavities, operating at 24 MV/m, in a static bath of 2 K liquid helium. The choice of a long RF pulse

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[1] Bunch compressors are also required, but these systems will not be covered here due to space limitations.

[2] A C-band option, operating at 5.7 GHz, is also under consideration at KEK[4].

Table 1: Linear Collider Options

Feature	TESLA		JLC/NLC		CLIC	
RF frequency [GHz]	1.3		11.4		30	
Beam energy [GeV]	250	400	250	500	250	1500
Luminosity [$\times 10^{34}$cm^{-2}s^{-1}]	3.4	5.3	2.5/2.0	2.5/3.0	2.1	8.0
Bunch population [$\times 10^{10}$]	2	1.4	0.75		0.4	
Rms vertical beam spot size at IP [nm]	5.0	2.8	3.0	2.1	1.2	0.7
Loaded accelerating gradient [MV/m]	24	35	50		150	
Two-linac length [km]	30		13.8	27.6	5.0	28.0
Number of accelerating structures	20592	21816	18288	37152	7272	44000
Number of klystrons	572	1212	4572	9288	448	
Linac cycle frequency [Hz]	5	4	150/120	100/120	200	100
Total AC power for linac [MW]	95	160	188/150	254/305	105	319
Total beam power [MW]	22.6	35	17.4/13.8	23/27.6	9.8	29.6
Efficiency (beam power/AC power) [%]	23.8	21.9	9.3/9.2	9.1/9.1	9.3	9.3

(1370 μs) is made possible by the ability of superconducting cavities to store energy with minimal losses. Because of the long RF pulse, the required peak RF power is relatively modest (240 kW), despite the substantial average beam power required to achieve high luminosity. Although small, the cavity losses are deposited at 2 K, and a large cryogenic plant is required to accommodate these losses.

JLC/NLC utilizes 60 cm long copper traveling-wave cavities, operating at a loaded gradient of 50 MV/m. The losses in the copper structure are limited by the use of a short RF pulse (0.4 μs). During the short RF pulse, the required peak power is quite high (56 MW), necessitating the use of high peak power X-band klystrons, together with a pulse compression scheme.

CLIC uses 50 cm long 30 GHz copper structures, operating at a loaded gradient of 150 MV/m and with a very short RF pulse (0.13 μs). Very high peak power (>200 MW) is required. As there is no available RF power source at this frequency and power, CLIC uses two-beam technology to transfer power from a low-energy, high current counter-propagating electron beam.

In addition to accelerating the beam, the main linacs are required to preserve the ultra-low emittance generated in the damping rings, which must be delivered to the interaction point. The principal emittance dilution mechanisms for an off-axis beam are dispersive growth, driven by energy spread in the linac quadrupoles; and wakefield-induced growth, driven by the transverse wakefields of the accelerating structures. To control long-range wakefields, the copper structures incorporate damping and detuning features in each cell, which require precise fabrication tolerances. The TESLA cavities use higher-order mode dampers at the cavity ends.

In practice, wakefield and dispersive emittance growth are controlled by alignment of the centers of the quadrupoles and the structures to the beam. Since the micron-level required precision cannot be attained in the *ab initio* survey, elaborate beam-based alignment schemes are required to determine the “gold orbit”, together with feedback systems to maintain the beam on this orbit in the presence of natural and cultural ground motion. The beam-based alignment performance is limited by the features of the beam instrumentation, such as the resolution of the beam position monitor (BPM) system, and the precision of the emittance measurement system.

Advantages and disadvantages

The principal advantage of the warm linacs is the high accelerating gradient, which allows a shorter linac than TESLA, for the same final energy. Depending on the unit costs, this can translate into a cost advantage. The TESLA linac has two principal advantages: higher efficiency and reduced wakefields.

The higher efficiency of TESLA (see Table 1) implies that less average RF power, and hence less capital investment in RF hardware, is required for a given luminosity. This is offset to some extent by the need for a cryogenic plant to provide the ultralow cavity temperature. Nonetheless, even including this, TESLA is more than twice as efficient as the warm linacs.

The peak RF power is much lower in TESLA than in the warm linacs. The absence of the need for pulse compression and high peak-power klystrons makes the high-level RF system in TESLA much less elaborate. The bulk of the more compact TESLA RF system can be housed in the same tunnel as the linac beamline, while, for JLC/NLC, the RF systems must be housed in a separate tunnel parallel to the linac beamline tunnel. The single tunnel arrangement is less costly than the dual tunnel scheme, but has open questions related to reliability and maintainability of the RF components in the beamline tunnel.

TESLA’s low frequency superconducting cavities have lower wakefields than the high frequency copper structures, leading to less stringent requirements on alignment tolerances and on the performance of beam position measurement instrumentation. Special structure BPM's in the warm structures provide information on the position of the beam relative to the structure. Since this information is not directly available for the TESLA cavities, *ab initio* cavity positioning is more critical in this case. Cavity alignment in TESLA is complicated by the presence of the cryostat.

Natural ground motion, and motion induced by technical systems in the tunnel, will cause the linacs to become misaligned with time. Feedback systems are required to combat this motion. Pulse to pulse feedbacks are generally only effective up frequencies of roughly a tenth of the linac cycle rate, which is much lower in TESLA than in the warm linacs.

Outstanding technical challenges

The most important R&D challenge facing both options is a convincing demonstration of the design gradient in the accelerating structures, at the design efficiency and reliability.

For JLC/NLC, the original 1.8 m long structures have operated reliably at 40-45 MV/m, but when pushed to higher gradients, they exhibited excessive breakdown rates, erosion at the irises, and evidence of pulsed heating at the input couplers. Redesigns have focused on shorter (60 cm) structures, with lower group velocity and improved coupler design. A structure of this type has recently reached the design unloaded gradient of 65 MV/m, with an acceptable breakdown rate[6]. Several such structures are being fabricated and will be tested at SLAC later in 2003 and early 2004.

For TESLA, a number of 9-cell cavities have operated at gradients in excess of 24 MV/m, the requirement for operation at 250 GeV/beam. Using the newly developed electropolishing procedure for cavity fabrication, a 9-cell cavity, with input coupler, has exceeded the 35 MV/m goal[7], required for operation at 400 GeV/beam. There are plans to test more such electropolished 9-cell cavities at 35 MV/m later in 2003 and 2004.

The high power RF system required for JLC/NLC offers a number of challenges. High efficiency 75 MW X-band klystrons, with permanent magnet focusing and operating at 120 Hz, are needed. Prototypes have been built at SLAC and KEK, and the KEK prototypes have been successfully tested at full peak power and half the design repetition rate. The high power RF pulses from a pair of klystrons must be further boosted by a factor of 3.3 for delivery to a series of 8 accelerating structures. The required dual-mode SLED II pulse compression system has yet to be demonstrated at full power; this demonstration is slated for later this year. The RF system for TESLA is less demanding. Several prototypes of the required 10 MW multibeam L-band klystrons have met design specifications, but the tube lifetime remains to be determined.

The extremely high gradients required for CLIC, together with the novel character of the two-beam power source, constitute severe challenges. Gradients required for the CLIC structures have been achieved using irises made from refractory metals[6], but only with short ($\sim$15-30 ns) pulses. The elaborate two-beam pulse compression and frequency multiplication scheme requires extensive prototyping, planned for execution at CERN's test facilities between now and 2008.

There also remain open questions on the ability of any of the linacs to preserve the beam emittance to the degree required. The complexity of the required beam-based alignment means that the demonstration of emittance preservation requires extensive simulations. The simulations done to date have included in only an approximate way such effects as dynamic ground motion and instrumentation failures during the determination of the "gold orbit". The instrumentation requirements for beam-based alignment have been realized to date only in individual prototypes, and will be challenging to achieve in a large scale system. Component vibration at the level of natural ground motion is tolerable with the use of feedback, but very little additional vibration can be allowed from cultural sources, either external to the tunnel or arising from equipment within the machine.

ELECTRON AND POSITRON SOURCES

The electron and positron sources must produce beams with the proper time structure and intensity, for injection into the damping rings. The electron beam is required to have $>$80% polarization. The positron beam may be unpolarized, but an option for an upgrade to a polarized beam is highly desireable.

Options

A suitable technology for the electron source is a laser-driven DC polarized electron gun, utilizing a strained GaAs photocathode, followed by bunching and acceleration systems. This technology, which was utilized at the Stanford Linear Collider (SLC), is adaptable to the needs of any design.

The conventional technology for positron production involves creation of unpolarized positrons in a thick, heavy metal target, under bombardment by a few GeV electron beam. An alternate technology for positron production utilizes a few hundred GeV electron beam to produce 10-20 MeV photons in an undulator. Positrons are produced when the photons generate electromagnetic showers in a thin target. This method can produce more positrons per second than the conventional technology, and if a helical undulator is used, a polarized positron beam can be produced.

The baseline for JLC/NLC and CLIC uses the conventional technology positron source, although three parallel targets must be used because of target shock wave damage limits. With its long bunch train, TESLA requires twice as many positrons per second, and the baseline design achieves this using a planar undulator-based source. An upgrade to a helical undulator would provide polarized positrons.

Advantages and disadvantages

The conventional positron source has the advantage of having an existence proof in the SLC source. However, the need for three parallel target and collection systems introduces additional complexity and cost. Moreover, the positron emittance from the source is sufficiently large that a positron pre-damping ring is required. In addition, there is no possibility of positron polarization with this option.

The undulator-based positron source is capable of producing a high positron flux, with a smaller emittance than the conventional source, and can be upgraded to produce polarized positrons. However, such a source has never been built. In addition, a high energy electron beam is required for its operation. This adds significant complexity to the commissioning and operation of the collider.

Outstanding technical challenges

For the electron source, the major technical challenge is the development of the laser which illuminates the photocathode, with the required bunch time structure and bunch-to-bunch intensity variation (∼1% for JLC/NLC and CLIC, ∼5% for TESLA).

The conventional positron source should be a straightforward extrapolation from the SLC source. For the TESLA undulator source, a 135 m long permanent magnet undulator is planned. For both options, the production target must rotate at high speed in a vacuum and radiation environment, which presents an engineering challenge.

DAMPING RINGS

The electron and positron beams from the sources are radiation cooled in the damping rings to produce ultralow transverse emittance flat beams, suitable for acceleration in the main linacs and high luminosity collisions at the interaction point. Most of the radiation damping in these rings is provided by wigglers.

Options

The length of the bunch train required by the linac is a major determining factor in the design of the damping rings.

For JLC/NLC and CLIC, the bunch train is sufficiently short that a 2 GeV damping ring of a few hundred meters in circumference is sufficient to store three trains. TESLA has a bunch train which is roughly 290 km in length. A ring of this size would be expensive, so the bunch train is stored in the ring in a compressed format, with about 20 ns between the bunches. The minimum bunch spacing is set by the pulse length of the injection and extraction kickers. Even in this compressed format, the bunch train still requires a ring of 17 km in circumference. To limit space charge effects in this large ring, the design energy is chosen to be 5 GeV. This energy still allows arcs of circumference about 2 km, so much of the ring can be straight. To reduce cost, this portion is placed in the same tunnel as the main linac.

Advantages and disadvantages

The small circumference of the damping ring for JLC/NLC and CLIC is its principal advantage. This translates directly into a cost benefit, as the technical components in the two ring options are similar, at least in the arcs.

The small ring has alignment tolerances similar to those of conventional synchrotron radiation rings of comparable size. The larger size of the TESLA ring makes it more sensitive to alignment tolerances, a situation which is the reverse of that obtaining for the linacs of the two options. In the TESLA ring, the beam must be coupled to generate a round cross section in the straight sections, to reduce space charge tune spread, while remaining flat to high precision in the arcs. This procedure appears feasible but is certainly an additional complexity.

The use of an undulator source for TESLA removes the necessity for a positron pre-damping ring. However, the positron damping ring must then have a large acceptance.

Outstanding technical challenges

Collective effects are currently thought to be the principal technical challenge for the damping rings. The electron cloud and fast ion effects may generate unacceptably large single and multi-bunch instabilities and tune spreads. To suppress the electron cloud effect, the vacuum chamber may be coated with materials which limit the secondary emission yield. Suppression of the fast ion instability may require a ringwide vacuum specification as low as 10^{-10} Torr. Elimination of classical instabilities, such as the microwave instability, requires a very low broadband impedance, roughly one-third of what has been achieved in existing machines.

Another major technical challenge for the damping rings is meeting the tight vertical emittance requirement. This is particularly challenging for CLIC. It requires very precise control of vertical dispersion and coupling in the rings, at the level which can only be realized through beam-based alignment, as in the main linacs. Simulations indicate that this is achievable, but there is not much margin. Experiments at the ATF[4] have demonstrated vertical emittances close to that required. To preserve the emittance after extraction, variations in the extraction kicker relative field strength must be limited to $< 10^{-3}$.

Particle loss is an issue because of the large beam power in the damping rings. The dynamic aperture is limited by nonlinear effects associated with the strong wigglers in the rings. Careful design of the wigglers and the machine lattice is needed to obtain the required aperture. This is particularly challenging in the TESLA positron damping ring.

BEAM DELIVERY SYSTEMS

The beam delivery systems transport the high energy electron and positron beams from the ends of the main linacs to the interaction point (IP). They must also transport the post-collision spent beam and the beamstralung cleanly to beam dumps. Essential elements include collimation systems, machine protection, the final focus, spent beam transport lines, and beam dumps.

Options

JLC/NLC and CLIC, with their small bunch separation, are required to have a crossing angle at the IP, to avoid the multibunch kink effect. Crab cavities are used to prevent luminosity loss. The crossing angle geometry allows the spent beam and the beamstralung to be transported in a separate channel to the beam dumps. Because of the extremely small vertical beam size at the IP, jitter in the final focus quadrupoles must be limited with an active stabilization system.

TESLA has a large bunch separation and does not require a crossing angle. The current design uses head-on collisions, although a crossing angle solution is under consideration. The spent beam and beamstralung are transported out of the interaction region through the incoming beam final focus magnets. Separation into a spent beam channel is accomplished using electrostatic separators and a magnetic septum.

The final focus optics for JLC/NLC and CLIC has a nonzero dispersion function through the final doublet. This allows a local chromatic correction system for the final focus. TESLA uses a more conventional optics, without local chromatic control, but could easily adopt the other design. Both options make use of beam-beam focusing to enhance the luminosity.

Advantages and disadvantages

A beam delivery system with a crossing angle design can deal cleanly with the high power spent beam. In addition, a locally corrected final focus system has a number of advantages: stronger dipoles may be used, and collimation of off-energy particles is easier.

The TESLA design, with its head-on collisions, is simpler and requires no crab cavities. On the other hand, it is considerably more difficult to handle the spent beam and the beamstralung, as they must share the beamline with the incoming beam in the interaction region.

Although the vertical beam size in TESLA is comparable to that in JLC/NLC, the long bunch train allows bunch-by-bunch feedback, based on beam-beam deflection measurements, to correct for jitter, so that active stabilization of the final focus system should not be needed.

TESLA has a longer bunch length than JLC/NLC or CLIC. This makes the luminosity falloff with collision offset more severe, and also increases the sensitivity of the luminosity to emittance correlations. This problem can be partially controlled by the use of luminosity optimization feedback during the long bunch train, but this requires accurate and rapid luminosity monitoring.

Outstanding technical challenges

For all options, a major challenge is the development of a robust collimation system, which can adequately suppress background sources such as muons and synchrotron radiation, in the presence of complications such as collimator-induced wakefields. Since it constitutes the limiting aperture, the collimation system must also be integrated into the overall machine protection system.

For JLC/NLC, and particularly for CLIC, vibration stabilization of the final focus doublet is a key issue. Clean delivery of the spent beam and the beamstralung to the appropriate dumps is an issue for all options, but is more difficult for a head-on crossing design.

CONCLUSIONS

Designing, building and operating a linear collider is envisioned to be a fully international effort from the outset. Proponents in the three major regions with interest in the project (Asia, Europe, and North America) have formed steering groups to develop requirements and technology options for their bid to host the project. An International Linear Collider Steering Committee has been formed under the auspices of the International Committee for Future Accelerators. This committee will promote the construction of the linear collider as an international project by developing a global consensus on the requirements and helping to facilitate the technology choice for the machine. The resolution of critical R&D issues in 2004 would open the way for this technology choice. Subsequently, a technically limited schedule for a collider built in the US would include a project design and engineering phase from 2006-2008, followed by 6-7 years of construction, with operation starting in 2015-16.

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