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TOWARDS THE NEXT LINEAR COLLIDER*

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1. Introduction

1.1 Parameters

There is presently a large international community of physicists and engineers working toward the realization of a Next-Generation Linear Collider. The 3rd International Workshop on the Next-Generation Linear Collider is being hosted this September by the INP at Protvino, USSR. The second workshop of this kind, held at the KEK laboratory in Japan, had two hundred participants. This month the 2nd International TESLA Workshop on Superconducting Linear Colliders is being held in Europe.

The situation as of July 1990 is well described in the 1990 Snowmass report.[1] There remains a broad range of opinion on many aspects of the design for such a collider. It is however generally accepted that the center-of-mass energy should be 0.5 TeV, upgradeable to 1.0 or 1.5 TeV, and the luminosity should be 10^{33} to 10^{34} $\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$. It is also generally agreed that these objectives can be met by an extension of present accelerator technologies, though different designs extend in different directions. Figure 1 is a schematic of the layout for such a collider. There are three basic functions: (1) beam preparation, which includes elements from the source through the compressor, (2) beam acceleration in the linac, and (3) beam delivery, which includes collimation, detector protection, and final focus.

1.2 Energy Issues

In obtaining the beam energy of 0.25 to 0.75 TeV there are three principal issues: capital cost, operating cost, and preservation of beam quality. Five distinct proposals for achieving the energy are listed in Table 1. The entries which have been underlined are the aspects of the designs which are found most dubious by proponents of competing designs. The Tesla design is questioned on the grounds of cost and reliability of superconducting cavities at the required gradients. The conventional S-Band design is criticized for its long length and many (172) bunches per cavity fill. The X-Band design is also criticized for its untested 10- to 20-bunch design. The INP design at 14 GHz has one bunch per pulse which extracts 20% of the cavity energy. This leads to large energy spreads and large transverse wakefields which must be carefully compensated. The CERN design is unique in that the RF is produced from a single drive beam rather than from many klystrons. In this case the dynamics and stability of the intense drive beam is questioned. Most designs agree on the need for a 4 to 6% wall-plug-to-beam-power efficiency, and consume about 60 MW of wall plug power for the 0.5 TeV center-of-mass machine. Table 2 gives two 0.5 TeV parameter sets for designs upgradeable to the 1.0 TeV set.[2]

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1.3 Luminosity Issues

Producing, preserving and delivering the small emittance beam required to achieve the required luminosity is also technically challenging. The small emittances can be produced by using damping rings similar to the SLC design, or perhaps by producing small emittance beams directly from a photo-cathode with a surface RF field to rapidly accelerate the electrons. Since damping rings have bunches too long for linac transverse wake effects and for depth of focus at the interaction point, two cascaded compressors are required to achieve an acceptable bunch length.

We have mentioned the control of wakefields required to preserve the beam emittance in the linac. Special feedback techniques are also required to maintain linac alignment, so that the dispersion arising there from displaced quadrupoles does not result in emittance growth.[3]

Delivering the small emittance involves: (i) collimating the beam to about 5σ so that not even one stray high energy particle will hit the beampipe in the final focus and interaction region, (ii) dispersal of all muons created in the collimator so that none enters the detector, (iii) final focus demagnification by a factor of 300, and (iv) protection of the detector from particles produced and disrupted at the interaction point. A collimation system has recently been proposed[4] with tolerances and length similar to final focus systems. For a .75 TeV beam the distance from linac to detector for the collimation, big bend, and final focus may be 1.5 km. Studies have shown that toroid spoilers to control muons, which were used successfully for the SLC, will not be adequate for an NLC.[5] As a result a large bend must be installed after the collimator, with strong focusing to control emittance growth from synchrotron radiation. A 10 mrad bend for a .75 TeV beam requires 200 m of continuous quadrupole.[6] An international collaboration is now building an NLC-type final focus system at SLAC (discussed below).

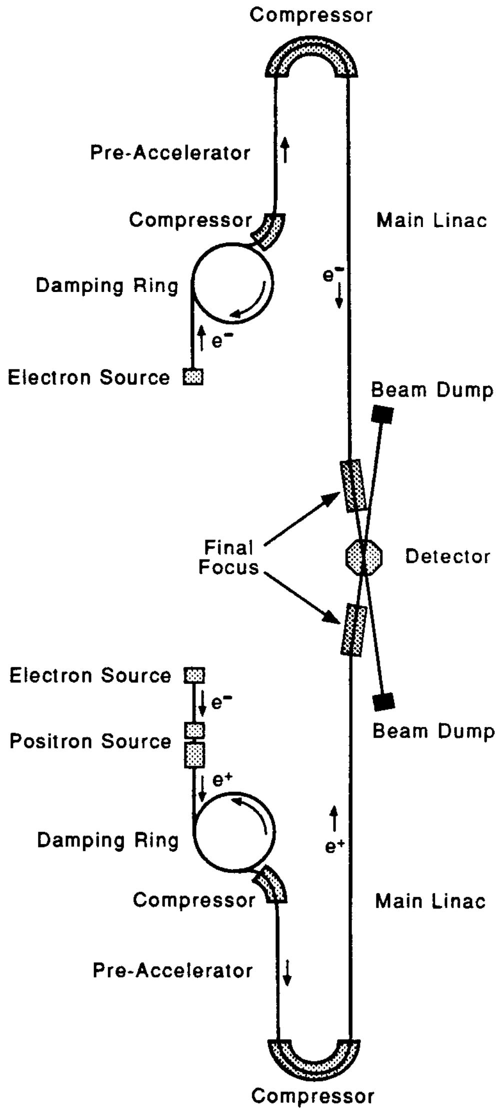

Fig. 1. Schematic layout of an NLC.

1.4 Systems Issues

In addition to the energy and luminosity issues we have mentioned, there are many general systems issues which must be addressed:

Table 1. Five design choices for an NLC energy source.

		Capital		5% Efficiency		Quality
	Freq. (GHz)	Gradient (MV/m)	Length (km)	Bunch/ Train	Train/Sec	BNS +
TESLA	2.8	20-40	25-13	1	10^4	?
DESY/Darmstadt	2.8	17	30	172	50	Detune (?)
SLAC/KEK	11.4	50-100	14-7	10	180	Damp & detune
INP (VLEPP)	14.0	100	12	1	100	10% $\Delta E/E$ Auto phase
CERN (CLIC)	30.0	80	25 (2 TeV)	1	1.7×10^3	Drive beam

Table 2. Typical X-Band NLC parameter sets.

Option	1	2	3
Energy	1/4+1/4 TeV	1/4+1/4 TeV	1/2+1/2 TeV
Luminosity	2×10^{33}	2×10^{33}	1×10^{34}
Linac length	7 km	14 km	14 km
Accelerator gradient	100 MV/m	50 MV/m	100 MV/m
RF frequency	11.4 GHz	11.4 GHz	11.4 GHz
Particles/bunch: DR	2×10^{10}	1×10^{10}	2×10^{10}
Linac	1.8×10^{10}	9×10^9	1.8×10^{10}
FF	1.5×10^{10}	7×10^9	1.5×10^{10}
Bunches, n_b	10	10	10
Repetition rate	120 Hz	180 Hz	180 Hz
Wall-plug power	93 MW	70 MW	280 MW
IP beam size: σ_y	4 nm	4 nm	2.5 nm
σ_x	320 nm	200 nm	220 nm
σ_z	100 μm	100 μm	100 μm

Machine protection. The beam at the end of the linac has an average power of 2 MW or more with a cross sectional area of 10 μ^2 or less. The area must be greater than 1000 μ^2 for even a thin piece of a durable material such as titanium to withstand a hit of one bunch train containing 10^{11} particles.

Mechanical stability. The linac quadrupole vibration at frequencies greater than the steering feedback system frequency must be less than 5 nm.

Electrical stability. One part in 10^5 for many elements.

Timing. The bunch length is 0.3 picoseconds.

Feedback. Is required throughout. In order to maintain adequate beam-based alignment a BPM precision of 2 μ in the X-Band linac and 0.2 μ in the final focus and collimator of that design is required.

Diagnostic precision. Beam Position Monitors at 0.1 μ and Beam Size Monitors in the 1 μ region are required, as well as multibunch diagnostics.

Complexity. Implies tuning of individual subsytems must be highly automated.

Reliability. More than 1600 klystrons are required in all but the two-beam design.

The remainder of this paper reviews past experience and R&D plans for assuring the adequacy of an X-Band design.

2. SLC Experience

The SLC is now achieving its original design goals,[7] and much has been learned in this difficult process that is important for the NLC design. Worthy of mention are:

Energy production. Production and maintenance of over two hundred 65 MW, 3 μsec pulse high power klystrons; reliable use of RF pulse compression to 180 MW for 0.8 μsec; linac phase control; single bunch energy spread compensation; and BNS damping for transverse wakefield compensation.

Small emittance production. Damping ring performance as designed; extraction kicker shaping, timing, and stabilization; and bunch compression from 5 to 0.5 mm.

Small emittance delivery. Collimation of high power beams; muon shielding; and chromatically corrected, demagnification 30, final focus system.

Systems development. Fast feedback beam trajectory control; single pulse beam postion measurement to 10 μ; noninvasive beam size measurements to 1.5 μ; bunch length measurement to 0.5 mm; precision (25 μ) magnet movers; and beam-beam interaction diagnostics and tuning.

The SLC will continue to be a valuable tool in testing NLC design ideas. Possible experiments are: (1) flat beam production and transportation; (2) multibunch experiments; (3) autophasing (with INP); (4) high power positron source tests; (5) polarization experience; (6) accelerator structure alignment and wakefield measurements (with INP); and (7) instrumentation improvements.

3. The Final Focus Test Beam (FFTB)

An international collaboration consisting of the INP [Novosibirsk and Protvino, USSR], KEK [Japan], Orsay [France], DESY and Max Planck Institute (MPI) [Germany], and SLAC [USA] is presently building a final focus system at the end of the SLAC linac (see Fig. 2) which should be operational by early 1993.[8] The system has a demagnification of 300, similar to that required for the NLC, with a design final spot size of 60 nm limited by the SLC damping ring emittance. The civil construction necesary to extend the SLAC beamline is well under way. The standard quadrupoles have arrived from the USSR. Magnet movers under each quadrupole having 1 μ precision have been designed and tested and are in the early manufacturing stages at the Max Planck Institute. Beam position monitors with 1 μ single pulse precision in lab tests have been built at SLAC. DESY is building an automatic wire alignment system to be mounted above the quadrupoles having 2 μ resolution, and Orsay has designed and is building a final spot size monitor. KEK has had a major role in the optics design and is building the final quadrupoles and their support systems. Much experience will be gained in aligning and maintaining beam trajectories with micron precision. Table 3 indicates the tolerances which must be met to achieve the design spot size.

4. Recent RF Development

Both SLAC and KEK have been doing research work at X-Band measuring power limits of klystrons, new pulse compression techniques, and breakdown limits and dark current in realistic accelerating structures. Gradients larger than 100 MV/m have been achieved. A several cell structure with detuning features for "damping" higher modes was taken to an Argonne facility and measured wakefields were found to agree with theoretical calculations. The SLAC klystron measurements are shown in Fig. 3.

Further klystron tests will be conducted after redesign of the RF window thought to be limiting the present performance.

Table 3. Important Final Focus Test Beam (FFTB) tolerances.

Section	Element	Tolerance	Attribute	Aberration	Time
FD	Quads	$0.2\,\mu$	Δx	Steering	τ_0
		12 nm	Δy	Steering	τ_0
		$50\,\mu$	Δx	Dispersion	τ_1
		$4.7\,\mu$	Δy	Dispersion	τ_1
		$16\,\mu$rad	Tilt	Skew Quad	τ_2
		2×10^{-5}	$\Delta k_Q/k_Q$	Normal Quad	τ_3
		1×10^{-4}	Bs/Bq at $.7a$	N/Sk Sextupole	
FT	Mid Quad	$1.5\,\mu$	Δx	Dispersion	τ_1
		$1.2\,\mu$	Δy	Dispersion	τ_1
CCY	Sextupole	$0.9\,\mu$	Δx	Normal Quad	τ_2
		$1.4\,\mu$	Δy	Skew Quad	τ_2
		3×10^{-3}	$\Delta k_S/k_S$	Sextupole	τ_3
		2 mrad	Tilt	Skew Sextupole	
	End Quad	2×10^{-4}	$\Delta k_Q/k_Q$	Normal Quad	τ_3
		1 mrad	Tilt	Skew Quad	τ_2
	Center Quad	$1.0\,\mu$	Δx	Normal Quad	τ_2
		$0.3\,\mu$	Δy	Skew Quad	τ_2
	Dipole	1×10^{-5}	$\Delta k_B/k_B$	Normal Quad	τ_2
BX	Mid Quad	$4\,\mu$	Δy	Dispersion	τ_1
CCX	Sextupole	$3.5\,\mu$	Δx	Normal Quad	τ_2
		$3.5\,\mu$	Δy	Skew Quad	τ_2
	End Quads	$.6\times10^{-3}$	$\Delta k_Q/k_Q$	Normal Quad	τ_3
		.3 mrad	Tilt	Skew Quad	τ_2
	Center Quad	$.7\,\mu$	Δx	Normal Quad	τ_2
		$4.0\,\mu$	Δy	Skew Quad	τ_2
	Dipole	2×10^{-5}	$\Delta k_B/k_B$	Normal Quad	

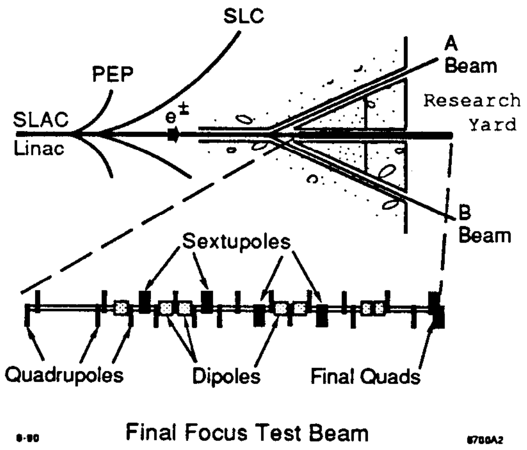

Fig. 2. The Final Focus Test Beam layout.

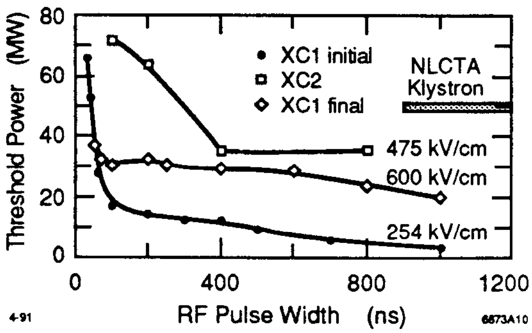

Fig. 3. Power levels achieved with X-Band klystrons.

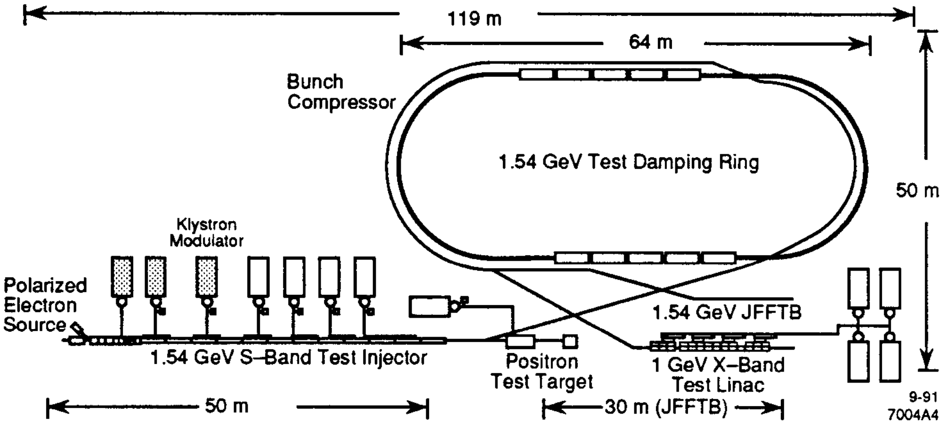

Fig. 4. The KEK accelerator test facility.

5. Test Accelerators

Most groups have plans to build accelerator test facilities. At KEK (see Fig. 4) the TRISTAN assembly hall is being modified to accomodate an S-Band accelerator, a positron source, a damping ring cabable of producing NLC emittances, a bunch compressor, an X-Band linac, and a final focus system. The use of wigglers to achieve small emittances will be tested in the dampng ring. Construction completion is planned for 1994.

At SLAC a test accelerator (NLCTA) has been proposed for installation in end-station B. The primary goal is to construct and reliably operate an engineered model of a section of an X-Band high gradient linac. Multi-bunch beam dynamics issues will be studied. Construction completion is scheduled for late 1994.

6. Future Prospects

Since the test accelerators at SLAC and KEK should be operational by 1995, we can conjecture that—barring unforseen complications— we would then have the experience and knowledge necessary to put together a proposal for construction of an NLC. If construction funds are forthcoming, we might optimistically imagine building an NLC by the end of the century.

References

[1] R.D. Ruth, *Linear Colliders*, in *1990 DPF Summer Study on High Energy Physics: Research Directions for the Decade*, Snowmass, CO; SLAC–PUB–5597 (1990).
[2] For more parameter sets see R.B. Palmer, *Prospects for High Energy Linear Colliders*, in *Ann. Rev. Nucl. Sci.* **40** (1990) 529.
[3] T. Raubenheimer and R.D. Ruth, *A Dispersion Free Trajectory Correction Technique fo Linear Colliders*, SLAC–PUB–5222 (1990).
[4] L. Merminga et al., *Collimation Systems in the Next Linear Collider*, SLAC–PUB–5436 (1991).
[5] L.P. Keller, *Calculation of Mucon Backgrounds in a 0.5 TeV Linear Collider* in 1990 Snowmass Proceedings.
[6] D. Helm, *Design for a 10 mrad Bend at 750 GeV* in LC91 Proceedings, Protvino, USSR, and to be published.
[7] N. Phinney, *The SLC*, these Proceedings.
[8] *Final Focus Test Beam Design Report*, SLAC Report–376 (1990).