SLAC-PUB-6244
April 1993
(A)

Overview of Linear Collider Designs

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I. INTRODUCTION

Linear collider design and development have become focused on a center-of-mass energy $E_{CM} = 0.5$ TeV and a luminosity $L \sim 5\times10^{33}\text{cm}^{-2}\text{sec}^{-1}$. There are diverse approaches to meeting these general objectives. The diversity arises from different judgements about the ease of developing new and improving existing technology, costs, extension to higher energies, experimental backgrounds and center-of-mass energy spectrum, and tolerances and beam power.

The parameters of possible colliders are given in Table 1 which is based on a compilation made by G. Loew at the LC-92 Conference and is reproduced with his permission.[1] The colliders described in that table are:

TESLA (being developed by an international collaboration) which is based on superconducting RF. All the others would use room temperature RF.

DLC (DESY/Darmstadt) which uses S-band (3 GHz) RF where there is extensive operating experience.

NLC (SLAC) which uses higher frequency X-band (11.4 GHz) RF in a modulator-klystron-accelerator configuration similar to S-band linacs.

JLC-I (KEK) which has three frequency options, S-band, C-band (5.7 GHz), and X-band. Multiple bunches are accelerated in each RF pulse as they are in TESLA, DLC, and NLC.

VLEPP (INP) which employs a single high intensity bunch rather than multiple bunches.

CLIC (CERN) which is a "two-beam" accelerator with klystrons replaced by an RF power source based on a high-current, low-energy beam travelling parallel to the high energy beam.

The discussion below focuses on some of the common themes of these designs and the differences between them.

II. EFFICIENCY AND MULTIPLE BUNCHES

The AC mains power is large for any of the colliders, and energy efficiency is critically important.[2] One way to achieve good efficiency is by accelerating multiple beam bunches per RF pulse.

For example, in the DLC a 150 MW, 2.8 μsec long RF pulse powers two 6 m long sections to a gradient of 17 MV/m. The beam has 172 bunches with 2.1×10^{10} particles per bunch spaced 10.7 nsec apart. The RF pulse has 420 J of energy; a single bunch extracts 0.685 J from the accelerator RF fields, and the bunch train extracts a total of 118 J leading to an efficiency, η_B, for converting RF to beam energy of $\eta_B = 0.28$. If only a single bunch was accelerated, the RF pulse could be shortened to 1 μsec, the accelerator filling time, but the efficiency would be low, $\eta_B = 0.0046$. A major advantage of multiple bunches is that the cost of filling the accelerator with RF energy has been amortized over a large number of bunches.

Multiple bunches have implications for both the fundamental and higher modes. The energy spread of the beam must be small to minimize emittance blow-up from dispersive effects in the linac and to minimize chromatic aberrations in the final focus. The bunch train lengths are comparable to filling times, and the accelerator structure must be prefilled and the RF amplitude ramped so that each bunch gains the same energy.[3]

The bunches are closely spaced, and they interact through higher modes. The transverse modes can cause emittance blow-up that is in addition to that from the short range transverse wakefield. The interaction between bunches must be reduced by damping higher order modes or by "detuning", varying cell dimensions to spread mode frequencies, leading to destructive interference between the deflections from different cells.[4] Detuning and damping may have to be combined to get adequate reduction of the long range wakefields.

VLEPP has a single, large bunch, 2×10^{11} particles, and that results in $\eta_B = 0.12$. The large bunch and relatively high RF frequency impose stringent tolerances on the linac for emittance preservation and requires a novel final focus, the "traveling focus" where a head-tail energy shift is introduced to shift the focal point during the collision and prevent enormous disruption. CLIC has parameters for between one and four bunches, and studies of energy compensation and transverse modes for four bunches are in progress.[5]

III. POWER SOURCES

Present day, conventional linacs are modular with each module consisting of a modulator, klystron, possibly an RF pulse compression system, and, finally, one or more accelerator sections powered in parallel. The modulator converts AC power to high voltage, pulsed power. Most use a low voltage, lumped element transmission line for energy storage, thyratrons as switches, and a pulse transformer to step-up the output voltage. SLAC modulators are typical and are roughly 75% efficient.[6] A substantial fraction of the inefficiency comes from the rise- and fall-times of the pulse transformer. Improving modulator efficiency would be significant. Ideas under consideration are a capacitor bank and high voltage switch tube rather than a pulse transformer (DLC) and a DC high voltage supply and avoiding the modulator by using a gridded klystron (VLEPP).

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* Work supported by the Department of Energy, contract DE-AC03-76SF00515.

Invited Paper at the Particle Accelerator Conference, Washington, DC, May 17 - 20, 1993

Table 1: Parameters for E_{CM} = 0.5 TeV Linear Colliders from LC-92(1,2)

	TESLA	DLC	JLC-I(S)	JLC-I(C)	JLC-I(X)	NLC	VLEPP	CLIC
Linac RF Frequency (GHz)	1.3	3.	2.8	5.7	11.4	11.4	14.	30.
Beam Loaded Gradient (MV/m) (3)	25.	17.	18.4	32.5	28.	37.6	96.	78. - 73.
Repetition Rate (Hz)	10.	50.	50.	100.	150.	180.	300.	1700.
Bunches/RF Pulse	800	172	55	72	90	90	1	1 - 4
σ_x/σ_y (nm) (with Disruption)*	310/50	250/190	300/1.9	260/1.9	260/2.0	300/2.2	1590/4	40/5.5
Beam Power/Beam (MW)	16.5	7.5	1.6	3.6	3.8	4.2	2.4	0.4 - 1.6
Υ (4)*	0.063	0.070	0.24	0.21	0.16	0.096	0.076	0.34
n_γ (4)*	5.7	3.1	1.6	1.4	0.9	0.8	5.1	4.6
Beam Posit. Monitor Precision(μm) (5)*	10.	10.	NA	NA	1.	1.	0.1	0.1
Luminosity (10^{33}cm^{-2}s^{-1}) (4)	11.1	6.5	4.4	6.5	6.3	8.2	15.	2.2 - 8.9
Particles/Bunch (10^{10})	5.15	2.1	1.3	1.0	0.63	0.65	20.	0.6
Bunch Separation (nsec)	1000.	10.7	5.6	2.8	1.4	1.4	-	0.33
Unloaded Gradient (MV/m)	25.	21.	22.	40.	40.	50.	108.	80.
Active Two-Linac RF Length (km)	20.	30.	28.	16.7	17.	14.	6.4	6.6
Section Length (m)	1.04	6.	3.6	2.	1.3	1.8	1.01	0.273
Two-Linac Number of Sections	19232	4900	7776	8360	13600	7778	5200	24000
Two-Linac Number of Klystrons	1202	2450	1944	4180	3400	1945	1300	2
Sections/Klystron	16	2	4	2	4	4	4	"12000"
Klystron Peak Power (MW)	3.25	150.	85.	45.	70.	94.	150.	700.
Klystron Pulse Length (μsec)	1300.	2.8	4.5	3.6	0.84	1.5	0.7	0.011
Pulse Length to Section (μsec)	1300.	2.8	1.2	0.6	0.21	0.25	0.11	0.011
Pulse Compression Ratio	-	-	3.7	6.	4.	6.	6.3	-
Pulse Compression Gain	-	-	2.4	4.2	3.2	4.	4.22	-
a/λ Ratio (Input/Output Cavity)	0.15	.154/.108	0.13	.160/.120	.236/.138	.210/.147	0.140	0.2
Total Two-Linac AC Power (MW) (6)	137.	114.	106.	193.	86.	152.	91.	175.
Damping Ring Energy (GeV)	3. or 14.	3.13	1.98	1.98	1.98	1.8	3.0	3.0
σ_L (μm)	1000.	500.	80.	80.	67.	100.	750.	170.
$\gamma\varepsilon_x/\gamma\varepsilon_y$ (10^{-8} m)	2000/100	500/50	330/4.5	330/4.5	330/4.5	500/5	2000/7.5	180/20
β_x^*/β_y^* (mm)	10/5	16/1	10/0.1	10/0.1	10/0.1	10/0.1	100/0.1	2.2/0.16
σ_{x0}/σ_{y0} (nm) (no Disruption)	640/100	400/32	300/3	260/3	260/3	300/3	2000/4	90/8
Disruptions, D_x/D_y	1.2/7.9	0.69/8.6	0.13/13.	0.13/11.5	0.07/6.	0.08/8.3	0.4/ -(7)	1.3/15.
H_D*	4.1	2.7	1.6	1.6	1.5	1.4	1.3	3.2
δ_B (4)*	0.13	0.078	0.098	0.081	0.043	0.027	0.14	0.35
Crossing Angle (mrad)	1. - 2.	2.	7.3	8.	7.2	3.	NA	1.

Notes

1) Based on a compilation made by Gregory A. Loew for LC92, ref. [1]. Modifications of and additions to his original table are indicated with a *.
2) Symbols are defined in the text.
3) Before applying further gradient reductions for off-crest running, BNS damping, etc (VLEPP excepted).
4) Including the effects of disruption, ref. [7].
5) From ref. [8].
6) DLC bases its number on a combined klystron-modulator efficiency of 45%. JLC and NLC have assumed this number to be closer to 35%. In addition, SLED-I (used for JLC-I(S)) and SLED-II (used for JLC-I(C), JLC-I(X), NLC and VLEPP) are assumed to be about 65% efficient. Power for klystron focusing is not included.
7) VLEPP employs a "traveling focus".

A short, high power RF pulse is the ideal for high frequencies because short sections and high group velocities are favored by efficiency and wakefields. The input power must be multiplied by $\tau^2/(1 - e^{-\tau})^2$ for the same average accelerating gradient ; $\tau \propto \zeta/(\lambda^{1.5}\beta_g)$ where ζ is the section length, β_g is the (normalized) group velocity, and λ is the RF wavelength.[9] The wavelength dependence comes from the skin effect. The maximum transverse wakefield behaves as $1/(a^3(\lambda/a)^{.8}))$ where a is the radius of the waveguide iris.[10] Increasing λ/a reduces the wakefield with the side effect of raising the group velocity.[9]

It is impractical to generate short RF pulses directly. Modulator efficiency would be poor because pulse rise-and fall-times would be a large fraction of the pulse and klystron peak power would be enormous. Pulse compression[11] which raises the peak power while shortening the RF pulse is used for matching klystron capabilities to an optimum accelerator configuration and is a feature of the high RF frequency colliders.

TESLA has unique power source requirements. The high Q and long pulse length reduce the peak power to 3.25 MW, but the modulator must be capable of delivering that power for over a millisecond.

All except CLIC have a large number of klystrons each of which is a major piece of apparatus requiring maintenance, etc. CLIC is a two-beam accelerator which replaces all of this with a single, low-energy beam travelling parallel to the high energy beam. This low-energy beam has a time structure appropriate for generating 30 GHz RF. It is accelerated by a superconducting RF system, and energy is extracted with transfer structures spaced roughly 1.5 m apart. If the two-beam approach is developed successfully, it will be a major simplification of linear collider design that could be key to reaching multi-TeV energies.

IV. EMITTANCE PRESERVATION

The vertical invariant emittances, $\gamma\varepsilon_y$, are small, and emittance preservation during acceleration is an important consideration. Emittance growth caused by the combination of injection jitter and wakefields must be controlled by tight tolerances on injection elements and BNS damping.[12] Those tolerances range from about 1 μm for NLC and JLC-I(X) to about 10 μm for the S-band accelerators and TESLA.[8]

Misalignments in the main linac cause emittance growth through wakefields and dispersion, that is different central trajectories for different energies. With straight one-to-one orbit correction, i. e. steering to the middle of beam position monitors, there would be extremely tight tolerances on accelerator, quadrupole, and beam position monitor alignment. As examples, those tolerances would be about 10 μm for DLC and half that for NLC.

Beam-based orbit correction procedures, where optical elements are varied and orbit changes measured, relieve these tolerances substantially.[8] The strengths of all the quadrupoles are increased, or decreased, in dispersion free (DF) steering to measure momentum dependence of the central trajectory; then, the orbit is corrected to minimize the dispersion. The strengths of focusing quadrupoles are reduced while those of defocusing quadrupoles are raised to approximate the defocusing effect of wakefields in wakefield free (WF) steering. WF steering requires good local alignment between quadrupoles and accelerator sections. Since these procedures depend on measuring orbit changes, the beam position monitor must be precise. Estimates of the required precisions are included in Table 1 and range from 0.1 μm for CLIC and VLEPP to 10 μm for DLC and TESLA.[8]

V. FINAL FOCUS

The beams are flat at the interaction point to minimize backgrounds (see below) with $\gamma\varepsilon_x >> \gamma\varepsilon_y$ and $\beta_x^* >> \beta_y^* > \sigma_L$ (for all but VLEPP with its traveling focus) where σ_L is the bunch length. The vertical dimension is the most demanding with the vertical sizes before disruption ranging from 100 nm (TESLA) to 3 nm (JLC, NLC).

The vertical spot sizes quoted are the first order sizes, $(\beta_y^*\varepsilon_y)^{1/2}$, and up to third order geometric and chromatic aberrations must be corrected to reach those sizes. This is done by using dipoles to introduce dispersion in a region with sextupoles separated by a -I transformation. Synchrotron radiation losses in the chromatic correction section and in the final quadrupoles introduce important aberrations.

There are extremely tight pulse-to-pulse jitter tolerances. For all but the final doublet those tolerances are about $10\sigma_y$ while for the final doublet they are roughly σ_y.[13] The Final Focus Test Beam (FFTB) at SLAC will test many of the techniques for reducing aberrations to the required level and will provide a test bed for studying and specifying jitter tolerances.

The beams cross at an angle. This avoids unwanted collisions for colliders with closely spaced bunches, and it allows the channel for focusing the incoming beam to be independent of the channel for the exiting disrupted beam. Crab crossing,[14] tilting the bunches with an RF deflector, prevents luminosity loss due to incomplete overlap.

VI. ELECTROMAGNETIC FIELDS AT THE COLLISION POINT

The luminosity is given by

$$L = \frac{N^2 f_c}{4\pi\sigma_{x0}\sigma_{y0}} H_D = \frac{N^2 f_c}{4\pi\sigma_x\sigma_y}\ ; \qquad (1)$$

N is the number of particles/bunch and f_c is the collision frequency. Focusing during the collision, disruption, is accounted for by an enhancement factor, H_D, in the left-hand expression where the beams sizes without disruption are used, and by using the disrupted beam sizes in the right-hand expression.

The electromagnetic fields at the collision point are parametrized by[7]

$$T = \frac{5r_e^2}{6\alpha}\,\frac{\gamma N}{\sigma_L(\sigma_x+\sigma_y)} \;. \tag{2}$$

Field enhancement due to disruption is accounted for approximately by using the disrupted sizes. This increases T for TESLA, DLC and CLIC because the horizontal size is reduced about 50% by disruption in those cases. The mean energy beamstrahlung energy loss, $\delta_B \propto T^2$, and backgrounds from beamstrahlung, e^+e^- pairs, and hadronic events depend on T. When $T \ll 1$ and $\sigma_x \gg \sigma_y$, the mean number of beamstrahlung photons per incident particle is[7]

$$n_\gamma = \frac{5\alpha^2\sigma_L}{2r_e\gamma}\,T = \frac{2\alpha r_e N}{\sigma_x} \;. \tag{3}$$

This parameter, n_γ, serves as an approximate measure of backgrounds.

The luminosity can be rewritten in terms of only three free parameters: n_γ, σ_y, and the beam power, $P_B = Nf_c\gamma mc^2$,

$$L = \frac{1}{8\pi\alpha r_e mc^2}\,\frac{P_B n_\gamma}{\gamma\sigma_y} \;. \tag{4}$$

VII. JUDGEMENTS

Table 1 shows the diverse approaches to meeting the general objectives of a 0.5 TeV collider. The diversity arises from different judgements about the following.

The ease of developing new and improving existing technology - DLC and JLC-I(S) are the most conservative in this regard. They take advantage of over forty years of experience with S-band RF. NLC, JLC-I(C), and JLC-I(X) extend the basis of present day linacs, high peak power klystrons and modulators, to higher frequencies. Klystrons and accelerator structures must be developed for those frequencies. TESLA relies on substantial improvements in the cost and accelerating gradient of superconducting RF. VLEPP requires innovations to meet demanding tolerances and relies on novel beam dynamics in the linac and final focus. CLIC has stringent tolerances because of its high frequency, and the RF power source development by itself is a major undertaking comparable to the complete development of other colliders.

Costs - Cost reduction and cost control must be dominant considerations as designs are developed. New technologies promise significant, but uncertain, cost reductions. Older technologies have better established costs, but these tend to be high and must be lowered through engineering and mass production.

The experience of the SSC, an accelerator based on mature technology and a detailed design, teaches us that present linear collider cost estimates should not be taken seriously.

Extension to higher energies - A recent ICFA Seminar[15] strongly endorsed an 0.5 TeV linear collider as the next natural step for high energy physics after the LHC and the SSC and as an important opportunity for international collaboration. It was stressed that this collider should be a step towards multi-TeV energies. High gradients and high RF frequencies tend to be better for reaching high energies with room temperature RF. NLC, JLC-I(X), and VLEPP are optimized for 0.5 - 1 TeV while it would be difficult to directly extend S-band colliders beyond 0.5 - 1 TeV. CLIC is a multi-TeV collider scaled down to 0.5 TeV for purposes of comparison. The energy reach of TESLA depends on how close the fundamental gradient limit of ~50 MV/m in Nb can be approached.

There are considerations that transcend specifics like the choice of RF frequency. Colliders based on room temperature RF have beam dynamics and technologies in common and, at the same time, substantially different from those for superconducting RF. The energy reaches of the generic approaches of room temperature and superconducting RF need to be understood and compared.

Experimental backgrounds and center-of-mass energy spread - The effects of beamstrahlung have been captured in eq. (4) above with a single parameter, n_γ. This parameter doesn't account for the energy spectra of photons, e^+e^- pairs, and hadronic events, and it doesn't account for the overlap of events in the detector. The complicated interface between collider and experiment cannot be reduced to a single number, and it is only through the ongoing studies of that interface that tolerable background levels can be estimated.

Tolerances and beam power - The trade-off is given in eq. (4). Increasing the beam power relaxes injection tolerances, beam position monitor precision, and pulse-to-pulse jitter in the final focus by allowing a larger σ_y. However, there are limits to beam power from efficiency and beam handling, collimation and accelerator protection.

Narrowing the range of choices depends on continuing operation of the SLC and on prototype research and development. The SLC is the foundation for future linear colliders. There there is a clearly measured bottom line, integrated luminosity in a low background environment. The system integration needed to meet it has shown what is and what is not possible and has lead to the development of numerous diagnostic and control procedures that are sure to be at the heart of any future collider.

There are system prototypes addressing beam dynamics and system engineering of the different colliders in Table 1. These include:

A 500 MeV TESLA prototype to be constructed at DESY to demonstrate a gradient of 15 MV/m, to meet cost goals, and to test a high gradient superconducting linac with beam.

A 450 MeV DLC prototype that will test long pulse, high power, multiple bunch operation of an S-band linac.

- The Accelerator Test Facility at KEK that combines a 1.5 GeV, S-band linac with a prototype damping ring. The damping ring will produce beams with brightness, single bunch charge, and bunch train structure covering many of the colliders in Table 1. New levels of tolerances, control of beam generated fields, extraction kicker stability, etc will be reached in accomplishing this.
- Interaction region optics and stability will be studied at the Final Focus Test Beam at SLAC. In addition, strong field QED, the regime of beamstrahlung in high energy linear colliders, will be explored experimentally.
- A 540 MeV prototype NLC linac has the goals of constructing, reliably operating, and studying beam dynamics in an X-band linac.
- A ~500 MeV VLEPP prototype will test the klystrons, accelerator, and beam dynamics of that collider.
- A beam with the time structure of the CLIC drive beam will be generated by an RF gun, accelerated and used for demonstrating energy extraction at the CLIC Test Facility.

We can look forward to several years of interesting developments as this work proceeds and plans for a high energy linear collider emerge.

VIII. ACKNOWLEDGEMENTS

Thanks to Greg Loew for letting me reproduce his LC-92 table and to Dave Burke, Pisin Chen, John Irwin, Bob Palmer, and Tor Raubenheimer for stimulating discussions.

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