

# High Frequency Linear Colliders

Wolfgang Schnell  
CERN-SL  
CH - 1211 Geneva 23

## Abstract

In a linear collider, low frequency favours efficiency of power transfer to the beam and high frequency favours a short overall length. There are two reasons why an increase of the operating frequency tends to permit an increased accelerating gradient. The first one is related to field emission phenomena; it is in particular the observation that the onset-gradient of dark current is proportional to frequency. The second reason is related to the total stored electromagnetic energy which is proportional to gradient times wavelength squared; in a normal-conducting linac it sets the minimum average RF power for given repetition rate. The reduced wakefields associated with a lower frequency facilitate acceleration of many bunches of particles by the same RF pulse and this multibunching greatly enhances efficiency. Nevertheless, the proposed parameters for linear colliders show a clear tendency towards increased gradient with increasing frequency. Two types of high-frequency linear collider are being actively developed. The first type, in the 11 to 14 GHz range, is to be powered by a large number

of discrete sources of pulsed RF power. The second type, at 30 GHz, is a two-beam device in which the power is derived from a relativistic drive beam running parallel to the main beam. Progress on both lines of development will be reported.

## 1. INTRODUCTION

The development work on linear  $e^+e^-$  colliders is, worldwide, still at the stage of feasibility studies. That this is so can be seen from the divergence of opinion expressed in Table 1 [1], which shows basic parameters for a 500 GeV collider proposed by the six main collaborations [2 to 7] working in this field. All proposals are based on acceleration in strings of radio-frequency cavities (as distinct from the much more exotic schemes discussed some years ago) but the technologies invoked span a large range. The sets of parameters are listed in order of increasing accelerating frequency. The first one is based on superconducting standing-wave cavities, all others on normal-conducting travelling wave

**Table 1**  
Six proposals under study for 0.5 TeV $e^+e^-$  colliders

	TESLA	S-Band	SLAC NLC	KEK JLC(X)	VLEPP	CLIC
Frequency (GHz)	1.3	3	11.4	11.4	14	30
Unloaded gradient (MV/m)	25	21	50	40	108	80
Beam-loaded gradient (MV/m)	25	17	38	31	96	78-73
Active length (km) <sup>1)</sup>	20	29	14	18	6.4	6.6
Particles per bunch	$5 \times 10^{10}$	$3 \times 10^{10}$	$7 \times 10^9$	$6 \times 10^9$	$2 \times 10^{11}$	$6 \times 10^9$
Bunches per pulse	800	170	90	90	1	1-4
Beam power (MW)	16.5	7.5	4.2	3.4	2.4	0.4-1.6
Number of klystrons	1202	2450	1945	3400	1300	"2"
Klystron peak power (MW)	3.25	150	94	70	150	700
Klystron pulse length ( $\mu$ s)	1300	2.8	1.5	0.84	0.7	0.012
Pulse compression gain	-	-	4	3.2	4.2	-
Pulses per second	10	50	180	150	300	1700
Horizontal normal emittance ( $10^{-8}$ m)	2000	1000	500	330	2000	180
Vertical normal emittance ( $10^{-8}$ m)	100	50	5	4.5	7.5	20
Beam width at collision <sup>2)</sup> ( $10^{-9}$ m)	1000	670	300	260	2000	90
Beam height at collision <sup>2)</sup> ( $10^{-9}$ m)	64	28	3	3	4	8
Luminosity <sup>2)</sup> ( $10^{33}$ cm $^{-2}$ s $^{-1}$ )	2.6	2.2	6	3.7	12	0.7-2.7

1) Actual length is 25 to 30% more

2) Without pinch enhancement

TESLA: TeV Superconducting Linear Accelerator (International Collaboration centred at DESY)  
S-Band: DESY/TH Darmstadt (Germany). There is also a KEK S-band version (Japan)  
SLAC-NLC: Stanford Linear Accelerator Center. Next Linear Collider (USA)  
KEK-JLC(X): Japan Linear Collider (X-Band-Version) (Japan); there are also versions at 3 and 5.7 GHz  
VLEPP: Protvino — Novosibirsk (Russia); a  $\gamma$ - $\gamma$  version of this design is now being considered  
CLIC: CERN Linear Collider (Europe)

structures. The proposals may be classed in *low-frequency* and *high-frequency* schemes, the latter, which are the subject of this review, being defined as working at frequencies substantially above the customary electron-linac frequency of 3 GHz. As can be seen from the table, high accelerating frequencies are concomitant with high accelerating gradients. There are two reasons for this.

Firstly, the total electromagnetic energy stored in the accelerating structure is proportional to the gradient times the square of the RF wavelength. In a normal-conducting pulsed linac the product of this stored energy and the repetition rate sets the minimum average power dissipation. The argument is partially offset by the greater ease with which the smaller wakefields associated with longer wavelengths permit employing a large number of consecutive bunches. Such multi-bunching leads to much increased efficiency of power transfer to the beam and permits a lower macroscopic repetition rate. It still remains that gradients in excess of 40 MeV/m, say, would seem to be problematic at frequencies much below 10 GHz from the point of view of required power alone.

Secondly, the threshold for gradient-limiting phenomena associated with field emission increases with increasing frequency. The lowest limitation of this kind is the onset of 'dark current' due to the RF capture of field emitted electrons. This dark current threshold is roughly 20 MeV/m at 3 GHz (it depends somewhat on the aperture to wavelength ratio) and increases proportionally with frequency. It appears, therefore, that a high accelerating frequency is more favourable for extension to centre-of-mass energies beyond 500 GeV and possibly beyond 1 TeV. On the other hand, the high beam power and large number of widely spaced long bunches naturally concomitant with a low frequency make it easier to create favourable conditions for physics: small energy spread low background due to beamstrahlung and reduced event overlap in the detector.

The two main problems specifically connected with a high acceleration frequency are the control of beam-induced wakefields and the generation of the necessary peak RF power. Transverse (self-deflecting) wakefields, in particular, tend to increase rapidly with increasing frequency. Their stabilization entails tight tolerances on alignment scatter; in multibunch mode it affects the design of the accelerating structure. The peak RF power required is in the terawatt range. It necessitates either a large number (thousands) of discrete sources at the limit of feasibility or, at the 30 GHz frequency of CLIC, a two-beam scheme.

## 2. WAKEFIELDS

Single-bunch transverse wakefields rise with the third power of frequency. In high-frequency machines they have to be stabilized by application of what is called BNS damping, namely focussing the tail of the bunch more strongly than the head. At moderate frequencies a small energy spread within the bunch is sufficient for this. At the CLIC frequency of 30 GHz, transverse wakes are very strong and will be stabilized by converting about 5% of the accelerating

structures to microwave quadrupoles. At the high frequency and gradient of CLIC this can be done simply by giving the cells of a fraction of accelerating structures a flat shape while maintaining a circular aperture. The chromatic effects and rapid filamentation associated with strong BNS damping reduce the tolerances for alignment scatter; they appear to remain manageable, however.

Multibunch transverse wakefields — the deflecting fields by which one bunch acts on the subsequent ones — cannot be stabilized by BNS damping — certainly not for the large number of bunches now contemplated at SLAC and KEK. Bunch-to-bunch wakefields have to be drastically reduced, therefore, by direct interference with the accelerating structure, as discussed below. In addition, the longitudinal wakefields and the fundamental-frequency beam loading have to be compensated by an appropriate modulation of the RF input power.

## 3. ACCELERATING STRUCTURES

In principle, the iris-loaded travelling-wave structures required here may be obtained simply by scaling from existing 3 GHz (S-band) electron-linacs such as SLAC. The higher frequency and (more so) the requirement of passing the beam exactly through the centre in order to avoid emittance growth by wakefields, leads to tighter mechanical tolerances. The high desired gradients require an excellent surface finish and complete freedom from contamination by brazing alloy. Direct copper-to-copper diffusion bonding, assisted by a brazed joint a small radial distance behind, has been developed at CERN and turned out to be very successful. Detailed studies carried out by industrial firms and specialized engineering institutes have shown that the tight tolerances and mirror-like surface finish for even the CLIC 30 GHz cells can be achieved in mass fabrication without excessive cost and this should be even truer at 11 or 14 GHz. Diffusion bonding technology is also a main feature of the KEK 11.4 GHz structures and major efforts are devoted to the construction of actual structure prototypes in all four laboratories.

A CERN-made 11 GHz structure tested at KEK has exceeded 100 MV/m accelerating field after very reasonable conditioning and was, in fact, limited by available power. A 30 GHz structure of the same construction has, so far, reached a power-limited gradient of 80 MV/m (at 12 ns pulse length) without any conditioning. High-gradient tests are currently being pursued at all laboratories concerned but it appears already that the achievement of the nominal gradients listed in Table I for high-frequency machines will not present difficulties.

Multibunch operation requires a drastic attenuation of interbunch deflecting wakes. The mechanically easiest way to obtain such an attenuation is to grade the cell diameters and coupling apertures within a section in such a way as to give the first dipole mode a truncated Gaussian distribution of resonance frequencies while the accelerating ( $E_{01}$ ) modes remain on resonance. In addition, section-to-section stagger tuning of dipole frequencies may be employed. Destructive interference between the different dipole frequencies rapidly

reduces the compound wake behind each bunch. The rate of decrease — and, thus, the minimum bunch spacing — is given by the spread in dipole frequencies (of the order of 10%), the maximum permanent attenuation by the necessity of truncation. Higher modes than the first deflecting one may be tuned by varying the iris widths as well as cell diameter and aperture.

Alternatively, or in addition, deflecting modes may actually be damped by power absorption. However, since dipole quality factors of the order of ten without deterioration of the accelerating mode are required, this entails serious and undesirable modifications to the accelerator structures. Early attempts at higher-mode damping introduced a geometrical discrimination between deflecting and accelerating modes by means of radial slots cut into the irises and coupled to power absorbers via radial waveguides. This proved to be impracticable. More recent proposals rely on frequency discrimination. In one proposal (SLAC) the resonant cell is formed by crossed waveguides which are in cutoff for the fundamental longitudinal mode but propagating for higher frequencies. In another solution, the “choke-mode cavity” (KEK), the cylindrical wall of each cell is replaced by an open, annular structure in cutoff at the fundamental frequency but propagating above. The circular symmetry is advantageous for precision machining although support and cooling still require the incorporation of spacers. External Q-values as low as 15 with only 15% degradation for the accelerating mode are reported from KEK where this solution is being studied.

An experimental study of the long-range bunch-to-bunch wakefield effects in actual model structures is being carried out in a special test facility (ASSET for Accelerator Structure Setup) at the SLC at SLAC. For this purpose a positron drive bunch carrying out vertical oscillations of controlled amplitude is followed by an electron witness bunch whose wake-induced excitation is measured at the structure output after magnetic separation from the positron drive bunch.

Giving all bunches the same energy in the face of beam loading and longitudinal wakefields presents a serious problem. With short trains of closely spaced bunches it may be sufficient to arrange the duration and timing of a flat RF power pulse so as to make the first bunch traverse the structure before it is completely filled. The bunch spacing then has to be chosen so as to make the remaining influx of energy compensate the beam loading. With the long bunch trains now envisaged at SLAC and KEK this is no longer possible. Instead, the power pulse must last for several filling times and be shaped so as to equalize the bunch energies within the tolerance (a fraction of a percent) required for the final focus and the physics research.

In spite of these problems, which are still under intense study, the JLC and NLC groups are optimistic that their 11 GHz colliders can accommodate as many as 90 bunches with concomitant benefits for luminosity, beamstrahlung and detector occupancy. The CLIC design at 30 GHz may employ a small number of bunches at most. A single bunch of very high intensity is one of the characteristic features of VLEPP.

#### 4. EMITTANCE CONTROL

In all linear colliders very precise alignment of quadrupoles and accelerating structures is required in order to preserve a small transverse emittance in the face of chromatic effects and wakefields. In high-frequency colliders the vertical emittance required for acceptable luminosity tends to be particularly small because of the limited beam power. On the other hand, the smaller size and weight of accelerating structures make precision alignment easier.

The strong wakefields and BNS damping of CLIC lead to especially tight tolerances for alignment scatter — a few micrometres rms at most for structures, beam-position monitors and quadrupoles — in spite of the application of alignment algorithms specially adapted to the given situation. It is reassuring, therefore, and significant for all high-frequency schemes, that even these tolerances have in fact been met in prototype experiments.

On the one hand, submicron accuracy has been demonstrated in a prototype system for automatic alignment. In this system, the accelerating structures, a fraction of which carries built-in beam-position monitors, are prealigned by means of an optical system, to be followed by beam-derived adjustment of the quadrupoles. The mechanically active components of this system are commercially available precision jacks of 0.1  $\mu\text{m}$  resolution, providing displacements and rotations to a string of silicon carbide girders carrying the accelerating structures (with beam position monitors) and the quadrupoles. Resolution down to one nanometre steps — albeit without the reproducibility of a digital system — has been demonstrated with analogue-type electromagnetic actuators and VLEPP accelerating structures.

On the other hand, a resolution below 0.1  $\mu\text{m}$  has been demonstrated in a prototype beam position monitor in response to the displacements of a beam-simulating antenna. The monitor consists of a 33 GHz  $E_{11}$  cavity with four diametrically opposite outputs. It is diamond-machined in the same way as the CLIC accelerating structure, of which it will form an integral part. Tests with beam are in progress at the CTF test facility (cf. below) at CERN.

#### 5. RADIO-FREQUENCY POWER

All designs except CLIC invoke a large number (between 1300 and over 3000) of individual power sources which are generally assumed to be klystrons, although less conventional sources (gyroklystrons, cluster klystrons, free-electron-lasers) are also being discussed. Design goals of about 100 MW peak klystron power are nominally adopted. The different prototypes under development include advanced features such as strong beam compression from the cathode to the small-aperture cavities, multi-gap outputs, permanent magnet focussing and very high input voltage. Particularly radical innovations are included in the VLEPP klystron which features 1 MV input voltage and grid-control, thus obviating the need of a modulator.

However, since no design has as yet reliably reached the 100 MW level with the pulse lengths required for subsequent

pulse compression, a tendency is discernible to settle for about 50 MW per klystron and a corresponding increase in their number, in spite of the undesirable impact on cost, of which the modulators form a large part. Klystrons with 50 MW power capability will indeed be used in the *NLC Test Accelerator* which is being built at SLAC (11 m active length, 540 MeV in a first phase).

In any case, RF pulse compressors with compression ratios between four and six (and power gains of about three to four) have to be inserted between the klystron outputs and the accelerating structures in order to limit the total number of power-source modules to a manageable value. The SLAC design, a scaled version of which is also foreseen for CLIC, features overmoded waveguides for the necessary energy storage; VLEPP employs a very high cavity mode for the same purpose.

In summary it may be said that modular power sources in the form of classical modulators (except VLEPP), basically classical klystrons and passive pulse compressors offer a solution which, at 10 to 15 GHz and up to about 200 MW unit peak power, is almost at hand technologically, albeit at the price of uncomfortable cost and considerable operational complexity.

Two-beam linacs were first proposed by Berkeley-Livermore [8]. In these original proposals the power-generating drive beam received its energy from induction linac units. Its energy, therefore, is in the range of tens of MeV and it has to be recreated in frequent intervals along the main linac. In the CLIC proposal, by contrast, the drive beam of roughly 3 GeV is ultrarelativistic and supposed to travel without reacceleration for up to about four kilometres. In a 500 GeV centre-of-mass collider, therefore, drive beam acceleration — by cw superconducting cavities in the 350 MHz range — is confined to the injector so that the main accelerator tunnel is kept free from all equipment of high power transfer, high voltage and limited operational life. In the opinion of this author, which is not universally shared, however, this feature of reducing the main linear accelerators to strings of passive and low-power equipment may turn out to be vital for an economic extension of linear colliders into the TeV range.

Of the many problems presented by the CLIC two-beam scheme, the one which appears closest to solution is the transfer structure for power extraction. This takes the form of smooth beam tubes of 12 mm diameter with two periodically loaded power-collecting waveguides running in parallel and coupled to the tube by continuous slots. The particle beam is in synchronous interaction with a forward  $2\pi/3$  mode.

Since the drive bunches suffer different and strong decelerations in the absence of longitudinal focusing, it is clear that the drive beam will accumulate a large energy spread along its path, as well as a large increase of transverse emittance. Tracking the beam energy spread and the associated chromatic growth of transverse emittance through a suitable FODO focusing system confirmed that the beam survives the full (active) length of 12.5 km of a 1 TeV main linac, albeit with over 20% energy spread and filling the available aperture

at the end. Preacceleration to about 6 GeV and three reacceleration stations, located at discrete access points to the machine, are foreseen for this case of a 2 TeV collider. No reacceleration is required in a 0.5 TeV machine where each of the two drive beams — after being preaccelerated to 3 GeV in the injector complex — travels the entire linac length of about 4 km (3.2 km active) without further acceleration.

The generation of the required drive beam is a difficult problem for which several solutions have been proposed. One of these employs a battery of laser-driven photocathodes in high-gradient RF guns. This has been the subject of a test facility (CTF for CLIC Test Facility) which has begun operation. Short bunches are obtained from a Cs<sub>2</sub>Te cathode excited at 262  $\mu$ m wavelength and exposed to 100 MV/m peak extraction field in a 3 GHz gun. So far, single bunch charges of up to 26 nC in 23 ps (fwhh) pulse length have been obtained and 40 MW peak power at 30 GHz, together with 80 MV/m decelerating field, have been produced in one of the prototype main linac structures through which a multibunch 60 MeV beam from this gun is passed.

Another promising scheme under active study employs a single-pass free electron laser for bunching. Only one preinjector is required which directly generates the complete configuration of drive bunches. An experimental test carried out in collaboration with a specialised laboratory is in preparation. A third proposal suggests the use of a recirculating linac (superconducting and at 350 MHz) in combination with an isochronous storage ring for the generation of the drive beam. Clearly, two-beam acceleration is still in an experimental stage. It holds the promise of efficient high-gradient acceleration beyond 1 TeV.

## 6. INJECTOR COMPLEX AND FINAL FOCUS

The injector complex of a linear collider includes positron generation, damping rings, preacceleration to the order of 10 GeV and multi-stage bunch compression. The final focus system comprises: chromaticity correction; collimation and background masking; vibration control; nanometre beam steering and concomitant diagnostics; spent-beam disposal and the collider-detector interface in general. None of these difficult matters can be discussed here in any detail; they do not, however, present themselves in qualitatively different ways in low-frequency and high-frequency colliders.

The positron flux required for a high-frequency machine tends to be lower and thus still within the range of more conventional solutions, such as a 2 to 3 GeV high-intensity  $e^-$  beam hitting a thick target. In the CLIC two-beam scheme, generation and acceleration of the multi-bunch high-intensity drive beam forms a major addition to the injector complex.

Final-focus beam cross-sections tend to be smaller and flatter in high-frequency machines, counteracting the tendency of smaller beam-power and increased beamstrahlung due to shorter and fewer bunches. The final focus is thus made more difficult and requires another extrapolation beyond what has now been reached at the SLAC Final Focus Test Facility [9].

## 7. CONCLUSIONS

It would appear that the developments of high-frequency and low-frequency linear colliders have come somewhat closer to each other since extensive multibunching is now considered possible at 11.4 GHz (X-band) while it also turns out that vigorous measures for wake attenuation are required at 3 GHz (S-band) as well. The required numbers and basic constructions of the klystron power sources do not change much over this frequency range and the modulators remain identical. In fact, the KEK group considers colliders operating at 3, 5.7 and 11.4 GHz and intends to postpone a decision to a more advanced stage of their study.

Compared with these extrapolations (albeit far-reaching ones) of present-day electron-linac technology, TESLA and CLIC represent more radical innovations. The superconducting TESLA collider with its very high beam power and large number of widely spaced, long bunches promises especially good experimental conditions at 500 GeV, but formidable problems of technology and cost have to be solved and the possibility of economic extension to higher energies remains to be demonstrated. This, precisely, is considered the strong point of CLIC which is, in fact, an attempt to develop technologies for a 2-TeV future collider to be built in a more distant future. However, experimental backgrounds, beamstrahlung energy spread, overlap of detector events and luminosity remain problematic.

Meanwhile, an intense effort is under way, worldwide, to construct and operate experimental test facilities. Among these, the SLC in general and the Final Focus Test Facility as well as the ASSET wakefield experiment are of the greatest general interest. More specialized are the following model tests (the first two being outside the scope of this paper but mentioned for completeness):

- a 500 MeV superconducting linac section at DESY (TESLA)
- a 450 MeV 3 GHz (S-band) section at DESY
- a 540 MeV 11.4 GHz (X-band) section, called Next Linear Collider Test Accelerator, at SLAC
- a 1.54 GeV 3 GHz linac injecting into an experimental damping ring, called Accelerator Test Facility at KEK, together with the development of X-band klystrons and structures.

- a test section containing 14 GHz klystrons, structures and sub-micron alignment for VLEPP at Protvino
- a CLIC Test Facility for 30 GHz drive-beam and power generation and a separate test section for sub-micron alignment at CERN.

A few years of further research are required and the various test facilities will have to be exploited before a well-founded choice between the different proposals can be made.

## 8. REFERENCES

- [1] G. Loew ed., Compilation of "Overall and Final Focus Parameters available at the end of LC93", Linear Collider Workshop 1993 SLAC, and R.H. Siemann, "Overview of Linear Collider Designs", Proc. IEEE 1993 Particle Accel. Conf., Washington D.C., p. 532.
- [2] M. Tigner, "Superconducting Linear Colliders", ECFA Workshop on  $e^+e^-$  Linear Colliders LC92, Max Planck Institut Munich report MPI-PhE/93-14 and ECFA 93-154 (1993), p. 229.
- [3] K. Balewski *et al.*, "A 500 GeV S-Band Linear Collider Study Status Report", *ibid.* p. 123,
- [4] R. Ruth, "The Development of the Next Linear Collider at SLAC", in Proc. Workshop on Physics and Experiments with Linear Colliders, Saariselkä, Finland (1991) and SLAC-PUB-5729.
- [5] KEK Report 92-16, Dec. 92 and K. Takata, in Proc. XV Internat. Conf. on High Energy Accelerators (1992), p. 811.
- [6] V. Balakin, as [2], p. 243.
- [7] The CLIC Study Group, in Proc. IEEE 1993 Particle Accel. Conf., Washington D.C., p. 540.
- [8] A.M. Sessler, Proc. Conf. on Laser Acceleration of Particles, AIP Conf. Proc. 91 (1982), p. 154.
- [9] D. Burke, Proc. IEEE 1991 Particle Accel. Conf., San Francisco, p. 2055.
- [10] H.T. Edwards and the TESLA collaboration, Proc. IEEE 1993 Particle Accel. Conf., Washington D.C., p. 537.
- [11] H. Holthamp for the S-band Study Group, DESY M-93-05 (1993).
- [12] R.D. Ruth, Proc. IEEE 1993 Particle Accel. Conf., Washington D.C., p. 543.
- [13] S. Takeda *et al.*, IEEE 1991 Particle Accel. Conf., San Francisco, p. 2047.