TECHNOLOGY AND CHALLENGES OF LINEAR COLLIDERS

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Abstract

In this talk I'll briefly review the design challenges of a high energy, high luminosity e+e- linear collider and discuss the layout and performance of various technical options. I'll then present the status of the R&D effort and review the performance of the integrated system tests now underway at several laboratories.

1 INTRODUCTION

With the approved LHC project at CERN the energy frontier of Particle Physics will be pushed into new territory, almost an order of magnitude higher than the reach of presently operating collider facilities. In the international community of High Energy Physics there is widespread agreement that an e+e- Linear Collider of 500 GeV center-of-mass energy (upgradable to about 1 TeV) should be the next project to continue the complementary research with hadron and lepton machines, which has proven extremely important and fruitful in the past. Studies towards a next generation Linear Collider are being pursued at several High Energy Physics Laboratories [1]. At present, one can distinguish three different approaches for such a future linear accelerator. The conventional concept of NLC/JLC (SLAC/KEK study) using travelling wave copper structures driven by high peak-power klystrons, similar to the SLC, but at X-band frequency (four times the 3 GHz frequency of the SLAC linac) in order to reach higher gradients. Second, the CLIC study (CERN) still using similar structures but at even higher frequency and replacing the klystrons by a relativistic high power drive beam from which the rf power is extracted. The third concept, pursued by a broad international collaboration centered at DESY, is the TESLA approach of a superconducting linear accelerator. In the following, a brief overview of the different linear collider concepts will be given and the status of the technical developments will be summarised.

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2 MACHINE PARAMETERS

The key parameter (in addition to the center-of-mass energy) of a linear collider is the luminosity

$$L = \frac{f_{rep} n_b N_e^2}{4\pi\sigma_x\sigma_y} \qquad (1)$$

where f_{rep} denotes the pulse repetition frequency of the linear accelerator, n_b the number of bunches per pulse, N_e the bunch charge and $\sigma_{x(y)}$ the horizontal (vertical) beam size at the interaction point (IP for short). It can be shown that the luminosity is essentially limited by the AC-power P_{AC} taken from the grid, the overall efficiency η of converting P_{AC} into beam power, the energy loss δ_B due to beamstrahlung at the IP and the normalized vertical beam emittance $\gamma\varepsilon_y$:

$$L \propto \eta P_{AC} \sqrt{\frac{\delta_B}{\gamma\varepsilon_y}} \qquad (2)$$

The power consumption has to remain within reasonable limits and the beamstrahlung has to be limited to a few percent of the beam energy in order to maintain good energy resolution and small background in the interaction region. Thus the only remaining free parameters to optimize the machine performance in terms of the luminosity are the efficiency and the emittance.

An overview of the basic parameters for the X-band, CLIC and TESLA 500 GeV designs is given in Table 1. A common feature of all approaches is operation with long trains of bunches per rf-pulse, necessary to achieve a high rf-to-beam power transfer efficiency. Due to the extremely low power losses in the walls of the superconducting resonators, the pulse length in TESLA can be several orders of magnitude larger than in a conventional accelerator, resulting in a low rf-peak power requirement. Furthermore, in that case the time structure of the beam with large spacing between bunches allows to apply energy and orbit feedback [2] on a bunch-to-bunch basis, thus making the superconducting linac almost immune with respect to pulse-to-pulse drift and jitter effects. The spot size at the IP is two orders of magnitude below what is routinely achieved at the SLC. In addition to a special magnet lattice for beam size demagnification (Final Focus System, see below), good control of emittance dilution in the linac is indispensable to achieve this ambitious goal [3-5]. Wakefields excited by the beam in the accelerating structures are the main cause of emittance blow-up. Since wakefields are strongly dependent on the linac frequency (the transverse wakefield scales approximately proportional to the 3rd power of the frequency), it is no surprise that the alignment tolerances and the needs for frequent orbit optimization and tuning are more stringent for the high-frequency conventional linacs than for TESLA (e.g. for the structure alignment 10 – 15μm as compared to

0.5mm). The realistically achievable beam emittance at the IP is thus lower for TESLA, which, together with the high efficiency, leads to a higher design value of the luminosity. On the other hand, the site length for the X-band and two-beam machines can be shorter thanks to the higher accelerating gradient.

Table 1: Main parameters of the TESLA, X-Band and Two-beam linear colliders at 500 GeV center-of-mass energy.

	TESLA	X-band	CLIC
Frequency [GHz]	1.3	11.4	30
Gradient [MV/m]	22	57	100
AC power [MW]	95	99	68
Efficiency η [%]	23	10	14
Emittance $\gamma\varepsilon_{x,y}$ [μm]	10, 0.03	5, 0.1	2, 0.1
Spot at IP $\sigma_{x,y}$ [nm]	553, 5	335, 4.5	196, 4.5
Beamstrlng. δ_B [%]	3	4	3.6
Lumin. [10^{33}cm^{-2} s^{-1}]	31	7	5
Peak power [MW/m]	0.2	31	230
# of klystrons	616	3312	-
Pulse length [ns]	$9\cdot10^5$	224	100
Rep. Rate [Hz]	5	120	200
Bunch spacing [ns]	337	2.8	0.67
# of bunches pp	2820	95	150
Bunch charge [10^{10}e]	2	0.95	0.6

Complete conceptual designs for the X-band [6,7] and TESLA [8] colliders have been worked out, including all sub-systems such as Final Focus, injection systems, etc. The layout of the sub-systems takes the possibility of energy upgrade into account. For TESLA E_{cm}= 800GeV can be reached within the foreseen 32km site with improved performance of the s.c. cavities at g = 34 MV/m. For X-band, the 30km site length accommodates an upgrade to 1 TeV, eventually extendable to 1.5 TeV.

The CLIC group has recently been focusing much attention on the two-beam linac layout and parameters in the very high energy regime, 3 – 5 TeV [9].

As part of the TESLA project study [8], the integration of a coherent (FEL) X-ray user facility in the Angstroem wavelength regime is foreseen. DESY as the co-ordinating laboratory of the TESLA collaboration has taken over the charge to investigate a site next to DESY suitable for the integrated Linear Collider/Free Electron Laser facility. A detailed study of the required civil construction work and the preparations for the legal procedure necessary for project approval are in progress.

3 TEST FACILITIES

The development of the technology required for the next generation linear collider is pursued in the framework of test facilities at several laboratories, see Table 2. The SLC as the only existing linear collider is included in this list. The experience gained from years of successful operation of the SLC in many fields of accelerator physics and technology has proven invaluable for the development of future linear collider projects. Furthermore, the 50 GeV SLC linac has been used to test a beam optical system (Final Focus system) required to provide de-magnification of the spot size to the tiny values foreseen for the next generation machine.

Table 2: Overview of linear collider test facilities

SLC	Only existing L.C.	SLAC
FFTB	Final Focus System	SLAC/int. coll.
NLC-TA	400 MeV X-band linac	SLAC
ASSET	structure test (wakefields, HOM)	SLAC
ATF	1.54 GeV low-ε damping ring	KEK
TTF	s.c. cavity development, 500 MeV linac	DESY/int. coll.
CTF	two-beam test acc.	CERN

3.1 FFTB

The Final Focus Test Beam experiment, set up at the end of the SLAC two-mile linac, was constructed in international collaboration of institutes from 6 countries led by SLAC. It comprises a complete beam line very similar to the system required for a future machine, except, of course, for the lower beam energy. First successful operation of the FFTB took place in 1994 [10].

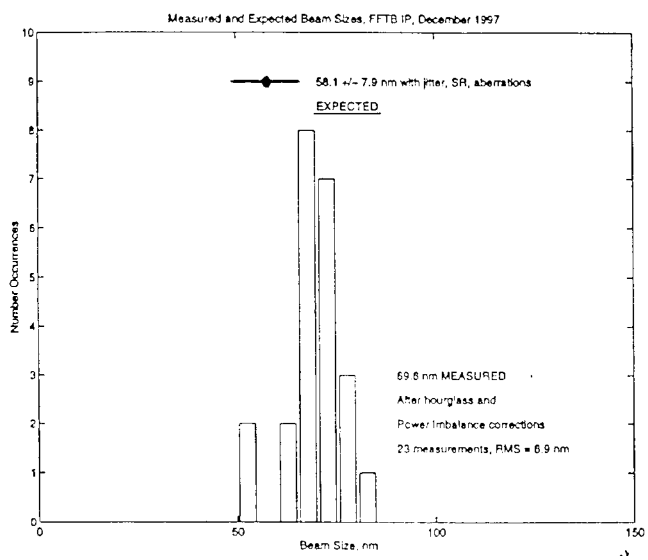

Figure 1: Vertical spot size measurements at the FFTB in comparison with the expected value (58±8nm).

Evaluation of measurements done in Dec. 1997 yield a vertical spot size of about 70nm in reasonable good agreement with the expected value (see Fig. 1). In the analysis, a measured orbit jitter of 40nm was taken into account.

3.2 NLCTA, ASSET

The X-band linac technology is under development at SLAC in collaboration with KEK. The 400 MeV test linac of NLCTA [11] represents a full integrated system test of of the components for the X-band collider. Beam acceleration with a maximum gradient of 40MV/m was achieved at 50% of the design intensity (600mA) and reduction of the multi-bunch energy spread to 0.3% peak-to-peak with beam loading compensation was successfully demonstrated. High power klystrons have been developed with periodic permanent magnet (ppm) focusing (Fig. 2), avoiding the considerable power consumption otherwise due to the focusing solenoid. With a peak power of 50MW at 2µs pulse length and an efficiency of 55% all specifications have been met. Work on a 75MW ppm focused klystron is in progress both at SLAC and KEK. RF-pulse compression by more than a factor of three was achieved with a SLED-II system. The application of a delay line distribution system for pulse compression is foreseen for the future [12,13]. It is also planned to replace the present conventional modulator concept by a more efficient and lower cost induction type device based on solid state technology.

Several 1.8m long X-band structures have been built and tested. The concept of detuning and damping of higher order modes (HOM) is applied to provide a sufficiently strong suppression of long-range wakefields. Beam tests of X-band structures at ASSET [14] (see Fig. 3) have demonstrated the wakefield suppression as well as the possibility to use the HOM signal for precise beam-based alignment of the structures as required for beam stability. Furthermore, the challenge of obtaining a structure straightness at the 10µm level has been addressed [15].

3.3 ATF

The accelerator test facility at KEK comprises a 1.54GeV electron beam injector linac and damping ring and represents an (almost) full size model of a low emittance injection system for the X-band linear collider. So far, operation took place at 1.29 GeV and with damping wigglers off, leading to a damping time of 30ms as compared to the design value of 9ms. With single bunch operation at 6 - $8 \cdot 10^9$ bunch charge, the measured emittances are approaching the ambitious design goals of $3 \cdot 10^{-6}$ m (horizontal, normalised) and $3 \cdot 10^{-8}$ m (vertical, norm.) [16].

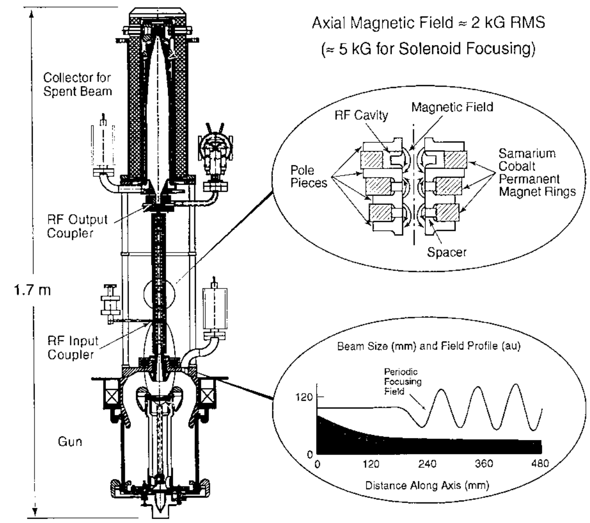

Figure 2: The ppm focused X-band klystron developed at SLAC.

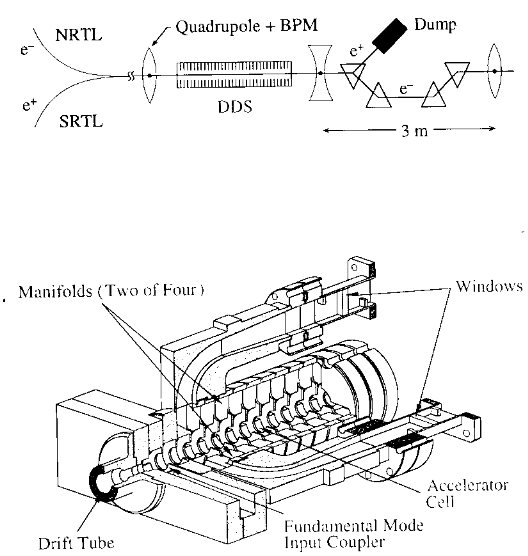

Figure 3: Sketch of the accelerating structure set up (top) at the SLC linac and of the X-band damped-detuned structure (bottom).

3.4 CTF

The main objective of the CLIC test facility at CERN is the demonstration of the two-beam acceleration concept at a frequency of 30GHz. The CTF drive beam line uses a high intensity RF-laser gun, S-band accelerating section and bunch compressor. In 1998 a bunch train with total charge up to 450nC was sent through the 30GHz decelerating/power transfer structure, generating up to 50MW of RF-power [9,17]. The maximum field produced in the main beam accelerating structure was 69MV/m. First test of an active alignment system for the linac components achieved a position stability of 2µm (rms).

For the future, it is planned to upgrade the CTF for a full system test of the newly developed drive beam generation scheme [18,19], as it would be used in a multi-TeV two-beam linear collider facility.

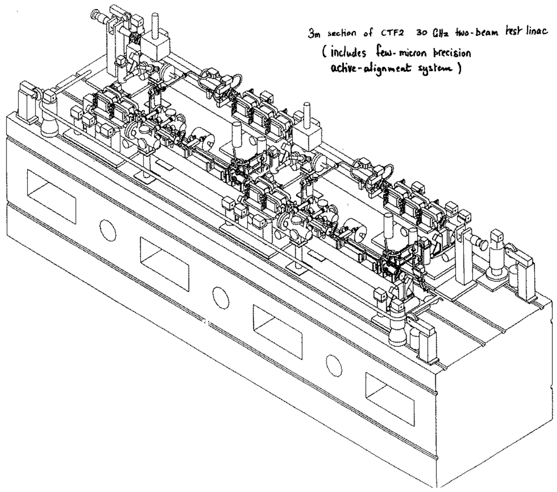

Figure 4: One section of the two-beam accelerator at CTF.

3.5 TTF

The development of high-performance 9-cell superconducting Niobium cavities (Fig. 5) is pursued by the international TESLA collaboration (involving more than 30 institutes from 9 countries) in the framework of the TESLA test facility at DESY.

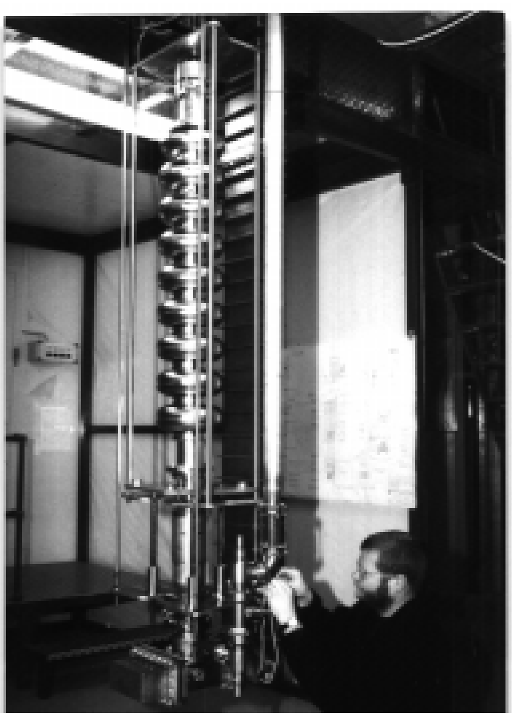

Figure 5: One of the TESLA Niobium resonators being prepared for CW-RF test in the vertical test stand.

The TTF includes the complete infrastructure for cavity processing (clean rooms, chemical and high-temperature treatment, high-pressure rinsing with ultra-pure water), vertical and horizontal test stands for CW- and pulsed-RF operation of the 1.3GHz resonators and a 500MeV linac for a full integrated system test of the accelerator modules with beam. The evolution of the achieved accelerating gradients in vertical test over the last years is shown in Fig. 6. High gradients above 20MV/m were reached already at an early stage, but the failure rate (cavities with poor performance due to fabrication errors) was rather high at that time. The results from the more recent production series shows a strong improvement in the performance statistics, so that the gradient of 22MV/m required for the 500GeV collider is now achieved on average (see ref. [20] for more details). Cavities equipped with RF- and HOM-couplers underwent pulsed power tests in the horizontal test stand. No systematic degradation of performancecompared to the vertical test was observed (Fig. 7).

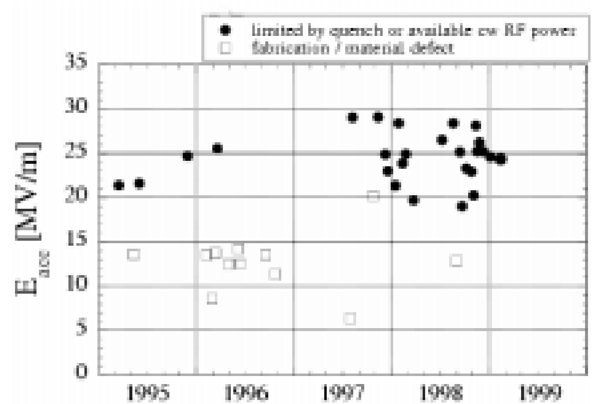

Figure 6: Evolution of accelerating gradient achieved with TESLA cavities on the vertical test stand.

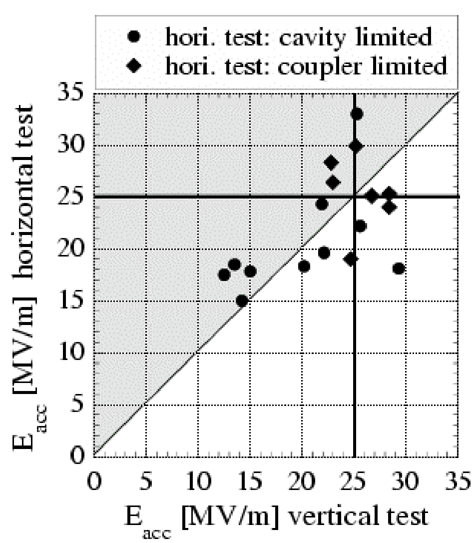

Figure 7: Horizontal vs. vertical test stand results.

Eight 9-cell cavities are assembled into a string and mounted in an accelerator module, which also contains focusing and beam diagnostics devices. So far two of these modules have been installed in the TTF linac and tested with beam. The 1st module reached a gradient of 16MV/m in May 1997. The 2nd module was tested early this year and showed a gradient of 18.5MV/m measured with beam and 20.8 MV/m obtained from RF-measurement, in both cases limited by insufficient RF-power coupler conditioning. From cryogenic measurements a resonator quality factor of $1.3 \cdot 10^{10}$ at T=2K, exceeding the TESLA design goal of 10^{10}, could be deduced. A 3rd module is presently being installed, replacing module #1, and expected (from test stand results for the individual resonators) to yield an average gradient of 25MV/m. The TTF beam line is also being prepared for a first test of the SASE FEL concept, which will take place after beam operation resumes in summer this year.

Accelerating gradients above 30MV/m have already been achieved with some of TESLA cavities (the record value being 33MV/m at full pulse length and rep. rate in the horizontal test stand). The TESLA cavity R&D will continue to define a reliable procedure, suitable for mass production, for obtaining an average gradient of 34MV/m as required for the energy upgrade to 800GeV. One very promising improvement of resonator performance was recently obtained by electro-polishing [21], with gradients up to 37MV/m obtained in single cell L-band cavities.

4 CONCLUSIONS

The technical developments towards a next generation linear collider are far advanced and the X-band and TESLA groups will present technical proposals, incuding cost estimates and schedule, within the next two years.

The recent progress of the CLIC group on both the test facility and the conceptual design of the two-beam linear collider is remarkable. These developments, to my mind, should be seen on a longer time scale. At present the two-beam approach appears to be the most promising concept for a multi-TeV lepton collider, which may be realised as a facility following the next generation linear collider.

Being left with two concepts for the next machine, the obvious question is which one to choose. This decision will have to involve a detailed comparison of the scientific potential as well as the cost of the X-band and TESLA facilities.

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