Chapter 1

Introduction

There is a widespread consensus within the high energy physics community that an electron–positron collider with a center of mass energy of 500 GeV and luminosity above $10^{33}\text{cm}^{-2}\text{sec}^{-1}$ should be considered as a possibility for the next accelerator facility after the LHC. Such a collider would provide for top analyses via $t\bar{t}$ production and discovery reach up to a Higgs mass of $\approx$350 GeV.

Worldwide, there are a number of groups pursuing different linear collider design efforts. These group activities have been reported in the yearly linear collider workshops, the accelerator conferences, and the usual journals. The TESLA activity is one of these R&D efforts, differing from the others in its choice both of superconducting accelerating structures and of low frequency (1.3 GHz). Several of these R&D groups, including TESLA, plan to have working prototype test facilities and well-developed collider designs in the 1997 time scale. After experience with implementation and operation of the test systems it will be possible to start to make relative evaluations of the different proposals, looking forward to the selection of the most promising technology.

Key in this selection will be technical merit, minimization of technical risk, and potential for optimization of performance. Equally important, however will be projected overall construction and operating costs.

In this competitive environment, the TESLA Collaboration has major challenges before it. Of highest priority is to prove the feasibility of reliably achieving accelerating gradients of 15 MV/m or more, and the clear potential for extrapolation to gradients of 25 MV/m, the TESLA 500 design goal.

(TESLA 500 would be the full-scale facility, to yield 500 GeV in the center of mass.) The TESLA Test Facility (TTF) is to prove that accelerating gradients greater than 15 MV/m are consistently obtainable, and that the cavities can be assembled into a linac test string (the TTF Linac or TTFL) that can be successfully operated with auxiliary systems to accelerate an electron beam to ≈500 MeV. The basic characteristics of the TTFL should be as consistent as possible with the parameters of the TESLA 500 design. The time scale for beam tests with four cryo modules of 8 cavities each is early 1997. The other collaborations are working to the same time scale.

In the Autumn of 1991, work began on the proposal for the TTF, to include state-of-the-art superconducting cavity processing capability, the electron linac that would reach 500 MeV at a gradient of 15 MeV/m as noted above, and necessary support and diagnostic equipment. The proposal was issued in April 1992.[1]

The TTF is to be located at DESY, with major components flowing in from the members of the collaboration. Since the proposal was issued, much of the processing and support facility has been completed, and plans for the linac have evolved considerably. This Conceptual Design Report is intended to summarize the present design status of the linac.

The design of the technical systems of the TTFL has developed substantially since the TTF Proposal. Though a complete description of the technical systems may not be possible within the bounds of reasonable effort and length, it is important that specific descriptions of the technical systems be given . This is needed so that everyone understands what is proposed to be built, whether it fits together, how to standardize it, just what is missing, needs to be changed, or is not necessary.

It is also necessary to define the experiments to be carried out on the TTFL. These experiments must to thought through and outlined in sufficient detail now so that the necessary diagnostics are built into the technical systems. This effort is especially important for those items needed in the cold cryostat and cryogenic system, where it will be difficult to make additions and modifications later.

The experiments that should be considered are not only the more typical beam experiments, but perhaps more importantly the cryogenic and RF measurements and operations to run the systems but may not require beam.

---

[1] *Proposal for a TESLA Test Facility*, TESLA Report 93-1, DESY 1992

The successful production of the cavity systems and the TTFL must be given first priority. To this end initial prototype components must be assembled to provide working subsystems and overall major systems in a timely manner. However once these efforts are underway, cost efficient designs must be explored and cost drivers for large scale production analyzed. Thus not only are successfully working systems a necessity, but convincing analysis of costs for the final TESLA 500 design must be carried out. In addition, prototypes of cost effective component designs should be tested when at all possible.

1.1 TESLA 500 and the TTFL

The various approaches to a next-generation linear collider design differ mainly in the choice of spot size, bunch charge, and frequency. The differences mainly come down to trade-offs between the amount of beam power that is required versus the spot size which must be provided at the interaction point. A higher beam intensity can be used to balance more relaxed beam emittance and final focus requirements. Typically, bunch intensities vary by an order of magnitude and vertical spot sizes by as much as a factor of 20. The different designs range from 1.3 to 30 GHz in accelerating structure excitation frequency.

The TESLA approach lies at the low frequency, high intensity end of the present parameter ranges. The use of superconducting RF cavities aids in reaching higher beam intensity. The beam power could as well be applied toward higher luminosity if more stringent emittance and focusing requirements were imposed. However, the major appeal of the superconducting RF approach is that it allows for more relaxed tolerances and less ambitious extrapolations from the state-of-the-art operation at the SLC.

The technical advantages of the superconducting RF cavities stem from their high Q values and low wall losses. This allows for the use of large aperture structures operating at relatively low frequency, with long pulse lengths and low peak RF power requirements. The large aperture of the cavities has the beneficial consequence of substantially reduced transverse and longitudinal wake field effects. As the aperture of an L-band cavity is $\approx$70 mm in diameter—about ten times larger than in some of the higher frequency designs—relaxed linac alignment and vibration tolerances should result even at the higher bunch charge of this design. With a larger emittance, more dilution can be tolerated in the linac, in the optics after the linac, and in the final focus. Benefits for the detector include more longitudinal space after the last focusing element and a longer beam pulse with considerable time between bunch interactions.

Despite these attractive features, a major effort is needed to demonstrate that a superconducting linear collider can be built at a cost competitive with its normal conducting counterparts. The maximum accelerating gradient for niobium structures is in principle about 50 MeV/m, but in practice the achievable gradient is limited by field emission from localized regions on the cavity surface. In the last few years, there has been significant progress in the understanding of this field emission process and its cures, and the gradient produced by multicell cavities has moved up from the 5 MeV/m range to above 25 MeV/m. Estimates carried out by the TESLA collaboration indicate that a competitive balance may be reached at an accelerating gradient of 25 MeV/m.

A short summary of the suggested advantages and possible disadvantages and challenges of the TESLA approach is listed below.

Advantages:

- High efficiency — ≈23% of linac plug power delivered to the beam
- Large aperture → low wake fields
- High Q → long RF pulse, large bunch spacing, more bunches per RF pulse
- “Conventional” RF systems
- Large bunch charge aids in energy resolution
- Large vertical emittance permits:
    - Large alignment tolerances
    - Easier final focus
    - More longitudinal space for detector
    - May permit zero crossing angle
    - Easy collimation — large collimator opening, many σ
- large bunch spacing permits:
    - Collimator protection & injection error protection easier

  - Multi-bunch servo & feedback easier for vibration compensation, energy control and other multi-bunch processes

- Possibly better detector backgrounds
- Result → Technical contingency—parameters, such as vertical spot size, are not pushed to extremes, or → easier extension to higher energy

Challenges:

- Cost and gradient improvements must be demonstrated in building the TTFL
- The complex cryogenic system
- Cryo/vacuum failure may result in cavity contamination; it should be demonstrated that, e.g., *in situ* high peak power processing can aid recovery (as has already been demonstrated in vertical tests with multicell cavities)
- Dark current capture may be a difficulty at the low TESLA frequency
- Lorentz force cavity detuning may be difficult to control
- Large damping ring and positron source may be required
- The implications of the large beam power must be examined (it is encouraging to note that 1.5 GHz storage ring cavities have handled beam currents as high as 26 mA at 5 GeV without any adverse effects. Recently, a 500 MHz single cell cavity was run in CESR at 5 GeV with a stored CW beam of 220 mA)

Some of these perceived advantages and challenges may be explored in the TTF program; others cannot. Tab. 1.1 illustrates the similarities and differences between TESLA 500 and the TTFL.

Two injectors are planned for the TTFL. The first, Injector I, is intended to be relatively straightforward in design, to provide the TESLA design current, but not the TESLA large bunch spacing and rather intense bunches. In its initial form, Injector I will employ a subharmonic buncher at one-sixth the linac frequency. The parameters of Injector I are shown in Tab. 1.2. The second, Injector II, is intended to provide the TESLA 500 spacing and bunch intensity. An RF photoemission gun is a candidate for Injector II; tentative parameters for this approach are shown in Tab. 1.3. Neither will have the transverse emittance ratio of TESLA 500.

Table 1.1: TESLA 500 – TTFL parameter comparison.

Parameter	TESLA 500	TTFL	
Linac Energy	250 GeV	500 MeV	
RF frequency	1.3 GHz	1.3 GHz	
Accel Gradient	25 MeV/m	15 MeV/m	
Q_0	5×10^9	3×10^9	
# Cryo modules	≈ 2500	4	
Energy spread, single bunch rms	1.5×10^{-3}	$\approx 10^{-3}$	
Energy variation, bunch to bunch rms	10^{-3}	$\approx 2 \times 10^{-3}$	
Bunch length rms	1 mm	1 mm	
Beam current	8 mA	8 mA	
Beam macro pulse length	0.8 ms	0.8 ms	
Lattice β typical	$\langle 66$ m$\rangle$	12 m max	
		Inj I	Inj II
Injection Energy	10 GeV	10 MeV	20 MeV
Emittances (x/y), $\gamma\sigma^2/\beta$	20/1μm	$\approx 5\mu$m	$\approx 20\mu$m
Beam size σ, end of linac	50/12 μm	250μm	500μm
Beam size σ, injection	260/60 μm	1.7 mm	3.5 mm
Bunch frequency	1 MHz	217 MHz	1MHz
Bunch separation	1 μsec	4.6 ns	1μsec
Particles per bunch	5×10^{10}	2.3×10^8	5×10^{10}

Table 1.2: Injector I

Gun Energy	250	keV
Output Energy	9.9	MeV
Accel Gradient (Capture Cav)	10	MV/m
Frequency Capture Cav	1300	Mhz
Phase spread, gun	±150	deg
Prebuncher Frequency	216.7	MHz
Bunch Population	2.3×10^8	per bunch
RMS Phase Width	0.77	deg
Total Phase Width	3.2	deg
RMS Energy Spread	0.078	MeV
Total Energy Spread	0.3	MeV
Emittance ($4\gamma\sigma^2/\beta$)	16.8	mm-mrad
RMS bunch length	0.49	mm
$\Delta E/E$ RMS	0.8	%

Thus, there are a number of respects in which TESLA 500 and the TTFL are sufficiently similar, so that the TTFL experience will feed directly into the TESLA 500 design. There are some aspects of the full scale linear collider that will be difficult to check, and still others that cannot be seriously investigated. These distinctions are characterized in the following lists.

What the TTFL does check:

- Gradient achievable
- Cavity construction and processing techniques
- Input and HOM coupler designs
- RF control of multi-cavity systems
- Lorentz detuning effects and control
- *In situ* high peak power processing (HPP)
- Vacuum failure recovery potential
- Cryostat design
- Cryogenic operation and heat load (except possibly HOM)
- Dark current

Table 1.3: Injector II: RF photoemission gun, accelerating section, and compressor nominal conditions.

Bunch spacing	1	μsec
Bunches per macropulse	800	
Electrons per bunch	5×10^{10}	
Brightness	4.8×10^{12}	A/m^2
Emittance, $\gamma\sigma^2/\beta$	20	mm-mrad
RF frequency	1.3	GHz
RF power—gun	2.5 typ, 4.5 max	MW
Solenoid focusing field on axis	0.14	T
Beam radius at cathode	3	mm
Bunch length, σ before compression	4.33	mm
Bunch length, σ after compression	1 typ	mm
Post gun kinetic energy	3.8 typ, 6 max	MeV
Injector output energy	20 typ	MeV
Gradient in acc sect	15 typ	MV/m
Momentum spread	4.2 typ	%
Longitudinal emittance	0.82 typ	MeV-deg
Laser pulse FWHM	28	ps
Photocathode QE	1	%
Micropulse energy	> 5	μJ
Time jitter	< 2	ps
Amplitude jitter	< 5	%
Pointing stability	< 100	μrad
Laser wavelength	< 300	nm

- Energy and position beam feedback and control
- Alignment and its stability (during thermal cycle also)
- BPM system
- First iteration on projected systems costs

What may be difficult to check:

- Q_0 and HOM measurements are not easy
- Wake field measurements only far off axis
- Cavity alignment via wake fields hard because of polarization
- TESLA 500 bunch charge hard to achieve in time scale of TTFL
- Accurate cost projection to mass production

What the TTFL does not check:

- Emittance growth
- Vibration sensitivity
- Many features of an overall TESLA 500 facility (damping, positrons, etc.)

1.2 Overview of the TTFL Program

The TESLA Test Facility is located in Building 28 (Halle 3) at DESY; a plan view of the layout is shown in Fig. 1.1. The linac itself is within a shielded enclosure in the upper part of the figure. An expanded view of the linac is shown in Fig. 1.2. The TTFL contains three major regions: the injector area, the main body of the linac, and the high energy beam analysis area. The injector area includes the electron gun, subharmonic prebuncher, the superconducting capture cavity, focusing lenses, and beam diagnostic equipment. The capture cavity is identical to one of the nine-cell structures in the main linac. The principal parameters of the injector (Injector I) have already been listed in Tab. 1.2.

Four cryomodules, each 12.2 m in length, comprise the main body of the linac. Each cryomodule contains eight nine-cell cavities and a “quadrupole package”. Each cavity has an input coupler for RF power, two higher-order-mode (HOM) output couplers, and a tuning mechanism. Selected parameters of the cavities are given in Table 1.4. The quadrupole package includes a

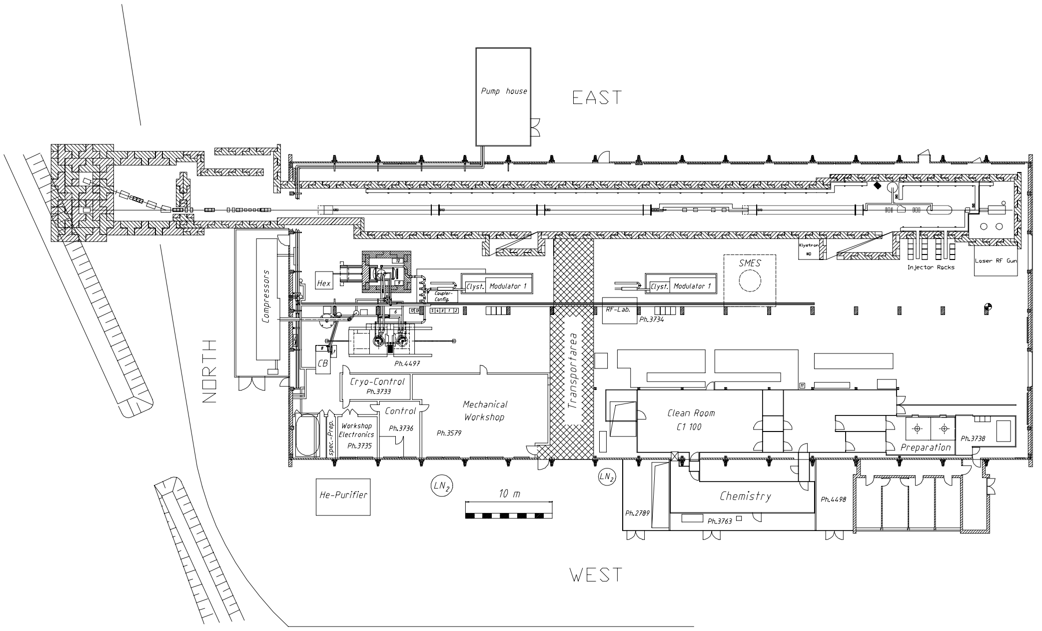

Figure 1.1: Layout of the TESLA Test Facility

Table 1.4: RF cavity parameters for the TTFL

Frequency	1.3	GHz
Cells per cavity	9	
Cavity length	1.036	m
Iris radius	35	mm
R/Q	1011	ohms/cavity
E_{peak}/E_{acc}	≈ 2.0	
RF power @ 25 MeV/m	206	kW/m
HOM k_{long}/cavity	8.5	V/pC (1mm bunch σ)
HOM k_{trans}/cavity	18	V/pC/m

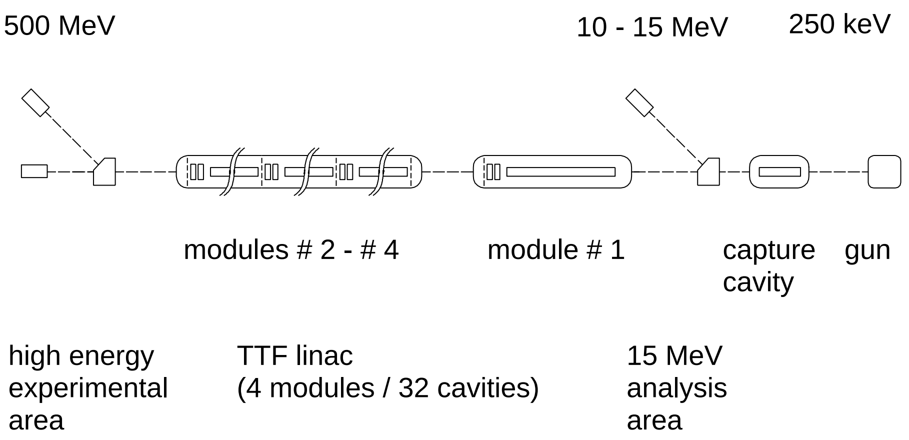

Figure 1.2: Schematic of the TTFL

Table 1.5: Summary of the cryogenic system heat budget for TTFL (4 modules and injector). Budget is 1.5 times estimated loss.

	Static Losses	Total Losses 15 MV/m Q=3×10^9	Total Losses 25 MV/m Q= 5×10^9
Summary—2 K			
2 K load, W/m	0.23	1.28	1.78
Budget, 5 modules, W	21	115	160
Summary—4.5 K			
4.5 K load, W/m	1.16	1.27	1.33
Budget, 5 modules, W	104	114	120
Summary—70 K			
70 K load, W/m	6.4	10.4	11.3
Budget, 5 modules	576	936	1017
w/o HOM	576	684	765

quadrupole doublet, transverse steering, a transverse beam position monitor, and an HOM absorber.

RF power for the main body of the linac will be provided by two klystrons and two modulators. Each klystron/modulator will deliver 4.5 MW with a pulse length of up to 2 ms. The cavities will operate at a temperature of 1.8 K, with refrigeration provided by a system of 100 W capacity at 1.8 K, which can be increased to 200 W capacity by the addition of a heat exchanger. A summary of the cryogenic system budget is given in Tab. 1.5. The loads per unit length have averaged the accelerating structure loads over the entire length of the cryomodule. The total cryogenic system budget for the TTFL is 1.5 times 5 modules (counting the capture cavity and end effects).

A summary schedule for the TTFL is shown in Tab. 1.6. The column labeled “Original” is the schedule established in May 1993, while the column headed “Actual” is either the date at which the event occurred or the best schedule estimate at this writing.

The TTF program relies heavily on making substantial progress in achieving high field gradients in the cavities. To this end, a major effort has gone into the installation of a state-of-the-art facility to carry out the cavity processing procedures, as noted earlier.[2] Many of the milestones in Tab. 1.6 are associated with the equipment which was needed to proceed with a systematic investigation of the most effective cavity processing steps. The infrastructure that has been assembled in Halle 3 consists of:

- Cleanrooms spanning classes 10–10000, of total area $\approx 300m^2$
- An automated chemical processing system for both inside and outside chemical etching
- A pure water rinsing system
- A very high pressure rinsing system
- A vacuum oven for titaniaum treatment to improve the thermal conduction properties of the cavities and RRR
- A vertical dewar cavity test setup and a 5 MW, 2 ms RF modulator for HPP of the cavities and for gradient measurements
- A horizontal test cryostat for one cavity, which will retest the individual cavities after the mounting of RF couplers and the helium vessel
- Cryogenics and controls to support the test program

A summary of the TTFL measurement program is outlined below; further detail will be found in the subsequent chapters of this report. The measurements may be considered to fall into three general categories: no beam, low bunch charge (Injector I), and high bunch charge (Injector II).

Major parts of the system can be checked without beam. These include pulsed mode operation and control of the low and high level RF systems with Lorentz force detuning compensation, and 16 cavities operated from one modulator system. Attempts at *in situ* HPP cavity processing and measurements of dark current can be performed. Cryogenic measurements of the static heat load, *in situ* $Q_\circ$ measurements, and cooldown and warmup procedures can be developed and carried out. Measurements of alignment stability and vibration can be made.

With the low bunch charge injector, beam acceleration, control and stability of position, energy, and emittance with full beam current are possible. Cryogenic load measurements under full beam power loading can be carried

---

[2] *Proposal for a TESLA Test Facility, op cit*

out. Major vibrational effects on the beam and studies of beam losses and associated radiation may be observed.

The high bunch charge injector allows for measurements of HOM losses, wake field effects, and the possibility of observation of cavity misalignment by mode excitation.

The lists below are organized under various subject headings, and, of course, the lists cannot be complete. Entries concluding with an asterisk, '*', need full bunch charge of Injector II.

Alignment-Vibration:

A–1 Measure cryomodule alignment stability during cooldown-warmup.

A–2 Measure vibration properties, i.e., vibration transfer function for cavities, quadrupoles, and couplers.

Cryogenics:

K–1 Measure heat leak with and without beam and RF. Measure Q_o versus the accelerating gradient calorimetrically or, at least, be able to detect low Q (leading to $\approx 1/4$ watt in a cavity) and quenches.

K–2 Measure temperature profile for each cell and coupler on at least one cavity.

K–3 Measure operation as a function of temperature.

K–4 Measure HOM power deposited in He and in the beam tube absorber.*

Cavity performance:

C–1 Measure Q versus E_{acc} with time, with and without beam, both calorimetrically and electrically.

C–2 Attempt high power peak processing *in situ.*

C–3 Transfer full pulse power to beam at full pulse length.*

C–4 Measure HOM power deposited in liquid helium, coming out beam pipe and deposited in the HOM absorber, and coming out of the HOM couplers.*

C–5 Look for transverse mode excitation as a function of beam position. Try to measure module/cavity alignment by looking for beam position that yields minimum transverse mode excitation.*

C–6 Measure dark current. Measure radiation patterns and spectrum without beam for field emission and captured dark current.

RF system

R–1 Develop tuning procedures for cavity and input coupler (frequency, voltage, phase, coupling) with Lorentz force compensation.

R–2 Develop beam loading compensation, and be able to switch from no-beam to beam conditions.

R–3 Develop quench and arc protection.

R–4 Measure gradient and phase as functions of time in each cavity with and without beam.

R–5 Look for microphonics, including radiation pressure effects. Look for coupler vibration effects.

Beam

B–1 Measure energy, energy spread, and energy stability within the macropulse.

B–2 Measure emittance.

B–3 Repeat measurements above with Injector II. Need to measure bunch length at injector end to assure that injected beam is not leading to excessive energy spread.*

B–4 Measure emittance blowup off axis, off momentum.*

B–5 Observe single and multi-bunch wakefields. Is an off-energy witness bunch needed? Wakefield measurements are coupled to emittance (head-tail) and mode excitation measurements as well.*

B–6 Look for transverse mode excitation.*

Operation

O–1 Develop tuneup procedures, practice beam alignment, focusing, and energy optimization.

O–2 Check BPM system operation for sensitivity, linearity, off-center line, etc.

O–3 Make precise beam transmission measurements.

O–4 Measure radiation pattern with beam. Determine amount of radiation coming from poor quality injected beam.

O–5 Simulate fault conditions of subsystems, such as RF trips, magnet trips, and so on.

Table 1.6: Summary schedule for TTFL as of January 1995.

Item	Condition	Original Milestone 5.93	Actual or Expected
Two prototype cavities	available	8.93	8.93
Cryosystem vertical dewar	available		12.93
1st proto cavity RF test	start	11.93	1.94
lst cavity order (1-6)	release	10.93	2.94
TTF chemical processing	available		4.94
HPP RF modulator # 1	available	2.94	5.94
lst cavities	start delivery		11.94
Treatment, cavities 1–6	start	3.94	1.95
lst cavity horizontal test	start	5.94	4.95
lst cryomodule	start assembly	11.94	8.95
lst cryomodule	assembly complete		11.95
Feed can	delivery		7.95
1st cryomodule	cold test	4.95	11.95
Injector I	start test Saclay		3.95
Injector I	start oper DESY		10.95
Beam test 1st cryomodule	start	8.95	12.95
Final cavity order	release	6.95	
Final cryomodule order	release	6.95	
Assembly modules 2-4	start	5.96	
Modules 2-4	install in linac		3.97
Beam tests, 4 modules	start	4.97	
Injector II	start DESY oper		3.97
Beam, linac & Inj II	start		5.97