STATUS OF THE TESLA DESIGN*

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The status of the layout of the linear collider project, TESLA, which employs superconducting accelerating structures, will be presented.

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1. Introduction

Since the first proposal for a superconducting linear e^+e^- collider by Tigner [1] in 1965, accelerator builders [2–4] have been fascinated by the potential of superconductivity for high energy linear e^+e^- colliders. The low resistive losses in the walls of superconducting cavities yield a high conversion efficiency from mains to beam power. As energy can be stored very efficiently in the cavities, a large number of bunches can be accelerated spaced far apart in a long RF pulse. This allows for a fast bunch to bunch orbit feedback which guarantees that bunches from the opposing beams hit head on at the IP.

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One of the most important parameters of a linear collider is the luminosity which is given by

$$L \approx \text{const.}\ \frac{\sqrt{\delta_B}}{E_{\text{CM}}}\ \frac{\eta}{\sqrt{\varepsilon_{y\text{N}}}}\ P_{\text{AC}}\ H_{\text{D}}\,, \tag{1}$$

where δ_B is the relative energy loss caused by beam-strahlung, E_{CM} is the centre of mass energy of the e^+e^- collision, η is the conversion efficiency from mains power P_{AC} to beam power, $\varepsilon_{y\text{N}}$ is the normalised vertical emittance at the IP and H_{D} is the luminosity enhancement factor caused by disruption.

To achieve high luminosity for given P_{AC} and beam-strahlung-losses one needs high conversion efficiency and a small vertical beam emittance at the IP.

The electromagnetic fields generated by the particle bunches travelling through the accelerating structures — the wakefields — act back on the generating bunch itself and the following bunches. In case of a small deviation of the bunch trajectory from the axis of the accelerating structure, the transverse wakefields generate an effective dilution of the emittance at the IP, thus reducing the luminosity. As these transverse wakefields scale with the third power of the RF frequency, it is obviously easier to transport low emittance beam through a low frequency structure.

Another very important parameter for the layout of a linear accelerator is the shunt impedance per unit length, which is the ratio of the accelerating gradient squared to the RF losses in the accelerator structure per unit length. Whereas this quantity scales with the square root of the RF frequency ω for normal conducting structures (thus favouring large RF frequencies) it depends on ω as

$$r_s \sim \frac{\omega}{A\omega^2 + R_{\text{res}}} \tag{2}$$

for superconducting cavities favouring RF frequencies around 1GHz. A is a function of temperature and material and R_{res} is the residual surface resistance. Because low frequencies are preferred for s.c. cavities, this make them ideally suited to accelerate low emittance beams, as the emittance dilution by wakefields is small ($W_\perp \sim \omega^3$). In addition tolerances on the fabrication and alignment of cavities are very relaxed. The combination of high conversion efficiency and small emittance dilution makes a superconducting linear collider the ideal choice with respect to the achievable luminosity.

2. A short history of TESLA

The major challenges to be mastered so that a superconducting linear collider becomes feasible were to increase the accelerating gradients from about 5 MV/m to 25 MV/m and to reduce the cost per length from existing systems by about a factor of four to obtain 2000 $/MV. Encouraged by results from R& D work at CEBAF, CERN, Cornell, DESY, KEK, Saclay and Wuppertal [12–14], several institutions — the nucleus of the TESLA Collaboration formally established in 1994 — decided in 1991 to set up the necessary infrastructure at DESY [8] to process and test 40 industrially produced 9 cell 1.3 GHz solid Niobium cavities. The aim was to achieve gradients of 15 MV/m at a Q value of 3×10^9 in a first step and finally reach 25 MV/m at a Q value of 5×10^9 suitable for the linear collider. The infrastructure of the TESLA Test Facility TTF consists of cleanrooms, chemical treatment installations, a 1400° C purification furnace, a high pressure water rinsing system, a cryogenic plant to operate vertical and horizontal cavity test stands at 1.8 K and a 1.3 GHz RF source.

In addition the collaboration decided to build a 500 MeV linac as an integrated system test to demonstrate that a linear collider based on s.c. cavities can be constructed and operated with confidence.

Considerable attention has been given to the subject of cost reduction [10,11]. For example:

- The number of cells per accelerating structure was increased to 9 compared to the customary 4–5. This reduces the number of RF input and HOM couplers, tuning systems and cryostat penetrations, it also simplifies the RF distribution system and increases the filling factor.

- Costly cryostat ends and warm to cold transitions were avoided by combining eight 9 cell cavities and optical elements, which were all chosen to be superconducting, into one long, simple cryostat. Also the complete helium distribution system has been incorporated into the cryostat using the cold low pressure gas return tube as support structure for cavities and optical elements.

From the work starting in 1990 [13] a concept for a 500 GeV cm energy superconducting linear collider emerged, operating at 1.3 GHz with a gradient of 25 MV/m at $Q = 5 \times 10^9$ and a luminosity of some $5 \times 10^{33}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$. A conceptual design report (CDR) was published in May 1997 [15] giving a complete description of the machine including all subsystems. The report includes a joint study with ECFA on the particle physics and the detector layout.

Since 1990 interest has grown [16,17] in linac driven X-ray FEL radiation, based on the Self-Amplified Spontaneous Emission (SASE) principle [18,19]. As the requirements on the emittance of the beam for a short wave length FEL are very demanding, again a superconducting low RF frequency linac lends itself as the best choice for such an application. The CDR includes the layout of an X-ray FEL facility integrated into the linear collider as well as various scientific applications of the FEL radiation. For a detailed report on the status of the X-ray facility, see [20]. The principle layout of the whole facility is shown in Fig. 1.

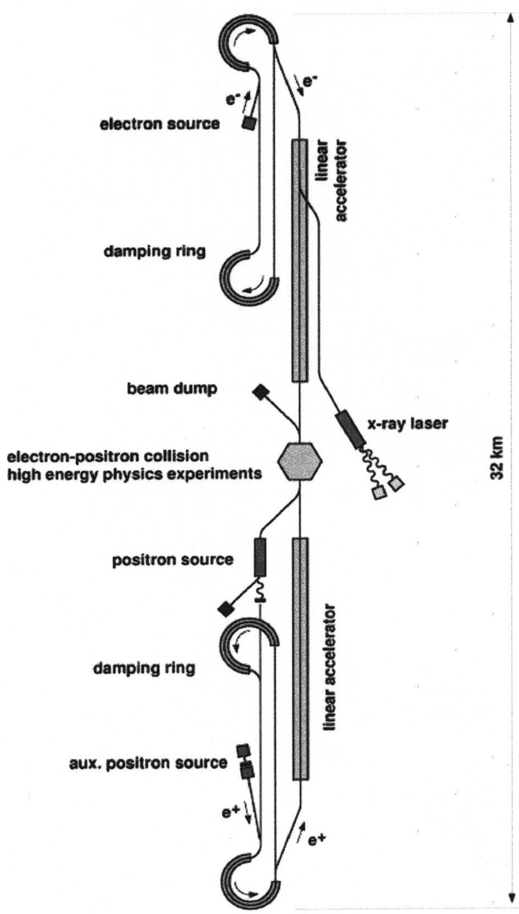

Fig. 1. Overall layout of TESLA

3. R&D results and activities

The cavities are fabricated up to now from Niobium sheet material by deep drawing and electron beam welding. High purity material with good thermal conductivity at low temperatures is used to avoid thermal quenches of the superconductor. In order to avoid field emission during high field operation great care is taken during the preparation of the cavities to get the inner surface of the cavities dustfree.

Therefore the cavities are only handled in a high quality cleanroom and the acids and the water used to clean the cavities are kept free from particle contamination by special filters. The final cleaning is done by a high pressure ultra clean water jet which is a very efficient way to remove dust particles from the cavity.

Up to now 38 9-cell Niobium cavities have been tested at the TTF. The majority of the cavities exceeded the initial TTF design goal of 15 MV/m at $Q = 3 \times 10^9$. Fig. 2 shows the measurements in the vertical test stand [26] of all cavities excluding only those with a well identified fabrication error. On average a gradient of 22 MV/m at $Q = 10^{10}$ is obtained. In a recent measurement in the horizontal test [25] a gradient of 33 MV/m at $Q = 4 \times 10^9$ has been achieved.

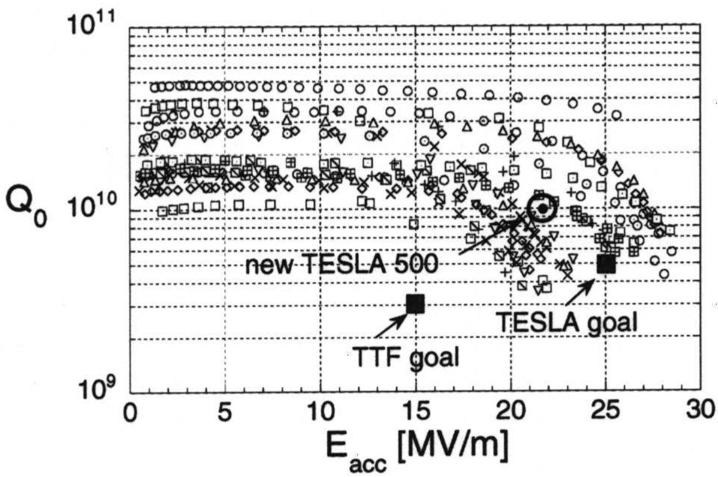

Fig. 2. Quality factor Q *versus* acc. gradient for all 9-cell cavities without fabrication error (vertical test).

The performance limitations seen in six cavities were due to an improper welding procedure and could be eliminated in the subsequent cavity production. In three cavities a hole was burned during welding. The remaining cavities not performing to expectations showed inclusions of Tantalum grains in the Niobium. Such defects will be avoided by scanning all Nb sheets for impurities with an eddy-current method. For a detailed information on cavity treatment procedures and results see [9,21,39].

Several alternatives to the welding of dumb-bells for the production of 9-cell Niobium cavities — like hydroforming [28,32], spinning [29], or plasma spraying of copper on thin walled Nb cavities [30] — are being pursued within the collaboration. If successful, these methods may eventually lead to a further cost reduction in the cavity fabrication.

All components for beam acceleration through the first cryomodule were installed in May 97. As the 14 MeV injector was already in operation at design values [22], stable beam acceleration in the first module could be established within a few days. Although the module contained 5 out of 8 cavities with fabrication errors, acceleration gradients of 16.7 MeV/m were obtained in a RF pulse of 100 μsec. For more details see [21].

Since September 1998 a second accelerating module has been installed into the linac together with a new RF photoinjector [23,24] and a magnet system to compress the bunch length by a factor of four. Mid December 1998 a train of 30 bunches from the RF photoinjector with 8 nC per bunch was accelerated to 15.5 MeV through the first section of the injector. A two months period of machine studies beginning January 99 is dedicated to prepare the beam parameters and the diagnostics for a proof of principle experiment of the SASE FEL in summer 99. Starting in March 1999 a third module and the undulator for the FEL operation will be installed.

A very important new development was initiated by the proposal of a cavity "superstructure" [31]. In this scheme the spacing between adjacent cavities is reduced from 1.5 to 0.5 RF wavelengths and a group of 4 or more of these closely spaced cavities is supplied with RF power by only one input coupler. In this way the filling factor — the ratio of active to total length — increases from 66 % to 76 % or more, thus reducing the required gradient for 500 GeV cm operation from 25 to 21.7 MV/m for fixed linac length. The cost reductions due to the smaller number of RF input couplers and cryostat penetrations, and the simplification of the RF distribution system are obvious.

4. TESLA parameters

In the Conceptual Design Report the machine parameters were chosen such that luminosity and beam-strahlung energy loss were comparable to other linear collider designs [33]. The potential of the superconducting linac to accelerate a very small emittance beam with small emittance dilution was not exploited intentionally, keeping requirements on the alignment and stability of the linac and final focus components quite relaxed. Since the completion of the CDR, however, this strength of the TESLA concept has been investigated to some extent [34] leading to a new parameter set [35] suited for high luminosity operation at 500 GeV cm energy (see Table I). The benefits of the new "superstructure" concept have been incorporated into the design.

The reduction of the required gradient (25 $\rightarrow$ 21.7 MV/m) leads to an increase of the quality factor from 5×10^9 to 10^{10}. Both effects lower the required power for the cryogenics. This power savings has been invested in

TABLE I

Updated parameters at $E_{\rm cm} = 500$GeV in comparison with the original reference parameters.

	TESLA (ref.)	TESLA (new)
site length [km]	32.6	32.6
active length [km]	20	23
acc. Gradient [MV/m]	25	21.7
quality factor $Q_0[10^{10}]$	0.5	1
$t_{\rm pulse}$ [μs]	800	950
# bunches n_b/pulse	1130	2820
bunch spacing Δt_b [ns]	708	337
rep. rate $f_{\rm rep}$ [Hz]	5	5
N_e/bunch $[10^{10}]$	3.6	2
$\varepsilon_x/\varepsilon_y$ (@ IP) $[10^{-6}$m]	14/0.25	10/0.03
beta at IP $\beta^*_{x/y}$ [mm]	25/0.7	15/0.4
spot size σ^*_x/σ^*_y [nm]	845/19	553/5
bunch length σ_z [mm]	0.7	0.4
beamstrahlung δ_B [%]	2.5	2.8
Disruption D_y	17	33
$P_{\rm AC}$ (2 linacs) [MW]	95	95
efficiency $\eta_{\rm AC\to b}$ [%]	17	23
luminosity $[10^{34}{\rm cm}^{-2}{\rm s}^{-1}]$	0.68	3

the beam power. The resulting lower loaded Q-value corresponds to a shorter filling time of the cavities, which in turn results in an increased conversion efficiency from mains to beam power ($17 \to 23$ %).

With the new "superstructure" concept the gradient needed for 800 GeV cm energy is 34 MV/m. From the results on cavity R& D (section 3) the optimism, that average gradients well above 30 MV/m at Q values of 5×10^9 can be reached within the near future, is well justified. The theoretical maximum gradient for our structures limited by the critical magnetic field is at about 55 MV/m.

All subsystems of the collider have been laid out for 800 GeV operation. The number of klystrons and modulators will be doubled. With the present layout of the cryogenics the repetition rate of the collider will have to be reduced from 5 to 3 Hz to maintain the level of available cooling capacity. By further reducing the normalised vertical emittance by a factor 3 to 10^{-8} m , a luminosity of 5×10^{34} cm^{-2} sec^{-1} can be obtained [35], the beamstrahlung energy loss staying below 5 %. The mains power requirement will go up to 130 MW. An upgrade of the cryogenic cooling capacity will allow luminosities close to 10^{35}cm^{-2}sec^{-1} to be reached by running the collider at a repetition rate of 5 Hz.

5. Layout of the collider facility

There has been consensus within the collaboration that the linear collider facility must be built at an existing high energy physics laboratory to make use of the existing infrastructure and staff. In the CDR two possible sites have been envisaged, one being DESY, the other Fermilab. Both sites allow for a future option to collide 500 GeV e^-/e^+ with high energy protons circulating in HERA or the Tevatron.

This option fixes the possible direction of the linear collider. At DESY the tunnel is foreseen with the main linac axis being tangential to the West straight section of HERA, extending about 32 km into the state of Schleswig-Holstein. The countryside is flat at about 10 m above sea level with maximum height variations of some 10 m. The tunnel axis is foreseen at 8 m below sea level, giving more than sufficient soil coverage for radiation protection. The soil, consisting mainly of sand, allows for easy tunneling by the hydroshield method, which was also used at HERA. The tunnel follows the earth's curvature over most of its length, except for a section of about 5 km length to direct the tunnel axis tangentially to HERA.

A view into the planned tunnel (diameter 5.2 m) is shown in Fig. 3 at a section which contains the straight sections of the "dogbone" damping ring (upper left side) and several beam lines (right below the cryomodule) to the FEL facility. At the top of the tunnel there is a monorail for the transportation of equipment and personnel.

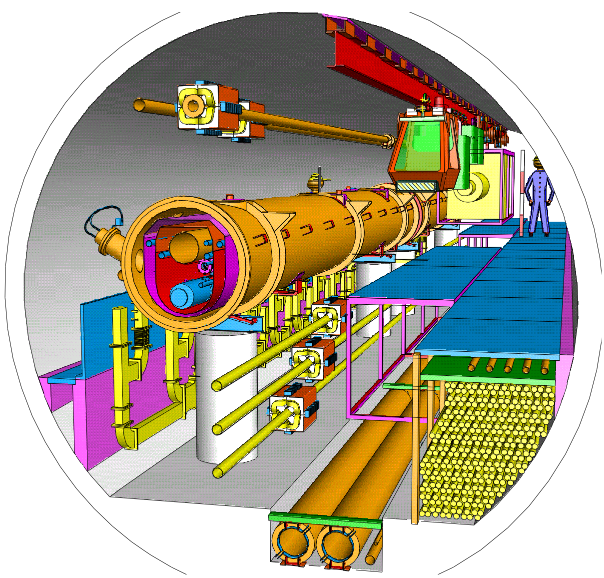

Fig. 3. View into the TESLA tunnel

Klystrons and their pulse transformers are installed horizontally below the floor in the middle of the tunnel above the cooling water tubes. There is a total of about 620 10 MW klystrons including about 2.5 % spare. Each klystron feeds 32 9-cell cavities corresponding to a length of about 48 m. With a lifetime of 40,000 hours about 10 klystrons will have to be replaced in a one day interruption once per month.

The experience of the SLC [36] on the failure rate of modulators does not permit an installation into the tunnel, inaccessible during machine operation. Therefore in the present layout the modulators are housed in service halls above ground connected to the pulse transformers in the tunnel by long cables (Fig. 3, lower right). However, the design of modulators reliable enough to be installed into the tunnel is being investigated.

Service halls, spaced along the collider at a distance of about 5 km are needed for the cryogenic plants [37] in any case. The length of superconducting linac that can be cooled by a cryoplant is about 2.5 km. This distance is mainly determined by the pressure drop in the large return tube (300 mm diameter) for low pressure Helium gas at about 2 K. The pressure in the tube determines the vapour pressure of the superfluid helium surrounding the cavities and thus the operating temperature of the cavities.

Each service hall houses two cryoplants each supplying a 2.5 km section of the linac. In case of a failure of one plant, the other one can supply two sectors operating the collider at a reduced repetition rate. The big cryogenic boxes are planned to be installed in the 14 m diameter shaft connecting the service hall with the tunnel (see Fig. 4).

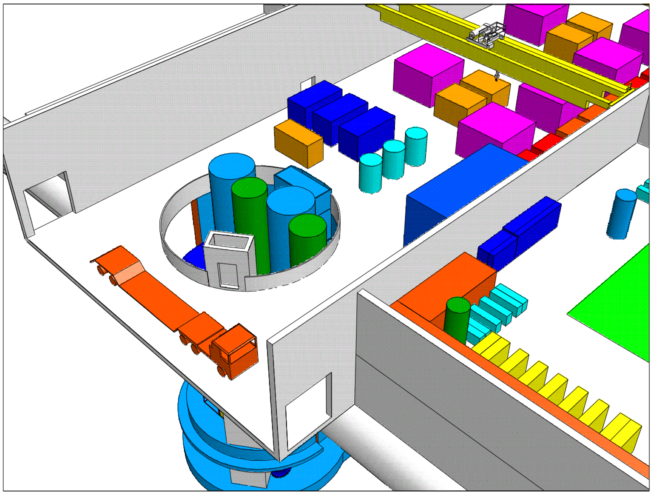

Fig. 4. Service hall with shaft connection to the tunnel

Due to the large spacing between consecutive bunches, there is no crossing angle required at the IP. The beams are deflected by electrostatic separators, having passed the interaction region and the large aperture, superconducting quadrupole doublet. A tunnel length of about 1.2 km between the IP and the ends of either superconducting linac is needed for the beam delivery system [15] containing beam collimation systems, beam diagnostics and orbit correction elements, and the final focus system, demagnifying the beam size and correcting chromatic effects [27]. These tunnel sections also house the beam dumps and the positron source.

To allow for a second interaction region for e^+e^-, ee or $\gamma\gamma$ interactions two additional tunnels are needed separating from the main linac tunnels at an angle of 15 mrad about 1.5 km away from the interaction point.

As the amount of positrons needed for a beam pulse exceeds the potential of conventional positron sources, the electron beam having passed the interaction region is used to produce the required number of positrons. In this scheme, proposed in the original VLEPP design [38], the spent electron beam is collimated and passed through a wiggler producing large quantities of γ-rays, which convert in a thin rotating target into e^+e^- pairs. The fraction of positrons which can be captured by the source optics, accelerated to 3 GeV and stored in the dogbone damping ring yields a sufficient number of particles for the operation of the linear collider.

On the basis of the existing know how, orders to industry are being issued to evaluate the requirements of large scale industrial cavity production. Together with a detailed layout of all subsystems of the collider the information from the industrial studies will allow for a technical design report of the facility, containing a reliable schedule and cost evaluation, in about two years from now.

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