STATUS OF THE TESLA DESIGN

D. Trines for the TESLA Collaboration *
Deutsches Elektronen-Synchrotron DESY, 22603 Hamburg, Germany

Abstract

The status of the layout of the linear collider project, TESLA, which employs superconducting accelerating structures, will be presented. Latest results from the R&D program on 1.3 GHz superconducting cavities, the accelerating gradients and quality factors which were achieved will be shown as well as the performance of the TESLA Test Facility linear accelerator.

1 INTRODUCTION

Since the first proposal for a superconducting linear e^+e^- collider by M. Tigner [1] in 1965, accelerator builders [2,3,4] 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 despite ground motion effects.

The shunt impedance per unit length for superconducting cavities depends on RF frequency ω as

$$r_s \sim \frac{\omega}{A\omega^2 + R_{res}} \tag{1}$$

favouring RF frequencies in the range of 0.5 to 3 GHz. 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 luminosity of a linear collider is given by [5,6]

$$L \approx const.\frac{\sqrt{\delta_B}}{E_{CM}} \cdot \frac{\eta}{\sqrt{\varepsilon_{yN}}} \cdot P_{AC} \cdot H_D \tag{2}$$

where δ_B is the relative energy loss caused by beamstrahlung, 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, ε_{yN} is the normalised vertical emittance at the IP and H_D is the disruption factor. Thus, the figure of merit [7] for the luminosity performance of a linear collider is given by $\eta/\sqrt{\varepsilon_{yN}}$. Therefore 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 [12,13,14], 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 $3 \cdot 10^9$ in a first step and finally reach 25 MV/m at a Q value of $5 \cdot 10^9$ 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. A detailed description of the infrastructure, which was completed by the end of 1995, will be given in [9].

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

* TESLA Collaboration: **Armenia:** Yerevan Physics Institute, **P.R. China:** IHEP Academia Sinica, Tsinghua Univ., **Finland:** Inst. of Physics Helsinki, **France:** CEA/DSM Saclay, IN2P3 Orsay, **Germany:** Max-Born-Inst. Berlin, DESY Hamburg and Zeuthen, GH Wuppertal, Univ. Hamburg, IAP Univ. Frankfurt, GKSS Geesthacht, FZ Karlsruhe, IfH TU Darmstadt, ITE TU Berlin, IKK TU Dresden, RWTH Aachen, Univ. Rostock, **Italy:** INFN Frascati, Legnaro, Milano, Univ. Roma II, **Poland:** Polish Acad. of Sciences, Univ. Warsaw, INP Krakow, Univ. of Mining & Metallurgy, Polish Atomic Energy Agency, Soltan Inst. for Nuclear Studies, **Russia:** JINR Dubna, IHEP Protvino, INP Novosibirsk, **USA:** Argonne National Lab., Cornell Univ., Fermilab, UCLA

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 $Q=5\cdot10^9$ and a luminosity of some $5\cdot10^{33}$ cm^{-2} 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. A detailed report on the status of the X-ray facility will be given at this conference [20].

3 R&D RESULTS AND ACTIVITIES

Up to now 25 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 $Q=3\cdot10^9$. Fig. 1 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 the most recent measurement in the horizontal test [25] a gradient of 33 MV/m at $Q=4\cdot10^9$ has been achieved.

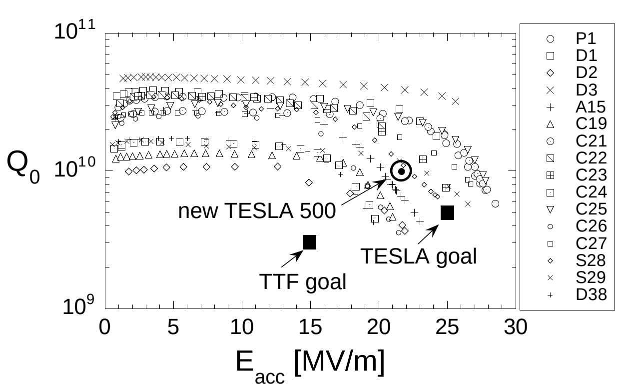

Figure 1: Quality factor Q versus acc. gradient for all 9-cell cavities without fabrication error (vertical test).

The performance limitations seen in six cavities were due to an improper welding procedure and could be eliminated in the subsequent cavity production. 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].

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 [21,27].

The measurement of cryogenic properties of the module such as cryogenic loads, behaviour of cavity positions during thermal cycles and vibrations stayed well within the expected limits [23]. Detailed reports on the low level RF control, achieving a very impressive stability of phase and amplitude of the accelerating fields, will be given at this conference [24].

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.

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 beamstrahlung 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 1). The benefits of the new "superstructure" concept have been incorporated into the design.

Table 1: Updated parameters at E_{cm}=500GeV 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_{pulse} [µs]	800	950
# bunches n_b/pulse	1130	2820
bunch spacing Δt_b [ns]	708	337
rep. rate f_{rep} [Hz]	5	5
N_e/bunch [10^{10}]	3.6	2
ε_x / ε_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_{AC} (2 linacs) [MW]	95	95
efficiency $\eta_{AC\rightarrow b}$ [%]	17	23
luminosity [10^{34} cm^{-2}s^{-1}]	0.68	3

The reduction of the required gradient (25→21.7 MV/m) leads to an increase of the quality factor from $5\cdot10^9$ to 10^{10}. Both effects lower the required power for the cryogenics. This power savings has been invested in 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→23 %).

Although the vertical emittance has gone down by almost an order of magnitude as compared to the CDR, tracking simulations [36] show that the emittance only grows by 23 % and 17 % due to single bunch and multi bunch effects respectively. However, most of the growth due to multibunch effects is not an incoherent spot size dilution but a systematic variation of the beam center along the bunch train at the IP. In combination with the larger disruption parameter - as compared to the CDR - these offsets may drive the opposing beams apart and critically reduce the luminosity. Fortunately, being mostly systematic, the offsets can be strongly reduced by the fast bunch to bunch orbit feedback. Further investigations of this topic will be needed, however.

As is to be expected the smaller spot sizes of the colliding beams put stronger requirements on the accuracy of the fast orbit feedback at the IP [37]. To keep the luminosity loss below 7 % the relative offset of the opposing beams at the IP has to be kept below 0.1 σ_y [38]. This requires a bpm resolution at the final focussing quadrupoles of 2 µm, which should be feasible.

As, for a given beam energy and beam power, the disruption parameter D_y is proportional to the product of luminosity and bunch length [35], the increase of D_y at a higher luminosity can be compensated by shortening the bunchlength. This handle has been applied only moderately up to now in the new design due to problems in the damping rings.

The TESLA damping rings are quite unconventional machines. At a beam energy of only 3.2 GeV they have a circumference of 17 km, of which 95 % are straight sections, located inside the TESLA tunnel (see Figure 2). Only two short return bends on either side with extra tunnels are needed ("dogbone"), thus saving substantially on civil engineering costs. However, the large circumference C and the low energy lead to an unfavourable enhancement factor of the incoherent space charge tune shift:

$$\Delta Q \sim \frac{C}{E^2} \cdot \frac{N_e}{\sigma_z \sqrt{\varepsilon_x \varepsilon_y}} \tag{3}$$

Already for the CDR parameters the vertical tune shift amounted to -0.18. Further reductions of bunchlength and emittances therefore would lead to uncomfortably large tune shifts. The proposed cure for this problem [39] is to increase the beam size in the long straight sections by coupling the longitudinal or horizontal emittance to the vertical plane. First calculations [40] show that the space charge tune shift can be very effectively reduced in this way without trading in problems due to intra-beam scattering.

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. 2 at a section which contains the straight sections of the "dogbone" damping ring (upper left side) and several beam lines (right below the cyromodule) to the FEL facility. At the top of the tunnel there is a monorail for the transportation of equipment and personnel.

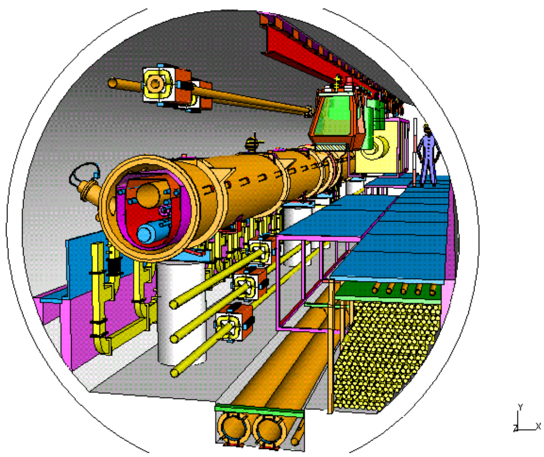

Figure 2: View into the TESLA Tunnel.

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 625 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 [41] 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. 2, 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 [42] 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 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. 3).

Due to the large spacing between consecutive bunches, there is no crossing angle required at the IP and consequently no angle between the tunnel axis of the two linacs. 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. These tunnel sections also house the beam dumps and the positron source.

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 [43], 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. With the new design parameters the fraction of the spent electron beam usable for positron production actually increases from 86 % to 93 % due to the smaller beam emittance, thus substantially reducing the power load on the collimators [44]. Although a detailed technical layout of the positron source is still missing, first investigations indicate that the whole system can well be accommodated into the tunnel.

6 ENERGY UPGRADE POTENTIAL

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 $5 \cdot 10^9$ 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 $5 \cdot 10^{34}$ 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.

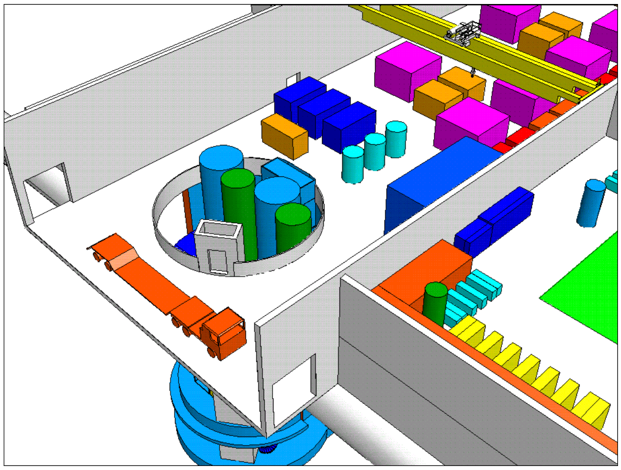

Figure 3: Service hall with shaft connection to the tunnel.

7 OUTLOOK

On the basis of the existing knowhow, 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 proposal containing technical design of the facility, and a reliable schedule and cost evaluation, to be submitted in two to three years from now. To obtain public acceptance the states, the communities, and the residents involved have been informed about the planning. An administrative procedure to eventually ensure the necessary legal conditions for the construction of the facility - if approved - is underway.

8 ACKNOWLEDGMENTS

I would like to express my respect to the many people in and outside the collaboration who have been working on the cavity R&D over the years. This work has been certainly cumbersome at times but finally lead to the beautiful cavity results, which we have today. Many people have contributed to the present status of the TESLA design, whom I cannot give proper credit to. But I would like to give special credit to the late G. Horlitz for designing the complete cryogenics system of TESLA.

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