

TESLA Technical Design Report

PART I
Executive Summary

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Dedicated to the memory of Bjørn H. Wiik (1937-1999)

TESLA – A Summary

This report describes the scientific aims and potential as well as the technical design of TESLA (TeV–Energy Superconducting Linear Accelerator), a superconducting electron–positron collider of initially 500 GeV total energy, extendable to 800 GeV, and an integrated X–ray laser laboratory. A large–scale interdisciplinary and international research campus will be created around TESLA to provide unique research possibilities for particle physics, for condensed matter physics, chemistry and material science, and for structural biology. In this way TESLA satisfies the criteria for new large endeavours in science: they should be unique, open completely new research possibilities and should carry the promise to advance our knowledge of nature in many branches of science.

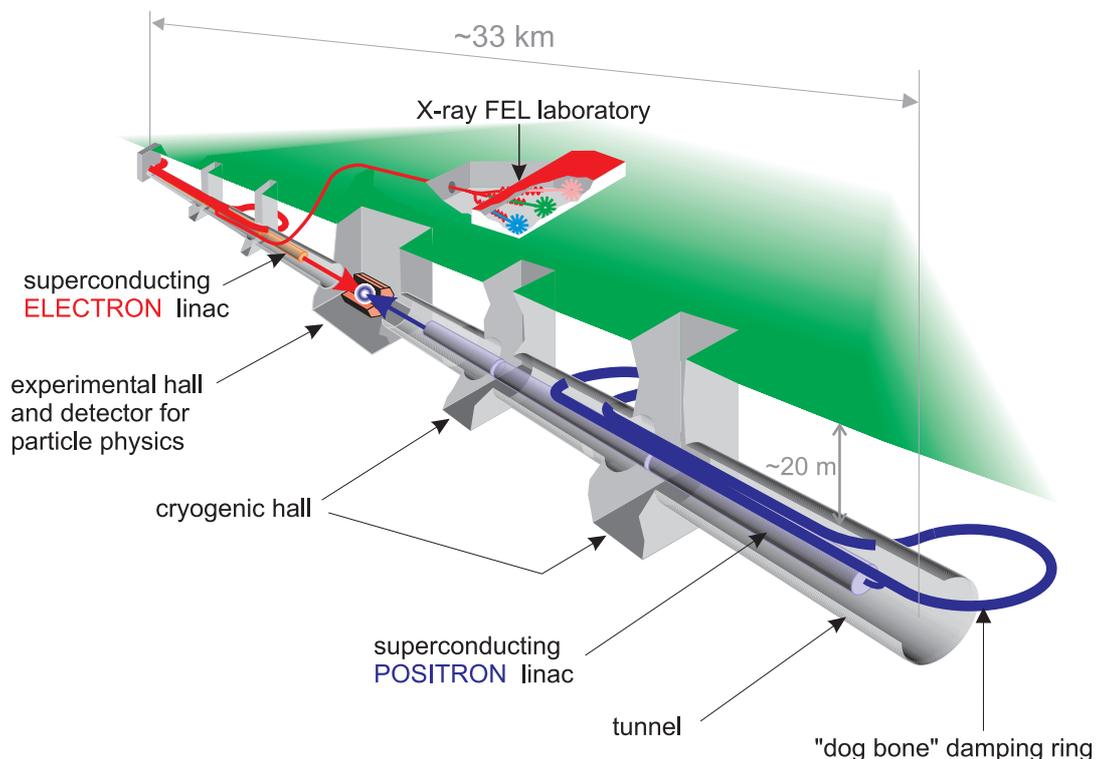


Figure 1: *An artist's view of the TESLA electron–positron linear collider with integrated X-ray laser laboratory.*

Revealing the Innermost Secrets of the Universe

Elementary particle physics has the ambitious goal to explain the innermost building blocks of matter and the fundamental forces acting between them. Symmetry principles determine the ordering of the building blocks and the nature of their interactions. The masses of particles and the exact strength of the forces played a key role in the evolution of the universe from the Big Bang to its present appearance in terms of galaxies, stars, black holes, chemical elements and biological systems. Discoveries in particle physics thus go to the very core of our existence.

Particle physics has made enormous progress in the past thirty years by pushing back the frontiers of accelerators, experiments and theory. Today we know that matter is composed of few fundamental building blocks, called quarks and leptons. A concise theoretical framework for the forces between these constituents has been developed which is based on the theoretical principle of gauge invariance. By applying this principle it has become possible to unify the seemingly disparate electromagnetic and weak interactions into a single electroweak interaction, and to develop a quantum field theory of the strong interaction, called Quantum Chromodynamics (QCD). The forces are mediated by the photon, the W and Z bosons and the gluons, the particles or quanta of the corresponding fields.

However, such a theory of matter particles and force fields suffers from a serious deficiency. The underlying gauge principle requires at first sight all field quanta to be mass-less. This is in striking contrast to the large masses of the W and Z bosons, which are 80–90 times heavier than the proton. At present the only compelling way to give the particles a mass while preserving the gauge principle is the so-called Higgs mechanism. The basic idea is that the a priori mass-less particles acquire “effective masses” by interaction with a background medium, the Higgs field. The idea of mass generation by the Higgs mechanism leads to a Higgs field which spreads out in all space. An analogous mechanism is in fact responsible for the attenuation of a magnetic field inside a superconductor. Associated with the Higgs field is a new observable particle, the Higgs particle, whose analogue in superconductivity is the Cooper pair.

The matter particles, the force fields of the electroweak theory and QCD, and the Higgs mechanism are the basis of the so-called “Standard Model” of particle physics, an extremely successful theory which has been tested and validated with high precision in a broad range of experiments. Only the Higgs particle has so far escaped observation.

Therefore, one of the most pressing challenges of particle physics is to establish the Higgs mechanism, to find the Higgs particle and to study its properties, or to find an alternative explanation of the masses of particles. With the help of the Heisenberg uncertainty principle of quantum mechanics one can get a first glimpse of the Higgs particle, even if it is too heavy to be produced directly. This principle allows a heavy particle to appear as a “virtual” particle for a tiny fraction of time and thereby to influence the measurements. Precision measurements made at electron–positron colliders

have confirmed this effect with two very important and striking results: First, the mass of the top quark has been determined in experiments at colliders which did not have enough energy to produce it directly, before it was observed in proton–antiproton collisions at that mass. This was convincing proof that the Standard Model is correct even at the level of effects produced by virtual particles, i.e., at the quantum level. Second, the upper limit for the mass of the Higgs particle has been determined to be less than 200 GeV in the Standard Model. Recently, events observed at the highest energy of the Large Electron Positron Collider (LEP) at CERN in Geneva have given a tantalising hint that the Higgs particle might indeed have a mass around 115 GeV. In order to produce the Higgs particle directly and in particular, to study its properties precisely, we require more energy, i.e. accelerators of higher energy than those available today. The Higgs particle is expected to play a central role in the experimental program at TESLA.

Discovering the Higgs particle and establishing the Higgs mechanism would not, however, close the book of particle physics because the Standard Model is based on too many assumptions and leaves too many facts unexplained. General arguments clearly point to the existence of an even more fundamental theory. Supersymmetry is the favoured idea underlying such an extension of the Standard Model. It leads to a consistent and calculable theory in which the Higgs mechanism can be accommodated in a natural way. Most importantly, supersymmetry provides a framework for the unification of the electromagnetic, weak and strong forces at large energies. It is deeply related to gravity, the fourth of the fundamental forces. Supersymmetry predicts several Higgs particles. The lightest Higgs particle should have a mass below 200 GeV, or even below 135 GeV in some specific models. In supersymmetric theories for every fundamental particle we know today another related and as yet undiscovered particle should exist. The lightest supersymmetric particle most likely is stable. Many of these supersymmetric particles may have masses such that they can be produced and studied in detail at TESLA.

A particularly tantalising challenge of fundamental physics is posed by gravity, the interaction responsible for the large–scale structure of the universe. Gravity can not be incorporated in the Standard Model because gravity can not be formulated consistently as a quantum field theory. Great efforts are devoted to formulating a theory in which gravity is unified with the weak, electromagnetic and strong forces. A goal of such a fundamental theory will be to predict the masses and properties of all particles based on a few fundamental principles. It will synthesise quantum physics and the theory of relativity, thus unifying the physical laws of the microcosm and the macrocosm. Recent theories, known as super–string theories, suggest that at very high energies, as they existed shortly after the Big Bang, all four forces between particles are united into a single force. The discovery of supersymmetry and the precision measurements of the properties of supersymmetric particles could provide a glimpse of the underlying fundamental theory.

Probing matter at its smallest dimensions thus leads us to a better understanding

of the laws governing the cosmos. The theories of particle physics describe matter also under extreme conditions, as realised during the earliest moments of the universe, when everything was very hot and dense. Collisions of particles in accelerators allow us to recreate in the laboratory what happened immediately after the Big Bang, 15 billion years ago, when matter in the form of quarks and leptons was created from energy. Nature has passed through this stage on the way to its current state. If we succeed in determining these laws of nature we will get clearer insights into the current state of development of the universe.

Astronomical evidence strongly suggests that more than 90% of the mass in the universe is invisible and of a nature totally different from the matter from which stars, planets and humans are made of. The nature of this so-called dark matter is completely unknown. Supersymmetric particles might be the explanation. In future large accelerators we expect to find such particles, if supersymmetry is indeed realised in nature. Thus, in developing more powerful accelerators, better experiments and theories, particle physicists contribute, together with astronomers and astrophysicists, to the understanding of the origin, evolution and destiny of the universe and the nature of space and time.

The large accelerators in operation today are the electron–proton collider HERA at DESY and the proton–antiproton collider Tevatron at Fermilab near Chicago. The next milestone on the road of particle physics is set by the large proton–proton collider (LHC), which is being built at CERN and which is scheduled to be completed in 2006. Many new discoveries are expected to come from the experiments there.

However, our previous experience clearly shows that a proton collider alone is not sufficient to adequately explore the subatomic world. It must be complemented with a high energy collider for electrons and positrons. A telling example from the past is the heavy Z boson, which was discovered at a proton–antiproton collider, while its detailed properties have only been measured with high precision at electron–positron colliders. These measurements were crucial for establishing the Standard Model. In particular, they allowed an indirect determination of the mass of the top quark and are responsible for our present constraint on the Higgs mass. Another illustrative example is the discovery of the carrier of the strong force, the gluon, which was not seen at a proton collider, where the strong force dominates, but was discovered at the electron–positron collider PETRA at DESY.

The complementarity of proton and lepton colliders is due to the different nature and properties of the particles which collide in the two types of accelerator. Electrons and positrons have no internal structure. Being fundamental particles they carry the full beam energy and interact through weak and electromagnetic forces, which can be calculated precisely. The conditions under which the collision takes place are defined very well, so that we can predict precisely what to expect after the collision. One can therefore determine the properties of new particles, such as mass, lifetime, spin and quantum numbers, unambiguously and with high precision. On the other hand, it

is easier to accelerate protons to very high energies than it is to accelerate electrons. Protons are, however, complicated objects, composed of quarks, antiquarks and gluons. The detailed collision process can not be well controlled or selected, the effective energy of the colliding fundamental particles is usually well below the total energy of the two protons, and the rate of unwanted collision processes is very high. For these reasons TESLA complements the LHC and will provide important new insights.

While most of the particle physics program will be using TESLA as an electron–positron collider, TESLA can also be operated to generate photon–photon, photon–electron and electron–electron collisions which would provide important additional insight. The electron beam of TESLA could also be used for other studies in particle and nuclear physics, such as the analysis of the inner structure of the nucleon and the properties of the strong force.

The electron–positron linear collider TESLA, in its baseline design, reaches a centre–of–mass energy of 500 GeV, five times higher than the first linear collider SLC at Stanford and 2.5 times higher than LEP at CERN. At the same time the luminosity of TESLA, a measure for the event rate which a collider can deliver, is about 1000 times higher than that of LEP at 200 GeV. Both, energy and luminosity are prerequisites for new discoveries. In a second phase, the energy range of TESLA can be extended to about 800 GeV without increasing the length of the machine. Parts III, IV and VI of this Technical Design Report present the detailed studies of the scientific case which have been performed and which illustrate that TESLA will be a very powerful instrument to substantially deepen our understanding of the microcosm and the universe.

The energy range and luminosity of TESLA will make possible precise measurements of masses, lifetimes, and interactions of particles. These measurements will be needed to understand the mechanism responsible for the generation of mass. If the world is supersymmetric, with matter and forces united in one theory, TESLA will be uniquely positioned to explore these new particles. The great experimental precision characteristic for electron–positron colliders can be exploited to probe for physics in an energy range well beyond the reach of the collider. The substantial understanding gained during the studies of the physics potential of linear colliders provides us with a firm prediction: With TESLA we expect unique and crucial new insights into the laws of particle physics. As the technology to build TESLA is available today it is now the time to start its construction.

New Insights into the Facets of Nature and Life

When the structural and electronic properties of matter are to be studied on an atomic scale – particularly when looking at atoms in molecules, in large biomolecular complexes and in condensed matter – then X–rays play a crucial role. Their wavelength

is of the same order as the inter-atomic distances, which makes them the ideal probe for determining the structure on the atomic and molecular scale. Furthermore, the penetration power of X-rays allows determination of the true bulk behavior of matter. As a result X-rays became one of the most important tools in basic science and medical diagnostics, as well as in industrial research and development.

Over the last thirty years tremendous progress has been made in X-ray science and its applications, largely stimulated by the availability of synchrotron radiation from storage ring facilities. Fig. 2 shows the gain in average and peak brilliance of the X-ray sources over the last 100 years. So far, the dream of an X-ray laser in the one Ångström (0.1 nanometer) wavelength range has not yet become a reality. It is the free-electron laser (FEL), which finally will provide lateral fully coherent polarised X-rays with peak brilliances that are more than a 100 million times higher than what is available today from the best synchrotron radiation sources. In addition, the X-rays will be delivered in flashes with a duration of 100 femtoseconds or less, allowing the observation of the fastest chemical processes. The availability of lateral fully coherent, that is fully parallel, X-ray beams will also stimulate the development of novel diffraction and imaging schemes.

The generation of radiation in an FEL has much in common with the generation of radiation in a conventional optical laser, the main difference being the gain medium. In a conventional laser the gain comes from stimulated emission from electrons bound to atoms, either in a crystal, liquid dye or a gas, whereas the amplification medium of the FEL is “free” (unbounded) electrons in bunches accelerated to relativistic velocities with a characteristic longitudinal charge density modulation. The radiation emitted by an FEL can be tuned over a wide range of wavelengths, which is a very important advantage over conventional lasers.

The free-electron laser concept was first realised for photons in the infrared wavelength range using a small electron linac and a periodic magnet structure, called an undulator, within an optical cavity. Later, in order to reach shorter wavelengths, free-electron lasers were realised by installing such optical cavities and undulators in electron storage rings. In this way a wavelength of 190 nm has been achieved recently at the Elettra storage ring in Italy. However, because of the strongly decreasing reflectivity of the mirrors in the optical cavity one cannot expect to reach wavelengths much below 150 nm with storage ring FELs. Instead, in order to reach the one Ångström wavelength range, a free-electron laser concept without optical cavity is needed. Such a concept, the so called Self Amplified Spontaneous Emission (SASE) scheme, has been demonstrated down to wavelengths of 80 nm using electron bunches of high charge density and low emittance from the linear accelerator at the TESLA Test Facility.

Linac driven X-ray FELs will open up fundamentally new opportunities in science. In his book “From X-rays to Quarks” Emilio Segrè writes: *In the 1920’s we used to joke that good physicists, once passed to their heavenly rewards, would find apparatus in paradise which, with a twist of some knobs, would give electromagnetic radiation of*

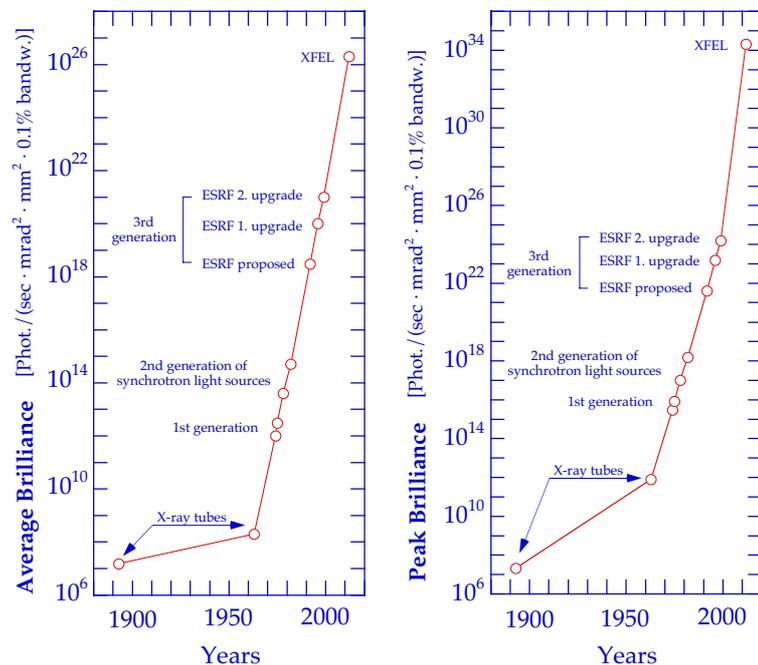


Figure 2: Increase of time average and peak brilliance of X-ray sources since Röntgen's discovery in November 1895. From the very beginning DESY has been active in developing synchrotron radiation sources and, together with external users, the appropriate instrumentation. (ESRF = European Synchrotron Radiation Facility in Grenoble, XFEL = X-ray free-electron laser at TESLA).

any desired frequency, intensity, polarisation, and direction of propagation. In a way he foresaw synchrotron radiation with its enormous potential for studies in physics, chemistry and materials science, for environmental and geo-sciences, as well as for structural biology. With the X-ray FEL at TESLA there is an even more fascinating vision and scientists address challenging questions such as:

- Can we take pictures of single macro-molecules?
- Can we see the dynamical behaviour of the electrons as they form chemical bonds?
- Can we make a movie of a chemical reaction?
- Can we make real-time studies of the formation of condensed matter?
- Can we make a movie of fast switching in magnetic storage devices?
- Can we follow, for instance, a viral infection in a cell at high resolution?

In Part V of the Technical Design Report these questions are discussed together with a large number of further applications of the TESLA X-ray free-electron laser.

Perhaps one of the most challenging, far-reaching applications suggested for X-ray free-electron lasers is the imaging of nanometer scale bio-molecular assemblies and the determination of their structure with atomic resolution. The X-ray laser is expected to play an important role in the structural and functional analysis of large molecular complexes, which are crucial in the functioning of cells, but which are extremely difficult to crystallise and can hardly be studied with present day techniques.

Another example is condensed matter physics: The objectives of modern condensed matter research are to determine the electronic states of matter and its geometric structure on the atomic length scale, to gain insight into the formation of condensed matter (either indirectly via inelastic scattering or directly via real time observations), to study the fundamental interactions in matter as well as the relation between microscopic and macroscopic properties of materials. This field of research forms the basis of modern materials science and its engineering applications. For many questions related to the study of novel materials, traditional techniques such as neutron scattering or spectroscopy at present synchrotron light sources face their limits of applicability, especially when trying to understand ultra-fast processes on a nanometer length scale.

In short: Present day X-ray and neutron experiments probe in most cases equilibrium states of matter. The X-rays from the free-electron laser at TESLA probe the dynamic state of matter and will mainly be used to study non-equilibrium states, and very fast transitions between the different states of matter. These non-equilibrium states are of eminent importance for many processes in biology as well as for tailoring of materials properties in nano-scale devices.

Technological Breakthroughs as a Basis for New Research

Accelerators have become a key tool to study the microcosm. Their development started about eighty years ago, and has since been boosted by many new ideas and technologies which extended the attainable energy by a factor of around 10 every decade – and thus the capacity to resolve ever smaller objects and to create heavier particles. This development of accelerators has led to important applications in other fields of science including medicine. Especially electron storage rings used for the production of X-ray beams of unprecedented brilliance provide key tools for modern research. Today they may be considered the most important spin-offs of particle physics driven accelerator research.

The most powerful accelerator concept to reach high energies is that of colliders, in which particles are made to collide head-on. Among existing facilities electron-positron colliders have played a very special role. In the collision electrons and their anti-particles, the positrons, annihilate each other and the resulting energy is converted back into new particles, whose properties are measured in the detectors surrounding

the interaction point. Since electrons and positrons are elementary point-like particles, they are the precision tools of particle physics, providing accurate knowledge of the reactions under study. These features were essential for many discoveries made with electron-positron colliders, including new quarks and leptons and the particle mediating the strong interaction, the gluon, and for precision tests of the Standard Model.

Except for the Stanford Linear Collider (SLC), electron-positron colliders have so far been built as storage rings, the largest being the Large Electron Positron collider (LEP) at CERN, with a 27 km circumference and a maximum energy per beam of just over 100 GeV. This concept, however, is not suitable for reaching even higher energies, as electrons radiate electromagnetic energy when forced on a circular path. The related energy loss increases by a factor 16 when doubling the particle energy.

Therefore the only way to reach electron energies substantially above 100 GeV is by accelerating them on a straight line. This leads directly to the concept of a linear collider, first proposed by Maury Tigner in 1965. In this concept electrons and positrons are accelerated in opposite directions in two linear accelerators and made to collide in the middle of a detector. Each linear accelerator consists mainly of a large series of electromagnetic radiofrequency resonators (cavities), which efficiently generate the required electric fields to accelerate the electrons and positrons.

Over the past decades, several groups world-wide have been pursuing different linear collider design concepts. Already in 1971 a group at the Institute of Nuclear Physics in Novosibirsk started detailed design work for a linear collider of several hundred GeV, addressing many of the relevant problems. Several years later, groups at CERN, at the Stanford Linear Accelerator Center (SLAC) in California, and the Japanese National Laboratory for High Energy Physics (KEK) in Tsukuba began work on linear collider designs. The feasibility of the concept has been demonstrated by the successful operation of the Stanford Linear Collider. All these concepts were based on normal-conducting copper cavities.

A major challenge for all linear collider concepts is to obtain a large collision rate (luminosity) of electrons and positrons at the interaction point. This requires very small spot sizes of the beams at the collision point and high beam powers.

The TESLA approach differs from the other designs by the choice of superconducting accelerating structures as its basic technology. As will be shown, the TESLA linear collider based on superconducting accelerating structures is ideally suited to meet the requirements needed for a large collision rate, namely very small beam sizes and high beam power. The advantage of superconducting technology, combined with the high efficiency to convert electrical energy to beam energy, has been acknowledged from the very beginning of the research and development on linear colliders, but the technology was considered to be considerably more expensive than conventional technologies.

By a focused development program, started in 1992, the international TESLA col-

laboration in co-operation with industry succeeded in developing superconducting microwave cavity structures which are capable of generating an accelerating voltage per meter, called gradient, five times larger than before 1990. In addition a reduction of the cost per meter of accelerator by a factor of four was achieved. Together, these achievements provide the basis for a realistic superconducting linear collider with all its advantages.

A prototype superconducting linear accelerator was built as part of the TESLA Test Facility in order to gain long term operating experience. To date it has been operated successfully for more than 8600 hours.

The development of a powerful linear accelerator for particle physics has also created the ideal accelerator for a light source with completely new properties: An X-ray free-electron Laser (XFEL) producing X-rays with true laser properties, as first proposed for the Stanford Linear Accelerator. The laser light is generated when electrons travel through a special magnet structure, after having been accelerated in a linear accelerator. The TESLA linear accelerator based on superconducting cavities is ideally suited to provide electron beams of the necessary quality. Using the TESLA Test Facility accelerator laser light was generated for the very first time in the wavelength range from 180 nm to 80 nm with an X-ray free-electron Laser. This was a first proof of principle that such an X-ray laser can be built and has stimulated intense activities in the field of XFELs world-wide.

Summarising the work of the past decade the following milestones in accelerator technology and development have been reached:

- Cavities exceeding an accelerating gradient of 25 MV/m are being produced routinely by industry, thus fulfilling the needs for a 500 GeV collider.
- Using a new surface treatment, gradients of greater than 40 MV/m have been reached in single cell cavities, giving access to energies of 800 GeV.
- The superconducting linear accelerator of the TESLA Test Facility has been operated for more than 8600 hours.
- The free-electron Laser principle has been demonstrated at wavelengths of 80–180 nm.
- Other technologically challenging components needed for the accelerator, like high-power klystrons, have successfully been developed, built and operated at the TESLA Test Facility.

These successes provide the firm basis for this technical proposal.

From Vision to Reality

TESLA opens new avenues of discoveries and addresses the most important riddles, as formulated by Sir John Maddox, former editor of *Nature*: *What was the origin of the universe? What does matter consist of? How did life originate and what is its nature?*

The scientific potential of TESLA as an electron–positron collider and an X–ray laser is far reaching and justifies the construction.

The TESLA project clearly demonstrates the close interaction and inter–connection of different fields of science and technology. In order to answer major questions of particle physics it became necessary to push the technology of linear electron–positron colliders considerably further, exceeding present facilities in energy and luminosity. This development also paved the way for an X–ray free–electron laser. TESLA clearly illustrates how fields of science as far apart as particle physics and biology can be advanced by a breakthrough in accelerator development. TESLA will become the motor of an innovative research centre.

The Deutsches Elektronen–Synchrotron DESY therefore proposes to the international scientific community, to the German federal government and to the northern German state governments (“Länder”) to build TESLA in the vicinity of Hamburg.

Based on the experience gained in building the TESLA Test Facility and on industrial studies the cost of the TESLA project for the baseline design has been evaluated in detail for:

- the 500 GeV electron–positron collider: 3136 million EUR
- the accelerator components for the X–ray FEL: 241 million EUR
- the equipment cost for the undulators, beam lines and experiments, including infrastructure – 5 laser beam lines, each equipped with 3 experiments, 5 other beam lines with 1 experiment each: 290 million EUR
- one detector for particle physics: 160 million EUR to 280 million EUR, depending on the choice of technology.

The person–years required to build the accelerators amounts to 6933, and the construction time is estimated to be 8 years.

Endeavours of the size and complexity of TESLA should be realised as truly international projects. From its onset in 1992 TESLA was therefore developed by a large international collaboration. The intention is to build and operate TESLA, once it is approved, as an international project of a limited duration of initially 25 years. A possible model for the realisation of TESLA in an international co–operation, a “Global Accelerator Network”, is proposed as a basis for further discussions.

About the Authors

The TESLA project has been developed in an international collaborative effort and represents the result of eight years of work by many people.

The superconducting accelerator and X-ray free-electron laser (XFEL) have been planned and developed by the TESLA collaboration, an international collaboration of scientists, engineers and technicians from more than 40 institutes in 9 countries. The collaboration has jointly built the TESLA Test Facility TTF at the Deutsches Elektronen-Synchrotron DESY in Hamburg, including a linear accelerator, which has been operated for four years.

Scientists, engineers and technicians from the following institutes have contributed either to the accelerator research and development or to the construction and operation of TTF (listed in alphabetical order of the country):

Armenia	Yerevan Physics Institute
China	IHEP Beijing, Tsinghua University
Finland	Institute of Physics, Helsinki
France	IN2P3/IPN Orsay, IN2P3/LAL Orsay, DSM/DAPNIA Saclay
Germany	RWTH Aachen, BESSY Berlin, HMI Berlin, MBI Berlin, TU Berlin, TU Darmstadt, TU Dresden, Frankfurt University, GKSS Geesthacht, DESY Hamburg and Zeuthen, Hamburg University, FZK Karlsruhe, Rostock University, Wuppertal University
Italy	INFN Frascati, INFN Legnaro, INFN Milano, INFN Roma 2
Poland	Inst. of Nuclear Physics Cracow, Univ. of Mining & Metallurgy Cracow, Soltan Inst. for Nuclear Studies Otwock-Swierk, Polish Acad. of Science Warsaw, Polish Atomic Energy Agency Warsaw, Warsaw University
Russia	JINR Dubna, MEPHI Moscow, INP Novosibirsk, BINP Protvino, IHEP Protvino, INR Troitsk
USA	Argonne National Laboratory, FNAL Batavia, Cornell University, UCLA Los Angeles

The following institutes or organisations have contributed, together with DESY, major hardware components to the TTF project: Argonne National Laboratory (USA), DSM/DAPNIA (France), FNAL (USA), INFN (Italy), and IN2P3 (France). The development of the technology of superconducting cavities was done in close collaboration with CERN (Switzerland), Thomas Jefferson National Accelerator Facility (USA), and KEK (Japan).

The scientific case for TESLA and the related experiments have been worked out by participants in a series of workshops on physics and detectors for particle physics and on the many facets of applications of X-ray lasers. The workshops in particle physics were organised jointly by the European Committee for Future Accelerators (ECFA) and DESY. The XFEL working group at DESY has organised 10 international workshops on the scientific potential of the X-ray FEL.

In total 1134 authors from 304 institutes in 36 countries have contributed to this Technical Design Report and its supporting studies, without necessarily implying an institutional commitment. The scientific community interested in TTF and TESLA continues to grow, as is the number of collaborating institutes and countries.

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1 Particle Physics with the Electron-Positron Linear Collider

The electron–positron collider TESLA in the baseline version reaches a centre–of–mass energy of 500 GeV, five times higher than SLC, the first linear collider built at SLAC, and 2.5 times higher than LEP. The luminosity of TESLA, a measure for the event rate a collider can deliver, is about 1000 times higher than that of LEP at 200 GeV. Both, energy and luminosity are prerequisites for new discoveries. In a second phase, by adding more cooling and radiofrequency power the energy range of TESLA can be extended to about 800 GeV without increasing the length of the machine. In addition, with some modifications, TESLA can be operated with high luminosity at lower energies, between 90 and 200 GeV centre–of–mass energy.

The substantial knowledge of particle physics accumulated during the past decades provides us with a firm prediction: We expect fundamentally new discoveries in the energy range of TESLA. In this chapter we summarise the present status of particle physics at the high energy frontier, the open questions and how our knowledge helps us define the next large step in particle physics. We discuss the importance of TESLA for particle physics and cosmology.

1.1 What do we know today?

For the last 30 years, particle physics has made dramatic progress in understanding the building blocks, the fundamental forces and the underlying symmetries of nature. These achievements were based on intensive interaction between experimental discoveries and precision measurements at accelerators and the development of a powerful theoretical concept: the electroweak theory which gives a unified description of weak and electromagnetic interactions and the theory of strong interaction, known as Quantum Chromodynamics (QCD).

The matter we are made of and which surrounds us is made of quarks and electrons. We have measured with great precision that three generations of quarks and leptons (electrons and neutrinos and their heavier partners) exist, which is of direct relevance for the Big Bang nucleosynthesis as the formation of light nuclei depends critically on the number of neutrino generations.

The forces are described by so-called gauge theories based on a fundamental symmetry principle, gauge invariance. The idea of gauge invariance was introduced in classical electrodynamics. By generalising the gauge principle it has been possible to show that the apparently very different electromagnetic and weak forces are just different manifestations of a single electroweak force which has been verified directly in electron proton scattering at HERA. This unification of the weak and electromagnetic interactions is of the same theoretical importance as was the merging of electricity and magnetism into the theory of electrodynamics. The forces are mediated by particles, the gauge bosons: photons, W^- and Z^- -bosons, and gluons.

Practically all of the many detailed and frequently very precise experimental observations are described by a beautiful and consistent theory, the *Standard Model* of weak, electromagnetic and strong interactions.

One of the most spectacular confirmations of the Standard Model was achieved when the experiments at LEP and SLC succeeded in predicting the mass of the top quark with remarkable precision although the energy of the accelerators was too low for the direct production of this heavy quark. Here use was made of a subtle quantum physical effect: the Heisenberg uncertainty relation allows the production of the top quark for a short instant of time as a so-called "virtual particle". The effect of these virtual particles was measured in the precision experiments at LEP and SLC. The prediction was verified by the subsequent observation of the top quark in proton-antiproton collisions at the Tevatron. Establishing the validity of the Standard Model at such a level of accuracy has been a major accomplishment and gives us confidence in the predictive power of the theory. The prediction demonstrated that the energy reach of an electron-positron collider can exceed substantially its total energy.

In summary, particle physics is presently in an excellent, yet curious state: on the one hand, practically all of the many detailed and precise experimental observations are perfectly accounted for by the Standard Model. On the other hand there are serious gaps in our understanding, like:

Which mechanism gives mass to the fundamental particles?

Since Newton, mass plays a central role in physics, yet the physical mechanism which generates this property of all matter has not been established so far. TESLA will allow clarification of this mechanism; in particular the generation of masses by the Higgs mechanism can be established unequivocally.

Can the four fundamental forces of nature, the electromagnetic, the weak, the strong force and gravity, be unified in a comprehensive theory?

A crucial step in finding the answer to this question can be taken by embedding the Standard Model into a supersymmetric theory in which matter and forces are united. Supersymmetric theories have predicted the unification of the electromagnetic, the weak and the strong forces at high energies in excellent agreement with precision measurements. These unified theories also explain why the electric charges of electron and

proton are identical to more than twenty digits, vital for the stability of the matter which surrounds us. But they also predict that eventually all visible matter is unstable. In the ever expanding universe it will turn after a very, very long time into photons, electrons, neutrinos and their antiparticles. Moreover, supersymmetric theories offer a rationale for the existence of gravity, in the same way as gauge theories do for electromagnetism. The high precision with which the properties of novel supersymmetric particles can be studied at TESLA, is indispensable for exploring this new particle world.

Since the Standard Model gives an accurate description of all experimental observations so far and at the same time leaves many questions unanswered, it provides a good starting point for extrapolations into areas where new physical phenomena might be expected. The fact that we can ask precise questions reflects the high level of understanding that has already been reached by particle physics.

We know that the answers lie hidden at high energies. Part of the answers will be found at existing accelerators and the large hadron collider (LHC), however, for many questions the energy and precision of the TESLA linear collider is indispensable to progress in our understanding.

The physics program for electron–positron linear colliders in the TeV range has been developed in the last decade through numerous theoretical analyses and experimentally oriented feasibility studies, many of which are presented in Part III of this Technical Design Report. In the following we summarise a few of the central questions of particle physics and demonstrate how TESLA will contribute to answer them.

1.2 The Origin of Mass

The clearest gap of all in our understanding is the present lack of any direct evidence how a fundamental symmetry as the electroweak symmetry is broken, and how the masses of quarks, leptons and the force mediating particles are generated. Without answers to this question the model is only an "effective theory" which is incomplete. There must be an underlying theory which will explain its apparently arbitrary features, including particle masses.

In a gauge–symmetric theory all fundamental particles, at first sight, should be mass–less. Why are weak interactions then mediated by the very heavy W and Z gauge bosons? At present only one compelling way is known to give the particles mass while preserving the gauge principle: the so–called Higgs mechanism. The basic idea is that the a priori mass–less particles acquire an "effective mass" by interaction with a background medium, the Higgs field. This idea leads to a definite and striking prediction: there should be a new particle, of a completely new kind, the Higgs particle.

Due to its central role the Higgs particle has been intensely searched for at LEP and

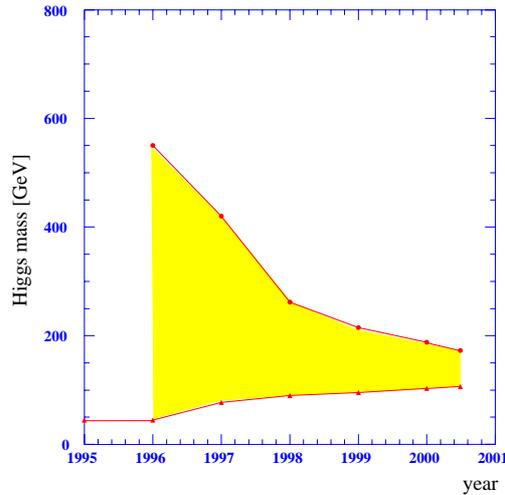


Figure 1.2.1: *The allowed mass region for the Higgs particle (the yellow region in the plot indicates the upper and lower 95% confidence limits) has shrunk considerably during recent years, due to the precision measurements at LEP, SLC and Tevatron. The analysis is done in the framework of the Standard Model.*

the Tevatron, but so far without success, though tantalising hints have been reported at LEP. From existing precision measurements and the quantum physical effects mentioned above we can infer today, within the Standard Model, that the Higgs particle should be lighter than 200 GeV (see Fig. 1.2.1).

Most probably the Higgs particle will be discovered at the Tevatron or at the LHC. The precise measurements of its properties however, indispensable for a complete understanding of the mechanism by which masses are generated, require a lepton collider. With TESLA all the properties of the Higgs particle (see Fig. 1.2.2) can be measured with high precision: the mass, the lifetime, the production cross sections, the branching ratios to quarks of different flavours, to leptons and to bosons (see Fig. 1.2.3), and the way it couples to the top quark. Moreover TESLA is unique in establishing the coupling of the Higgs particle to itself which induces the electroweak symmetry breaking. A comparison with the properties predicted by the Standard Model will establish whether or not the Higgs mechanism is responsible for electroweak symmetry breaking and test the self consistency of the picture. TESLA will achieve a precision of 50 (70) MeV on the mass of a 120 (200) GeV Higgs, and will measure many of the branching ratios to a few percent accuracy. The Higgs coupling to the top quark will be measured to 5%. The accuracy of all these measurements is vital for establishing the full understanding of the origin of mass.

The option to add a second interaction region for photon collisions will supplement the picture by precise measurements of the way the Higgs particle couples to photons, which is a process particularly sensitive to effects from new particles with masses beyond the direct reach of TESLA.

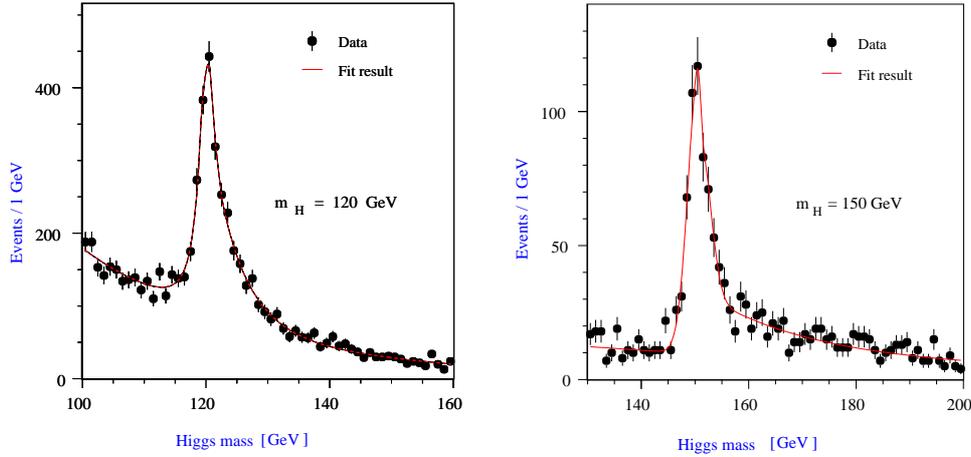


Figure 1.2.2: Signals expected for a Higgs particle for two different assumed Higgs masses. The distributions are nearly background free, illustrating the clean environment in which a Higgs particle can be reconstructed at the linear collider.

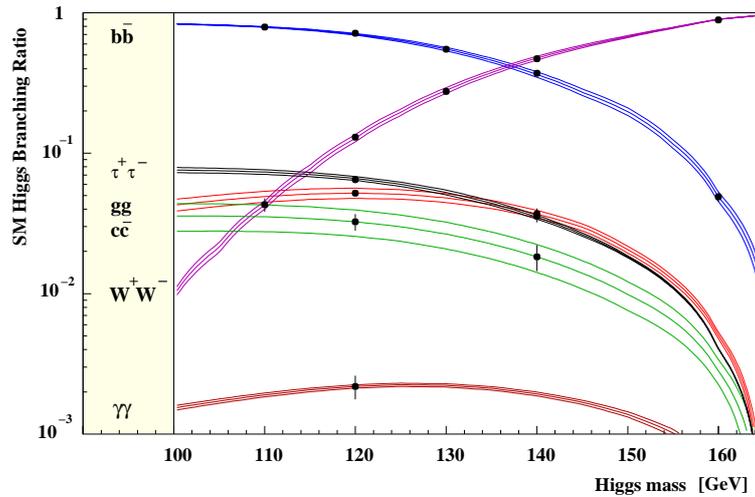


Figure 1.2.3: The predicted branching ratios of the Higgs particle in the Standard Model (SM) (i.e. the probability for the Higgs particle to decay into different particles), as a function of the mass of the Higgs particle. The points with error bars show the expected experimental accuracy which can be obtained after two years of data taking, while the lines show the theoretical values and uncertainties of the Standard Model predictions.

If the Higgs particle does have the properties as predicted by the Standard Model, the next stage of the program will be to refine even further the existing precision measurements which constrain the model at the level of effects introduced by virtual particles, i.e. at the level of quantum physical effects, by measuring the relevant parameters as precisely as possible. One parameter is the mass of the top quark which can be

measured at TESLA to an accuracy of about 100 MeV. Other important constraints will come from the value of the electroweak parameter $\sin^2 \theta_W$ and from the mass of the W boson. Both can be measured very precisely by lowering TESLA's energy into the range between 90 and 200 GeV. TESLA can deliver a hundred times more data at these energies than LEP with the corresponding increase in accuracy. Inconsistencies between the Higgs properties and the parameters derived from precision measurements of the electroweak bosons would give direct information about physics scenarios beyond the Standard Model at high energies.

1.3 Supersymmetry: The Way to Grand Unification

While theoretical arguments clearly point to the existence of a more fundamental theory which incorporates the Higgs particle, at present we cannot predict the energy needed to fully explore this underlying theory. It may reveal itself entirely or in part at the LHC and TESLA or may only appear through deviations observed between Standard Model predictions and precision measurements done at TESLA.

Supersymmetry (SUSY) is the favoured candidate for an extension of the Standard Model because it preserves the successes of the Standard Model and provides a consistent and calculable theory which can solve important theoretical issues. It eliminates the problem encountered in calculating the quantum physical corrections to the Higgs mass and gives a natural explanation of the Higgs mechanism responsible for the generation of masses.

Most importantly, SUSY provides a consistent framework for the unification of the three forces (electromagnetic, weak and strong) at very high energy. When embedded in such a grand-unified theory, the size of the electroweak parameter $\sin^2 \theta_W$ can be predicted very precisely. Its value has been confirmed experimentally at LEP at the per-mille level. Last but not least, supersymmetry is deeply related to gravity, the fourth of the fundamental forces.

SUSY predicts that each matter and force particle has a supersymmetric partner, which has the same properties except the spin. Each particle with integer spin has a partner with half-integer spin and vice versa. As we have so far not found any direct evidence for SUSY particles, their masses are expected to be very large. The lightest SUSY particle may be stable.

In contrast to the Standard Model, supersymmetric models include more than one Higgs particle. The lightest Higgs particle mass is predicted to be below 200 GeV, or even below 135 GeV in specific models. Measuring the properties of this particle will reveal its origin in a new world of matter, the supersymmetric world, and will shed light on the other heavy particles in the Higgs spectrum which may lie outside the range covered directly by TESLA (and the LHC). The experiments at the LHC can observe the lightest Higgs particle and access the spectrum of the heavy Higgs particles

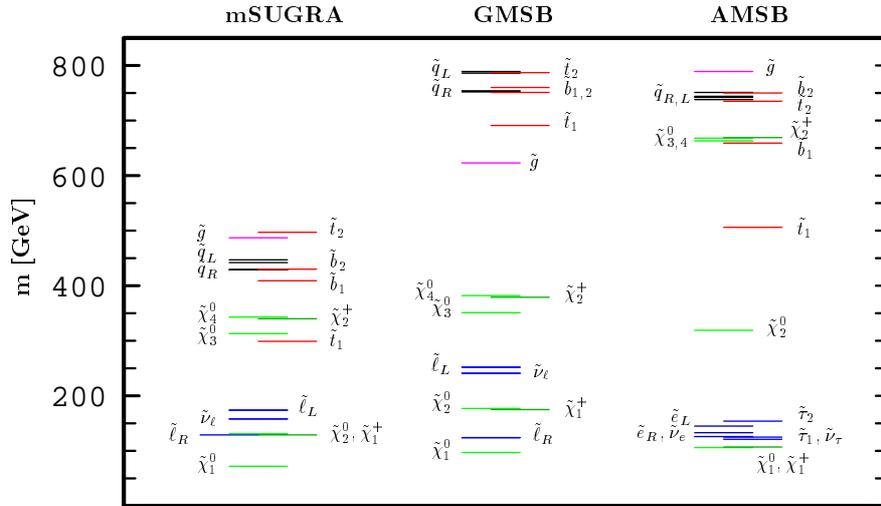


Figure 1.3.1: *Examples for the masses of supersymmetric partners of leptons, quarks, gauge and Higgs particles, in three different models. The abbreviations on top label these models (mSUGRA: minimal supergravity, GMSB: gauge mediated supersymmetry breaking, AMSB: anomaly mediated supersymmetry breaking). Each line represents one particle, with its name indicated next to it, and the vertical scale indicates the respective masses.*

in certain circumstances. With TESLA the Higgs particles can be directly observed if their masses are below its highest beam energy (400 GeV), or in photon–photon collisions even beyond this limit. Within specific supersymmetric models TESLA’s sensitivity can be extended to about 1 TeV through a precise measurement of the decay properties of the light Higgs particle.

If supersymmetry is realised in nature an explanation is needed why it is not observed at low energies. Several alternative theories have been developed which lead to a potentially rich spectrum of supersymmetric particles within the reach of TESLA. Most of the schemes predict light gauginos (these are the supersymmetric partners of the photon, the W , the Z and the Higgs particle) which TESLA should be able to measure with high precision already in its baseline configuration of 500 GeV. As in optical spectroscopy, even the observation of only parts of the spectrum will be sufficient to establish unambiguously which SUSY model is realised in nature. LHC on the other hand has an excellent potential to study the supersymmetric partners of quarks and gluons. Figure 1.3.1 shows some examples of mass spectra in three representative models. Many of the predicted masses lie in the experimentally accessible mass range.

The great variety of TESLA’s precision measurements is required to accurately determine the parameters of the supersymmetric theory. The polarisation of the electron beam, available at TESLA, is particularly important for these analyses. By varying the

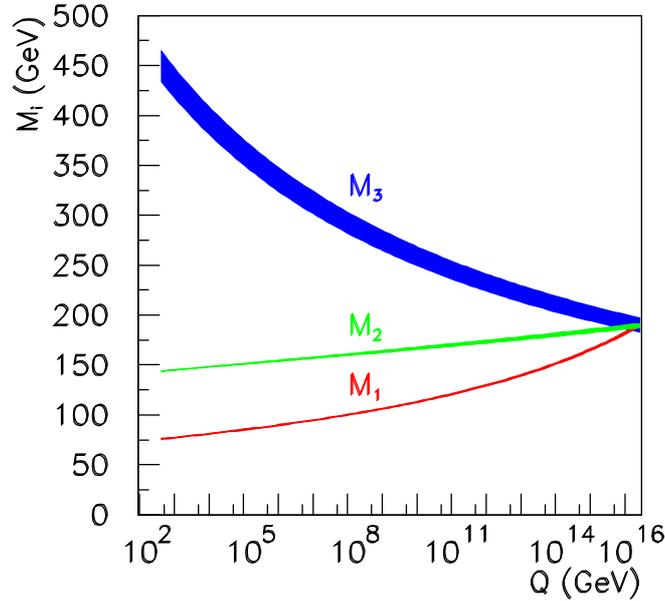


Figure 1.3.2: Evolution of the mass parameters for gauginos, the supersymmetric partners of the photon, the W , Z and Higgs particles, as a function of the energy scale Q , in a specific supersymmetric model (minimal supergravity). These mass parameters are proportional to the strength of the interaction. At the unification scale all mass parameters should have the same value. The results from the precision measurements done at TESLA energies ($Q \sim 10^3$ GeV) are extrapolated to high energies. The validity of the model can be tested by verifying whether the extrapolated mass parameters meet within errors at the unification scale.

well defined centre-of-mass energy of TESLA across the thresholds for new particle production it will be possible to identify the individual particles one by one and to measure supersymmetric particle masses with very high precision. At the LHC part of the supersymmetric particle spectrum can be resolved. Many final states however are overlapping which will complicate the reconstruction of some of the supersymmetric particles. Therefore, only the combination of the results from TESLA and the LHC will provide a complete picture.

The highest possible precision is needed to extrapolate the supersymmetric parameters measured at the energy attainable with TESLA to higher energy scales, where the mechanism of supersymmetry breaking and the structure of the grand-unified supersymmetric theory may be revealed (see Fig. 1.3.2). This is one of the most important aspects of TESLA's physics potential, and may be the best way to link particle physics with gravity through an experiment.

1.4 The Link with Cosmology

It has become increasingly clear that testing elementary particles under extreme conditions in accelerators not only reveals the basic building blocks and forces of nature, but also sheds light on how the universe developed during the earliest moments of its existence. Many aspects in the research at TESLA are therefore of great relevance for both, particle physics and cosmology. Two aspects have previously been mentioned in passing: dark matter and the unification of forces.

Understanding the unification of the weak, electromagnetic and strong forces will tell us how during the process of expansion and cooling of the universe one universal force has split into three distinct forces, each of which plays a key role in our existence.

Moreover, if the unification involved supersymmetry, as is generally expected, one of the most intriguing scientific riddles may find a natural explanation. Astronomy and astrophysics have revealed that more than 90% of all the mass in the universe must be of a kind entirely different from the quark-based matter that makes up the stars, the planets and ourselves. It neither emits nor absorbs light and therefore cannot be seen in telescopes; it has appropriately been named *dark matter*. Its presence is revealed by the gravitational attraction that it exerts on the matter of celestial bodies. It appears very curious that the dominant kind of matter in our universe is of a nature completely unknown today. Supersymmetry however accommodates such a kind of matter in a natural way: Some of the particles in the hot primordial gas of the early universe could be the lightest supersymmetric particle, which is stable in many supersymmetric models. These particles effectively de-couple from the 'normal' matter and have survived as dark matter, creating substantial gravitational effects due to their large number and mass. With an accelerator like TESLA these particles can be produced and studied if they indeed exist.

Astrophysical observations have revealed another remarkable fact: In many of its aspects the universe appears as if it originated from a Big Bang driven by an inflationary expansive behaviour of a scalar field. Until now scalar fields have never been observed however, they are purely hypothetical. It is obviously of great interest to know whether such fields can and do indeed exist in nature. The Higgs field would be a generic example of a scalar field. Hence establishing the Higgs mechanism, one of the foremost research domains of TESLA, would be of great potential relevance also for cosmology.

1.5 Alternative New Physics

In spite of the many elements supporting the above picture which incorporates a fundamental Higgs field for mass generation and which can be extrapolated to high energy scales near the Planck energy (which is of order 10^{19} GeV), there is no direct experimental proof that this is correct. In fact numerous alternative theoretical ideas have been

developed, of which two concepts and their consequences for the TESLA experiments have been analysed at some detail.

Kaluza and Klein first proposed many years ago to unify gravity and electromagnetism. In this attempt they were led to assume that nature has more than the four dimensions (three for space and one for time) we seem to live in. This concept of extra spatial dimensions, which we do not see, re-emerged in the attempt to unify gravity and the weak, electromagnetic and strong forces. So far these extra dimensions were considered within a theory of quantum gravity, called super-string theory, and were expected to be curled up into invisibility at 10^{-33} cm, a scale at which gravity becomes as strong as the other forces, but also a scale totally inaccessible to any conceivable accelerator experiment.

Very recently however it has been realised that one can consistently introduce even macroscopic extra dimensions, at the level of micrometer, without being in conflict with any direct observation. In such models a new mass scale appears which could be of order of only a few TeV. This has opened the possibility that we may be reaching a new landmark in our quest for the fundamental theory.

The question naturally arises of how to test these ideas with accelerators, with neutrino beams, with micro-gravity experiments or in cosmology. If this mass scale is indeed a few TeV, one can hope to observe various signals directly both at TESLA and at the LHC. The observations at TESLA will allow us to draw unambiguous conclusions. Thus with TESLA we can tackle fundamental problems of the structure of space and time.

Although the Higgs mechanism in the Standard Model or its supersymmetric extension remains the most compelling approach for the generation of mass, there exist alternative schemes in which the electroweak symmetry breaking is induced by new strong interactions. Composite particles built up by new quarks, in the same way as pions are made of quarks, would replace the Higgs field and play a dynamical role in generating the masses of the electroweak gauge bosons. In this approach the interaction between W bosons becomes strong at energies close to one TeV. This would lead to anomalous values of the strength of the coupling between the electroweak bosons, from which effective scales for the new strong interactions can be extracted. Precision measurements of e^+e^- annihilation into WW pairs at 500 GeV and of WW scattering with TESLA's high luminosity at 500 and 800 GeV have been shown to be sensitive to the onset of these strong interactions in a range up to ~ 3 TeV. However theoretical scenarios of this kind are difficult to reconcile with existing data and they must be given rather complex structures.

1.6 Challenging the Standard Model

The importance of the precision measurements made at LEP/SLC/HERA/Tevatron has already been mentioned repeatedly. They provide a firm foundation for our present understanding of the Standard Model. Yet within the TESLA program it would be possible to achieve even greater precision on some of the quantities measured at LEP/SLC, which will constrain the possibilities for new physics even more tightly. TESLA operating at LEP energies could deliver a hundred times more luminosity than LEP, with polarised electrons and positrons, neither of which were available at LEP.

The physics impact of running at lower energies depends strongly on the results obtained at 500 GeV. It may happen for instance that at TESLA and at the LHC only a single light Higgs particle is observed, and that no sign of any new phenomena are found. With the precise knowledge of the Higgs and top masses and their properties derived from measurements at TESLA (these masses dominate the quantum physical corrections in the Standard Model) one could then verify the consistency of the theory with high precision: Are these measurements fully consistent with each other, or do we see signs for instance from new and very heavy particles or from extra dimensions which influence the measurements in a way which can not be explained by the Standard Model? This information would allow us to look far beyond the direct energy reach of TESLA.

1.7 Colliding Light with Light or Electrons with Electrons

Although TESLA is primarily conceived as an e^+e^- collider, it can easily be transformed into an e^-e^- collider. A second interaction region, which is not part of the baseline design, can be either used to operate TESLA as an e^+e^- collider, as a $\gamma\gamma$ or as a γe^- collider. Each of these different modes opens new experimental possibilities, both for exploring the Higgs mechanism or supersymmetric theories. Further refinements of work now being done on QCD at HERA and with LEP data may be envisaged. The TESLA design allows to realise these additional options.

1.8 Other Research Options

Electrons from TESLA can also be used to explore the electromagnetic and hadronic structure of the nucleon and the photon, and the properties of the strong force. These options are called THERA, TESLA-N and ELFE.

THERA uses the polarised and/or unpolarised electrons at the full TESLA beam

energy (or even at twice, when both accelerator arms are used) and brings them into collision with the 920 GeV protons of HERA. This will be by far the most powerful electron microscope for the study of the structure of the proton and the strong force. It gives access to a new domain not yet explored by HERA and will contribute to answering the fundamental question, why quarks and gluons are not observed as free particles but confined in hadrons. It also opens a window to physics beyond the Standard Model with a particular sensitivity to exotic particles like lepton–quark and lepton–gluon bound states and excited fermions.

TESLA–N uses the interactions of the 250 - 400 GeV longitudinally polarised electrons of TESLA with a solid state target. ELFE would use 15 - 25 GeV electrons from TESLA, store them in HERA and finally extract them as a quasi–continuous beam onto a polarised target. The main goal of both experiments is the precision measurement of a number of so far completely unknown structure functions of the nucleon, which will widen our understanding of its detailed structure and provide unique precision tests of the predictive power of Quantum Chromodynamics (QCD).

1.9 Doing Experiments at TESLA

An electron–positron collision is a very well defined process. This explains the key role electron–positron colliders have played in the past for the progress of particle physics. Most of these advantages stem from the following three unique strengths:

- A well defined initial state. This means that one knows that the interaction originates from an e^+e^- annihilation at a precise energy. In the case of TESLA one can in addition define the spin alignment (the polarisation) of the initial particles, providing a powerful discrimination on electroweak interactions which depend crucially on this alignment.
- Comparable rates for standard physics and new physics. Higgs production for example has a rate comparable to other processes with the same topology.
- Very favourable environment for measurements. Backgrounds are low. Particles can be observed very close to the collision point, allowing for excellent precision on the decay points of particles with short lifetimes. The final states of most events can be completely reconstructed.

In Parts III and IV these features are explained in greater depth. The detector described in this TDR will allow almost perfect reconstruction of most topologies, even with high complexity. Specific properties of the detector are directly aimed at specific aspects of the physics. As example, the identification of the final states produced by bottom and charm quarks and by tau leptons plays an essential role in Higgs physics. Furthermore, the detector has been optimised for a precise measurement of the energy of jets of particles, which are the experimental signature of quarks.

1.10 Conclusion

The successful experiments of the past decades and intense theoretical work have led us to the firm prediction of new discoveries at the next generation of colliders, both the LHC and an electron–positron collider like TESLA. The favoured prediction is a light Higgs particle (with a mass most probably below 200 GeV), likely within a supersymmetric extension of the Standard Model. This prediction is supported by the existing precision measurements and by the requirement that all forces including even gravity should be unified. At LEP a tantalising indication of a Higgs signal has been observed which could be confirmed at the Tevatron or the LHC. It appears most probable though not guaranteed that a light Higgs particle will be found. In this case TESLA will be the ideal machine to test thoroughly all of its aspects. However regardless of the scenario nature has chosen a large variety of detailed studies confirm that TESLA will lead to new discoveries and key results in particle physics.

The detailed strategy for the experiments will depend on the interplay of the results from LHC and TESLA:

- If there is only one single light Higgs particle within the range of LHC and TESLA, its properties must be measured as precisely as possible. One must establish whether this Higgs particle comes alone, whether it is a supersymmetric Higgs particle, or whether it is the first sign of something completely new. The essential next steps then will be to accumulate data at 800 GeV and also at low energies, around 90 GeV, in order to measure all Standard Model parameters as accurately as possible, and to search for possible deviations from the expectations.
- If there is a light Higgs particle and if supersymmetric particles are found in the energy range of TESLA, then the experiments at TESLA, combined with results from the LHC, will be for supersymmetry what optical spectroscopy was for quantum mechanics: the establishment of precision data from which the underlying theory can be developed.
- If there is no light Higgs particle, then supersymmetry is not the correct theory at low energies. In this case there must be new strong interactions at a scale of a few TeV. The effects of such a theory would show up at the LHC and at TESLA. The precision measurements at TESLA would provide a clear picture of the onset of the new interactions.

Even if all these scenarios are not realised in nature, TESLA with its high resolution power can cope with the unexpected.

In a study of the scientific case for a 500 GeV electron–positron linear collider the American Linear Collider Working Group came to very similar conclusions.

The sensitivity of experiments at TESLA may be improved by operating the collider as an electron–electron, photon–photon, or electron–photon collider, providing additional valuable information, for example for the study of the Higgs particle.

All analyses require a machine delivering very high luminosity and a high quality detector. The TDR shows that this can be achieved with the TESLA collider and detector.

Lepton colliders will continue to play a key role in the progress of understanding of particle physics and nature. To explore the energy range beyond LEP the technology of linear colliders has to be pushed to new limits. TESLA with its initial energy of 500 GeV, high luminosity, the option to perform measurements of the Z boson decays of unprecedented accuracy, and its planned extension to 800 GeV is an ambitious, but technically already well founded and justified step into the future. Any further step in energy will rely on the lessons learned at LHC and at TESLA.

2 The X-Ray Free Electron Laser Laboratory

The X-ray free-electron laser laboratory proposed as part of the TESLA project is conceived as a multi-user facility following the experience of existing large synchrotron radiation facilities like the Hamburger Synchrotronstrahlungslabor HASYLAB at DESY and the European Synchrotron Radiation Facility ESRF in Grenoble.

At storage ring based synchrotron radiation sources a gain in brilliance by more than ten orders of magnitude has been achieved over the last thirty years. Each new generation of synchrotron radiation facilities opened new, often fundamentally new applications, without making the earlier applications less valuable. Therefore the user community has been growing steadily and new storage ring based facilities are under construction all over the world. World-wide the number of users of synchrotron radiation is estimated at about 20 000 scientists from many different disciplines: from physics, chemistry and materials science, to structural biology and environmental and geo-sciences. About 15 modern synchrotron radiation facilities world-wide serve large multi-disciplinary user communities. Quick and reliable access to a suitable experimental station is often decisive for the success of the individual research project. The synchrotron radiation community has therefore developed its own culture different from that in particle physics.

Modern third-generation synchrotron radiation facilities provide micro-focus beams of very high brilliance, with cross sections in the sub-micrometer range, beams of almost complete circular or linear polarisation, and beams with a significant degree of coherence. These X-ray beam properties allowed to develop novel imaging techniques of static and dynamic features of condensed matter including magnetic properties, as well as the development of instrumentation for high resolution inelastic scattering experiments to study phonon driven processes or elementary electronic excitations. In protein crystallography the structure of large macro-molecular complexes can be determined, even in cases where only very small crystals are available, and first sub-nanosecond time resolved studies have been performed. After identification of the most promising research areas the third-generation facilities put a lot of effort into improving the quality of photon beams and optics, of instrumentation in general and detectors in particular, in order to best serve the new demands of the users. Today and for many years to come, research and development activities at synchrotron radiation facilities are and will be flourishing.

The storage ring technology itself approaches its theoretical limits of performance with respect to average and peak brilliance, as well as to minimal pulse duration. Mak-

ing use of the principle of Self Amplified Spontaneous Emission (SASE) the extremely high quality electron beams of TESLA together with carefully designed magnet structures (undulators) allow the production of laser-like X-ray beams with wavelengths in the one Ångström regime. Compared to present day synchrotron radiation sources their peak brilliance is more than a 100 million times higher, the radiation has full transverse coherence and the pulse length is reduced from the 100 picosecond down to the 100 femtosecond time domain. Thus, the X-ray free-electron lasers will provide radiation of the proper wavelength and the proper time structure, so that materials and the changes of their properties can be portrayed at atomic resolution in four dimensions, not only in space but also in time.

These outstanding research opportunities offered by linear accelerator driven free-electron X-ray lasers create a deep excitement among a rapidly increasing number of scientists all around the world. Many of the early ideas developed in Italy, the USA and the former Sowjet Union have been discussed in a series of workshops in the years from 1990 to 1994 at Sag Harbor, New York, and SLAC, Stanford, USA. In February last year in a proof of principle experiment for SASE at the TESLA Test Facility in Hamburg, lasing has been demonstrated for the first time for wavelengths between 80 and 180 nm. At the LEUTL facility at the Advanced Photon Source APS in Argonne, USA, saturation of SASE has been reached for the wavelengths of 530 and 390 nm in October 2000. In the same month the scientific case for the proposed Linac Coherent Light Source (LCLS) to be built at Stanford, USA, has been presented to the Basic Energy Science Advisory Committee (BESAC) of the Department of Energy (DOE). It was favourably received and a positive decision for appropriate funding is expected, so that construction could start in fiscal year 2003. In May of this year a collaboration of KEK (Tsukuba) and SPring-8 (Himeiji) will start an ambitious R&D program for SASE free-electron X-ray lasers in Japan. Recently in Italy a research and development program for linac driven X-ray FELs of the order of 100 million EUR has been launched.

The recent successes at LEUTL and at the VUV-FEL at the Tesla Test Facility, together with several other studies which have demonstrated the validity of the SASE free-electron laser theory, give us the confidence to propose an X-ray FEL laboratory with a large number of experimental stations serving many users (Fig. 2.0.1). At present, the TESLA collaboration is in the forefront of this exciting development of X-ray free-electron lasers. It is expected that, as in the case of the third-generation X-ray synchrotron radiation facilities like the ESRF in Europe, the APS in the USA and Spring-8 in Japan, three mayor free-electron laser facilities will be needed world-wide. Therefore, decisions for a strategy towards a European multi-user FEL facility for hard X-rays are urgently needed.

World-wide, a challenging R&D program has been started in order to learn how to make optimal usage of coherent FEL X-ray beams in the one Ångström wavelength range with highest brilliance and very short pulse lengths. It is of great advantage that the FEL for vacuum ultra-violet (VUV) and soft X-ray radiation at the TESLA Test Facility at DESY-Hamburg, reaching down to a wavelength of 6 nm in its fundamental

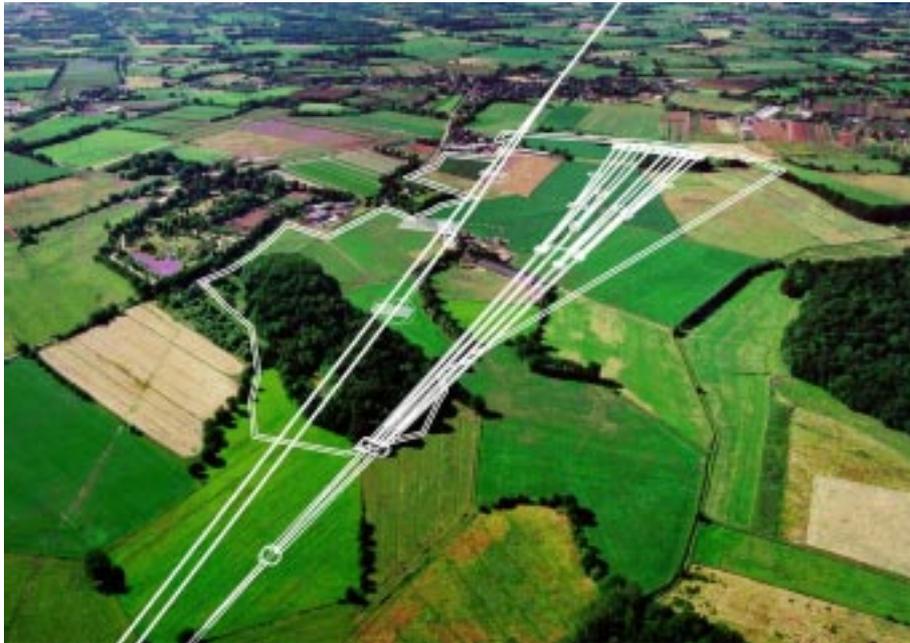


Figure 2.0.1: *Aerial view of the research campus at Ellerhoop with an outline of the hall for the particle physics experiment and the X-ray free-electron laser laboratory superimposed. Most buildings are planned to be underground.*

mode, will become available for users in 2004. In its third harmonics this FEL will reach photon energies up to 600 eV. It will permit a number of experiments of fundamental interest and will pave the way for science at one Ångström wavelengths at free-electron lasers.

In the coming years we will also see strong synergy between R&D for X-ray FELs and laboratory based laser systems. For example, novel UV laser systems have been developed for the photo cathode of the TESLA X-ray FEL and for pump and probe experiments at the VUV FEL at the TESLA Test Facility. Compared to modern storage ring based synchrotron radiation facilities the average brilliance of laboratory based lasers is still rather low and this difference is even rapidly increasing at shorter wavelengths. However, in the UV and VUV wavelength range the peak brilliance is becoming sufficient for preparing in university institutes experiments in the femtosecond time domain, which will finally be performed at appropriate wavelength and brilliance at a facility like the X-ray free-electron laser laboratory at TESLA. The interest in the science with X-ray free-electron lasers is growing rapidly in the very large laser community. This community is familiar with coherence, high power and femtosecond pulses of light at optical wavelengths. Their fascination is due to the possibility to do similar experiments at atomic resolution. In summary, the development of linear accelerator driven X-ray lasers and the preparation of their optimal use will play the role of a technology driver for various disciplines in the years to come.

The proposed X-ray free-electron laser laboratory at TESLA will consist of five FEL beam lines and five beam lines for spontaneous, ultra-short pulse undulator radiation only. All together we expect that up to thirty experimental stations can be distributed among the ten beam lines according to the needs of the user community.

As discussed in Part V of this report the TESLA X-ray laser will open up most interesting new opportunities both for basic research and applications in a wide variety of fields. In the following three examples for research with an X-FEL are sketched: First, the study of the early steps of formation and breaking of chemical bonds. Second, the creation and analysis of new extreme states of matter. Third, the new ways to determine structure and function of complex bio-molecular assemblies.

2.1 Analysis of Chemical Reactions at Ultra-fast Time Resolution

Chemical compounds are described in terms of atoms, bond lengths and angles. In order to describe a chemical reaction the molecular structure and its evolution in time has to be known. This involves the breaking and rearranging of intra- and intermolecular bonds for which the time scale of fundamental steps is of the order of femtoseconds to picoseconds and distances are typically in the Ångström-range. Today, extremely short wavelength lasers in the optical and ultra-violet spectral range make it possible to observe dynamic events on the time scale of a molecular vibration period. However, the lack of spatial resolution on the atomic scale limits the entire field. Modern spectroscopy can tell us how fast a molecular structure is changing, but hardly how it is changing.

The importance of ultra-fast spectroscopy for studying chemical reactions is increasing rapidly and has been recognised with awarding the 1999 Nobel Prize in chemistry to Ahmed Zewail. However, since optical spectroscopy only probes the energy of bound electrons, a detailed theoretical knowledge of the energy levels of the system's ground state and of all accessible excited states is required for interpreting the spectroscopic data and indirectly deducing structural information. Because of the large number of parameters describing complex systems this knowledge can only be gained from these data by computer simulations in the frame of accepted approximations. X-ray based diffraction methods will provide new approaches for the investigation of ultra-fast phenomena, complementing the information accessible through ultra-fast optical spectroscopy alone. In particular the combination of the two techniques is expected to give for the first time detailed insight into the real-time formation of chemical bonds.

In principle, table-top short-pulse X-ray and electron sources, when utilised in pump-probe experiments together with visible long-wavelength lasers, have the right wavelength to provide us with such a view of chemical and physical transformation processes. However, their brilliance and temporal resolution is by far too low. The

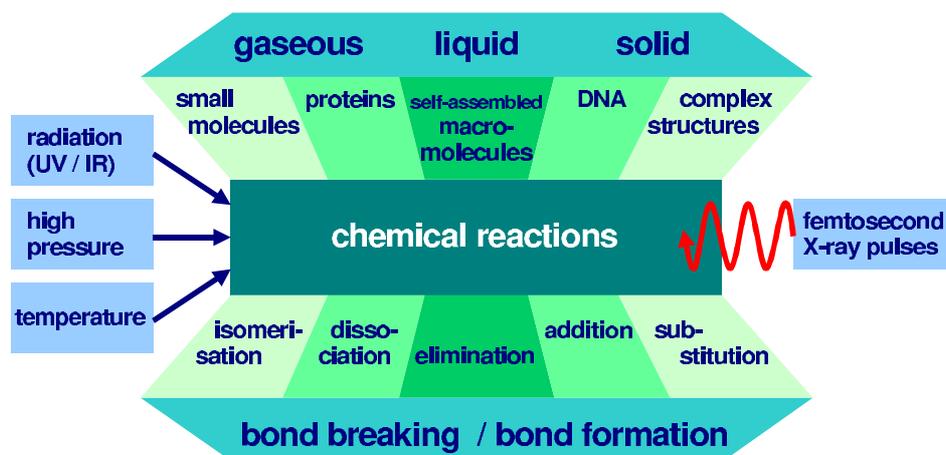


Figure 2.1.1: *Fields of applications for time-resolved investigation of chemical reactions. Systems in different phase (top) can undergo various chemical processes (bottom), which can be triggered by a variety of methods (left) and investigated by femtosecond X-ray pulses (right).*

TESLA X-ray FEL is ideally suited to the purpose of this emerging scientific field. Its brilliance is many orders of magnitude higher than achieved by table-top X-ray sources and the temporal resolution of the order of 100 femtoseconds will make it possible to resolve events on sub-vibrational time periods for many molecular systems. Utilising a set-up where e.g. an ultra-fast optical laser pulse initiates a photo-reaction which then is probed with the X-ray laser pulse, enables one to follow ultra-fast structural changes accompanied by electronic rearrangements, bond breakings and bond formations. These are exactly the processes which determine some of the most important chemical and biological reactions.

Fig. 2.1.1 summarises possible experimental schemes and their applications in the field of classical chemistry (organic, inorganic, physical) and biochemistry, as well as materials science. After the initiation of a chemical reaction its mechanism can be followed with one X-ray pulse alone or a time sequence of X-ray pulses. Due to the high flux provided by the X-ray laser, the time-resolved behaviour of small molecules as well as of complex large molecules can be examined in the gaseous, liquid and solid phases.

Today, light-triggered time-resolved studies with 100 picoseconds resolution are performed at third generation synchrotron radiation sources. However, recent results in ultra-fast optical spectroscopy lead to the conclusion that the exact description of reaction dynamics cannot be obtained within the usual theoretical approaches such as the Born-Oppenheimer approximation which firmly links the nuclear and electronic motion during the transformation. In particular in all processes, where electrons are excited into delocalised states (e.g. in semiconducting systems, aromatic chromophores like in the light harvesting complex of the photo-reaction center) this picture seems to

break down. Especially here, more detailed studies about structural rearrangements are needed.

A femtosecond light excitation may synchronise molecules in the sample for a couple of picoseconds. This phenomenon offers amazing new possibilities for structural investigations with femtosecond X-ray pulses through the observation of coherent reaction dynamics. On longer time scales chemical reactions do not proceed synchronously. Here intermediates may be present simultaneously, but they are vibrationally decoupled and thus unsynchronised. The interpretation of all time-resolved experiments outside the femtosecond domain is invariably compromised by this factor today. The TESLA X-ray FEL will allow to study the structural reorganisation processes related to chemical reactions in all phases, including liquids. These experiments will profit both from the accessible time range and the much increased number of X-ray photons per pulse, which will yield far better photon statistics. This is particularly important when considering ultra-fast phenomena, as the magnitude of the structural motions yield signals, which are likely to be much smaller than those occurring on slower time-scales. Fig. 2.1.2 one example of a photo-induced relaxation process is shown, which is the rearrangement of a N,N-dimethylaminobenzonitrile molecule induced by an electron transfer process. With the X-ray laser it will be possible to follow such ultra-fast structural reorganisations, providing information about the picosecond dynamics of this system at atomic scale resolution.

A broad range of chemical reactions occurs on slower time scales. Most of the reactions are not triggered by light but by temperature-jump, pressure-jump or a combination of both. Currently the available X-ray flux is not sufficient to follow non-cyclic reactions (i.e. reactions which do not repeatedly go through the same cycle of processes) on the nanosecond or even microsecond time-scale. With the X-ray FEL time-resolved X-ray diffraction and absorption experiments can be performed on non-cyclic reactions. This will enable chemical, thermal and pressure triggered processes to be used for initiation of the reaction, in particular for systems with complex structural response characteristics like self-assembled macromolecules, proteins or DNA. In combination with the flexible bunch-to-bunch time structure of the TESLA X-ray FEL, there will be sufficient X-ray photons per pulse to yield high quality structural information from a single exposure. This approach will open windows for investigating a huge domain of dynamic chemical phenomena, which cannot be structurally characterised with current X-ray sources or classical spectroscopic tools.

Experimental and theoretical studies of electronic relaxation processes leading to molecular reactions and/or phase transitions in condensed matter are among the most exciting goals in molecular and condensed matter science. These processes occur on the femto- to sub-femtosecond time scale and it has been demonstrated that optical spectroscopy with ultra-short laser pulses can provide new information on the nature of chemical reactions, however, atomic scale resolution is missing. Novel experiments and theoretical approaches are needed to gain better understanding of these extremely fast processes. The excellent intrinsic time resolution in the sub-femtosecond spike-

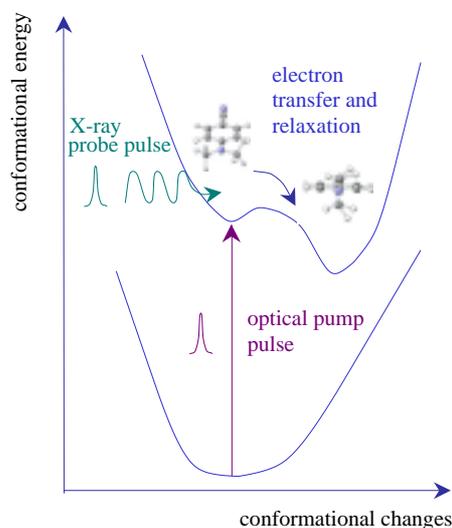


Figure 2.1.2: Conformational rearrangements of a photo-excited *N,N*-dimethylaminobenzonitrile molecule. After excitation with an optical femtosecond laser as a pump the molecule changes its conformation by electron transfer and relaxation processes. Probing the excited state with X-ray FEL radiation without affecting the decay process, allows to follow this conformational change in time.

structure of the X-ray pulses produced by SASE free-electron lasers, as well as the application of a time-slicing techniques to reduce the pulse duration to 10 femtoseconds or even shorter, hold high promise for the detection of space-time fluctuations of the electron density within chemical bonds. Such changes of the electronic structure of specific elements at specific sites could be measured by means of X-ray spectroscopy on the appropriate time scale.

2.2 A Tool for Plasma Physics

The X-ray laser, with its high brilliance and high energy density per pulse, is also a powerful instrument to generate and probe extreme states of matter in form of strongly coupled plasmas. It will allow to heat much bigger volumes uniformly than those possible by other means to unprecedented states of plasma with temperatures up to the keV level (10^7 K) and pressures up to the Gbar (10^{14} Pa) range. In a more general sense the properties of these plasmas are closely related to states of matter like in the interior of Brown Dwarfs, main sequence stars, White Dwarfs, or the giant planets such as Jupiter or the recently found extra-solar planets. Understanding the behaviour of matter under extreme conditions is of fundamental importance to develop improved models for plan-

etary and stellar structure and its formation, as well as for understanding the evolution of the universe (see Fig. 2.2.1).

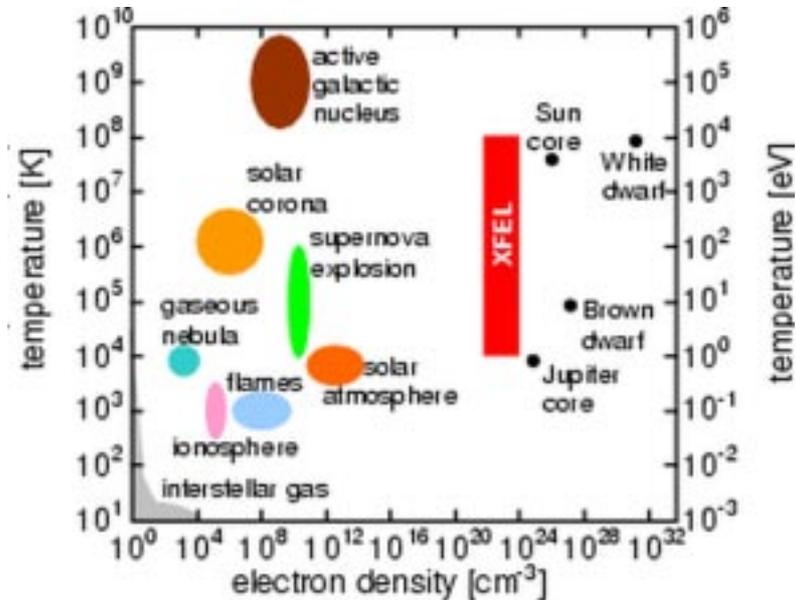


Figure 2.2.1: *Density–temperature diagram for astro–physical objects and the range accessible by the TESLA X–ray free–electron laser.*

Because hydrogen and helium (and their mixtures) are the simplest and most abundant elements in nature it is of special interest to study them in the plasma state over a wide range of densities and temperatures. For instance, metallic like conductivities in hydrogen have been observed for the first time in dense hydrogen fluid at pressures around 1.4 Mbar and temperatures around 2500 K in multiple shock-compression experiments. Furthermore, substantial deviations from standard equations-of-state have been found. Such data provide in many cases the basic ingredients for inertial confinement fusion, which employs both laser driven or heavy ion driven compression of deuterium-tritium capsules. The X-ray FEL will provide new diagnostic methods to determine the equation-of state independently of model assumptions.

Today dense, strongly coupled plasmas can be produced by using heavy-ion beams, as well as by high-power or ultra-short pulse lasers. For instance, optical laser pulses of 100-1000 femtoseconds duration and about 200-1000 nm wavelength generate plasmas by photo- and field-ionisation of valence electrons of atoms in a thin surface layer. The X-ray free-electron laser laboratory at TESLA will provide beams of 100 femtosecond pulse duration and with much shorter wavelengths (0.1-2.5 nm). In contrast to optical wavelengths radiation the X-ray pulse will interact with the inner shell electrons of atoms and the pulse will penetrate the entire sample. The power can reach

$10^{18} - 10^{20}$ W/cm². The X-ray FEL will allow to study specific plasma states for a variety of parameters and thus provide the data needed for comparison with the results of computer simulations studying the generation and evolution of plasmas including radiation transport and hydrodynamic expansion. The data will also allow for a better theoretical description of the interaction between energetic X-rays and cold, warm, and hot matter. Focused X-ray FEL pulses, which will be available at the TESLA X-ray FEL laboratory, will convert solid target matter into a dense plasma at record temperature / pressure values and, thus, open a new branch in dense plasma research.

In summary, the X-ray free-electron laser laboratory at TESLA opens a new path to generate and diagnose dense and strongly coupled plasmas by hard X-rays, which penetrate into the sample and heat it. This is due to the high energy density and the short pulse duration of the radiation, which produce a plasma in the volume of the target with minimum gradients rather than in a surface layer as produced by optical lasers. Thus, the production of dense, strongly coupled plasmas by means of the X-ray FEL combines the advantages of using ultra-short laser pulses with those of using heavy-ion beams.

2.3 Opportunities for Life Sciences

During the last years the face of biology has changed dramatically and new knowledge is acquired at an astonishing rate. Structural analysis on a molecular level has become an important tool to study the functions of individual components of biological systems in detail. This refers in particular to protein crystallography revealing the three-dimensional structures of many proteins and even of large multiple-protein assemblies at atomic resolution. Structural results provide a basis for the development of new drugs and offer novel therapeutical procedures. Atomic resolution insight has, however, been limited to bio-molecules that can be crystallised.

These days the sequence of the human genome is almost fully determined, the genomes of many other organisms are known already. The next step is to interpret this information, to determine the proteins encoded therein and to investigate their function. Structural and functional genomics projects are trying to address these issues. It is anticipated that the main applications of the X-ray FEL in this field will be in the post-genomic era, where the extreme intensity and the very short duration of the pulses could open up new avenues for investigations, especially on non-repetitive and non-reproducible samples, like living cells. The X-ray FEL will open new possibilities in the study of biological systems and their function. However, this path of accumulating more and more information is not free of obstacles.

For almost any functional analysis the three-dimensional structure of a macromolecule is required. However, preparing crystals of sufficient size and quality for diffraction is one of the main bottlenecks to retrieve high resolution structure models.

This is one of the main reasons that three-dimensional protein structures can presently be obtained from only 15-25% of the cloned genes.

A special case are membrane proteins where only a small number of three-dimensional structures are known today. They have hardly any tendency to form crystals. Various estimates show that there are at least as many different membrane proteins as soluble proteins, yet there are only a handful of independent structures known today for integral membrane proteins, simply because they cannot be crystallised. However, an understanding of the structure-function relationships in membrane proteins would make invaluable contributions to biochemistry, physiology and medicine, and would produce a substantial socio-economical impact (about 75% of all known drugs act on membrane proteins).

Another very interesting and important class of objects are multiple protein, RNA, DNA complexes. From the structure and behaviour of these complexes, information on the mutual interaction of the individual components can be deduced and will show how biology works on a molecular or atomic level. Like membrane proteins these large complexes are often very difficult to crystallise. Therefore, any method capable of retrieving high resolution structural information without the need for conventional diffraction-size crystals would be extremely helpful.

For both cases X-rays from free-electron lasers have the potential to provide such insights. The large number of photons per pulse, the very short pulse width and the possibility to focus to extremely small focal spots open the way for diffraction from nano-clusters of macromolecules, nano-crystals, single virus particles, two-dimensional arrays of macromolecules, or of large macromolecular complexes. Also the analysis of a number of individual macromolecules attached to some sort of scaffold of known structure may become feasible.

The power density in the focused beam conditions would be extreme and no sample will survive very long after the passage of a single pulse due to “Coulomb explosion”, since the incoming radiation will ionise a large fraction of the atoms. However, as the pulse can be much shorter than the initiation time of the Coulomb explosion it can in turn be possible to record a diffraction image before the atoms leave their original positions, and the sample is destroyed. Alignment procedures similar to those developed in image reconstruction for cryo-electron microscopy will help to obtain averages from a large number of individual images and provide a high resolution molecular transform of the molecule of interest (see Fig. 2.3.1). The continuous molecular transform, which is the modulus square of the Fourier transform of the molecule, is significantly over-sampled as compared to the information that can be measured from a crystal. In this case the phase problem can be circumvented and the solution of the structure is straightforward. Due to the coherence properties of XFEL radiation one can also envisage holographic imaging techniques.

Macromolecules can have a wealth of different functions, which in most cases can not be derived from the static three-dimensional structure alone. The typical time

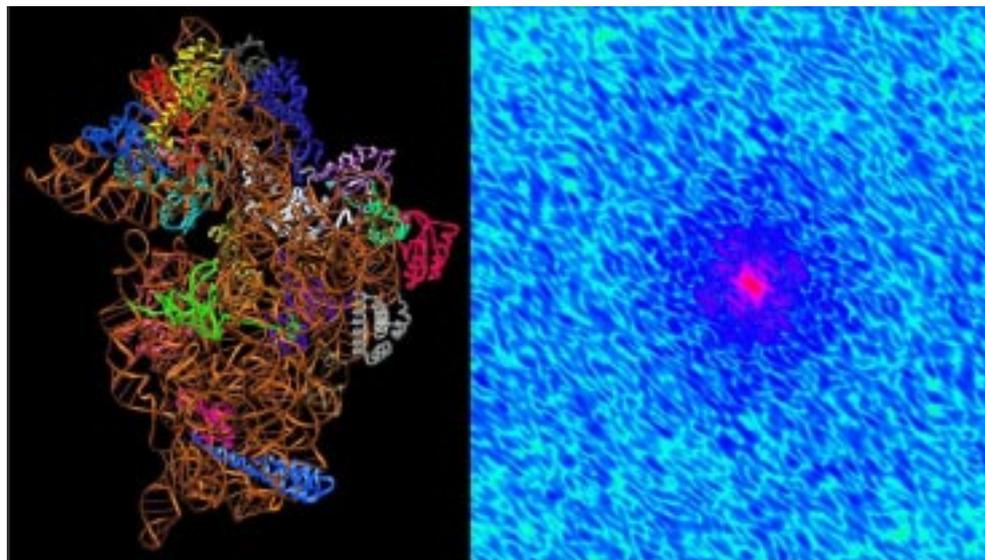


Figure 2.3.1: *Typical example for the structure of a large macromolecular assembly and its molecular transform. Left: Structure of the small 30S subunit of the Thermus Thermophilus ribosome; Right: slice through the 3-dimensional molecular transform of this ribosome, which is closely related to the distribution of the scattering power in momentum space; this pictures corresponds to a spatial resolution of around 4\AA .*

scale of biological processes spans many orders of magnitude (Fig. 2.3.2). With its very short, 100 femtoseconds radiation pulses and wavelengths down to one Ångström the X-ray FEL provides the potential for a time resolution three orders of magnitude better than at any present day source. A femtosecond excitation may synchronise molecules in the sample for a short time (a couple of picoseconds). This phenomenon offers amazing new possibilities for structural investigations with femtosecond X-ray pulses through the observation of coherent reaction dynamics.

Investigations concerning the dynamics of macromolecules exploiting inelastic scattering effects (e.g. nuclear resonant inelastic scattering) are nowadays significantly limited by the number of photons available in the very narrow band pass required. The seeding option for the X-ray FEL will provide an ideal tool for inelastic studies with an intensity in an extremely narrow wavelength band, which is orders of magnitude higher compared to third-generation light sources.

In summary the X-ray free-electron laser laboratory at TESLA will give us an entirely new tool permitting to determine the three-dimensional structures of macromolecules without the need for diffraction-size crystals, and to identify and characterise them in their cellular environments. A number of technically challenging issues have to be solved in order to fully exploit the potential of the X-ray free-electron laser for biology. Basic aspects of the interaction of femtosecond X-ray pulses of extreme power density with atoms and molecules in soft matter, including non-linear effects, have to

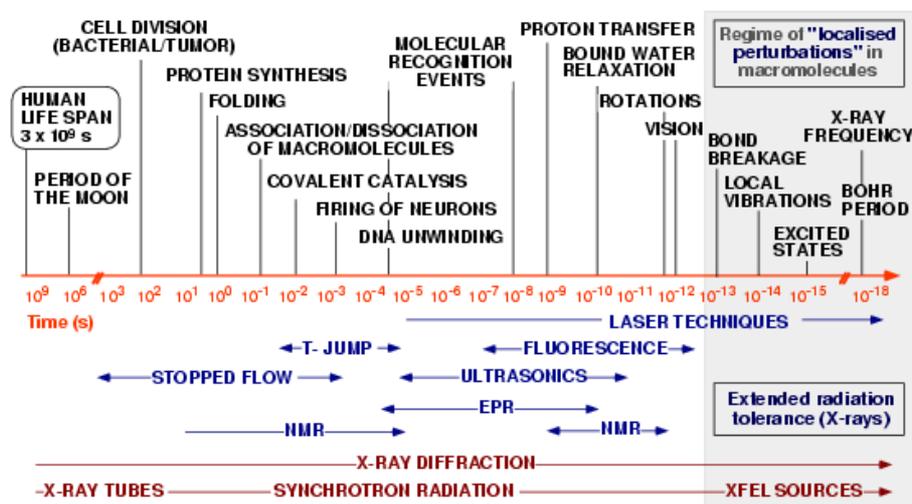


Figure 2.3.2: Relevant time scale for a number of biochemical processes. With present day sources time scales down to $\sim 10^{-9}$ seconds are accessible albeit not with enough single pulse intensity. This time-scale is much too long to study key events at the heart of chemical transformations. The fastest bio-chemical processes occur within a few hundred femtoseconds. Structural experiments in this time domain will be possible with the XFEL radiation, and will lead to a synthesis of femtosecond spectroscopy and femtosecond structural methods. Such studies cannot be done without an X-ray free-electron laser laboratory.

be studied. Radiation damage and its evolution on the femtosecond time scale will be investigated and many biochemical preparation techniques have to be improved or novel ones have to be developed in order to provide well defined samples without changing their physiological properties. One may foresee that ultra-short, high intensity X-ray pulses, in combination with novel container-free sample handling methods, will open up new horizons for structural and functional studies on both the molecular and cellular level.

3 The Technical Layout

3.1 Introduction

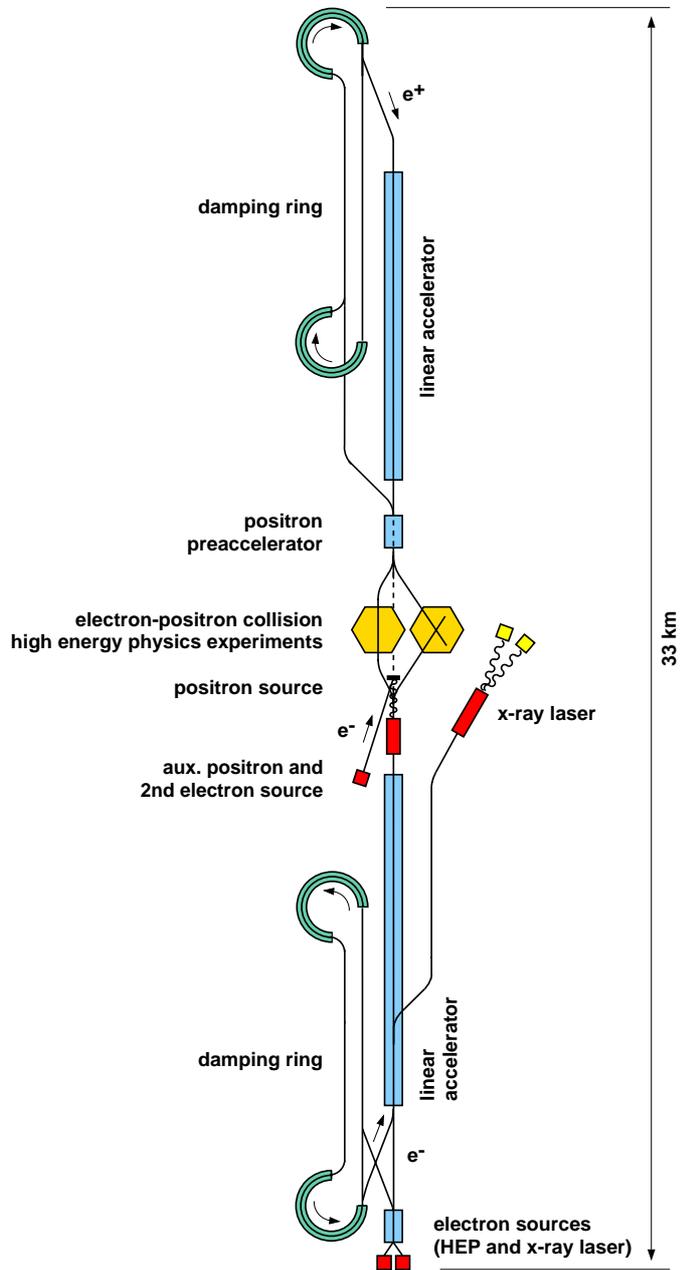
The overall layout of the TESLA linear collider and laser facility is shown in Fig. 3.1.1. The total site is 33 km long. The main components are a pair of linear accelerators, one for electrons and one for positrons, pointing at each other. The first low energy part of the electron accelerator also provides the electron beam for the X-ray Free Electron Laser. Each linear accelerator is constructed from about ten-thousand one-meter long superconducting cavities. Pulsed radio frequency (1.3 GHz) electromagnetic fields are guided five times per second for the duration of one millisecond into the cavities to accelerate the particles.

Superconducting technology provides important advantages for a linear collider. As the power dissipation in the cavity walls is extremely small, the power transfer efficiency from the radio frequency (RF) source to the particles is very high, thus keeping the electrical power consumption within acceptable limits (~ 100 MW), even for a high average beam power. The high beam power is the first essential requirement to obtain a high rate of electron-positron collisions.

The second requirement is extremely small sizes of the electron and positron beams at the interaction point (IP). The relatively low RF frequency of the TESLA linear accelerators is ideally suited for conserving the ultra-small size of the beams during acceleration. When a beam is accelerated in a linear accelerator, the charged particles induce electromagnetic fields (so-called wakefields) which act back on the beam itself and can spoil its quality by increasing the energy spread and the beam size. As these wakefield effects decrease strongly with increasing distance between the beam and the surrounding cavity walls, wakefields are much weaker in the larger cavities of accelerators working at low RF frequencies than in smaller cavities operating at higher frequencies.

For the same reasons, the superconducting linear accelerator of TESLA is also extremely well suited to drive an X-ray Free Electron Laser (XFEL), which also requires an electron beam with large average power, high bunch charge, small energy spread, and small beam size.

Due to the large aperture of the TESLA cavities the alignment accuracy of the cavity axis with respect to the beam is relatively easy to achieve. Moreover the bunch



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Figure 3.1.1: Sketch of the overall layout of TESLA (the second interaction region with crossing angle is optional and not part of the baseline design.)

separation of more than 300 ns permits orbit control by a fast feedback system. Such a feedback system will maintain the beams in collision at the interaction point, making TESLA quite insensitive to mechanical vibrations which could otherwise lead to a serious reduction of the interaction rate.

The benefits of superconducting cavities have been known since the beginning of linear collider research and development. However, the accelerating fields achieved in the early 1990's were too low and the projected costs based on the then existing superconducting installations were too high for a collider facility. The main challenge for TESLA was therefore a reduction in the cost per unit accelerating voltage by a factor of 20.

Building on existing experience with superconducting cavities from CERN, CEBAF, Cornell, DESY, KEK, Saclay and Wuppertal, the TESLA collaboration succeeded in meeting the challenge:

- By continued improvements of the base material (niobium), the cavity treatment, and the welding/assembly procedures, accelerating fields exceeding 25 Million Volts per meter (MV/m) have been reliably achieved.
- Through numerous design optimisations the costs per unit length of the superconducting structures and the cryostat were reduced by a factor four for a large scale production.

3.2 The Superconducting Cavities: Basic Elements of the Accelerator

The basic elements of TESLA are 9-cell superconducting cavities, made from niobium (Fig. 3.2.1) and cooled by superfluid helium to -271 C. The operating frequency is 1.3 GHz. For the chosen length of TESLA the accelerating field of the cavities (gradient) needed to reach a total collision energy of 500 GeV is 23.4 MV/m.

In order to demonstrate the technical feasibility of high gradients in superconducting cavities, the TESLA collaboration began in 1992 to set up a test facility for superconducting cavities, the TESLA Test Facility (TTF) at DESY. The infrastructure of TTF incorporated all the experience gained in the collaborating institutions, providing through all steps of cavity treatments a dust free environment, which had been found essential in obtaining high gradients.

To date, more than sixty 9-cell cavities have been fabricated by industry and tested at TTF. Fig. 3.2.2 shows the average gradient obtained in the years 1995 to 2000. The steady improvement of the average gradient over the past years clearly indicates that the high performance cavities required for the 500 GeV collider can now be reliably produced.



Figure 3.2.1: *The 9-cell niobium cavity for TESLA.*

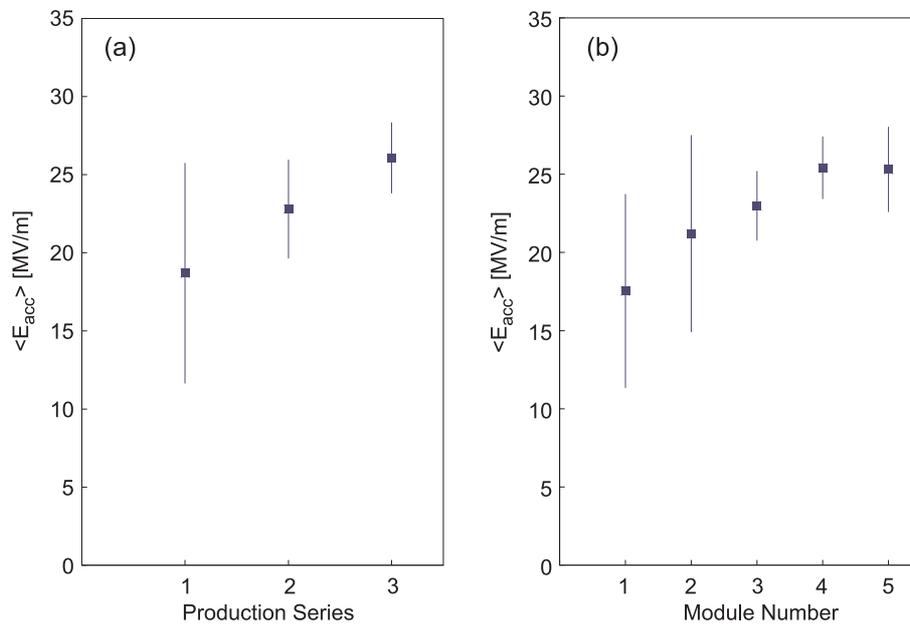


Figure 3.2.2: *Average accelerating gradients at a quality factor $Q_0 > 10^{10}$ measured in the vertical test cryostat:*

(a) of the cavities in the three production series; (b) of the cavities installed in the first five cryogenic modules for TTF. The error bars give the standard deviation.

Further progress in cavity performance has recently been obtained by applying electro-polishing to the niobium surface. Test results with single-cell resonators repeatedly show gradients well above 35 MV/m: The best single-cell performance obtained to date is 42 MV/m. First results for 9-cell electro-polished cavities show gradients above 30 MV/m.

The TESLA collaboration also decided in 1992 to construct a short prototype linear accelerator (500 MeV) as an integrated system test, and to demonstrate that a linear collider based on superconducting cavities can be built and operated reliably. The commissioning and operation of the TTF linear accelerator has been the second



Figure 3.2.3: *Assembly of a string of eight 9-cell cavities in the clean room at TTF.*

essential milestone reached on our way to demonstrate the feasibility of the TESLA technology. The linear accelerator is constructed from accelerator modules similar to those required for the collider. Each 12 m long module is comprised of a string of eight 9-cell cavities (Fig. 3.2.3), plus beam focusing and diagnostic components. We have so far tested three modules and operated the linear accelerator for more than 8600 hours.

3.3 The Linear Collider Complex

The electron beam for the TESLA collider is generated in a polarised laser-driven source. After a short section of conventional normal conducting linear accelerator, the beam is accelerated to 5 GeV in superconducting structures identical to the ones used for the main accelerator. The electrons are stored in a damping ring at 5 GeV to reduce the beam size to values adequate for high luminosity operation. As the train of 2820 bunches is 300 km long, a compression scheme is used to store the bunches in the damping ring. Reducing the distance between bunches by a realistic factor of 16 yields an 18 km circumference. Using the so-called “dog bone” design with two 8 km straight sections, most of the circumference can be placed inside the main accelerator

tunnel. Only two 1 km loops are needed at either end. After damping, the bunch train is decompressed and injected into the main linear accelerator.

A conventional positron source cannot provide the total charge of about $5 \cdot 10^{13}$ positrons per beam pulse, needed for the high luminosity operation of the TESLA collider. Therefore an intense photon beam is generated by passing the high energy electron beam through an undulator magnet placed after the main linear accelerator. Positrons are produced by directing the photons onto a thin target in which they are converted into pairs of electrons and positrons. After acceleration to 250 MeV in a normal-conducting linear accelerator the positron beam is transported to a 5 GeV superconducting accelerator, after which it is injected into the positron damping ring. This source can also generate a polarised positron beam.

The RF-power to excite the superconducting cavities is generated by some 300 electron tubes (klystrons) per linear accelerator. The required peak power per klystron is about 10 MW. The high-voltage pulses for the klystrons are provided by conventional power sources (modulators).

The cryogenic system for the TESLA accelerators is comparable in size and complexity to the one currently under construction for the Large Hadron Collider (LHC) at CERN. Seven cryogenic plants cool the linear accelerators to 2 K. The cooling capacity of the first section of the electron accelerator is higher than the rest to accommodate the additional load from the XFEL beam pulses.

The about 1.6 km long beam delivery systems between the linear accelerators and the collision point, where the experiment is located, consist of sections to remove the beam halo, beam diagnostics and correction, and the final focus system, consisting of magnetic lenses which focus the beams at the collision point down to spot sizes of about 550 nm width and 5 nm height. The design of the final focus is essentially the same as the Final Focus Test Beam (FFTB) system successfully tested at the Stanford Linear Accelerator Centre (SLAC) and the beam optics requirements of TESLA are comparable to those achieved at the FFTB. The beams can be kept in collision at the interaction point to a high precision by using a fast bunch-to-bunch feedback, which measures and corrects the beam-beam offset and crossing angle on a time scale comparable to the time between bunches. A prototype of the orbit feedback system has been installed and successfully tested at the TTF linear accelerator. The beam delivery systems have been optimised for a single head-on interaction point. The magnet systems and the beam line layout are designed for a beam energy of up to 400 GeV.

The two linear accelerators as well as the beam delivery systems will be installed in an underground tunnel of 5.2 m diameter (see Fig. 3.3.1). One experimental hall is foreseen to house the big high energy physics detector setup at the collision point; it can be extended for a second detector should a second interaction region be constructed. The seven surface halls for the cryogenic plants are connected to the underground tunnel by access shafts. The halls also contain the power sources (modulators) which

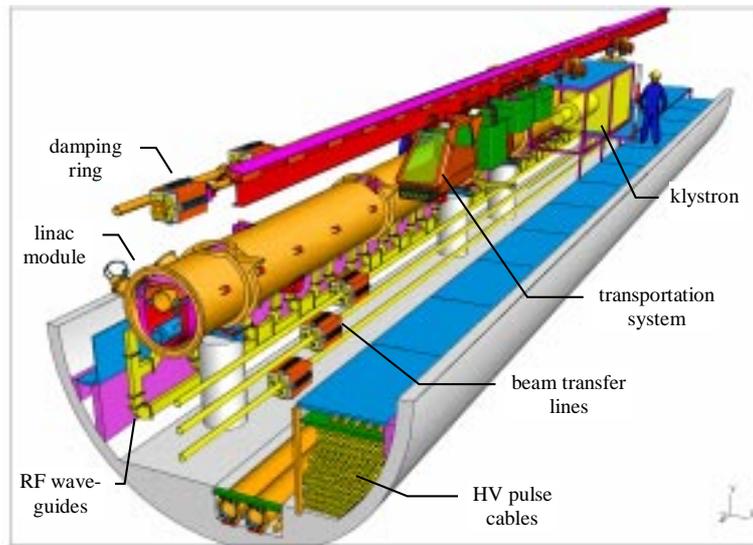


Figure 3.3.1: *Sketch of the 5.2 m diameter TESLA tunnel.*

generate the high voltage pulses for the klystrons located in the accelerator tunnel, thus allowing access to the modulators during machine operation. The exchange of klystrons, however, will require an interruption of the machine operation. Assuming an average klystron lifetime of 40,000 hours, a maintenance day every few weeks will be necessary.

The baseline design for the 500 GeV machine relies entirely on the components installed and tested at TTF, the only exception being a further optimisation of the mechanical layout of the modules. The modified module improves the fill factor (ratio of active length to total length) and hence increases the beam energy for a fixed accelerator length. A further improvement is expected from the so-called superstructure: in this concept multi-cell cavities are joined together to form a single unit supplied by one RF power coupler, thus reducing the cost of the RF power distribution system. To be on the conservative side the parameters and cost estimate for the 500 GeV machine are based on the TTF-like accelerator modules, since tests of the superstructure are still in preparation.

Some key parameters of the linear collider operating at 500 GeV are given in Table 3.3.1, showing the very high luminosity which is provided by the TESLA concept based on low frequency superconducting cavities.

		TESLA-500
Accelerating gradient	MV/m	23.4
Total site length	km	33
No. of accelerating structures		21024
No. of klystrons		584
Klystron peak power	MW	9.5
Repetition rate	Hz	5
Beam pulse length	μs	950
No. of bunches per pulse		2820
Bunch spacing	ns	337
Charge per bunch	10^{10}	2
Beam size at IP (width,height)	nm	553, 5
Bunch length at IP	mm	0.3
Luminosity	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	3.4
Power per beam	MW	11.3
Two-linac primary electric power	MW	97

Table 3.3.1: *TESLA parameters for the 500 GeV baseline design. The machine length includes a 2% overhead for energy management. The klystron power and primary electric power quoted include a 10% regulation reserve.*

3.4 Energy Potential of the Linear Collider

Higher beam energies than for the baseline design are possible within the site length since:

- The filling factor of the linear accelerators can be further increased by about 6% by a modified design of the cavity structure (superstructures), and hence the maximum energy for a fixed accelerating gradient and site length.
- The physical limit for the gradient in niobium structures at 2 K is above 50 MV/m, and several 9-cell cavities have already reached gradients around 30 MV/m at TTF. Electro-polishing, followed by low-temperature bake-out, has yielded systematically higher performance single-cell cavities, with gradients up to 42 MV/m.
- A method has been developed and successfully demonstrated at TTF which compensates the mechanical deformation of the cavities resulting from the strong electromagnetic fields. This active mechanical stabilisation using fast tuners, thus stabilizes the resonant frequency of the cavities and maintains an optimal power transfer from the RF generator.

Based on the described and ongoing progress in building high gradient cavities we assume that TESLA will be built from the very beginning with superstructures and

with cavities reaching gradients of on average 35 MV/m, thus allowing a total collision energy of 800 GeV. The beam delivery system and the magnets in the linear accelerators have been designed for a beam energy of up to 400 GeV.

Collision energies above 500 GeV can be reached in two steps:

- A total energy of 650 GeV can already be obtained in the baseline design as the cooling plant capacity has a 50% overhead, thus allowing the gradient in the cavities to be increased by 20-30%.
- In order to reach 800 GeV at maximum luminosity two upgrades are required: the cooling capacity of the cryogenic plant must be increased and the number of the RF stations must be doubled.

The positron production scheme maintains the required yield for high luminosity operation down to electron energies of 160 GeV, thus allowing high luminosity operation at the threshold of top quark pair production.

For high luminosity operation at the mass of the Z boson, an electron beam is extracted at 45 GeV after the first ~ 3 km of the linear accelerator and transported to the interaction region using a bypass line. A second pulse is accelerated in the remainder of the accelerator and is used to produce the positrons.

3.5 Second Interaction Region and Further Options

The baseline design of TESLA plans for a single particle physics interaction region. Unlike a storage ring collider, a linear collider cannot serve several interaction regions (IR) simultaneously with the same beam. It is possible, however, to switch the beam between two experimental stations. The option of a second IR has been investigated. This IR can be used for electron-positron collisions, with the same luminosity as the primary IR (assuming that the so-called crab-crossing scheme is used). Unlike the primary IR, the second IR will have a crossing angle of ~ 34 mrad, and is therefore also suitable for the $e\gamma$ and $\gamma\gamma$ collider modes of operation described in Part VI-1.

Electron-electron collisions (at one or both of the IRs) can be provided by reversing magnet polarities and adding an electron beam source to the (nominal) positron branch of the collider. The expected performance for the $\gamma\gamma$ and e^-e^- modes of operation are included in the discussion of machine parameters.

In addition to the collider operation, TESLA also offers options for fixed target physics. It is possible to accelerate (in parallel with the main collider beam) a low-intensity spin-polarised electron beam which can be deflected into a separate beam line

and used for a polarised target experiment (see Part VI-3). Except for the additional experimental beam line and low-current polarised electron source, the impact on the accelerator itself is marginal, since the required additional RF-power is far less than 1% of the nominal power.

The first part of the electron linear accelerator can be used as an injector for the electron ring of the existing HERA collider, which could be operated as a pulse stretcher to deliver a continuous beam at 15 to 25 GeV for fixed target nuclear physics experiments. This option provides a beam with properties very similar to a recent design worked out at CERN (see Part VI-4).

As another option, the TESLA tunnel can be connected to the straight section West of the HERA proton ring, allowing the electron beam from TESLA to collide with protons stored in HERA (see Part VI-2).

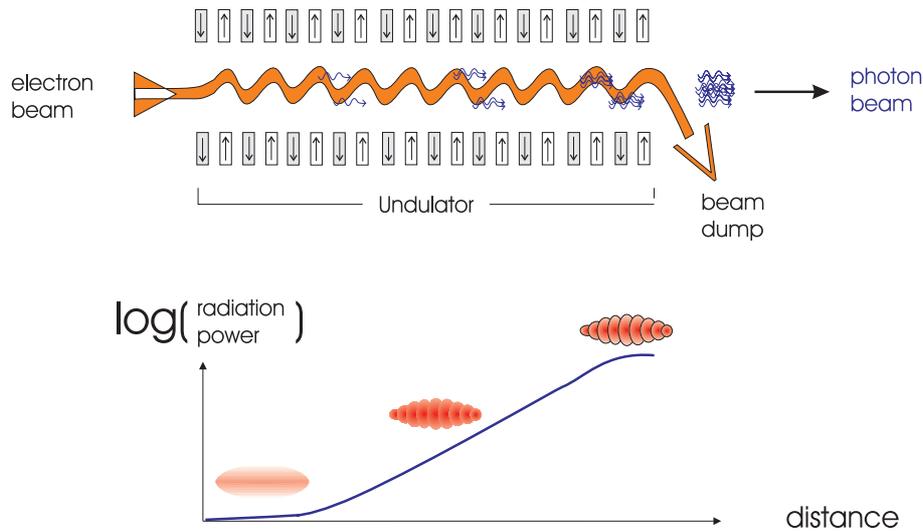
These additional possibilities for experiments at TESLA are not part of the baseline design and have therefore not been evaluated at the same level of detail as the collider and X-FEL.

3.6 The X-ray Free Electron Laser (XFEL)

The conservation of the high beam quality during acceleration also makes the TESLA linear accelerator an excellent driver for an X-ray Free Electron Laser (XFEL). The X-ray Free Electron Laser functions by passing an electron beam pulse of small cross section and high peak current through a long periodic magnet structure (undulator). The interaction of the emitted synchrotron radiation with the electron beam pulse within the undulator leads to the buildup of a longitudinal charge density modulation (micro bunching), if a resonance condition – determined by the electron beam energy and the undulator period – is met. The electrons in the developing micro bunches eventually radiate coherently and the number of emitted photons grows exponentially. This is the basic principle of a Single-Pass Free Electron Laser (FEL) operating in the Self-Amplified-Spontaneous-Emission (SASE) mode. The concept of using a high energy electron linear accelerator for building an X-ray Free Electron Laser (FEL) was first proposed for the Stanford Linear Accelerator.

The principle is shown schematically in Fig. 3.6.1. The bunch density modulation (micro-bunching), developing in parallel to the radiation power, is schematically shown in the lower part of the figure. The SASE-FEL does not require the optical cavity resonator normally used in multi-pass Free Electron Lasers, working at longer wavelength. It can therefore deliver radiation with a wavelength down to X-ray wave lengths, where mirrors no longer work.

The SASE FEL delivers coherent X-ray pulses of about 100 fs length, compared to about 30 ps at state-of-the-art synchrotron radiation sources. As shown in Fig. 3.6.2 the



Free Electron Laser in the Self Amplified Spontaneous Emission (SASE) mode

Figure 3.6.1: *Schematic Diagram of a Single-Pass Free Electron Laser (FEL) operating in the Self-Amplified-Spontaneous-Emission (SASE) mode. The bunch density modulation (micro-bunching), developing in parallel to the radiation power, is shown in the lower part of the figure. Note that in reality the number of slices is much larger.*

peak brilliance per pulse exceeds present sources by eight or more orders of magnitude.

As the SASE FEL does not depend on atomic excitation levels, it can be tuned over a wide range of wavelengths. This tunability was recently demonstrated at the TESLA Test Facility in the wavelength range between 80 nm and 180 nm.

To achieve photon wavelengths as small as atomic dimensions (Ångström), an electron beam of about 30 GeV is required. Since the X-ray FEL concept represents a considerable extrapolation of present day FEL technology, a test of the SASE FEL concept at the TTF, in a wavelength region previously inaccessible ($\lambda \approx 100$ nm) has been performed. Lasing was first observed in February 2000, and a number of experimental studies at the TTF-FEL have since been carried out. An upgrade of the TTF linear accelerator to 1 GeV beam energy is in preparation, allowing the FEL to reach 6 nm wavelength. The facility will provide operational and scientific experience for the proposed X-ray FEL laboratory.

Fig. 3.6.3 shows a sketch of the laboratory as part of the overall layout of TESLA. The XFEL electron beam is provided by a special injector. The first 3 kilometers of the electron accelerator are used to accelerate the beam which drives the X-ray FEL laboratory. Two extraction beam lines are planned for supplying electron energies typically between 13 and 35 GeV. About 900 meter in front of the XFEL laboratory, the beams are deflected into a 4 m diameter tunnel, separating the beams from the

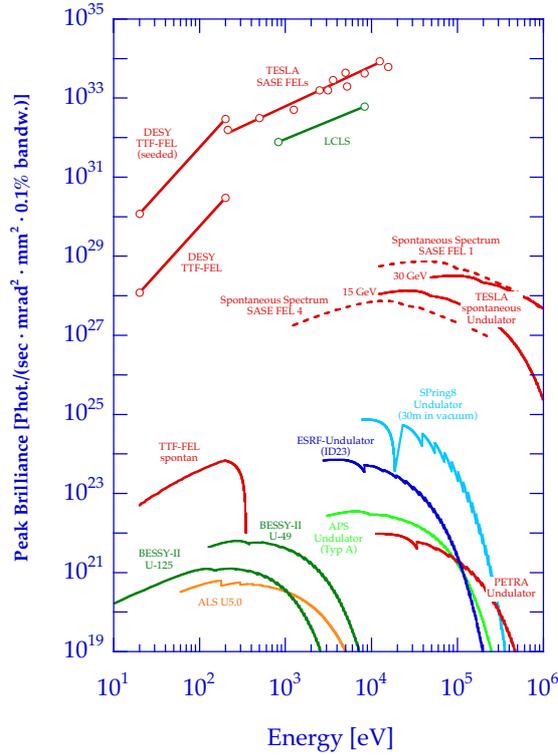


Figure 3.6.2: *Spectral peak brilliance of XFELs and undulators for spontaneous radiation at TESLA, together with that of third generation synchrotron radiation sources. For comparison, the spontaneous spectrum of an XFEL undulator is also shown.*

collider tunnel. The extraction lines can be used in parallel, so that various beam energies are available in the X-ray laboratory.

At the end of the extraction tunnel, a beam switchyard distributes the beams to different undulators, as shown in Fig. 3.6.4. The quality of the electron beam behind the FEL is still very good, so that it can be passed through another FEL or through further undulators generating spontaneous radiation.

The electron pulse structure consists of trains of electron bunches with a repetition rate of 5 Hz. The accelerator will run in a mode where pulses for high energy collisions and the XFEL alternate. This means that the first part of the electron linac, which serves both the XFEL and the collider, operates at a rate of 10 Hz. Both user communities can define the beam properties like energy, emittance, current, time structure, etc., to a very large extent independently of each other, since separate injectors will be used, and the RF system allows for changes to power and pulse length from pulse to pulse.

The FEL laboratory building is located at the new campus close to the collider interaction region. The layout of the laboratory follows a similar approach as used for the third generation light sources: For the baseline design, the plan is to build five laser

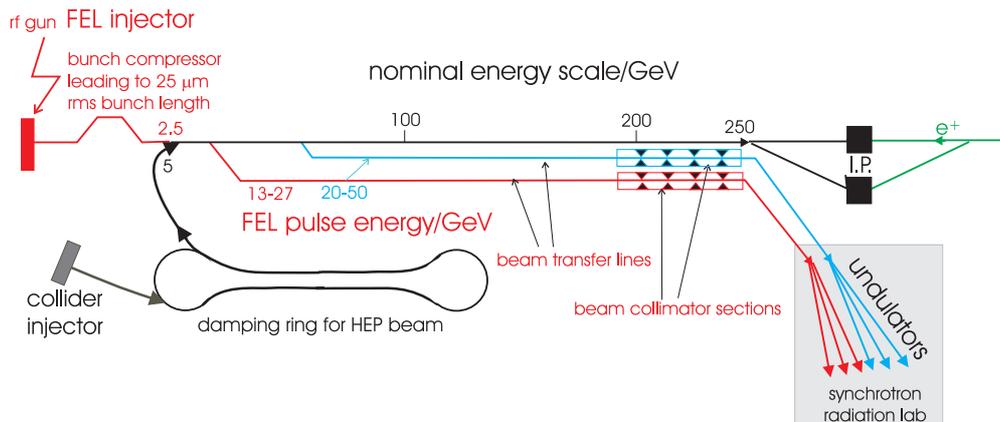


Figure 3.6.3: Sketch of a coherent X-ray source laboratory based on the TESLA linear collider installation. Two electron beam lines, extracted from the electron linear accelerator at energies between 11 and 35 GeV, are guided inside the accelerator tunnel to the X-ray laboratory.

beam lines, each equipped with three experiments, and five beam lines for spontaneous radiation, each with one experiment.

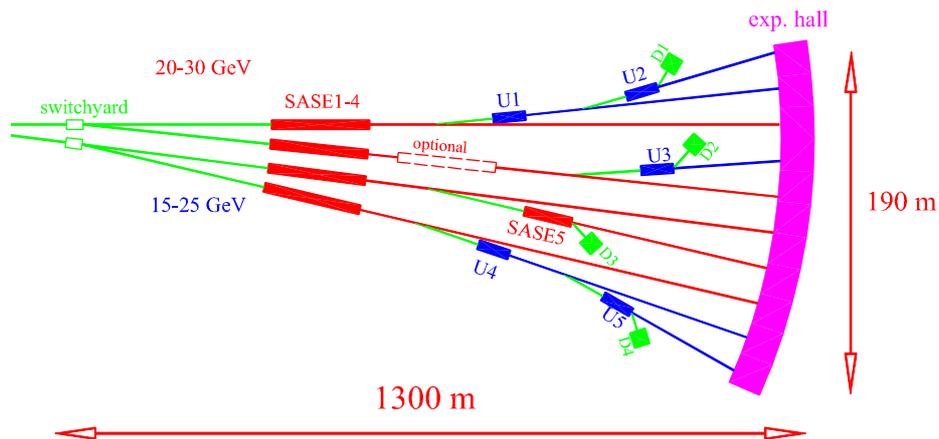


Figure 3.6.4: Beam switchyard distributing two electron beam lines of different energies to various undulators. SASE1 through SASE5 are FEL undulators while U1 through U5 are undulators for spontaneous radiation.

Linac Parameters		
Optimised gradient for XFEL operation	MV/m	18
Linac repetition rate for XFEL	Hz	5
Bunch length (rms)	fs	80
Bunch spacing	ns	93
Number of bunches per train		11500
Bunch train length	μ s	1070
Bunch charge	nC	1
Over-all power efficiency AC to electron beam	%	30
FEL Parameters		
Energy	keV	0.5 - 14.4
Wavelength	\AA	25 - 0.85
Saturation length	m	60 - 220
Peak power	GW	100 - 37
Average power	W	550 - 210
Photon divergence (FWHM)	μ rad	6 - 0.8
Beam diameter/ experiment (FWHM)	mm	1
photons/pulse	10^{12}	10 - 2

Table 3.6.1: *Parameters for the XFEL operation.*

In Table 3.6.1 some key parameters of the XFEL are summarised.

4 Project Cost Estimate and Schedule

The costs for the TESLA project are given separately for the 500 GeV electron-positron linear collider, the X-ray Free Electron Laser (incremental cost for accelerator, beam delivery and the X-ray laboratory), and one detector for particle physics. All costs are given in Euro and in year 2000 prices.

4.1 The Linear Collider

The cost for the 500 GeV linear collider baseline design with one interaction region is

- 3136 million EUR.

The cost for the major subsystems is detailed in Fig. 4.1.1, Fig. 4.1.2 and table 4.1.1.

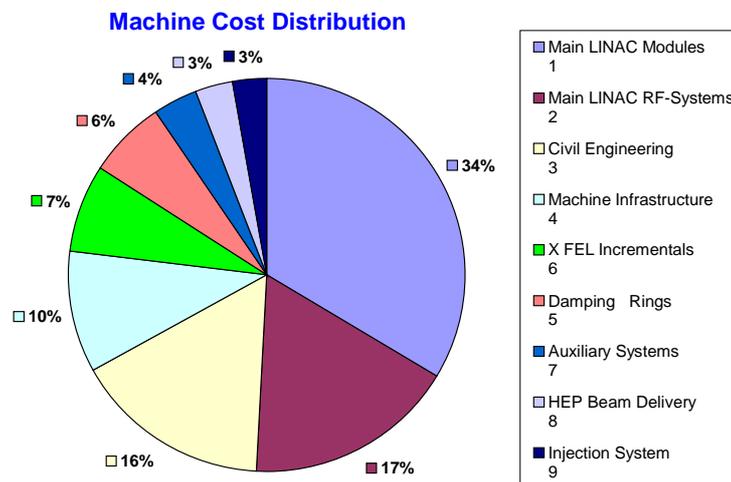


Figure 4.1.1: *Distribution of the accelerator sub-systems in percent of the total cost. The costs of the X-ray FEL laboratory and the detector for particle physics are not included here.*

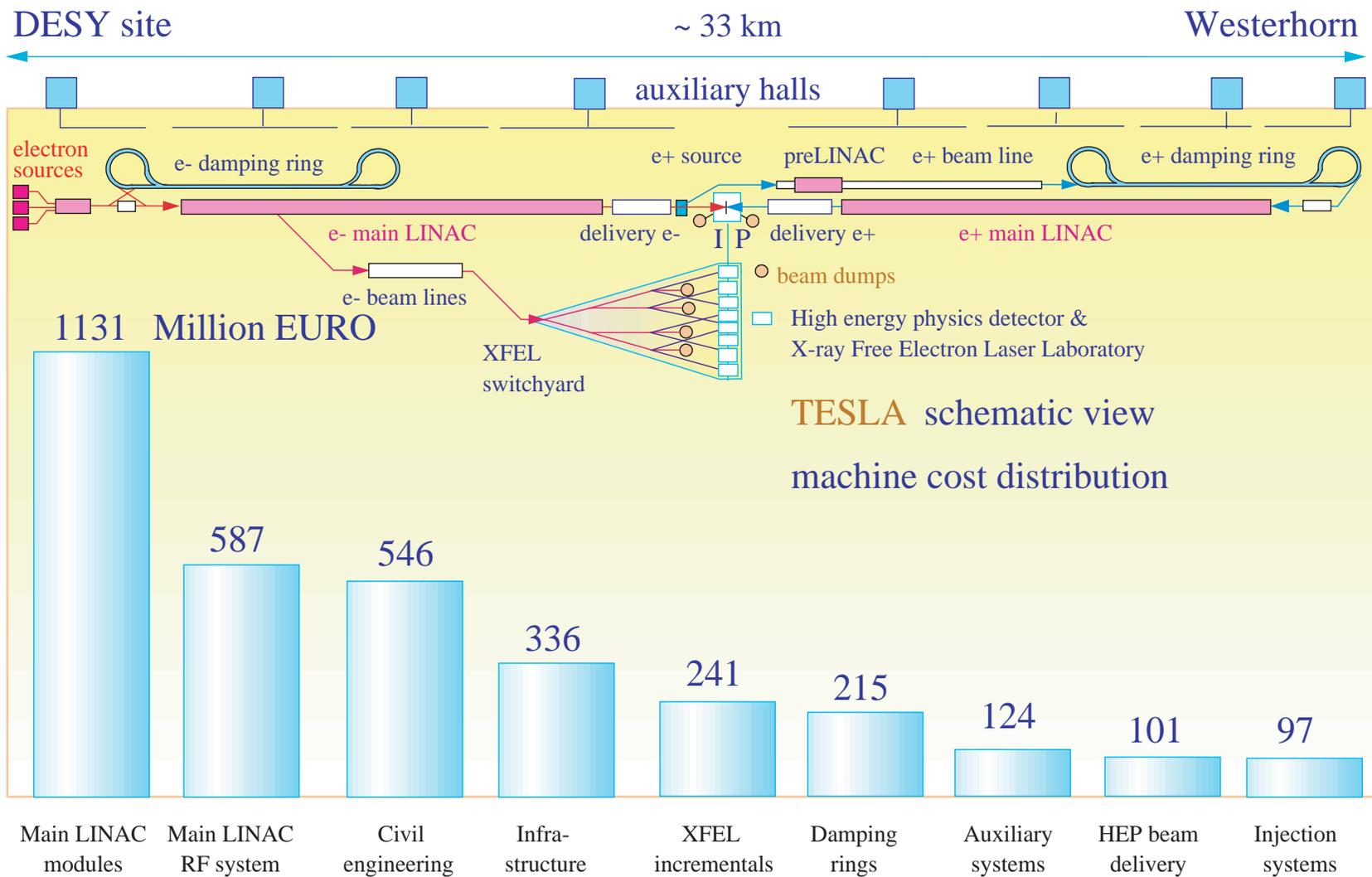


Figure 4.1.2: Overview of the accelerator investment costs.

Sub-system	Component included	cost million EUR
Main acceleration structure	cavity string, input couplers, modules, HOM couplers, tuning system, cryostats, s.c. quadrupoles, steering magnets, instrumentation	1131
Main linac RF system	RF power supplies, modulators, HV pulse cables, transformers, klystrons, wave guide system, low level RF controls, interlocks and cables	587
Injection system	RF gun system, accelerator modules and RF system for 5 GeV linac for electrons and positrons, positron source, conventional pre-accelerator, beam transfer lines, diagnostics	97
Damping ring	magnet-, vacuum-, RF-system, power supplies, beam instrumentation, bunch compressor, injection and ejection systems	215
Beam delivery system of LC	beam transport lines, beam collimation, beam dump systems, vacuum systems, power supplies, feedback systems, diagnostics	101
Civil engineering	33km tunnel, surface buildings, connecting shafts, experimental hall for high energy experiment, damping ring tunnels, beam dump halls	546
Infrastructure	tunnel infrastructure, cable trays, power distribution, main power connection, cryoplants and cryogenic distribution system, ventilation, test facility, water cooling system	336
auxiliary systems	control systems, vacuum pump stations, cabling, interlocks, magnet supplies, miscellaneous	124

Table 4.1.1: *The cost for the subsystems of the TESLA 500 GeV collider.*

The cost goal of 2000\$/MV for the complete accelerating modules (including superconducting cavities, power couplers, cryostat, quadrupoles etc.), set by Bjørn H. Wiik for the TESLA collaboration in 1992, has been met to within 8%.

Capital Cost Estimate Basis

The cost estimates for all major components have been obtained from studies made by industry, and are based on a single manufacturer supplying the total number of a given component. A schedule of three years peak production plus one year for start-up for the total number of each component was specified. The four-year production cycles required for the various components are scheduled within the total construction time of eight years. The schedule was considered feasible by the companies involved in the study.

A production period of four years corresponds to an average production rate of 32 m of machine per working day. The corresponding numbers for the proton storage ring of the Hadron Electron Ring Accelerator HERA at DESY were about 25 m/day; for the Large Hadron Collider LHC at CERN about 40 m/day are planned.

Several collaborating institutes were in charge of evaluating parts of the cost. A planning group consisting of the persons responsible for each of the major subsystems, together with experienced senior scientists from the collaboration has been continuously reviewing the technical layout of the system and the cost evaluations. The procedures which were followed in the cost evaluation for the major components can be found in Part II.

No additional contingency has been added, since the last two major particle physics facilities in Europe – the Large Electron Positron collider LEP at CERN and HERA – were built within budget and on time.

Manpower Requirements

The personnel needed for the different stages of the project – design, procurement, fabrication and assembly, testing, installation and commissioning – has been estimated mainly on the basis of the experiences gained at the TESLA Test Facility and in large projects like HERA. A total of 6933 person-years will be required. It is assumed that this manpower will be supplied by the collaborating institutes. The manpower needed for manufacturing of components in industry is included in the investment costs.

Maintenance and Operating Cost

The operating costs include the electrical power, the regular refurbishing of klystrons, water, and the helium losses. The numbers are determined assuming current prices and an annual operation time of 5000 hours. Costs for general maintenance and repair have been estimated assuming 2% per year of the original total investment costs, corresponding to the DESY experience. In total, the costs for the operation of the accelerators has been estimated at 120 million EUR per year. For critical components

(such as accelerator modules) a number of spares will be produced; these costs have been included in the investment costs.

Time Schedule

The construction time of TESLA is 8 years. The estimate is based on industrial studies and the experience gained from the construction of HERA and the TESLA Test Facility. In Fig. 4.1.3 a and b the construction and installation schedule is shown, indicating the major activities. For details see part II.

4.2 Additional Cost of the XFEL Laboratory

The additional costs of the accelerator components required for the X-ray FEL amount to

- 241 million EUR,

the dominant part being the civil engineering of the FEL experimental hall and the beam distribution system. The equipment cost for the undulators, beam lines and experiments, including infrastructure – 5 laser beam lines, each equipped with 3 experiments, 5 other beam lines with 1 experiment each – is estimated at

- 290 million EUR.

The incremental cost of the XFEL-laboratory is listed in table 4.2.1.

Component	Comment	million EUR
incremental cost for XFEL	RF gun, 500 MeV linac, upgrade of 50 GeV linac to 10 Hz (RF system and cryo system), bunch compressors, FEL and LC beam merging and separation, collimation, beam transport, electron beam abort system, civil construction, diagnostics	241
XFEL laboratory	Undulators, beam lines, experiments	290

Table 4.2.1: *Incremental cost for XFEL*

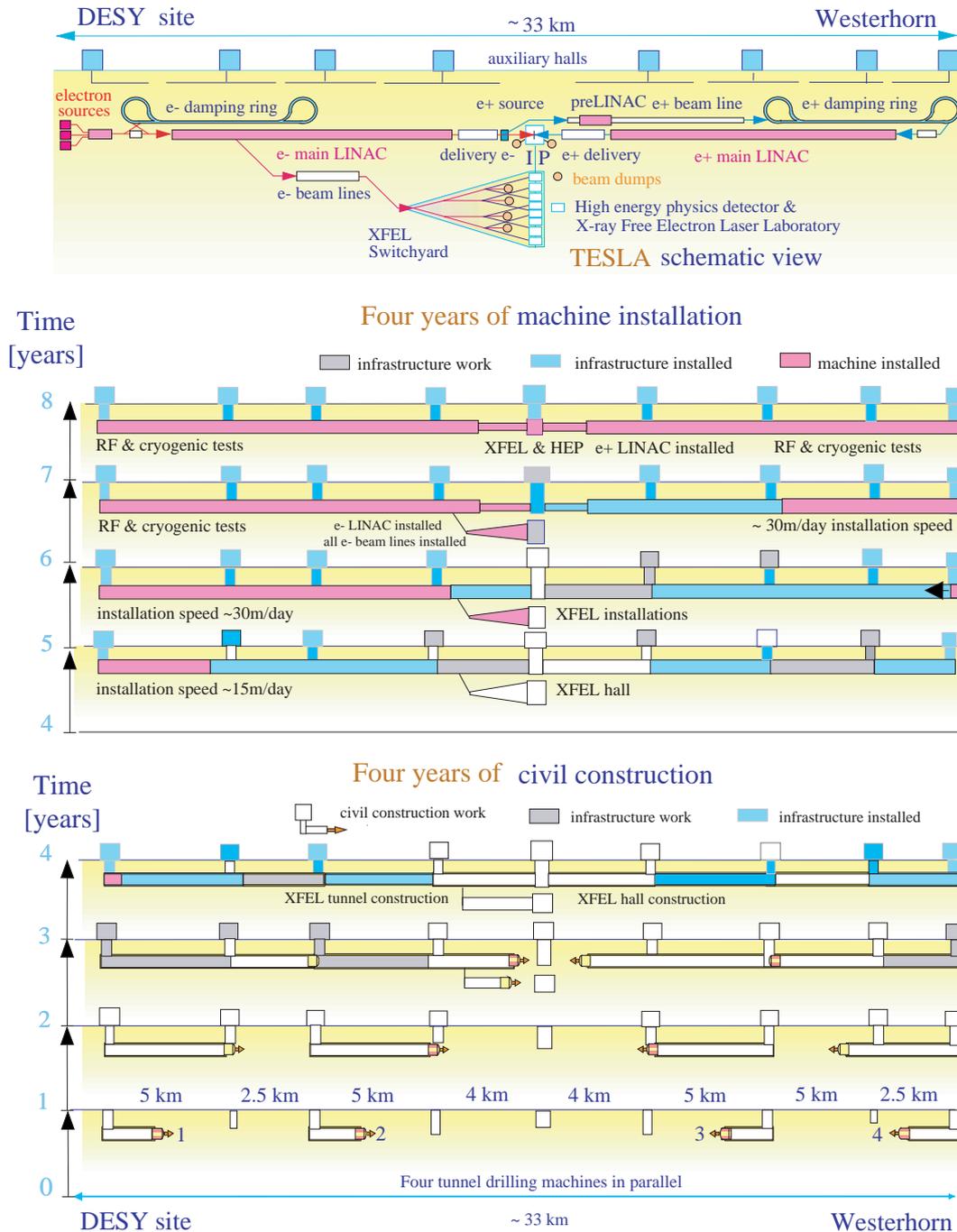


Figure 4.1.3: Time schedule of work for civil construction (bottom) and for the installation work (top). Tunneling starts from four points along the tunnel in parallel and proceeds towards the interaction region. Civil construction, infrastructure work, and accelerator installation happen concurrently at different regions in the tunnel.

4.3 A Detector for Particle Physics

The physics requirements have led to the design of a detector with a high magnetic field and a calorimeter of unprecedented granularity, as described in part IV. The cost estimates of detector parts are based on the experience with detectors already built or presently under construction for the LHC experiments.

Depending on the choice of technologies, the detector is priced between

- 160 and 280 million EUR,

including data acquisition system and detectors to measure beam energy and polarisation. The price bracket is mainly due to the different approaches to the electromagnetic calorimeter. The final price can only be decided after intense further development work, more simulation studies and after the collaboration has formed.

5 TESLA as an International Laboratory

5.1 Basic Considerations

Endeavours of the size and complexity of TESLA should be realised as truly international projects.

The OECD Megascience Forum report on "Particle Physics" of 1995 distinguishes four organisational models for future accelerators:

1. National and regional facilities are built, financed and operated by the host country or host region. Planning, project-definition and definition of parameters are done in international co-operation.
2. 'HERA-model': Large facilities which are not financed by one country or one region alone. The host country or host region receives contributions – mostly in kind – from participating countries or institutions. Planning and project-definition are done in international co-operation. The host country or institution is responsible for the operation.
3. Very large projects where construction and operation are realised through contributions in more equal shares by the participating countries or institutions. The partners contribute through components or subsystems in a similar way as large collaborations in particle physics are building jointly a major detector facility. A facility under this model would be the common property of the participating countries or laboratories. These would also share the responsibility and cost for operation.
4. Very large projects in the frame of an international organisation like CERN.

Model 2 was very successfully implemented for the construction of HERA at DESY, where the overall costs (excluding the DESY-infrastructure) were financed to 78% by the German Federal Government and the State of Hamburg, while major hardware contributions were made by collaborating countries.

For the TESLA project a larger international participation than for the HERA-project will be required. A possible approach is that of a 'Global Accelerator Network', which is based on model 3 and has the following features:

- The project is open for participation of international and national research and academic institutions.
- The project would be part of the national programs of the participating countries.
- The capital investments would be made under the responsibility of the participating institutions.
- The participating laboratories and institutes would be able to maintain and foster the scientific and technical in-house culture. They would remain attractive for young scientists and contribute at the same time to and participate in large, unique projects.
- The accelerator facility would be maintained and run to a large extent remotely from the participating laboratories, using the modern tools for communication and controls.
- This approach would effectively combine world-wide competence, ideas, manpower and financial resources.
- The site selection would become a less critical issue.

In order to make optimal use of experience, manpower and infrastructure, the accelerator built according to this model should be put close to an existing laboratory. The site selection would lead to specific financial obligations for the host country.

The 'Global Accelerator Network' is presently being investigated by the International Committee for Future Accelerators (ICFA), which has set up two specific working groups, one dealing with the general aspects of the model, the other with the specific questions of remote operation of accelerators. The recommendations and conclusions of these working groups are to be published in 2001.

The model described above is in principle applicable for the entire project and can assure for all parties involved the proper representation in the decision making processes. Special attention must be paid to balance the needs of the particle physicists and the users of the lasers.

The international nature of the project has to be reflected in its organisational structure. The international partners have to be fully and formally involved in all decision-making processes, as it is their project and not a project of the host country to which they contribute.

The concept of a TESLA project organisation with its own legal identity is considered to be the most appropriate and adaptable to the needs of the project. DESY offers to be the host laboratory for TESLA.

5.2 TESLA as Project of Limited Duration

Taking into consideration the scientific program as outlined in this report, the initial project duration should be 25 years, including 8 years of construction. After 10 years of operation a possible extension of the project should be decided upon.

5.3 Project Contributions

Each partner assumes responsibility for a specific component. The components are designed, built, tested, installed, operated and maintained under the responsibility of the respective partner. This responsibility for specific components is maintained throughout the project duration and includes also further developments. This allows national money to be spent according to the national rules and not as contribution to an international organisation which spends it according to its rules. It also makes sure that the volume of the financial involvement is directly linked to the technical responsibility of each partner. In addition contributions in manpower are possible and welcome.

It might be necessary that a small fraction of the project cost would be paid from a Common Fund to which each partner makes a financial contribution.

The cost of operation of the facilities will be shared among all partners according to a pre-defined procedure.

The mode of financing of the participating laboratories and institutes, including the host, would remain unchanged and their staff would remain employees of their individual institution.

5.4 International Project Convention

TESLA as an international project can only be realised on the basis of a long term involvement of the participating institutions and countries, which secure the financing and operation of the project. Basis for the project should therefore be an agreement between the participating countries or institutions (Project Convention) in which they declare their intention

- to construct and operate TESLA,
- to finance the project,
- to set up a project organisation, and

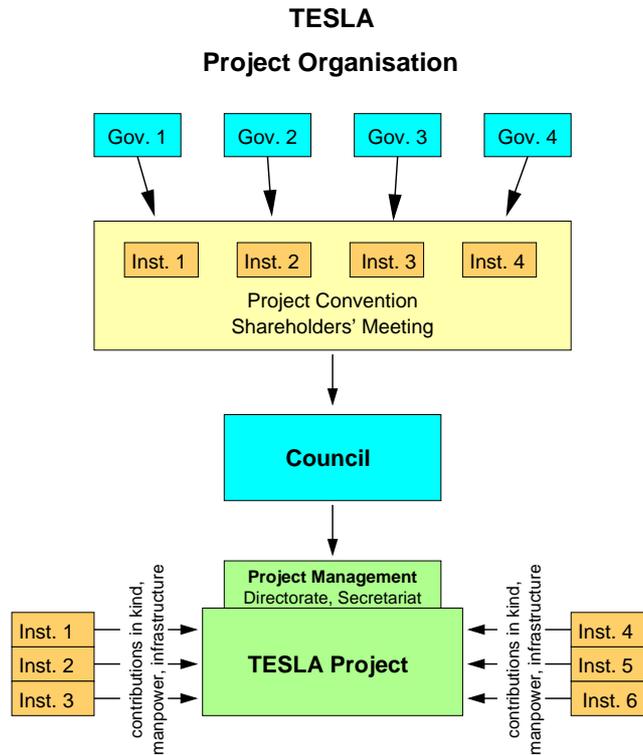


Figure 5.5.1: *TESLA project organisation*

- to define the basic rules (e.g. financing, purchasing, and settlements of disputes).

In view of the long-term and substantial involvement this convention should be signed by the governments of the participating countries or by bodies to whom the governments delegate their authority. Alternatively it could be signed by the participating institutes.

5.5 Legal Structure of the Project

As shown in Fig. 5.5.1 all partners form a shareholders meeting. Following the example of the ESRF the governments are either represented themselves in this meeting or they delegate their membership to one of their national participating institutes. The shareholders' meeting elects a council, which is the supervisory body for the project management. This basic structure is common practice in international scientific co-operation.

The project management will be responsible for the strategic planning, project co-ordination, external relations and supervision of tasks carried out by the participating partners or industries. It will be supported by a co-ordination team, a secretariat and project groups, responsible for their respective sub-projects.

The influence of each participant in the decision-making has to reflect the importance of its contribution. However, smaller partners will only identify themselves with the project if an effective minority-protection is organised. Here the rules of the ESRF can serve as an example. If the importance of the contribution is measured in shares, simple majority at the ESRF means at least 50% of the shares and the opposition of not more than half of the votes, each partner having one vote; unanimity means 2/3 of the shares and no opposition – abstentions always being possible.

The structure described above can be implemented in any national legal system, in Germany it would be a Gesellschaft mit beschränkter Haftung, GmbH, which corresponds to a Limited Liability Company in English and American Law.

5.6 The Specific Role of the Host Laboratory

In order to make optimal use of experience, manpower and infrastructure, the accelerator built according to this model should be put close to an existing laboratory. In this case, the host lab will make its infrastructure, personnel and services available to the project.

A well defined legal relation has to be established between the project management and the host laboratory. This can be done on the basis of a management- and service-contract, whereby the host laboratory assumes the responsibility for e. g.

- security, radiation safety
- site- and facility management
- technical infrastructure
- guest-services
- coordination of external communication/ media service.

The contract between the project management and the host laboratory must clearly define the respective responsibilities and obligations.

To ensure a close and smooth co-operation between the project management and the host laboratory a steering committee is proposed, with the directors of the project and of the host laboratory as members, chaired by the project-chairman and co-chaired by the chairman of the host laboratory.

6 Organisational Methods and Tools

From an engineering point of view, TESLA shares many features with other large-scale projects. With major contributions from many countries or institutions, TESLA needs a well defined project organisation and supporting methods and tools. Resources and responsibilities, also with respect to documentation, change management, and quality control, will be defined by the TESLA collaboration. Based on the experience with LHC at CERN and with large-scale projects in industry, the TESLA linear collider has to be described in its systems and subsystems. The full life cycle of TESLA has to be supported with consistent data. This includes design, construction and installation, commissioning, and operation of TESLA in the proposed 'Global Accelerator Network'. The present section summarises the methods and tools for information management, which are regarded as the technical basis for the project management at TESLA (see Fig. 6.0.1).

During the design, 3D mechanical CAD models of parts and complete systems, as well as 2D projections of these items, very likely from more than one mechanical CAD system, will be produced. These documents are used in all later phases of the project. Electronic CAD schematics, layouts, part lists, and many less strictly structured documents like preliminary construction and installation procedures, project plans, schedules and structures, contracts, meeting minutes etc. will be produced as well and need distribution. In terms of information management tools, the documents mentioned are accommodated in an Engineering Data Management (EDM) system. Such a system is evaluated in a pilot project at the TESLA Test Facility.

During construction and installation, information records per individual object, referring back to the appropriate design document will be collected. Quality control and documentation are main issues. The construction phase may provide feedback to the design documents yielding new versions and even unique versions for some of the individual objects. The documents of this phase are mainly accommodated in an Asset Management (AM) system for the individual objects and in a Facility Management (FM) system for the larger assemblies and for the buildings with their technical infrastructure as a whole. For both systems the requirements are set up at DESY and a pilot AM system is evaluated for information technology related assets.

In the operation phase, access to all of the documents mentioned above is needed. In addition, this phase requires efficient support for troubleshooting and maintenance. Documents include a complete object history in the information records per individual object, describing operational performance, faults, and replacements, detailed opera-

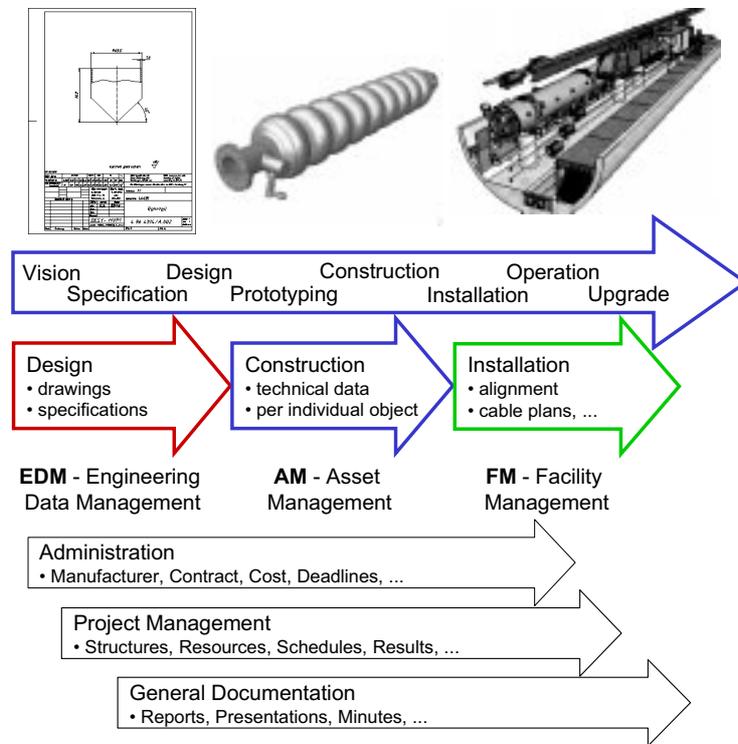


Figure 6.0.1: *Tasks supported by information management during the TESLA project.*

tion and maintenance procedures with associated workflow support, as well as relations of the individual objects' construction parameters to the accelerator control system parameters, maybe in the form of automated electronic interfaces. Possible future upgrade programs of TESLA will require access to the design documents for doing major revisions.

Apart from the EDM, AM, and FM systems, the organisation also requires standard project planning tools as well as a close connection to the administrative (financial) information management systems. In addition, the design data from the various CAD tools used must be viewed and checked for consistency by many persons in a CAD tool independent way, through inexpensive Web interfaces. The installation and maintenance personnel need supporting devices like barcode scanners for parts identification integrated with mobile computers for remote access to the information management systems as an example. The automated interface between EDM and the administrative standard software (SAP) in use at DESY, the viewing tool, and a barcode system are evaluated in pilot projects.

7 Site Considerations for the Construction of TESLA

The TESLA facility should be built at an existing High Energy Physics laboratory in order to reduce project costs and construction time. In the Conceptual Design Report of 1997 both DESY and Fermilab have been considered as possible sites.

Following up on this study a detailed plan for the TESLA site north-west of the DESY-Laboratory has been worked out for this Technical Design Report (see Fig. 7.0.1) and preparatory planning work has been pursued in close co-operation with authorities in the region. The tunnel of the linear accelerator starts at the DESY site in a direction tangential to the straight section West of HERA. The central research campus of the TESLA laboratory is situated about 16 km from the DESY site in a rural part of the North German State ("Land") of Schleswig-Holstein, and accommodates both the collider detector hall for Particle Physics, and the FEL radiation user facility.

In March 1998 the State Governments of Hamburg and Schleswig-Holstein signed a treaty to jointly prepare all the necessary planning steps and documents for the legal procedure (Planfeststellungsverfahren) which can start immediately after the project authorisation. The environmental aspects and the public participation are integral parts of this procedure. The state treaty has been ratified by both state parliaments.

7.1 Radiation Safety

The radiation safety requirements for the TESLA linear collider have been evaluated in detail. Different scenarios of beam losses were investigated. The radiation level has been minimised and is far below the natural dose.

The German regulations require that the maximum allowed personal dose due to direct radiation and radiation from radioactive release (activated air, water etc.) for the public does not exceed 1 mSv per year and for radiation from radioactive release alone to be less than 0.3 mSv per year. TESLA will stay below 1/10 of the above limits. This corresponds to a personal dose for the public of 0.1 mSv per year from direct radiation and radiation from radioactive release. In comparison, the natural doses in the northern part of Germany are about 1-2 mSv per year.

Our studies of the radiological impact on the environment were evaluated by two independent German institutes. They confirmed the internal analysis and made some suggestions for improvement which were included in the technical design.

7.2 General Safety Aspects

Safety of personnel and equipment in the tunnel has to be provided during construction, shutdown, maintenance, and operation of TESLA. The tunnel has segments between access shafts with a longest distance of 5 km. The resulting escape and access times largely determine the organisational and technical means for rescue as well as for fire protection:

- Access to the tunnel is restricted to instructed personnel.
- Fire loads are minimised and kept in compartments or small hermetic containers acting as fire compartments.
- Several levels of fire control and fire fighting are in place which react very early to keep fires well localised. The automated or remotely controlled levels foreseen include (1) component malfunction detection and early smoke detection, (2) cutting the electric power to components and (3) tunnel segments, (4) local fire control or suppression, and (5) remotely controlled fire fighting using the monorail trains. The final level includes human emergency intervention in the tunnel.

The experience gained with HERA in matter of safety is incorporated in the technical design. The technology available for tunnel safety is developing rapidly and TESLA will benefit from this development. Staff specially trained for rescue and for fire fighting in the tunnel as well as in the experimental halls will be made available.

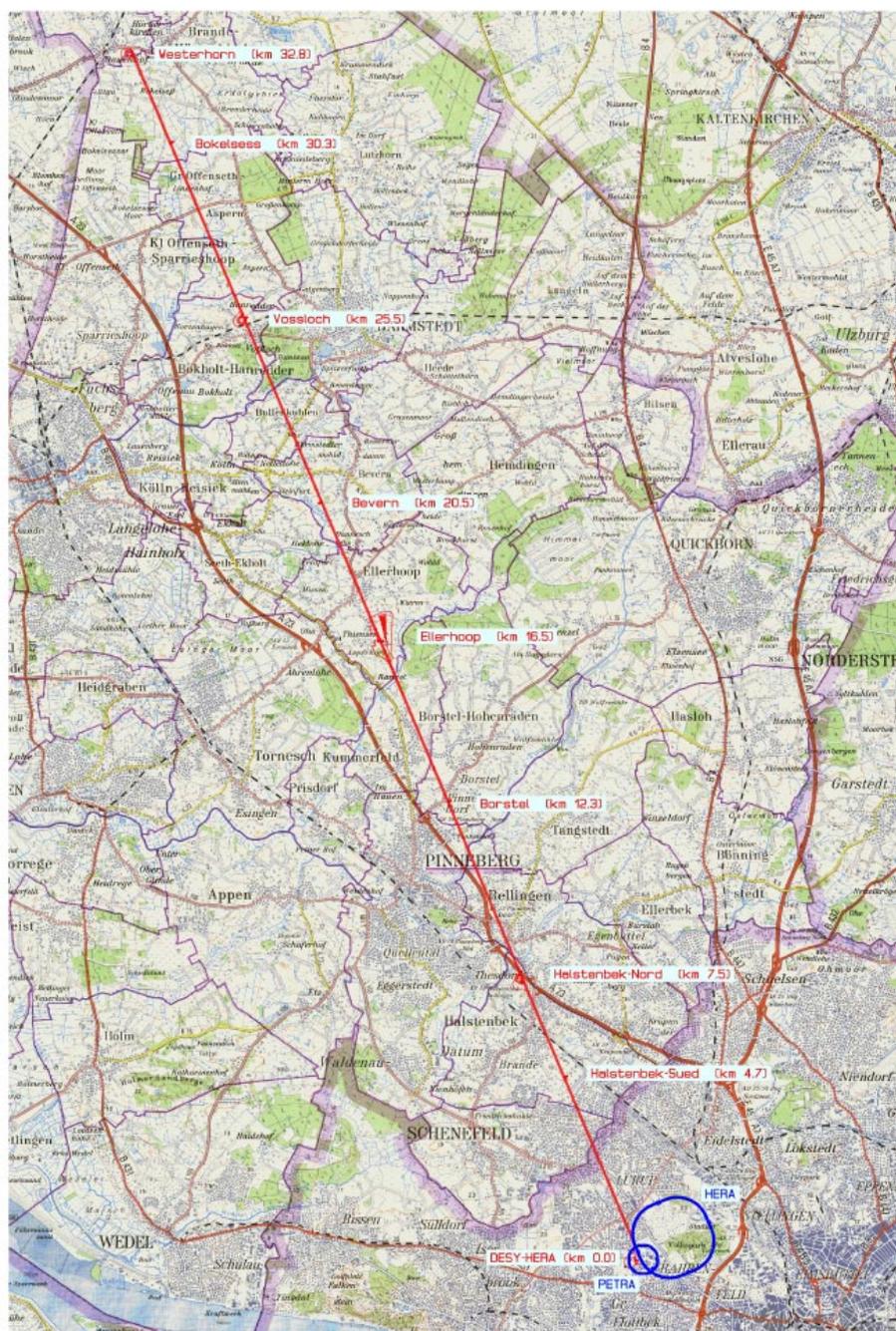


Figure 7.0.1: TESLA the region to the north-west of the DESY-Laboratory

8 The Next Steps

This Technical Design Report is the result of an intense collaboration of many scientists from around the world. As shown by the scientific and technical studies TESLA opens unique possibilities in particle physics and for research with the X-ray FEL.

By building and operating the TESLA Test Facility and the associated laser the TESLA collaboration has shown that the technology is at hand to build a 500 GeV electron-positron collider with an integrated X-ray laser. Results from an advanced R&D on superconducting cavities provide a credible path for an energy upgrade of the linear collider towards a total energy of 800 GeV. The test facility also provides an excellent basis for a reliable cost estimate, which has been worked out in detail by many experts.

The Deutsches Elektronen-Synchrotron DESY proposes to the international scientific community, to the German Federal Government and to the northern German state governments (“Länder”) to build TESLA in the vicinity of Hamburg.

In preparation of the German position concerning the approval of the TESLA project the German Research Ministry has asked the German Science Council (Wissenschaftsrat) to review TESLA together with other large scale projects presently under consideration. The Science Council is an independent body set up to advise the federal and state governments of the Federal Republic of Germany on matters of higher education and research policy. The planned large scale facilities include besides TESLA the European Spallation Source and a Heavy Ion Accelerator Facility.

In parallel to this evaluation a number of international review processes are taking place on a European and world-wide scale, addressing the long-term road map of particle physics, the scientific potential of an electron-positron collider and of X-ray lasers, the technologies for building linear colliders and XFELs, and models for building and operating large international research facilities.

This in-depth scientific and technical report on TESLA will provide the necessary input for these reviews.