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TESLA X-ray Free Electron Laser (TESLA X-FEL)

Note:

This statement given by a subgroup of the steering committee „Large research facilities for basic research“ of the German Science Council concentrates on the scientific and technical investigation of the project. The statement if the project should be funded or not is given by the Science Council itself by a final evaluation of all nine projects. This statement is given in a seperate report.

A. Introduction and Background

A.I Field of Research

Over the last thirty years remarkable progress has been made in X-ray science and its applications, largely stimulated by the availability of synchrotron radiation (SR) from storage ring facilities. In such storage rings, SR is emitted by relativistic electrons that are radially accelerated in a magnetic field. Modern synchrotron radiation facilities provide important tools for research in a large number of different fields of science, like physics, chemistry and biology as well as in material-, geo- and environmental sciences. So far, the pace of progress in the various fields of research has been closely tied to the development of synchrotron radiation sources for which the tunability, output power, brilliance and polarization are unmatched by any other short wavelength source.

SR was first regarded as an unwanted by-product of high energy storage rings and was first exploited for research in the late 1960s at SPEAR I (Stanford) and DORIS I and II (DESY). These facilities were followed by so-called 2nd generation synchrotron light sources (in Germany DORIS III at DESY, BESSY I at Berlin-Wilmersdorf and ANKA at Karlsruhe), dedicated storage ring facilities which produce the radiation in bending magnets and wigglers. In the 1980s and 1990s many 3rd generation synchrotron light sources were built (e.g. BESSY II at Berlin-Adlershof) in which periodic magnetic structures, so-called wigglers or undulators were inserted into low emittance storage rings. These undulators provide stable vacuum-ultraviolet (VUV) and/or X-ray beams and enhance the brilliance of the radiation by several orders of magnitude. Due to intellectual input by a large number of scientists the construction of low emittance storage rings has become a proven technology and the innovation at 3rd generation facilities is mainly in the design of undulators, beam lines and instrumentation.

The high brilliance micro-focus beams of 3rd generation synchrotron radiation facilities allow for new imaging techniques and micro-spectroscopy on the sub-micrometer length scale, as well as for protein crystallography on very small crystals. Microbeams are also used for interface studies revealing the internal atomic and electronic structure of nanoscale structures, liquid surfaces, catalysts, magnetic layers etc. First real time structural studies are reported down to picosecond resolution. Special efforts are made to provide hard X-ray beams of a high degree of lateral coherence in the 0.1 nm wavelength range. X-ray pulses in the femtosecond (fs) time domain have been produced at storage rings by means of a synchronized interaction of fs optical laser pulses with the electron bunches. Because these short pulses are generated by a slicing technique their brilliance is limited, however, further progress is expected.

Studies have been made for diffraction limited hard X-rays storage rings with a circumference of 2.2 km where one expects an additional gain of about 2 orders of magnitude in brilliance compared to 3rd generation facilities. Such very large storage rings may be considered the ultimate step in the development of this technology.

While the storage ring based sources with respect to brilliance, degree of coherence and pulse length approach their theoretical performance limit, the development of linear accelerators (LINAC), providing low emittance electron bunches of high energy, very short bunch length and high electron charge, has stimulated a world-wide effort to develop LINAC driven synchrotron radiation sources, especially X-ray free electron lasers (X-FEL). In the USA, the LINAC-driven LEUTL FEL at the Advanced Photon Source in Argonne was the first device reaching saturation in the SASE (Self Amplified Spontaneous Emission) process at wavelengths down to 385 nm. In this scheme, an electron beam with an extremely high density passes through a long undulator. The interaction with the electric field of the photons that are spontaneously emitted in the undulator causes a spatial modulation of the electron bunch. This in turn results in coherent emission of photons by the electrons in the bunch and thus leads to an amplification of the spontaneous radiation of the undulator by several orders of magnitude. The whole process occurs in a single pass and does not require an optical cavity with mirrors, thus the SASE-principle is well suited for X-rays. In 2000, by using the TESLA Test Facility (TTF) at DESY, laser light was generated for the very first time in the wavelength range from 80 to 180 nm. This proof of principle has stimulated intense activities in the field of short wavelength SASE FEL's world-wide.

The following table contains synchrotron light sources, storage rings (SR) and free electron lasers (FEL) that are presently being operated as well as FELs currently being under study. IR-FELs are not included in this list since these have developed into standard facilities world-wide by now:

Type	Name	Location (Start of operations)
2nd Generation SR (dedicated sources)	ANKA	Karlsruhe (2000)
	BESSY I	Berlin-Wilmersdorf (1981)
	DORIS III	DESY, Hamburg (1993)
	SPEAR II	SLAC, Stanford, USA (1982)
3rd Generation SR (undulator sources)	ALS	Berkeley, USA (1993)
	APS	ANL, Chicago, USA (1995)
	BESSY II	Berlin-Adlershof (1998)
	ELETTRA	Trieste, Italy (1993)
	ESRF	Grenoble, France (1992)
	MAX II	Lund, Sweden (1997)
	SLS	PSI, Villingen, Switzerland (2000)
	SPEAR III	SLAC, Stanford (2003)
	Spring-8	Harima, Japan (1997)
1st Generation SASE-FEL	LEUTL	ANL, Chicago, USA
	TTF I, II	DESY, Hamburg
2ndGeneration SASE-FEL (under study)	LCLS	SLAC, Stanford, USA
	TESLA X-FEL	DESY, Hamburg
	Soft X-ray-FEL	BESSY, Berlin

However, storage ring based synchrotron radiation facilities are expected to continue to play a crucial role in many different fields of science and will not be replaced by LINAC-driven X-ray free-electron lasers. The LINAC-driven light sources are still in the development phase and it will take several years and a large world-wide effort by accelerator physicists and potential users to develop the LINAC and the appropriate instrumentation before such a device will become a research tool of the reliability appreciated at modern storage ring facilities. By now many synchrotron radiation facilities see their long term future in adding LINAC-driven light sources to their existing storage rings and devote substantial R&D efforts to this new technology.

The two most important open issues for experimentation with X-FELs are the radiation load on a solid sample or even a single large biomolecule, and the huge signal (photons, electrons, or ions) emitted from the sample during a single 100 fs pulse. Although these aspects are not considered detrimental, they certainly require additional technological and experimental actions to be taken before X-FELs come into operation. Along these lines first ablation experiments have been performed recently at the TTF 1 FEL at DESY with 98 nm wavelength radiation with a peak power of 1 GW and a pulse duration of the order of 50 fs. The observed damage threshold for optical elements like mirrors is above the assumptions made for the layout of the VUV FEL user facility at DESY (TTF 2). In addition, first experiments have been performed on Coulomb explosion on free Xenon clusters using a focussing mirror which did not cause any problem. The development of suitable detectors with fast recording/readout times, sufficient resolution, and with the capability of accepting the large number of events occurring in a single pulse or a pulse sequence will be an important task for the potential X-FEL user community.

To complete the picture, the successful application of energy recovery (ERL) schemes in a superconducting LINAC of the IR FEL at the Jefferson Laboratory, USA, opens the possibility of single pass operation of undulators with low emittance electron bunches. The same concept is also being studied at Cornell University, USA, and could produce normal undulator radiation of higher quality with a peak brilliance expected to be 5 orders of magnitude higher than at present 3rd generation storage rings. Similar studies are being pursued at Brookhaven National Laboratory and Lawrence Berkeley National Laboratory, USA, as well as in Daresbury, UK. These ERL facilities offer a large variety of different options with respect to pulse duration and sequence and degree of coherence of the X-ray beams. The ERL's are expected to be cheaper than both 4th generation storage ring based sources and X-ray FEL multi-user facilities. ERL facilities could become available in 10 to 15 years and they have the potential to significantly extent the range of applications of X-rays in different fields of science. According to the proponents, LINAC-driven free-electron lasers, complemented by a number of ERL facilities, would be the long-term future of X-ray research.

German SR research has a long tradition starting with DESY in Hamburg almost 30 years ago. The German SR community had e.g. a strong impact on the construction and the usage of the European Synchrotron Radiation Facility ESRF in Grenoble, which is currently the most important facility of this kind in Europe. At BESSY in Berlin a LINAC-driven FEL facility for the VUV and soft X-ray wavelength range is planned. BESSY is member of the TESLA collaboration and relies on the accelerator technology developed by the TESLA collaboration. At DESY the TTF1 FEL is in operation at wavelengths around 100 nm. The TTF2 FEL for the VUV is currently under construction and will be available for users in 2004. In order to further improve the performance of the photo-cathode electron gun, a dedicated test station (PITZ) was built by a collaboration of DESY, BESSY, TU Darmstadt and the Max-Born-Institute at DESY-Zeuthen. An “Electron Accelerator of High Brilliance and Low Emittance” (ELBE) with a high power FEL in the infra red, driven by a TESLA type LINAC, is currently under construction at the Research Center Rossendorf (FZR).

In addition, important activities towards the construction of LINAC-driven X-FEL’s are pursued in Italy, mainly by institutions which are members of the TESLA collaboration. FEL’s for the spectral range of the VUV are discussed in Lund, Sweden, and at Daresbury, UK, and in the U.K., the possibility of constructing an ERL source related to the CASIM project is discussed. At SLAC in Stanford (USA) a new short pulse, high brilliance radiation source for hard X-rays, the “Sub-Picosecond Photon Source” (SPPS), has been proposed as a test facility, which will use the existing Stanford Linear Accelerator in its full length and could be in operation by 2003. The SPPS will provide 80 fs hard X-ray pulses allowing for high brilliance X-ray experiments. The Conceptual Design Report for the Linear Coherent Light Source (LCLS) at Stanford aiming for laser light at 0.15 nm is being prepared and funding for construction might start in fiscal year 2003, so that the first beam could be available in 2006/7. In Japan, an X-ray laser for wavelengths down to 3.6 nm is under construction at the Spring-8 site using a thermionic gun with a Cerhexaborid single crystal followed by slicing and the usual bunch compression techniques. In order to reduce the overall length of the FEL undulators the consortium of KEK and Spring-8 suggests very small (2 mm), short period, high field in-vacuum undulators.

A.II The Proposed Facility

II.1 Scientific Objectives and Research Prospects

The TESLA X-FEL is a coherent, tunable light source of extremely short wavelength (typically 0.1 nm) with an average power comparable to synchrotron radiation sources. The average and peak brilliance of the X-FEL exceeds any other existing X-ray source by 5 or 10 orders of magnitude, while the pulse duration is reduced by almost three orders of magnitude down to the 100 fs domain. The presently achieved time structure at TTF, with pulse lengths down to approximately 50 fs, is remarkable, but is still far from the theoretical limit, thus further developments into the attosecond regime are expected.

The science case for the X-FEL at TESLA focuses on time-resolved structural studies at atomic resolution using X-rays in the spectral range around 0.1 nm. It will also provide an FEL beam line for soft X-rays from 6 to 0.1 nm.

Time-resolved investigation of structural properties of short-lived states and of chemical reactions are expected to be possible. For example, the high flux could allow single shot experiments to investigate non-reproducible biological structures. The coherence of the photon beam is expected to open new opportunities for the investigation of dynamical properties of surfaces and interfaces, of soft-matter and liquids as well as for new imaging techniques.

II.1.1 Research Program

The research program planned at the TESLA X-ray laboratory has been established in a series of workshops focused on the various scientific fields. The proposed experiments utilize in particular the properties of FEL radiation available for the first time in the X-ray regime.

Atomic, Molecular and Cluster Phenomena

This field of research in particular benefits from the very large number of photons within a 100 fs long X-ray pulse. The X-ray burst will lead to multiple ionization of atoms and molecules and the photon energy provides the means to investigate deep inner-shell excitations. Processes like multiple core hole formation, multiple ionization of inner-shells, excitation and ionization of highly charged ions could be investigated in atoms. In molecules, multiple ionization and resonant elastic scattering are expected to lead to non-linear effects. In clusters, one would be able to study the processes of multiple ionization and fragmentation. Coulomb explosion is expected to take place in clusters and molecules at a certain stage of ionization. The X-FEL would allow the detailed investigation of this process, which is of crucial importance for single shot imaging of single bio-molecular complexes.

Plasma Physics

Plasma at or near solid state density can both be generated and investigated by means of X-FEL radiation. Because these plasma states always occur when plasmas are created from solid or near solid density targets they are also of high technological importance. Presently only limited information about these plasmas is available. With its intensity and photon energy the X-FEL could be used to investigate the phase diagram and the dynamics of such plasmas. Because fundamental plasma parameters, not accessible so far, could be determined by means of the X-FEL it is expected that a broad field of research in plasma physics will be opened. Using selective pumping of atomic excitations one could disentangle the processes of pumping and emission and study dynamic plasma state parameters which are important for the development of compact X-ray lasers. Finally, calculations have shown that the X-FEL pulse can generate very hot solid state density plasmas of up to a Gigabar pressure and several hundreds of eV temperature. Due to the high energy of the X-ray photons the excitation process differs fundamentally from the process induced by optical lasers.

Condensed-Matter Physics

The proposed experiments take advantage of the high peak brilliance and the high coherent flux. The aim is to investigate dynamical processes in time scales ranging from femto- to microseconds, in order to gain a deeper understanding of the formation of condensed matter in its very early stages. Attempts will be made to study the fastest processes in condensed matter, which are low-lying electronic excitations with time-scales ranging from attoseconds to a few femtoseconds. Calculations show that magnetic switching processes can be studied with the X-FEL.

Surface and Interface Studies

The X-FEL radiation could lead to a better understanding of several phenomena not yet accessible by experiment. These are e.g. transient states occurring during melting and solidification of surfaces, in laser-induced processes or in confined liquids. The dynamical properties of liquids, surfaces and soft interfaces can be further investigated using coherent spectroscopy methods to determine correlation properties. Using high resolution inelastic spectroscopy the investigation of low-dimensional collective excitations would become feasible.

Materials Science

In this field of research the X-FEL has been proposed to investigate structural transitions of complex matter. Today, hard X-rays allow the microscopic investigation of grains and grain boundaries in a static manner. Since the properties of complex materials are determined by the processes occurring during their production it is of interest to investigate these processes in real time. Present day X-ray sources do not allow such investigations, whereas the X-FEL would provide the necessary flux per time interval. For hard X-rays in the regime of 50-100 keV the use of spontaneous emission is proposed with a pulse duration of ~200 fs (FWHM) for time resolved studies of bulk properties of large samples. Other examples for materials research are the investigation of the dynamics of polymers applying coherence spectroscopy and the imaging of nano-particles, again using the coherence of the X-FEL radiation.

Chemistry

The main emphasis of the proposed investigations lies on the time-resolved structural investigation of solid- and liquid-state chemical compounds. The direct information about the structural processes during chemical reactions (bond lengths and bond angles) are presently only available for time-scales of nanoseconds or longer, but many fundamental processes are of much shorter duration. The X-FEL could match the time scale of these processes and therefore yield important information to complement spectroscopic information obtained by fs optical laser experiments. In addition to diffraction methods also absorption spectroscopy has been proposed using the inelastic Raman scattering of X-rays. This method would allow for the first time to investigate light elements (Be, Li, C etc.) without the constraint of studying samples under vacuum conditions.

Biology

Protein crystallography at synchrotron radiation facilities has become an indispensable tool for structural biology. Today the limitation of the technique is due to the need for crystallization. NMR in solution can only be used to solve structures of smaller and sometimes medium size bio-molecules. For the X-FEL it has been proposed to investigate large biological assemblies without crystallizing them. This can increase the applicability of the method of structural determination to a very wide range of non-reproducible biological structures, such as large virus molecules, membrane proteins or even entire living cells. The X-ray flashes from the X-FEL would interact with individual molecular complexes offered in a stream of free particles. The effect of radiation damage could be minimized by shortening the X-ray pulses. In addition, time-resolved studies of structural processes during biological reactions would be possible similar to what has been proposed for chemical reactions. Another application of the coherent X-FEL radiation could be imaging of cells and other biological structures of similar dimension.

Non-linear Phenomena and Quantum Optics

This field is presently dominated by optical lasers since X-ray sources of high enough flux and coherence are not available at the moment. This may change with the advent of X-FELs and experiments have been proposed to study fundamental processes like side-band excitation or phase conjugation. The cross-sections for these reactions will still be small, but calculations indicate that observation would be possible. Another prospect is to use the X-FEL photon beam to generate in matter a very high electric field leading to various fundamental physical processes that can be described by quantum electro-dynamics (QED). For these experiments extremely short and highly focused pulses are needed to generate the very high field strength.

II.1.2 Services

The X-FEL facility is planned as a multi-user facility with a number of dedicated beam lines serving the different needs of the various users. Auxiliary equipment like high power pump lasers, and equipment for special sample environment like cryostats and high pressure devices will be available to the users together with the required infrastructure. Researchers apply for beam time which is granted on the basis of the scientific excellence of the proposal. Users can expect services similar to those at existing synchrotron radiation sources like ESRF in Grenoble.

II.1.3 National/international Networks

Driven by the common goal and similar technical problems a world-wide collaboration has been established between the laboratories involved in building FEL's. The Global Accelerator Network, proposed for the construction and operations of TESLA, is by definition an international network which is outlined in the equivalent chapter on the TESLA linear collider.

A network has been established and funded by the EU to develop and implement novel hardware at the VUV FEL of the TTF. Further activities are planned to be implemented in the European network FEMTO, as well as in the national DFG-Schwerpunkt "Intensive Felder".

II.2 Technology

The proposed X-ray free-electron laser laboratory is planned as part of the TESLA project and is based on the SASE-principle. Bunches of electrons are generated by a dedicated laser driven source, compressed to a few micrometers in length and then injected into the superconducting accelerating structure of TESLA. The beams are accelerated to energies between 13 and 35 GeV over the length of 3 km, extracted into transfer lines to the beam switch yard which directs pulses of different energy to different undulators. The electron beams consists of trains of bunches produced at a repetition rate of 5 Hz. The first 3 km of the accelerator are shared between the X-FEL and the collider, but separate injectors are used and the RF system permits changes in power and pulse length from train to train. As a result beam parameters like emittance, energy, current, and time structure can be chosen separately for the two user communities.

The electron beam composed of bunches of high charge, small emittance, narrow energy spread and short duration is fed into the undulators of a multi-user X-FEL laboratory. The proposed X-FEL laboratory will consist of five FEL lines and five beam lines for spontaneous radiation, which will serve up to 30 experimental stations.

The X-FEL project relies on the development of low emittance, high current photocathode guns, superconducting cavities allowing flexible timing operation and reduction of wake field effects, and long, extremely precise undulator systems with novel beam diagnostics and controls. The innovative technology for the production of the electron beams is discussed in the equivalent chapter on the TESLA linear collider.

For the transport of the laser radiation from the undulator to the sample, novel schemes for the optical components, new lenses and mirrors are under development. For optimal use of the facility new strategies to avoid radiation damage and new detectors will have to be developed.

However, due to the sharing of the LINAC between the linear collider and the X-FEL continuous wave (CW) operation (operation with a pulse structure evenly distributed in time) is not possible.

The quality of the emitted radiation can be further increased by shortening of the pulse length, narrowing of the spectral line width and by providing shorter wavelengths. For this purpose additional space will be needed for optical elements (‘seeding’ with monochromatised light), for short pulse optical lasers and additional undulator modules. The present layout at the Ellerhop site provides sufficient space to realize such upgrades.

II.3 Transfer of Research Results

Transfer mechanisms through close relation with industry and technology transfer have been put into place at the existing synchrotron radiation facilities to enable private sector companies to use the facility and also to transfer knowledge from scientific staff to the private sector. Up to now, DESY has concluded co-operation agreements with five companies, which regularly use synchrotron radiation from the DORIS storage ring for their research. A number of optical and electronic components developed at DESY have been licensed to industrial companies, which offer the construction of complete synchrotron radiation beamlines.

R&D work on the TTF has already provided substantial experience on the type and possible utilization of knowledge that will be gained through research on TESLA. Novel technologies that are being developed for the accelerator are discussed in the equivalent chapter on the TESLA linear collider.

Spin-offs in the technological domain are expected from the R&D for the X-FEL ranging from improved magnet materials for undulators to highly sophisticated novel instrumentation, including fast data acquisition schemes and detectors. In order to support commercialization of these components the technology transfer office at DESY has established means of support, which range from the preparation of patents to provision of space and infrastructure for spin-off companies.

A.III The Institutions Participating in the Project

The international TESLA collaboration is based at DESY Hamburg. 263 scientists from 66 university institutes and from 48 research laboratories have developed the scientific case and the technical layout of the TESLA X-FEL, based on results of a series of eight workshops.

For more than 30 years DESY has gained experience in building and operating synchrotron radiation user facilities. Presently DESY is operating the HASYLAB synchrotron radiation sources, i.e. the DORIS and PETRA storage rings. In addition, the first VUV FEL world-wide is currently operating at the TTF 1. This self-seeding project for the VUV FEL user facility is realized by DESY and the GKSS in collaboration with Århus University. An EU-network including researchers from Dublin City University, Research Center Jülich, Lund-Laser-Centre, LURE, Max-Lab, Max-Born-Insitute (MBI), BESSY and DESY is currently developing a local facility for ‘pump-probe’ techniques with optical lasers which will be implemented at the TTF VUV-FEL. This facility is expected to allow the study of ultra-fast processes initiated by a high power optical laser beam.

The theoretical work by scientists from Samara and JINR Dubna in Russia (member of the TESLA collaboration) represents an important step towards the extrapolation of FEL’s into the X-ray regime. Self-seeding options and regenerative FEL amplifier schemes for producing beams of inherent coherence also in the time domain have been developed at DESY and are currently implemented at the TTF FEL or under construction.

The institutes participating in the project, their contributions and specific competence are presented in detail in the equivalent chapter of the TESLA linear collider.

DESY intends to work out detailed concepts for the undulators and the beam lines, including vacuum systems, monochromators, optics and diagnostics. Part of these components will be built in collaborations with other institutions: the X-ray optics is being designed in collaboration with scientists at SSRL in Stanford and at Lawrence Berkeley National Laboratory, whereas the soft X-ray beam line would be built in cooperation with BESSY. The development and construction of the individual instruments will be performed in close co-operation with national and international groups from universities as well as from extra-university institutions.

In the coming years, DESY expects a strong synergy between research and development for FEL’s and laboratory based compact laser systems. The well established collaboration with the Max-Born-Institute in Berlin-Adlershof for the development of the electron gun of the TTF VUV FEL would in addition play an important role in the construction of a pump-probe facility for the investigation of ultra-short processes.

A.IV Users of the Facility

The number of world-wide users of synchrotron radiation is presently estimated to be more than 20.000 scientists from many different disciplines. Scientists who aim to exploit the specific X-FEL radiation properties, which exceed the performance level of present-day synchrotron sources by many orders of magnitude, are potential users of the X-FEL. Specifically, the proponents foresee

- experiments with a temporal resolution better than ~50 picoseconds,
- experiments that need coherent X-rays, and also
- experiments that rely on the extremely high number of photons per single pulses.

The principal user groups are expected to come from structural biology, materials science, surface science, cluster physics, condensed and warm dense matter physics and fs chemistry. The synchrotron community considers the combination of Ångstrom spatial resolution with a 100 fs time resolution as the most interesting feature, which allows non-equilibrium states and fast transitions between different states of matter to be studied with atomic resolution. For the laser community, the most attractive features are the broad tunability and the high average brilliance of a short wavelength light source. Finally, the plasma community, already using highly specialized conventional X-ray lasers, would face a remarkable increase in repetition rate and pulse power, allowing studies of new domains in sample volumes and temporal evolution of plasmas.

The utilization of the laboratory would be similar to the use of HASYLAB at DESY and ESRF in Grenoble. However, since many new techniques have first to be brought to full potential the initial operation phase will be more like a development and testing period with strong user involvement. Potential users have been involved in the planning of the facility through a series of ten workshops which took place at DESY in 1999 and 2000.

The access to the facility for scientists from universities and other external scientists as well as the public relations of DESY are outlined in the equivalent chapters on the TESLA linear collider. In addition to the explanations on the training of the future generation of scientists, also summed up in the equivalent chapters on the TESLA linear collider, DESY states that in 2001 approximately 50 diploma and 120 PhD-students worked at the HASYLAB synchrotron source.

A.V Project Management, Location, Costs and Schedule

The proposed project management as well as the layout of the site are outlined in the equivalent chapter on the TESLA linear collider.

V.1 Costs

V.1.1 Costs for X-FEL development

Components	Total Staff (FTE)[1]	Capital Cost (million €)	Staff Cost[2] (million €)	Total Cost incl. Staff (million €)
R&D, construction of VUV-FEL	80	21,8	4,0	25,8

V.1.2 Cost estimates for X-FEL construction

The additional cost for the construction of the accelerator for X-FEL are estimated to be 241 Mio. €. This estimate is dominated by the civil construction of the experimental hall and the beam distribution system. The equipment cost for the undulators, beam lines and experimental set-ups are estimated to be 342 Mio. €. In addition, a total staff of 1,800 FTE will be needed to build the X-FEL facility.

Components	Total Staff (FTE)	Capital Cost (million €)	Staff Cost (million €)	Total Cost incl. Staff (million €)
Increment to TESLA[3]	662	241	33,0	274,0
X-FEL Laboratory[4]	1.145	342	57,3	399,3
Construction Total	1.807	583	90,3	673,3

[1] FTE= full time equivalent one man per year.
[2] The staff cost at DESY of 50.000 € for 2000 (average over all qualifications) has been used.
[3] Civil engineering of the FEL experimental hall and the beam distribution system.
[4] For a construction in stages over about 20 years.

Development and construction Total	1.887	604,8	94,3	699,1

V.1.3 Cost estimates for X-FEL laboratory operation[5]/a

It is estimated that 362 FTE per year will be required for the operation of the X-FEL laboratory. This compares to a staff of 509 at the ESRF. The recurrent and capital budget of the ESRF has been scaled according to this staff relation to derive an estimate for the other operation costs of the X-FEL laboratory.

Operation	**Capital Cost (1.000 €)**	**Staff Cost (1.000 €)**	**Total Cost incl. Staff (1.000 €)**
Staff	0	18.100	0
Recurrent	8.100		
Capital	9.900	0	0
Operation Total/a	18.000	18.100	36.100

The operation of the TESLA facility is planned in a Global Accelerator Network. The institutions will remain responsible for the components they have contributed to the common project and will supply the required manpower for the operation of their components. Assuming that DESY as host laboratory will take main responsibility for a substantial part of the investment costs of the accelerators and assuming further that DESY will have the responsibility for the civil construction, some of the infrastructure and auxiliary systems as well as a fraction of the accelerating modules for the linear accelerators, the present manpower at DESY would be sufficient for the operation of the linear collider and the accelerator part of the X-FEL. However, in order to meet the needs of the current synchrotron radiation user community a continuation of the HASYLAB storage ring operation in parallel to the construction and medium term operation of TESLA is planned. For this reason additional manpower will be needed at DESY.

For the TESLA X-FEL a funding scheme similar to what was realized at the ESRF in Grenoble is envisaged both for construction and operation of the X-ray laboratory. The organization of the interplay between the TESLA Global Accelerator Network and the X-FEL is not yet defined.

V.2 Schedule

The schedule of the whole TESLA-project covering eight years of construction is outlined in the equivalent chapter on the TESLA linear collider. In addition, the applicants state that after the first 10 years of construction 10 undulators, 10 photon beam lines and the first 4 experimental stations would be operational. To fulfil this schedule an early start of R&D activities for undulators and photon beam line instrumentation would be required. Construction and commissioning of the remaining experimental stations would stretch out over the following 10 years to reach the final goal of 30 stations for user operation.

The annual period of use is set by TESLA linear collider program, typically 5.000 hours of operation per year are foreseen, and the total length of operation for the facility is estimated to be 15 years or more, with periodic upgrades of the beamlines and experimental facilities.

[5] Operation of the accelerator part of the X-FEL is included in the TESLA linear collider operation.

B. Statement and Recommendations

B.I Field of Research

The world-wide interest in synchrotron radiation (SR) based research has been strongly increasing during the last decades. This results from the constant improvement of the SR sources quality. Since the first scientific exploitation of SR in the late 1960s, a gain of more than three orders of magnitude in brilliance has been achieved every 10 years. These technical achievements have opened up new fields of research. Today, the unique properties of SR enable research in a very large variety of fields like physics, chemistry, materials-, geo- and life sciences. However, traditional techniques, such as reactor based neutron scattering or spectroscopy at present synchrotron storage rings, face their limits of applicability. With regard to time resolution, brilliance and degree of coherence the development of SASE-based X-ray free electron lasers (FEL) will definitely enlarge current SR opportunities and furthermore open up new experimental methods and fields of research. However, FEL facilities will not replace present-day SR storage rings but rather complement them in multiple ways.

X-ray lasers are expected to play an important role in time resolved studies and in structural and functional analysis of large molecular complexes, which are crucial to the functioning of cells, but which are extremely difficult to crystallize and thus cannot be studied with present day SR techniques. There is no doubt that FELs will be able to provide radiation of the appropriate wavelength and time structure so that materials and the changes of their properties can be portrayed at atomic level in both space and time. Such devices are likely to revolutionize experimentation in many areas of research. The further development of the FEL-concept is essential because it will

- make possible an extension of existing techniques to ultra-short time resolution for structural studies;
- open up new domains in coherent radiation, time resolution, wavelengths, and intensity;
- allow for broad interdisciplinary research.

Since the international SR community is ready for new scientific approaches that will only become accessible with FEL facilities the sub-panel strongly recommends the implementation of the most advanced projects in the not too distant future.

German SR research has been for many years a highly successful multi-disciplinary activity. Germany has also gained international leadership in many areas that are crucial for the development and exploitation of large scale FEL facilities. Germany would certainly lose this world-wide head start in X-ray science if none of the proposed facilities would be implemented.

B.II Scientific Program

The envisaged scientific program is extremely strong and well defined. It is complementary to the scientific program of the proposed BESSY Soft X-ray-FEL. Both programs are at the forefront of international research and will certainly have a strong impact on basic as well as applied science.

The main strength of the X-FEL can be seen in the high spatial resolution in combination with ultra short time resolution that is especially appropriate for structural studies like ultra-fast dynamics in chemistry. New insights in the structure of materials will be possible that are e.g. crucial for materials science. Also, particularly important prospects at the forefront of international science are novel opportunities in nano-science (e.g. nano-manipulation), the generation and characterization of new non-equilibrium states of matter and the potential single-molecule imaging that willt revolutionize biological sciences. A large impact on both basic and applied scientific research is certain.

The scientific program as well as the technical characteristics of the TESLA X-FEL laser beam will be unique in Europe. The TESLA X-FEL is also the most advanced project on an international scale, though the LCLS in the USA will potentially be constructed sooner (by 2006). However, this facility will be less flexible due to its normal conducting accelerator technology and it will not support the large number of beamlines planned at DESY. Hence, it is unlikely that Europe will be able to get any substantial volume access to the LCLS since its few lines will be in very high demand in the USA. Japan will undoubtedly be active in this area, too, given its longstanding commitment to SR research and its excellent facilities such as Spring-8, but there is yet no proposed project of the magnitude of the TESLA X-FEL.

B.III Technology

The international TESLA collaboration is world-leading in the development of superconducting linear accelerators[6], RF components and LINAC-driven FELs. Furthermore, due to the enormous progress made by the international TESLA collaboration, Europe is now at the forefront of development of this new technology.

LINAC-driven X-FEL's promise a huge gain in brilliance and coherence as well as reduction of the pulse length to the femtosecond time domain. The TESLA Test Facility (TTF) has shown an excellent VUV and soft X-ray capability. The SASE-principle was successfully demonstrated at 100 nm, and the SASE theory is well in hand for 0.1 nm. The sub-panel believes that the more difficult tolerances at 0.1 nm can be achieved.

The TTF has shown that the undulator technology under development is of high quality. The TESLA collaboration is to be commended for their constant R&D on beam seeding, which will be an on-going effort during the whole project to improve beam bandwidth, pulse structure and pulse-to-pulse stability. The X-ray optics design will also present an on-going challenge. Efforts by the TESLA collaboration on further gun development are appreciated since gun improvements are necessary to achieve the design performance and progress in gun performance will cause advantages in design flexibility. In addition, the sub-panel is pleased to see efforts on further improvements of the beam splitting technology. CW operation of the cavities and micropulse switching will be very important for ultimate flexibility in the exploitation of the beams.

[6] See chapter on the TESLA linear collider.

There is a concern with respect to time-sharing of the particle physics community and the FEL-community on TTF 1 and TTF 2. Since it will be absolutely necessary to test the LINAC RF components under conditions suitable for FEL operation it should be guaranteed that the FEL-community is given sufficient time for R&D at TTF.

Superconducting microwave cavities are the most promising technology for building linear accelerators for a new generation of light sources. More suitable techniques do not exist for producing such high quality VUV and hard X-ray laser beams. DESY should be commended for its excellent superconducting development program which has demonstrated the high accelerating gradients, operational reliability and constructibility necessary for use in FEL LINACs and other applications.

LINACs are inherently flexible to accommodate modifications and upgrades. In addition, the TESLA collaboration has proven to be capable of moving rapidly to incorporate innovation.

B.IV Project Management, Location, Costs, Schedule

The sub-panel is strongly impressed by the international network that DESY has initiated by means of the international TESLA collaboration. This network stimulates a fruitful exchange of people and assures a strong interplay between experiment and theory.

DESY, having long-lasting experiences in planning and constructing large-scale facilities, is well prepared to not only host the X-FEL but also to take the main responsibility for its realization. For construction and operation of the TESLA linear collider and X-FEL facilities additional manpower would be needed. That would also mean an extension of infrastructures at the DESY site. However, these extensions would enable DESY to further strengthen its unique position as one of the major research centers in Europe that also can take leadership on an international scale.

It is essential that the X-FEL will be built in close proximity to an existing laboratory. DESY's outstanding technical expertise both in accelerator systems and hard X-ray science is judged to be a great advantage for the proposed location. The proposed

TESLA site is extensive and allows for a high degree of flexibility and possible later modifications of the X-FEL facility.

The geological conditions of the proposed location in Hamburg/Schleswig-Holstein generally seem appropriate for the TESLA project.

The sub-panel appreciates DESY's excellent track record on cost performance and is convinced that the DESY management will continue to examine and review costs in detail which is critical to the success of such a large project.

The proposed schedule for construction appears reasonable though further attention should be paid to this topic. The date of availability of the superconducting cavities will be, at least, a crucial milestone in the schedule.

The joint design and development of the TESLA linear collider and the X-FEL have so far resulted in a very fruitful synergy, in particular, it has attracted a large world-wide community that has contributed significantly to the challenging scientific and technical developments and the preparation of the proposals. However, the sub-panel welcomes steps already taken by DESY towards the development of a decoupled design and operation of the X-FEL and the TESLA linear collider. From an experimental point of view a decoupled version would give more flexibility and independence to both user communities since e.g. changes of configurations could be much better realized. Also, delays in the realization of the collider project could have unexpected consequences on the X-FEL construction. However, the sub-panel has every confidence that DESY can adapt to changing circumstances with respect to the linear collider so that the X-FEL project can be fully optimized for cost and performance and realized in a timely fashion.

The costs for the superconducting cavities depend significantly upon the linear collider. However, the sub-panel expects that the cost estimate on the LINAC components can also be realized if the construction of the TESLA linear collider took place at a site other than DESY. Still, the X-FEL and the linear collider would depend upon the same know how and maintenance personnel, so that an adjacent location might be the most efficient solution.

B.V Users of the Facility

The TESLA X-FEL will be open to international scientists on the basis of proposals following review and approval by an advisory panel. The main strength of this novel multi-user laboratory is its potential to enable new experiments in many different fields of research. The X-FEL is expected to attract large and diverse user groups from national as well as international research and commercial laboratories. There are large potential user communities world-wide that are particularly interested in hard X-ray studies.

DESY plans to provide instruction and support in the use of FEL beam lines, instrumentation and experimental set ups which is judged to be a very effective program for training of a wide range of users within different disciplines. In this regard DESY would be at the forefront of training a future generation of scientists.

The efforts of DESY to communicate the new technology as well as research goals and results to the public, schools and universities are outstanding. Also, in cooperation with the University of Hamburg DESY pursues a very effective recruitment program to encourage students to study natural sciences or engineering.

B.VI Transfer of Research Results

The research carried out at FEL laboratories is expected to contribute to the understanding of structural dynamics of plasmas and condensed matter which is barely accessible with present-day sources. This gain in knowledge is supposed to directly influence research activities in more applied and industrial research. It will be of special importance in the fields of bio-engineering and nano-science applications.

The sub-panel expects an enhanced technology transfer through joint development with industry, development contracts, licensing agreements and patents as well as a strong impact through novel applications and techniques on industrial and applied research.

Also, the FEL is a novel research tool that will have a strong impact on the design and development of technology and instrumentation, in particular lasers, precision tools and alignment, detectors and imaging devices.

C. Conclusion

The proposed TESLA X-FEL is a scientific facility of enormous potential which will support an outstanding and far reaching research program for many years to come. LINAC driven X-FEL's promise a huge gain in brilliance and coherence as well as reduction of the pulse length to the femtosecond time domain. The high spatial resolution in combination with ultra short time resolution are especially appropriate for structural studies. New insights in the structure of materials will be possible that are e.g. crucial for materials science. Also, the generation and characterization of new non-equilibrium states of matter and the potential single-molecule imaging will revolutionize biological sciences. The SASE-based X-ray free electron laser will open up new experimental methods and fields of research; a very large impact on both basic and applied scientific research is certain. However, FEL facilities will not replace present-day SR storage rings but rather complement them in multiple ways.

The TESLA-Collaboration headed by DESY is worldwide leading in the development of superconducting cavities. The technology for the VUV and soft X-ray range has been convincingly demonstrated at the TESLA Test Facility. The extension of this technology into the hard X-ray regime is judged to be feasible.

DESY, having long-lasting experiences in planning and constructing large-scale facilities, is well prepared to not only host the X-FEL but also to take the main responsibility for its realization. DESY's outstanding technical expertise both in accelerator systems and hard X-ray science is a great advantage for the proposed location. The sub-panel appreciates DESY's excellent track record on cost performance.

The subpanel welcomes steps already taken by DESY towards the development of a decoupled design and operation of the X-FEL and the TESLA linear collider. Delays in the realization of the collider project could have unexpected consequences on the X-FEL construction. From an experimental point of view, a decoupled version would give more flexibility and independence to both user communities.