WISSENSCHAFTSRAT

Drs. 5367/02
Berlin, July 12, 2002

Soft X-ray Free Electron Laser (Soft X-ray-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 longtime regarded as an unwanted by-product of high energy synchrotrons and storage rings and was first exploited for research in the late 1960s at SPEAR I (Stanford) and at the DESY I synchrotron and later in the 1970s, at TANTALUS (Wisconsin) and at DORIS I and II (Hamburg). These facilities were followed by so-called dedicated or 2nd generation synchrotron light sources (BESSY I at Berlin-Wilmersdorf , DORIS III at DESY, ANKA at Karlsruhe). These dedicated storage ring facilities of the 2nd generation produced the radiation still predominantly in bending magnets and wigglers, although a first in vacuum undulator and a crossed field undulator were operated in BESSY I as early as 1987 and 1991. In the 1980s and 1990s the 3rd generation synchrotron light sources were built in which wigglers or undulators were inserted into storage rings specially designed for low emittance (BESSY II at Berlin-Adlershof). These undulators provide stable vacuum-ultraviolet (VUV) and/or X-ray beams and enhance the brilliance of the radiation by several orders of magnitude. The construction of low emittance storage rings has become a proven technology and the innovation at 3rd generation facilities is by now mainly in the design of undulators, beam lines and instrumentation.

The undulator based beams at 3rd generation synchrotron radiation facilities not only deliver high brilliance beams for new imaging techniques and spectroscopy with nanometer resolution and for structural determinations of very small protein crystals, but also allow for a very flexible control of the polarization properties. The latter is extremely useful in the investigation of specific magnetic properties of matter. 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.

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

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 SASE - 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.

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 3 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. 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, followed by the first German dedicated synchrotron radiation source BESSY I and at the end of the 1990s by BESSY II, the first 3rd generation source in Germany. 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 for hard x-rays in Europe. At DESY Hamburg a LINAC driven FEL facility for the hard X-ray wavelength range is planned (TESLA X-FEL). At the TESLA Test Facility (TTF 1) an FEL is being operated 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, Technical University 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. 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.

A.II The Proposed Facility

II.1 Scientific objectives and research prospects

Following the successful demonstration of the SASE principle at the LEUTL free electron laser in Argonne (USA) and the TESLA Test Facility (TTF) at DESY Hamburg and based on the superconducting accelerator technology developed by the TESLA collaboration, BESSY proposes the construction of a SASE-type free electron laser for a spectral range of the VUV to soft X-ray (1.2 to 60 nm; 1keV to 20 eV). The Soft X-ray-FEL is planned to be built close to the BESSY II storage ring at the WISTA site in Berlin-Adlershof.

The Soft X-ray-FEL is expected to generate light-pulses in selectable pulse patterns which have a ten orders higher magnitude peak brilliance compared to present 3rd generation synchrotron light-sources. In addition, seeding the FEL will permit a substantial reduction of the pulse length reaching values of about 20 fs and possibly even as short as the attosecond range. It is also possible to synchronize the FEL with external lasers that will allow pump-probe experiments in order to investigate ultrafast phenomena such as electronic relaxation, magnetization and dissociation processes in condensed matter systems as well as in isolated species in molecular beams. The extreme brilliance of the FEL will convert directly into spectral, spatial and time resolution in spectroscopic and structural investigations unattainable up to now. Varying the focus of the high power photon beam, the load on the sample can be changed by six to eight orders of magnitude, thus setting parameters from high resolution investigations up to specific modifications of samples including fabrication of nanostructures. The mJ pulse energies of the FEL correspond to powers exceeding 5 GW opening up the field of study of nonlinear processes at photon energies in the soft X-ray range, whereas the pulses of coherent photons would allow new possibilities of imaging processes, microscopy, and holography.

II.1.1 Research Program

The proposed research programs of TESLA X-FEL and BESSY Soft X-ray-FEL address complementary fields of research. TESLA X-FEL offers hard X-rays whereas the BESSY Soft X-ray-FEL provides radiation from the VUV to soft X-rays which is the traditional spectral range of the BESSY scientific user community. According to the „Komitee für Forschung mit Synchrotronstrahlung“ the TESLA X-FEL would be especially useful for time resolved structure determinations whereas the proposed BESSY Soft X-ray-FEL would particularly enable studies of dynamical processes of electronic properties.[1] According to the applicants, the X-FEL would be able to determine the time evolution of the spatial structure of a system, while the BESSY Soft X-ray-FEL would clarify how the system functions and how its properties change dynamically. Pointing to discussions with prospective users who contributed to the scientific case of the BESSY FEL the applicants conclude, that the quasi CW pulse structure of the BESSY Soft X-ray-FEL would offer a significant advantage over the planned pulse structure of TESLA. The proponents also state that an extension of the TESLA X-FEL to lower energies could not offer comparable capabilities and would be even more expensive, especially if comparable facilities would be implemented.

BESSY proposes the following research program:

Femtochemistry: Understanding the dynamics and formation of a chemical bond

On the fs timescale the nuclei in a molecule or solid are "standing still". Typical vibrational periods are between 20 and several 100 fs. Therefore spectroscopy with fs time resolution allows to observe the effects of the motion of the nuclei on the electronic structure in a molecule, a solid, or adsorbate on a surface. In pump-probe

[1] Bericht des Komitees für Forschung mit Synchrotronstrahlung 2001.

experiments the development of the electronic states in a dissociating or desorbing molecule can be followed, yielding insight into the transition states and the nature of barriers determining the pathways for chemical reactions. Thus the dynamics of the complete electronic structure can be observed using photoemission as a tool.

Magnetization dynamics of nanostructures on the fs time scale

Magnetic data storage is continuously increasing in density and speed. In order to explore and expand the limits of this important technology, the BESSY FEL would enable studies of the magnetization dynamics of small magnetic nanostructures and clusters on the fs timescale in conjunction with nm spatial resolution. Dichroic effects in the soft X-ray regime are an ideal probe to monitor the magnetic moments with elemental specificity in space and time.

Atoms and molecules: New fundamental limits

Novel exotic states of matter can be prepared by Bose condensation of atoms in electrodynamic and optical traps. The BESSY-FEL would offer unique possibilities for spectroscopy and selective preparation or excitation of dilute assemblies and condensates of atoms in various traps. Thus elementary steps for the experimental realization of quantum computers may be explored. Furthermore, linear and non-linear interaction of radiation with atoms and molecules would serve to test very basic theoretical models with the highest possible precision.

The nature of complex solids

Until now, the mechanism of superconductivity in superconducting oxides is still not understood. In general, these oxidic materials exhibit a wealth of phenomena. Apart from the high temperature superconductivity of the cuprates this includes also the colossal magnetoresistance phenomenon of the manganates. These materials exhibit complex phase diagrams with interesting stationary and dynamic phases. Resonant inelastic soft X-ray scattering, which can also be carried out in the presence of magnetic fields, as well as electron spectroscopy with ultimate energy and momentum resolution hold the promise to furnish decisive data to resolve some of these mysteries of solid state physics. The BESSY Soft X-ray-FEL would enhance the resolution capabilities for electron spectroscopy and soft X-ray scattering by orders of magnitude in the spectral and spatial domain.

Dynamics in biological systems

The BESSY soft X-ray FEL would open the unique possibility to combine microscopy with a resolution in the nm range, spectroscopy with high energy resolution and accordingly high chemical selectivity, and a superb time resolution in the fs range in investigations of biological systems in their natural wet environment. This would open a new route to develop an understanding of functional systems such as ion channels, molecular motors and pumps embedded into cellular membranes. Furthermore, the dynamics of various steps in biological functional cycles in photosynthesis or in enzymatic reactions may be followed and resolved in real time. Radiation damage is a concern, however some of it may be alleviated by the fact that sufficient signal may be recorded within the timeframe of a single FEL pulse, faster than the important fragmentation processes are occurring.

Radical chemistry

Understanding the factors and key processes influencing the global change in climate is one of the most important scientific problems of present times. The chemistry of radicals as well as photophysical reactions on the surfaces of suspended nanoparticles play an important role in understanding the processes and interactions in the upper atmosphere. The FEL, possibly in conjunction with a storage facility for ions, would be a new spectroscopic tool to study these processes, reaction pathways, cross sections and the formation of elusive chemical species. Furthermore, the FEL is expected to open fascinating prospects for the study and the simulation of the processes and reactions occuring in interstellar clouds in the presence of intense VUV and X-ray radiation.

Clusters as new materials

Clusters of almost any element of the periodic table may be assembled with an exactly defined number of atoms and thus open the pathway to new materials tailored with unprecedented precision. The fullerenes are presently the best known example of such cluster materials. Upon condensation the fullerenes form a semiconducting solid, the third modification of carbon next to graphite and diamond. Upon doping the C_{60} solid, superconductivity has been observed at transition temperatures exceeding 30K and 50 K respectively. Until now, mass resolved clusters can only be produced and studied in molecular beams using lasers, because of their low density. Consequently, with a few exceptions, for individual clusters neither the atomic geometry nor the electronic structure has been determined. The FEL with a photon energy range in the VUV and soft X-ray range and pulse energy comparable to present day lasers would be a unique tool for the characterization of these new materials.

Ultra high resolution spectroscopy

The dramatic increase in brightness of the FEL would open up the possibility to perform investigations of the electronic structure with resolutions much better than 1 meV corresponding to the thermal energy scales (K).

New perspectives on catalysis

Spectroscopy of catalysts under ‘real conditions’, i.e. under a gaseous atmosphere or submerged into a liquid is one of the visions to advance research in catalysis from the study of model systems towards real catalysts. Photons are able to penetrate this environment and to carry spectroscopic information. Using sum frequency generation (IR + VUV), for example a specific vibrational mode can be detected originating at a specific atom selectable via the chemical shift of its core electrons. Resonant inelastic X-ray scattering is another probe that allows to distinguish the electronic structure at atomic centers according to their chemical environment, promising new insights about local electronic interactions at the reaction centers in this complex environment with a high potential for impact on industrial technology.

Materials and processes observed under technologically relevant conditions

Electrochemical reactions, thin film growth, corrosion, and friction are, apart from catalysis, technologically and economically highly relevant processes, where surfaces are in contact with a gas or a liquid. The FEL photons have sufficient intensity to penetrate this liquid or gaseous environment. This would open the field for spectroscopic investigations of these surfaces under process conditions using the methods of resonant inelastic soft X-ray scattering for the investigation of the electronic structure with not only elemental but even chemical specificity.

Characterization of fusion plasmas

The diagnostics of elementary processes in fusion reactors rely on the analysis of the characteristic radiation emerging from the reactor. Important parameters for these diagnostics are absolute cross sections and lifetimes of highly excited states of multiply charged ions, which are currently only partially known. Using the FEL a reliable database may be established in studies of dilute plasmas or on ion beams to provide a better understanding and diagnostics for the development of this future energy source.

Environmental chemistry and analysis

Chemical and biological processes occurring at the complex interfaces between organic and anorganic matter, aqueous solutions, and gases control the composition of the environment and determine the migration and toxicity of pollutants in the biosphere. Understanding these processes and their dynamics at the molecular nm size scale in their natural environment is a key factor for the development of better models for the spreading and to develop better strategies for environmental remediation. Soft X-rays from the FEL would uniquely enable a characterization of these systems and processes in their natural state with nm spatial and sub ps time resolution.

Nanofabrication of materials using soft X-rays

Materials with a structural size on the nm size scale offer unprecedented possibilities for atomic scale engineering of materials which is synonymous for tailoring the electronic, optical, magnetic, chemical or even mechanical properties. Already today, thin film systems, where one dimension is reduced to the nanometer size scale, form the basis of the high tech electronics and information industries. Laterally or even 3-D structured materials with controlled features in the nm range are still a challenge for the future. At the BESSY FEL, corresponding to a wavelength limit as short as 1.2 nm, feature sizes may be realized that would be much smaller than envisioned for the next step in industrial applications of EUV Lithography (at 13.5 nm). Furthermore, the FEL, where the high power is concentrated in an extremely narrow spectral range, would be an ideal source for nanolithography.

New frontiers in time resolved spectroscopy

Intrinsically the FEL has pulses about 200 fs in length. Advanced seeding concepts which have been explored in close collaboration with the Max Born Institute Berlin (MBI) hold the promise to reach pulse lengths shorter than 20 fs. Ultimately for soft X-ray pulses the time resolution could be pushed into the as region, far beyond the limits of lasers at photon energies in the visible optical spectrum. These timescales correspond to electronic scattering processes for highly excited electronic states or to the lifetime of core electron excitations, which are typically <10 fs.

II.1.2 Services

The Soft X-ray-FEL is planned to be operating as a multi user facility in parallel to the BESSY II light source. The facility is expected to be operated for two periods per year of five months duration each, 7 days per week, 3 shifts per day.

Services at BESSY II include:

- development, construction, and access to highly advanced undulator sources and beamlines providing monochromatic synchrotron radiation and support in using these beamlines;
- development of experimental techniques and support in using these beamlines;
- characterization of optical elements for the soft X-ray range.

Users have the choice of installing their own experimental stations for their specific experiments or of making use of CRG or BESSY owned end stations with standard experimental equipment. In addition, BESSY offers scientific advice for preparation of experiments and infrastructure support. It also assists users with logistics, temporary housing etc.

For the operation of Soft X-ray-FEL, BESSY expects that in a close co-operation with user groups special experimental endstation equipment, such as a microscope facility for wet samples of the life sciences, atom or ion traps, a cluster beam facility and others would be installed for certain time periods at one of the FEL stations. Additionally, through a collaboration with the MBI, state of the art fs-lasers in the IR, visible, and near UV photon energy range would be made available for pump-probe experiments with extensive scientific, technical and engineering support from BESSY.

Services relating to the operation of the Soft X-ray-FEL are planned to be outsourced as widely as possible, such as the operation of the user guest facilities, the servicing of technical infrastructure and possibly the full operation and maintenance of the cryogenic system for the superconducting linear accelerator.

II.1.3 National/international Networks

Being a member of the TESLA collaboration since 1998, BESSY is involved in the layout of beam lines for the X-FEL and the preparation of pump and probe experiments as well as in the development of a cluster beam facility for electron spectroscopy on mass selected clusters in a molecular beam at TTF. In addition, BESSY together with DESY Zeuthen and the MBI is currently working at the Photo-Injector Test Stand at Zeuthen (PITZ), which represents a test program for the implementation of both the TESLA X-FEL and the BESSY Soft X-ray-FEL. DESY and MBI are also partners in an EU project with the goal to design, construct and test a synchronized visible light laser at the TTF for pump-probe experiments.

BESSY and the Hahn-Meitner Institute Berlin (HMI), a shareholder of BESSY, have signed a co-operation agreement in November 1998 to intensify the scientific and technological co-operation with strong emphasis on R&D at their large-scale facilities. Following the by now almost completed design and construction of two insertion devices and beamlines for altogether eight synchrotron radiation experiments at BESSY II, HMI and BESSY have decided to work together on the FEL project in order to further strengthen Berlin as a center of excellence in condensed matter research and the life sciences.

The Soft X-ray-FEL is supposed to be integrated into the “Verbundforschung” of the Bundesministerium für Bildung und Forschung (BMBF). On the European scale the FEL is planned to be part of the program “Large Scale Facilities” like BESSY II.

BESSY is in the process of establishing additional collaborations with other synchrotron radiation facilities. The applicants state that such facilities would contribute manpower and/or hardware to be used for the construction of one of the optional FEL lines. BESSY also expects that research groups of the Deutsche Forschungsgemeinschaft (DFG), which have recently been established or are presently being established in the general field of fs spectroscopy of solids and clusters, would be highly interested in the BESSY Soft X-ray-FEL project.

II.2 Technology

The main components of the proposed Soft X-ray-FEL facility are a laser driven pulsed electron source ("photoinjector"), a superconducting CW–linear accelerator, beam compression optics and undulators feeding the experimental beamlines. The electron bunches from the photoinjector are compressed and then injected into the rf cavities for acceleration to 2.3 GeV. The electrons then reach the undulators that feed various photon beam lines. The BESSY Soft X-ray-FEL will have three beamlines at the beginning, and five beamlines in the final extension, with two experimental stations at each beamline and two to four additional undulators. These additional undulators will produce photon pulses by spontaneous emission for pump-probe studies, intrinsically synchronized with the FEL pulses, with a beam quality and intensity significantly better than the values attainable at present synchrotron radiation sources.

One important strength of the proposed facility would be its high flexibility to deliver photon pulse patterns due to the CW operation of the superconducting LINAC. This would require an increase of cooling capacity in the cryomodules for the superconducting cavities of the TESLA design of about 20% which could be realized by a modification of the existing design. (The superconducting technology is outlined in the equivalent chapter on the TESLA linear collider and the X-FEL.) BESSY plans to test these design modifications at its own test facility in 2003.

The proponents do not consider the relatively small number of six to ten SASE experiment end stations - a consequence of the SASE technique itself - a weakness, as the new experimental techniques to be developed require larger and highly experienced groups to tackle the challenges starting from high power optics to elaborate sample environments and time resolved detection schemes with high throughput and high speed data acquisition. The limited spectral purity and the irregular time profile of the SASE photon pulse, which is due to the build-up of the pulse from the spontaneously emitted radiation, is expected to be overcome by sophisticated “seeding” techniques which will be tested in one version of possible implementations at the TESLA Test Facility (TTF) in the coming years. For the BESSY FEL, additional seeding concepts by externally generated pulses are envisioned, originating from high harmonic generation of fs visible laser pulses. A successful implementation of this seeding scheme could open the pathway to a new generation of ultra-short (20 fs or less) pulses of controlled shape and phase, similar in quality and control as offered by present fs laser systems in the visible and near UV photon energy range, but with about 6 orders of magnitude higher pulse energy.

The high peak power levels delivered at the output of the Soft X-ray-FEL require further research concerning the stability of the optics and of condensed matter samples. By varying the focus of the beam a wide range of adjustments (6 to 8 orders of magnitude) can be achieved. Furthermore, experiences from the laser community, where similar power loads are presently produced (though at much lower photon energies), might give additional guidance.

After constructing and commissioning the basic facility a number of extensions and performance improvements would be possible that could be realized without major changes of the available building space. The brilliance of the Soft X-ray-FEL could be further enhanced to deliver highly flexible, low energy spread fs-photon pulses by:

- increasing the number of SASE undulators from three to five with a corresponding increase in the number of experimental stations from six to ten;
- adding three more spontaneous emission undulators;
- implementing a superconducting CW photoinjector to enable the use of the full flexibility of the CW LINAC in order to choose variable pulse repetition frequencies according to the experiment's requirements;

- increasing the micro pulse repetition frequency to expand the average photon flux by several orders of magnitude. This would require energy recuperation for RF power and radiation safety reasons.

II.3 Transfer of Research Results

Like the TESLA X-FEL, the Soft X-ray-FEL is expected to have an impact on superconducting accelerator techniques, including the construction and operation of large cryogenic facilities. The Soft X-ray-FEL would also require high performance laser systems at visible and UV wavelengths for various key components and experiments such as the laser for the photocathode gun, lasers for external seeding of the SASE process, and synchronized lasers for pump-probe experiments. The BESSY FEL with a 1KHz repetition rate would match existing high power fs lasers. Improving the performance of those state of the art laser systems is expected to also have an impact on future laser applications. In addition, optical components for high power loads of soft X-rays would be useful for EUV lithography which is being considered by industry as production tool for future generations of micro- and nanoelectronics.

New optical components developed for Soft X-ray-FEL are expected to be marketed by the OpTecBB, a network of business companies and research centers in Berlin-Brandenburg that co-ordinates development and utilization of new optical technologies in order to strengthen those regional scientific and economical activities.

Furthermore, it is expected that the Soft X-ray-FEL would have an impact on information technology, including magnetic and holographic data storage, chemistry and catalysis, the bioscience and health sector via time resolved imaging of processes in cell biology, and also the energy sector in connection with both solar cells and fusion research.

Concerning expected spin-offs the applicants state that the campus Berlin-Adlershof, managed by WISTA, was explicitly created to support small start-up companies.

During the construction phase of BESSY II, several companies were founded, which now market various products under license agreements with BESSY world-wide.

A.III The Institutions Participating in the Project

The BESSY GmbH was evaluated by the German Science Council in 1994. It certified that BESSY is a service institution with high national and international reputation as well as high scientific potential.[2]

BESSY can look back to more than 20 years of experience in developing, constructing and operating synchrotron radiation facilities starting with the first German dedicated synchrotron light source BESSY I in Berlin-Wilmersdorf and continuing with BESSY II in Berlin-Adlershof. BESSY also points to its recently acquired in-house experiences with fs lasers and pump-probe spectroscopy. Currently, BESSY is active in the preparation of pump-probe experiments at TTF. In addition, for the PITZ project at DESY Zeuthen BESSY has contributed fast (ps) photon beam diagnostics, a time correlation photon beam set-up, electron intensity and pulse shape diagnostics, software modules of data analysis, magnets and power supplies.

Following institutions participate in the project:

- Hahn-Meitner Institute, Berlin (HMI)

  The HMI is one of the 15 members of the Hermann von Helmholtz Association of National Research Centers (HGF) in Germany. It is working in the field of solid state physics and materials sciences, its R&D-activities being Structural Research and Solar Energy Research. The HMI is very experienced in building and operating large-scale facilities. BER II, a 10 MW research reactor with widely diversified instrumentation for neutron scattering, provides neutron beams for structural and materials research. The Ion Beam Laboratory (ISL) generates high

[2] Wissenschaftsrat: Stellungnahme zur Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung (BESSY). 11.11.1994: „BESSY II bietet (...) günstige Rahmenbedingungen sowie ein leistungsfähiges Umfeld für Nutzergruppen aus dem gesamten Bundesgebiet, stellt aber auch einen spezifischen Beitrag zur internationalen Weiterentwicklung der Forschung mit Synchrotronstrahlung dar. (...) Die Hauptaufgabe der BESSY GmbH liegt in der Bereitstellung eines anspruchsvollen Angebots an Serviceleistungen für externe Nutzergruppen und deren Experimente.“

energy ion beams that are used for analyses of surfaces and internal structures of solid matter. At BESSY, HMI initiated the installation of especially designed insertion devices and is responsible for several beamlines and instruments being currently under construction that are supposed to complement the research activities at BER II and ISL.

- DESY, Hamburg

  For a characterization of DESY see the equivalent chapter on TESLA X-FEL. BESSY extensively relies on DESY's competence in the development and industrial fabrication of superconducting accelerator modules and on its expertise in SASE technology.

- Max-Born-Institute (MBI)

  The MBI focuses on basic research on and with short-pulse lasers and pursues applications in emerging key technologies. Its competence and experience in the field of high power, ultra short pulse lasers for photoinjectors and seeding techniques at FEL's is essential for the BESSY Soft X-ray-FEL project as well as for TTF.

University scientists are also involved in the planning of the Soft X-ray-FEL, e.g. from the University of Technology Dresden, Institut für Energiemaschinen und Maschinenlabor, Lehrstuhl für Kälte- und Kryotechnik. This institute has influenced the cryotechnique layout of HERA and TESLA at DESY and is active as a subcontractor co-operating with BESSY in the field of cryotechnique for the superconducting accelerator.

In addition, scientists from German, European and north American universities and research institutions as well as from several "Sonderforschungsbereiche" at universities in Berlin have contributed to the scientific case of the Soft X-ray-FEL which was outlined in two workshops in 2000 and 2001. More than 70% of the international participants were scientists from German or European universities.

Presently, the in-house research at BESSY is being expanded, following the recommendations of the German Science Council. The additional research activities are focused on the following three fields:

- clusters and cluster based materials;
- magnetic thin films and nanostructures;
- development of soft X-ray elastic and inelastic scattering methods for the investigation of novel materials and processes.

These three areas are chosen to match the capabilities at the existing BESSY II facility and are fields of science that would benefit from the planned Soft X-ray-FEL. Pump-probe experiments with fs timing are now being carried out using visible lasers and in the near future soft X-rays at BESSY II. These experiences would be transferred to the Soft X-ray-FEL.

The HMI places special emphasis on providing outstanding sample environments covering a wide range of temperatures and, in particular, magnetic fields. (For further information on the HMI see the equivalent chapter on the proposed High Magnetic Field Laboratory for Neutron Scattering Research.)

The MBI focuses on the development of novel light sources and applications at short wavelengths (present commercial lasers extend to 157 nm), at higher average power (beyond typically ~10W for short-pulse lasers), and at shorter pulse durations (sub-fs), all with improved compactness, efficiency and user-friendliness. In this respect the interests of the MBI are complementary to BESSY.

A.IV Users of the Research Facility

The potential users are expected to come from the present BESSY user and laser community (about 600 scientists from 150 national/international research groups). In the course of several workshops BESSY and its user community have identified fields of research that would particularly benefit from the extreme brilliance combined with fs-pulses of the Soft X-ray-FEL.

In Berlin, there are currently several “Sonderforschungsbereiche” based at universities that could scientifically benefit from the new facility (SFB 290: “Metallische dünne Filme”; SFB 429: “Molekulare Physiologie, Regulation und Energetik des Primärstoffwechsels höherer Pflanzen”; SFB 450: “Analyse und Steuerung ultraschneller photoinduzierter Reaktionen”, SFB 546: “Struktur, Dynamik und Reaktivität von Übergangsmetalloxid-Aggregaten”).

For access to the facility the following approved procedure would be applied: BESSY will call for research proposals semi-annually. All proposals would be treated equally regardless of origin of the applicants or the funding source. In a first step, BESSY scientists will check the technical feasibility of all submitted proposals, given the available beamlines and instrumentation. At the next stage all feasible proposals will be sent to an independent expert panel for evaluation of scientific merit. Each proposal will be reviewed in detail by several panel members and based on the ranking and the recommendations of the panel beam time will be scheduled.

IV.1 Scientific Education

Many of the experiments are usually carried out by graduate students and postdocs who are trained by BESSY scientists. Seminars on the scientific program are scheduled regularly. In the past more than 1.000 scientists and engineers have been educated and trained at BESSY. The majority of these young scientists have joined high tech companies in the field of information technology (semiconductor technology, software), chemical industry, automobile industry, optics suppliers as well as small and medium-sized enterprises and consulting agencies. In addition, a substantial number of scientists and engineers have pursued academic careers. More than 30 faculty positions so far have been awarded to scientists who performed their research predominantly at BESSY.

IV.2 Public Relations

Groups from publicly funded institutions, universities, industrial companies and school classes regularly visit BESSY. In order to further inform the general public, BESSY regularly arranges open house events. On these occasions, BESSY presents its activities in exhibitions and lectures and organizes tours of the facilities ("Tag der offenen Tür", "Lange Nacht der Wissenschaften", "Forschungstage", "Wissenswertes Wochenende"). In January/February 2002 BESSY presented the Soft X-ray-FEL project at the automotive industry pavilion of the Volkswagen corporation in Berlin. In addition, BESSY is currently preparing an educational program for schools.

A.V Project Management, Location, Costs and Schedules

V.1 Project Management

BESSY plans to follow the same concept that has been applied during the BESSY II construction phase between 1993 and 1998. There will be three major divisions:
M) accelerator and buildings;
E) undulators, beamlines, and experimental equipment; including scientific planning jointly with the user community
V) project administration and controlling.
Each division will be headed by a member of the BESSY directorate who will take responsibility for the budget and will allocate the funds according to the budgetary plan and the allocations by the funding agency. There will be internal oversight by the BESSY control group and external reviews by the department of the Bundesministerium für Bildung und Forschung (BMBF).

Scientific and technical activities of BESSY are regularly evaluated by a Scientific Advisory Committee (SAC) that meets at least twice a year. The SAC plans to form a Machine Advisory Subcommittee and a Program Advisory Subcommittee and will be involved in the evaluation of the TDR.

The BESSY directorate will be responsible for maintaining continuous operation and will appoint the heads of the machine operation and the experimental services groups.

V.2 Location

The Soft X-ray-FEL is planned to be built on the 64.000 m^2 BESSY-site in Berlin-Adlershof next to the synchrotron source BESSY II. BESSY is owner (free of charge) of long-term building rights for the site and holds options for a further extension.

The complete infrastructure and technical expertise of the BESSY research center would serve the users of the proposed Soft X-ray-FEL. Another advantage of this location is the close vicinity to the natural sciences campus of the Berlin Humboldt University and various institutes of the Adlershof WISTA-site such as the Max-Born-Institute and the Ferdinand-Braun-Institut für Höchstfrequenztechnik.

V.3 Costs

V.3.1 Cost estimates for Soft X-ray-FEL development

Components	**Total Staff (FTE[3])**	**Capital Cost (million €)**	**Staff Cost (million €)**	**Total Cost incl. Staff (million €)**
R&D	43,5	3	2,1	5,1

V.3.2 Cost estimates for Soft X-ray-FEL construction[4]

The total cost for the BESSY FEL is estimated to be 148 Mio. €, according to FY 2001 pricing. This estimate has been based on the final costs of BESSY II as well as on information obtained from the TESLA project. It is judged by the proponents to be accurate within 15%. This figure includes operating costs during the construction phase. Of the total of 300 FTE, 125 FTE are BESSY personnel.

[3] FTE = full time equivalent one man per year.
[4] Cost estimates are based on FY 2001 pricing.

Components	Total Staff (FTE)	Capital Cost (million €)	Staff Cost (million €)	Total Cost incl. Staff (million €)
Civil Engineering	–	25,5	–	–
accelerator, undulators, beamlines	–	104,6	–	–
Operating costs during project phase	–	4,1	–	–
Construction Total	300	134,2	13,8	148,0

Development and construction Total	343,5	137,2	13,8	153,1

V.3.3 Cost estimates for Soft X-ray-FEL operation/a

Operation	Capital Cost (1.000 €)	Staff Cost (1.000 €)	Total Cost incl. Staff (1.000 €)
Staff[5]	–	2.300	
Electricity	3.300		
regular replacement or refurbishing	2.700		
maintenance	4.100		
Operation Total/a	10.100	2.300	12.400

Although much of the operating know-how from the present operations crew of BESSY would be also available for the Soft X-ray-FEL, special expertise in the field of superconducting RF, gun-laser operation, and sophisticated diagnostic methods would be needed for operation. Therefore, besides having persons on call for these three additional fields (“supervisors”), one extra control room operator would have to be on duty. Altogether 20 operators and supervisors would have to be recruited from the project personnel to permanently secure operation of the FEL.

The experiments at the FEL would be at a level of sophistication that far exceeds present-day experiments at synchrotron radiation sources. Apart from the FEL

[5] 50 persons in addition to the present staff of BESSY II needed for the operation of the Soft X-rayFEL.

beamlines, synchronized lasers for pump-probe experiments would be required. Furthermore, the experimental end stations would be more complex with sample environments ranging from high to low temperatures, UHV to high pressures, magnetic fields, aqueous environments for living cells, or ion beams and atom traps. This would also require a dedicated scientific and technical support staff with various skills. The Soft X-ray-FEL initially would have three and later on optionally five beamlines which are planned to be operating in parallel. At each line two experimental stations would time-share the FEL beam on an 8-12 hour shift basis. Based on the personnel that supports experiments at the ESRF the applicants expect that for operation of the FEL one scientist and two post-docs for each experimental station would be needed as well as a technical engineering staff pool of 12 engineers/technicians with skills covering tasks such as UHV, electronics, mechanical design, optics, computing/data acquisition and fs-laser technology.

In order to finance the Soft X-ray-FEL project BESSY will apply for funding to the BMBF and the Berlin Senatsverwaltung für Wissenschaft, Forschung und Kultur (SenWFK) expecting that funds would be shared in the ratio of 90% (BMBF) to 10% (SenWFK).

The development of the high frequency photoinjector for linear accelerators (PITZ) is already financed by BMBF with an amount of 0.580 Mio € for a three year period starting in July 1999. In addition, the development of a cluster beam facility for electron spectroscopy of mass selected clusters as well as the design for a soft X-ray monochromator at the TTF FEL is funded by the BMBF "Verbundforschung"-program in 2001-2004. The State of Berlin is currently funding the R&D planning group on the Soft X-ray-FEL for a 3.5 years period. The funding amounts to 2.4 Mio € including investment costs of 1.175 Mio € for developing prototype equipment. In addition, the project on a visible/UV laser system synchronized with the TTF FEL for pump-probe experiments is being funded by the EU (1.2 Mio € for 2000-2003).

The central investments in cryogenics and accelerator structures are designed for manufacturing in close contact with industry.

V.4 Schedule

A study group funded by the „Zukunftsfonds des Landes Berlin” is presently working on the detailed R&D issues for the project and the preparation of the Technical Design Report (TDR) which will be submitted by end of 2003. Considering a construction phase of four years, the experimental program is expected to start in 2008.

Date	**Construction**
until end of 2003	working out of a detailed TDR by the FEL study group
2004	start of project
2005	- detailed planning of hardware components - civil engineering - procurement of accelerator components
2006-2008	- installation - commissioning of systems
2008	start of scientific program

The date for the availability of industrially produced superconducting accelerator modules which are being designed by DESY will be of great importance to the proposed schedule. The applicants expect that the undulator sections produced by industry and measured and shimmed at BESSY would be available in time. The in-time availability of the buildings to allow installation and commissioning of the cryogenic supply systems as well as early system tests on the superconducting linear accelerator is also a crucial point.

Details concerning planning, construction, time of commissioning, and periods of utilization remain to be analyzed by the study group.

The total period of operation of the facility would be at least 15-20 years.

B. Statement and Recommendations

B.I Field of Research

See Statement and Recommendations on the TESLA X-FEL.

B.II Scientific Program

The planned scientific program of the Soft X-ray-FEL is extremely strong and well defined. It is complementary to the scientific program of the TESLA X-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 technical features of the proposed VUV and soft X-ray FEL at BESSY will be a tremendous improvement of current facilities like SR storage rings and conventional lasers. It will extend existing techniques to ultra-short time resolution for investigations of the electronic structure of matter. Nano-scale magnetic phenomena, for instance, can be analysed in an unprecedented precision. Also, the Soft X-ray-FEL will allow for significant progress in the analysis of surfaces and interfaces, e.g. ultra-fast processes in catalytic reactions. Compared to the TESLA X-FEL the spatial resolution of the Soft X-ray-FEL will be lower and the lower energy of photons will e.g. provide better opportunities to follow chemical processes on an individual molecule.

Concerning the scientific program and the technical characteristics of the laser beam the TESLA X-FEL as well as the Soft X-ray-FEL will be unique in Europe. Both facilities will open up new domains in coherent radiation, time resolution, wavelenghts and intensity and allow for a broad interdisciplinary research that certainly extends current X-ray science.

B.III Technology

As a member of the international TESLA collaboration, BESSY is involved in the design of beam lines and the injector for the X-FEL as well as in the preparation of pump and probe experiments at TTF. The proposed Soft X-ray-FEL will use the TESLA superconducting cavities. (For the TESLA-technology see Statement and Recommendations on the TESLA X-FEL.) The Soft X-ray-FEL will be operated, however, in continuous wave (CW) mode. Given the space available at the BESSY site, an accelerating gradient of 15 MV/m is compatible with the maximum electron energy required for the spectral range of the Soft X-ray-FEL.

The sub-panel is convinced that BESSY in collaboration with the MBI will overcome remaining uncertainties concerning seeding. Special R&D on undulators which is also needed is well underway at BESSY.

B.IV Project Management, Location, Costs, Schedule

Over the last 20 years BESSY has become one of the major synchrotron radiation sources world-wide in the VUV and soft X-ray domain. It is well experienced in developing, constructing and operating large scale facilities like BESSY I and II. BESSY is especially successful in femtosecond laser research as well as pump-probe spectroscopy. Also, the already existing collaboration with the MBI will be of special importance to the proposed Soft X-ray-FEL since the MBI brings in a unique expertise in laser development and laser applications.

It is essential that the planned facility will be built in close proximity to an existing laboratory. BESSY's outstanding expertise in VUV and soft X-ray science and the possibility to combine the Soft X-ray-FEL with the BESSY II SR source are judged to be a great advantage for the envisaged location. The BESSY site is adequate for the proposed facility with, however, limited room for expansion and upgrades.

For construction and operation of the Soft X-ray-FEL facility additional manpower would be needed. That would also mean an extension of infrastructures at the BESSY site. However, these extensions would enable BESSY to further strengthen its leading position in this field of research on an international scale.

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

The costs for the superconducting LINACs depend significantly upon the TESLA linear collider. The sub-panel expects that some cost savings on the LINAC components could be realized if TESLA is constructed on the current schedule. However, for the BESSY Soft X-ray-FEL with only a 2.2 GeV LINAC, the total savings would not be a significant fraction of the project cost.

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.

B.V Users of the Facility

The Soft X-ray-FEL will be open to international scientists on the basis of proposals following review and approval by an advisory panel. Like the TESLA X-FEL, this facility is expected to attract large and diverse user groups from national as well as international research and commercial laboratories. In particular, the large scientific community that has been working at the BESSY storage rings for many years is strongly interested in the new opportunities of soft X-ray science that will become possible with the Soft X-ray-FEL.

BESSY will provide training and support in the use of beam lines, instrumentation and experimental set ups thereby strongly contributing to the training of a future generation of scientists in different fields of research. Also, the sub-panel welcomes BESSY's effort on integrated seminars and lab courses for university students in order to integrate universities like the Humboldt-University in the FEL-project.

In order to attract the general public and to encourage students to study science or engineering BESSY is currently developing educational material for high schools. This activity is highly appreciated by the sub-panel.

B.VI Transfer of Research Results

See Statement and Recommendations on the TESLA X-FEL.

C. Common statement on TESLA X-FEL and Soft X-ray-FEL

The sub-panel strongly supports both FEL projects from the scientific as well as the technical perspective. In terms of technical characteristics of the laser beams as well as the scientific research opportunities both facilities will be unique in Europe.

The future FEL user community would best be served by a scientific program that is developed in close collaboration by the TESLA X-FEL and the Soft X-ray-FEL teams, since both teams have a very high degree of unique and largely complementary expertise. It is highly recommended that the DESY and BESSY laboratories commit to jointly develop an overall strategic roadmap for the realization of FEL beams that is adaptable to the changing circumstances and future developments. The combined expertise in accelerator systems, VUV, soft and hard X-ray-science is necessary to optimize R&D on FEL facilities. By a close collaboration redundancies will be avoided and the overall cost can be reduced.

It should be examined how the cost-benefit relation of providing FEL radiation to the diverse user communities would depend on whether there is a single facility providing beams over the entire spectrum or two facilities, each optimized to cover a narrower spectral range.

The technical design and the R&D have advanced to a stage that the proponents should proceed with the detailed design of experimental facilities that will provide the capability to explore the full energy spectrum, from the VUV to hard X-rays, over a wide range of intensities. There are many challenging components that need to be designed, built and commissioned before continuous operation of the FEL facilities will be possible. Extensive R&D, prototyping and tests under realistic conditions will be needed and should be undertaken in close collaboration of DESY and BESSY.

D. Conclusion

The technical features of the proposed BESSY Soft X-ray FEL will be a tremendous improvement of current synchrotron radiation (SR) and conventional laser facilities. The Soft X-ray-FEL will provide laser like, coherent radiation with extremely short light pulses that have a many orders of magnitude higher brilliance and peak power than any present SR source. It will extend existing research techniques to ultra-short time resolution for investigations of the electronic structure of matter. The Soft X-ray-FEL will enable studies of dynamical processes, e.g. ultra-fast processes in catalytic reactions. A large impact on both basic and applied scientific research is certain.

Compared to the TESLA X-FEL the spatial resolution of the Soft X-ray-FEL will be lower; the lower energy of photons will e.g. provide better opportunities to follow chemical processes on an individual molecule.

BESSY's outstanding expertise in VUV and soft X-ray science and the possibility to combine the Soft X-ray-FEL with the BESSY II SR source are a great advantage for the envisaged location. BESSY is well experienced in developing, constructing and operating large scale facilities like BESSY I and II.

The proposed Soft X-ray-FEL is based on the TESLA superconducting LINACs. BESSY is a member of the international TESLA collaboration and is involved in the design of beam lines and the injector for the TESLA X-FEL as well as in the preparation of pump and probe experiments at the TESLA Test Facility. The costs of the superconducting LINACs will significantly depend upon the TESLA linear collider.

It is highly recommended that DESY and BESSY commit to jointly develop an overall strategic roadmap for the realization of FEL beams that is adaptable to the changing circumstances and future developments. The combined expertise on accelerator systems, VUV, soft and hard X-ray-science is necessary to optimize R&D on FEL facilities. By a close collaboration redundancies will be avoided and the overall cost can be reduced.