TESLA XFEL - An Executive Summary

A technical design has been developed for a laboratory dedicated to the scientific applications of X-ray free-electron laser (XFEL) radiation in user experiments. The TESLA XFEL laboratory comprises an injector, a superconducting 20 GeV electron linear accelerator, an electron beam distribution switchyard, five undulators for FEL and synchrotron radiation and an experimental hall with ten experiments. XFEL radiation of unprecedented peak brilliance and full transverse coherence is provided in the wavelength range of 0.1 to 6.4 nanometer (corresponding to a photon energy range of 0.2 to 12.4 keV) with the option to reach a wavelength of 0.086 nm. The pulse duration is of the order of 100 femtoseconds. The laser-like X-ray FEL radiation will provide unique research possibilities for condensed matter physics, chemistry, materials science, and structural biology.

Introduction

The technical design of the TESLA XFEL laboratory described in this report is based on the TESLA Technical Design Report (hereafter quoted as TDR-2001) for a 500 GeV linear collider with an integrated XFEL laboratory, published in March 2001. The 2001 design of the TESLA XFEL laboratory has been modified and now includes a dedicated electron accelerator in a second tunnel. This design removes the constraints of the shared operation of one accelerator for both the linear collider and the XFEL operation and provides higher flexibility to both parts of the TESLA project. On the other hand, the additional accelerator and the required tunnel building lead to higher costs. In order to build the TESLA XFEL laboratory within the total incremental costs for the XFEL laboratory as given by the TDR-2001, a design is proposed with an accelerator at reduced maximum electron energy and with a partial installation of the XFEL laboratory. However, the properties of XFEL radiation for the present design do not differ significantly from those described in TDR-2001. The synergy effects of building both the XFEL and the linear collider with the same accelerator technology and of operating and maintaining the accelerators with the same personnel are not effected by the new scheme.

Effectively, the present design can be understood as phase-I of the full-scale laboratory described in TDR-2001. This first phase includes about half of the undulators, photon beamlines and experiments, as well as half of the buildings for the electron and photon beam switchyard and the experimental hall. Phase-II is not discussed in any detail in the present report, but the design of the TESLA XFEL laboratory described in the present report provides a high degree of flexibility for an extension to the full-scale laboratory at a later time.

Scientific and Technological Scope

XFEL radiation is expected to have a strong impact in a wide range of scientific domains ranging from atomic and cluster physics, via plasma physics and condensed-matter physics to chemistry and structural biology. The peak brightness and ultrashort duration of X-ray FEL sources will allow the investigation of dynamical properties, the resolution of time-dependent structural changes, and the investigation of transient states in many systems, often for the first time. The coherence of XFEL radiation will enable to use new scattering and imaging techniques in the investigation of single particles, disordered matter, and of nanomaterials. All this information is widely inaccessible at present. Due to its particular properties XFEL radiation is regarded to be a complementary source to synchrotron radiation and other X-ray sources used today.

To achieve the XFEL radiation performance presented below several technological goals of the project have to be fulfilled. These are concerned with the performance of the electron beam, in particular its emittance, and the performance of the X-ray optical elements guiding the FEL radiation to the experiments. The realization of the linear accelerator in superconducting technology combines several advantages for the generation of high-power low emittance electron beams with a high efficiency to convert electrical energy to beam power. The aim is to accelerate electrons to energies around 20 GeV while preserving their emittance and pulse duration, to steer the electron beam through long magnetic structures, so-called undulators, to generate XFEL radiation in the undulators by self-amplified spontaneous emission (SASE), and to guide the XFEL radiation to the experiments. The successful operation of the TESLA Test Facility (TTF) accelerator and the initial FEL experiments have demonstrated that the challenging goals of the proposed TESLA XFEL project can be met because of the advances made both in technology and understanding of the science.

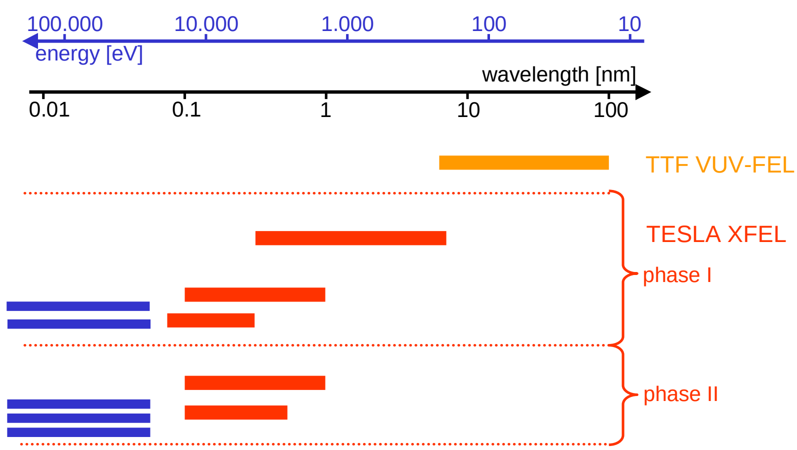

Figure 1: *Wavelength ranges covered by the various FEL undulators at the VUV-FEL at TTF, DESY Hamburg, and the TESLA XFEL. Red and blue bars represent undulators for FEL and short-pulse synchrotron radiation, respectively.*

Variable	Unit	Value		
electron energy range	GeV		10-20	
electron bunch length (rms)	fs		80	
electron bunch charge	nC		1	
normalized emittance	mrad mm		1.4	
uncorrelated energy spread (rms)	MeV		2.5	
photon pulse length (FWHM)	fs		100	
photon energy	keV	0.2	3.0	12.4
wavelength	nm	6.4	0.4	0.1
number of photons per bunch	$\times 10^{12}$	430	20	1.2
peak brilliance	$\times 10^{33}$	0.06	1.7	5.4
peak power	GW	135	100	24

Table 1: *Performance goals for the electron beam (top) and FEL radiation (bottom) at the TESLA XFEL. Peak brilliance is given in common units of photons / (sec·mrad^2·mm^2·0.1 % bandwidth).*

The wavelength range for FEL radiation covered at the TESLA XFEL is indicated in Fig. 1. It can be seen that the longest wavelength is of the order of 6 nanometer, which is the shortest possible wavelength for the VUV-FEL at TTF, and that the shortest wavelength will be in the hard X-ray regime at 0.1 nm or slightly below. Table 1 lists the most important performance goals for the electron beam and the XFEL radiation. Due to the progress made in increasing the performance of the accelerator cavities it is expected to reach 15 keV photon energies in a later stage. In Fig. 2 the peak brilliance of XFEL radiation is shown as a function of photon energy. A comparison to the most recent synchrotron X-ray sources shows the drastic improvement of peak brilliance at the FEL sources. The proposed performance of the LCLS project in Stanford, U.S.A. is very similar to that of the TESLA XFEL, which, however, provides a higher average brilliance. In Fig. 2 also the peak brilliance for spontaneously emitted radiation at the TESLA XFEL is indicated, showing that the photon energy range for ultrashort pulse X-ray radiation extends to several 100 keV.

Layout of the Facility

Most of the installations will be on the proposed site for TESLA in Ellerhoop, 16 km northwest of DESY, Hamburg. Only the linear accelerator to generate the high performance 20 GeV electron beam will be outside this area. It is installed in a 3.7 km long tunnel starting from a shaft building that is adjacent to the cryo building for the TESLA linear collider in Borstel-Hohenraden. The accelerator tunnel at 8 m below sea level goes straight to the Ellerhoop site, where it ends at the beam distribution switchyard. This switchyard contains the electron and photon beamlines, the undulators, and the electron beam dumps. To optimize several constraints, the switchyard was inclined so that the experimental hall at its end is situated at ground level. Figure 3 depicts the layout of the accelerator and switchyard tunnels, and of the main buildings. The site in Ellerhoop also provides the necessary infrastructure for a user facility.

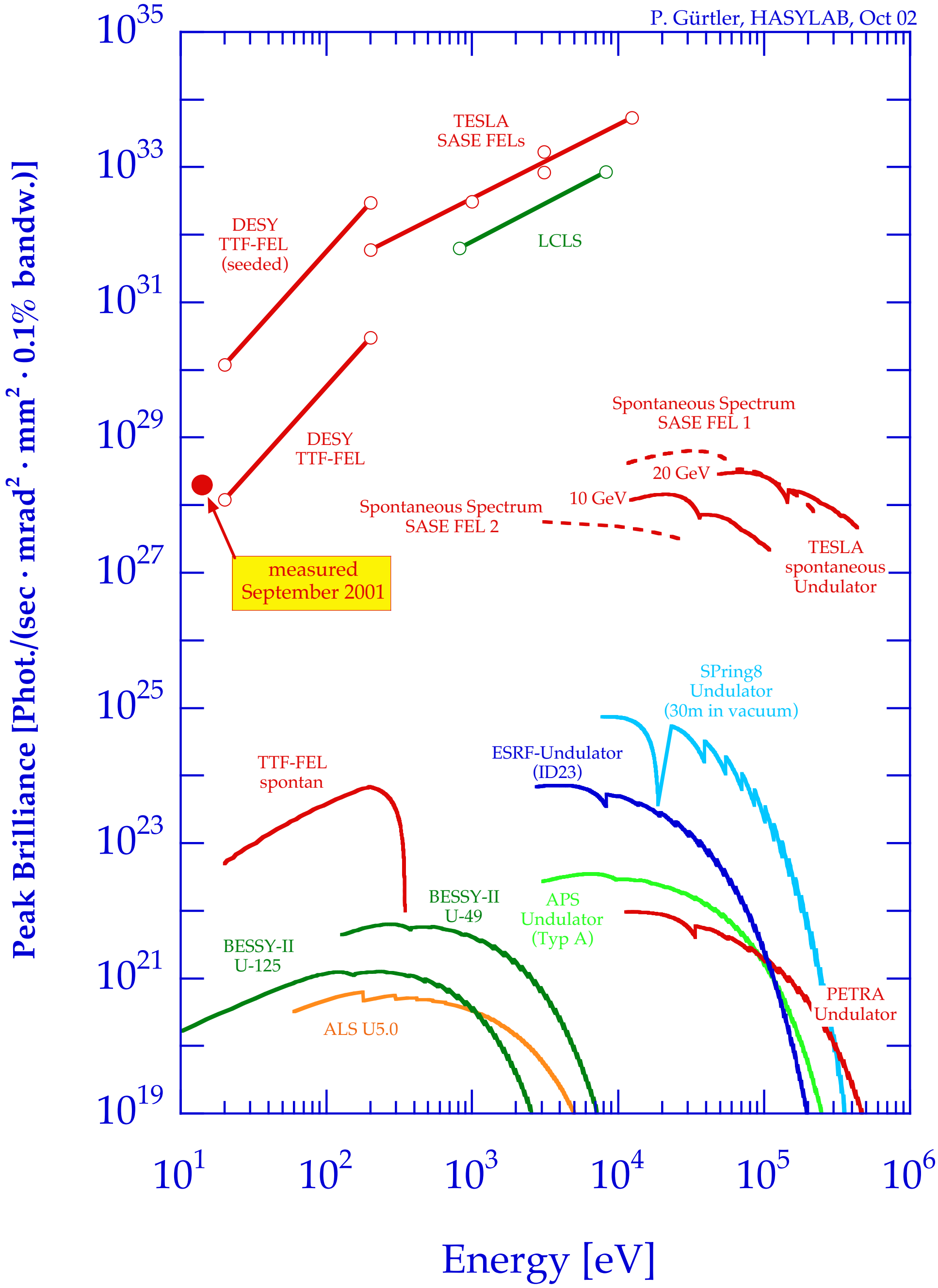

Figure 2: *Peak brilliance of the TESLA XFEL and TTF VUV-FEL radiators. The performance of the LCLS (Stanford U.S.A.) and undulators at present third generation synchrotron radiation sources is shown for comparison.*

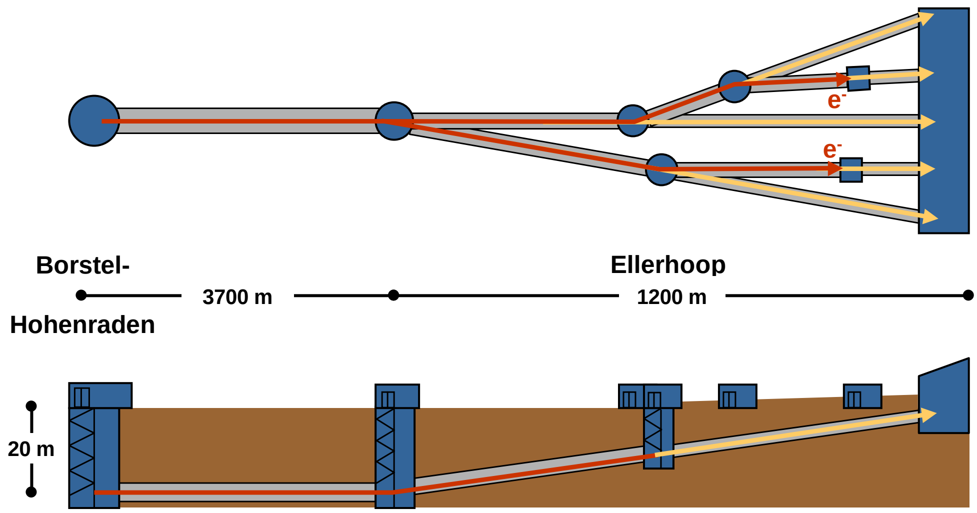

Figure 3: *Schematic layout of the TESLA XFEL in a top and side view (not to scale). Red and yellow lines indicate electron and photon beam lines, respectively.*

Project Costs and Schedule

In contrast to the TDR-2001 the present design foresees a dedicated linear accelerator in its own tunnel as part of the TESLA XFEL laboratory. This design decouples the commissioning and the operation of the linear collider and the XFEL. It also would allow an earlier start of the TESLA XFEL project, which, however, would lose the cost benefit of large scale production of accelerator components. Both changes (i.e. the additional linac and separated construction) lead to increased project costs compared to the TDR-2001. In order to stay within the cost frame of the TDR-2001 the energy of the linear accelerator has been reduced to 20 GeV at the nominal gradient of 23.5 MV/m, and the number of experimental stations has been reduced to 10.

The cost evaluation for the TESLA XFEL laboratory includes the investment costs for the linear accelerator with all its subcomponents, for the electron distribution and beam dumps, for the XFEL undulators, for the X-ray photon beamlines including the X-ray optics, for the experiments, for the civil engineering and preparation of the site, for the infrastructure, for XFEL laboratory equipment, and it includes the costs for the required personnel during the construction phase. All numbers are quoted at year 2000 prices.

The total costs for the TESLA XFEL have been estimated at

- **684 million EUR** for capital investment and manpower.

This number includes 2800 man years (at 50.000 EUR/man year) for design, procurement, fabrication and assembly, testing, installation and commissioning. The distribution of these costs onto the various items is depicted in Fig. 4. Additional expenses of 25 million EUR have been estimated for R&D (7 million EUR), spare components (12 million EUR) and pre-operation (6 million EUR).

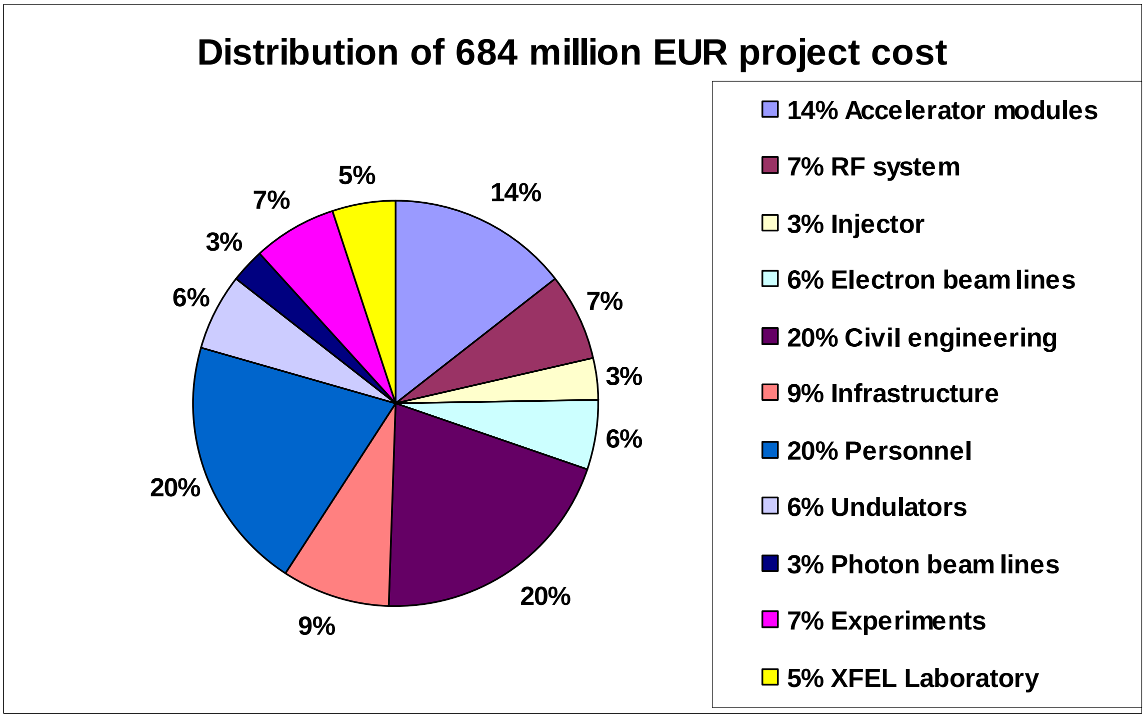

Figure 4: *Overview of the TESLA XFEL project cost distribution in percent of the total cost indicated in the text.*

It should be mentioned that in case of a parallel construction of the XFEL and the linear collider the total cost for capital investment and personnel would be reduced by 145 million EUR due to the benefit of large scale industrial production.

The technical specification of the facility includes a safety margin (e.g. rf power, cryogenic plant capacity, etc.), which is necessary to guarantee the envisaged performance and also contributes to the reliability of the cost figure above. However, to cover uncertainties in the cost estimates, unforeseen events and delays, which can not be completely ruled out, we estimate that a risk budget of 10% of the total cost quoted above would have to be allocated for equipment and personnel.

The construction time of the XFEL is 6 years, counting from the start of civil construction to the beginning of commissioning the linear accelerator.