THE EUROPEAN XFEL PROJECT

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Abstract

The European X-ray Free Electron Laser XFEL is a 4th generation synchrotron radiation facility based on the SASE FEL concept and the superconducting TESLA technology for the linear accelerator. This multi-user facility will provide photon beams in a wavelength regime from 0.1nm to 5nm in three FEL beam lines and hard X-rays in two spontaneous radiation beam lines, serving in total 10 experimental stations in the first stage. The project is in an advanced planning and technical preparation stage and its construction as a European/International facility near DESY in Hamburg will start in 2007. This talk gives an overview of the overall layout and parameters of the facility, with emphasis on the accelerator design, technology and physics.

INTRODUCTION

The XFEL was originally proposed as part of the TESLA facility, first in a version integrated with the linear collider using the same linac [1,2], in a later version with its own separate linac [3]. In February 2003 the German Government announced the decision that the XFEL should be realized as a European project, with 60% of the funding provided by Germany (Bund and Länder Hamburg and Schleswig-Holstein) and 40% requested from partner countries. In mid-2003 an XFEL project group was established at DESY which, together with partner institutes, pushed forward the preparation work necessary to achieve the status of readiness for start of construction by 2006. Besides the optimization of the overall design, main objectives in this phase are preparations for the site and civil construction (including the legal procedure for construction permission), industrialization of major technical components and detailed studies of beam physics and the FEL process. The XFEL has a strong link to the FLASH (VUV-FEL) facility at DESY [4 – 6], which is in nearly all respects (accelerator technology, FEL operation, photon beam lines and user experiments) truly a pilot facility for the future project.

The project organization at the international level is supervised by a steering committee (ISC) with members from all countries interested in participating in the project. Up to date, 13 countries (Figure 1) have signed the XFEL Memorandum of Understanding for the preparation phase.

The ISC is supported by two working groups: STI for scientific and funding issues and AFI for administrative and funding issues. In 2005 ISC nominated a European Project Team (EPT), with the main charge to deliver the technical and administrative documents required for the process of negotiations and decisions at the political level towards achieving the final go-ahead for the project.

Figure 1: Signature countries of the European XFEL MoU as of August 2006.

In July 2006, an updated Technical Design Report (TDR) was completed [7] and delivered to ISC. The report had previously been reviewed and endorsed by STI and additional experts from the international scientific community. In addition, the administrative documents have been essentially completed and reviewed by AFI.

LAYOUT AND PARAMETERS

The main components of the XFEL Facility are the injector, the linear accelerator, the beam distribution system, the undulators, the photon beam lines, and the instruments in the Experiments Hall (see Figure 2).

These components are distributed along an essentially linear geometry, 3.4 km long, starting on the DESY campus in the northwest part of the city of Hamburg, and ending in the neighbouring Federal State of Schleswig-Holstein, south of the city of Schenefeld, where the Experimental Hall is located. Permission for construction and operation on this site was recently (July 2006) obtained (concluding a so-called Plan Approval Procedure) and publicly announced by the authority in charge *(LBEG Clausthal-Zellerfeld).*

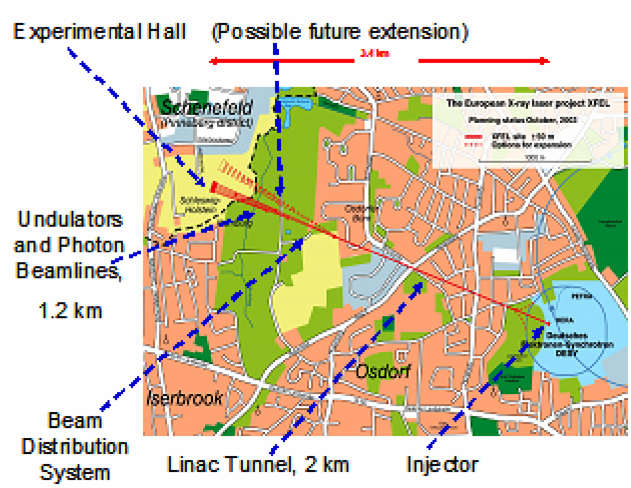

Figure 2: Site and schematic layout of the European XFEL Facility.

The basic functions of the main components are schematically described in the following: In the injector, electron bunches are extracted from a solid cathode by a laser beam, accelerated by an electron RF gun and directed towards the linear accelerator with an exit energy of 120 MeV. In the linear accelerator, consisting of a 1.6 km long sequence of superconducting accelerating modules, magnets for beam steering and focusing, and diagnostic equipment, the electrons are accelerated to energies of up to 20 GeV (17.5 GeV is the energy foreseen for the standard mode of operation of the XFEL facility at 0.1nm FEL wavelength). Along the accelerator, two stages of bunch compression are located, to produce the short and very dense electron bunches required to achieve saturation in the SASE process. At the end of the linac follows a beam transport section with collimation, stabilization feedback and diagnostics systems, after which the individual electron bunches are fed into one or the other of two electron beam lines by the beam distribution system. The linac and beam transport line are housed in a 2.1 km long underground tunnel (Figure 3).

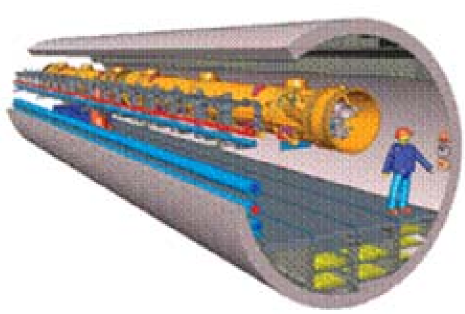

Figure 3: Layout of the 5.2 m diameter linac tunnel.

In the initial configuration the user facility has 3 SASE-FEL and two spontaneous radiation undulator beam lines (Figure 4) with in total 10 experimental stations. The site layout permits a later extension of the facility by another 5 beam lines. Independent wavelength tuning by undulator gap variation is foreseen and, together with electron beam energy variation, a total wavelength range of 0.1 – 5 nm (FEL) and 0.014 – 0.2 nm (spontaneous radiation) can be covered. The peak brilliance of FEL radiation (Figure 5) is in the range 10^{32} - $5{\cdot}10^{33}$ photons/0.1%bw/s/mm^2/mrad^2. The baseline operating point for 0.1nm wavelength (SASE1) at 17.5 GeV electron energy has been chosen on the basis of extensive studies of the FEL process with a relatively conservative assumption on the minimum undulator gap (10mm). At the design electron beam emittance (ε_N = 1.4 mrad·mm, see below) very good transverse coherence of the FEL radiation is predicted [8]. The magnetic lengths of the undulators (105 – 210 m) include a safety margin of at least 20% w.r.t. the calculated saturation lengths.

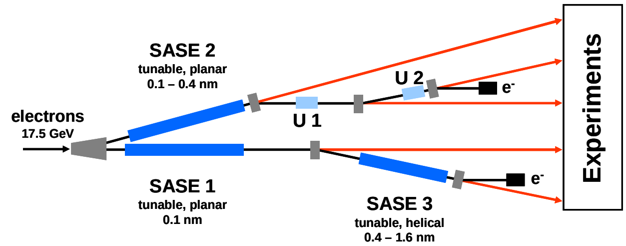

Figure 4: Schematic layout of the beam lines in the user facility.

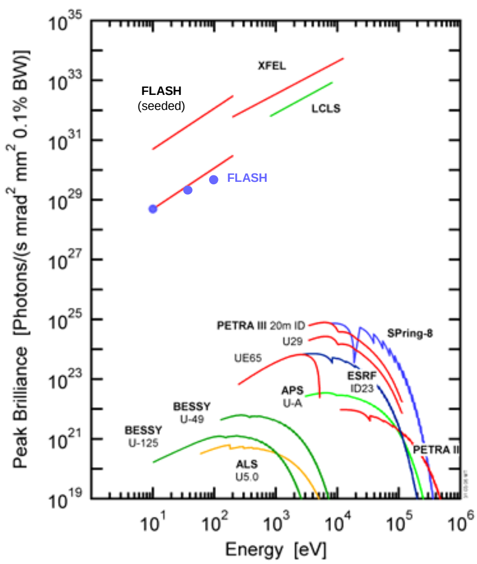

Figure 5: Peak brilliance of X-ray FELs versus 3rd generation SR light sources. Blue spots show experimental performance of the FLASH facility.

ACCELERATOR COMPLEX

The layout of the accelerator is schematically shown in Figure 6 and its main parameters are summarized in Table 1. The beam energy required for 0.1 nm photon wavelength in the SASE1 and SASE2 beam lines is 17.5 GeV. The linac design energy of 20 GeV thus already includes the potential to reach a lower wavelength of about 0.08 nm. The required peak power per RF station is well below the limit of the 10 MW multibeam klystrons. This de-rated mode is beneficial for highly reliable operation on one hand and for an upgrade potential regarding beam energy or duty cycle on the other. Likewise, the cryogenic system is laid out with an overhead of 50% with similar operational benefits.

The electron beam is generated in a laser-driven photocathode RF gun and pre-accelerated in a single superconducting accelerator module. The injector is housed in an underground enclosure separate from the linac tunnel, so that it can be commissioned at an early stage, well before installation work in the linac tunnel is completed. Furthermore, there is space foreseen for a completely separate and radiation-shielded second injector, which can be constructed, commissioned and maintained independently from the operation of the first injector.

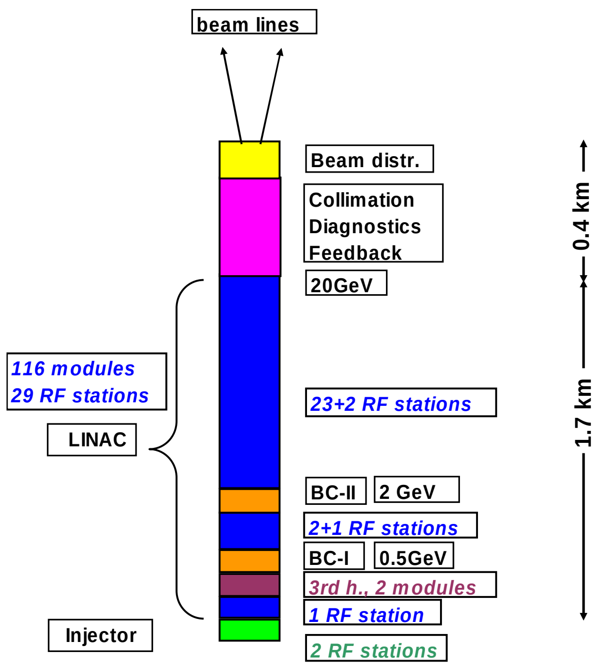

Figure 6: Schematic layout of the accelerator.

Table 1: Main parameters of the XFEL accelerator.

Energy for 0.1 nm wavelength	17.5 GeV
(max. design energy)	*(20 GeV)*
# of installed accelerator modules	116
# of cavities	928
Acc. Gradient (104 act. mod.) at 20 GeV	23.6 MV/m
# of installed RF stations	29
Klystron peak power (26 active stations)	5.2 MW
Loaded quality factor Q_{ext}	4.6×10^6
RF pulse length	1.4 ms
Beam pulse length	0.65ms
Repetition rate	10 Hz
Max. average Beam power	600 kW
Unloaded cavity quality factor Q_0	10^{10}
2K cryo load (incl. transfer line losses)	1.7 kW
Max. # of bunches per pulse *(at 20 GeV)*	3,250 *(3,000)*
Min. bunch spacing	200 ns
Bunch charge	1 nC
Bunch peak current	5 kA
Emittance (slice) at undulator	1.4 mm×mrad
Energy spread (slice) at undulator	1 MeV

The results from simulation studies of the RF gun show that a normalized beam emittance below 1mrad·mm at the design RF field of 60MV/m on the cathode is achievable, even if the thermal emittance is somewhat larger than originally expected, as measurements performed at the PITZ facility (DESY-Zeuthen) indicated [9]. A high priority of the future program [10] at PITZ will be on the verification of the XFEL gun design parameters, with improvements expected from higher cathode field and optimized laser profile.

After transfer to the main accelerator tunnel (see the layout sketched in Figure 7), the beam is further accelerated by one linac unit (4 accelerator modules with 8 cavities each, driven by one RF station) to an energy of 0.5 GeV before entering the first bunch compression stage. A third harmonic (3.9 GHz) RF system is foreseen to optimize the longitudinal phase space properties. After acceleration to 2 GeV with three linac units the beam enters the second (final) compression stage, after which the 1nC bunch peak current has increased to 5 kA (σ_z = 23µm for a 1nC bunch), a factor of 100 higher than the initial peak current from the RF gun. Considerable attention has been paid to foresee beam diagnostics stations in order to assess the beam phase space properties after the compression process in great detail [11]. Beam simulation studies of the compression system (see [12] for a recent overview of simulation code developments) show that the slice emittance growth due to space charge and CSR effects can be kept at a low level and there is room for further parameter optimization beyond the nominal design bunch parameters [13].

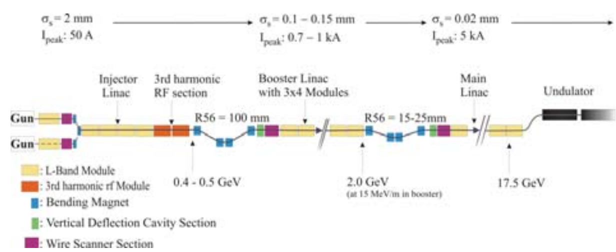

Figure 7: Layout of the XFEL bunch compression system.

The large compression factor and resulting short bunches (70fs rms) require timing, synchronization and diagnostics devices at the fs level. A considerable R&D program is ongoing in this field, see e.g. [14 – 16] for recent developments. Furthermore, extremely accurate RF control is required in the low-energy part of the accelerator [17].

Final acceleration to a nominal maximum beam energy of 20 GeV takes place in the main part of the linac, consisting of 25 RF stations and 100 accelerator modules in total. Downstream from the linac follows a conventional beam line for installation of the beam collimation and trajectory feedback systems, as well as providing distribution of the beam into the different undulator beam lines, including the connection to a future upgrade of the user facility with more beam lines. A combination of slow and fast switching devices permits to generate bunch trains of different time patterns for different experiments without having to generate and accelerate bunch trains with strongly varying transient beam loading. A fraction of each bunch train will be used to accurately stabilize the following bunches in position and energy by means of a fast feedback system [18]. After having passed through the undulators, the "spent" beam is stopped in radiation shielded solid absorbers. An additional beam dump is installed in the beam distribution shaft XS1, just upstream from the undulator beam lines. It allows to commission or to operate the accelerator while installation or maintenance work is ongoing in the undulator tunnels.

The layout of the linac includes precautions for energy management in case of RF component failure. The section between the two bunch compression stages consists of three RF units with four accelerator modules each, out of which only two have to be active to accelerate the beam to 2 GeV at the design gradient. Likewise, the main section of the linac (from 2 to 20 GeV) has an overhead of two RF stations. This guarantees that in case of an RF unit failure there is sufficient energy reserve to maintain both the beam energy at the second bunch compressor stage as well as at the end of the linac. Tunnel access for repair of RF stations during scheduled operation time can thus be safely avoided. In practice, the reserve stations will not be left idle when not needed. Instead, all available stations will be operated with reduced gradient and in case a station fails the gradient will be increased in the other sections such as to keep the beam energy constant.

Operational Flexibility

The single set of basic reference parameters in Table 1 does not cover the full range of operational flexibility of the linac. There is, within certain limits, a considerable flexibility regarding operation parameters, based on built-in performance reserves of its technical components. Operation at lower beam energy, thus extending the photon wavelength range to softer X-rays, is an obvious possibility. On the other hand, based on the experience gained with the superconducting TESLA cavities, it can be realistically expected that the linac can be operated at an accelerating gradient somewhat above the specified design value of 23.6 MV/m at 20 GeV. An increase of the gradient to about 28 MV/m would permit a maximum beam energy of 24 GeV, thus significantly extending the photon wavelength range to harder X-rays, provided that simultaneously also an improved injector beam quality becomes available to be able to maintain saturation of the SASE FEL process. In addition to the possibility of higher beam energies, the available reserve in the RF and cryogenic systems can also be used for increasing the linac repetition rate and thus the duty cycle of the pulsed linac. At sufficiently low beam energy, a 100% duty cycle, i.e. continuous wave (CW), mode of operation is conceivable, an option which is only possible with a superconducting linac. This option is viewed as not being part of the first stage of the XFEL facility but is considered as a future option. A preliminary set of possible parameters for CW operation is shown in Table 2.

Table 2: Sketch of possible parameters for a future option of operating the linac in CW mode.

Beam energy	7 GeV
Accelerating Gradient	7.5 MV/m
# of CW RF stations	116
RF power per accelerator module	≈20 kW
Beam current	0.18 mA
Loaded quality factor Q_{ext}	2×10^7
Bunch frequency	180 kHz
Unloaded quality factor Q_0	$2 \cdot 10^{10}$
2K cryogenic load	≈3.5 kW

PROJECT COST AND SCHEDULE

An in-depth re-evaluation of project construction costs has been performed as part of the project preparation work (see the TDR [7] for more details). In year 2005 prices, the construction costs are 986 M€, out of which 736 M€ are capital investment and 250 M€ personnel costs (including overhead). A breakdown of the construction costs is shown in Figure 8 and the budget time profile in Figure 9.

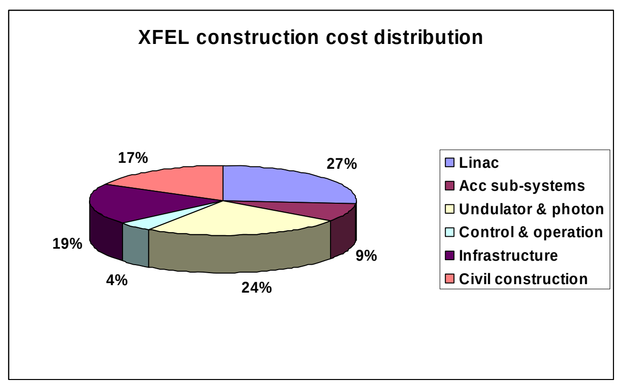

Figure 8: XFEL construction cost distribution.

The project schedule assumed for the profile of Figure 9 is based on an expected project go-ahead decision in the beginning of 2007. After a construction period of 6.5 years, beam through the linac and the first beam line (SASE1) is scheduled for 2013 and first user operation for 2014. There will be a transition phase until end of 2015, during which operation of beam lines takes place in parallel with completion of construction and commissioning of others. By 2016 the entire facility will be operational. The yearly operation budget (in 2005 prices) has been estimated at 83 M€, including administrative overhead and user support.

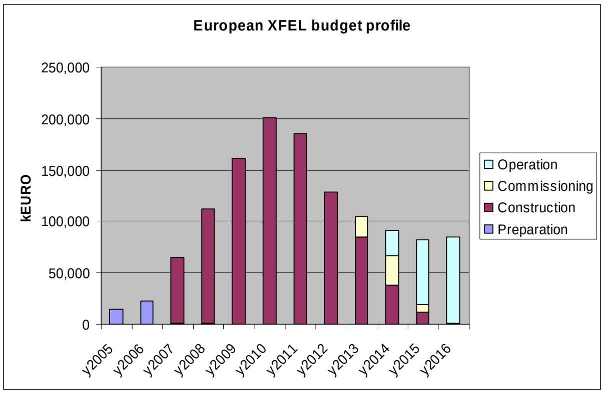

Figure 9: XFEL budget profile, including preparation phase and transition from construction to operation.

ACKNOWLEDGEMENT

The paper presented here is based on the recently published XFEL Technical Design Report. The author would like to express his thanks to the co-editors and co-authors of the TDR, who contributed and shaped a vast amount of material for that comprehensive report, of which this paper can be viewed as a short summary.

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