THE EUROPEAN XFEL SC LINAC PROJECT

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Abstract

The European XFEL project is entering the construction phase, based on the very successful experience of the TESLA linac technology and the SASE FEL concept, now serving the FLASH user facility at DESY.

The EU-XFEL will be realized by a widespread international collaboration and it is also relevant for the ILC planning. A description of the overall layout of the facility, of the tchnical developments and industrialization efforts for the accelerator components, and of the international collaboration will be given.

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 at least 40% funding contributions requested from partner countries. After this decision an intense preparation phase followed in which DESY, together with partner institutes, pushed forward the work necessary to achieve the status of readiness for start of construction. Besides the optimization of the overall design, main objectives in this phase where preparations for the site and civil construction, 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. 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. In July 2006, an updated Technical Design Report (TDR) was completed [7] and delivered to ISC. The progress in the negotiations with the partner countries on contributions to the project then led to the official go-ahead for project construction on June 5, 2007, on the basis of an initially de-scoped startversion of the facility (see below). The nominal construction cost (in year 2005 prices) of the start version amounts to 850 M€, to which approximately 90 M€ have to be added for project preparation and commissioning.

Up to date, 14 countries have made commitments to contribute to the project (Figure 1), summing up to a total of 1,060 M€ (on year 2005 basis). In addition to covering the cost for the startversion including preparation and commissiong, there remains an overhead which will with first priority be used to cover cost risks, but which may to a limited extent also permit to remove part of the initial de-scoping of the facility.

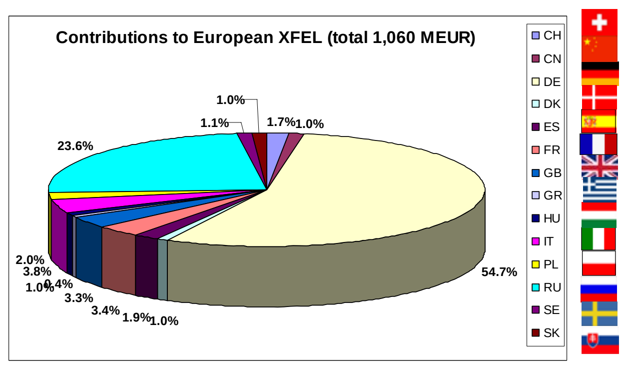

Figure 1: Distribution of funding contributions to the European XFEL project. Contributions are in cash as well as in-kind.

The administrative documents, in particular the Intergovernmental Convention, are essentially ready for signature by the partner countries. After that event, foundation of the XFEL company, of which all partners are shareholders, will take place. The company has the overall supervision and responsibility for the European XFEL and will also manage the civil construction and photon beam systems parts of the project. For the accelerator complex, an international consortium is being set up, which will contribute the entire accelerator and the related technical infrastructure essentially as an in-kind contribution to the project. At present 17 institutes from 10 of the XFEL member states have joined the consortium. DESY will provide approximately 60% of the in-kind contributions to the accelerator complex and act as the consortium coordinator.

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 obtained in July 2006, concluding a so-called Plan Approval Procedure. After the official project start in 2007, the call-for-tender procedure for civil construction was launched. The offers from different civil construction companies are at present being evaluated and placing of the orders for underground construction is expected to happen before the end of 2008.

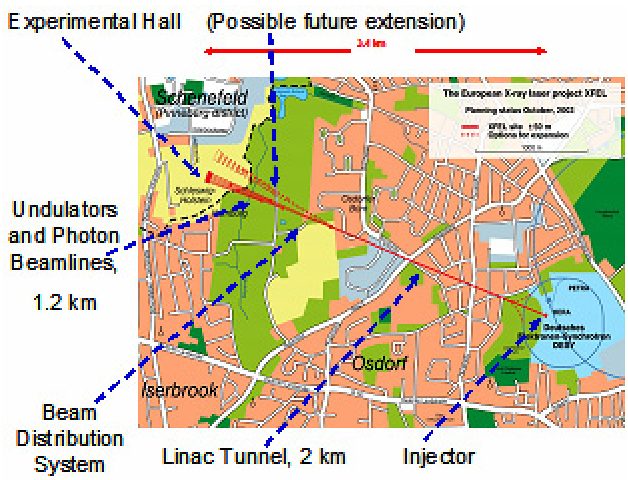

Figure 2: Site and schematic layout of the European XFEL Facility.

The main sections of the facility, as schematically shown in Figure 2, are 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 17.5 GeV, which is the energy foreseen for the standard mode of operation of the XFEL facility at 0.1nm FEL wavelength. The original design energy of 20 GeV was reduced by shortening the linac as part of the initial de-scoping scenario of the startversion. A later upgrade back to the full linac length as foreseen in the TDR remains possible. 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).

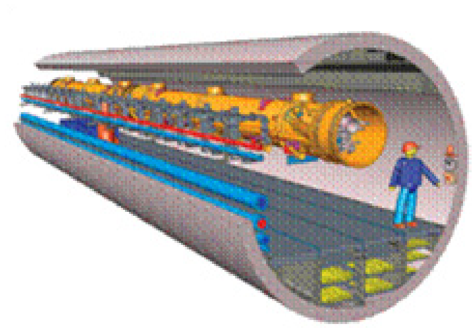

Figure 3: Layout of the 5.2 m diameter linac tunnel.

In the startversion the user facility has 3 SASE-FEL undulator beam lines (Figure 4) with in total 6 experimental stations (Figure 5). The space foreseen for two more undulator beam lines remains initially unoccupied, but since the buildings, technical infrastructure and electron beam line remain unchanged w.r.t. the TDR layout, these beam lines and 4 additional experimental stations can be added at any time as soon as funding permits. Furthermore, the site layout also allows for 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) can be covered. The peak brilliance of FEL radiation 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 of ε_N = 1.4 mrad·mm very good transverse coherence of the FEL radiation is predicted [8]. The magnetic lengths of the undulators include a safety margin w.r.t. the calculated saturation lengths.

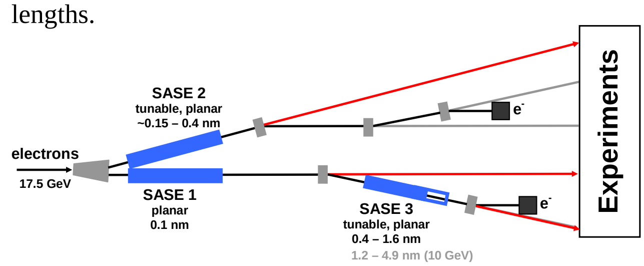

Figure 4: Schematic layout of the beam lines in the user facility.

	Instrument	Brief description of the instrument
Hard X-rays	SPB	Ultrafast Coherent Diffraction Imaging of Single Particles, Clusters, and Biomolecules – **Structure determination of single particles: atomic clusters, bio-molecules, virus particles, cells.**
	MID	Materials Imaging & Dynamics –**Structure determination of nano- devices and dynamics at the nanoscale.**
	FDE	Femtosecond Diffraction Experiments – **Time-resolved investigations of the dynamics of solids, liquids, gases**
	HED	High Energy Density Matter – **Investigation of matter under extreme conditions using hard x-ray FEL radiation, e.g. probing dense plasmas.**
Soft X-rays	SQS	Small Quantum Systems – **Investigation of atoms, ions, molecules and clusters in intense fields and non-linear phenomena.**
	SCS	Soft x-ray Coherent Scattering –**Structure and dynamics of nano-systems and of non-reproducible biological objects using soft X-rays.**

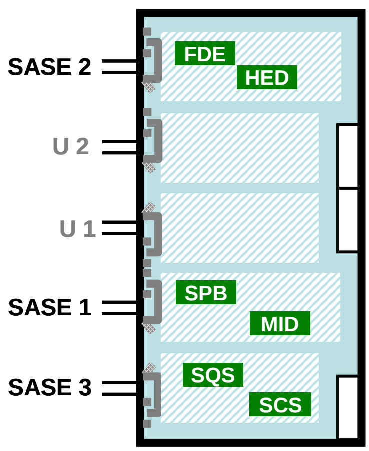

Figure 5: Selection of first scientific instruments and their arrangement in the experimental hall.

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 required peak power per RF station is well below the limit of the 10 MW multibeam klystrons (for recent test results from one of the three XFEL MBK prototype manufacturers, see [9]. 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.

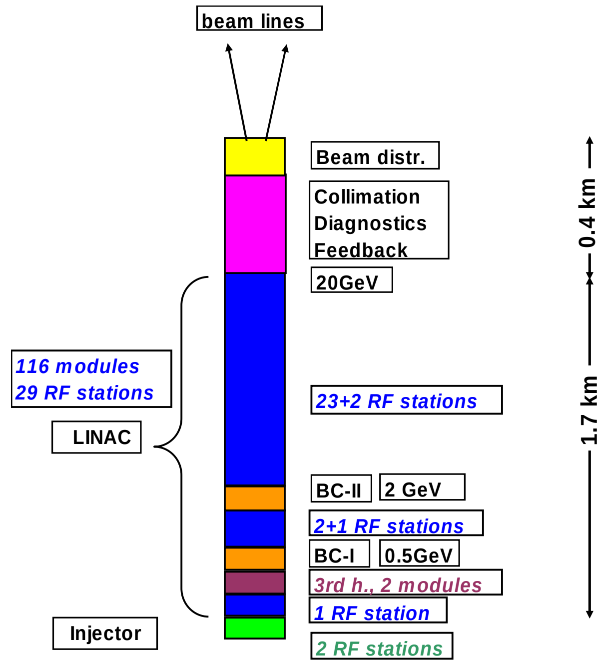

Figure 6: Schematic layout of the accelerator as described in the TDR. In the startversion 4 RF stations and 16 accelerator modules will initially not be installed.

Table 1: Main Parameters of the XFEL Accelerator for the Startversion with 17.5 GeV Design Energy. Numbers in Brackets Correspond to the Full TDR Version

Design beam energy	17.5 GeV *(20 GeV)*
# of installed accelerator modules	100 *(116)*
# of cavities	800 *(928)*
Accelerating gradient	23.6 MV/m
# of installed RF stations	25
Klystron peak power (24 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	3,250
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 [10]. Emittance measurements at PITZ with high gun gradient [11] indicate a beam quality very close to the XFEL design goal [12]. The programme at PITZ continues with emphasis on further optimization of the laser profile and reduction of the gun dark current [13] at high gradients.

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. In order to suppress micro-bunching instabilities, the uncorrelated bunch energy spread is intentionally increased by a laser heater [14] after the injector. 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. Beam simulation studies of the compression system 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.

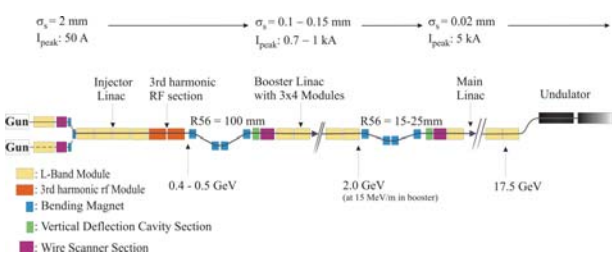

Figure 7: Layout of the XFEL bunch compression system.

The large compression factor and resulting short bunches (70fs rms) require timing, synchronization and diagnostics devices at the fs level as well as excellent RF field control. A considerable R&D program is ongoing in these fields, see e.g. [15 - 21] for recent developments.

Final acceleration to the nominal maximum beam energy of 17.5 GeV takes place in the main part of the linac, consisting of 25 RF stations and 100 accelerator modules in total (an extension to the full scope of the TDR layout with 116 modules and 29 RF stations remains possible). Out of the 25 stations, two are reserve for energy management in case of RF system failures. For the linac technology R&D and industrialization programme, the new cryomodule test bench (CMTB) at DESY, operational since autumn 2006, permits RF tests of cold modules independent from FLASH operation [22]. So far, four modules have passed through extensive test procedures (three of which are now installed at FLASH), a 5th module was used for an intentional "crash test" [23]. Besides verifying good performance in terms of accelerating gradient, important results also include short RF coupler processing times and cold-warm cycling without performance degradation. Regarding the 9-cell superconducting Niobium cavities [24], important progress towards industrialization of series production was achieved by successfully commissioning and operating electropolishing facilities at two companies.

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 [25] 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.

In the undulator sections, the effects of undulator gap errors and quadrupole misalignments on the SASE process have been studied [26, 27]. The results show that errors up to a few μm are permitted before the gain length or the peak radiation power are seriously affected. Investigations of quadrupole magnets and on the optimization of the focusing lattice are also ongoing [28, 29].

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.

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. An increase of the gradient may thus permit beam energies well above the design value, 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 (see table 2) is viewed as not being part of the first stage of the XFEL facility but is considered as a future option.

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

CONCLUSION

After an intense phase of preparation at the scientific-technical, organizational and political level, the European XFEL project is now entering into its realization phase. An approximately 6 year construction phase is lying ahead and we are looking forward to seeing the first photon beam at this facility in 2014.

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