EUROPEAN XFEL CONSTRUCTION STATUS

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Abstract

The European XFEL is presently being constructed in the Hamburg region, Germany. It aims at producing X-rays in the range from 260 eV up to 24 keV out of three undulators that can be operated simultaneously with up to 27000 pulses/second. The FEL is driven by a 17.5 GeV linear accelerator based on TESLA-type superconducting accelerator modules. This paper presents the status of major components, the project schedule and a summary of beam parameters that are adapted to the evolving needs of the users.

INTRODUCTION

The European XFEL [1] construction has started in 2009 with the ground-breaking for the underground buildings - about 5.5 km of tunnels, six access shafts, two underground dump halls, the injector building and the 4500 m^2 experimental hall. The underground construction is finished and the erection of the above ground buildings on three different sites is well underway. The series production of components is in full swing with many parts already being ready for installation. The completion of the construction phase was planned for end of 2015. Due to the delayed delivery of several components, a new schedule was adopted with the completion date shifted to end of 2016.

Encouraged by the successful operation of LCLS and SACLA and based on the small emittances measured for the XFEL photo-cathode RF-gun at PITZ (DESY/Zeuthen) [2], the European XFEL has adjusted its target parameters in 2011, see Table 1. The new parameter set enlarges the performance range of the facility [3], but puts a strain on different sub-systems, especially for operation at very low charge (20 pC). All beam diagnostics are affected as well as the RF stabilization and the beam-stabilizing feedback systems. As a rule, the original 1 nC-case specifications could be extended down to 0.1 nC and a limit to the deterioration in performance for even lower charges was set.

Table 1: European XFEL Electron Beam Properties

Quantity	Target Parameters
Electron Energy	8/12/14/17.5 GeV
Bunch Charge	0.02 - 1 nC
Norm. Slice Emittance at Und.	0.4 - 1.0 mm mrad
Slice Energy Spread at Und.	4 - 2 MeV
Peak Current	5 kA

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Figure 1 summarizes the photon energy reach of the European XFEL for different accelerator energies and undulator gap settings. The facility covers the photon energy range from the Carbon K-edge up to above 25 keV in the first SASE harmonic.

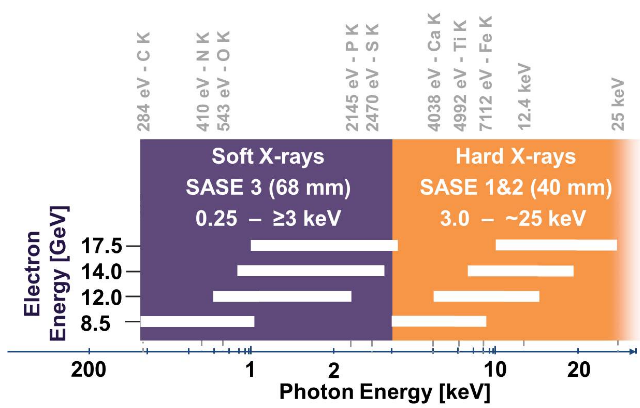

Figure 1: Photon energy reach of the two undulator types of the European XFEL at different electron energies.

ACCELERATOR

Injector and Bunch Compression

The XFEL RF gun is similar to the operating gun at FLASH, DESY. It has been conditioned at PITZ [4]. RF operation in the design configuration in the XFEL injector tunnel took place in December 2013 [5]. The photo-cathode laser - a Nd:YLF laser operating at 1047 nm converted to UV wavelength in two stages - has been delivered by the Max Born Institute, Berlin [6]. The RF gun should produce its first beam after the completion of the laser beam line in October 2014. The injector tunnel will host, in addition to the gun, one standard XFEL superconducting 1.3 GHz module, a superconducting 3.9 GHz module with an accelerating voltage of up to 40 MV, a laser heater and a diagnostic section. The final installation of all components is scheduled for mid 2015. The complete injector can be commissioned and operated independently from the ongoing installation work in the main accelerator tunnel.

The European XFEL employs a three-stage bunch compression scheme to reduce both micro-bunching and the required 3.9 GHz voltage. All magnetic chicanes are tunable within a wide range of R_{56} to allow for flexible compression scenarios, for instance balancing peak current and arrival time stability with LLRF performance. The tuning is achieved by means of large pole width dipole magnets and accordingly wide (400 mm) vacuum chambers. All

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dipole magnets are produced and measured, fulfilling the stringent requirements on the field quality over the complete width of the pole. After the second and third compression stage, diagnostic stations similar to the one in the injector are placed.

Linear Accelerator

At the heart of the facility is the superconducting linear accelerator. 100 TESLA-type accelerator modules can deliver a 17.5 GeV electron beam with an average beam power of 600 kW. The linac will be operated in a pulsed mode with 10 Hz repetition rates and up to 2700 bunches per pulse. Production of cavities is in full swing, with more than 1/2 of the total of 800 industry-built cavities already being delivered to DESY. The average accelerating gradient is exceeding the specified 23.6 MV/m and 2/3 of the cavities are accepted for accelerator module assembly immediately after their initial rf test; the gradient reached for those cavities is almost 30 MV/m. About 1/3 of the cavities undergo an additional ultra pure, high pressure water treatment after test, boosting the achievable average gradient clearly above XFEL specifications. A forecast until the end of production gives a potential additional energy of 1.3 GeV in excess of the XFEL design energy of 17.5 GeV [7].

The tested cavities are then integrated into a string of eight cavities at CEA Saclay [8] and installed together with a quadrupole and beam position monitor into a cryostat, thus forming an accelerator module. So far nine series modules have been produced. Most of the sub-components are available in sufficient quantities to sustain the required production rate of 1 module/week. Still, to achieve the project goal of installation of the last of the 100 modules in the tunnel by mid 2016 an accelerated assembly is necessary.

The accelerator modules are supported from the ceiling with a beam height of about 2.2 m above the tunnel floor (see Figure 2). This allows for klystrons, pulse transformers as well as the LLRF and other electronics racks to be installed below the accelerator. The modulators are installed in one single hall above ground and the high-voltage pulse is fed to the pulse transformer by up to 2 km long cables. Almost all of the modulators and 2/3 of the klystrons are delivered and will be installed and put into operation following the installation of the modules in the tunnel.

The LLRF system is completely based on the MTCA.4 technology and is now successfully in operation at FLASH [9]. It is for instance capable of manipulating the RF phase and amplitude along one RF pulse, which would allow to deliver bunches with different properties to different users within one 600 μs RF pulse. The beam dynamics potential and issues for this operation mode are under investigation [10].

Electron Beam Distribution and Dumps

After the linac almost 3 km of electron beam lines distribute the beam through the SASE undulators to three different beam dumps. Most of the electromagnets have already been delivered by the Efremov Institute, St. Petersburg, while the vacuum system is under preparation at DESY and Budker Institute, Novosibirsk.

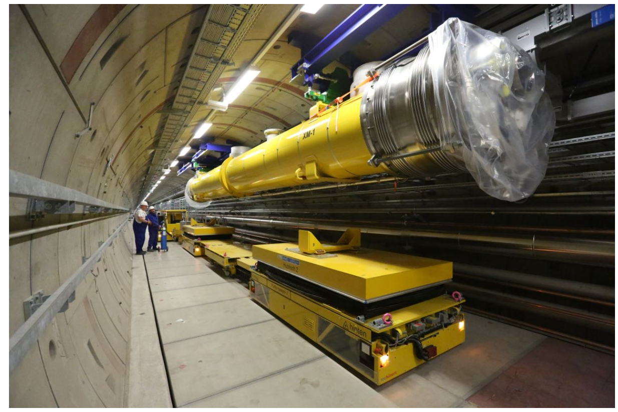

Figure 2: First accelerator module installed at its final position in the main accelerator tunnel [11].

Downstream of the linac the electron beam line will also be supported from the ceiling, over a length of 600 m. This keeps the tunnel floor free for transports and installation of electronics. Especially at the end of the 5.4 m diameter tunnel, where 3 beamlines (to SASE1&3, SASE2 and into the linac dump) run in parallel, installation and maintenance of the components pose a considerable challenge.

The electrons are distributed with a fast rising flat-top strip-line kicker in one of the two electron beam lines. A similar system is already in operation at FLASH2 [12], the second undulator beamline recently being commissioned at FLASH, DESY. Another kicker system is capable of deflecting single bunches in a dump beam line [13]. This allows for a free choice of the bunch pattern in each beam line even with the linac operating with constant beam loading.

Three solid state beam dumps will be placed at the end of the accelerator beam lines, capable of absorbing 300 kW of beam power each, while the beam dump at the end of the injector (see Figure 3) allows to operate the injector stand alone up to full beam power. Two tuning dumps after the bunch compressors complete the beam absorbers. All beam dumps are manufactured by industry and the high power dumps come with a semi-automated exchange device, that allows replacement of the dumps in case of a failure.

Beam Diagnostics

State of the art electron beam diagnostics is of pivotal importance for the success of an FEL. 64 screens and 12 wire scanner stations, 460 beam position monitors of eight different types, 36 toroids and 6 dark-current monitors are distributed along the accelerator. Production of the sensors and read-out electronics is well underway and prototypes of all devices have been tested at FLASH. BPM electronics is developed by the Paul-Scherrer-Institut, Villigen and shows together with the DESY built pick-ups performance already exceeding the specifications [14, 15], of - for example - a single bunch resolution of 1 micron for the undulator cavity BPM's.

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Figure 3: Test installation of the injector dump [11]. The dump is placed on the exchange device ready to be moved into its concrete housing to the right.

Energy measurement will be performed with dedicated beam position monitors in dispersive sections. In addition time of travel measurements through compressor chicanes using beam arrival time monitors, precision aligned screens and synchrotron radiation monitors [16] in the chicanes can be used.

Longitudinal and slice parameters of the bunches can be measured at dedicated diagnostic sections in the injector at 130 MeV, after the second bunch compressor BC1 at about 600 MeV and after the final bunch compression stage at 2400 MeV. The diagnostic sections rely on transverse deflecting structures and kicker systems to distribute single bunches onto off-axis screens to measure transverse slice beam parameters on-line during a bunch train [17]. The dispersive diagnostic beam lines at these positions can only be operated in a dedicated mode with a DC deflector that steers the beam in the tuning dumps. At high energies after the linac the bunch compression [18] and beam arrival time [19] will be measured.

PHOTON BEAM SYSTEM

The photon beam system (PBS) starts at the undulator sections and ends inside the experimental hutches. The layout of these sections is shown in Figure 4.

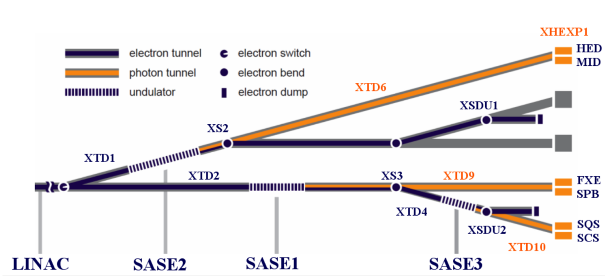

Figure 4: Photon Beam System layout

While the control systems DOOCS is used for the electron accelerator, Karabo controls the components related to the transport and diagnostic of the photon beam to be delivered to the experimental areas. In addition to that, Karabo will be used for acquiring, manipulating and managing the huge amount of data to be collected by the multi mega-pixel detectors installed at the various instruments [20, 21]. The challenge of the photon system, which includes various state of the art optics and instrumentations, will be to cope with the structure of the electron beam and the peak power density per bunch. As a reminder, each electron bunch train is comprised of 2700 bunches distant of 220 ns (4.5 MHz) and 2 trains are distant by 100 ms (10 Hz).

We will in the following sections show some highlights of the various components of the photon beam system.

Undulator System

The undulator system consists of movable gap out-of vacuum undulator segments of 5 m length and intersections with a phase-shifter, a movable quadrupole, a photon absorber and a cavity beam position monitor. Undulator parameters are summarized in Table 2 [22]. In total 91 undulator segments have to be built and tuned. At the time of writing 81% of the undulators have been measured and tuned in three dedicated measurement labs (see Figure 5). Measured segments are placed into storage before the start of installation at the beginning of 2015. The phase shifters are produced by three different companies. Tight tolerances and a special shimming procedure [23] ensure that they can be operated over a wide range with no influence on the electron beam trajectory.

Table 2: European XFEL Undulator Parameters

Quantity	**SASE1/SASE2**	**SASE3**
System length	213.5 m	128.1 m
Number of segments	35	21
λ_0	40 mm	68 mm
K-Range	3.9 - 1.65	9.0 - 4.0
Operational Gap Range	10 - 20 mm	10 - 25 mm

Figure 5: Undulators in the measurement hall [11].

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Photon Beam Transport

The photon bunches emitted at the end of an undulator section will have a high peak power density (20 GW/mm^2 for pulses of up to 150 fs). This is sufficiently high to damage any material placed in its way. The photon beam transport concept is to let the beam expand before cleaning and steering to the experimental areas could happen. Various mirrors are going to be installed in the 3 initial beam lines. Their properties are shown in Table 3. The mirrors will be in vacuum and coated with B_4C to sustain the beam power. The SASE2 mirror will be partially coated with B_4C and Pt. Pt coating is necessary to reflect higher harmonics of the FEL beam (>24 keV) to the samples. The substrate length is 900 mm for the flat mirrors and 950 mm for the bendable ones.

Table 3: Mirrors Specifications - All mirrors shape error (peak to valley) should be <2 nm; and the RMS roughness <3Å. The overall optical length for all mirrors is 850 mm [24]

Mirror	Type	Radius (km)	Heat Load (W)	Energy (keV)
M1 (SASE1)	flat	>600	7.0	3 - 24
M2 (SASE1)	bendable	54 to ∞	2.5	3 - 24
M3 (SASE1)	flat	>600	1.2	3 - 24
M1 (SASE2)	flat	>600	7.0	3 - 80
M2 (SASE2)	bendable	58 to ∞	2.5	3 - 80
M3 (SASE2)	flat	>600	1.2	3 - 80
M1 (SASE3)	flat	>600	140	0.26 - 3
M2 (SASE3)	bendable	10 to ∞	40	0.26 - 3
M5 (SASE3)	flat	>600	10	0.26 - 3

In addition to the mirrors described above, 2 curved mirrors and 3 flat monochromators for the soft-XR beam line will be provided.

Photon Beam Diagnostics

While being transported it is also important to know the quality of the photon beam, its pulse energy, position, wavelength, polarization and more photon parameters, see [25,26] and ref therein. X-ray Gas Monitors, designed and produced by DESY, will allow for non-invasive on-line monitoring of intensity and beam position. The first complete device was tested at the PTB (Physikalisch-Technische Bundesanstalt) beamlines at BESSY2, Berlin in July 2014. Photoelectron Spectrometers will, online and non-destructively, measure the photon wavelength and bandwidth as well as the beam polarization. Invasive diagnostics such as imagers are implemented throughout the beam transport for alignment of the optical elements. Special commissioning diagnostics like the undulator K-parameter spectrometers and MCP-based detectors were constructed and are ready for installation.

Delivering Sample

The first SASE experiment to be operating in 2017 for users will include advanced sample systems suited to meet the special requirements of the extremely high peak power density and the 4.5 MHz repetition rate within a pulse train. Sample environment systems include a fast solid sample scanner that will be able to swap micro scale targets fixed on surfaces within two pulse trains. For handling of liquid samples for biological imaging and crystallography and for spectroscopy of chemicals in liquid solvation, a versatile liquid jet system is under development. To provide a fresh stream of sample for each pulse of the European XFEL, the liquid jets need to have high speeds in the order of 100 m/s. With aerodynamic focusing of a liquid jet by a surrounding stream of supersonic helium gas, liquid jet diameters below a μm can be reached. This results in low sample consumption and reduced background from evaporation [27].

Detectors and Laser systems in the Experimental Areas

After the sample interaction of the X-Ray, GB of data per photon pulse will be recorded by some fast imaging detectors, Figure 6. The challenge of the detectors is to acquire, preprocess the data and transmit them to a computing center before the next train of photon bunches arrives. The detectors will be either installed permanently or be movable from instruments to instruments, as well as allowing dismounting for re-calibration.

A significant amount of the experiments at the European XFEL (up to 75%) will require optical lasers for pump-probe experiments [29]. Naturally, such a laser must be adapted to the European XFEL bunch pattern. Some degree of freedom in the choice of pulse width and wavelength (around 800 nm) is also desirable. Energy requirements for single pulses usually range from μJ to mJ. Moreover, different experiments need different repetition rates and pulse patterns inside the burst. In consideration of such difficult demands, the European XFEL embarked on a development project to overcome the lack of commercial laser technology, capable of fulfilling them. The scheme consists a multi-stage non-collinear parametric amplifier, employing an Yb-based synchronized front-end, Yb:YAG Innoslab pump amplifiers and dispersion managed super-continuum seed [30–34]. With the exception of further scaling of pulse energy and average power, all essential features were achieved with the R&D prototype: pedestal-free 15 fs pulses at an intra-burst repetition rate of up to 4.5 MHz, a pulse energy of 180 μJ with an intra-burst repetition rate of 188 kHz, long pulse generation up to 75 fs, wavelength tuning over a range of more than 100 nm, random pulse selection and the production of a diffraction-limited laser beam. Current plans foresee the installation of one pump-probe laser per SASE beamline.

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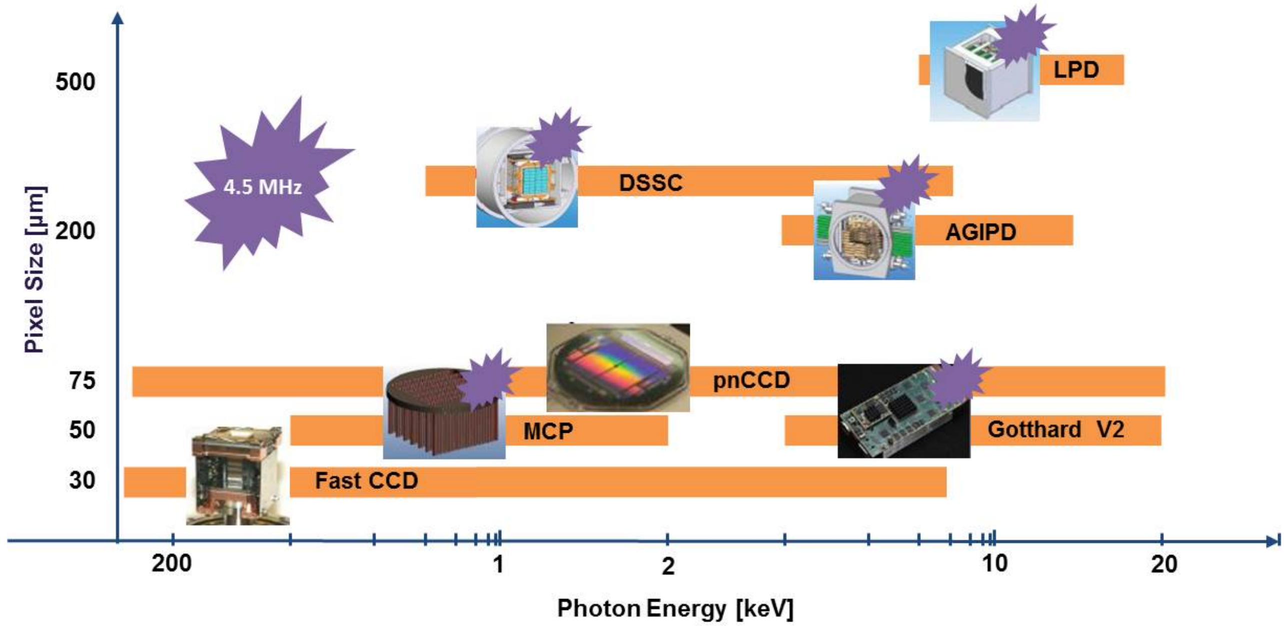

Figure 6: Planned photon detectors at the Soft and Hard X-ray beamlines. Most of them are capable of operating at the intra-bunch frequencies (4.5 MHz) [28]

CONCLUSION

The European XFEL is constantly evaluating its target beam parameters. Recent studies show the potential of the facility within [35–38] or even beyond its baseline design [39–41]. Fabrication and installation of components for the European XFEL is in full swing. The 6 scientific instruments serving the initial 3 SASE lines have now completed their Technical Design Reports hence completing a necessary milestone before the start of their construction [42]. The aim is to close the main accelerator tunnel by mid 2016. The subsequent beam commissioning follows an ambitious schedule with the goal to have the possibility of first lasing by end of 2016.

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